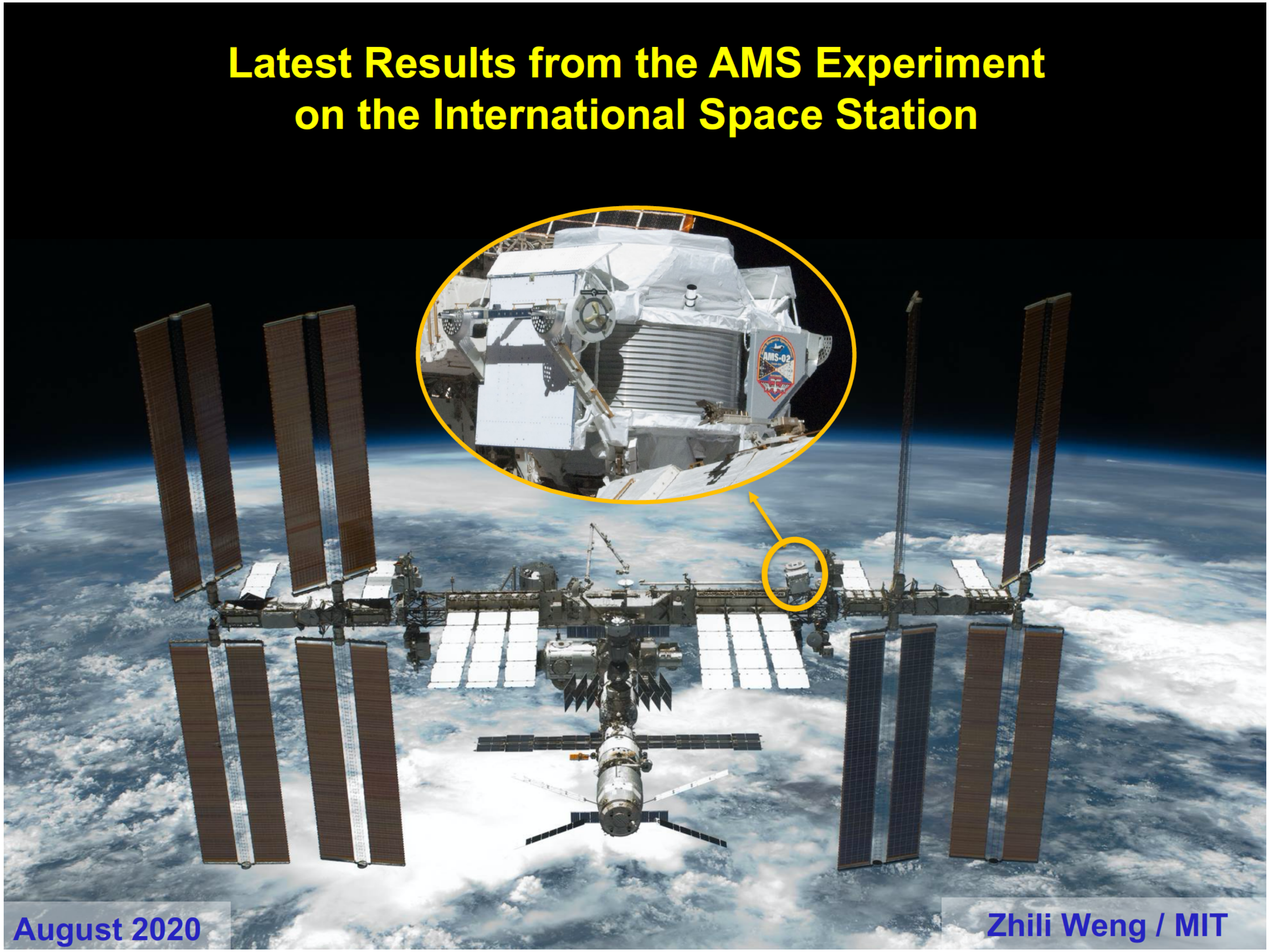
Astrofisica Nucleare e Subnucleare

Dark Matter Searches

AMS



Latest Results from the AMS Experiment on the International Space Station

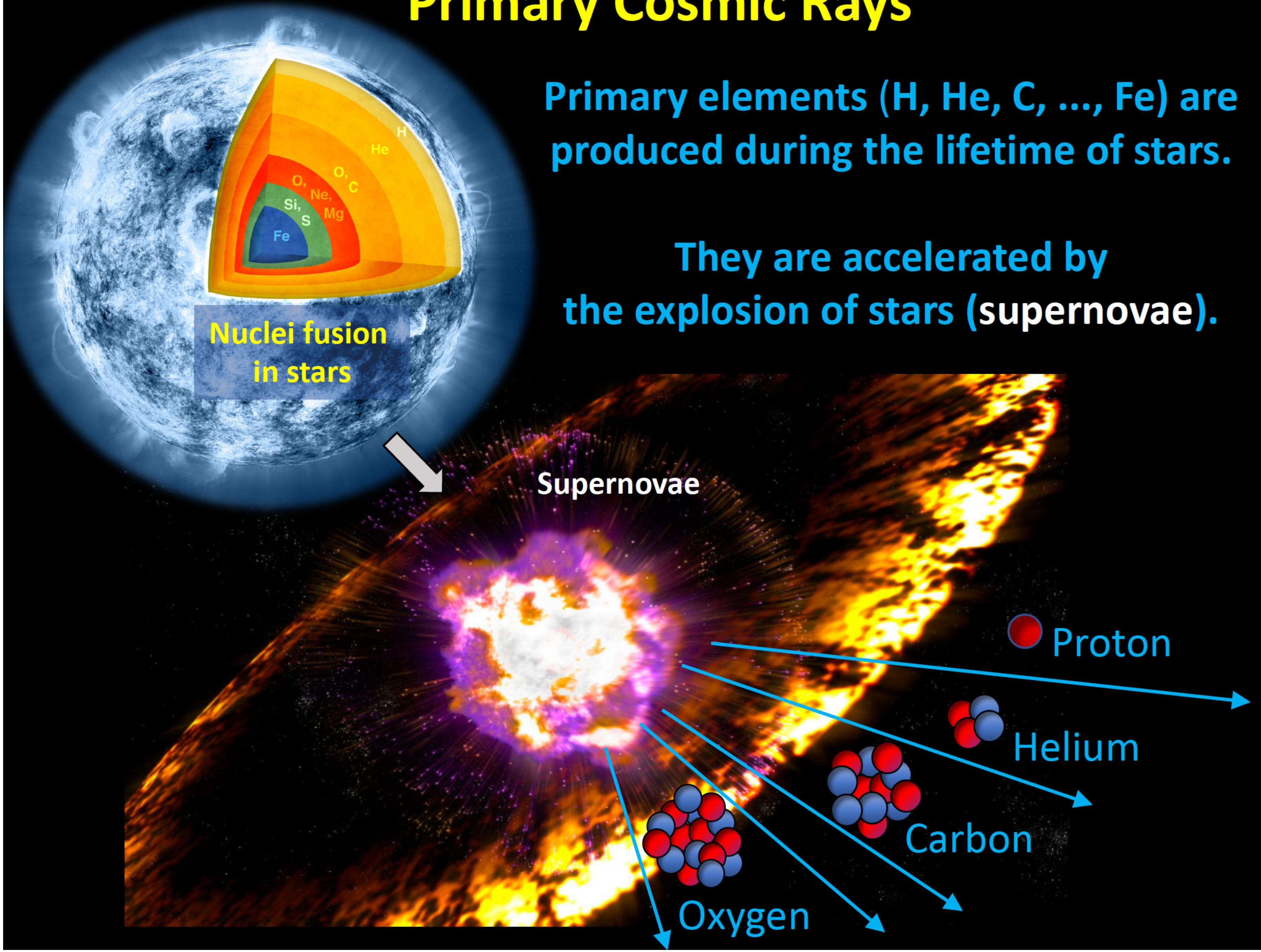
August 2020

Zhili Weng / MIT

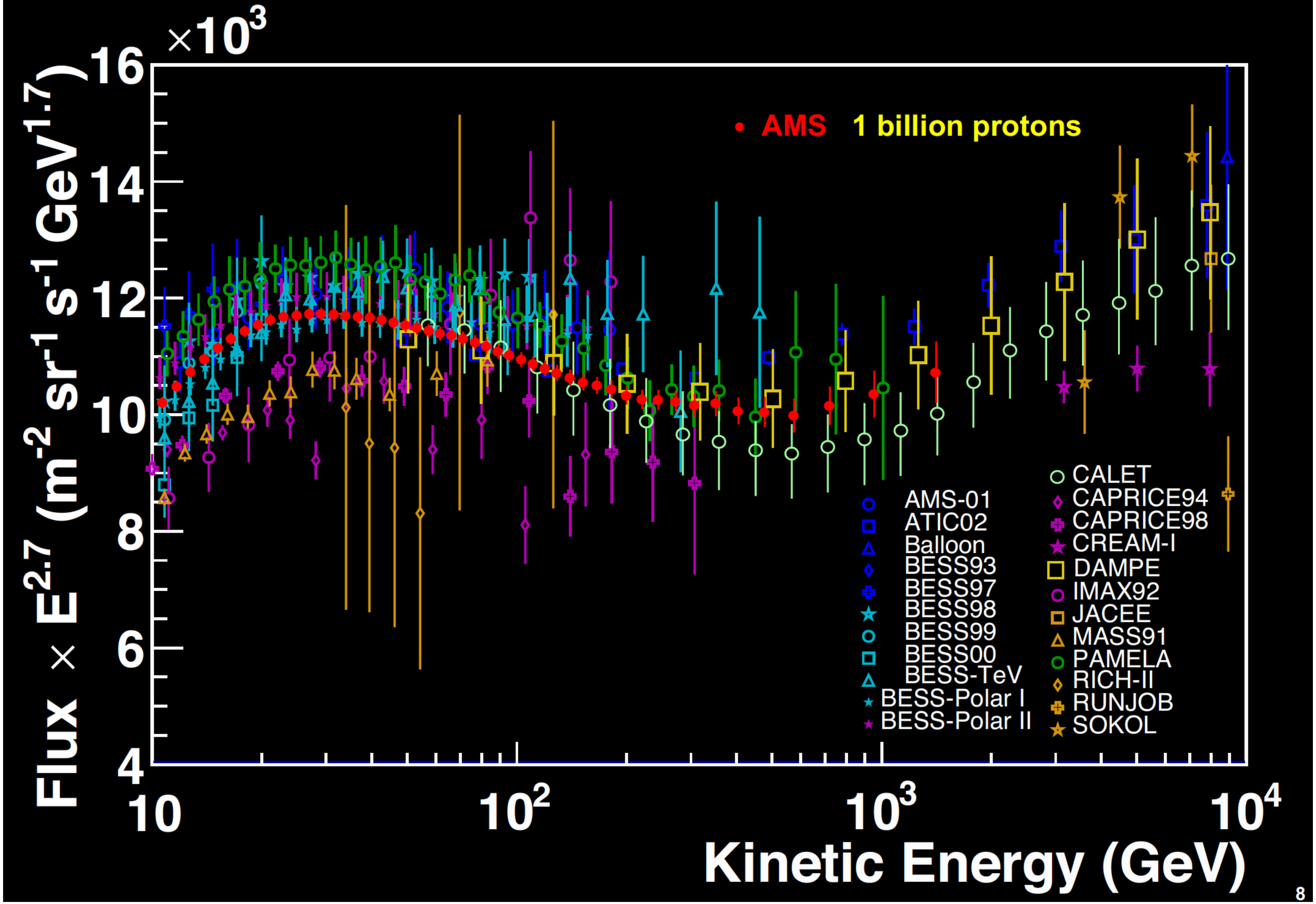
Primary Cosmic Rays

Primary elements (H, He, C, ..., Fe) are produced during the lifetime of stars.

They are accelerated by the explosion of stars (**supernovae**).

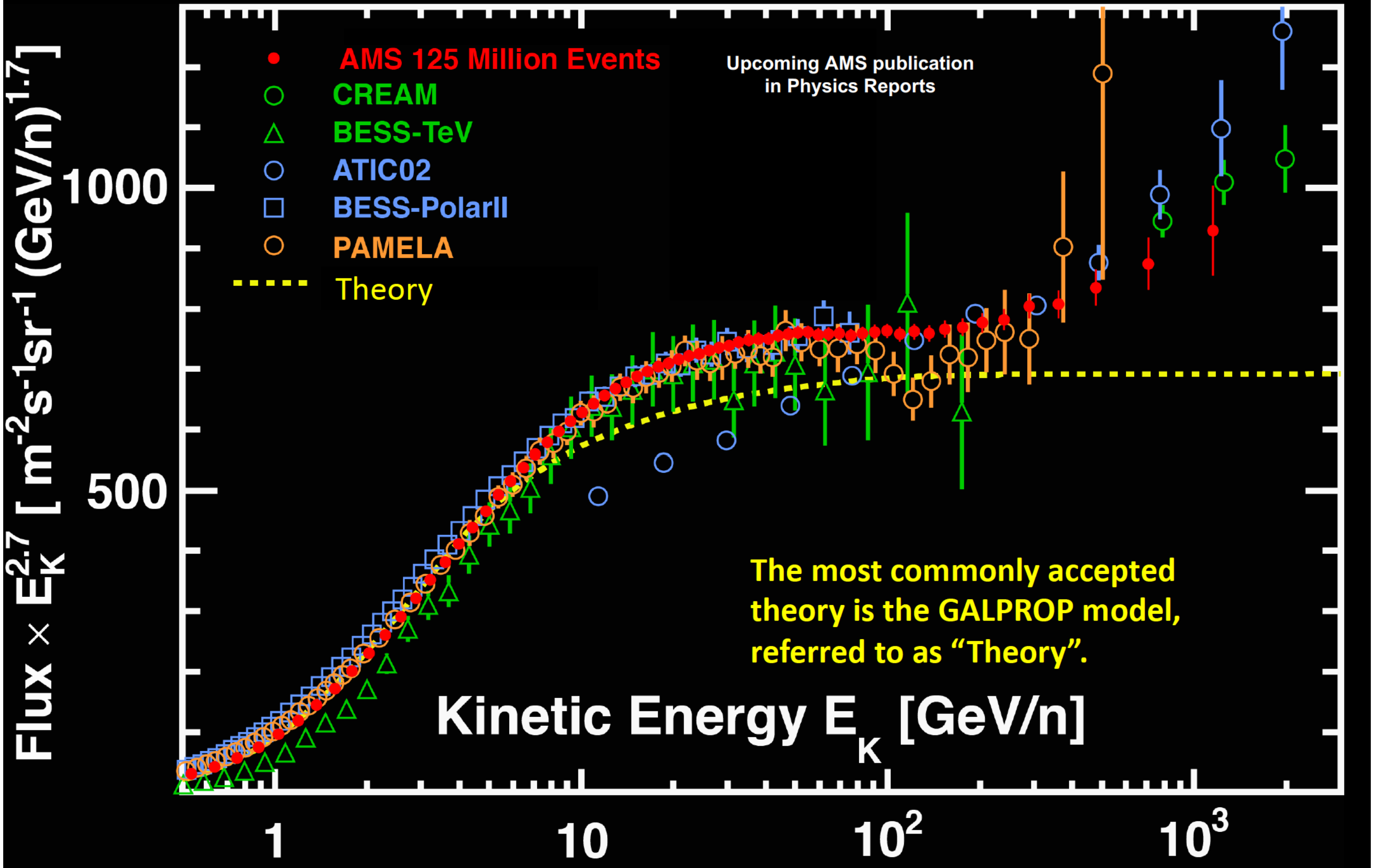


Protons (Z = +1) are the most abundant cosmic ray



AMS Primary Cosmic Ray Helium (Z = +2)

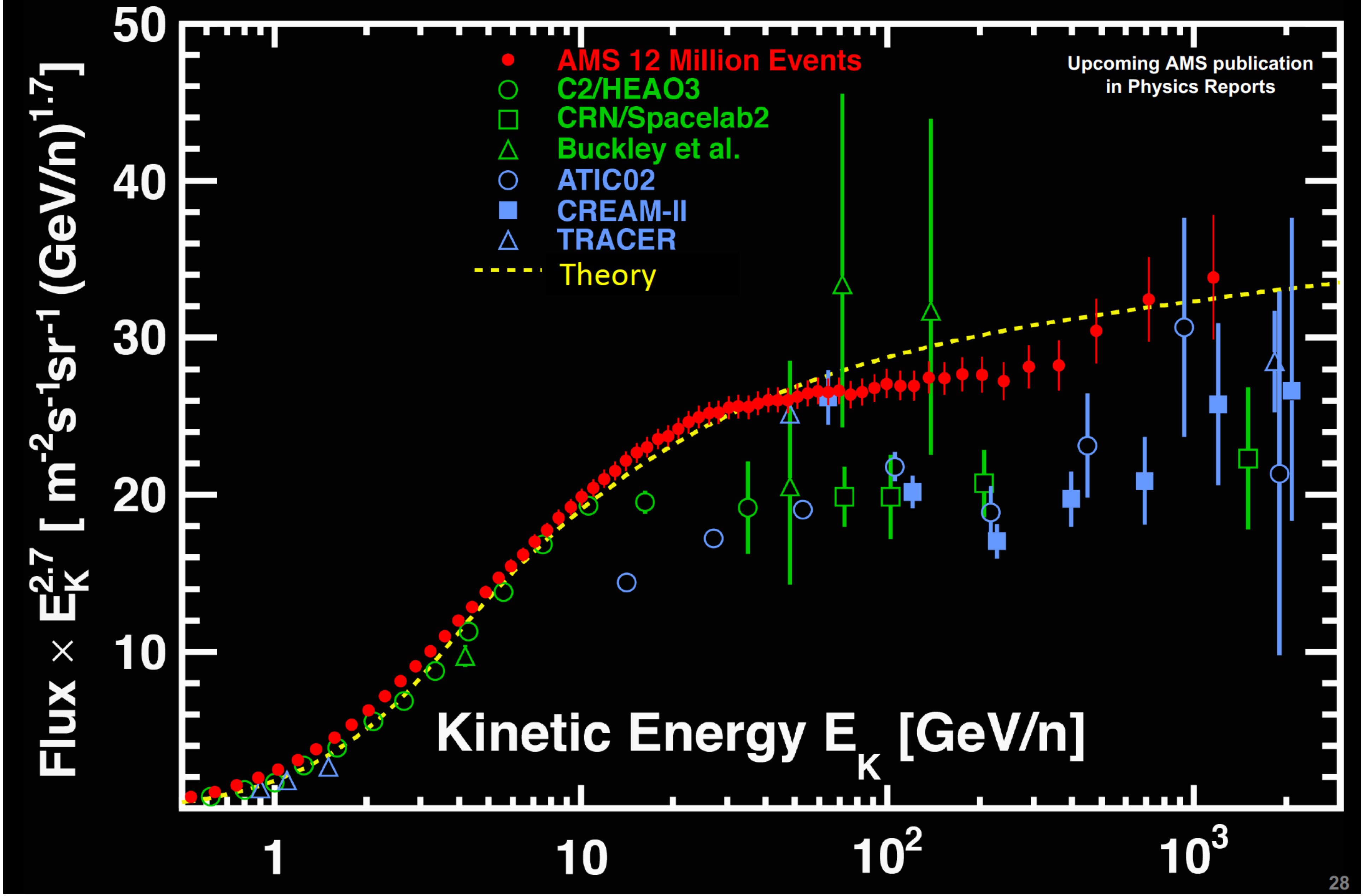
(^{3}He + ^{4}He)



Upcoming AMS publication
in Physics Reports

The most commonly accepted theory is the GALPROP model, referred to as “Theory”.

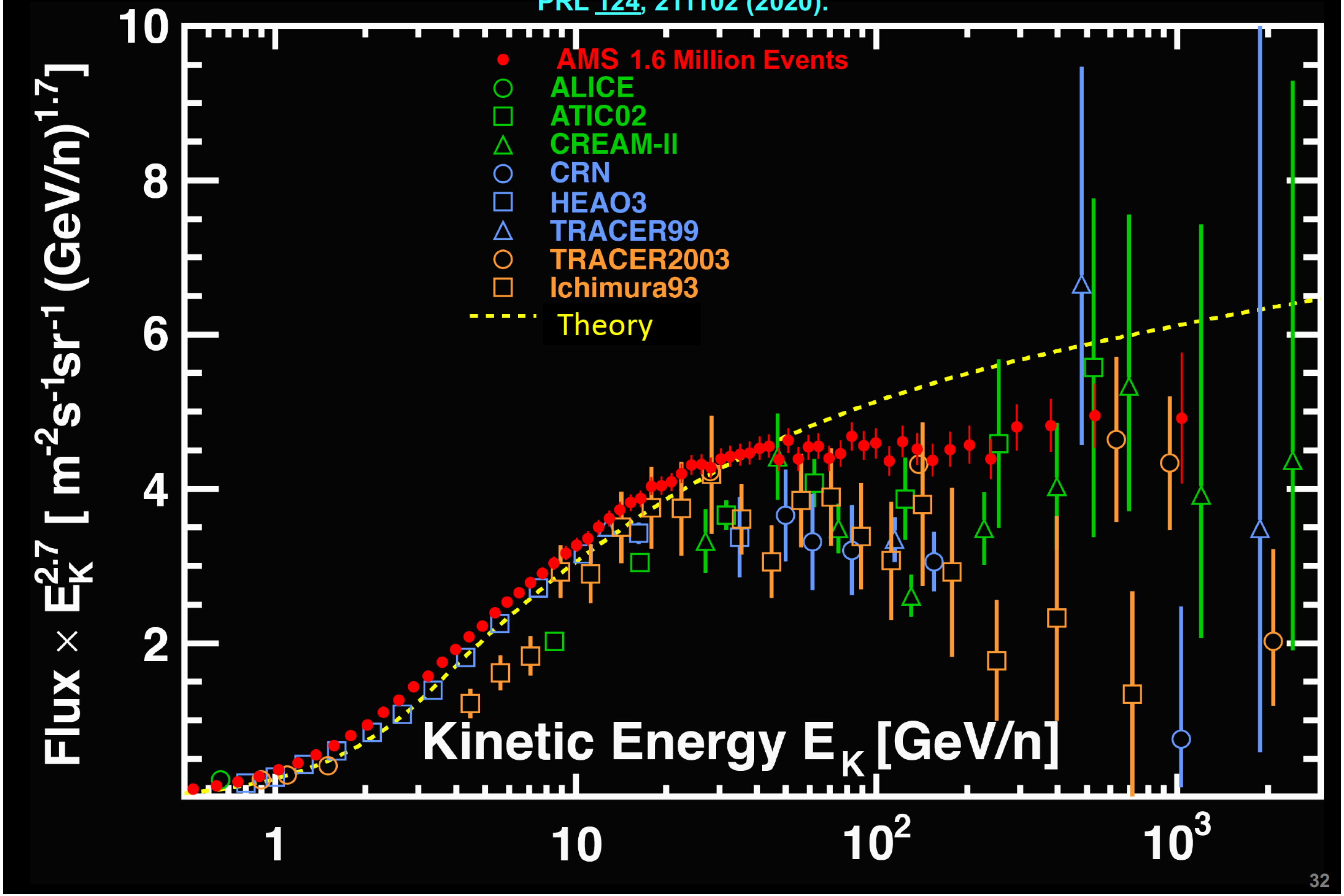
AMS Primary Cosmic Ray Oxygen (Z = +8)



Upcoming AMS publication in Physics Reports

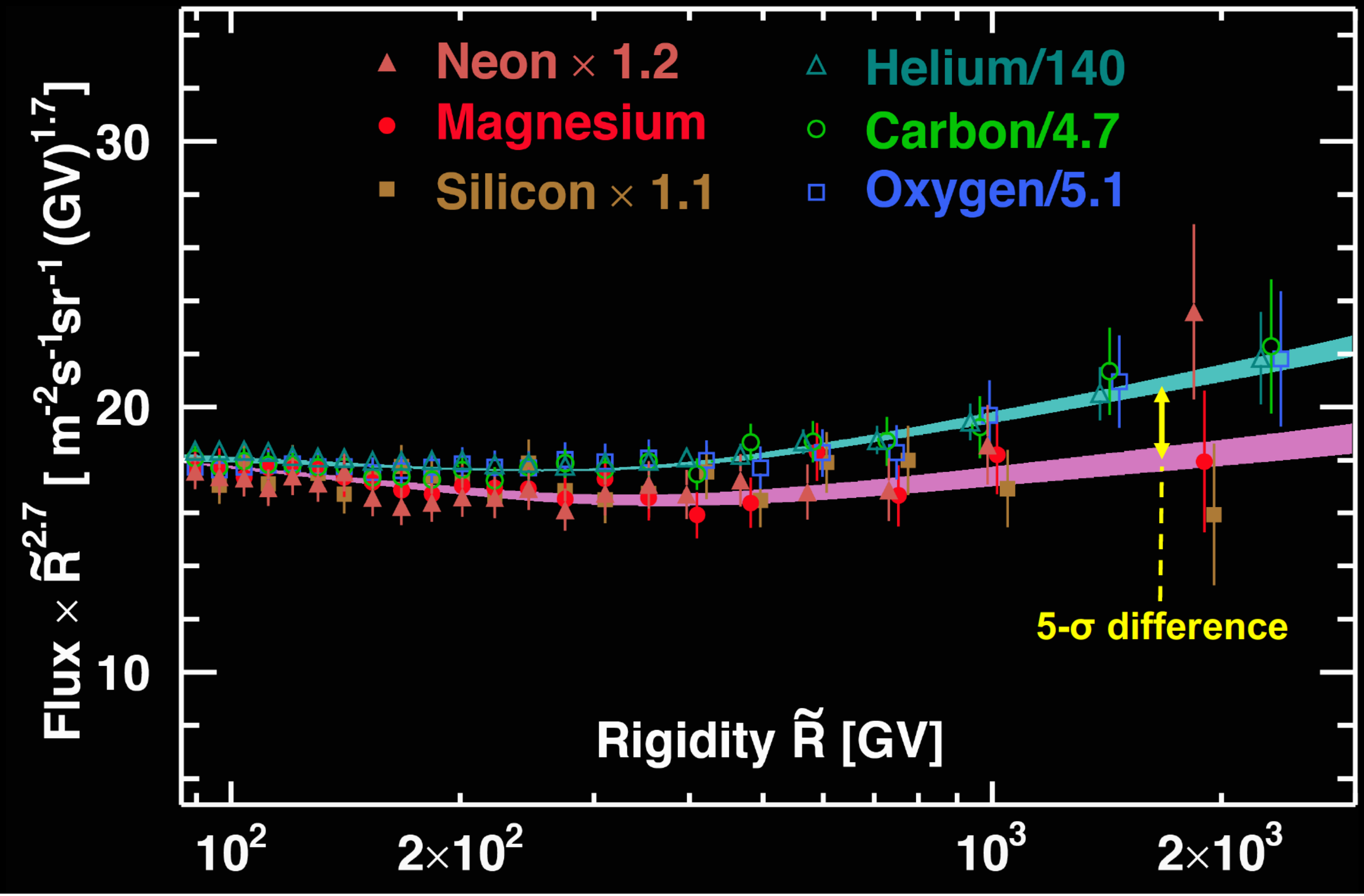
AMS Primary Cosmic Ray Silicon (Z = +14)

PRL 124, 211102 (2020).

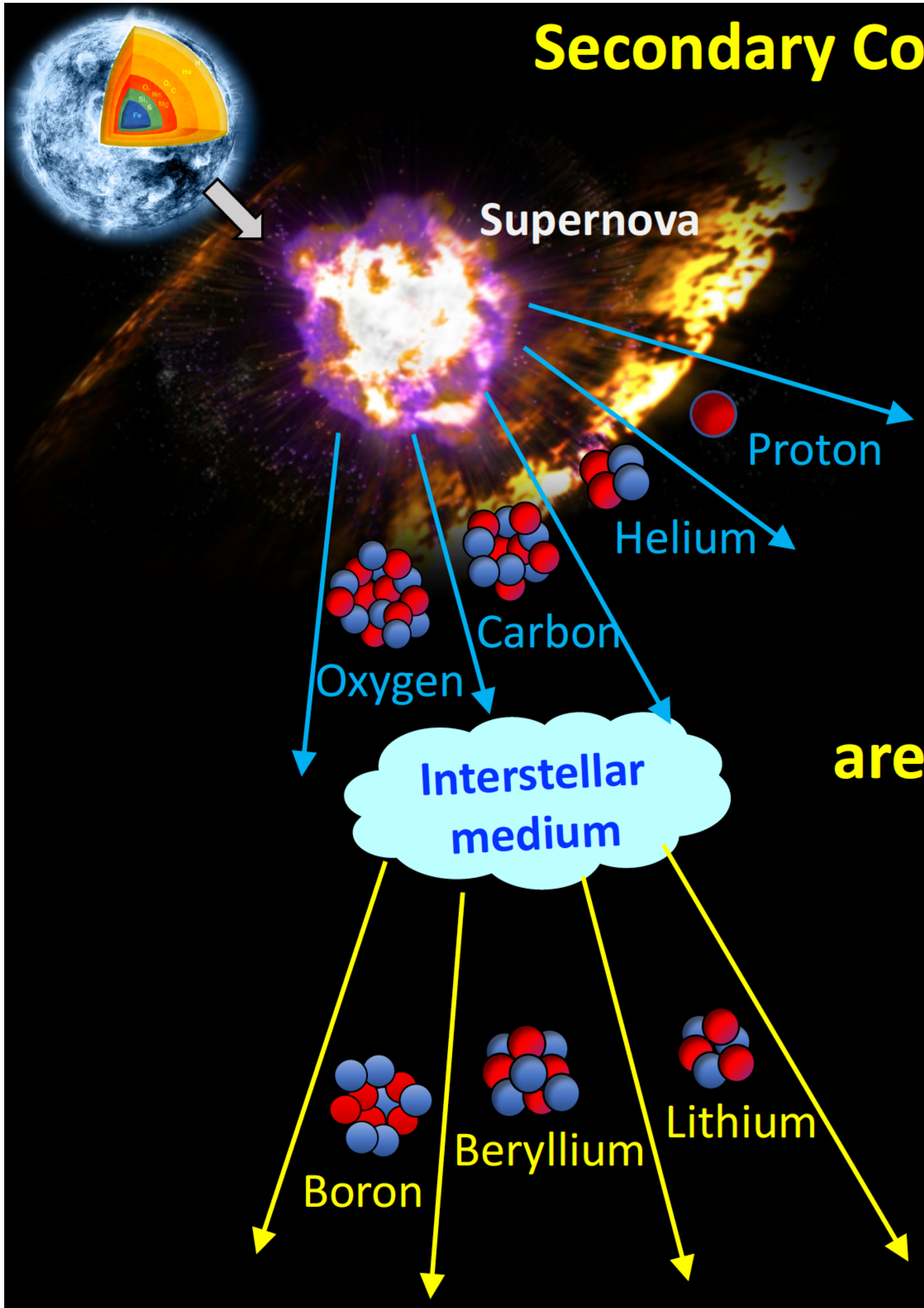


Unexpected result on heavier primary cosmic rays Ne, Mg, Si:
They have their own identical rigidity behavior, different from He, C, O.
At the 5-σ level, primary cosmic rays have at least two classes.

PRL 124, 211102 (2020).

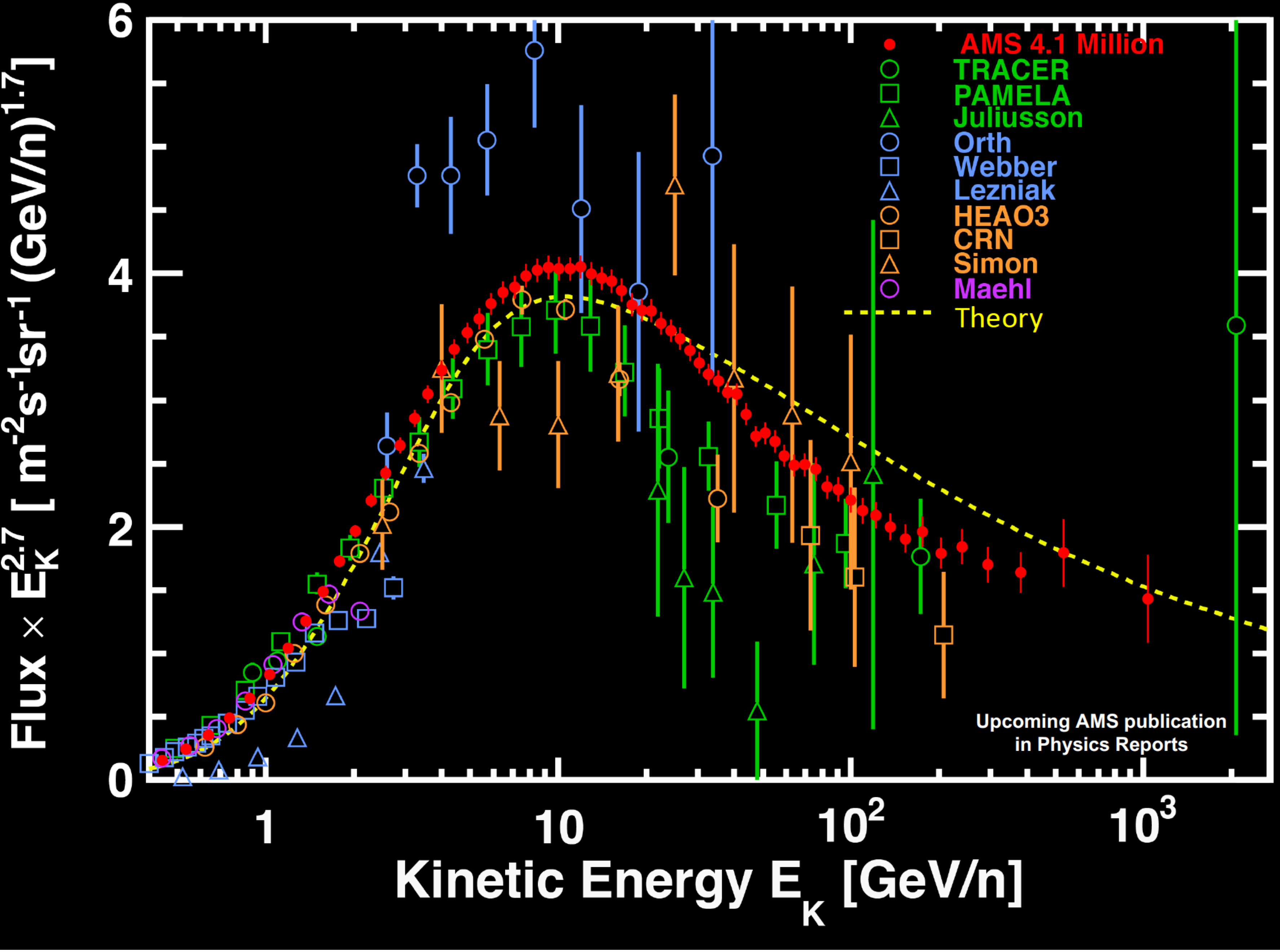


Secondary Cosmic Rays



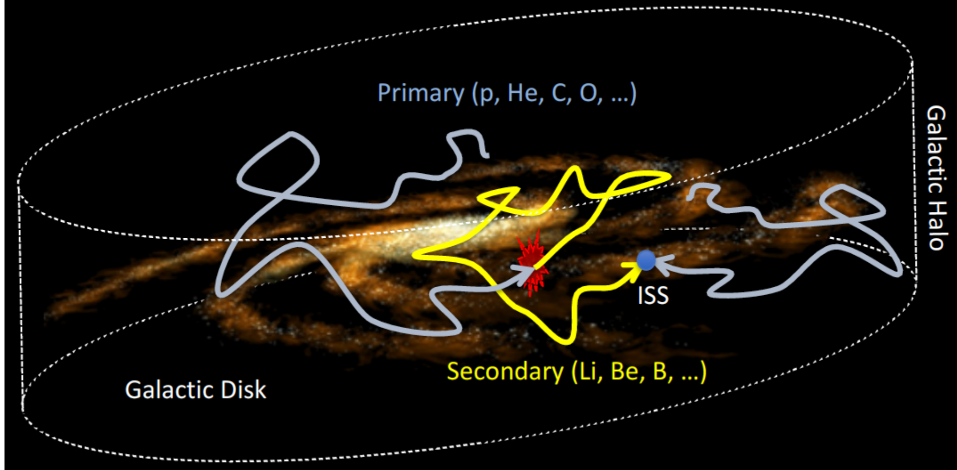
Secondary cosmic nuclei
(Li, Be, B, …)
are produced by the collision of
primary cosmic rays and
interstellar medium

AMS Secondary Cosmic Ray Boron (Z = +5)



Upcoming AMS publication
in Physics Reports

Secondary/Primary Flux ratios



Cosmic rays are commonly modeled as a relativistic gas diffusing into a magnetized plasma.

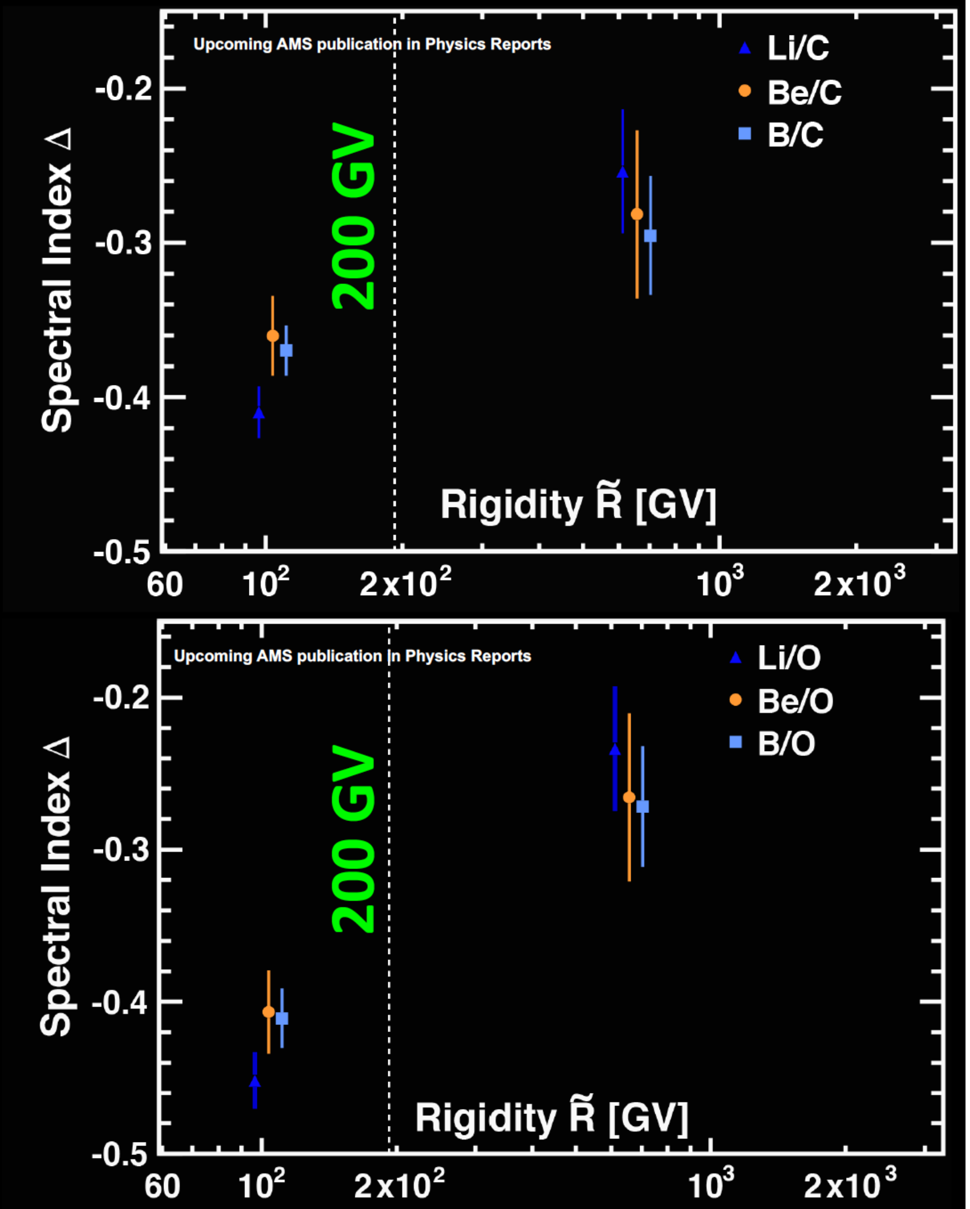
Diffusion models based on different assumptions predict a Secondary/Primary ratio asymptotically proportional to R^δ.

AMS Physics Results:

The Secondary/Primary Ratios ≠ kR^{Δ}

Δ is not a constant at 5-σ

$\Delta[192\text{-}3300\,\mathrm{GV}] - \Delta[60\text{-}192\,\mathrm{GV}] = 0.140 \pm 0.025$



This AMS data provides new and unexpected information on the interstellar medium

The Origins of Cosmic Positrons and Electrons

Dark Matter

Electrons

Dark Matter

Interstellar Medium

Protons, Helium, e^-...

Supernovae

$e^\pm$ from Collisions

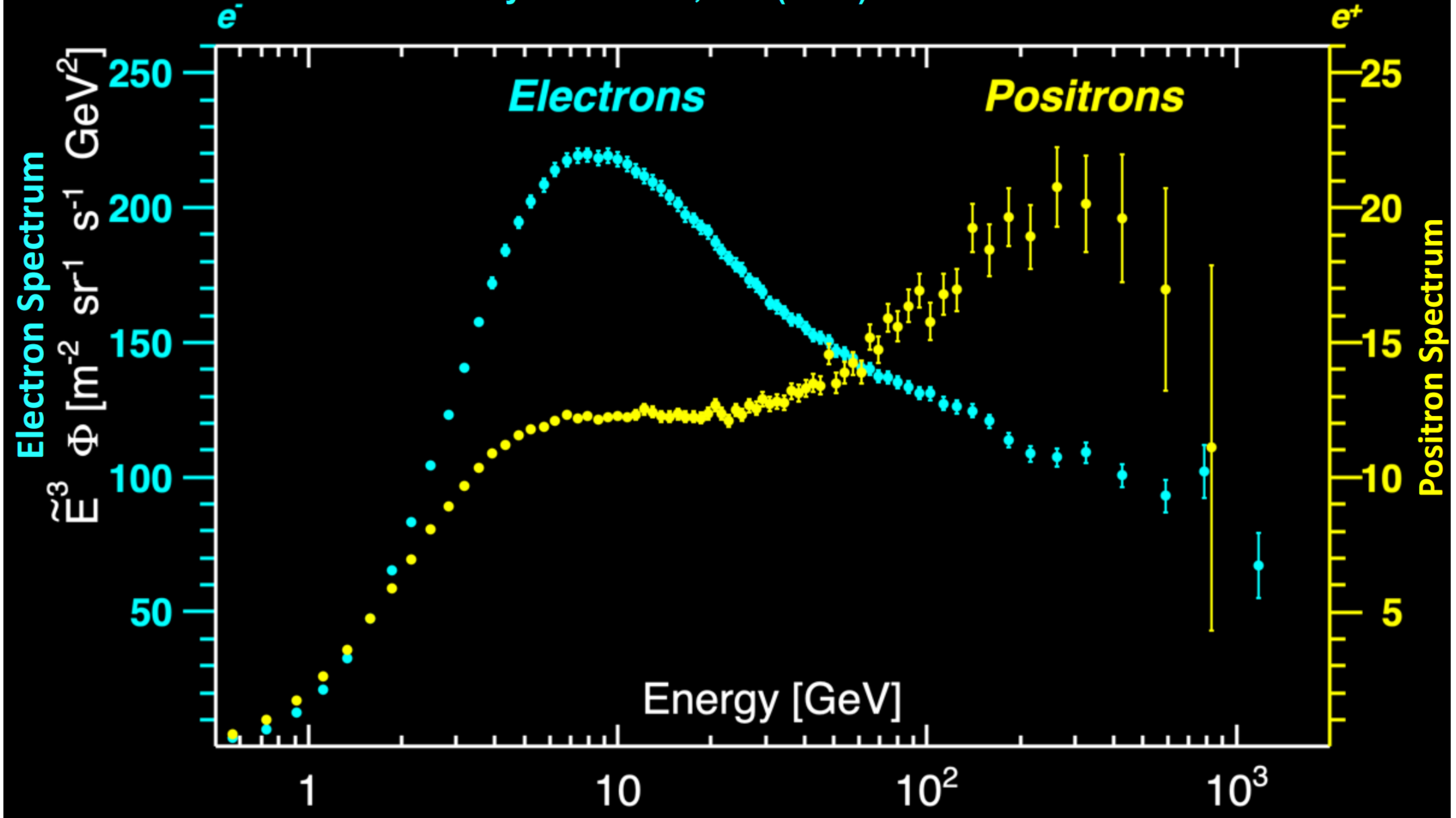
$e^\pm$ from Dark Matter

$e^\pm$ from Pulsars

New Astrophysical Sources
(Pulsars, ...)

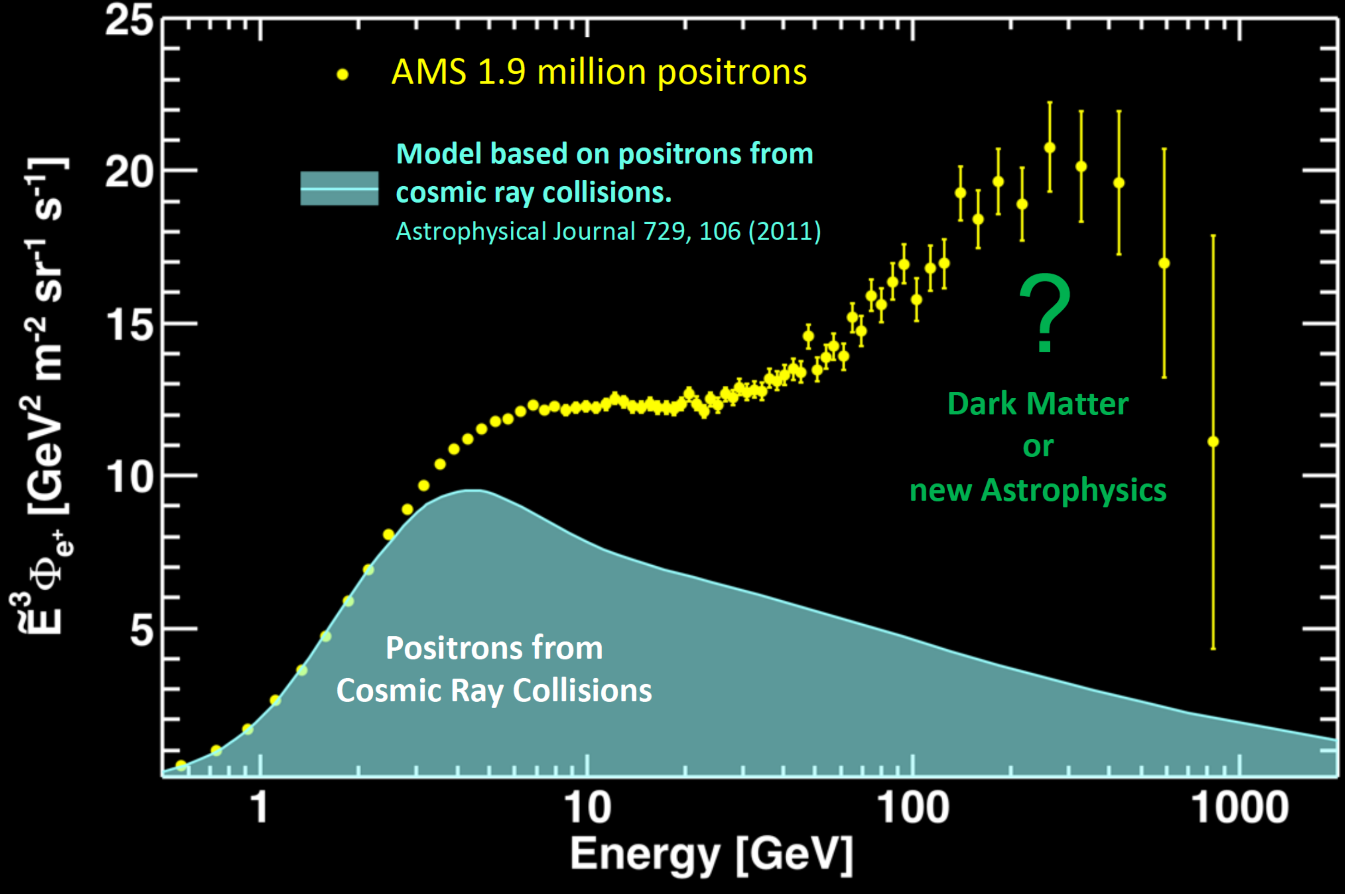
Cosmic Ray Positron and Electron spectra measured by AMS

Phys. Rev. Lett. 122 (2019) 041102.
Phys. Rev. Lett, 122 (2019) 101101.



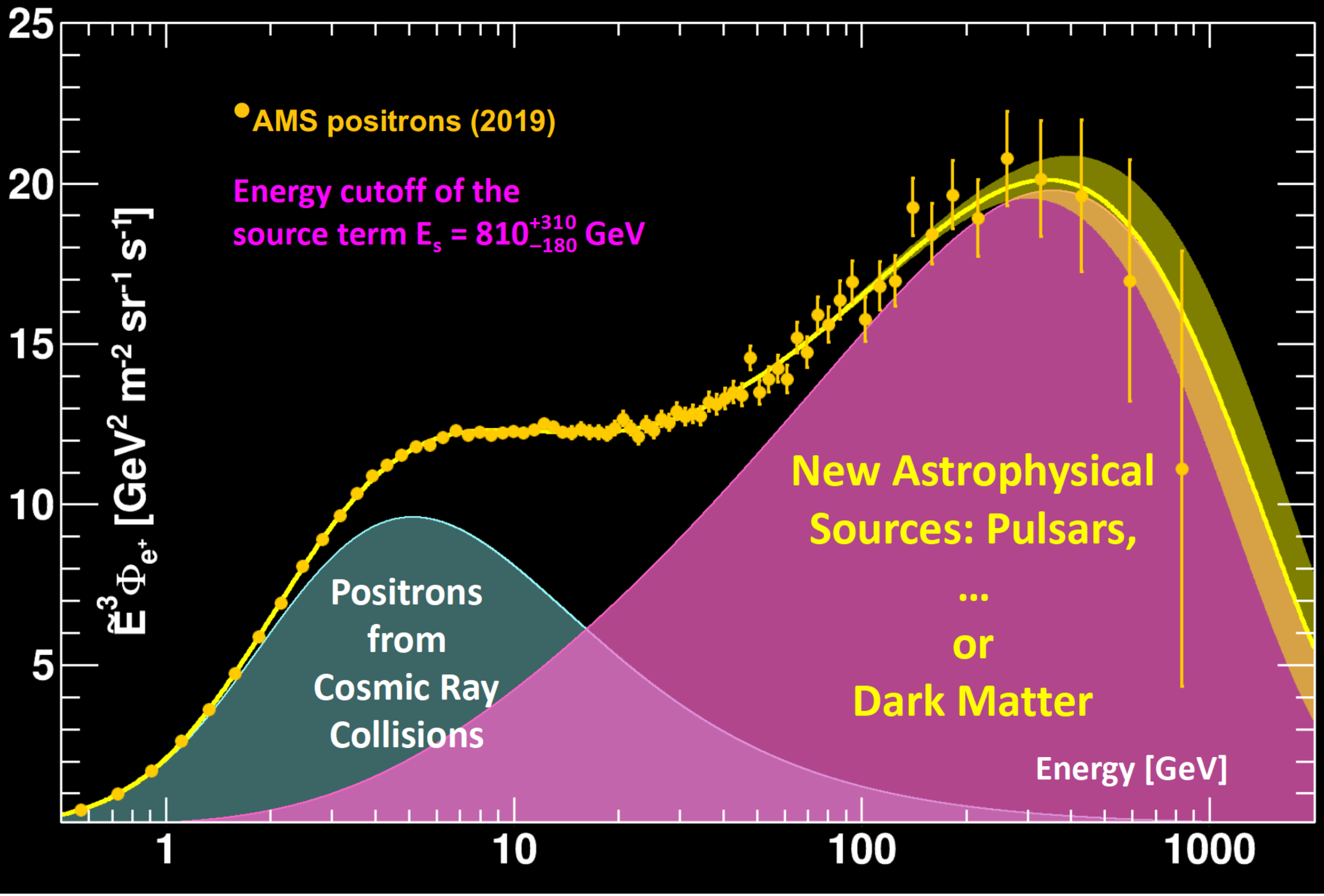
AMS Physics Results: The Origin of Cosmic Positrons

Low energy positrons mostly come from cosmic ray collisions



The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from pulsars or dark matter.

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$



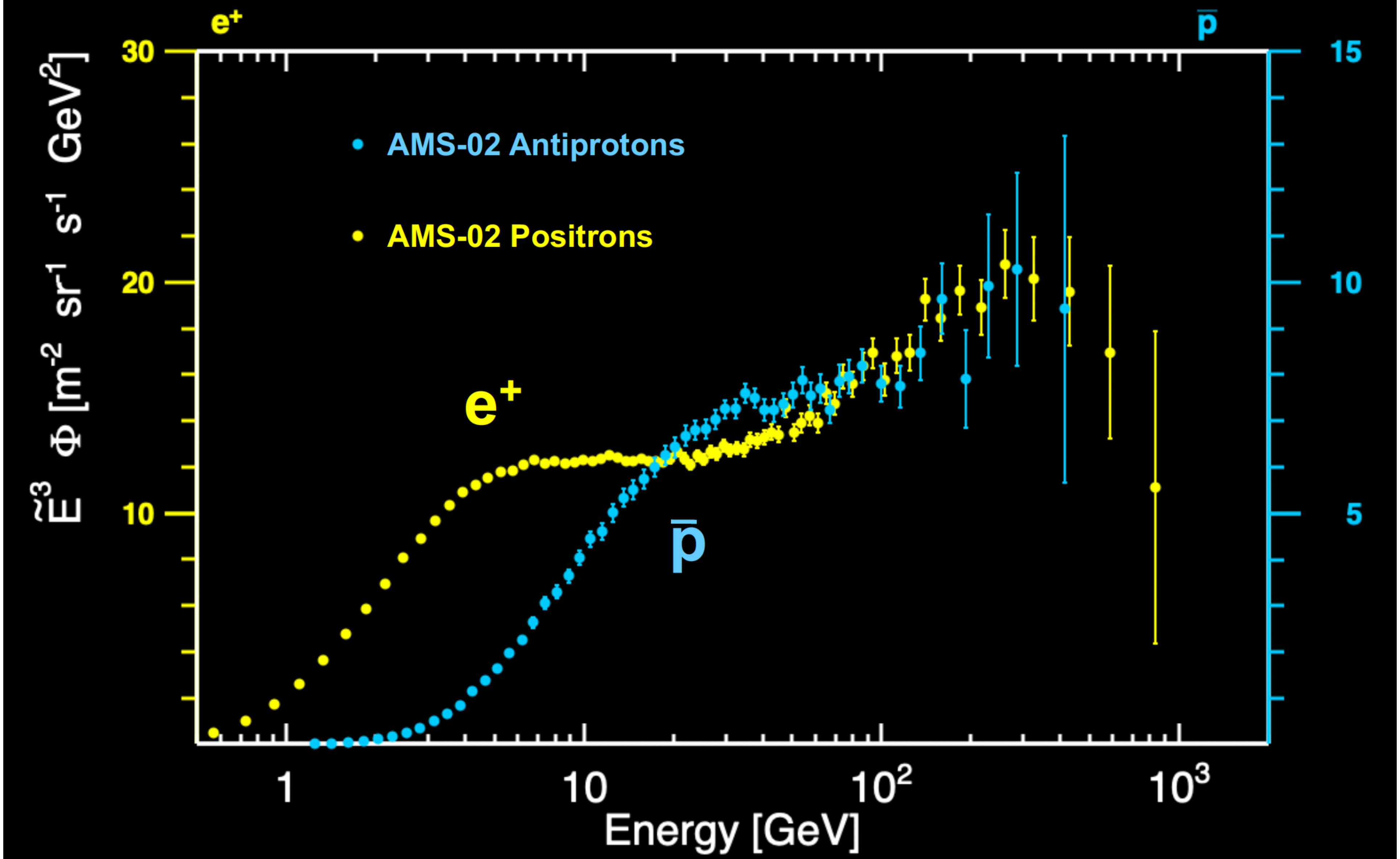
Energy cutoff of the source term $E_s = 810^{+310}_{-180}$ GeV

Positrons from Cosmic Ray Collisions

New Astrophysical Sources: Pulsars, … or Dark Matter

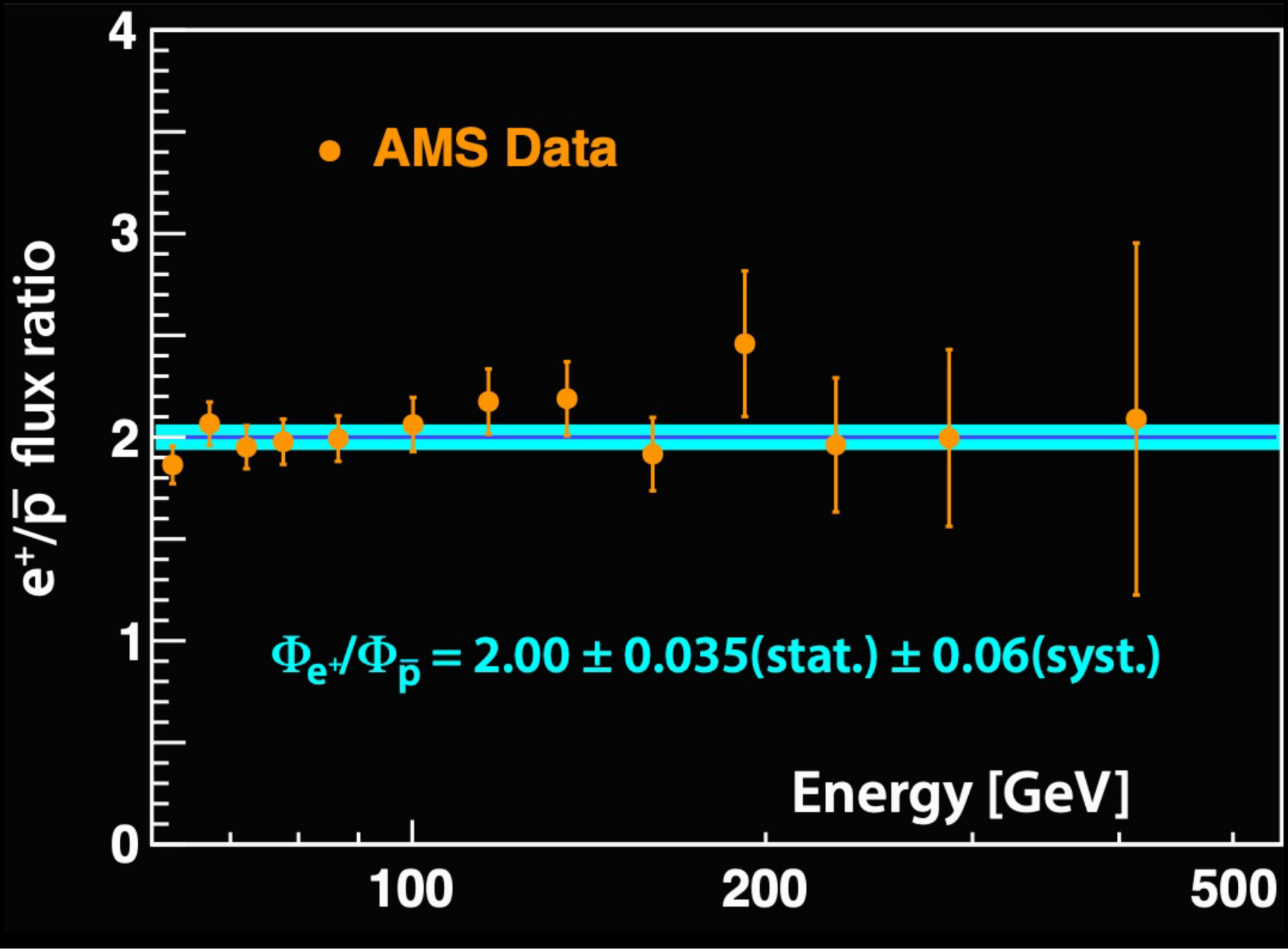
AMS Physics Results:

Antiproton data show a similar trend as positrons.

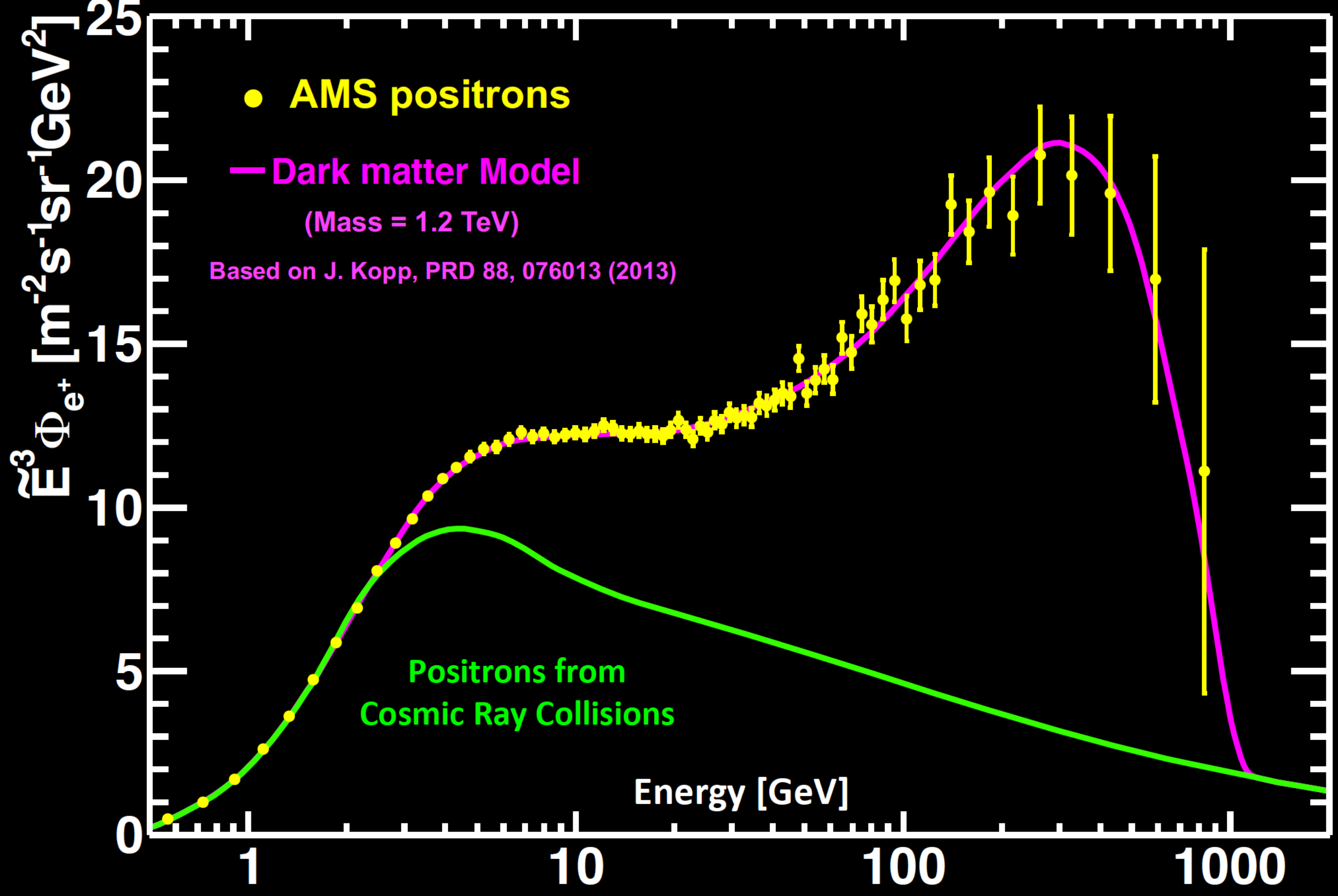


AMS Physics Results:

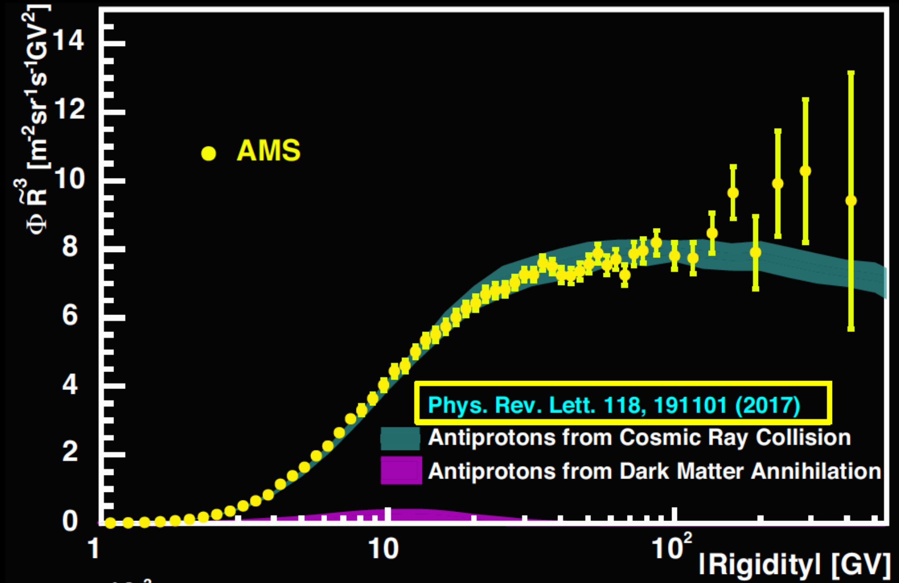
The positron-to-antiproton flux ratio is independent of energy. Antiprotons cannot come from pulsars.

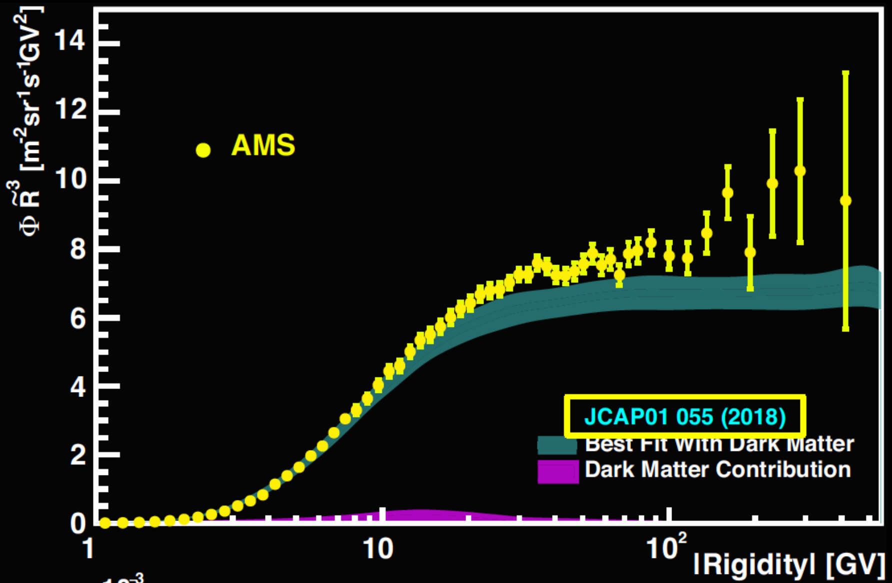


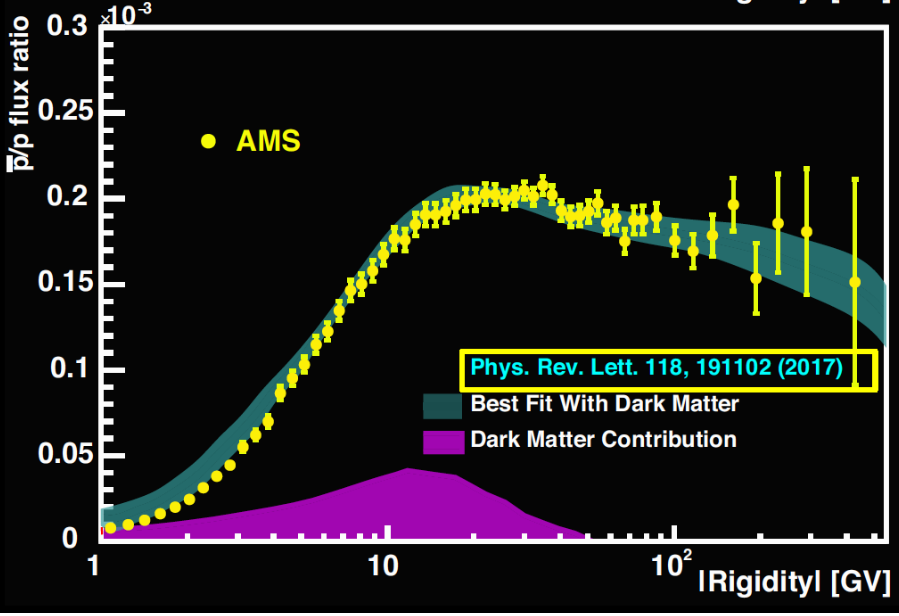
AMS Positron spectrum and a Dark Matter Model

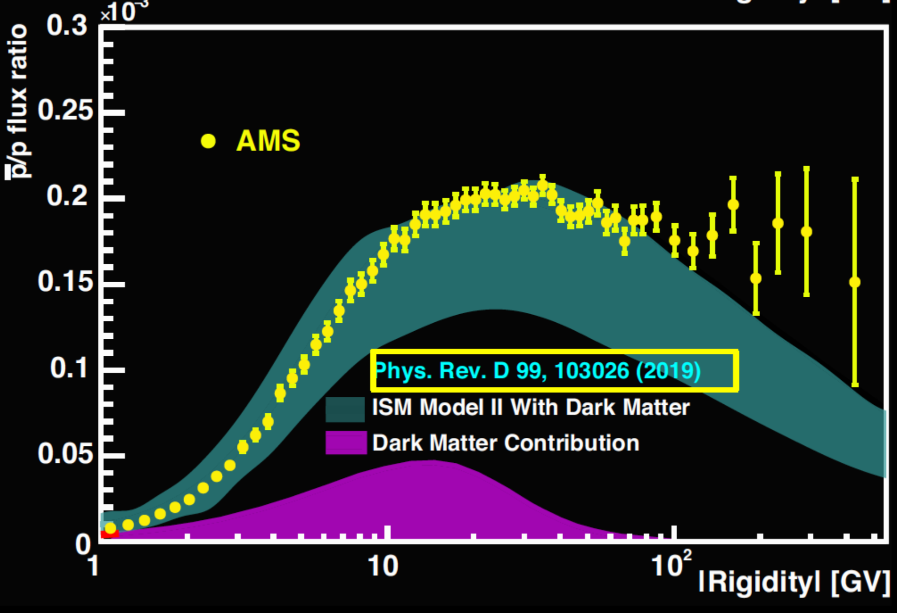


There is a large class of dark matter models that require an excess of antiprotons. The current cosmic ray models deviate from the high energy antiproton spectrum. The models also limit comparison of low energy dark matter.









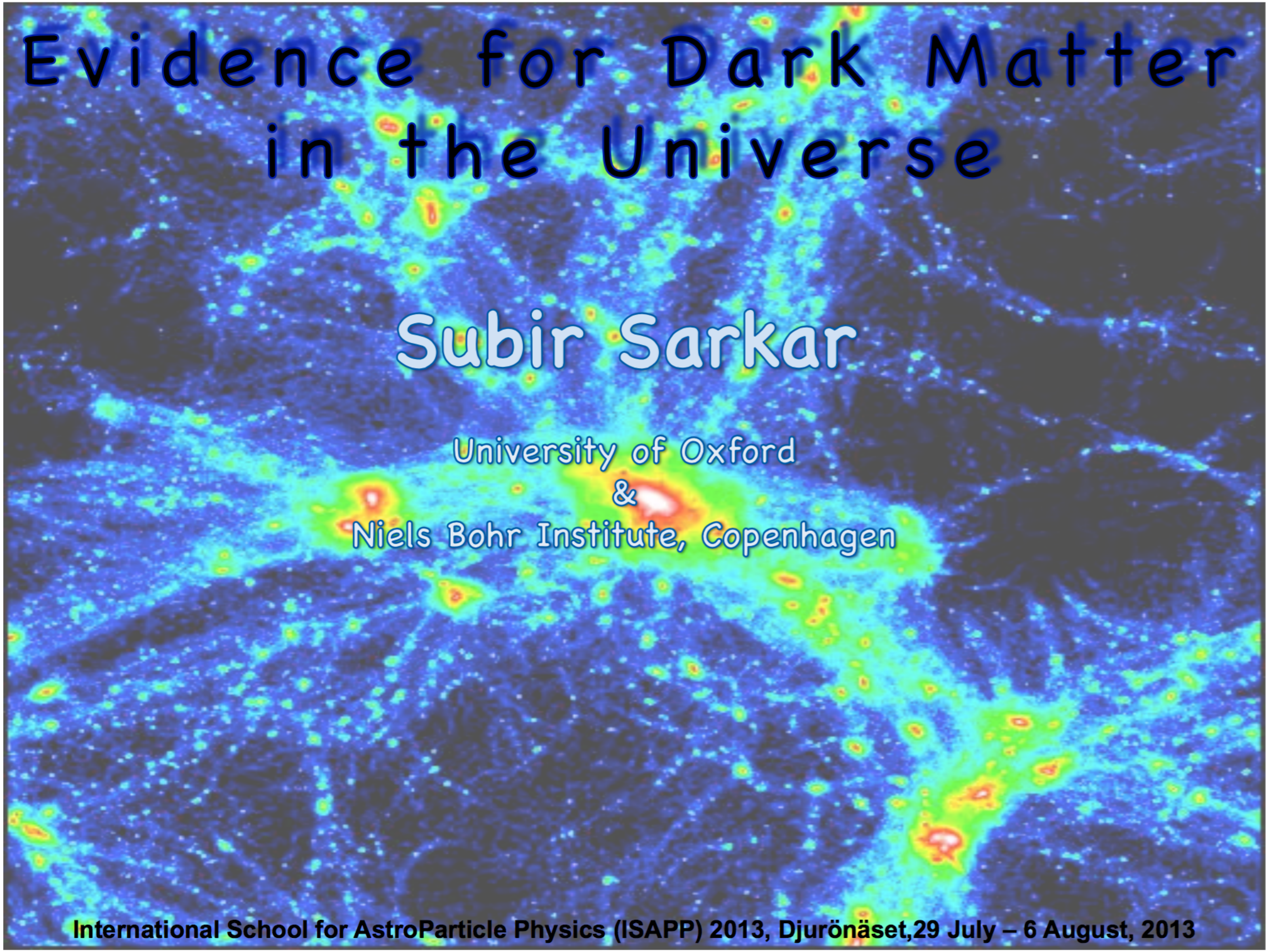
ISAPP2013 Stockholm

from 29 July 2013 to 06 August 2013

Djurönäset Conference Centre, Stockholm region

The International School for AstroParticle Physics (ISAPP) 2013, Djurönäset:

Dark Matter Composition and Detection, July 29 to August 6, 2013



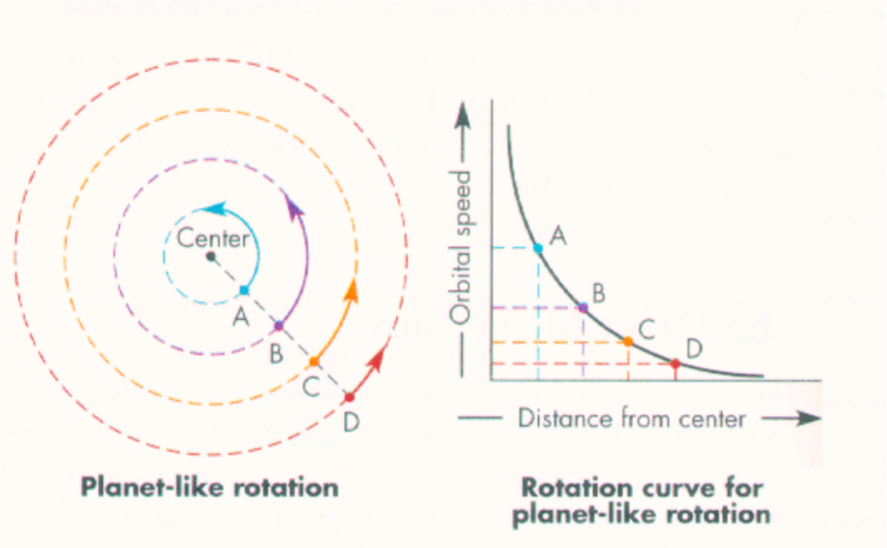
Evidence for Dark Matter in the Universe

Subir Sarkar

University of Oxford
&
Niels Bohr Institute, Copenhagen

International School for AstroParticle Physics (ISAPP) 2013, Djurönäset,29 July – 6 August, 2013

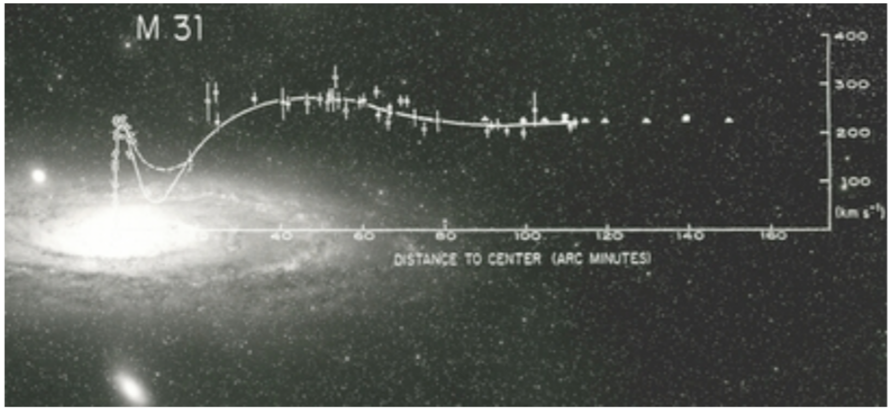
The modern saga of dark matter starts with the rotation curves of spiral galaxies



At large distances from the centre, beyond the edge of the visible galaxy, the velocity would be expected to fall as 1/√*r* if most of the matter is contained in the optical disc

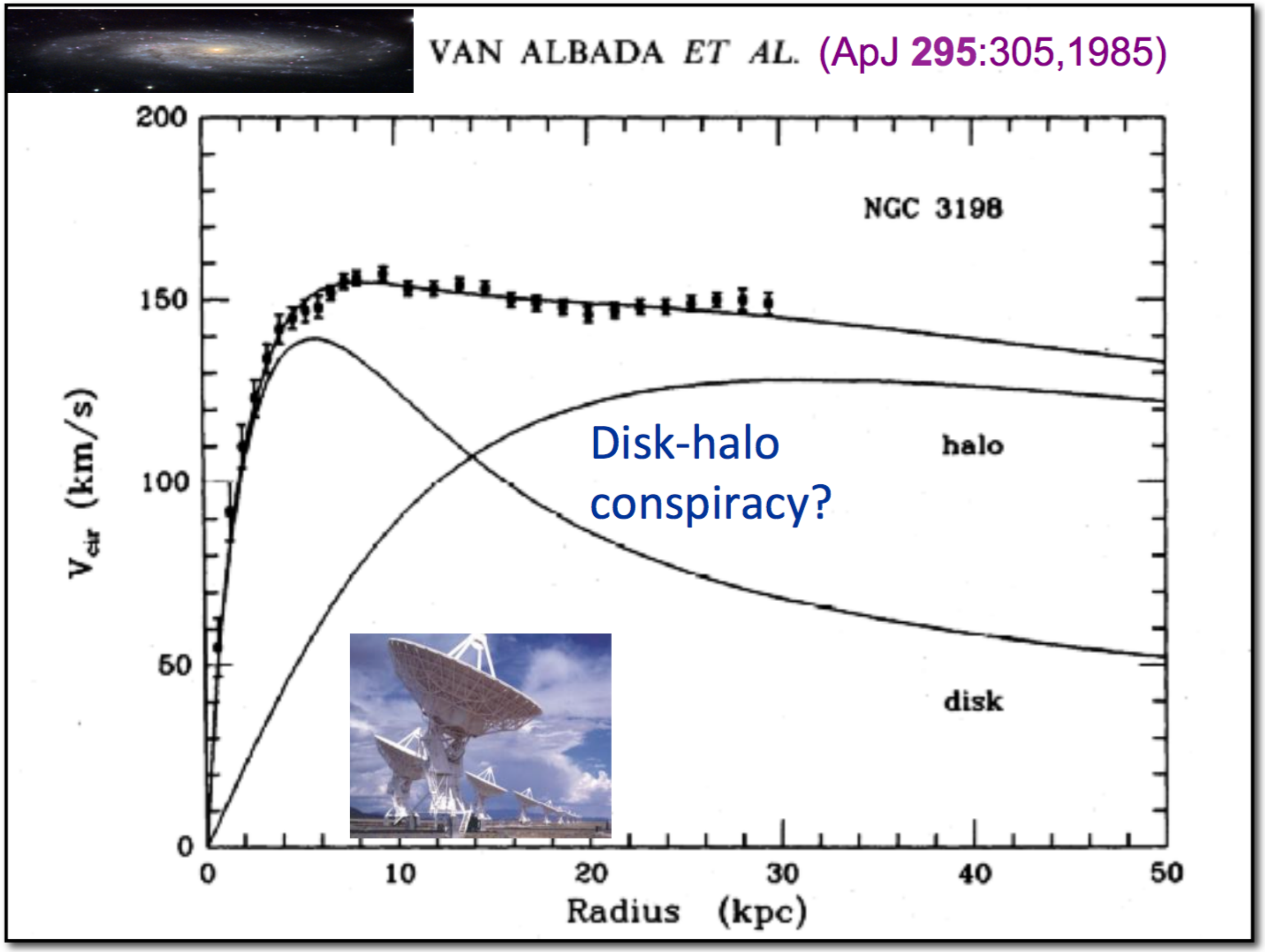
$$v_{\rm circ} = \sqrt{\frac{G_{\rm N} M(<r)}{r}}$$

… but Rubin & Ford (ApJ **159**: 379,1970) observed that the rotational velocity remains ~constant in Andromeda, **implying the existence of an extended dark halo** (earlier Babcock 1939, later Roberts & Whitehurst 1975, Bosma 1978)



$$v_{\rm circ} \sim {\rm constant} \quad \Rightarrow \quad M(<r) \propto r \quad \Rightarrow \quad \rho \propto 1/r^2$$

The really compelling evidence for extended halos of dark matter came from observations in the 1980's of 21-cm line emission from neutral hydrogen (orbiting around Galaxy at ~constant velocity) well *beyond* the visible disk



VAN ALBADA *ET AL.* (ApJ **295**:305,1985)

Disk-halo conspiracy?

Cored isothermal sphere:

$$\rho_{\mathrm{isothermal}} = \frac{\rho_{\mathrm{s}}}{\left(1+\frac{r}{r_{\mathrm{s}}}\right)^2}$$

Navarro-Frenk-White profile:
(indicated by CDM simulations)

$$\rho_{\mathrm{NFW}} = \frac{\rho_{\mathrm{s}}}{\frac{r}{r_{\mathrm{s}}}\left(1+\frac{r}{r_{\mathrm{s}}}\right)^2}$$

Burkert profile:
(fits observations better)

$$\rho_{\mathrm{Burkert}} = \frac{\rho_{\mathrm{s}}}{\left(1+\frac{r}{r_{\mathrm{s}}}\right)\left[1+\left(\frac{r}{r_{\mathrm{s}}}\right)^2\right]}$$

Hernquist profile:

$$\rho_{\mathrm{Hernquist}} = \rho_{\mathrm{s}}\left(\frac{r}{r_{\mathrm{s}}}\right)^{-\gamma}\left[1+\left(\frac{r}{r_{\mathrm{s}}}\right)^{\alpha}\right]^{\frac{\gamma-\beta}{\alpha}}$$

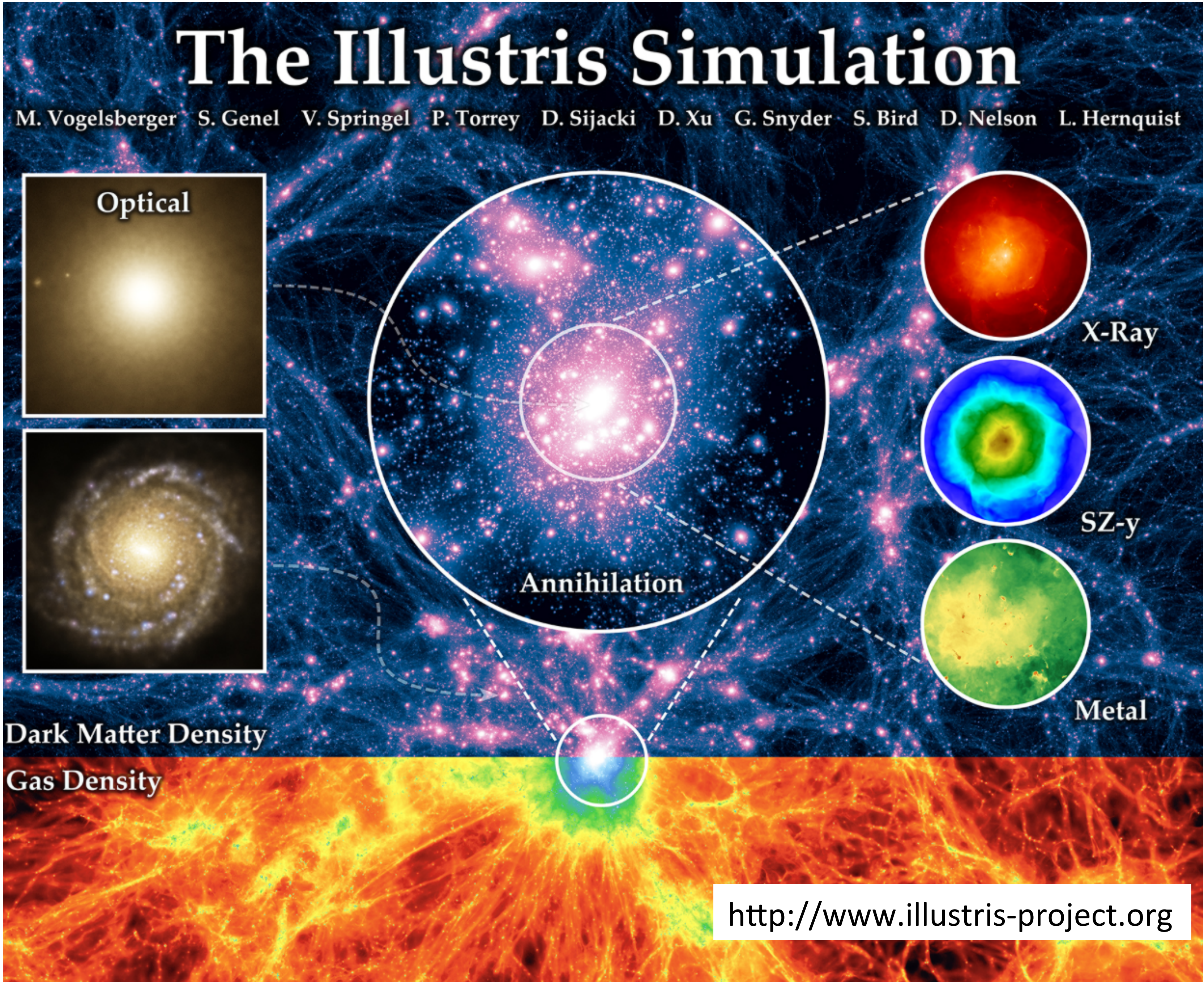
where r_s is a characteristic scale and α controls the sharpness of the transition from the inner slope $\lim_{r\to 0} \mathrm{d}\ln(\rho)/\mathrm{d}\ln(r) = -\gamma$ to the outer slope $\lim_{r\to\infty} \mathrm{d}\ln(\rho)/\mathrm{d}\ln(r) = -\beta$

… e.g. the NFW profile corresponds to choosing $\alpha = 1$, $\beta = 3$, $\gamma = 1$, whereas a cored isothermal profile corresponds to choosing $\alpha = 1$, $\beta = 2$, $\gamma = 0$, and a Moore profile is obtained by setting $\alpha = 1.5$, $\beta = 2$, $\gamma = 1.5$ *et cetera*

Einasto profile:

$$\rho_{\mathrm{Einasto}} = \rho_{\mathrm{s}} \exp\left\{-d_n\left[\left(\frac{r}{r_{\mathrm{s}}}\right)^{1/n} - 1\right]\right\}$$

where d_n is defined such that ρ_s is the density at the radius r_s which encloses half the total mass

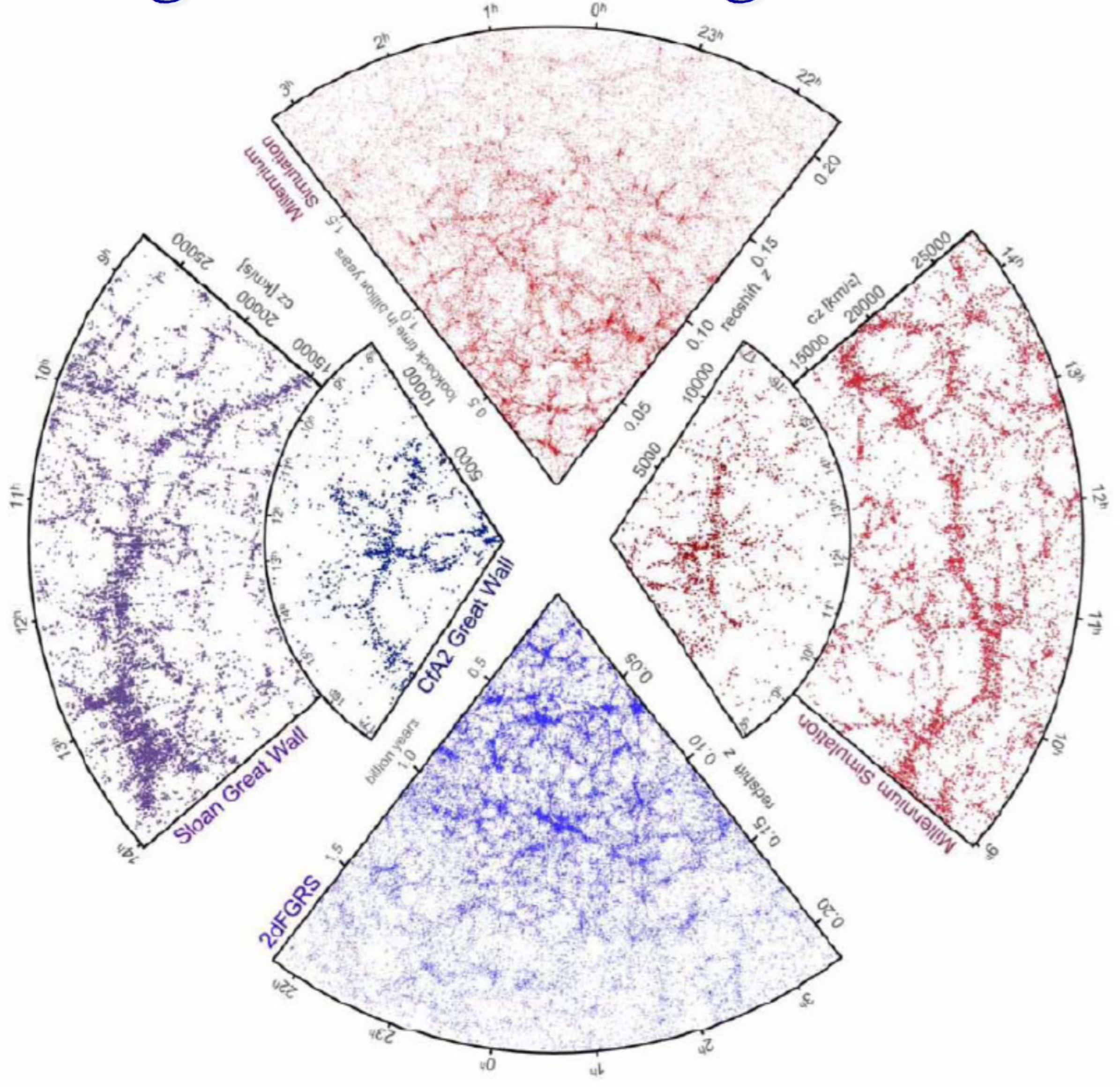


The Illustris Simulation

M. Vogelsberger S. Genel V. Springel P. Torrey D. Sijacki D. Xu G. Snyder S. Bird D. Nelson L. Hernquist

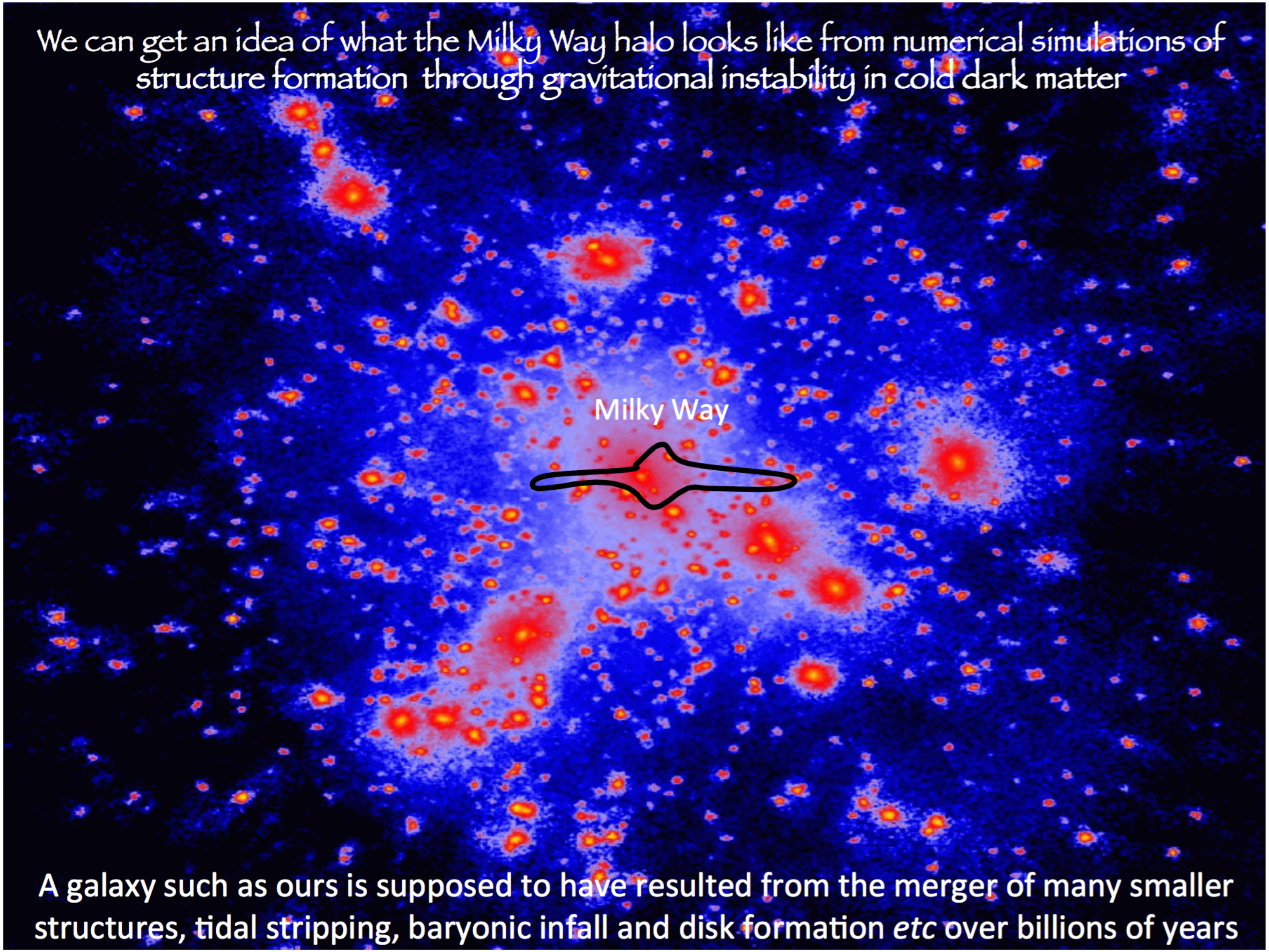
http://www.illustris-project.org

Such numerical simulations provide a pretty good match to the observed large-scale structure of galaxies in the universe



Springel, Frenk & White, Nature **440**:1137,2006

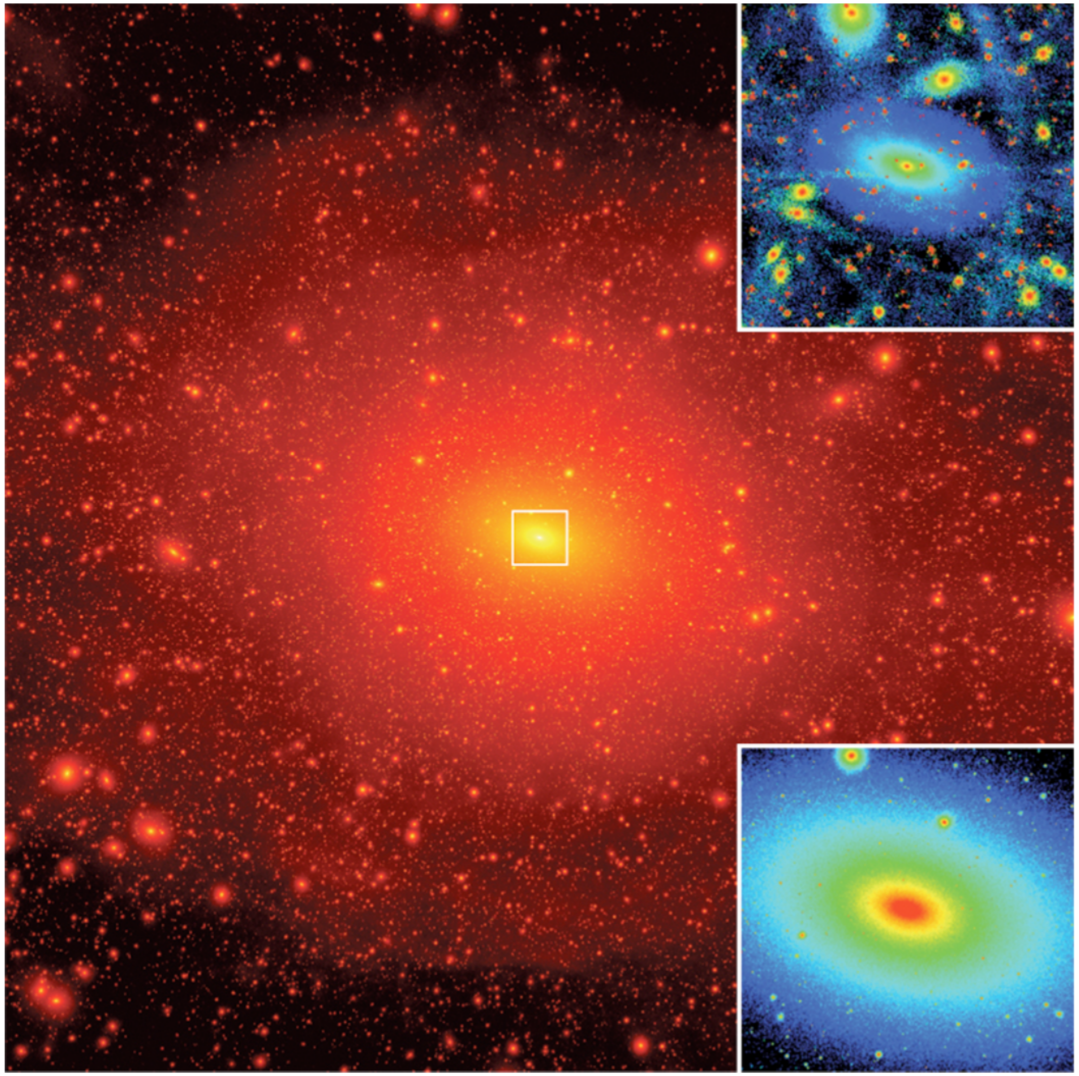
We can get an idea of what the Milky Way halo looks like from numerical simulations of structure formation through gravitational instability in cold dark matter



A galaxy such as ours is supposed to have resulted from the merger of many smaller structures, tidal stripping, baryonic infall and disk formation *etc* over billions of years

So the phase space structure of the dark halo is pretty complicated …

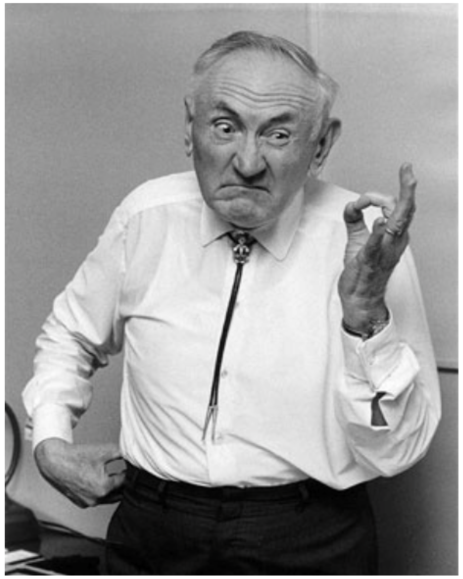
Via Lactea II projected dark matter (squared-) density map



phase space

real space

Diemand, Kuhlen, Madau, Zemp, Moore, Potter & Stadel, Nature **454**:735,2008



Fritz Zwicky (1933) measured the velocity dispersion in the Coma cluster to be as high as 1000 km/s

$\Rightarrow M/L \sim O(100)\ M_\odot/L_\odot$

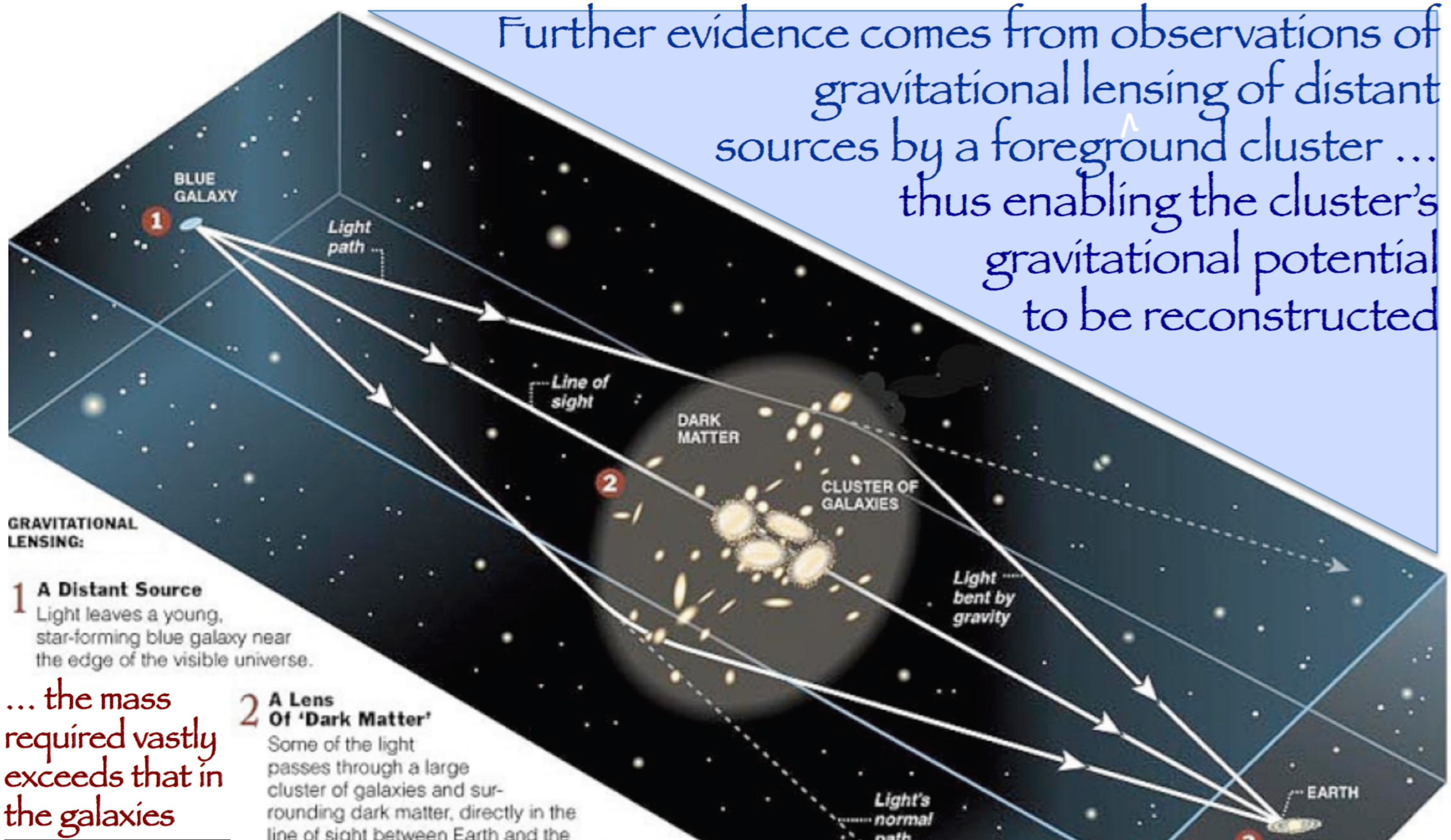
"… If this overdensity is confirmed we would arrive at the astonishing conclusion that dark matter is present (in Coma) with a much greater density than luminous matter"

Virial Theorem: $$\langle V\rangle + 2\langle K\rangle = 0$$

$$V = -\frac{N^2}{2} G_{\mathrm{N}} \frac{\langle m^2\rangle}{\langle r\rangle}, \quad K = N\frac{\langle mv^2\rangle}{2}$$

$$M = N\langle m\rangle \sim \frac{2\langle r\rangle\langle v^2\rangle}{G_{\mathrm{N}}} \gg \sum m_{\mathrm{galaxies}}$$

Further evidence comes from observations of gravitational lensing of distant sources by a foreground cluster … thus enabling the cluster's gravitational potential to be reconstructed



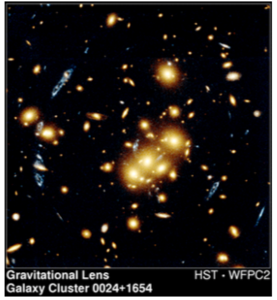
GRAVITATIONAL LENSING:

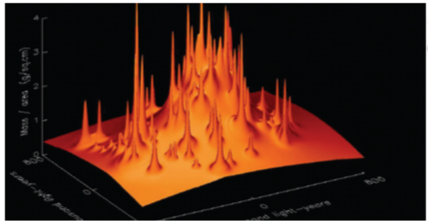
1 **A Distant Source**
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.

2 **A Lens Of 'Dark Matter'**
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.

3 **Focal Point: Earth**
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.

… the mass required vastly exceeds that in the galaxies

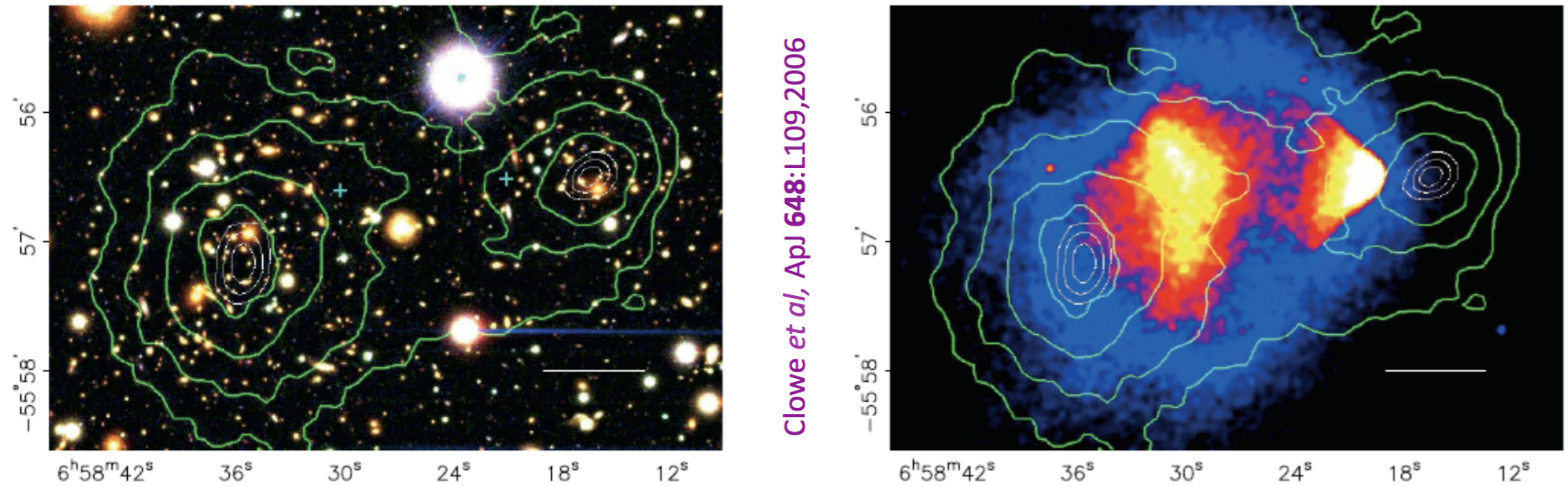




Source: Bell Labs, Lucent Technologies

Tony Tyson, Greg Kochanski and Ian Dell'Antonio
Frank O'Connell and Jim McManus/ The New York Times

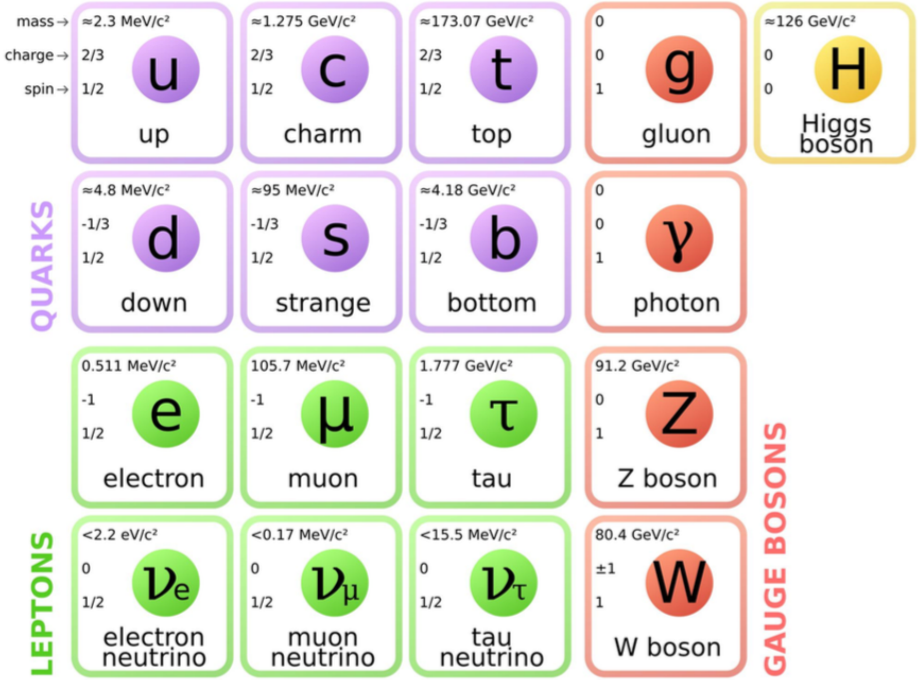
The Chandra picture of the ‘bullet cluster’ (1E 0657-558) shows that the X-ray emitting baryonic matter is *displaced* from the galaxies and the dark matter (inferred through gravitational lensing) … convincing evidence of dark matter?



Clowe *et al*, ApJ **648**:L109,2006

FIG. 1.—*Left panel*: Color image from the Magellan images of the merging cluster 1E 0657−558, with the white bar indicating 200 kpc at the distance of the cluster. *Right panel*: 500 ks *Chandra* image of the cluster. Shown in green contours in both panels are the weak-lensing κ reconstructions, with the outer contour levels at $\kappa = 0.16$ and increasing in steps of 0.07. The white contours show the errors on the positions of the κ peaks and correspond to 68.3%, 95.5%, and 99.7% confidence levels. The blue plus signs show the locations of the centers used to measure the masses of the plasma clouds in Table 2.

The standard model is the THEORY of elementary particles and their interactions (excluding gravity). It is a renormalizable relativistic quantum field theory with a gauge symmetry, part of it spontaneously broken by the “Higgs mechanism”, and the following particles



mass → charge → spin →	≈2.3 MeV/c² 2/3 1/2 u up	≈1.275 GeV/c² 2/3 1/2 c charm	≈173.07 GeV/c² 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c² 0 0 H Higgs boson
	≈4.8 MeV/c² -1/3 1/2 d down	≈95 MeV/c² -1/3 1/2 s strange	≈4.18 GeV/c² -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c² -1 1/2 e electron	105.7 MeV/c² -1 1/2 μ muon	1.777 GeV/c² -1 1/2 τ tau	91.2 GeV/c² 0 1 Z Z boson	
	<2.2 eV/c² 0 1/2 ν_e electron neutrino	<0.17 MeV/c² 0 1/2 ν_μ muon neutrino	<15.5 MeV/c² 0 1/2 ν_τ tau neutrino	80.4 GeV/c² ±1 1 W W boson	

Problems of the SM

So far the SM has been enormously successful, proven to be right in the 100's of experimental tests (maybe too successful at this point). But we believe it cannot be the last word.

- It does not include gravitational interactions

- Has many (too many?) free parameters: 20 for massless neutrinos + 7(9) for Dirac (Majorana) neutrinos. It does not explain why the electric charge of quarks is exactly related to that of electrons, so that atoms are neutral (in the SM this is an accident). There is no explanation of why there are 3 generations of repeated fermions and of their mass hierarchy.

- There is no explanation of neutrino masses.

- No solution for the "strong CP problem" (due to a term $\theta F_{\mu\nu} \widetilde{F^{\mu\nu}}$ in the QCD Lagrangian -only viable solution so far is to add a global Peccei-Quinn symmetry)

- There are no cold or warm Dark Matter particle candidates (so the bulk of the dark matter cannot be accounted for within the SM)

- There is no explanation of the Dark Energy

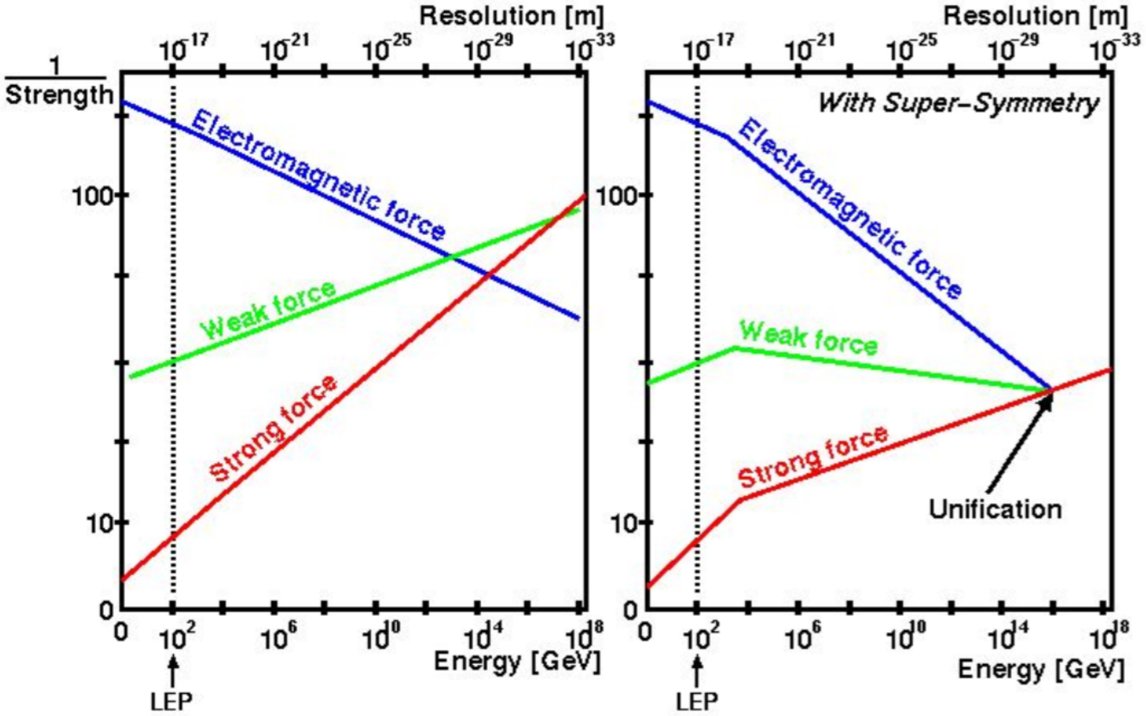
- Problem of stability of the Higgs mass if there is any physical scale Λ where new physics arises. The tree-level (bare) Higgs mass, the one which appears in the Lagrangian we dealt with, receives quadratically-divergent corrections from one loop diagrams, $M_H^2 = (M_H^2)_{bare} + O(\lambda, g^2, h^2)\Lambda^2$, which take the corrected mass to $O(\Lambda)$, much larger than measured

(Solutions: TeV scale supersymmmetry (so far not found by the LHC) where there is cancellation of fermionic and bosonic contributions to the loop, Little Higgs models, where the Higgs is light because it is almost a Goldstone boson... all already constrained by the LHC)

Ideas to go beyond the SM

- More symmetry

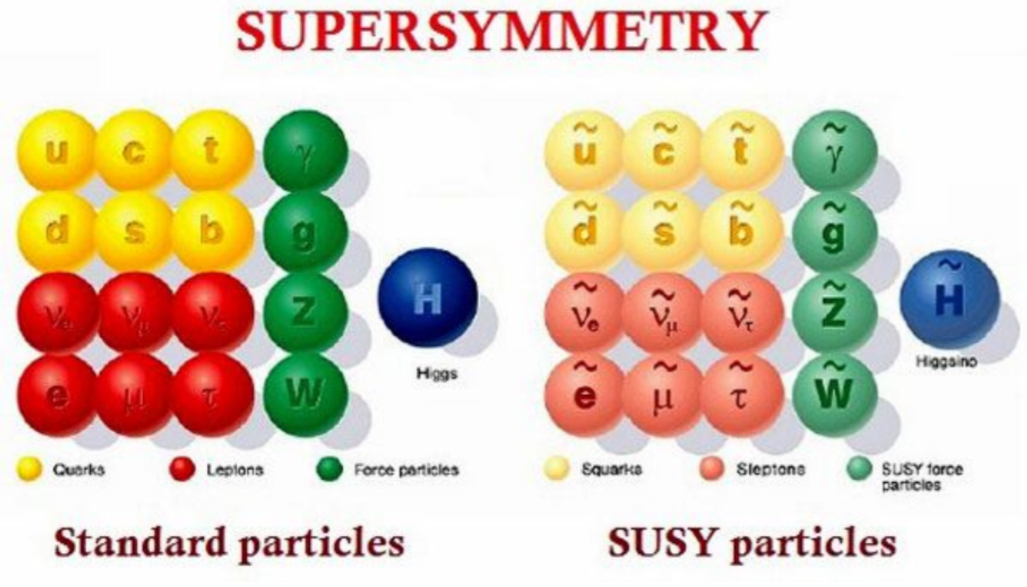
Grand Unified Theories (GUT), unifications of electroweak and strong interactions at high energies?



Ideas to go beyond the SM

- More symmetry

Supersymmetry (SUSY): Symmetry between bosons and fermions (need to duplicate all the particles of the SM, and at least an additional Higgs doublet)!



Astrophysics and Cosmology for Particle Physicists

Marc Kamionkowski
Johns Hopkins University

Dark matter properties:

- Must have no (or no more than very weak) coupling to photons
- Cross section for self-scattering must be $<10^{-24}$ cm^2
- Interactions with baryons must be very weak

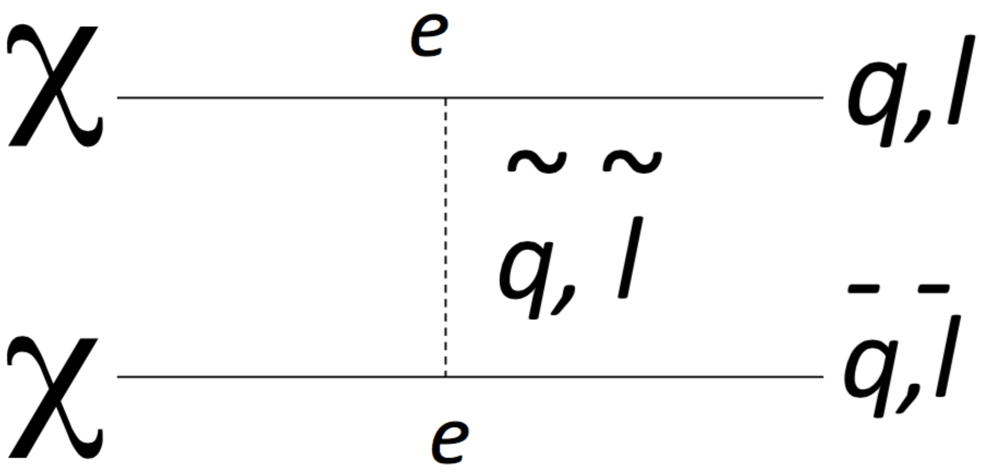
Supersymmetric models:

WIMP (weakly-interacting massive particle) is
neutralino = (photino + Z-ino + higgsino)

$$\tilde{\chi} = \xi_\gamma \tilde{\gamma} + \xi_Z \tilde{Z} + \xi_h \tilde{h}$$

Mass m_χ ~ 10s - 1000s GeV
Spin=1/2 (Majorana fermion)

WIMP interactions:



$$\alpha \sim \frac{1}{137}$$

$$m_{\tilde{q}} \sim 100\,\mathrm{GeV}$$

Cross Section:

$$\sigma \sim \frac{\alpha^2}{m_{\tilde{q}}^2} \sim 10^{-8}\,\mathrm{GeV}^{-2} \sim 10^{-36}\,\mathrm{cm}^2$$

WIMP Freezeout

Annihilation Rate

$$\Gamma(\chi\chi \leftrightarrow q\bar{q}, l\bar{l}, \cdots) = n_\chi \langle \sigma |v| \rangle$$

Expansion Rate

$$H = \left(\frac{8\pi G\rho}{3}\right)^{1/2} \propto T^2$$

Early Times:

$$k_B T \gg m_\chi c^2$$

$$n_\chi \propto T^3$$

$$\Gamma \gg H$$

Equilibrium Holds

Late Times:

$$k_B T \ll m_\chi c^2$$

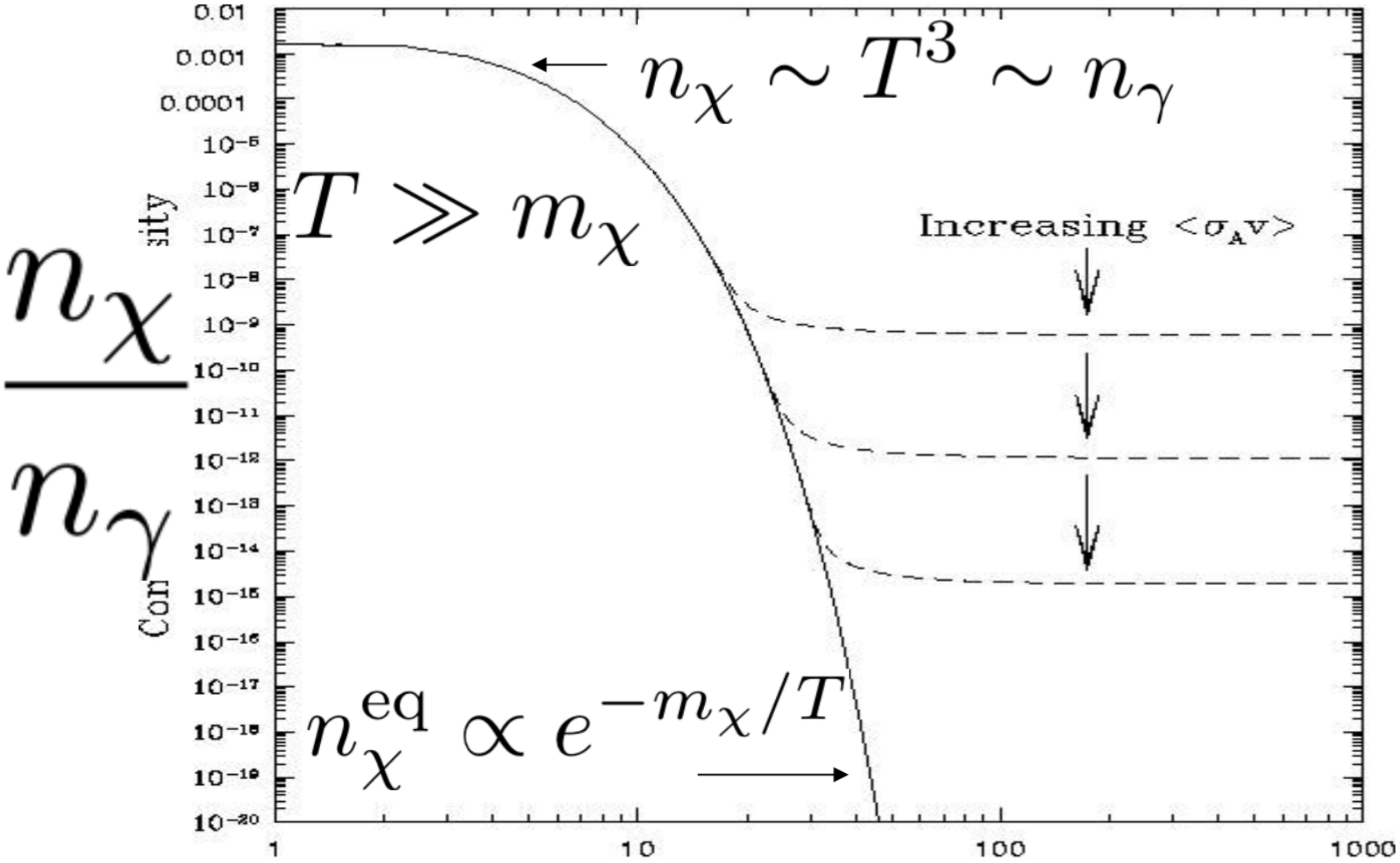
$$n_\chi^{\mathrm{eq}} \propto e^{-m_\chi/T}$$

$$\Gamma \ll H$$

Annihilations can not occur

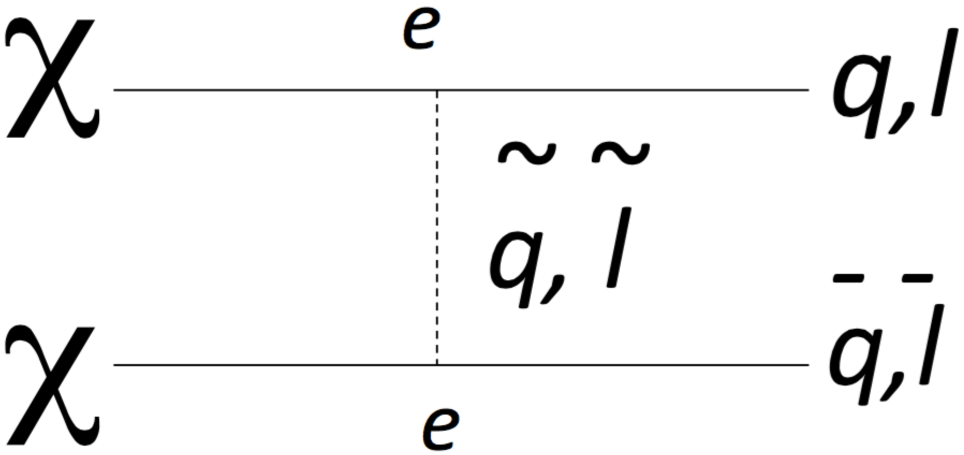
"Freezeout" at $$\Gamma(T_f) = H(T_f)$$

Afterwards, comoving WIMP # constant



Freezeout Calculation:

$$\Omega_\chi h^2 \simeq 0.1 \left(\frac{\langle \sigma v \rangle}{3\times 10^{-26}\,\mathrm{cm}^3\,\mathrm{sec}^{-1}} \right)^{-1}$$



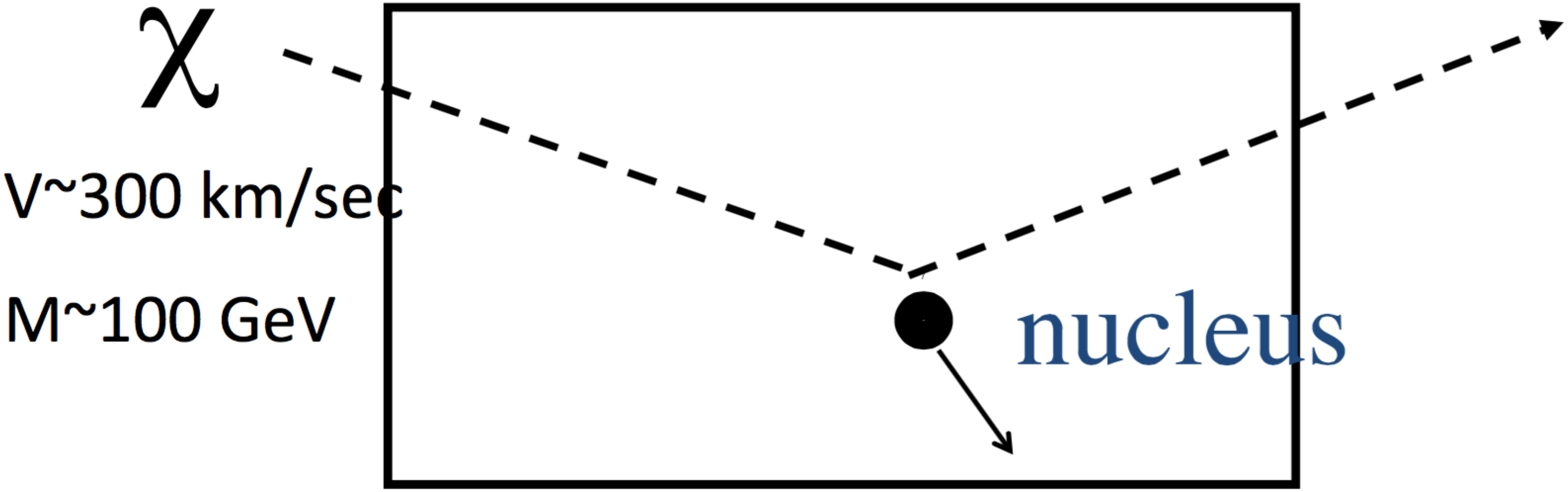
$$\sigma \sim \frac{\alpha^2}{m_\chi^2}$$

Direct detection:

$$\chi q \xrightarrow{\text{QCD}} \chi n \xrightarrow{\text{nuclear physics}} \chi N$$

$$\sigma_{\mathrm{WIMP-nucleus}} \sim 10^{-36}\,\mathrm{cm}^2$$

E.g., Ge or Xe detector


χ

V~300 km/sec

M~100 GeV

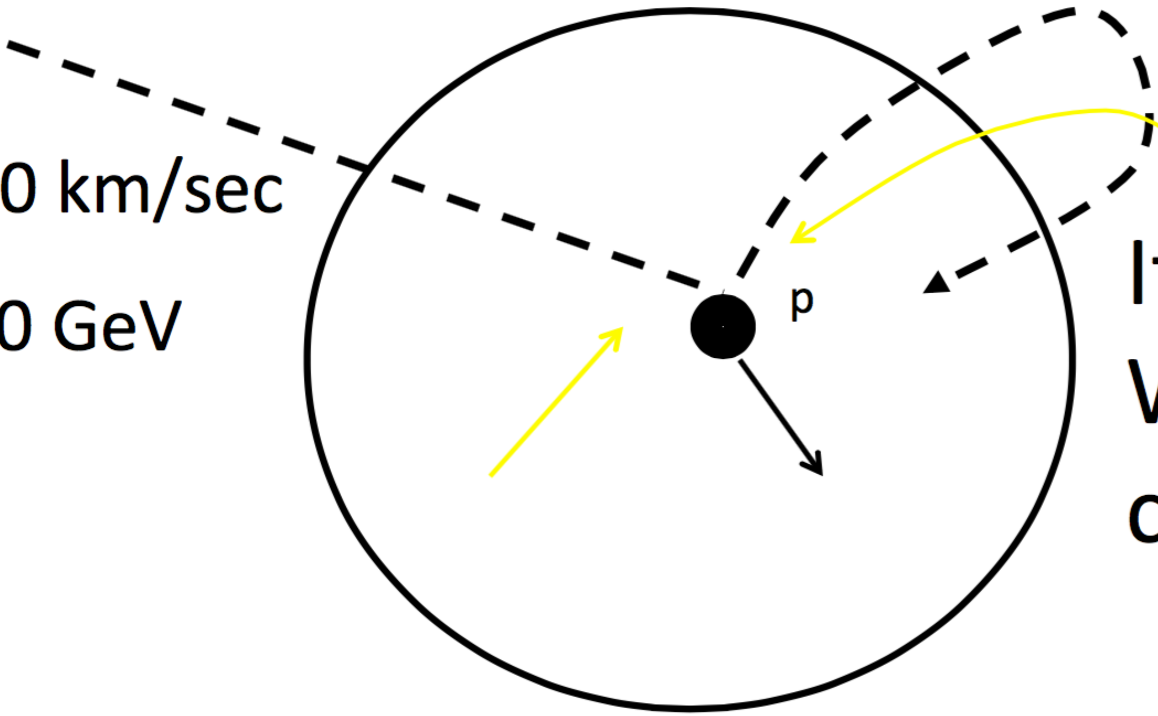
nucleus

$E_{recoil} \sim (1/2)mv^2 \sim 50$ keV

Rate:

$$\begin{aligned} n\sigma v N_{\rm nuclei} &\sim (10^{-36}\,{\rm cm}^2)\left(\frac{0.4\,{\rm GeV/cm}^3}{100\,{\rm GeV}}\right)(3\times10^7\,{\rm cm/sec})\left(\frac{6\times10^{23}\,{\rm kg}^{-1}}{A}\right) \\ &\sim {\rm few\ kg}^{-1}\ {\rm yr}^{-1} \end{aligned}$$

Indirect Detection: Energetic neutrinos from WIMP annihilation in Sun/Earth



χ

V_0~300 km/sec

M~100 GeV

If $v<v_{esc}$, WIMP captured

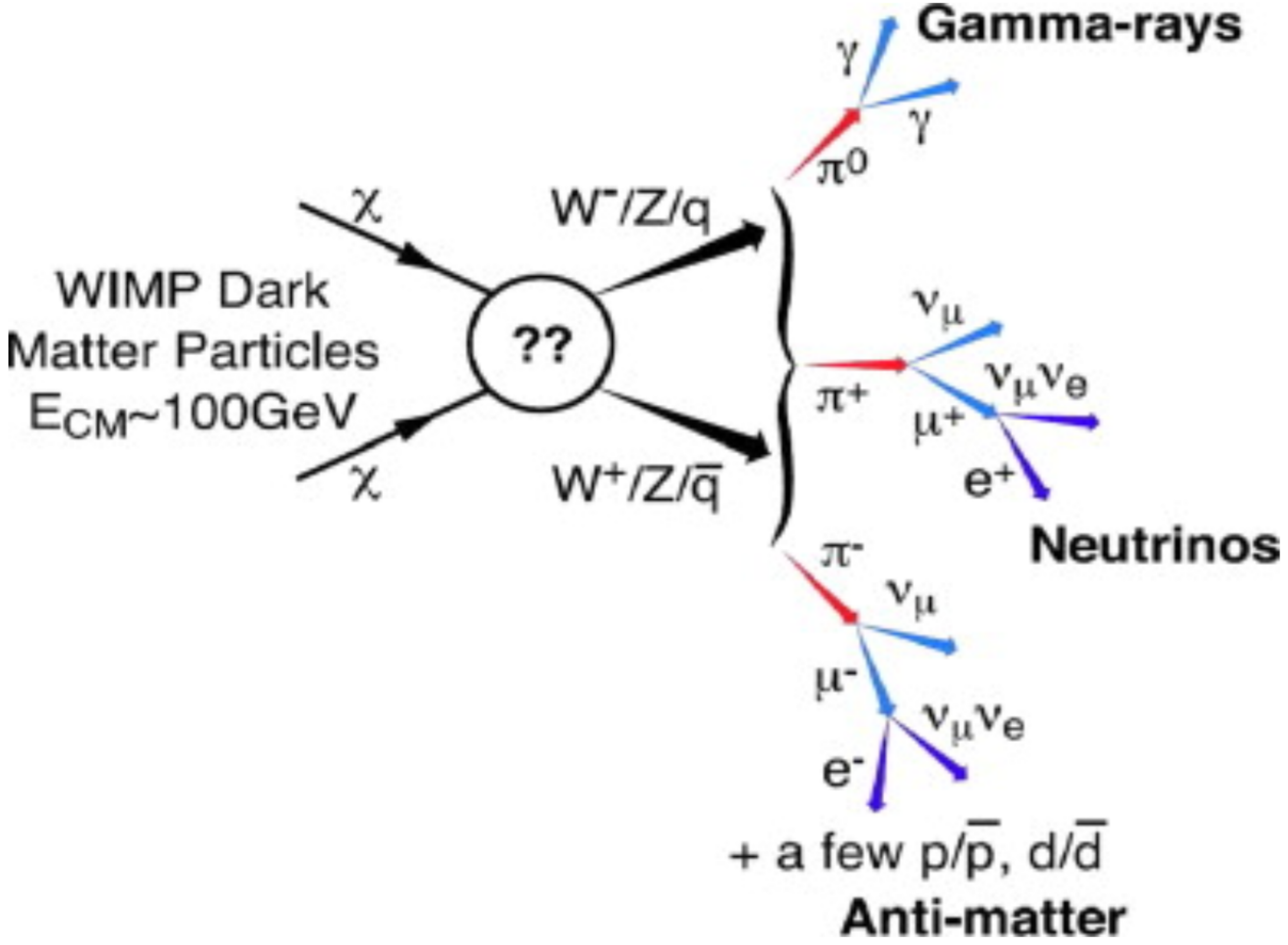
Inside Sun and/or Earth:

$$\chi\chi \to (W^+W^-, Z^0Z^0, q\bar{q}, l\bar{l}, \cdots) \to \nu\bar{\nu}$$

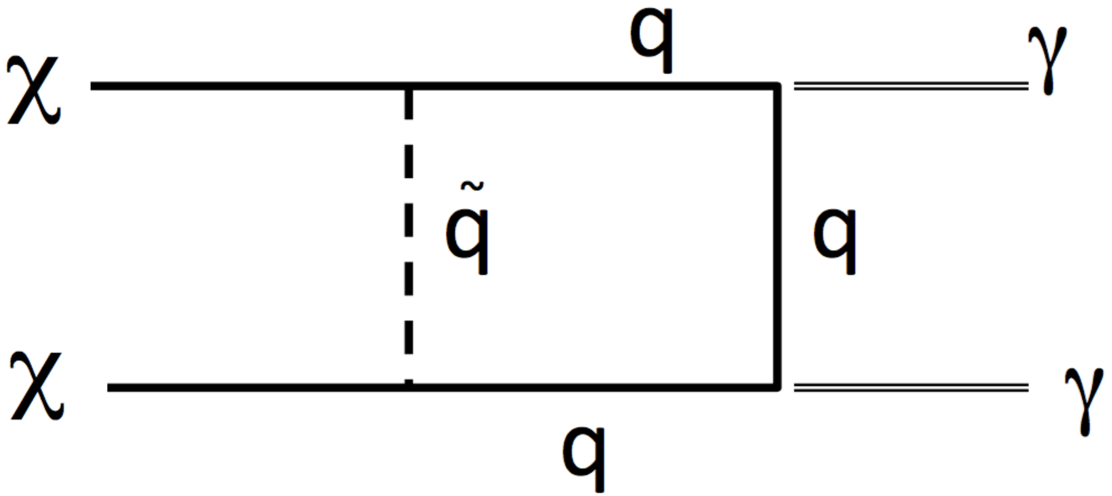
$$E_\nu \sim (1/10 - 1/2)m_\chi \sim 10 - 1000s\,\mathrm{GeV}$$

Neutrinos sought in, e.g., MACRO, IMB,
Super-Kamiokande, IceCube…..

Indirect detection: Exotic cosmic rays from WIMP annihilation in Galactic halo



Indirect Detection: Gamma-rays from WIMP annihilation in Galactic halo



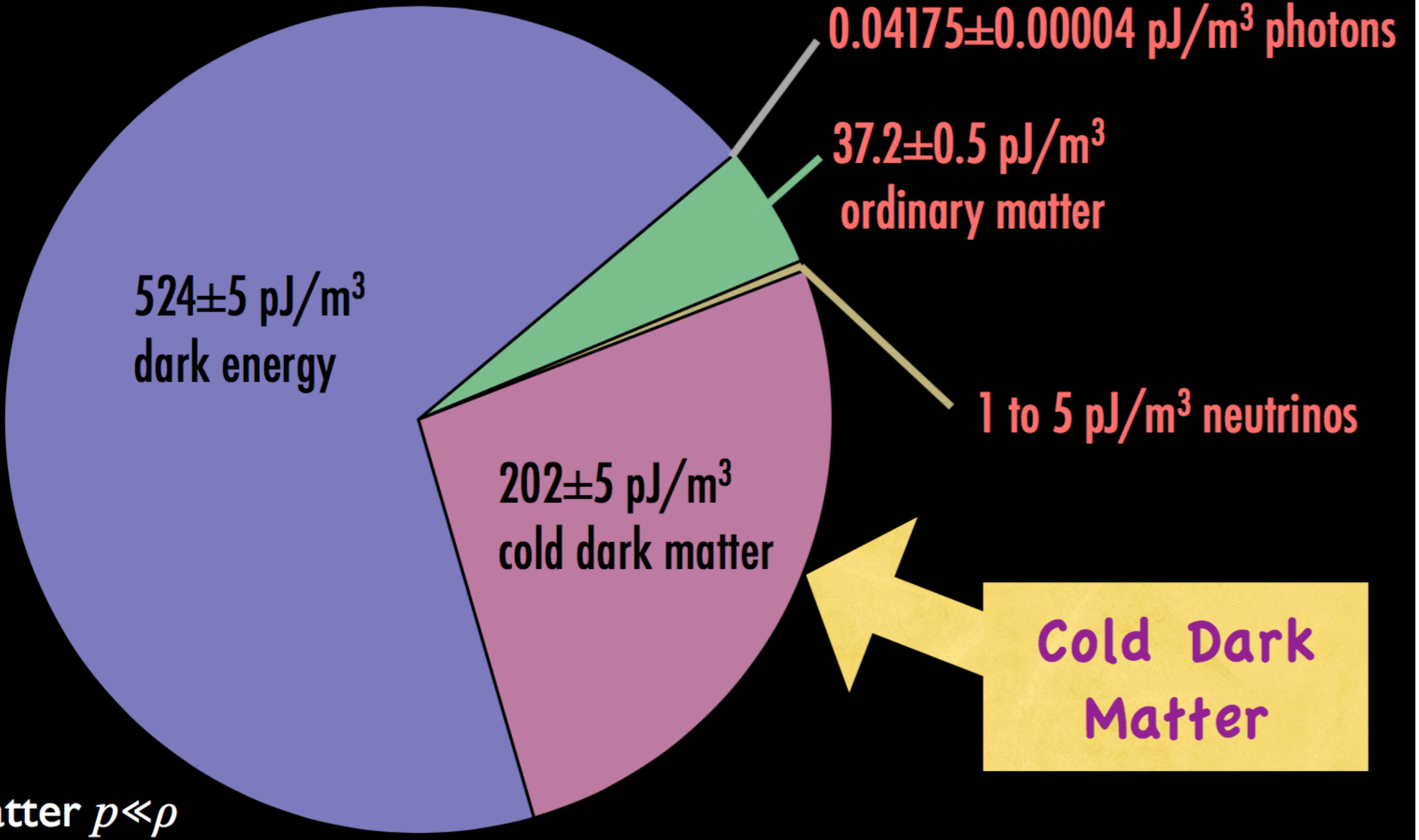
$$E_\gamma = m_\chi$$

Can be sought in Fermi, air Cherenkov telescopes (e.g, CTA)

Particle Physics Models for Dark Matter

Paolo Gondolo
University of Utah

The observed content of the Universe



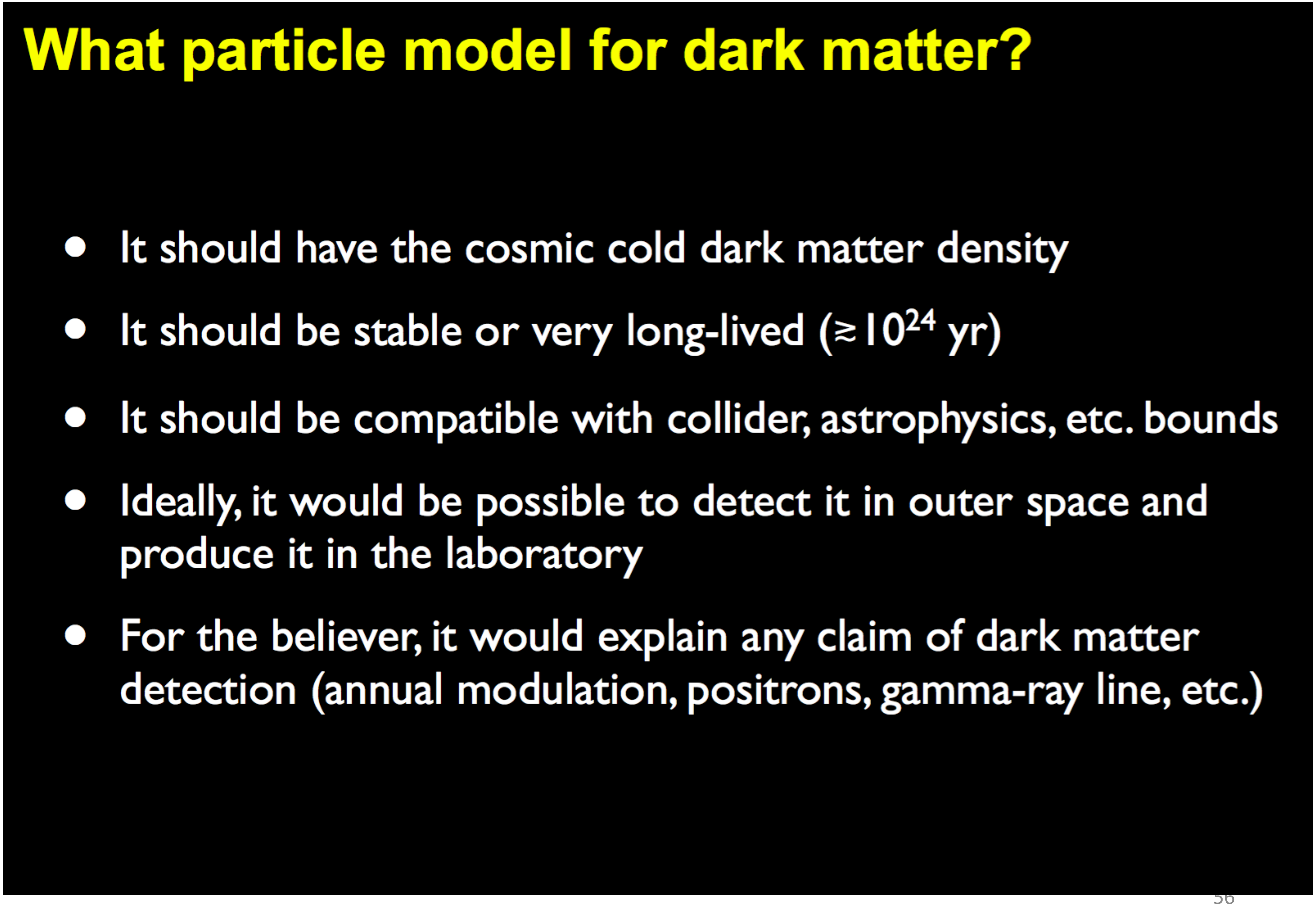
matter $p \ll \rho$

radiation $p = \rho/3$

vacuum $p = -\rho$

Planck (2013)

1 pJ = 10^{-12} J



What particle model for dark matter?

- It should have the cosmic cold dark matter density
- It should be stable or very long-lived ($\gtrsim 10^{24}$ yr)
- It should be compatible with collider, astrophysics, etc. bounds
- Ideally, it would be possible to detect it in outer space and produce it in the laboratory
- For the believer, it would explain any claim of dark matter detection (annual modulation, positrons, gamma-ray line, etc.)

Cold dark matter, *not* modified gravity

The Bullet Cluster

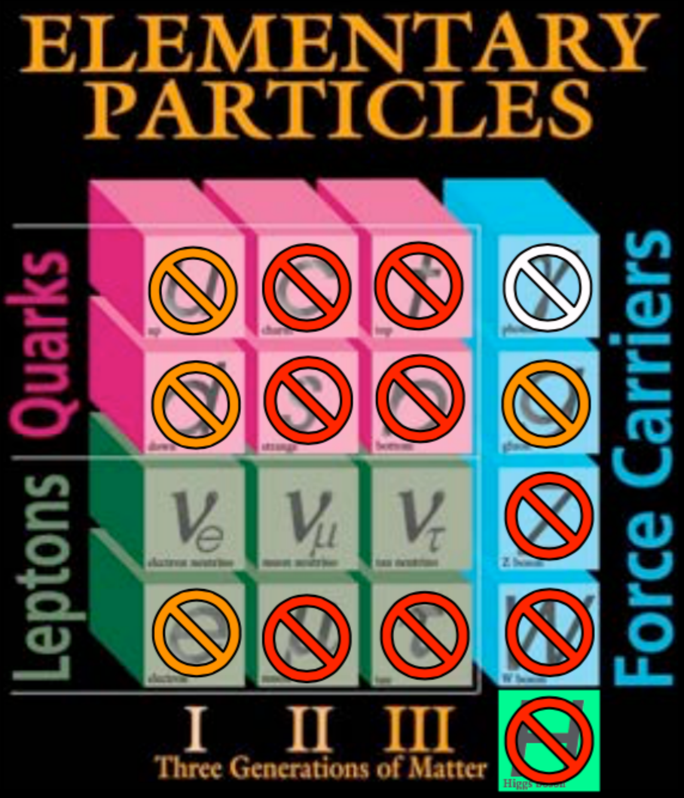
Symmetry argument: gas is at center, but potential has two wells.

Galaxies in optical (Hubble Space Telescope)

X-ray emitting hot gas (Chandra)

Gravitational potential from weak lensing

Which particle is cold dark matter?



🛇 is the particle of light

🛇 couples to the plasma

🛇 disappears too quickly

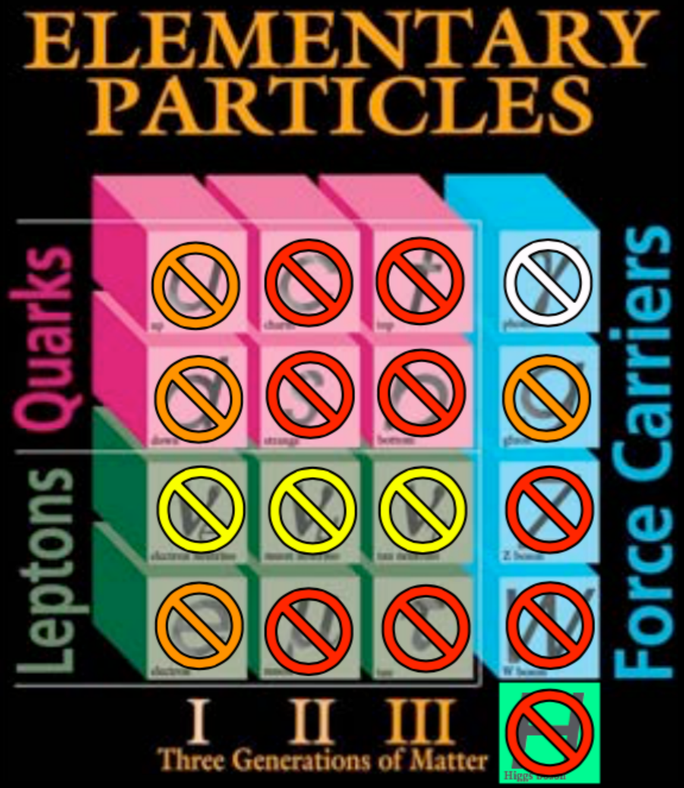
Known active neutrinos

- Neutrino oscillations (largest Δm^2 from SK+K2K+MINOS) place a lower bound on one of the neutrino masses, $m_\nu > 0.048$ eV
- Cosmology (CMB+LRG+H_0) places an upper bound on the sum of the neutrino masses, $\sum m_\nu < 0.44$ eV
- Therefore neutrinos are *hot dark matter* ($m_\nu \ll T_{eq}=1.28$ eV) with density $0.0005 < \Omega_\nu h^2 < 0.0047$

Detecting this Cosmic Neutrino Background (CNB) is a big challenge

Known neutrinos are hot dark matter

Which particle is cold dark matter?



⊘ is the particle of light

⊘ couples to the plasma

⊘ disappears too quickly

⊘ is hot dark matter

No known particle can be cold dark matter!

Particle dark matter

Thermal relics

in thermal equilibrium in the early universe

neutrinos, neutralinos, other WIMPs, ...

Non-thermal relics

never in thermal equilibrium in the early universe

axions, WIMPZILLAs, solitons, ...

Particle dark matter

Hot dark matter

- relativistic at kinetic decoupling (start of free streaming)
- big structures form first, then fragment

light neutrinos

Cold dark matter

- non-relativistic at kinetic decoupling
- small structures form first, then merge

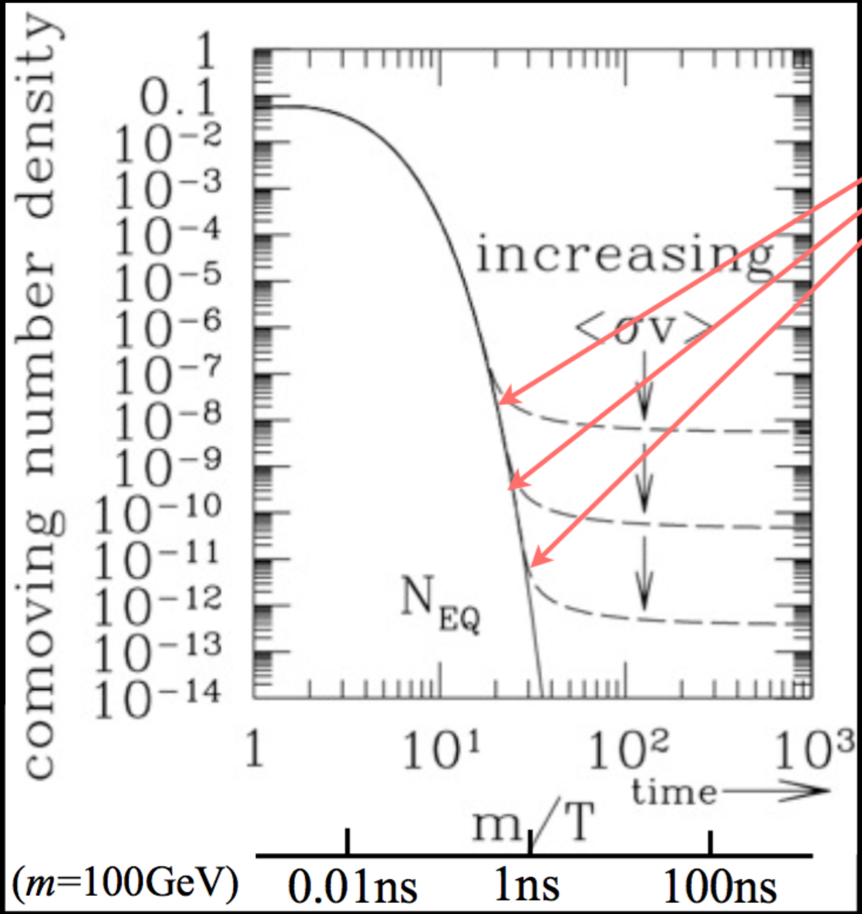
neutralinos, axions, WIMPZILLAs, solitons

Warm dark matter

- semi-relativistic at kinetic decoupling
- smallest structures are erased

sterile neutrinos, gravitinos

Cosmic density of heavy active neutrinos



freeze-out

$$\Gamma_{\rm ann} \equiv n\langle\sigma v\rangle \sim H$$

annihilation rate *expansion rate*

$$\boxed{\Omega_\chi h^2 \simeq \frac{3\times 10^{-27}\,{\rm cm}^3/{\rm s}}{\langle\sigma v\rangle_{\rm ann}}}$$

$$\Omega_\chi h^2 = \Omega_{\rm cdm} h^2 \simeq 0.1143$$

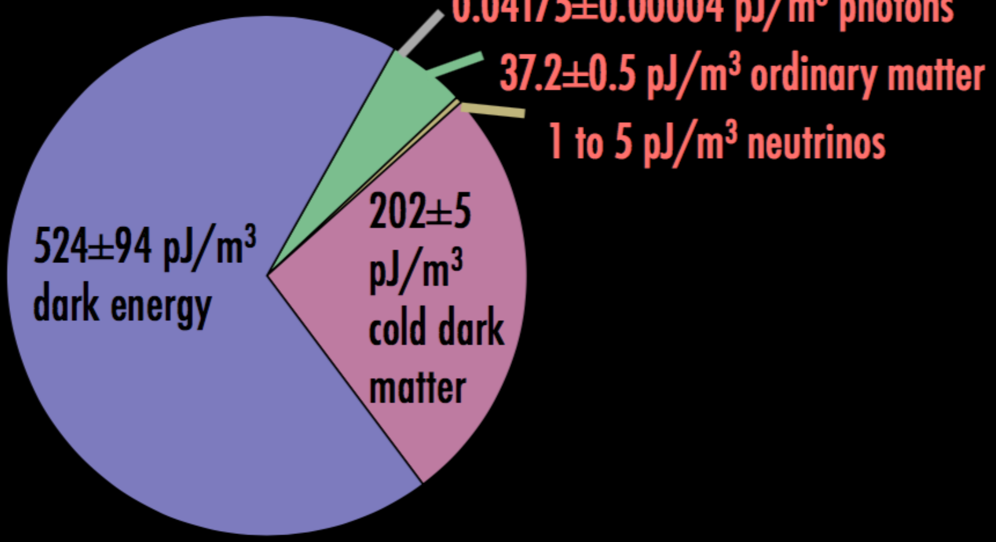
for $\langle\sigma v\rangle_{\rm ann} \simeq 3\times 10^{-26}\,{\rm cm}^3/{\rm s}$

This is is why they are called Weakly Interacting Massive Particles
(WIMPless candidates are WIMPs!)

The Magnificent WIMP
(Weakly Interacting Massive Particle)

- One naturally obtains the right cosmic density of WIMPs

  Thermal production in hot primordial plasma.



- One can experimentally test the WIMP hypothesis

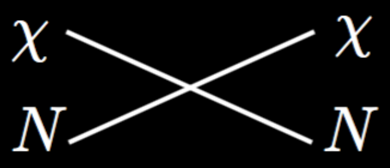
  The same physical processes that produce the right density of WIMPs make their detection possible

The magnificent WIMP

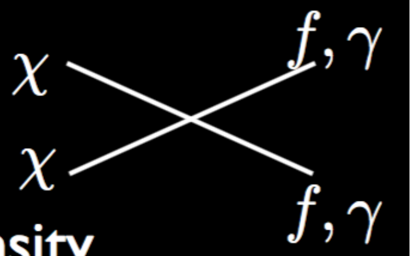
To first order, three quantities characterize a WIMP

- Mass m
  - Simplest models relate mass to cosmic density: $1-10^4$ GeV/c^2

- Scattering cross section off nucleons σ_{XN}
  - Usually different for protons and neutrons
  - Spin-dependent or spin-independent governs scaling to nuclei

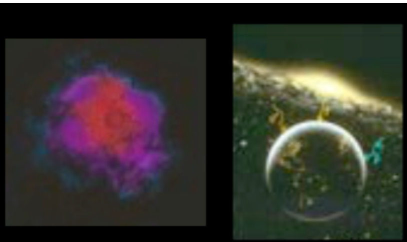


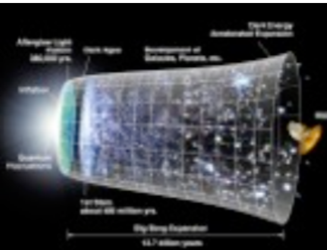
- Annihilation cross section into ordinary particles
  - $\sigma \simeq \text{const}/v$ at small v, so use σv
  - Simplest models relate cross section to cosmic density



The power of the WIMP hypothesis

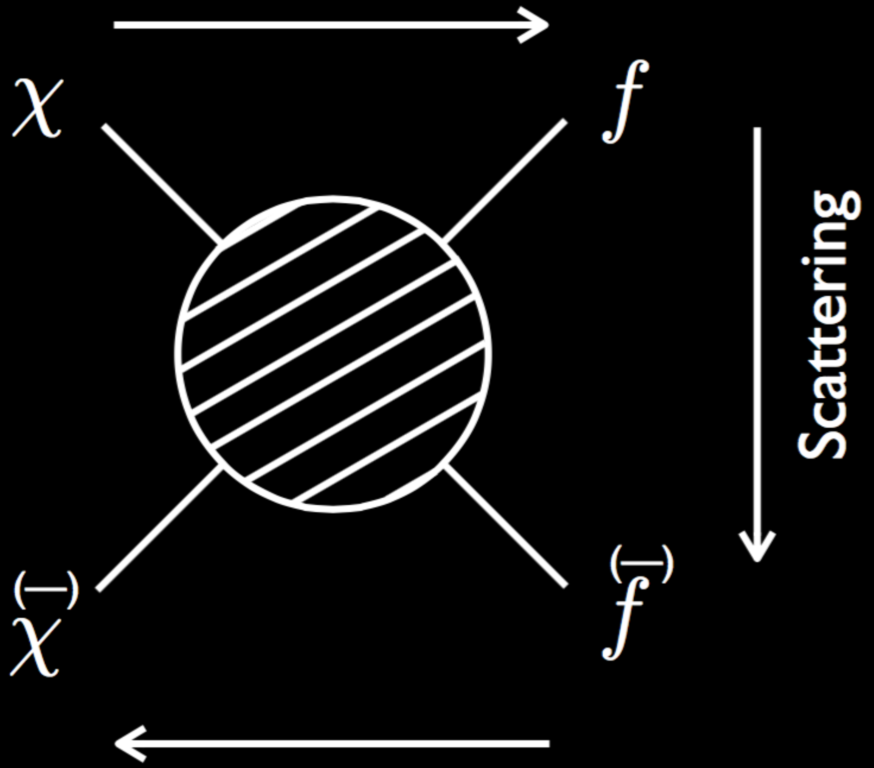
Indirect detection



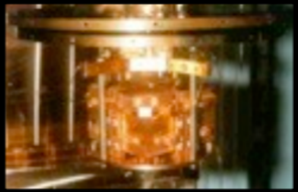


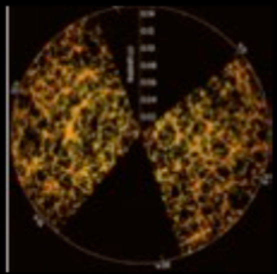
Cosmic density

Annihilation



Direct detection

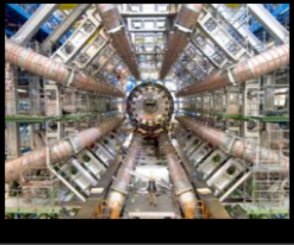


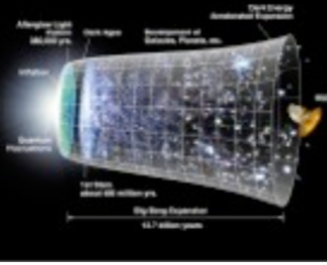


Large scale structure

Production

Colliders





Cosmic density

Supersymmetry

A supersymmetric transformation Q turns a bosonic state into a fermionic state, and viceversa.

$$Q|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle$$
$$Q|\mathrm{Fermion}\rangle = |\mathrm{Boson}\rangle$$

$$\{Q_\alpha, Q^\dagger_{\dot\alpha}\} = P_\mu \sigma^\mu_{\alpha\dot\alpha},\ \{Q_\alpha, Q_\beta\} = \{Q^\dagger_{\dot\alpha}, Q^\dagger_{\dot\beta}\} = 0,\ [P^\mu, Q_\alpha] = [P^\mu, Q^\dagger_{\dot\alpha}] = 0$$

A supersymmetric theory is invariant under supersymmetry transformations

- bosons and fermions come in pairs of equal mass
- the interactions of bosons and fermions are related

Supersymmetric dark matter

Neutralinos (the most fashionable/studied WIMP)

Goldberg 1983; Ellis, Hagelin, Nanopoulos, Olive, Srednicki 1984; etc.

Sneutrinos (also WIMPs)

Falk, Olive, Srednicki 1994; Asaka, Ishiwata, Moroi 2006; McDonald 2007; Lee, Matchev, Nasri 2007; Deppisch, Pilaftsis 2008; Cerdeno, Munoz, Seto 2009; Cerdeno, Seto 2009; etc.

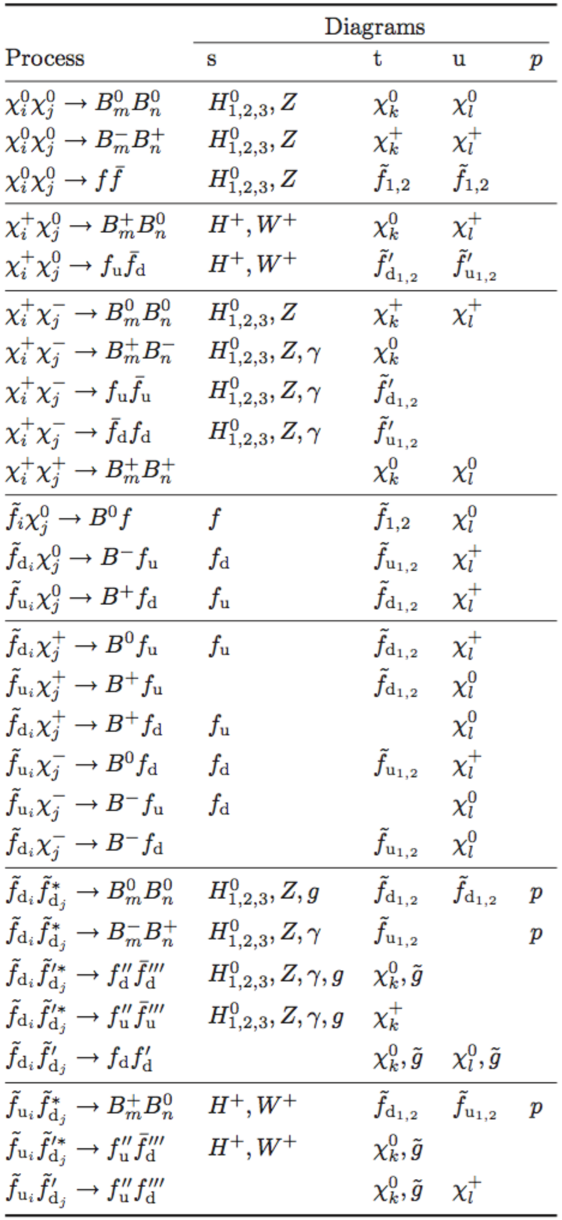
Gravitinos (SuperWIMPs)

Feng, Rajaraman, Takayama 2003; Ellis, Olive, Santoso, Spanos 2004; Feng, Su, Takayama, 2004; etc.

Axinos (SuperWIMPs)

Tamvakis, Wyler 1982; Nilles, Raby 1982; Goto, Yamaguchi 1992; Covi, Kim, Kim, Roszkowski 2001; Covi, Roszkowski, Ruiz de Austri, Small 2004; etc.

Neutralino dark matter



	Diagrams			
Process	s	t	u	p
$\chi_i^0\chi_j^0 \to B_m^0 B_n^0$	$H_{1,2,3}^0, Z$	χ_k^0	χ_l^0	
$\chi_i^0\chi_j^0 \to B_m^- B_n^+$	$H_{1,2,3}^0, Z$	χ_k^+	χ_l^+	
$\chi_i^0\chi_j^0 \to f\bar{f}$	$H_{1,2,3}^0, Z$	$\tilde{f}_{1,2}$	$\tilde{f}_{1,2}$	
$\chi_i^+\chi_j^0 \to B_m^+ B_n^0$	H^+, W^+	χ_k^0	χ_l^+	
$\chi_i^+\chi_j^0 \to f_\mathrm{u}\bar{f}_\mathrm{d}$	H^+, W^+	$\tilde{f}'_{\mathrm{d}_{1,2}}$	$\tilde{f}'_{\mathrm{u}_{1,2}}$	
$\chi_i^+\chi_j^- \to B_m^0 B_n^0$	$H_{1,2,3}^0, Z$	χ_k^+	χ_l^+	
$\chi_i^+\chi_j^- \to B_m^+ B_n^-$	$H_{1,2,3}^0, Z, \gamma$	χ_k^0		
$\chi_i^+\chi_j^- \to f_\mathrm{u}\bar{f}_\mathrm{u}$	$H_{1,2,3}^0, Z, \gamma$	$\tilde{f}'_{\mathrm{d}_{1,2}}$		
$\chi_i^+\chi_j^- \to \bar{f}_\mathrm{d} f_\mathrm{d}$	$H_{1,2,3}^0, Z, \gamma$	$\tilde{f}'_{\mathrm{u}_{1,2}}$		
$\chi_i^+\chi_j^+ \to B_m^+ B_n^+$		χ_k^0	χ_l^0	
$\tilde{f}_i\chi_j^0 \to B^0 f$	f	$\tilde{f}_{1,2}$	χ_l^0	
$\tilde{f}_{\mathrm{d}_i}\chi_j^0 \to B^- f_\mathrm{u}$	f_d	$\tilde{f}_{\mathrm{u}_{1,2}}$	χ_l^+	
$\tilde{f}_{\mathrm{u}_i}\chi_j^0 \to B^+ f_\mathrm{d}$	f_u	$\tilde{f}_{\mathrm{d}_{1,2}}$	χ_l^+	
$\tilde{f}_{\mathrm{d}_i}\chi_j^+ \to B^0 f_\mathrm{u}$	f_u	$\tilde{f}_{\mathrm{d}_{1,2}}$	χ_l^+	
$\tilde{f}_{\mathrm{u}_i}\chi_j^+ \to B^+ f_\mathrm{u}$		$\tilde{f}_{\mathrm{d}_{1,2}}$	χ_l^0	
$\tilde{f}_{\mathrm{d}_i}\chi_j^+ \to B^+ f_\mathrm{d}$	f_u		χ_l^0	
$\tilde{f}_{\mathrm{u}_i}\chi_j^- \to B^0 f_\mathrm{d}$	f_d	$\tilde{f}_{\mathrm{u}_{1,2}}$	χ_l^+	
$\tilde{f}_{\mathrm{u}_i}\chi_j^- \to B^- f_\mathrm{u}$	f_d		χ_l^0	
$\tilde{f}_{\mathrm{d}_i}\chi_j^- \to B^- f_\mathrm{d}$		$\tilde{f}_{\mathrm{u}_{1,2}}$	χ_l^0	
$\tilde{f}_{\mathrm{d}_i}\tilde{f}^*_{\mathrm{d}_j} \to B_m^0 B_n^0$	$H_{1,2,3}^0, Z, g$	$\tilde{f}_{\mathrm{d}_{1,2}}$	$\tilde{f}_{\mathrm{d}_{1,2}}$	p
$\tilde{f}_{\mathrm{d}_i}\tilde{f}^*_{\mathrm{d}_j} \to B_m^- B_n^+$	$H_{1,2,3}^0, Z, \gamma$	$\tilde{f}_{\mathrm{u}_{1,2}}$		p
$\tilde{f}_{\mathrm{d}_i}\tilde{f}'^*_{\mathrm{d}_j} \to f''_\mathrm{d}\bar{f}'''_\mathrm{d}$	$H_{1,2,3}^0, Z, \gamma, g$	$\chi_k^0, \tilde{g}$		
$\tilde{f}_{\mathrm{d}_i}\tilde{f}'^*_{\mathrm{d}_j} \to f''_\mathrm{u}\bar{f}'''_\mathrm{u}$	$H_{1,2,3}^0, Z, \gamma, g$	χ_k^+		
$\tilde{f}_{\mathrm{d}_i}\tilde{f}'_{\mathrm{d}_j} \to f_\mathrm{d} f'_\mathrm{d}$		$\chi_k^0, \tilde{g}$	$\chi_l^0, \tilde{g}$	
$\tilde{f}_{\mathrm{u}_i}\tilde{f}^*_{\mathrm{d}_j} \to B_m^+ B_n^0$	H^+, W^+	$\tilde{f}_{\mathrm{d}_{1,2}}$	$\tilde{f}_{\mathrm{u}_{1,2}}$	p
$\tilde{f}_{\mathrm{u}_i}\tilde{f}'^*_{\mathrm{d}_j} \to f''_\mathrm{u}\bar{f}'''_\mathrm{d}$	H^+, W^+	$\chi_k^0, \tilde{g}$		
$\tilde{f}_{\mathrm{u}_i}\tilde{f}'_{\mathrm{d}_j} \to f''_\mathrm{u} f'''_\mathrm{d}$		$\chi_k^0, \tilde{g}$	χ_l^+	

Cosmic density

Thousands of annihilation (and coannihilation) processes

Use publicly-available computer codes, e.g. DarkSUSY, micrOMEGAs

Direct Dark Matter Searches

0- Context

1- Elastic scattering rates

2- Detection principle: signal and backgrounds

3- Review of current experiments

J. Gascon
UCB Lyon 1, CNRS/IN2P3/IPNL

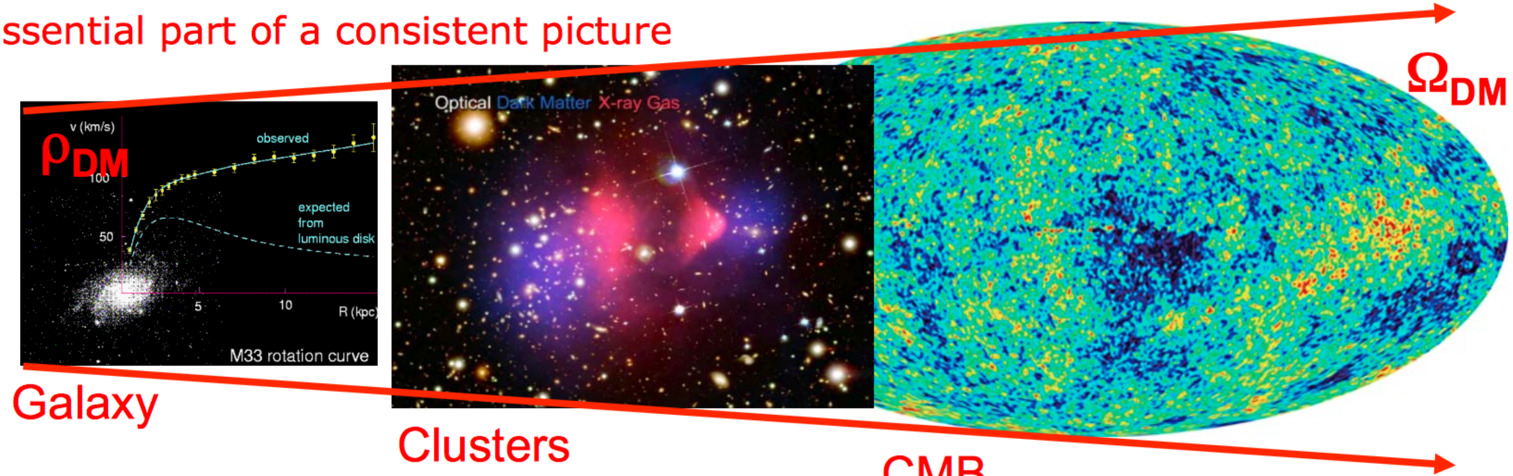
Recommended reading

- *Particle Dark Matter : observations, models and searches*, G. Bertone (dir.), Cambridge University Press, 2010.
  - *Recent and complete review of direct dark matter searches*
- *Supersymmetric Dark Matter*, G. Jungman, M. Kamionkowski and K. Griest, Phys. Rep. **267**, 195 (1996).
  - *First comprehensive reviews on all aspects of supersymmetric dark matter and its detection*
- *Particle Dark Matter: Evidence, Candidates and Constraints*, G. Bertone, D. Hooper, and J. Silk, Phys. Rep. **405**, 279 (2005).
  - *A more recent reviews on dark matter and its detection*
- *Review of mathematics, numerical factors, and corrections for dark matter experiments based on elastic nuclear recoils*, J. D. Lewin and P. F. Smith, Astropart. Phys. **6**, 87 (1996).
  - *Complete – and easy to follow – presentation of all ingredients needed to calculate experimental recoil spectra in a given detector for a given WIMP model. Must-read for all.*
- Particle Data Group: sections *Cosmology*, *Dark Matter* et *Detectors for non-accelerators physics*
  - http://pdg.lbl.gov/

Cold Dark Matter in the Universe

- Cold Dark Matter present at all scales in the Universe…

Essential part of a consistent picture



ρ_{DM}

Ω_{DM}

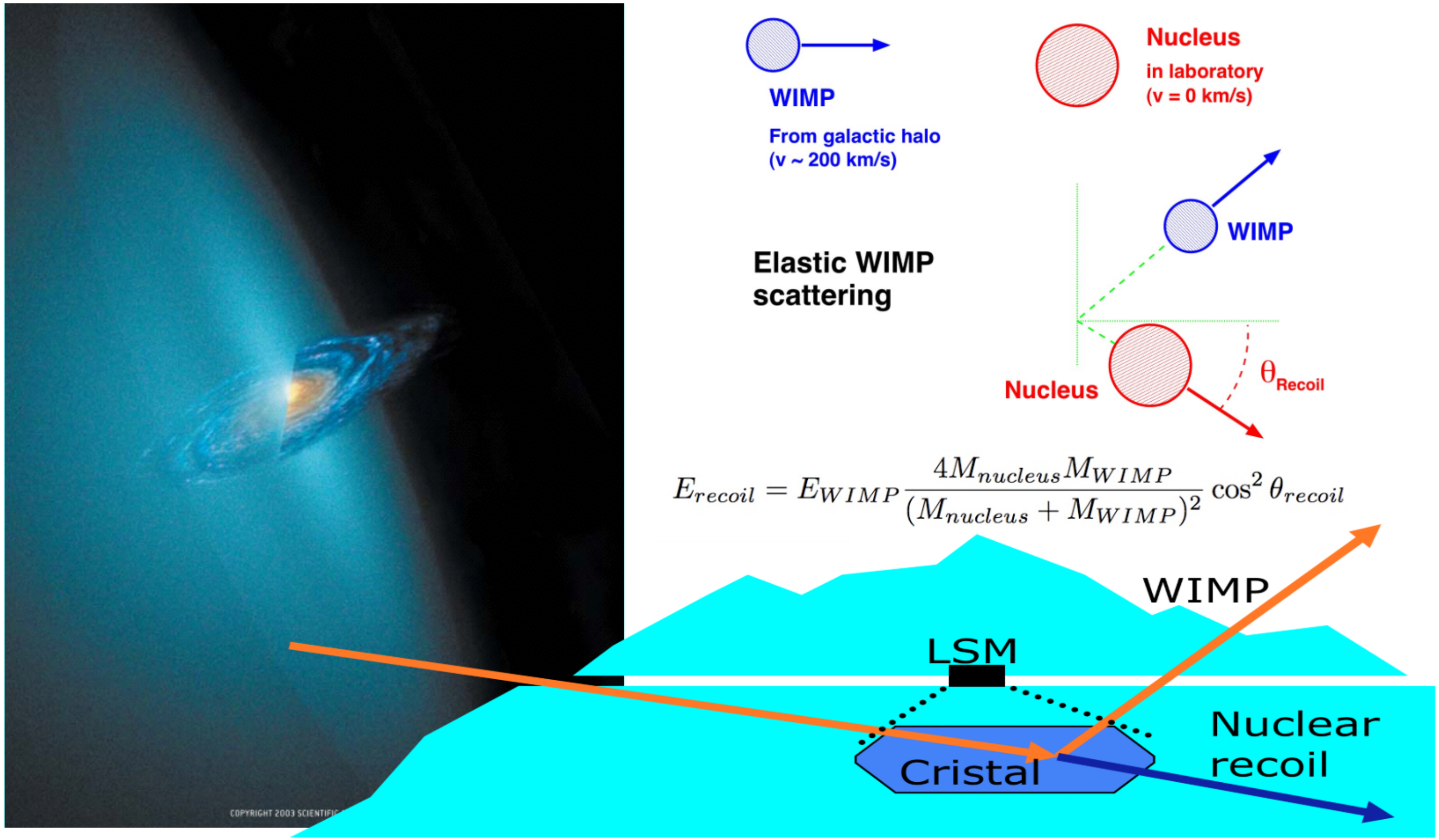
Galaxy

Clusters

CMB

- Searched as a new particle at LHC
- Searched via the remains of its decay in cosmic rays (γ, ν, e+, antimatter)
- *… Direct seach: collision of WIMPs from our galactic halo on target nuclei I a laboratory on Earth*
  - Proof that Dark Matter is present in our environment
  - After discovery: observatory for WIMP velocity distribution in our environment?
  - Sensitive to local WIMP density ρ_{DM} (not to the cosmological density Ω_{DM})

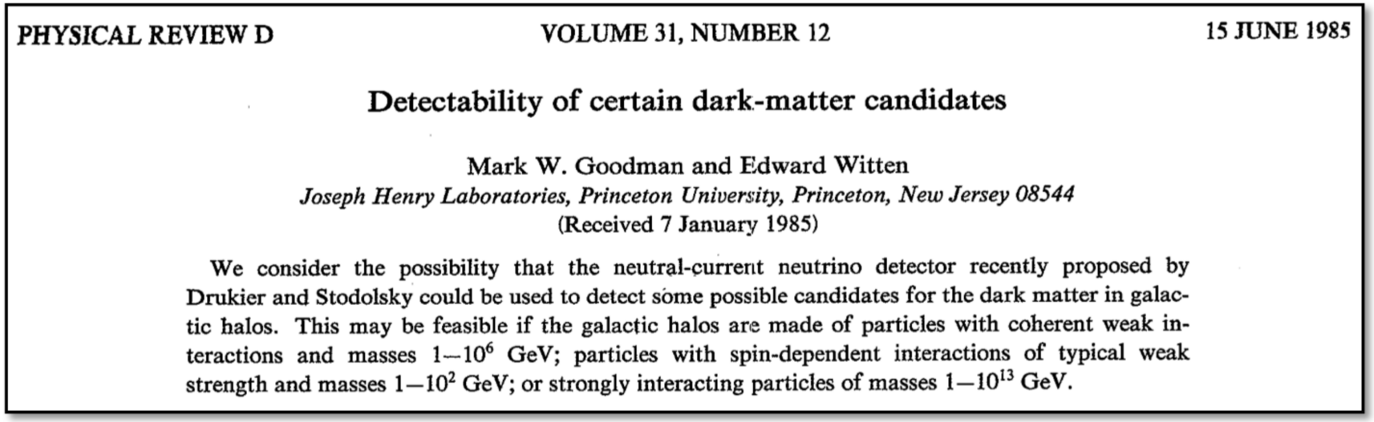
Direct search schematics



$$E_{recoil} = E_{WIMP} \frac{4M_{nucleus}M_{WIMP}}{(M_{nucleus} + M_{WIMP})^2} \cos^2 \theta_{recoil}$$

Observables: Event rate, E_{recoil} , θ_{recoil} (recoil range is related to E_{recoil})

Historical notes



PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses 1—10^6 GeV; particles with spin-dependent interactions of typical weak strength and masses 1—10^2 GeV; or strongly interacting particles of masses 1—10^{13} GeV.

Method suggested in 1985 (28 years ago!) by Goodman + Witten

- Predict rates between 4 and 1400 events/kg/day for heavy ν.
  M_ν = 100 TeV ↵ ↳ M_ν = 100 GeV

- As early as 1987, first significant constraints (*exclusion of a heavy ν*) with ionization Ge and Si detectors: sensitivity to ~ few evts/kg/day
  - Ge: S. P. Ahlen, et al., Phys. Lett. B 195 (1987) 603
  - Ge: D. O. Caldwell, et al., Phys. Rev. Lett., 61 (1988) 510
  - Si: D. O. Caldwell, et al., Phys. Rev. Lett. 65 (1990) 1305
- To do better, need better rejection of radioactive backgrounds
  - Competition between techniques: Pulse-shape discrimination in NaI? Phonon+ Ionization detectors *[Shutt et al, PRL 69 (1992) 3531]*? CsI? Liquid Ar? 2-phase Xenon? Bubbles? Etc …

Basic questions

- Direct Dark Matter searches are simple: just look at a large number of nuclei and see if any of them recoils due to a hit-and-run collision with a WIMP, but…

- How many such events can we expect per unit time and per number of target nuclei?

- How big is the kinetic energy involved in such collisions?

- What is the fake rate and how can we reject it?

Scattering probability

- Collision rate (per unit time) R:

$$\mathbf{R = \varphi\ \sigma_A\ N_{target}}$$

φ = WIMP flux (WIMP/cm^2/s) = $(\rho_W/M_W)\ v$

σ_A = cross-section for the elastic scattering of a WIMP on a nucleus (cm^2, barn or picobarn) 1 pb = 10^{-36} cm^2

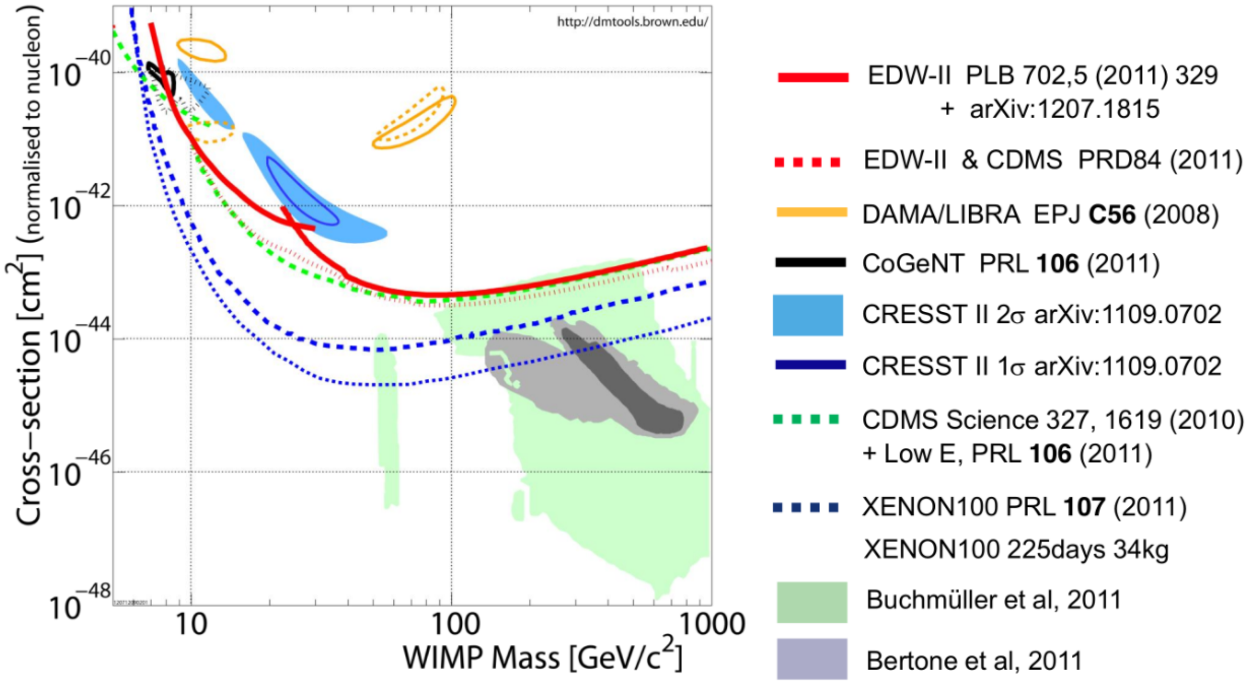
N_{target} = number of target nuclei exposed to the flux φ

➔ Need massive detectors (N_{target})

The search domain

- We don't know (yet) what is the mass of the WIMPs
- We don't know (yet) what is the cross-section for WIMP-nucleus scattering
- Generic searches for ALL WIMPs masses M_W and ALL cross-section σ.
- A given experiment will be able to probe a certain region of (M_W, σ):

"exclusion plots"

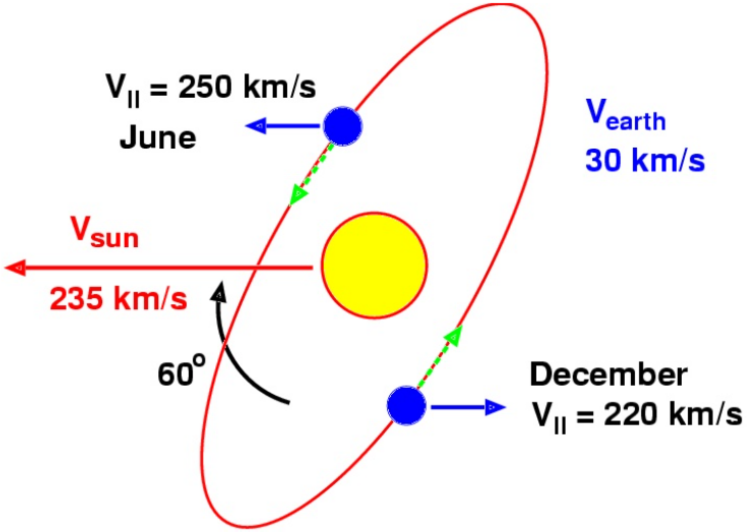


Flux: WIMP velocity distributions

- Exact calculation extremely difficult
  - N-body calculation, N=∞, Gravity range = ∞
  - No dissipation: WIMPs don’t “stick” together as ordinary matter
- Equilibrium: Kinetic energy ~ -Potential energy/2
- Simplest (crudest) case: spherical isothermal halo
  - Maxwellian velocity distribution: $\frac{dP(v)}{v^2 dv} = \frac{1}{(\pi v_0^2)^{3/2}} \exp(-\frac{v^2}{v_0^2})$
  - $v_0 \sim 220$ km/s ($v_{rms} =$ sqrt(3/2)v_0 = 270 km/s)
  - Truncated to escape velocity from Galaxy ($v_{esc} \sim 544$ km/s)
- More realistic halo model: heated debate
  - Central cusp? clumps? triaxial? caustics? tidal flows? Comoving?
  - Direct search mostly sensitive to *average* v^2 (if not too clumpy)

Sun and Earth velocities

- Sun around the galaxy: ~235 km/s
- $\exp(-v^2/v_0^2) \rightarrow \exp(-|\vec{v}+\vec{v}_{||}|^2/v_0^2)$ (energy boost)
- Earth around the sun: 30 km/s (~60° to Galactic plane)



f (v) =

f (v; v_o, v_{escape}, v_{sun}, v_{earth})

- Annual modulation of ± 7% of $v_{||}$ → ~ ± 3% on WIMP flux
- Modulation more sensitive to detailed halo model

Kinematics

- For M_{WIMP} ~ 100 GeV/c^2 and v_{WIMP} ~ 200 km/s:
- (v_{WIMP}/c) = 0.7 %

Good news #1: non relativistics! Use Newtonian kinematics…

- $M_{WIMP} = 10^{+8}$ keV/c^2
- $E_{kinetic} = ½\ M_{WIMP}\ (v/c)^2 = 22$ keV

Good news #2: a single 22 keV deposit is detectable in (good) conventional detectors used in nuclear physics

- Momentum = pc = sqrt(2 M_{WIMP} v_{WIMP} c) ~ 66 MeV
- Associated wavelenght $\lambda = h/p$ ~ 20 fm : larger but comparable to nuclear radii (2-7 fm)

~Good news #3: we can first consider the whole nucleus as a "point-like" particle but will need to consider quantum physics corrections

Total scattering rate (1)

- We want a rate R per unit time and per kilograms, for a target of atomic mass A (in a.m.u.=g/mol).

  $R = (1000\ N_0/A)\ \sigma_0\ \phi$ $(N_0 = 6.022\text{x}10^{23})$

- The flux is due to n_0 WIMP per volume, $n_0 = \rho_{WIMP}/M_{WIMP}$
- σ_0 = scattering cross-section on a *nucleus*:.

- Must integrate over the velocity distribution. Contribution *d*R from the flux $n_0\ v\ dP(v)$ of WIMPs with velocity v:

  $dR = (N_0/A)\ \sigma_0\ n_0\ v\ dP(v)$

- Total rate is thus obtained by averaging v over P(v)

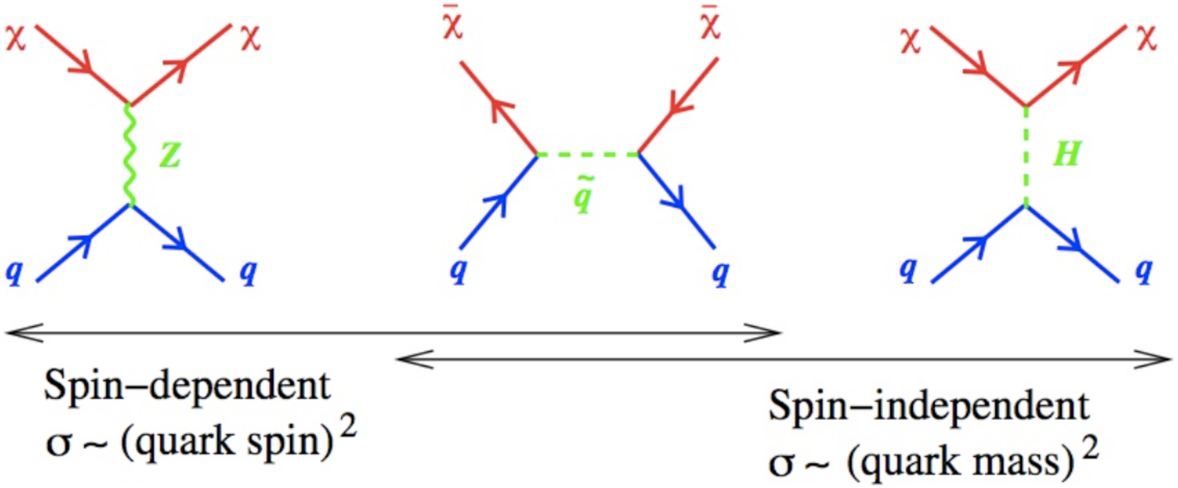
  $R = (N_0/A)\ \sigma_0\ n_0 <v>$

Cross-sections

- Now that we know how to hande the WIMP flux in our calculation, let’s turn to the cross-section
- So far σ_0 was a cross-section for the scattering on a *nucleus* with A nucleons, of radius $r \ll h/p_{WIMP}$
- Fundamental particle physics theories (for example: the WIMP is a neutralino χ) begin with a prediction for a scattering cross-section on a *quark*
  - *Hadronic physics* will give what is the relation between this cross-section and the cross-section on a *nucleon* (n or p)
  - *Nuclear physics* will give what is the relation of this second cross-section with the one for a nucleus containing Z protons and (A-Z) neutrons

From the quark to a nucleon (1)

- χ-nucleon scattering cross-section can be calculated within SUSY



- Separation spin dependent (SD) / independent (SI): most general expression for most types of interactions, even beyond SUSY
- In a nucleus, spin of quarks add incoherently
  - Spin of most nucleons cancels out in most nucleus: incoherent sum
  - In a nucleus, quark masses add coherently
  - Strange quark content dominates! (ok, known to some precision)
  - Expect large coherence effects for SI (Good,that will help!)

Summary of ingredients (1)

First three ingredients usually taken from the Lewin and Smith's prescriptions for comparing experiments.

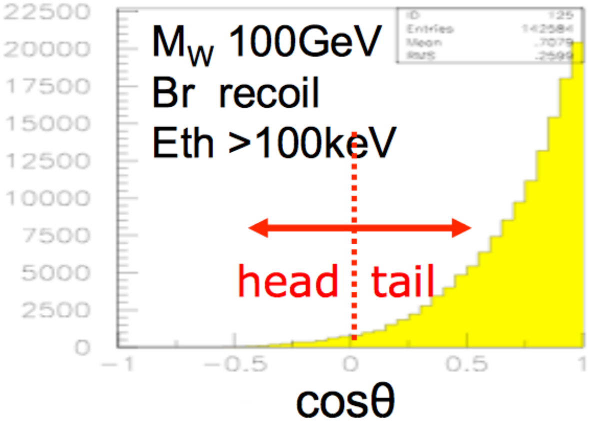
- ρ_W , WIMP density in the laboratory
  - Local measurements suggests ~0.4 GeV/cm^3 but adopted reference is 0.3
  - Observed rate $\propto \sigma_n \times \rho_W$
- f(v), WIMP velocity distribution
  - Dependence on average v_{rms}, not much on f(v) details (except: modulation)
  - Adopted reference: Isothermal halo, v_{rms} = 270 km/s (v_0 = 220 km/s), v_{escape} = 544 km/s, + sun (235 km/s) and earth (0±15 km/s) velocities.
- σ_A/σ_n , nucleon-to-nucleus scaling of scattering cross-section
  - Nuclear form factors matter (from ~0.2 to 1).
  - $A^2\ \mu^2$ scaling (spin-indep. case) dominates for $A > 30$ in MSSM.
  - $A < 30$, non-MSSM WIMPs: spin-dependent may dominate. No large gains from scaling, more model-dependence, poor rates.

Summary of ingredients (2)

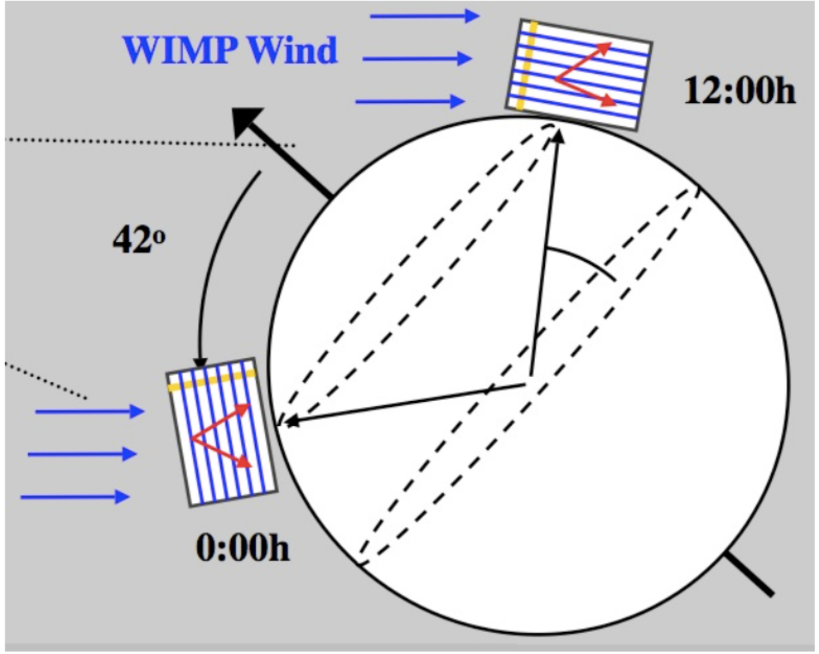
- Last two ingredients usually left as free parameters of the searches:
- M_W , WIMP mass
  - Taken from SUperSYmmetric (or other) Model prediction
  - Method works from a few GeV/c^2 to >10 TeV/c^2
  - Typical SUSY range: from 50 GeV/c^2 to 1 TeV/c^2
- σ_n, WIMP-nucleon cross-section
  - Taken from SUperSYmmetric (or other) prediction
  - Method *could maybe* work down to 10^{-11} pb
  - Typical SUSY range: 10^{-6} to 10^{-11} pb (kg.day -> ton.year)
- Generic search: test all values of (M_W , σ_n)

Directionality: use v_{Earth} to detect WIMP wind

- Average WIMP wind direction due to v_E
- $\theta_{RECOIL} \neq \theta_{WIMP}$ but $<\theta_{RECOIL}> = <\theta_{WIMP}>$



Naka, IDM2008

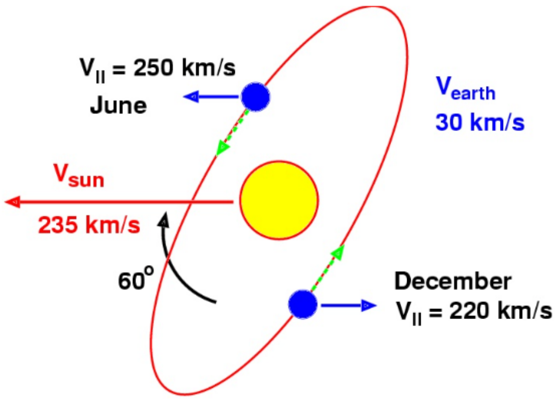


Spooner, IDM2008

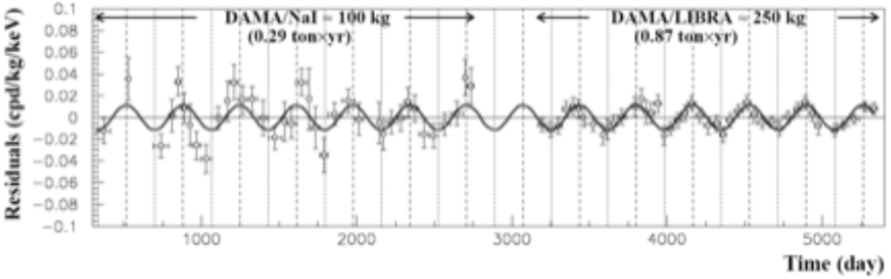
- Need a good resolution on the recoil direction (and head/tail discrimination) despite the very short range of the recoil
- Astrophysics bonus: measure of f(v)

Annual modulation

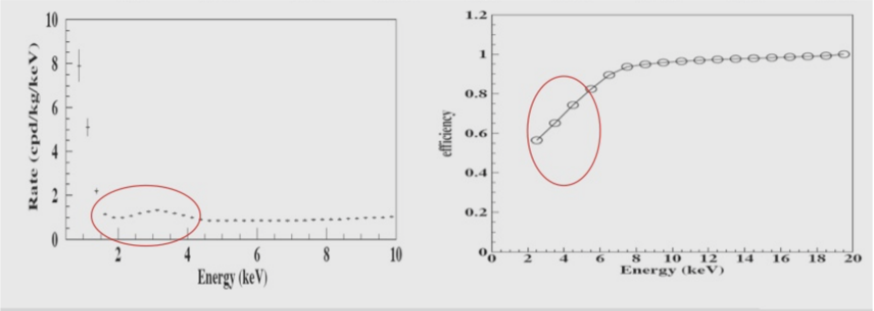
- Need large statistics: flux modulation is ~½ (±15/235) = ±3%, or less when considering experimental thresholds



- Claimed to be observed (~±2%) at low-energy in NaI (DAMA)



- Non-modulating component (~1 evt/kg/day) is ~total rate in NaI, but not observed in Ge, Xenon, CaWO$_4$ and CsI.
- Signal in low-efficiency, near-threshold region
- No "source off" expt. possible



Recommended surfing + browsing

- IDM2012 conference slides

  https://hepconf.physics.ucla.edu/dm12/agenda.html

  - Most recent and complete collection of talks on almost all Direct Search experiments and projects

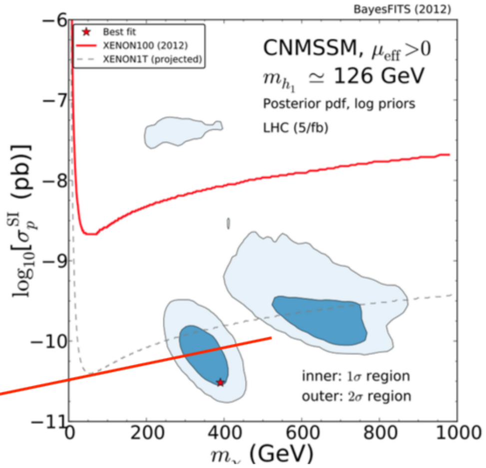
Direct searches Domain

Apply to any particle able to scatter elasticaly on an atomic nucleus

(Neutralino χ, Kaluza-Klein, mirror, scalar...)

- *... If the kinetic energy of the WIMP* E_{WIMP} *is not too small*
  - $M_{WIMP} \sim 100$ GeV/c^2 (supersymmetry) and v ~ 200 km/s correspond to an average $E_{WIMP} \sim 20$ keV (hard X ray).
- *… If* $M_{WIMP} \sim M_{nucleus}$
  - Optimal momentum transfer for $M_{WIMP} = M_{nucleus} \sim 100$ GeV/c^2 corresponding to A ~ 100 g/mol
- *... If the scattering probability is not zero*
  - Small, otherwise already seen?
  - WIMP miracle suggests Weak scale
  - Weak force, supersymmetry:

    kilo.day… to ton.year (10^{-10} pb).



PRD 87 (2013) 115010

Signals in direct searches

- Exponential recoil spectrum
- A^3 dependence of rate

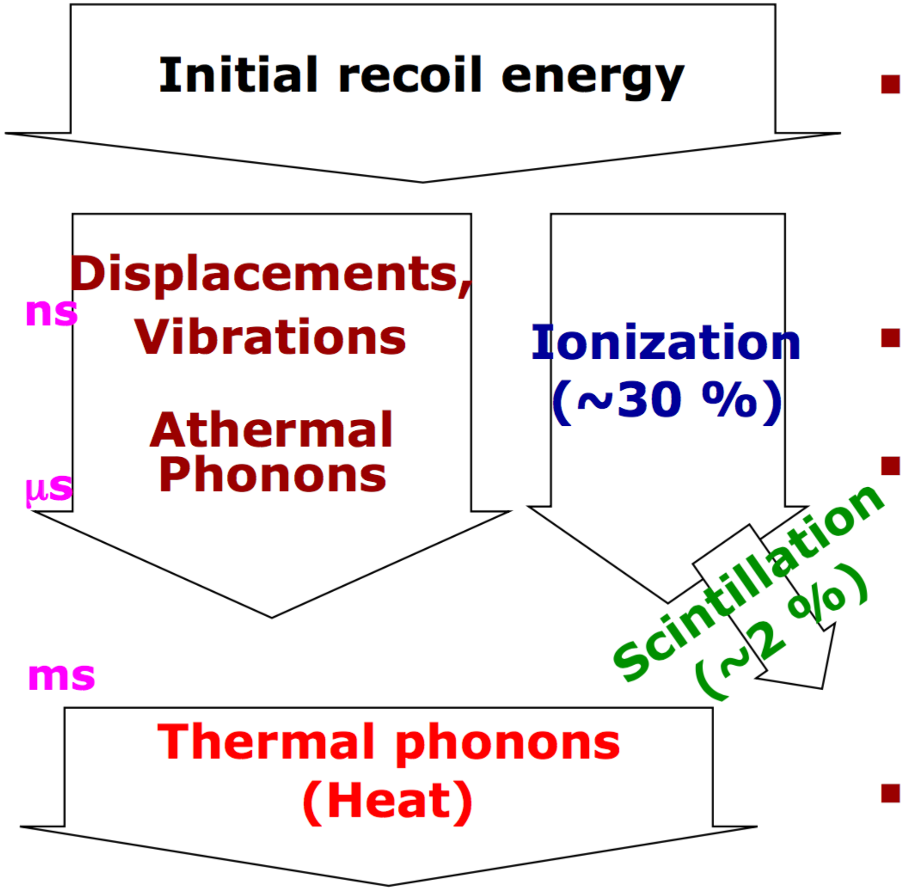
It's not a neutron-induced nuclear recoil ($\sigma = \pi R^2 \propto A^{2/3}$)

- No coincidence between adjacent detectors (detector array)
- Uniform rate within the fiducial volume (large detectors)

- Directionality (correlation with $\vec{v}_{SUN}$ direction): need to measure nuclear recoil trajectory
- Annual modulation (large statistics needed)

- ***Identification of nuclear recoils (vs electron recoils)***

Effect of a nuclear recoil in matter



Initial recoil energy

ns

Displacements, Vibrations

Athermal Phonons

µs

Ionization (~30 %)

Scintillation (~2 %)

ms

Thermal phonons (Heat)

(+ Permanent crystaline defects?)

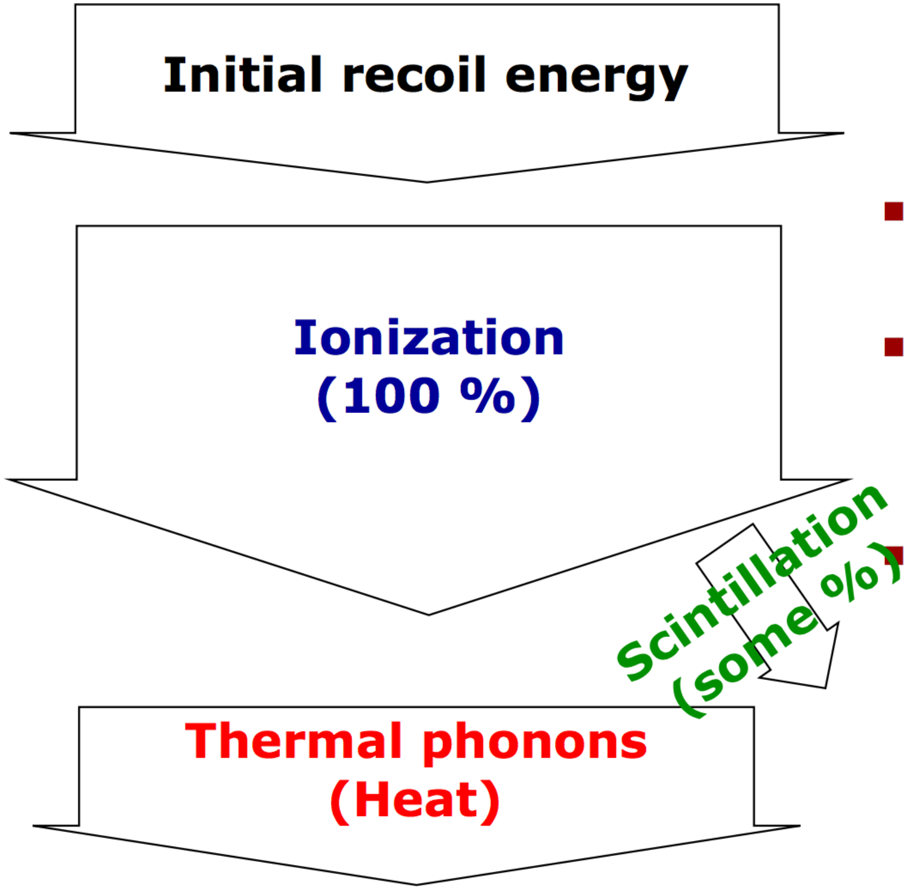
Two type of energy losses:

- Ion-ion collisions (producing displacements and vibrations in the crystal: athermal phonons): nuclear dE/dx.
- Ionization (electronic dE/dx)

- Cascade of collisions and mix of nuclear & electronic dE/x well described by Lindhard's theory + measured dE/dx

- In a closed system, after a while, all excitation decays into thermal energy -> rise in temperature

Effect of an electron recoil in matter



Initial recoil energy

Ionization (100 %)

Scintillation (some %)

Thermal phonons (Heat)

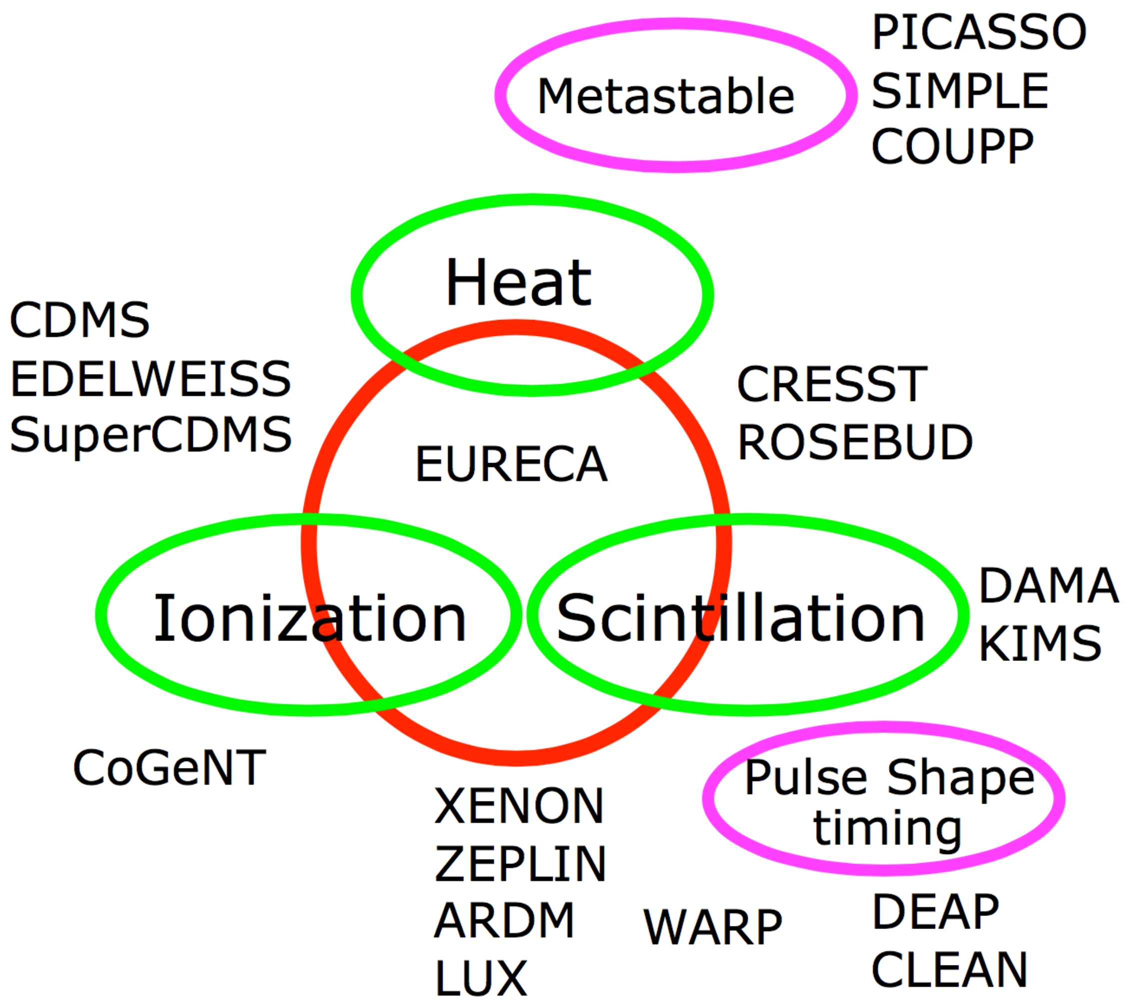
- Most common (long range) radioactive background: γ-rays, producing electron recoils (photoelectron, Compton)
- No ion-ion collisions only electronic dE/dx
- Comparing ionization and scintillation yields is a powerful tool to separate nuclear and electron recoils
- Other effects due to difference in dE/dx: density of energy deposit are not the same. This may also affect the risetime of the scintillation signal (pulse shape discrimination)

(+ No permanent crystaline defects?)

Detection techniques

γ, β discrimination:

- Two simultaneous signals
  - Heat/Phonon
  - Ionisation
  - Scintillation
- Pulse shape discrimination
  - Noble gas/liq.
  - Cristal
- Other "dE/dx" related ideas



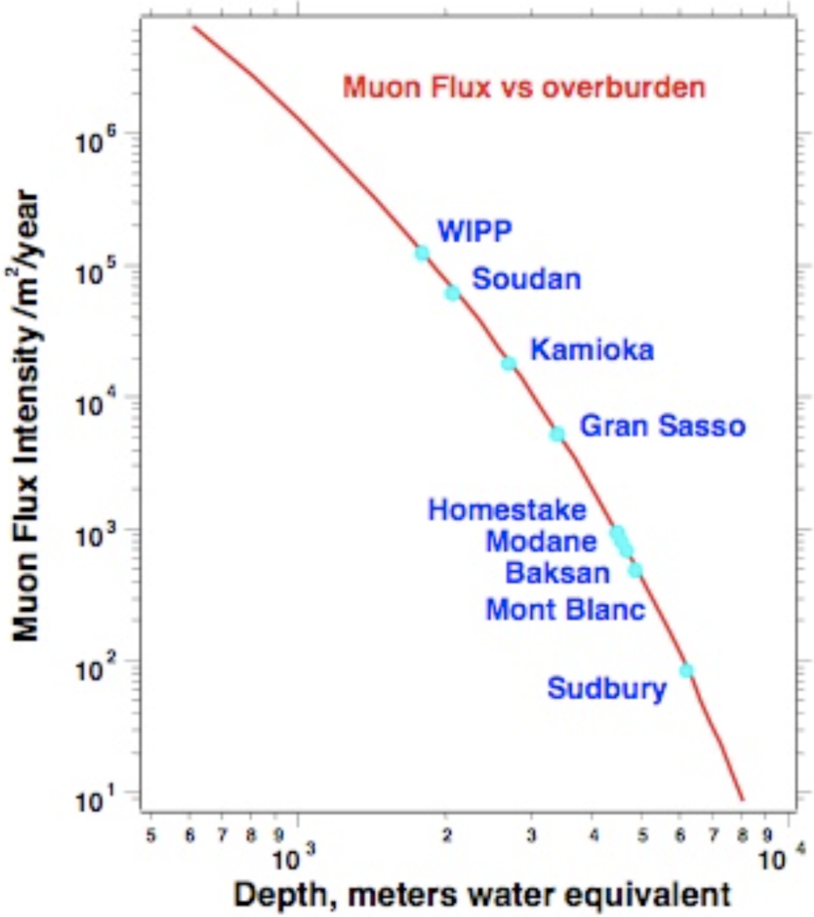
List of radioactive backgrounds

- Neutrons (~MeV) are a real nuisance because they create nuclear recoils, with recoil spectra comparable to those made by WIMPs
  - Can use ~3cm range to reject coincidences and use self-shielding
- Surface events (<1mm) matters because of mis-reconstruction problems

Type	**Attenuation Range in solids**	**Finite Range**	**Produces neutrons**	**Produces nuclear recoils**
Muon	100 m		Yes	
Gamma	Few cm			
Beta		<1 mm		
Alpha		<20 μm	Yes (~10^{-5})	
Neutron	3 cm			Yes

Radioactive background (1): cosmics

- About half of the radioactive background in your body is due to activation by cosmic rays
  - Direct hits: 1 /hand/second
  - Later decays of activated nuclei
- Solution: deep underground laboratories in mine or road tunnels
- Ex: LSM (Frejus tunnel)
  - 1.6 km of rock
  - 4.8 km equivalent of water
  - 5 μ / m^2 /day
  - ~1 nuclear recoil /kg/month from n in Pb shield: μ veto!



Radioactive background (2): Uranium + Thorium

- One of the most common radioactive background

^{238}U: $T_{1/2}$ = 4.5 x10^9 years ^{232}Th: $T_{1/2}$ = 14 x10^9 years

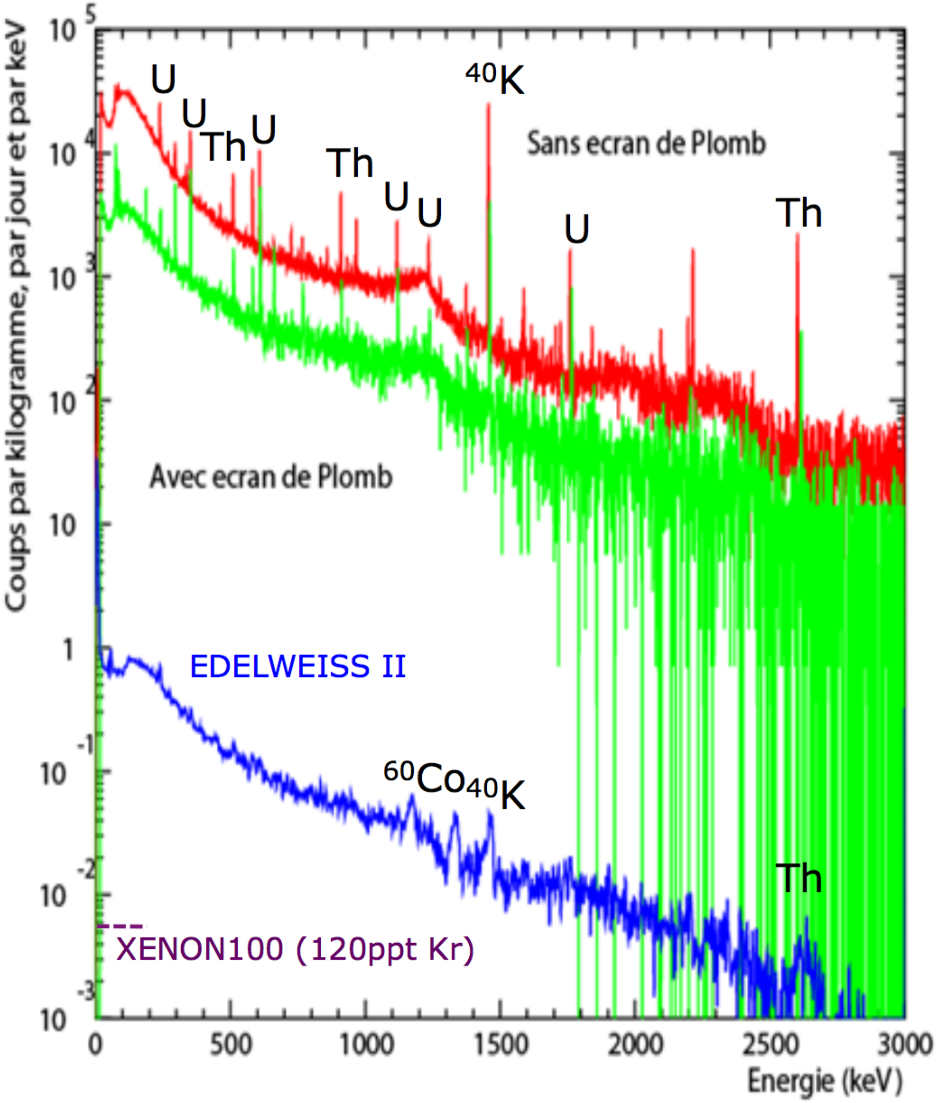
  - Ratio 10^{-6}:1 in ordinary rock: ~10^6 decay / kg / day
  - Long decay chain down to ^{206}Pb and ^{208}Pb, respectively
    - Multiplies by ~10 the activity once the chain is in equilibrium
  - Alpha and beta emitter ("contained" inside the rock)
    - Range of particles: Alpha = 20 microns, beta < 1 mm
    - *But some gamma's, + beta bremmstrahlung …*
    - *Neutrons from U fission + alpha reactions with Al, F, Pb, …*
  - *Radon: 10^6 produced per kg/day*
    - *Can escape the rock! Travels in air at sonic speed! Deposits ^{210}Pb daughters down to ~20 nm below the surface of all materials! Difficult to get rid with a $T_{½}$ of 22 years, + diffusion inside solids!*

Example of gamma background in Ge detector

- Red: natural background in a « normal » environment (Undergraduate students work there…)
- Green: ~5 cm lead shield (large Z), reduction x ~10
- Blue: EDELWEISS-II in LSM, before the rejection of electron recoils.

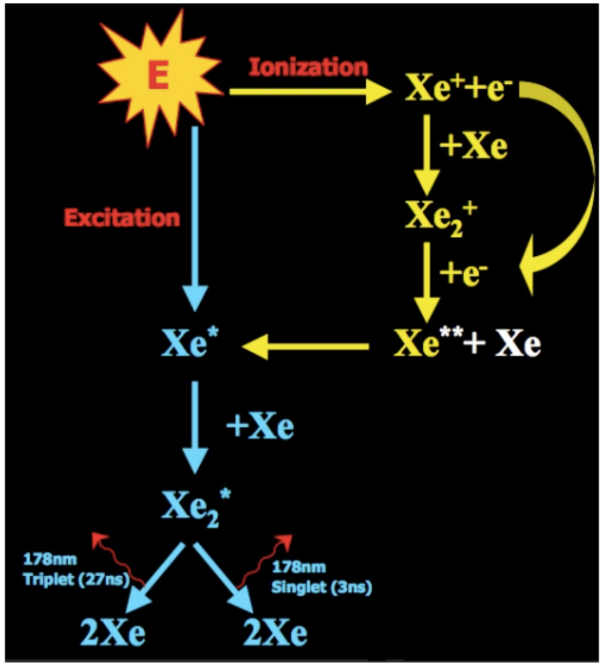
  Reduction 3x10^4 at ~50 keV (Pb shield, material selection)

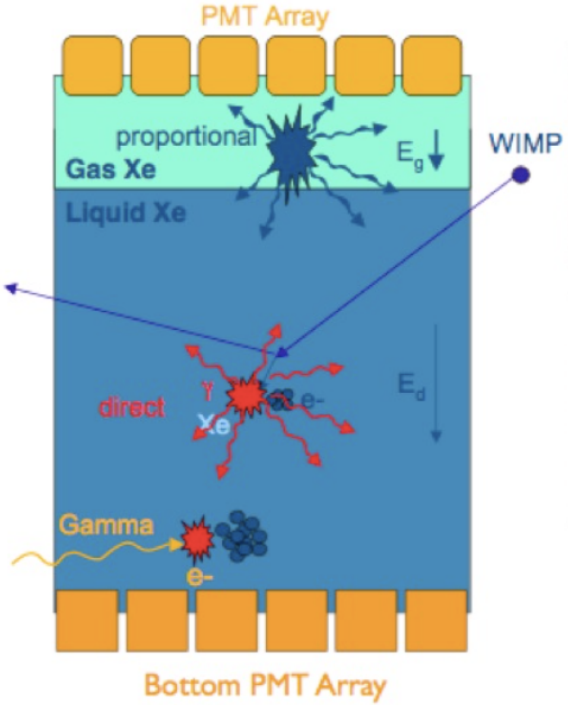
- Further reduction >10^4 after nuclear recoil identification

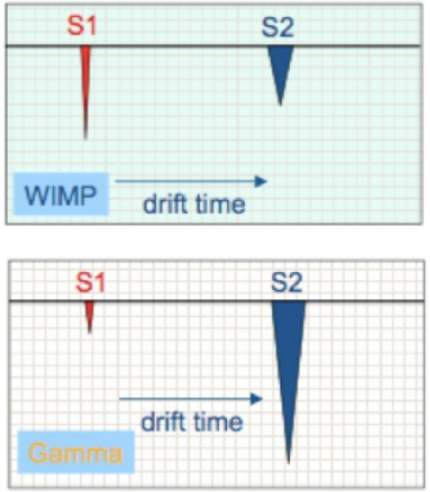


XENON S1/S2 discrimination

- Different scintillation (S1) and ionisation (S2) yields for nuclear / electronic recoils
- PMT array for (x,y), drift time for z : fiducial volume
- **Xenon 100**: 170 kg LXe, 34 kg fiducial, 30 cm drift, 98(top)+80(bottom) PM's
- *Trigger on 3 PM coincidence: bad energy resolution, but excellent noise suppression*
- 10 keV nuclear recoil: S1 ~ 5 P.E. S2 ~ 800 P.E. (from ~30 ionization e^-)







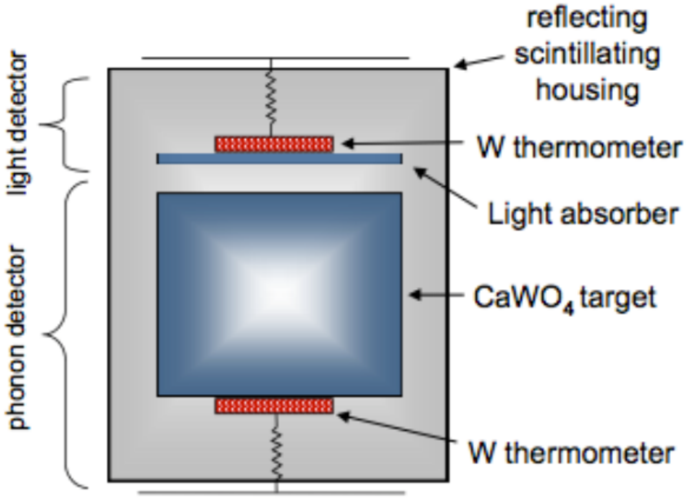
$(S2/S1)_{wimp} << (S2/S1)_{gamma}$

Heat-scintillation: CRESST

- 300 g $CaWO_4$ Crystals with Tungsten film thermometer
- Light detector = thin Si wafer + same type of thermometer
- 3 targets in same detector

  A = 16, 40 and 184

  Q = 0.10, 0.06 and 0.04



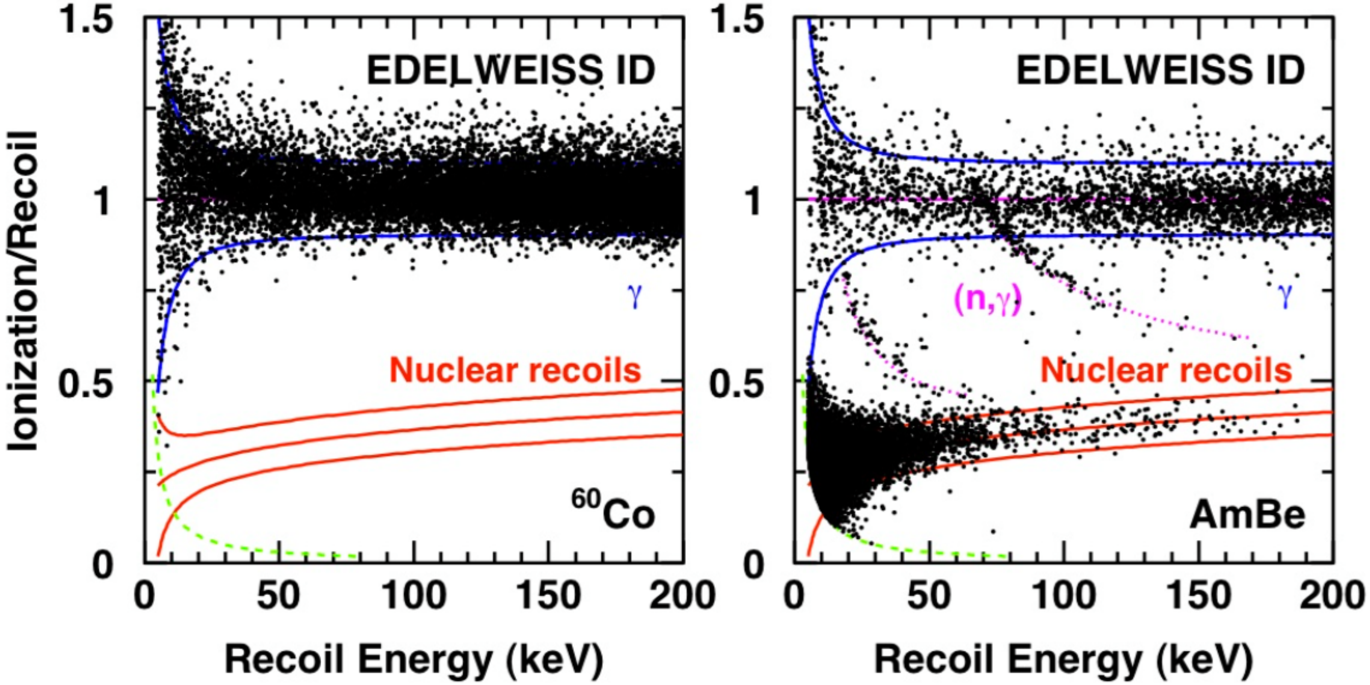
Reflecting scintillating housing to increase light yield

BONUS: tags $^{210}Po \rightarrow \alpha + ^{206}Pb$ two body decay

^{206}Pb recoil ~ W recoil

Nuclear recoil / gamma discrimination

- With good resolution on both ionization & heat, very clear discrimination based on the different ionization yields for *nuclear recoils* (WIMP or neutron scattering) and *electronic recoils* (β,γ decays)
  - discrimination of dominant background
  - Stable and reliable rejection performances



DARK MATTER
STATUS AND PERSPECTIVES

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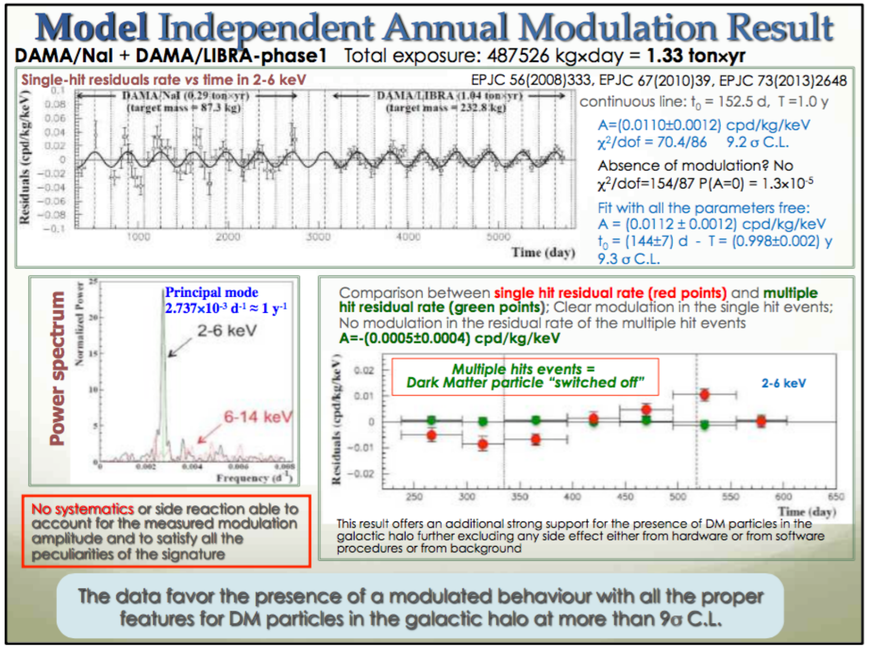
Giornate di studio sul Piano Triennale INFN
Centro “Le Ciminiere”, Catania – 3.12.2015

Annual modulation: DAMA, 9.2σ with 1.33 ton x yr, 15 cycles



Model Independent Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = **1.33 ton×yr**

Single-hit residuals rate vs time in 2-6 keV

EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

continuous line: t_0 = 152.5 d, T =1.0 y

A=(0.0110±0.0012) cpd/kg/keV
χ^2/dof = 70.4/86 9.2 σ C.L.

Absence of modulation? No
χ^2/dof=154/87 P(A=0) = 1.3x10^{-5}

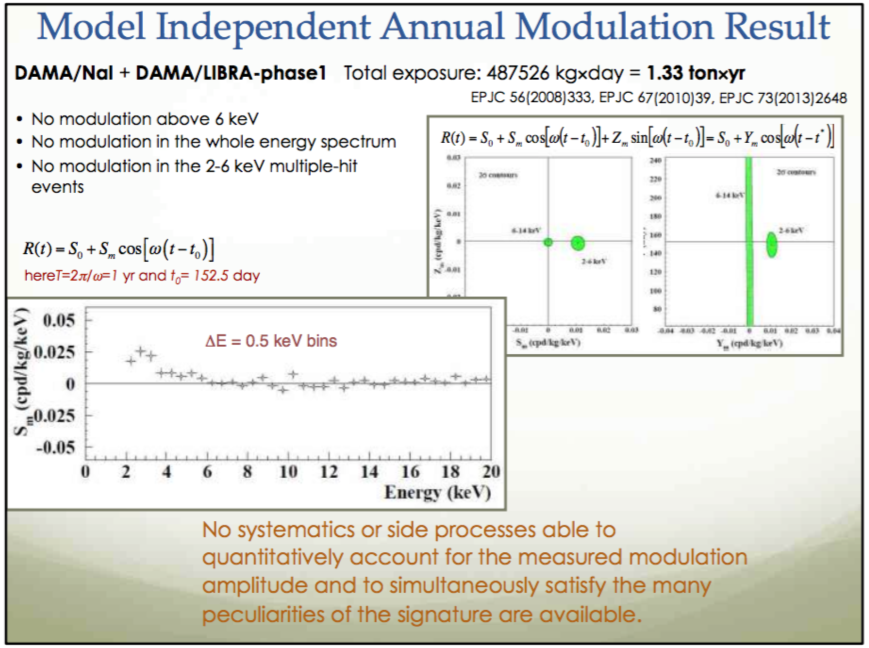
Fit with all the parameters free:
A = (0.0112 ± 0.0012) cpd/kg/keV
t_0 = (144±7) d - T = (0.998±0.002) y
9.3 σ C.L.

Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)**; Clear modulation in the single hit events; No modulation in the residual rate of the multiple hit events
A=-(0.0005±0.0004) cpd/kg/keV

This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at more than 9σ C.L.



Model Independent Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = **1.33 ton×yr**

EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

- No modulation above 6 keV
- No modulation in the whole energy spectrum
- No modulation in the 2-6 keV multiple-hit events

$$R(t) = S_0 + S_m \cos[\omega(t - t_0)] + Z_m \sin[\omega(t - t_0)] = S_0 + Y_m \cos[\omega(t - t^*)]$$

$$R(t) = S_0 + S_m \cos[\omega(t - t_0)]$$

here $T=2\pi/\omega=1$ yr and t_0= 152.5 day

No systematics or side processes able to quantitatively account for the measured modulation amplitude and to simultaneously satisfy the many peculiarities of the signature are available.

From Belli's talk at TAUP 2015, http://taup2015.to.infn.it

Compatible with: DM scattering on nuclei (5-100) GeV WIMPs
DM scattering on electrons (0.3-6) KeV ALPs

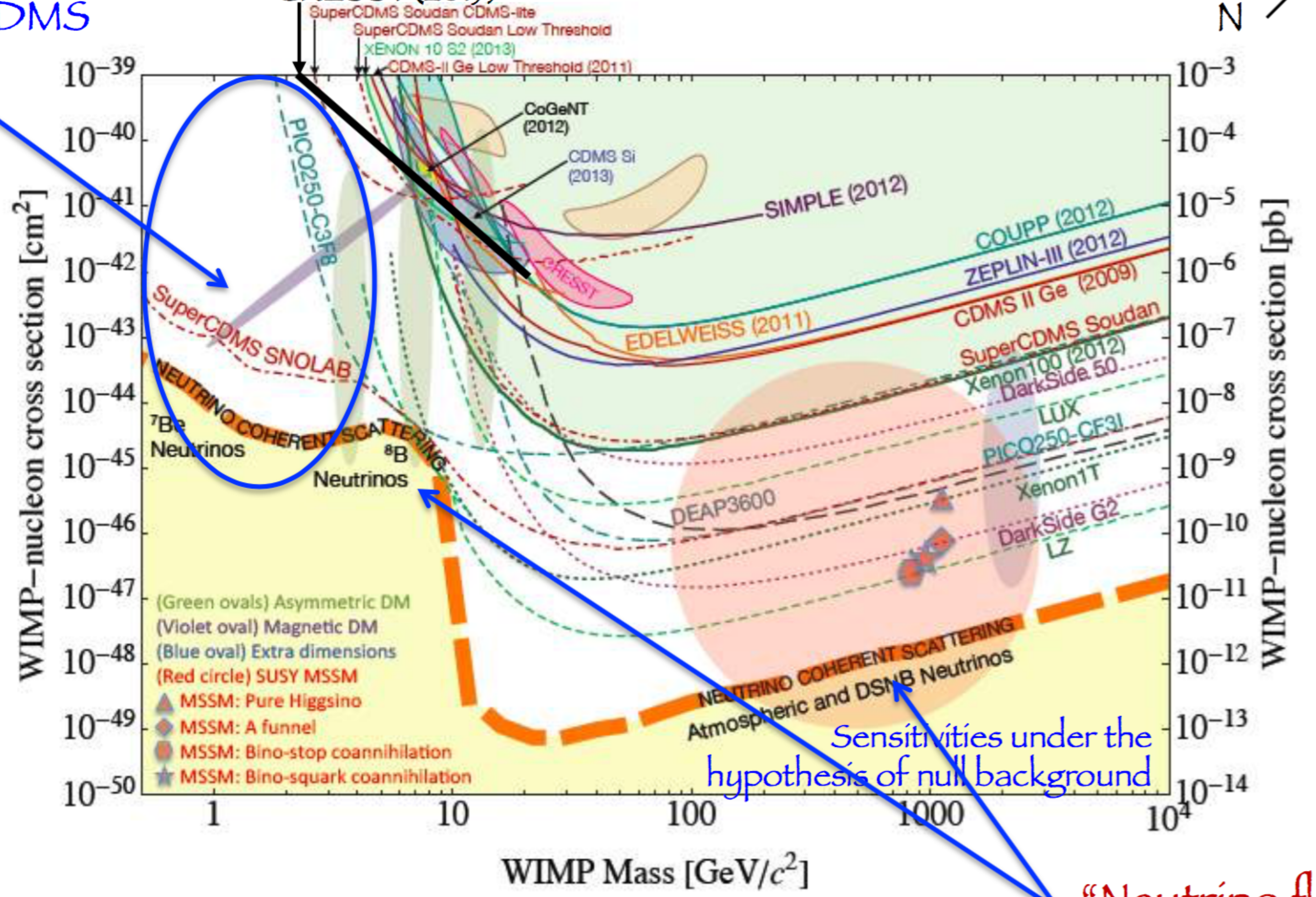
Light WIMPs window

CRESST

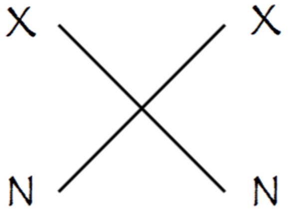
SuperCDMS

…

CRESST (2015)



Sensitivities under the hypothesis of null background



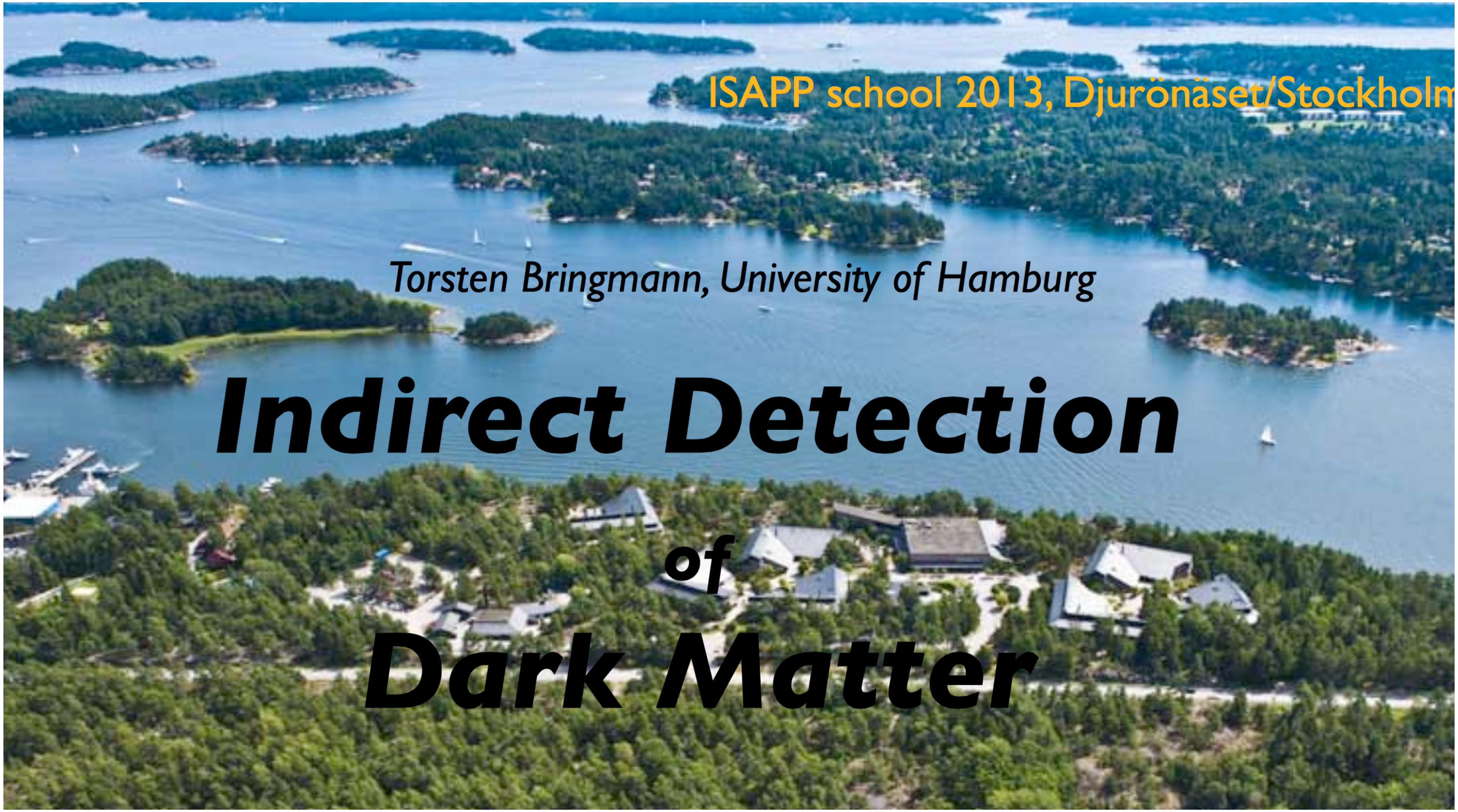
"Neutrino floor"

XENON1T (LXe)

DarkSide (LAr)

Lux, LZ, …

Bounds and expected sensitivities for DM-nucleus scattering
Under the hypothesis of contact-type interactions

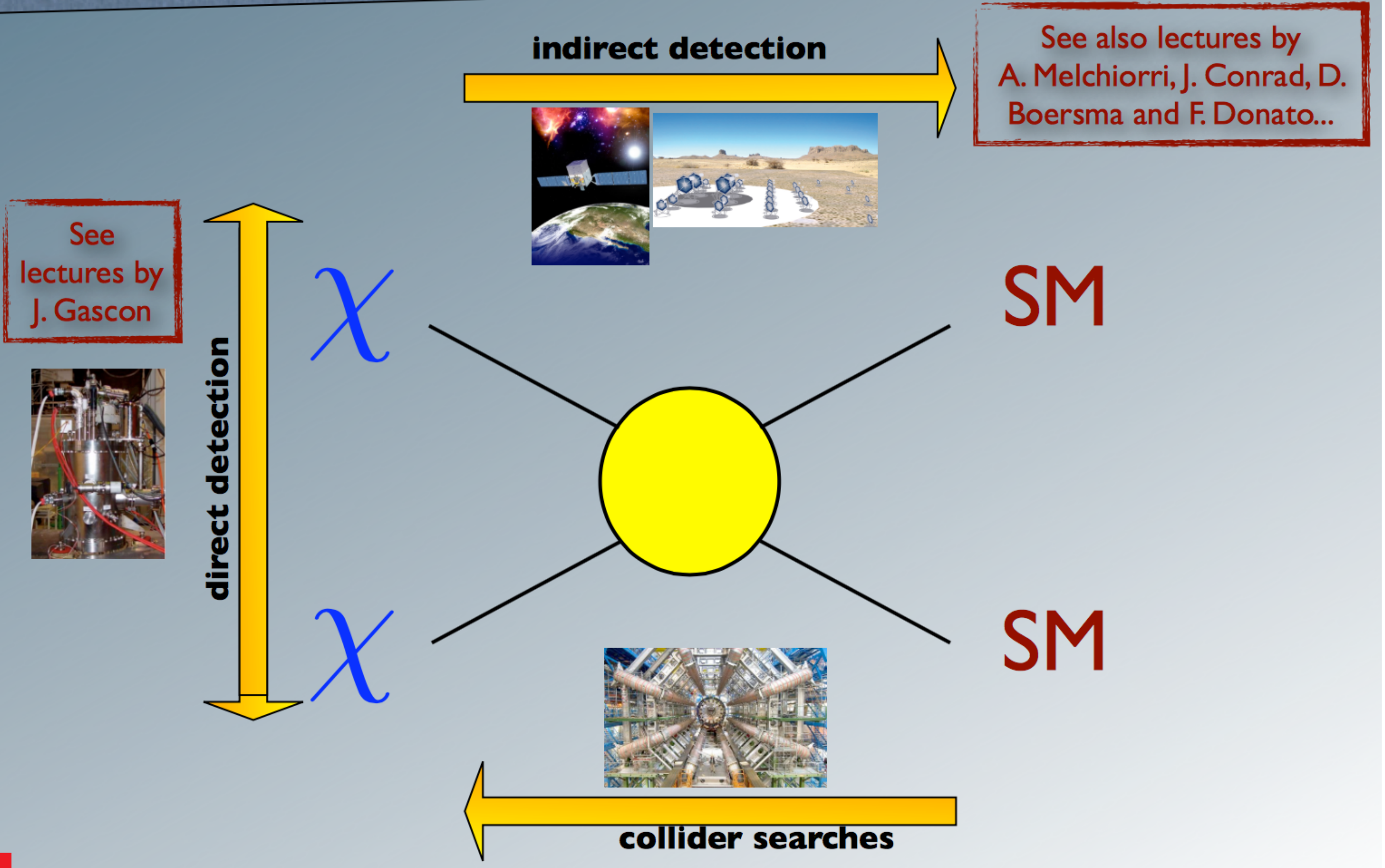


ISAPP school 2013, Djurönäset/Stockholm

Torsten Bringmann, University of Hamburg

Indirect Detection of Dark Matter

WIMPs do interact with the SM!



indirect detection

See also lectures by
A. Melchiorri, J. Conrad, D.
Boersma and F. Donato...

See
lectures by
J. Gascon

direct detection

χ

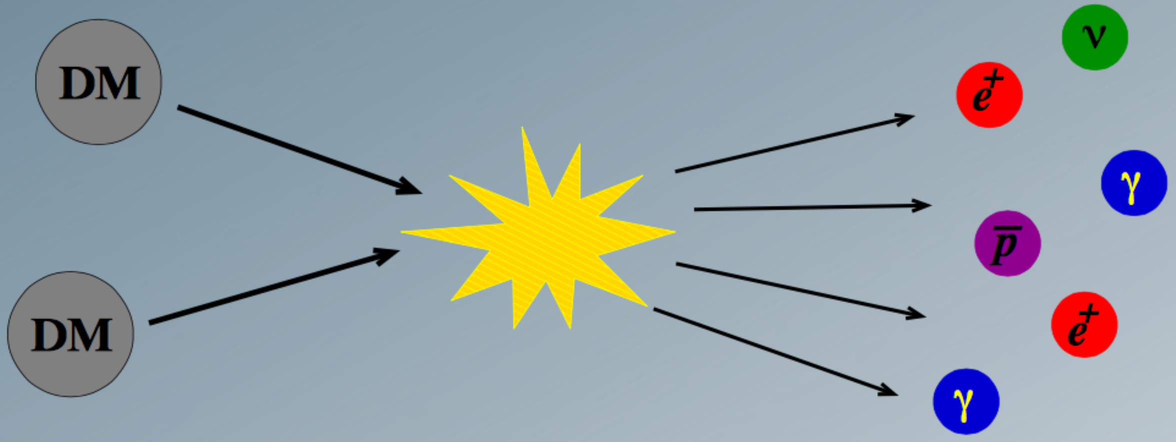
χ

SM

SM

collider searches

Indirect detection in one slide



- DM has to be (quasi-)stable against decay...
- … but can usually pair-annihilate into SM particles
- Try to spot those in cosmic rays of various kinds

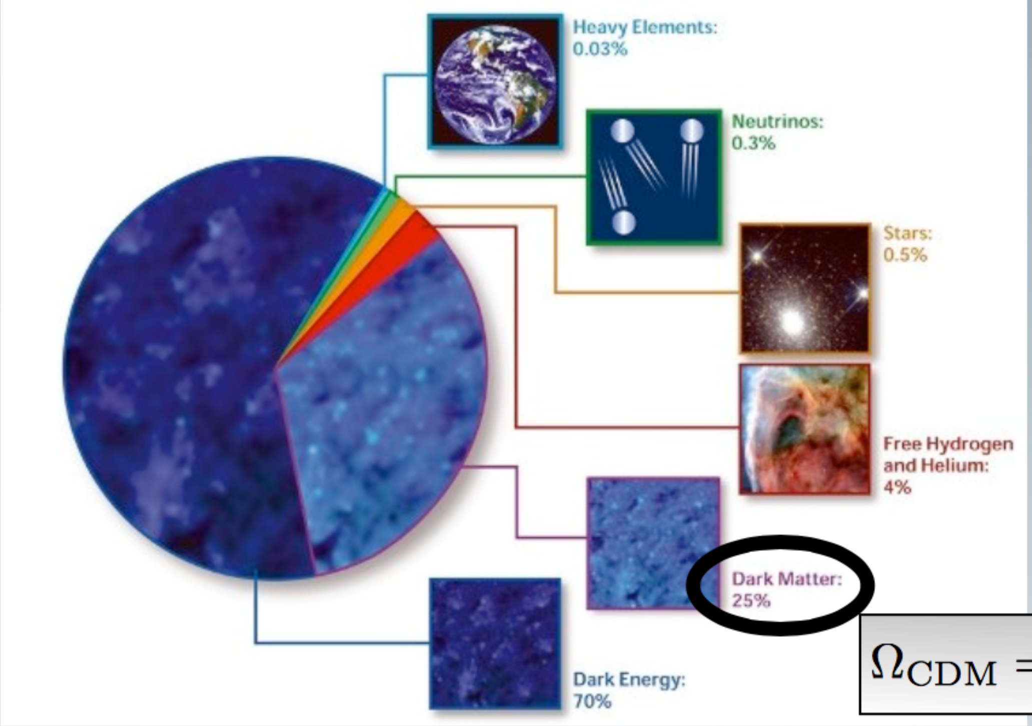
- The challenge: i) absolute rates
  - $\rightsquigarrow$ regions of high DM density

  ii) discrimination against other sources
  - $\rightsquigarrow$ low background; clear signatures

Distribution of dark matter

- Annihilation sensitive to DM density *squared*

  ⇨ need to know this quantity very well!



NB: in general

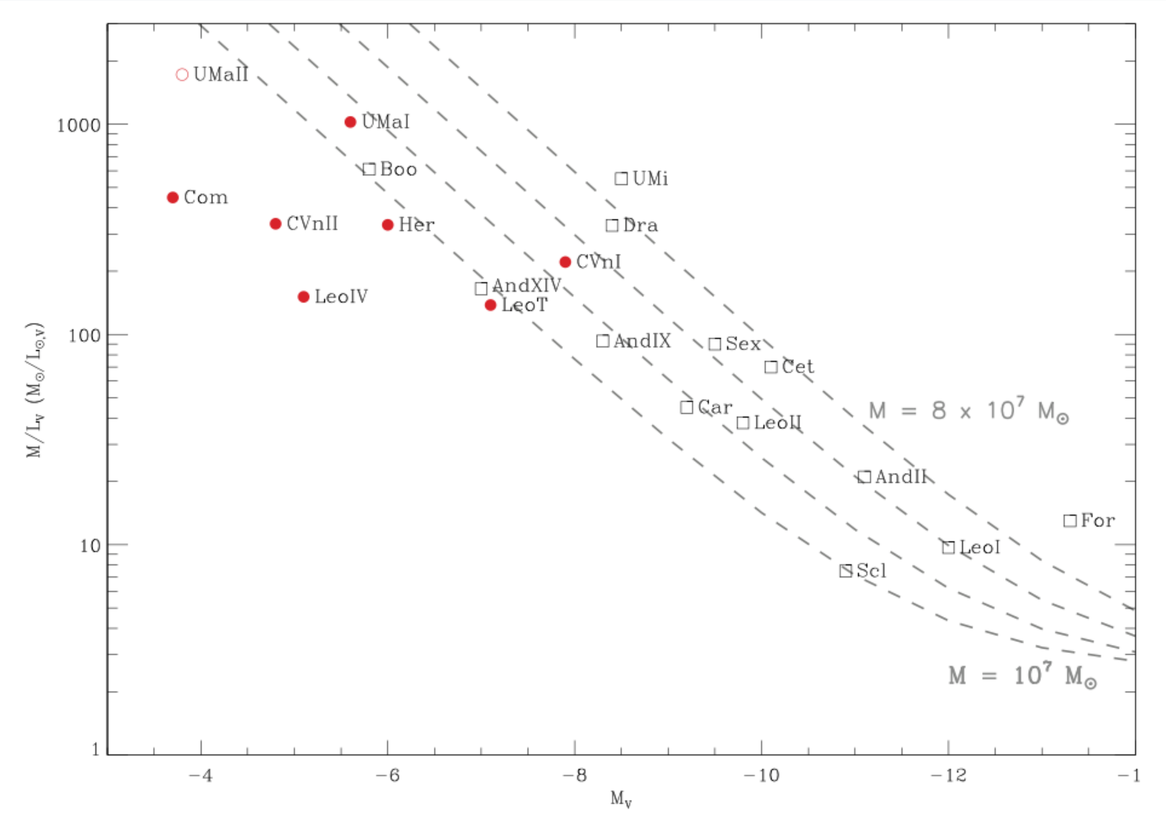
$\Omega_\chi^{\mathrm{local}} \neq \Omega_{\mathrm{CDM}}$!!!

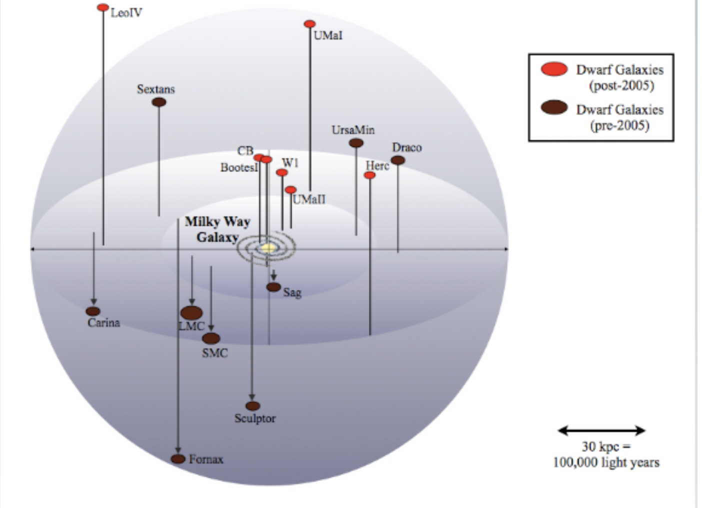
$\boxed{\Omega_{\mathrm{CDM}} = 0.233 \pm 0.013}$ on **large** scales

- [For comparison: *decaying* DM directly proportional to density]

Dwarf galaxies

- Use Jeans equation to relate observed velocity dispersion of stars to total mass distribution
  ➡ highest known mass-to-light ratios!





J.~D.~Simon, M.~Geha, ApJ 670, 313 (2007)

Substructure

- *N*-body simulations: The DM halo contains not only a smooth component, but a lot of substructure!
- Indirect detection effectively involves an averaging:

$$\Phi_{\rm SM} \propto \langle \rho_\chi^2 \rangle = (1 + {\rm BF}) \langle \rho_\chi \rangle^2$$

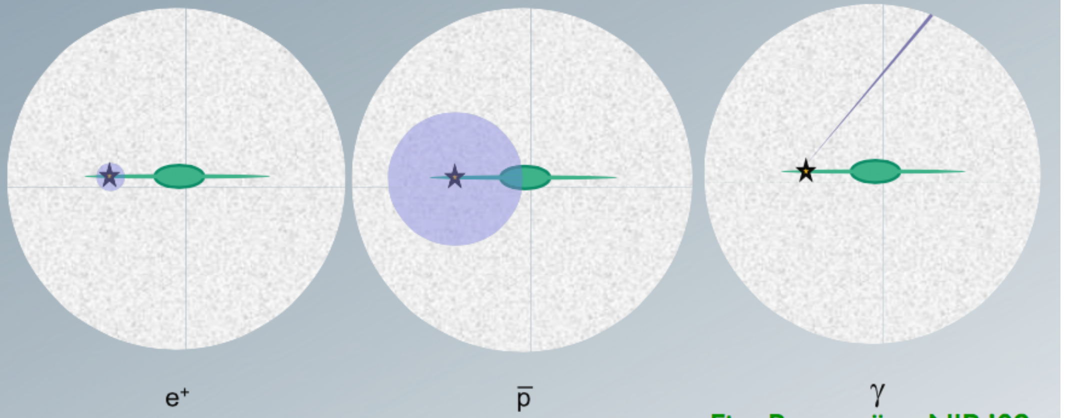


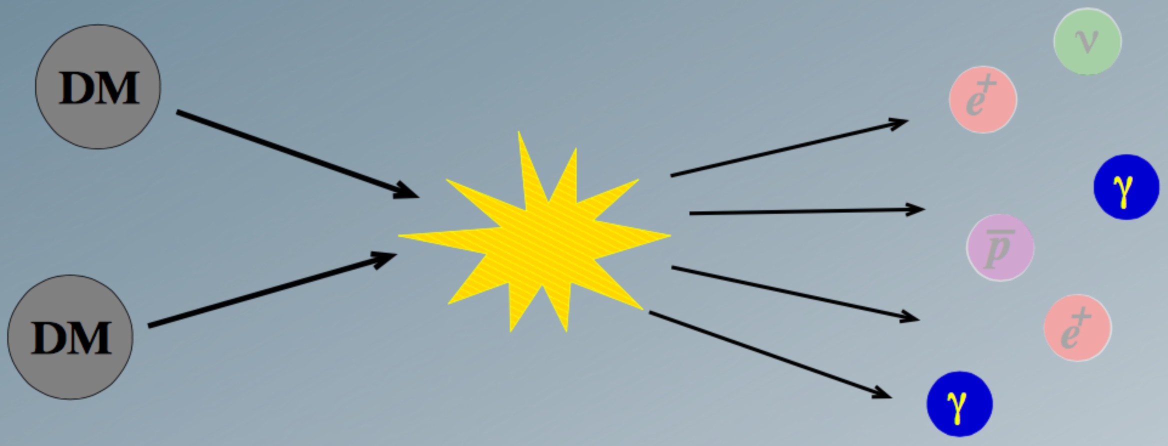
Fig.: Bergström, NJP '09

- "Boost factor"
  - each decade in $M_{\rm subhalo}$ contributes very roughly the same

    e.g. Diemand, Kuhlen & Madau, ApJ '07

    ⇨ *important to include realistic value for* $M_{\rm cut}$ *!*
  - depends on uncertain form of microhalo profile ($c_{\rm V}$ ...) and dN/dM (large extrapolations necessary!)

Indirect DM searches



Gamma rays:

- Rather high rates
- No attenuation when propagating through halo
- No assumptions about diffuse halo necessary
- Point directly to the sources: clear spatial signatures
- Clear spectral signatures to look for

Gamma-ray flux

The expected gamma-ray flux [GeV^{-1}cm^{-2}s^{-1}sr^{-1}] from a source with DM density ρ is given by

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\Delta\psi) = \underbrace{\int_{\Delta\psi}\frac{d\Omega}{\Delta\psi}\int_{\text{l.o.s}} d\ell(\psi)\rho^2(\mathbf{r})}_{\text{astrophysics}} \underbrace{\frac{\langle\sigma v\rangle_{\text{ann}}}{8\pi m_\chi^2}\sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}}_{\text{particle physics}}$$

for point-like sources: $\simeq (D^2\Delta\psi)^{-1}\int d^3r\,\rho^2(\mathbf{r})$

$\Delta\psi$: angular res. of detector

D : distance to source

angular information
\+ rather uncertain normalization

$\langle\sigma v\rangle_{\text{ann}}$: total annihilation cross section

m_χ : WIMP mass $(50\,\text{GeV} \lesssim m_\chi \lesssim 5\,\text{TeV})$

B_f : branching ratio into channel f

N_γ^f : number of photons per ann.

high accuracy
spectral information

Local DM density

- standard value:

$$\boxed{\rho_\odot^{\rm DM} \sim 0.3 \to 0.4\ \frac{\rm GeV}{\rm cm^3}}$$

...

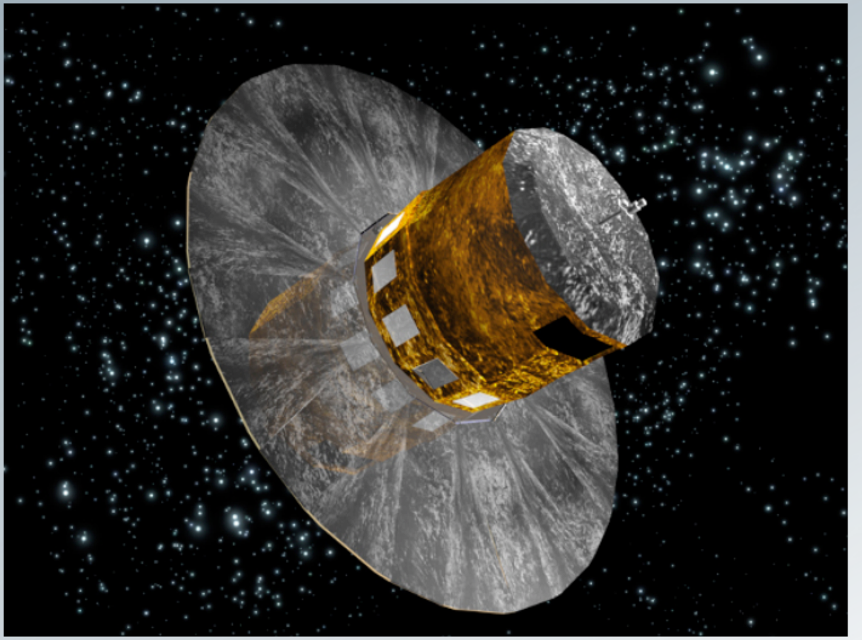
0.30 ± 0.05
Wydrow, Pim & Dubinski, ApJ '08

0.39 ± 0.03
Catena & Ullio, JCAP '10

0.43 ± 0.11 ± 0.10
Salucci et al, A&A '10

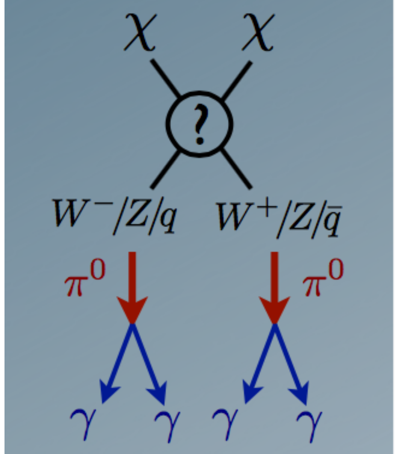
...

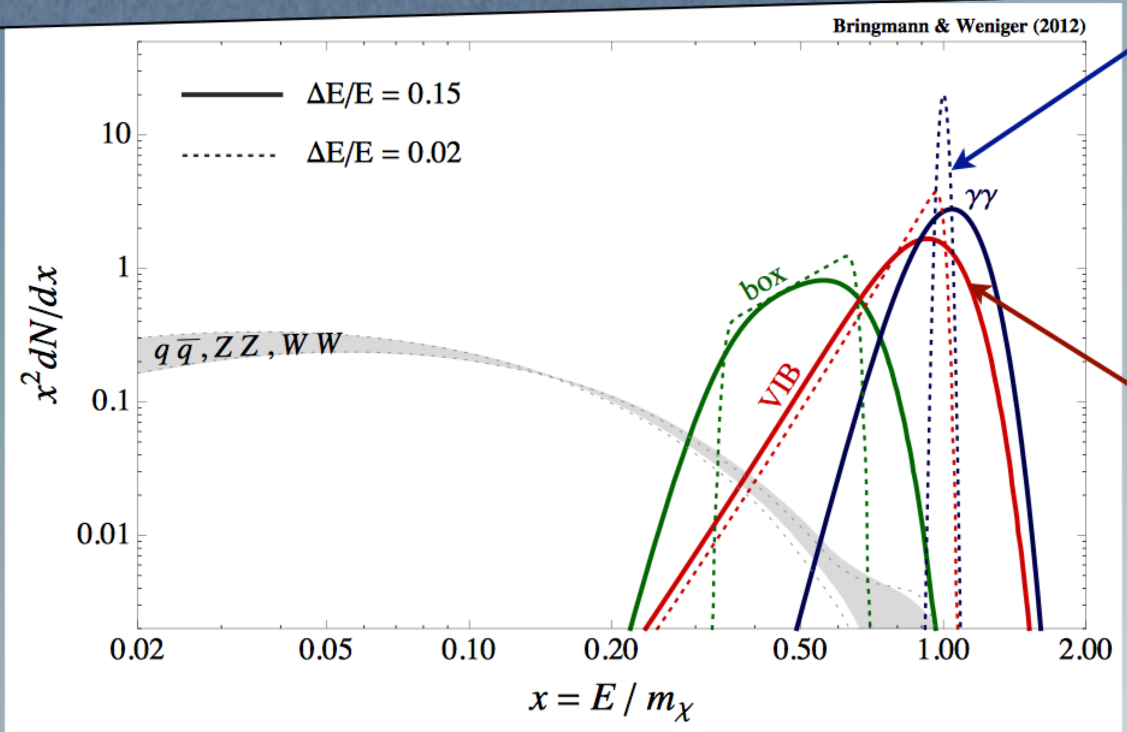
- Gaia (ESA mission, launch 11/13) will collect position and radial velocities of ~10^8 stars



➡ *will settle the issue…!*

Annihilation spectra





Bringmann & Weniger (2012)

Monochromatic lines

$\chi\chi \to \gamma\gamma, \gamma Z, \gamma H$

$\mathcal{O}(\alpha_{\rm em}^2)$

(Virtual) Internal Bremsstrahlung

$\chi\chi \to \bar{f}f\gamma, W^+W^-\gamma$

$\mathcal{O}(\alpha_{\rm em})$

Secondary photons

- *many* photons but
- featureless & model-independent
- difficult to distinguish from astro BG

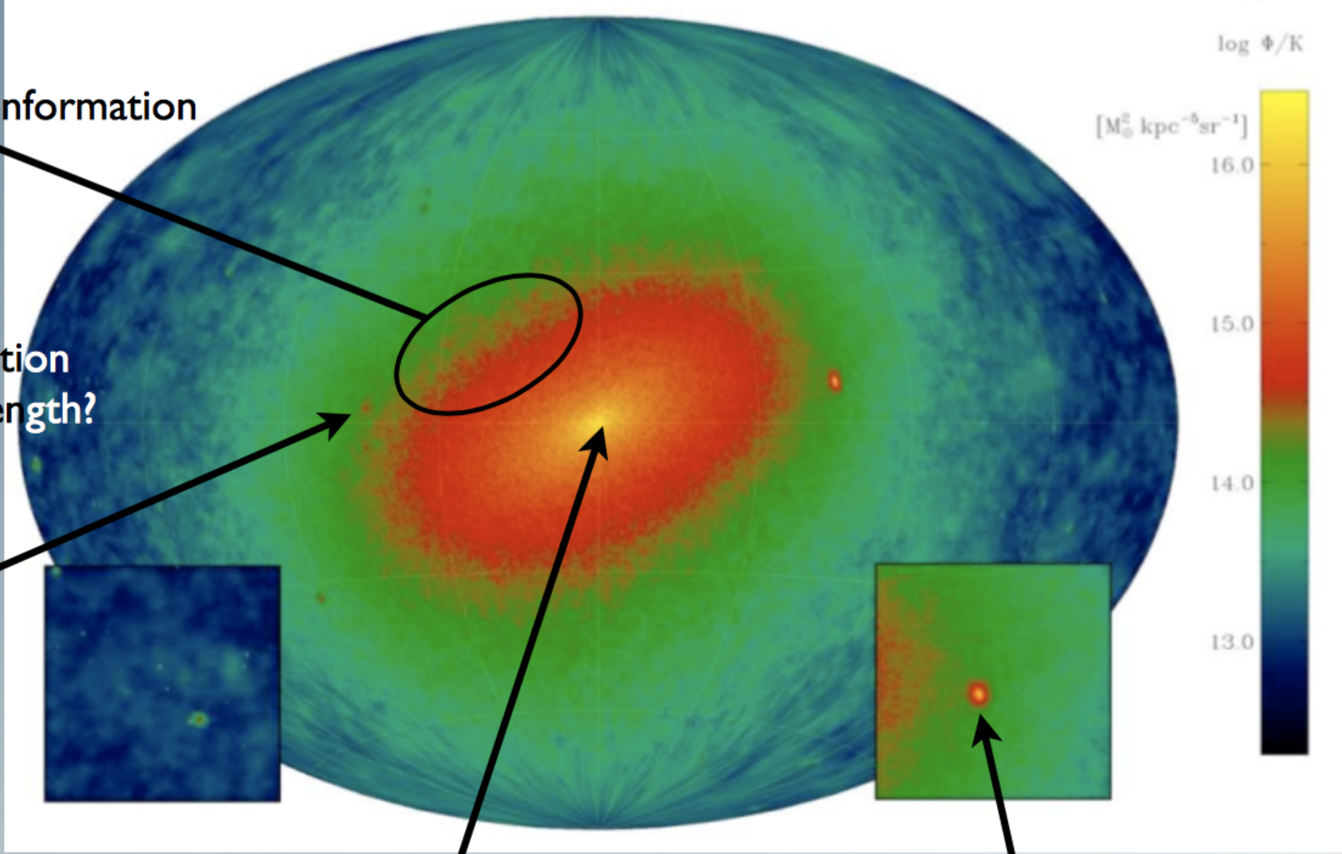
➡ *good constraining potential*

Primary photons

- direct annihilation to photons
- model-dependent 'smoking gun' spectral features near $E_\gamma = m_\chi$

➡ *discovery potential*

Possible targets



Diemand, Kuhlen & Madau, ApJ '07

Galactic halo

- good statistics, angular information
- galactic backgrounds?

Galaxy clusters

- cosmic ray contamination
- better in multi-wavelength?
- substructure boost?

Dwarf Galaxies

- DM dominated, M/L~1000
- fluxes soon in reach!

Extragalactic background

- DM contribution from all z
- background difficult to model
- substructure evolution?

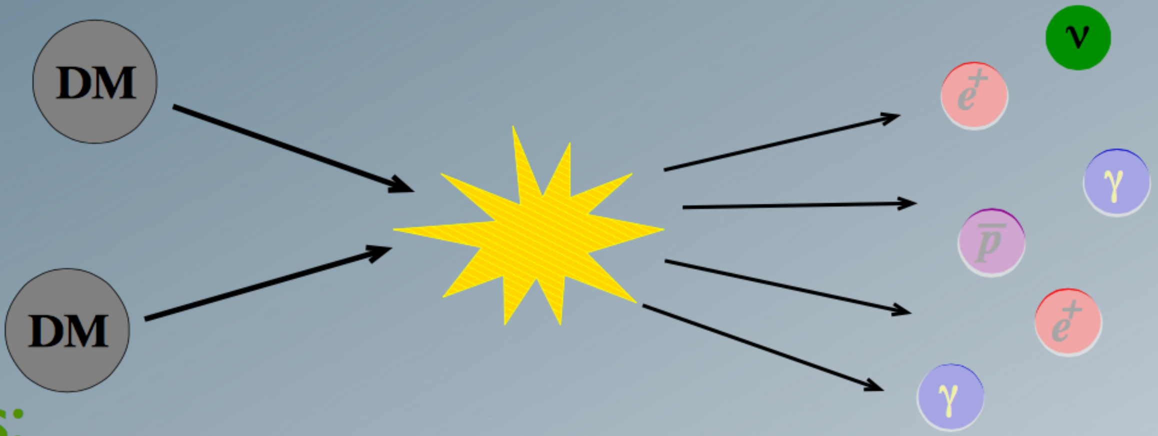
Galactic center

- brightest DM source in sky
- large background contributions

DM clumps

- easy discrimination (once found)
- bright enough?

Indirect DM searches



Neutrinos:

- Unperturbed propagation like for photons
- But signal significance (for the same target) usually considerably worse
- New feature: signals from the center of sun or earth!

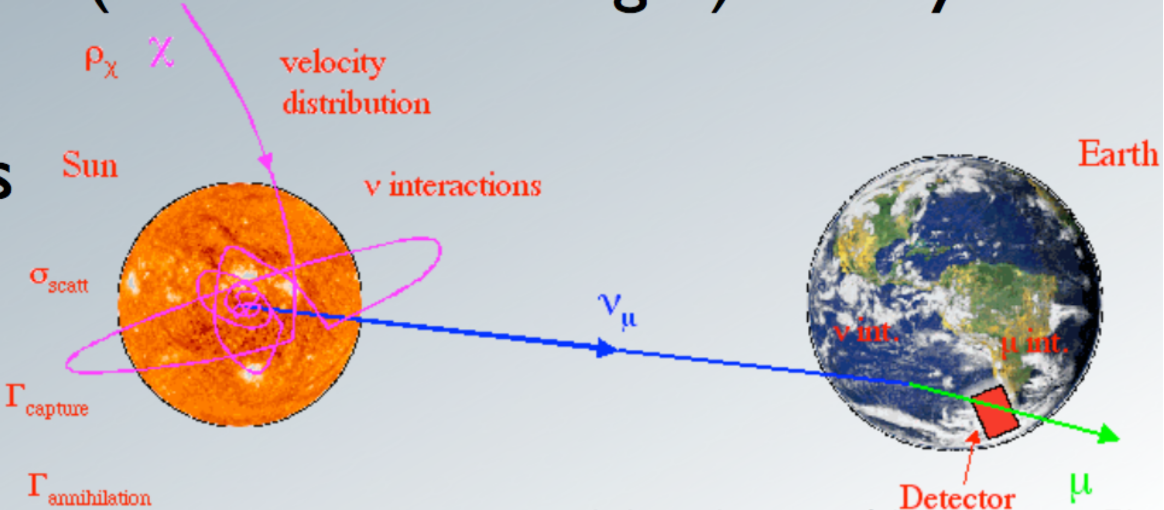
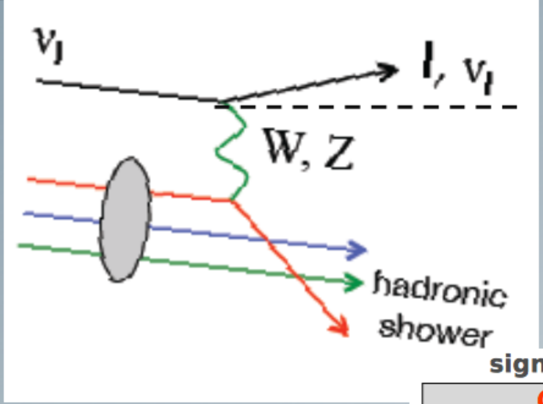


Fig. from J.Edsjö

Detection principle

- Array of optical modules in transparent medium (ice/water) to detect Cherenkov light from relativistic secondaries
  (mostly sensitive to muons because they have the longest tracks)

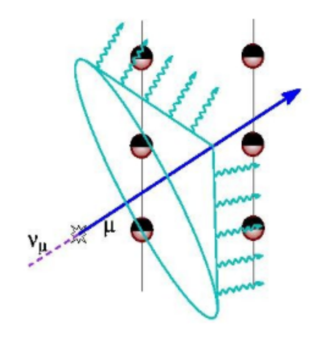


- opening angle: $\Theta_{\mu\nu} \approx 0.7^\circ \cdot (E_\nu / \mathrm{TeV})^{-0.7}$
  ⇨ possible to do neutrino astronomy!
- tiny *x*-sections & fluxes: *need HUGE volumes!*
- background muons:
  - down-going: atmospheric neutrinos
  - up-going: also induced by cosmic rays
    (hitting the atmosphere the far side of the earth)

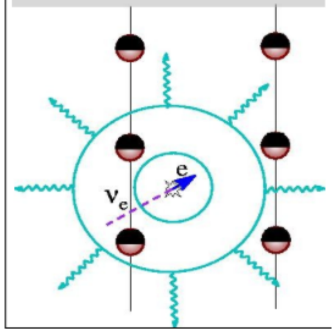
  ⇝ look for excesses in any given direction

signatures

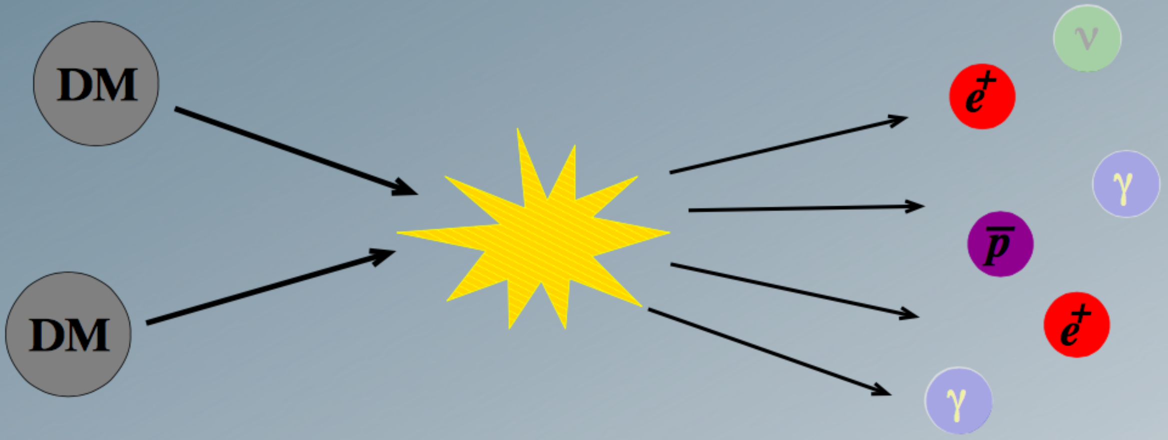
***O*(km) long muon tracks**



***O*(10m) cascades, ν_e ν_τ neutral current**



Charged cosmic rays

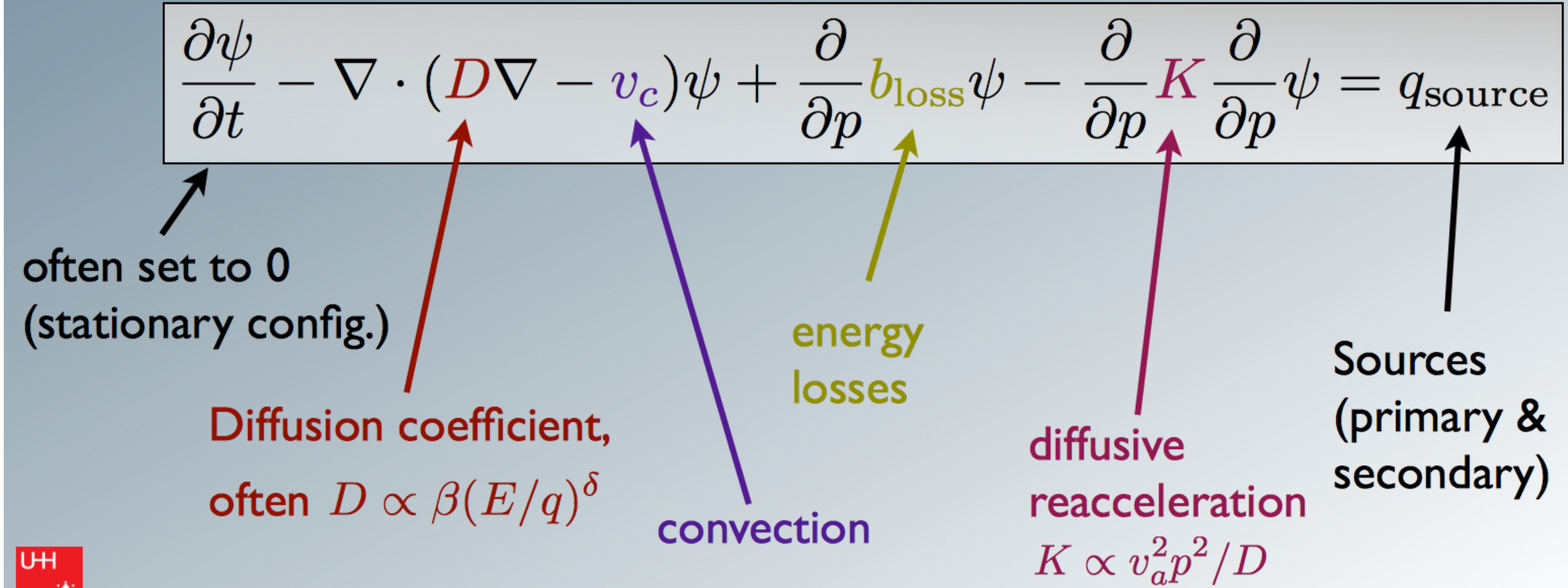


- GCRs are confined by galactic magnetic fields
- After propagation, no directional information is left
- Also the spectral information tends to get washed out
- Equal amounts of matter and antimatter

  ⇨ focus on antimatter (low backgrounds!)

Cosmic ray propagation

- Little known about Galactic magnetic field distribution
- Magnetic fields confine CRs in galaxy for $E \lesssim 10^3\,\mathrm{TeV}$
- Random distribution of field inhomogeneities
  $\rightsquigarrow$ propagation well described by diffusion equation



$$\frac{\partial\psi}{\partial t} - \nabla\cdot(D\nabla - v_c)\psi + \frac{\partial}{\partial p} b_{\mathrm{loss}}\psi - \frac{\partial}{\partial p} K \frac{\partial}{\partial p}\psi = q_{\mathrm{source}}$$

often set to 0
(stationary config.)

Diffusion coefficient,
often $D \propto \beta(E/q)^\delta$

convection

energy
losses

diffusive
reacceleration
$K \propto v_a^2 p^2/D$

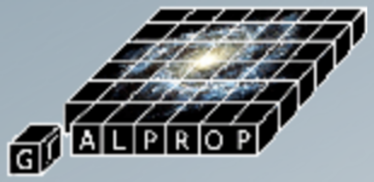
Sources
(primary &
secondary)

Analytical vs. numerical

How to solve the diffusion equation?

- Numerically
  - + 3D possible
  - + any magnetic field model
  - + realistic gas distribution, full energy losses
  - − computations time-consuming
  - − for most users a "black box"

e.g.

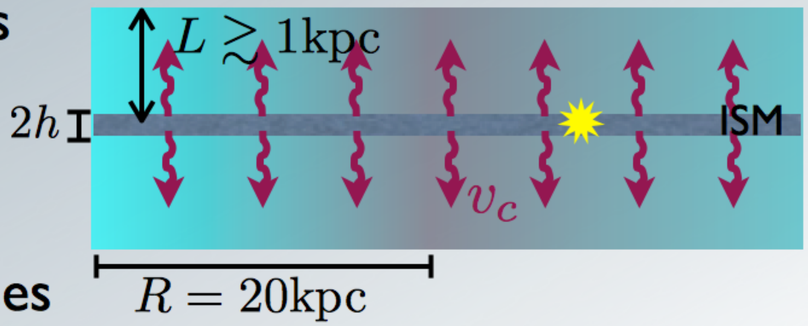


Strong, Moskalenko, …

DRAGON
Evoli, Gaggero, Grasso & Maccione

- (Semi-)analytically
  - + Physical insight from analytic solutions
  - + fast computations allow to sample full parameter space
  - − only 2D possible
  - − simplified gas distribution, energy losses

e.g. Donato, Fornengo, Maurin, Salati, Taillet, …

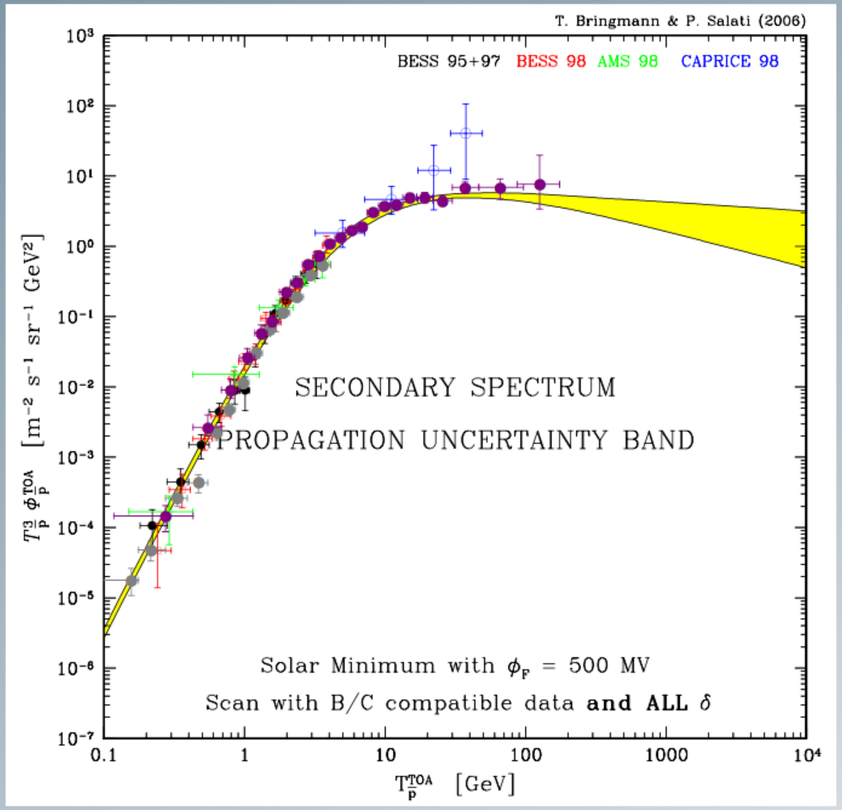


E.g. secondary antiprotons

- Propagation parameters $(K_0, \delta, L, v_a, v_c)$ of two-zone diffusion model strongly constrained by B/C

Maurin, Donato, Taillet & Salati, ApJ '01

- This can be used to predict fluxes for other species:



TB & Salati, PRD '07

excellent agreement with new data:

BESSpolar 2004

Abe *et al.*, PRL '08

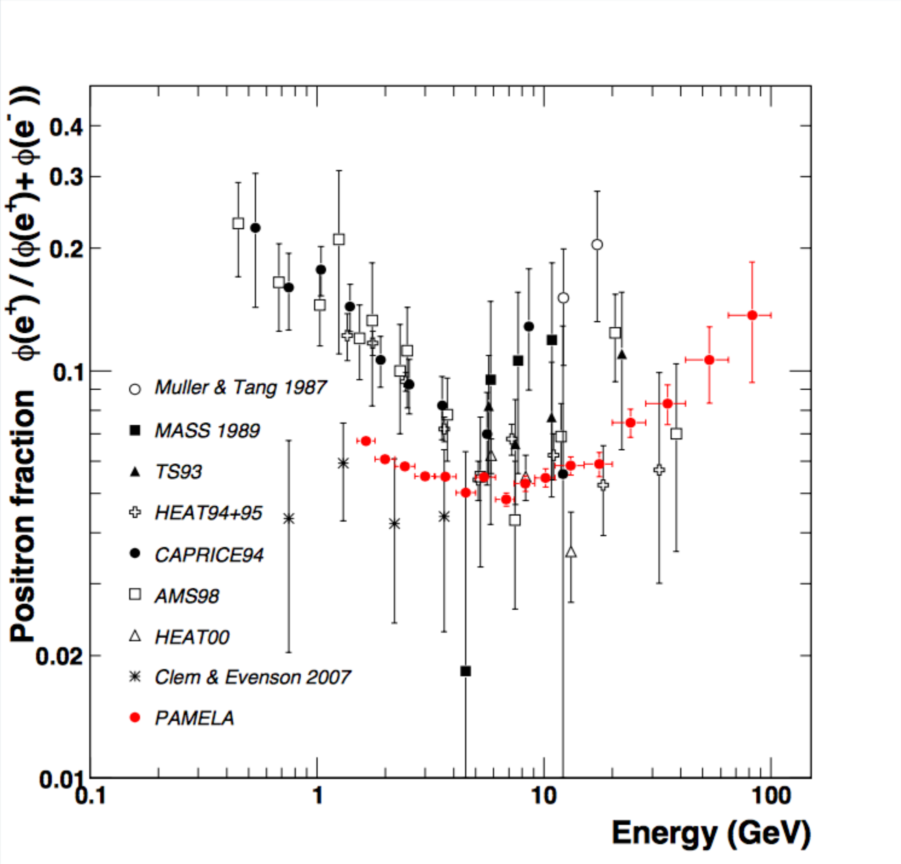
PAMELA 2008

Adriani *et al.*, PRL '10

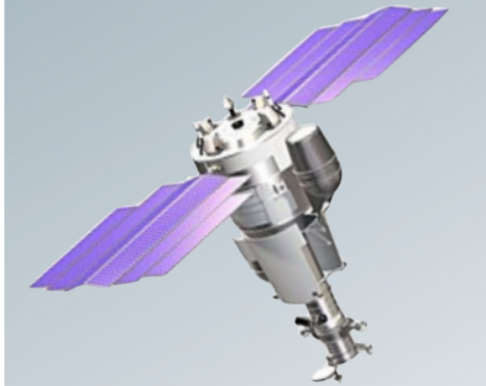
➡ very nice test for underlying diffusion model!

Positrons

Excess in cosmic ray positron data has triggered great excitement:



PAMELA

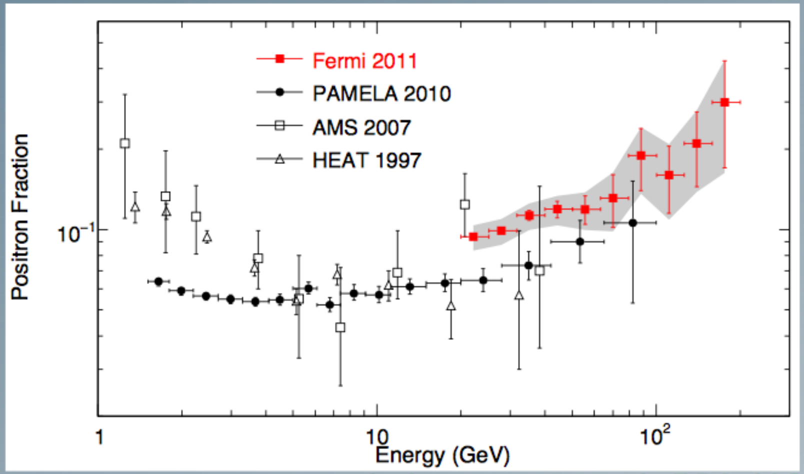


Adriani *et al.*, Nature '09

➩ Are we seeing a DM signal ???

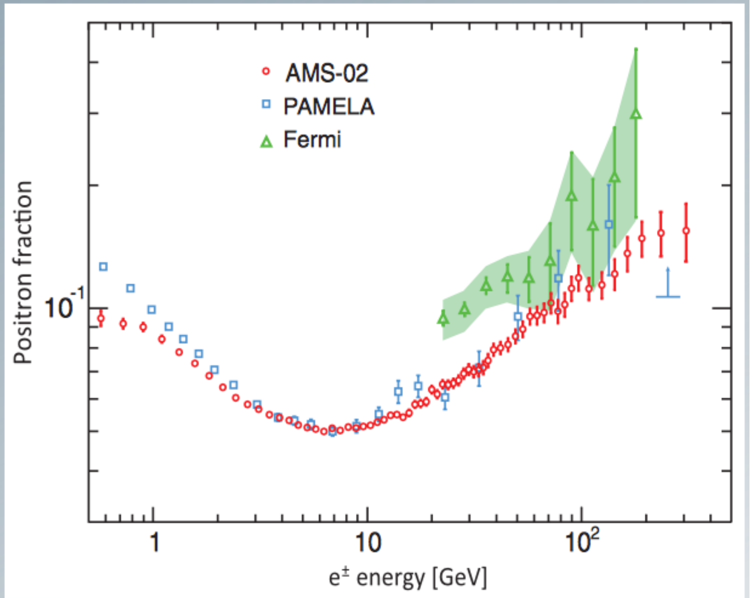
Independent confirmation

- By Fermi (!):



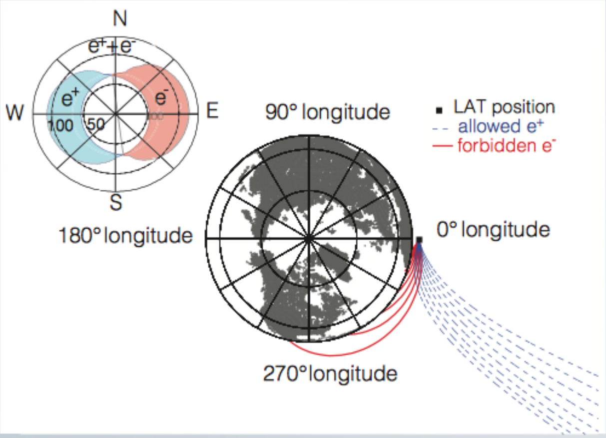
Ackermann *et al.*, PRL '12

- By AMS:



Aguilar *et al.*, PRL '13

NB: Fermi does not have a magnet on board, but uses the earth magnetic field!



S. Ting:

"Over the coming months, AMS will be able to tell us conclusively whether these positrons are a signal for dark matter, or whether they have some other origin"

Lepton propagation

- $e^{\pm}$ can also be described in same framework as $\bar{p}$!

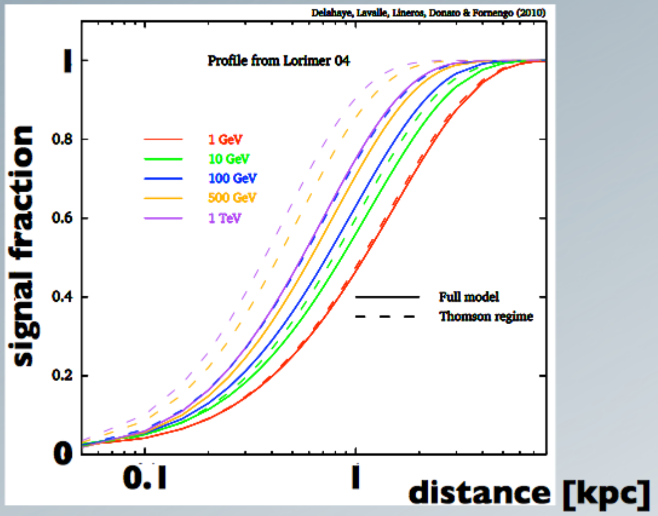
Delahaye *et al.*, PRD '08, A&A '09, A&A '10

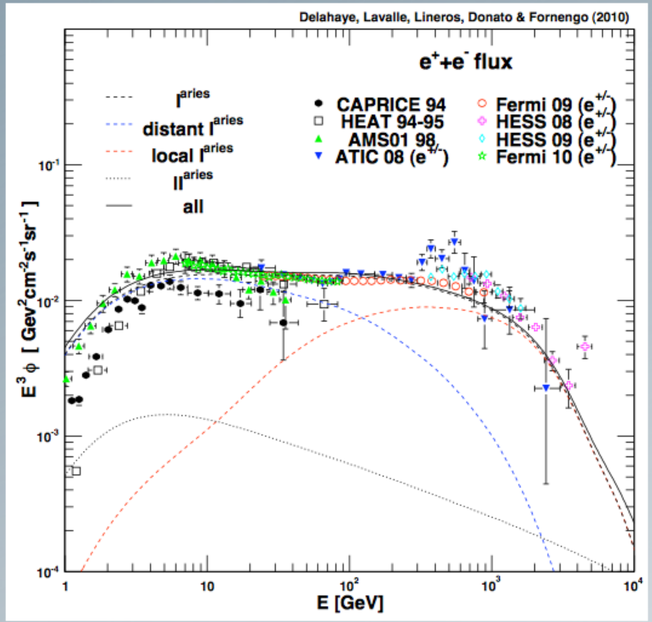
- Main difference to nuclei:

  energy losses are dominant

  [synchrotron + inverse Compton]

  ➡ mainly locally produced (~kpc for 100 GeV leptons)





- propagation uncertainties:
  - secondaries ~ 2-4
  - primaries ~5

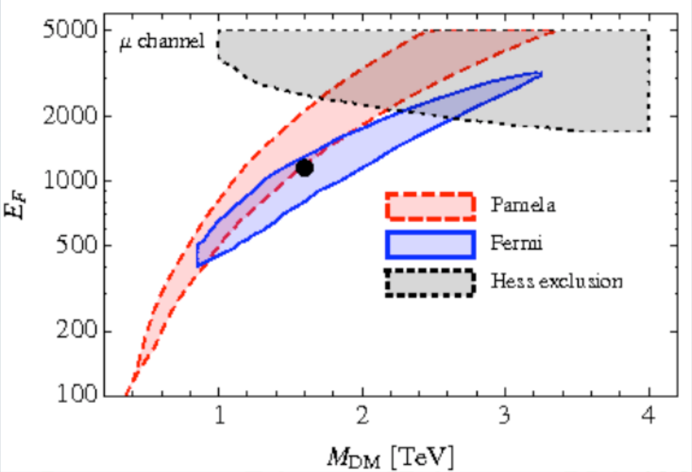
➡ need for local primary source(s) to describe data well above ~10 GeV

DM explanations

- Model-independent analysis:
  - strong constraints on hadronic modes from $\bar{p}$ data
  - $\chi\chi \rightarrow e^+e^-$ or $\mu^+\mu^-$ favoured
  - large boost factors *generic* – $\mathcal{O}(10^3)$

➔ highly non-conventional DM!

+ significant radio/IC constraints, see later!



Bergström, Edsjö & Zaharijas, PRL '09

- *and*: many good astrophysical candidates for primary sources in the cosmic neighbourhood:
  - pulsars Grasso *et al.*, ApP '09
Yüksel *et al.*, PRL '09
Profumo, 0812.4457
  - old SNRs Blasi, PRL '09
Blasi & Serpico, PRL '09
  - and further proposals...

take home message:

> *Positrons are certainly not the best messengers for DM searches!*

DarkSUSY

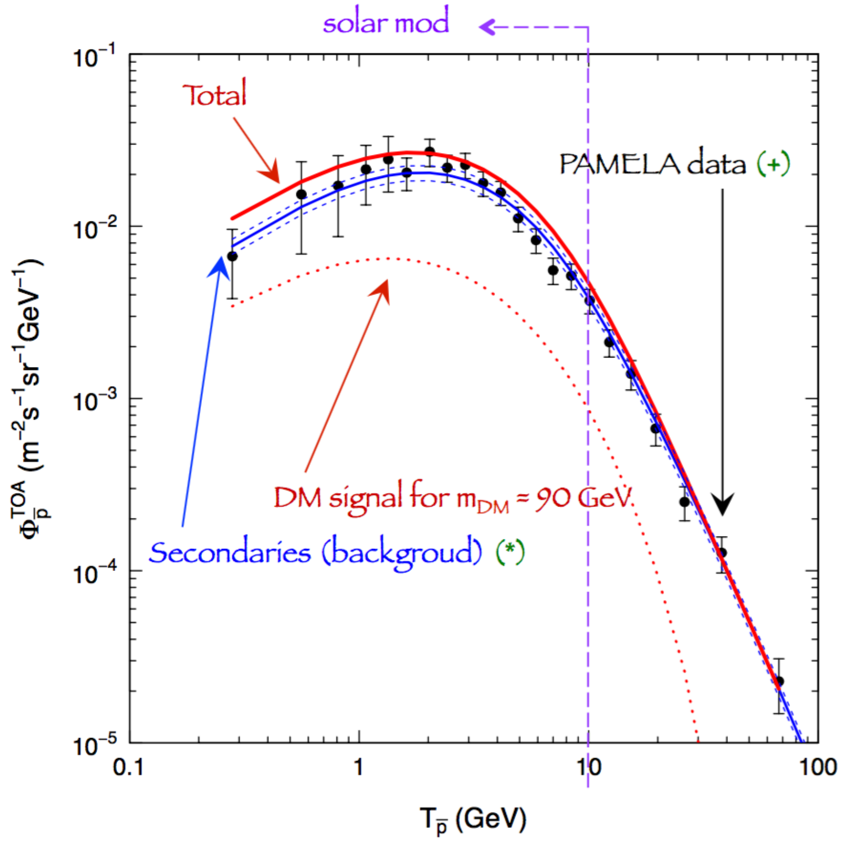
P. Gondolo, J. Edsjö, P. Ullio, L. Bergström, M. Schelke, E.A. Baltz, T. Bringmann and G. Duda

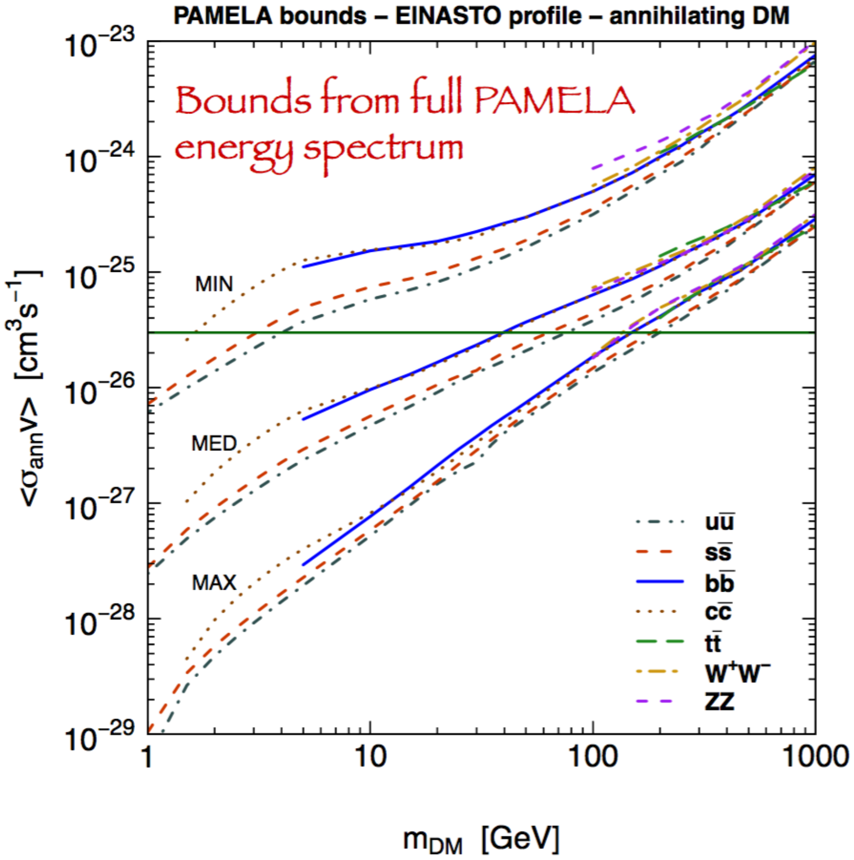
FREE DOWNLOAD ;)

http://darksusy.org

- Fortran package to calculate "all" DM related quantities:
  - *relic density + kinetic decoupling*
  - *generic SUSY models + laboratory constraints implemented*
  - *cosmic ray propagation*
  - *indirect detection rates: gammas, positrons, antiprotons, neutrinos*
  - direct detection rates
  - ...

Antiprotons





PAMELA

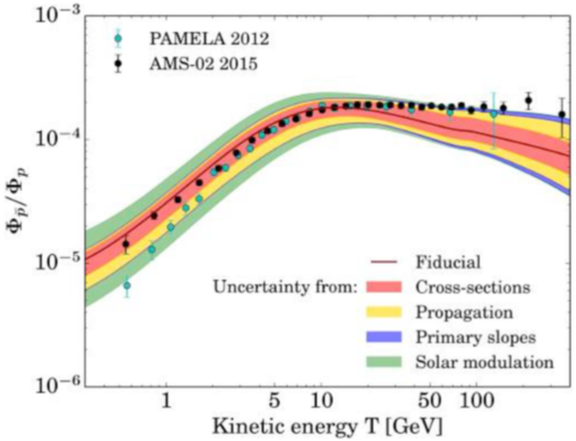
No evidence for deviation from astrophysical secondaries

Set stringent bounds on DM properties

Uncertainties from nuclear physics and galaxy transport

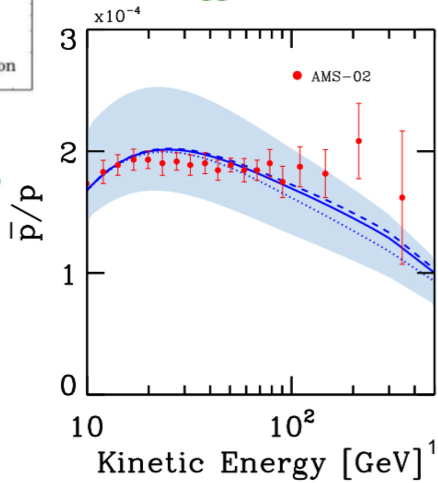
AMS-02 pbar/p

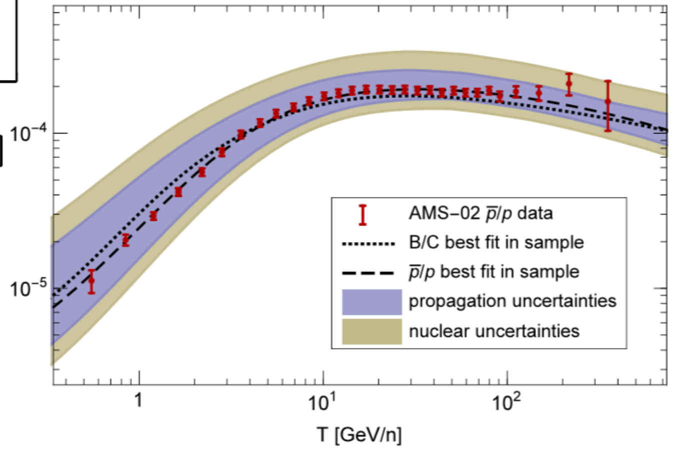
Kounine, 'AMS days at CERN, April 2015



Giesen et al., JCAP 1509 (2015) 023

Evoli, Gaggero, Grasso, arXiv:1504.05175





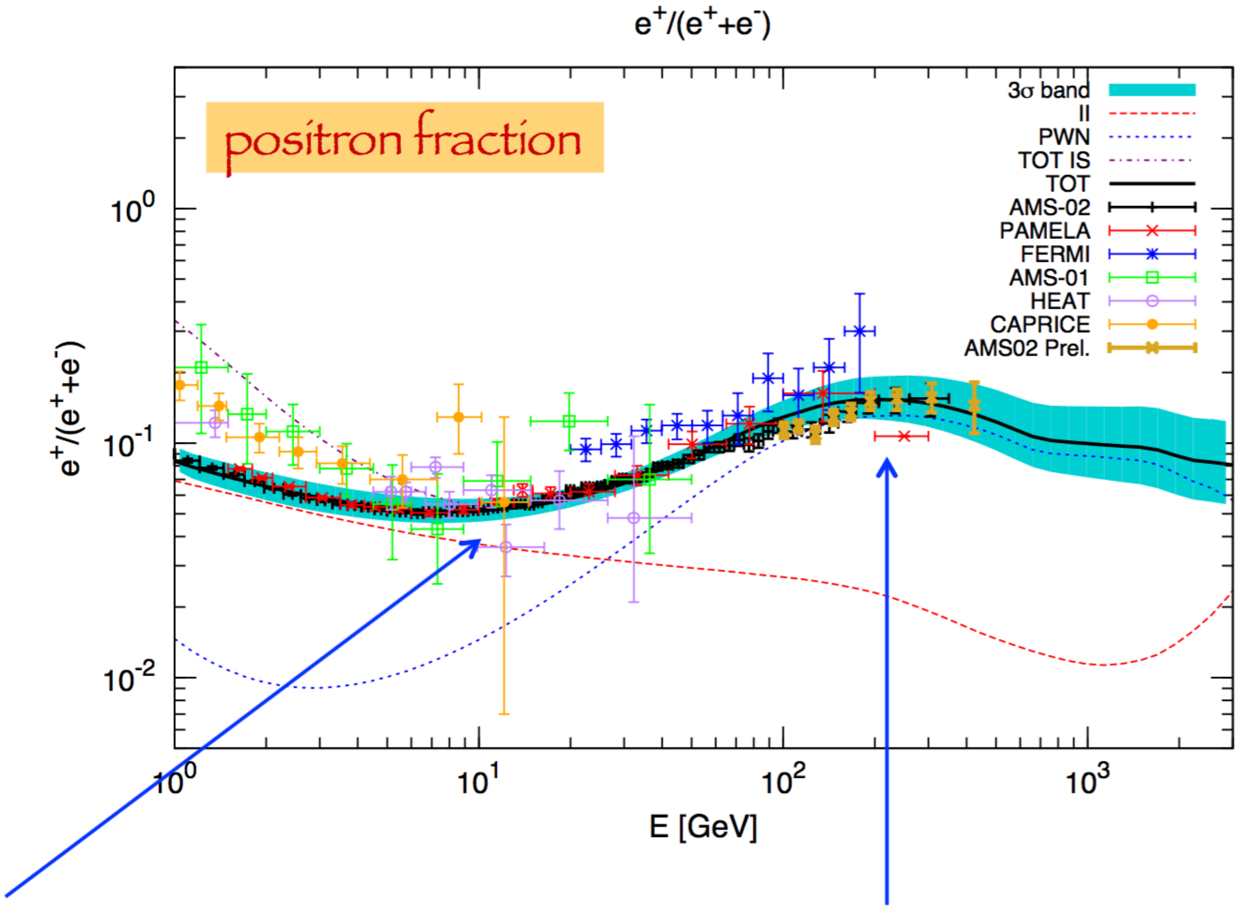
Kappl, Reinert, Winkler, JCAP 1510 (2015) 034

In addition AMS is bringing very detailed Information on cosmic rays nuclei (e.g. B/C) which will allow shaping the CR transport models

(DRAGON, Galprop, Usine, non public codes)

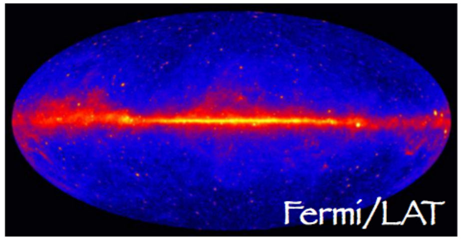
This is relevant for both DM signals and its backgrounds

Positrons



Low energies: reproduced by secondary production

High-energy: (local) sources needed

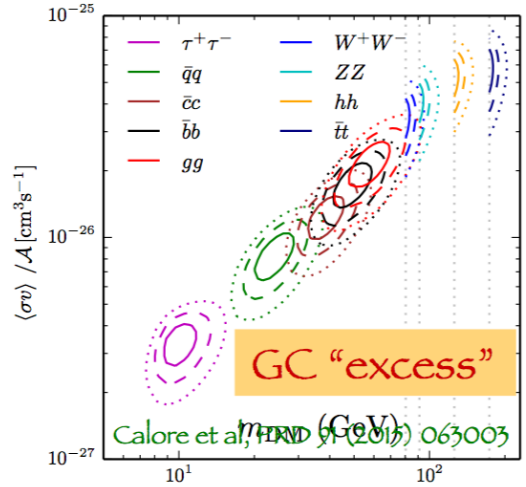


Gamma rays

Galactic center

Very interesting target, but difficult

Potential hints, under hot discussion



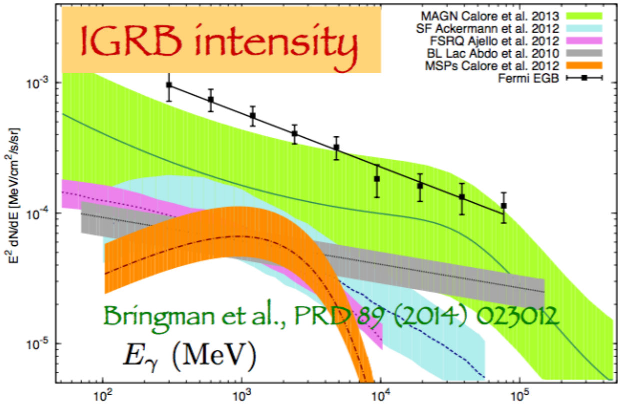
GC "excess"

Calore et al, PRD 91 (2015) 063003

Isotropic gamma ray background

Relevant for extragalactic DM

Complex to seperate a DM signal from astrophysical sources



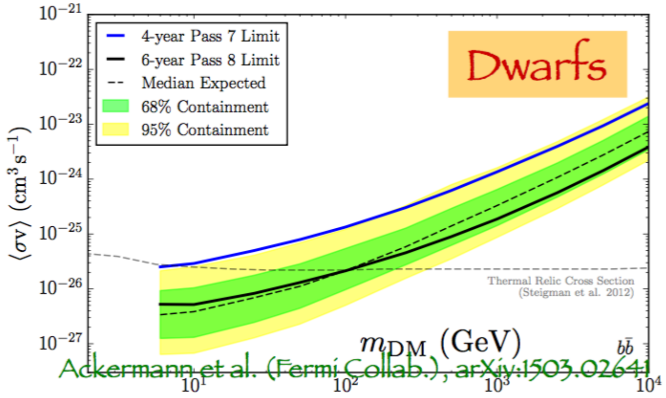
IGRB intensity

Bringman et al., PRD 89 (2014) 023012

Dwarf galaxies

One of the best targets (DM dominated)

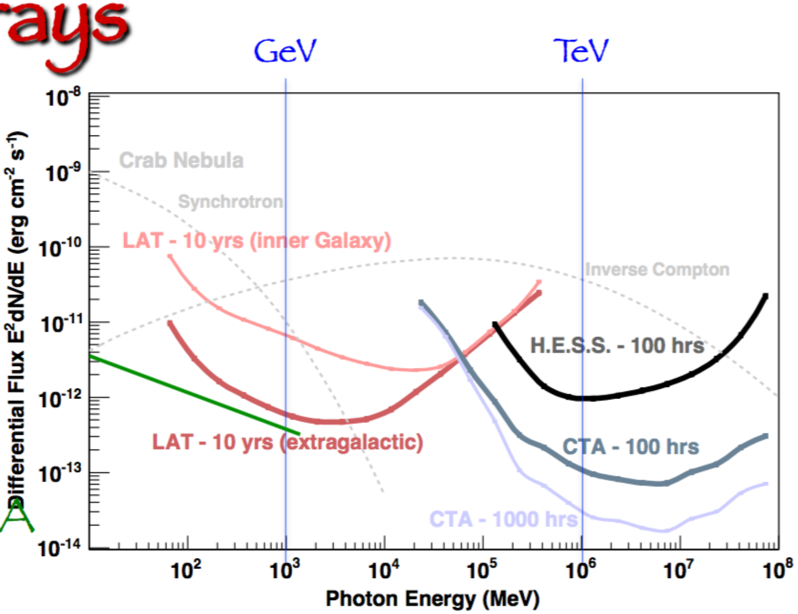
Recently, new dwarfs have been discovered (DES): great potentiality



Dwarfs

Ackermann et al. (Fermi Collab.), arXiv:1503.02641

Gamma rays



- Higher energies (ground): >300 GeV

  Probe TeV+ DM

  Targets
    Galactic center
    DM clumps
    dSphs galaxies
    Galaxy clusters

  Magic, HESS, Hawc, LHAASO, CTA

- GeV – TeV energies (space) or even higher

  Probe GeV-TEV DM

  Improved energy and angular resolution

  DAMPE (2 GeV – 10 TeV), GAMMA400, HERD (up to PeV), …

- Lower energies (space): MeV – GeV

  Probe subGeV DM or the low-energy tail of WIMP DM

  AstroGam, PANGU, …