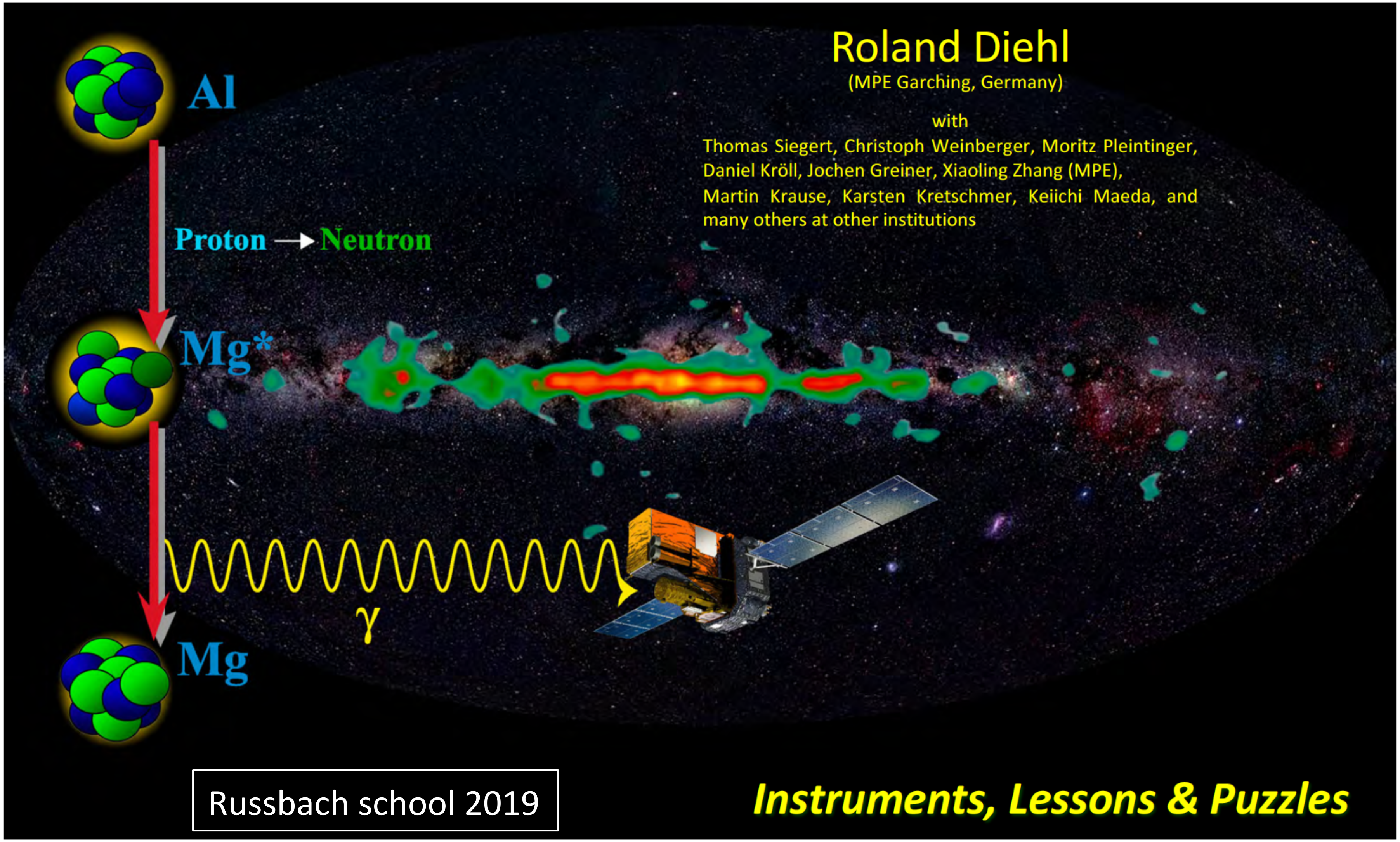
Astrofisica Nucleare e Subnucleare

Nuclear Astrophysics - III

Observing cosmic nuclei through γ ray spectroscopy



Roland Diehl

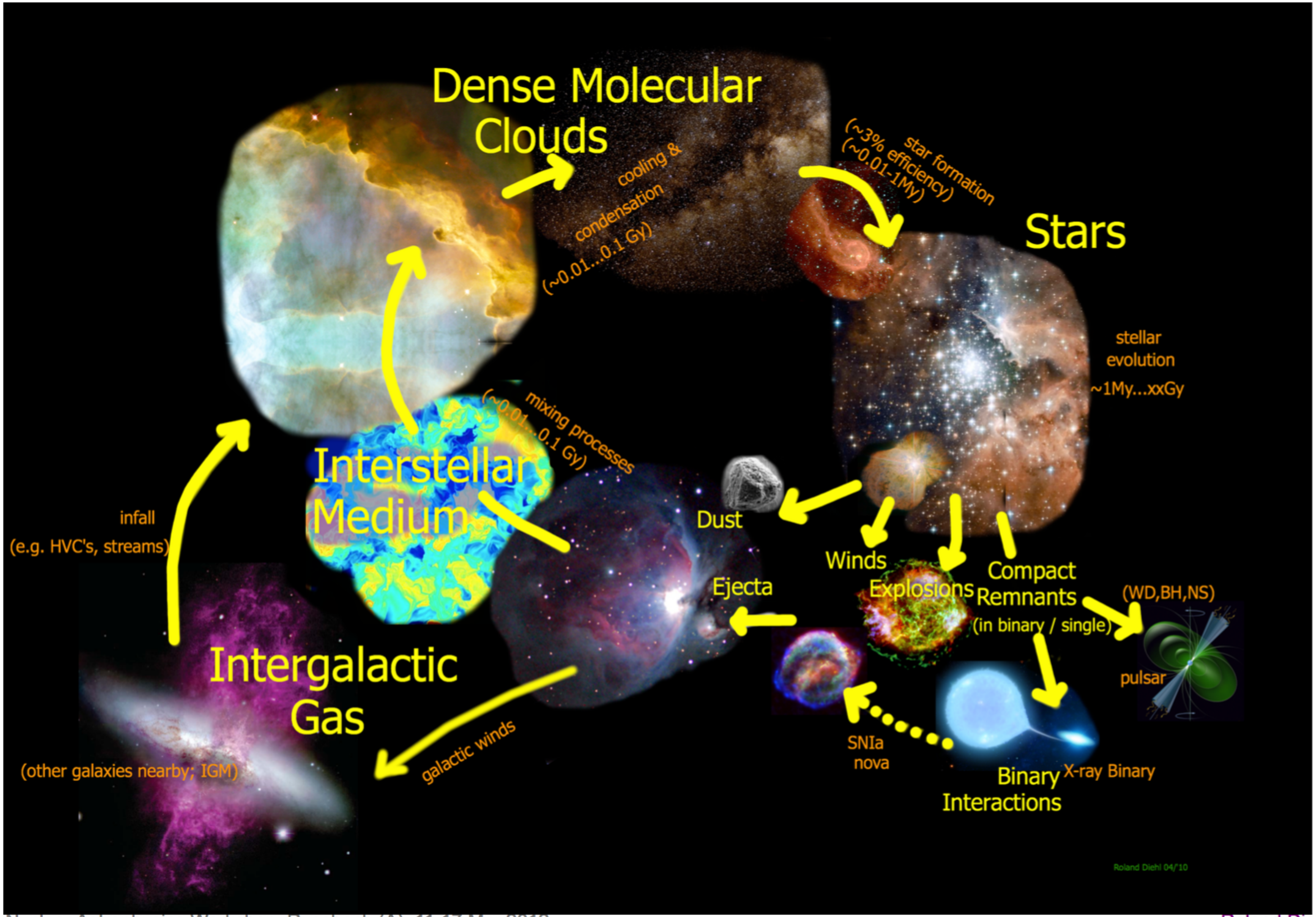
(MPE Garching, Germany)

with
Thomas Siegert, Christoph Weinberger, Moritz Pleintinger, Daniel Kröll, Jochen Greiner, Xiaoling Zhang (MPE), Martin Krause, Karsten Kretschmer, Keiichi Maeda, and many others at other institutions

Russbach school 2019

Instruments, Lessons & Puzzles

How Stars Shape Galaxies



Dense Molecular Clouds

cooling & condensation (~0.01...0.1 Gy)

star formation (~3% efficiency) (~0.01-1My)

Stars

stellar evolution ~1My...xxGy

Dust

Winds

Explosions

Compact Remnants (in binary / single)

(WD,BH,NS)

pulsar

Binary Interactions

X-ray Binary

SNIa nova

Ejecta

mixing processes (~0.01...0.1 Gy)

Interstellar Medium

galactic winds

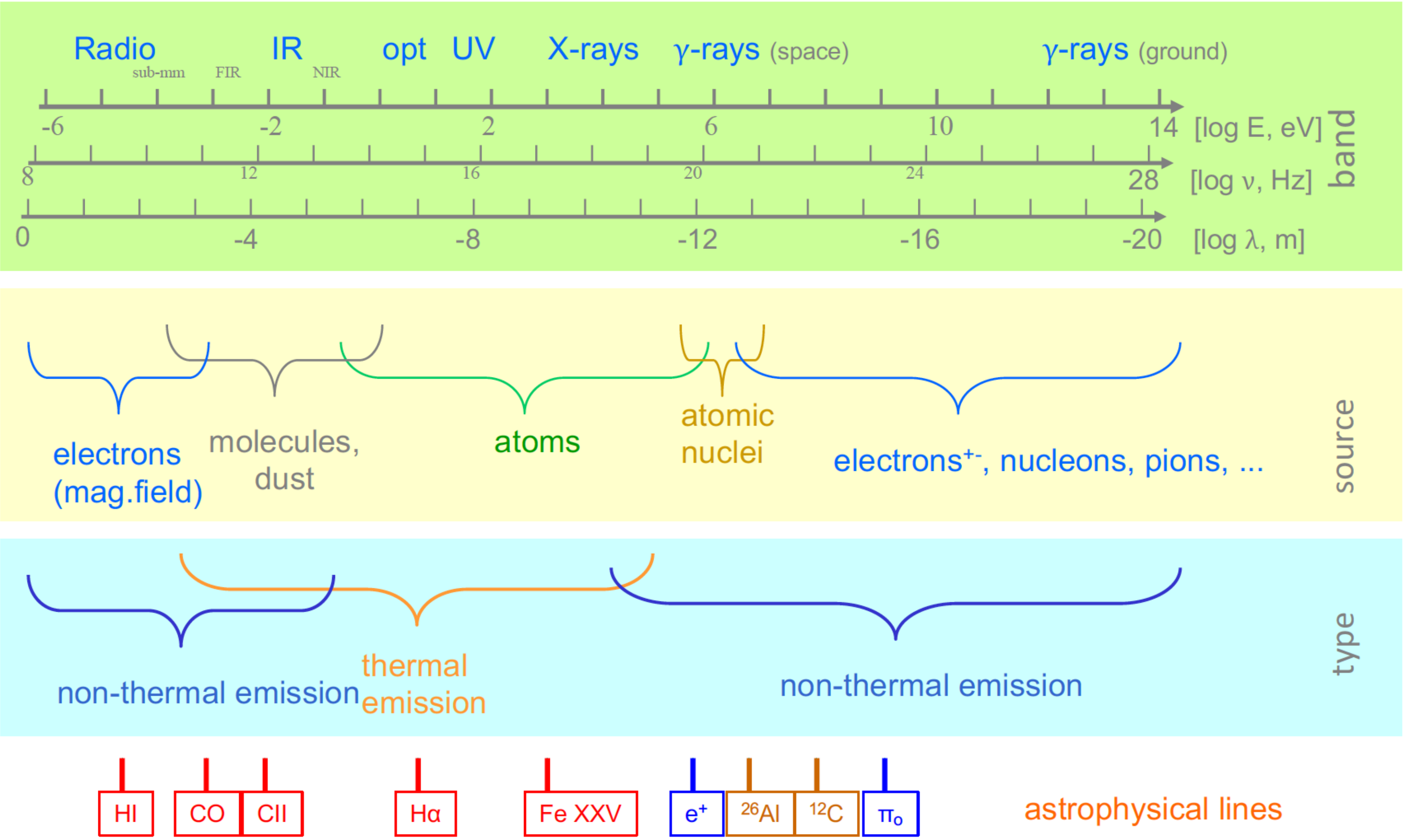
Intergalactic Gas

(other galaxies nearby; IGM)

infall (e.g. HVC's, streams)

Roland Diehl 04/'10

Line Spectroscopy across the Electromagnetic Spectrum



Radio sub-mm FIR IR NIR opt UV X-rays γ-rays (space) γ-rays (ground)

-6 -2 2 6 10 14 [log E, eV]

8 12 16 20 24 28 [log ν, Hz]

0 -4 -8 -12 -16 -20 [log λ, m]

band

electrons (mag.field)

molecules, dust

atoms

atomic nuclei

electrons^{+-}, nucleons, pions, ...

source

non-thermal emission

thermal emission

non-thermal emission

type

HI CO CII Hα Fe XXV e^+ ^{26}Al ^{12}C π_o

astrophysical lines

Radioisotope Gamma-Ray Lines and their Messages

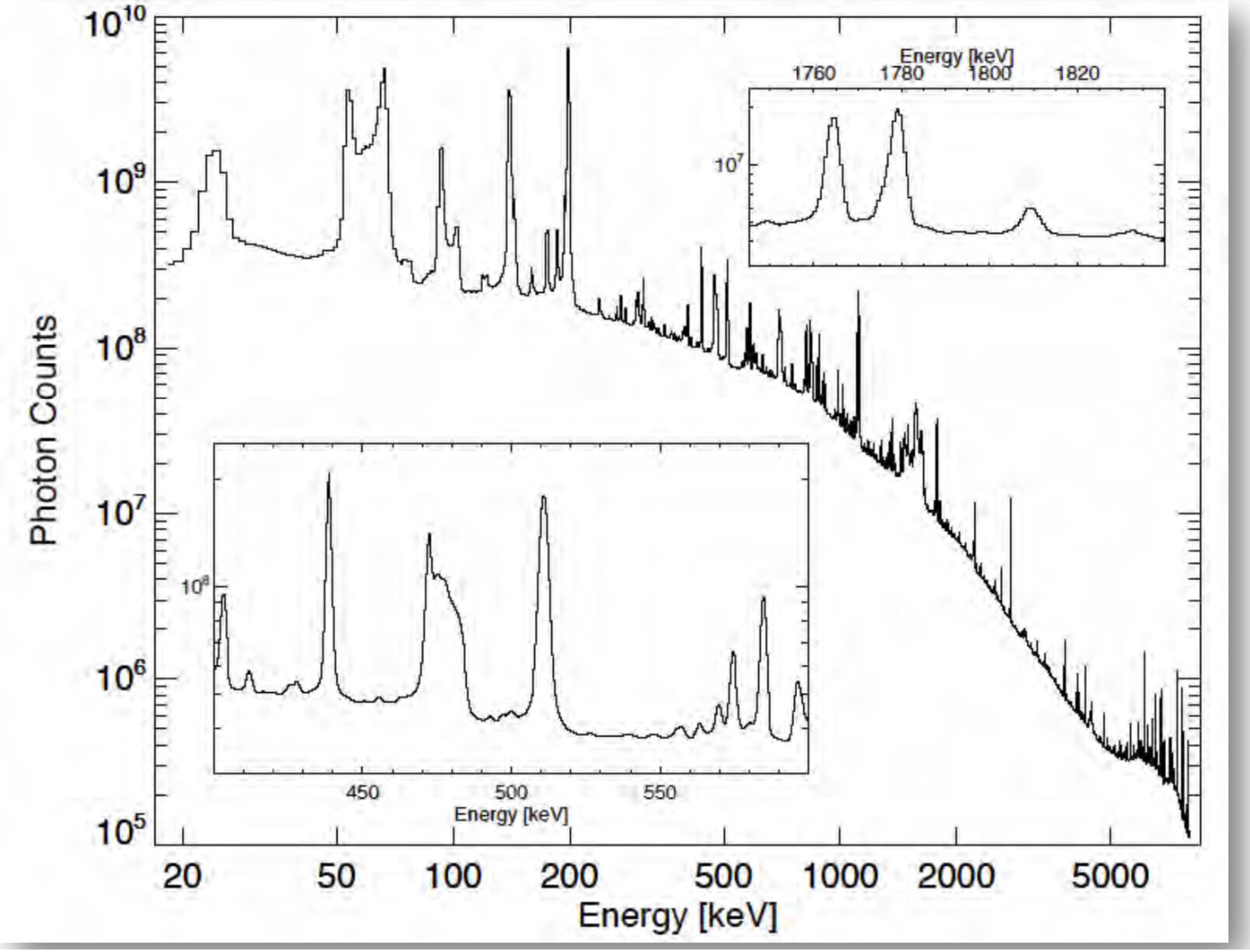
Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
$^{7}\mathrm{Be}$	77 d	$^{7}\mathrm{Be} \rightarrow {}^{7}\mathrm{Li}^*$	478
$^{56}\mathrm{Ni}$	111 d	$^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co}^* \rightarrow {}^{56}\mathrm{Fe}^* + e^+$	158, 812; 847, 1238
$^{57}\mathrm{Ni}$	390 d	$^{57}\mathrm{Co} \rightarrow {}^{57}\mathrm{Fe}^*$	122
$^{22}\mathrm{Na}$	3.8 y	$^{22}\mathrm{Na} \rightarrow {}^{22}\mathrm{Ne}^* + e^+$	1275
$^{44}\mathrm{Ti}$	89 y	$^{44}\mathrm{Ti} \rightarrow {}^{44}\mathrm{Sc}^* \rightarrow {}^{44}\mathrm{Ca}^* + e^+$	78, 68; 1157
$^{26}\mathrm{Al}$	1.04 10^{6}y	$^{26}\mathrm{Al} \rightarrow {}^{26}\mathrm{Mg}^* + e^+$	1809
$^{60}\mathrm{Fe}$	3.8 10^{6}y	$^{60}\mathrm{Fe} \rightarrow {}^{60}\mathrm{Co}^* \rightarrow {}^{60}\mathrm{Ni}^*$	59, 1173, 1332
e^+	…. 10^{5}y	$e^+ + e^- \rightarrow \mathrm{Ps} \rightarrow \gamma\gamma..$	511, <511

individual object/event

cumulative from many events

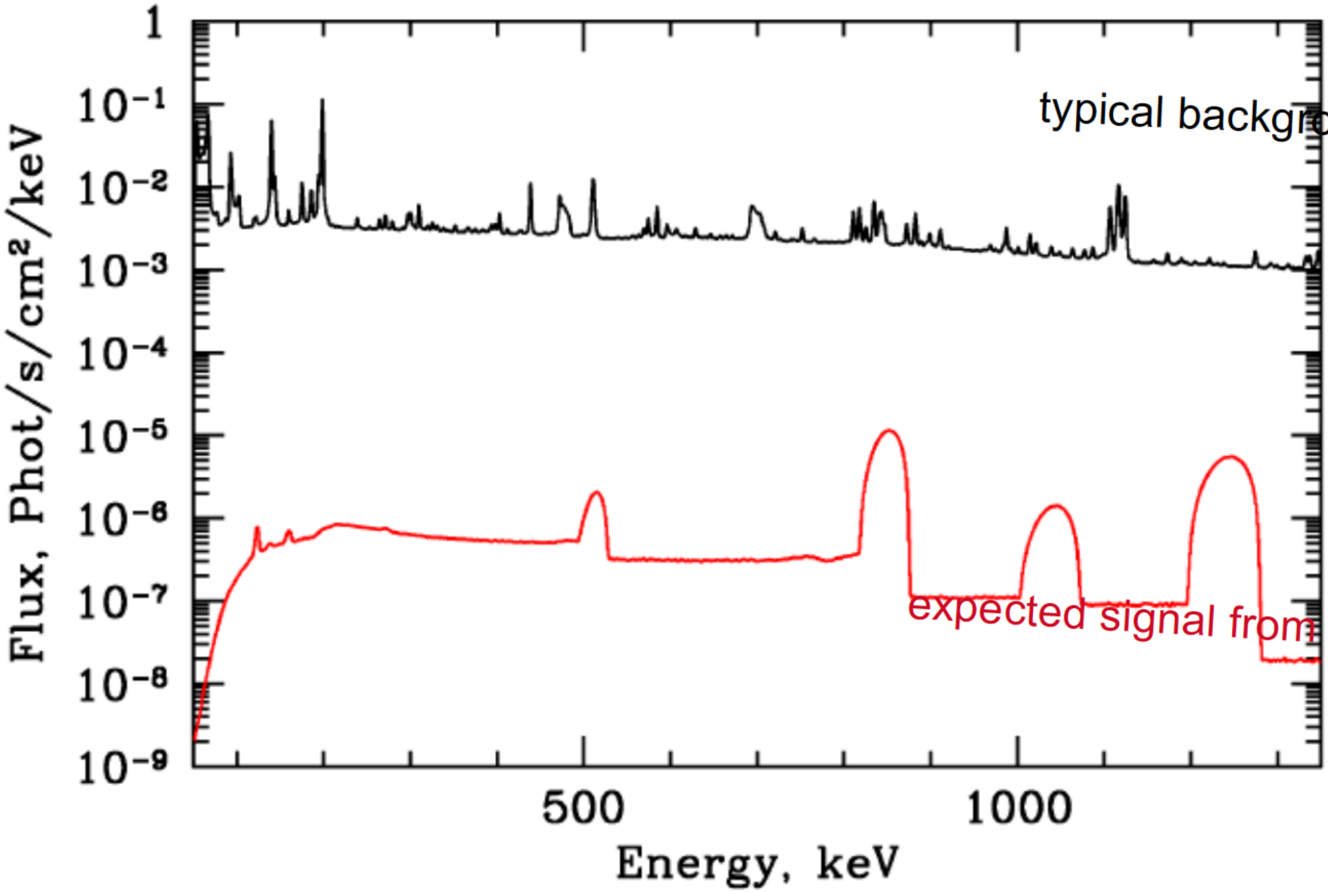
Dominance of instrumental background

SPI Ge detector spectra



The Challenge of Finding SN2014J Gamma-Rays

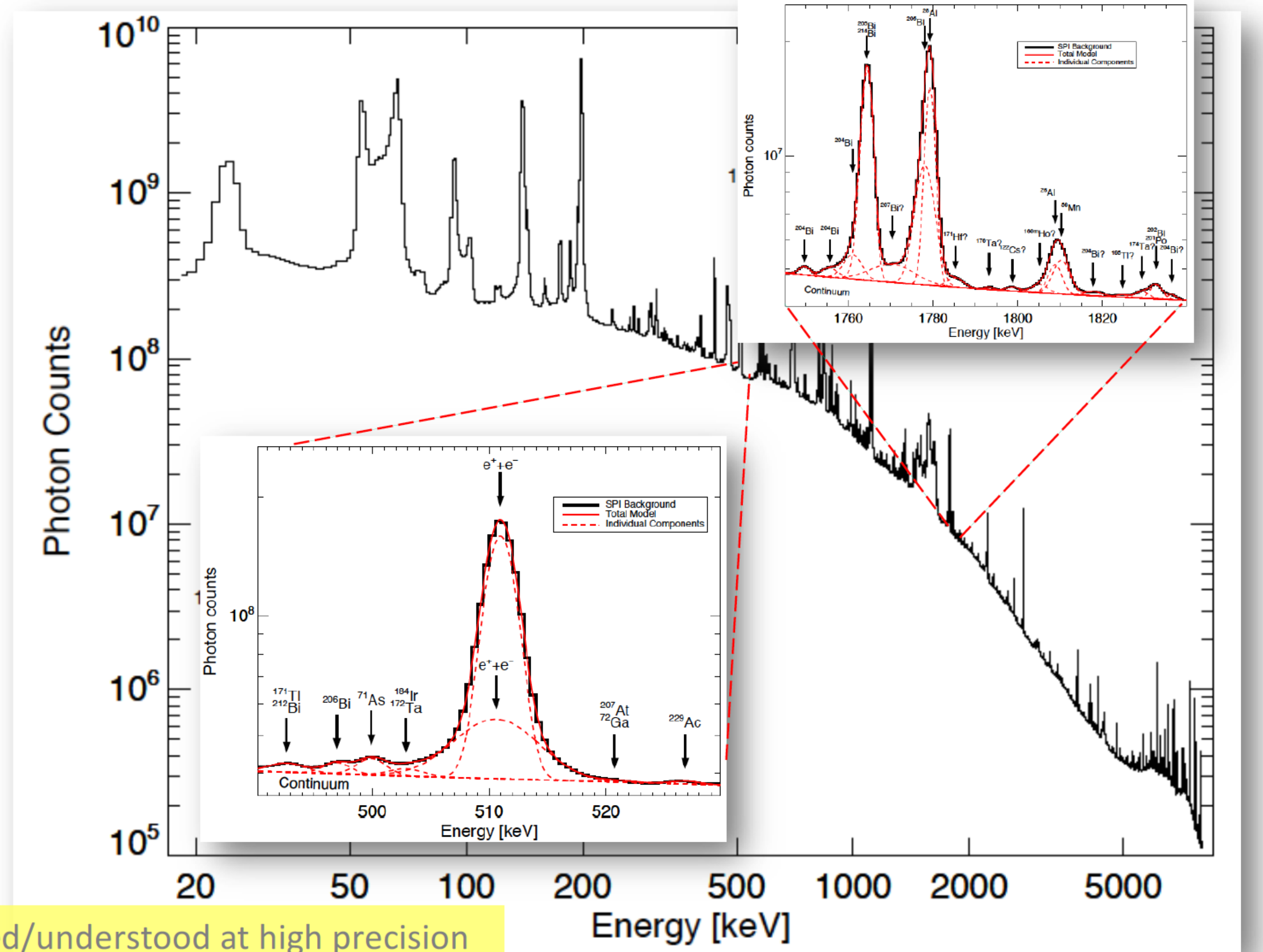
- ☆ Current Gamma-Ray Telescopes Have Large Intrinsic Background
  - ☞ Cosmic Ray Activation of Spacecraft and Instrument



from Churazov et al., 2014

Dominance of instrumental background

SPI Ge detector spectra

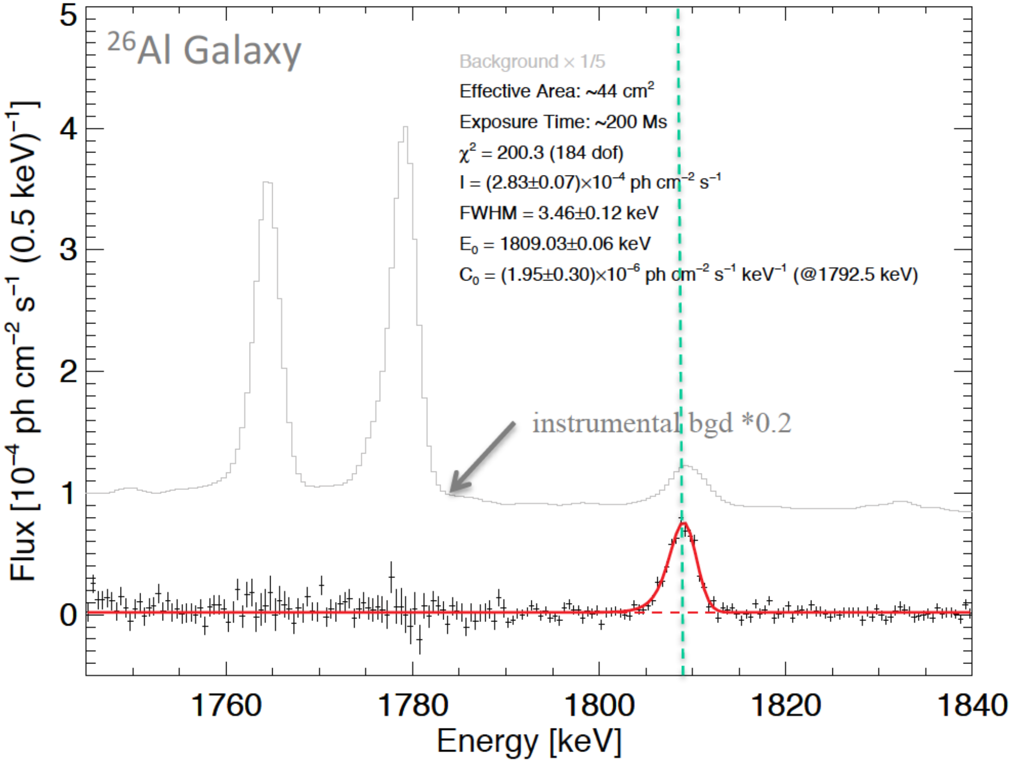


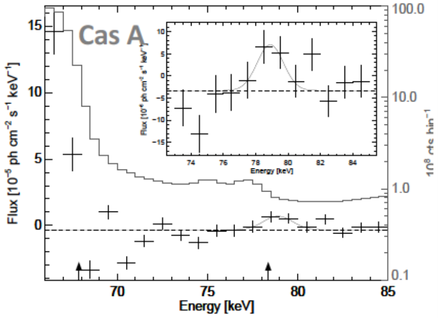
Modelled/understood at high precision

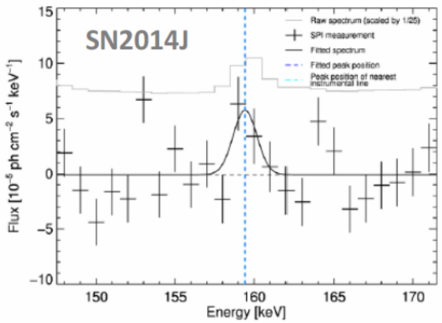
Gamma ray spectroscopy with SPI

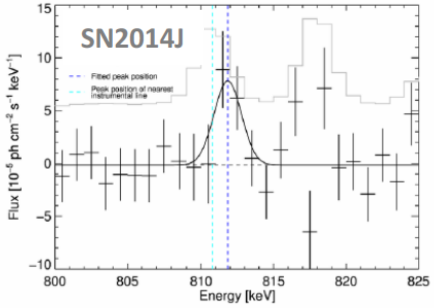
...it works!

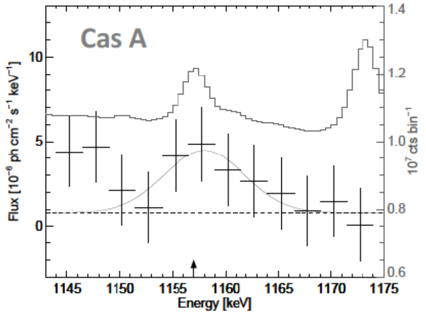
- ☆ ^{26}Al line 1808.6 keV
- ☆ instrumental lines
  - ☞ 1810 keV
  - ☞ 1779 keV
  - ☞ 1764 keV
- ☆ ...also: SN ^{56}Ni, ^{44}Ti











Nucleosynthesis

Basic Understanding of SNe Ia

What we know…:

- WD in binary system accretes hydrogen
- when Chandrasekhar mass is reached, WD collapses, explosively ignites Carbon, and is destroyed completely
- SNe Ia are very good *standard* candles: same maximum luminosity
- Powered by the decay of $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$

  $\sim 0.6\ M_{sun} = 10^{43}$ erg/s at peak

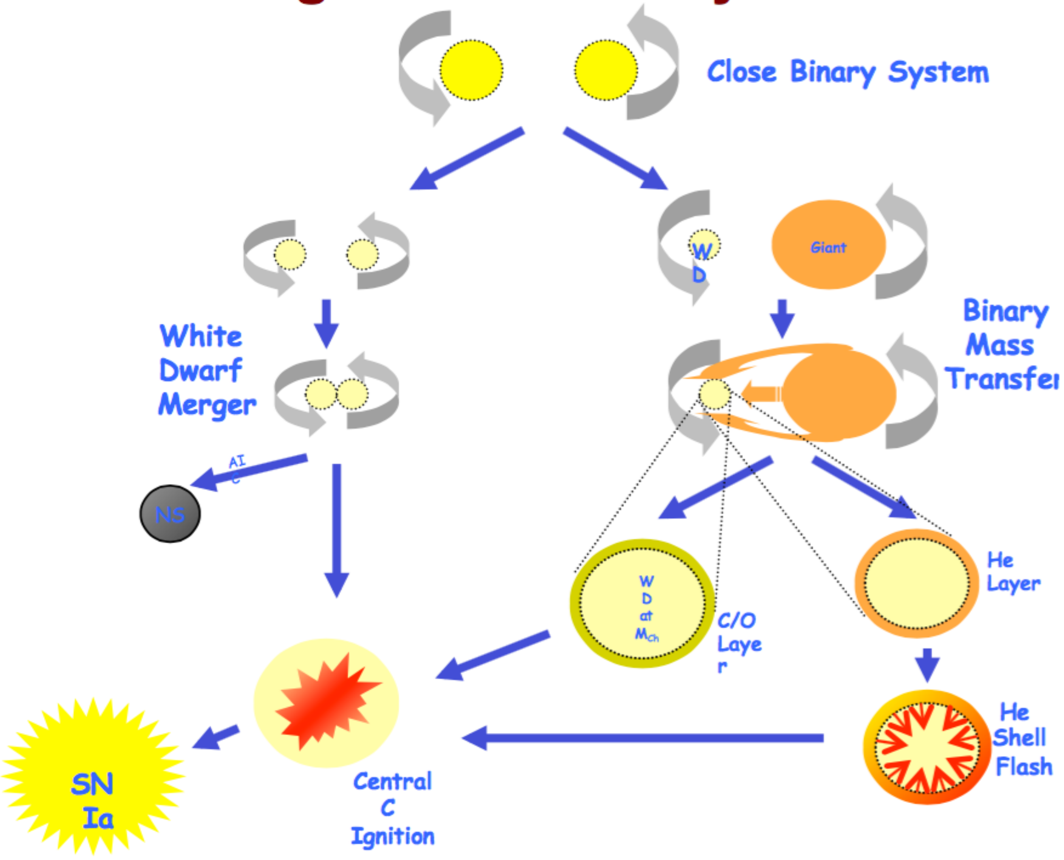
  this explains the light curves (temporal evolution of photometry)
- produces velocities ~ 0.1c
- Lack H/He, show strong intermediate mass and iron peak elements
- They occur in all types of galaxies

…and what we don't:

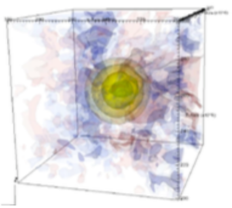
- Evolution with redshift
- Asphericities

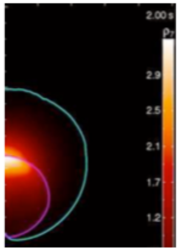
- # SNIa Diversity

☞ Progenitor Diversity?



☆ Ignition Physics?





Nucleosynthesis

Modeling the SNe Ia

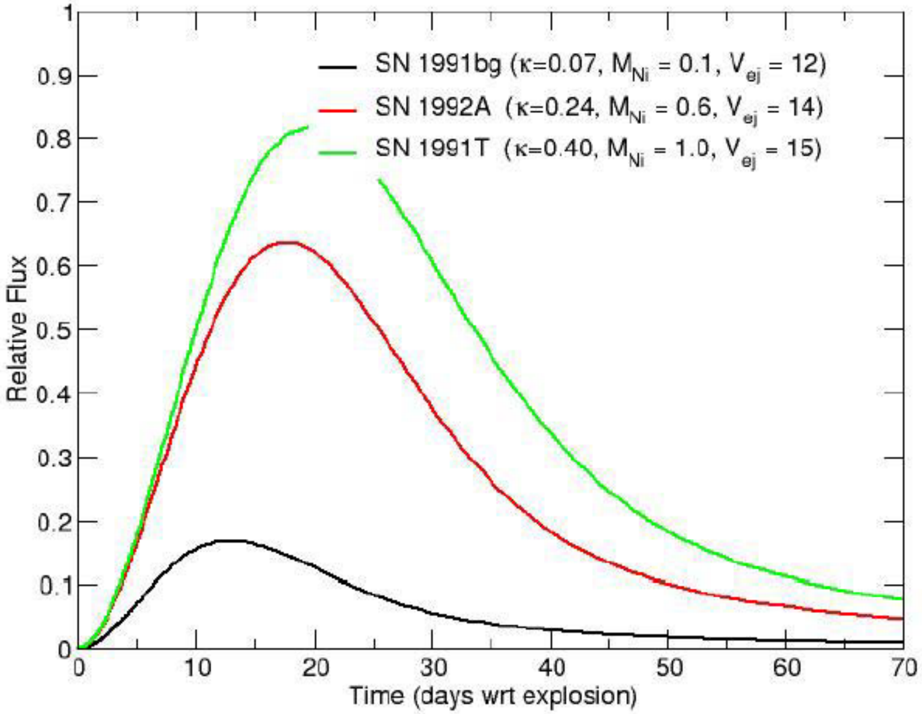
Simple relationship: More ^{56}Ni → Higher Temperatures → Higher Opacities

= Brighter/Broader SNe Ia

The higher opacities allow to trap the radiation more effectively and release it later making for broader light curves.

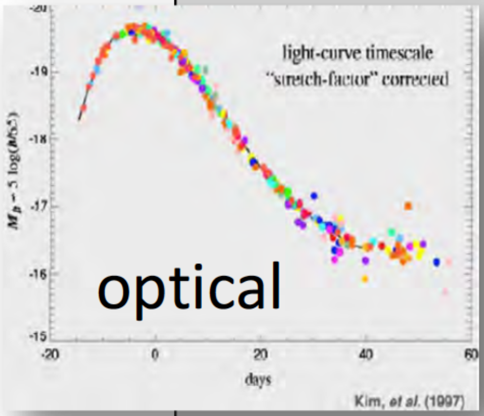
Parameters for modelling SN Ia light curve:

- ^{56}Ni mass
- Opacity
- Kinetic Energy

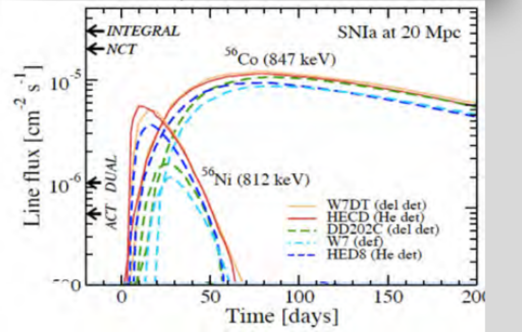


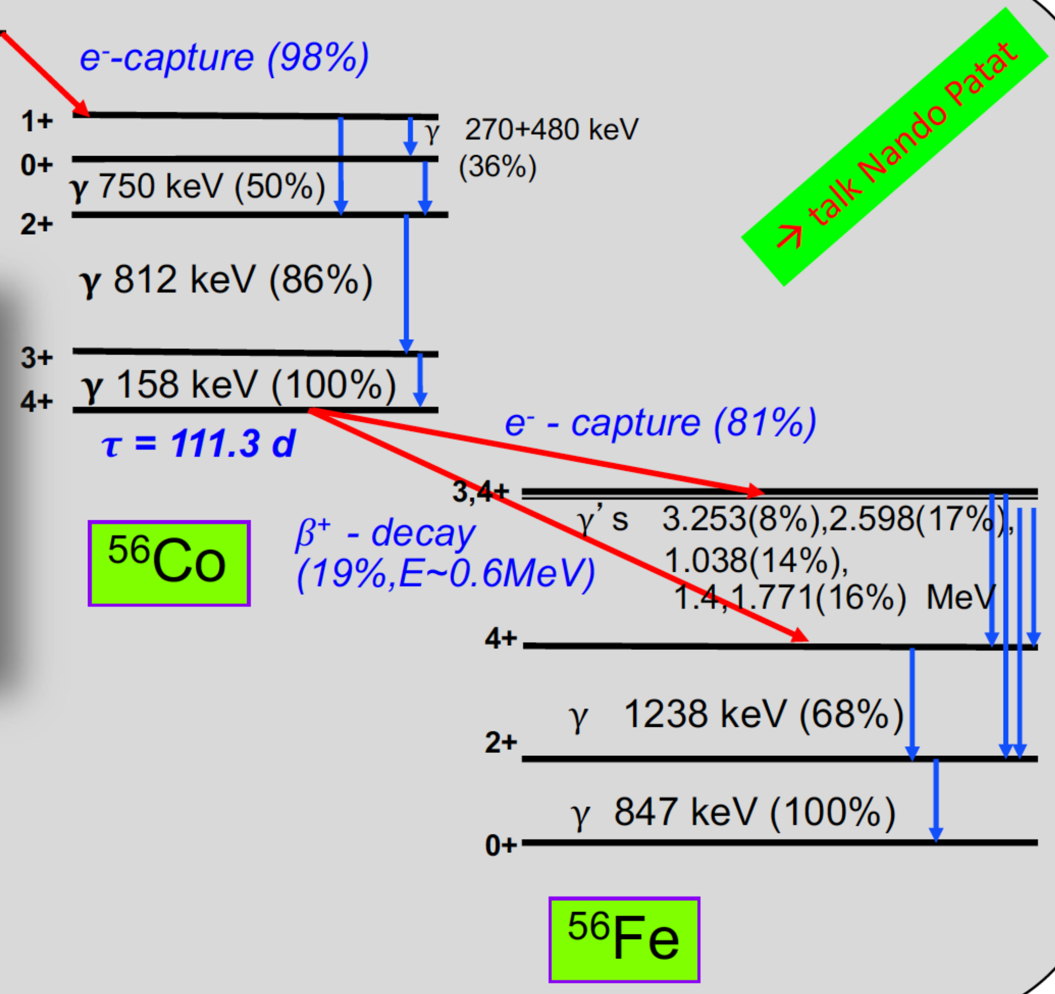
^{56}Ni padioactivity → γ-Rays, e^+ → leakage/deposit

SN Ia



optical





0+

τ =8.8 d

e^--capture (98%)

^{56}Ni

1+

0+

2+

γ 270+480 keV (36%)

γ 750 keV (50%)

γ 812 keV (86%)

3+

4+

γ 158 keV (100%)

τ = 111.3 d

e^- - capture (81%)

β^+ - decay (19%,E~0.6MeV)

^{56}Co

3,4+

γ's 3.253(8%),2.598(17%), 1.038(14%), 1.4,1.771(16%) MeV

4+

γ 1238 keV (68%)

2+

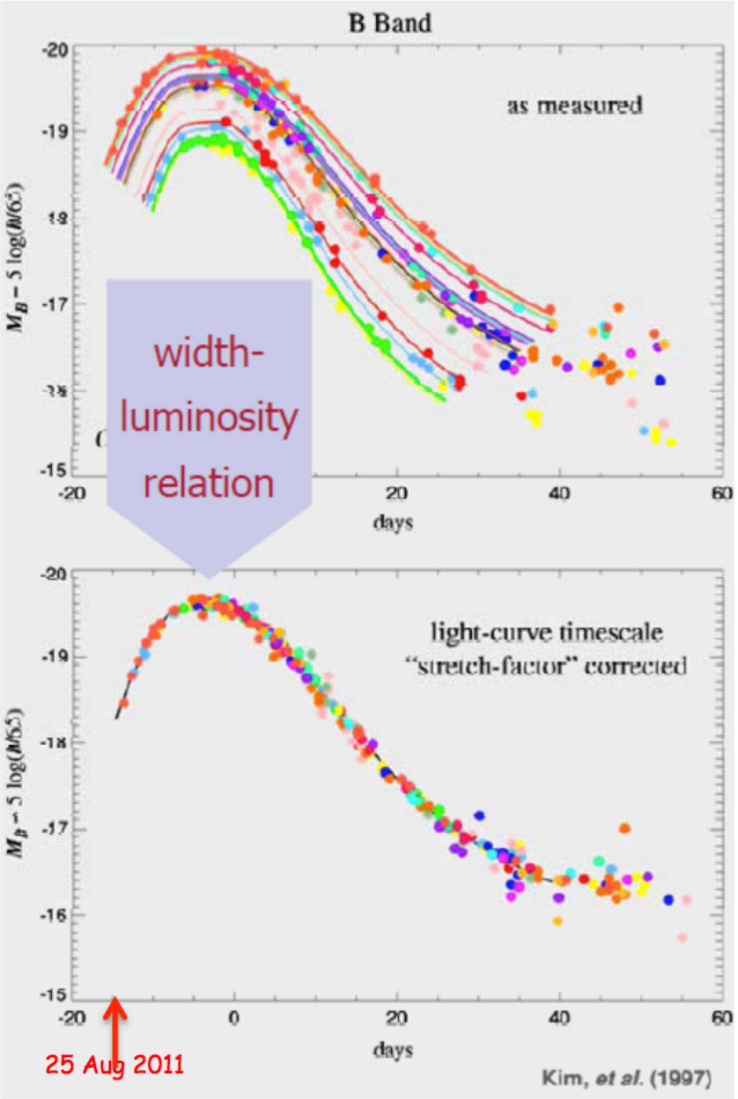
γ 847 keV (100%)

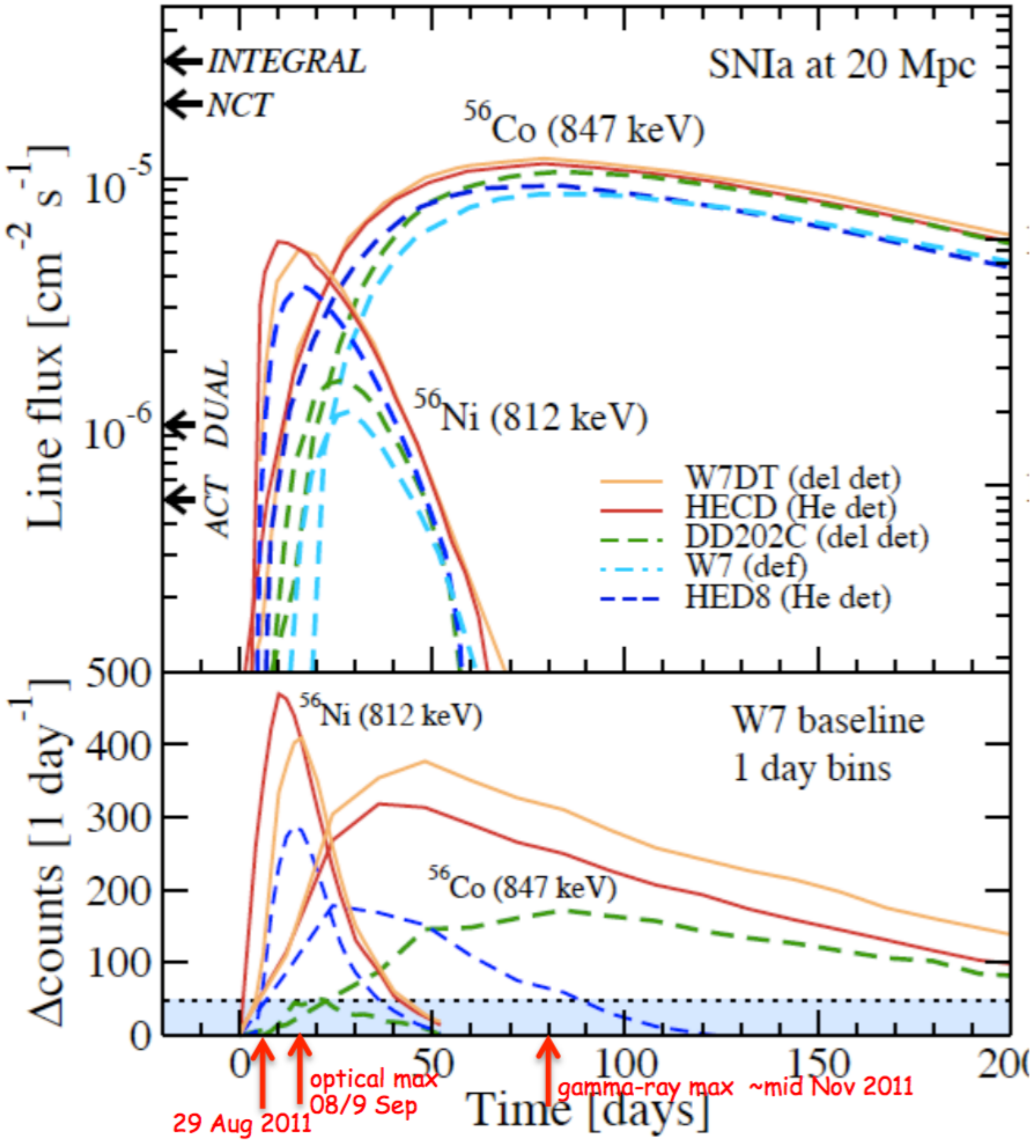
0+

^{56}Fe

→ talk Nando Patat

SNIa Models and Radioacivity Gamma-Rays

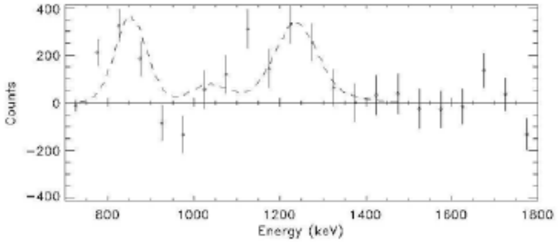




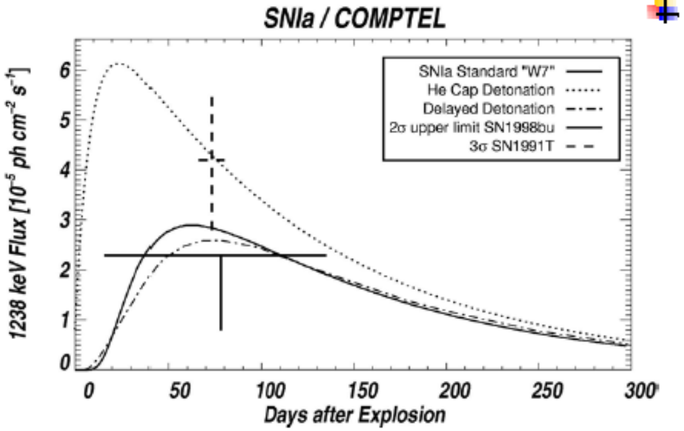
- **SN 2011fe in M101 is a Chance to Gamma-Calibrate SNIa Models** (d~6.4 Mpc)
  - ☆ **Phillips Relation, Light Transport Codes from Gamma to X/UV/OPT/IR**

Nucleosynthesis

Gamma-Rays from Supernovae Ia



- Rarely SNIa ^{56}Ni Decay Gamma-Rays are Above Instrumental Limits (~10^{-5} ph cm^{-2} s^{-1})
  - ~2 Events / 9 Years CGRO
  - ~1 Event / Year INTEGRAL Mission?

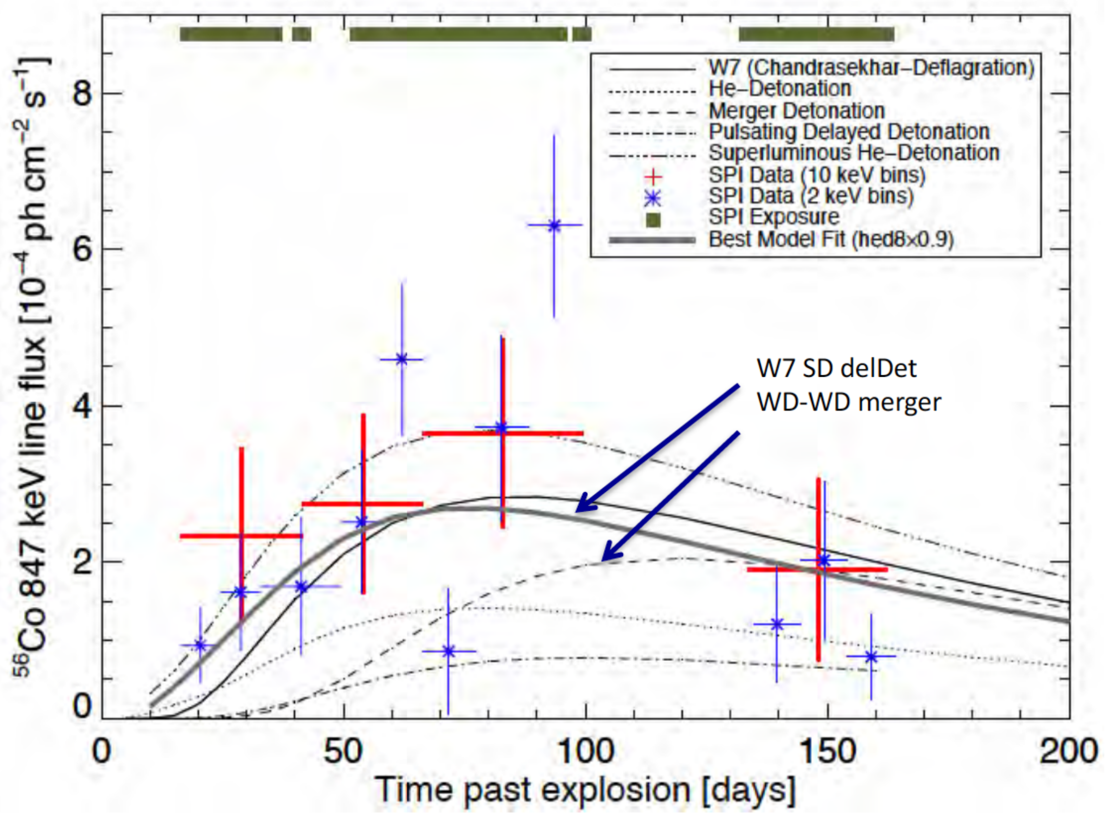


- COMPTEL
  - ☞ Signal from SN1991T (3σ) (13 Mpc)
  - ☞ Upper Limit for SN1998bu (11 Mpc)

- ☆ The ^{56}Ni Power Source: 0.5 M_o of ^{56}Ni ??
- ☆ Which Burning Profile and Mixing ?

SN2014J data Jan – Jun 2014: 847 keV ^{56}Co line

- ☆ Track emergence of gamma rays i.e. fading energy deposit



→ Calibration of optical emission against ^{56}Ni amount!

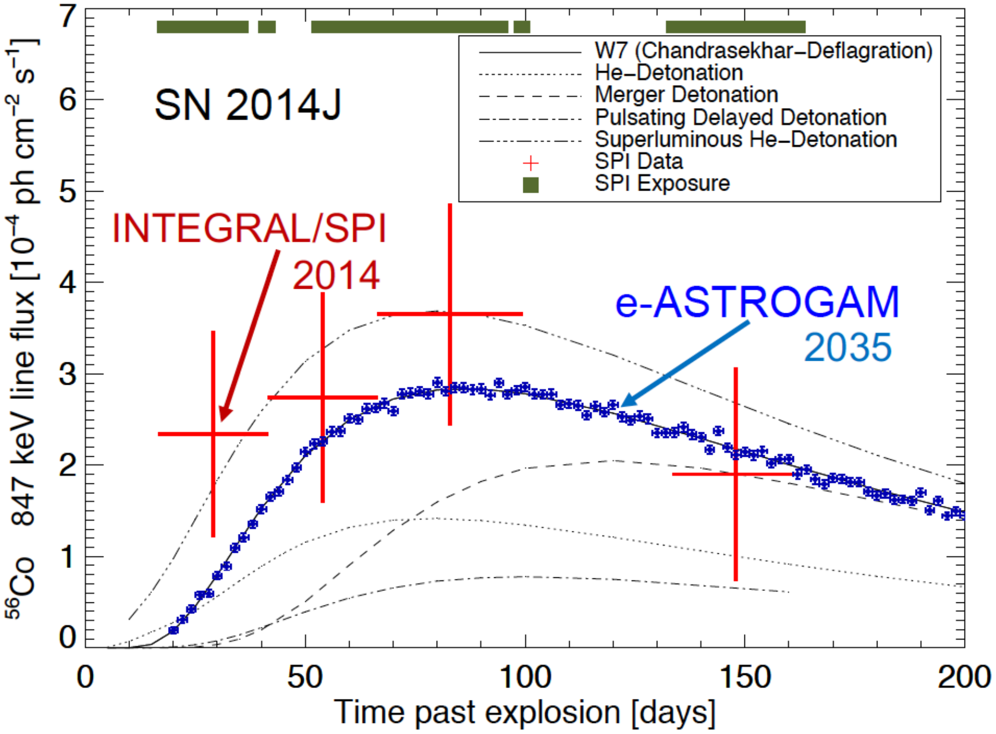
- ☆ ^{56}Ni mass (fitted): 0.49 +/-0.09 $M_{\odot}$

(cmp from empirical law) → 0.42 +/-0.05 $M_{\odot}$

(from models) → 0.5 +/-0.3 $M_{\odot}$

If we had a new gamma-ray telescope mission...

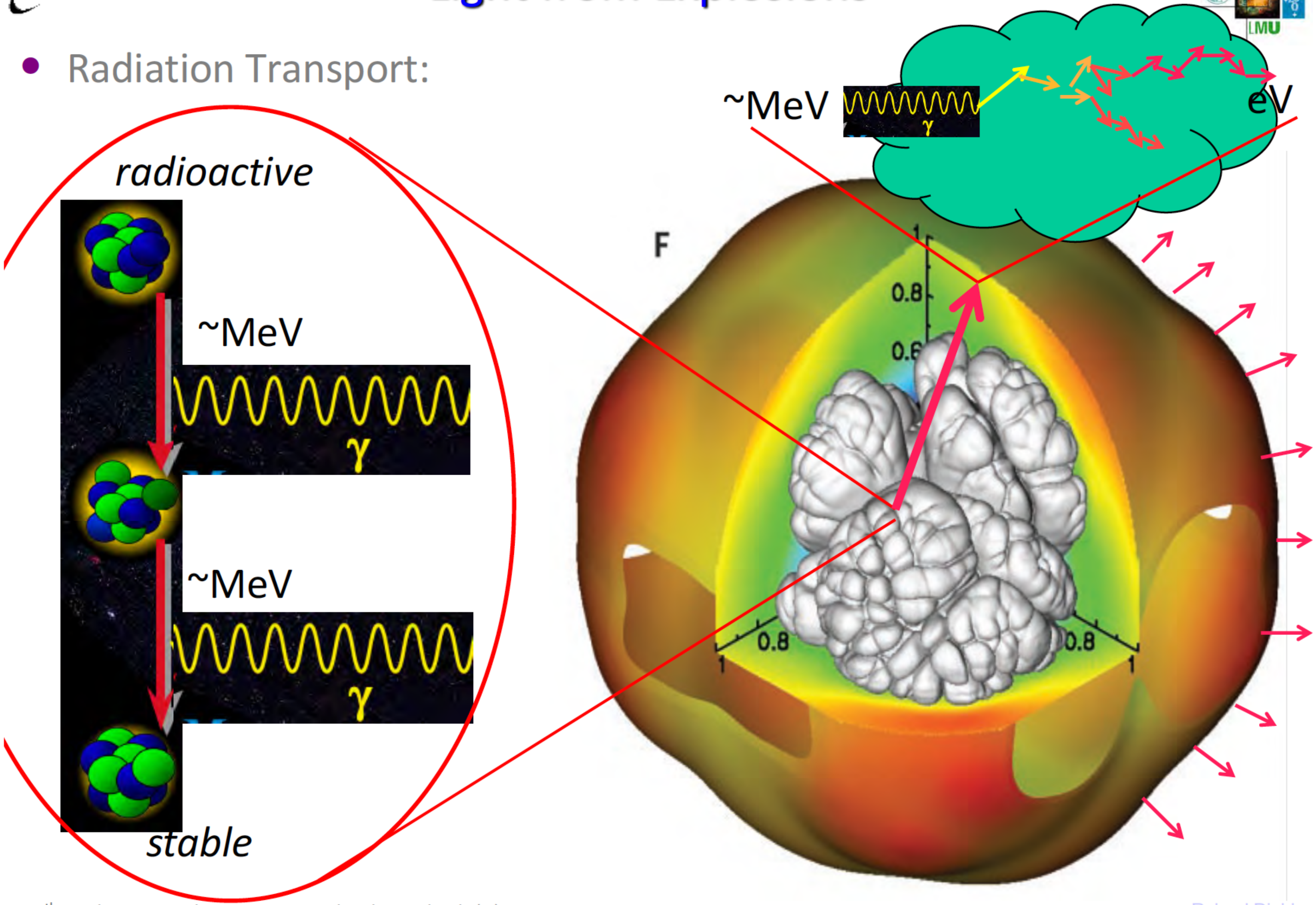
...we would have THIS:


INTEGRAL/SPI 2014

e-ASTROGAM 2035

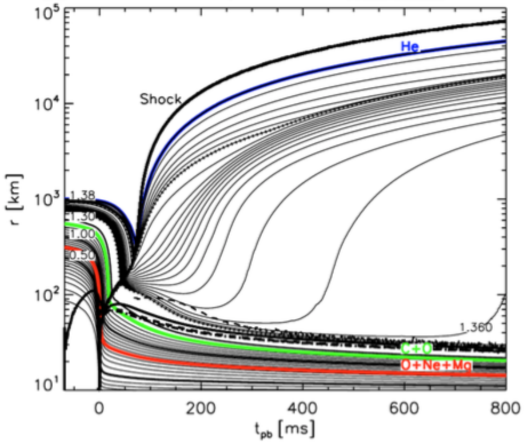
Light from Explosions

- Radiation Transport:



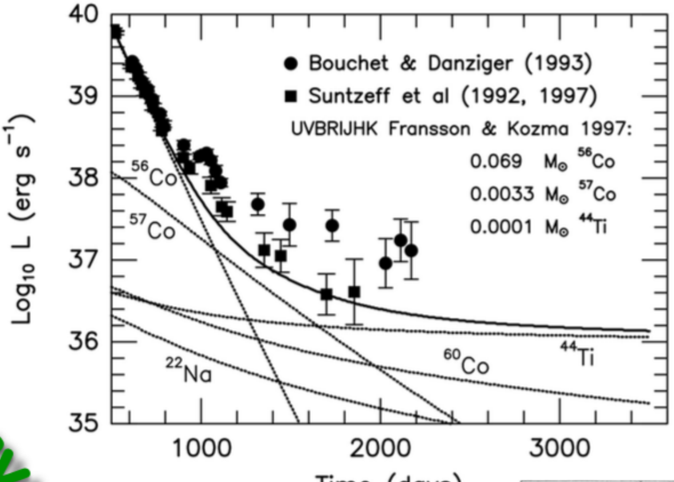
Aspects of a Core-Collapse Supernova

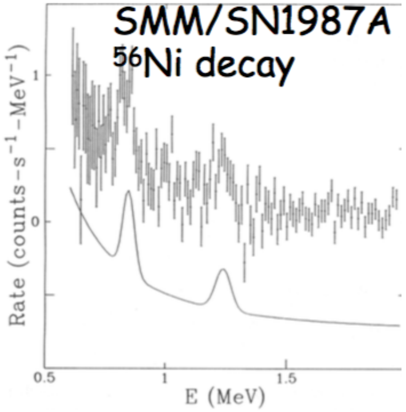
- **Nuclear Energy Conversions +...**
  - ☆ **Dynamics of Explosions**
  - ☆ **Structure of Stars**

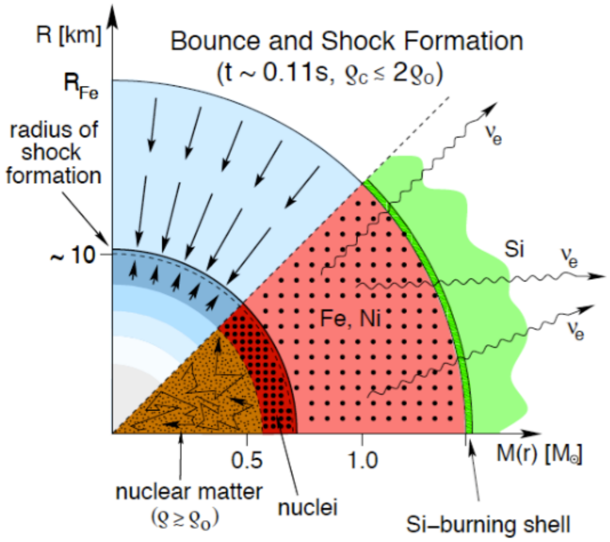


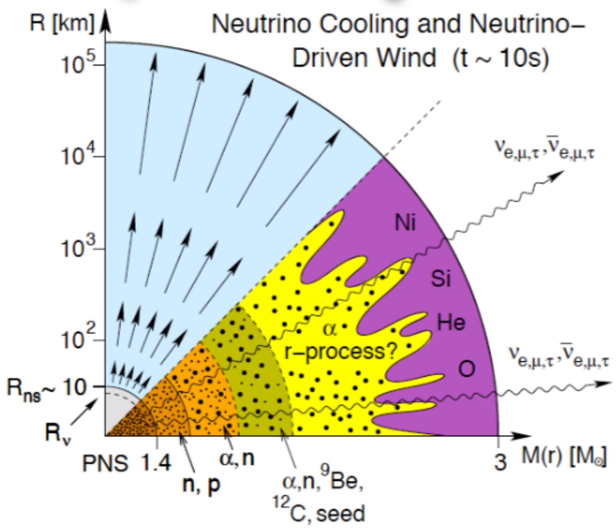
Models

Observations

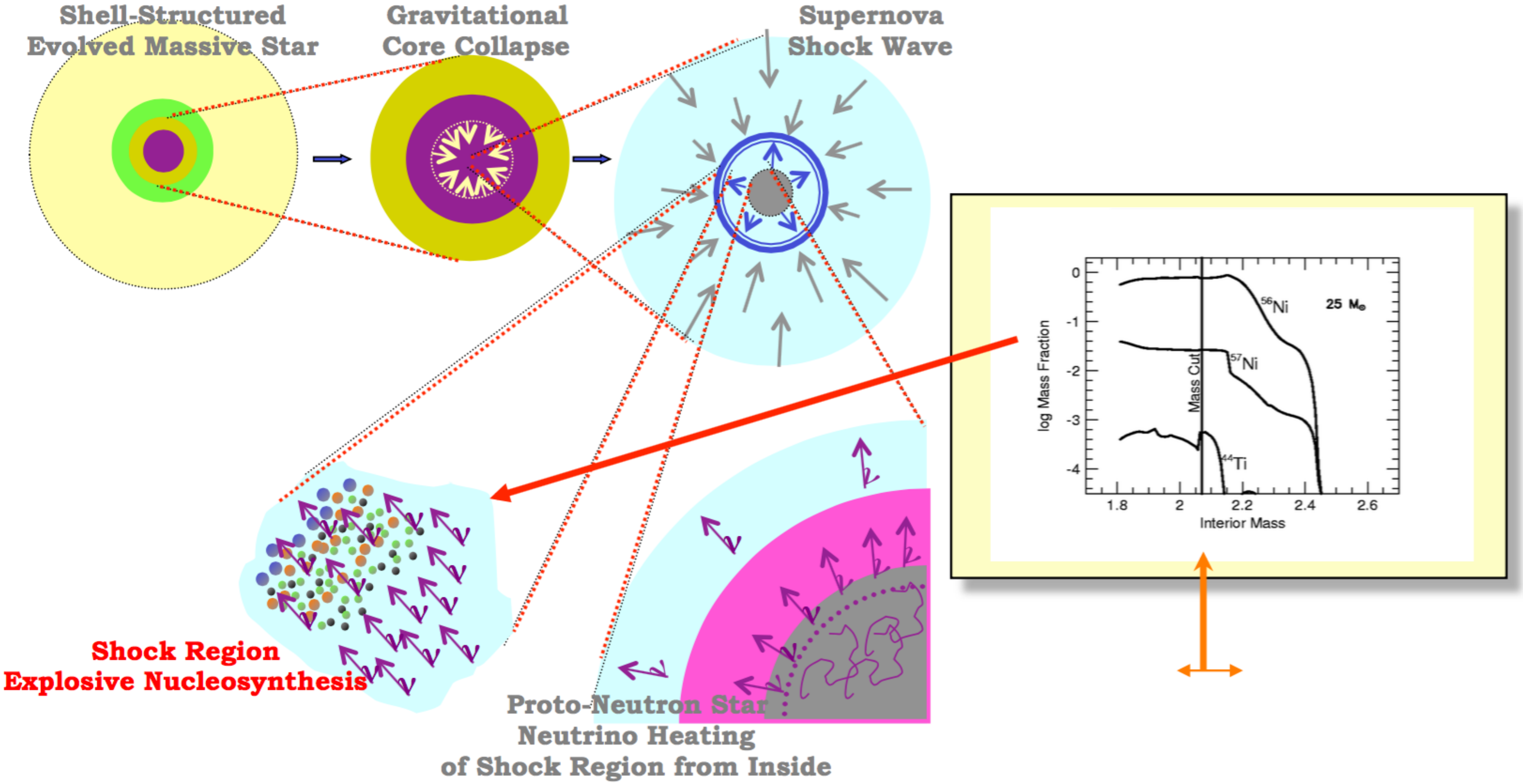








Nucleosynthesis in CC-Supernova Models and ^{44}Ti



Shell-Structured Evolved Massive Star

Gravitational Core Collapse

Supernova Shock Wave

Shock Region Explosive Nucleosynthesis

Proto-Neutron Star Neutrino Heating of Shock Region from Inside

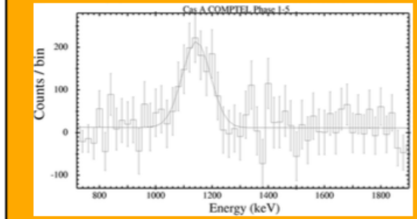
- ^{44}Ti Produced at r < 10^3 km from α-rich Freeze-Out,

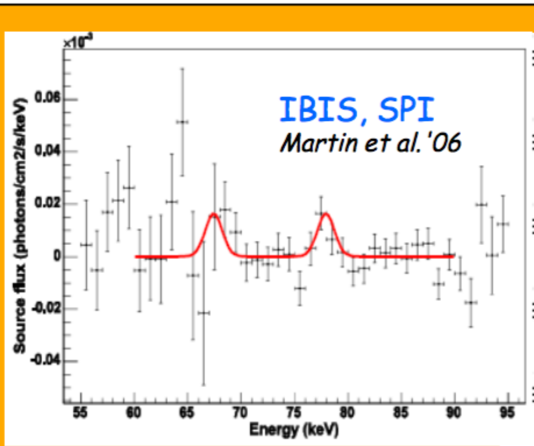
  => Unique Probe (+Ni Isotopes)

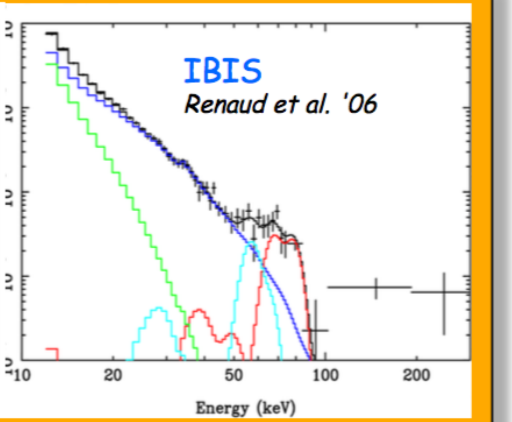
^{44}Ti γ-rays from Cas A

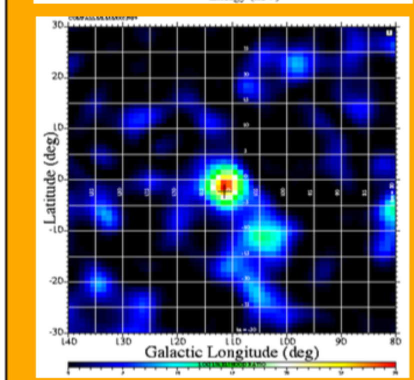
τ=85y (Ahmad et al. 2006)

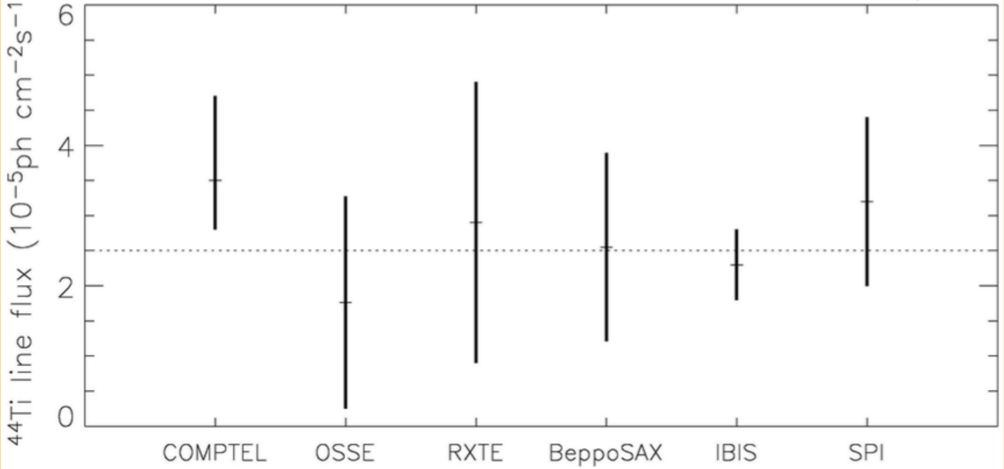
89 y	**$^{44}Ti \rightarrow {}^{44}Sc^* \rightarrow {}^{44}Ca^* + e^+$**	**78, 68; 1157**

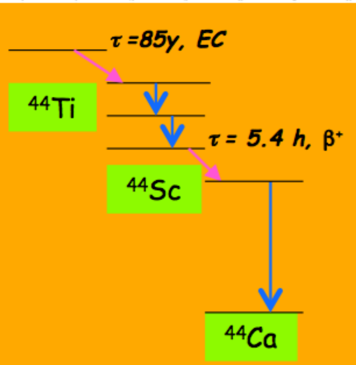


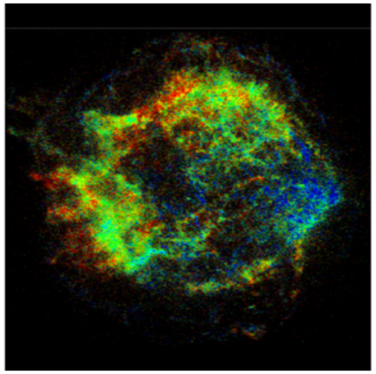


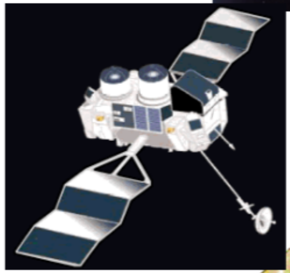


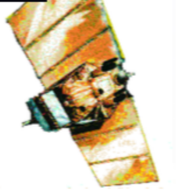


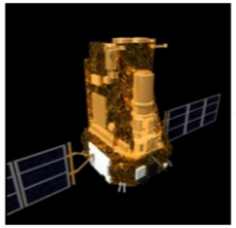






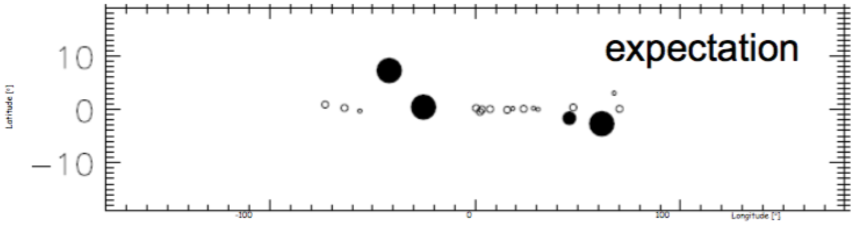




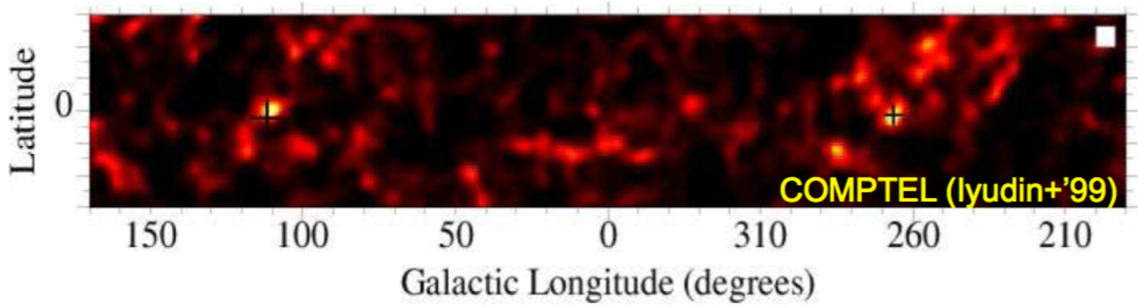


^{44}Ti Ejected Mass ~0.8-2.5 10^{-4} $M_\odot$

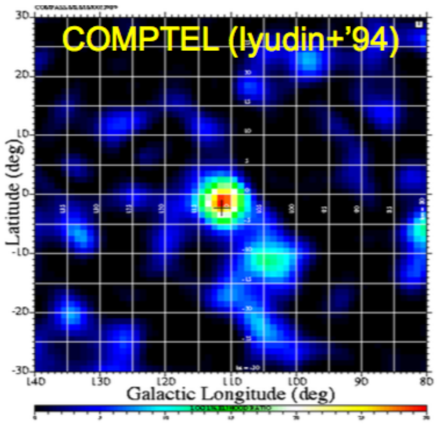
Are Core Collapse Supernovae ^{44}Ti Sources?

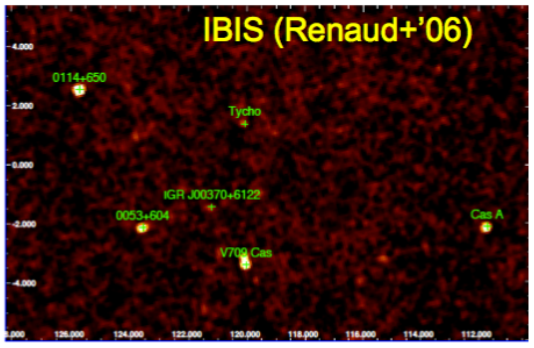


- ☆ Sky Regions with Most Massive Stars are ^{44}Ti Source-Free (COMPTEL, INTEGRAL)



- ☆ Cas A is the ONLY Source Seen in our Galaxy



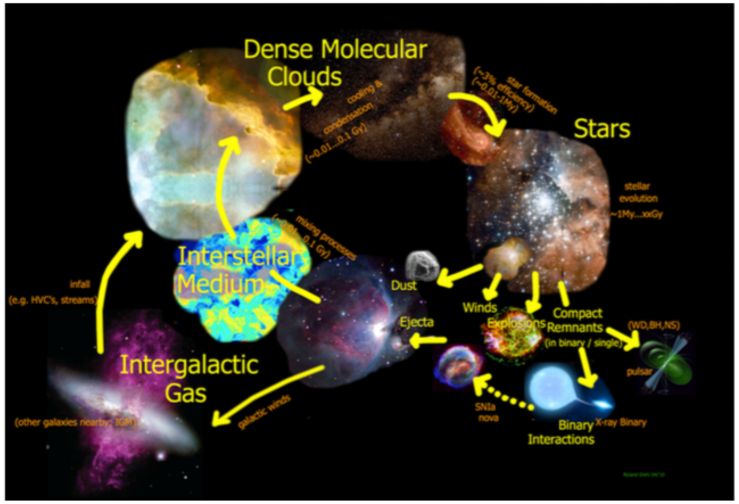


- ☆ ***^{44}Ti is from Rare Events??***

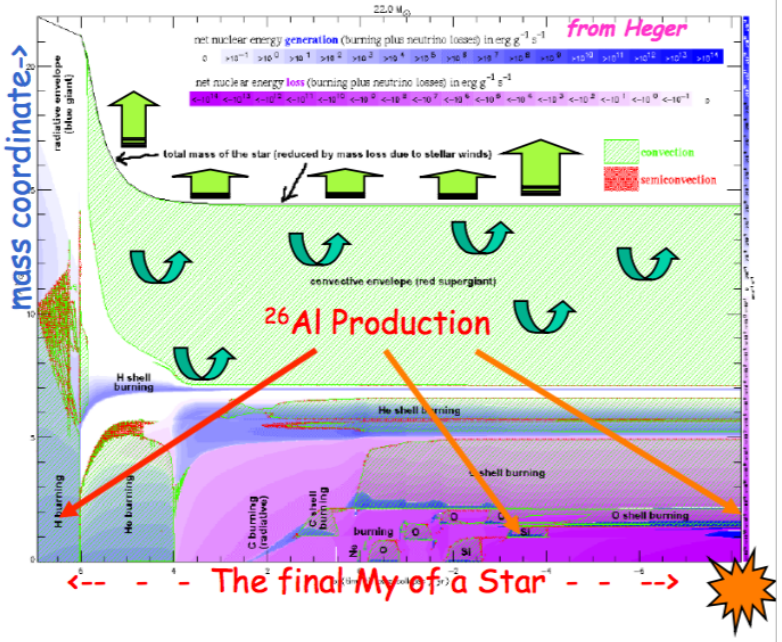
⇨ *The et al. 2006*

Massive-Star Interiors

- ☆ **Massive Stars are:**
  - ☞ **Key Producers of Cosmic 'Metals'**
  - ☞ **Key Agents for Cosmic Evolution in Galaxies**



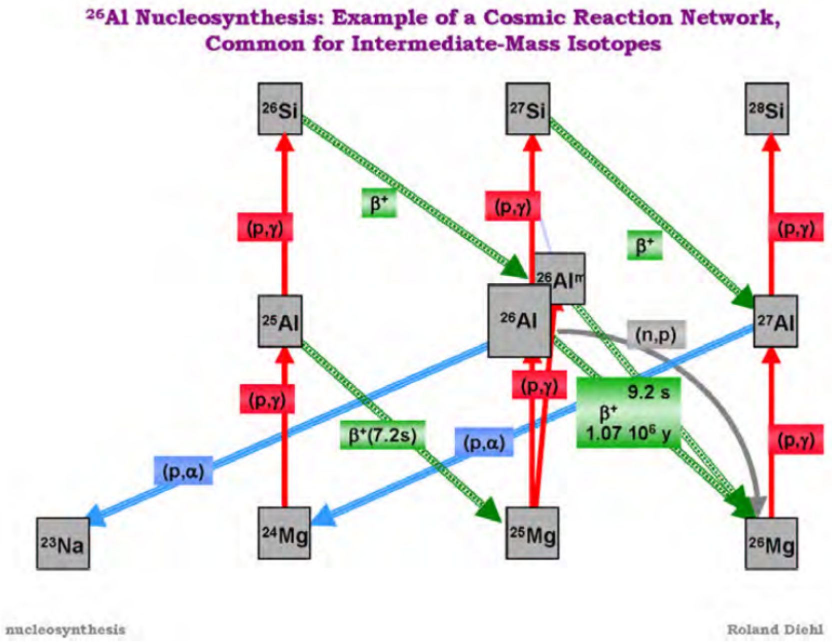
- ☆ **How does the Interior Structure Evolve in Late Stages?**
  - ☞ **Which "Shells" are Active?**
  - ☞ **Which Nuclei are Produced? (ejected?)**
  - ☞ **What are the Time Scales?**
  - ☞ **How does all this Depend on Rotation?**
  - ☞ **How does all this Depend on Metallicity?**



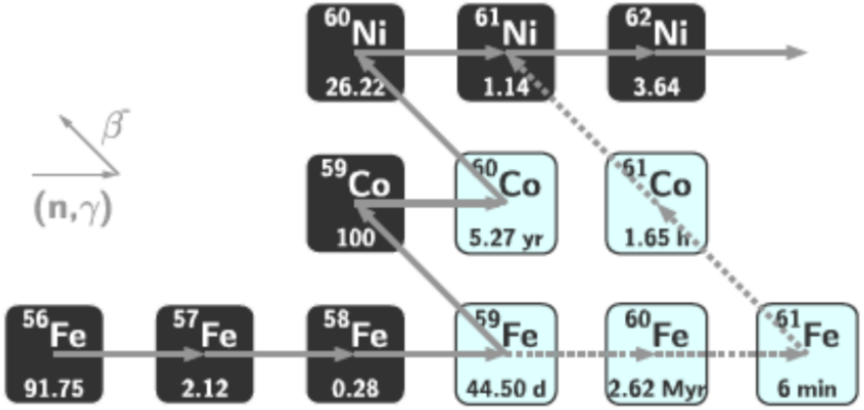
Main Sources of ^{44}Ti, ^{26}Al, ^{60}Fe

Nuclear reactions to produce ^{26}Al , ^{60}Fe

- The Na-Al-Mg cycle: p captures (H burning, +…)

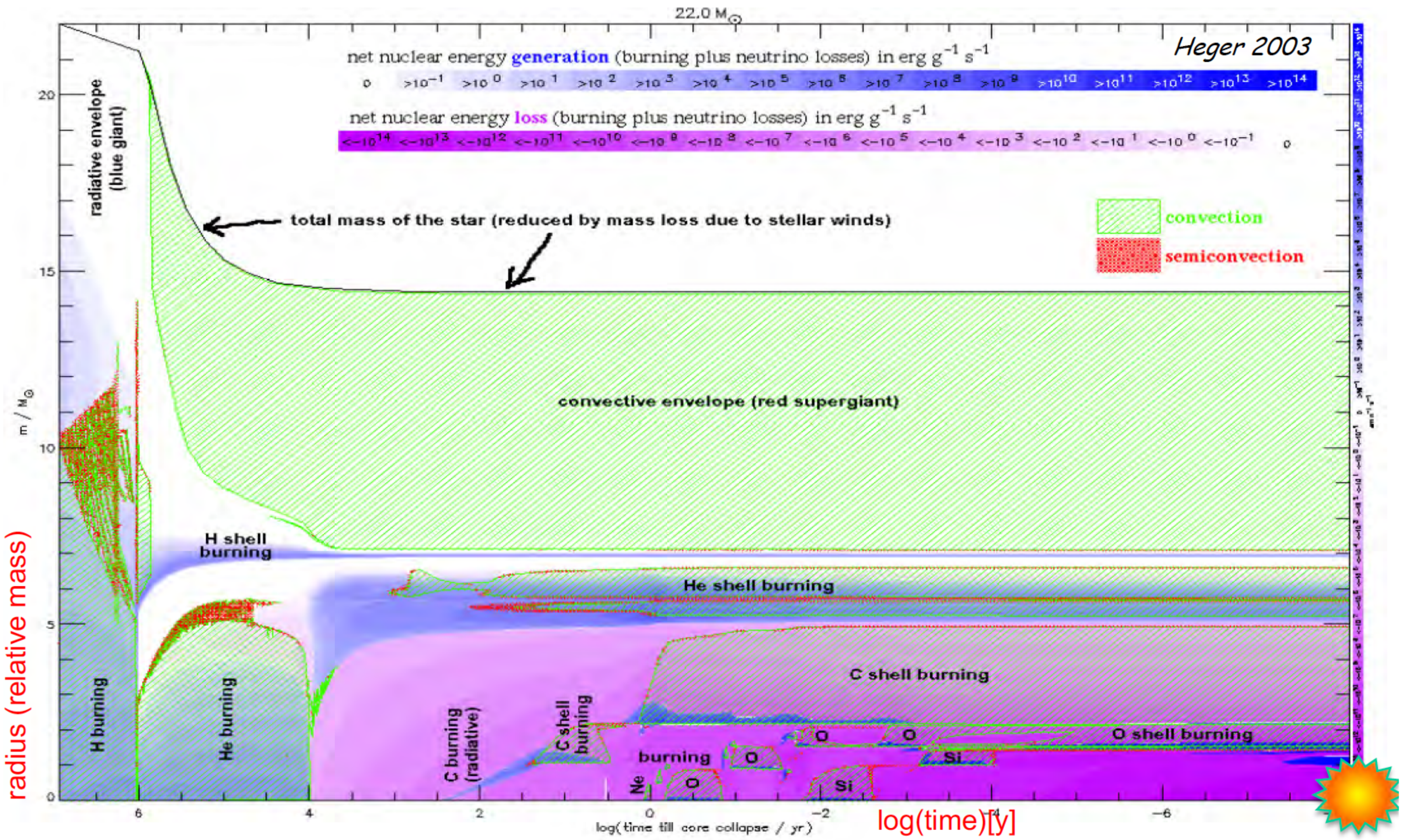


- Neutron capture on Fe in massive-star shells



Stellar Evolution

- Stars evolve into a complex interior structure

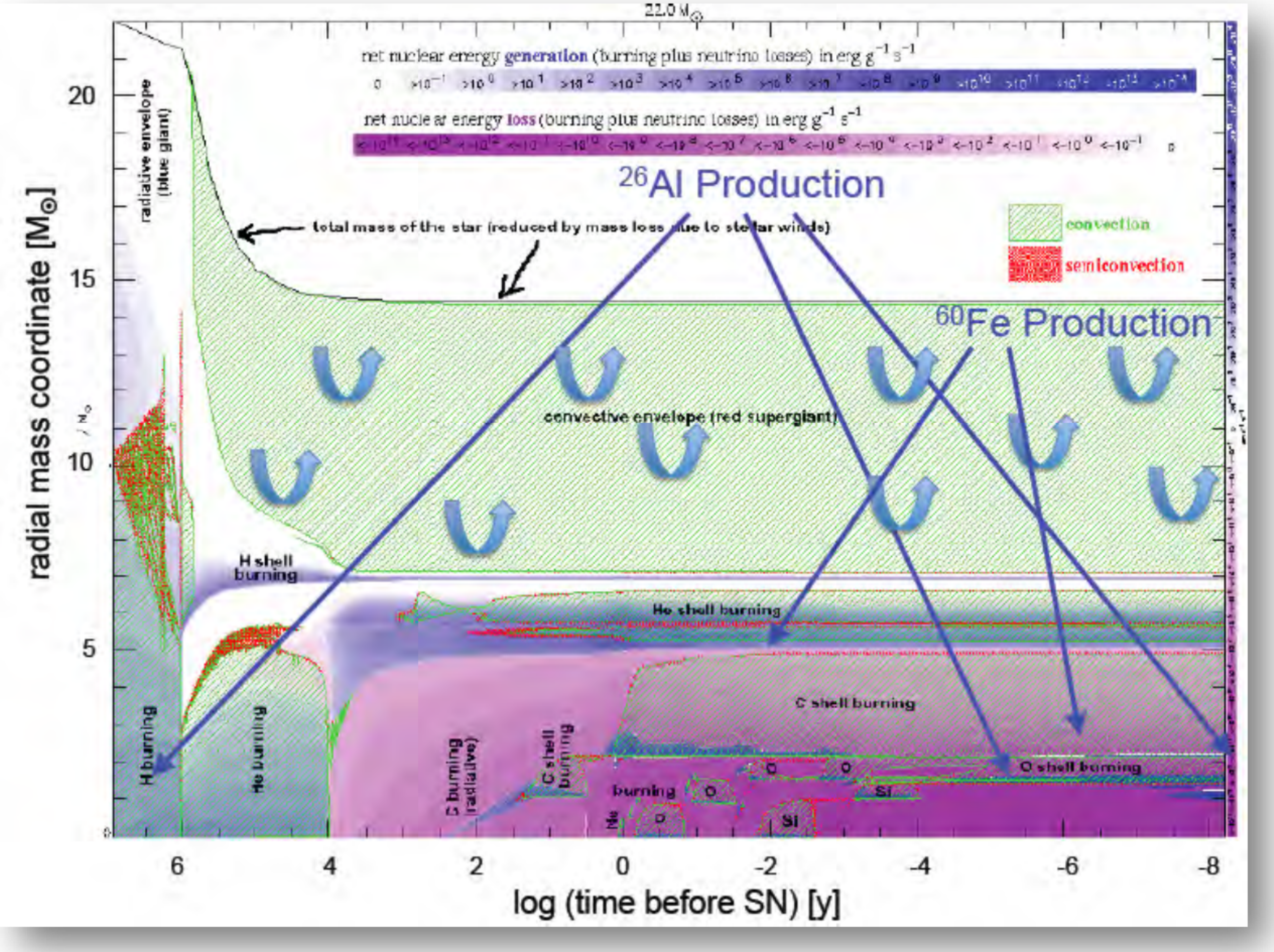


Radioactivities from massive stars: ^{60}Fe, ^{26}Al

Massive-Star Interiors

(adapted from Heger)

- *Hydrostatic fusion*
- *WR wind release*
- *Late Shell burning*
- *Explosive fusion*
- *Explosive release*



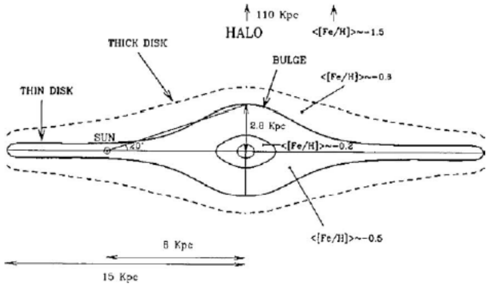
Using the ^{26}Al Line to Characterize the Galaxy's SN Activity

→ *Diehl et al., Nature 2006*
→ *Diehl et al., A&A 2010**
→ *Diehl et al., in prep. (2019)**

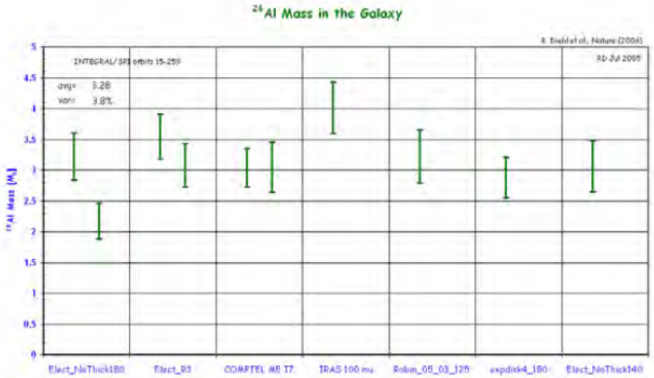
Measured Gamma-Ray Flux*

Galaxy Geometry

*) *better account for foreground emission*

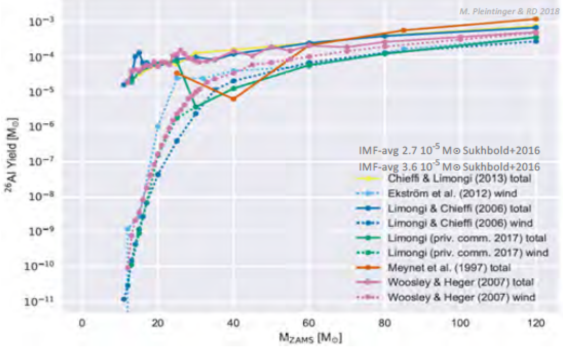


➢ ^{26}Al Mass in Galaxy = 2.0 (±0.3) $M_\odot$

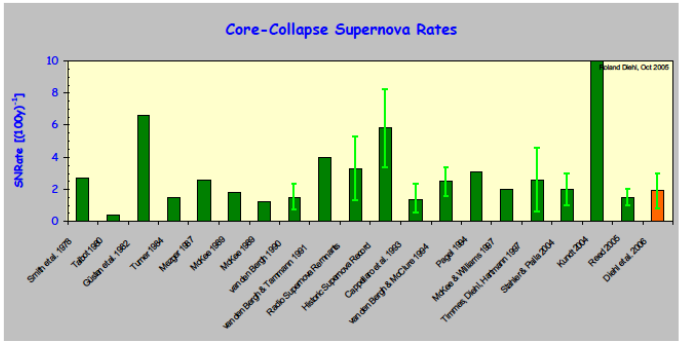


^{26}Al Yields per Star

Stellar Mass Distribution

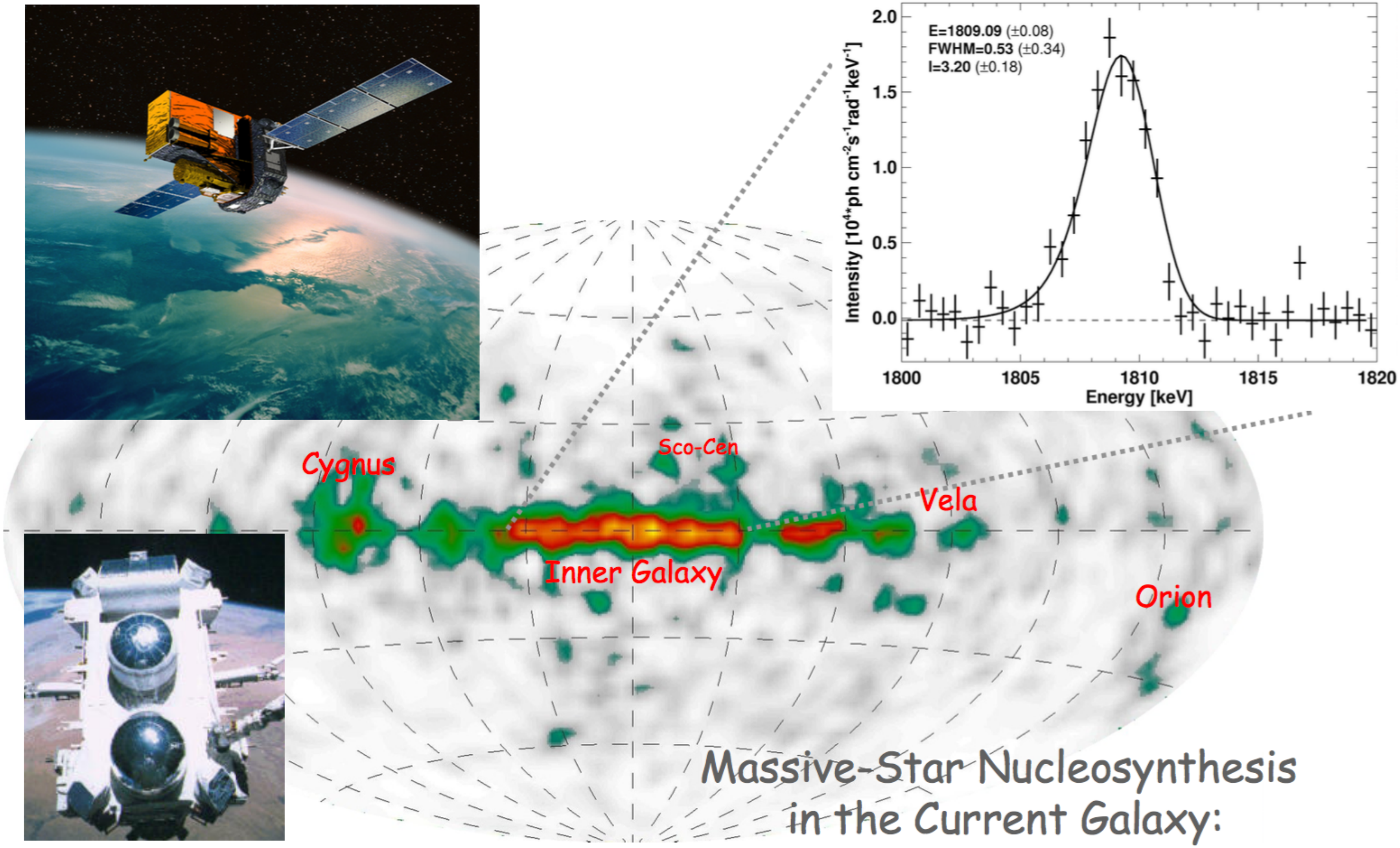


✓ cc-SN Rate = 1.3 (± 0.6) per Century



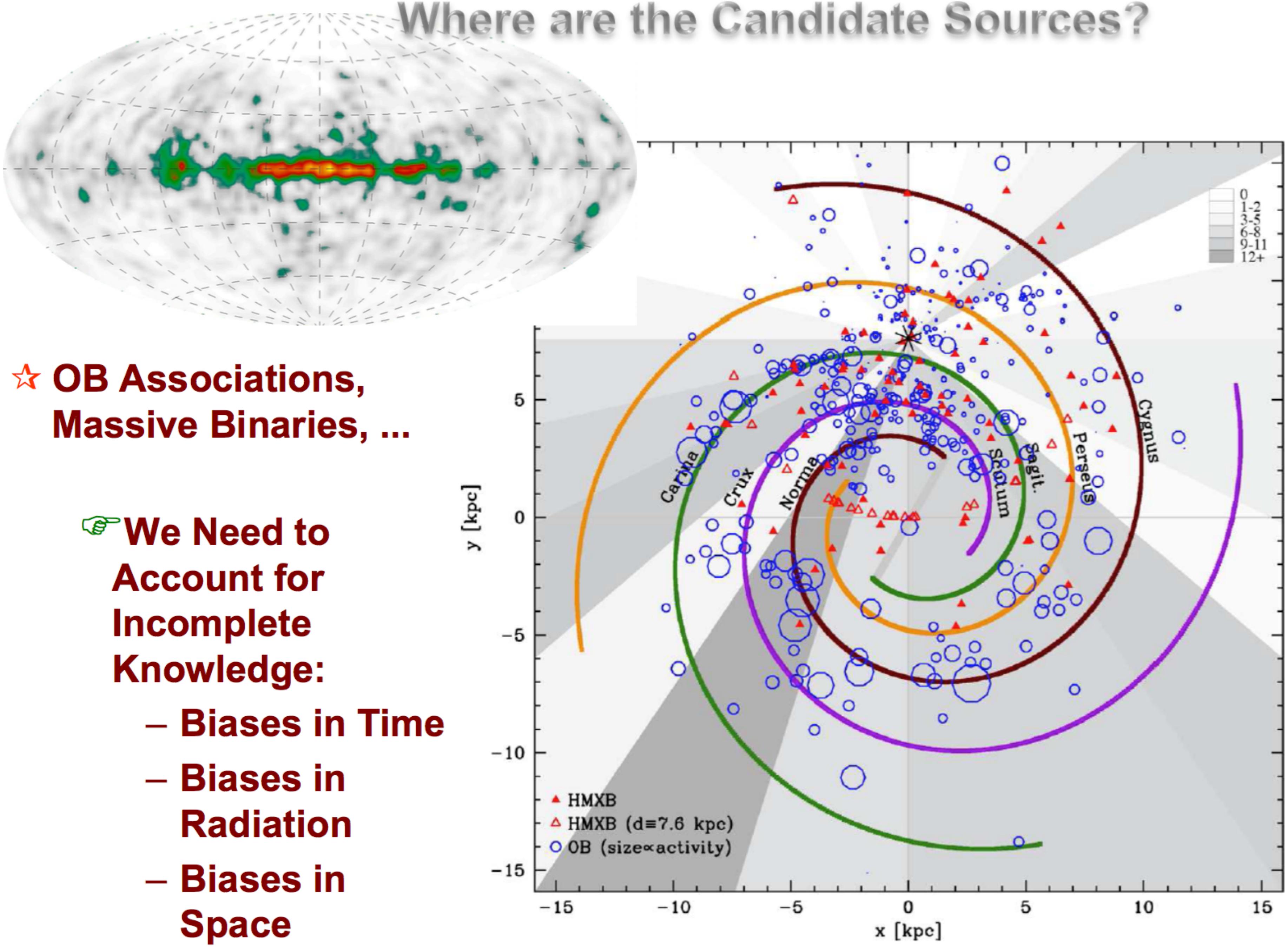
✓ Star Formation Rate = 2.8 $M_\odot$/yr

^{26}Al in our Galaxy: γ-ray Image and Spectrum



Massive-Star Nucleosynthesis
in the Current Galaxy:
Exploiting the Message from ^{26}Al γ-rays

Where are the Candidate Sources?

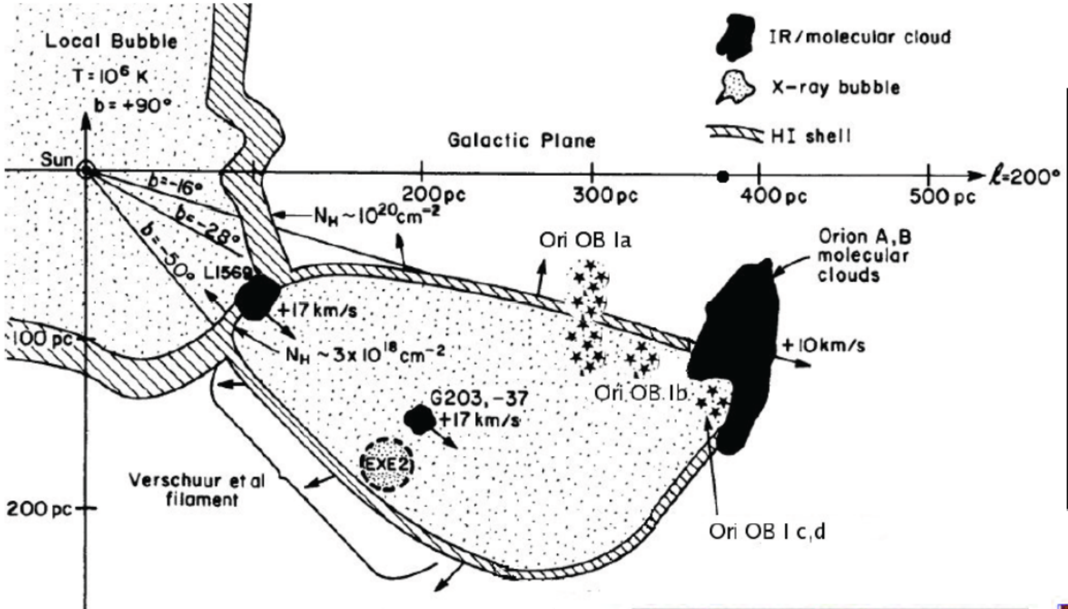


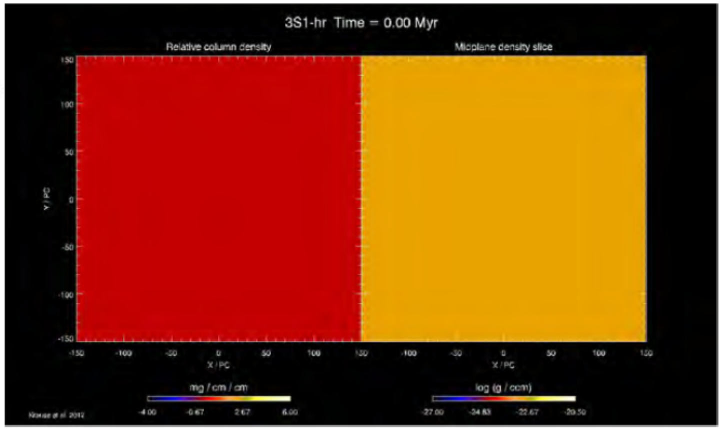
- ☆ **OB Associations, Massive Binaries, ...**
  - ☞ **We Need to Account for Incomplete Knowledge:**
    - **Biases in Time**
    - **Biases in Radiation**
    - **Biases in Space**

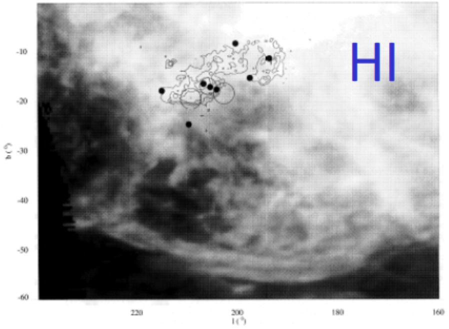
Nucleosynthesis Ejecta and the Dynamic ISM

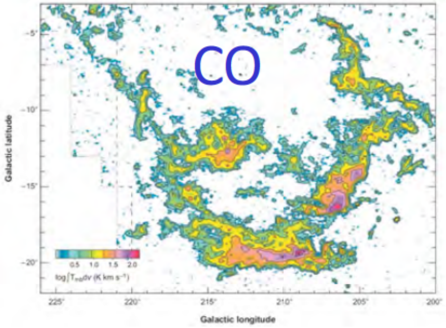
ISM is Driven by Stars and Supernovae → Ejecta in (Super-)Bubbles

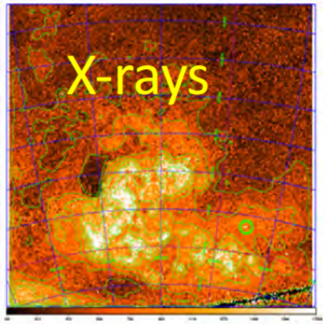
- ☆ Study Multi-Messenger Observations, also through Simulations (here: Orion Region)

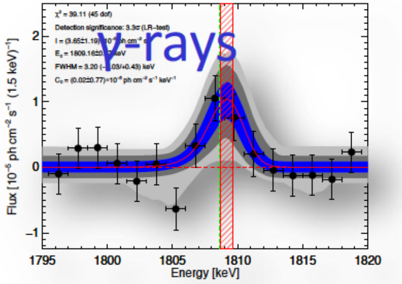






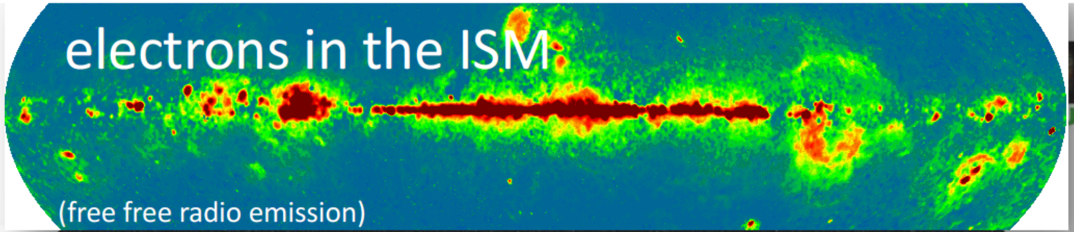






^{26}Al Radioactivity: Special Messengers

- Radioactivity provides a clock
- ^{26}Al radioactivity gamma rays trace nucleosynthesis ejecta over ~few Myrs
- Radioactive emission is independent of density, ionisation states, …



electrons in the ISM

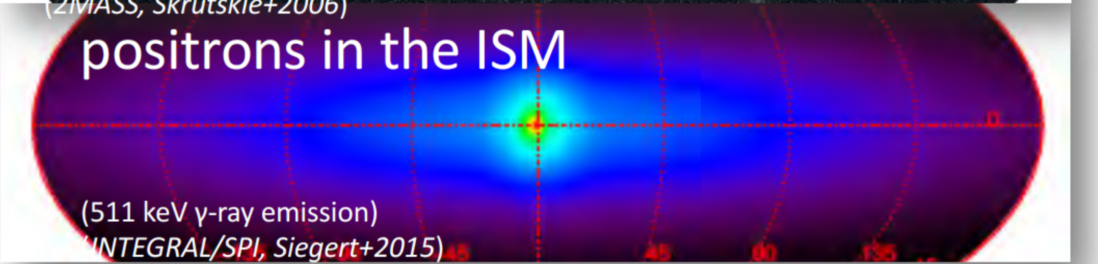
(free free radio emission)

(*WMAP, Bennett+2003*)

starlight

(2 µm IR emission)

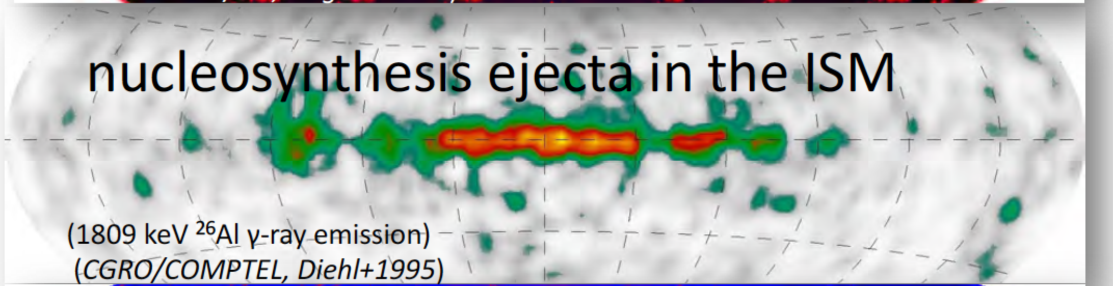
(*2MASS, Skrutskie+2006*)



positrons in the ISM

(511 keV γ-ray emission)

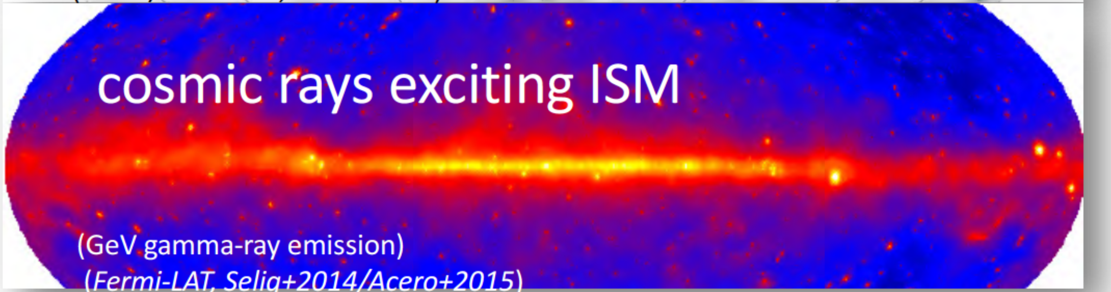
(*INTEGRAL/SPI, Siegert+2015*)



nucleosynthesis ejecta in the ISM

(1809 keV ^{26}Al γ-ray emission)

(*CGRO/COMPTEL, Diehl+1995*)

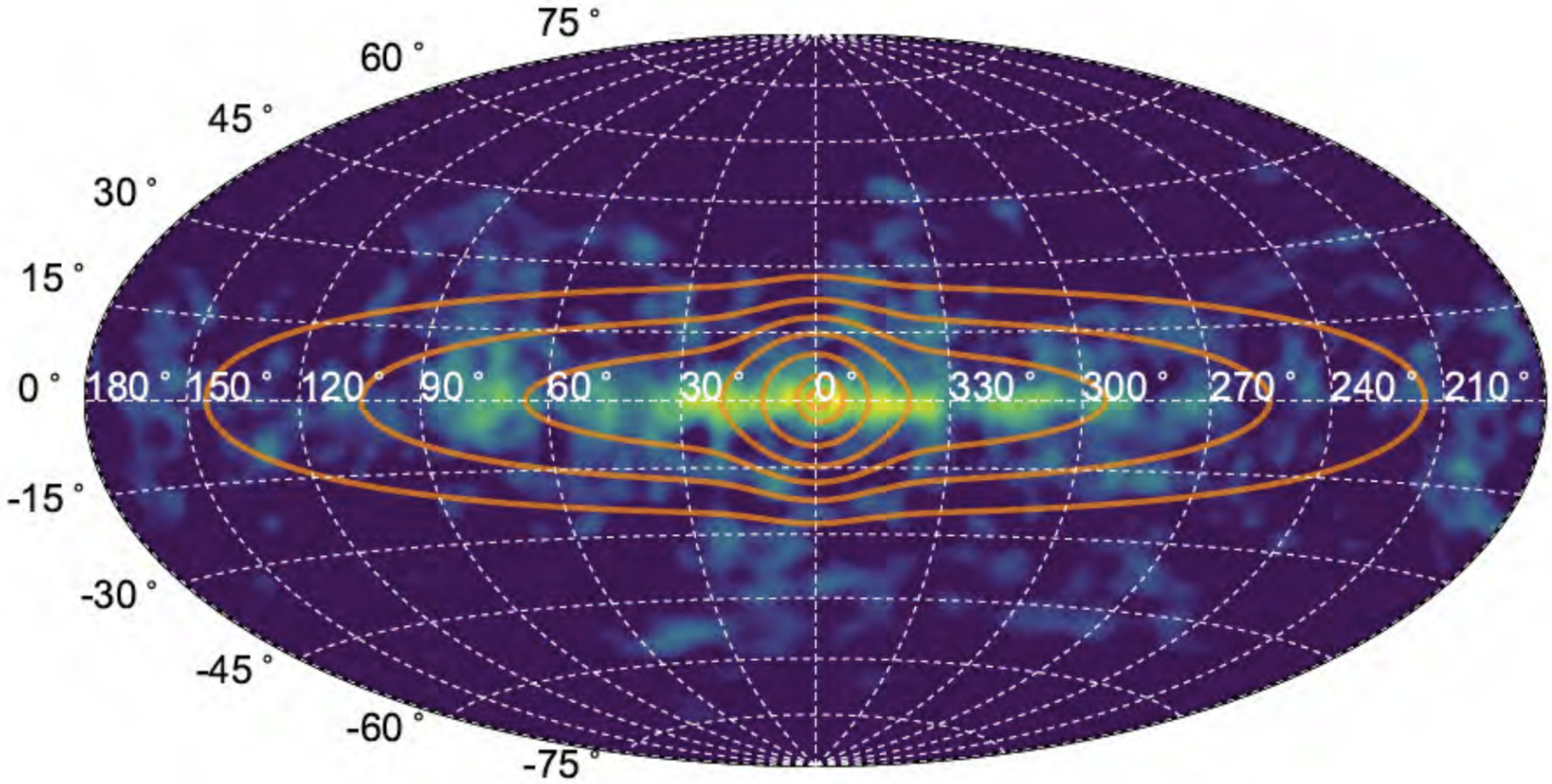


cosmic rays exciting ISM

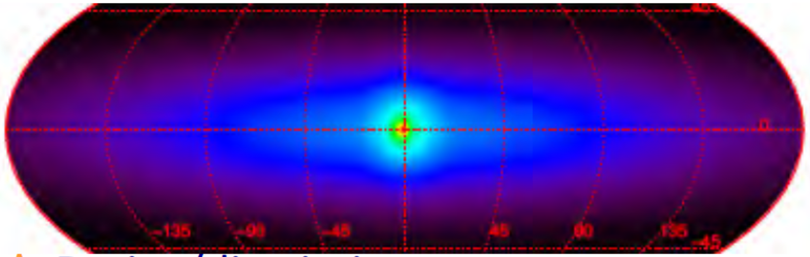
(GeV gamma-ray emission)

(*Fermi-LAT, Selig+2014/Acero+2015*)

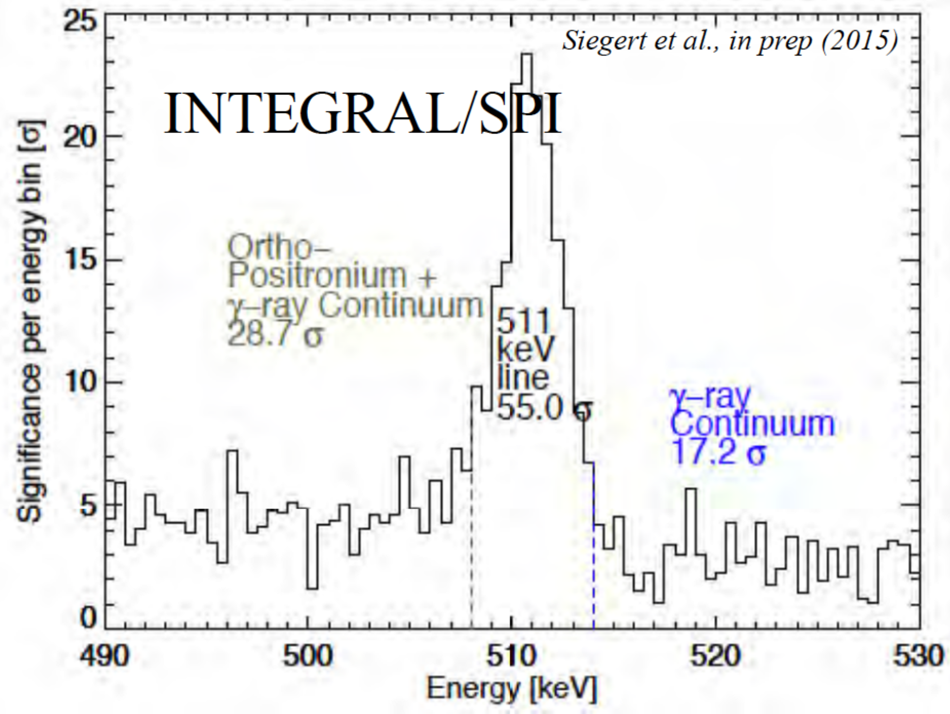
^{26}Al radioactivity versus positron annihilation

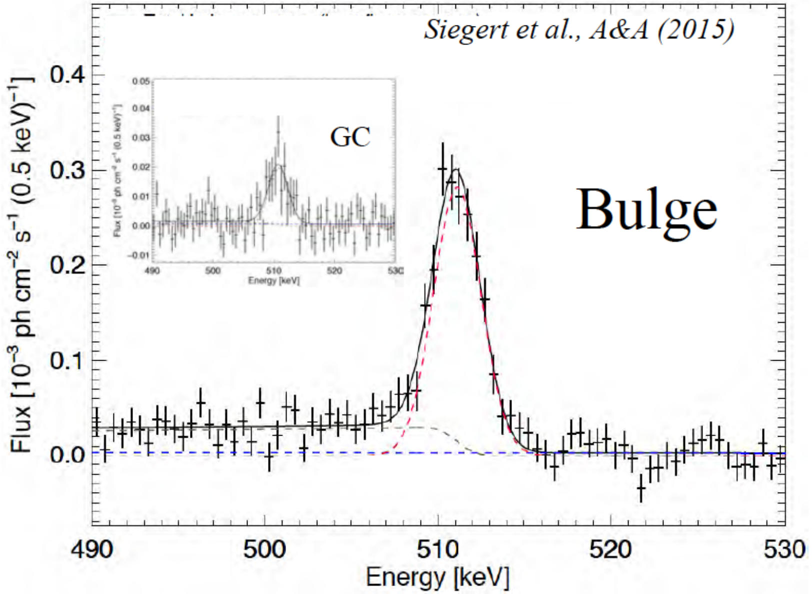


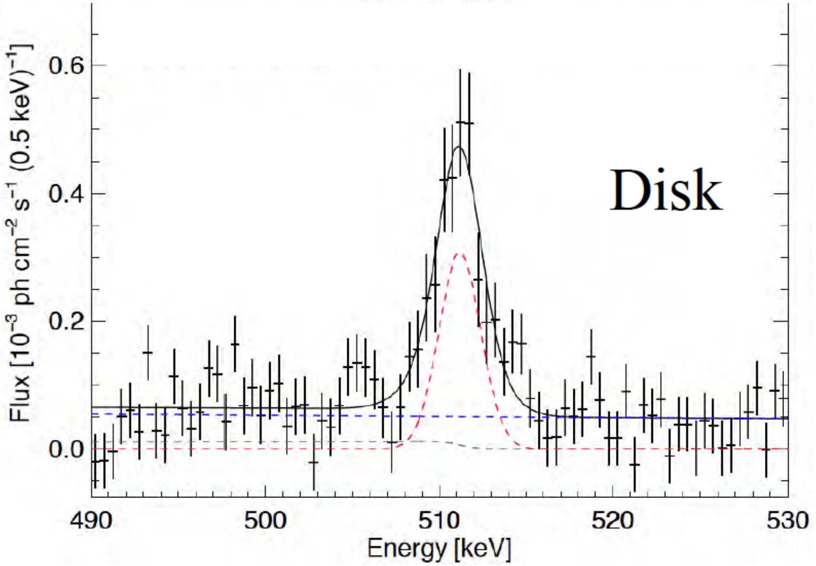
Insights from spectral details?

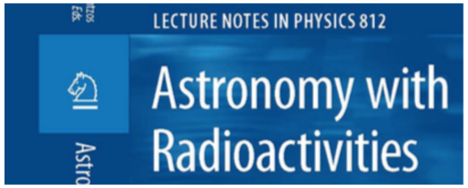


- ☆ Derive/discriminate spectra from different regions



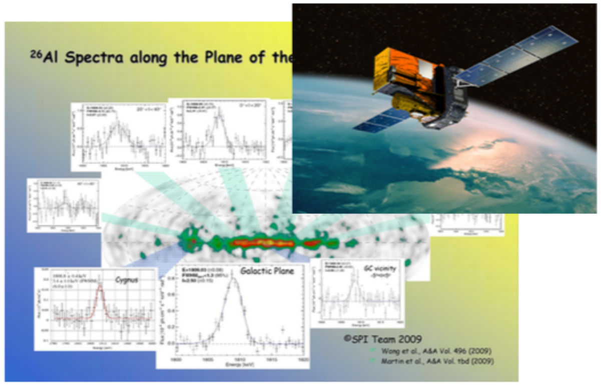




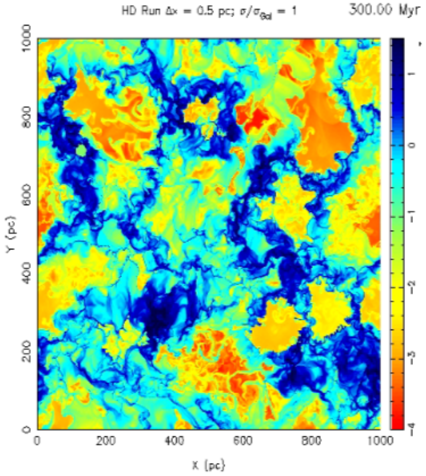


Lessons from Cosmic Radioactivities
Summary

- ☆ **Radioactivity provides a unique / different astronomical tool**
  - **Intensity change only due to radioactive decay**
  - **Thermodynamic gas state unimportant**



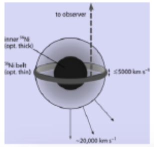
- ☆ **Supernova interiors can be explored**
  - **SNIa brightness evolution and ^{56}Ni yield calibration**
  - **Core collapse evolution into an explosion with ^{56}Ni and ^{44}Ti production**
- ☆ **Massive-star shell structure and evolution can be explored**
  - **^{26}Al production in core H burning and late shell burning**
  - **^{60}Fe production in C and He shells**

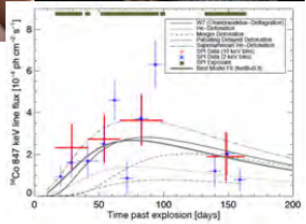


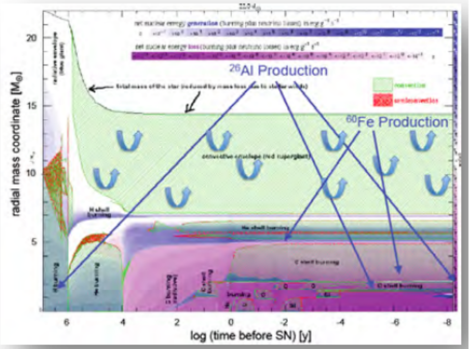
- ☆ **Chemical evolution uncertainties can be explored**
  - **ISM state and dynamics around massive-star regions**
  - **Nucleosynthesis ejecta recycling times**

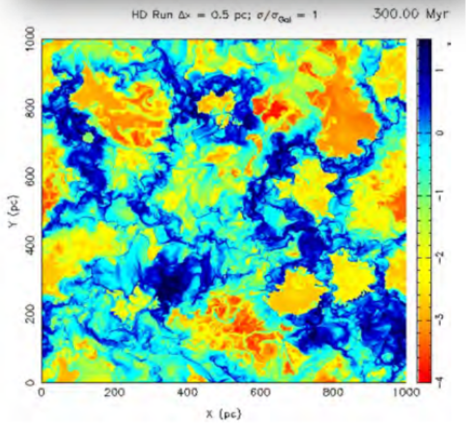
Cosmic Radioactivities **Summary**

- Radioactivity γ-rays provide a unique / different view
  - Yield constraints for SNe and Novae, Independent of complexity from unfolding of the explosion
  - Radioactivity traces diluted ejecta at late phases
- SNIa ^{56}Ni and how the explosion generates SN light
  - SN2014J reveals its ^{56}Ni,^{56}Co irregularly → 3D effects?
- ccSupernova ^{44}Ti demonstrates SN asymmetries
  - Only Some SN Eject ^{44}Ti, but then much, and clumpy
- Massive-star shell structure & evolution tests: ^{26}Al, ^{60}Fe
  - ^{26}Al as a tool: understand groups of massive stars (Mys)
  - How much ^{60}Fe from n captures in C and He shells?
- ISM in the Galaxy: Role of superbubbles; e^{+} sources
  - ^{26}Al spreads into large (super)bubbles
  - e^{+} sources are a variety & puzzle; incl μQSOs









Astrofisica Nucleare e Subnucleare

Dark Matter Searches

ISAPP

ISAPP2013 Stockholm

from 29 July 2013 to 06 August 2013

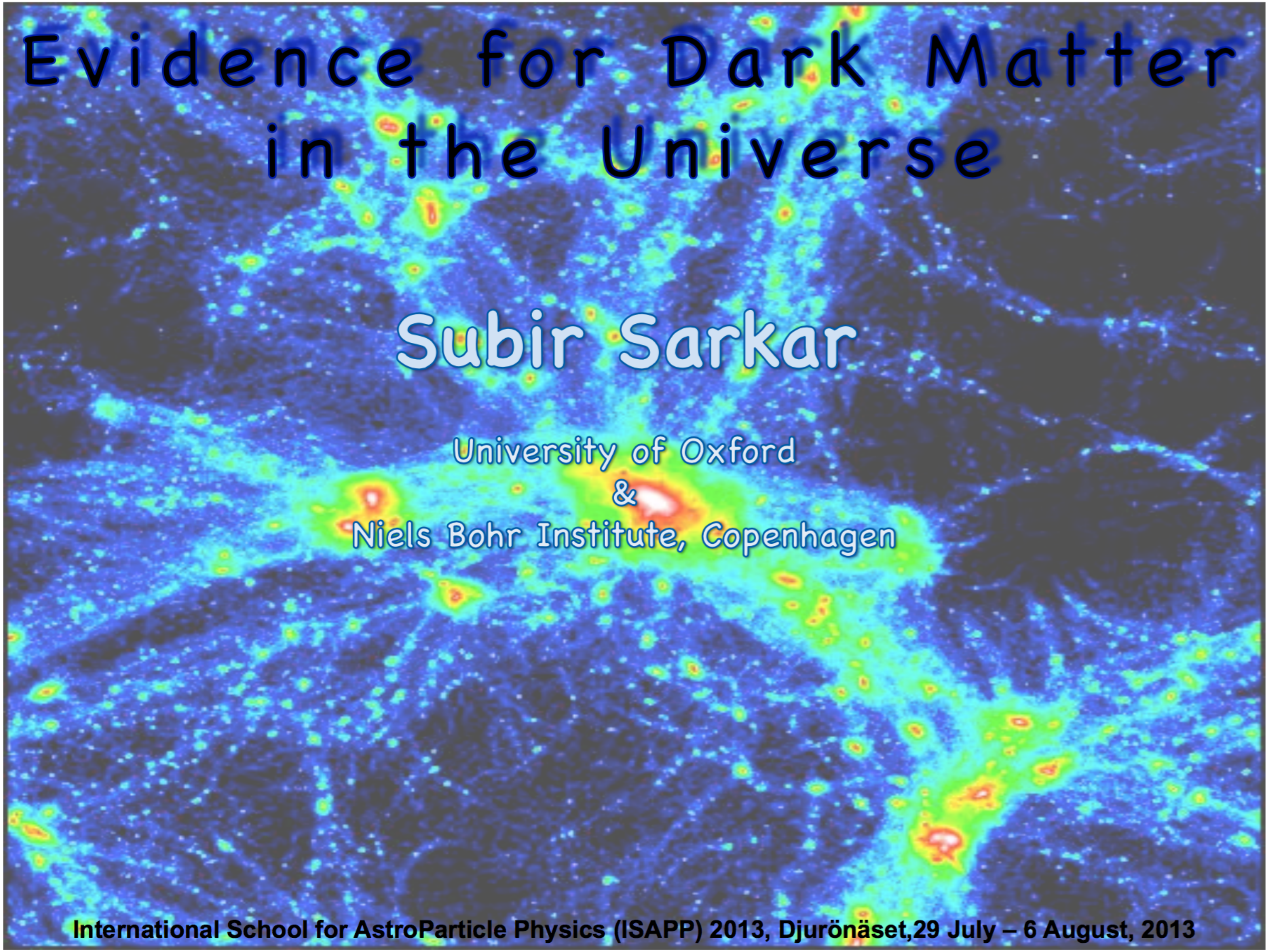
Djurönäset Conference Centre, Stockholm region

- Overview
- Presentation slides and additional material
- Schedule
- Circular #1
- Circular #2
- Local Organizing Committee
- Posters
- Poster listing
- Group picture
- Photo gallery
- List of participants

Home

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

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



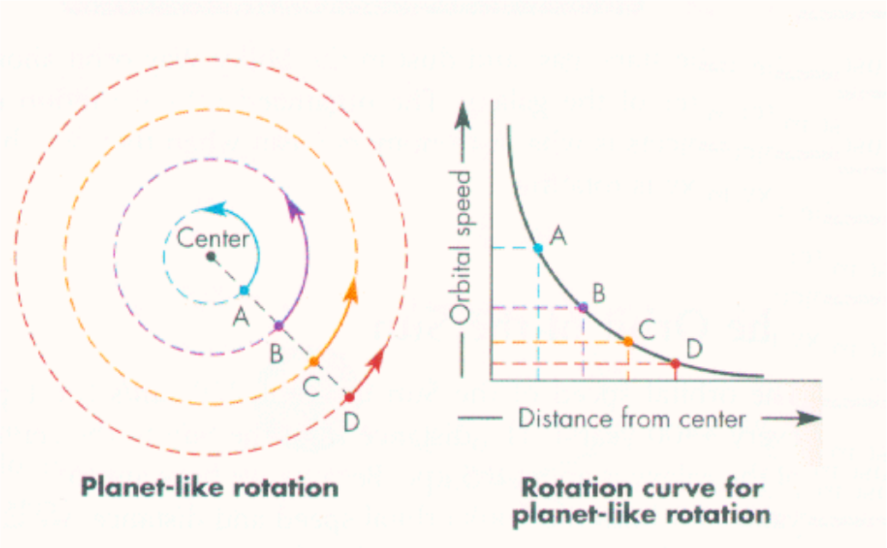
Evidence for Dark Matter in the Universe

Subir Sarkar

University of Oxford
&
Niels Bohr Institute, Copenhagen

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

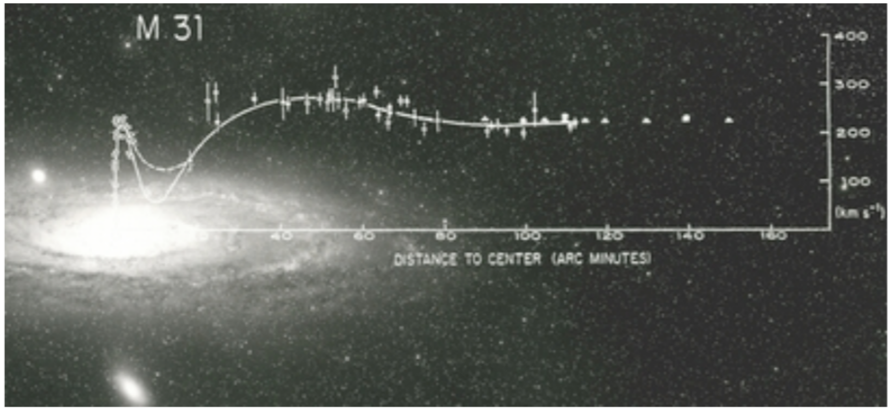
The modern saga of dark matter starts with the rotation curves of spiral galaxies



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

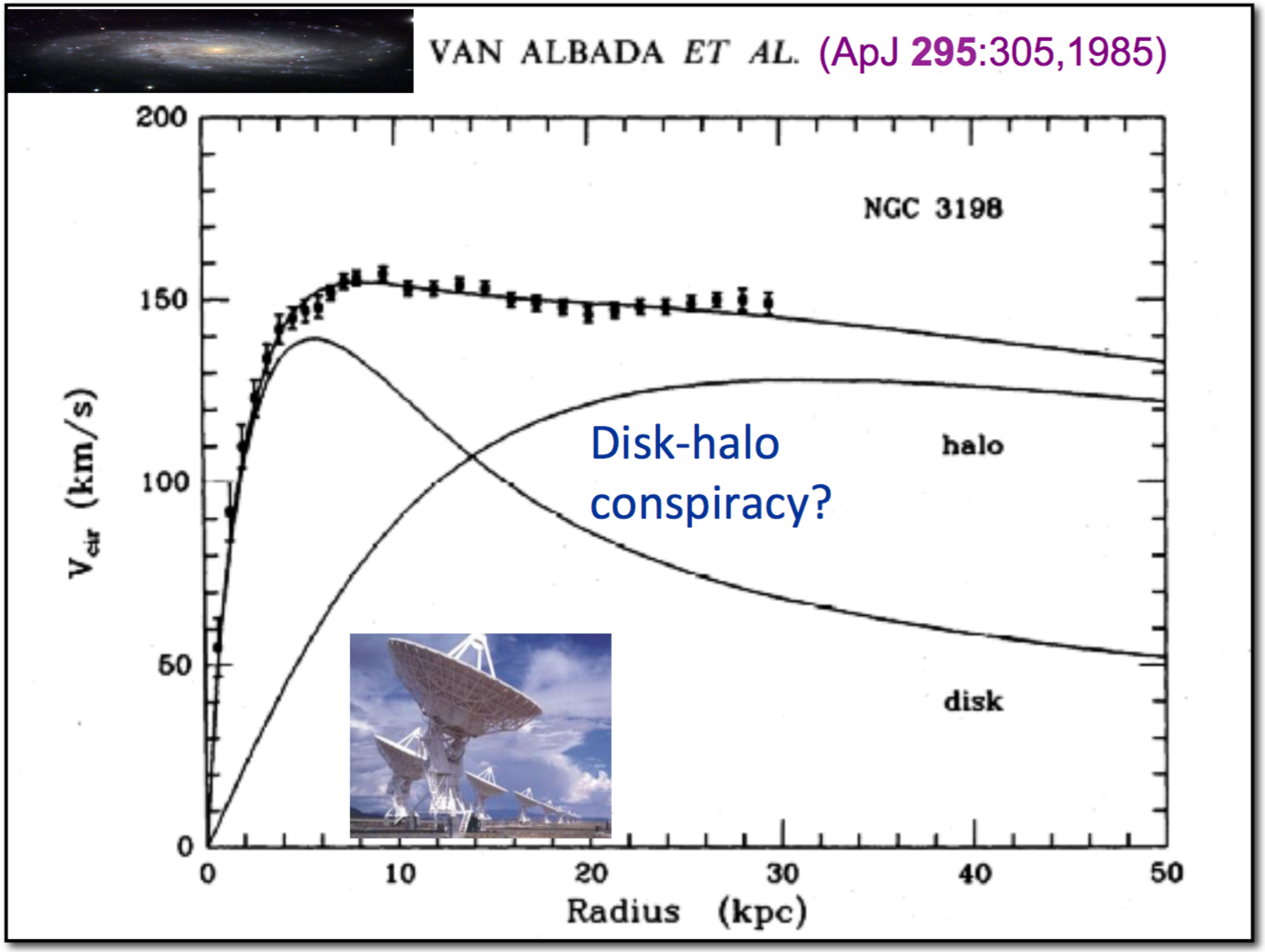
$$v_{\rm circ} = \sqrt{\frac{G_{\rm N} M(<r)}{r}}$$

… 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:

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

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

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

Burkert profile:
(fits observations better)

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

Hernquist profile:

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

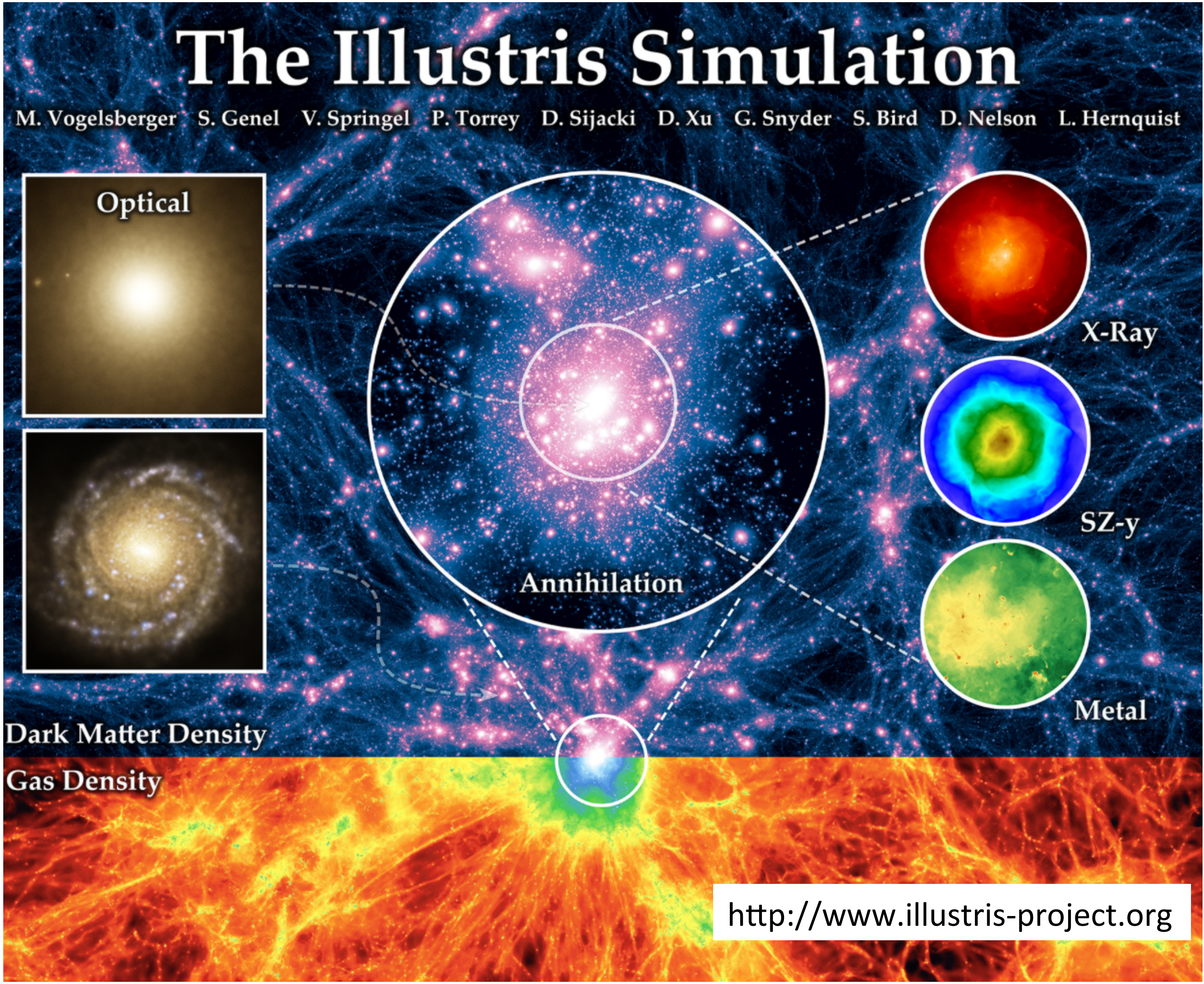
where $r_{\rm s}$ is a characteristic scale and α controls the sharpness of the transition from the inner slope $\lim_{r\to 0} {\rm d}\ln(\rho)/{\rm d}\ln(r) = -\gamma$ to the outer slope $\lim_{r\to\infty} {\rm d}\ln(\rho)/{\rm d}\ln(r) = -\beta$

… 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:

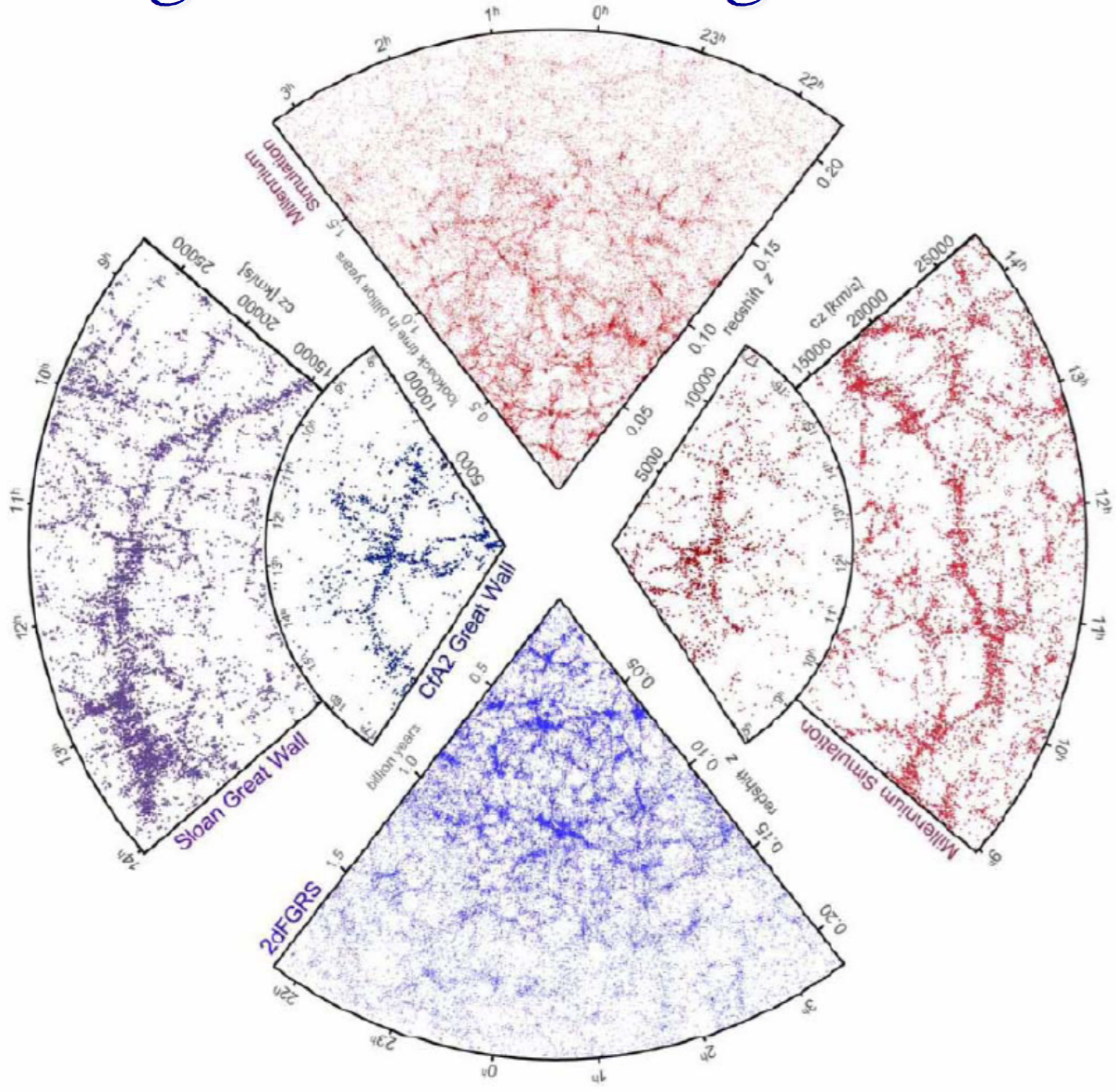
$$\rho_{\rm Einasto} = \rho_{\rm s}\exp\left\{-d_n\left[\left(\frac{r}{r_{\rm s}}\right)^{1/n} - 1\right]\right\}$$

where d_n is defined such that $\rho_{\rm s}$ is the density at the radius $r_{\rm s}$ which encloses half the total mass



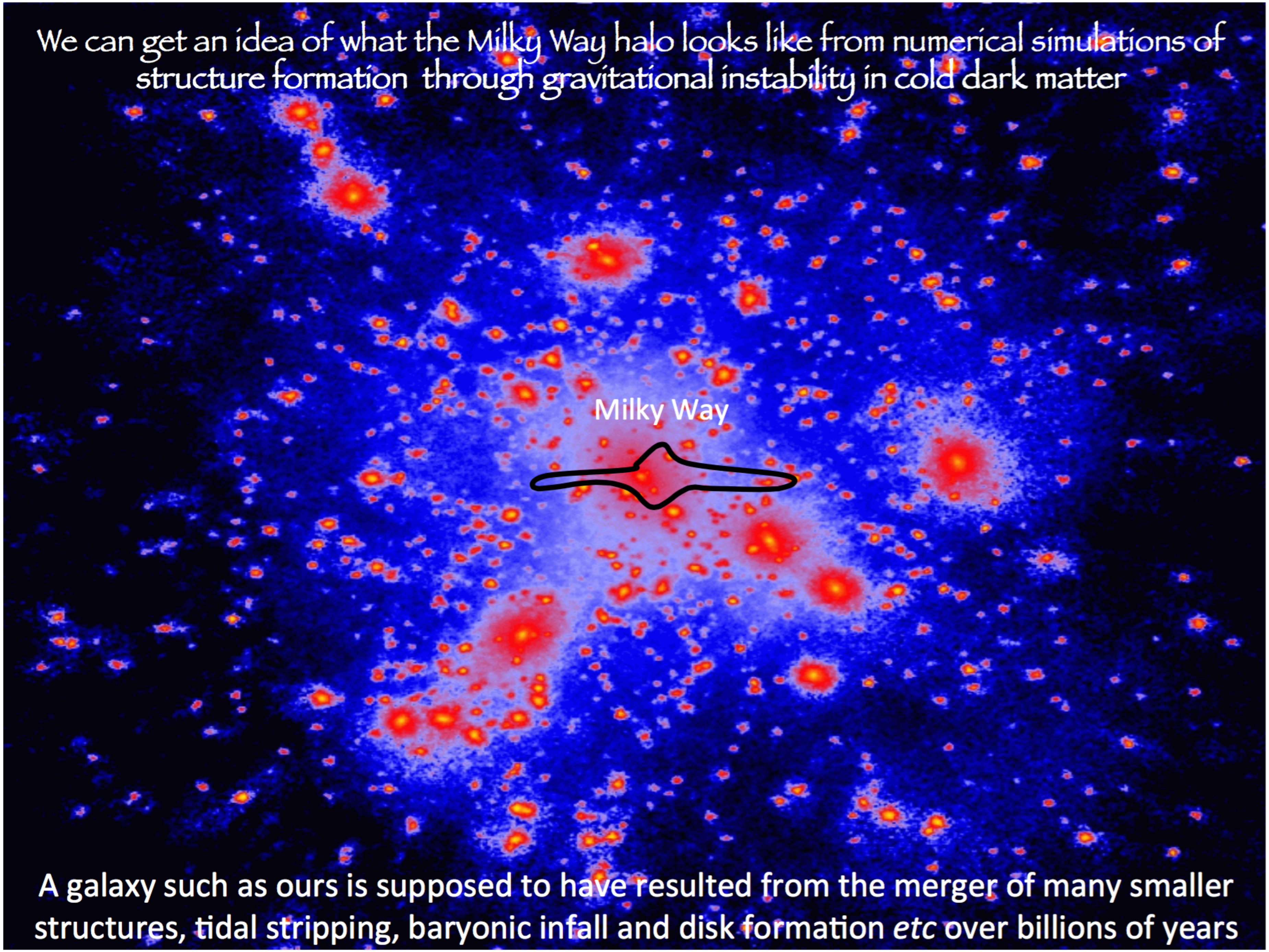
http://www.illustris-project.org

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

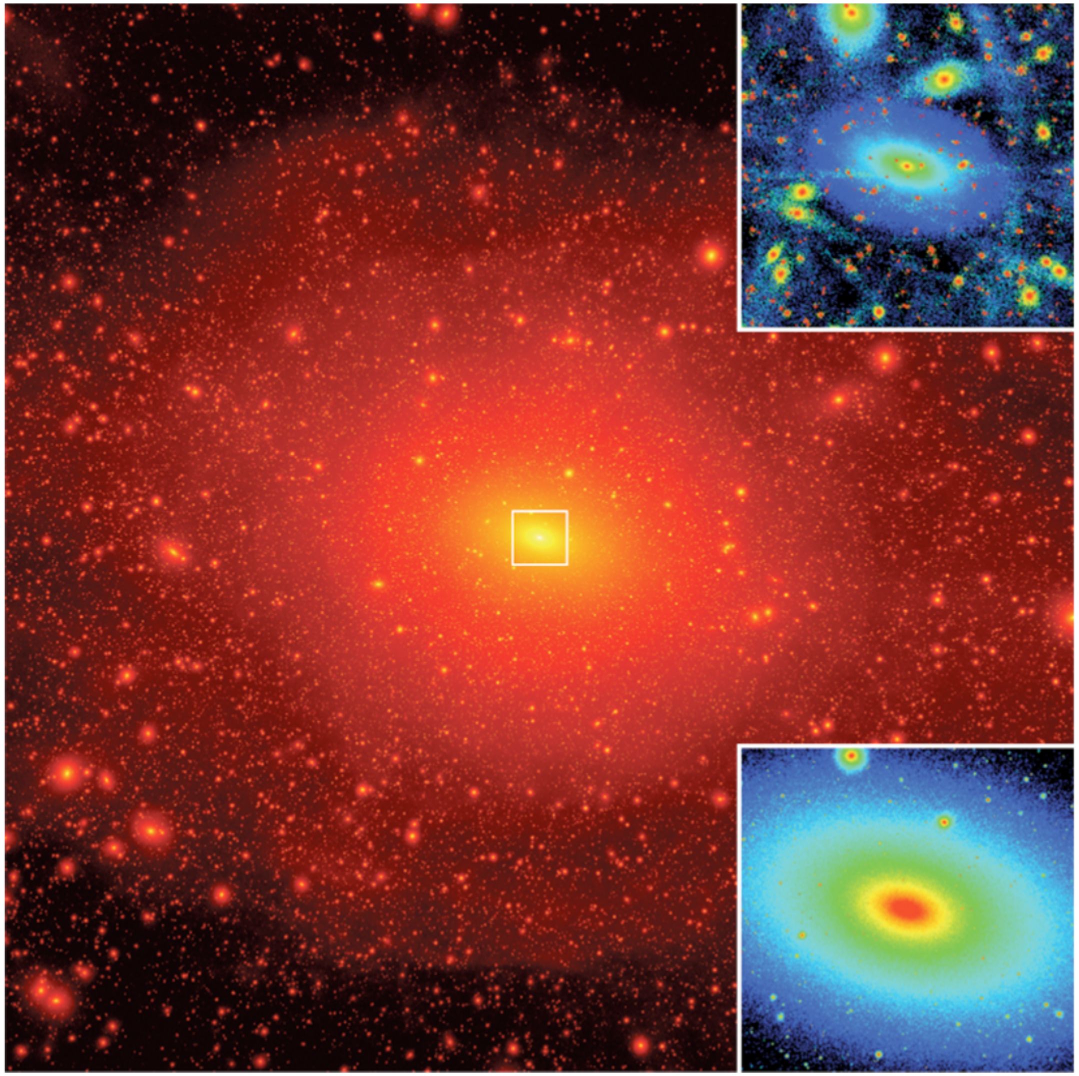
We can get an idea of what the Milky Way halo looks like from numerical simulations of structure formation through gravitational instability in cold dark matter



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 …

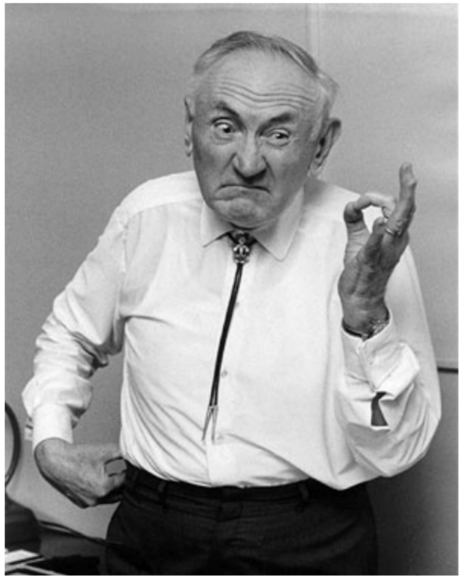
Via Lactea II projected dark matter (squared-) density map



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

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

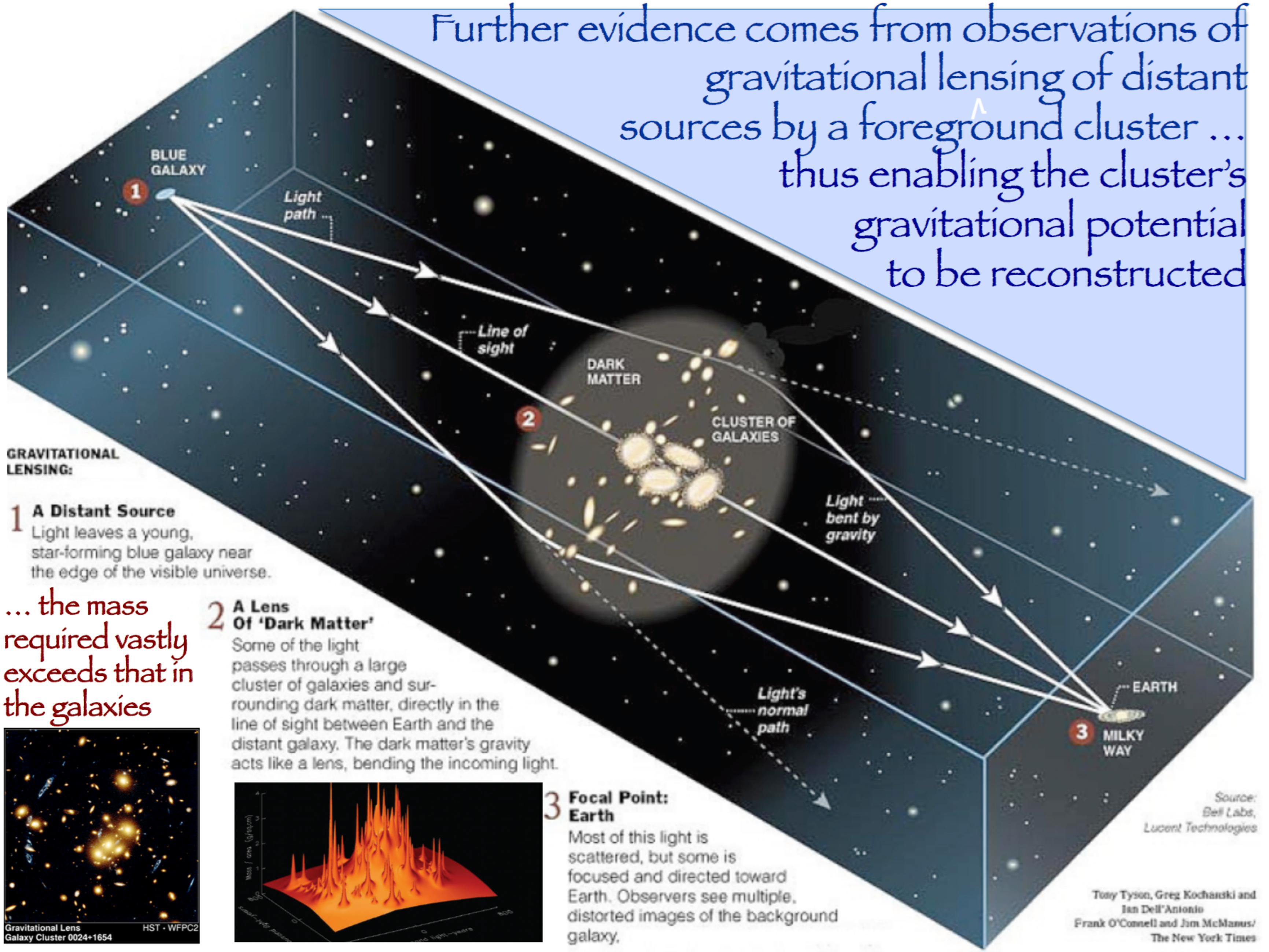
"… If this overdensity is confirmed we would arrive at the astonishing conclusion that dark matter is present (in Coma) with a much greater density than luminous matter"

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

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

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

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.

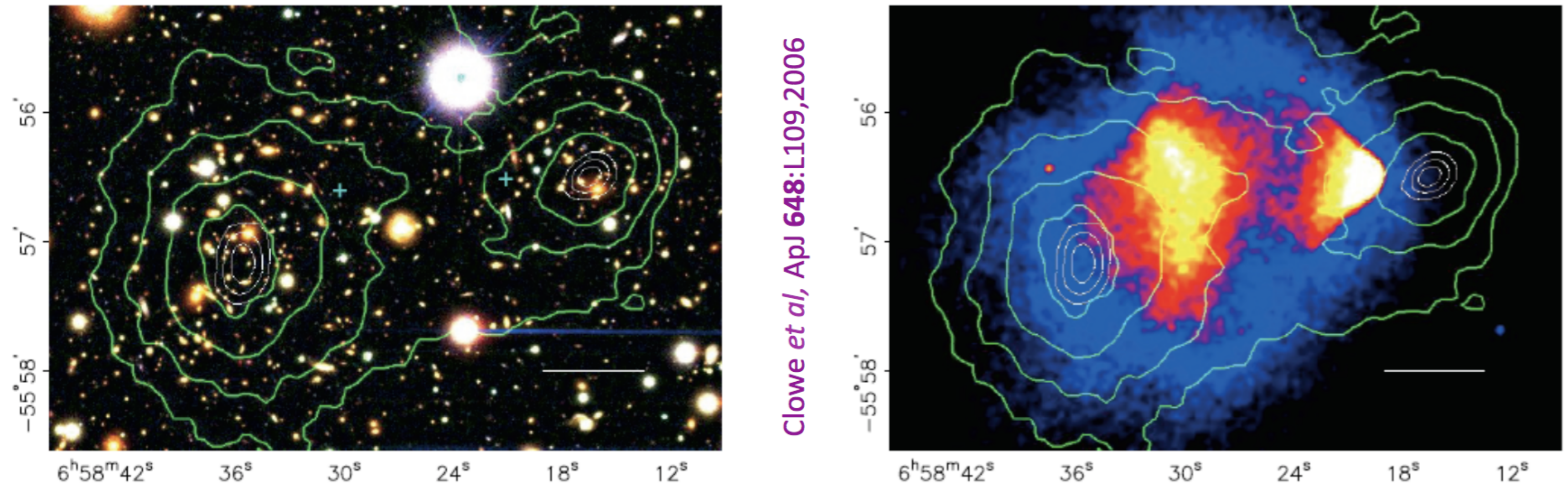
3 **Focal Point: Earth**
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.

… 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

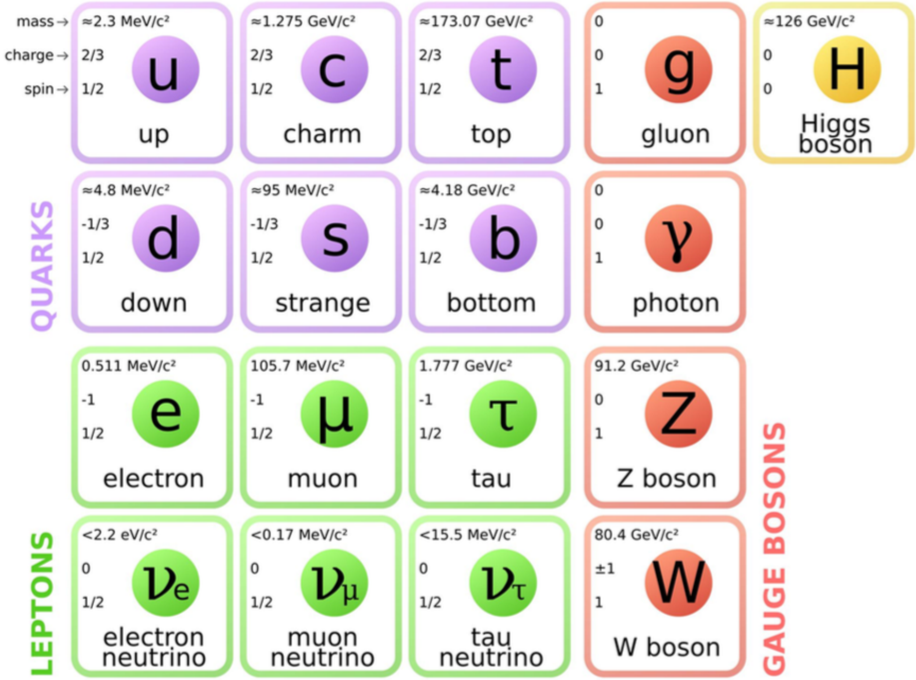
The Chandra picture of the 'bullet cluster' (1E 0657-558) shows that the X-ray emitting baryonic matter is *displaced* from the galaxies and the dark matter (inferred through gravitational lensing) … convincing evidence of dark matter?



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



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

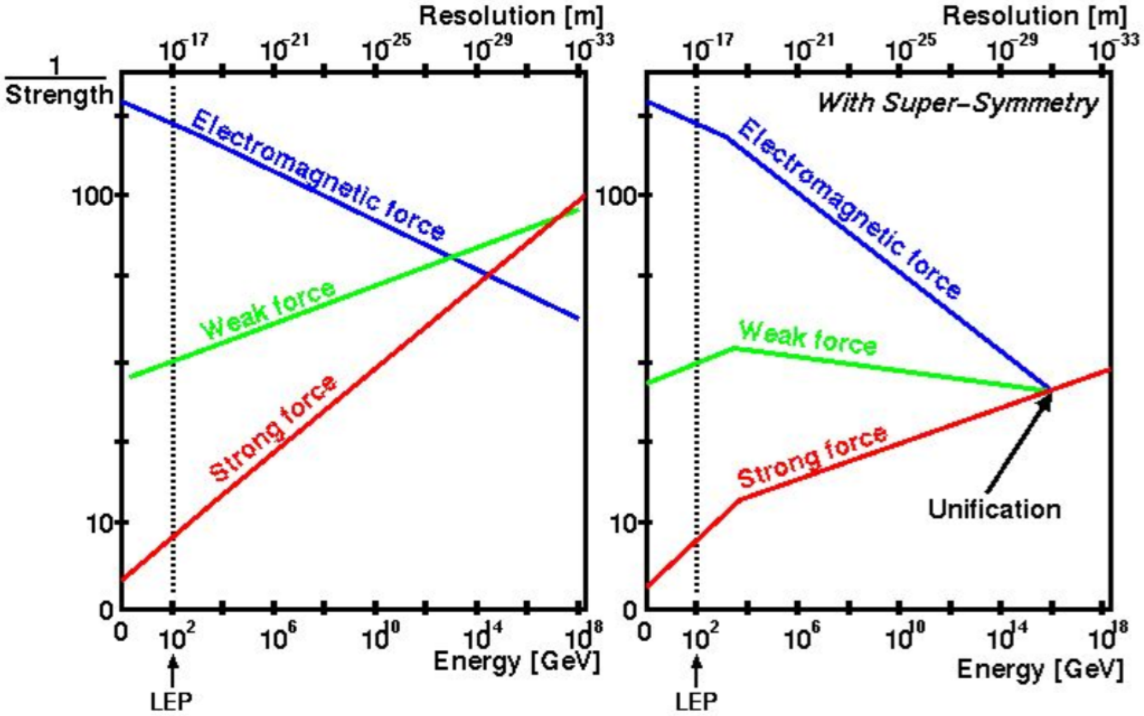
- Problem of stability of the Higgs mass if there is any physical scale Λ where new physics arises. The tree-level (bare) Higgs mass, the one which appears in the Lagrangian we dealt with, receives quadratically-divergent corrections from one loop diagrams, $M_H^2 = (M_H^2)_{bare} + O(\lambda, g^2, h^2)\Lambda^2$,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

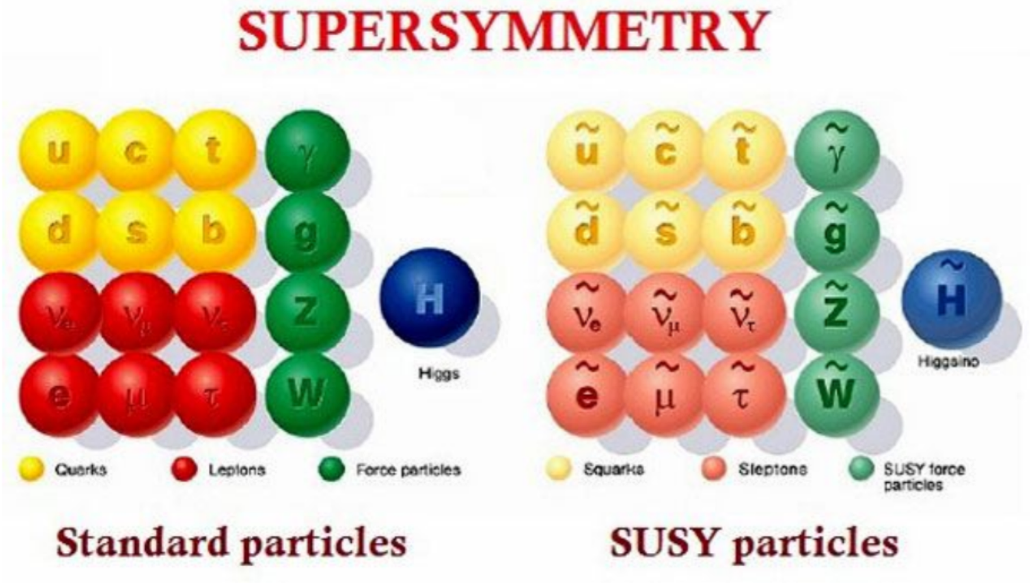
Grand Unified Theories (GUT), unifications of electroweak and strong interactions at high energies?



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)!

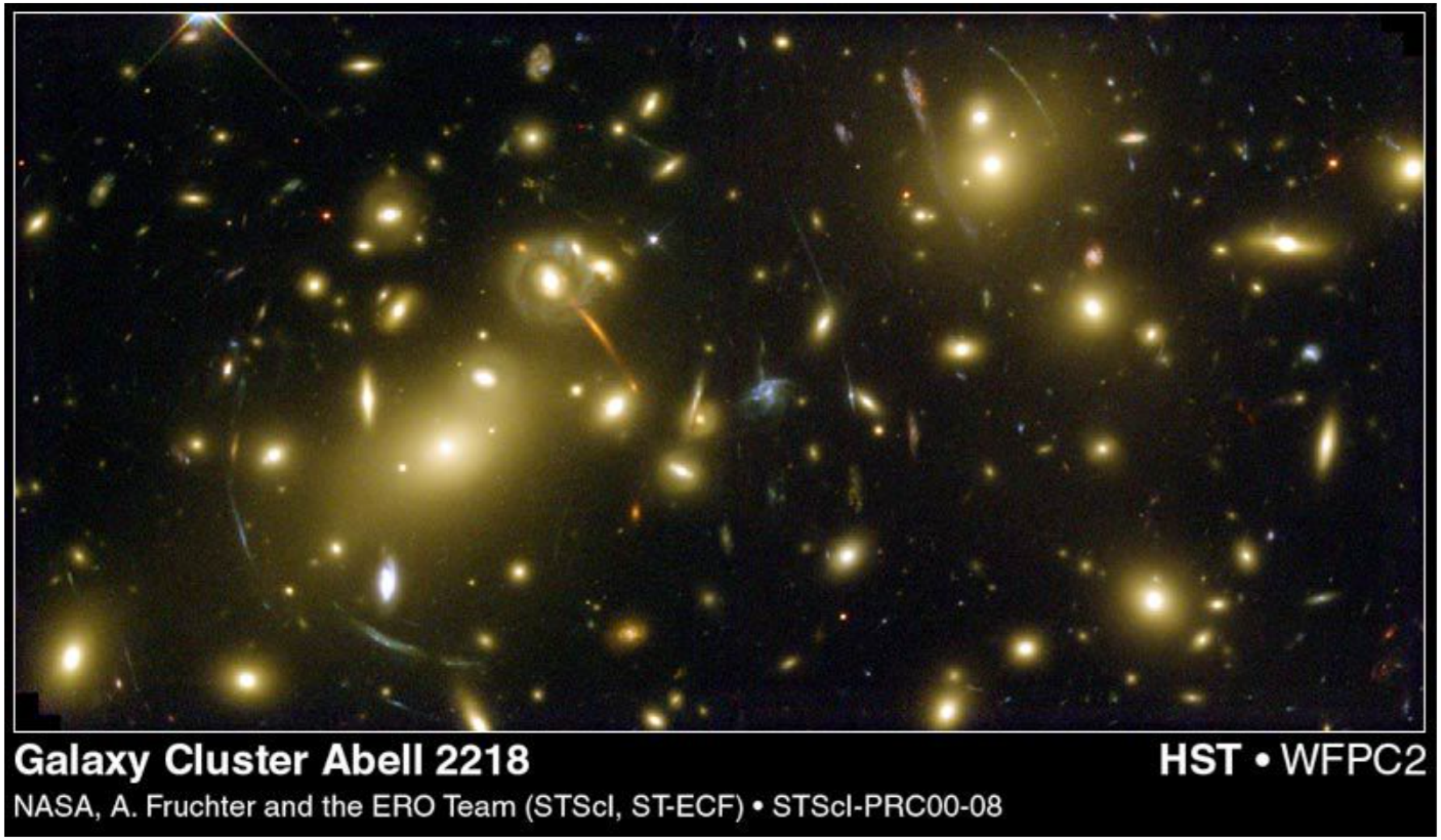


Astrophysics and Cosmology for Particle Physicists

Marc Kamionkowski
Johns Hopkins University

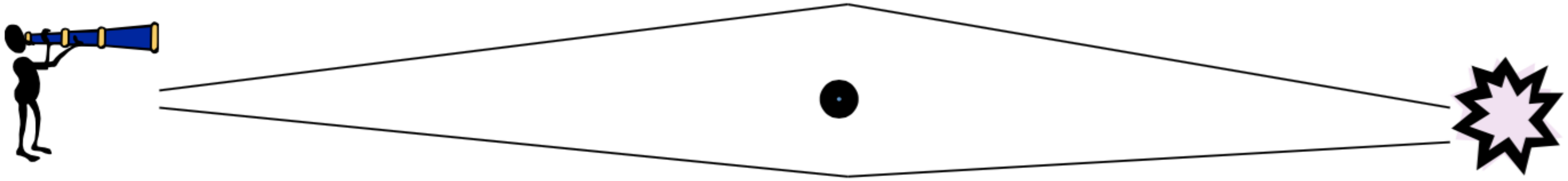
https://arxiv.org/abs/0907.1912

Lensing effect of dark matter



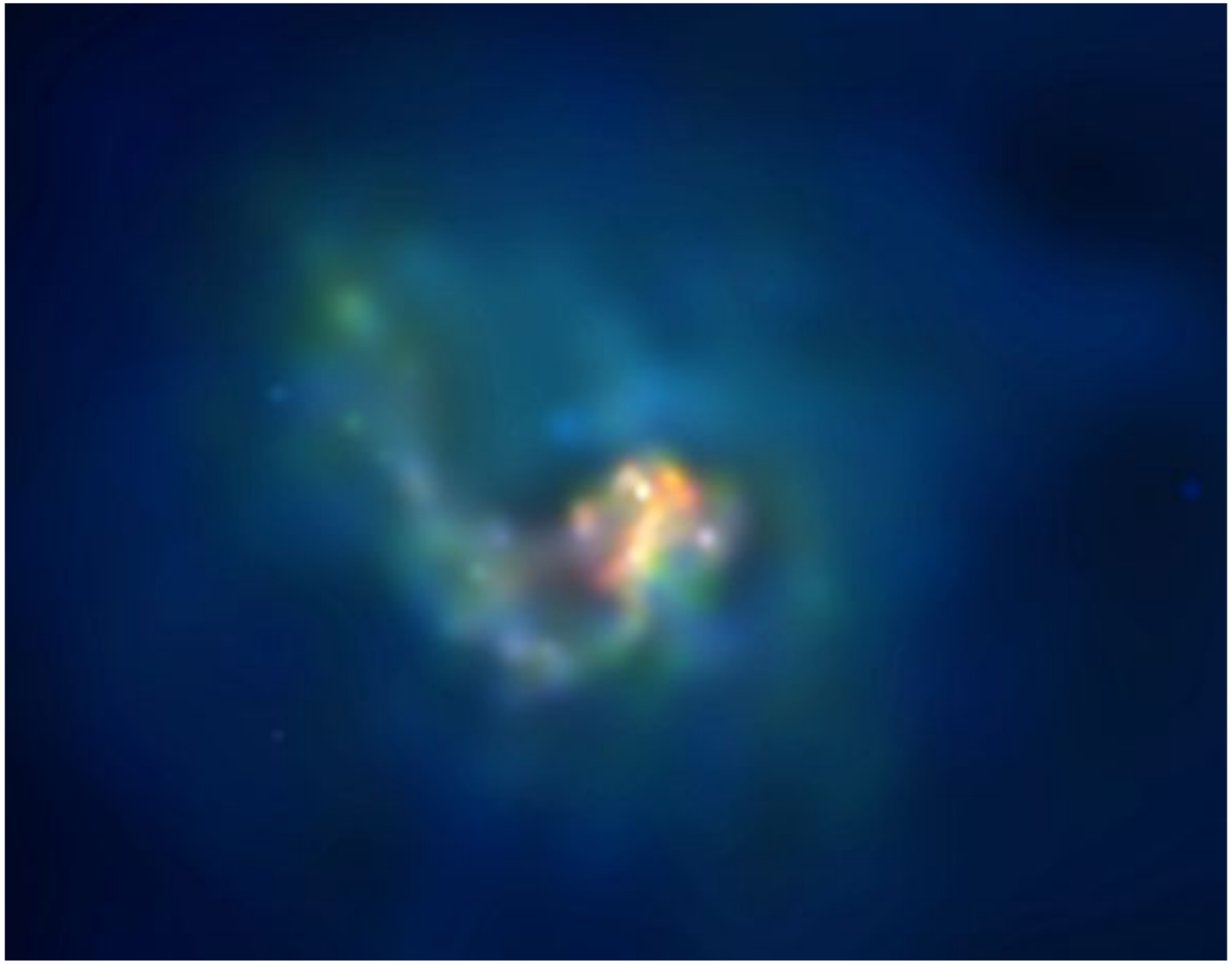
Galaxy Cluster Abell 2218 **HST** • WFPC2

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08



X-ray clusters: Gas in hydrostatic eq

$$dP/dr = -G\rho_{\rm tot}(r)m_b(r)/r^2$$



$$M_{\rm total} \gg M_{\rm baryons} \quad \text{in clusters}$$

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

Could dark matter be neutrino?

No!

Quantum mechanics: $\Delta x \Delta p > \hbar$

$$\Delta x \sim n_\nu^{-1/3} \sim (\rho_0/m_\nu)^{-1/3}$$

$$\Delta p \sim m_\nu v \quad (v \sim 300\,\mathrm{km/sec})$$

$$\rightarrow m_\nu > 50\,\mathrm{eV}$$

But $m_\nu < 10\,\mathrm{eV}$ if $\Omega_\nu h^2 < 0.1$

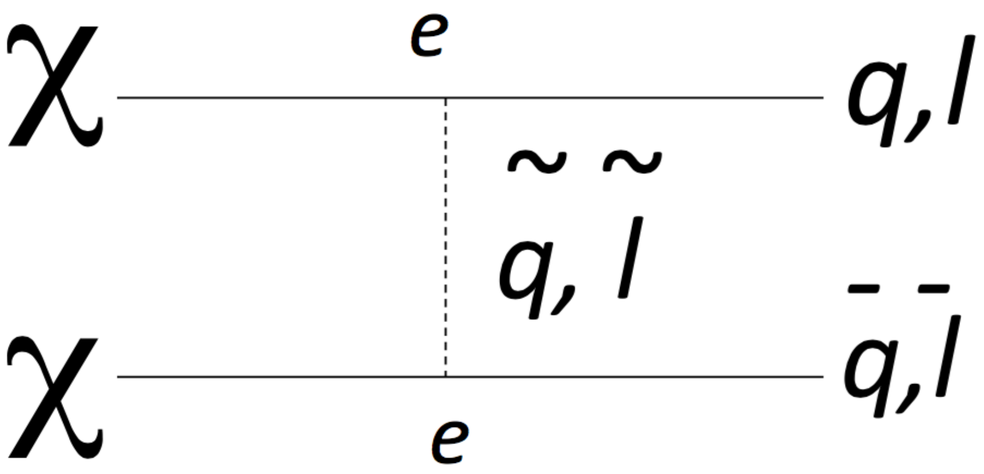
Supersymmetric models:

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:

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

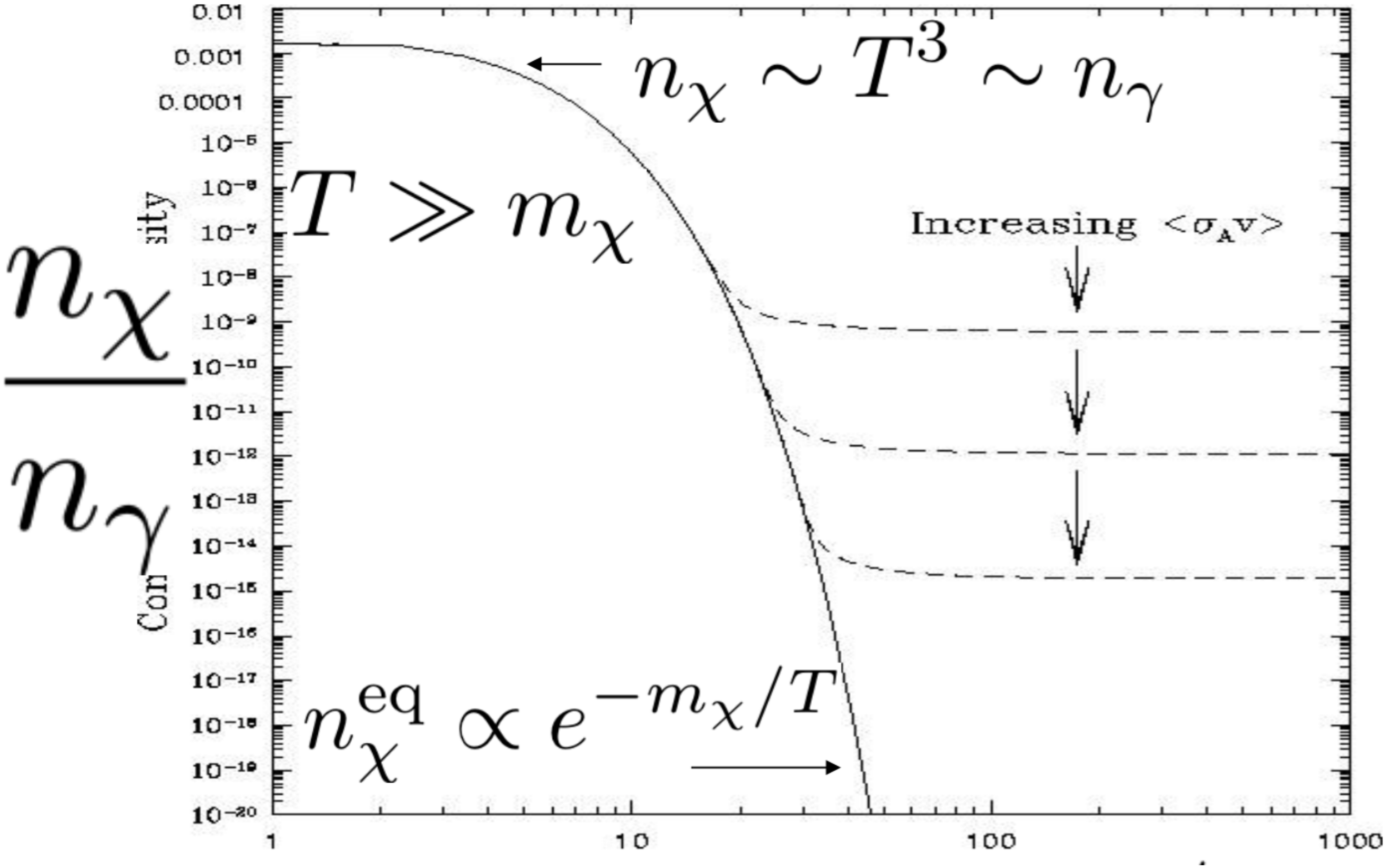
$$n_\chi^{\mathrm{eq}} \propto e^{-m_\chi/T}$$

$$\Gamma \ll H$$

Annihilations can not occur

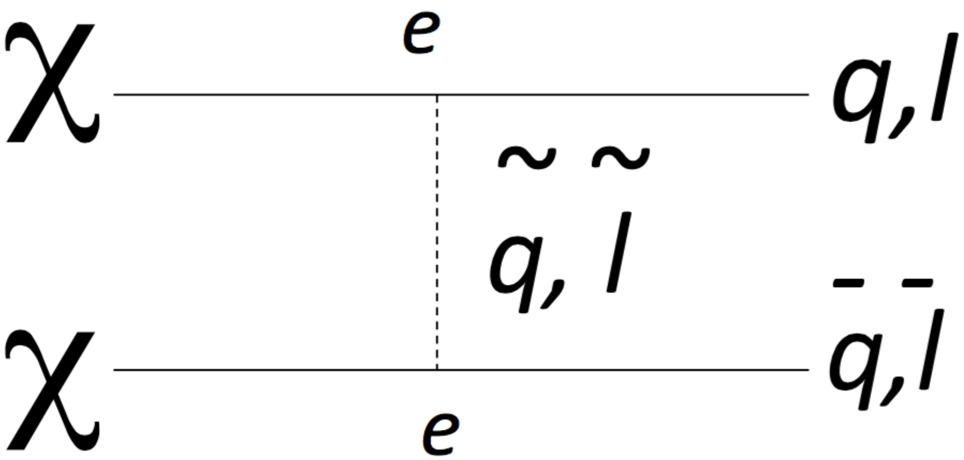
“Freezeout” at $\Gamma(T_f) = H(T_f)$

Afterwards, comoving WIMP # constant



Freezeout Calculation:

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



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

$\Omega_\chi h^2 \sim m_\chi^2$ from $\langle \sigma v \rangle \sim m_\chi^{-2}$

$\langle \sigma v \rangle \lesssim m_\chi^{-2}$ with $\Omega_\chi h^2 \lesssim 0.1$

leads to WIMP-mass limit,

$$m_\chi \lesssim 100\,\mathrm{TeV}$$

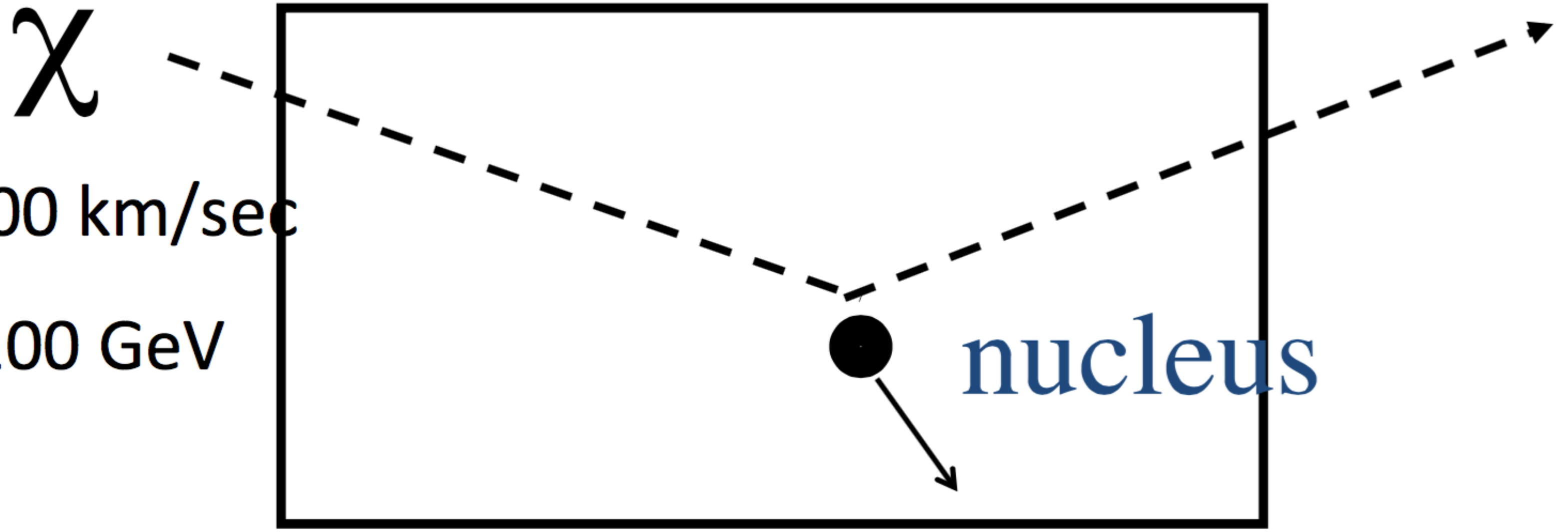
Griest&MK 1991

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



V~300 km/sec

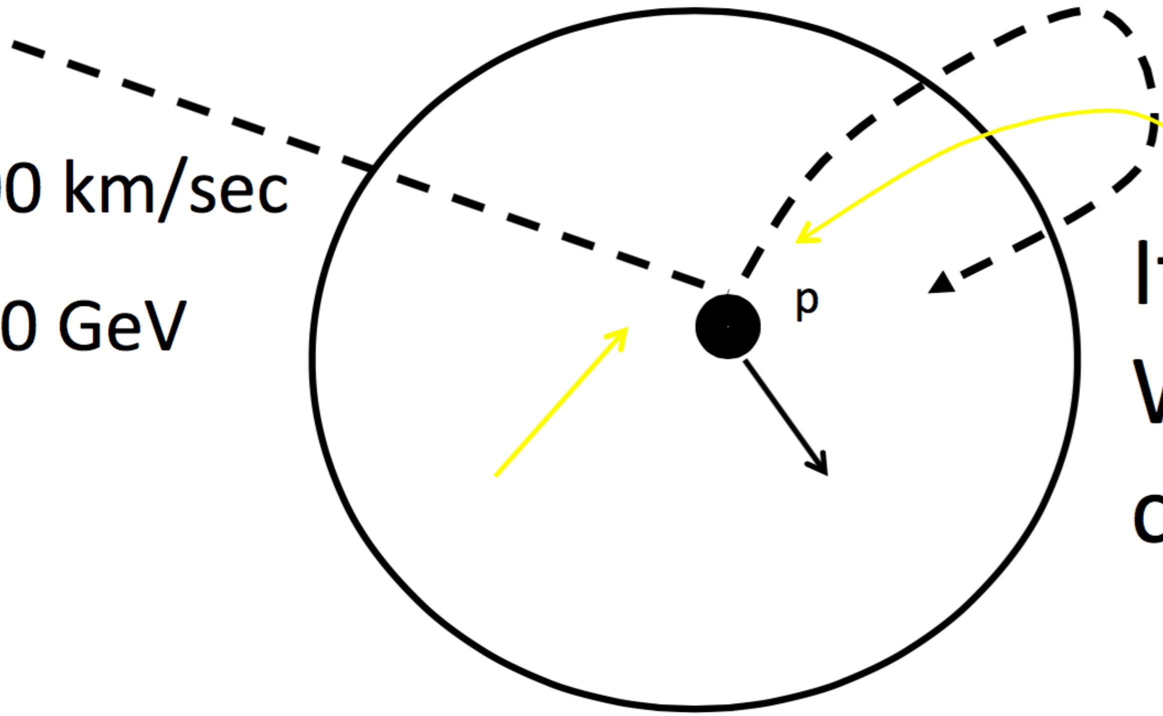
M~100 GeV

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

Rate:

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

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

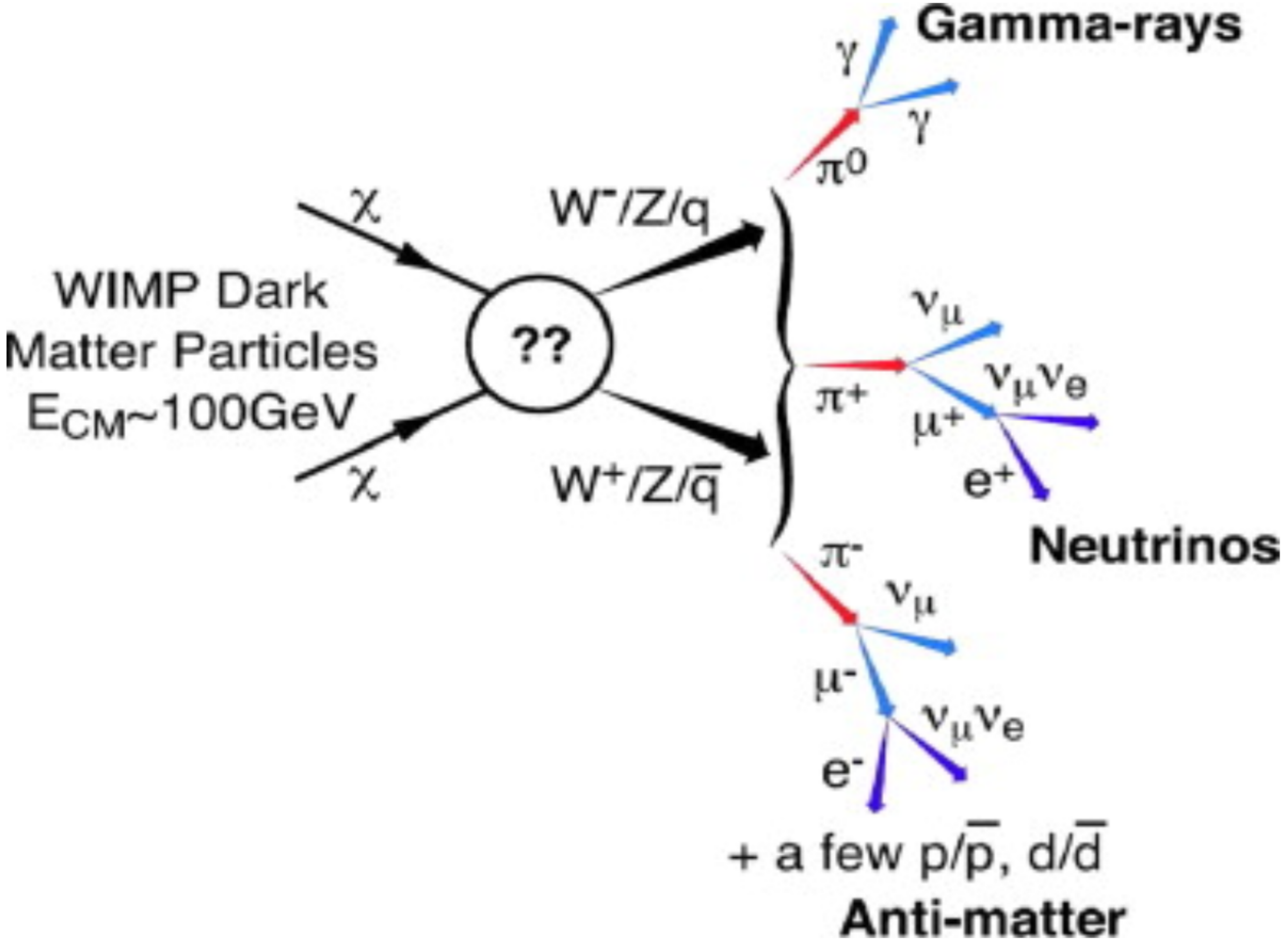
Inside Sun and/or Earth:

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

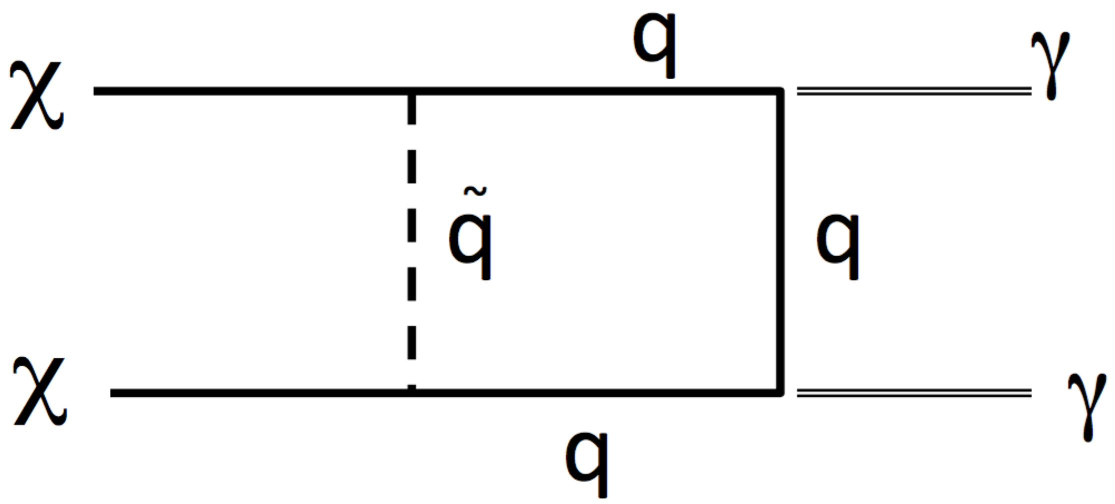
$$E_\nu \sim (1/10 - 1/2)m_\chi \sim 10 - 1000s\,\mathrm{GeV}$$

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



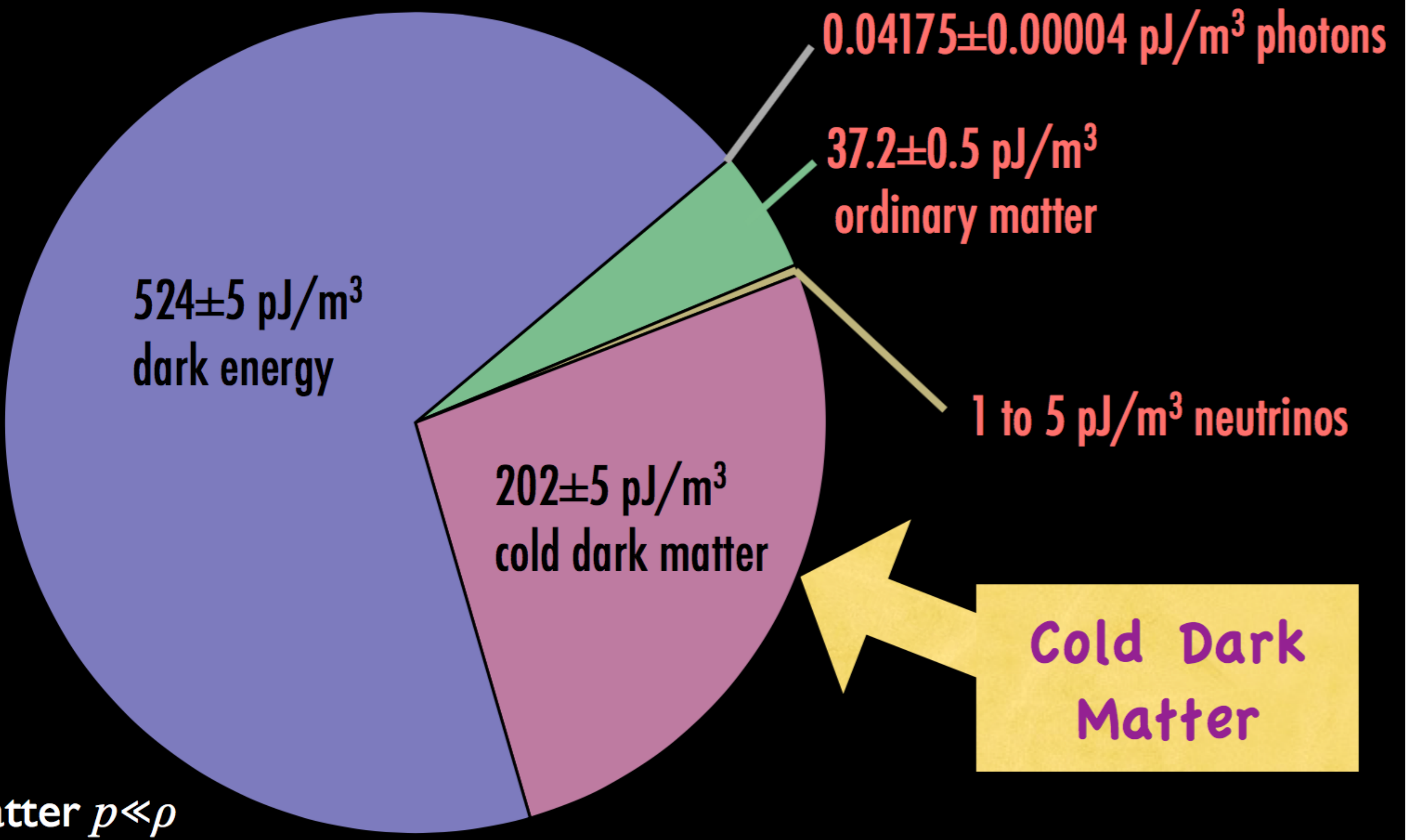
$$E_\gamma = m_\chi$$

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

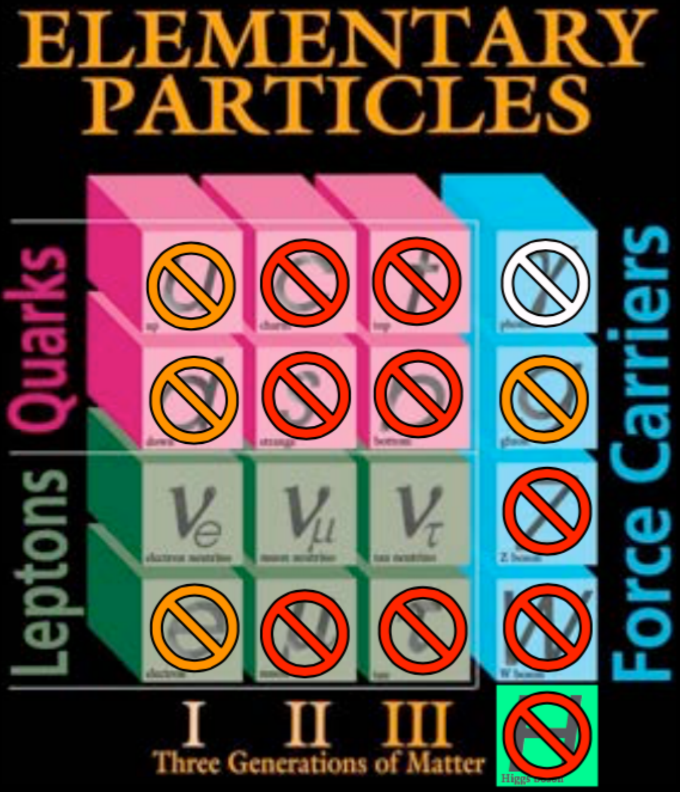
Symmetry argument: gas is at center, but potential has two wells.

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

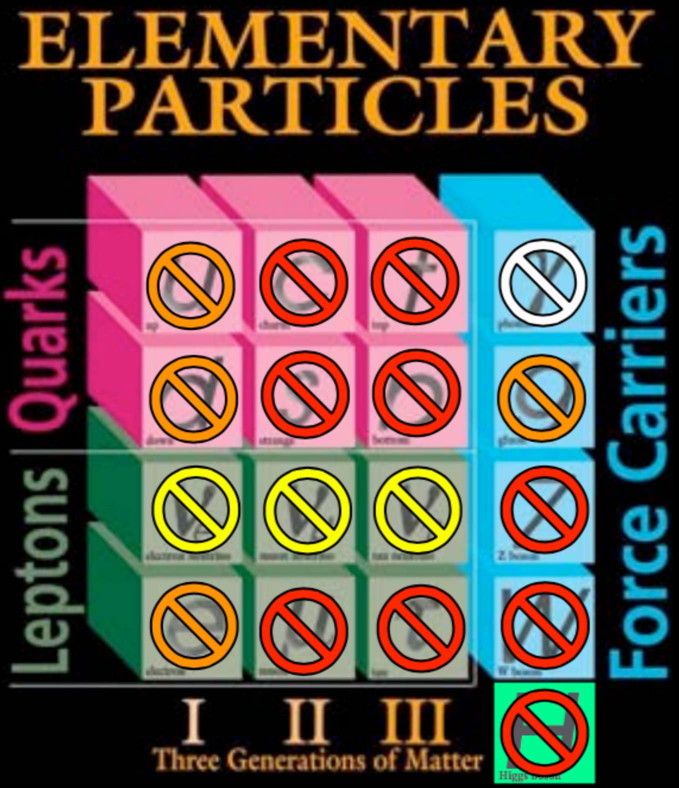
Known active neutrinos

- 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

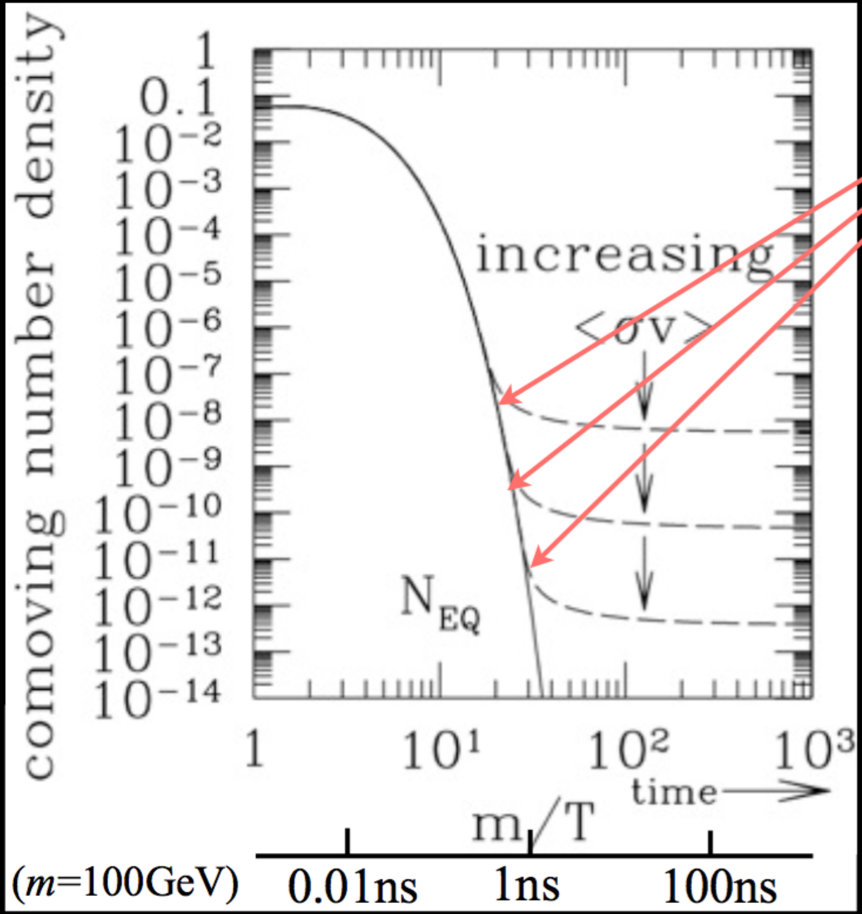
neutralinos, axions, WIMPZILLAs, solitons

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*

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

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

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

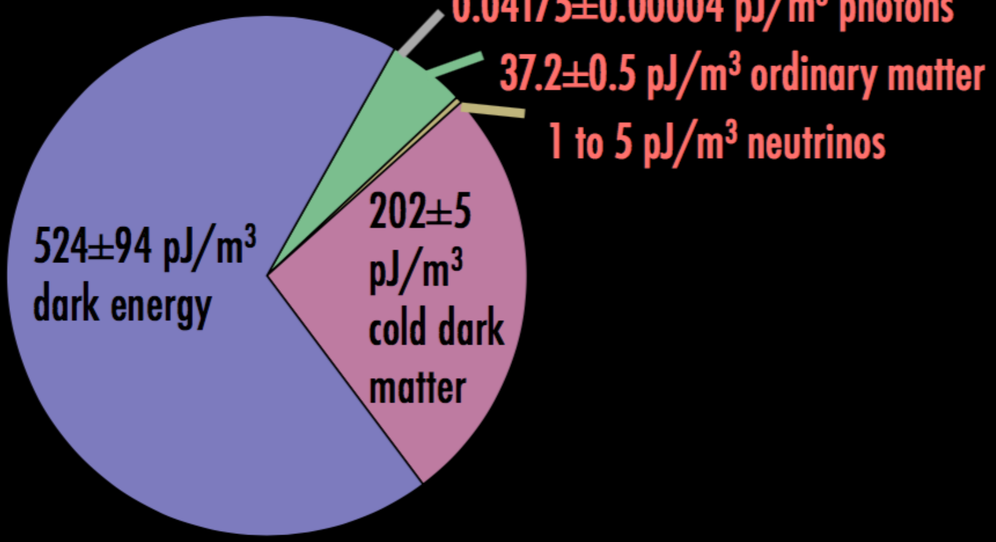
This is why they are called Weakly Interacting Massive Particles

(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

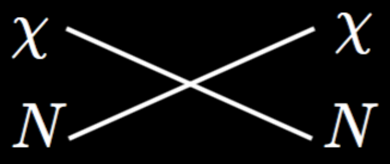
  The same physical processes that produce the right density of WIMPs make their detection possible

The magnificent WIMP

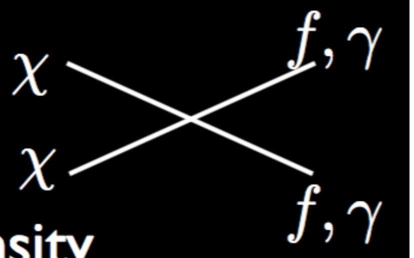
To first order, three quantities characterize a WIMP

- 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

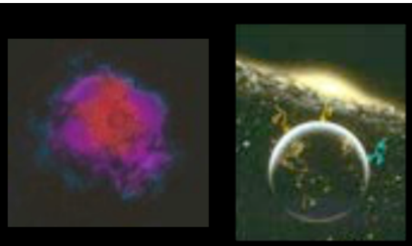


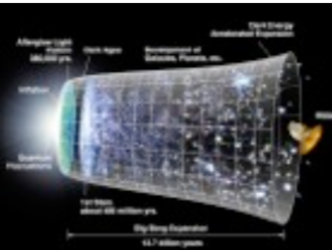
- Annihilation cross section into ordinary particles
  - $\sigma \simeq \text{const}/v$ at small v, so use σv
  - Simplest models relate cross section to cosmic density



The power of the WIMP hypothesis

Indirect detection

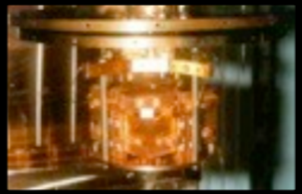


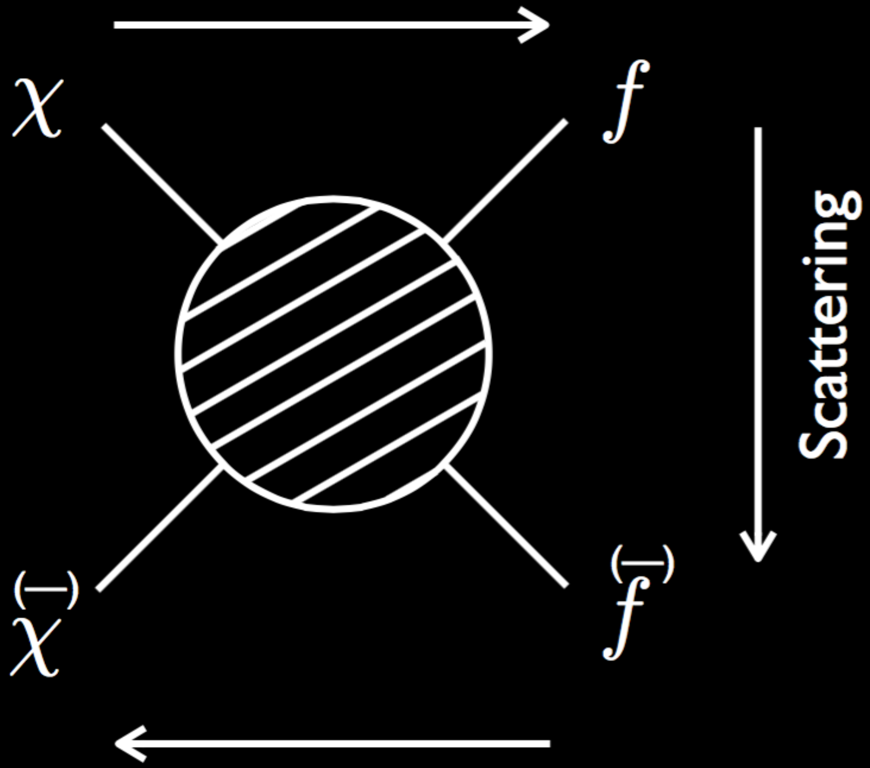


Cosmic density

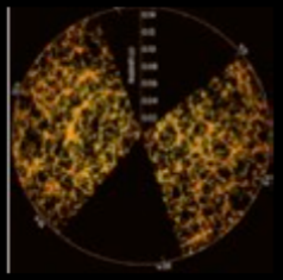
Annihilation

Direct detection





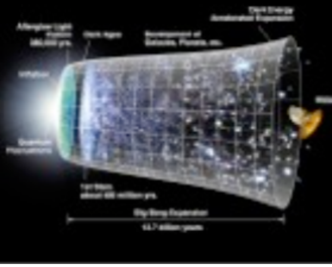
Scattering



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.

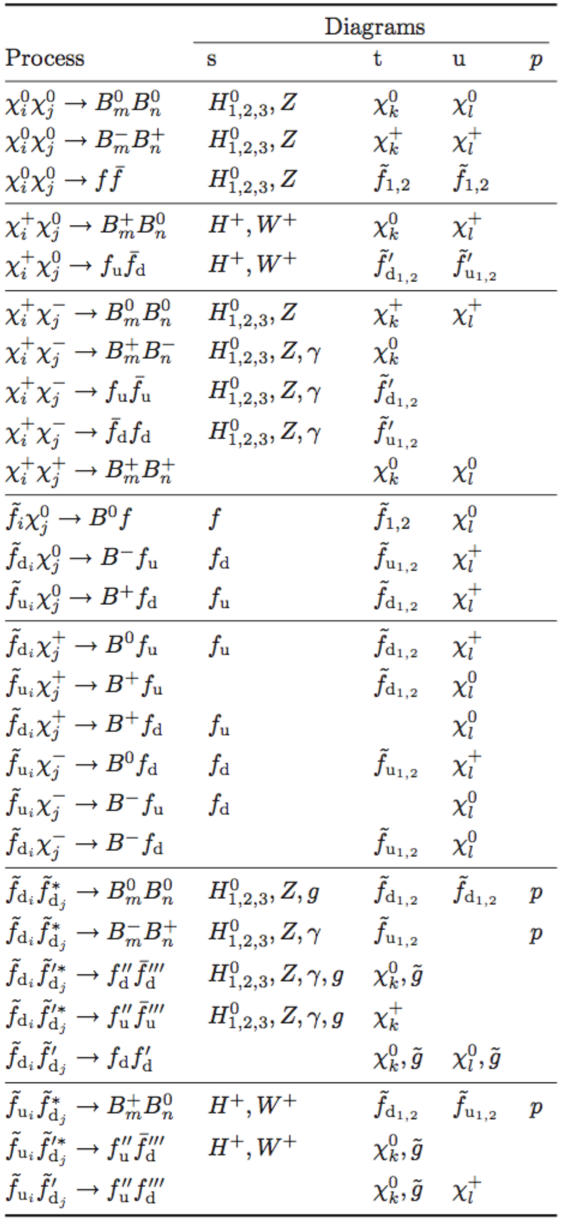
Gravitinos (SuperWIMPs)

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

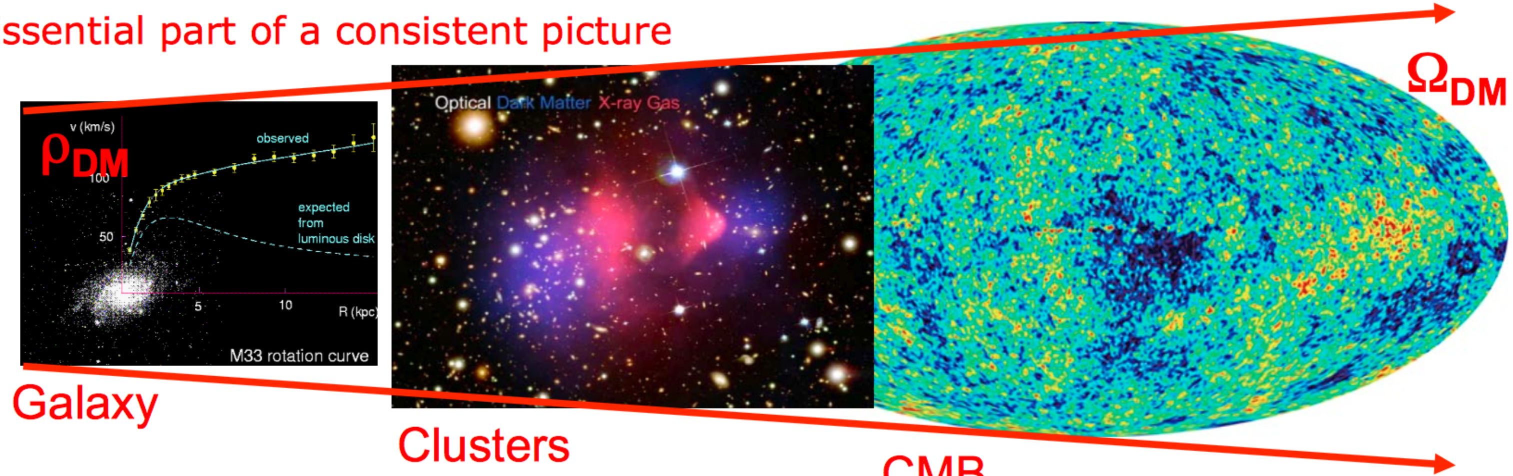
Recommended reading

- *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



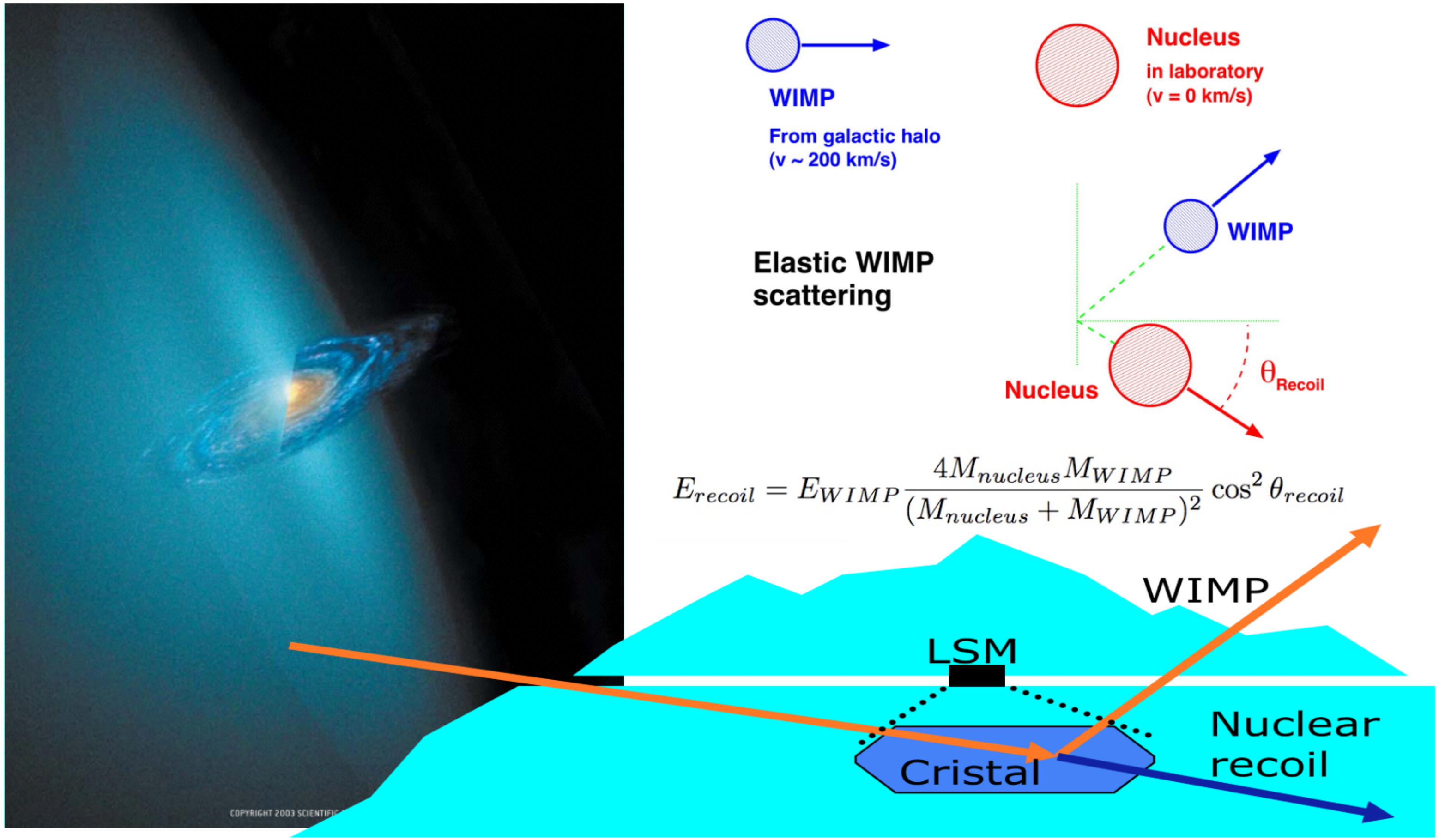
Galaxy

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})

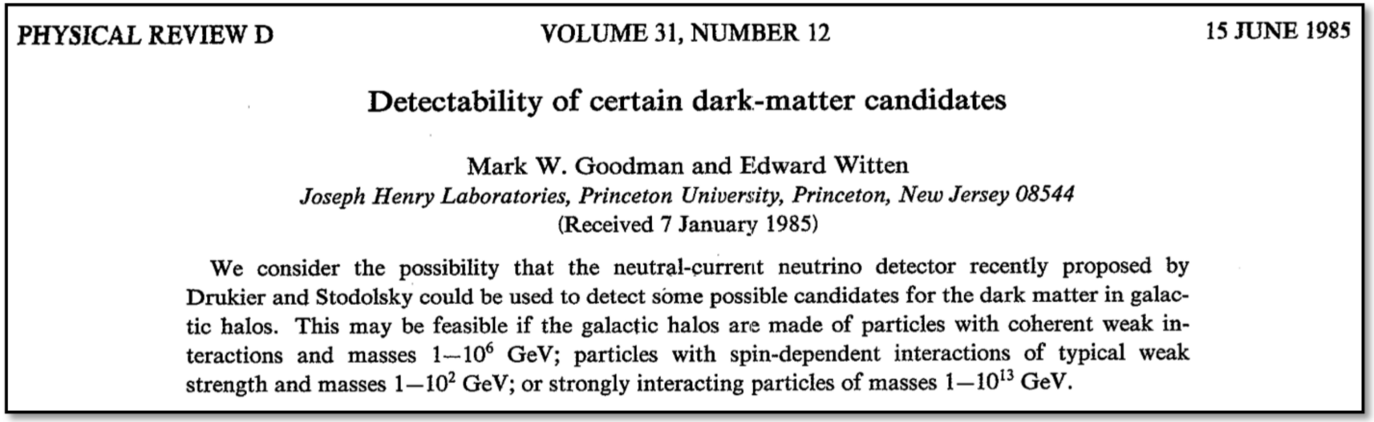
Direct search schematics



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

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

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

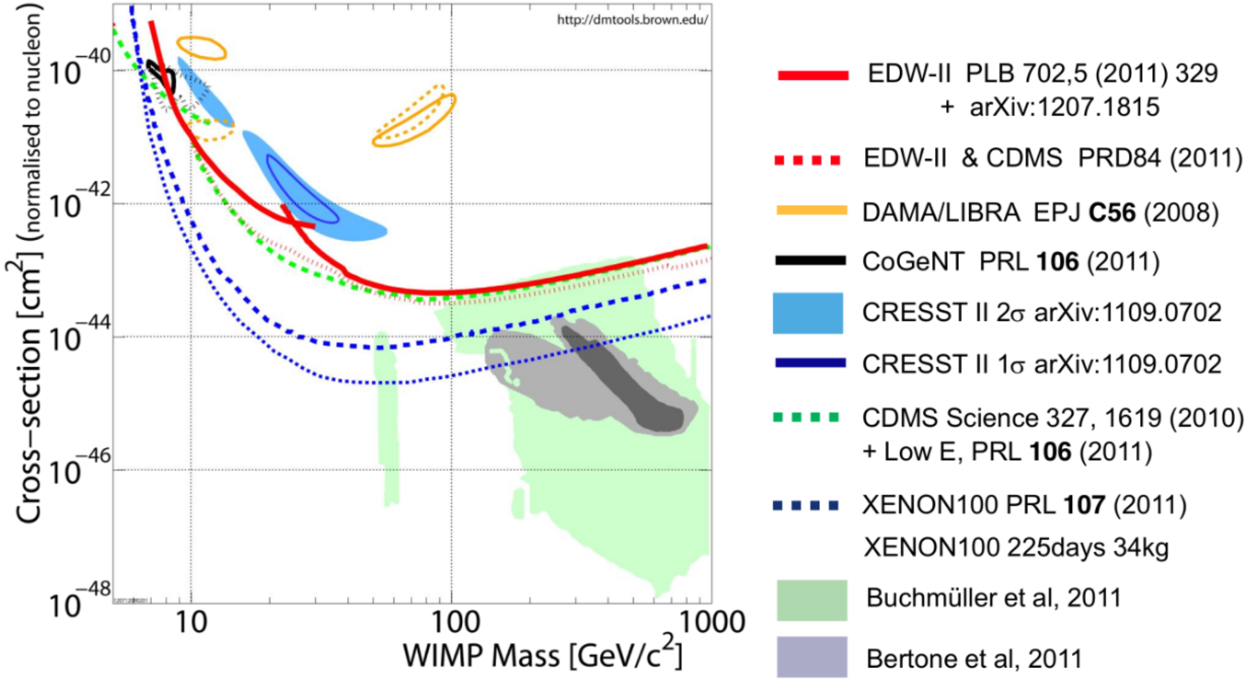
N_{target} = number of target nuclei exposed to the flux φ

➔ 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”

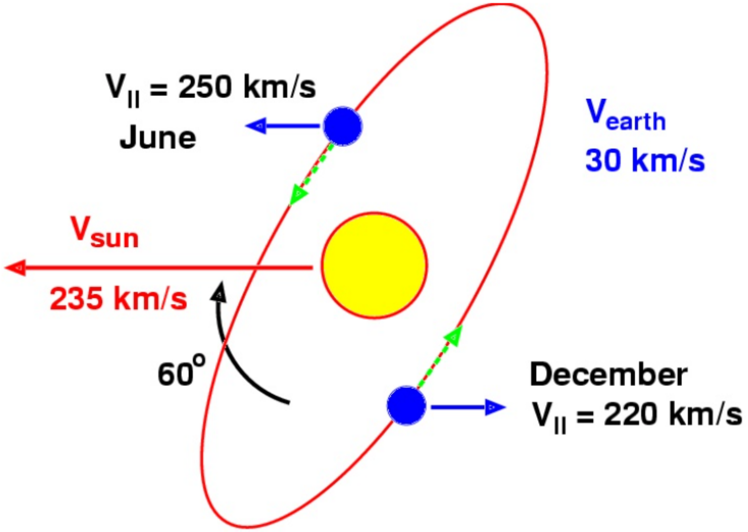


Flux: WIMP velocity distributions

- 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 ~ 220 km/s (v_{rms} = sqrt(3/2)v_0 = 270 km/s)
  - Truncated to escape velocity from Galaxy (v_{esc} ~ 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 $v_{||} \rightarrow \sim \pm 3\%$ on WIMP flux
- Modulation more sensitive to detailed halo model

Kinematics

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

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 = $sqrt(2\ M_{WIMP}\ v_{WIMP}\ c) \sim 66\ MeV$
- Associated wavelenght $\lambda = h/p \sim 20\ fm$: 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).

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

- 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)

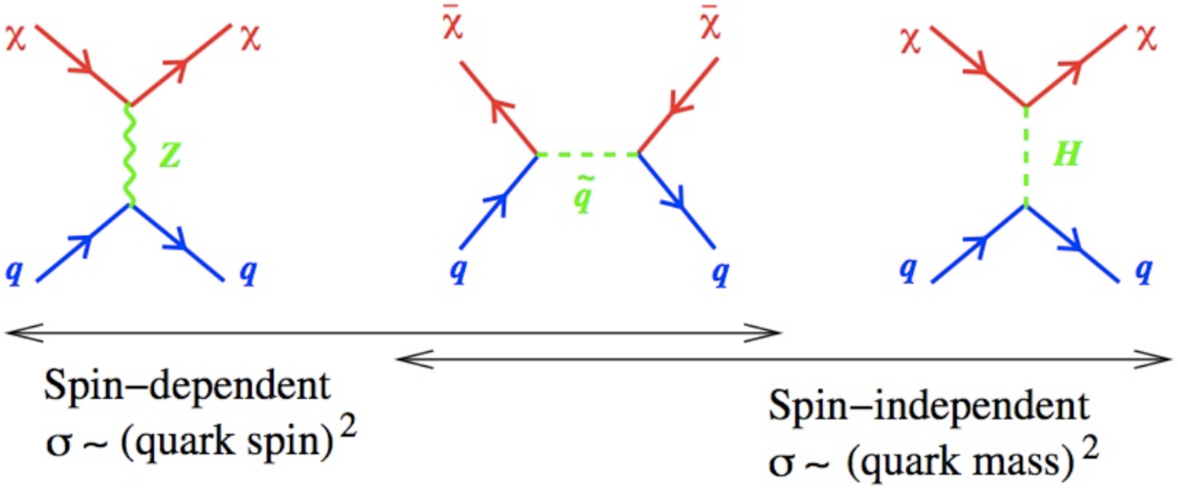
  $R = (N_0/A)\ \sigma_0\ n_0\ \langle v \rangle$

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



Spin–dependent
$\sigma \sim (\text{quark spin})^2$

Spin–independent
$\sigma \sim (\text{quark mass})^2$

- 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.

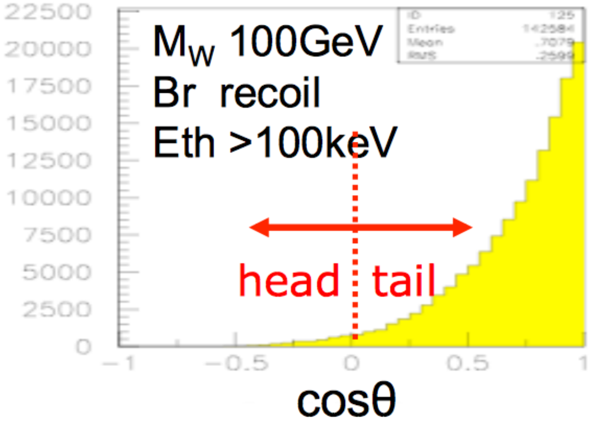
- ρ_W , WIMP density in the laboratory
  - Local measurements suggests ~0.4 GeV/cm^3 but adopted reference is 0.3
  - Observed rate $\propto \sigma_n \times \rho_W$
- f(v), WIMP velocity distribution
  - Dependence on average v_{rms}, not much on f(v) details (except: modulation)
  - Adopted reference: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

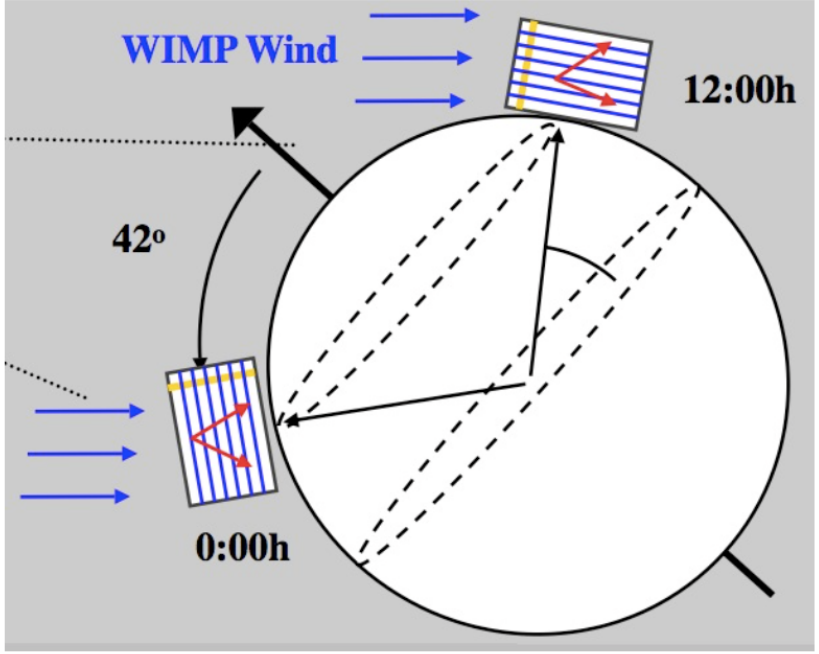
- Last two ingredients usually left as free parameters of the searches:
- M_W , WIMP mass
  - Taken from SUperSYmmetric (or other) Model prediction
  - Method works from a few GeV/c^2 to >10 TeV/c^2
  - Typical SUSY range: from 50 GeV/c^2 to 1 TeV/c^2
- σ_n, WIMP-nucleon cross-section
  - Taken from 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



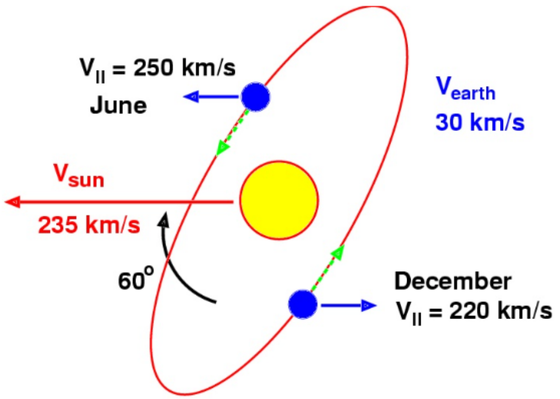
Spooner, IDM2008

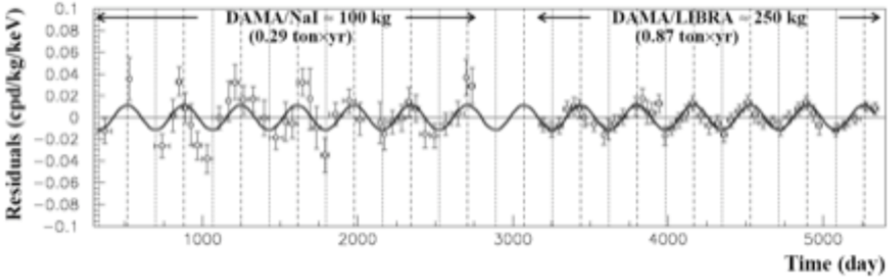
- Need a good resolution on the recoil direction (and head/tail discrimination) despite the very short range of the recoil
- Astrophysics bonus: measure of f(v)

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