Dark Matter Detection

INDIRECT [and DIRECT]

Paolo Lipari
LC09 workshop
Perugia 24th september 2009

DARK MATTER: we know a lot :

It exists (no modified gravity for the bullet cluster!)

Good estimate of the cosmological average (22%)

Most of it is non baryonic

Most of it is “cold”

It cannot be explained by the Standard Model
in Particle Physics

PHYSICS beyond the STANDARD MODEL is **REQUIRED** to explain Dark Matter !!

Extension of the Standard Model are EXPECTED at the electroweak mass scale

These extensions can "naturally" result in the existence of Dark Matter !

Are LHC/ILC and DARK Matter searches studying the same Physics ?

Are LHC/ILC and DARK Matter searches studying the same Physics ?

This is certainly possibles !
[... but not necessary ...]

The physics may or may not be related

Lines of investigations that are independent and complementary

Problems with a different status:
DM problem : direct observational puzzle.
New physics at EW scale : theoretically motivated prediction

...there is a lot we do not know about DM....

Possible theoretical ideas:

THERMAL RELIC (WIMP + variants)

AXION (phase space condensate)

SUPERMASSIVE particles ...

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The “WIMP miracle”

$$\langle\sigma\, v\rangle_{T_F} \simeq 3 \times 10^{-26}\ \mathrm{cm}^3\, \mathrm{s}^{-1}$$

Relic density

$$\Omega_\chi \propto \frac{1}{\langle\sigma\, v\rangle}$$

$$\sigma \sim \frac{\alpha^2}{M^2}$$

$$M \sim 100\ \mathrm{GeV}$$

Electroweak scale !

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Warning !
Loopholes
are possible

$$M \sim 100\ \mathrm{GeV}$$

Electroweak scale !

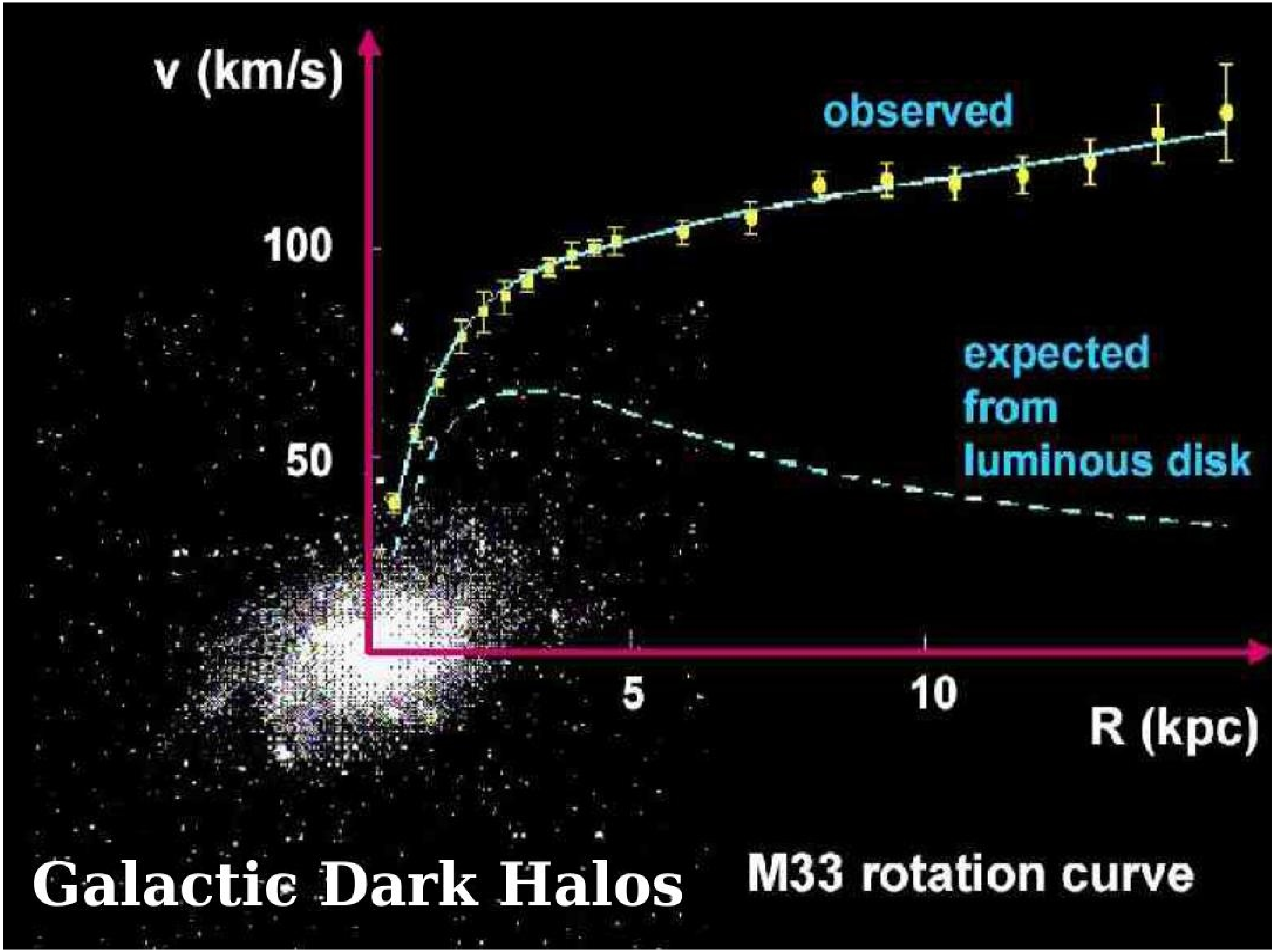
Evidence of DM at different Length scales

Cosmological

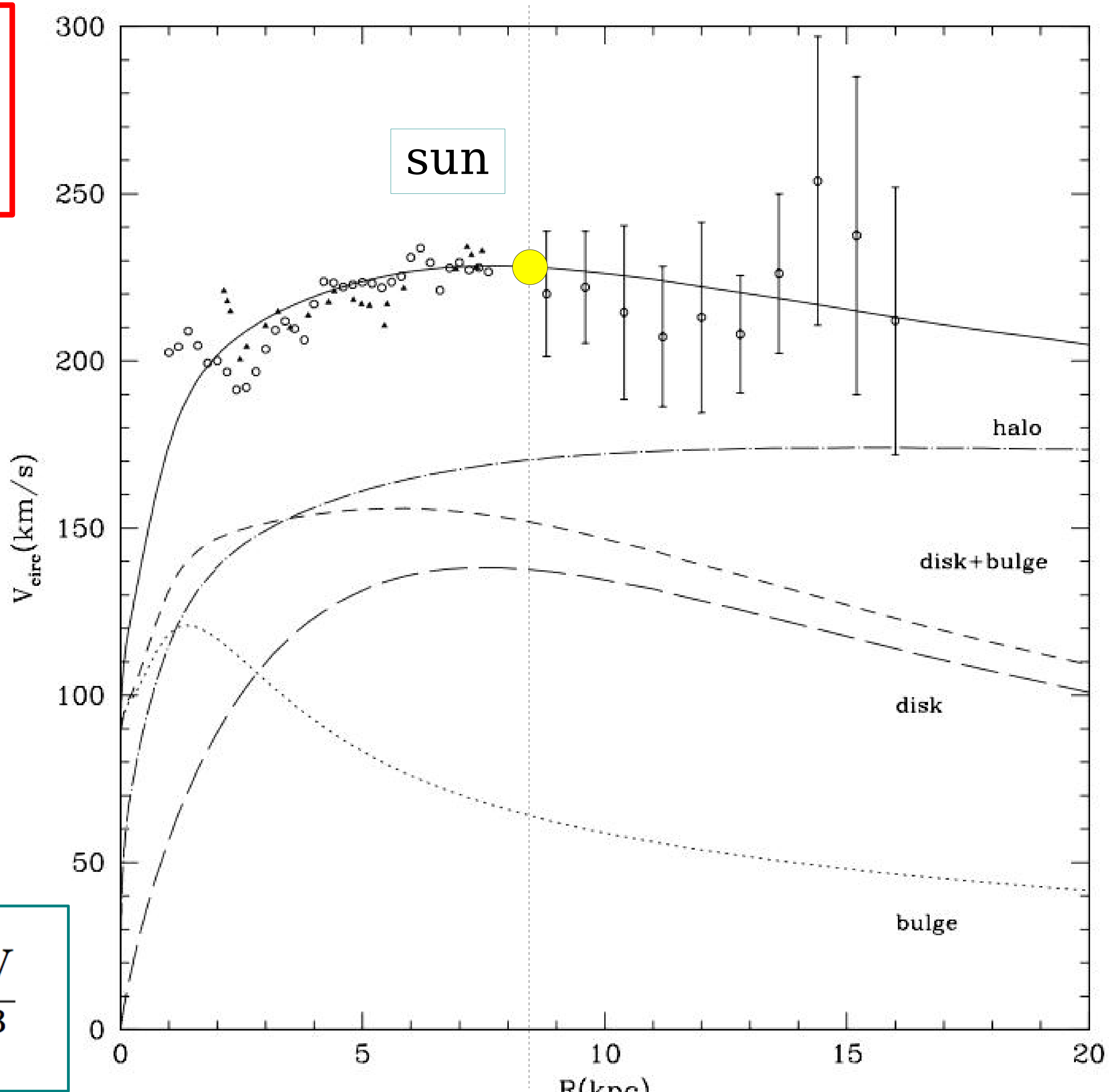
Very Large Scale

Clusters of Galaxies

GALAXIES



MILKY WAY



$$\rho_\oplus \simeq 0.3\ \frac{\text{GeV}}{\text{cm}^3}$$

Astrophysical information

Dark Matter in the Milky Way

$$\rho_{\rm dm}(\vec{x})$$

Dark Matter
density distribution

$$f_{\rm dm}(\vec{v}, \vec{x})$$

Velocity distribution

[consistency requirement]

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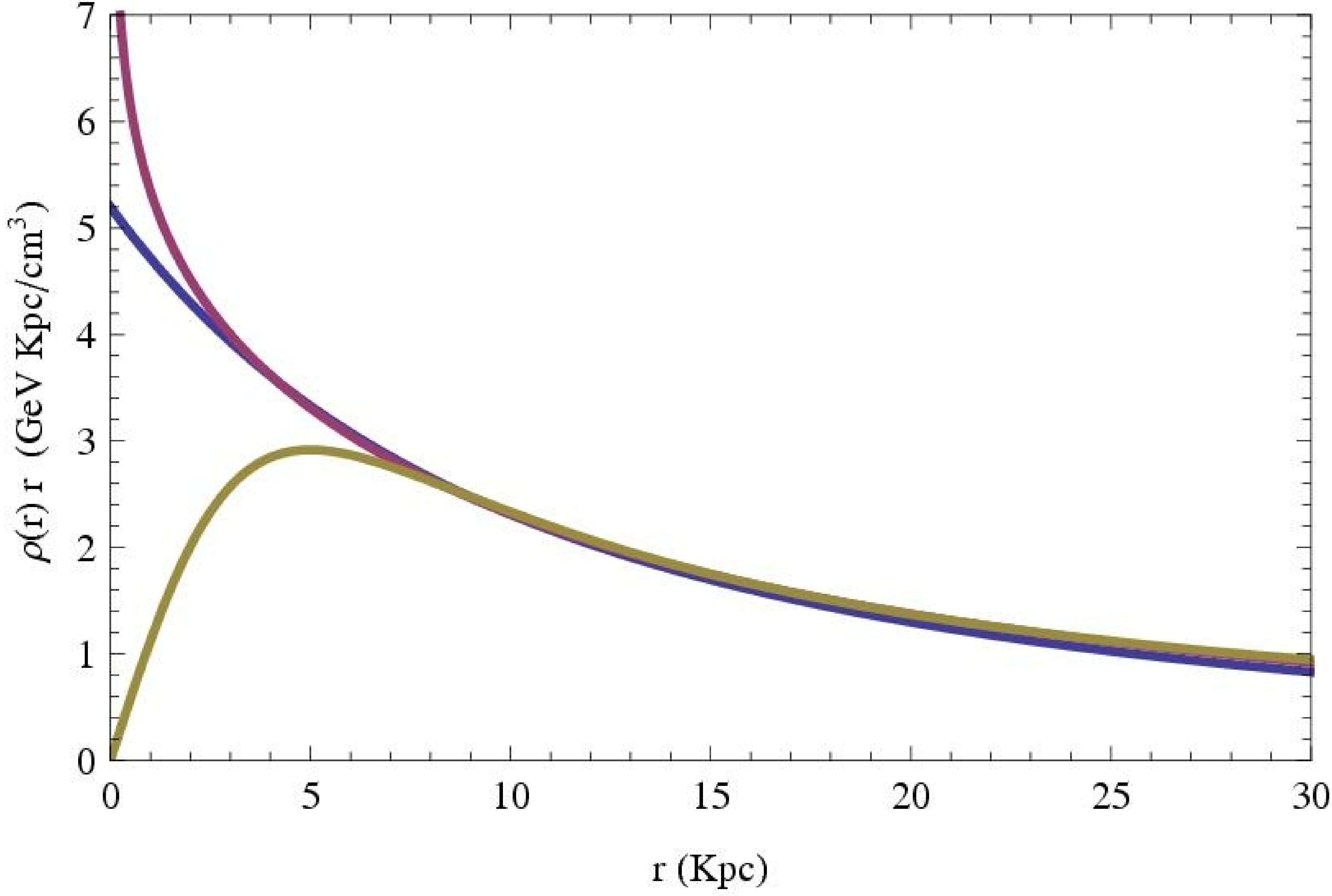
Velocity distribution

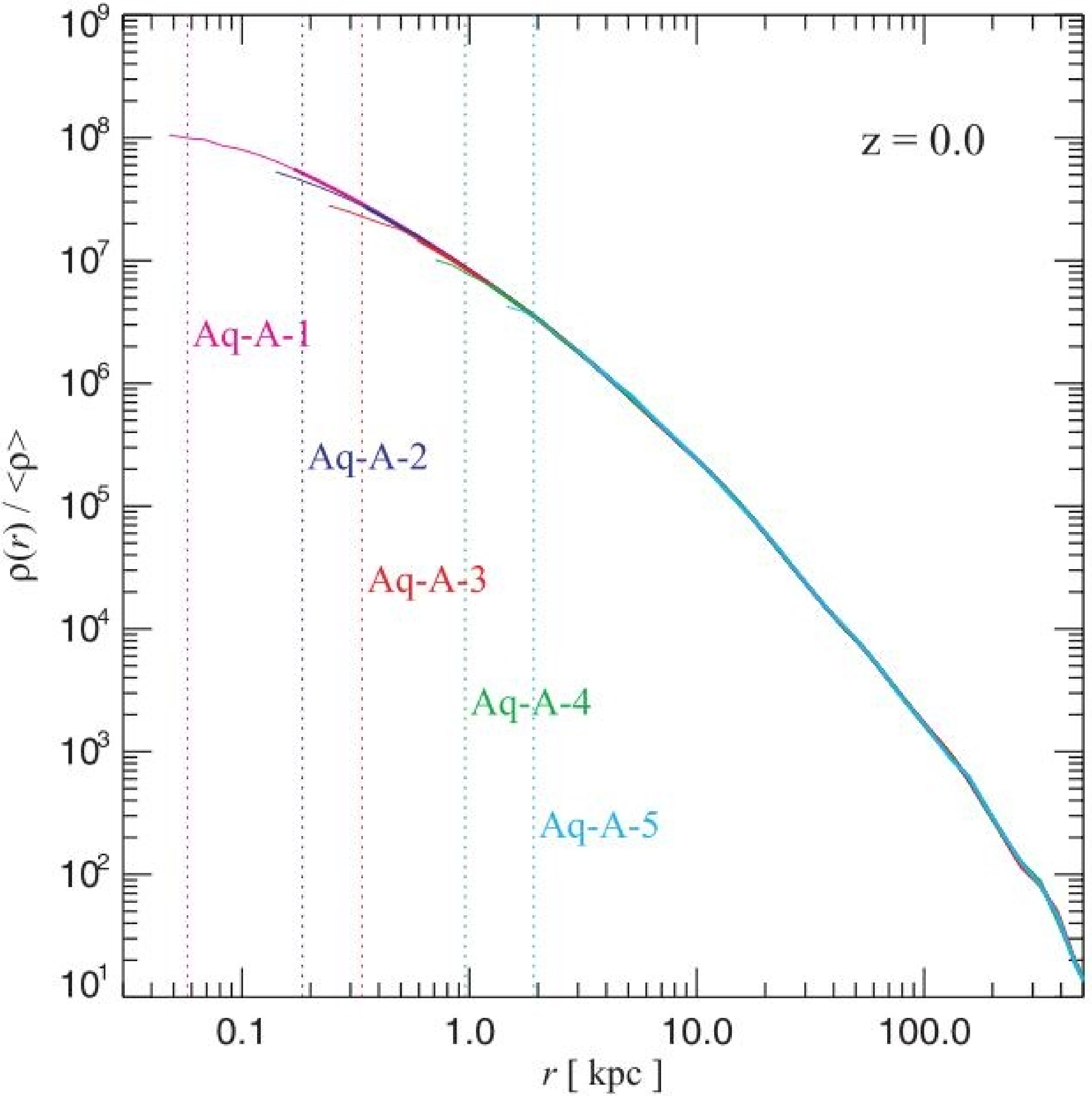
[consistency requirement]

Problems:

- "The CUSP"
- "Granularity" ["the BOOST factor"]

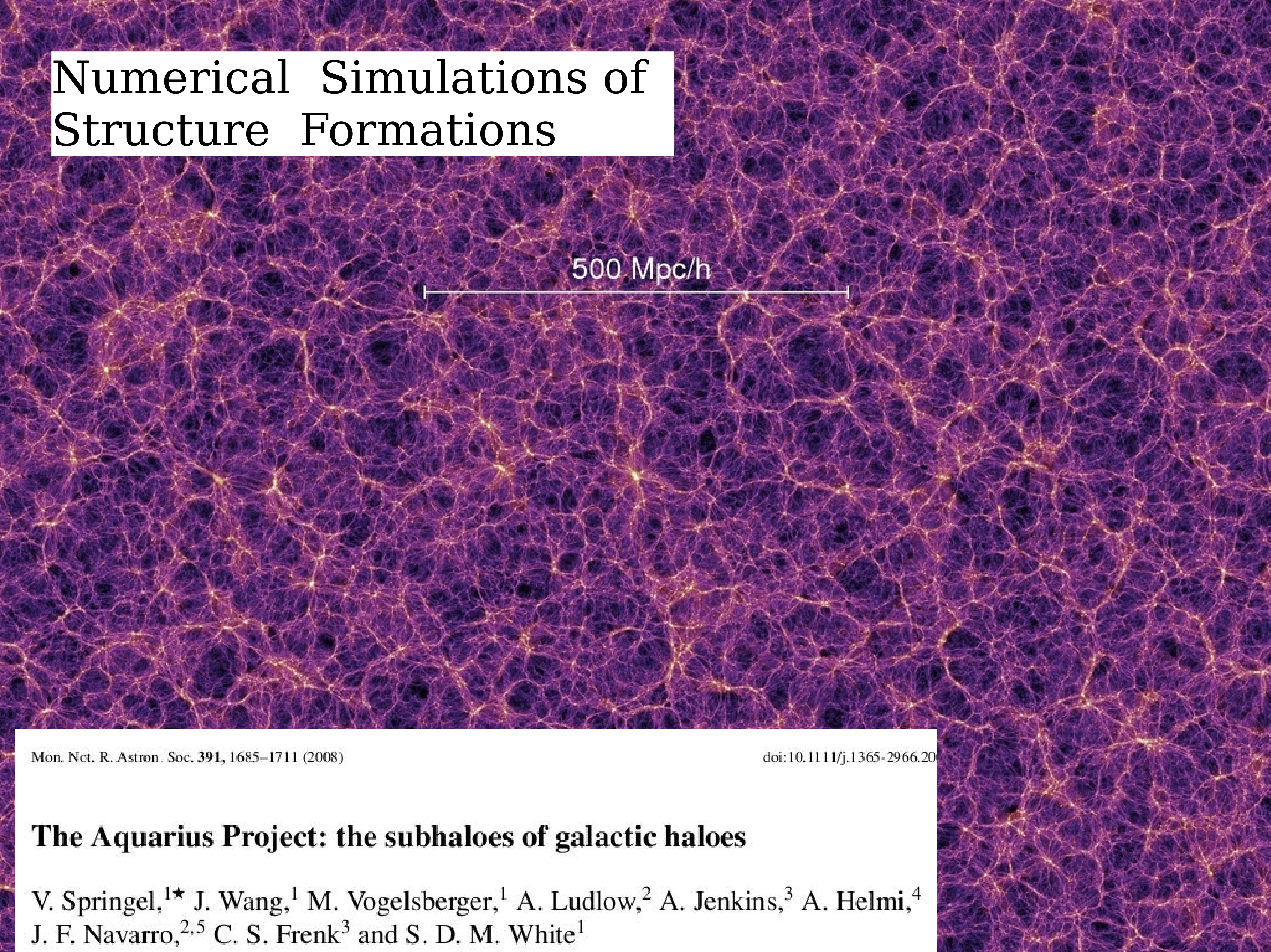
Isothermal		(constant)
"NFW"	(Navarro-Frenk-Wolf)	(1/r divergence)
"Moore"		(stronger divergence)





Shape of the
"CUSP"

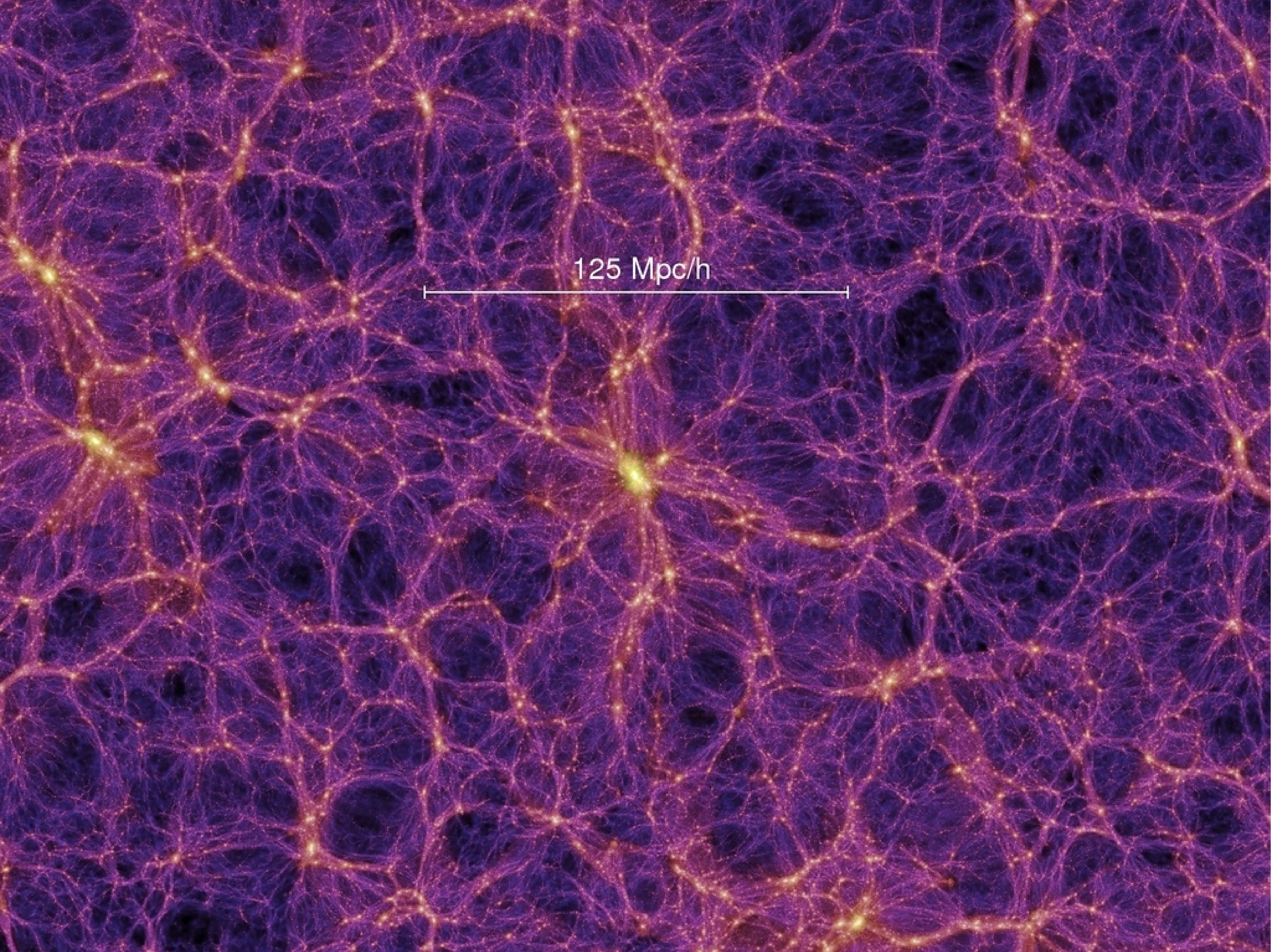
Numerical Simulations of Structure Formations

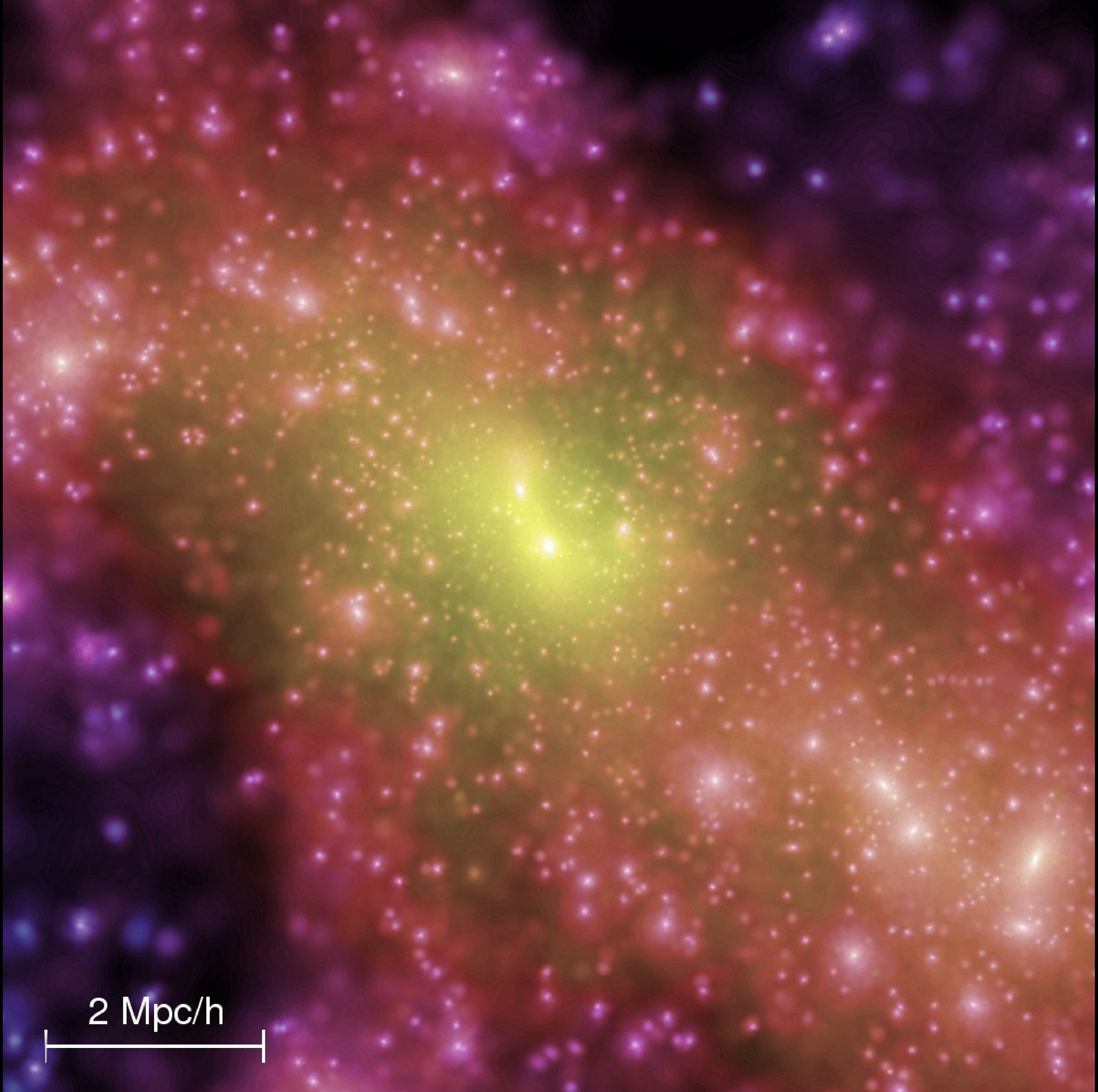


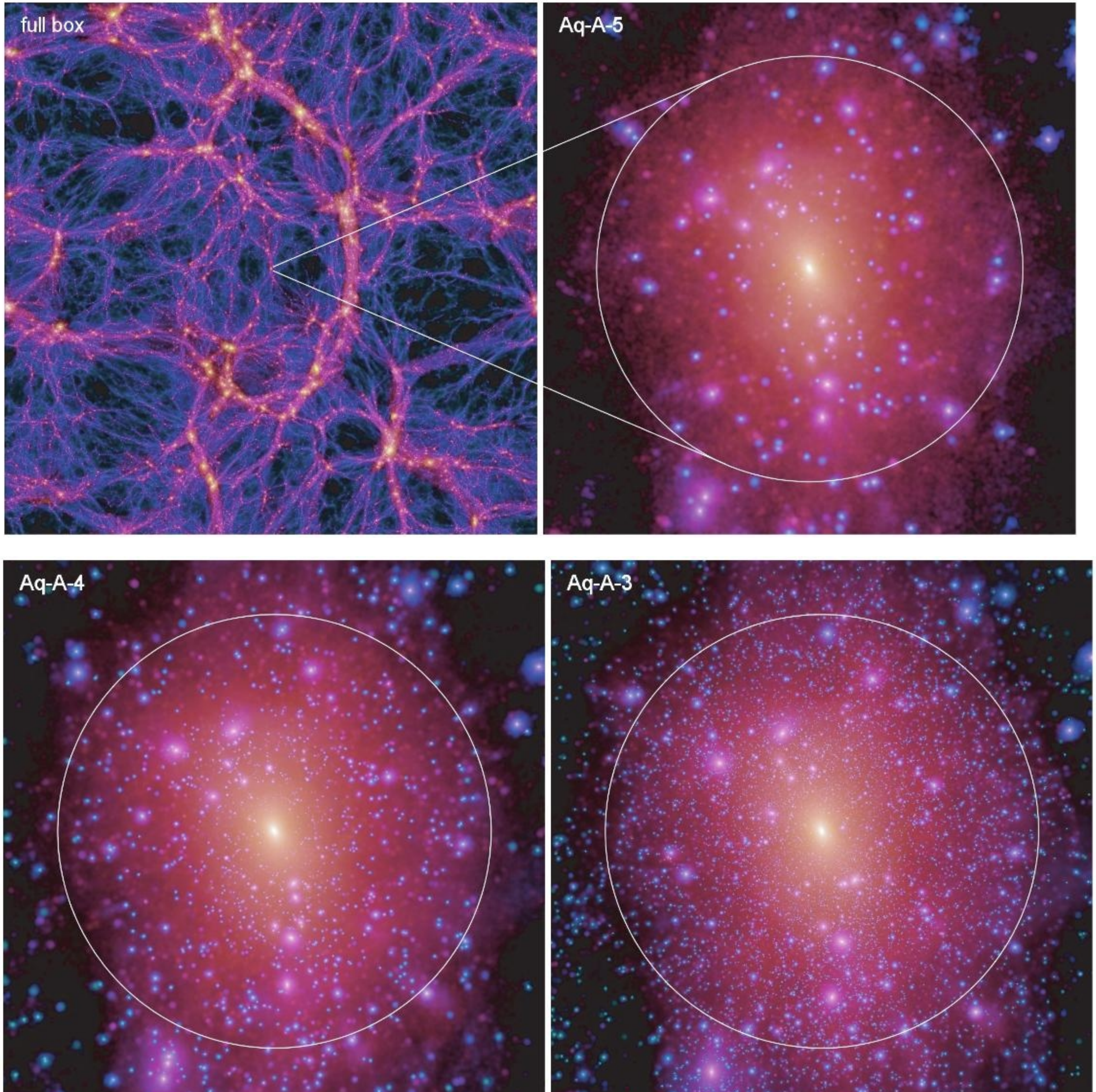
Mon. Not. R. Astron. Soc. **391,** 1685–1711 (2008) doi:10.1111/j.1365-2966.20

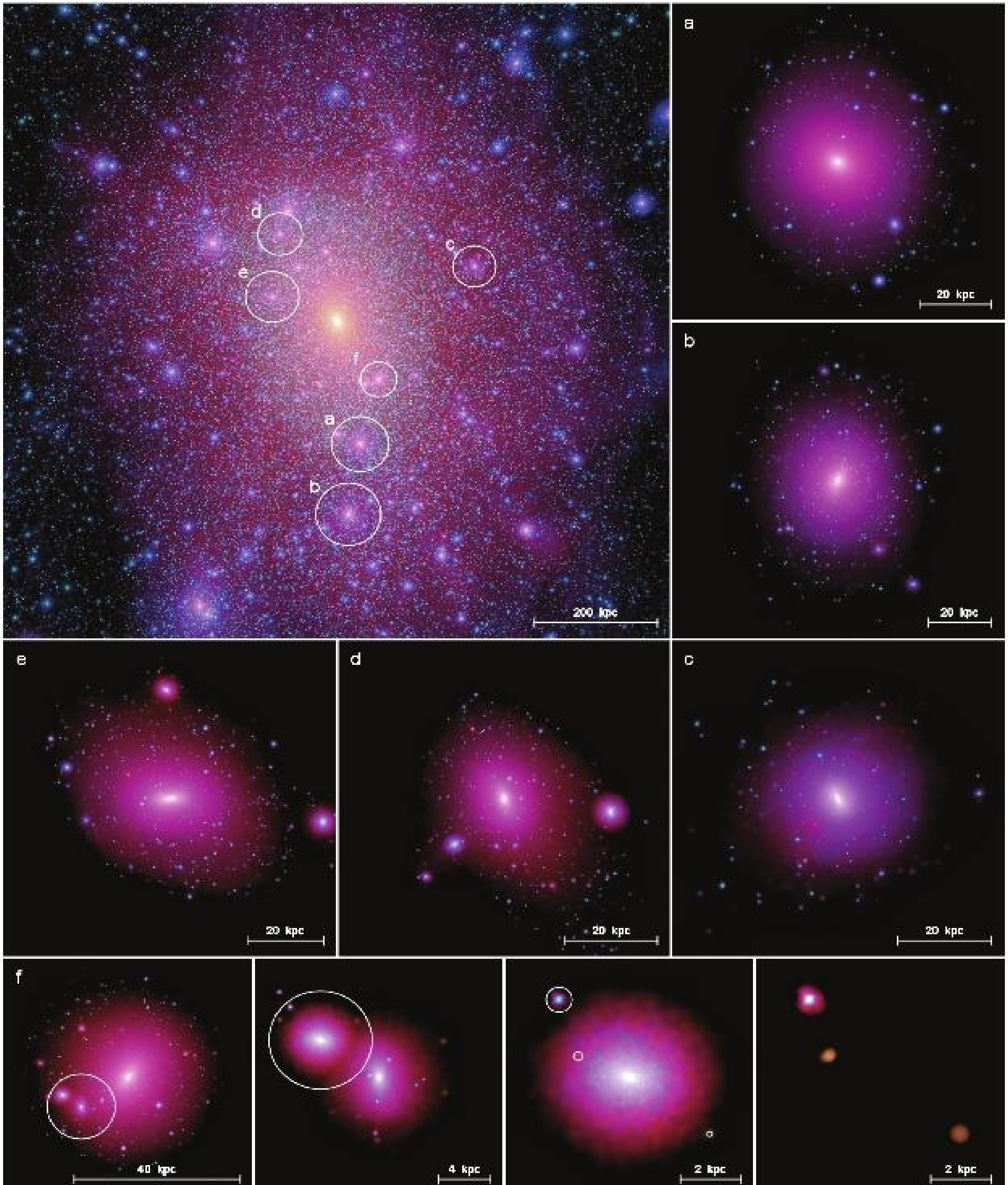
The Aquarius Project: the subhaloes of galactic haloes

V. Springel,[1★] J. Wang,[1] M. Vogelsberger,[1] A. Ludlow,[2] A. Jenkins,[3] A. Helmi,[4]
J. F. Navarro,[2,5] C. S. Frenk[3] and S. D. M. White[1]


125 Mpc/h


2 Mpc/h


full box
Aq-A-5
Aq-A-4
Aq-A-3



Significant Structure in DM

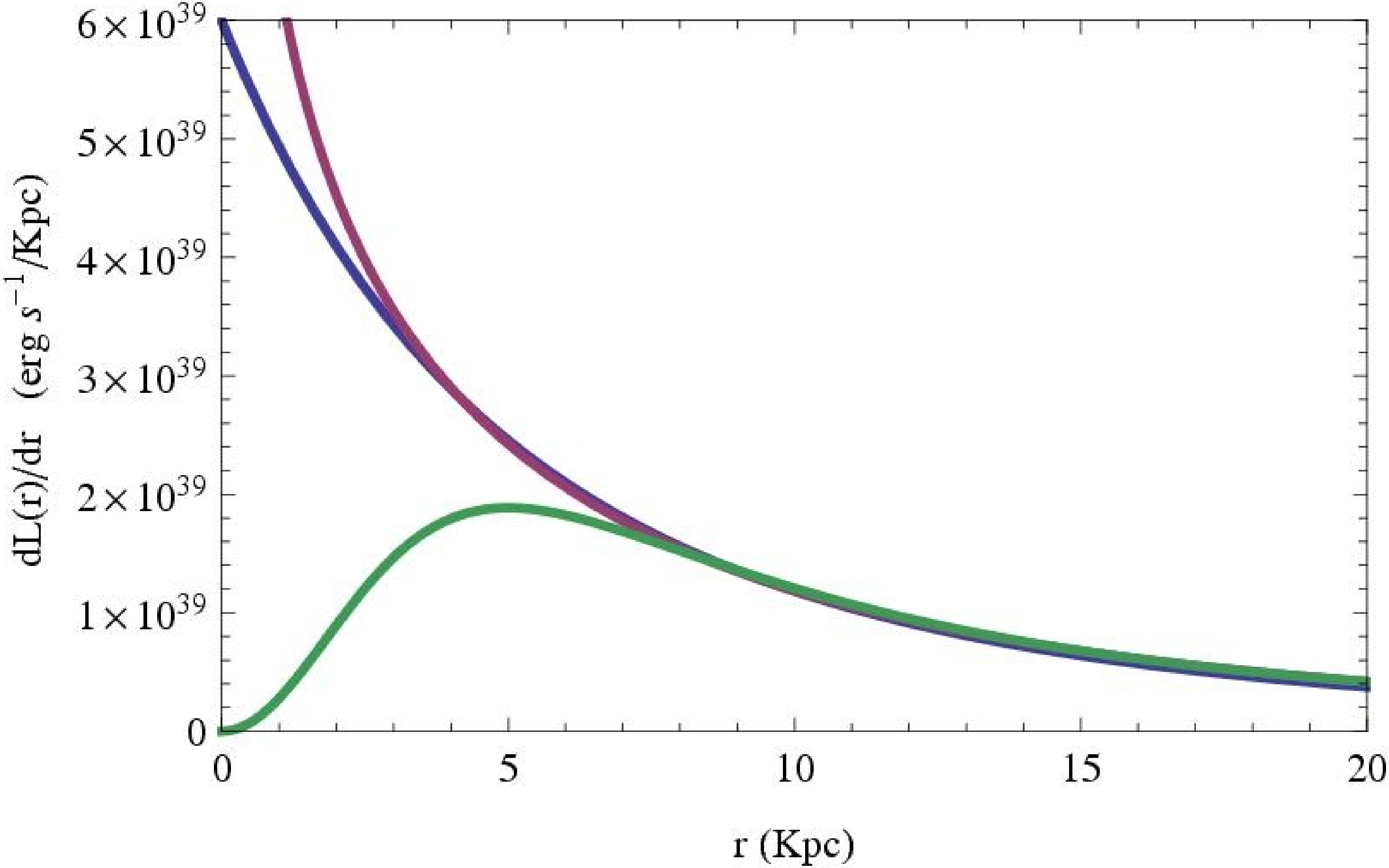
“Boost factor”

Power injection for Dark Matter annihilation

$$L(\vec{x}) = \frac{\rho(\vec{x})^2}{{M_\chi}^2} \langle \sigma \; v \rangle \; M_\chi$$

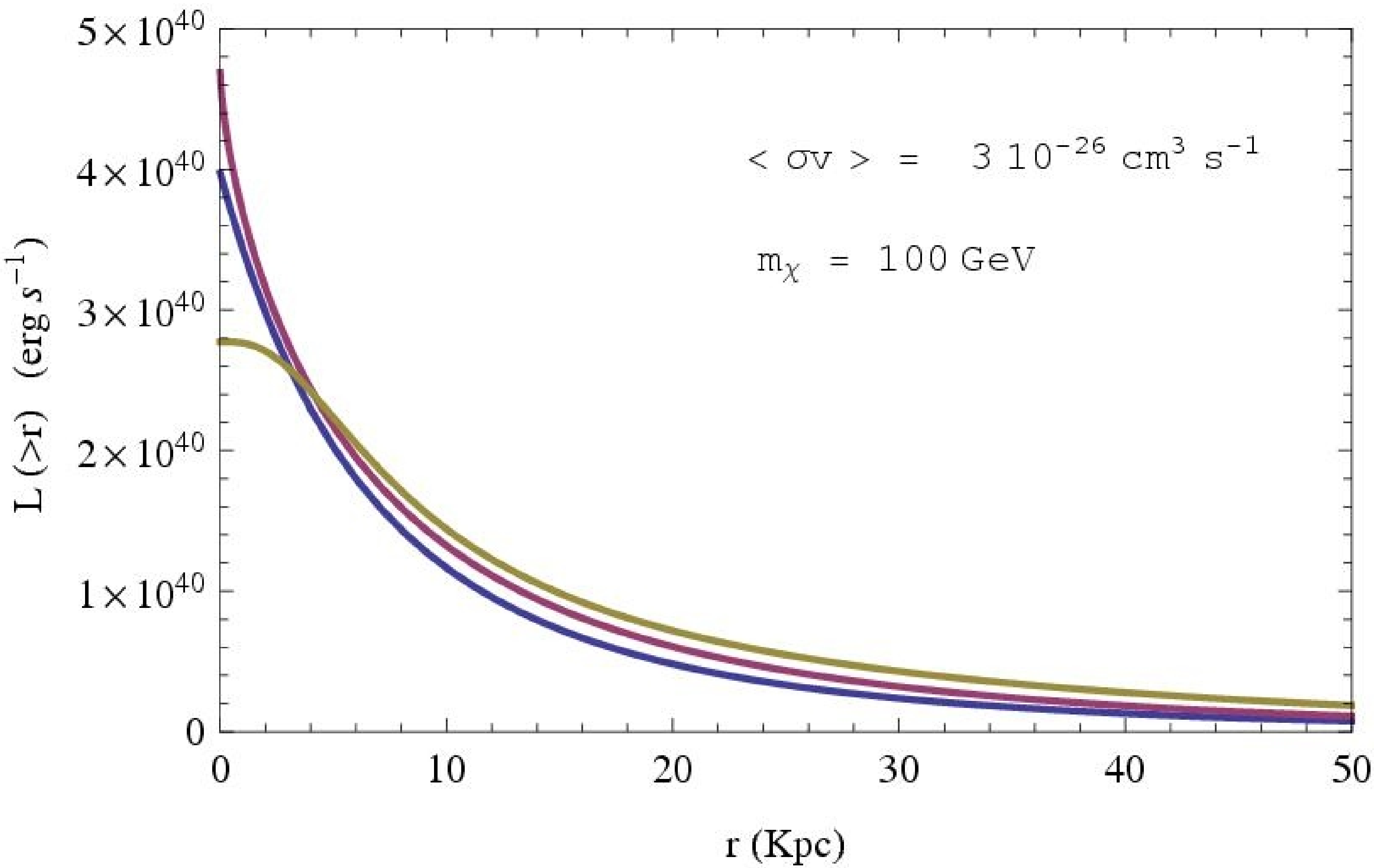
$$\chi + \chi \to \gamma \qquad e^+ \qquad \overline{p} \qquad \nu_\alpha$$

Power injection from DM annihilation



Power injection from DM annihilation

$$L_{\rm Galaxy}^{\rm DM} \simeq 4 \times 10^{40}\ \frac{\rm erg}{\rm s} \left[\frac{\langle \sigma v \rangle}{3 \times 10^{-26}\,{\rm cm}^3\,{\rm s}^{-1}}\right] \left[\frac{100\ {\rm GeV}}{M_\chi}\right] \times {\rm Boost}$$



$$L(\vec{x}) = \frac{\rho(\vec{x})^2}{{M_\chi}^2} \langle \sigma \; v \rangle \; M_\chi$$

- $$L_{\rm DM} \propto \frac{1}{M_\chi}$$

- $$\langle \rho(\vec{x})^2 \rangle \geq \langle \rho(\vec{x}) \rangle^2$$

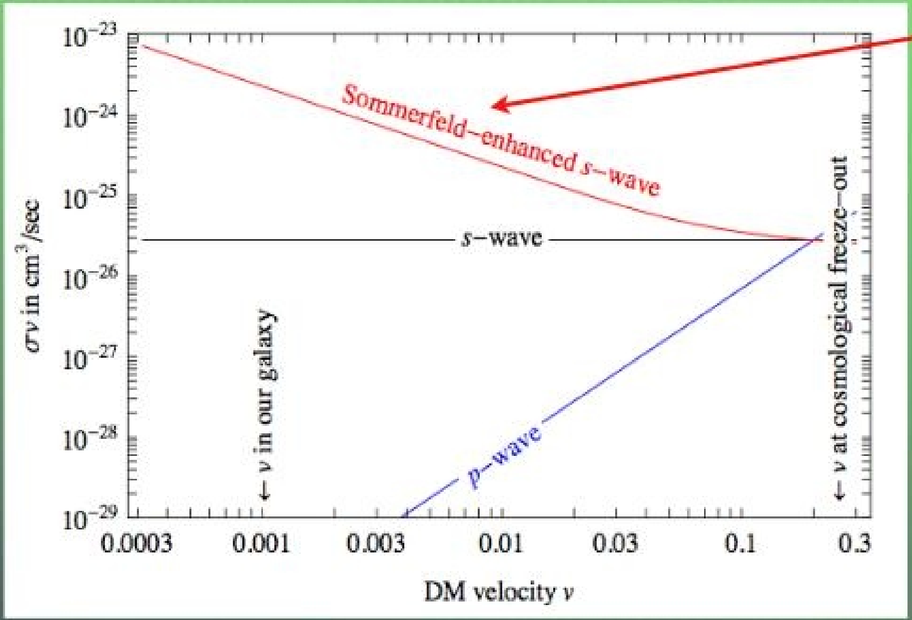
  "Granularity" boosts the power output.

- The "WIMP miracle" $\quad v_{\rm freeze\ out} \simeq 0.2 \div 0.3$

$$\langle \sigma \, v \rangle \simeq 3 \times 10^{-26} \ {\rm cm}^3 \, {\rm s}^{-1} \qquad v_{\rm Galaxy} \simeq 10^{-3}$$

First possibility: Sommerfeld effect

Different possibilities for extrapolating the cross section from the early Universe:



a non-perturbative enhancement in the cross section at low velocities

Hisano, Matsumoto & Nojiri,(2003); e.g.: Cirelli et al., arXiv:0809.2409

DM is charged under a (new) gauge force, mediated by a "light" boson: this sets a non-perturbative long-range interaction, analogously to Coulomb interaction for positronium:

$$V(r) = -\frac{\alpha}{r}$$

gives the enhancement in the cross section:

$$S = \left|\frac{\psi(\infty)}{\psi(0)}\right|^2 = \frac{\pi\,\alpha/v}{1 - e^{-\pi\,\alpha/v}} \xrightarrow{v \ll \alpha} \frac{\pi\,\alpha}{v}$$

The same 1/v enhancement is obtained for a Yukawa potential. In a DM context, first studied in the MSSM for pure very massive Winos or Higgsinos and weak interaction as gauge force (light W boson l

Piero Ullio

Annihilation cross section

$$\sigma(\chi + \overline{\chi} \to \text{anything}, v_{\rm rel})$$

$$\left.\frac{dn}{dE}\right|_{(\chi+\chi\to\gamma)}$$

$$\left.\frac{dn}{dE}\right|_{(\chi+\chi\to\gamma,e^+,\overline{p},\nu_\alpha)}$$

Inclusive spectra

$$B(\chi + \overline{\chi} \to F)$$

Branching Ratios
in different final states F

In most models
DM particle =
Majorana particle

DM – Nuclei Elastic Scattering

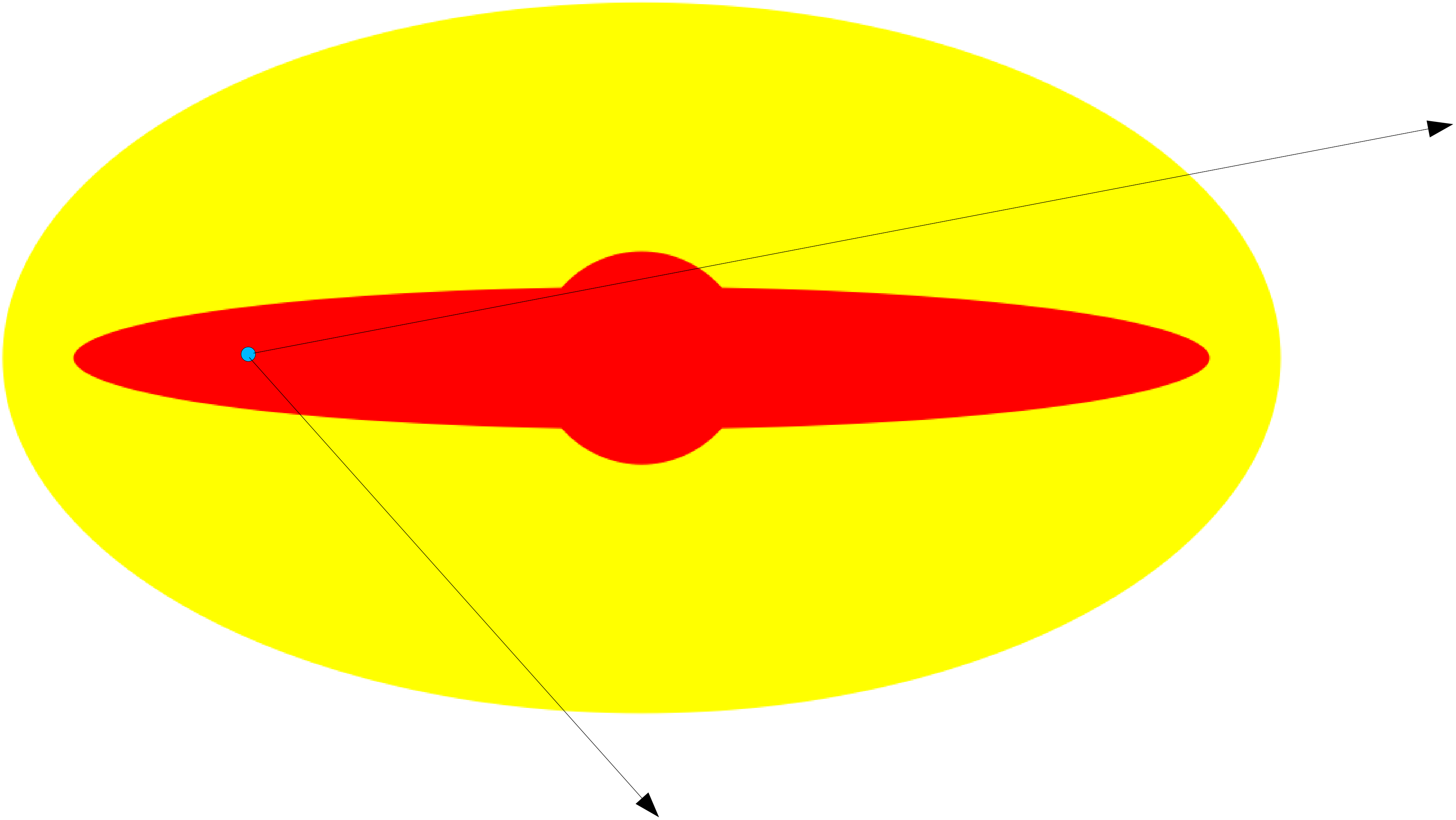
$$\sigma(\chi + A \to \chi + A)$$

$$\left.\frac{d\sigma}{d\cos\theta^*}\right|_{(\chi+A\to\chi+A)}$$

Direct detection
Accretion in Sun, Stars….

[effect on Star formation
near the galactic center]

Photon emission from DM annihilation



$$J(\Omega) = \frac{1}{R_\odot} \int_0^\infty d\ell \; \rho(\ell;\Omega)$$

Photons from Dark Matter

$$\phi_\gamma(\Omega) = K_\gamma \; J(\Omega) \; \frac{dn}{dE}(E)\Big|_{\chi\chi\to\gamma}$$

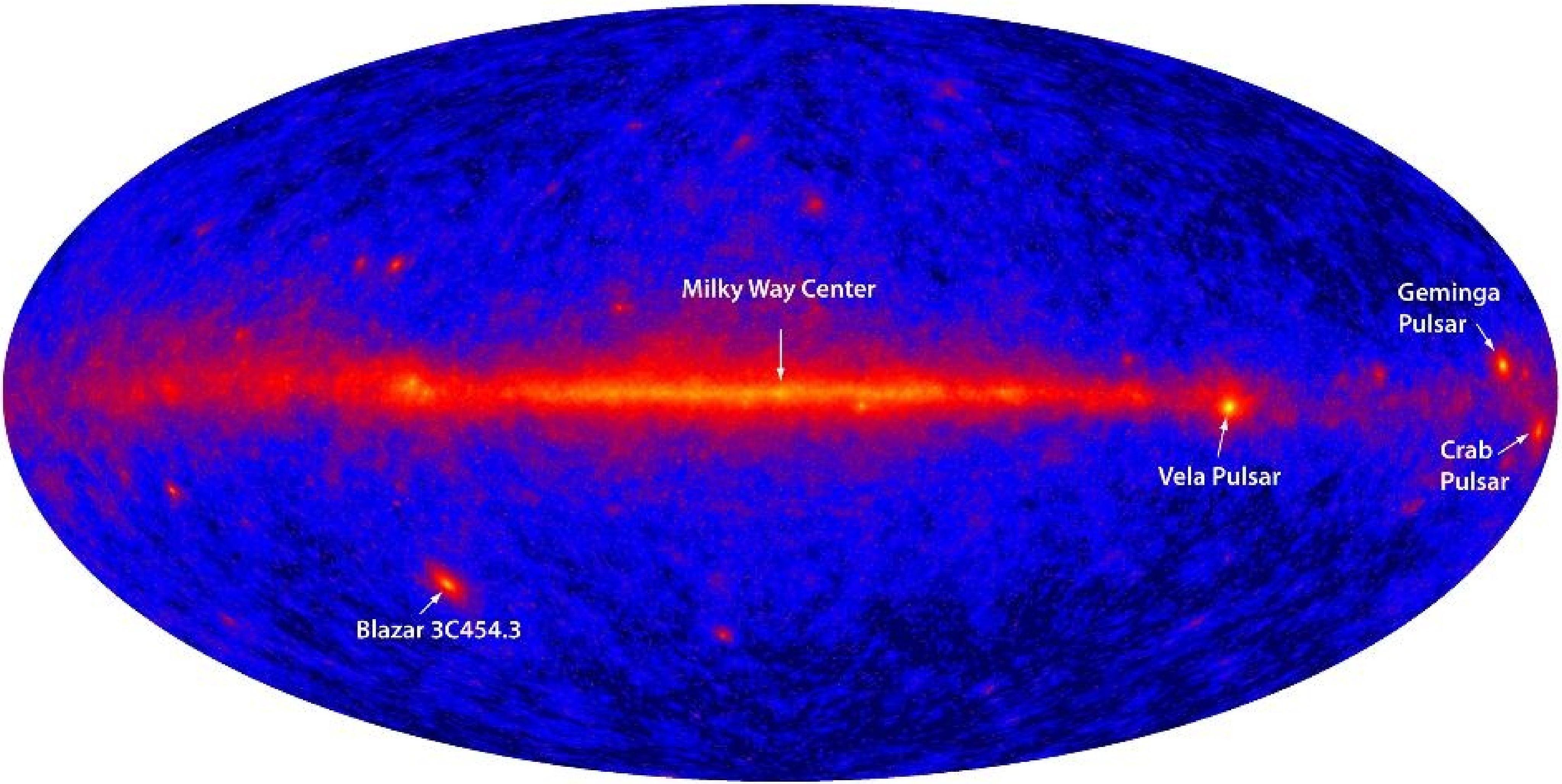
Spectrum

$$K_\gamma = \frac{1}{4\pi} \; \frac{\langle \sigma \, v \rangle}{2} \; \frac{\langle \rho_\odot \rangle^2}{{M_\chi}^2} \; R_\oplus$$

$$K_\gamma \simeq 3.7 \times 10^{-10} \; \left[\frac{\langle \sigma \, v \rangle}{3 \times 10^{-6} \, \mathrm{cm}^3 \, \mathrm{s}^{-1}}\right] \; \left[\frac{100 \; \mathrm{GeV}}{M_\chi}\right]^2$$

$$J(\Omega) = \frac{1}{R_\odot} \int_0^\infty d\ell \; \rho(\ell; \Omega)$$

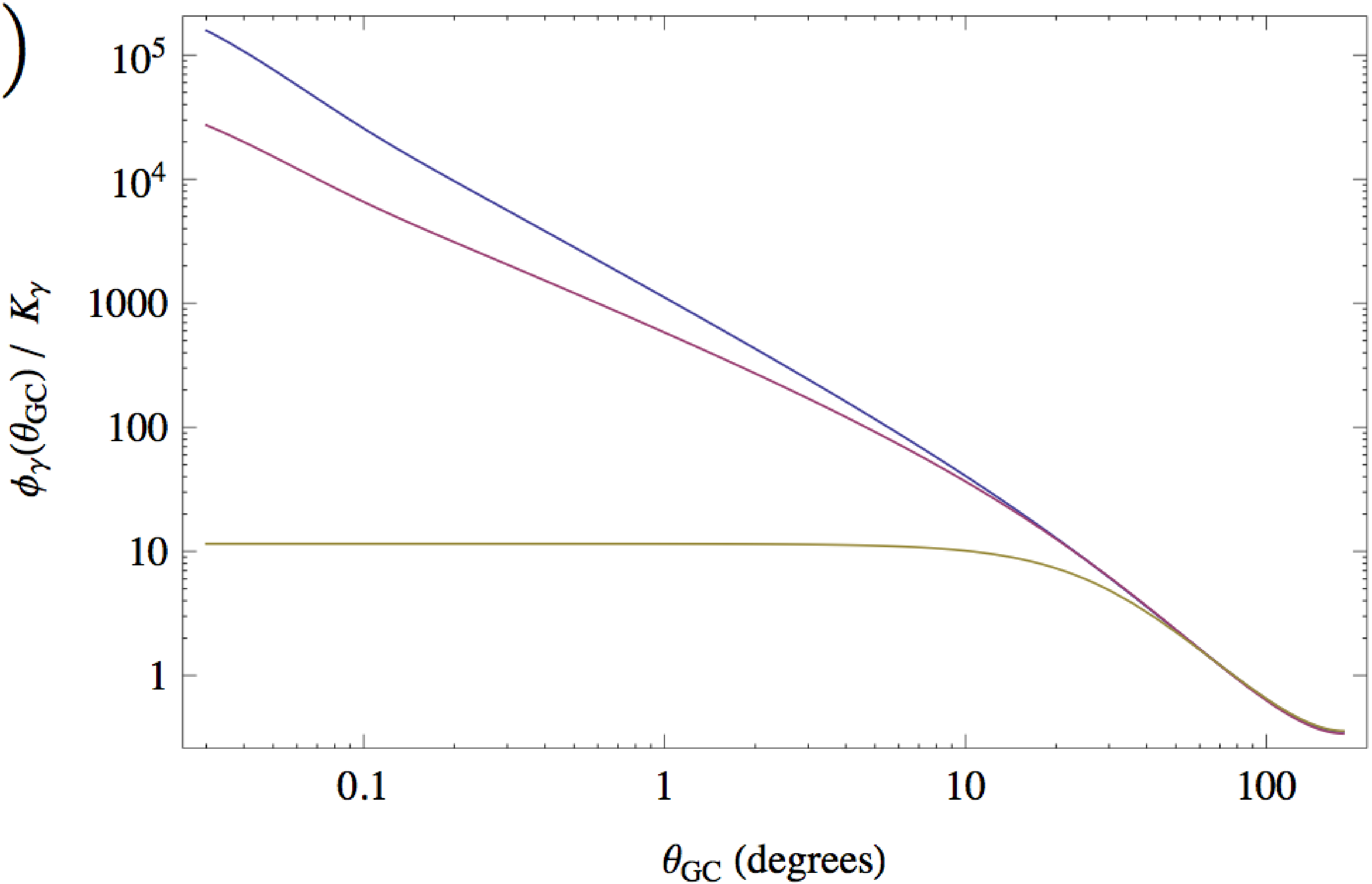
Adimensional
Angular factor



$E_\gamma > 100$ MeV

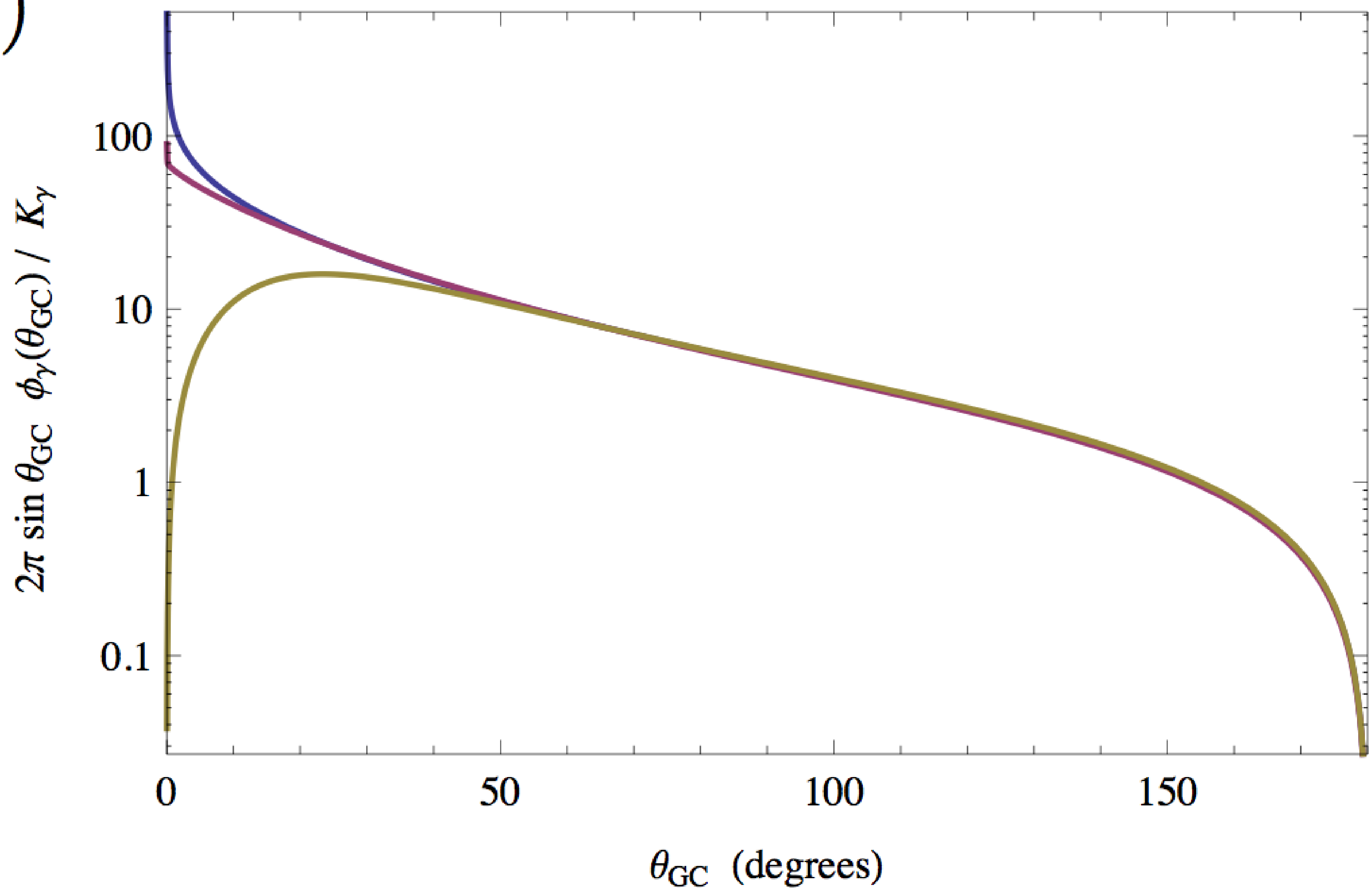
Angular dependence of the Photon flux

$J(\Omega)$

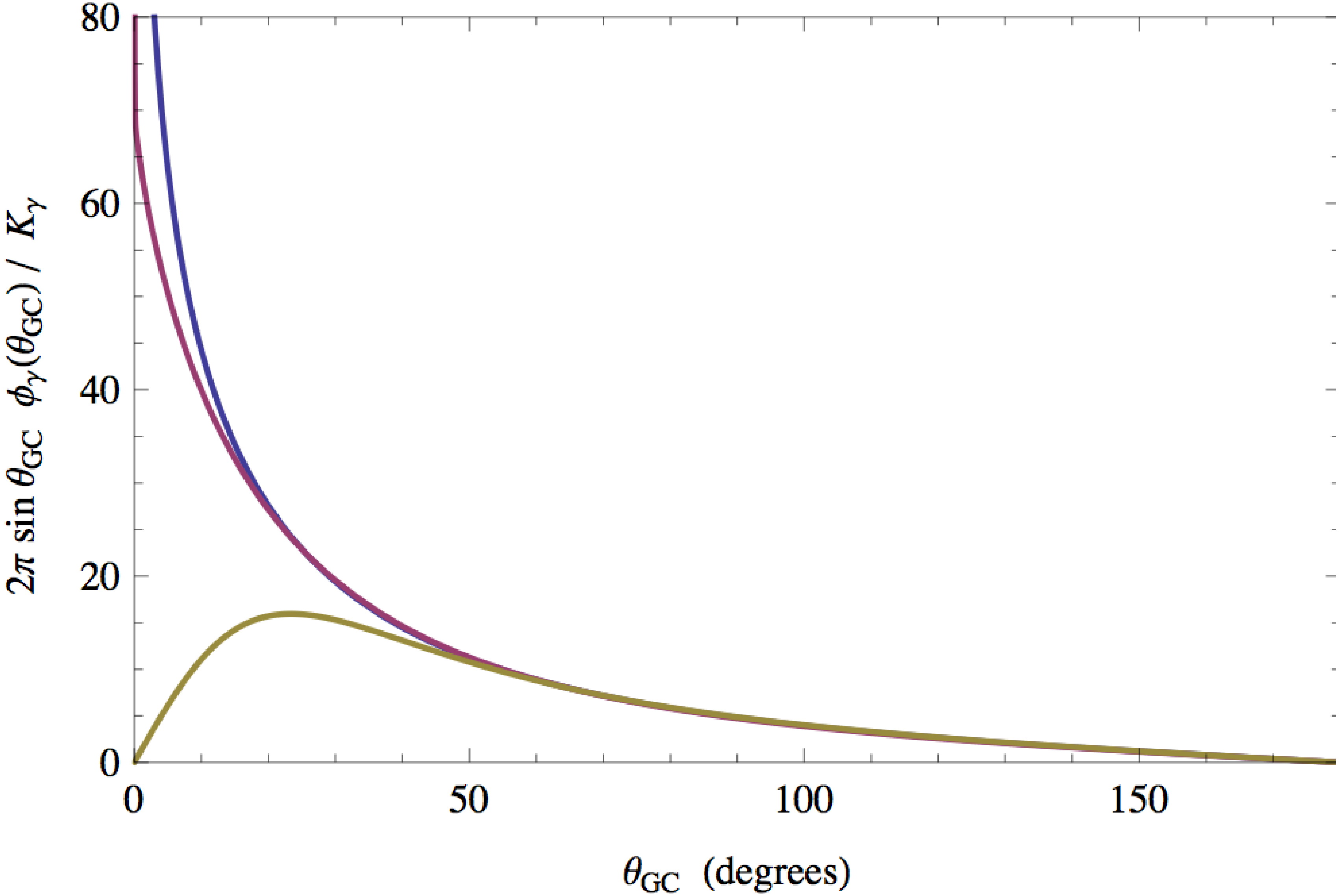


Angular dependence of the Photon flux

$J(\Omega)$



Photon rate



$$\frac{1}{4\ \pi}\int d\Omega\ J(\Omega) \simeq 3.0 \qquad (3.5, \quad 1.8)$$

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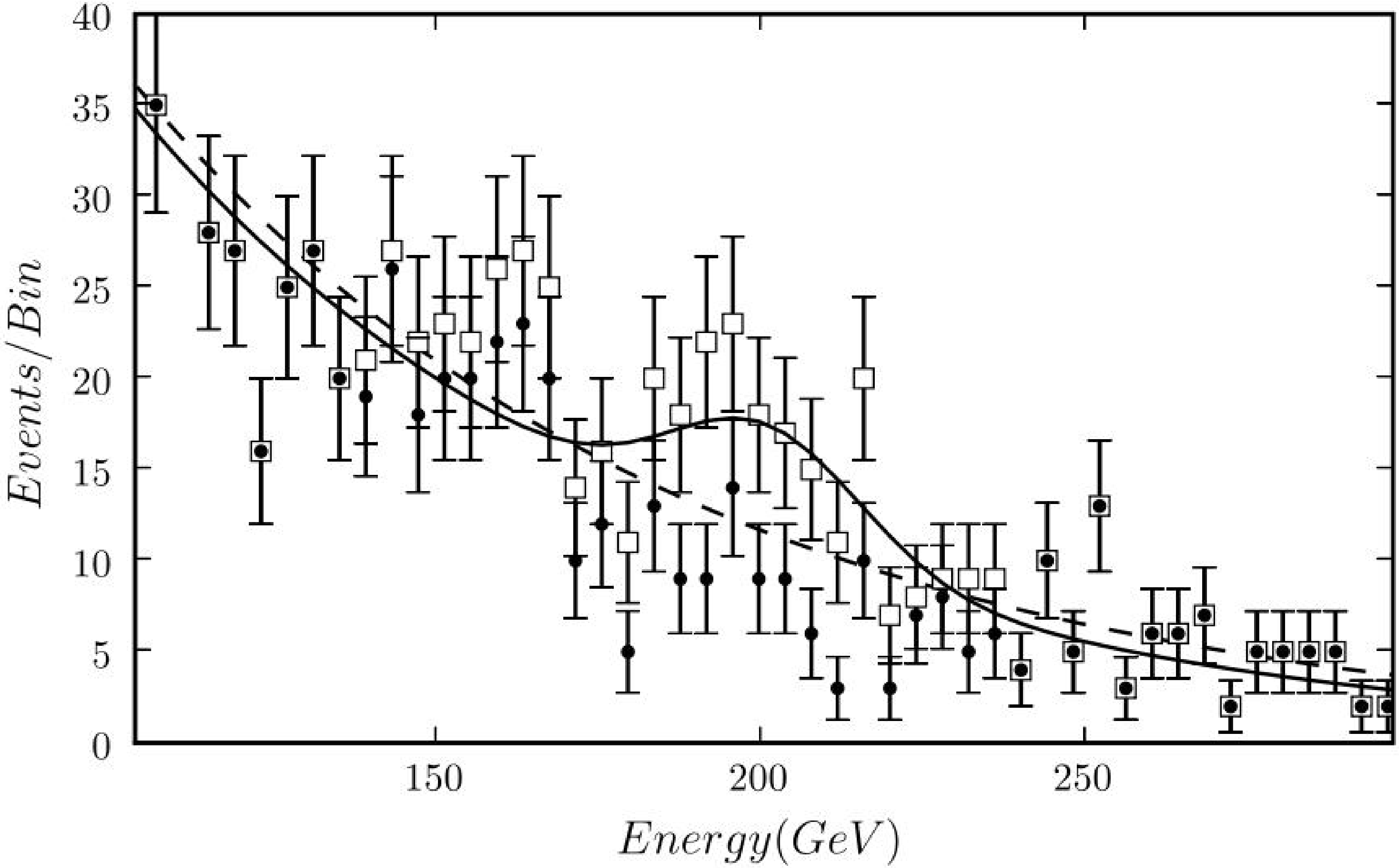
Fermi sensitivity: A = 9500 cm2

$$AT \simeq 0.45 \times 10^{11}\ \mathrm{cm}^2\ \mathrm{s}\ N_{\mathrm{years}}$$

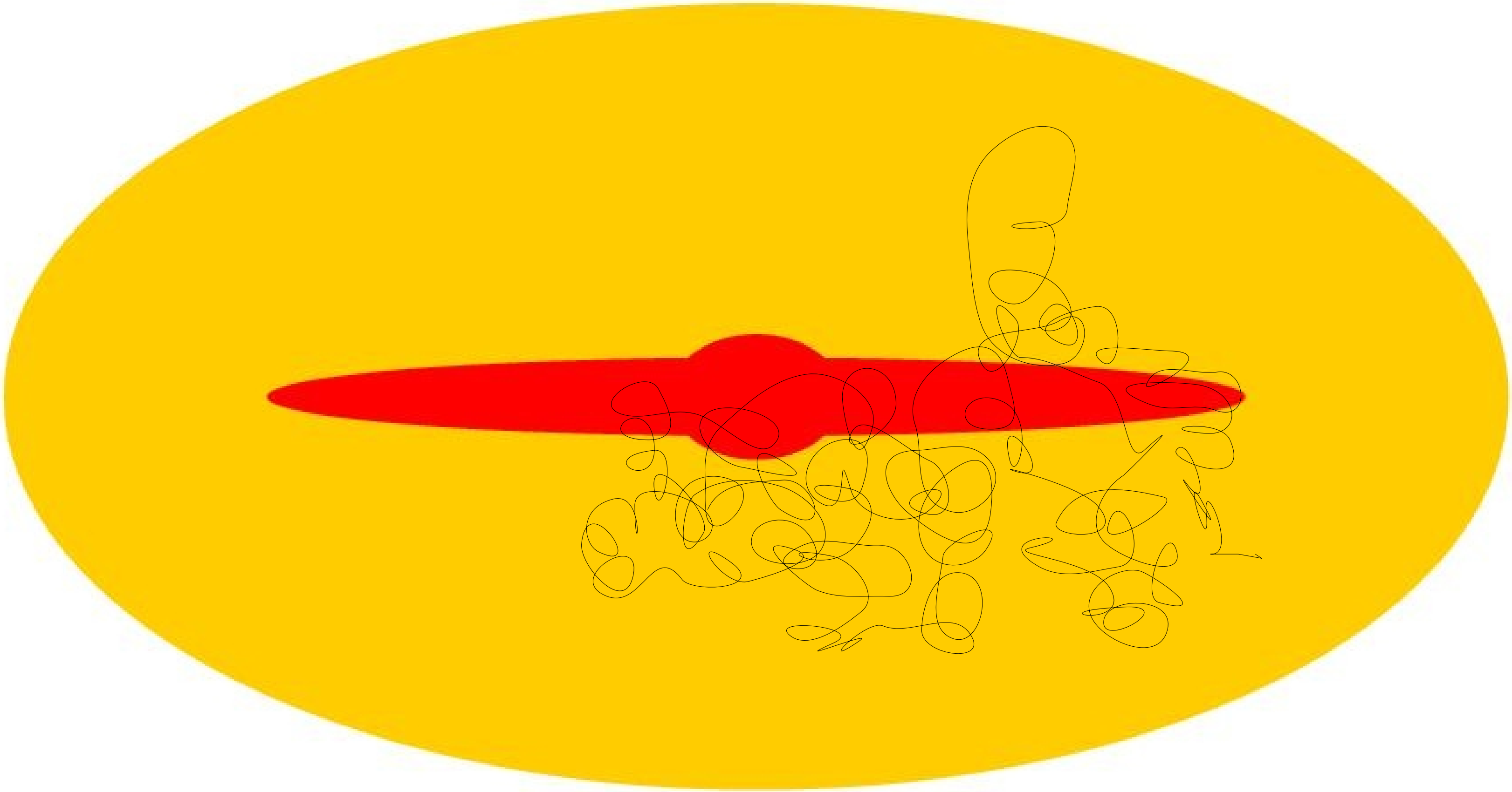
$$\boxed{N_\gamma^{\mathrm{NFW}} \simeq 430\ \left[\frac{\langle \sigma\, v\rangle}{3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}\right]\ \left[\frac{100\ \mathrm{GeV}}{M_\chi}\right]^2\ N_{\mathrm{years}}}$$

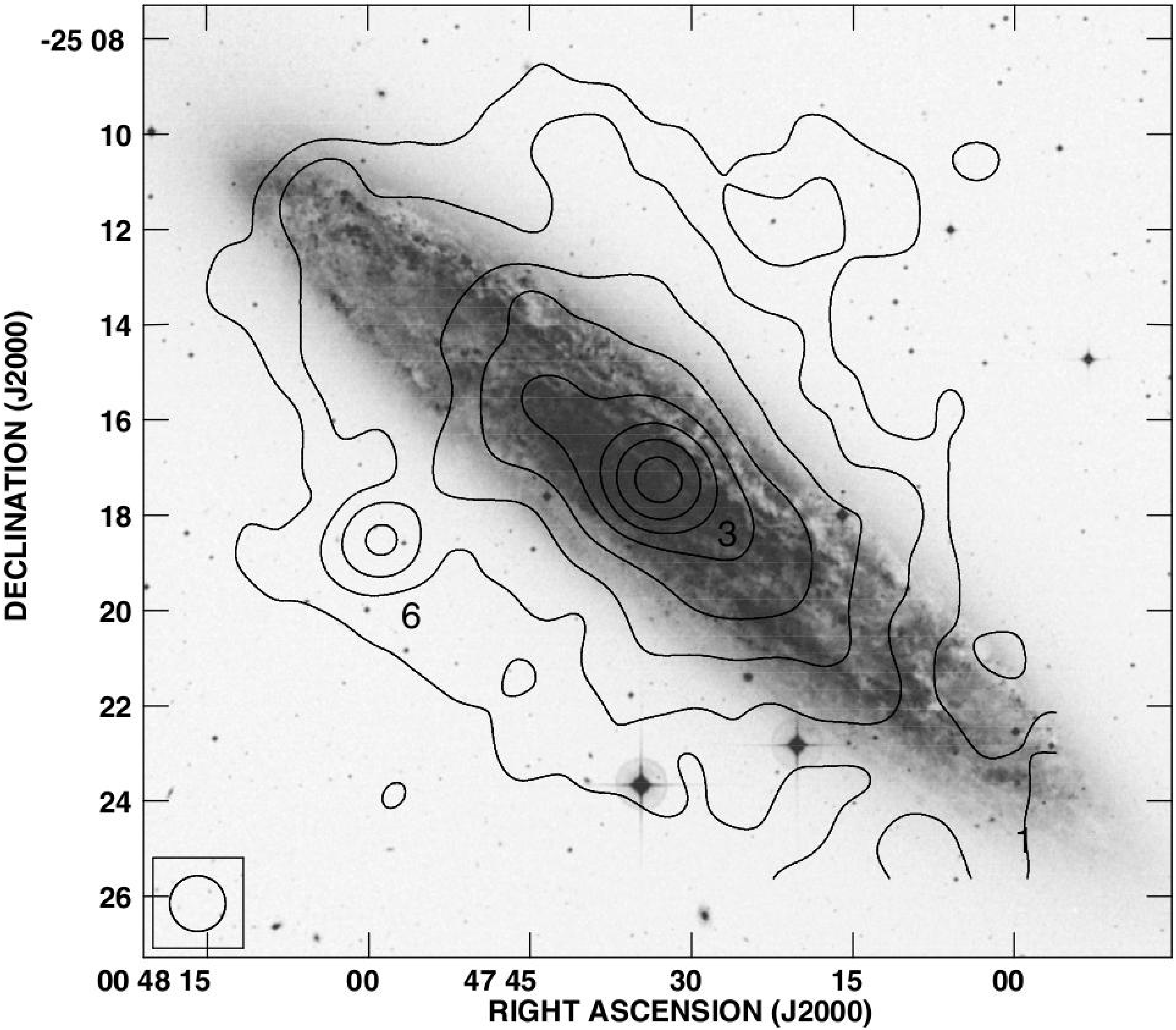


40
35
30
25
20
15
10
5
0
Events/Bin
150
200
250
Energy(GeV)

Charged Particles:

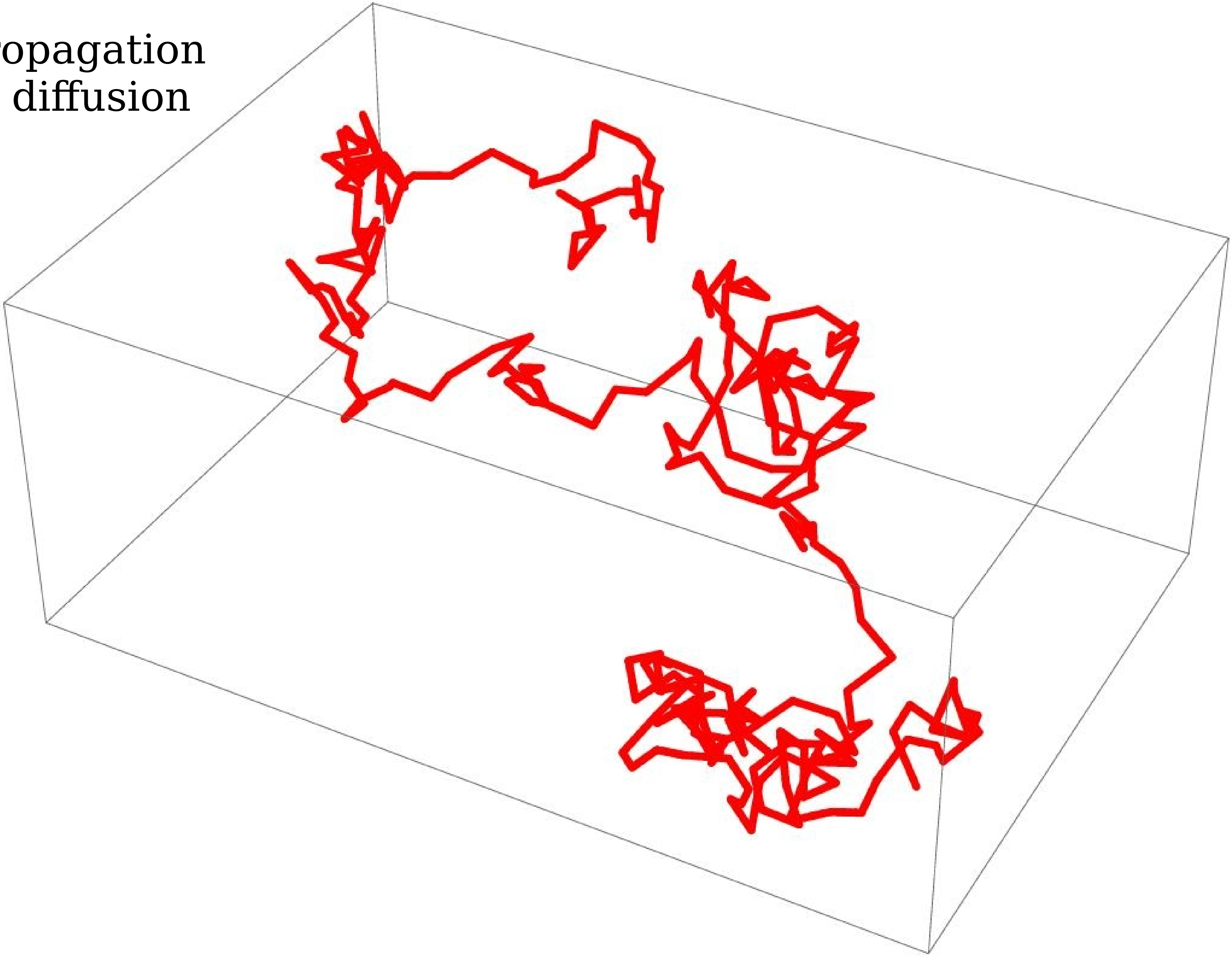
Magnetic confinement
Energy Loss





Total power radio continuum at λ90 cm obtained from VLA observations with 70″ resolution. Contours are at 3, 6, 12, 24, 48, 96, 192, 384, 768, 1536, and 3077 × 8 mJy/beam.

Propagation
as diffusion



The PAMELA

Positron DATA

Evidence for DM

or

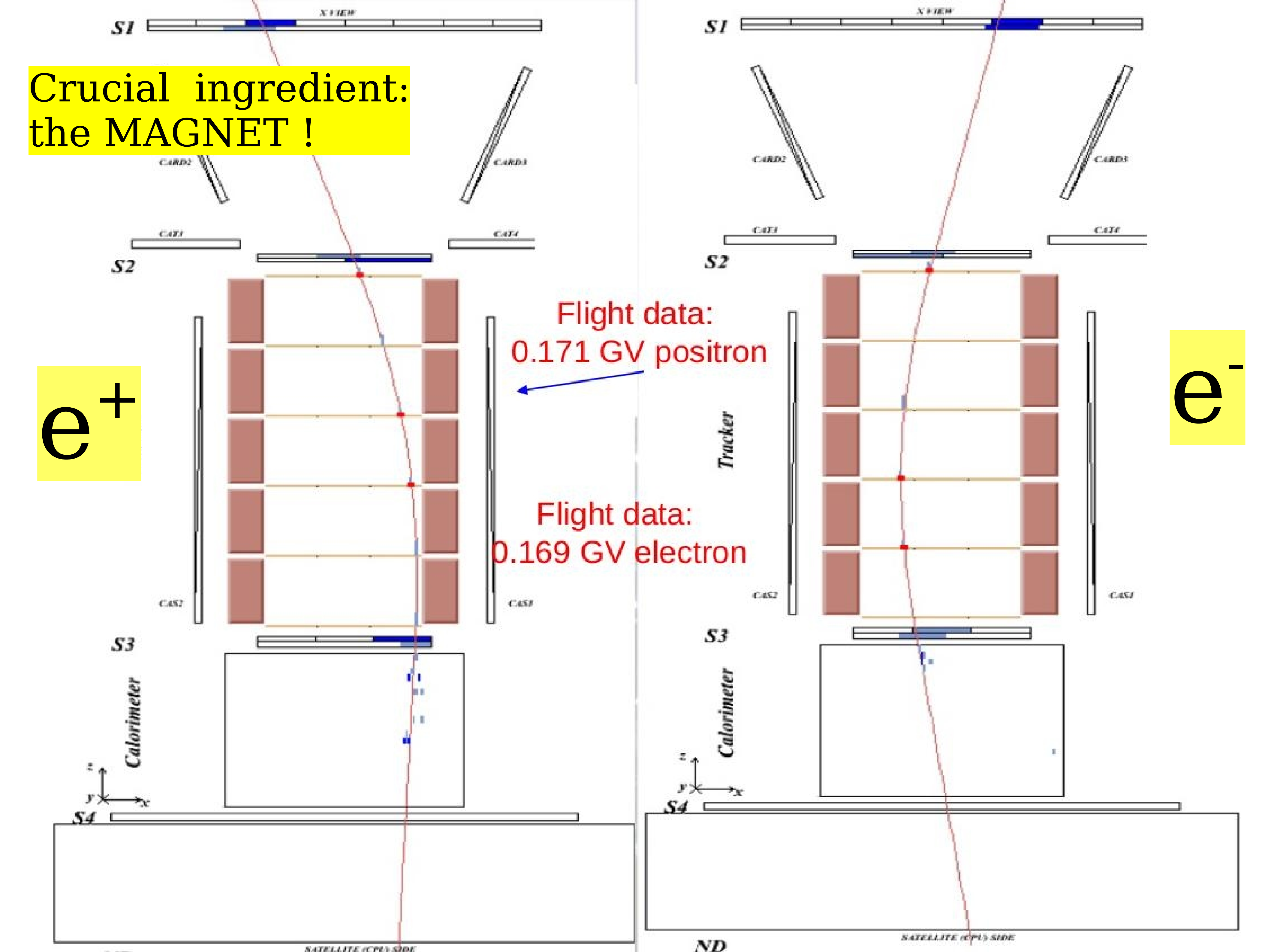
New Astrophysical processes ?


PAMELA

detector

Launch
15th june 2006

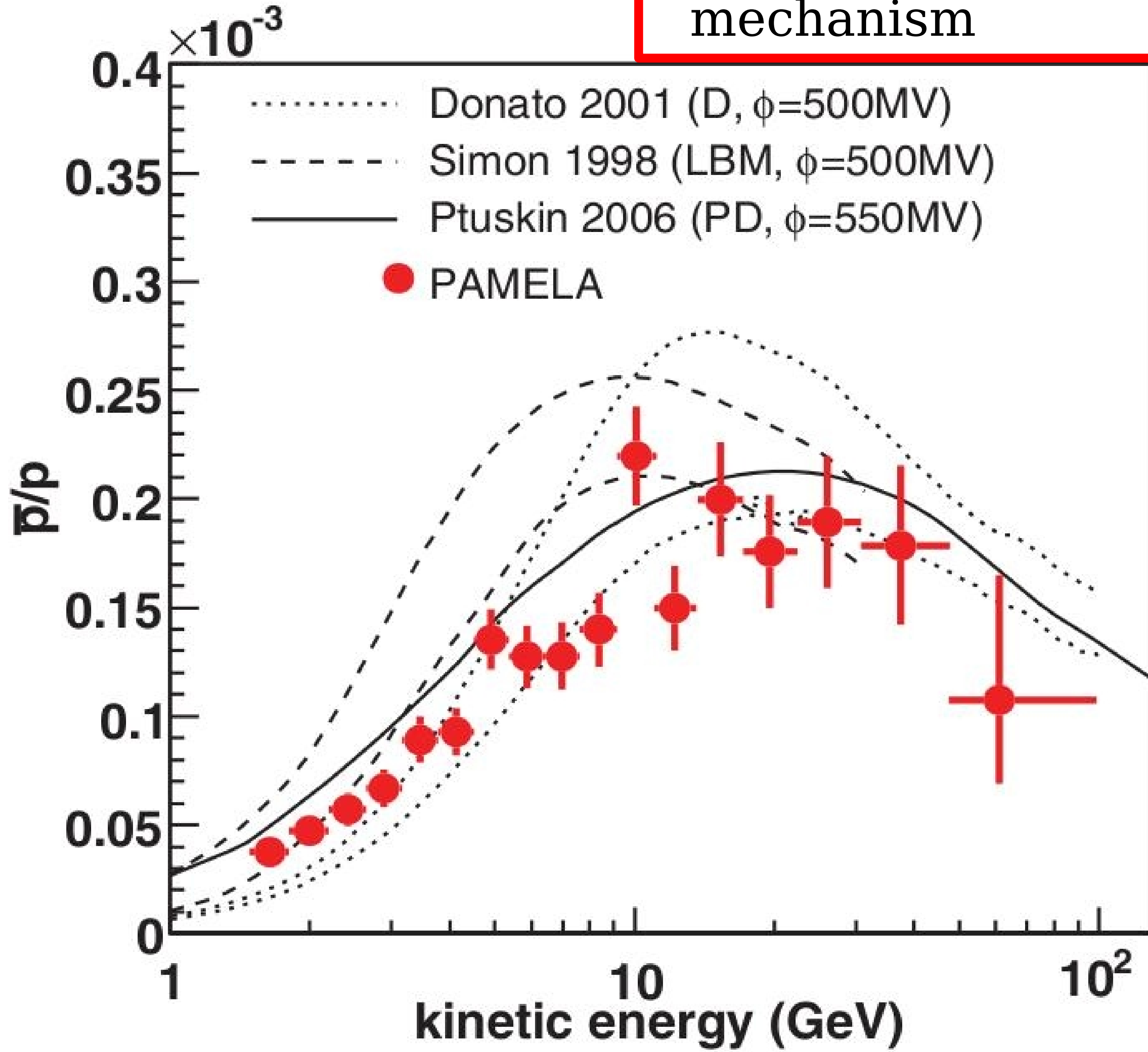
(3 years ago)



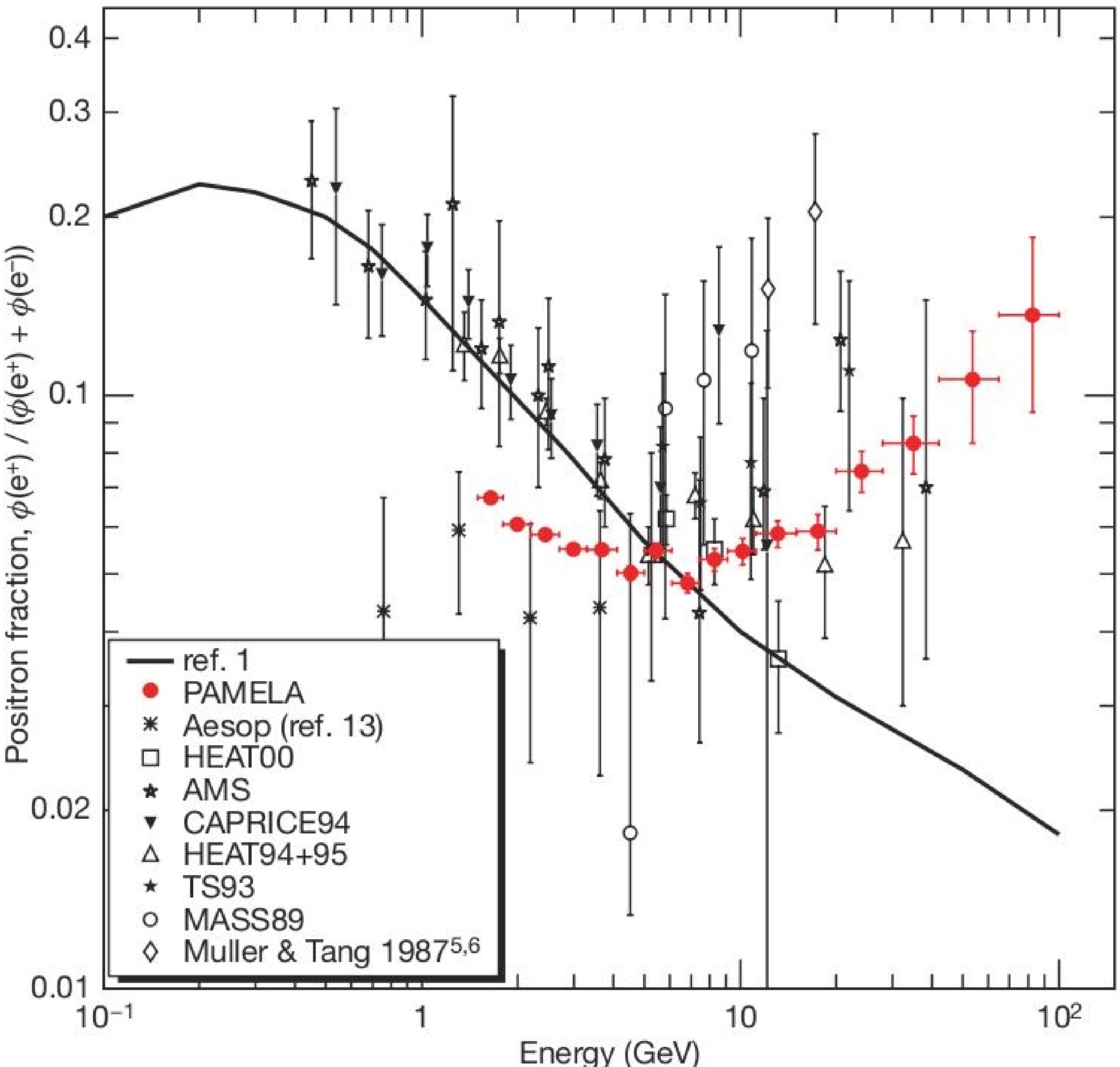
Crucial ingredient:
the MAGNET !
e^+
e^-
Flight data:
0.171 GV positron
Flight data:
0.169 GV electron
S1
S2
S3
S4
X VIEW
CARD2
CARD3
CAT3
CAT4
CAS2
CAS3
Tracker
Calorimeter
SATELLITE (CPU) SIDE
ND

Antiproton result

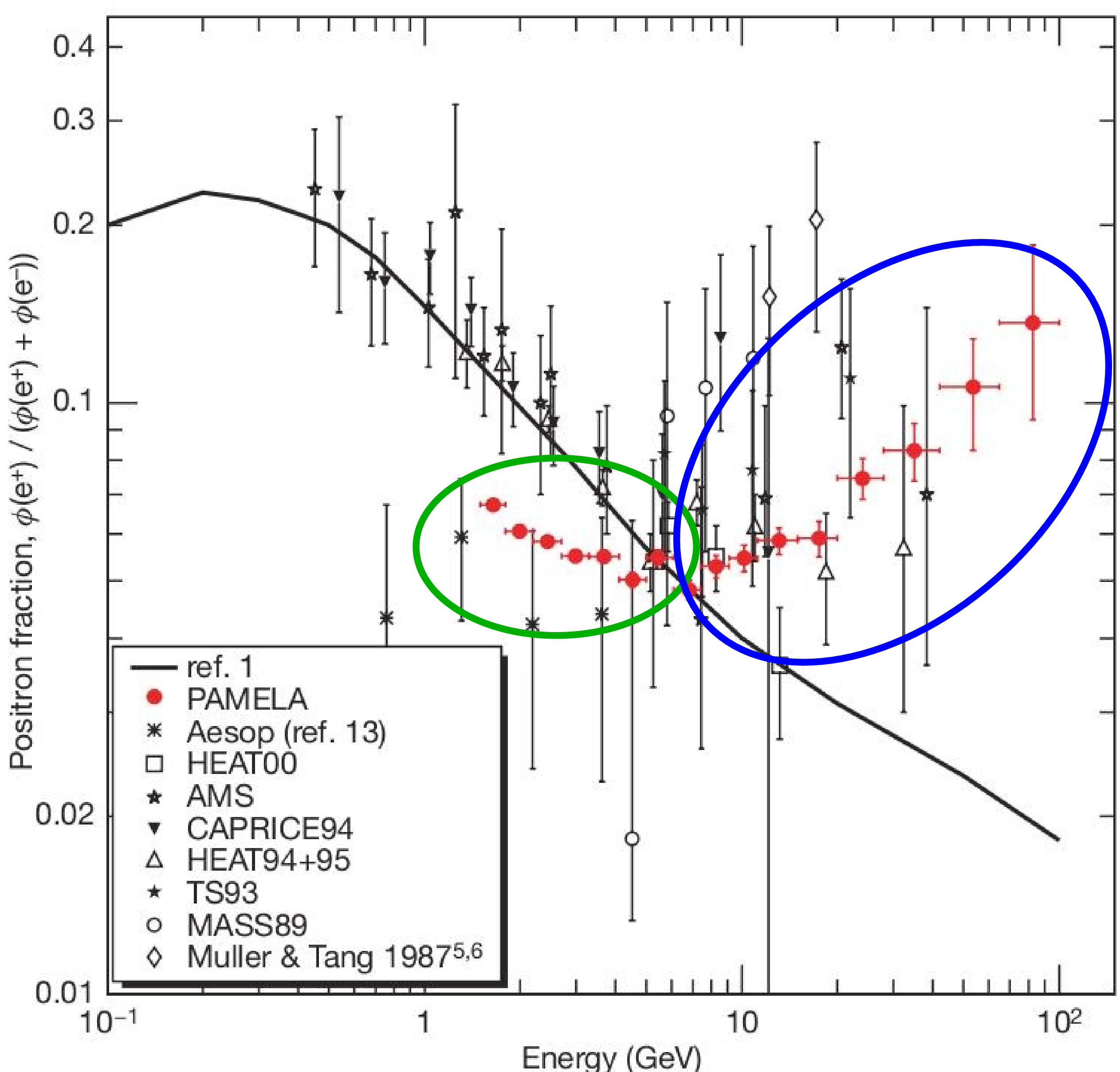
Agreement
With standard production mechanism



An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV



An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV



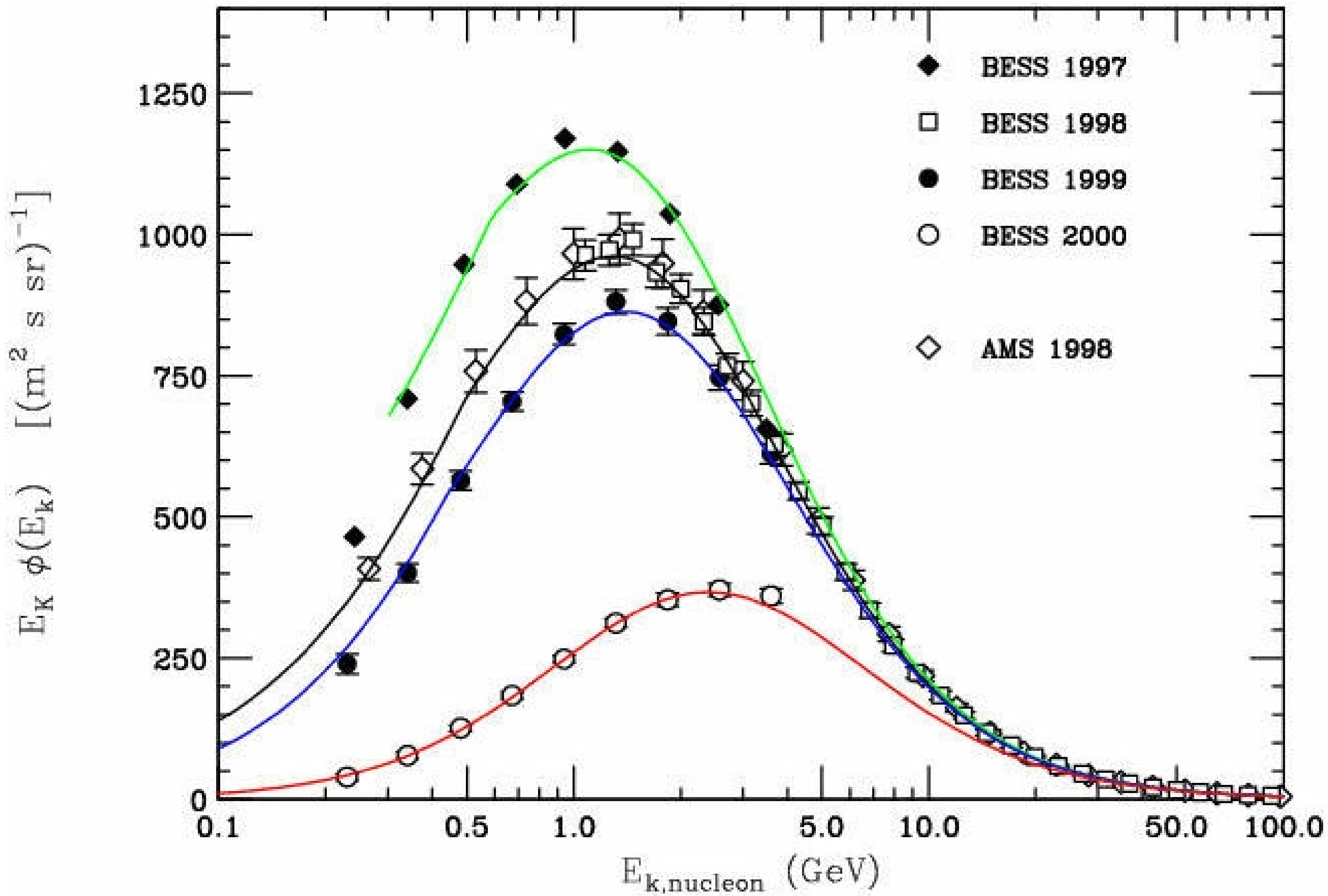
"Low energy problem"
[solar modulation]

"High energy problem"

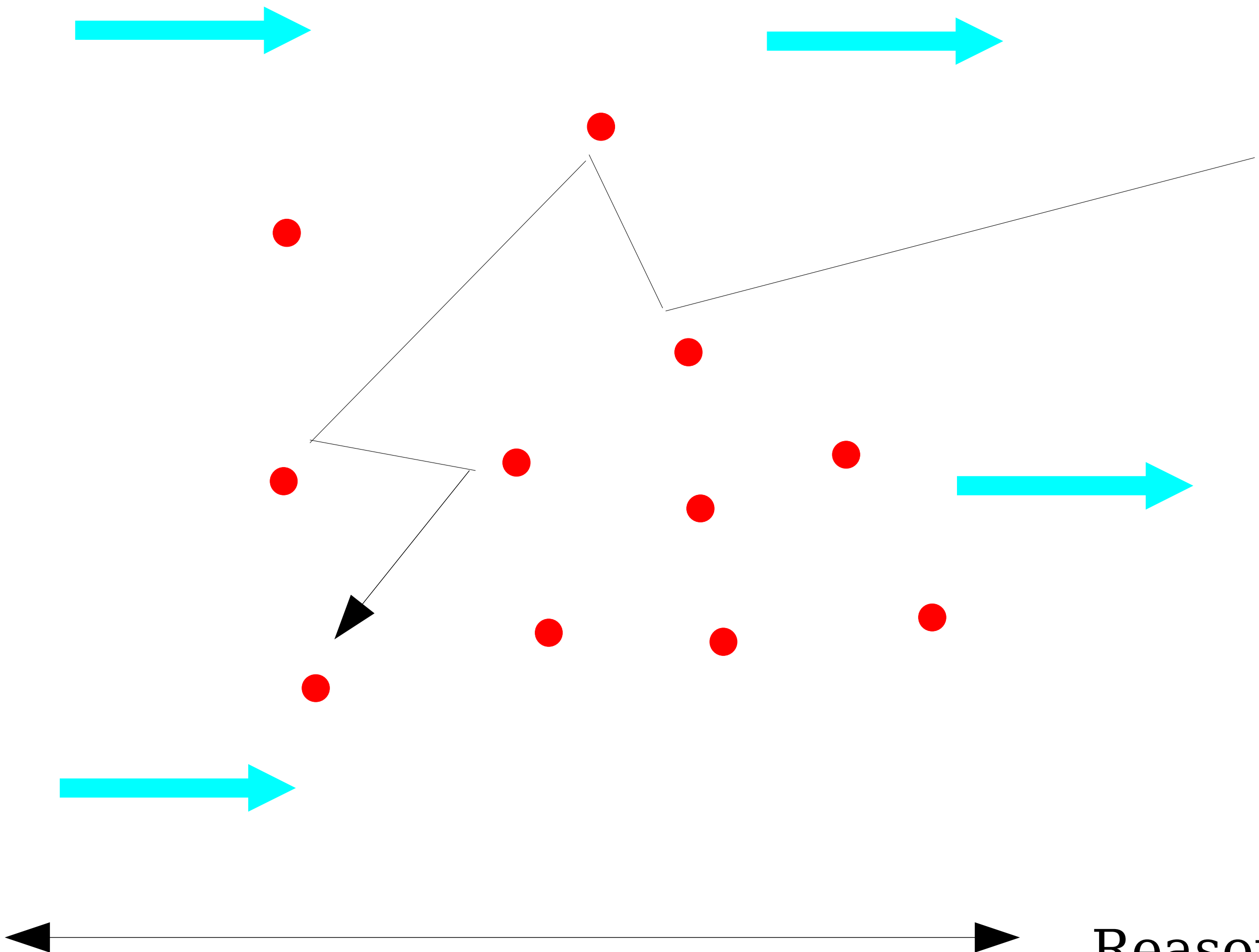
at the center of intense interest

Solar Modulations

BESS proton flux measurements



Moving magnetic scattering centers

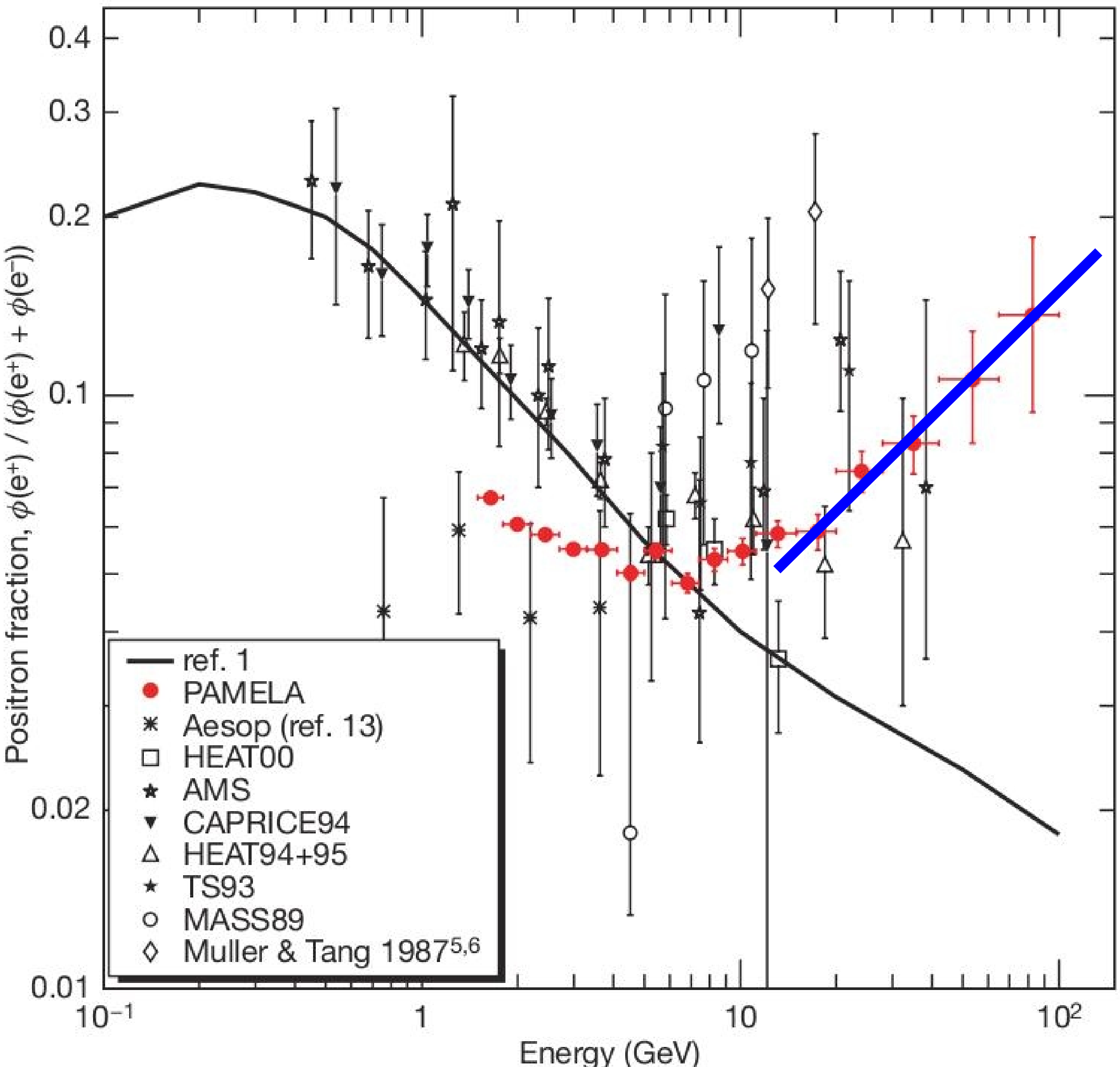


Reasonably good approximation:

The effect of the solar wind
is equivalent to a POTENTIAL
with particles losing an energy
$\Delta E = Z V$

$$\mathbf{E_f = E_i - Z\,\Delta V}$$

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

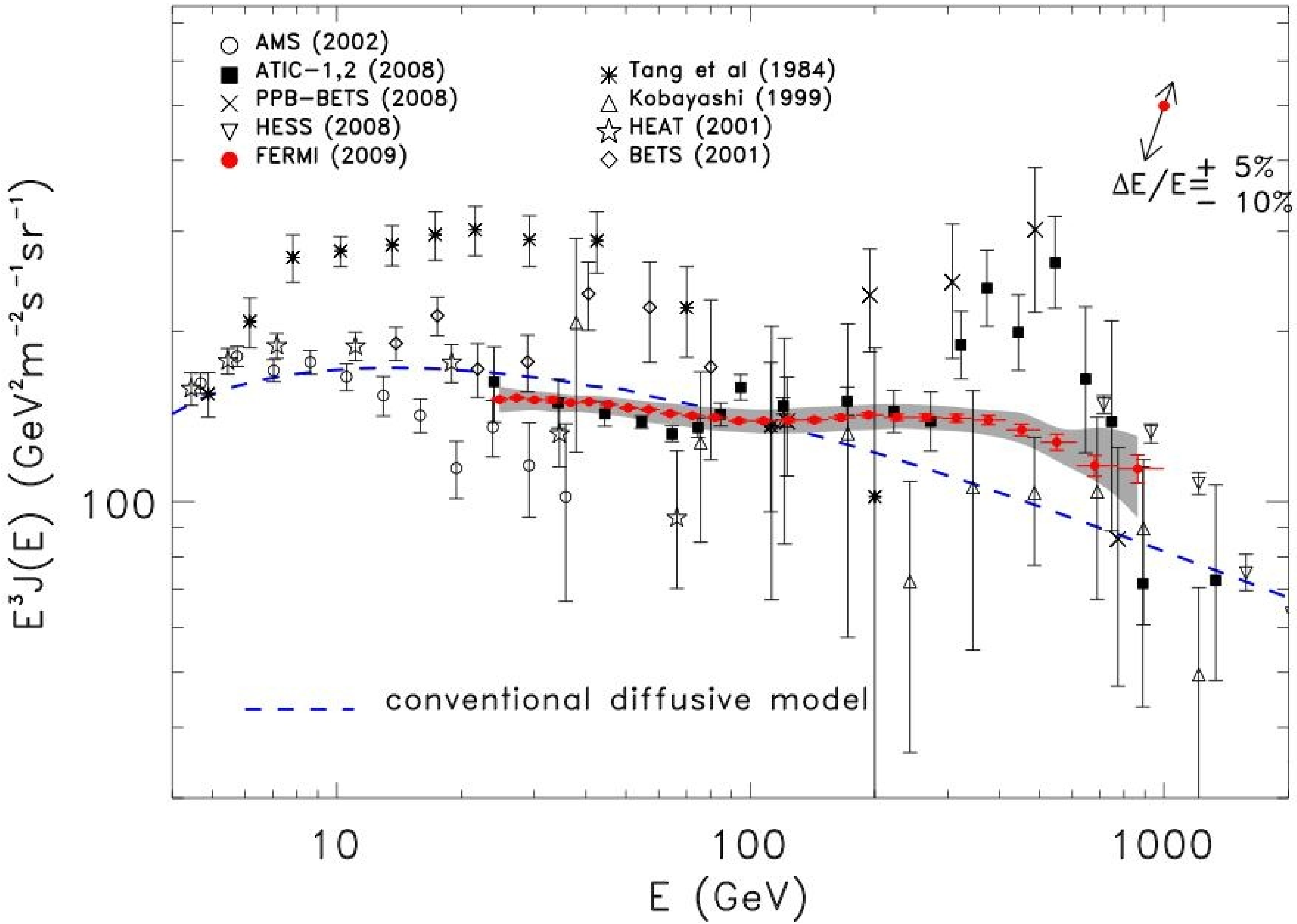


High energy: ratio e+/e- grow with E !!

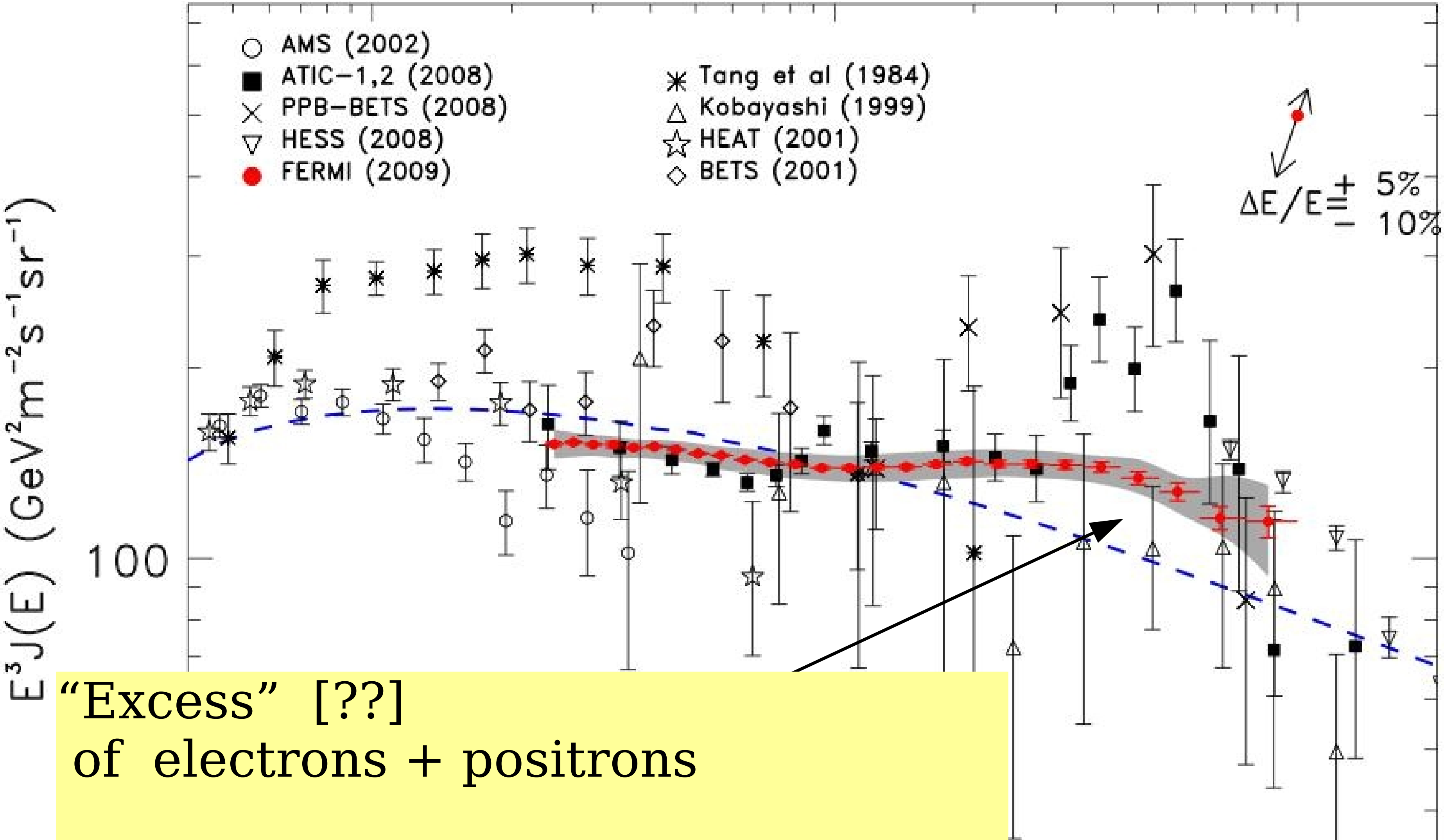
$$\frac{\phi_{e^+}}{\phi_{e^-}} \propto E^{0.52}$$

Very unexpected result for the "astrophysical background"

FERMI: electron + positron flux



FERMI: electron + positron flux



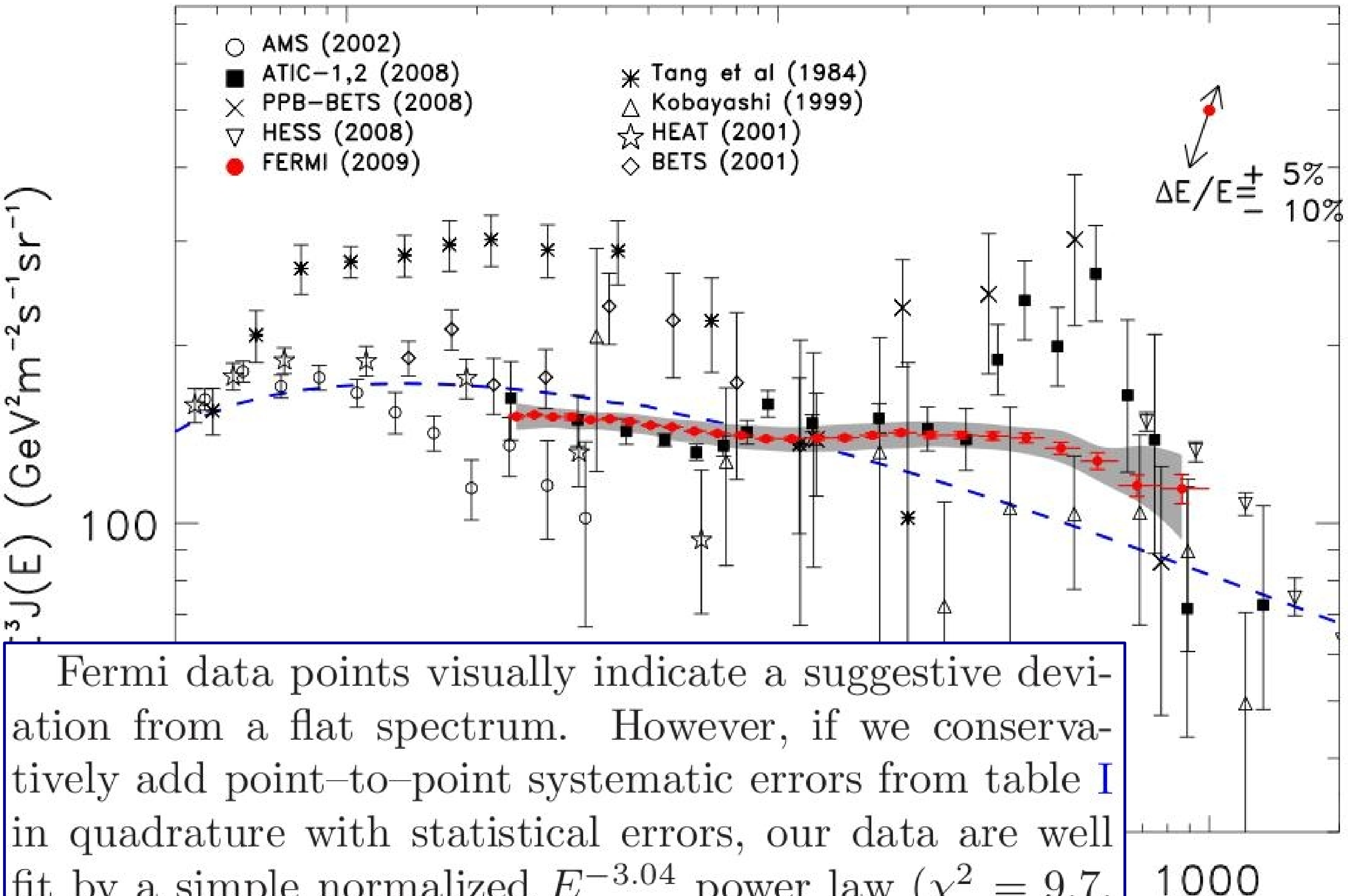
"Excess" [??]
of electrons + positrons

....
Possible...

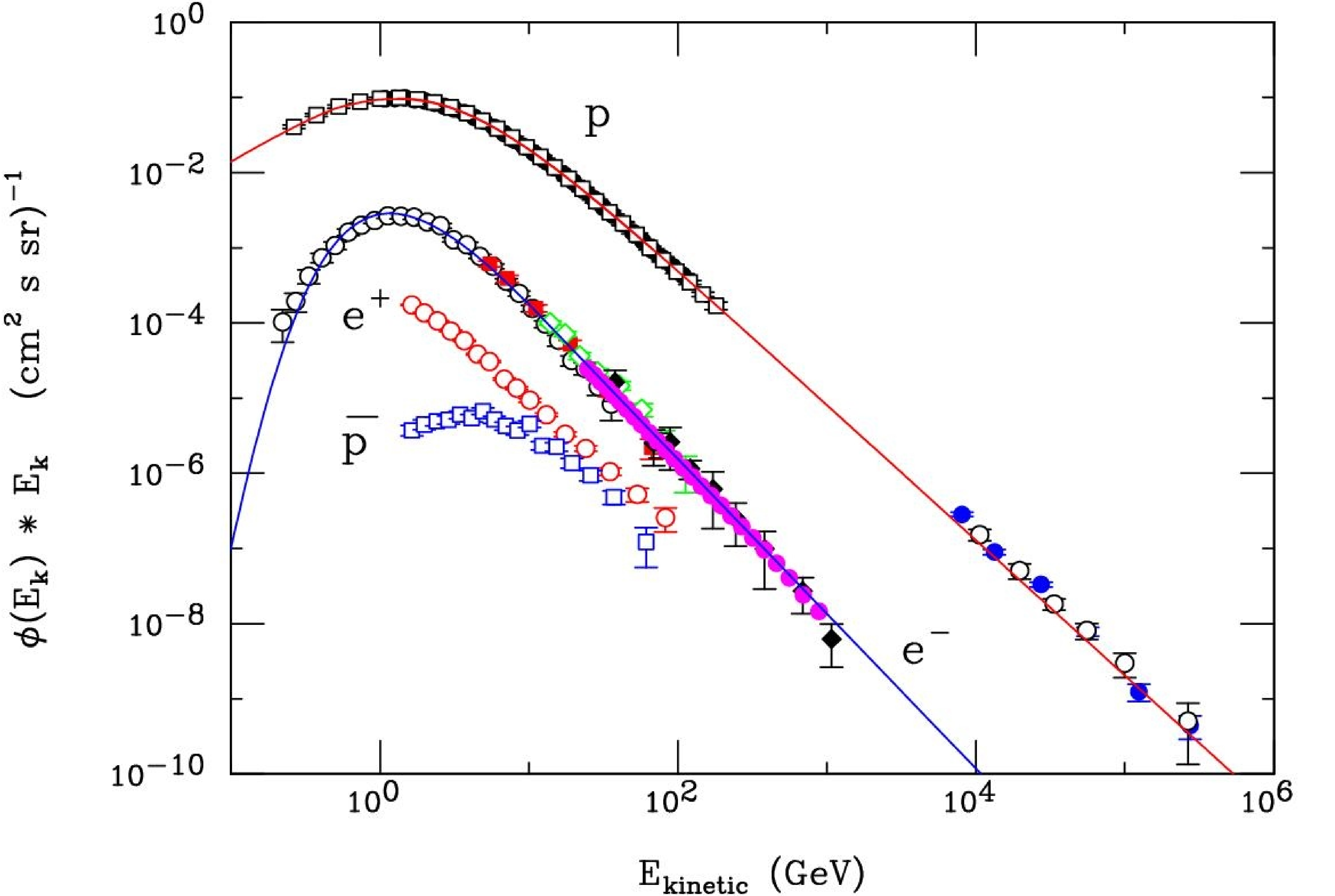
$$J_{\rm extra}(E) \propto E^{-\gamma_e} \exp\{-E/E_{\rm cut}\}$$

but certainly **not necessary**

FERMI: electron + positron flux

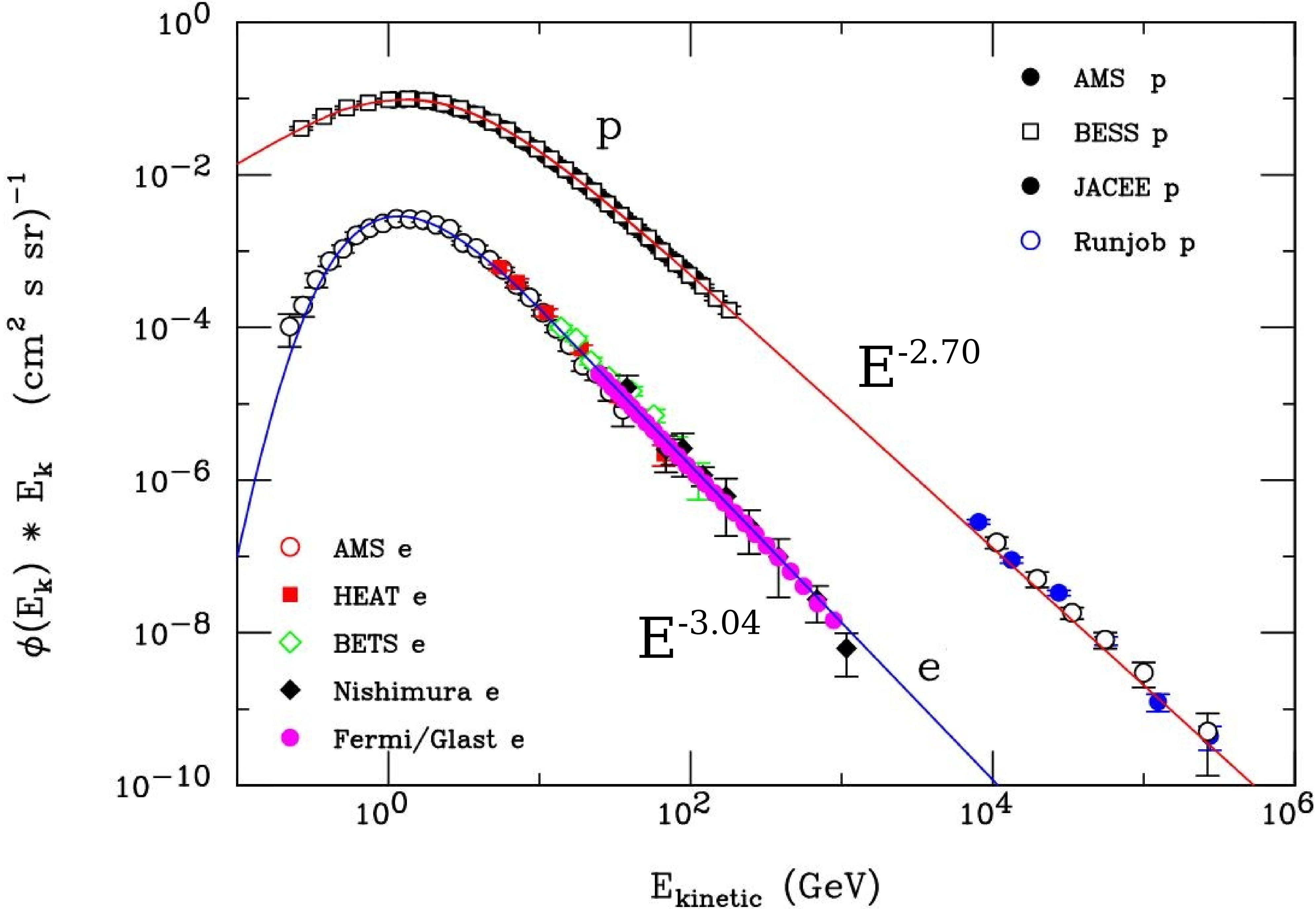


Fermi data points visually indicate a suggestive deviation from a flat spectrum. However, if we conservatively add point–to–point systematic errors from table I in quadrature with statistical errors, our data are well fit by a simple normalized $E^{-3.04}$ power law ($\chi^2 = 9.7$, d.o.f. 24).

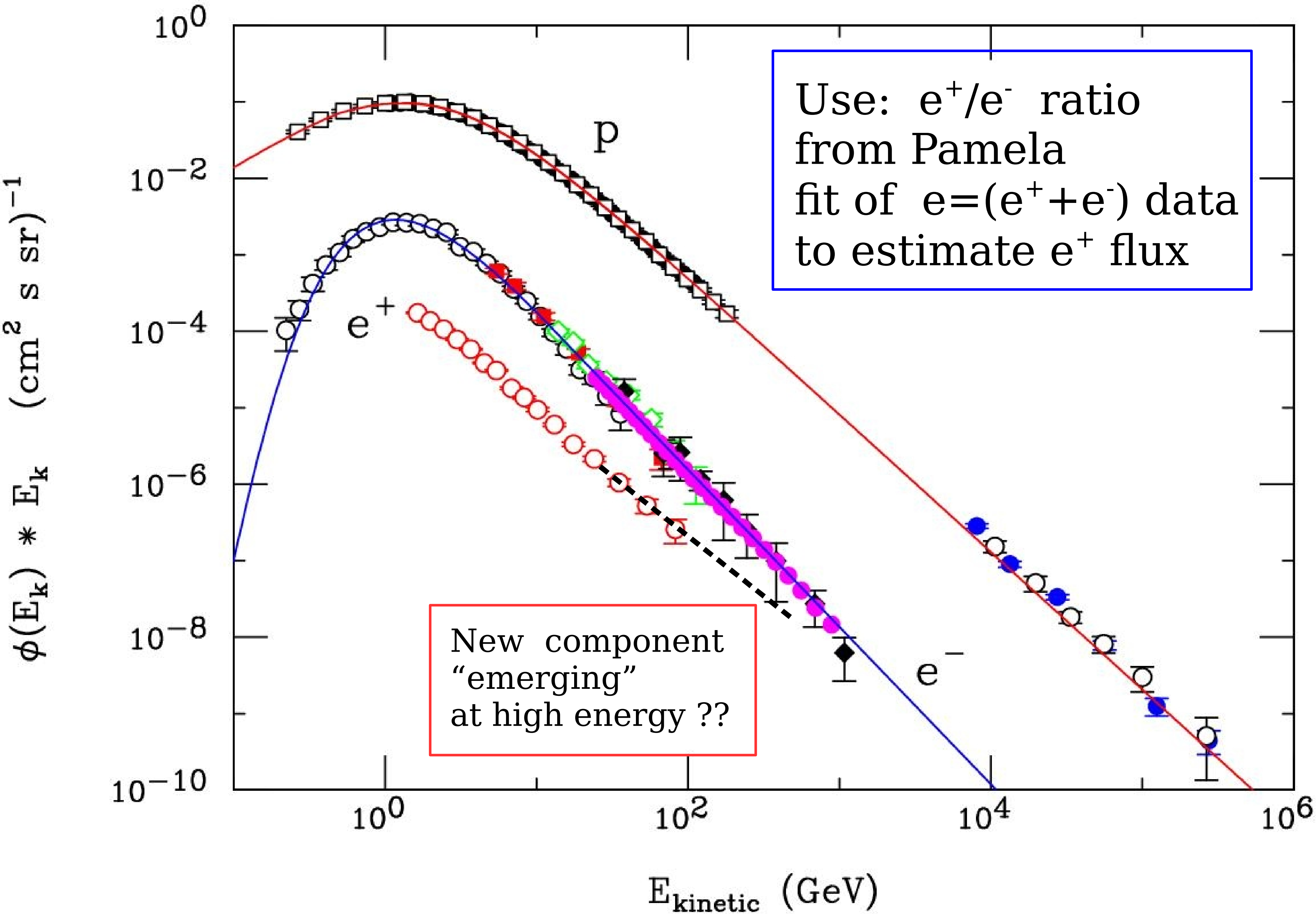


10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{0}
10^{2}
10^{4}
10^{6}
p
e^{+}
$\bar{p}$
e^{-}
$\phi(E_k) * E_k \quad (cm^2\ s\ sr)^{-1}$
$E_{kinetic}$ (GeV)

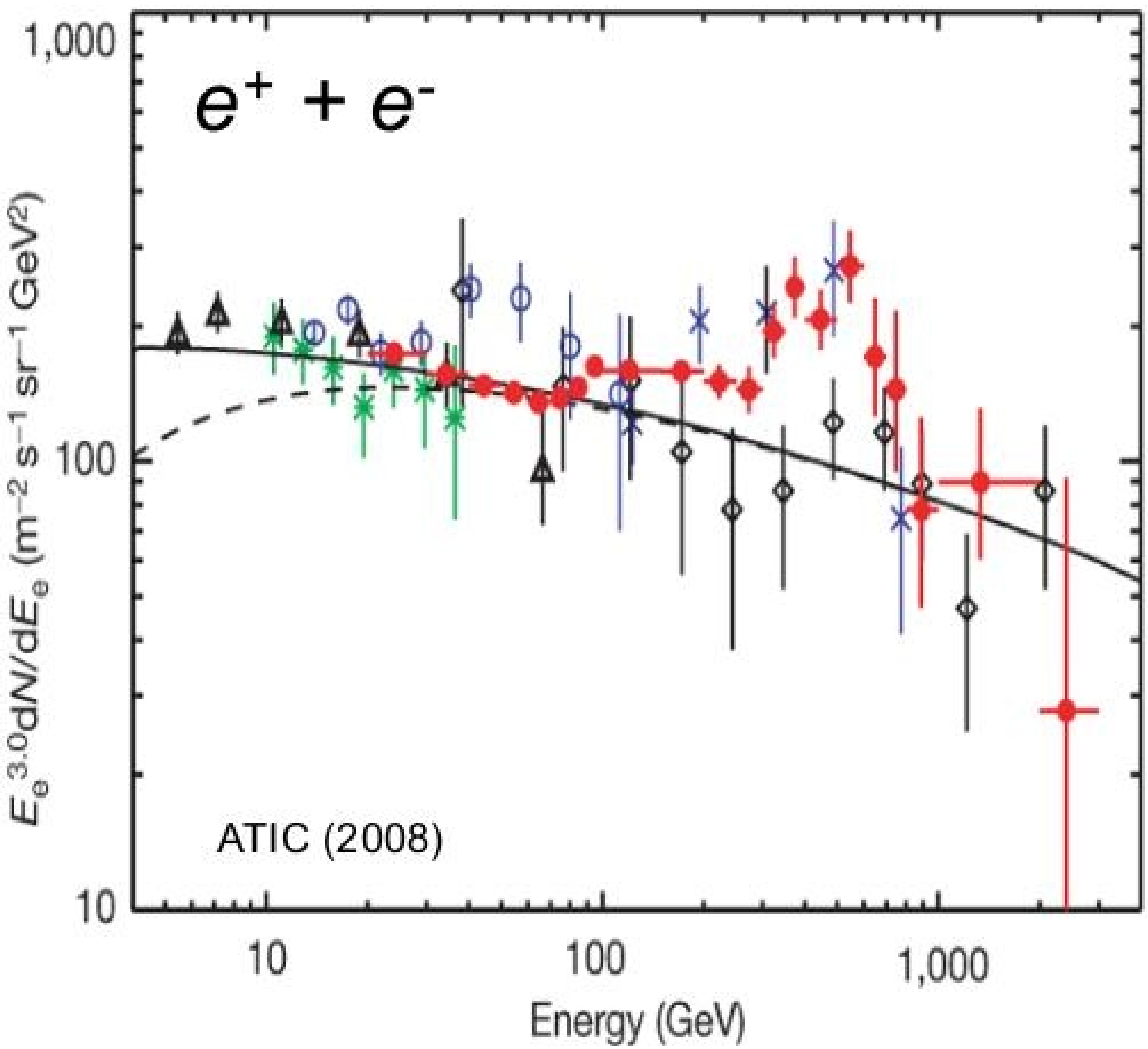
Proton and electron energy spectra

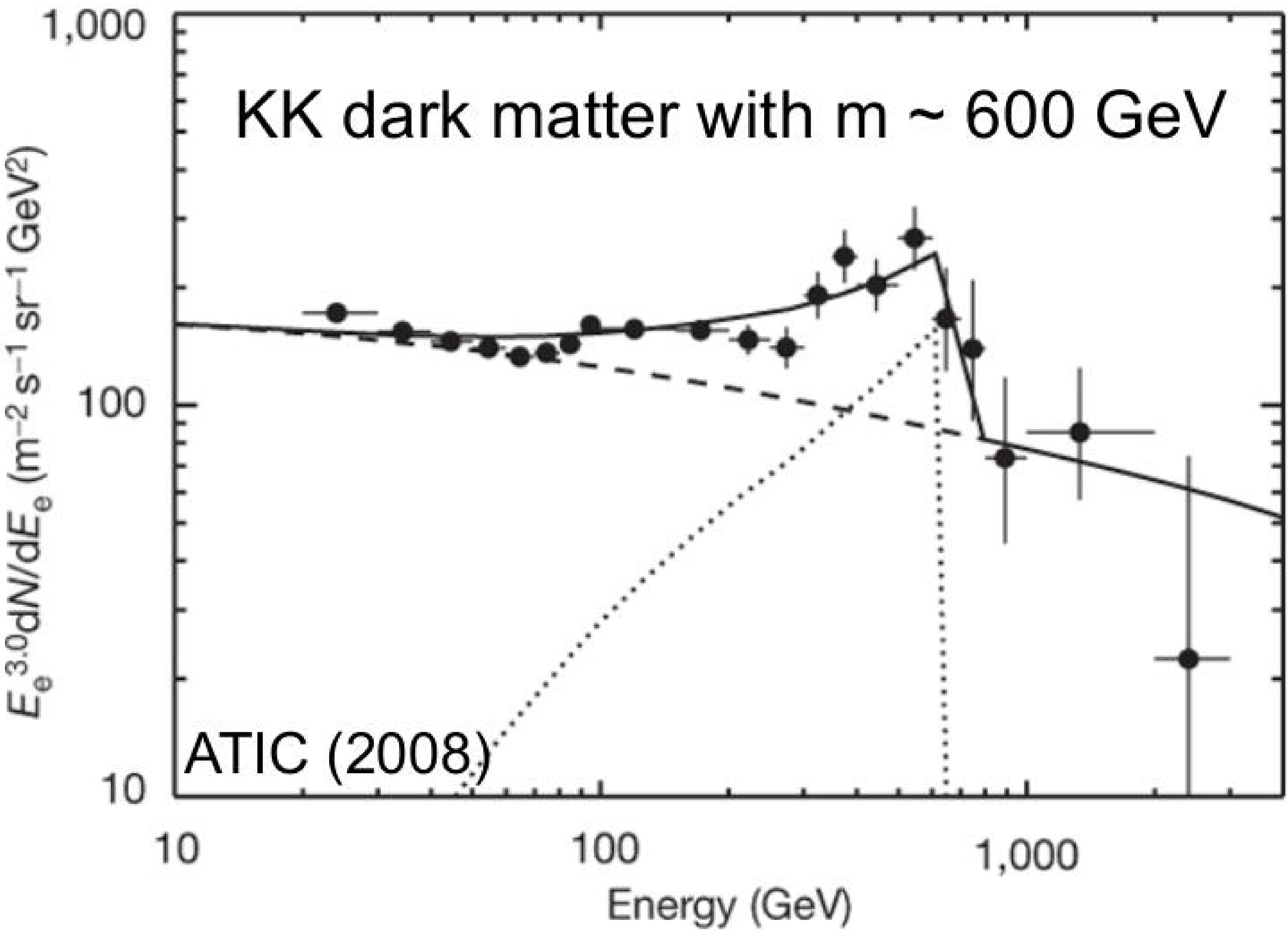


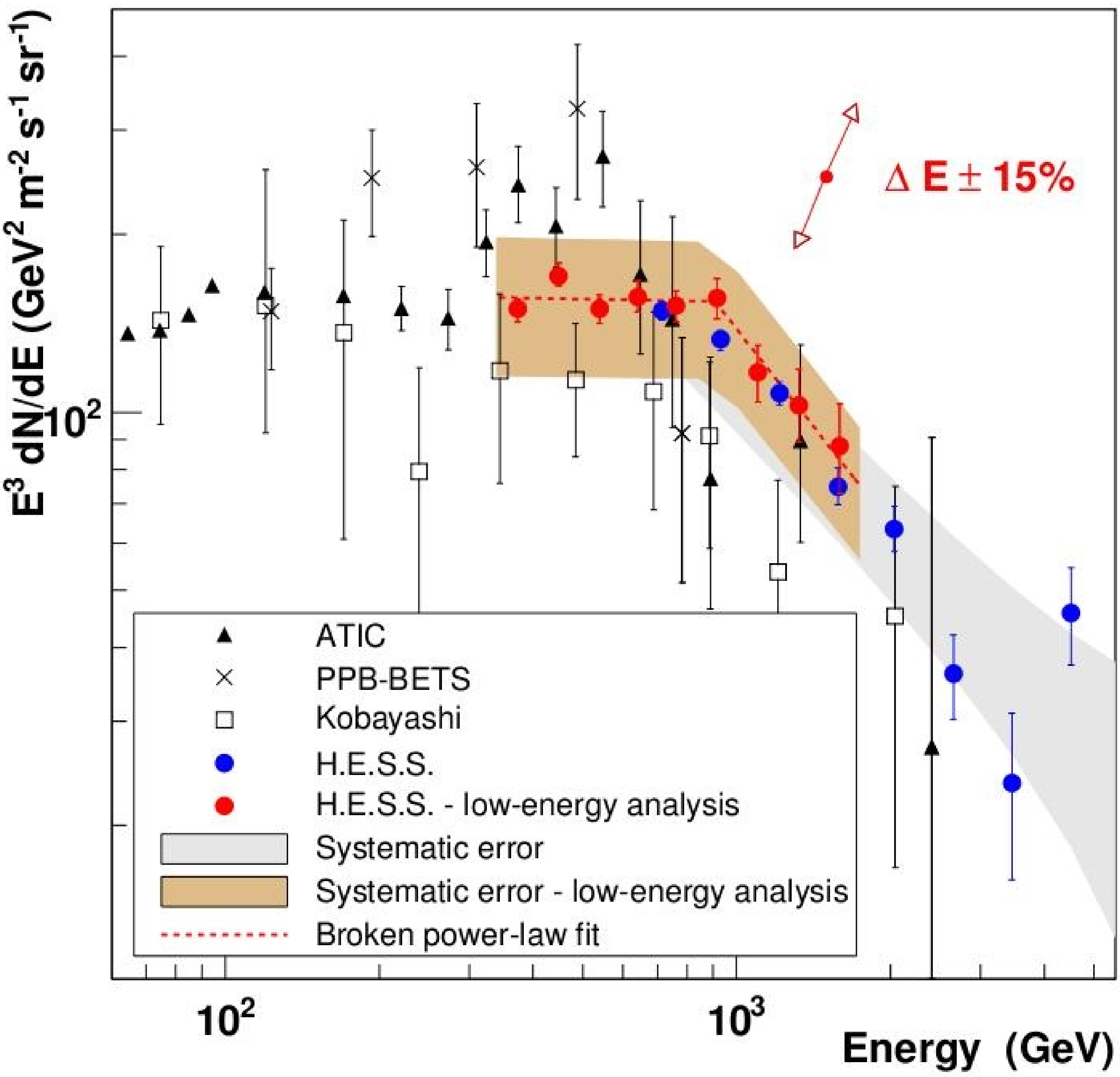
Proton and electron + Positron energy spectra



ATIC Balloon experiment (electron + positron)




KK dark matter with m ~ 600 GeV
ATIC (2008)
1,000
100
10
10
100
1,000
Energy (GeV)
$E_e^{3.0}dN/dE_e$ (m^{-2} s^{-1} sr^{-1} GeV^2)



E^3 dN/dE (GeV^2 m^{-2} s^{-1} sr^{-1})
10^2
Δ E $\pm$ 15%
ATIC
PPB-BETS
Kobayashi
H.E.S.S.
H.E.S.S. - low-energy analysis
Systematic error
Systematic error - low-energy analysis
Broken power-law fit
10^2
10^3
Energy (GeV)

Results

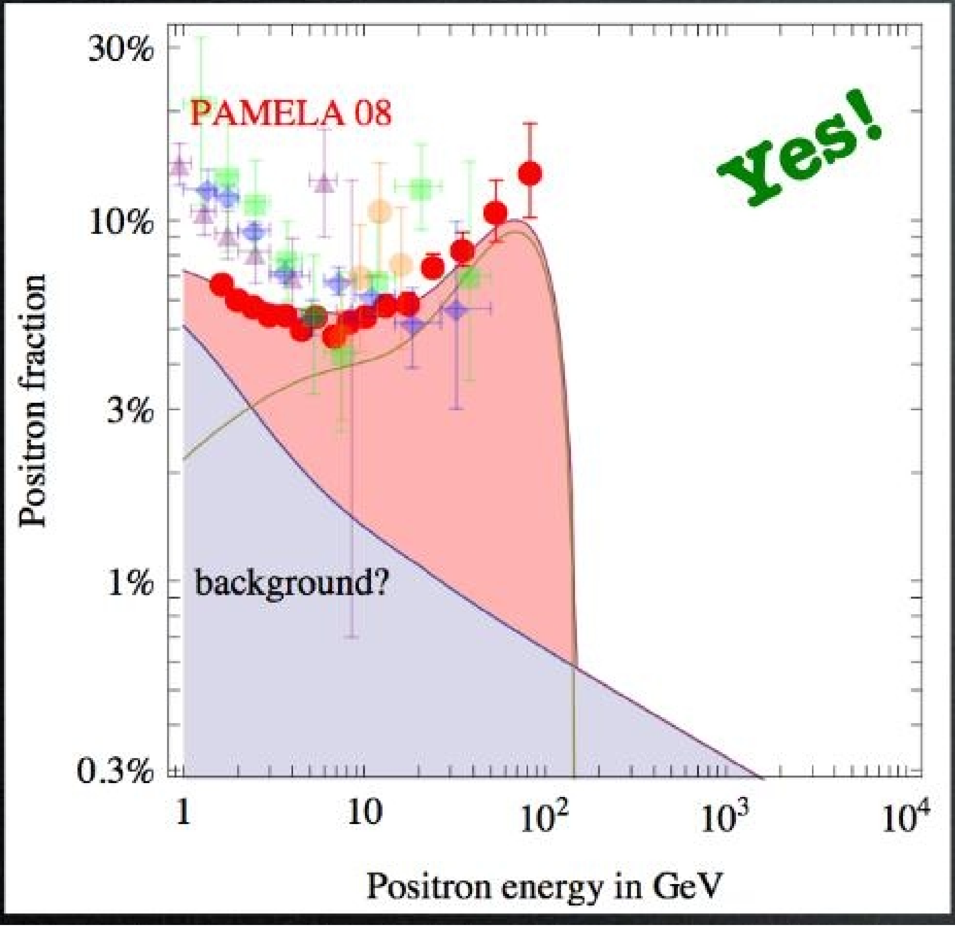
Which DM spectra can fit the data?

E.g. a DM with: -mass $M_{\rm DM} = 150\,{\rm GeV}$

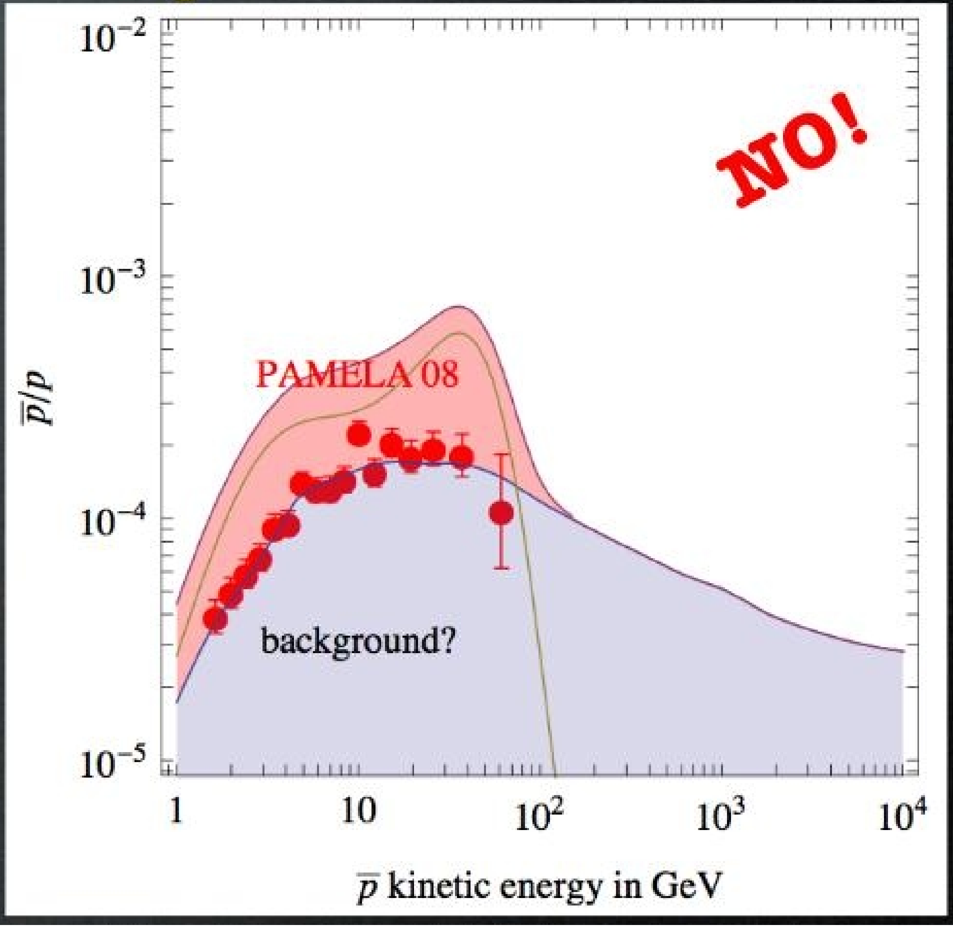
-annihilation $\rm DM\ DM \to W^+W^-$

(a possible SuperSymmetric candidate: wino)

Positrons:



Anti-protons:



Results

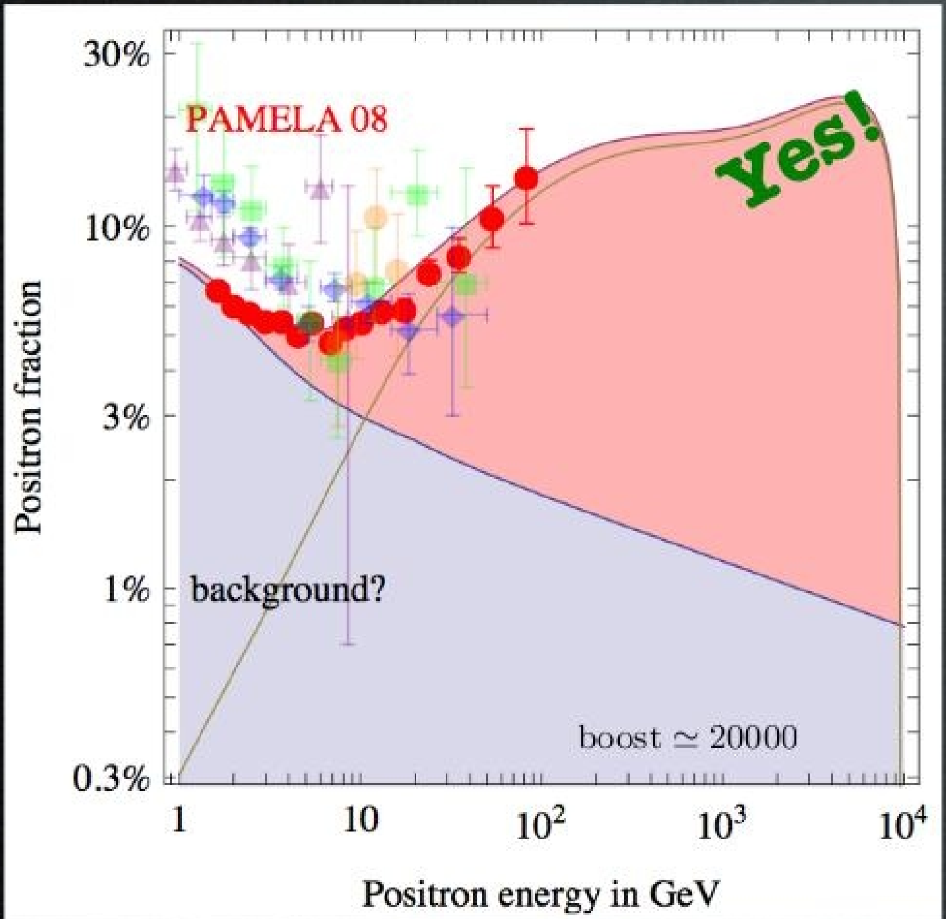
Which DM spectra can fit the data?

E.g. a DM with: -mass $M_{\rm DM} = 10\,{\rm TeV}$

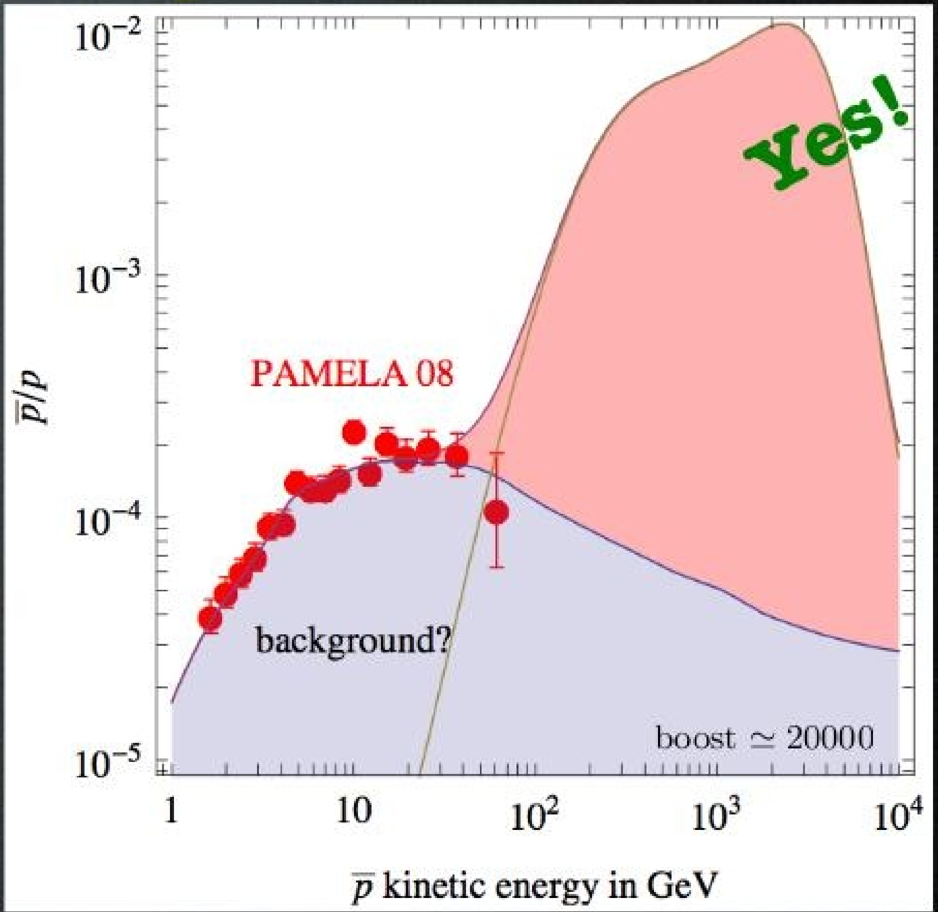
-annihilation $\mathrm{DM}\ \mathrm{DM} \to W^+W^-$

but...: -boost $B = 2 \cdot 10^4$ No...

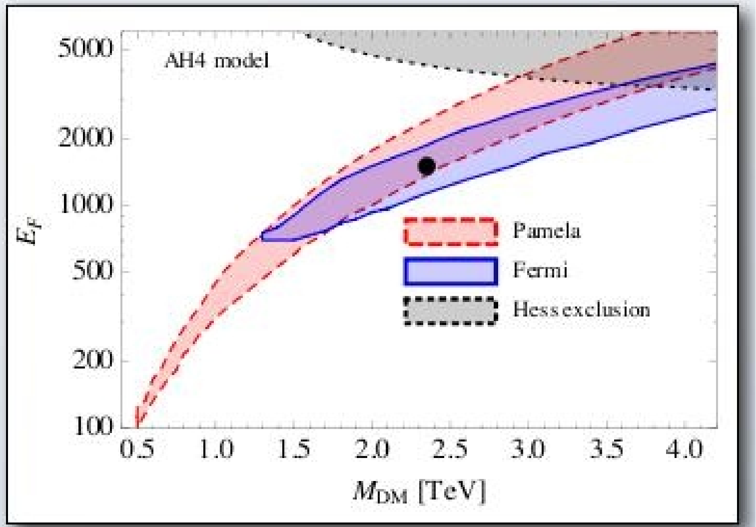
Positrons:

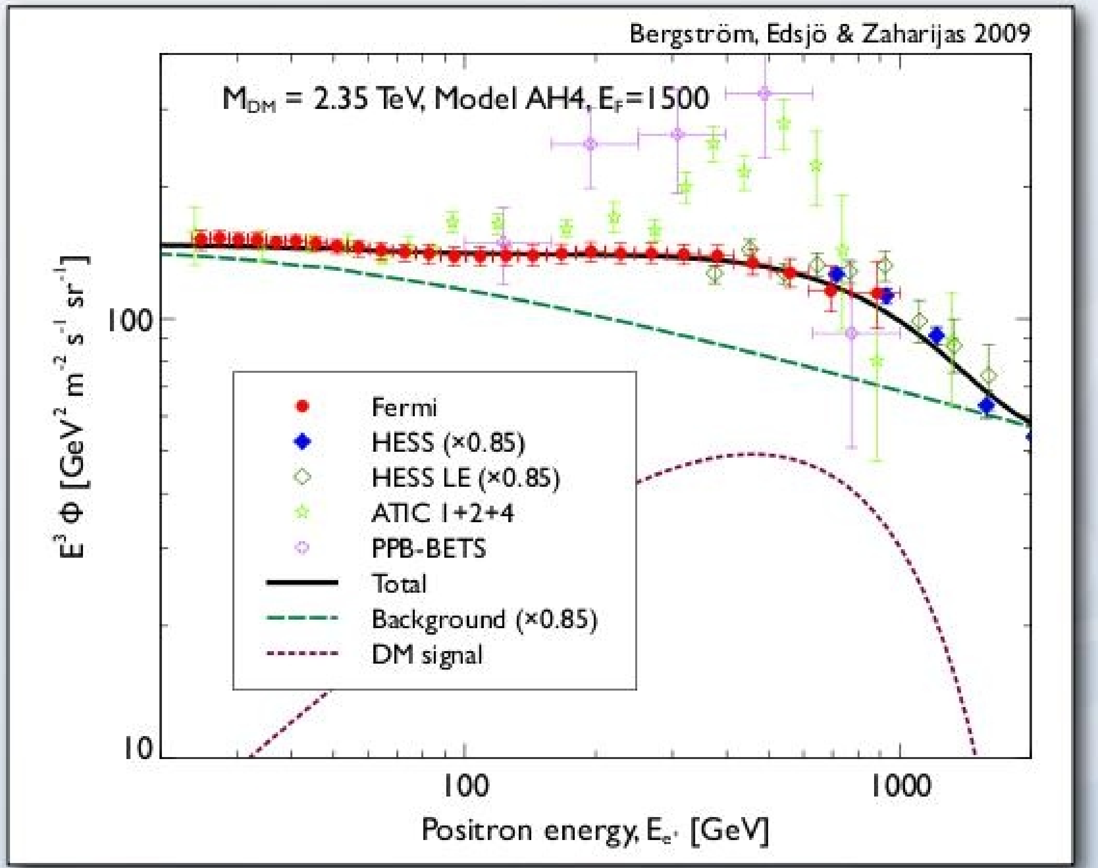


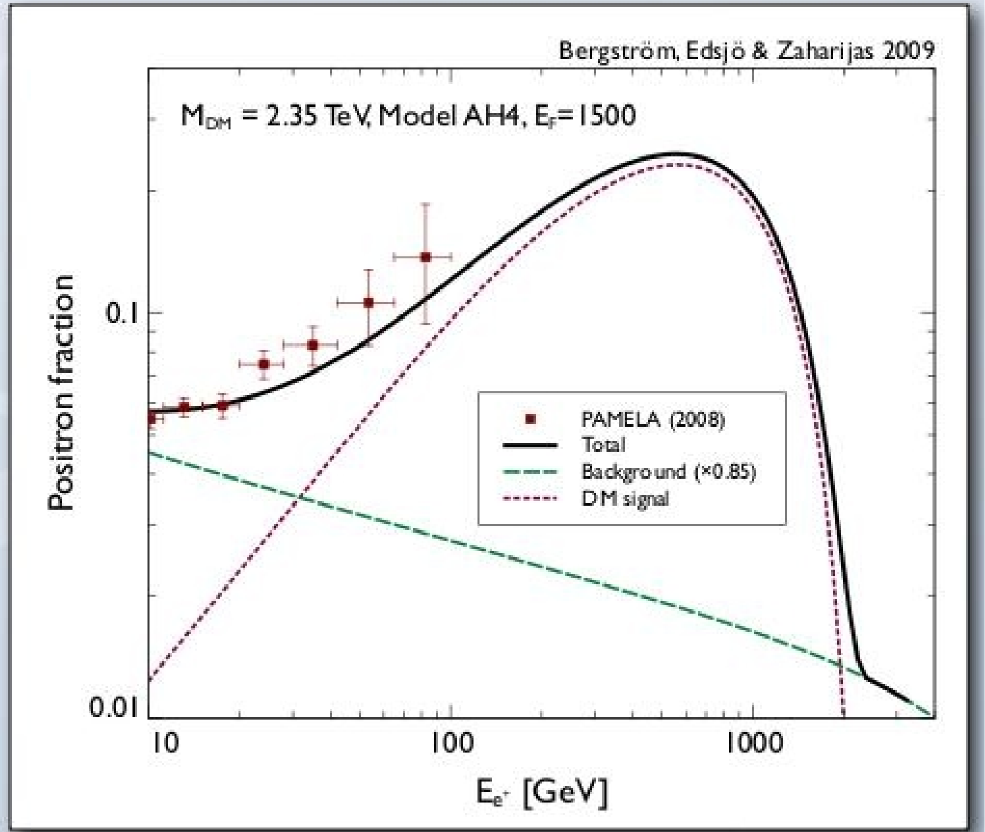
Anti-protons:



Results – AH4 model







$$DM + DM \to \phi\phi, \phi \to \mu^+\mu^-$$

$$m_\phi = 0.25 \text{ GeV}$$

Requires non standard DM properties

“Leptophilic” DM ?

Leptonically decaying DM ?

Boost Factor from clumpy DM ?

Sommerfeld enhancement ?

"STANDARD DESCRIPTION"

of the Cosmic Ray fluxes

$$\alpha_p = \alpha_0 + \delta$$

protons

$$\alpha_e = \alpha_0 + 1$$

electrons

$$\alpha_A^{\mathrm{secondary}} = \alpha_0 + 2\,\delta$$

Secondary nuclei

$$\alpha_{e\pm}^{\mathrm{secondary}} = \alpha_0 + \delta + 1$$

Pair production

Fundamental propagation equation:

$$\frac{\partial n(E,\vec{r},t)}{\partial t} = \boxed{q(E,\vec{r},t)} + \boxed{\vec{\nabla}\cdot D(E,\vec{r})\,\vec{\nabla} n(E,\vec{r},t)} \boxed{-\frac{\partial}{\partial E}\left[\beta(E,\vec{r})\,n(E,\vec{r},t)\right]}$$

Source Diffusion Energy Loss

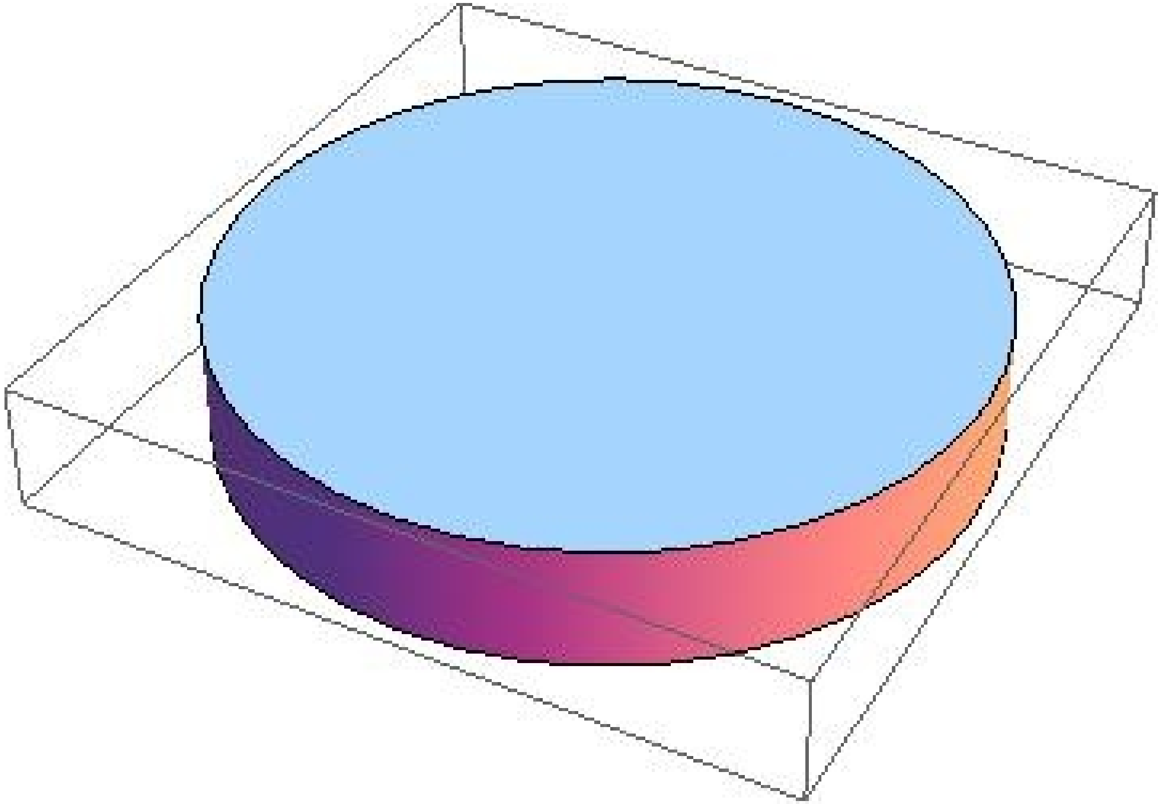
- Source $q(E,\vec{r},t)$
- Diffusion coefficient $D(p/Z,\vec{r})$
- Energy Loss $\beta(E,\vec{r})$

$$-\frac{n(E,\vec{r},t)}{\tau_{\rm int}(E)} - \frac{n(E,\vec{r},t)}{\tau_{\rm dec}(E)} \cdots$$

additional terms:

interaction
decay
convection
reacceleration

Escape as "absorbing boundary condition"
The diffusion coefficient become infinity at the boundary



Galaxy as a cylinder

$$\tau_{\mathrm{escape}}(E) = \frac{z_{\mathrm{halo}}^2}{4\,D(E)}$$

$$\tau_{\mathrm{loss}}(E) = \frac{1}{b\,E}$$

$$-\frac{dE}{dt} = \boxed{\left(\frac{4}{3}\,\sigma_{\mathrm{Th}}\,\frac{B^2}{8\pi}\,\frac{1}{m^2}\right)} E^2$$

$$\tau_{\mathrm{interaction}}(E) = \frac{1}{\sigma_{pp}\,c\,\langle n_{\mathrm{ism}}\rangle}$$

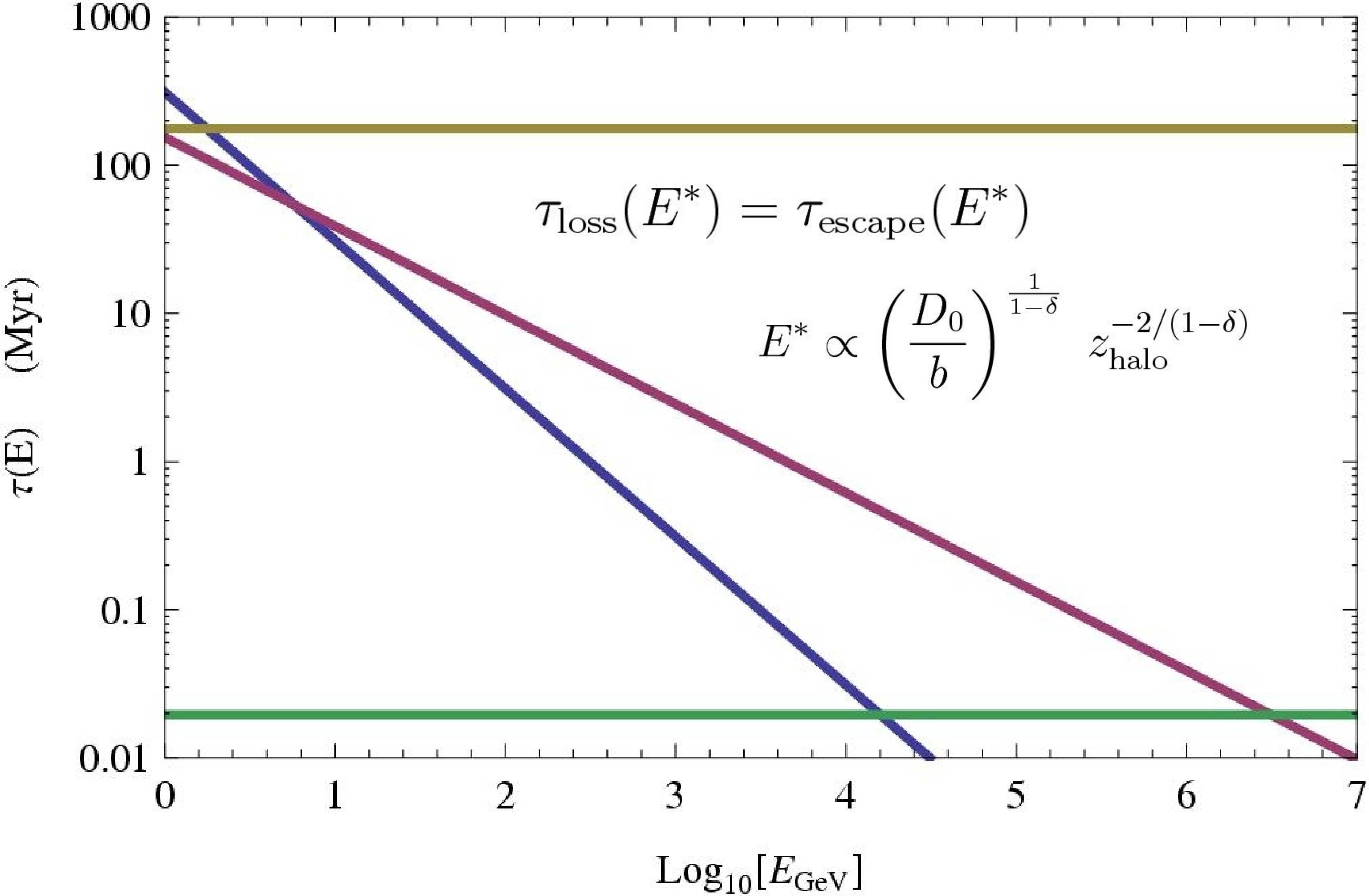
$$\tau_{\mathrm{linear}} = \frac{z_{\mathrm{halo}}}{c}$$

$$\tau_{\mathrm{escape}}(E) = 39 \times \left[\frac{z_{\mathrm{halo}}}{3\ \mathrm{Kpc}}\right]^2 E_{\mathrm{GeV}}^{-\delta}\ \mathrm{Myr}$$

$$\tau_{\mathrm{loss}}(E) = 350 \times \left[\frac{6\ \mu\mathrm{Gauss}}{\langle B \rangle}\right]^2 E_{\mathrm{GeV}}^{-1}\ \mathrm{Myr}$$

$$\tau_{\mathrm{interaction}} = 175 \times \left[\frac{\mathrm{cm}^{-3}}{\langle n_{\mathrm{ism}} \rangle}\right]\ \mathrm{Myr}$$

$$\tau_{\mathrm{linear}} = 3.26 \times 10^3 \left[\frac{z_{\mathrm{halo}}}{\mathrm{Kpc}}\right]\ \mathrm{years}$$



1000
100
10
1
0.1
0.01
$\tau(E)$ (Myr)
0
1
2
3
4
5
6
7
$\mathrm{Log}_{10}[E_{\mathrm{GeV}}]$
$\tau_{\mathrm{loss}}(E^*) = \tau_{\mathrm{escape}}(E^*)$
$E^* \propto \left(\frac{D_0}{b}\right)^{\frac{1}{1-\delta}} z_{\mathrm{halo}}^{-2/(1-\delta)}$

$$n_p(E) \simeq q_p(E)\ \tau_{\rm esc}(E)$$

$$n_{e^-}(E) \simeq q_{e^-}(E)\ \tau_{\rm loss}(E)$$

Primary particles

$$q_p(E) \propto q_{e^-}(E) \propto E^{-\alpha_0} \simeq E^{-2.1}$$

Injection

$$\tau_{\rm esc}(E) \simeq \frac{R^2}{4\,D(E)} \propto E^{-\delta}$$

$$\tau_{\rm loss}(E) = \frac{1}{b\,E}$$

Secondaries

$$n_{\overline{p}}(E) \propto n_p(E)\ \tau_{\rm esc}(E) \propto q_p(E)\ \tau_{\rm esc}(E)\ \tau_{\rm esc}(E)$$

$$n_{e^+}(E) \propto n_p(E)\ \tau_{\rm loss}(E) \propto q_p(E)\ \tau_{\rm esc}(E)\ \tau_{\rm loss}(E)$$

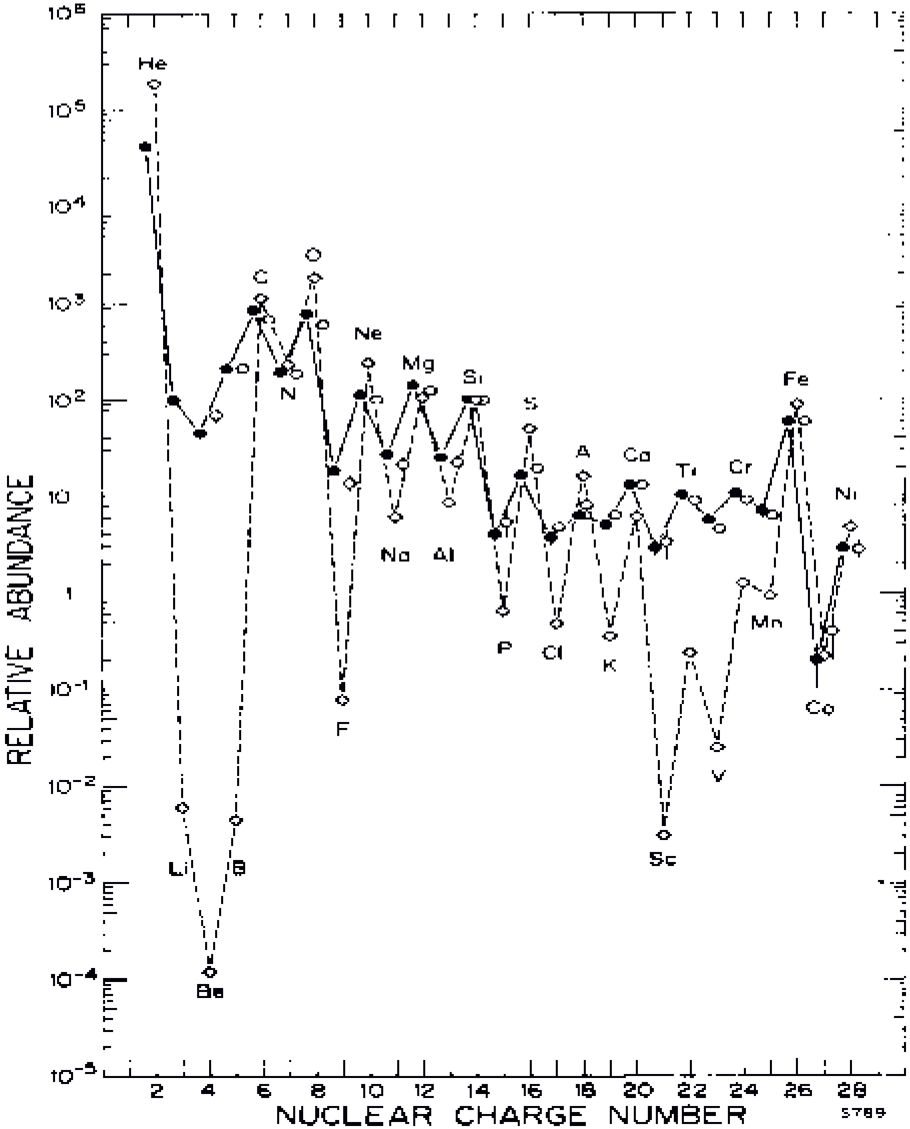
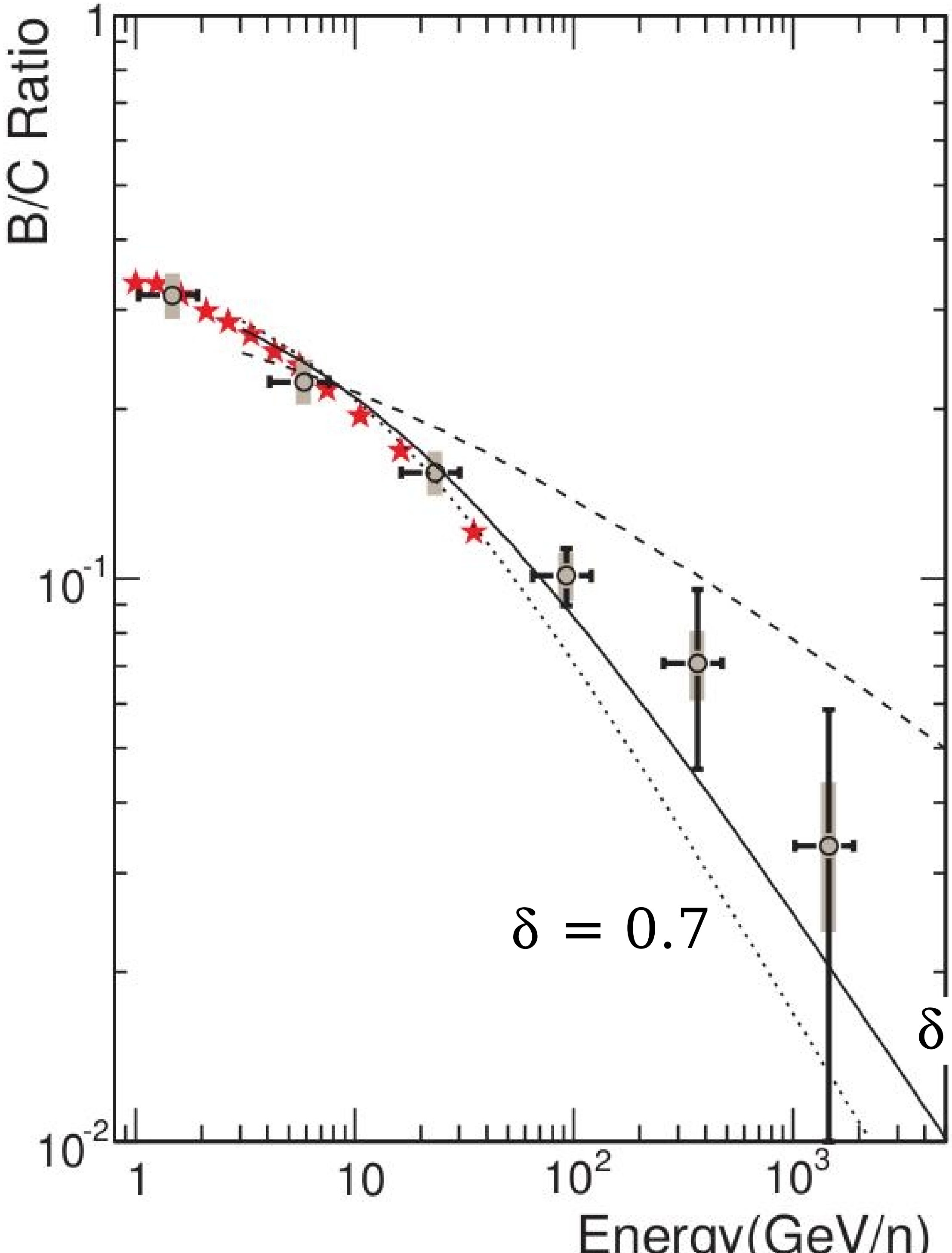


Figure 1. The relative abundance distribution of the elements in the cosmic radiation and in the solar system (normalized to Si = 100) from He to Ni (solid circles, 70–280 MeV per nucleon; open circles, 1000–2000 MeV per nucleon; open diamonds, solar system abundance distribution). [*Reproduced with permission from J. A. Simpson (1983)*. Ann. Rev. Nucl. Part. Sci. **33** *by Annual Reviews, Inc.*].

Secondary nuclei

$$A + p \rightarrow A_1 + A_2$$



Secondary Nuclei

CREAM

$\delta = 0.33$

$\delta = 0.6$

POSITRON EXCESS possible explanations:

"Near Sources"

"NEW Sources"

Dark Matter

New Astrophysical Source (Pulsars)

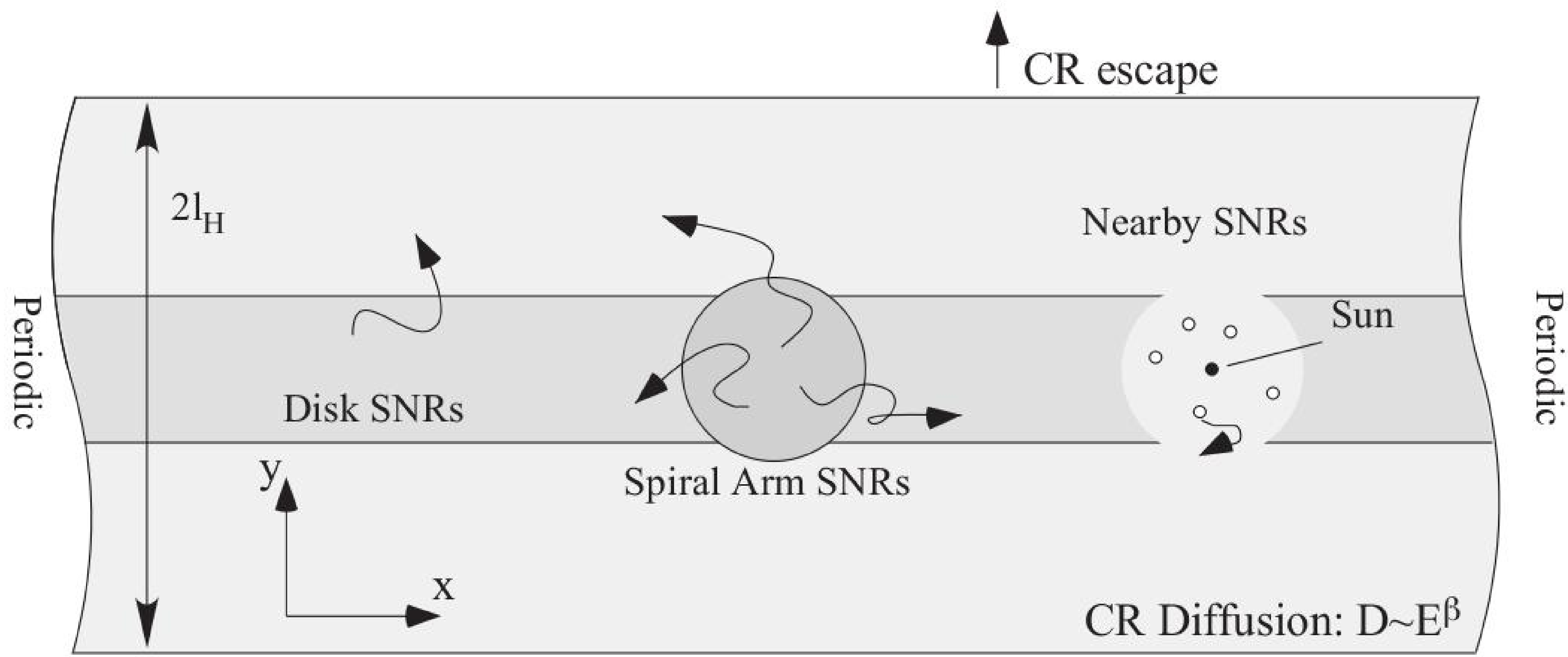
New mechanism in standard sources

Cascade pair injection

P.Blasi

Inhomogeneity in the Supernova Remnant Distribution as the Origin of the PAMELA Anomaly

Nir J. Shaviv[1], Ehud Nakar[2] & Tsvi Piran[1]



The origin of the positron excess in cosmic rays

Pasquale Blasi

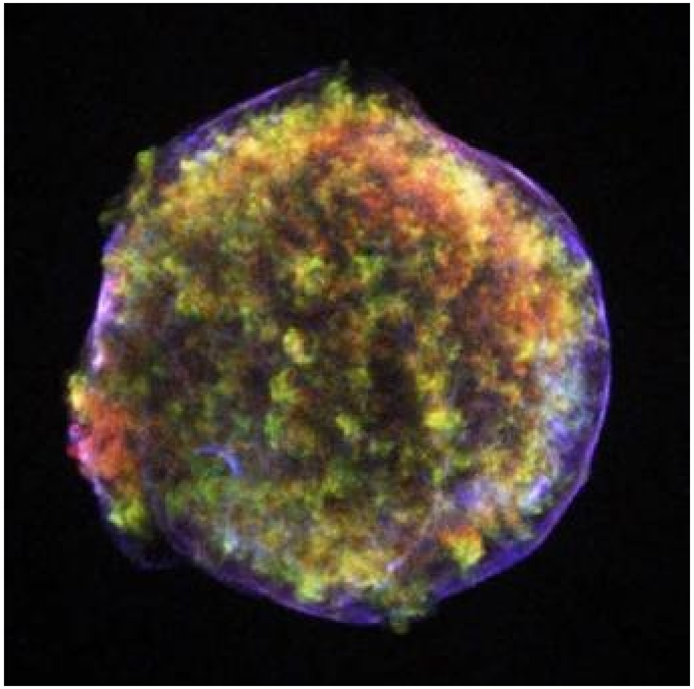
astro-ph/0903.2794

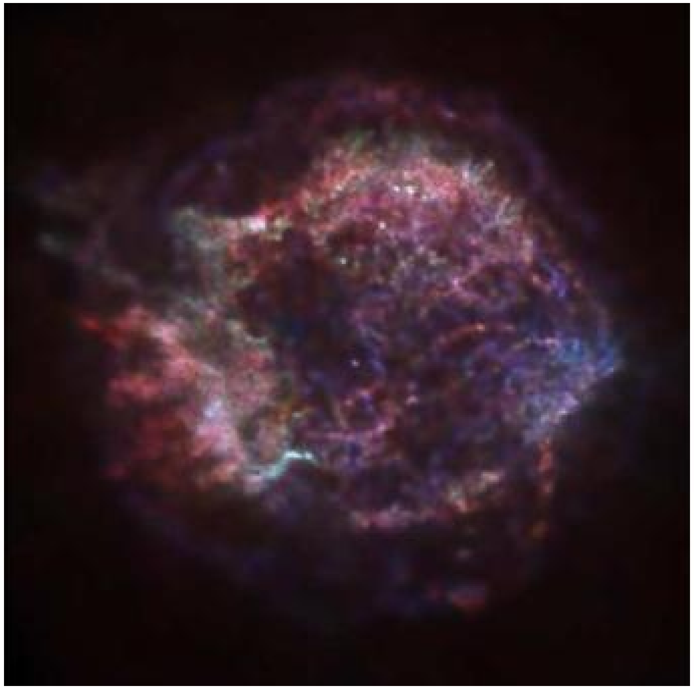
New mechanism in
“standard Supernova acceleration” scenario

INJECTION of e+e- pairs
from accelerated particles at the source

Crucial problems:
Normalization
Spectrum

SuperNovae as main sources of galactic CR



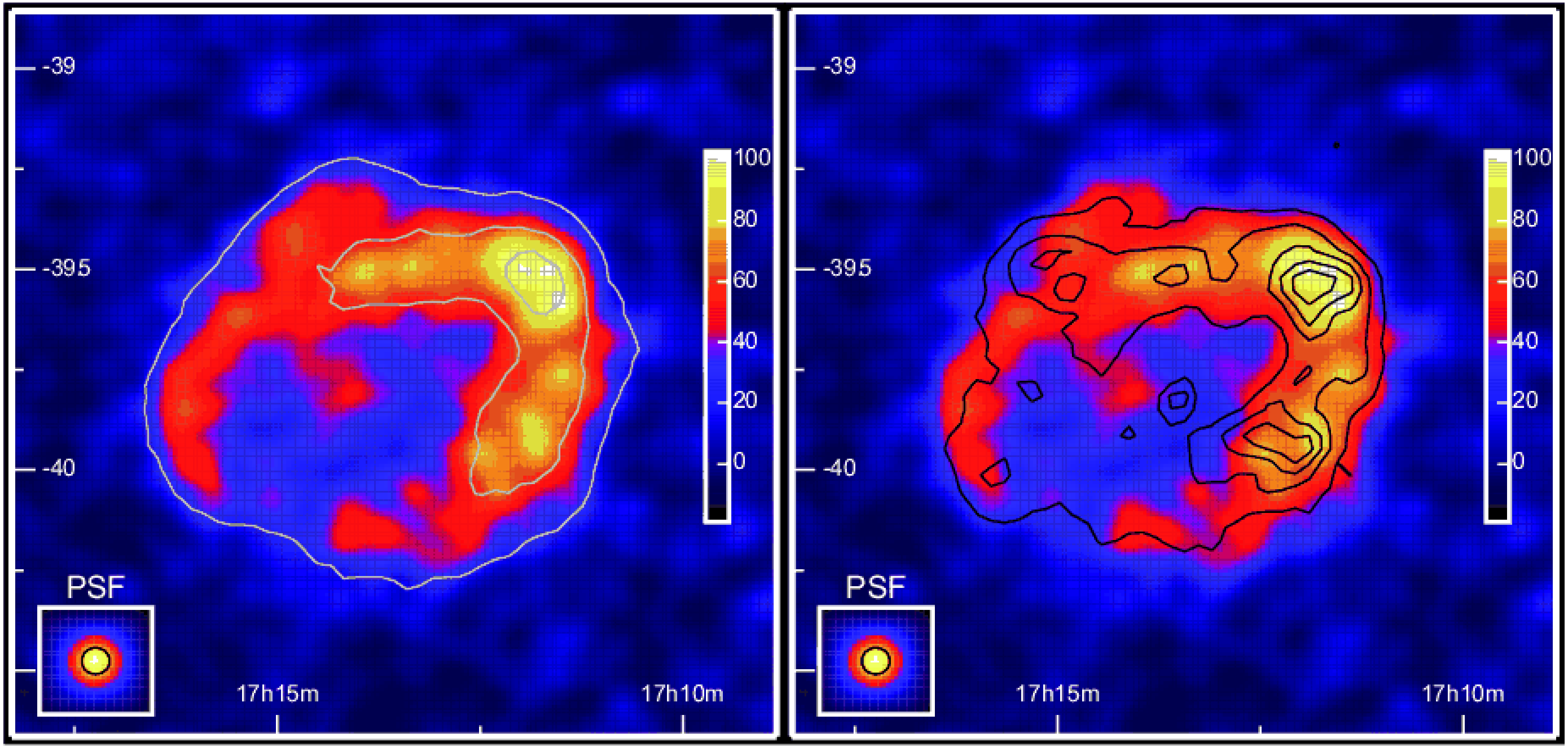


a

SN1006 Tycho Cas A

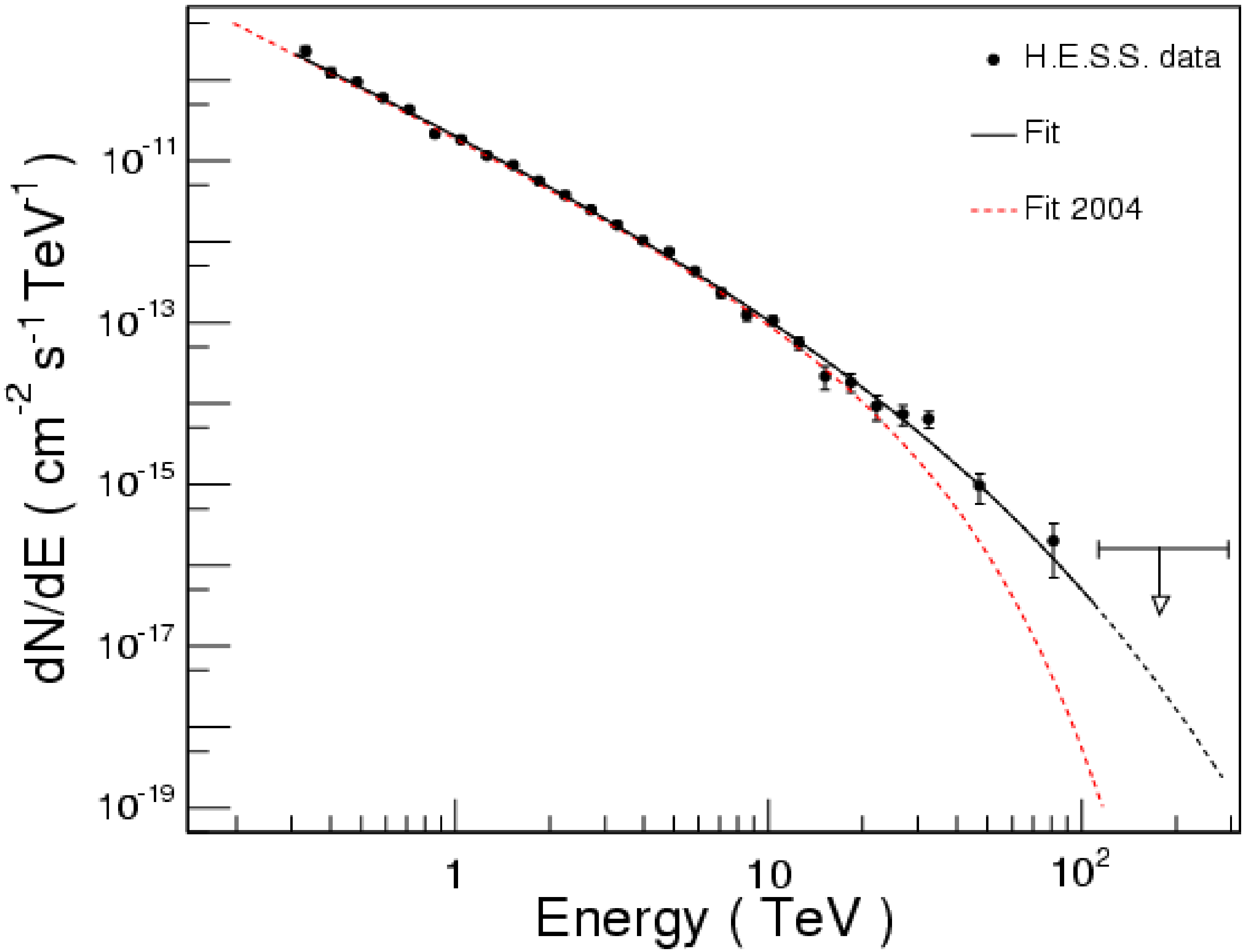
HESS Telescope

Observations with TeV photons



Comparison with ROSAT observation

ENERGY Spectrum

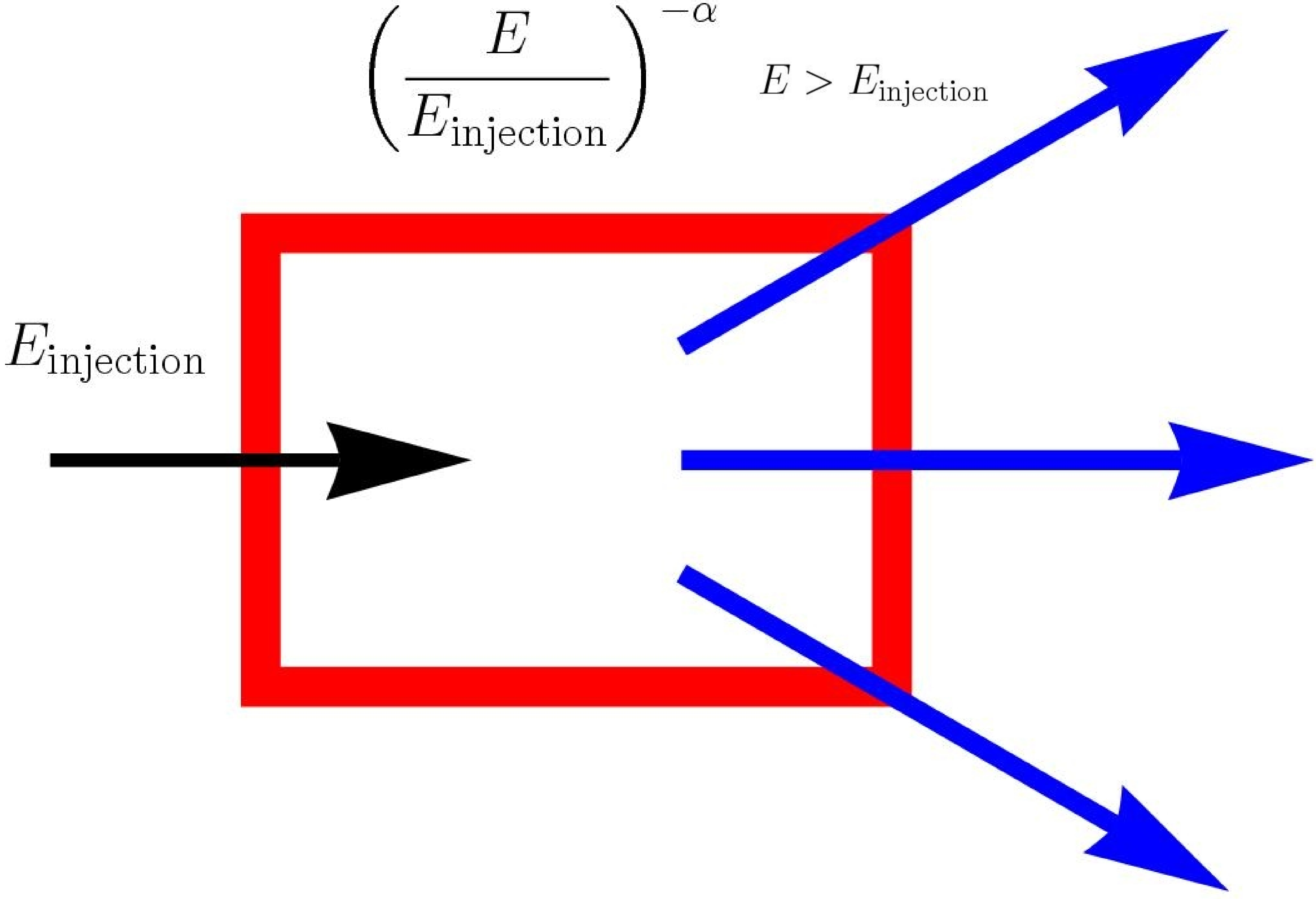


If gamma-rays are from π^0 decay, spectrum requires acceleration of protons to 200 TeV.

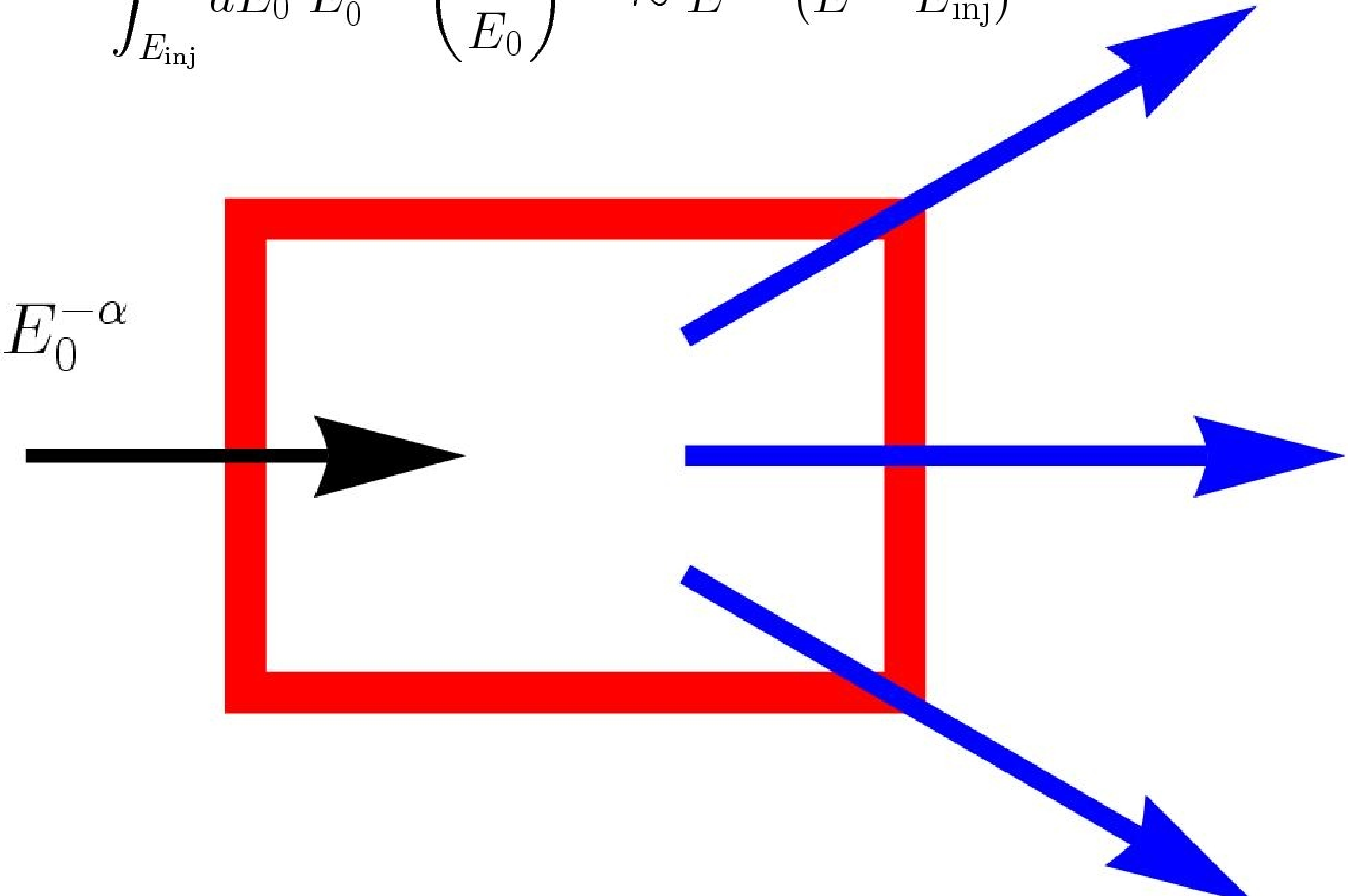
$$\phi_\gamma(E) = K\,E^{-\Gamma}$$

$$\Gamma = 2.19 \pm 0.09 \pm 0.15$$

$$\phi_\gamma(>1\ \text{TeV}) = (1.47 \pm 0.17 \pm 0.37) \times 10^{-7}\ \text{m}^{-2}\,\text{s}^{-1}$$


$\left(\frac{E}{E_{\rm injection}}\right)^{-\alpha}$
$E > E_{\rm injection}$
$E_{\rm injection}$

$$\int_{E_{\rm inj}}^{E} dE_0 \; E_0^{-\alpha} \; \left(\frac{E}{E_0}\right)^{-\alpha} \sim E^{-\alpha} \, (E - E_{\rm inj})$$



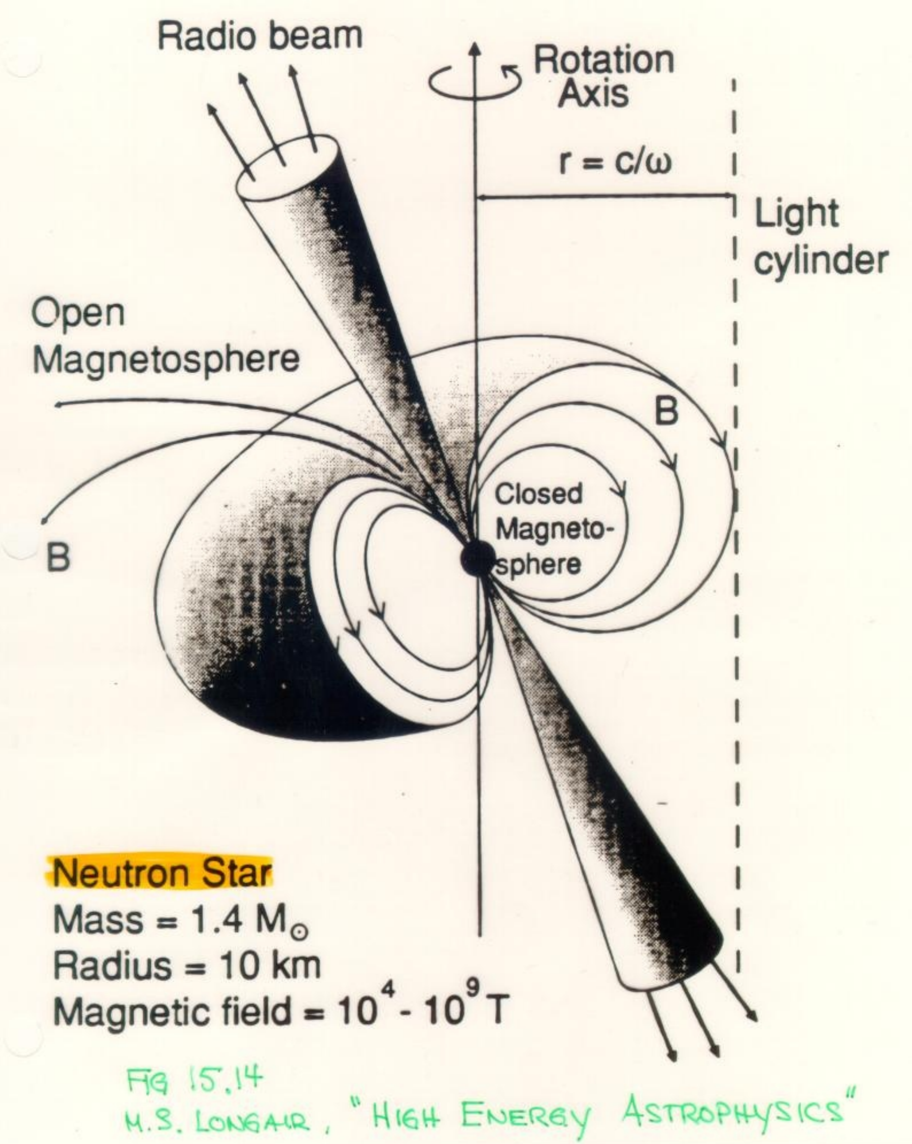
PULSARS

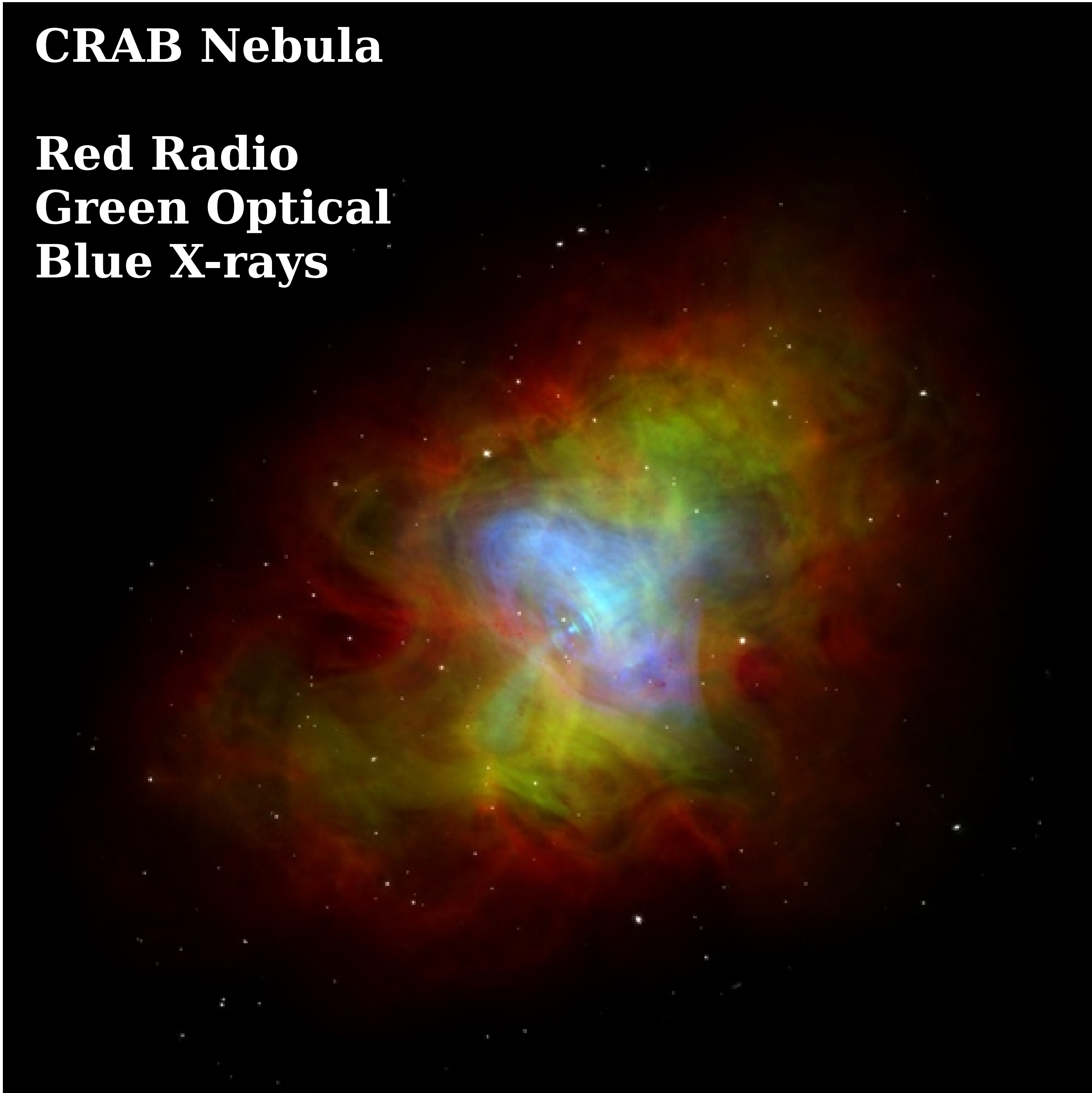
CRAB Nebula

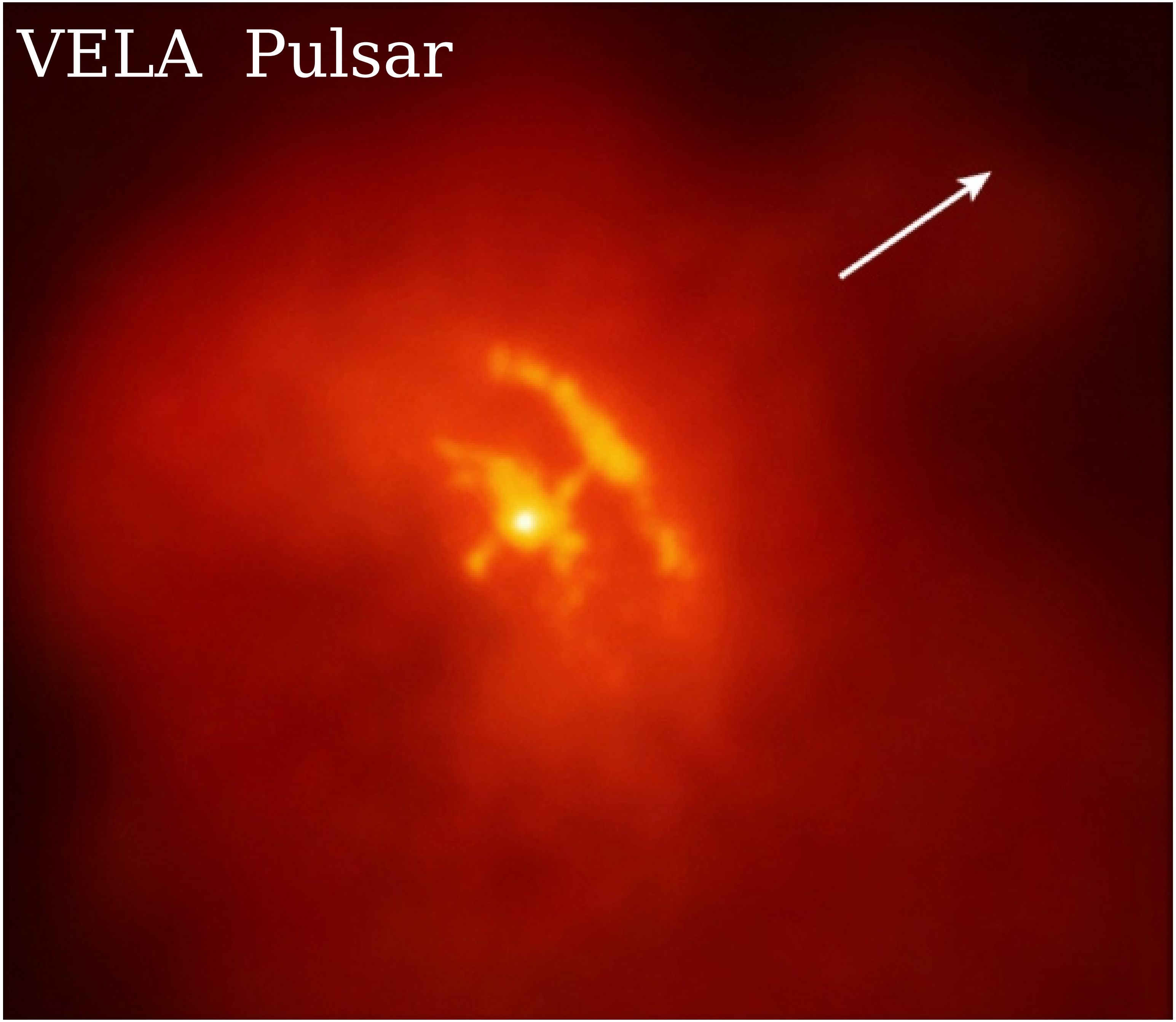
$$P_{\rm Crab} = 0.0334 \text{ s}$$

$$\dot{P}_{\rm Crab} = 4.2 \times 10^{-13} \text{ s}$$

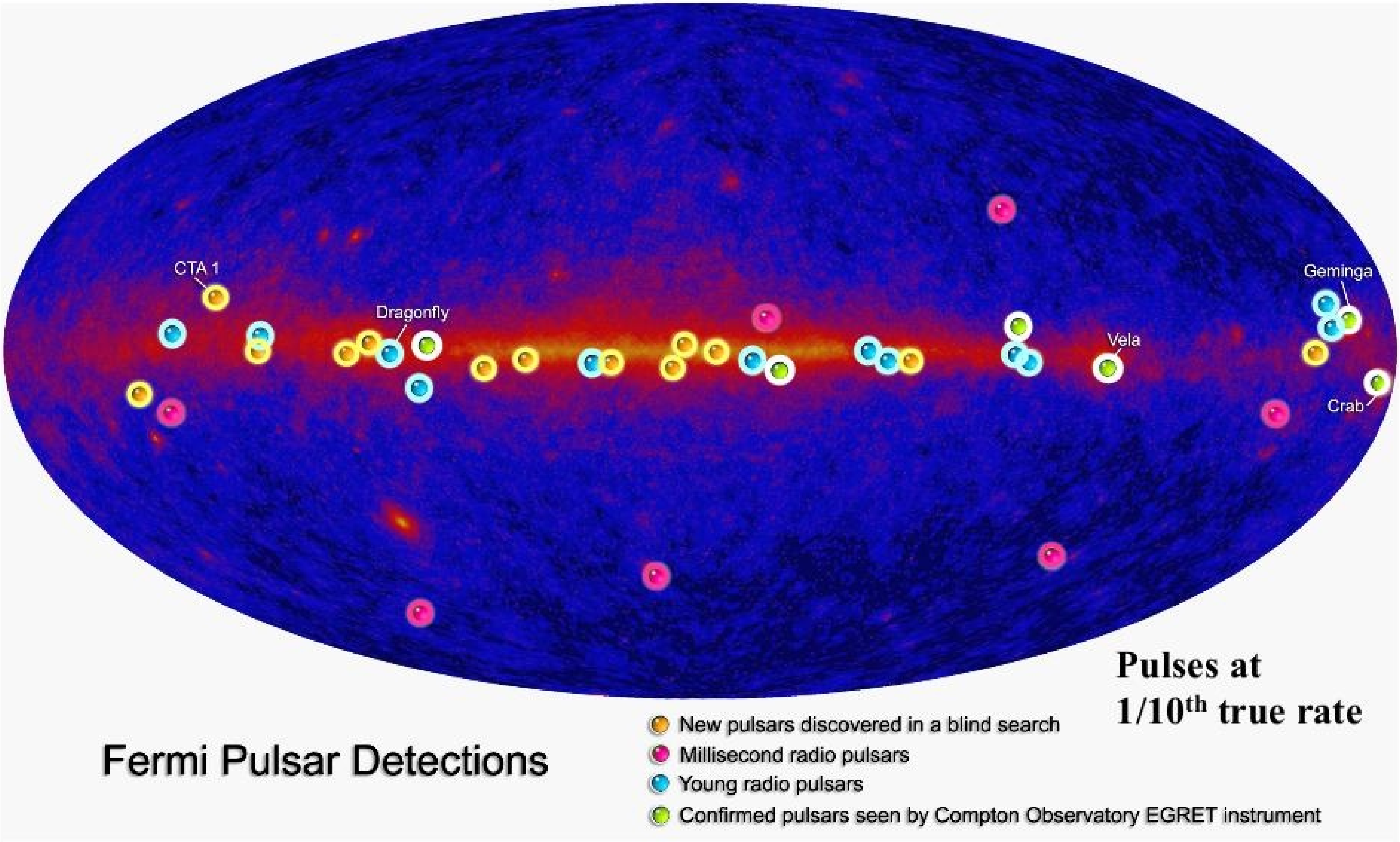
$$(\Delta P_{\rm Crab})_{\rm year} = 13.2 \times 10^{-6} \text{ s}$$




CRAB Nebula
Red Radio
Green Optical
Blue X-rays

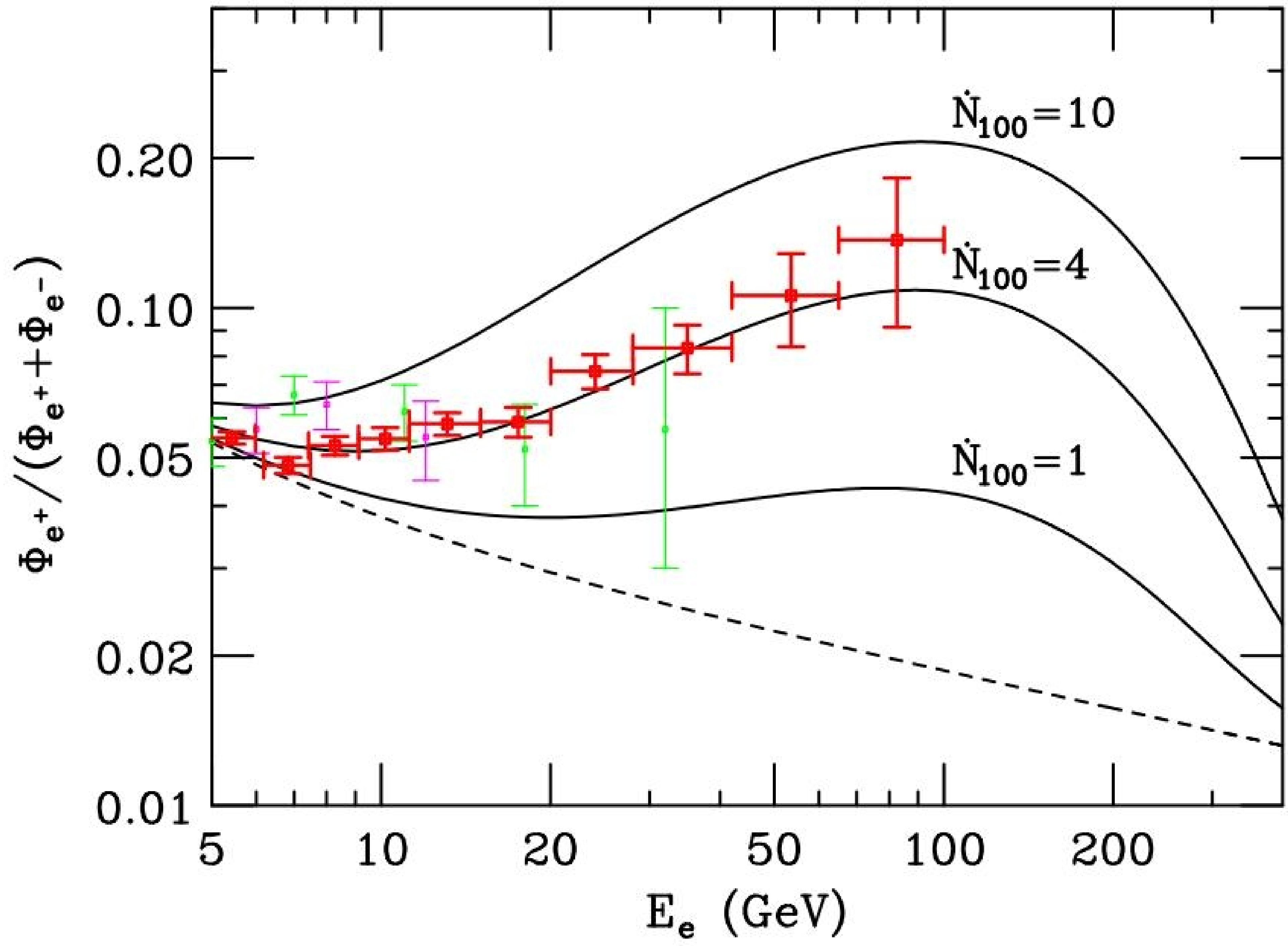

VELA Pulsar

Fermi Pulsar detection



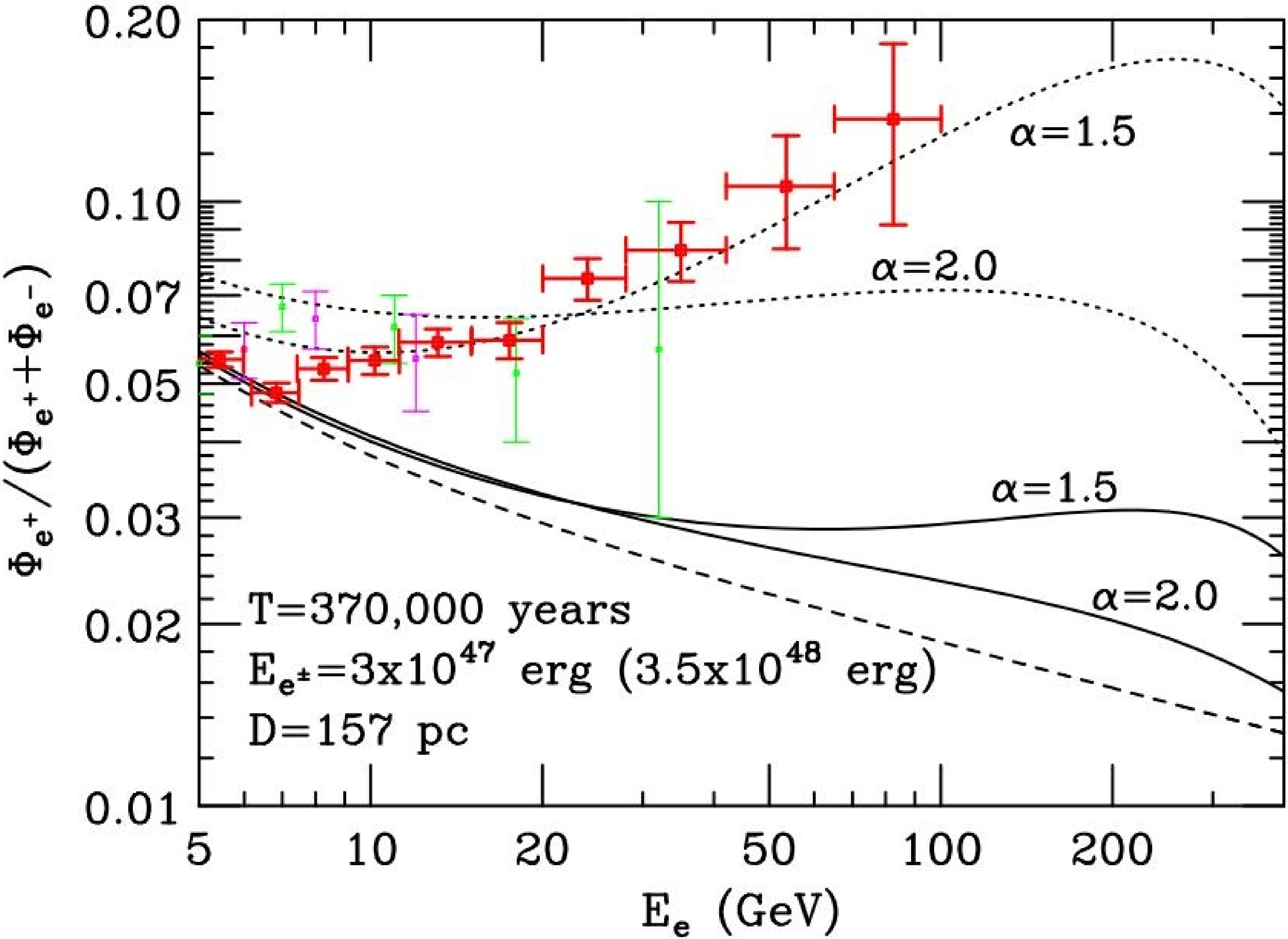
Hooper, Blasi, Serpico 2008

Contribution from all Pulsars



Hooper, Blasi, Serpico 2008

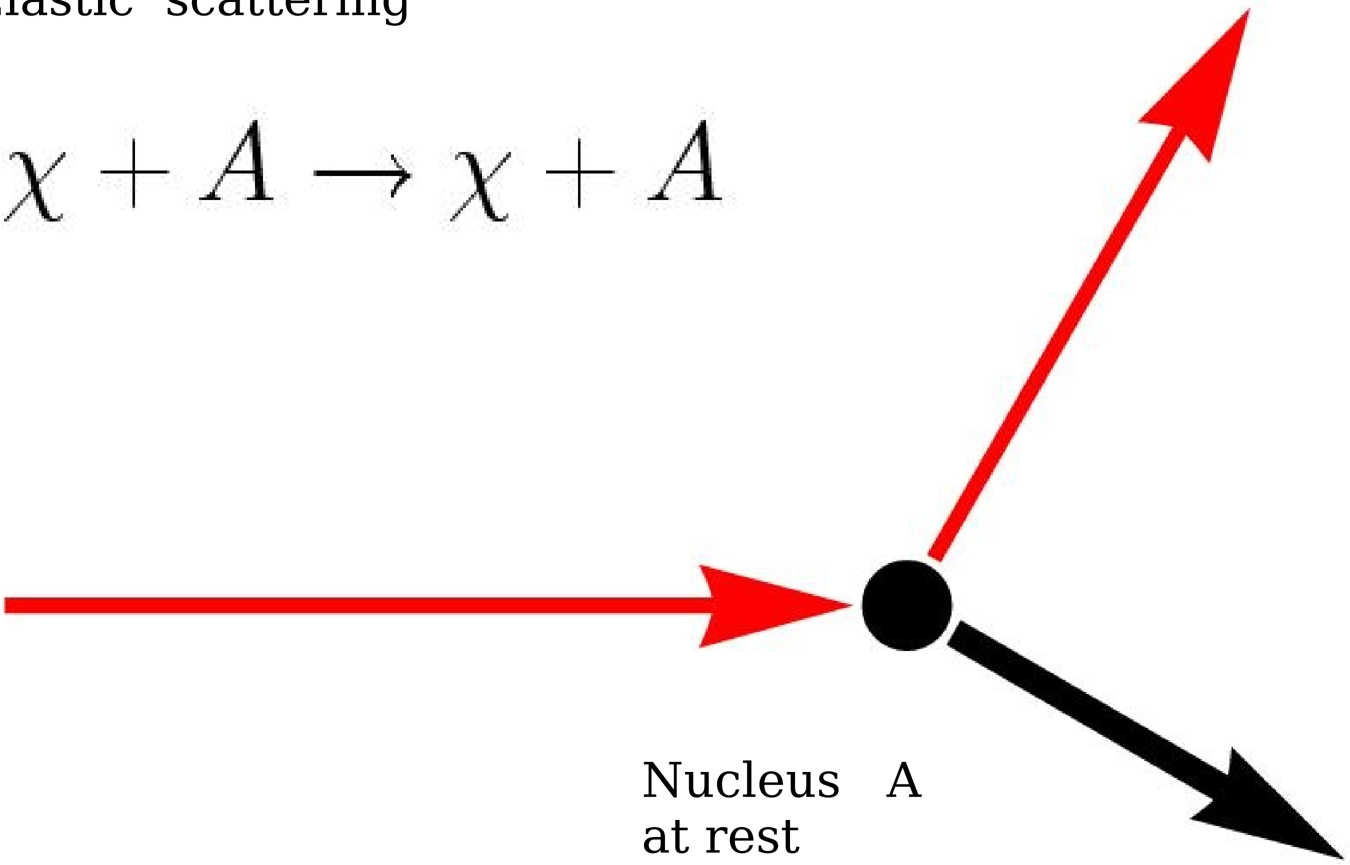
Contribution from single close Pulsar



"Direct" Search for Dark Matter

Elastic scattering

$$\chi + A \to \chi + A$$

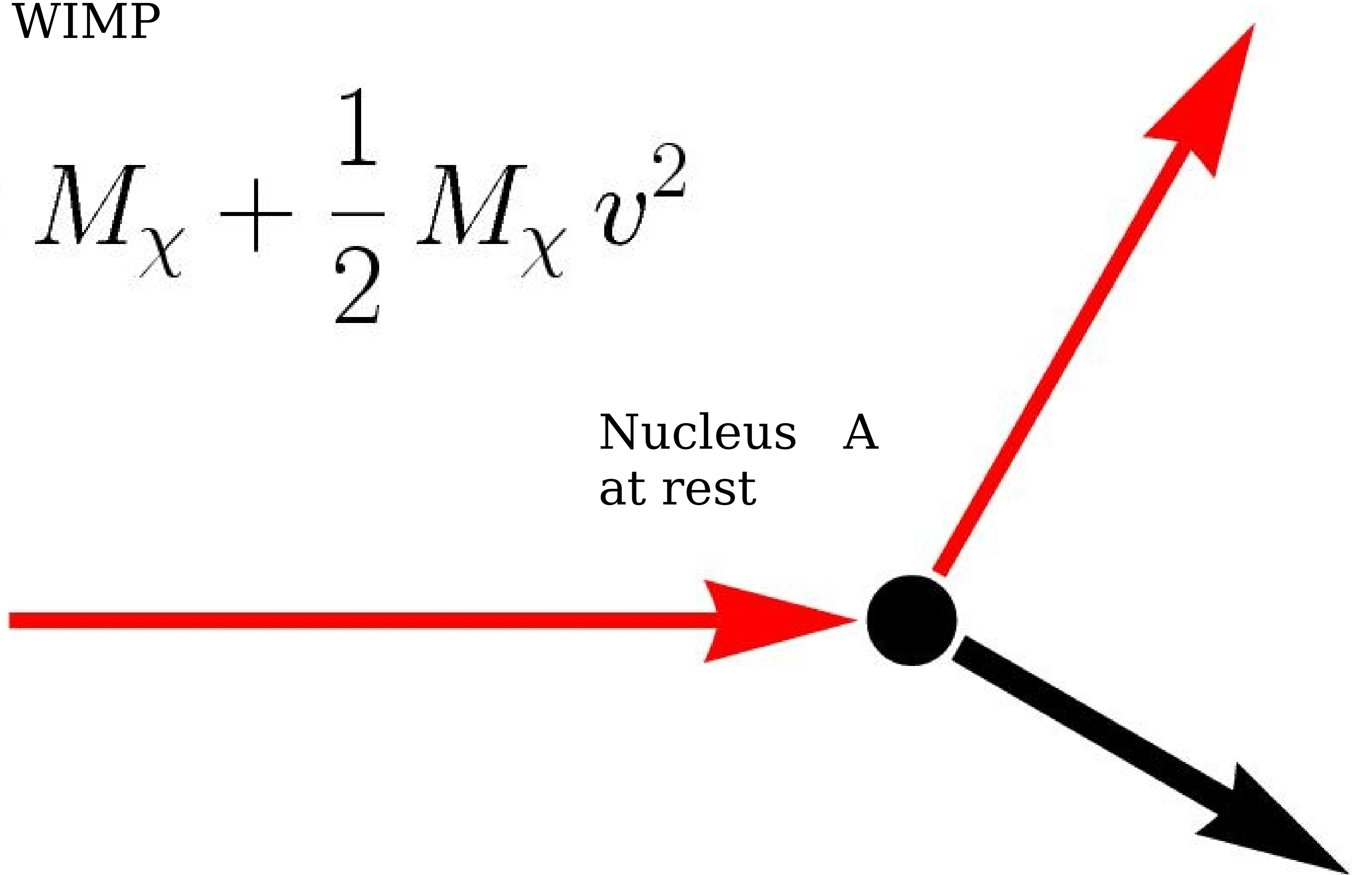


"Direct" Search for Dark Matter

$$\chi + A \to \chi + A$$

Non relativistic WIMP

$$E_{\rm wimp} \simeq M_\chi + \frac{1}{2} M_\chi \, v^2$$



$$E_{\rm nucleus} = M_A \quad + \quad \left[\frac{1}{2} M_\chi \, v^2\right] \, \frac{4 \, M_A \, M_\chi}{(M_A + M_\chi)^2} \, \left(\frac{1 - \cos\theta^*}{2}\right)$$

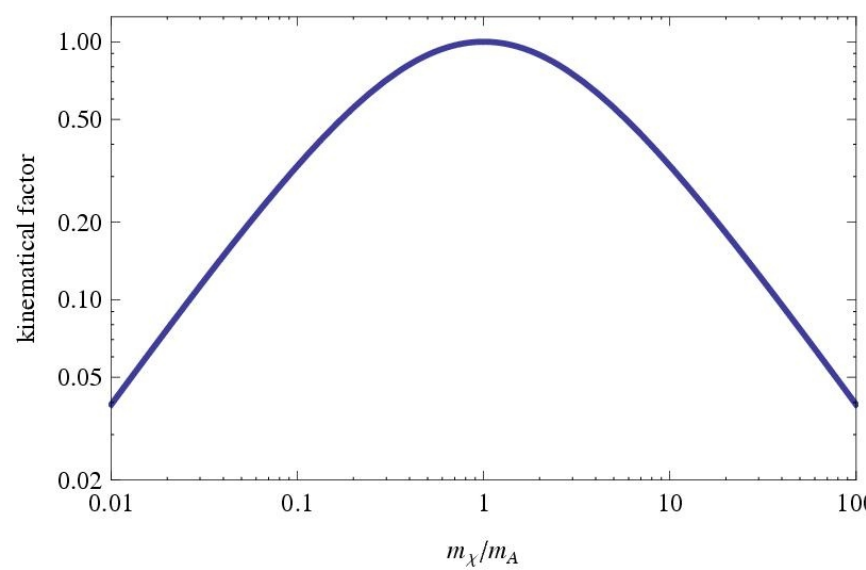
$$E_{\mathrm{nucleus}} = M_A \quad + \quad \left[\frac{1}{2} M_\chi v^2\right] \frac{4\, M_A\, M_\chi}{(M_A + M_\chi)^2} \left(\frac{1 - \cos\theta^*}{2}\right)$$

$$0 \leq E_{\mathrm{recoil}} \leq \left[\frac{1}{2} M_\chi v^2\right] \frac{4\, M_A\, M_\chi}{(M_A + M_\chi)^2}$$

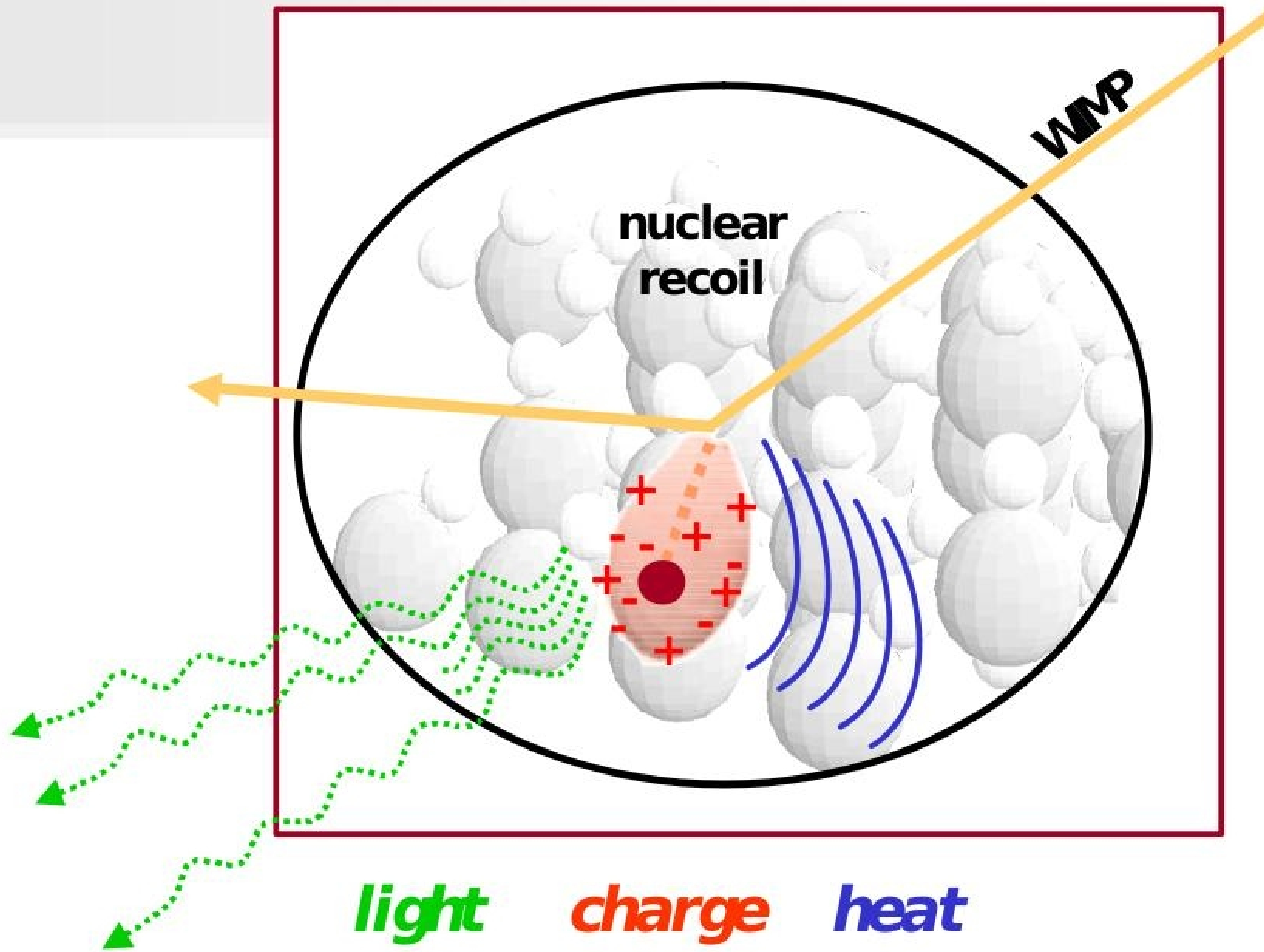
$$E^*_{\mathrm{recoil}} \simeq 39 \text{ KeV} \left[\frac{M_\chi}{100 \text{ GeV}}\right] \left[\frac{v_0}{220 \text{ km s}^{-1}}\right]^2 r$$

Kinematical factor r

$$r = \frac{4\, M_A\, M_\chi}{(M_A + M_\chi)^2}$$



WIMP detection



$$\boxed{\sigma_{\chi A} = \sigma_{\text{spin independent}} + \sigma_{\text{spin dependent}}}$$

Target not point-like:
Form Factor

$$Q^2 = 2\, M_A\, E_{\text{recoil}}$$

$$\frac{d\sigma_p}{d\cos\theta^*} = \frac{\sigma_p}{2}\, F_p(Q^2) \qquad \sigma_p \propto \left(\frac{M_\chi\, M_p}{M_\chi + M_p}\right)^2$$

$$\frac{d\sigma_A}{d\cos\theta^*} = \frac{\sigma_A}{2}\, F_A(Q^2) \qquad \sigma_A \propto \left(\frac{M_\chi\, M_A}{M_\chi + M_A}\right)^2$$

Spin independent : coherent scattering + kinematics

$$\sigma_A = \sigma_p \, A^2 \left(\frac{M_\chi \, M_p}{M_\chi + M_p} \right)^{-2} \left(\frac{M_\chi \, M_A}{M_\chi + M_A} \right)^2$$

$$M_A \simeq A \, M_p$$

$$\sigma_A = \sigma_p \, A^4 \left(\frac{M_\chi + M_p}{M_\chi + A M_p} \right)^2$$

Strong dependence on mass number A

Scattering RATE

$$K \equiv E^*_{\text{recoil}}$$

$$K^* = \frac{1}{2} M_\chi \, v_0^2 \, \frac{4 \, M_\chi \, M_A}{(M_\chi + M_A)^2}$$

$$\boxed{\frac{dR_A}{dK} = \left[\frac{\rho_\chi}{M_\chi \, M_A} \, v_0 \, \sigma_A \right] \, F_A^2(2 \, M_A \, K) \, \left\{ \frac{1}{K^*} F\left(\frac{K}{K^*}, t \right) \right\}}$$

Prefactor

$$\frac{9.3}{A} \, (\text{Kg day})^{-1} \, \left[\frac{50 \text{ GeV}}{M_\chi} \right] \left[\frac{\sigma_A}{10^{-36} \text{ cm}^2} \right] \left[\frac{v_0}{220 \text{ km/s}} \right]$$

Nuclear
Form
Factor

Universal
(A
independent)
function

Velocity
Distribution

$$K \equiv E^*_{\rm recoil}$$

Scattering RATE

$$K^* = \frac{1}{2} M_\chi \, v_0^2 \, \frac{4\, M_\chi \, M_A}{(M_\chi + M_A)^2}$$

$$\boxed{\frac{dR_A}{dK} = \left[\frac{\rho_\chi}{M_\chi \, M_A} \, v_0 \, \sigma_A\right] \, F_A^2(2\, M_A \, K) \, \left\{\frac{1}{K^*} F\left(\frac{K}{K^*}, t\right)\right\}}$$

Prefactor

$$\frac{9.3}{A} \, ({\rm Kg\ day})^{-1} \, \left[\frac{50 \ {\rm GeV}}{M_\chi}\right] \left[\frac{\sigma_A}{10^{-36}\ {\rm cm}^2}\right] \left[\frac{v_0}{220\ {\rm km/s}}\right]$$

Nuclear Form Factor

Universal (A independent) function

Velocity Distribution

CRUCIAL signature A-dependence

Scattering RATE

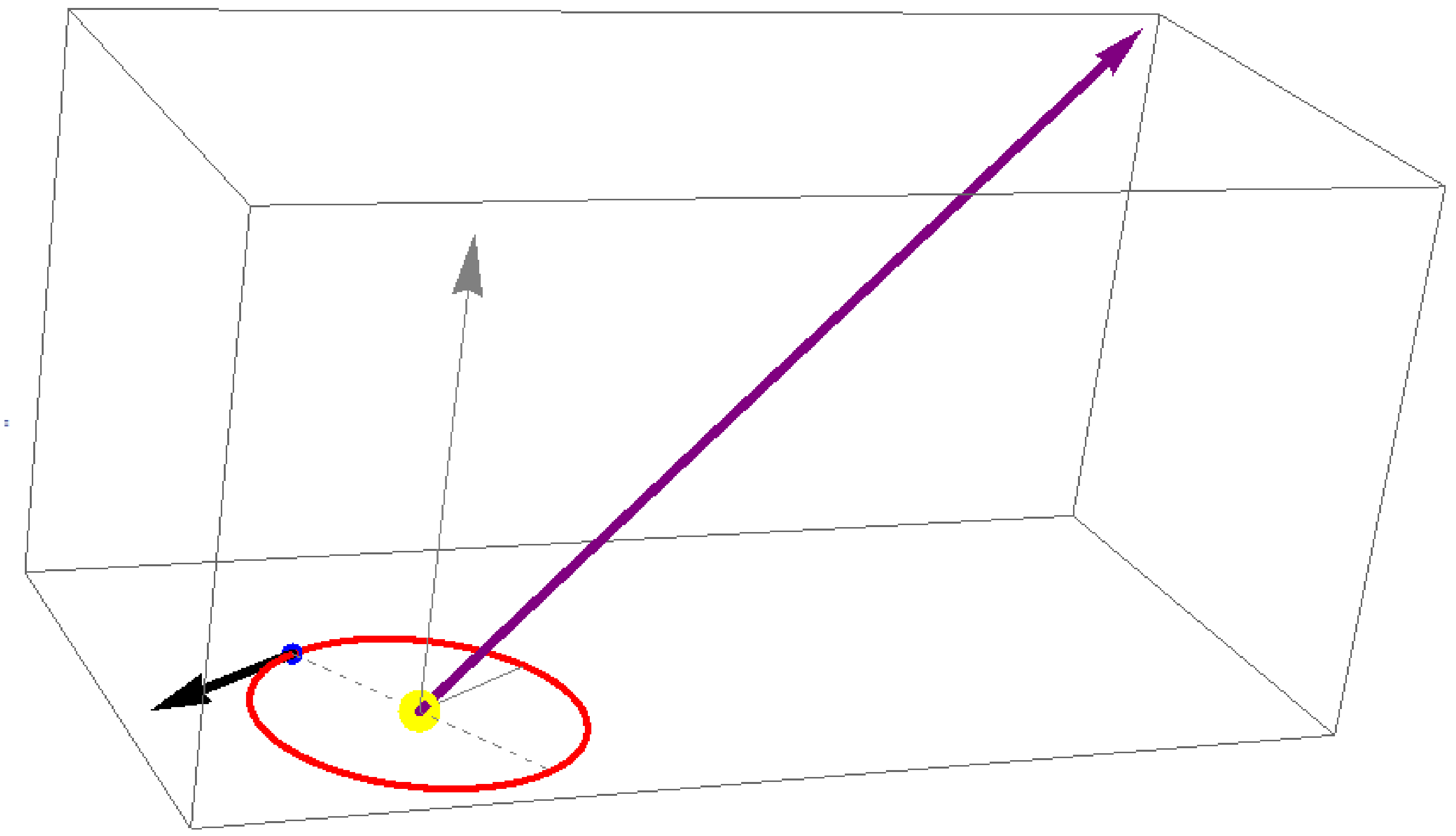
$$K \equiv E^*_{\rm recoil}$$

$$K^* = \frac{1}{2} M_\chi \; v_0^2 \; \frac{4\, M_\chi \, M_A}{(M_\chi + M_A)^2}$$

$$\boxed{\frac{dR_A}{dK} = \left[\frac{\rho_\chi}{M_\chi \, M_A} \; v_0 \; \sigma_A \right] \; F_A^2(2\, M_A\, K) \quad \left\{ \frac{1}{K^*} F\left(\frac{K}{K^*}, t \right) \right\}}$$

$$F\left(\frac{K}{K^*}, w_\oplus(t) \right) = \frac{1}{v_0} \int_{\rm vmin(\mathit{K})}^{\infty} dv \; \frac{f(v,t)}{v}$$

$$v_{\rm min}(K) = \sqrt{\frac{K}{2\, M_\chi \; r}} = \frac{v_0}{\sqrt{2}} \; \sqrt{\frac{K}{K^*}}$$



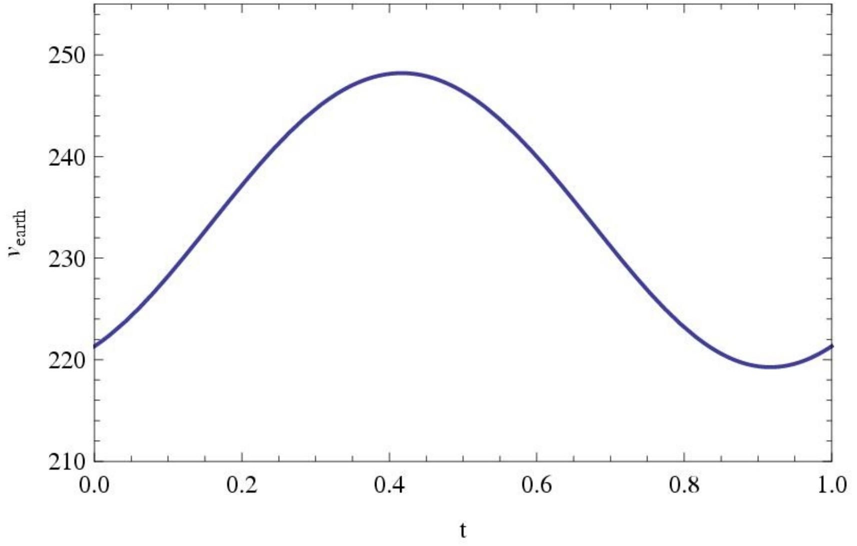
$$\vec{w}_{\oplus}(t) = \vec{w}_{\odot} + \vec{v}_{\mathrm{orbit}}(t)$$

$$w_{\oplus}(t) \simeq w_{\odot} + \sin\gamma\ v_{\mathrm{orbit}}\ \cos[\omega(t - t_0)]$$

“Halo rest frame”

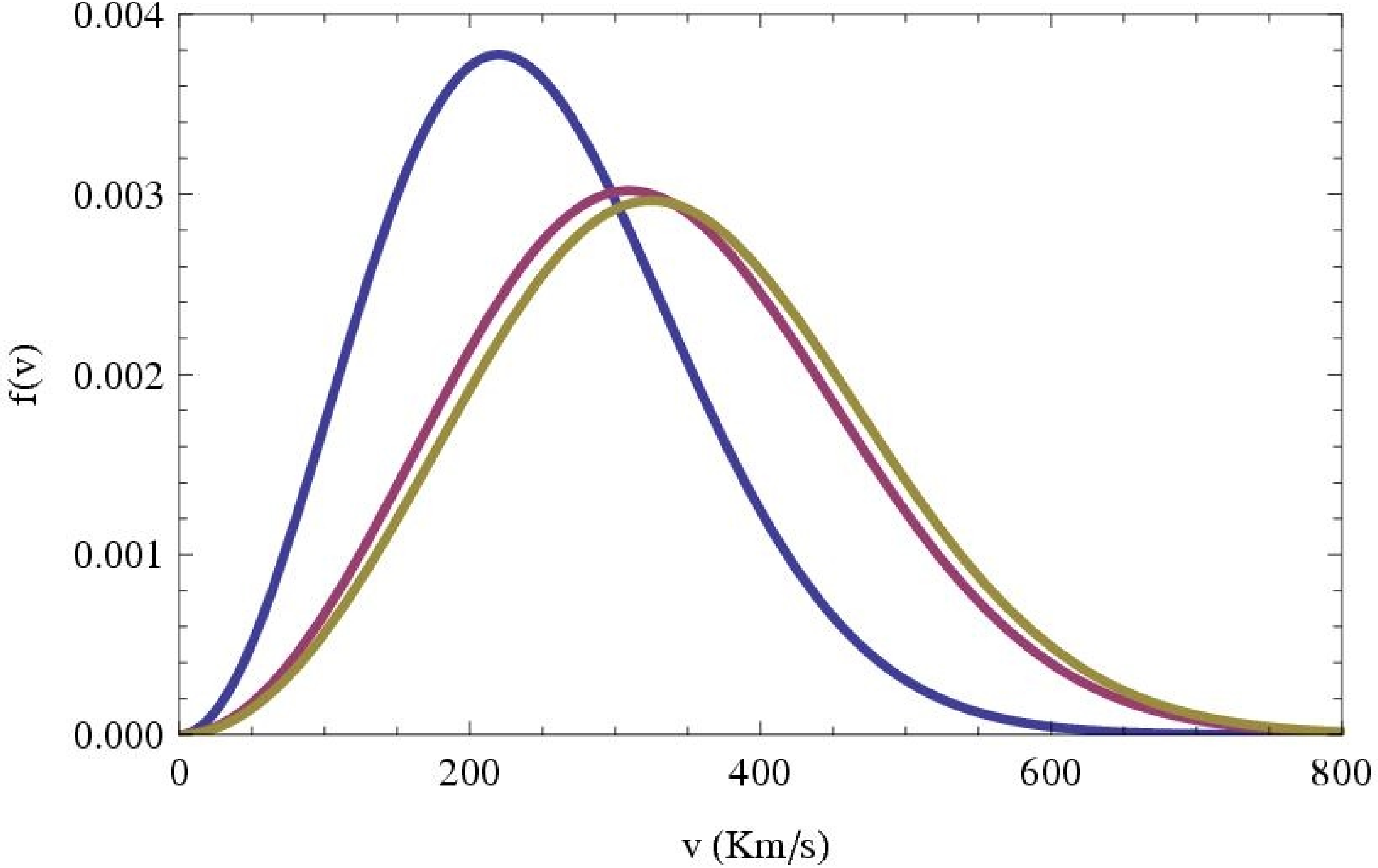
Velocity of Earth in the Halo rest frame

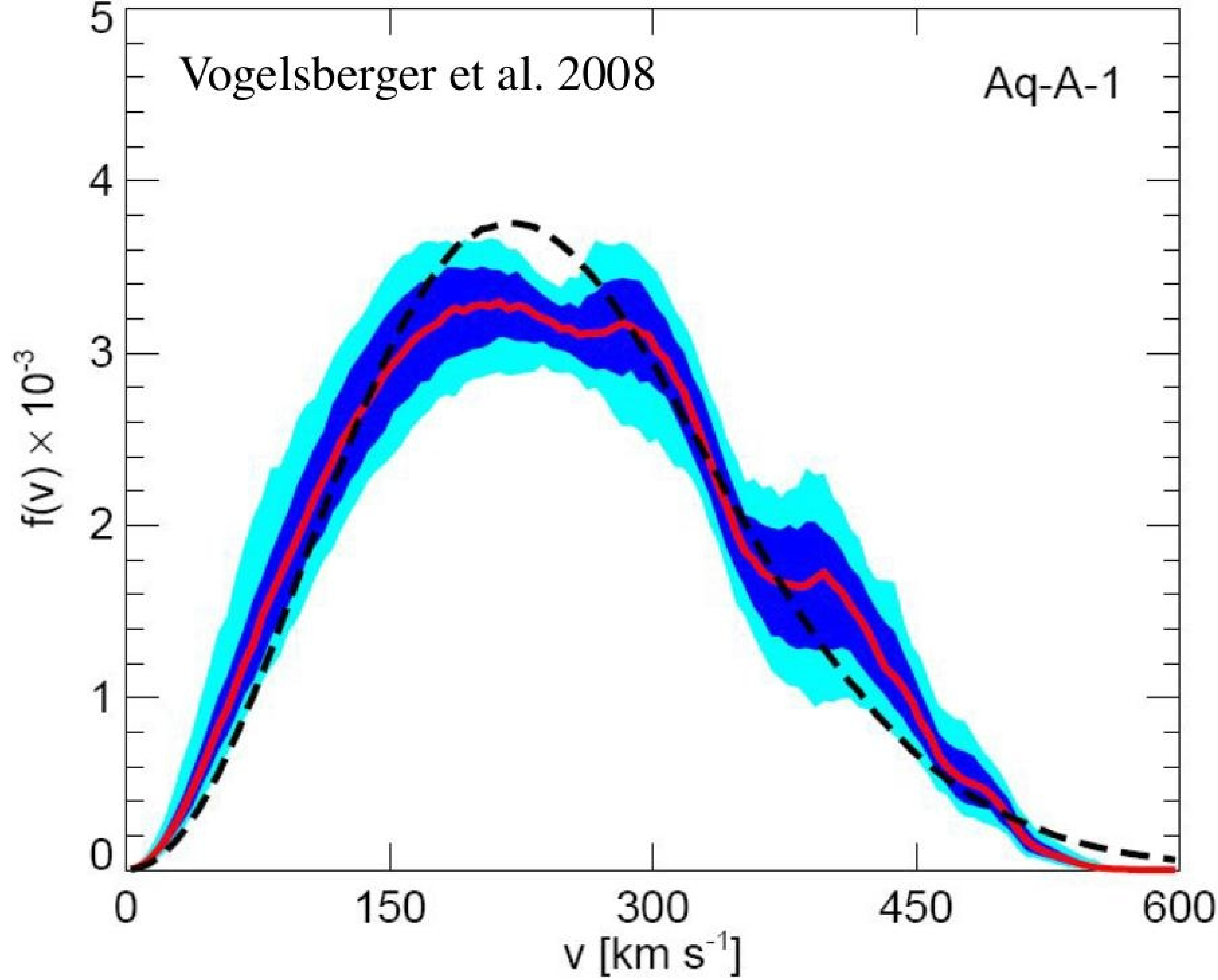
[Co-rotation ?]



Velocity distribution in "halo rest frame"

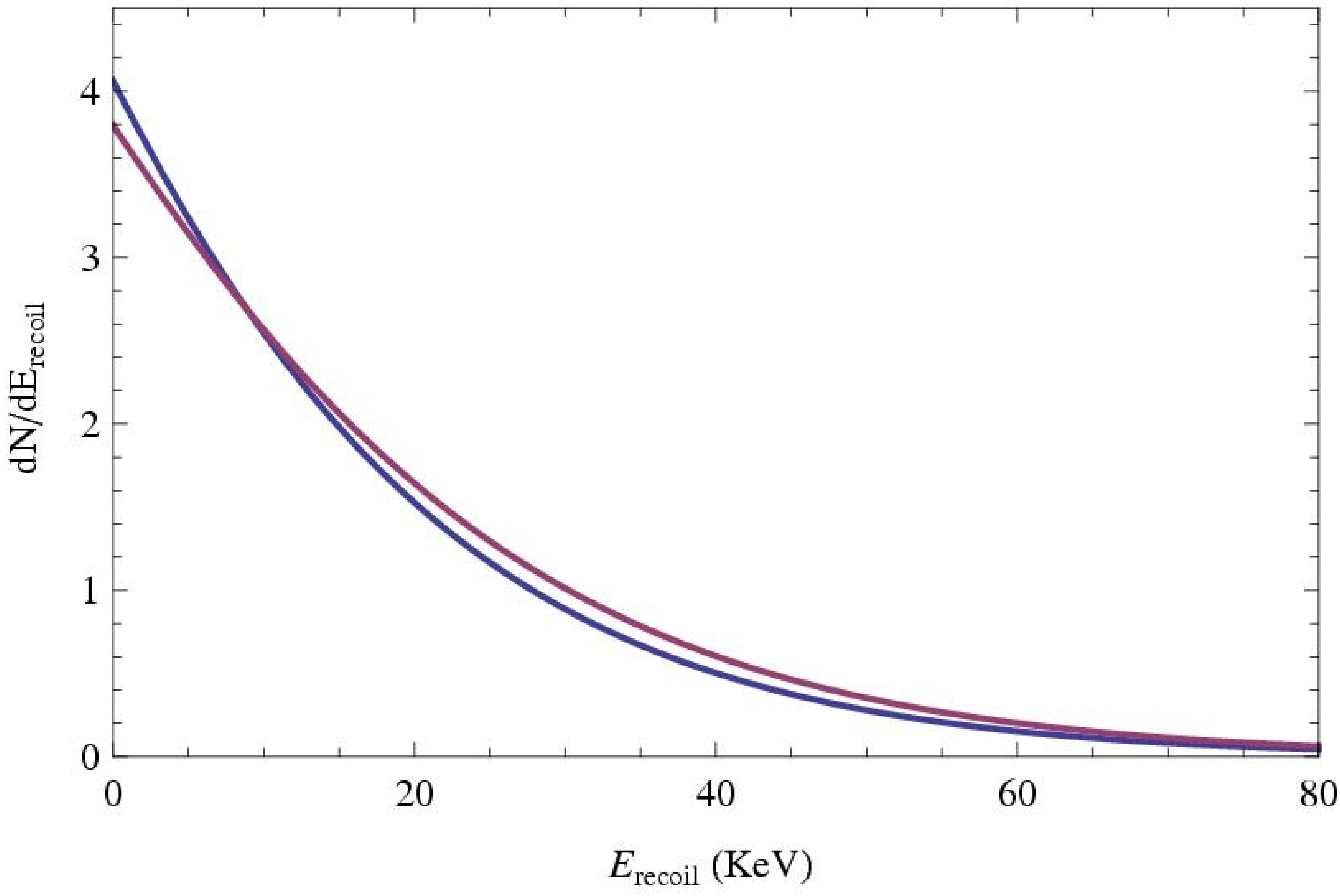
$$f_0(v) = \frac{1}{\pi^{3/2}\, v_0^3}\ \exp\left[-\frac{v^2}{v_0^2}\right]$$




Vogelsberger et al. 2008
Aq-A-1
$f(v) \times 10^{-3}$
v [km s^{-1}]
0
1
2
3
4
5
0
150
300
450
600

$A = 127$ (Iodium)
$M_{wimp} = 50$ GeV

Quasi exponential distribution

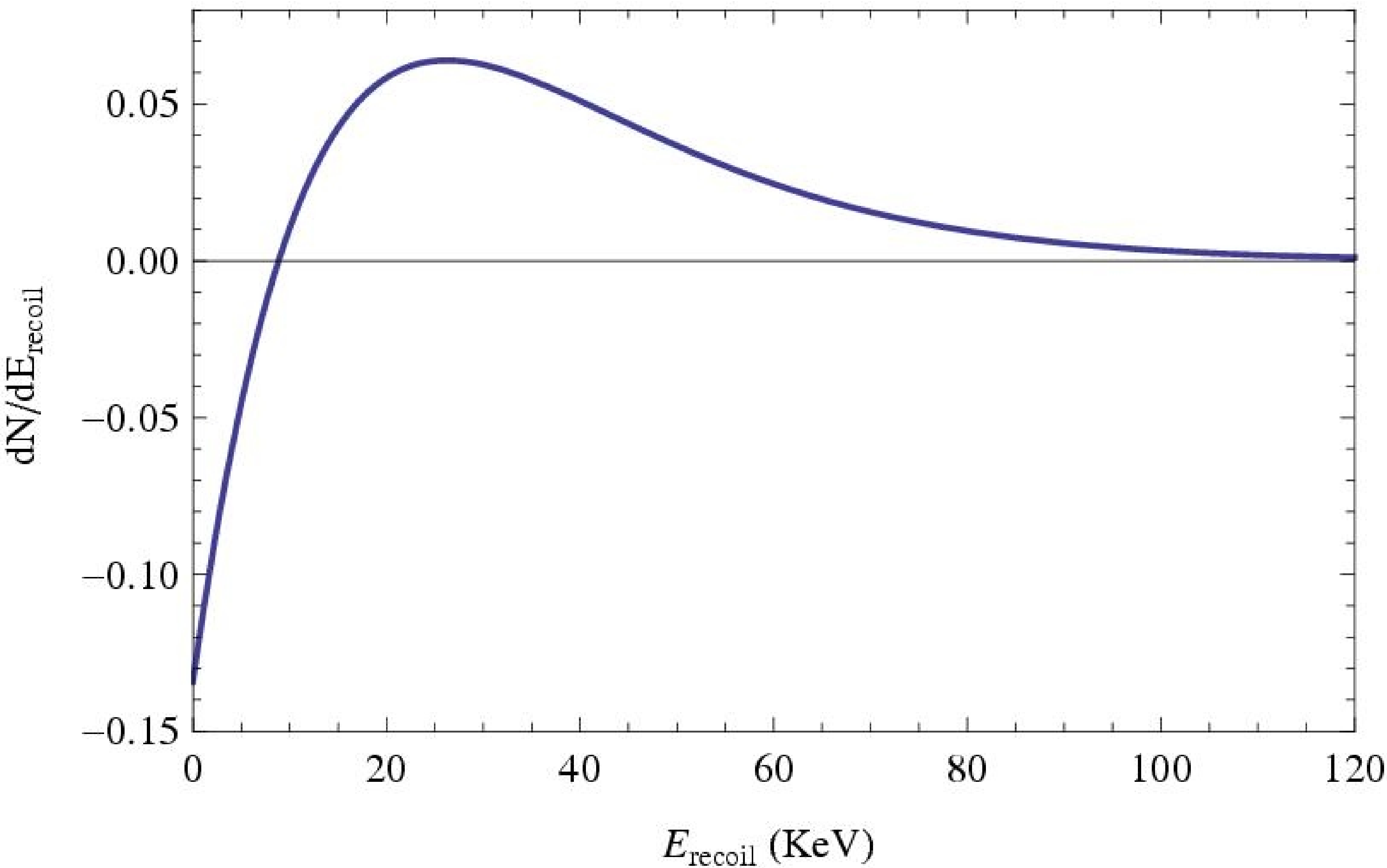


$$\boxed{\frac{dR}{dE_{\mathrm{recoil}}}(E_{\mathrm{recoil}}, t) = R_0(E_{\mathrm{recoil}}) + A(E_{\mathrm{recoil}})\ f(t)}$$

$$f(t) \simeq \cos\left[\frac{2\,\pi}{T_0}\,(t - t_0)\right]$$

$$A(K) = \left[\frac{\rho_\chi}{M_\chi\, M_A}\ \sigma_A\right]\ [\sin\gamma\ v_{\mathrm{orbit}}]\ F_A^2(2\,M_A\,K)\ \left\{\frac{1}{K^*} G\left(\frac{K}{K^*}\right)\right\}$$

$$G(x) = v_0\ \ \frac{d}{dw} F(x, w)\bigg|_{w=w_\odot}$$



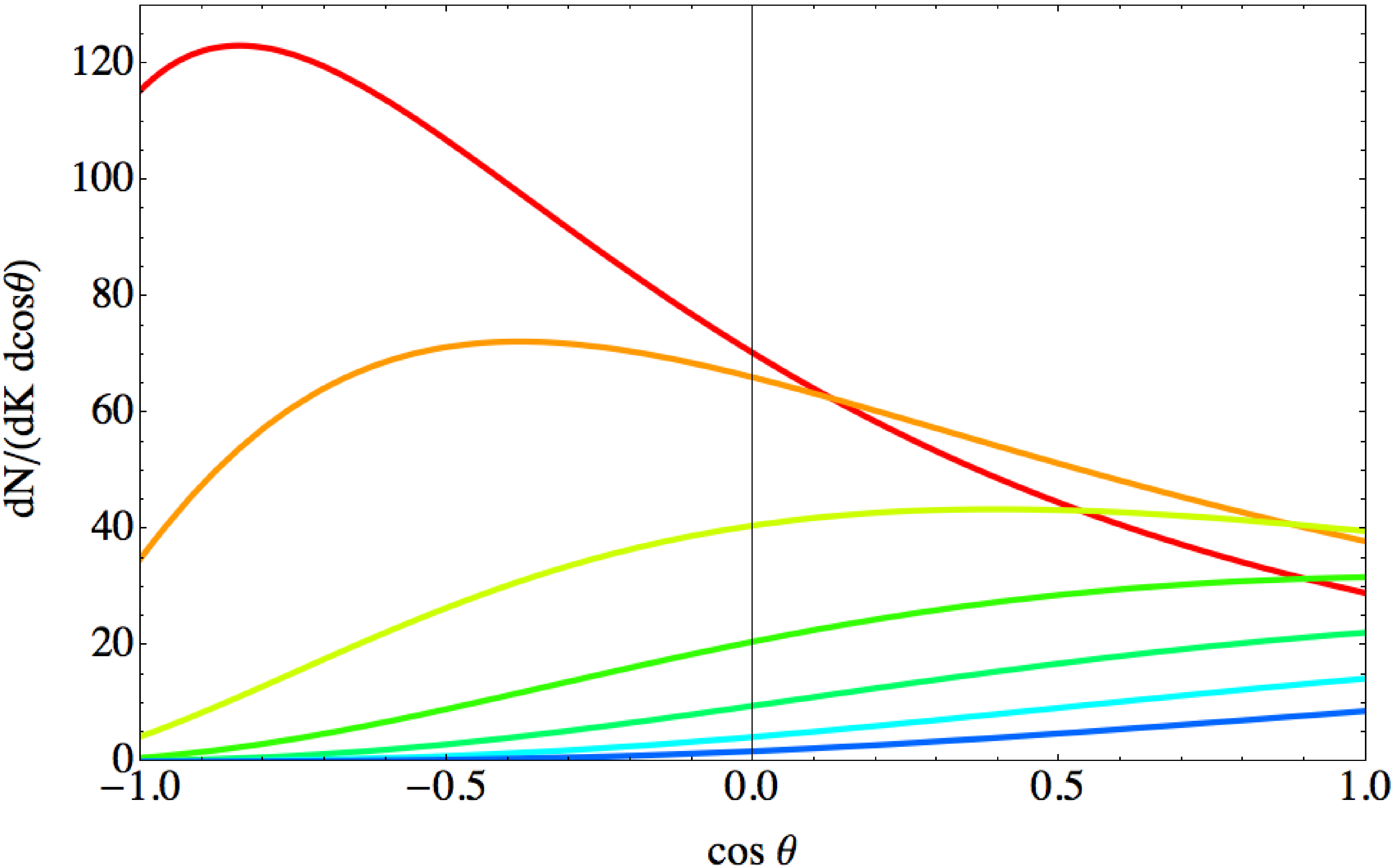
0.05
0.00
−0.05
−0.10
−0.15
dN/dE$_{recoil}$
0
20
40
60
80
100
120
E_{recoil} (KeV)

Directional Response

$M_\chi = 11.6 \text{ GeV}$

$A = 127$

$K = 0.5, 1, 2, 3, 4, 5, 6 \text{ KeV}$

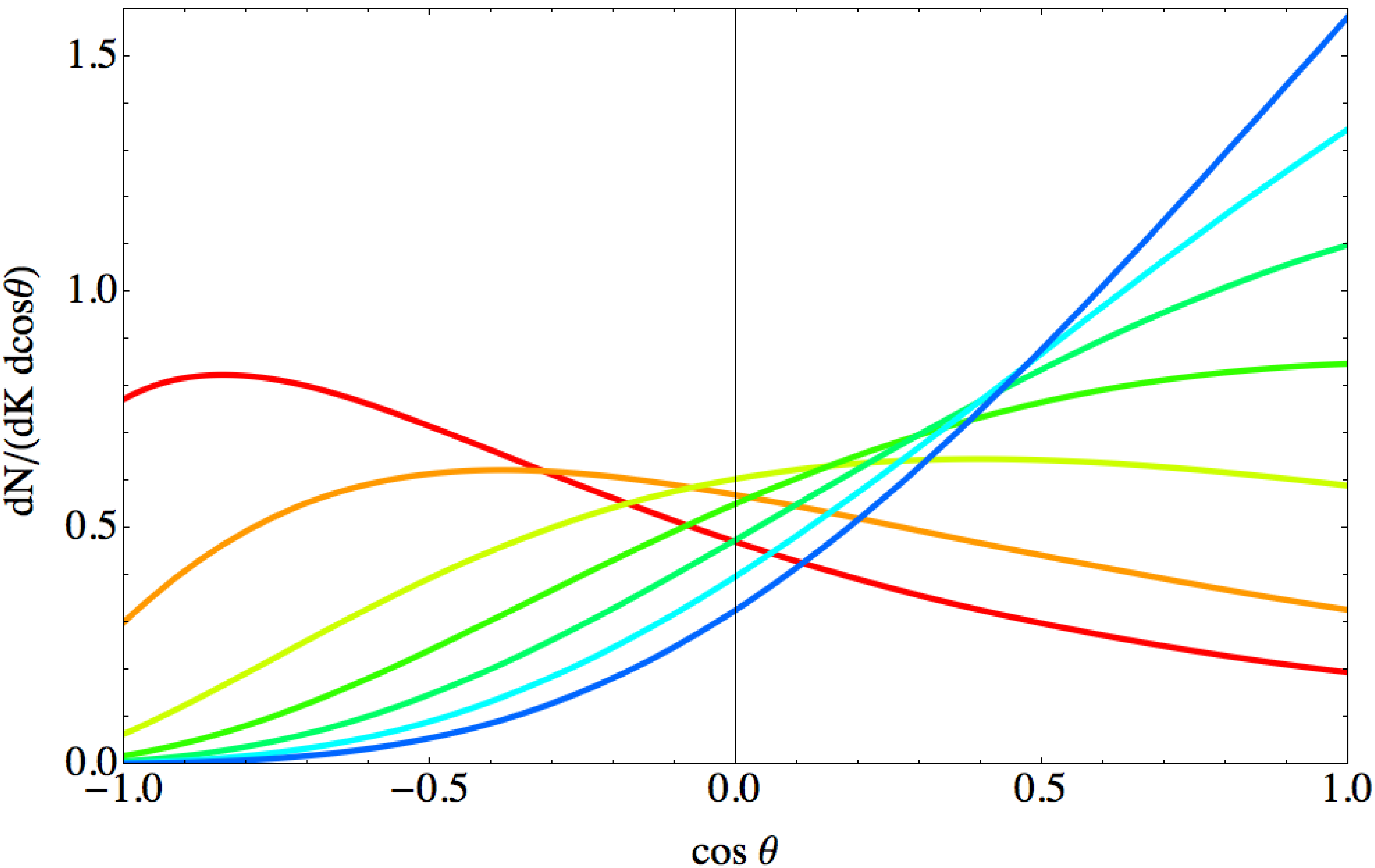


Directional Response

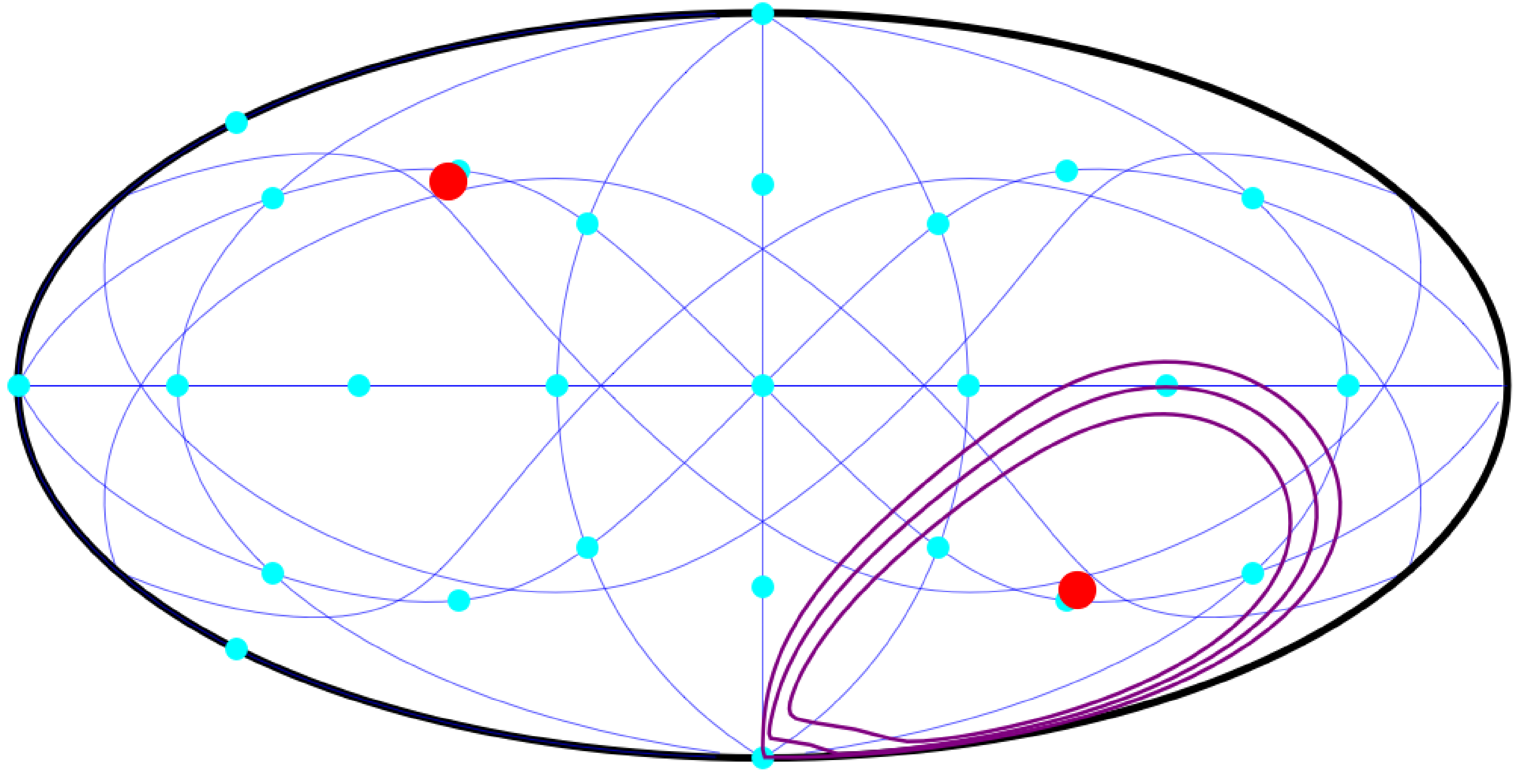
$M_\chi = 11.6 \text{ GeV}$

$K = 0.5, 1, 2, 3, 4, 5, 6 \text{ KeV}$

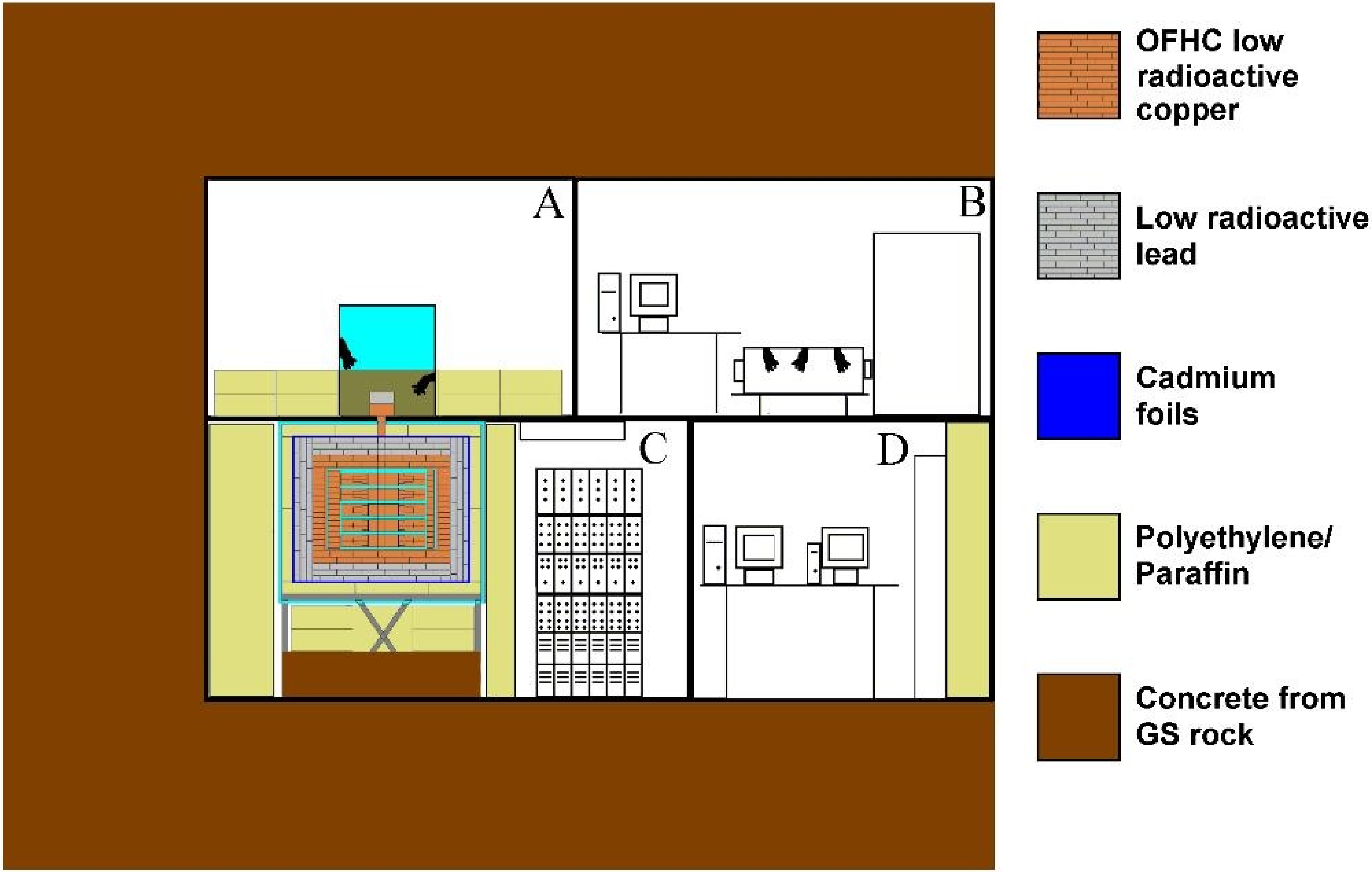
$A = 127$



Detector at LNGS position

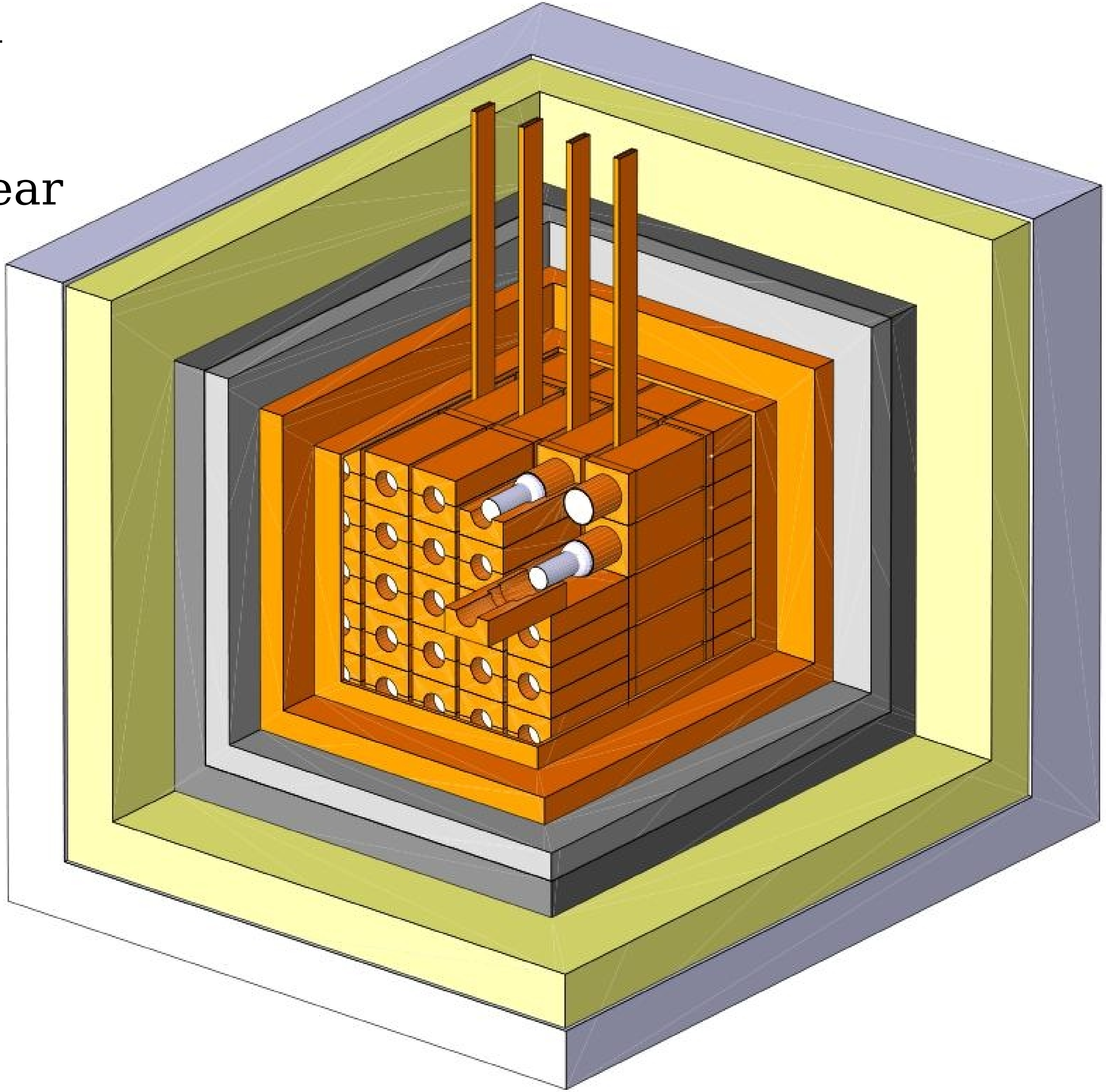


DAMA-LIBRA (Gran Sasso)

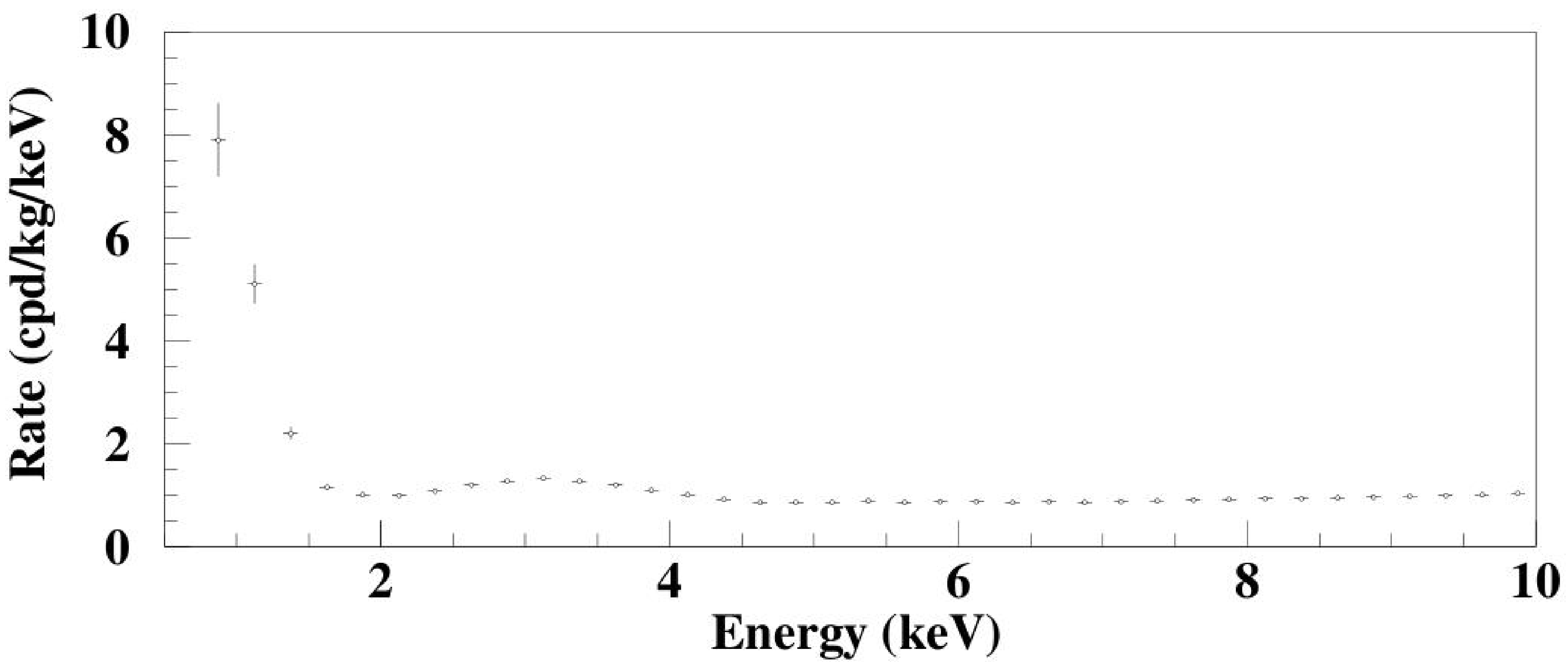


Dama-Libra
250 Kg NaI

0.82 ton=year

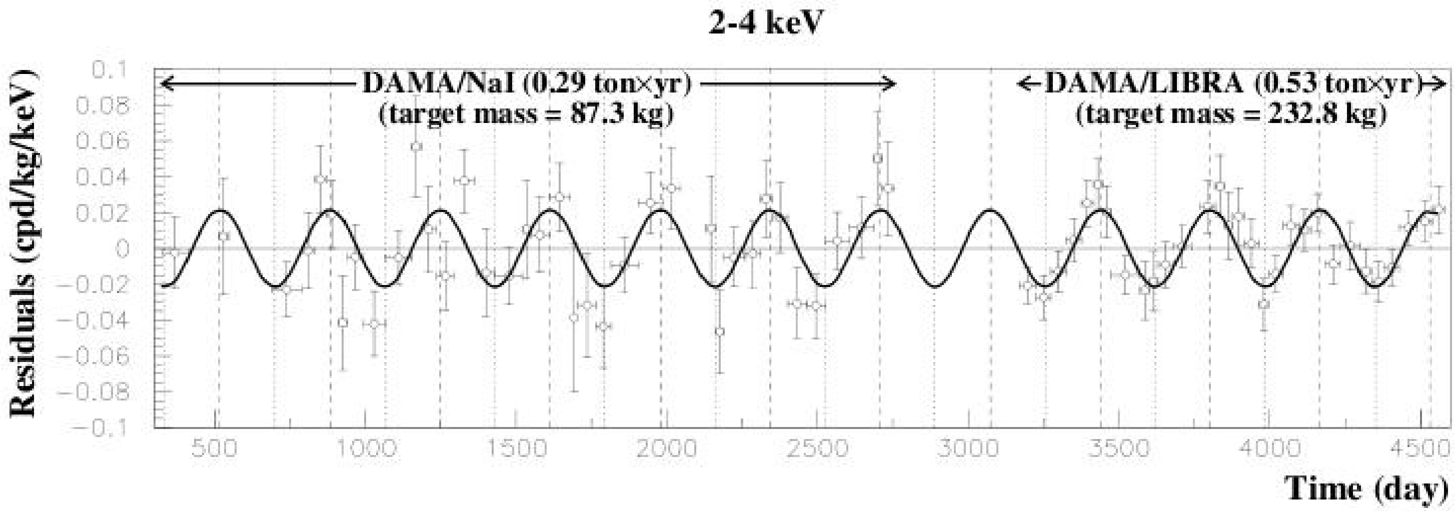


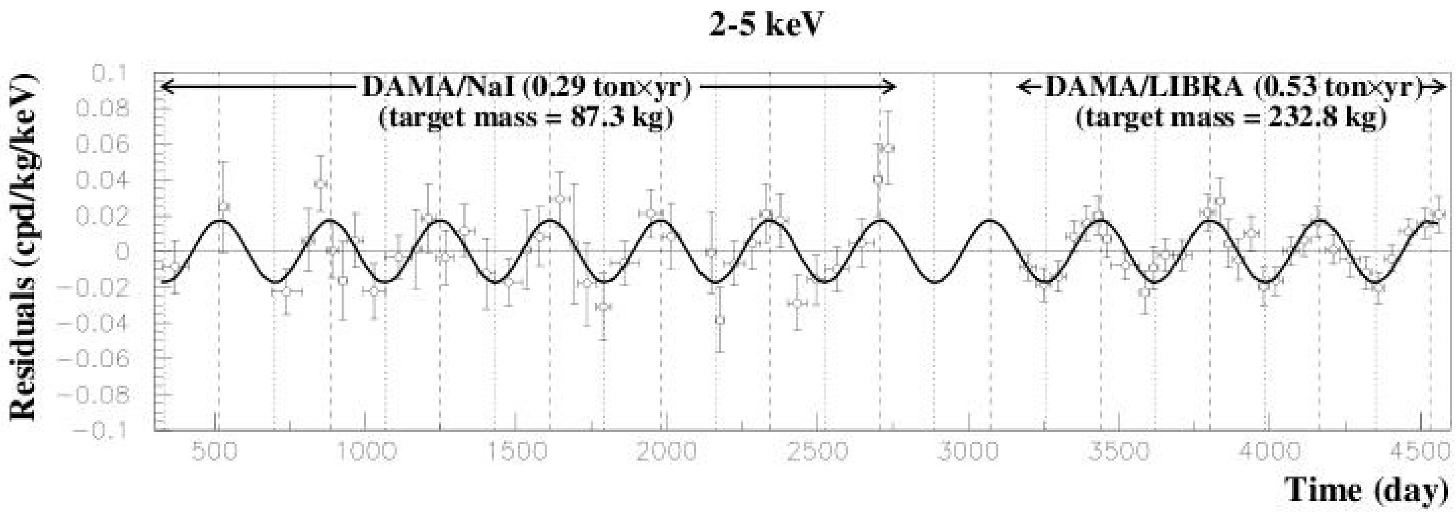
Dama average Counting Rate

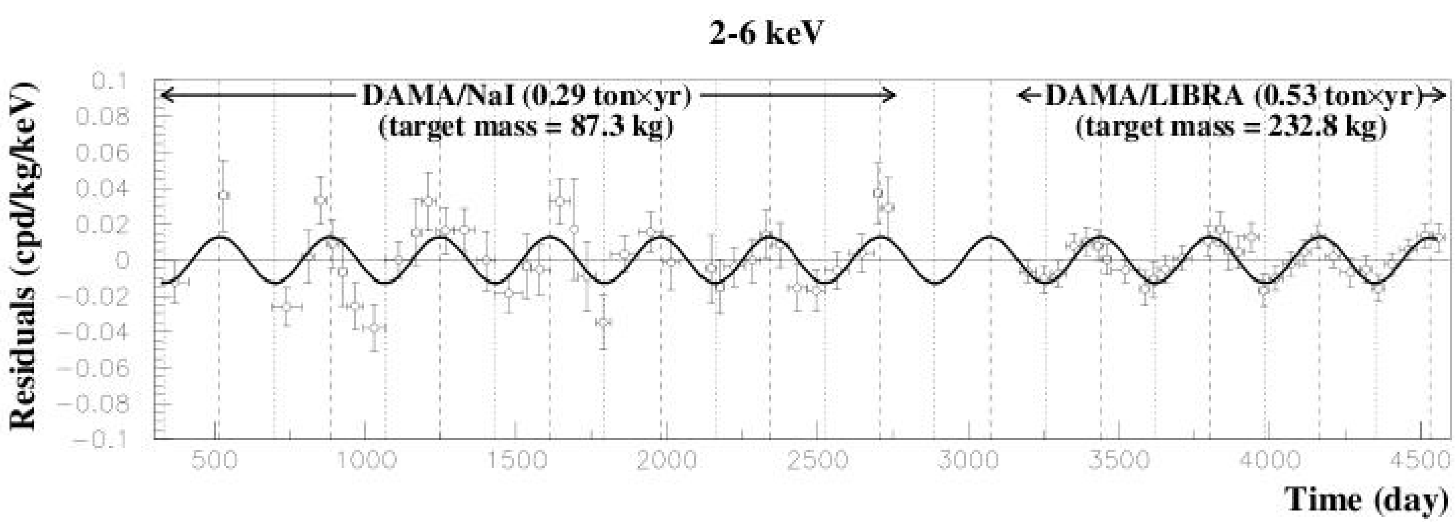


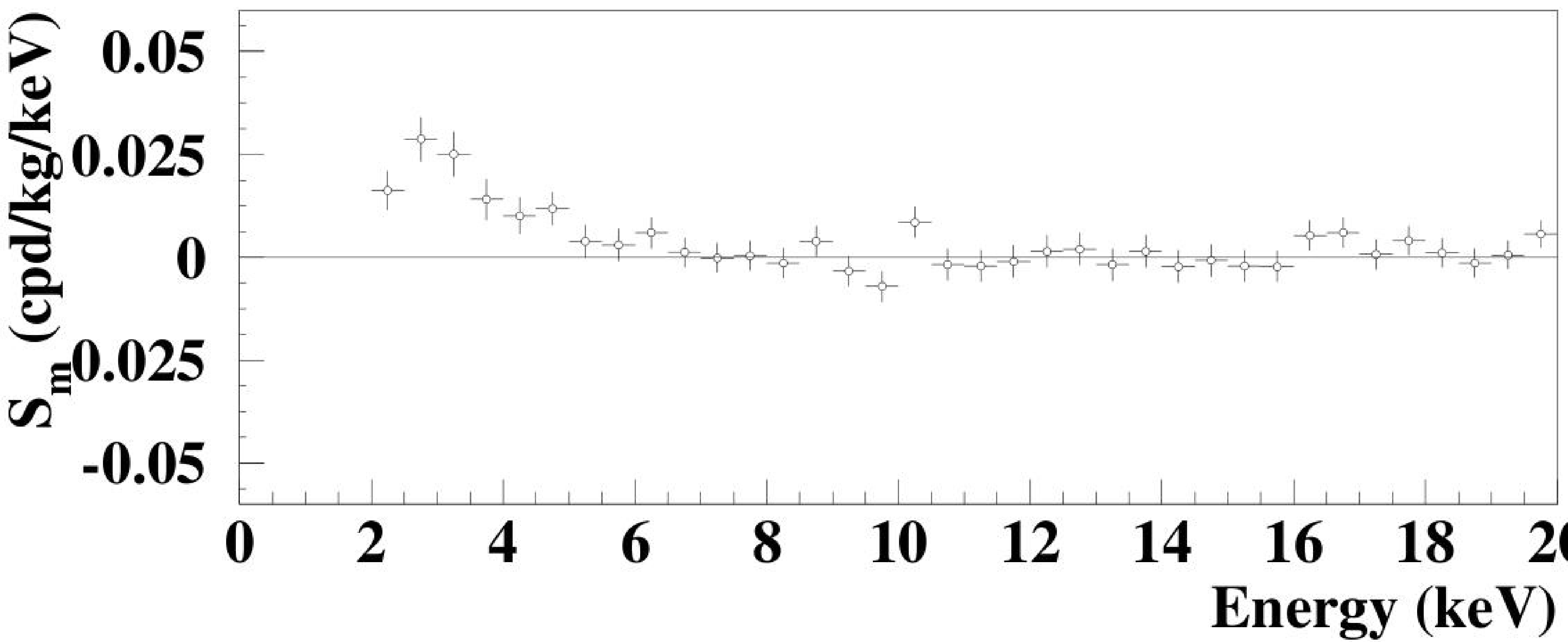
$$1\ \mathrm{KeV}_{ee} \simeq 11\ \mathrm{KeV}_{\mathrm{recoil}}$$

ee [electron equivalent]

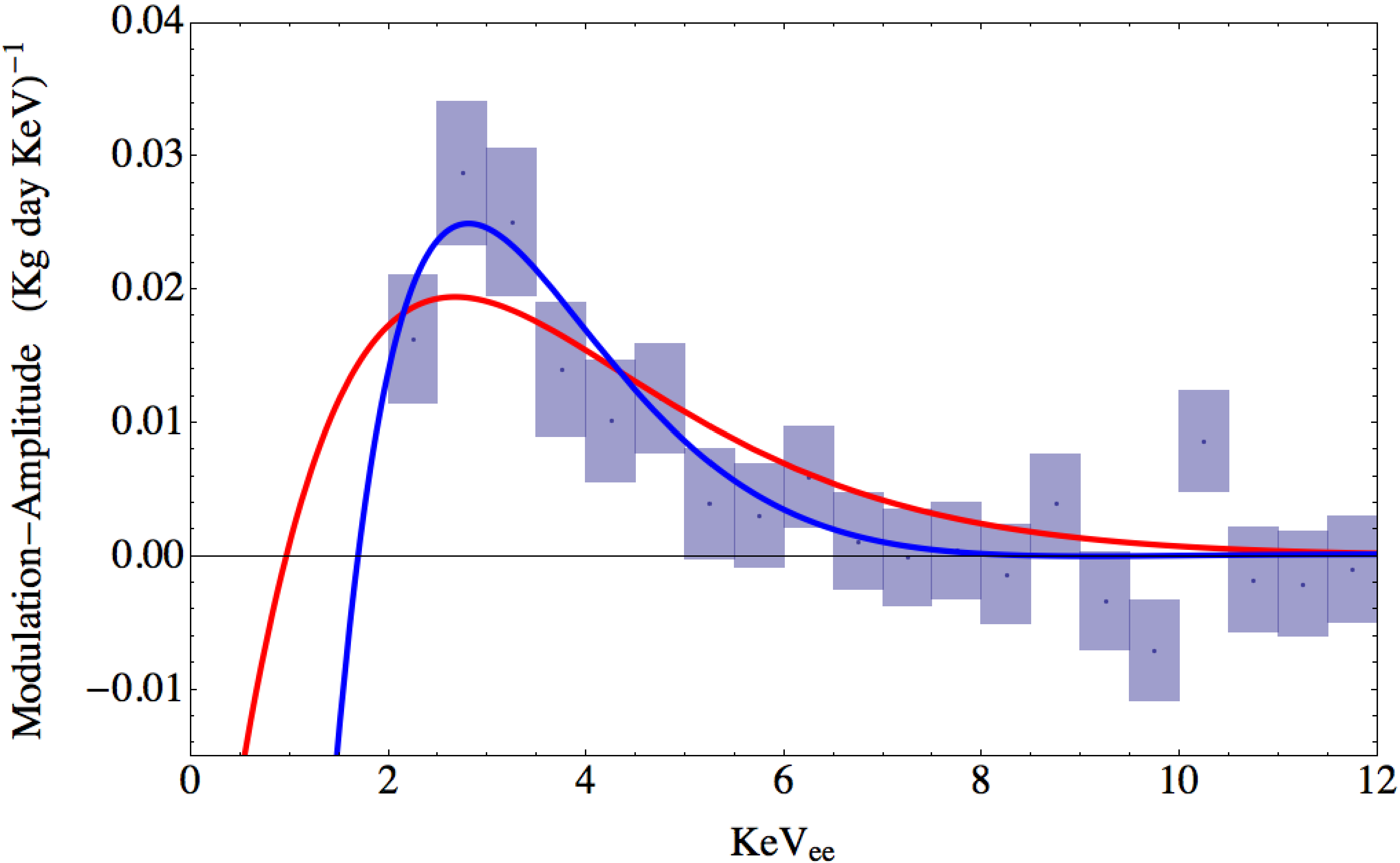

2-4 keV
DAMA/NaI (0.29 ton×yr)
(target mass = 87.3 kg)
DAMA/LIBRA (0.53 ton×yr)
(target mass = 232.8 kg)
Residuals (cpd/kg/keV)
Time (day)


2-5 keV
DAMA/NaI (0.29 ton×yr)
(target mass = 87.3 kg)
DAMA/LIBRA (0.53 ton×yr)
(target mass = 232.8 kg)
Residuals (cpd/kg/keV)
Time (day)

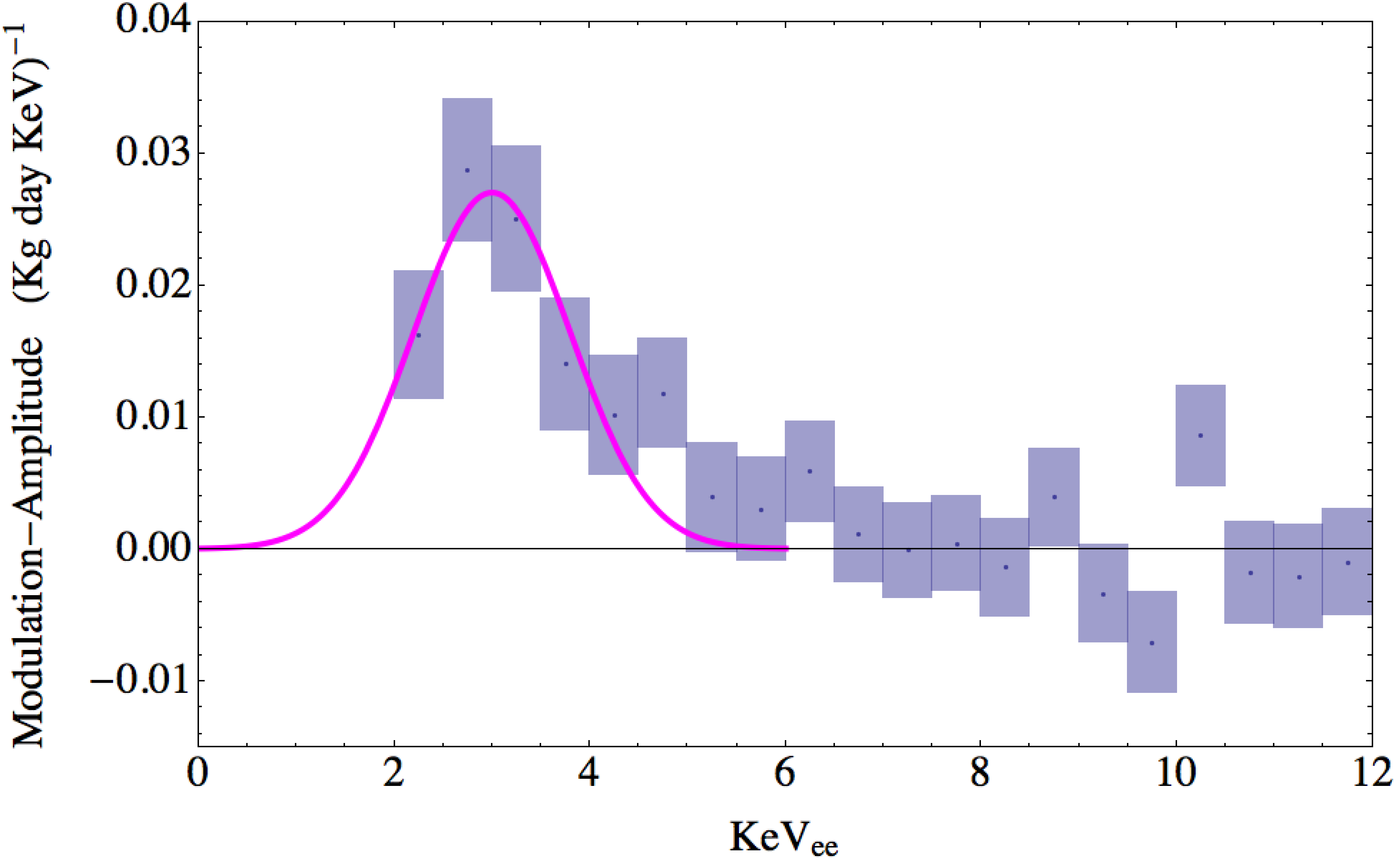

2-6 keV
DAMA/NaI (0.29 ton×yr)
(target mass = 87.3 kg)
DAMA/LIBRA (0.53 ton×yr)
(target mass = 232.8 kg)
Residuals (cpd/kg/keV)
Time (day)



S_m (cpd/kg/keV)
0.05
0.025
0
-0.025
-0.05
0
2
4
6
8
10
12
14
16
18
20
Energy (keV)

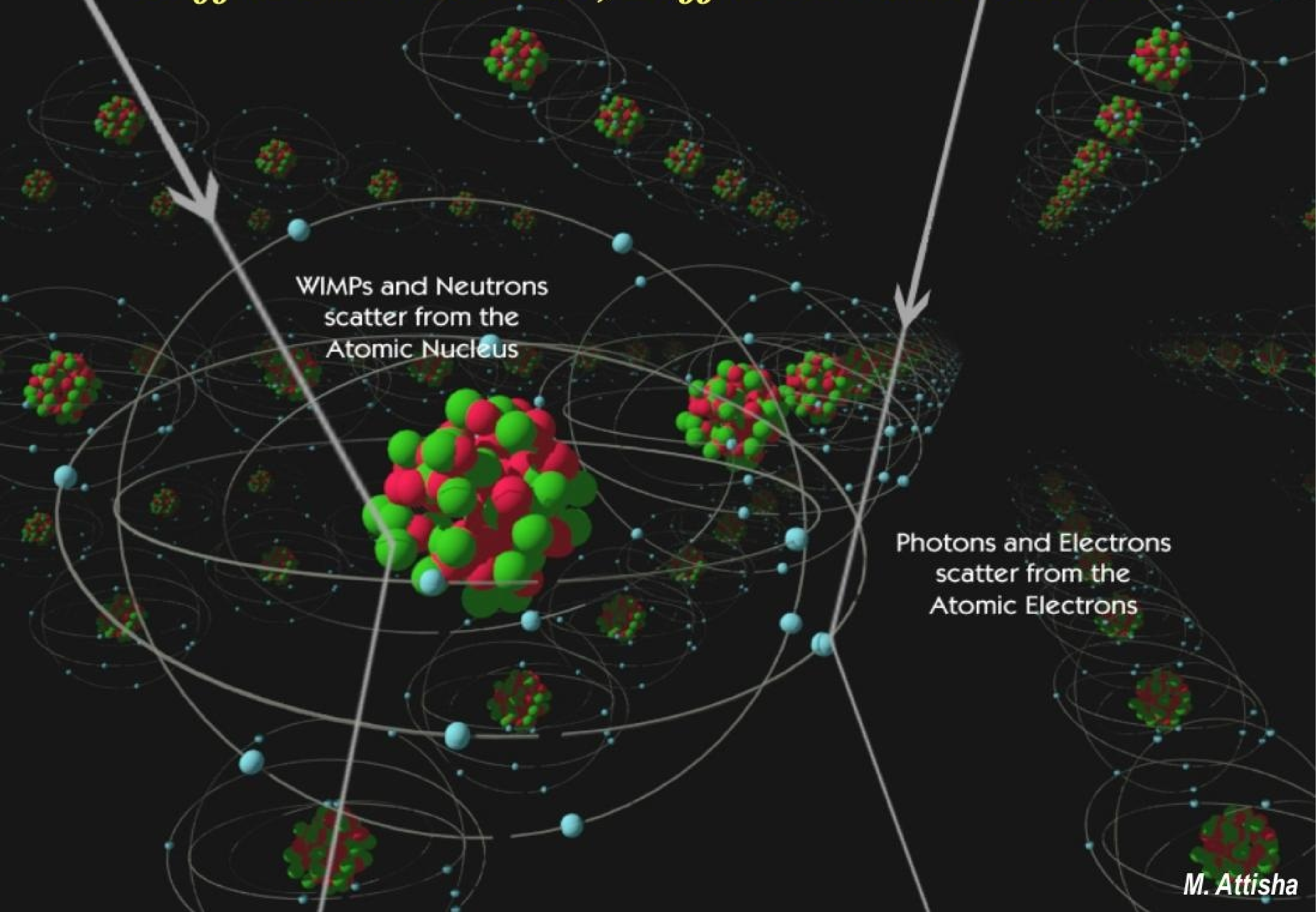


Modulation-Amplitude (Kg day KeV)$^{-1}$
0.04
0.03
0.02
0.01
0.00
−0.01
0
2
4
6
8
10
12
KeV$_{ee}$

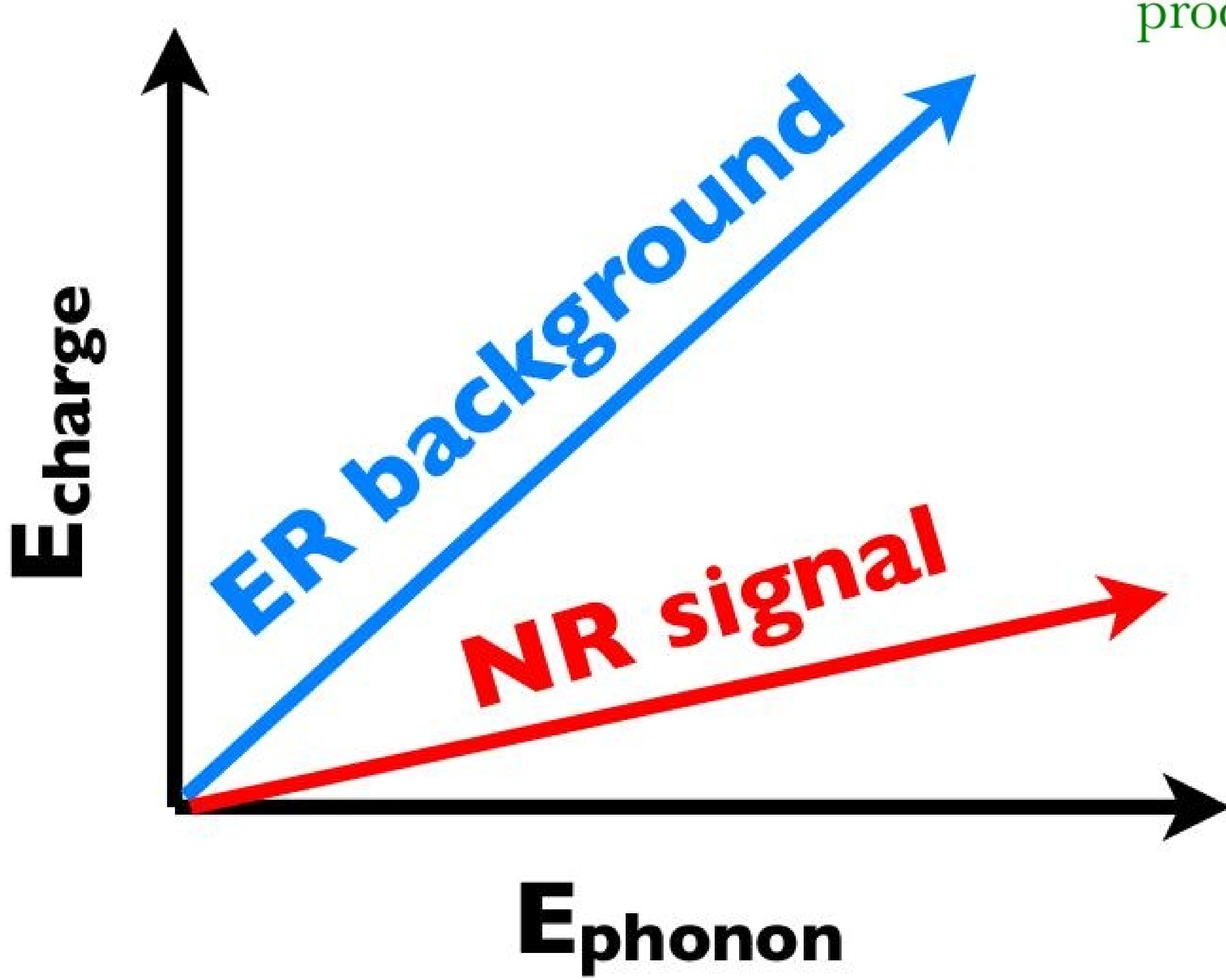


Gaussian with detector resolution

Different Particles, Different Interactions

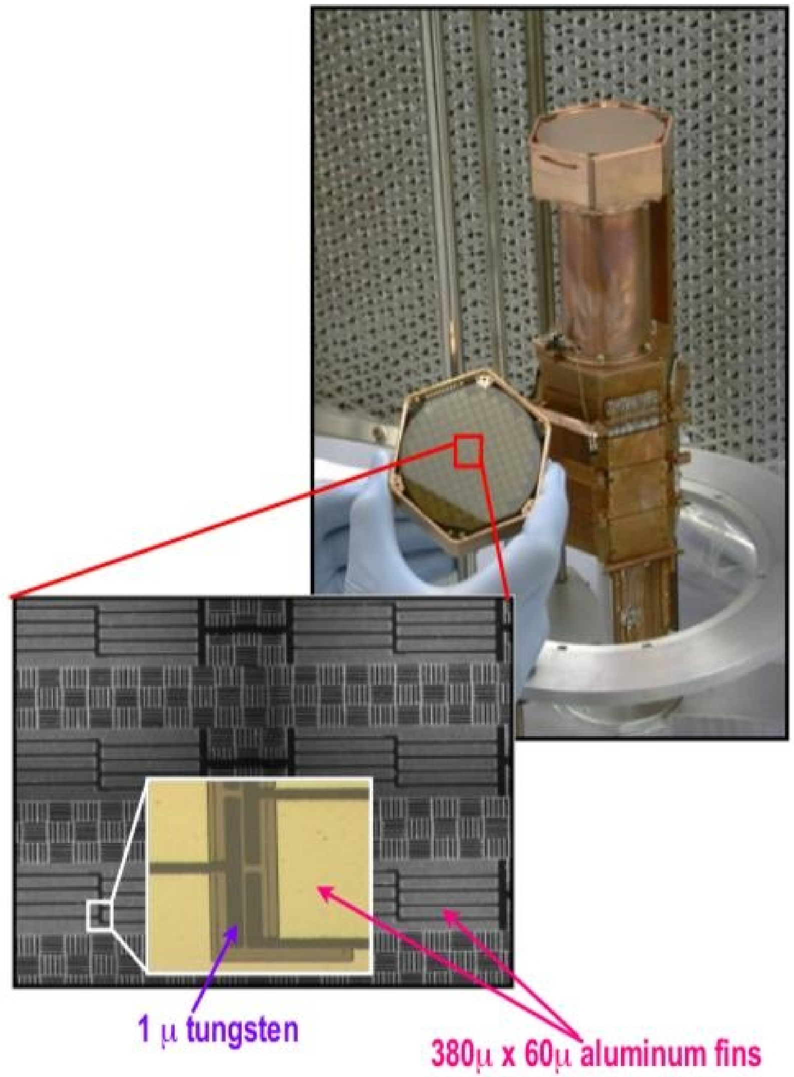


- Most backgrounds (e, γ) produce electron recoils
- WIMPS and neutrons produce nuclear recoils.

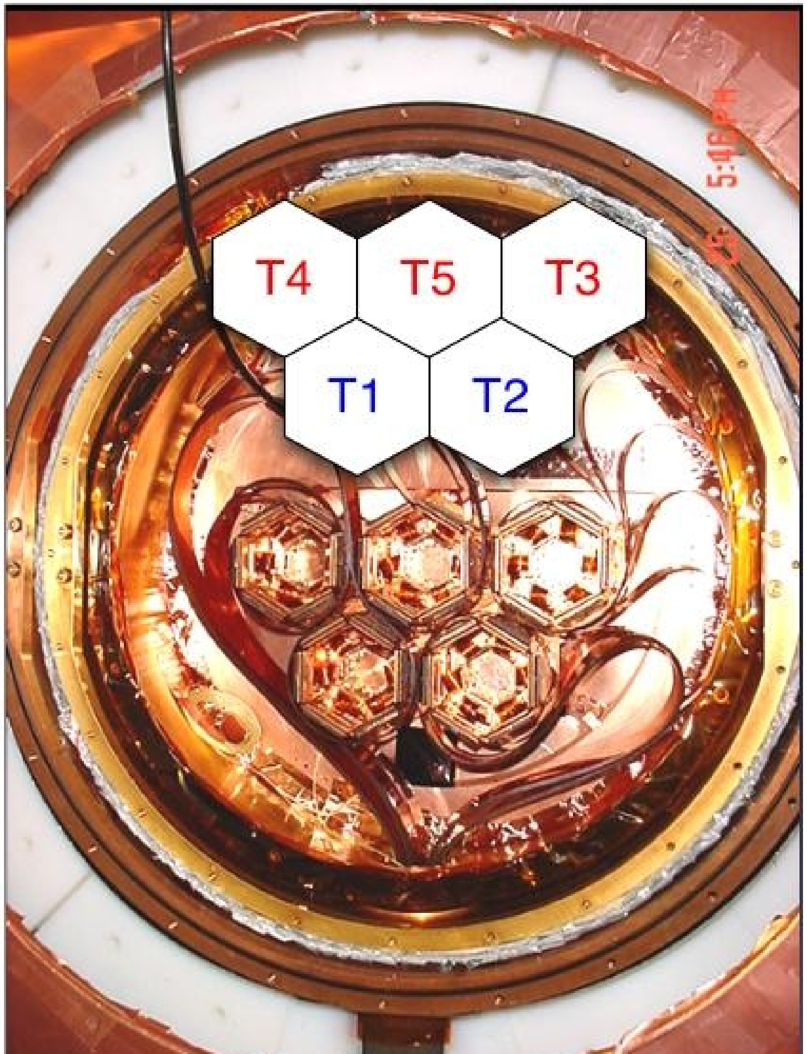


CDMS II ZIP Detectors

- Z-sensitive Ionization and Phonon mediated
- 250 g Ge, 100 g Si crystals
  1 cm thick, 7.5 cm diameter
- Photolithographically patterned to collect phonon and ionization signals
  - xy position imaging
  - surface rejection from pulse shapes
- 30 detectors stacked into 5 towers of 6 detectors



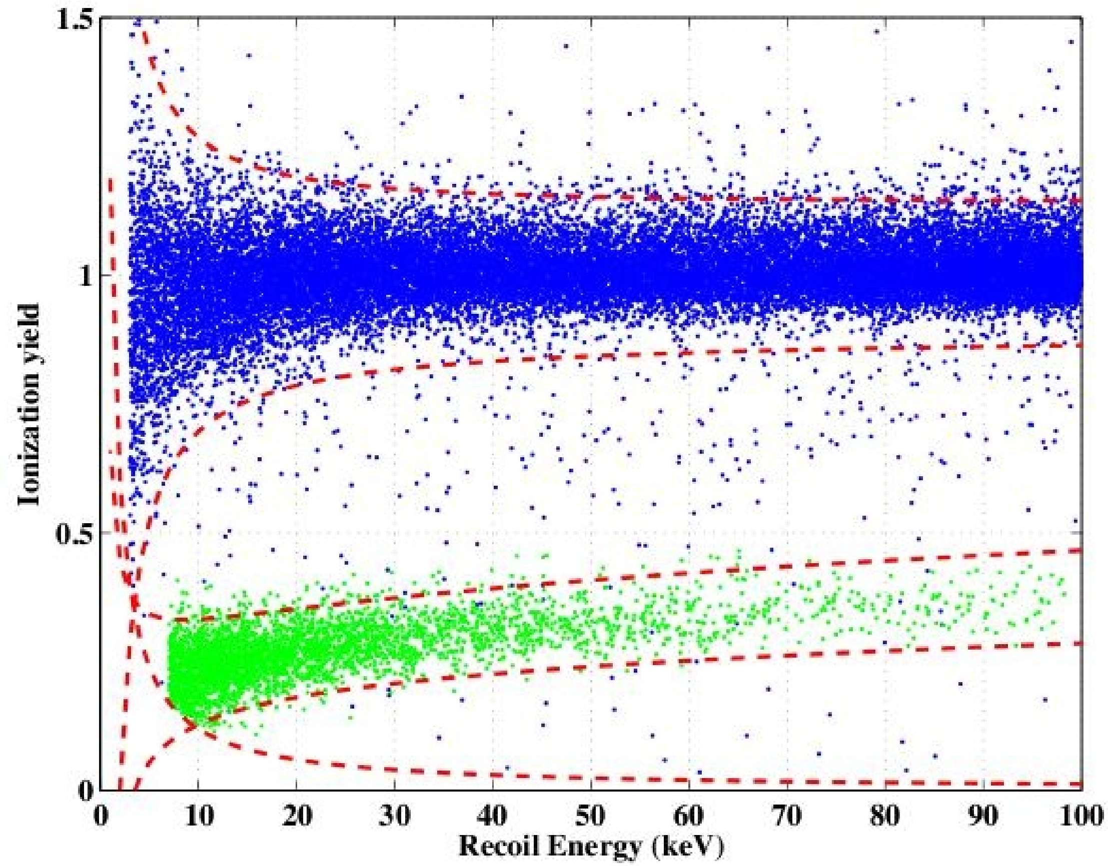
CDMS II Experiment



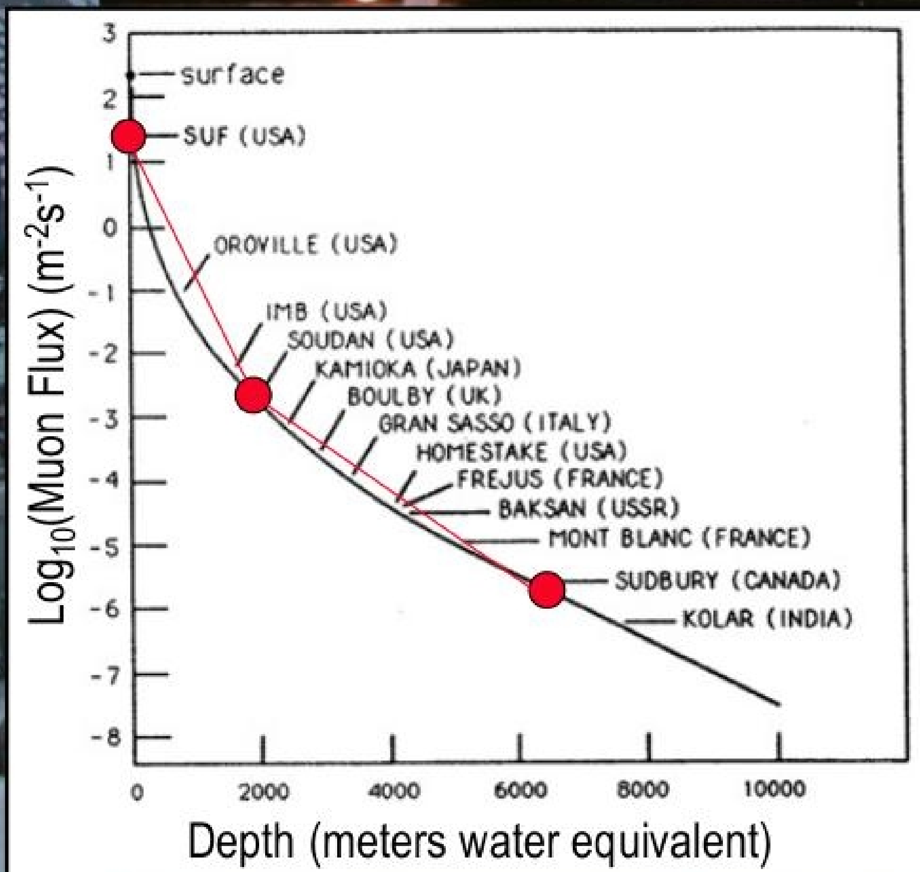
- 30 detectors installed and operating in Soudan since June 06.
  - 4.75 kg of Ge, 1.1 kg of Si
- Seven Total Data Runs:
  - R123 - R124:
    - taken: (10/06 - 3/07) (4/07 - 7/07)
    - exposure: ~400 kg-d (Ge "raw")
    - PRL 102, 011301 (2009)
  - R125 - R128
    - taken: (7/07 - 1/08) (1/08 - 4/08) (5/08 - 8/08) (8/08 - 9/08)
    - exposure: ~ 750 kg-d (Ge "raw")
    - Under Analysis
  - R129:
    - taken: (11/08 - 3/09)

Background Rejection

- Most backgrounds (e, γ) produce electron recoils
- WIMPS and neutrons produce nuclear recoils.
- Ionization yield (ionization energy per unit phonon energy) strongly depends on particle type.



Jodi Cooley - Stanford University



SUF

17 mwe

0.5 n/d/kg

(182.5 n/y/kg)

Soudan

2090 mwe

0.05 n/y/kg

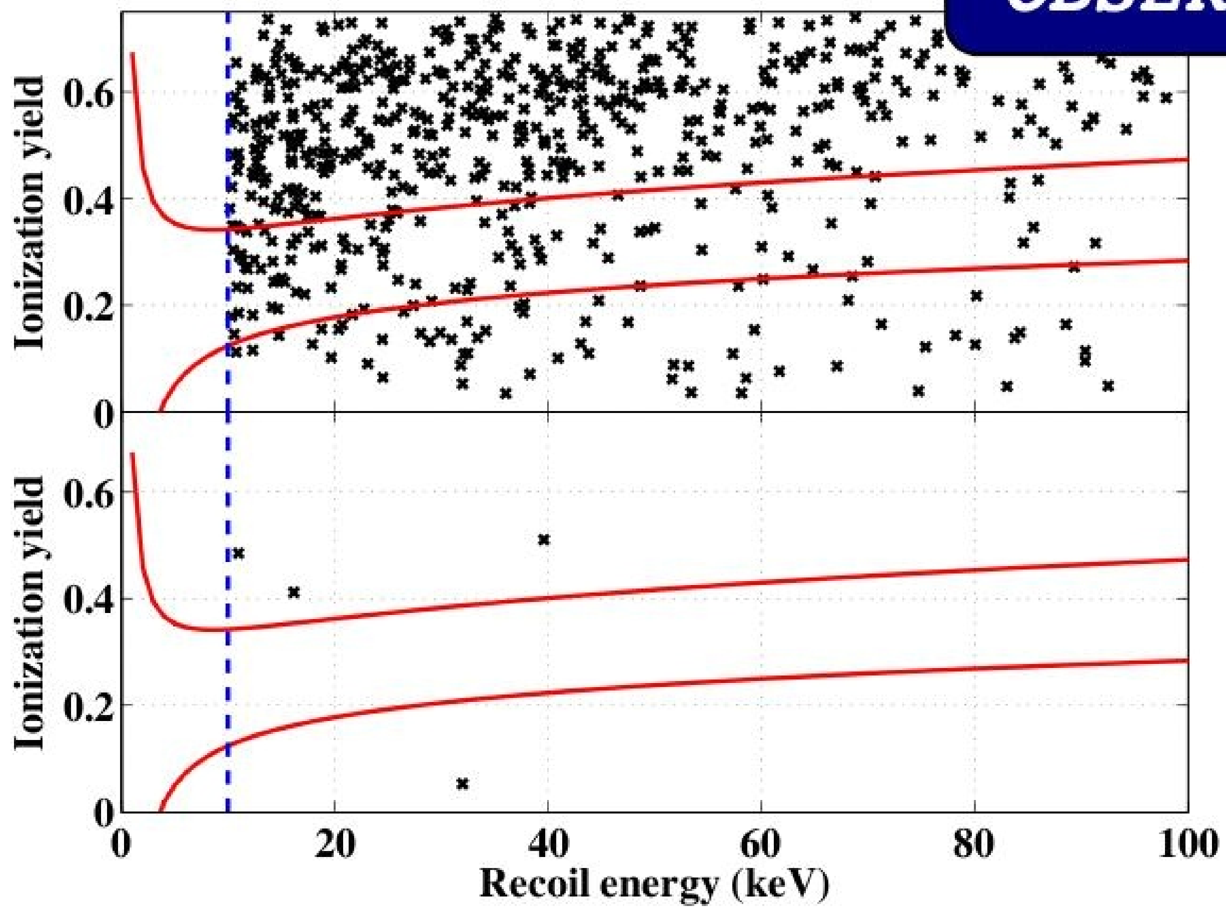
SNOLAB

6060 mwe

0.2 n/y/ton

(0.0002 n/y/kg)

CDMS II Results



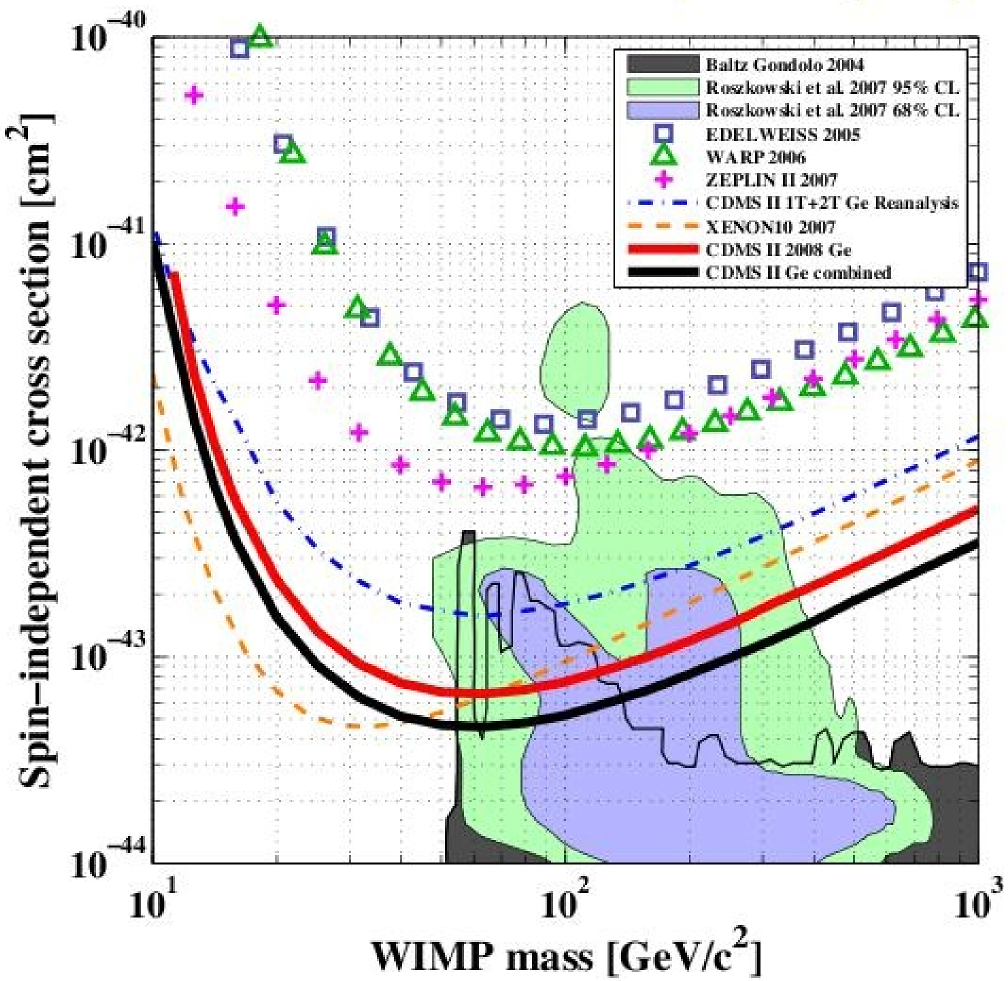
NO EVENTS OBSERVED!

PRL 102, 011301 (2009)

CDMS II Results

Upper limit at the 90% C.L. on the WIMP-nucleon cross-section is **4.6×10^{-44} cm²** for a WIMP of mass **60 GeV/c²**

PRL 102, 011301 (2009)



From CDMS to SuperCDMS to GEODM

CDMS II

7.5 cm x 1 cm ~ 0.25 kg / det
16 detectors = 4 kg
~ 2 yrs operation

SuperCDMS

7.5 cm x 1 in ~ 0.64 kg / det

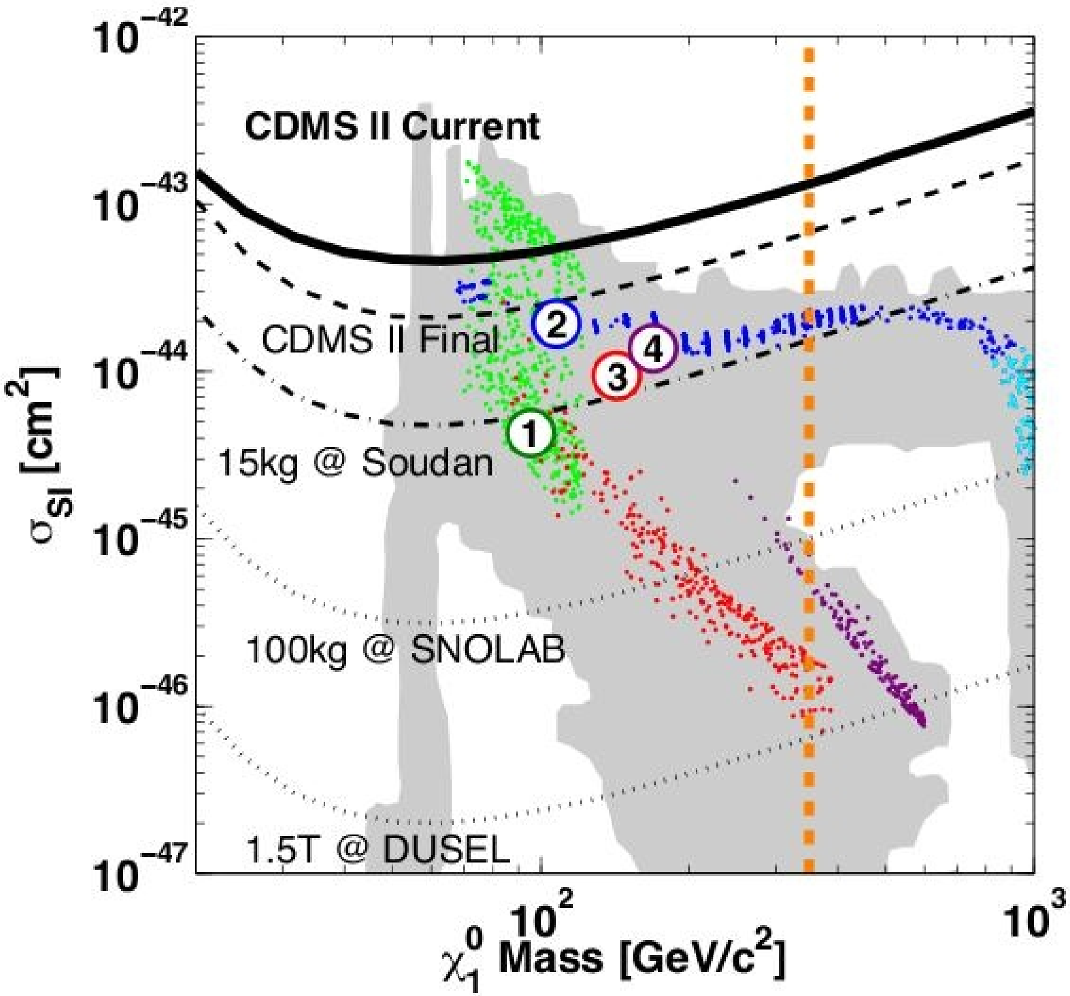
Soudan
25 detectors ~ 15 kg
2 yrs ~ 8000 kg-d

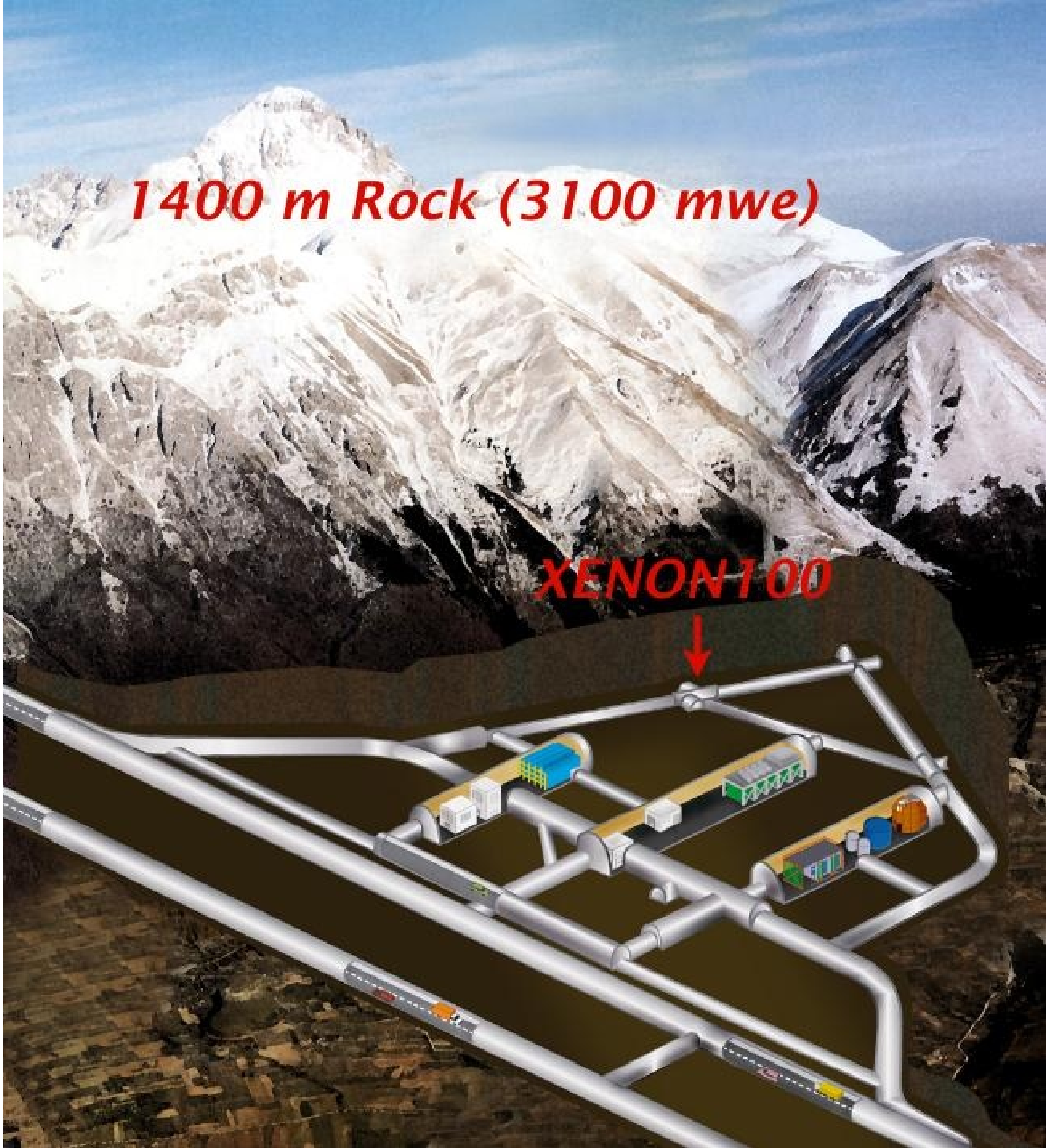
SNOLAB
150 detectors ~ 100 kg
3 yrs ~ 38,000 kg-d

SuperCDMS SNOLAB and Germanium Observatory for Dark Matter (GEODM)
15 cm x 2 in ~ 5.1 kg / det

SNOLAB
20 detectors ~ 100 kg
3 yrs ~ 100,000 kg-d

DUSEL
300 detectors ~ 1.5 T
4 yrs ~ 1.5 Mkg-d

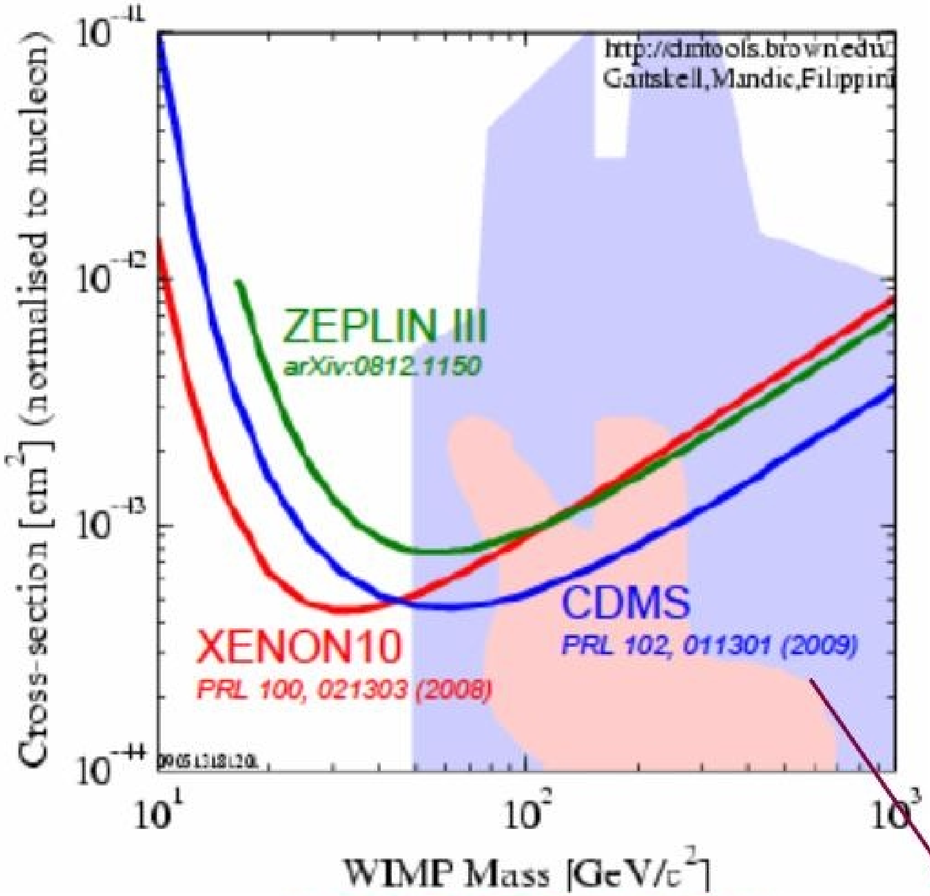


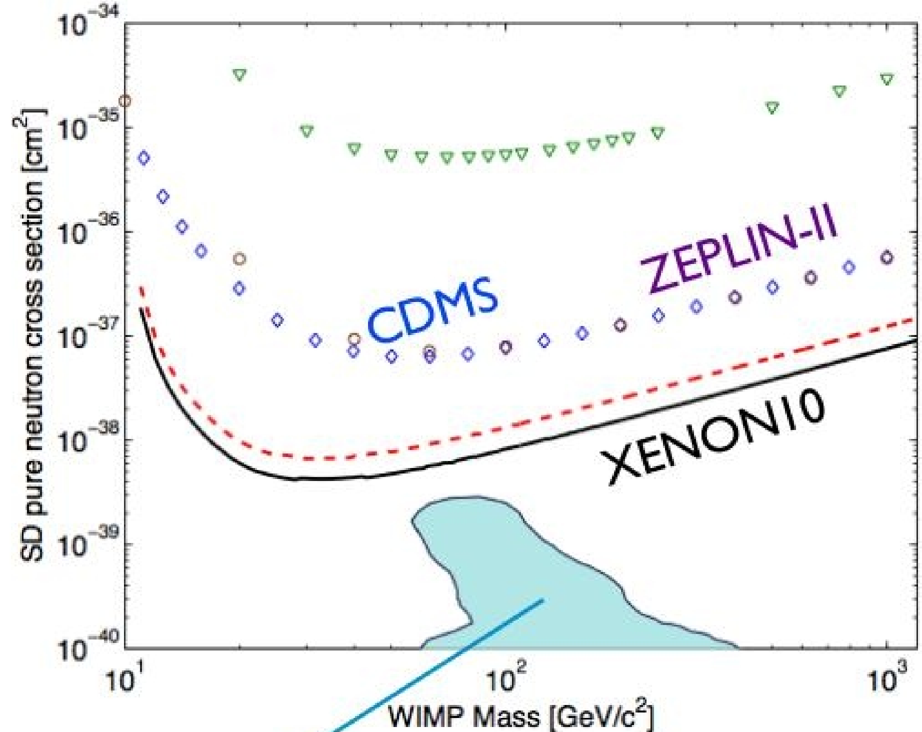

1400 m Rock (3100 mwe)
XENON100

XENON10 Results

Spin-independent
Phys. Rev. Lett. ***100****, 021303 (2008)*

Spin-dependent
Phys. Rev. Lett. ***101****, 091301 (2008)*





(NO BKG SUBTRACTION)

8.8 x 10^{-44} cm^2 at 100 GeV

4.5 x 10^{-44} cm^2 at 30 GeV

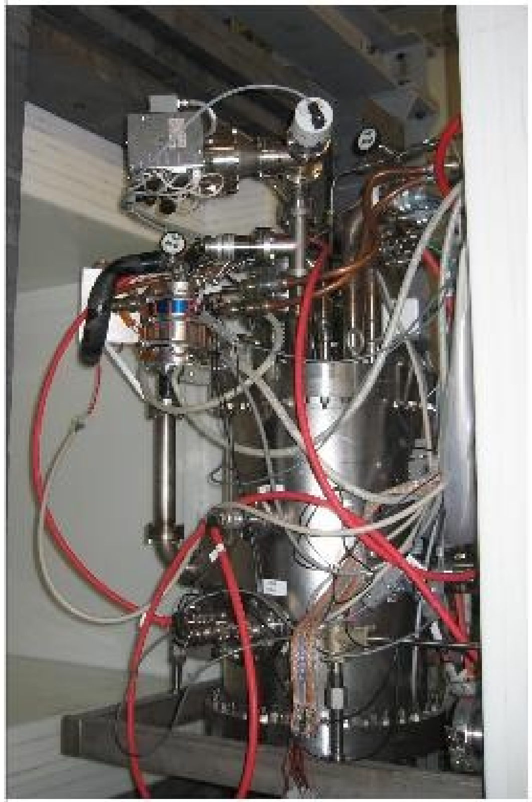
Constrained Minimal Supersymmetric Model

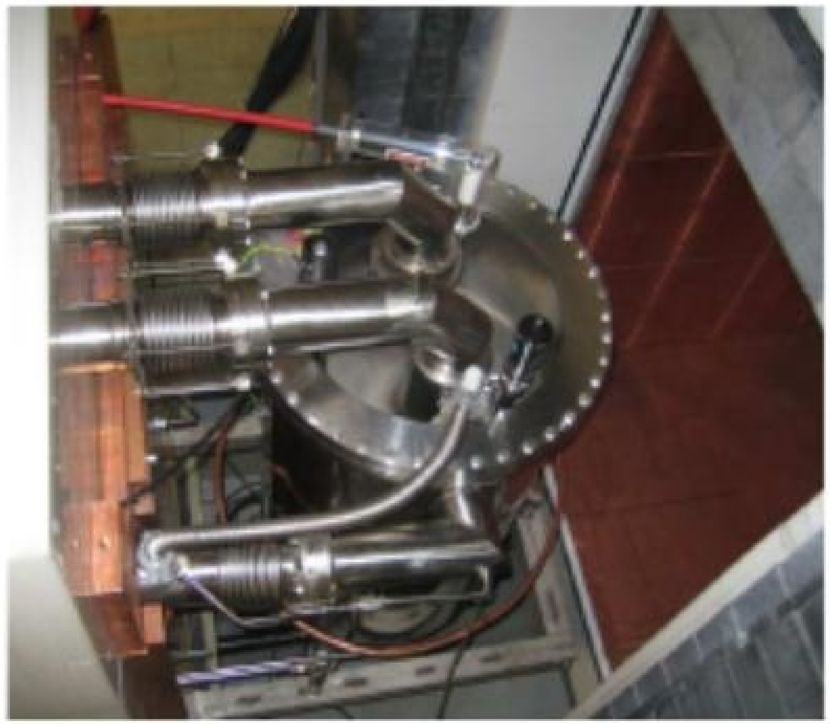
(NO BKG SUBTRACTION)

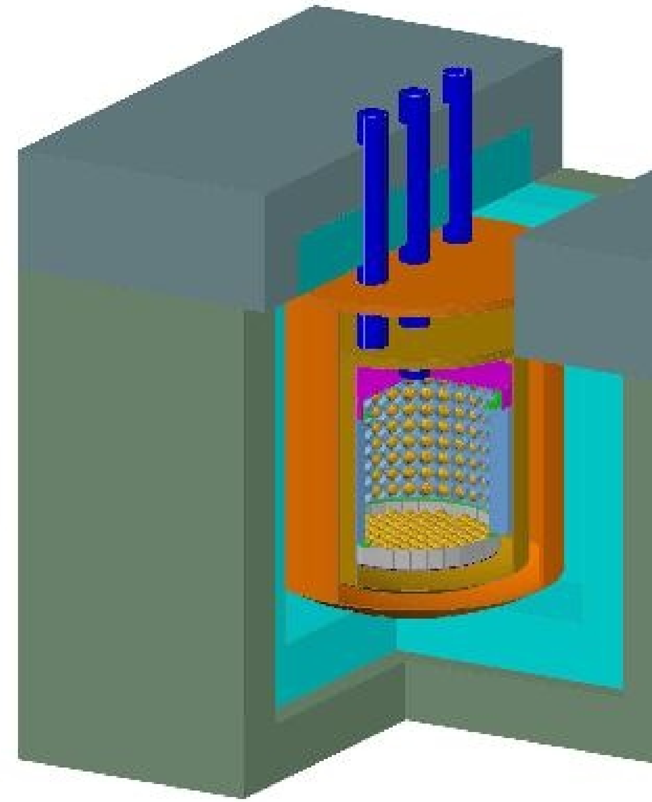
6 x 10^{-39} cm^2 at 30 GeV

The XENON program for Dark Matter Detection

past (2005 - 2007)	*current* (2008-2012)	*the future* (2013-2015)







XENON10

Achieved (2007) σ_{SI}=8.8 x 10^{-44} cm^2

XENON100 & 100+

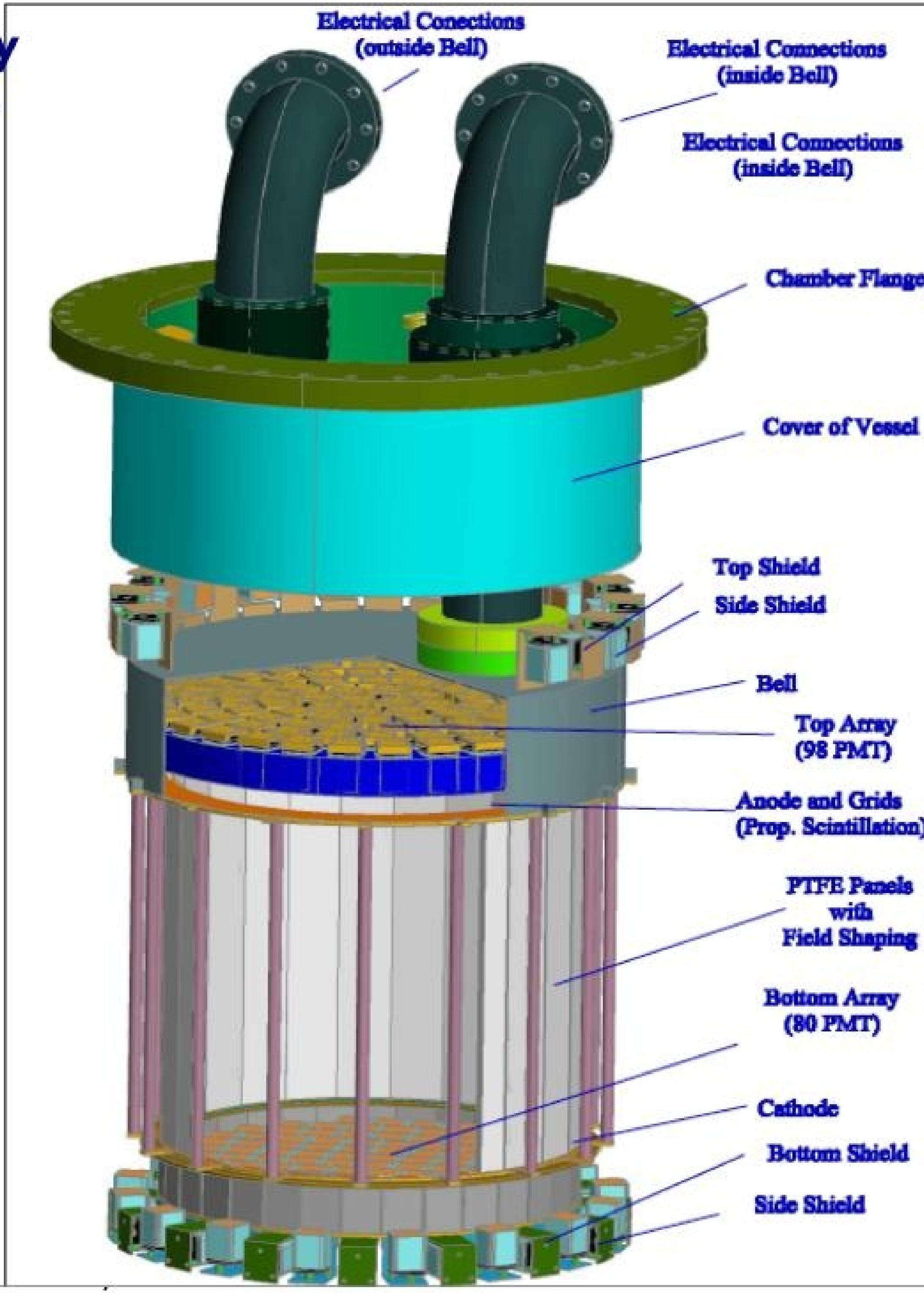
Projected (2010) σ_{SI}~2x10^{-45} cm^2

Projected (20012) σ_{SI}~2x10^{-46} cm^2

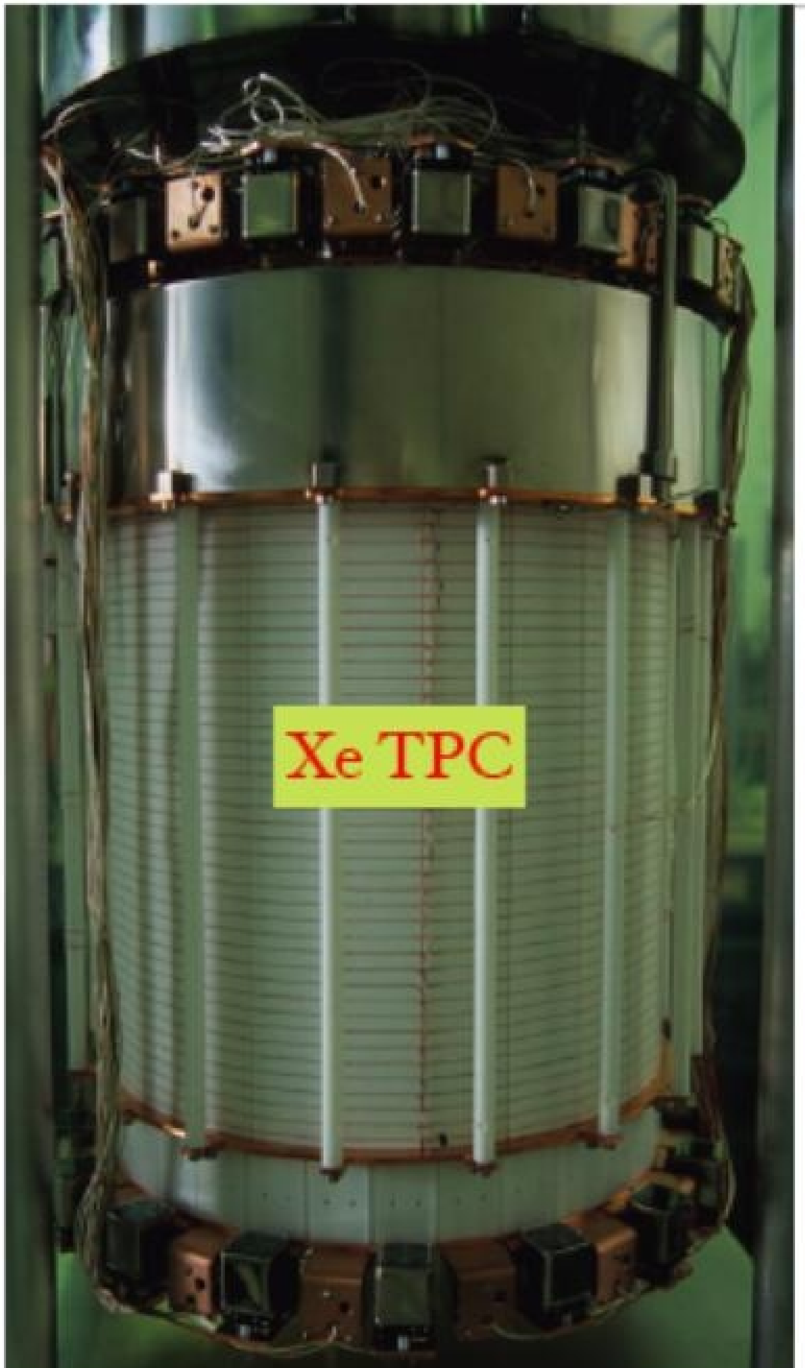
XENON1T

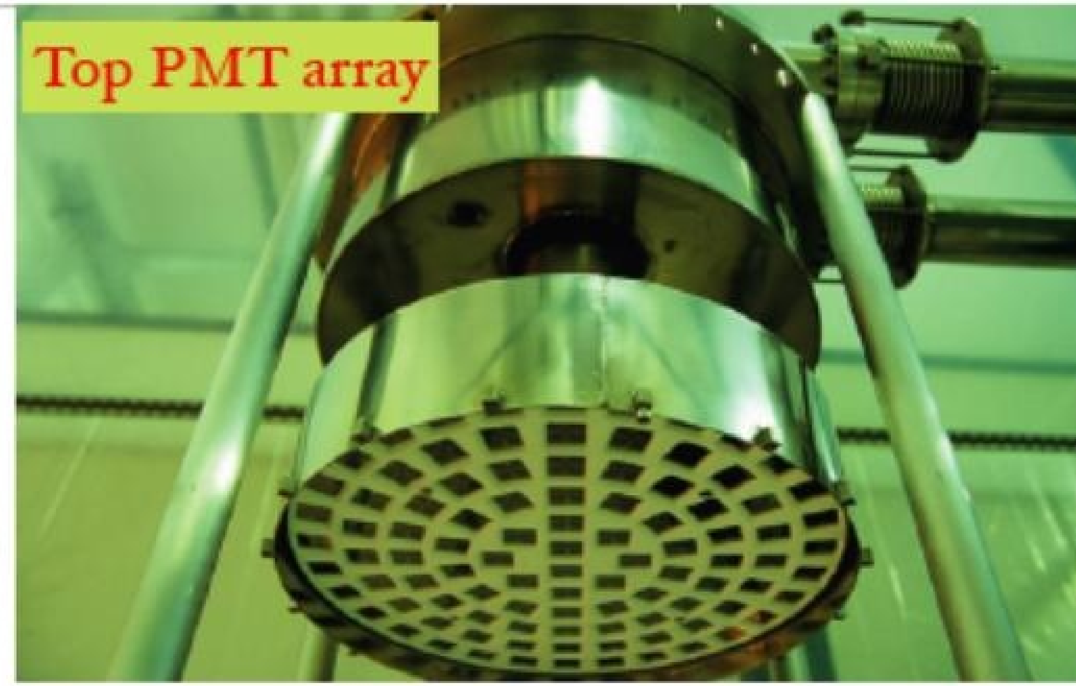
Projected (2015) σ_{SI} <10^{-47} cm^2

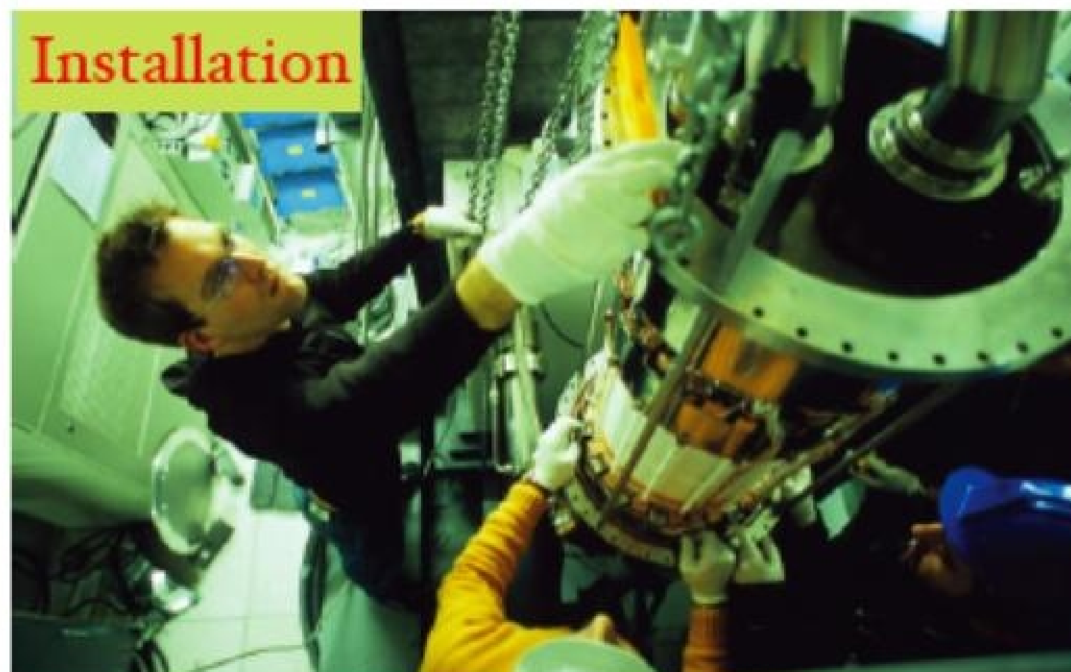
XENON100: The TPC Assembly



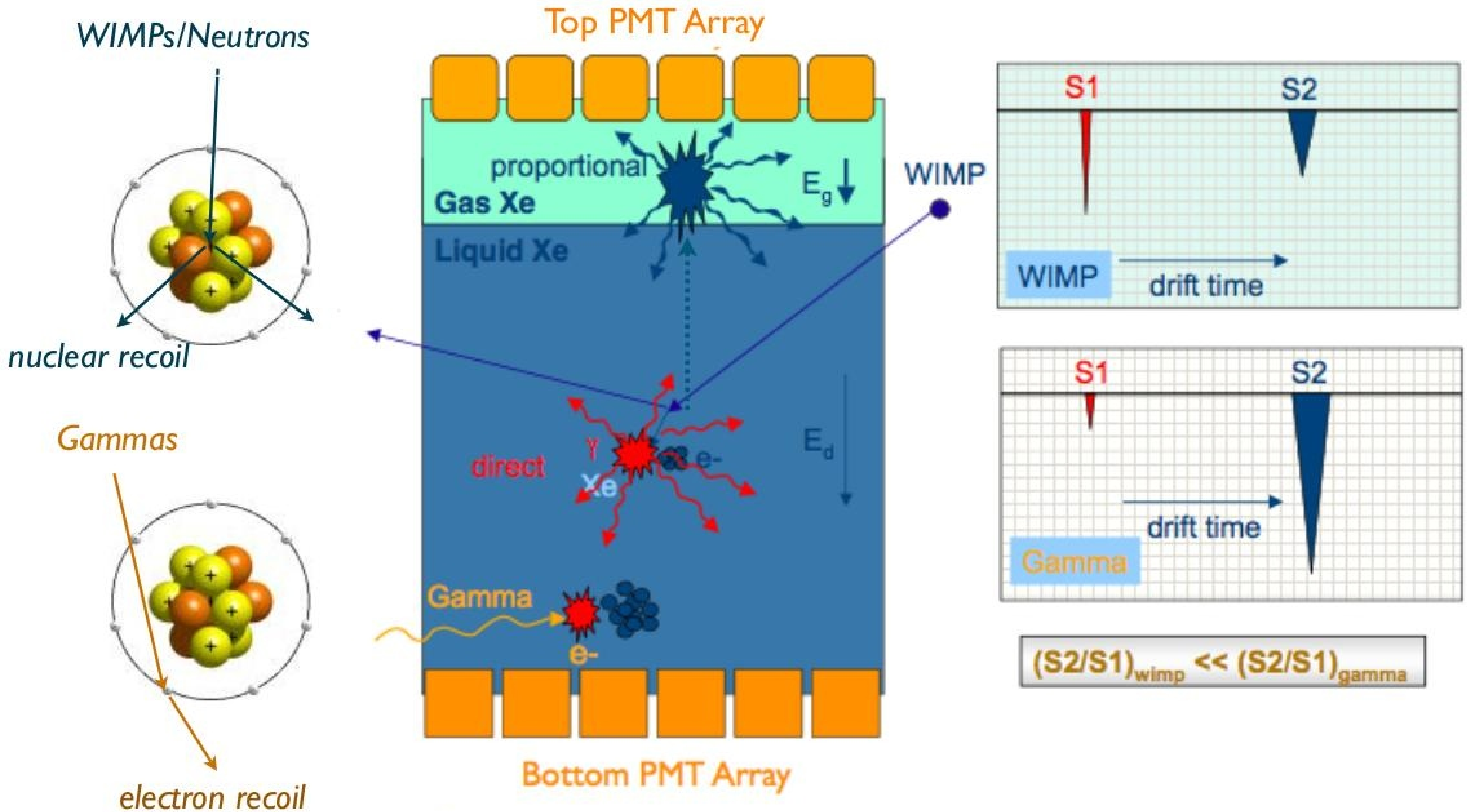
more detector photos at:
http://xenon.astro.columbia.edu/





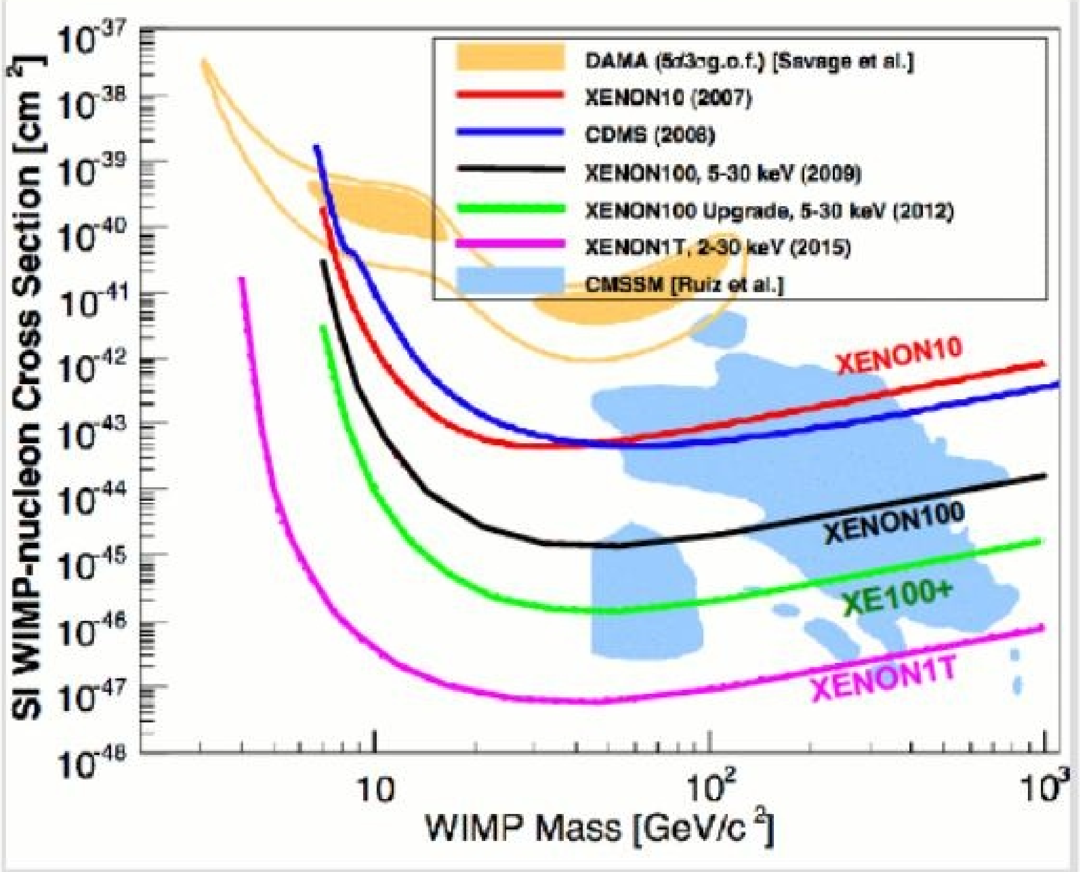


The XENON two-phase TPC



- Single electron and single photon measurement sensitivity
- > 99.5% ER rejection via Ionization/Scintillation ratio (S2/S1)

Summary



- XENON100: 1st 100 kg scale LXe dark matter experiment operating underground
- Two-phase TPC works as designed: currently optimizing response with sources
- Neutron Calibration by Fall 09 and 1st dark matter search before end of 2009
- XENON100+ :funded and moving ahead with design and tests of key technologies

Conclusions - Perspectives

Dark Matter searches [Indirect and Direct] are sensitive and Powerful and study a significant fraction of [but not the entire] space of the "WIMP hypothesis" (weakly interacting relic particle) for the nature of the Dark Matter.

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PAMELA: e^+ excess" + Standard $\overline{p}$

Possibly a real breakthrough:

DM with non standard properties

["leptophilic", large Boost factor]

"Astrophysical explanations" are possible

[indeed more likely]

[e+ acceleration in Pulsars, SNR]

DAMA-LIBRA:

Tension with the null-results of other experiments
Becomes increasingly strong.
[tension is reduced considering channeling]

“ (VERY) non standard models for DM” could be viable:

Inelastic Dark Matter

Mirror Matter

“Axion Like particle”

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Tension with the null-results of other experiments
Becomes increasingly strong.
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“ (VERY) non standard models for DM” could be viable:

Inelastic Dark Matter

Mirror Matter

“Axion Like particle”

Prediction (and wish):

Life will be interesting in DM searches