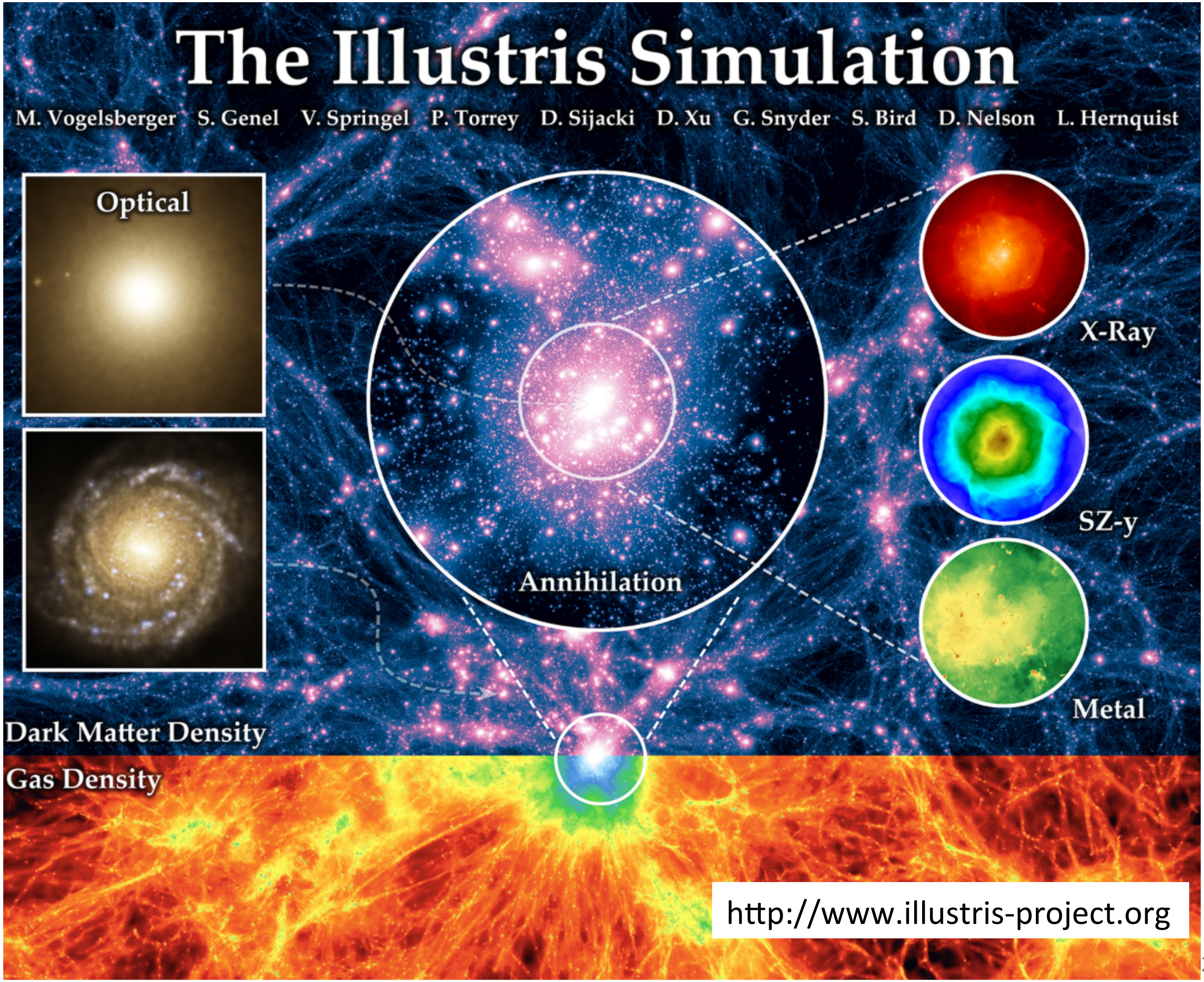
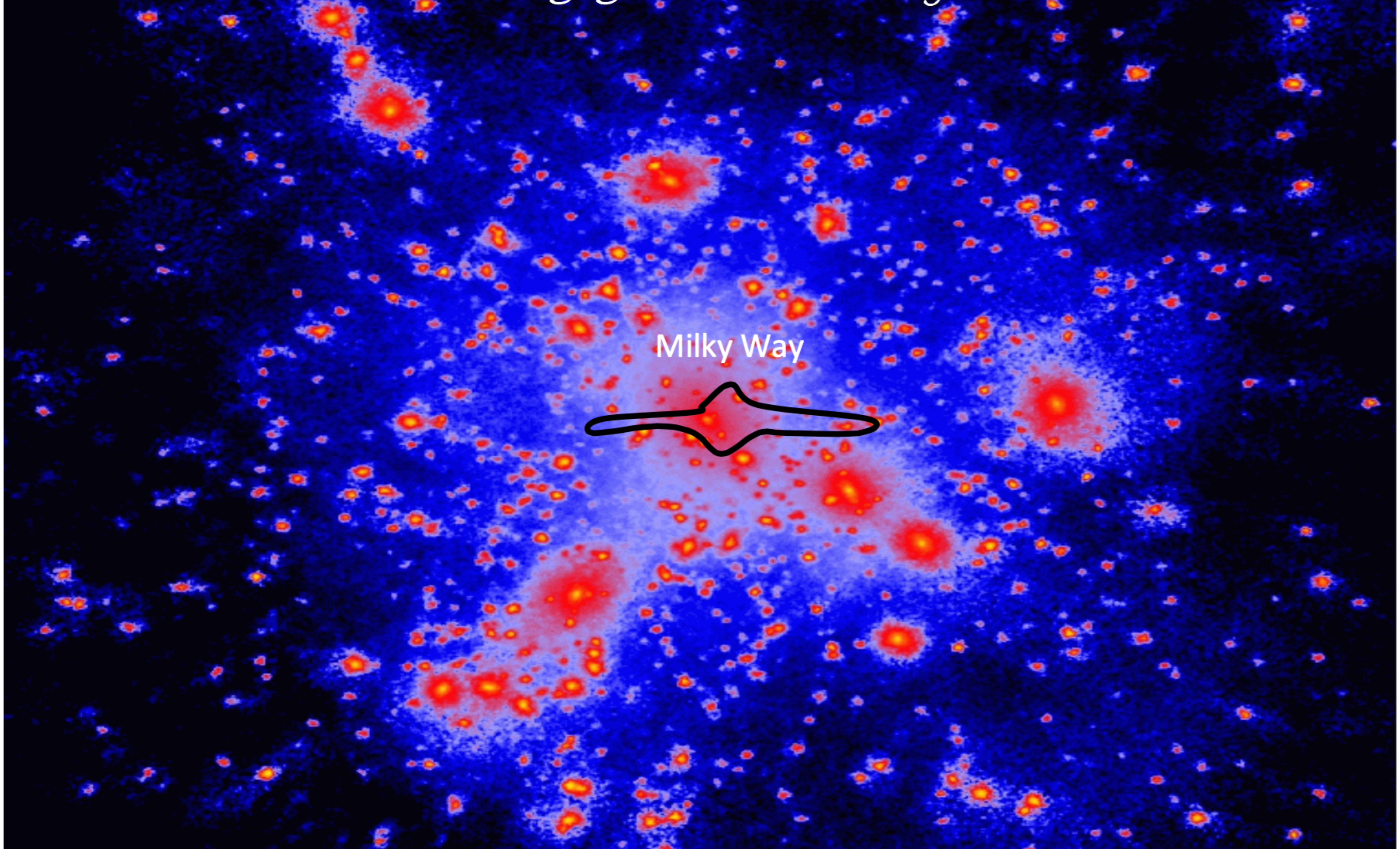
Astrofisica Nucleare e Subnucleare
Dark Matter Searches


The Illustris Simulation
M. Vogelsberger S. Genel V. Springel P. Torrey D. Sijacki D. Xu G. Snyder S. Bird D. Nelson L. Hernquist
Optical
X-Ray
SZ-y
Annihilation
Metal
Dark Matter Density
Gas Density
http://www.illustris-project.org

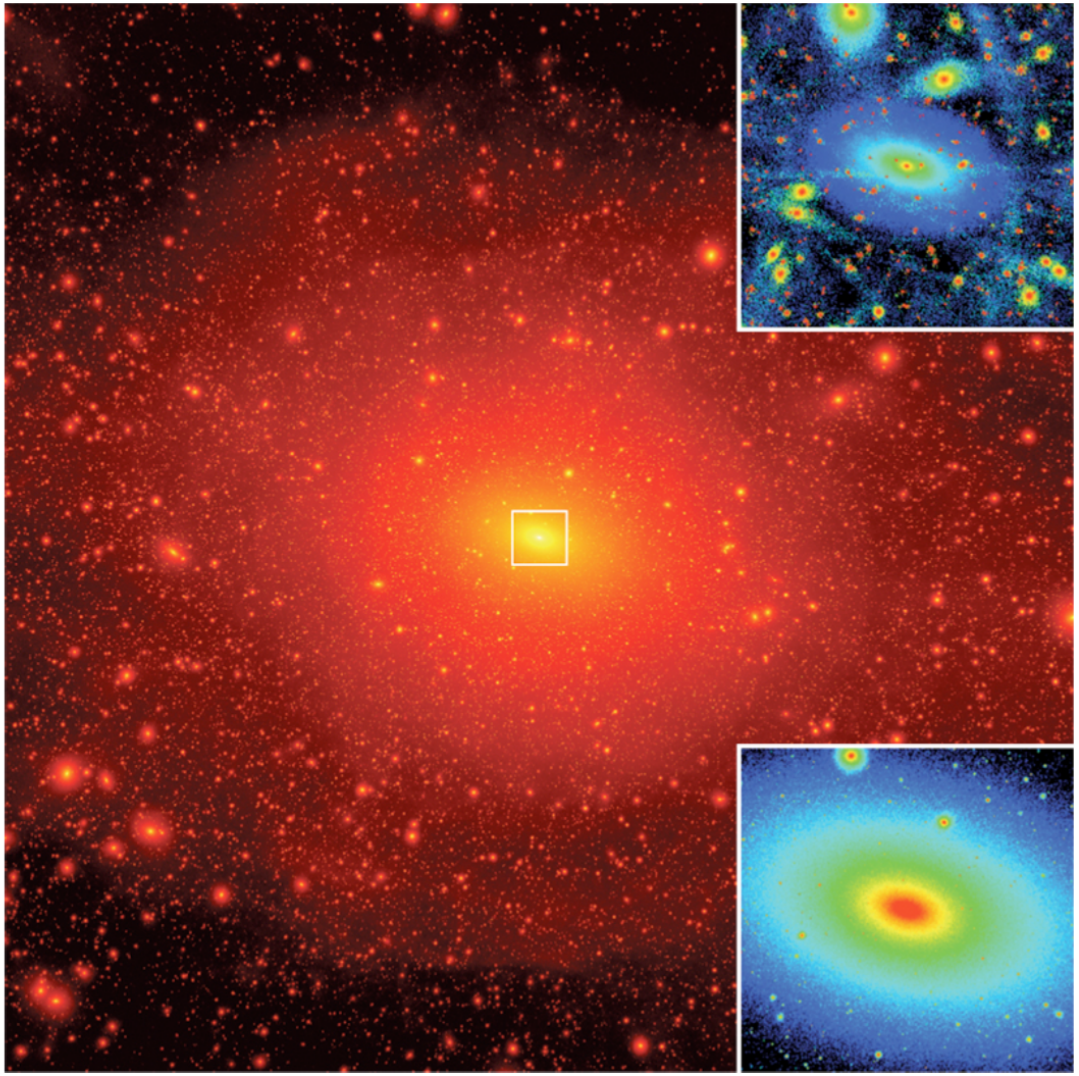
We can get an idea of what the Milky Way halo looks like from numerical simulations of structure formation through gravitational instability in cold dark matter



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

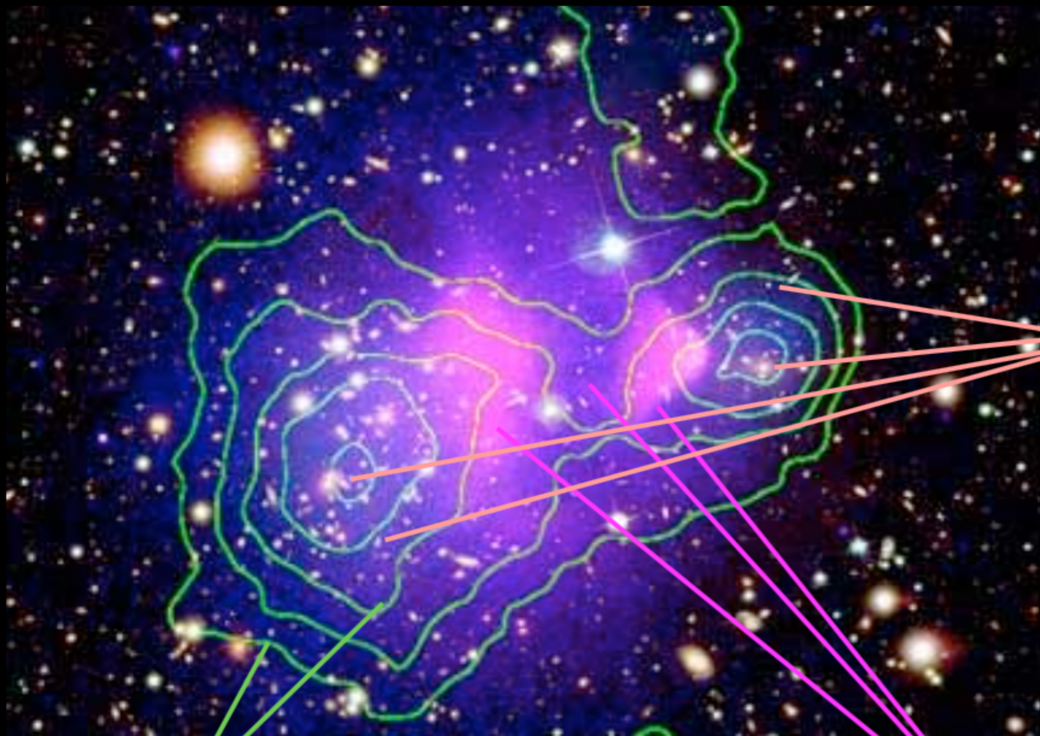
real space

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

Cold dark matter, *not* modified gravity

The Bullet Cluster

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



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

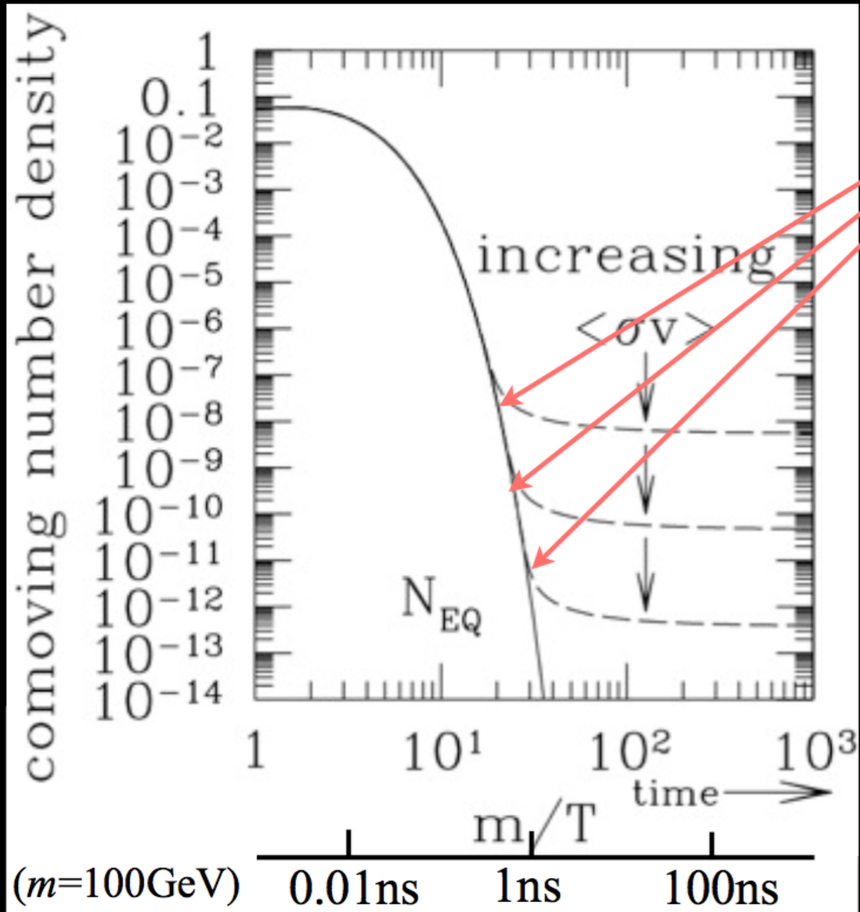
neutralinos, axions, WIMPZILLAs, solitons

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*

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

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

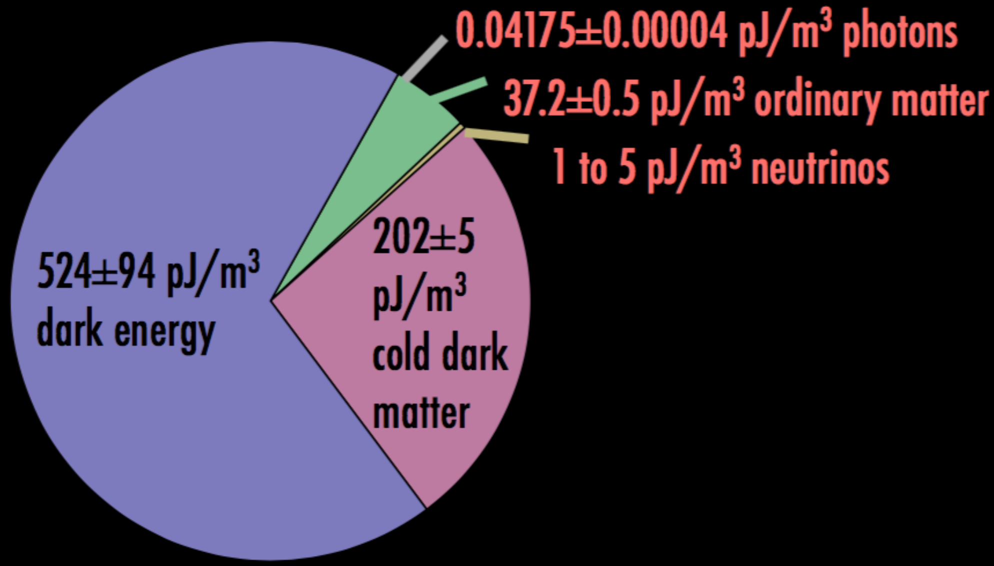
for $\langle\sigma v\rangle_{\rm ann} \simeq 3\times 10^{-26}{\rm cm}^3/{\rm s}$

This is 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

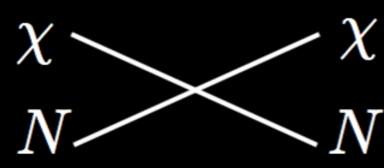
  The same physical processes that produce the right density of WIMPs make their detection possible

The magnificent WIMP

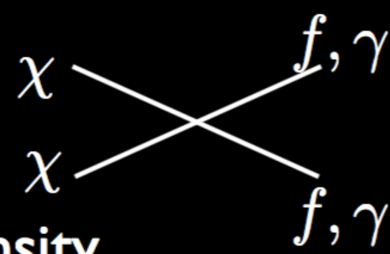
To first order, three quantities characterize a WIMP

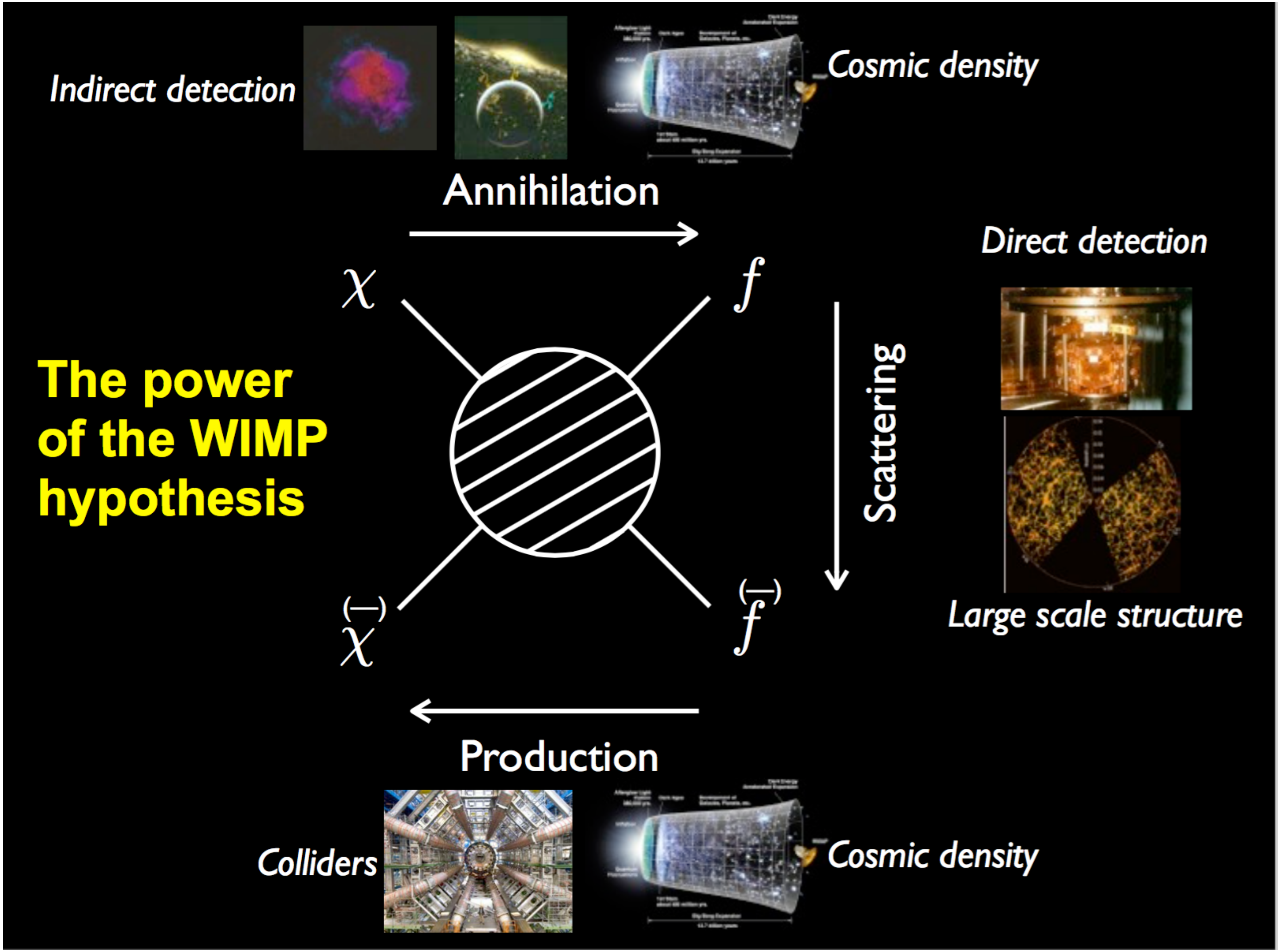
- Mass m
  - Simplest models relate mass to cosmic density: $1-10^4$ GeV/c^2

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



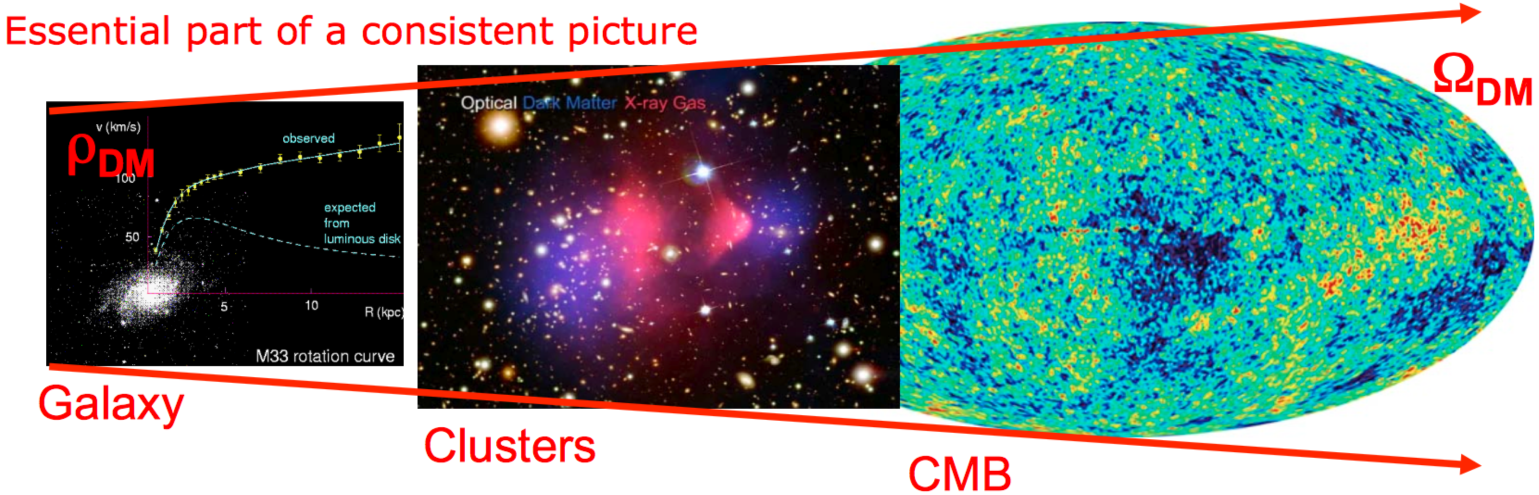
- Annihilation cross section into ordinary particles
  - $\sigma \simeq \text{const}/v$ at small v, so use σv
  - Simplest models relate cross section to cosmic density




Indirect detection
Cosmic density
Annihilation
Direct detection
χ
f
The power of the WIMP hypothesis
Scattering
$\overset{(-)}{\chi}$
$\overset{(-)}{f}$
Large scale structure
Production
Colliders
Cosmic density

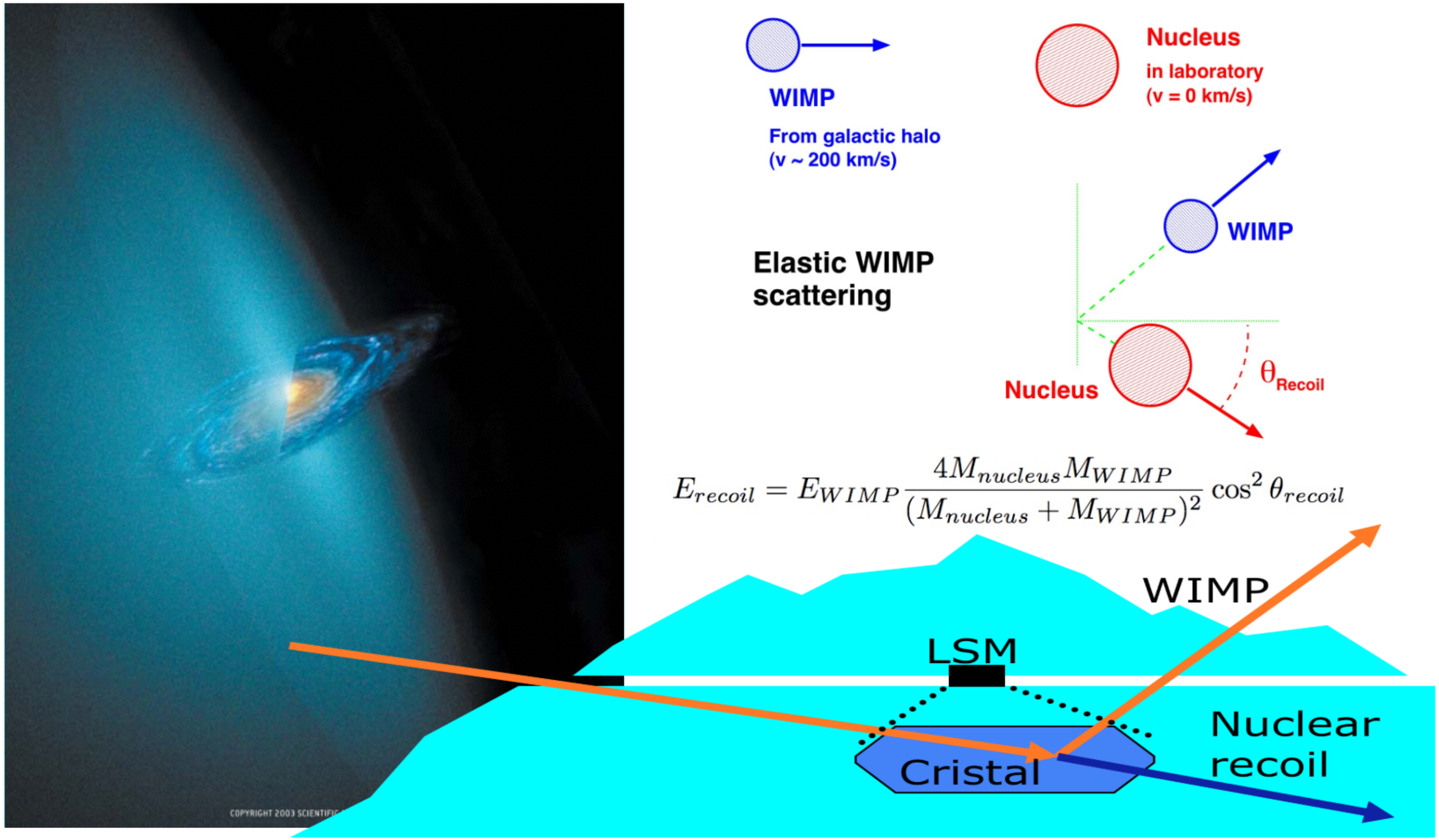
Cold Dark Matter in the Universe

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



- 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



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

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

- Collision rate (per unit time) R:

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

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

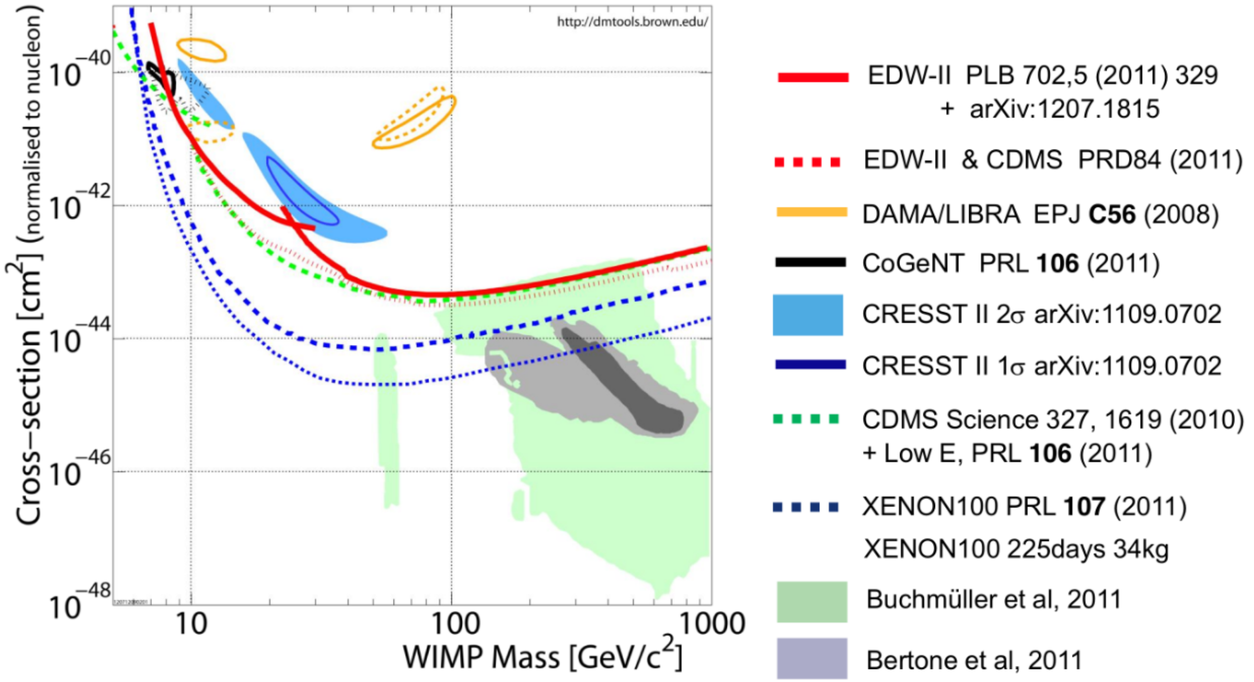
σ_A = cross-section for the elastic scattering of a WIMP on a nucleus (cm^2, barn or picobarn) 1 pb = 10^{-36} cm^2

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

➔ Need massive detectors (N_{target})

- 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"



Summary of ingredients (1)

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

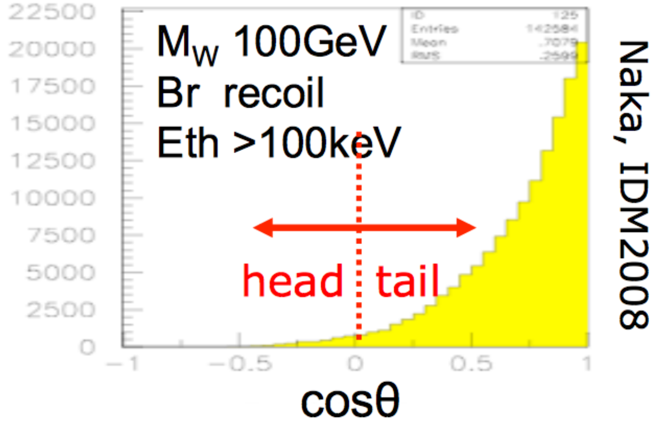
- ρ_W , WIMP density in the laboratory
  - Local measurements suggests ~0.4 GeV/cm^3 but adopted reference is 0.3
  - Observed rate $\propto \sigma_n \times \rho_W$
- f(v), WIMP velocity distribution
  - Dependence on average v_{rms}, not much on f(v) details (except: modulation)
  - Adopted reference: 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.

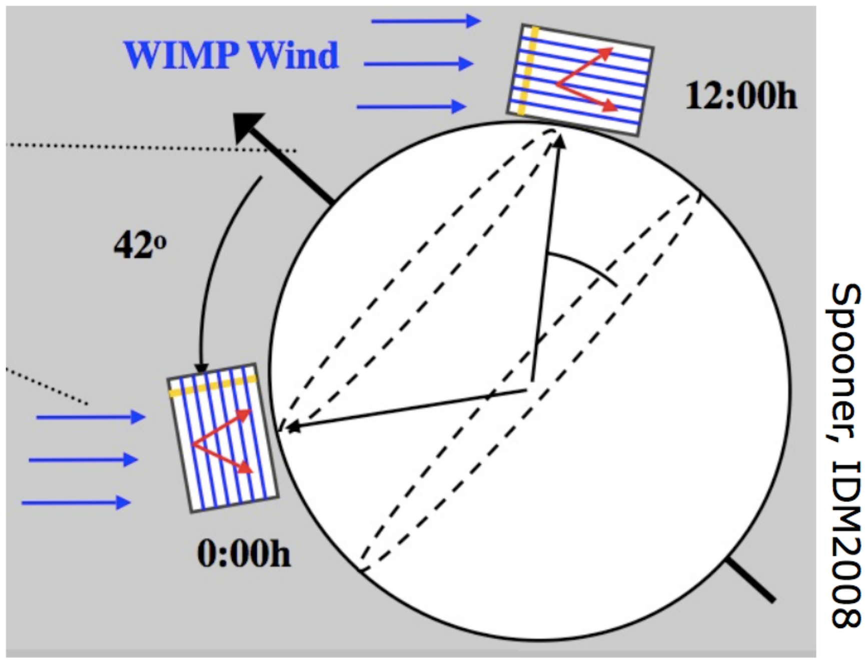
Summary of ingredients (2)

- 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 $<\theta_{RECOIL}> = <\theta_{WIMP}>$

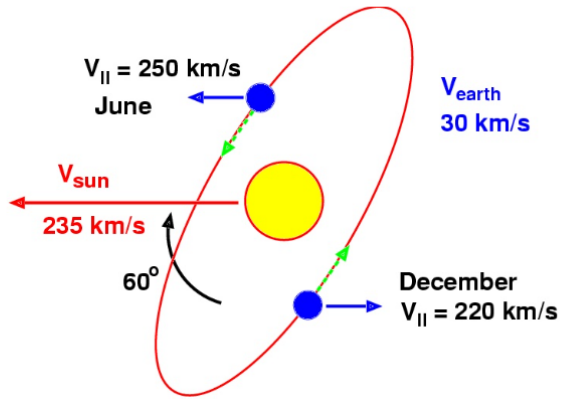




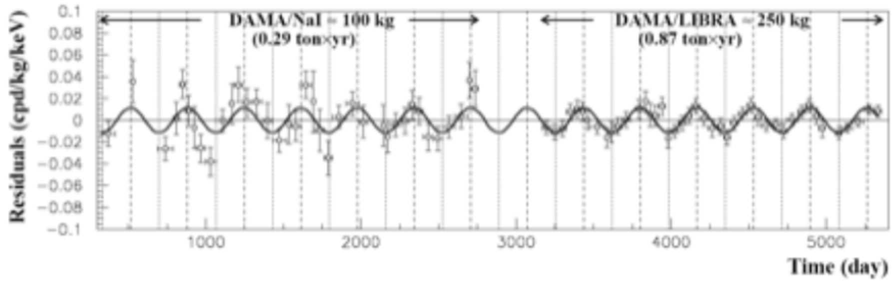
- Need a good resolution on the recoil direction (and head/tail discrimination) despite the very short range of the recoil
- Astrophysics bonus: measure of f(v)

Annual modulation

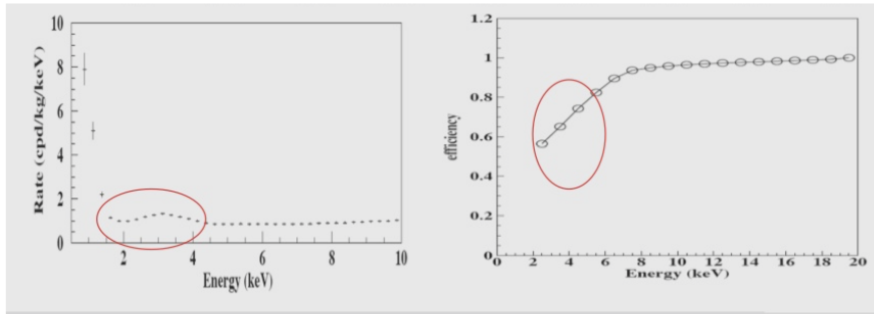
- Need large statistics: flux modulation is ~½ (±15/235) = ±3%, or less when considering experimental thresholds



- 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

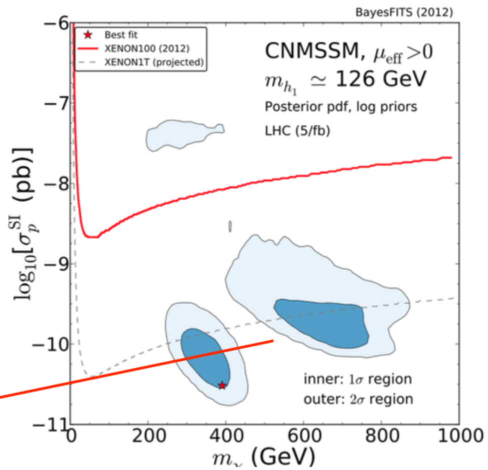
  - Most recent and complete collection of talks on almost all Direct Search experiments and projects

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

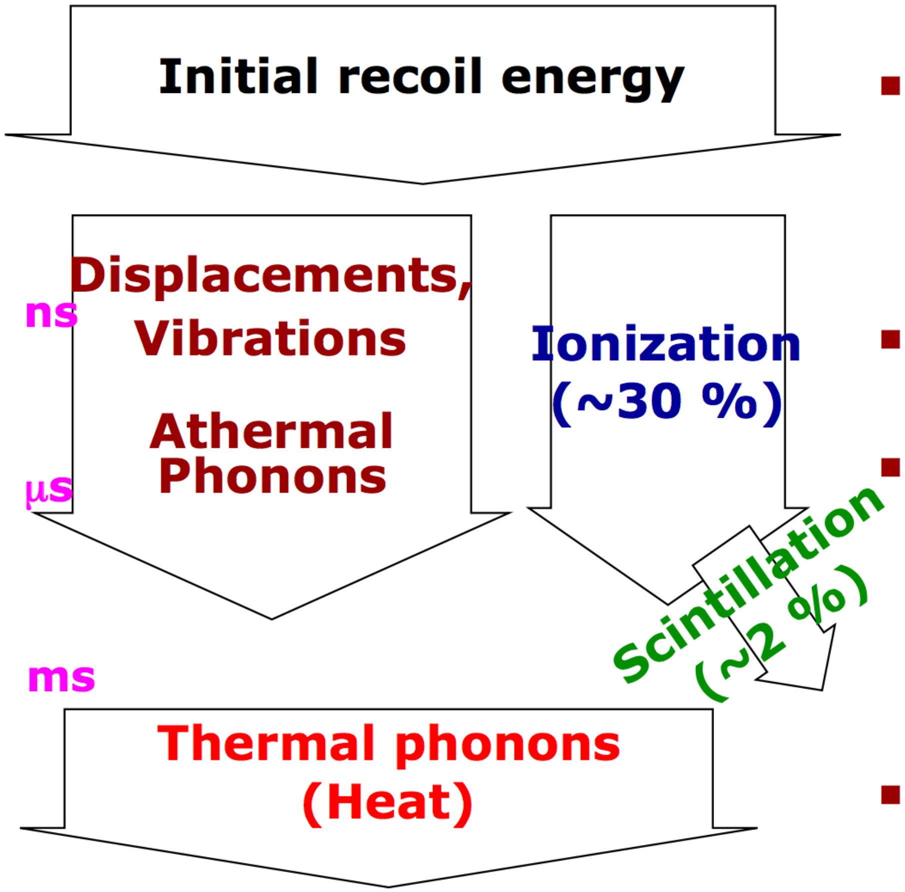
It's not a neutron-induced nuclear recoil ($\sigma = \pi R^2 \propto A^{2/3}$)

- 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

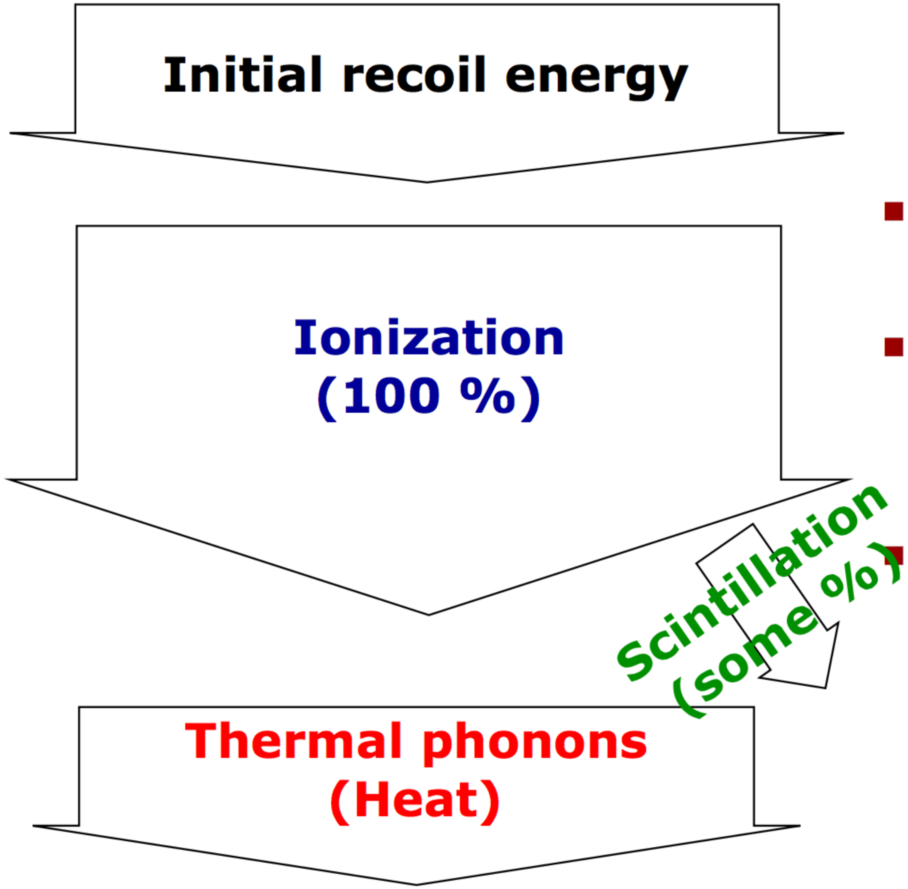


(+ Permanent crystaline defects?)

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

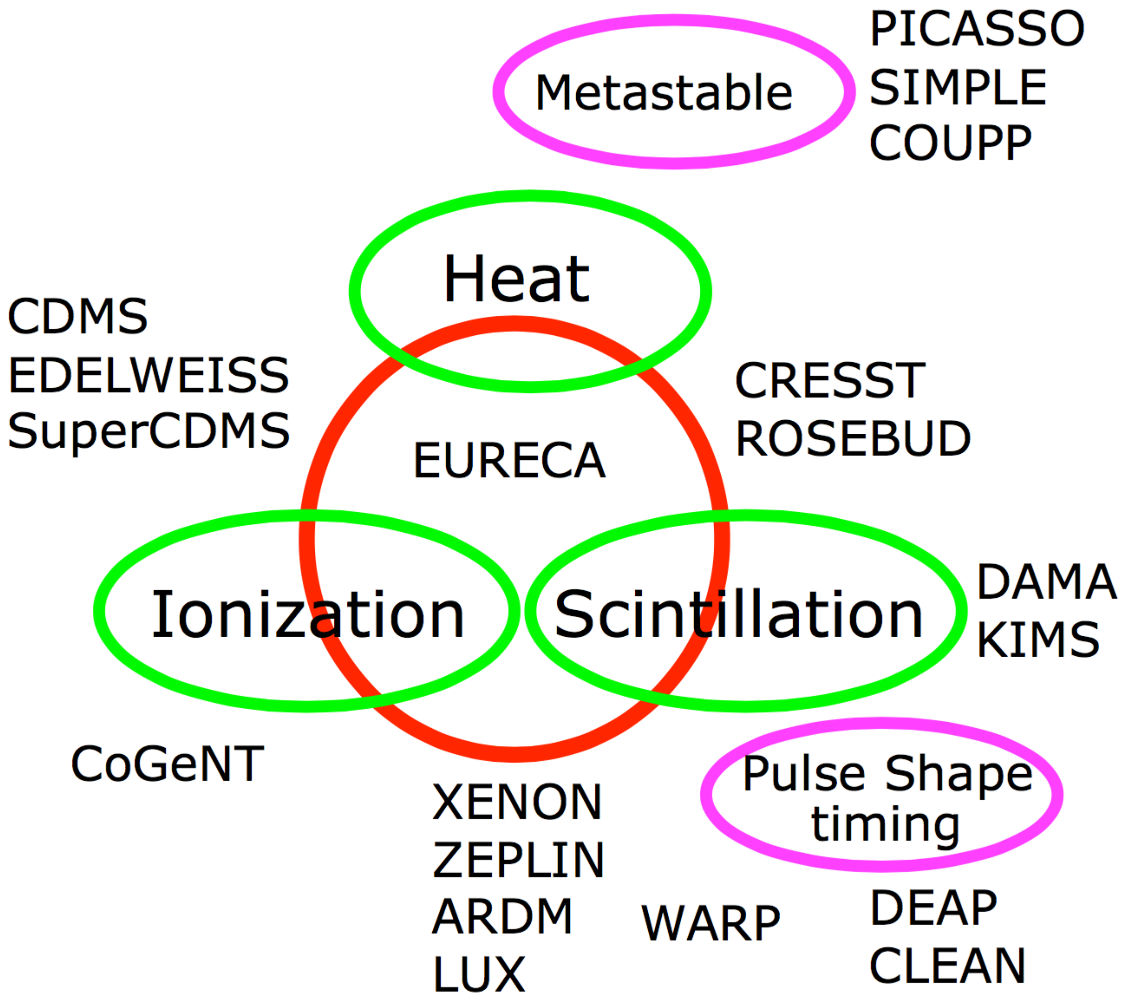


- Most common (long range) radioactive background: γ-rays, producing electron recoils (photoelectron, Compton)
- No ion-ion collisions only electronic dE/dx
- Comparing ionization and scintillation yields is a powerful tool to separate nuclear and electron recoils
- Other effects due to difference in 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?)

γ, β discrimination:

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



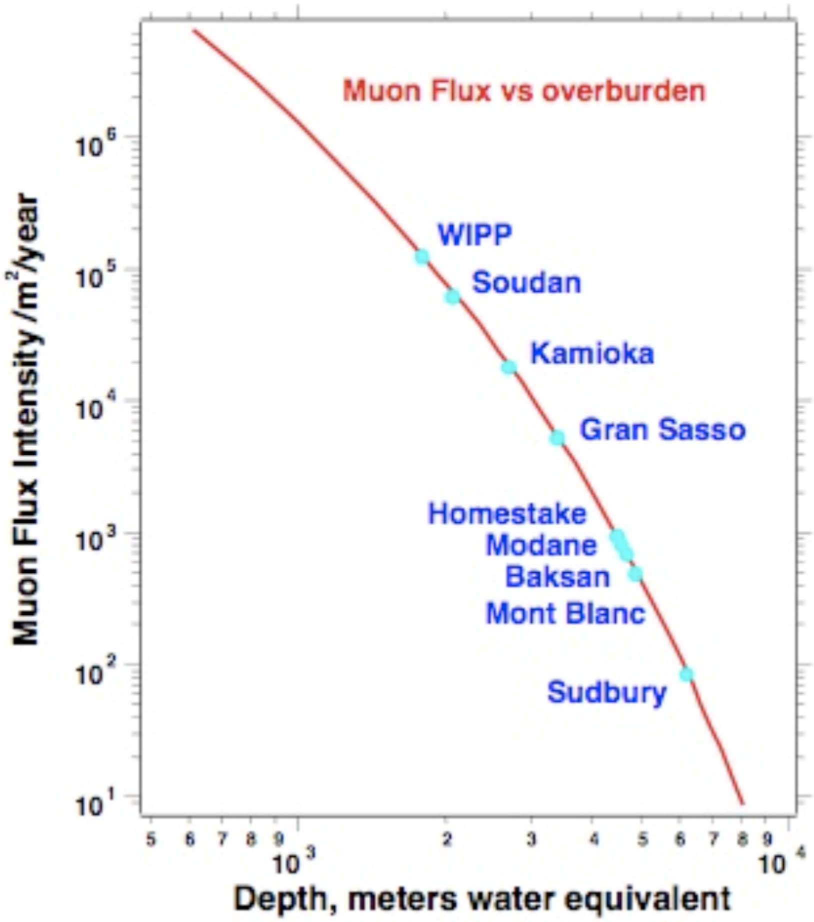
List of radioactive backgrounds

- 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

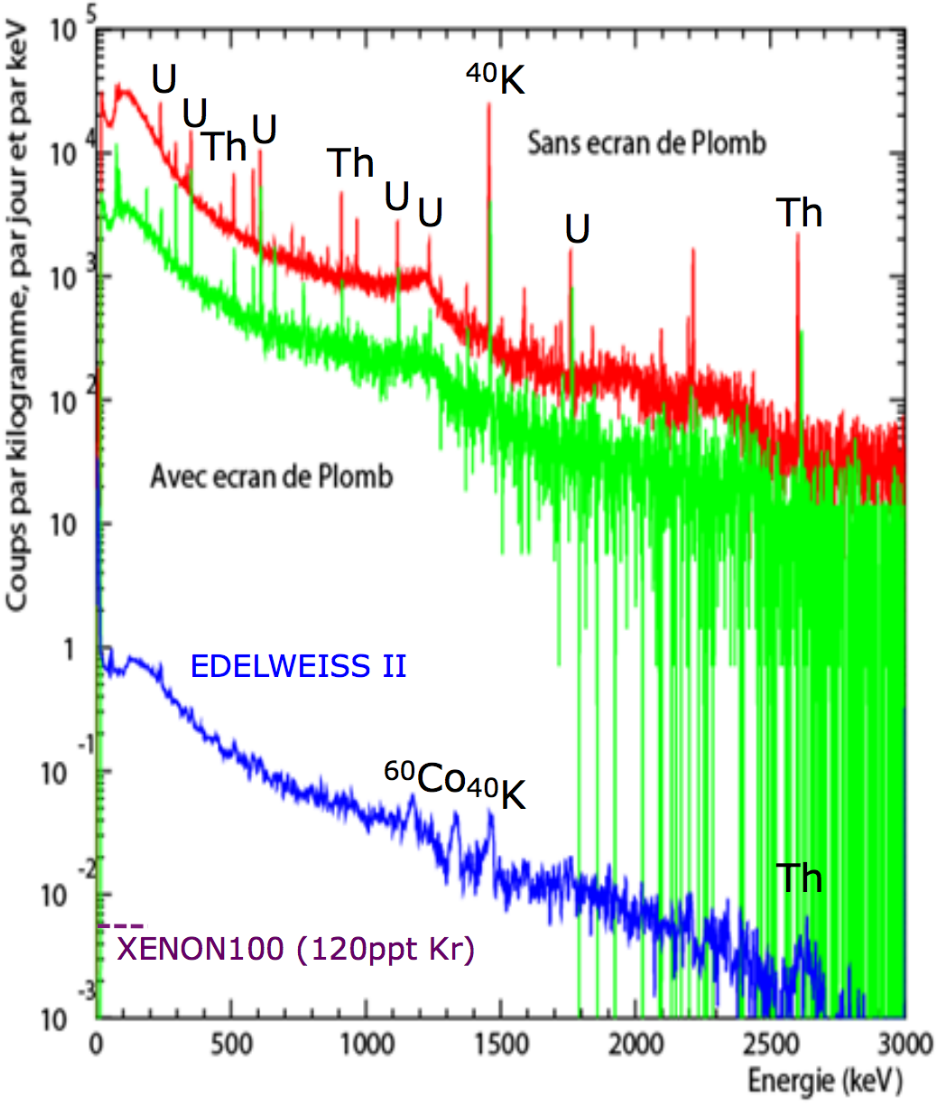
  - Ratio 10^{-6}:1 in ordinary rock: ~10^6 decay / kg / day
  - Long decay chain down to ^{206}Pb and ^{208}Pb, respectively
    - Multiplies by ~10 the activity once the chain is in equilibrium
  - Alpha and beta emitter ("contained" inside the rock)
    - Range of particles: Alpha = 20 microns, beta < 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.

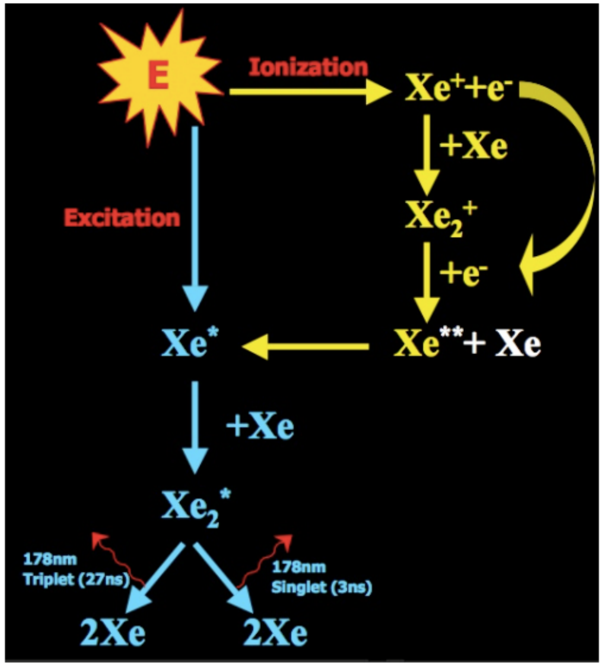
  Reduction 3x10^4 at ~50 keV (Pb shield, material selection)

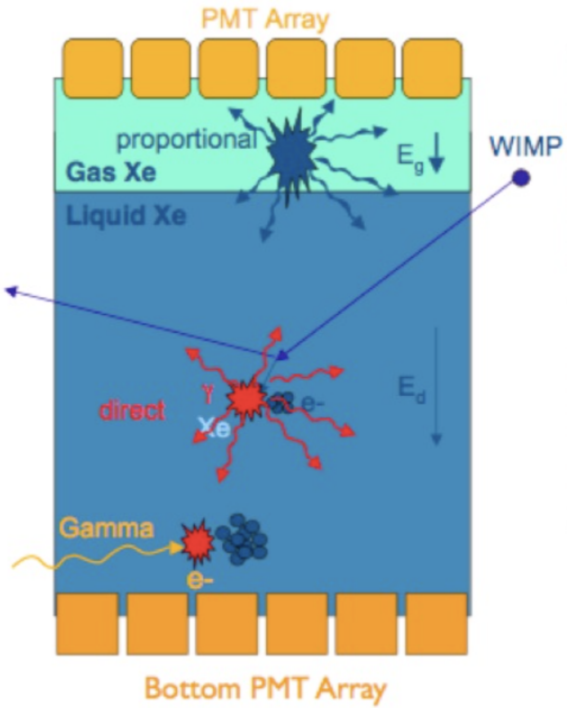
- Further reduction >10^4 after nuclear recoil identification

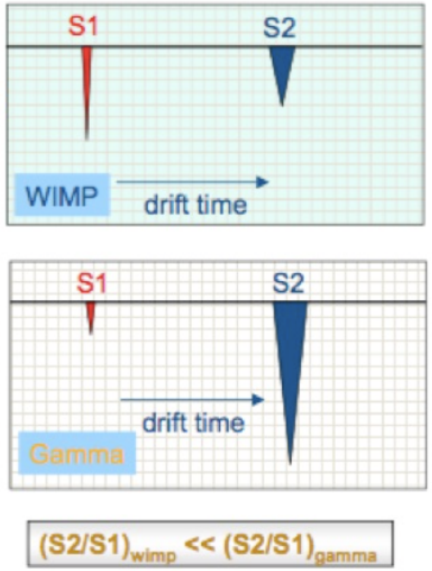


XENON S1/S2 discrimination

- 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^-)

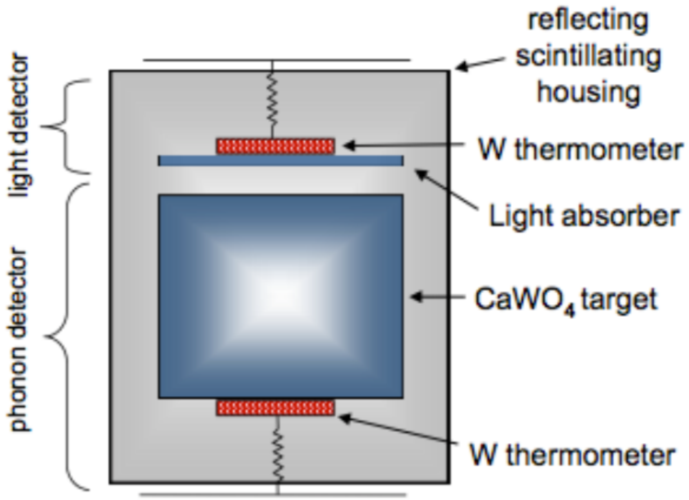






Heat-scintillation: CRESST

- 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



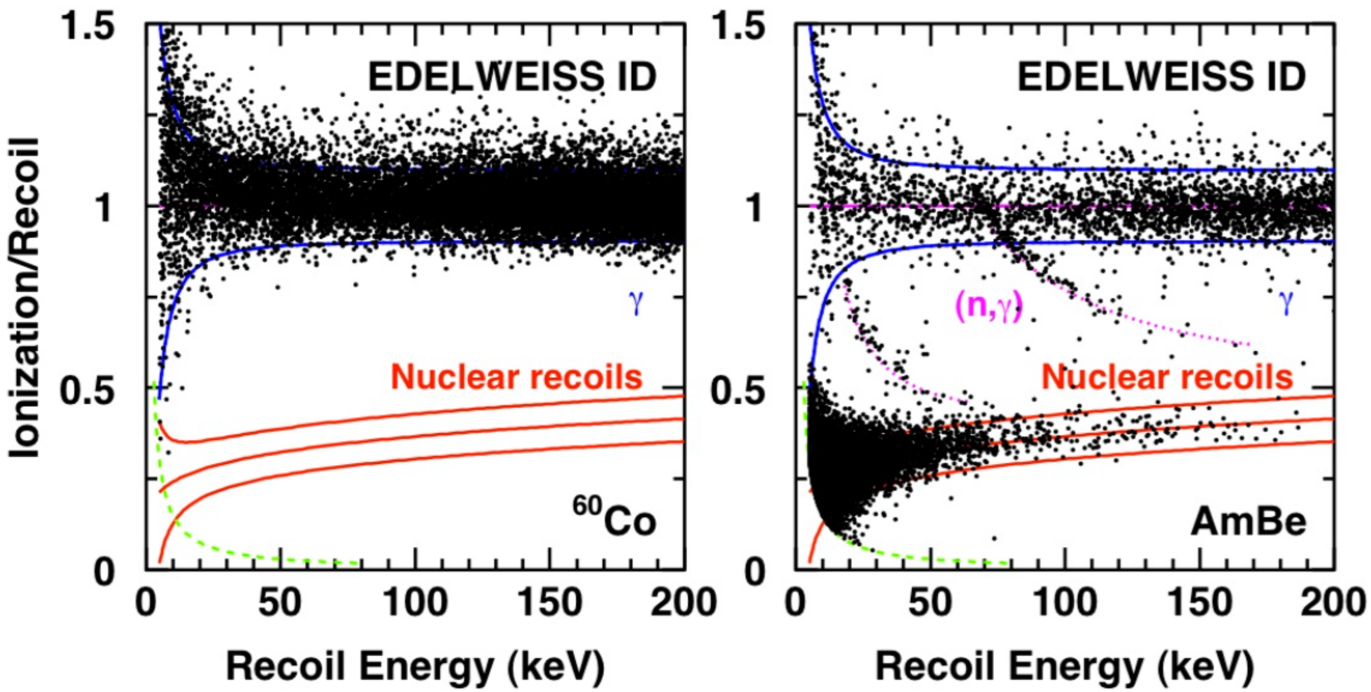
Reflecting scintillating housing to increase light yield

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

Nicolao Fornengo

Department of Physics (Theory Division) – University of Torino
and Istituto Nazionale di Fisica Nucleare (INFN) – Torino
Italy

UNIVERSITA' DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

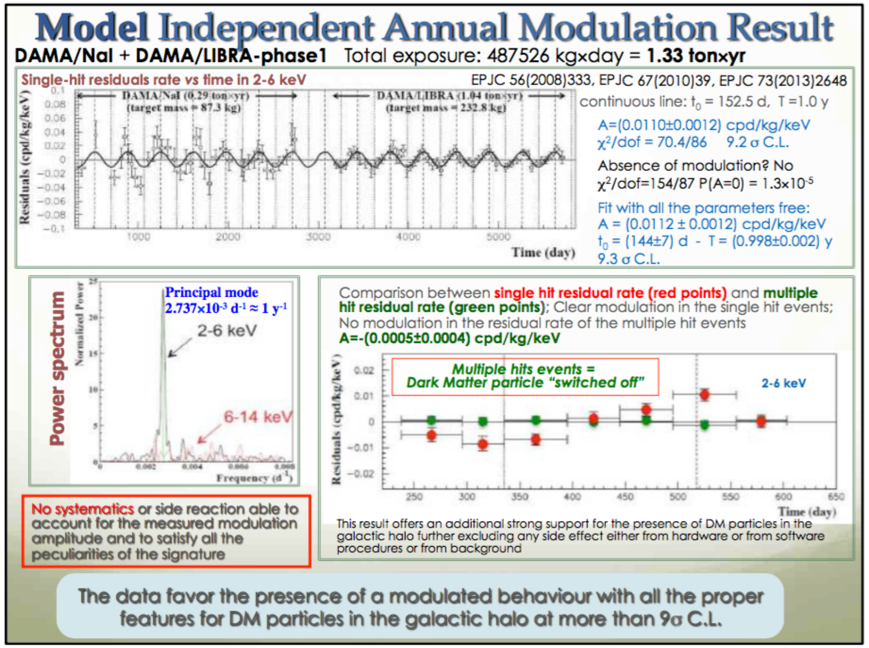
fornengo@to.infn.it
nicolao.fornengo@unito.it

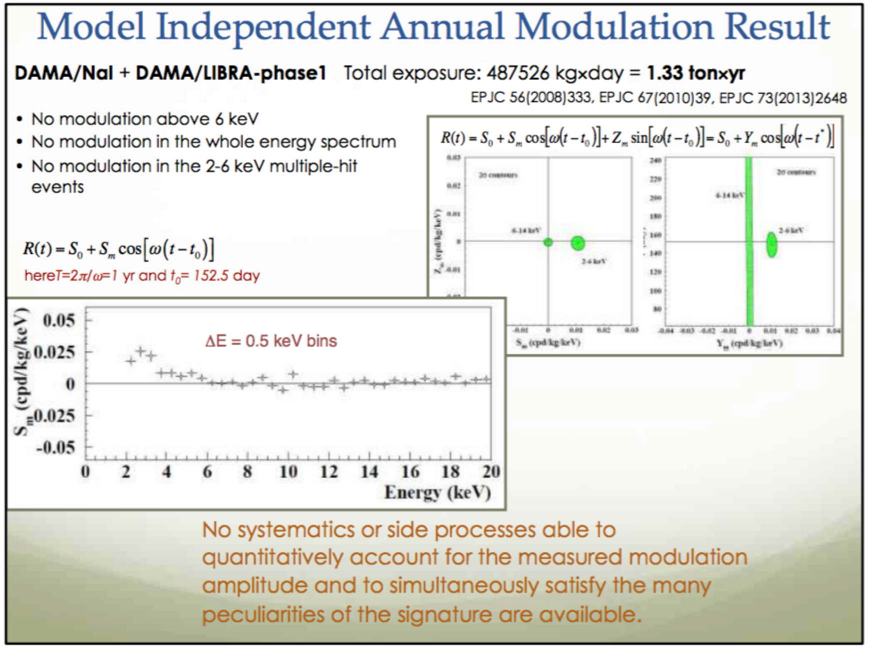
www.to.infn.it/~fornengo
www.astroparticle.to.infn.it

Torino INFN

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



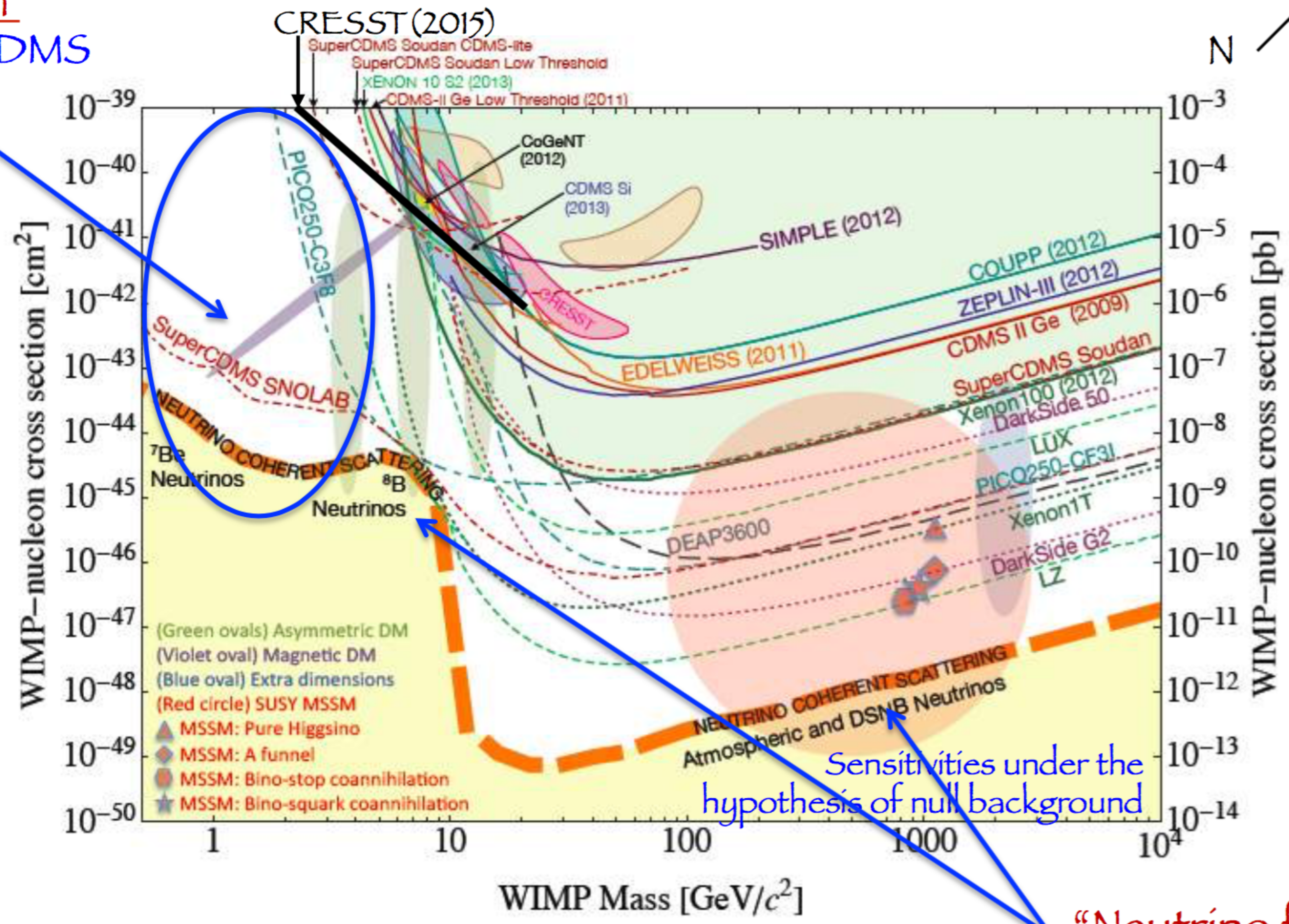


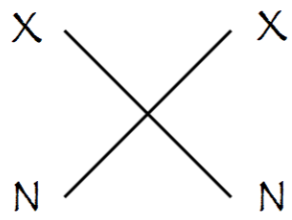
From Belli's talk at TAUP 2015, http://taup2015.to.infn.it

Compatible with: DM scattering on nuclei (5-100) GeV WIMPs

DM scattering on electrons (0.3-6) KeV ALPs

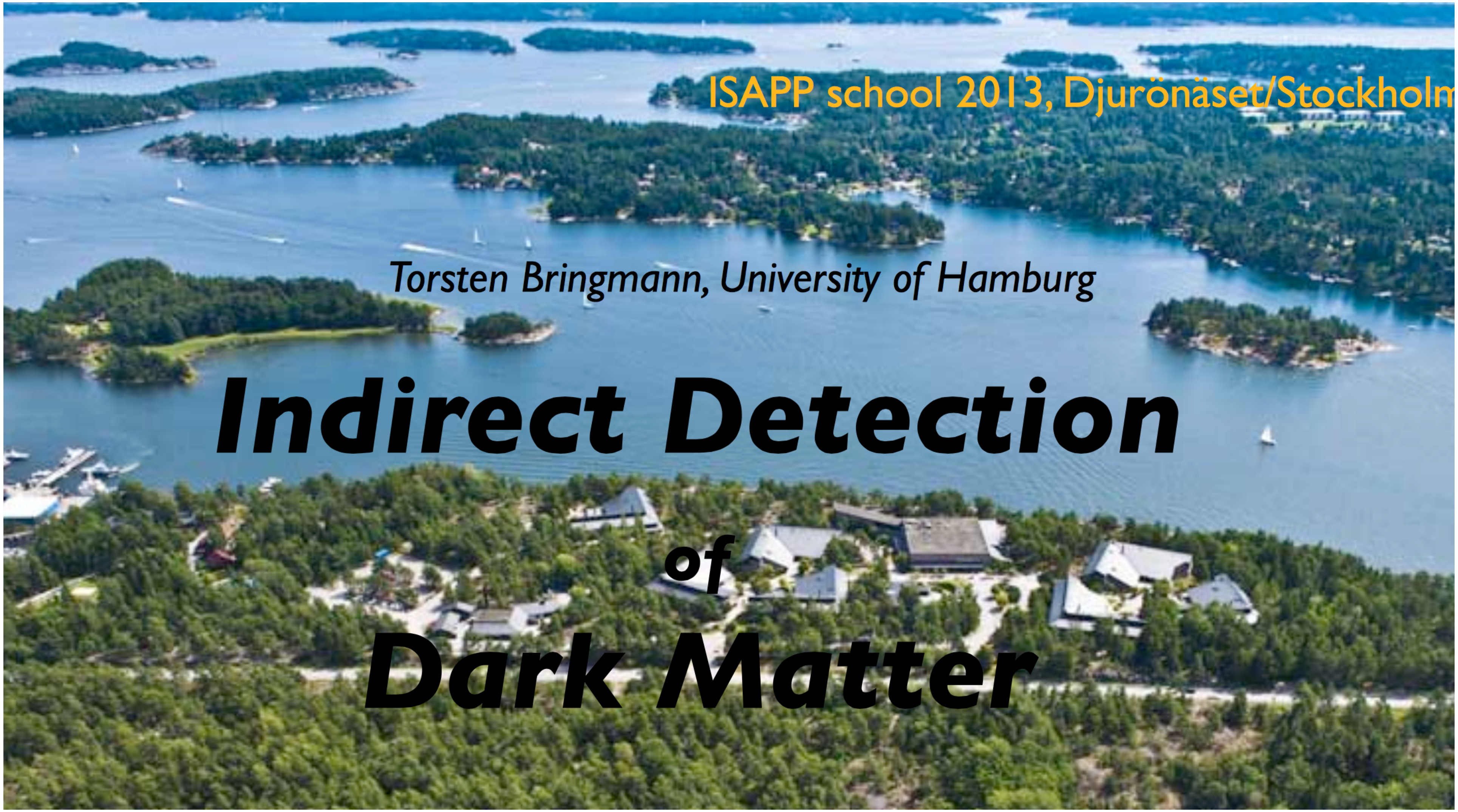
Light WIMPs window
CRESST
SuperCDMS
...



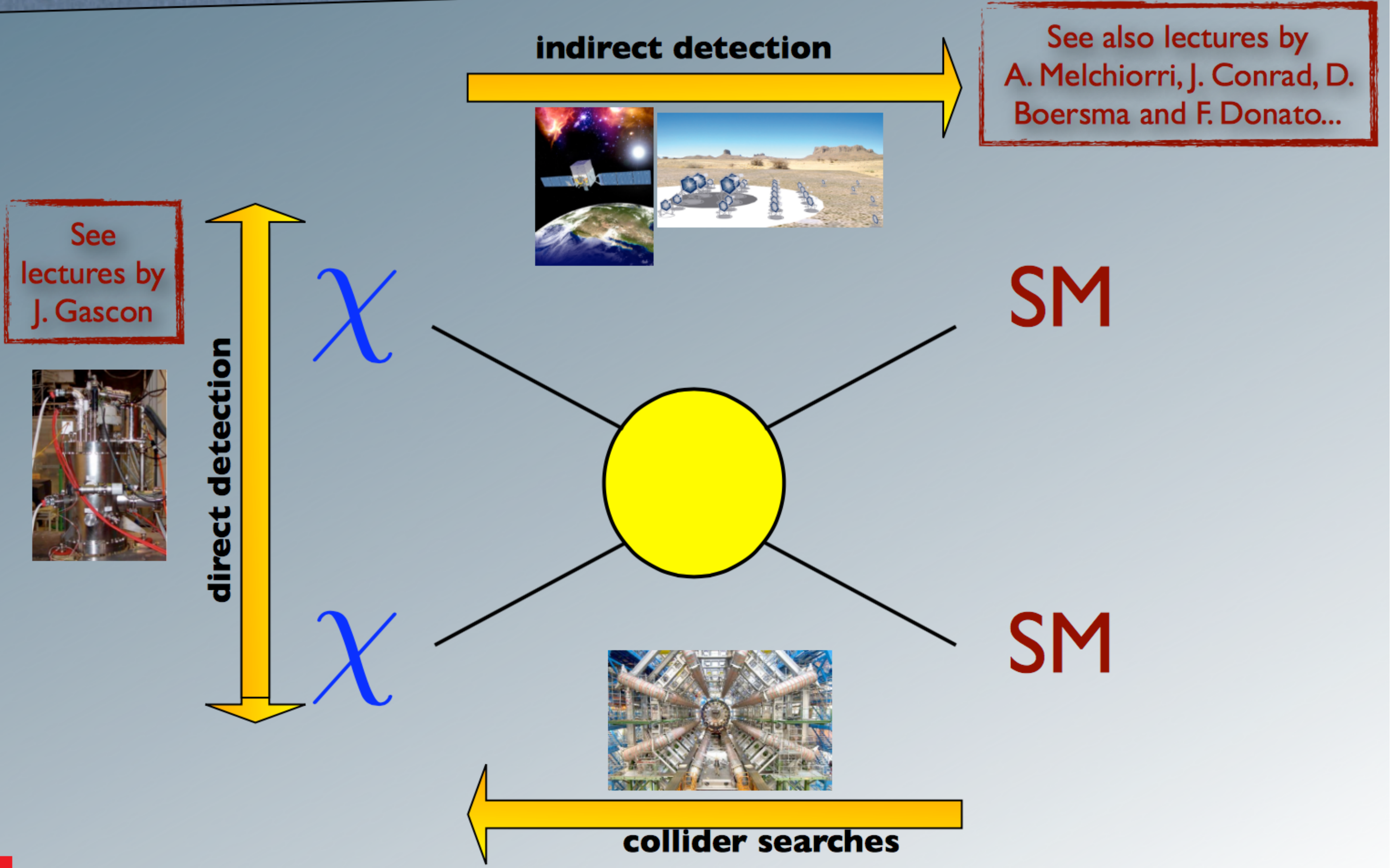


"Neutrino floor"
XENON1T (LXe)
DarkSide (LAr)
Lux, LZ, ...

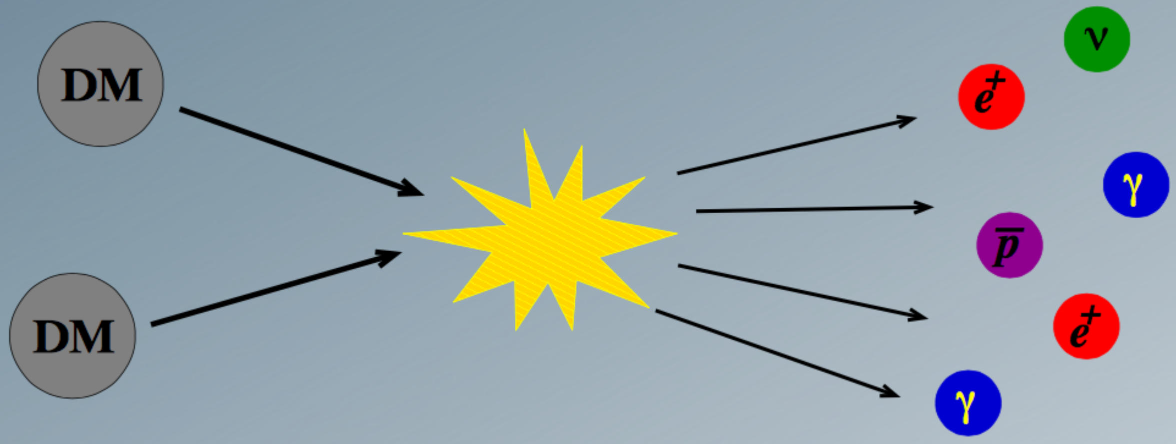
Bounds and expected sensitivities for DM-nucleus scattering
Under the hypothesis of contact-type interactions


ISAPP school 2013, Djurönäset/Stockholm
Torsten Bringmann, University of Hamburg
Indirect Detection
of
Dark Matter

WIMPs do interact with the SM!



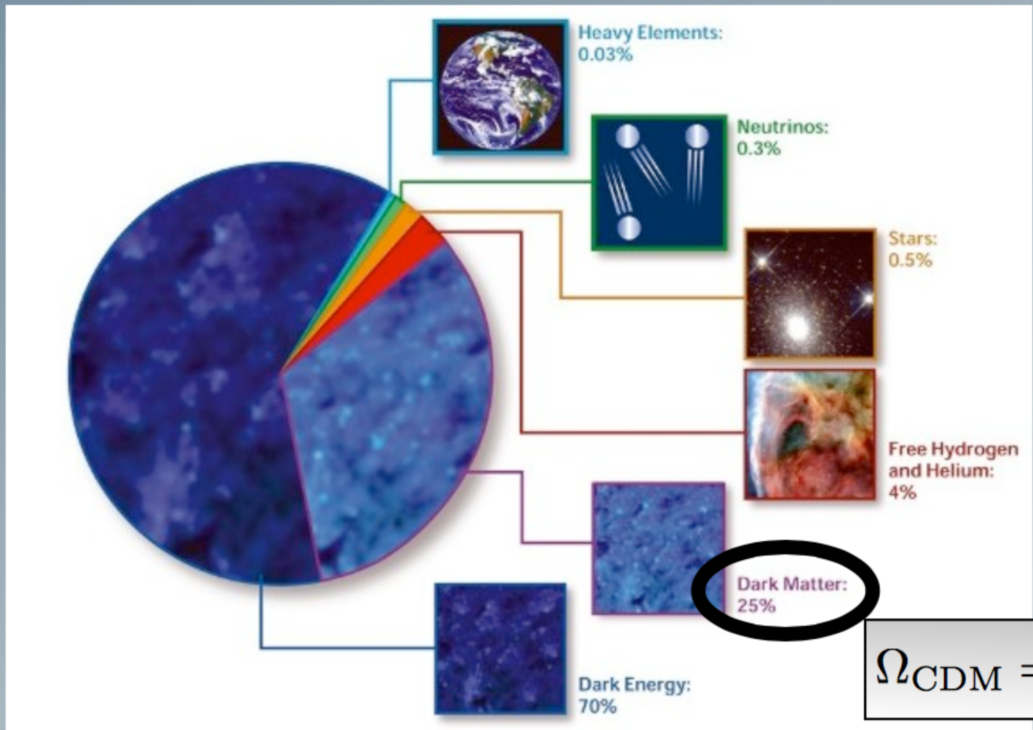
Indirect detection in one slide



- 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
  ⇝ regions of high DM density
  ii) discrimination against other sources
  ⇝ low background; clear signatures

Distribution of dark matter

- Annihilation sensitive to DM density *squared*
  → need to know this quantity very well!



NB: in general

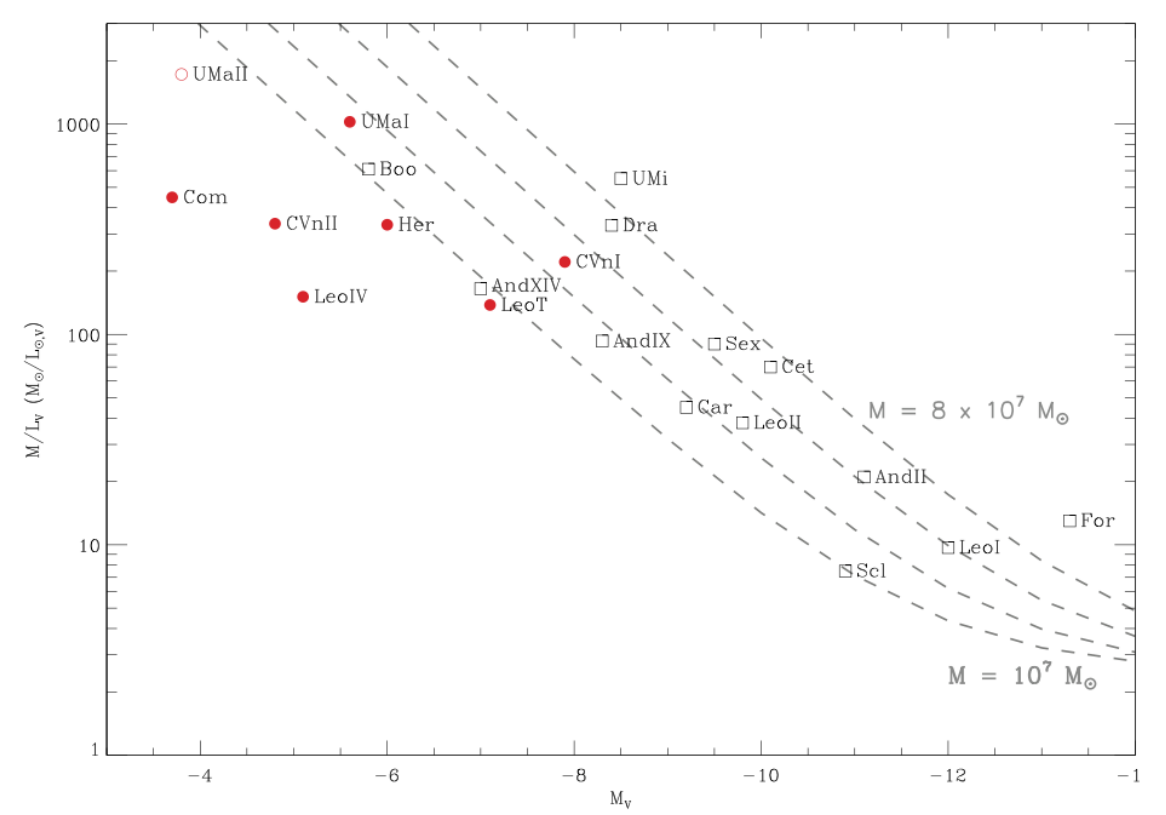
$$\Omega_\chi^{\rm local} \neq \Omega_{\rm CDM} \;!!!$$

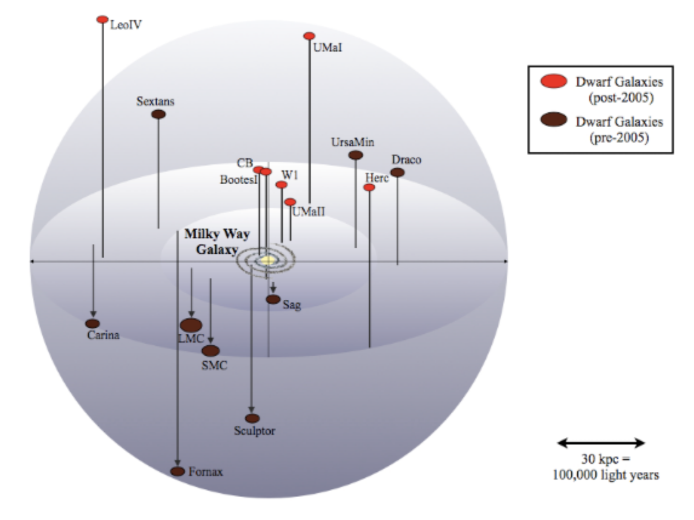
$\Omega_{\rm CDM} = 0.233 \pm 0.013$ on **large** scales

- [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:

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

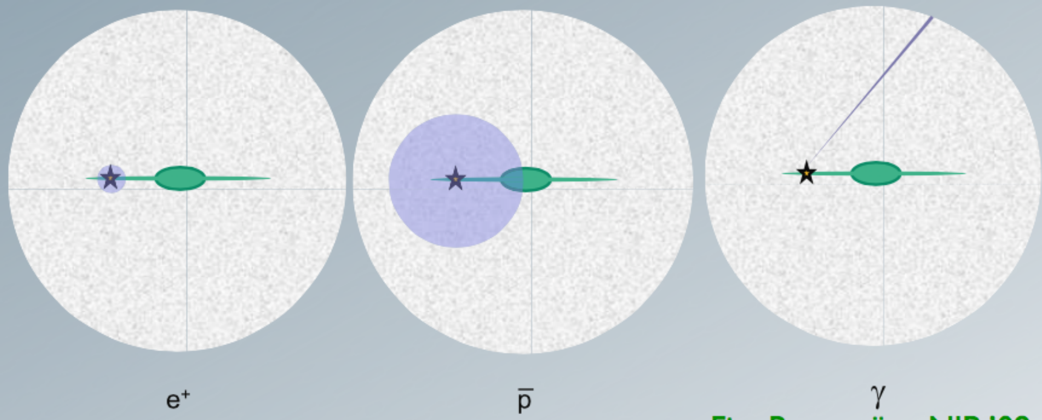


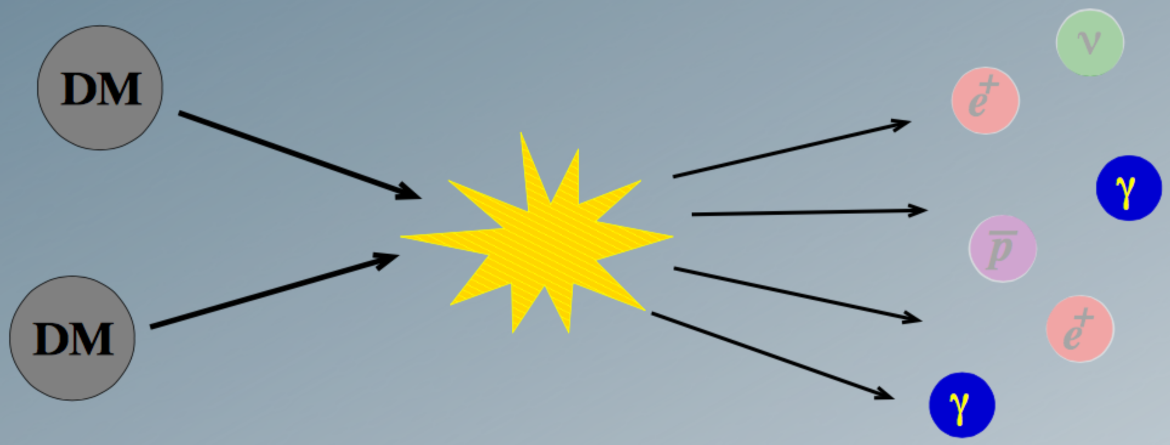
Fig.: Bergström, NJP '09

- "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 [$\mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}$] from a source with DM density ρ is given by

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

astrophysics | 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

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

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

B_f : branching ratio into channel f

N_γ^f : number of photons per ann.

⇓ angular information + rather uncertain normalization

⇓ high accuracy spectral information

Local DM density

- standard value:

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

• • •

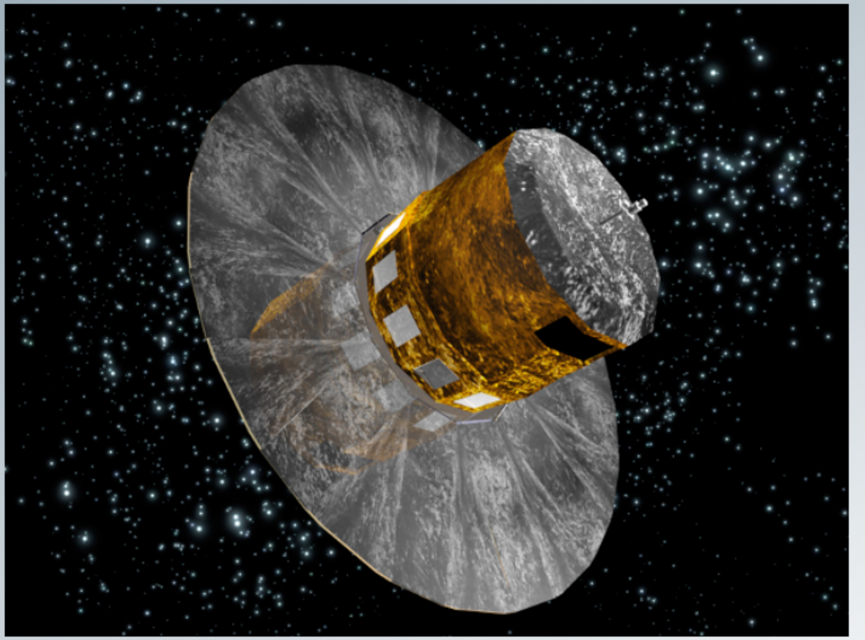
0.30 ± 0.05
Wydrow, Pim & Dubinski, ApJ '08

0.39 ± 0.03
Catena & Ullio, JCAP '10

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

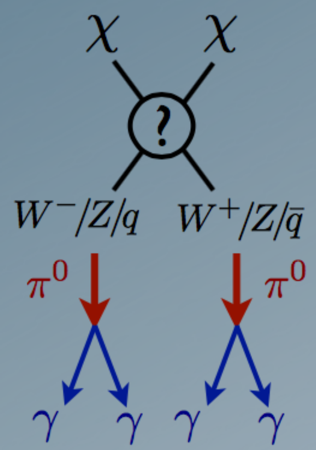
• • •

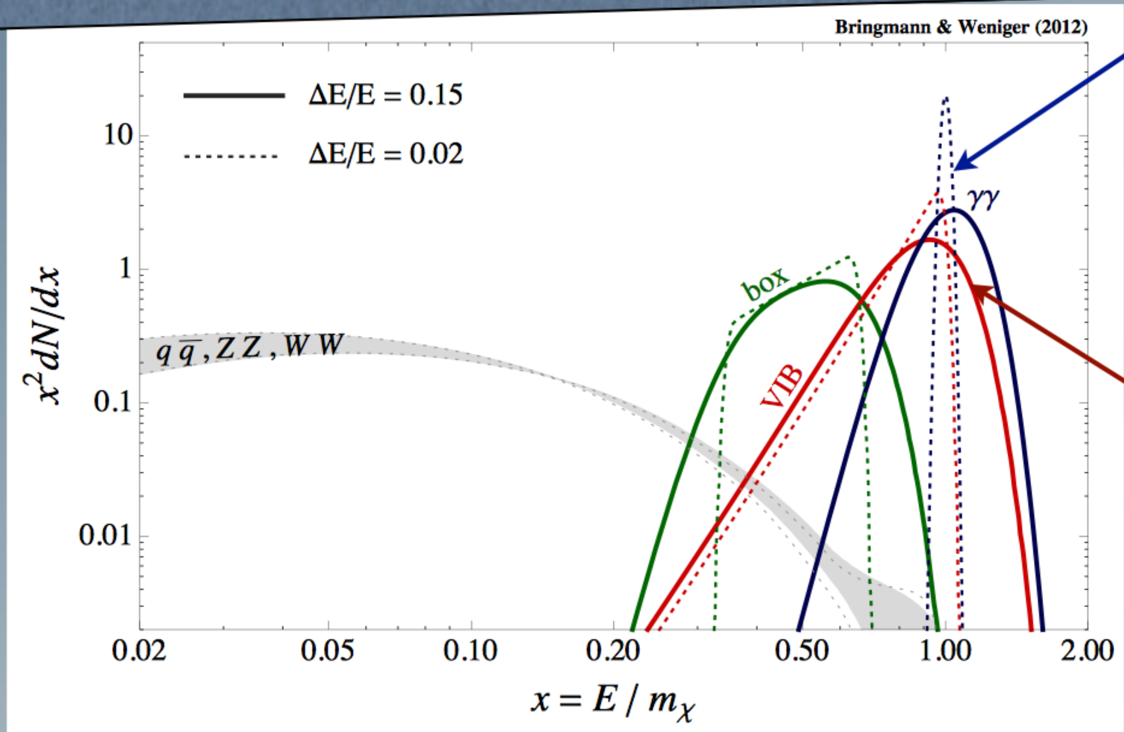
- Gaia (ESA mission, launch 11/13) will collect position and radial velocities of $\sim 10^8$ stars



➡ *will settle the issue…!*

Annihilation spectra





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*

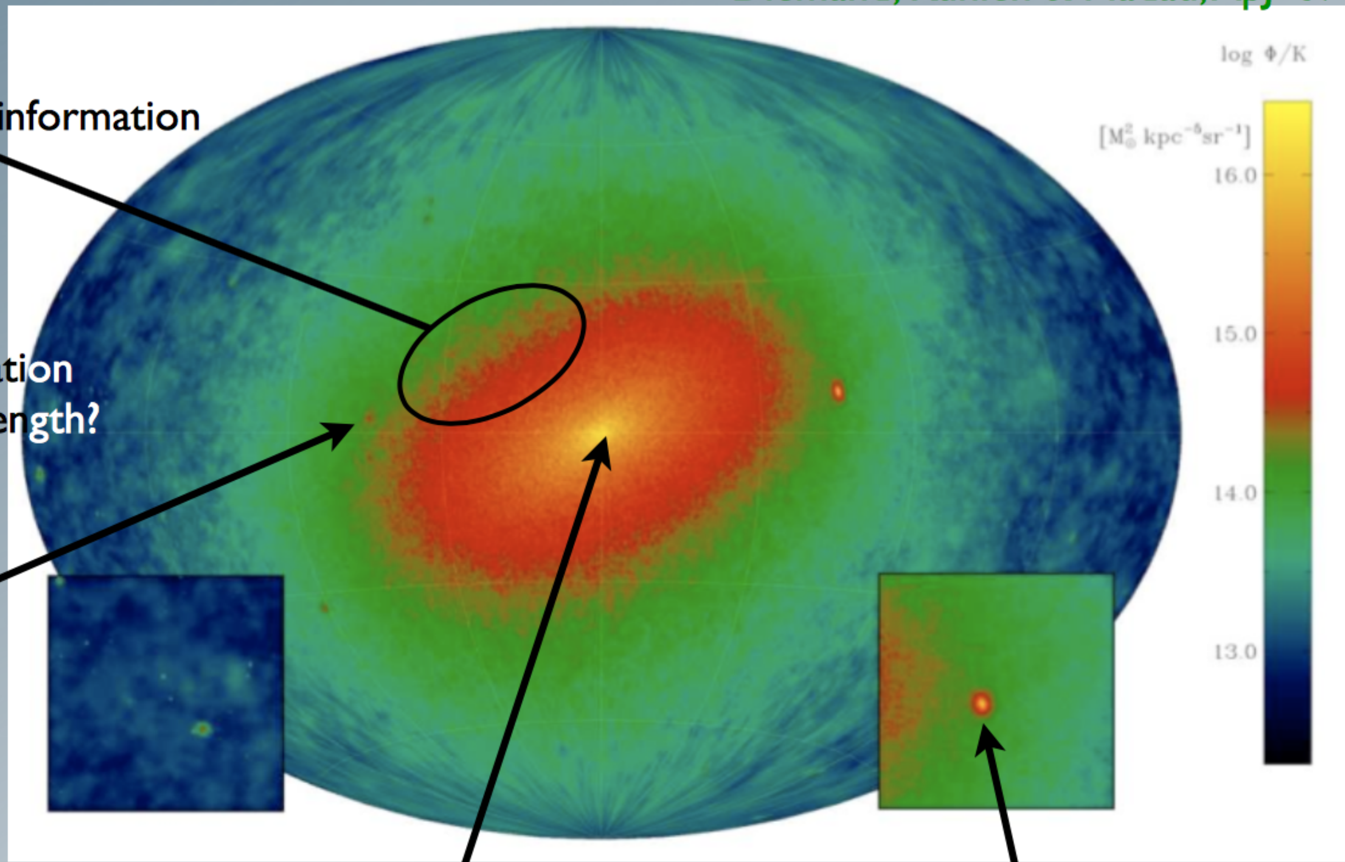
Primary photons

- 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?

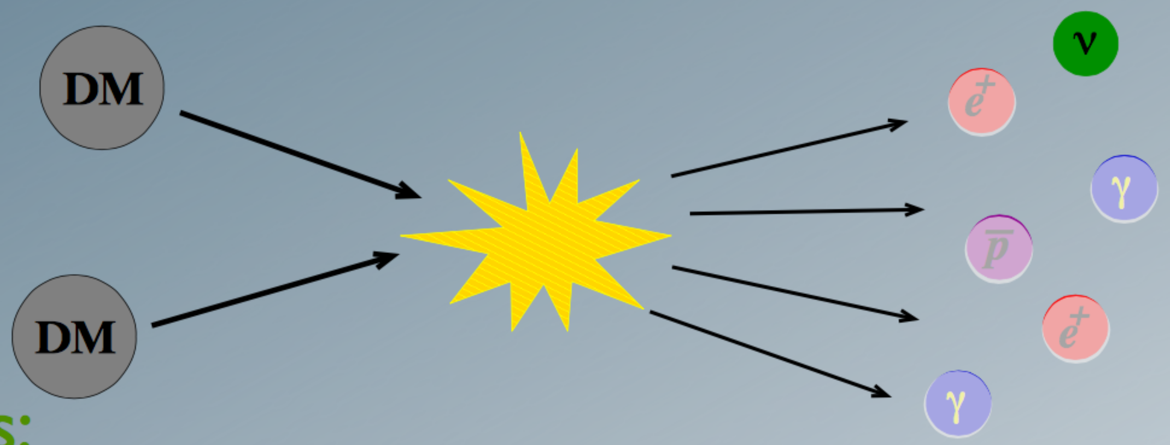
Galactic center

- 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!

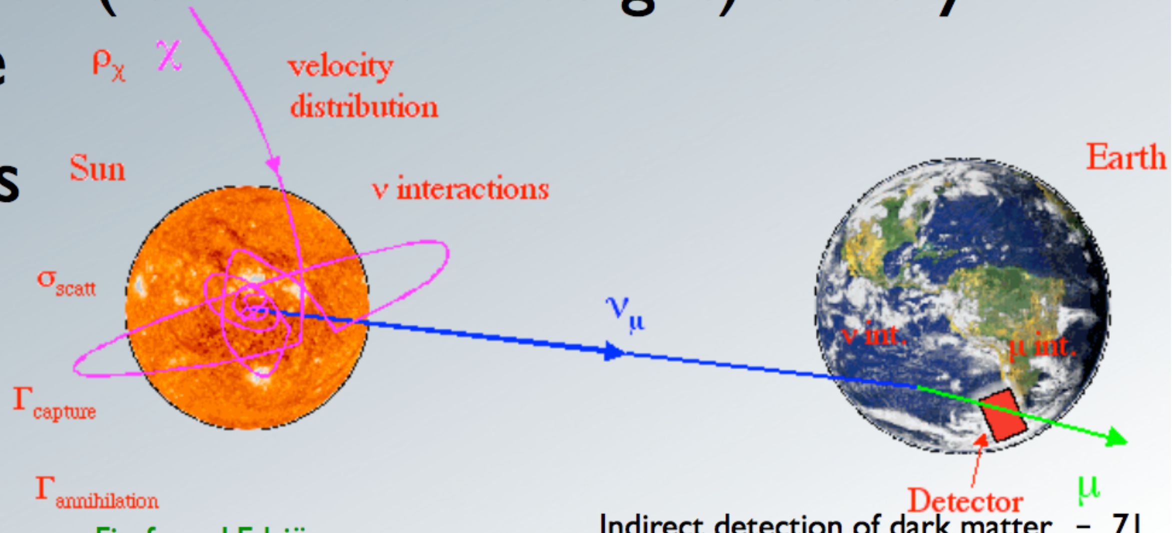
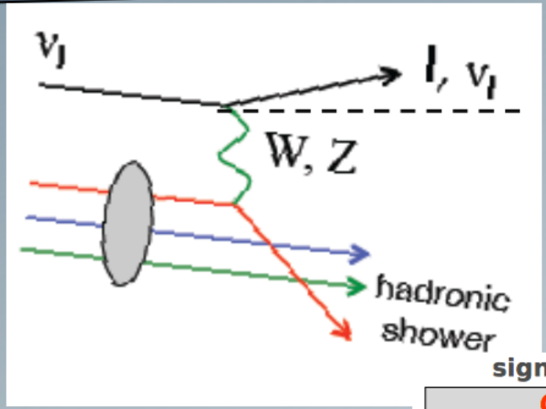


Fig. from J.Edsjö

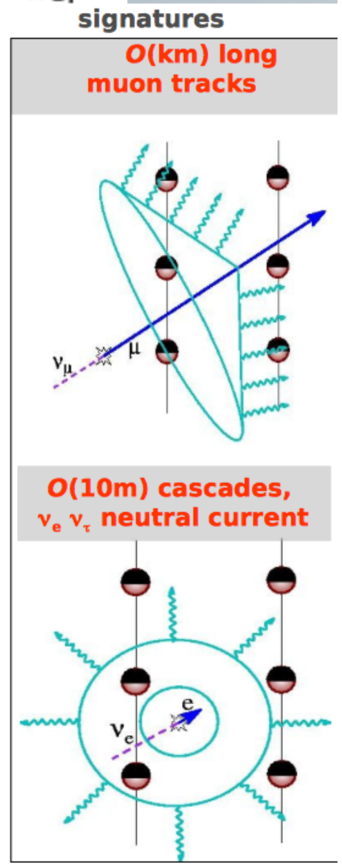
Detection principle

- 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)

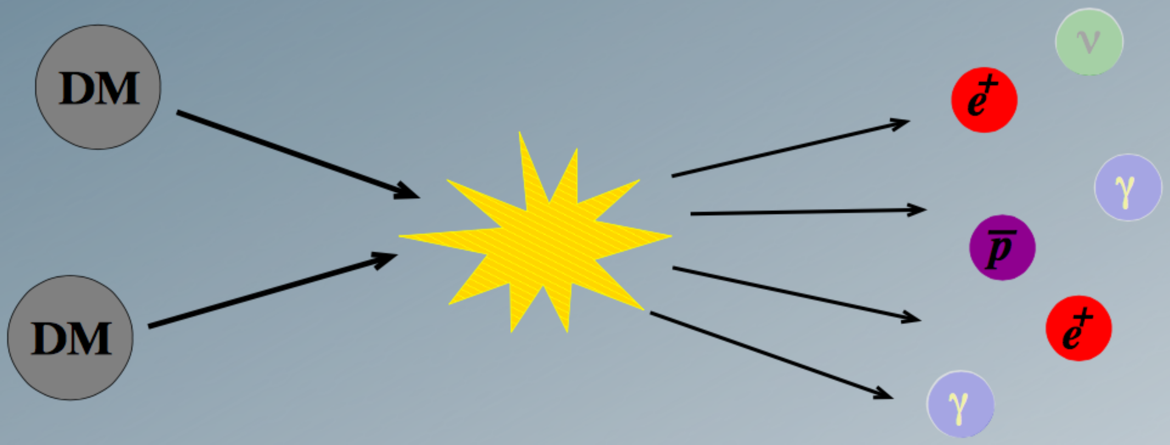


- opening angle: $\Theta_{\mu\nu} \approx 0.7° \cdot (E_\nu / \mathrm{TeV})^{-0.7}$
  ⇨ possible to do neutrino astronomy!
- tiny *x*-sections & fluxes: *need HUGE volumes!*
- background muons:
  - down-going: atmospheric neutrinos
  - up-going: also induced by cosmic rays
    (hitting the atmosphere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

  ⇝ look for excesses in any given direction



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. GALPROP

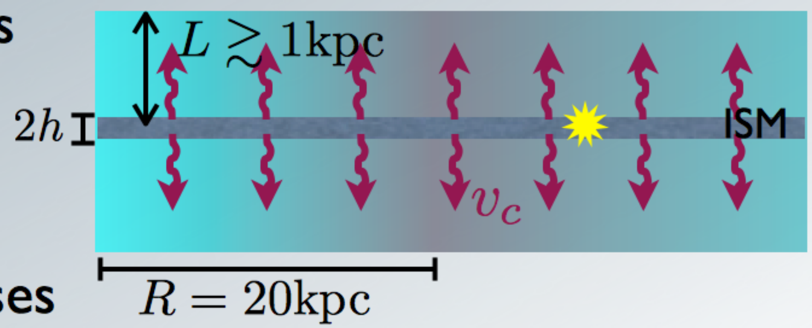
Strong, Moskalenko, …

DRAGON

Evoli, Gaggero, Grasso & Maccione

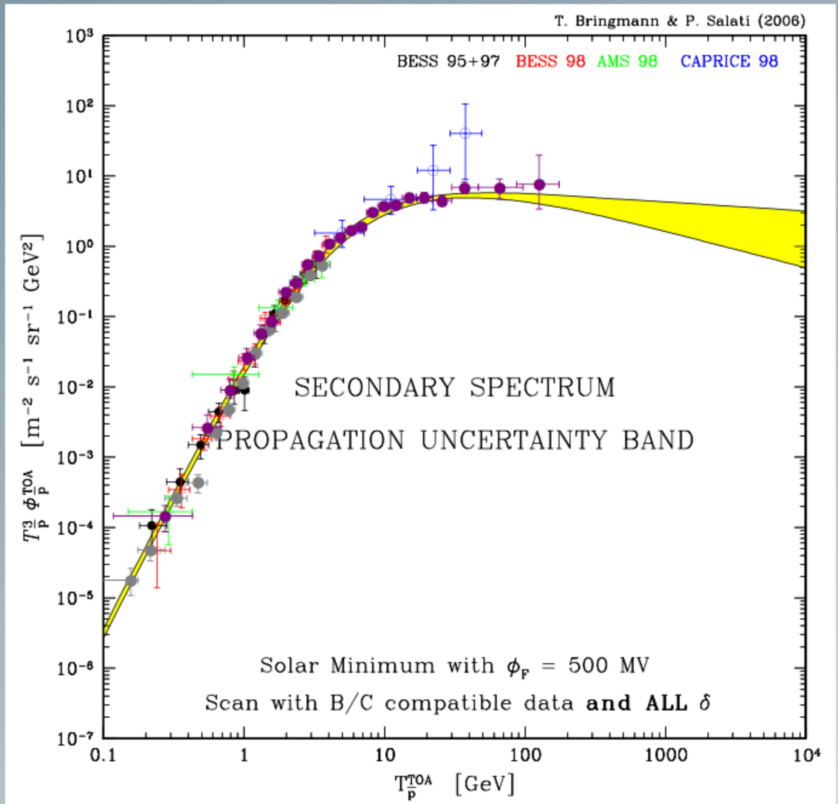
- (Semi-)analytically
  - ⊕ Physical insight from analytic solutions
  - ⊕ fast computations allow to sample full parameter space
  - ⊖ only 2D possible
  - ⊖ simplified gas distribution, energy losses

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:

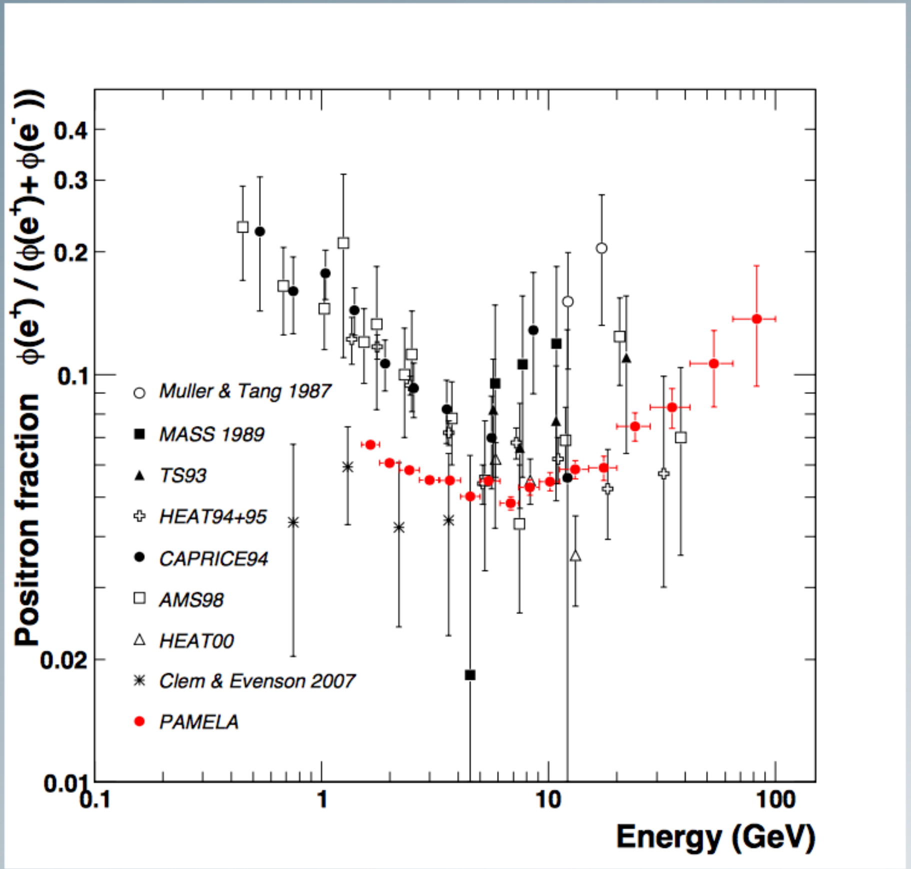
BESSpolar 2004
Abe *et al.*, PRL '08

PAMELA 2008
Adriani *et al.*, PRL '10

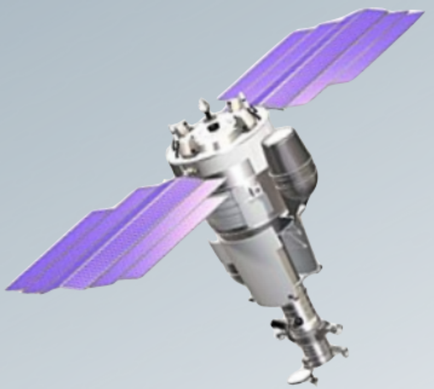
➡ very nice test for underlying diffusion model!

Positrons

Excess in cosmic ray positron data has triggered great excitement:



PAMELA

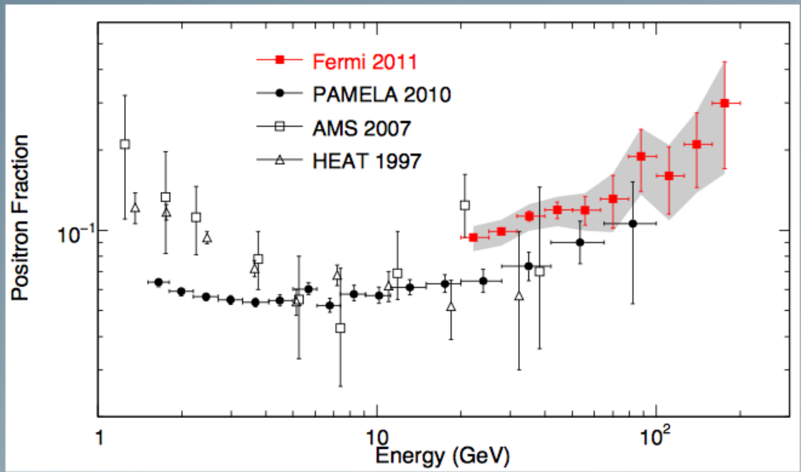


Adriani *et al.*, Nature '09

➔ Are we seeing a DM signal ???

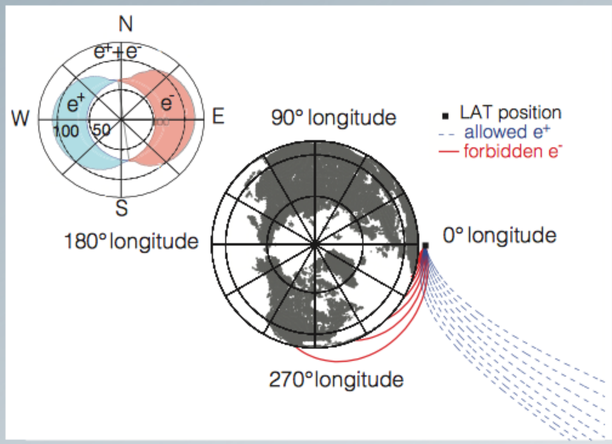
Independent confirmation

- By Fermi (!):

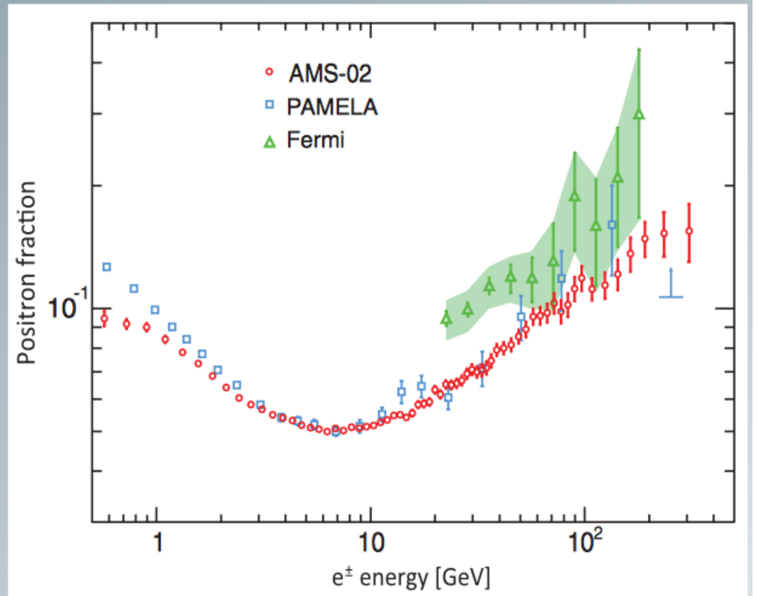


Ackermann *et al.*, PRL '12

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



- By AMS:



Aguilar *et al.*, PRL '13

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 $\bar{p}$!

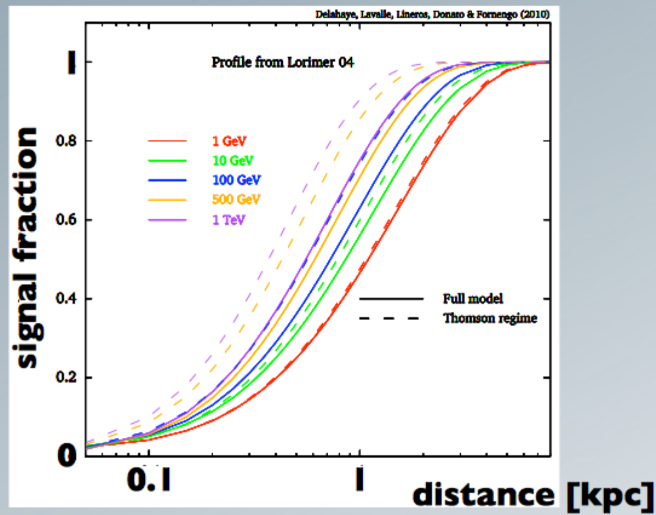
Delahaye *et al.*, PRD '08, A&A '09, A&A '10

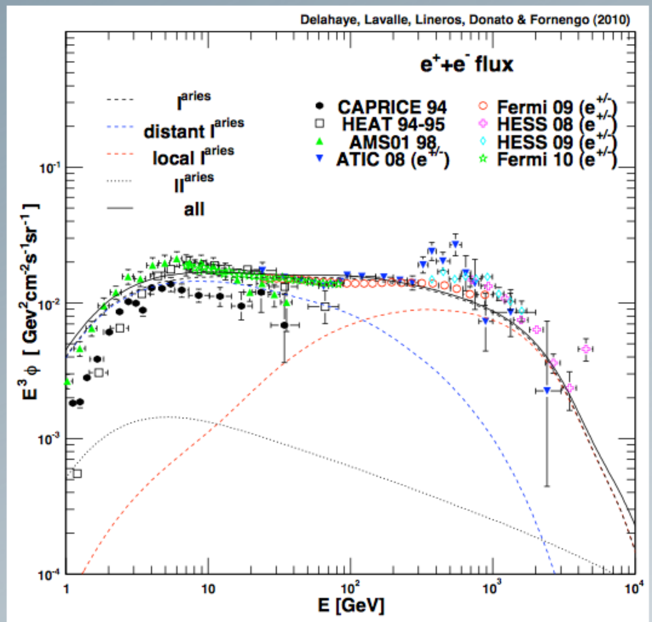
- Main difference to nuclei:

  energy losses are dominant

  [synchrotron + inverse Compton]

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





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

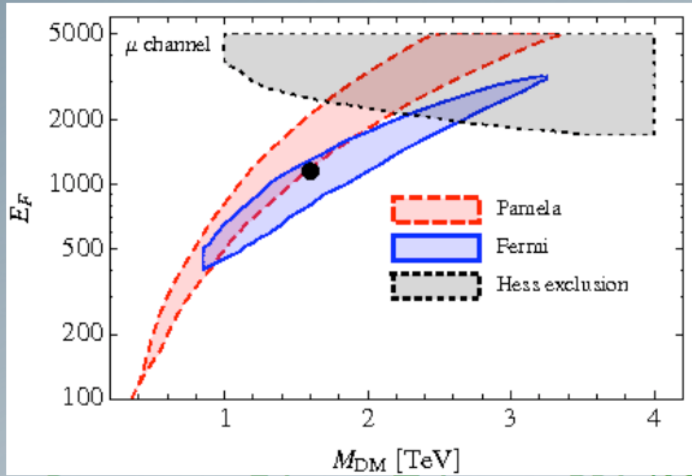
➩ need for local primary source(s) to describe data well above ~10 GeV

DM explanations

- Model-independent analysis:
  - strong constraints on hadronic modes from $\bar{p}$ data
  - $\chi\chi \to e^+e^-$ 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

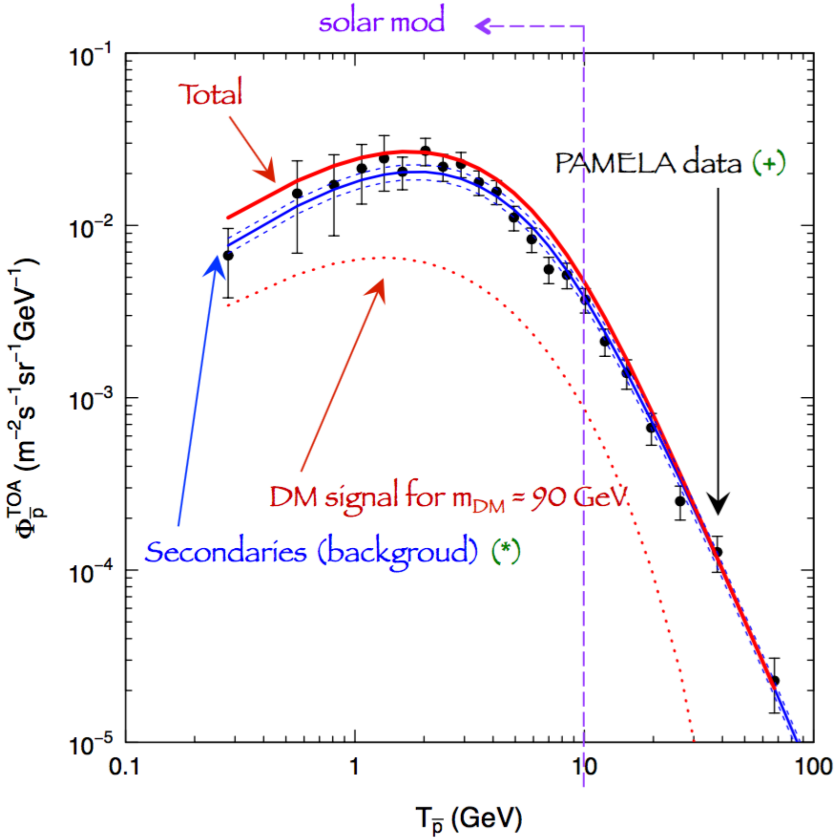
P. Gondolo, J. Edsjö, P. Ullio, L. Bergström, M. Schelke,
E.A. Baltz, T. Bringmann and G. Duda

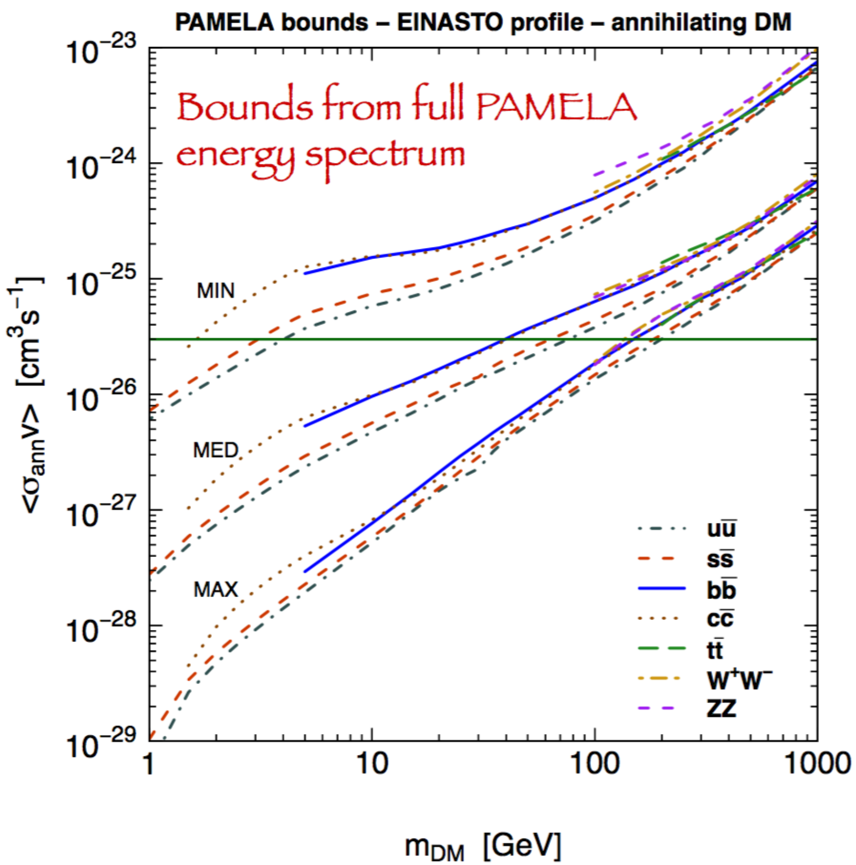
FREE DOWNLOAD ;)

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



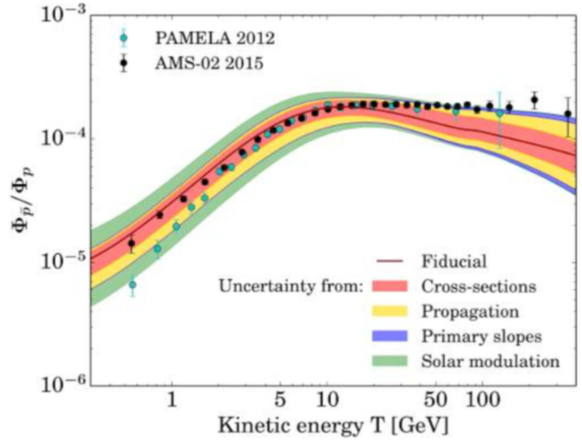


PAMELA

No evidence for deviation from astrophysical secondaries
Set stringent bounds on DM properties
Uncertainties from nuclear physics and galaxy transport

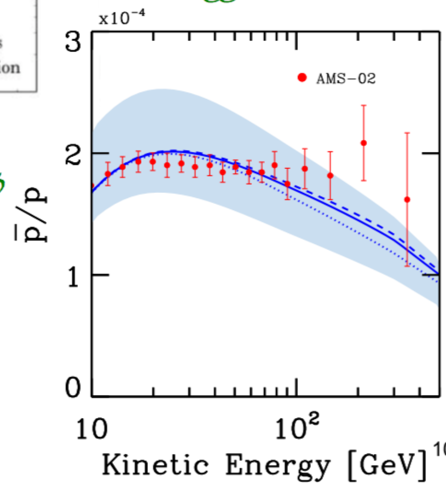
AMS-02 pbar/p

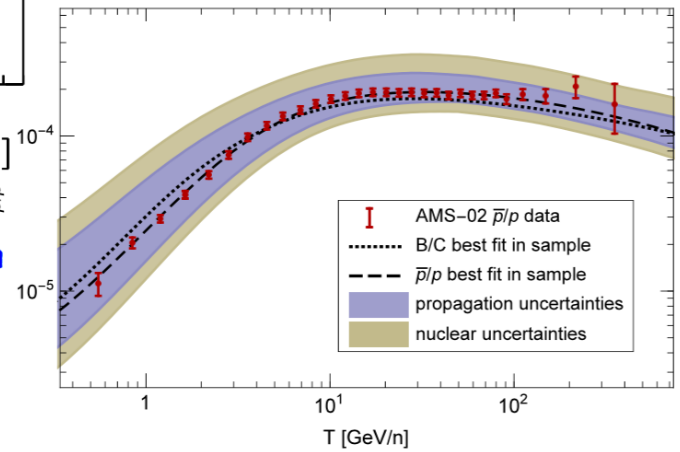
Kounine, 'AMS days at CERN, April 2015



Giesen et al., JCAP 1509 (2015) 023

Evoli, Gaggero, Grasso, arXiv:1504.05175



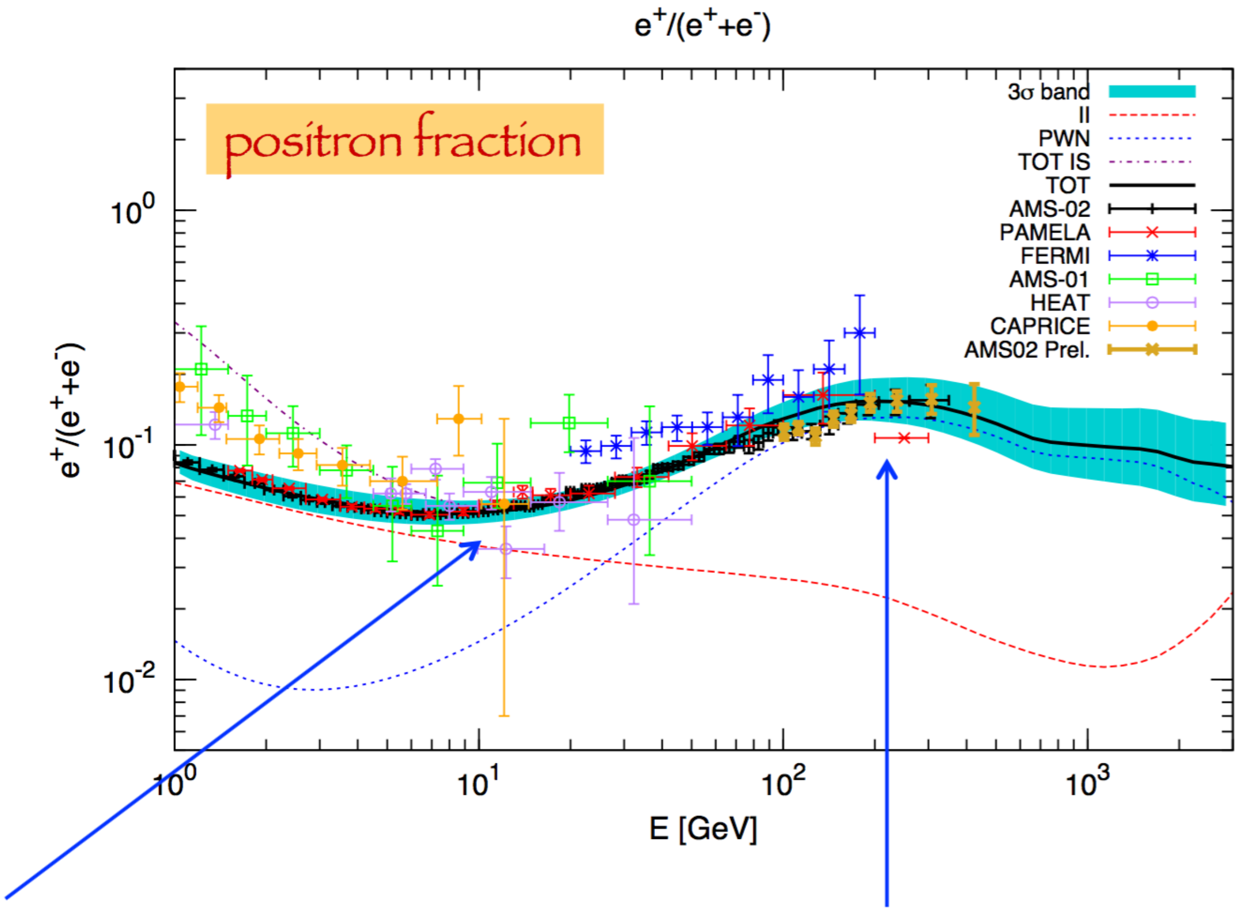


Kappl, Reinert, Winkler, JCAP 1510 (2015) 034

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)

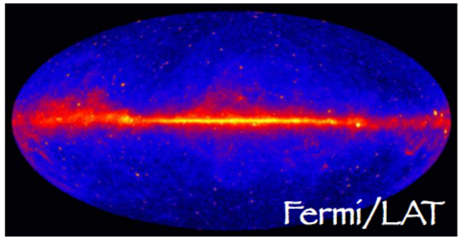
This is relevant for both DM signals and its backgrounds

Positrons

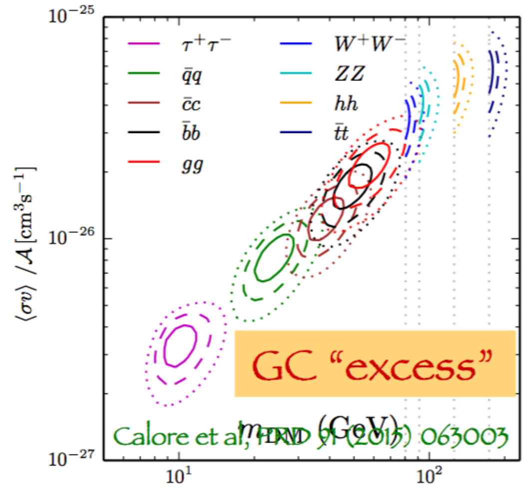


Low energies: reproduced by secondary production

High-energy: (local) sources needed



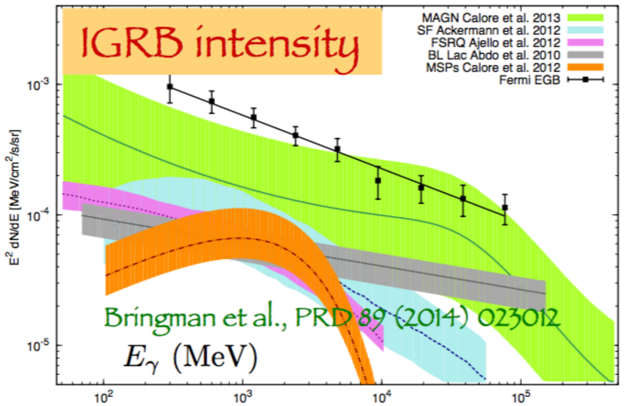
Gamma rays



Galactic center

Very interesting target, but difficult

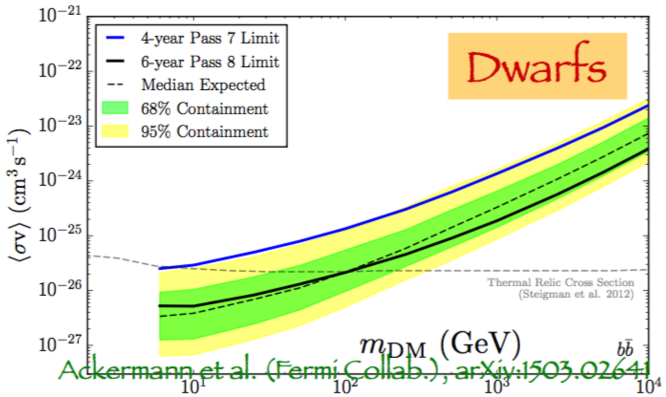
Potential hints, under hot discussion



Isotropic gamma ray background

Relevant for extragalactic DM

Complex to seperate a DM signal from astrophysical sources



Dwarf galaxies

One of the best targets (DM dominated)

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

Gamma rays

- Higher energies (ground): >300 GeV

  Probe TeV+ DM

  Targets

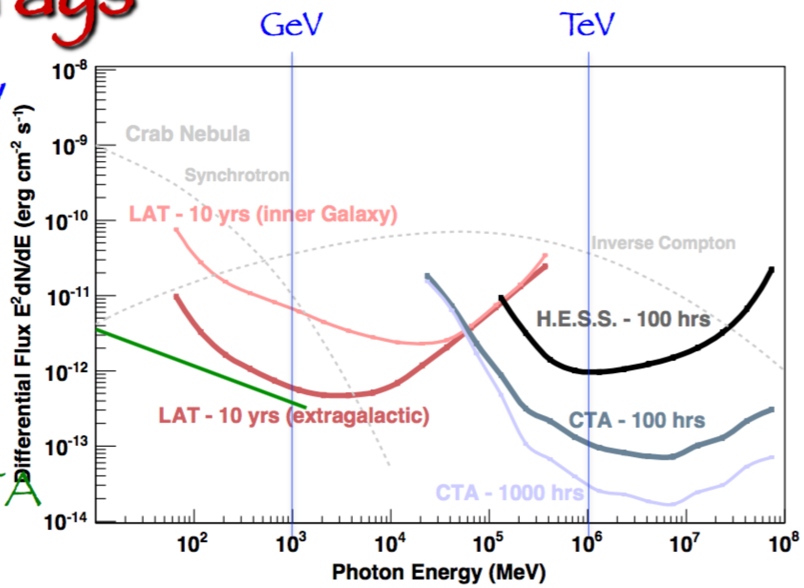
  Galactic center

  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, ...

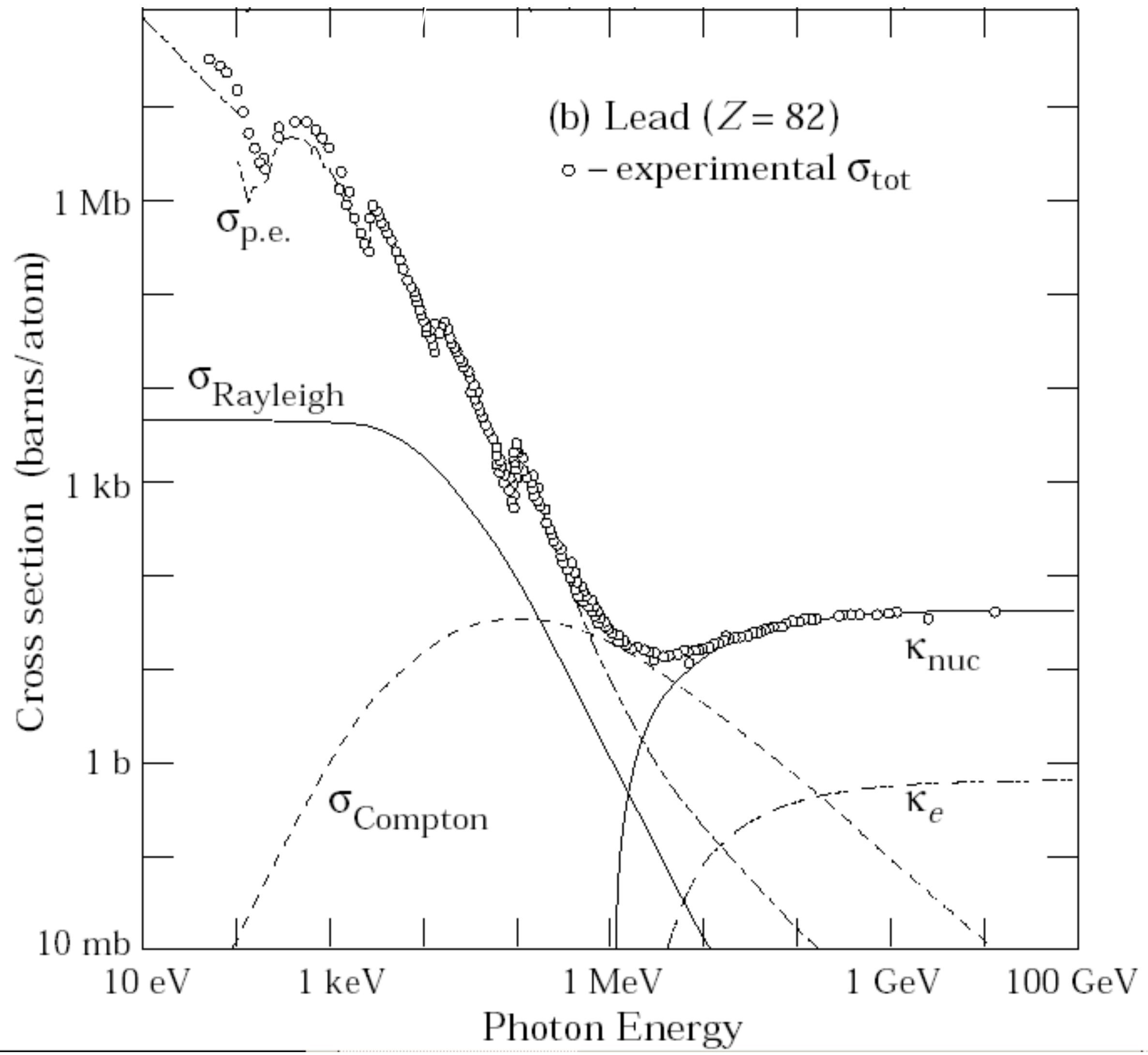
Astrofisica Nucleare e Subnucleare

GeV Astrophysics

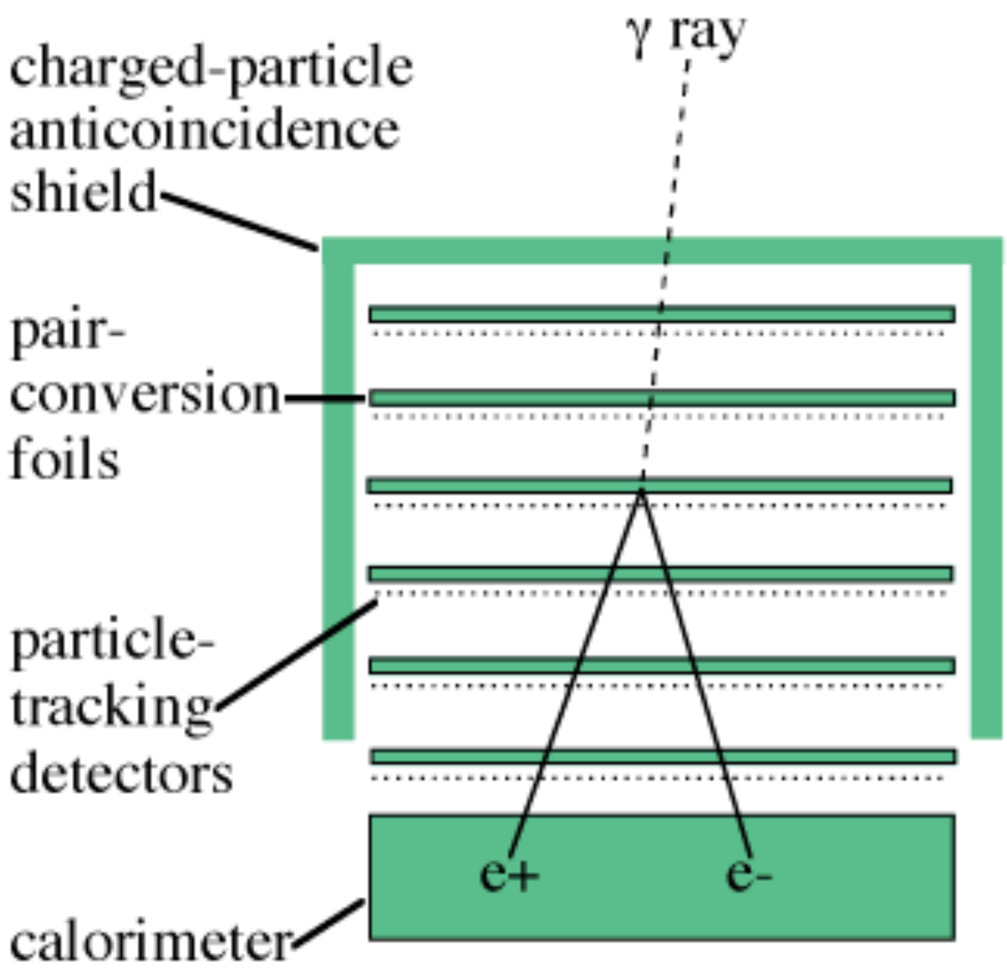
Exercise #4

- Find the web sites of AGILE and Fermi/LAT
- Check the status of future gamma-ray detectors (CALET, DAMPE, Gamma-400, HERD)

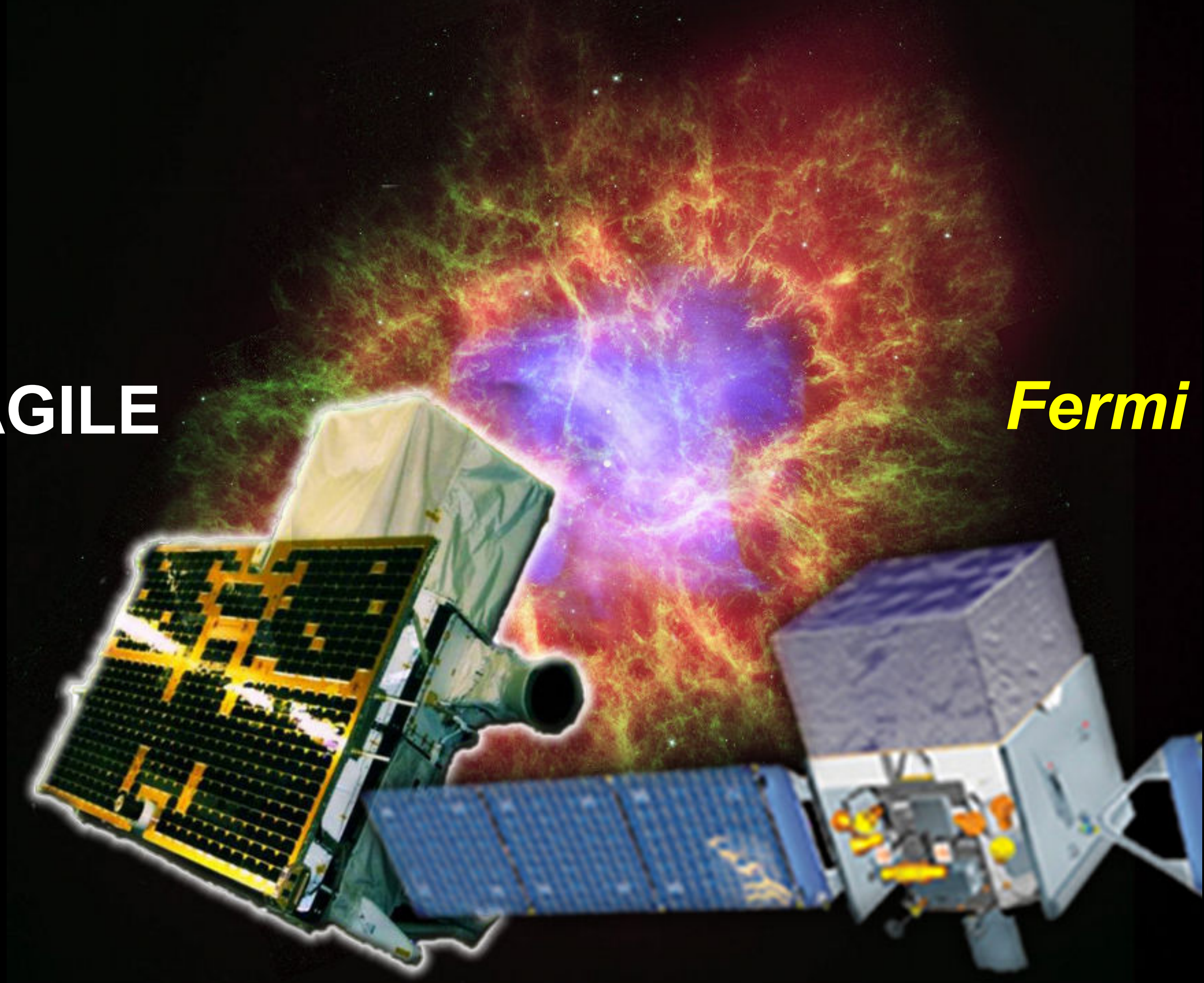
Photon Interactions



Detector Project



Gamma-ray astrophysics above 100 MeV



Picture of the day, Feb. 28, 2011, NASA-HEASARC

Astrofisica Nucleare e Subnucleare

Electromagnetic Showers

ELECTROMAGNETIC SHOWERS

SCIAMI ELETTROMAGNETICI

$$-\frac{dE}{dX} \simeq \frac{E}{X_0}$$

SIA $e^{\pm}$ CHE γ

$$E = E_i e^{-\frac{x}{X_0}}$$

ΔX DOPO UNA LUNGHEZZA DI RADIAZIONE $= X_0$
(AFTER ONE RADIATION LENGTH)

$$-dE = \frac{E\,dX}{X_0} \qquad \Delta E \simeq E\frac{\Delta X}{X_0} \simeq E$$

RADIAZIONE (RADIATION) $e^{\pm} \rightarrow e^{\pm}\gamma$ BREMSSTRAHLUNG

CONVERSIONE (CONVERSION) $\gamma \rightarrow e^{+}e^{-}$ CREAZIONE COPPIE (PAIR CREATION)

$$1 \rightarrow 2$$

$$E_i \rightarrow 2\left(\frac{E_i}{2}\right)$$

DOPO TANTE LUNGHEZZE DI RADIAZIONE
(AFTER MANY RADIATION LENGTHS)

$$X = tX_0 \qquad t = \frac{X}{X_0}$$

$$1 \rightarrow 2^{t} \equiv N$$

$$E_i \rightarrow 2^{t}\left(\frac{E_i}{2^{t}}\right) = N\left(\frac{E_i}{N}\right) = N E(t)$$

$$E(t) = \frac{E_i}{N} = \frac{E_i}{2^{t}}$$

QUANDO $E(t)$ ARRIVA A E_c
(WHEN) (REACHES) $\left(E = \frac{E_i}{N} = E_c\right)$

DIVENTANO DOMINANTI :
(BECOME DOMINANT)

PER $e^{\pm}$: IONIZZAZIONE

PER γ : COMPTON E FOTOELETTRICO

N SMETTE LA CRESCITA ESPONENZIALE

N RAGGIUNGE IL MASSIMO

$$N_{MAX} = \frac{E_i}{E_c}$$

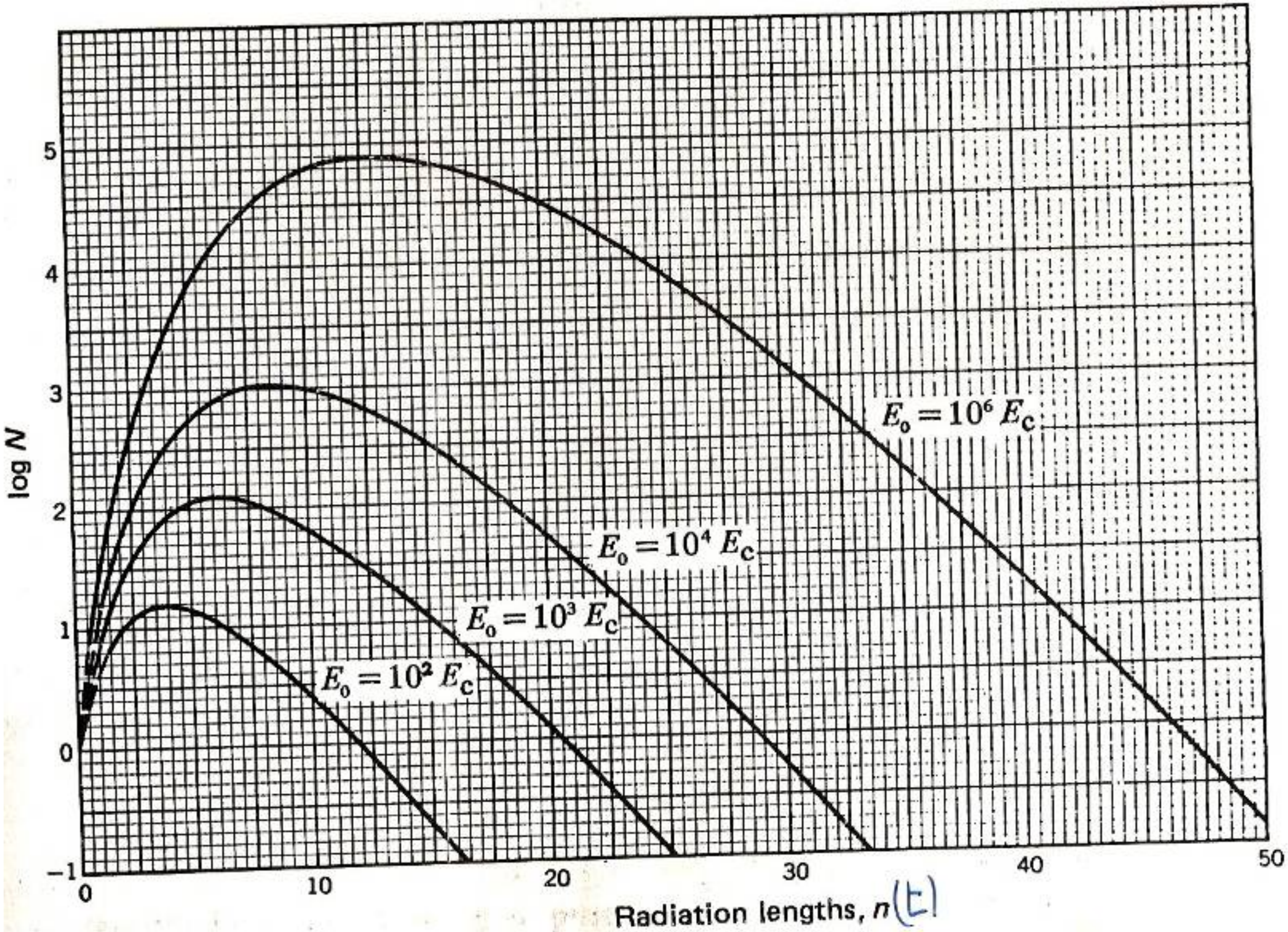
$$N_{MAX} = 2^{t_{MAX}} = \frac{E_i}{E_c}$$

$$t_{MAX} = \ln \frac{E_i}{E_c} \cdot \frac{1}{\ln 2}$$

N POI DECRESCE PER

PROGRESSIVA PERDITA DELLE
ENERGIE RESIDUE

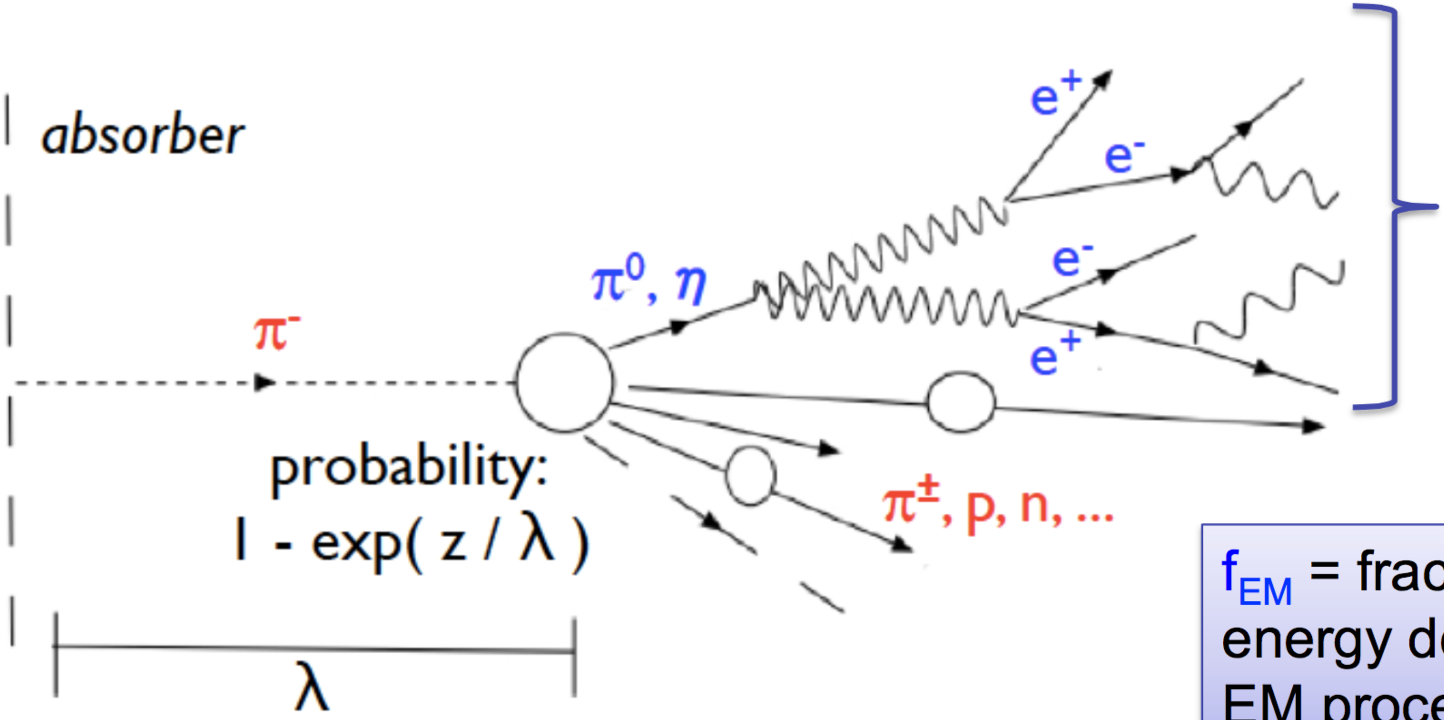
Fig. 4.6. The total number of particles N in a shower initiated by an electron of energy E_0, as a function of depth n, measured in radiation lengths; E_c is the critical energy of the material. (From Leighton, 1959, p. 693, after Rossi & Greisen, 1941.)



Astrofisica Nucleare e Subnucleare

Hadronic showers

Hadronic showers



π_0 production is a one way street: all energy deposited via EM processes

f_{EM} = fraction of hadron energy deposited via EM processes

Electromagnetic → ionization, excitation (e±)
→ photo effect, scattering (γ)

Hadronic → ionization (π±, p)
→ invisible energy (binding, recoil)

Hadronic shower

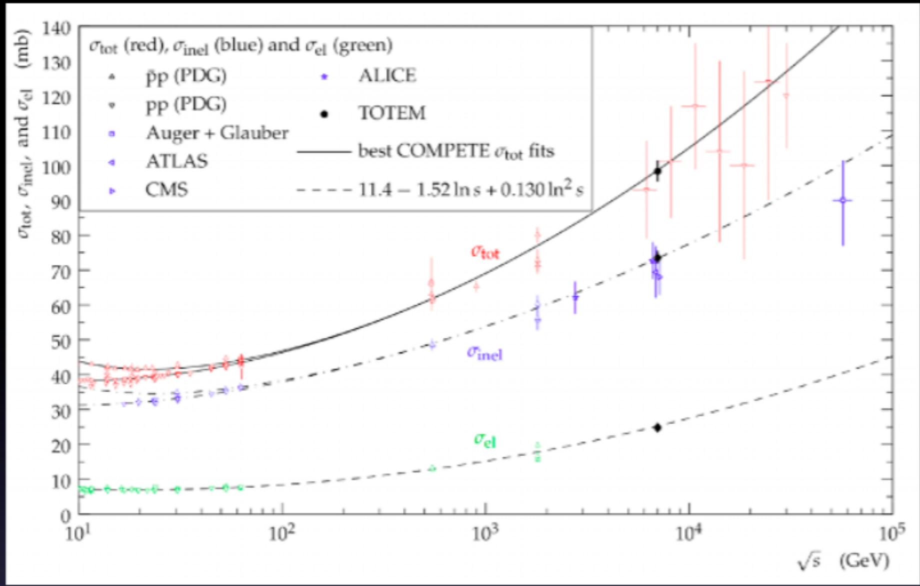
- Hadronic interaction Cross section

$$\sigma_{Tot} = \sigma_{el} + \sigma_{inel}$$

$$\sigma_{el} \approx 10mb \qquad \sigma_{inel} \approx A^{2/3}$$

$$\sigma_{Tot} = \sigma_{tot}(pp) A^{2/3}$$

where: $\sigma_{tot}(pp)$ increases with $\sqrt{s}$



- Hadronic interaction length

$$\lambda_{\text{int}} = \frac{1}{\sigma_{tot} \cdot n} = \frac{A\rho}{\sigma_{pp} A^{2/3} N_A} \approx \left(35 g / cm^2\right) A^{1/3}$$

$$N(x) = N(0) e^{-x/\lambda_{\text{int}}}$$

- λ_{int} characterizes both longitudinal and transverse shower profile

Rule of thumb argument: the geometric cross section goes as the square of the size of the nucleus, a_N^2, and since the nuclear radius scales as $a_N \sim A^{1/3}$, the nuclear mean free path in gm/cm^2 units scales as $A^{1/3}$.

Hadronic shower

Hadronic interaction:

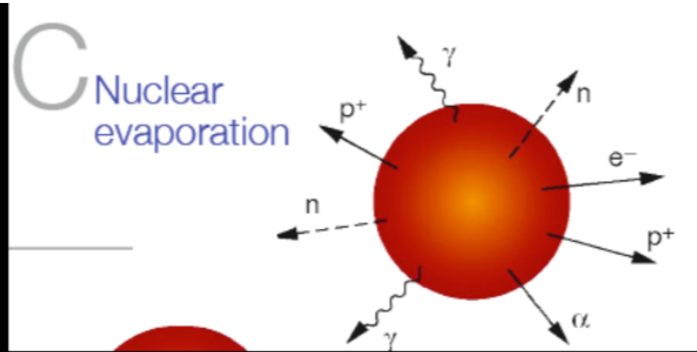
Elastic:

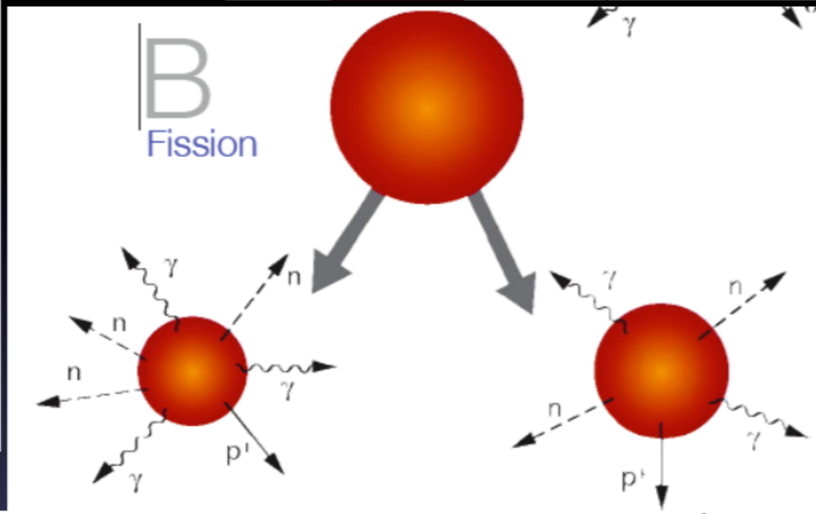
$$p + \text{Nucleus} \rightarrow p + \text{Nucleus}$$

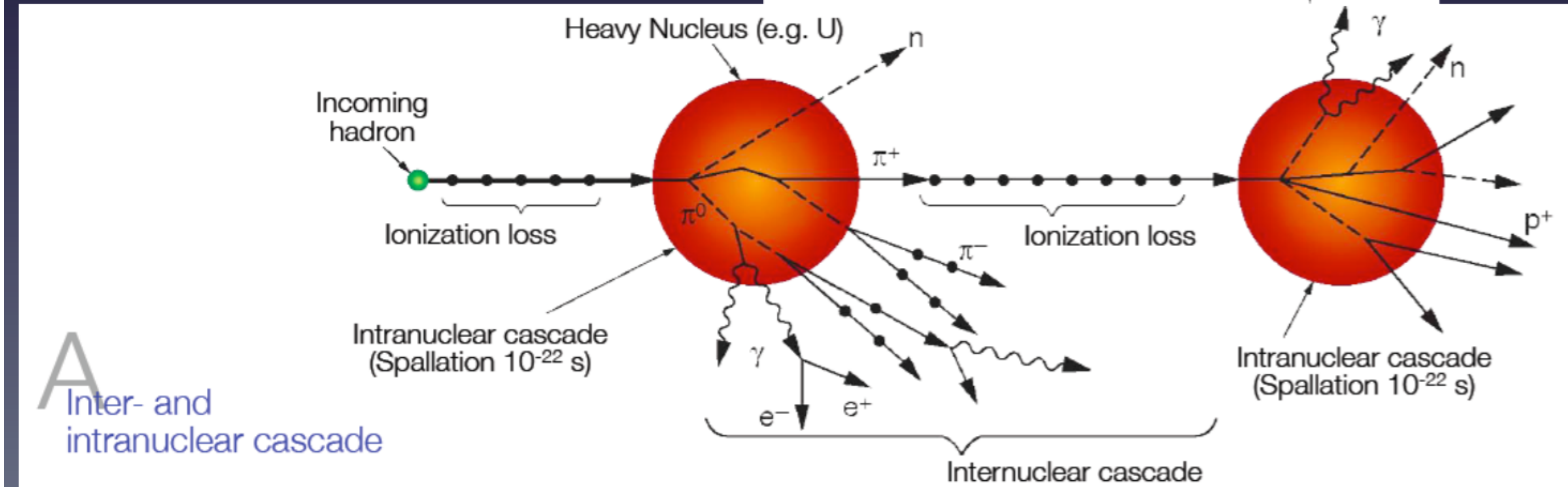
Inelastic:

$$p + \text{Nucleus} \rightarrow$$
$$\pi^+ + \pi^- + \pi^0 + \ldots + \text{Nucleus}^*$$

$$\left[\begin{array}{l} \text{Nucleus}^* \rightarrow \text{Nucleus A} + n, p, \alpha, \ldots \\ \qquad\qquad \rightarrow \text{Nucleus B} + 5p, n, \pi, \ldots \\ \qquad\qquad \rightarrow \text{Nuclear fission} \end{array}\right]$$

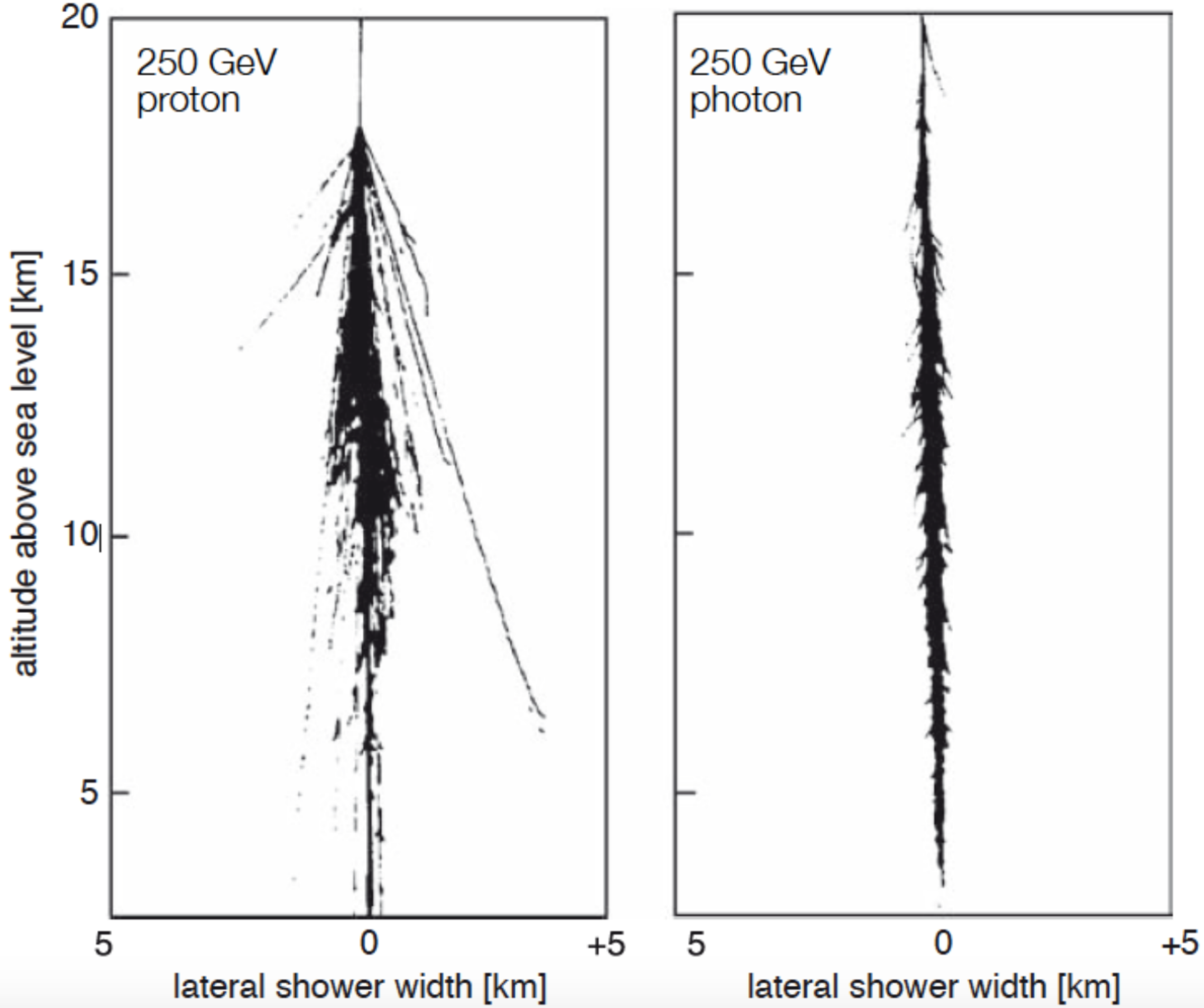






Courtesy of H. C. Schoultz Coulon

Comparison hadronic vs EM showers

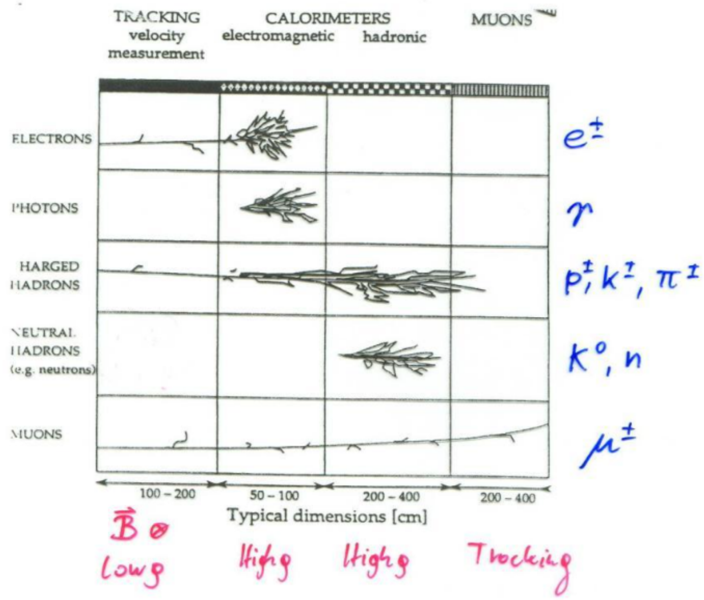


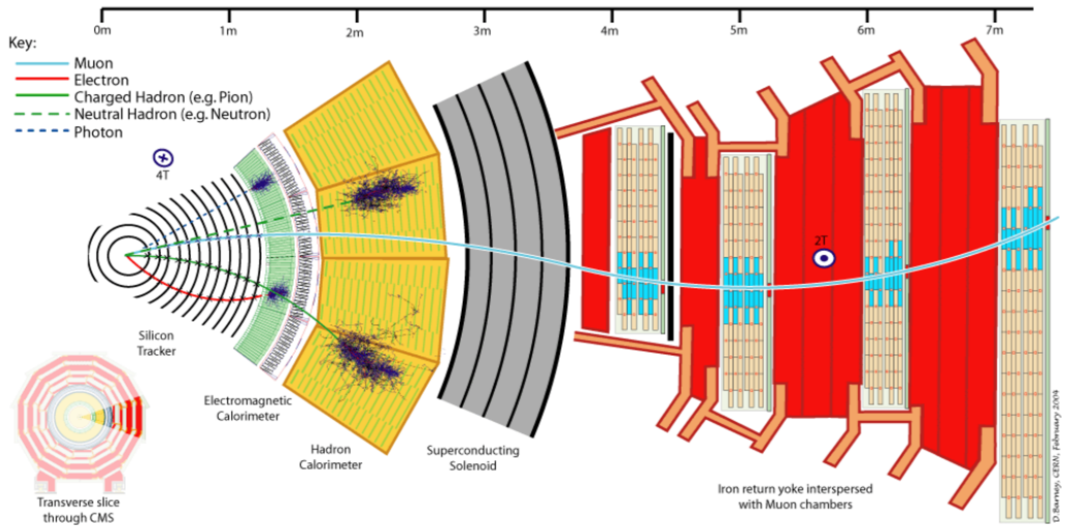
Simulated air showers

Astrofisica Nucleare e Subnucleare

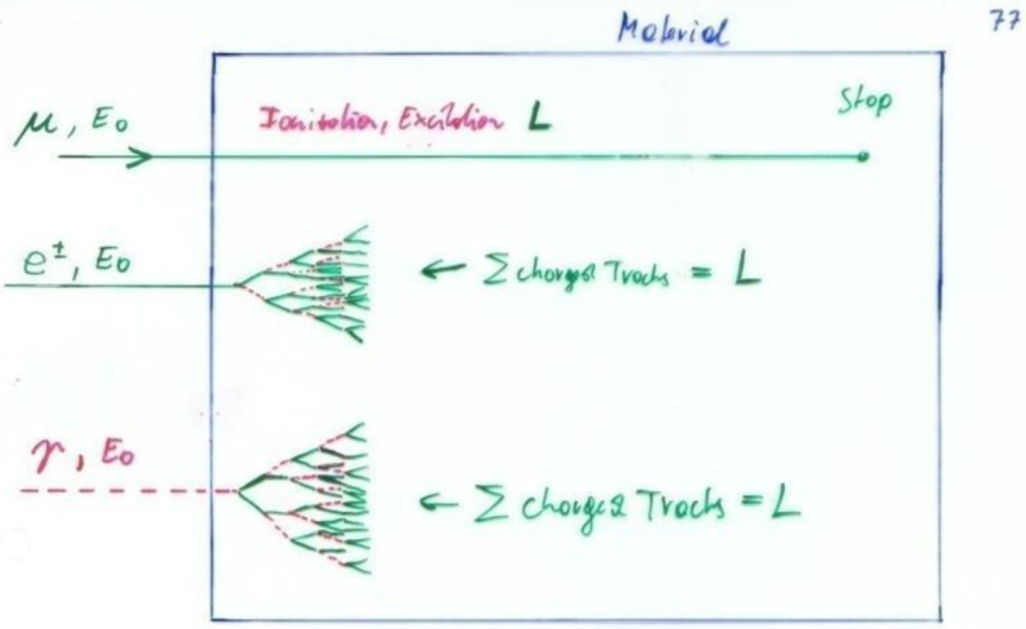
Calorimeters

Calorimetry





Calorimetry: Energy Measurement by total Absorption of Particles



If N is the total Number of e^+, I^+ pairs or photons, or $N = c_1 E_0$:

$\Delta N = \sqrt{N}$ (Poisson Statistics)

$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = \frac{1}{\sqrt{N}} = \frac{a}{\sqrt{E}}$$ → Resolution

The $e^\pm$ in the Calorimeter ionize and excite the Material

Ionization: e^-, I^+ pairs in the Material

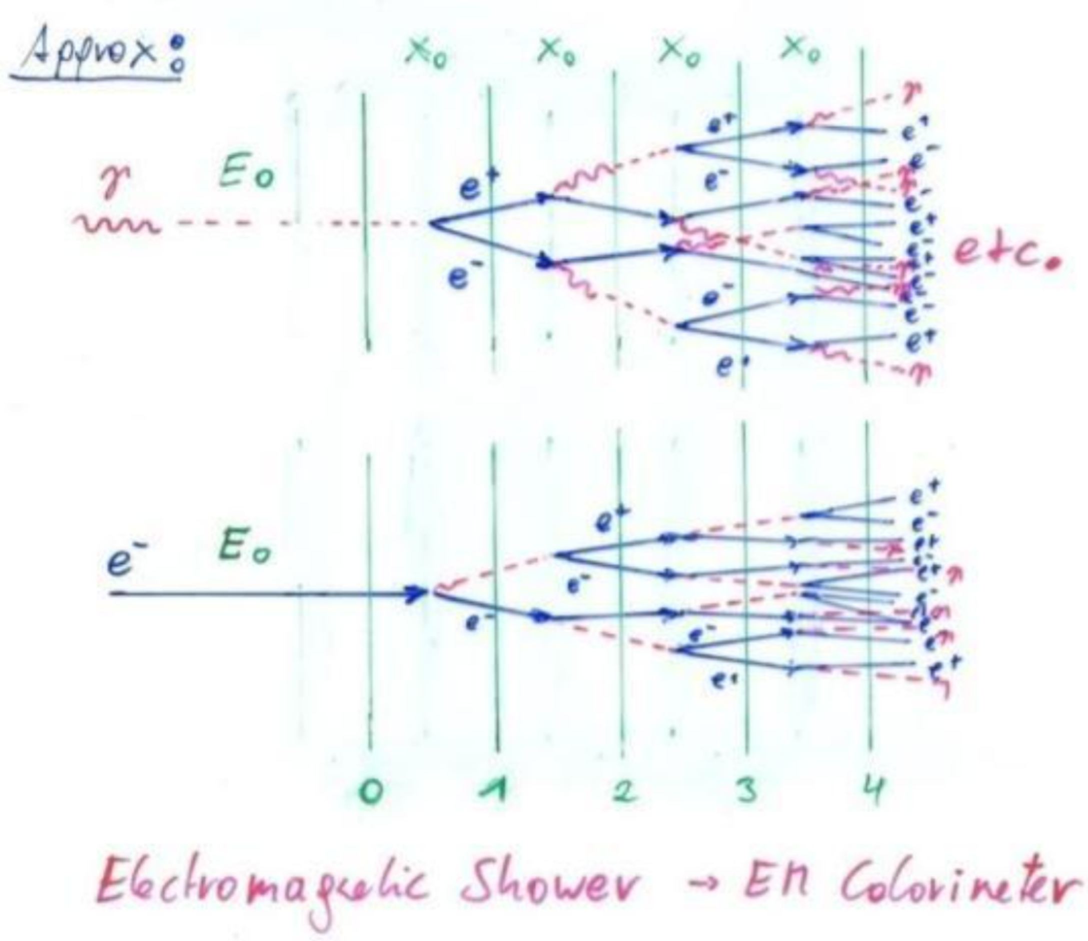
Excitation: Photons in the Material

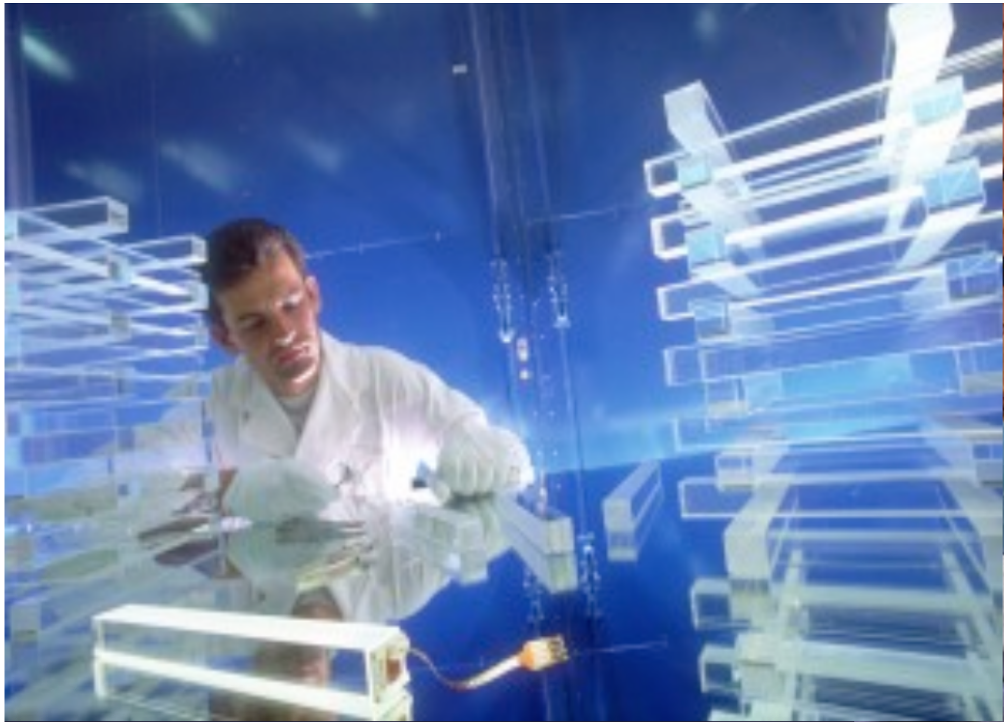
Measuring the total Number of e^-, I^+ pairs or the total Number of Photons gives the particle Energy.

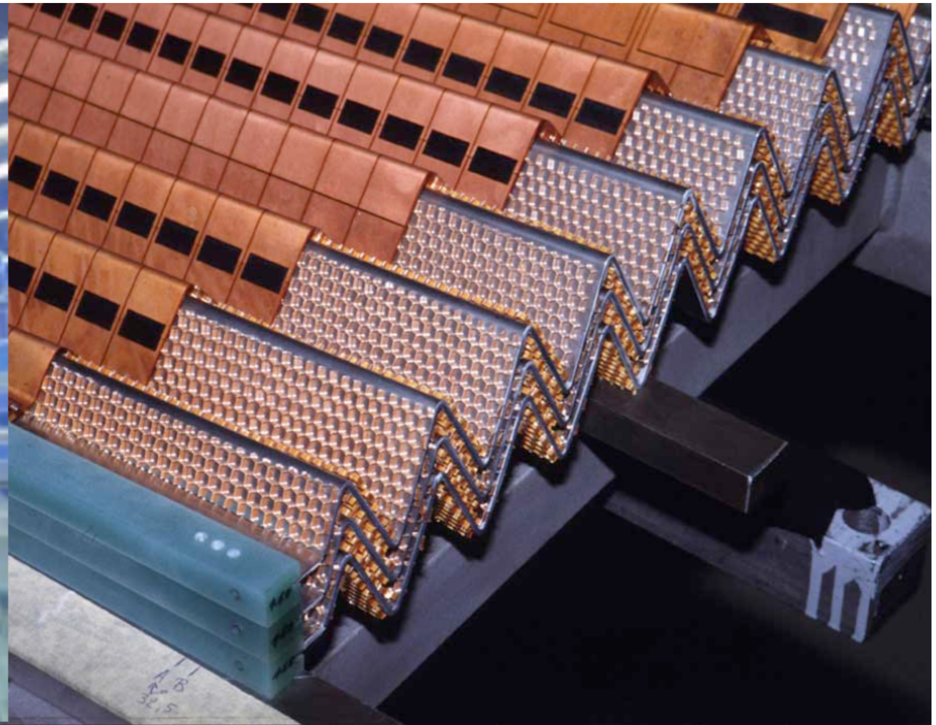
Only Electrons and High Energy Photons show EM cascades at current GeV-TeV level Energies.

Strongly interacting particles like Pions, Kaons, produce hadonic showers in a similar fashion to the EM cascade →Hadronic calorimetry

Bremsstrahlung + Pair Production → EM Shower







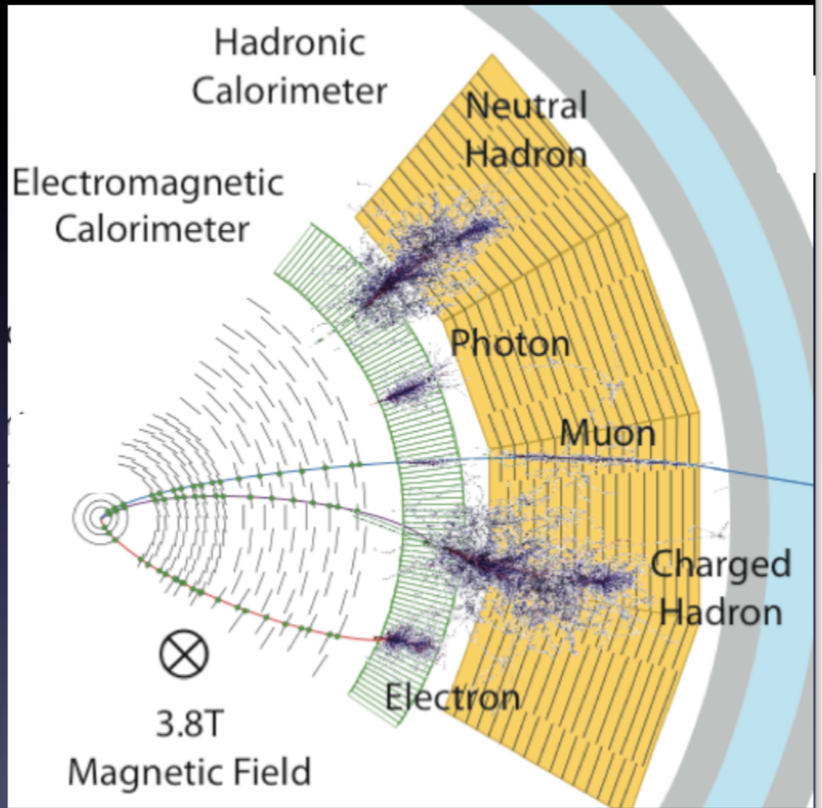
Detectors for Particle Physics

Calorimetry

D. Bortoletto

What is a calorimeter ?

- In nuclear and particle physics calorimetry refers to the detection of particles through total absorption in a block of matter
  - The measurement process is destructive for almost all particle
  - The exception are muons (and neutrinos) → identify muons easily since they penetrate a substantial amount of matter
- In the absorption, almost all particle's energy is eventually converted to heat → calorimeter
- Calorimeters are essential to measure neutral particles



Electromagnetic shower

- Dominant processes at high energies (E > few MeV) :

- Photons: Pair production

$$\sigma_{pair} \approx \frac{7}{9}\left(4\alpha r_e^2 Z^2 \ln\frac{183}{Z^{1/3}}\right) = \frac{7}{9}\frac{A}{N_A X_0}$$

$$I(x) = I_0 e^{-\mu x} \qquad \mu = \frac{7}{9}\frac{\rho}{X_0}$$

μ= attenuation coefficient
X_0 = radiation length in [cm] or [g/cm^2]

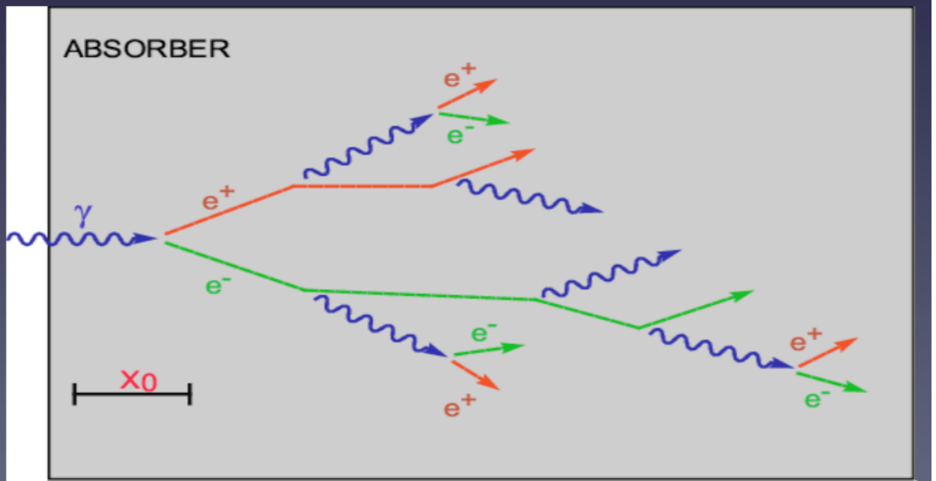
$$X_0 = \frac{A}{4\pi N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}$$

- Electrons: Bremsstrahlung

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln\frac{183}{Z^{1/3}} = \frac{E}{X_0}$$

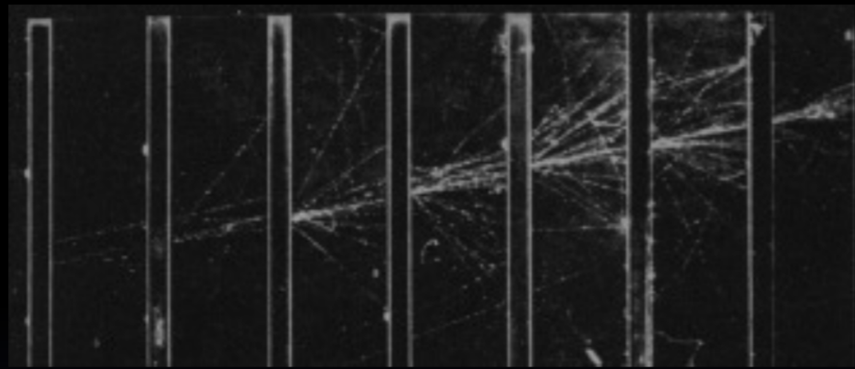
$$E = E_0 e^{-x/X_0}$$

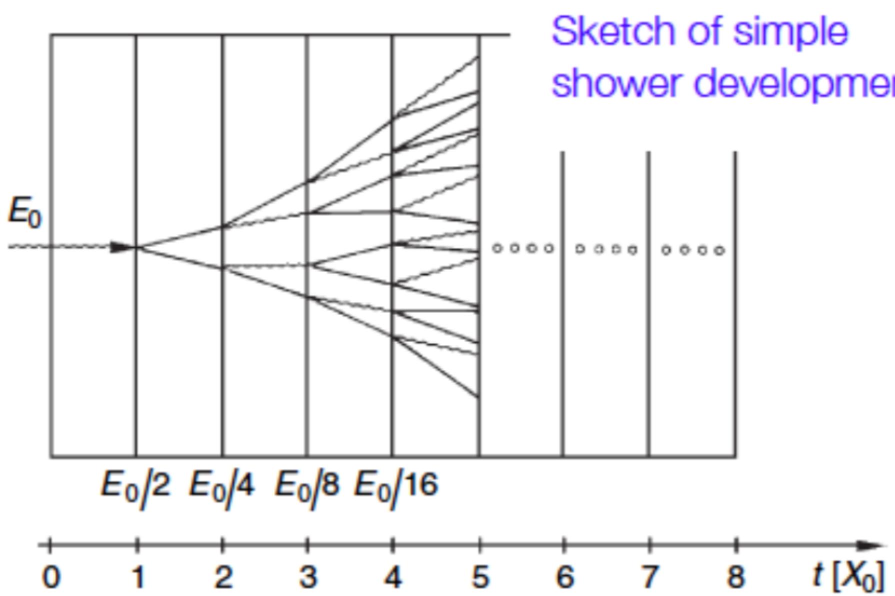
After traversing $x=X_0$ the electron has only 1/e=37% of its initial energy



Analytic shower Model

- Simplified model [Heitler]: shower development governed by X_0
  - e^- loses [1 - 1/e] = 63% of energy in 1 X_0 (Brems.)
  - the mean free path of a γ is 9/7 X_0 (pair prod.)
- Assume:
  - $E > E_c$: no energy loss by ionization/excitation
- Simple shower model:
  - $N(t)=2^t$ particles after $t = x/X_0$ each with energy $E(t)=E_0/2^t$
  - Stops if $E(t) < E_c = E_0 2^{tmax}$
  - Location of shower maximum at

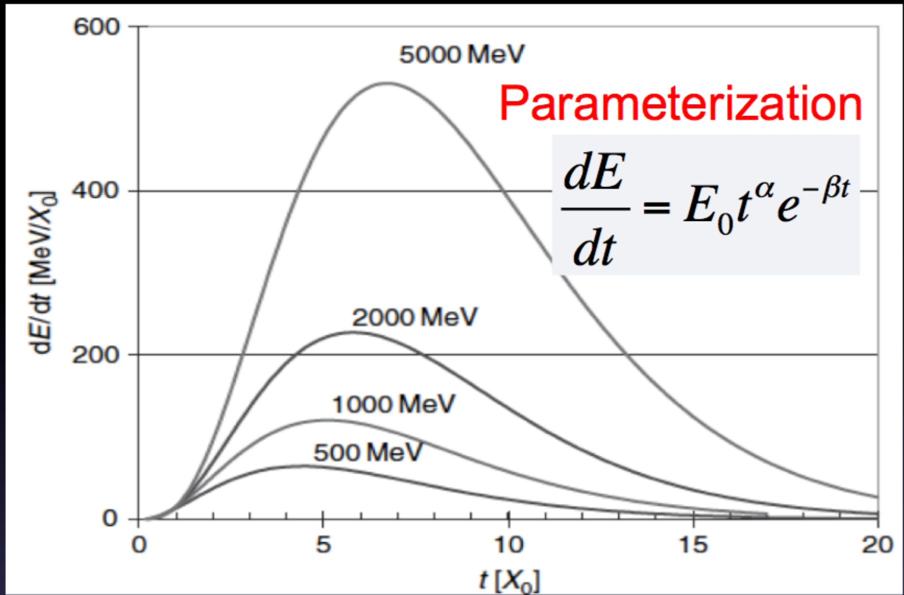


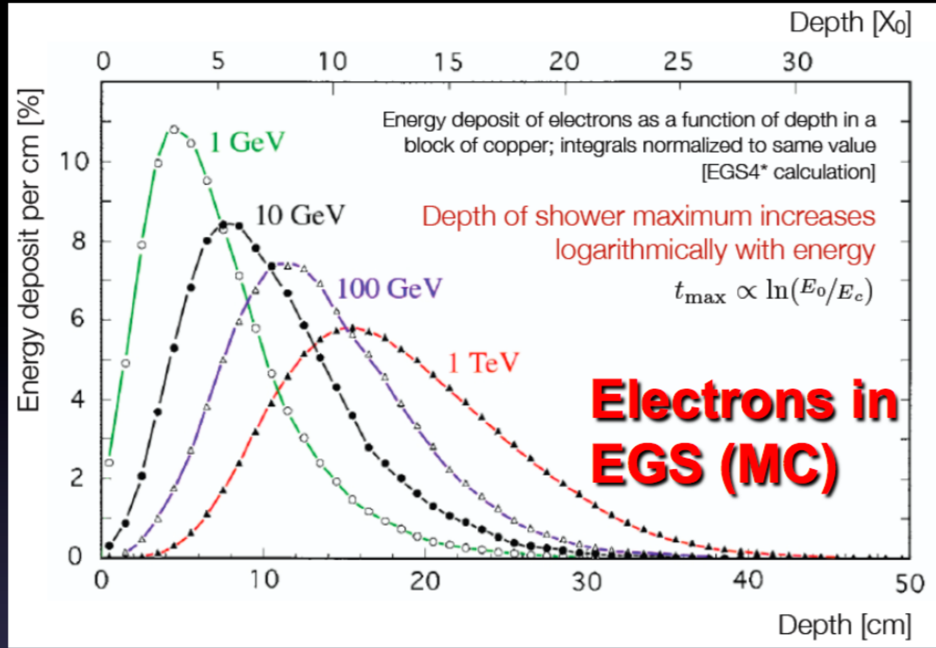


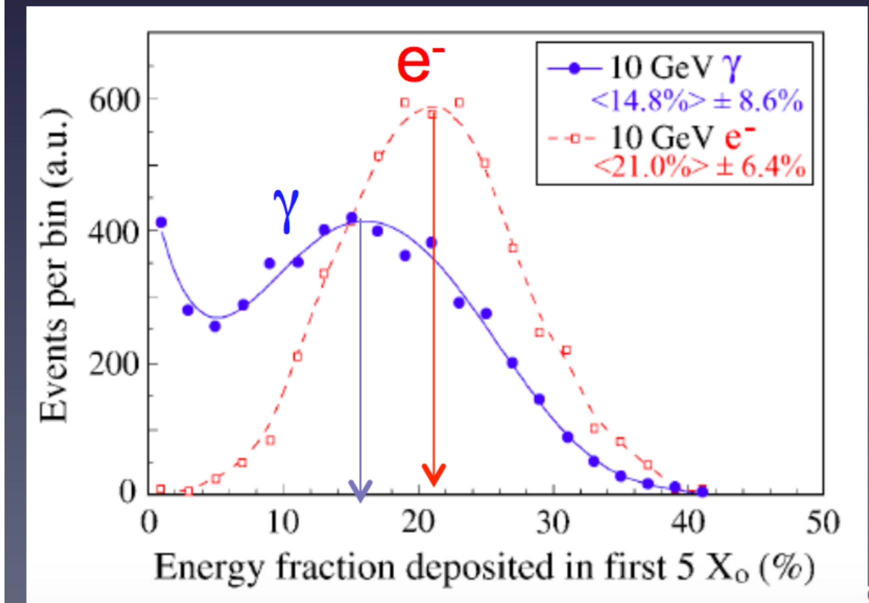
$$t_{\max} = \frac{\ln(E/Ec)}{\ln 2} \propto \ln\left(\frac{E}{E_c}\right)$$

$$N_{\max} = 2^{t_{\max}} = \frac{E_0}{E_C}$$

Longitudinal shower distribution







- Differences between electrons and photons generated showers
- Some photons penetrating (almost) the entire slab without interacting (peak at 0)

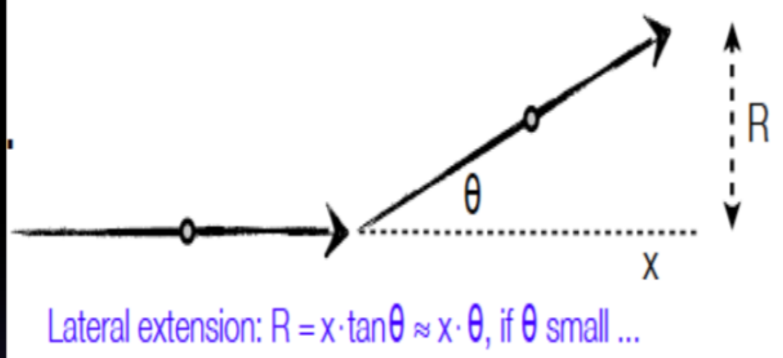
$$t_{max} = \ln\left(\frac{E_0}{E_c}\right) + C_{e\gamma}$$

$C_{e\gamma}$=-0.5 for photons
$C_{e\gamma}$=-1 for electrons

Lateral development of EM shower

- Opening angle:
  - bremsstrahlung and pair production

$$\langle \theta^2 \rangle \approx \left(\frac{m_e c^2}{E_e} \right)^2 = \frac{1}{\gamma^2}$$



  - multiple coulomb scattering [**Molière** theory]

$$\langle \theta \rangle = \frac{E_s}{E_e} \sqrt{\frac{x}{X_0}} \quad \text{where} \quad E_s = \sqrt{\frac{4\pi}{\alpha}} \left(m_e c^2 \right) = 21.2 MeV$$

- Main contribution from low energy e^- as $<\theta> \sim 1/E_e$, i.e. for e^- with $E < E_c$

- **Molière** Radius

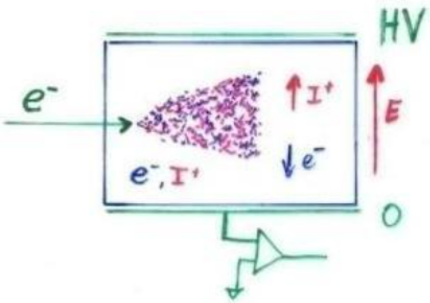
$$R_M = \frac{E_s}{E_c} X_0 \approx \frac{21.2 MeV}{E_c} X_0$$

- Assuming the approximate range of electrons to be X_0 yields $<\theta> \approx 21.2$ MeV/E_e ➝ lateral extension: $R = <\theta> X_0$

Calorimetry: Energy Measurement by total Absorption of Particles

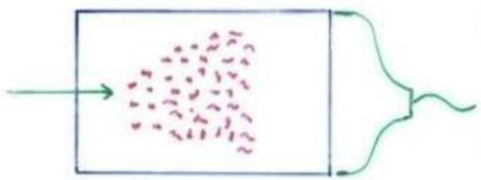
The measurement is destructive. The particle can not be subject to further study.

Energy Measurement by



Collecting the produced Charge

Liquid Nobel Gases (Nobel Liquids)



Measuring the Photons produced by the collision of the $e^\pm$ with atom electrons of the material.

Scintillating Crystals, Plastic Scintillators

Total Amount of e^-, I^+ pairs or Photons is proportional to the total track length is proportional to the particle Energy.

Calorimetry

Calorimeters can be classified into:

Electromagnetic Calorimeters,
to measure electrons and photons through their EM interactions.

Hadron Calorimeters,
Used to measure hadrons through their strong and EM interactions.

The construction can be classified into:

Homogeneous Calorimeters,
that are built of only one type of material that performs both tasks, energy degradation and signal generation.

Sampling Calorimeters,
that consist of alternating layers of an absorber, a dense material used to degrade the energy of the incident particle, and an active medium that provides the detectable signal.

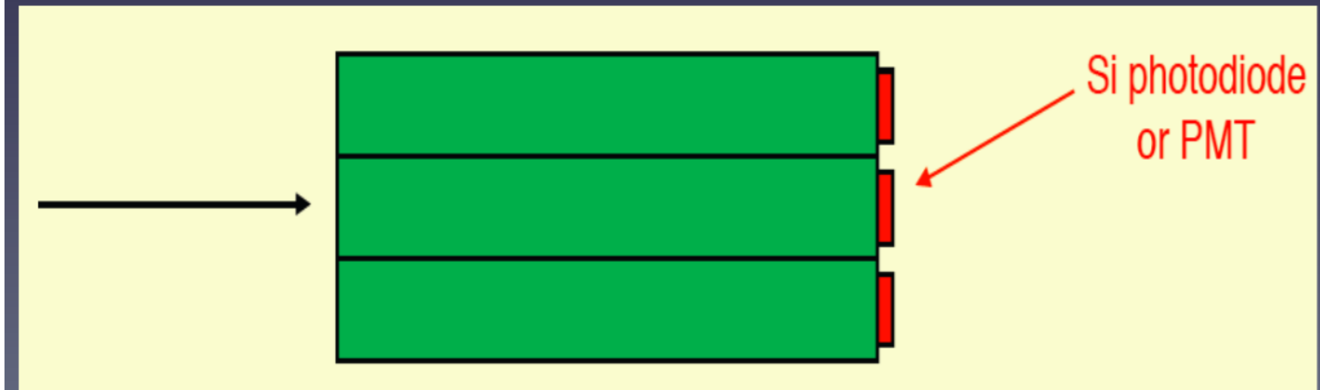
C.W. Fabjan and F. Gianotti, Rev. Mod. Phys., Vol. 75, N0. 4, October 2003

EM Calorimeter configurations

- Total absorption
  - Electrons and photons stop in calorimeter
  - Scintillation proportional to energy of electron
  - Usually non-organic scintillator (BGO, $PbWO_{4,...}$) or liquid Xe
  - Advantage: Excellent energy resolution
    - see all charged particles in the shower (but for shower leakage) ➔best statistical precision
    - Uniform response ➔good linearity
  - Disadvantages:
    - cost and limited segmentation

If W is the mean energy required to produce a signal (eg an e^--ion pair in a noble liquid or a 'visible' photon in a crystal)

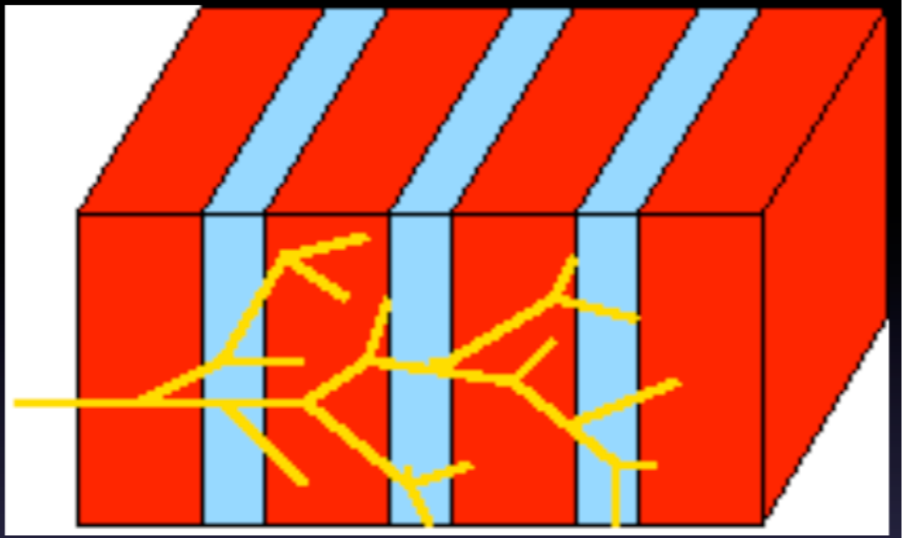
$$\frac{\sigma_E}{E} = \frac{1}{\sqrt{n}} = \frac{1}{\sqrt{E/W}}$$



- Examples:
  - B factories: small photon energies
  - CMS ECAL which was optimized for $H \rightarrow \gamma\gamma$

EM Calorimeter configurations

- Sampling Calorimeter
  - One material to induce showering (high Z)
  - Another to detect particles (typically by counting number of charged tracks)
  - Many layers sandwiched together
  - Resolution $\propto E^{-1/2}$



- Advantages
  - Depth segmentation
  - Spatial segmentation
- Disadvantages:
  - Only part of shower seen, less precise
- Examples
  - ATLAS ECAL
  - Most HCALs

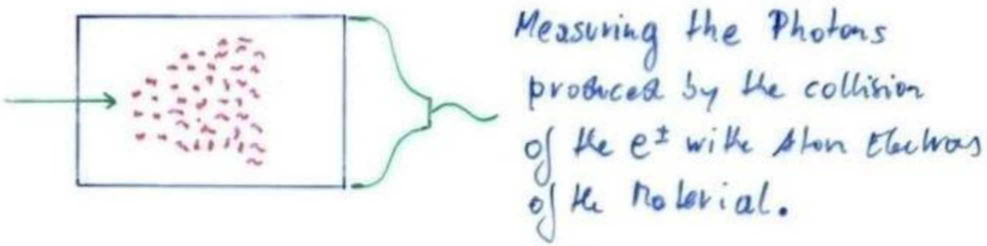
- Sampling fraction

$$f_{sampling} = \frac{E_{visible}}{E_{deposited}}$$

Crystals for Homogeneous EM Calorimetry

In crystals the light emission is related to the crystal structure of the material. Incident charged particles create electron-hole pairs and photons are emitted when electrons return to the valence band.

The incident electron or photon is completely absorbed and the produced amount of light, which is reflected through the transparent crystal, is measured by photomultipliers or solid state photon detectors.



Crystals for Homogeneous EM Calorimetry

	NaI(Tl)	CsI(Tl)	CsI	BGO	$PbWO_4$
Density (g/cm^3)	3.67	4.53	4.53	7.13	8.28
X_0 (cm)	2.59	1.85	1.85	1.12	0.89
R_M (cm)	4.5	3.8	3.8	2.4	2.2
Decay time (ns)	250	1000	10	300	5
slow component			36		15
Emission peak (nm)	410	565	305	410	440
slow component			480		
Light yield γ/MeV	4×10^4	5×10^4	4×10^4	8×10^3	1.5×10^2
Photoelectron yield (relative to NaI)	1	0.4	0.1	0.15	0.01
Rad. hardness (Gy)	1	10	10^3	1	10^5

Barbar@PEPII, 10ms interaction rate, good light yield, good S/N

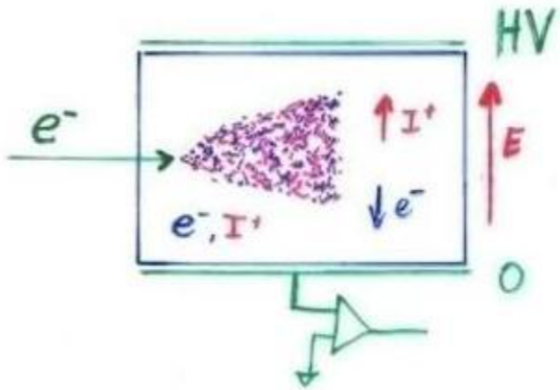
KTeV@Tevatron, High rate, Good resolution

L3@LEP, 25us bunch crossing, Low radiation dose

CMS@LHC, 25ns bunch crossing, high radiation dose

Noble Liquids for Homogeneous EM Calorimetry

	Ar	Kr	Xe
Z	18	36	58
A	40	84	131
X_0 (cm)	14	4.7	2.8
R_M (cm)	7.2	4.7	4.2
Density (g/cm^3)	1.4	2.5	3.0
Ionization energy (eV/pair)	23.3	20.5	15.6
Critical energy ϵ (MeV)	41.7	21.5	14.5
Drift velocity at saturation (mm/μs)	10	5	3

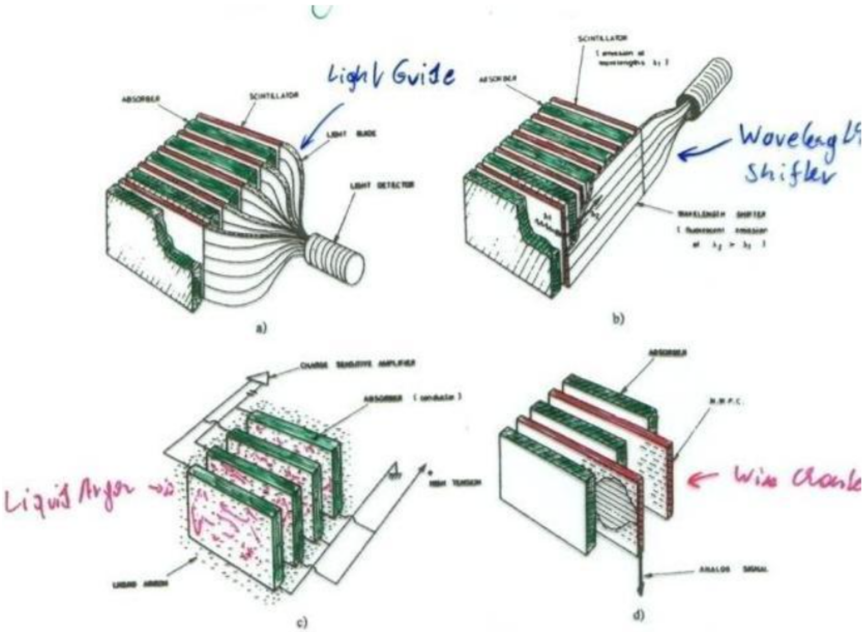


When a charge particle traverses these materials, about half the lost energy is converted into ionization and half into scintillation.

The best energy resolution would obviously be obtained by collecting both the charge and light signal. This is however rarely done because of the technical difficulties to extract light and charge in the same instrument.

Krypton is preferred in homogeneous detectors due to small radiation length and therefore compact detectors. Liquid Argon is frequently used due to low cost and high purity in sampling calorimeters (see later).

Sampling Calorimeters



Alternation of "passive" absorber plates and "active" readout sections

Advantage:
- optimum choice of Absorber Material
- optimum choice of Signal Readout
- Compact and cheap Construction

"passive": Pb, Fe ....

"active": Scintillator (Signal $\rightarrow$ Photons)

Noble Liquid, e.g. Ar (Signal $\rightarrow e^-, I^+$)

Wire Chambers (Signal $\rightarrow e^-, I^+$)

Energy resolution of sampling calorimeters is in general worse than that of homogeneous calorimeters, owing to the sampling fluctuations – the fluctuation of ratio of energy deposited in the active and passive material.

The resolution is typically in the range 5-20%/Sqrt[E(GeV)] for EM calorimeters. On the other hand they are relatively easy to segment longitudinally and laterally and therefore they usually offer better space resolution and particle identification than homogeneous calorimeters.

The active medium can be scintillators (organic), solid state detectors, gas detectors or liquids.

Sampling Fraction = Energy deposited in Active/Energy deposited in passive material.

Hadron Calorimeters are Large because λ is large

Hadron Calorimeters are large and heavy because the hadronic interaction length λ, the 'strong interaction equivalent' to the EM radiation length X_0, is large (5-10 times larger than X_0)

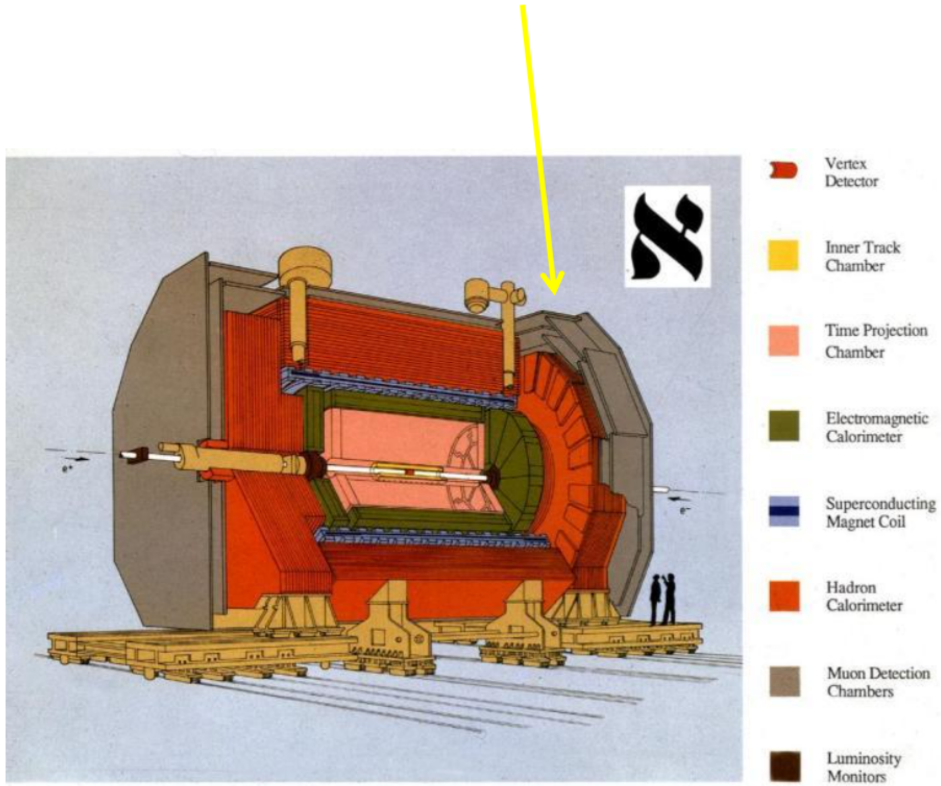
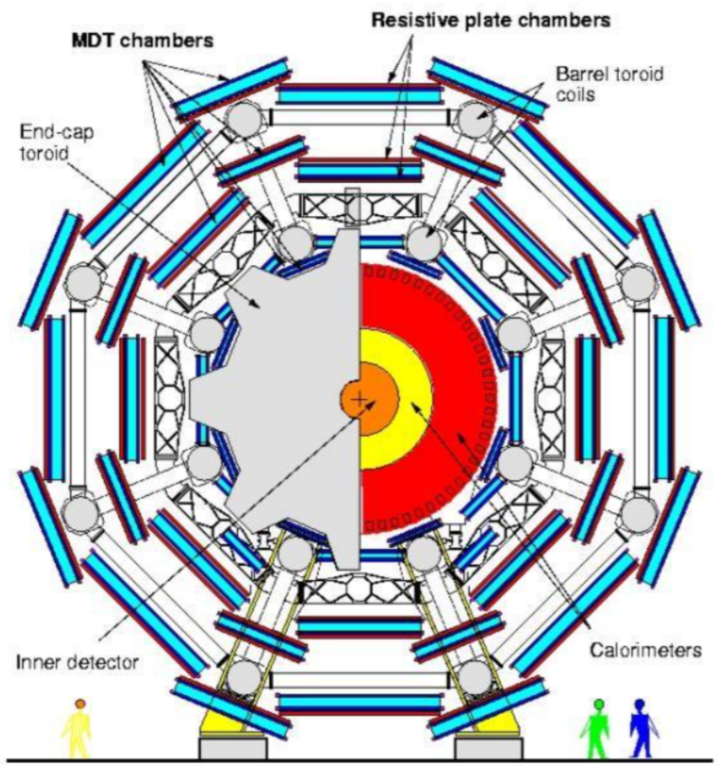


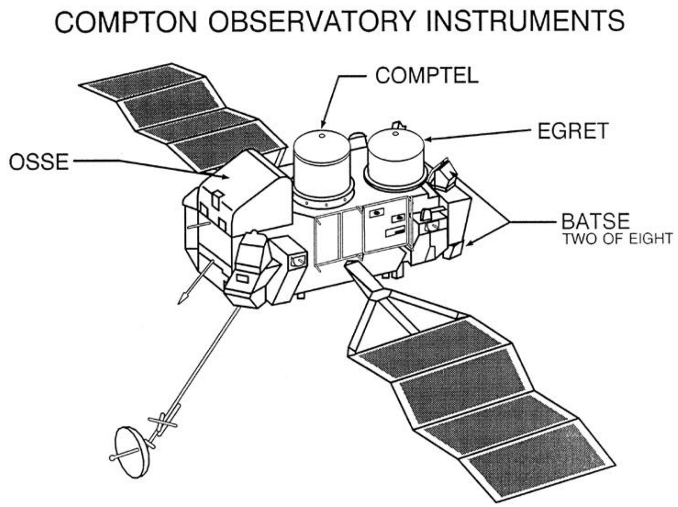
Fig. 1 - The ALEPH Detector

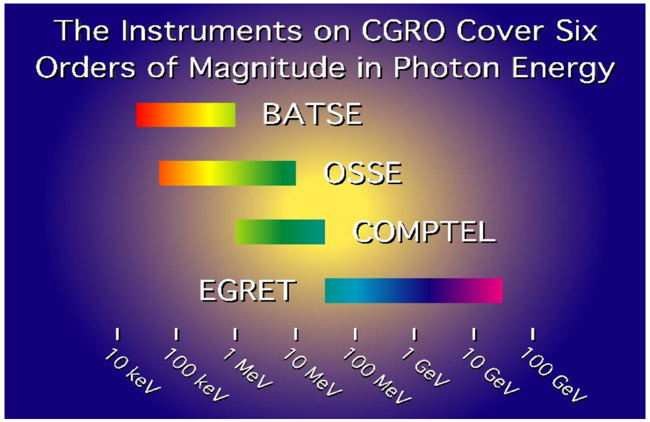


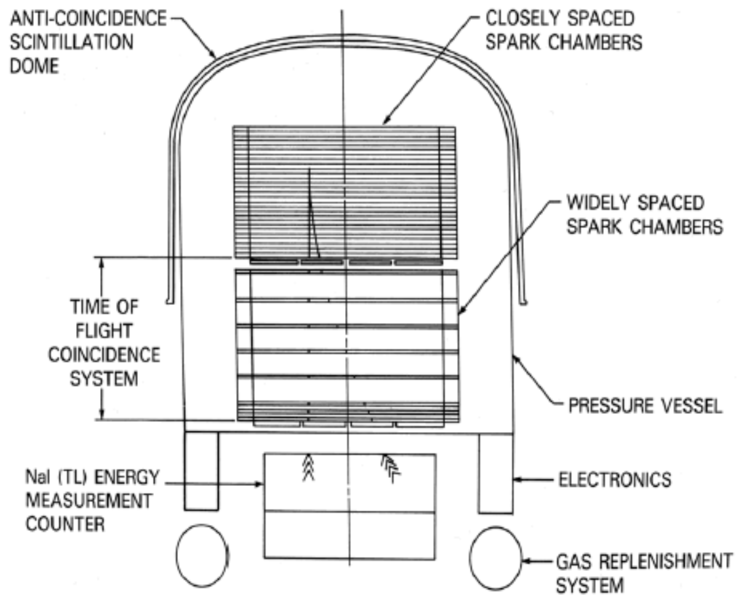
Because part of the energy is 'invisible' (nuclear excitation, slow nucleons), the resolution of hadron calorimeters is typically worse than in EM calorimeters 20-100%/Sqrt[E(GeV)] .

HE Gamma-ray Astrophysics
The EGRET legacy

EGRET



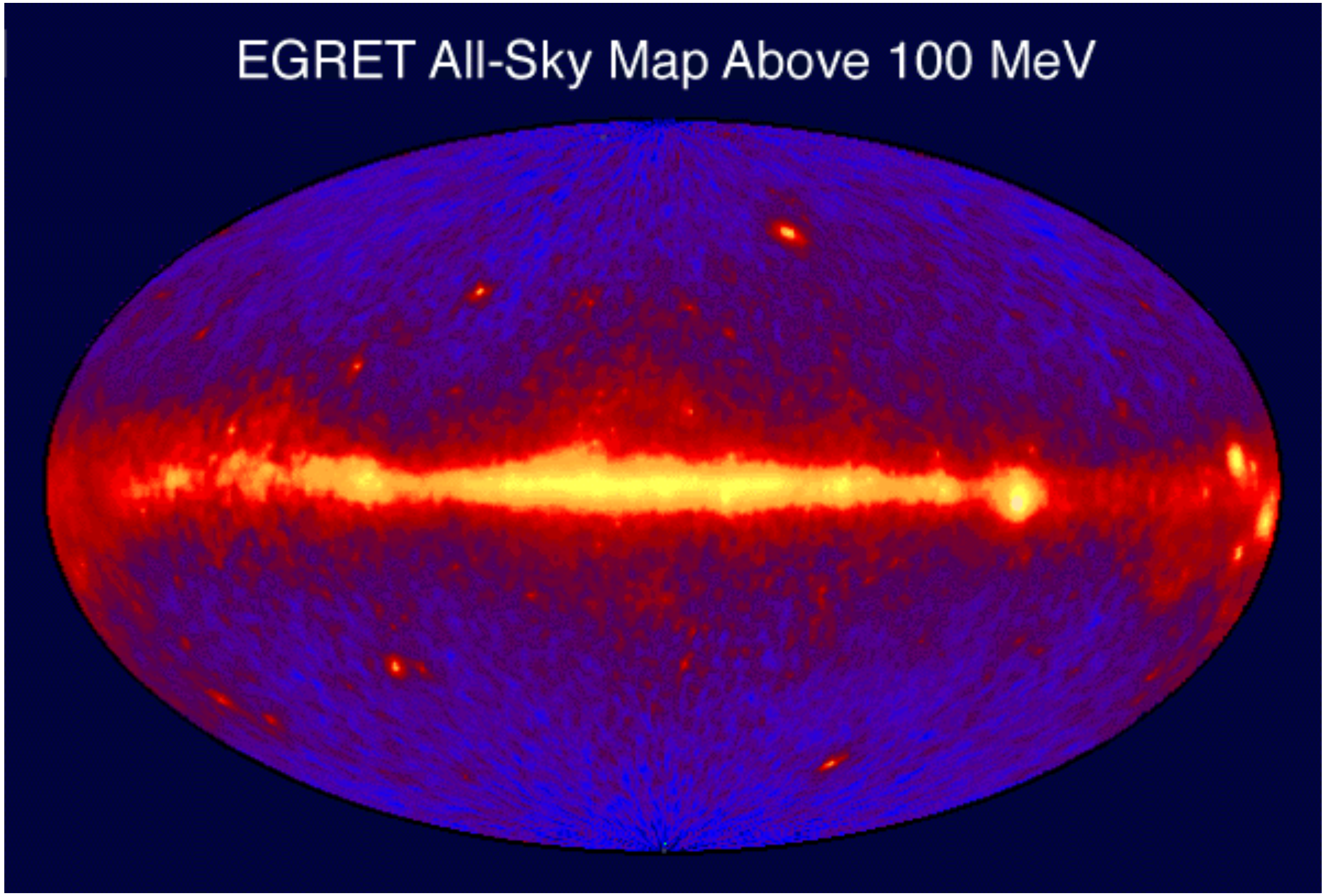




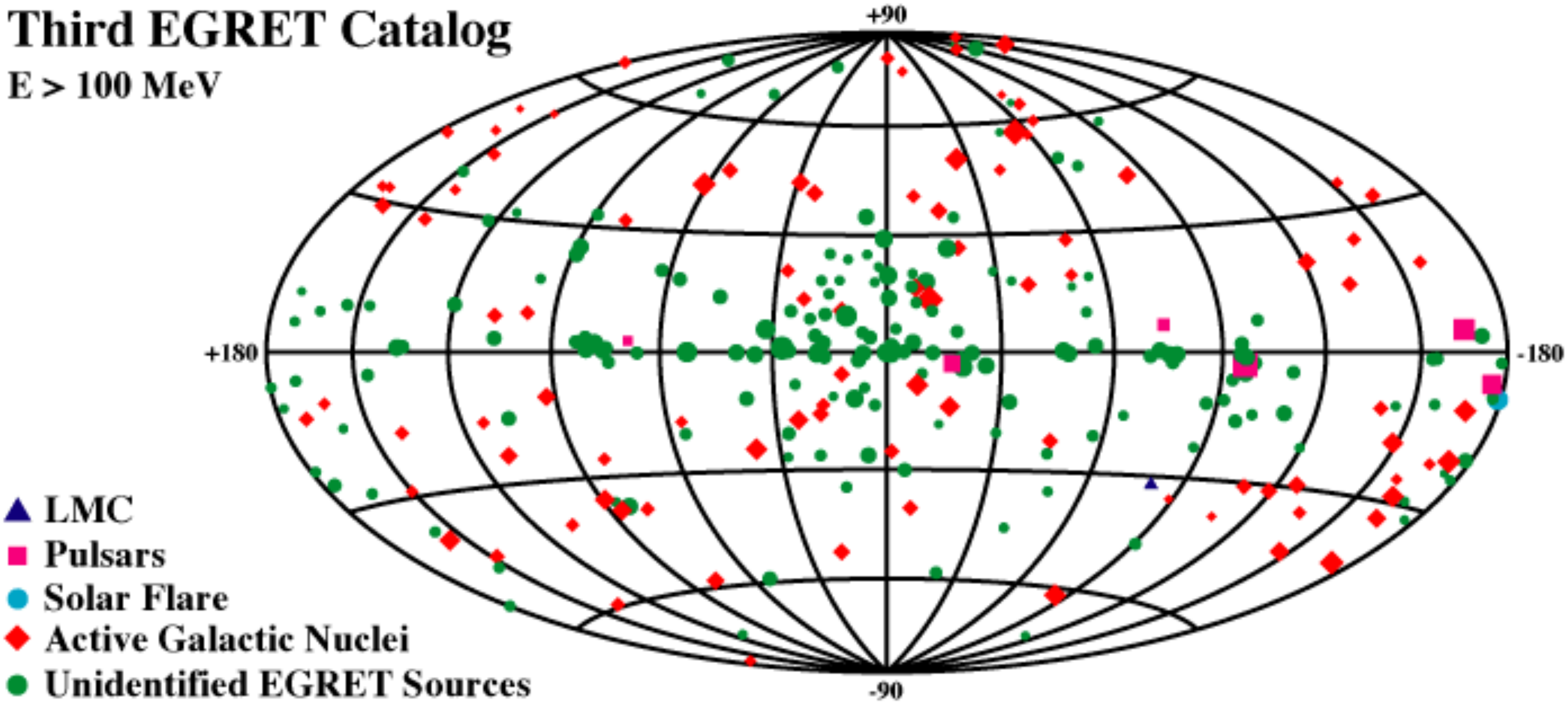
EGRET

- 1991-2000
- 30 MeV - 30 GeV
- AGN, GRB, Unidentified Sources, Diffuse Bkg

The HE sky from EGRET

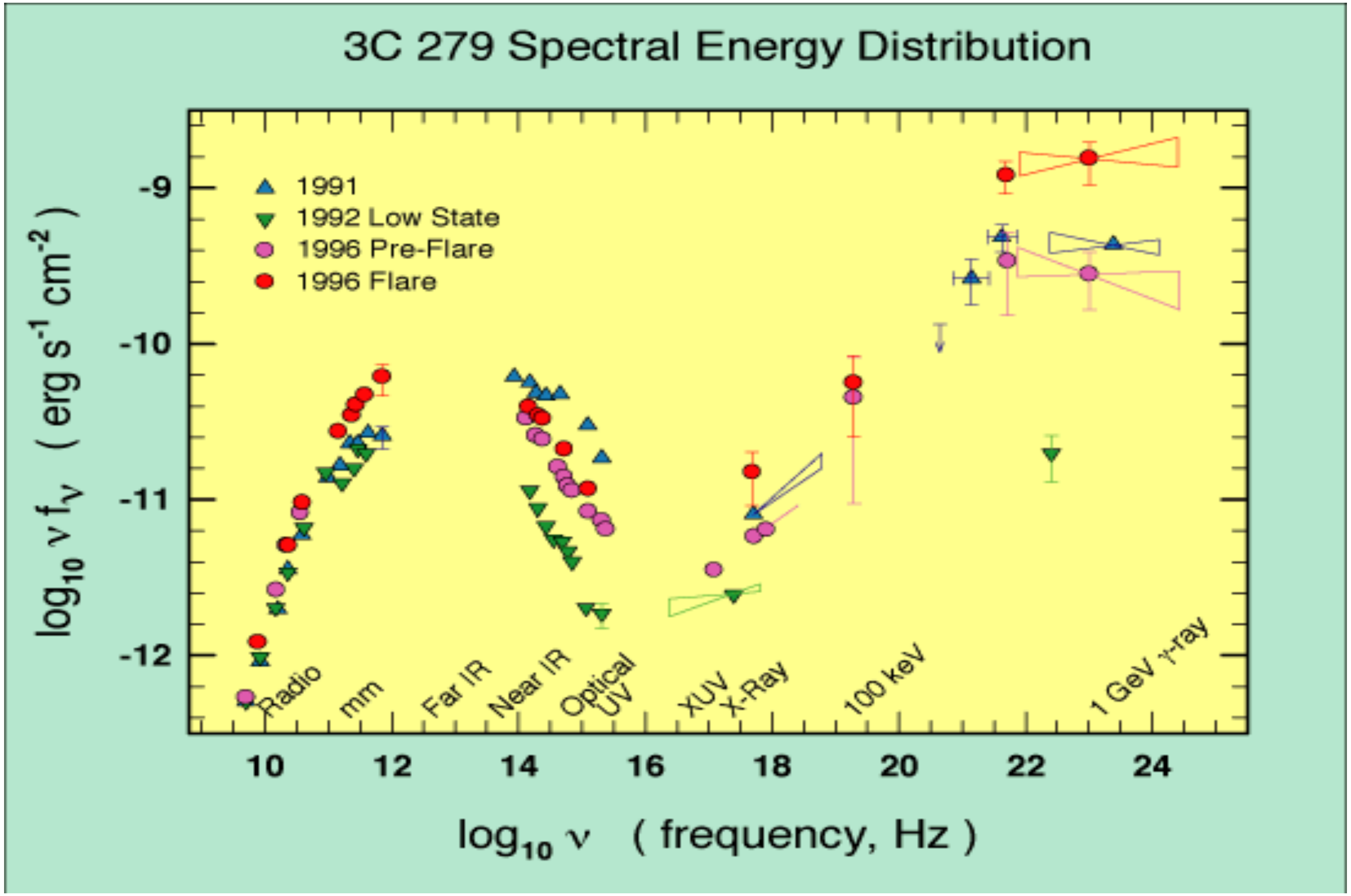


EGRET Gamma-ray Sources



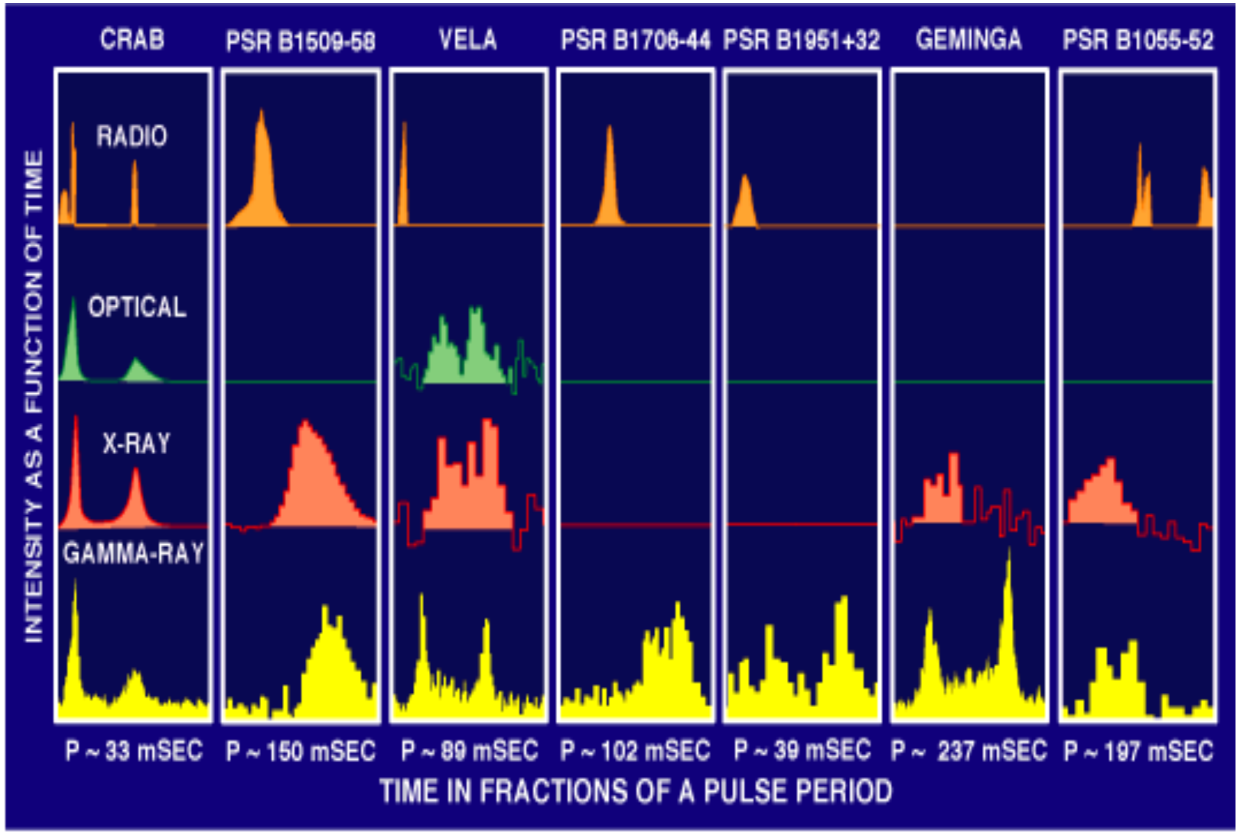
Challenge # 1

- Need simultaneous multiwavelength data to study variability and emission processes



Challenge # 2

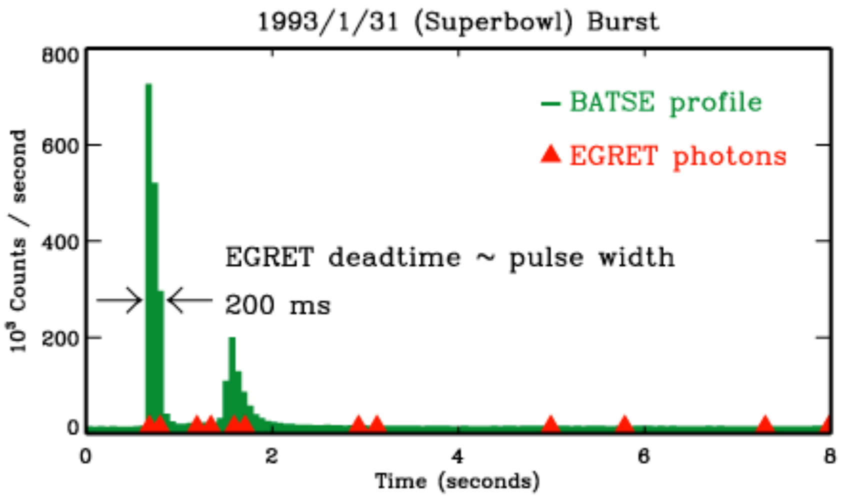
- Need more exposure and optimal timing (and radio monitoring) to discover more gamma-ray PSRs.



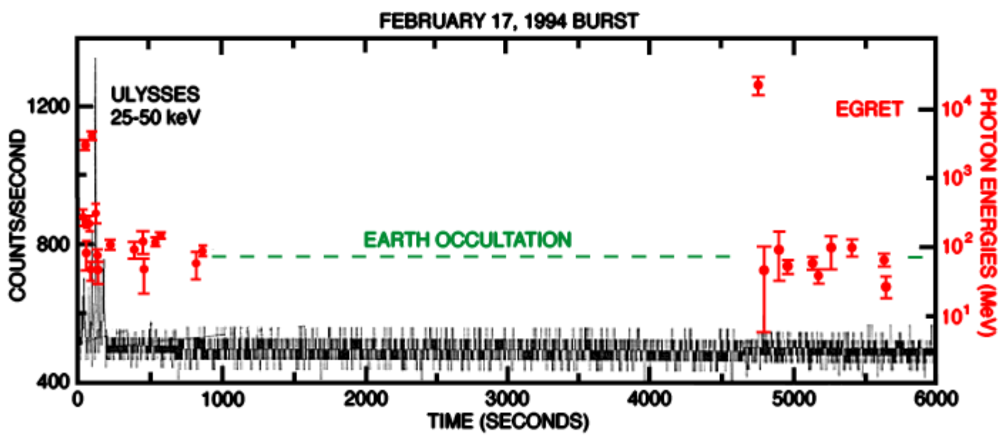
Challenge # 3

- Need fast timing for gamma-ray detection (improving EGRET deadtime, 100 msec → 100 microsec or less).

Prompt Emission (GRB 930131)

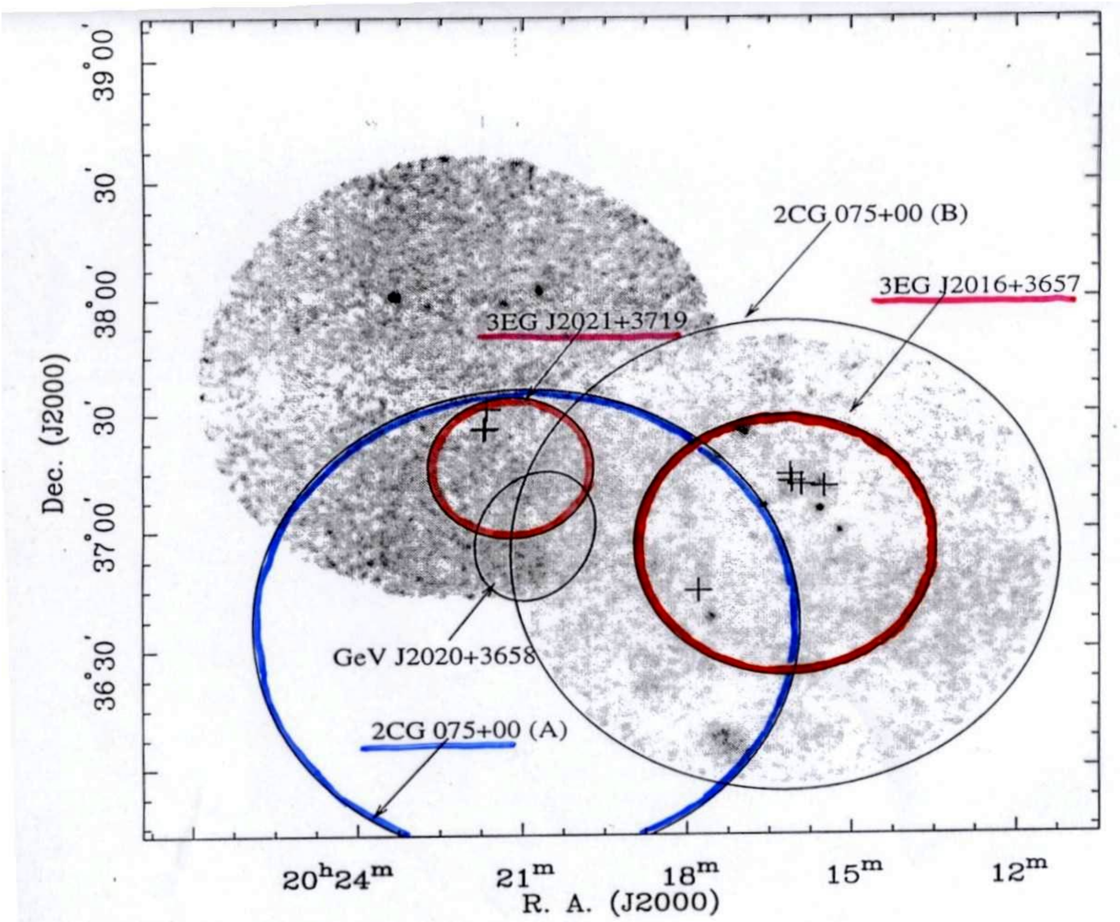


Delayed Emission (GRB 940217)



Challenge # 4

- Need arcminute positioning of gamma-ray sources (improving EGRET error box radii by a factor of 2-10).



Challenge # 5

- Need improvements in Spectral Resolution fo check for DM signals