DARK MATTER

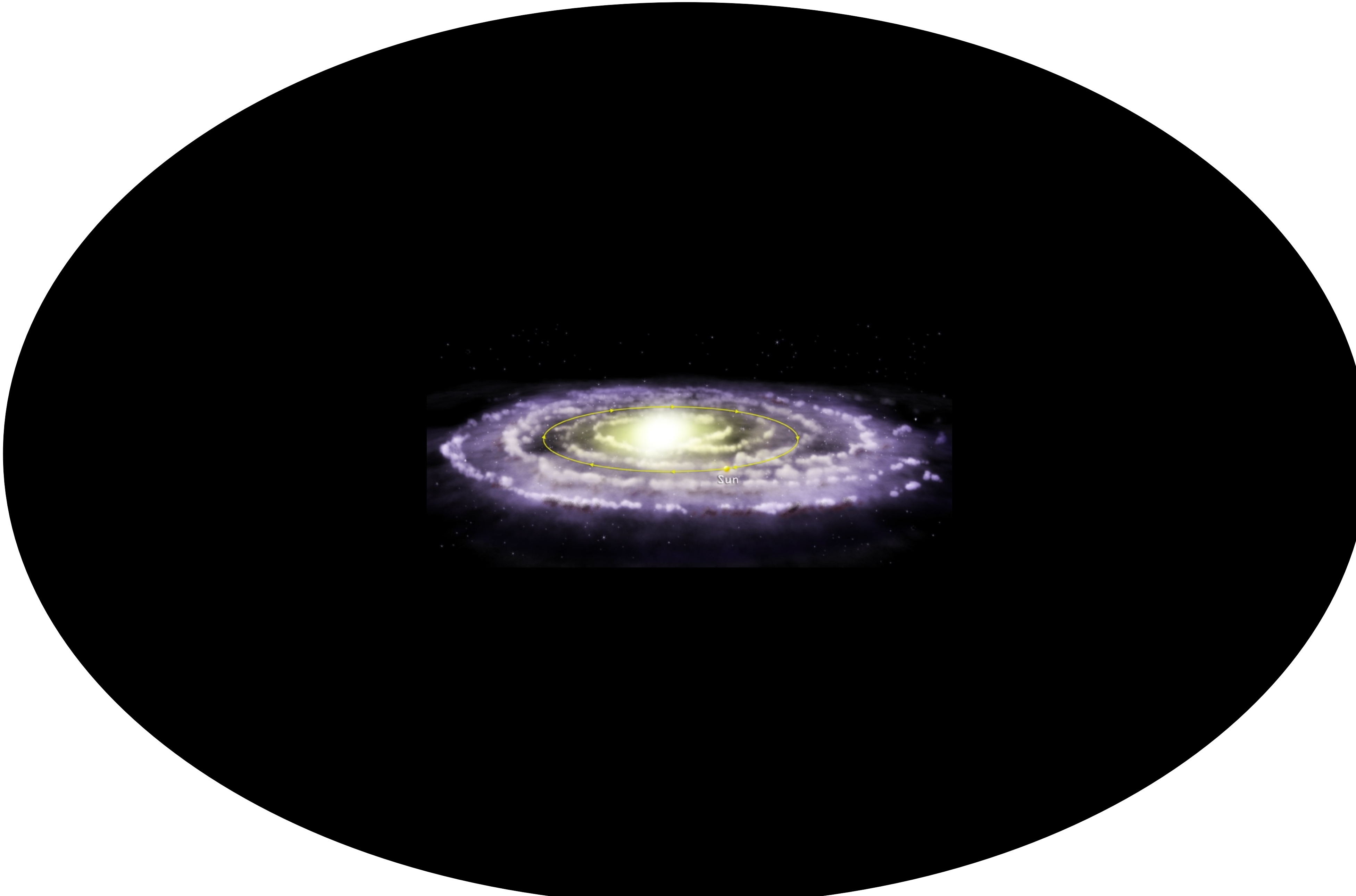
and

COSMIC RAYS

3rd part

Paolo Lipari
4th school on Cosmic Rays and Astrophysics
UAFBC Sao Paulo, 1st september 2010

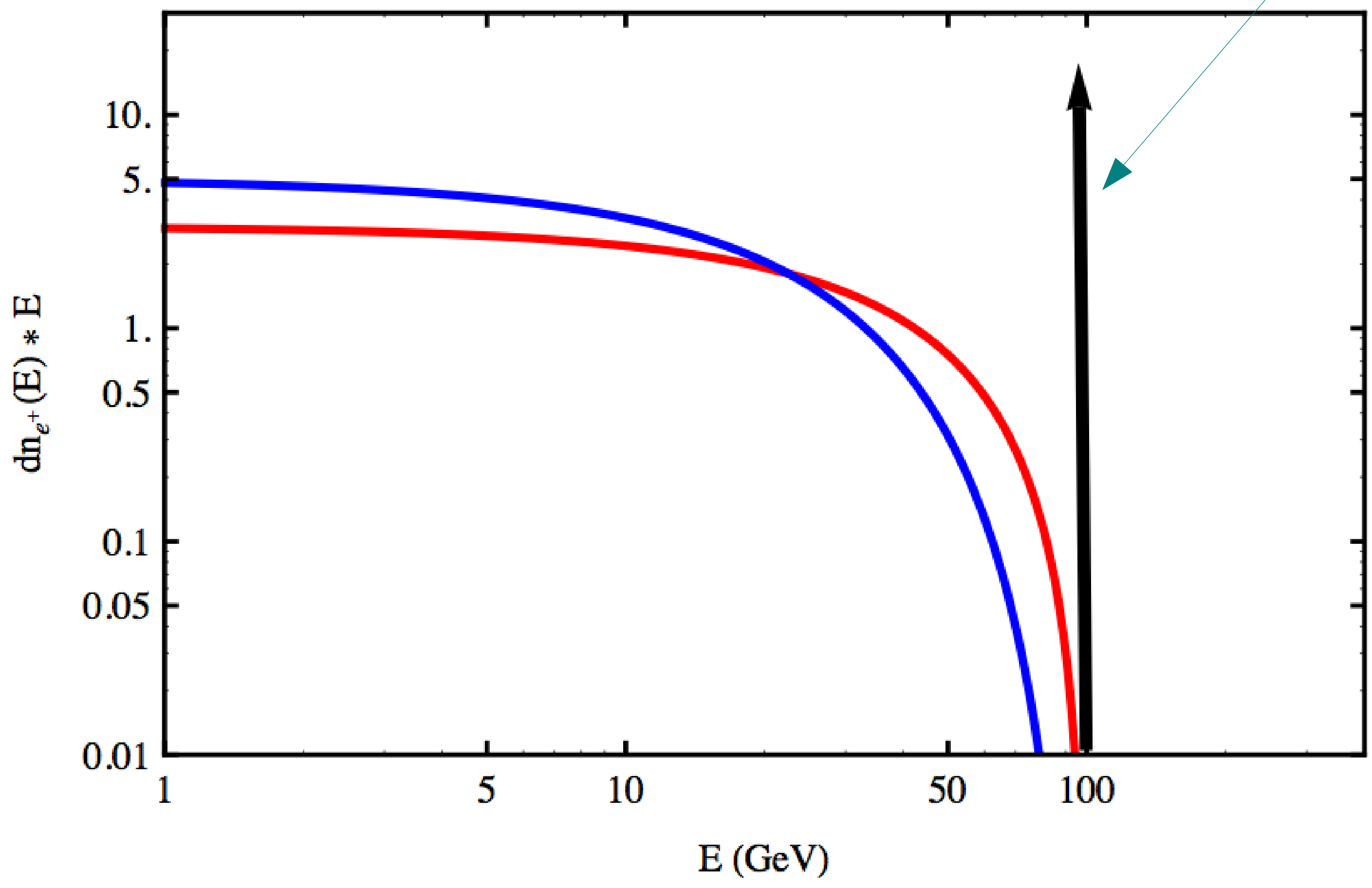
Indirect searches for DARK MATTER



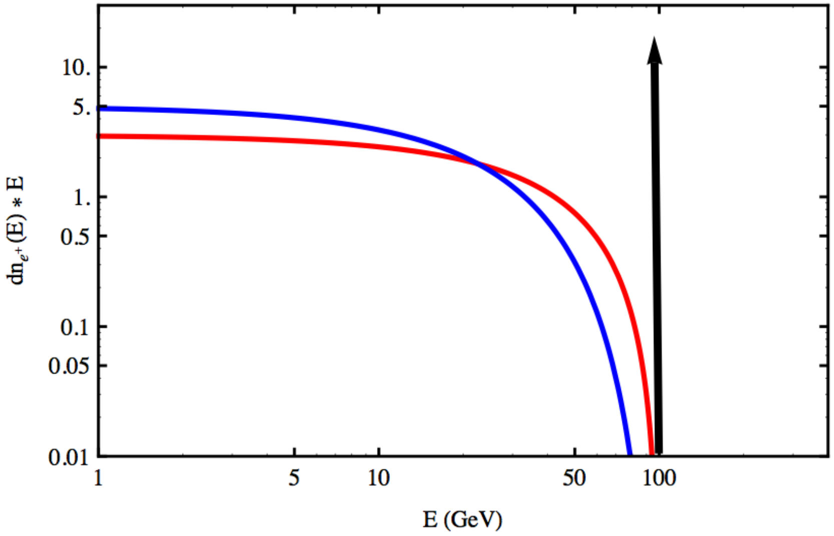
Annihilation of 2 Dark-Matter particles
Produce particles in our Galaxy, with
Energy spectrum that extends to E = m

$$\chi + \chi \rightarrow e^+ + e^-$$

Example of electron, positron spectrum

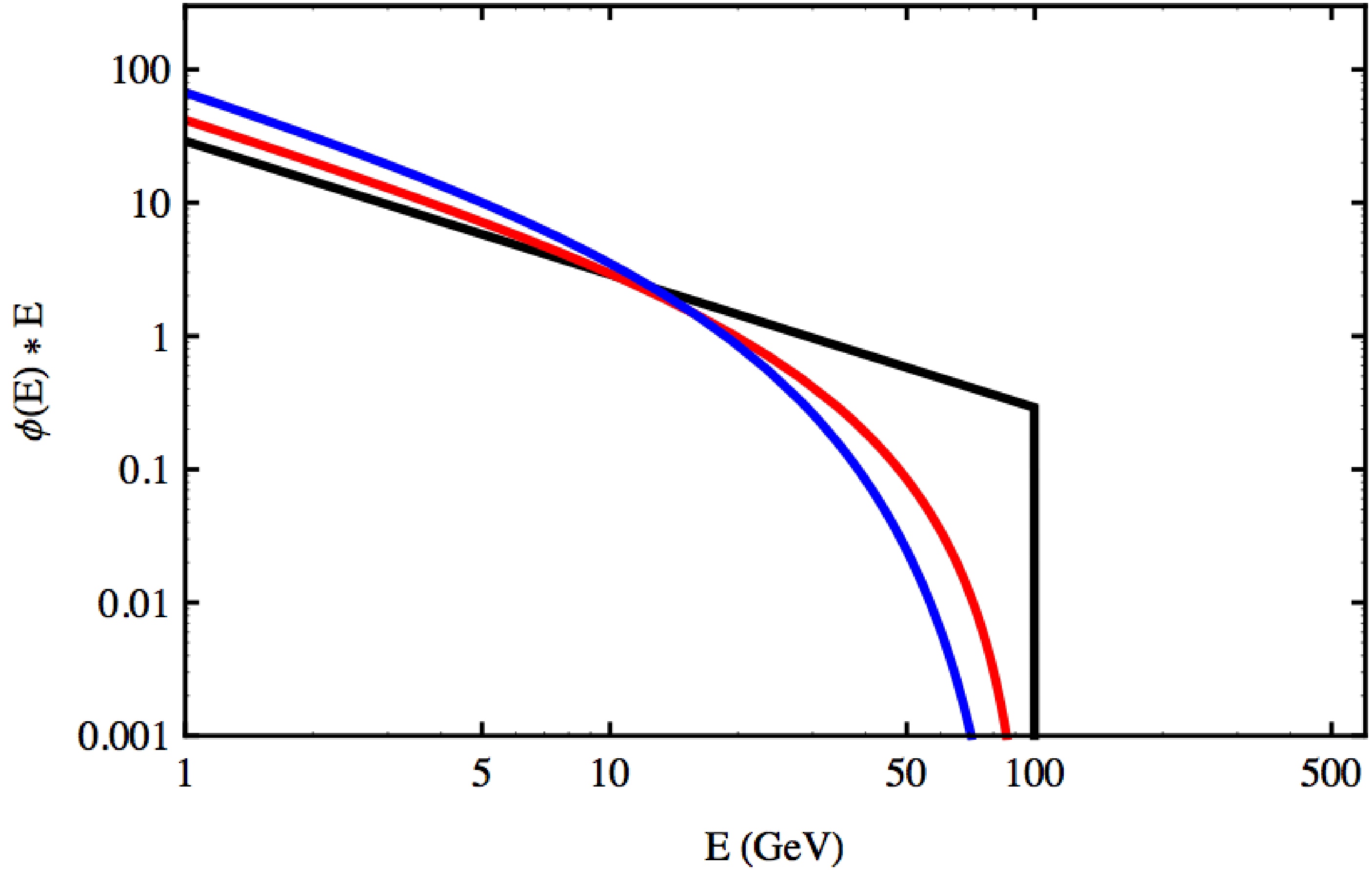


These particles remain magnetically trapped in the Galaxy
[Electrons and positrons lose continuously energy]



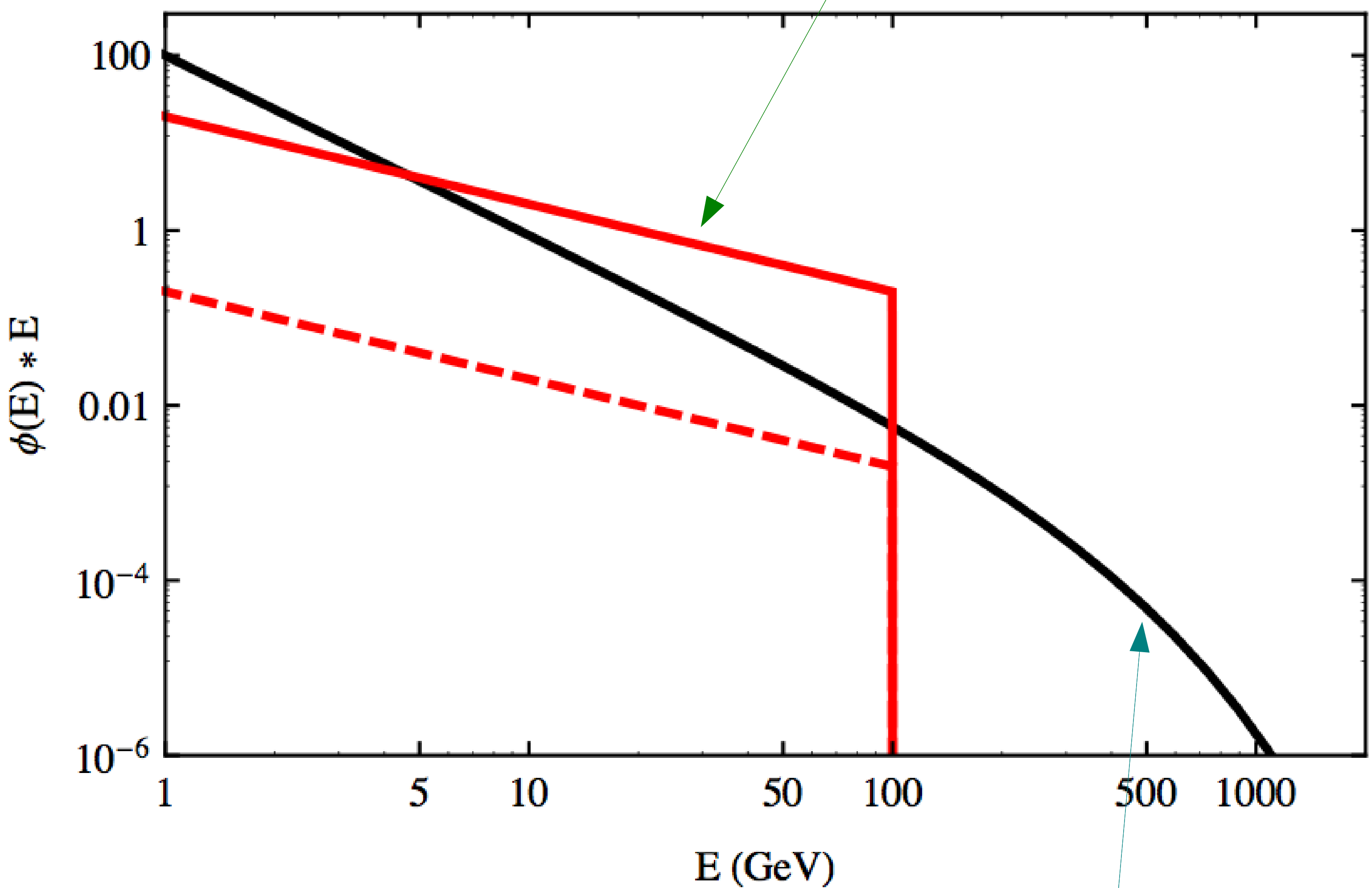
Injection spectrum

Observable
Flux



Signal from
Dark-Matter annihilation

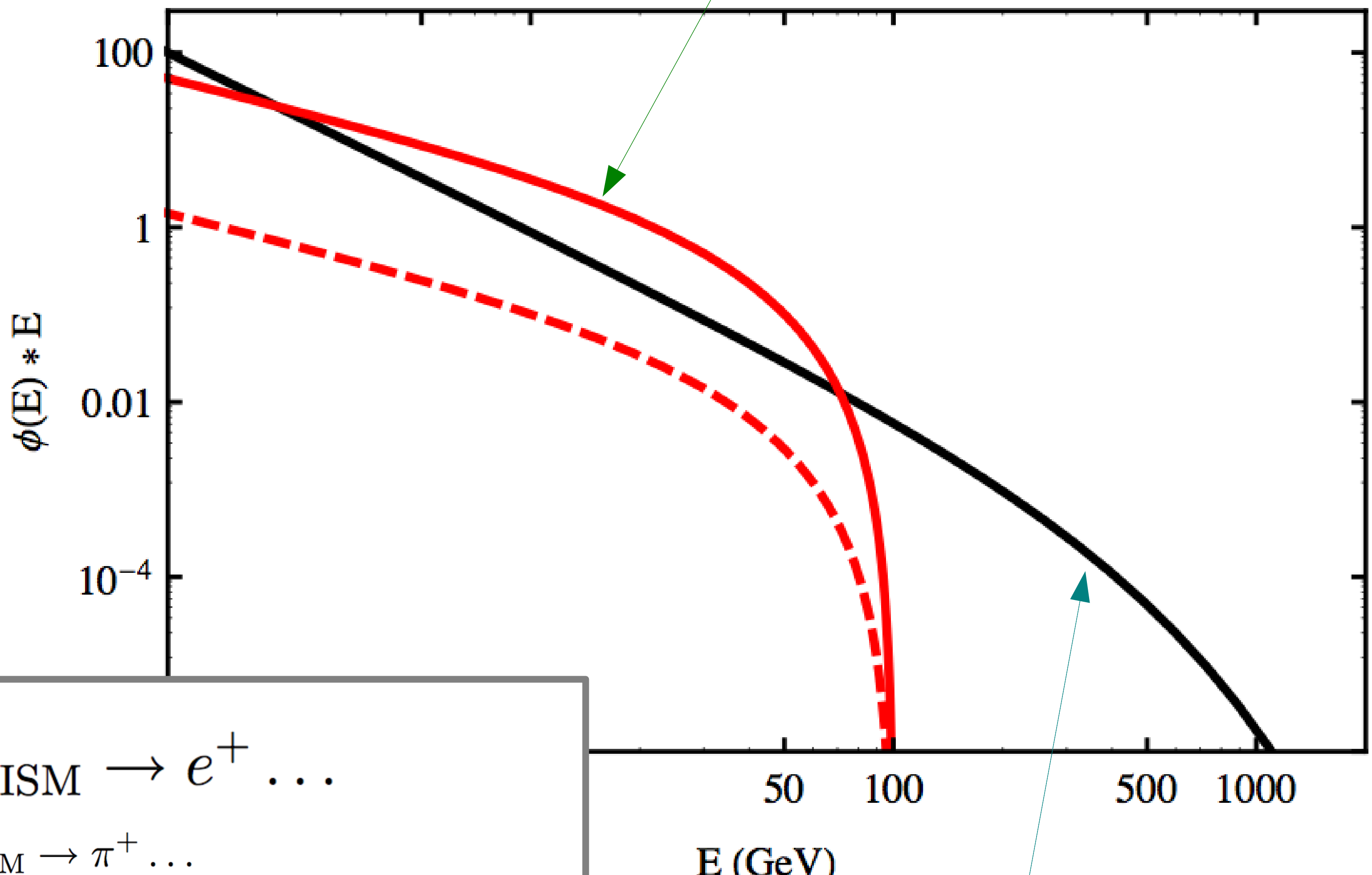
$$\chi + \chi \rightarrow e^+ + e^-$$



“Background” of
astrophysical origin

$$\chi + \chi \rightarrow e^+ + \ldots$$

Signal from
Dark-Matter annihilation



$$p + p_{\rm ISM} \rightarrow e^+ \ldots$$

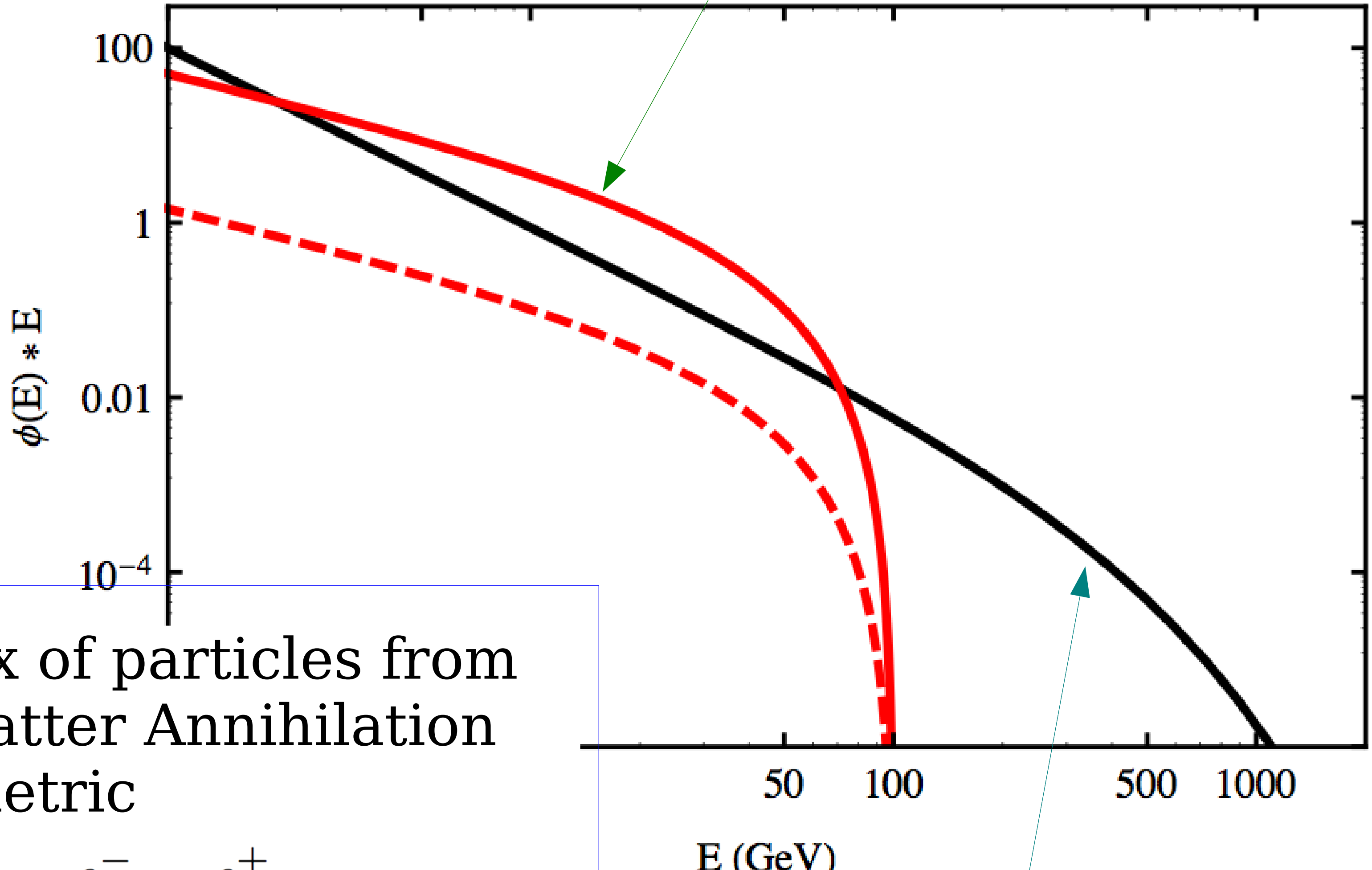
$$p + p_{\rm ISM} \rightarrow \pi^+ \ldots$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

“Background” of
astrophysical origin

Signal from
Dark-Matter annihilation



The flux of particles from
Dark Matter Annihilation
is symmetric

$$p = \overline{p} \qquad e^- = e^+$$

But the “background” is not

“Background” of
astrophysical origin

To measure positrons and anti-protons you need
To go to space, above the atmosphere.

A magnet for charge separation is essential

Published online 16 June 2006 | Nature | doi:10.1038/news060612-15

News

PAMELA, or virtue rewarded

After a decade's work, physicists are flying an antimatter observatory.

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News

PAMELA, or virtue rewarded

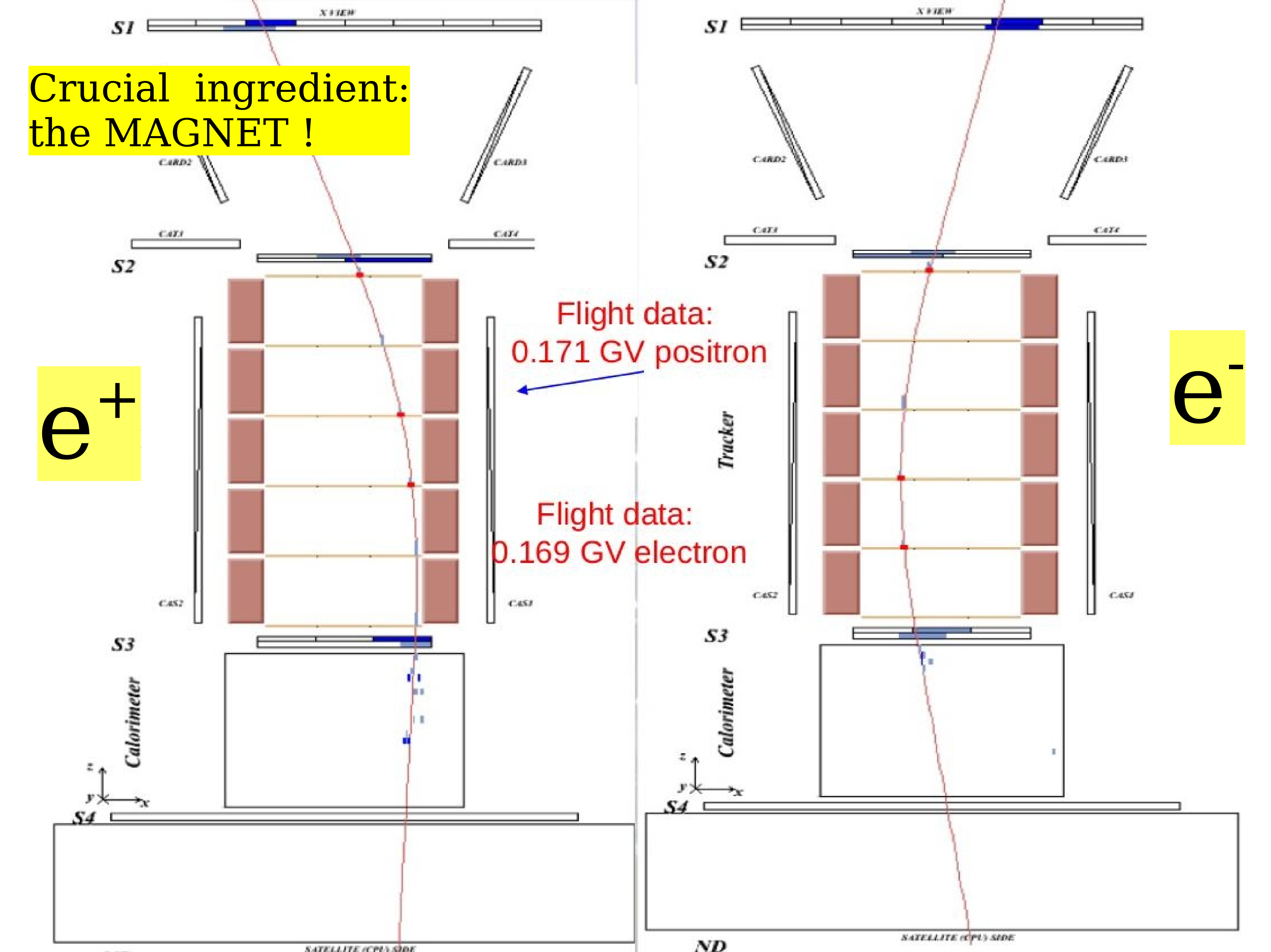
After a decade's work, physicists are flying an antimatter observatory.

The first satellite built to detect antimatter in space launched safely yesterday, boosting the chances of identifying the mysterious 'dark matter' that makes up more than 80% of the stuff in the Universe.

The PAMELA probe (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) took off from the Baikonur Cosmodrome in Kazakhstan on 15 June, carrying instruments that will catch antiprotons and positrons, the mirror particles of protons and electrons.

The physicists' day in the sun

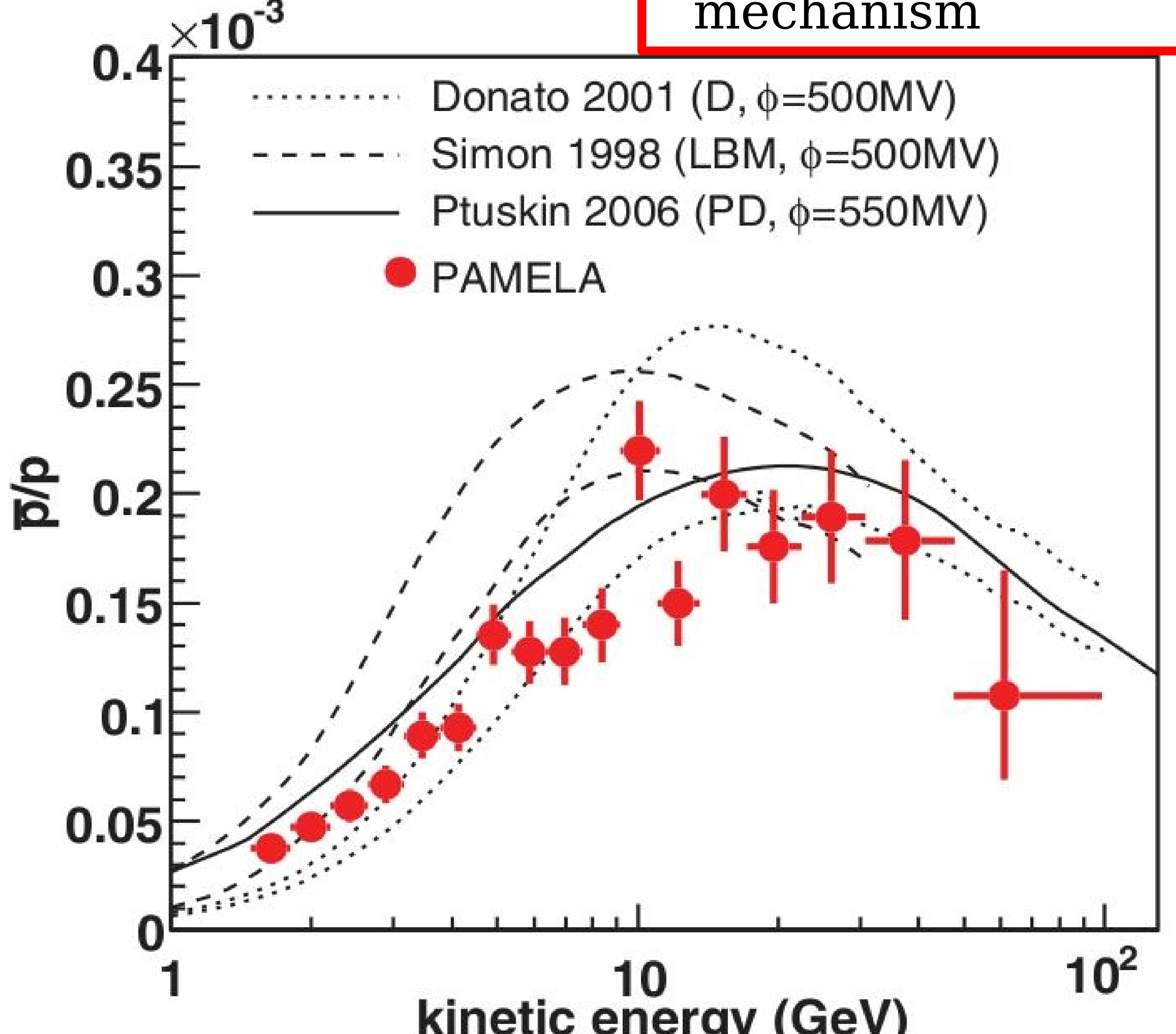
The project began in 1995 as a collaboration between Russian and Italian scientists, which expanded to include colleagues from many other countries.



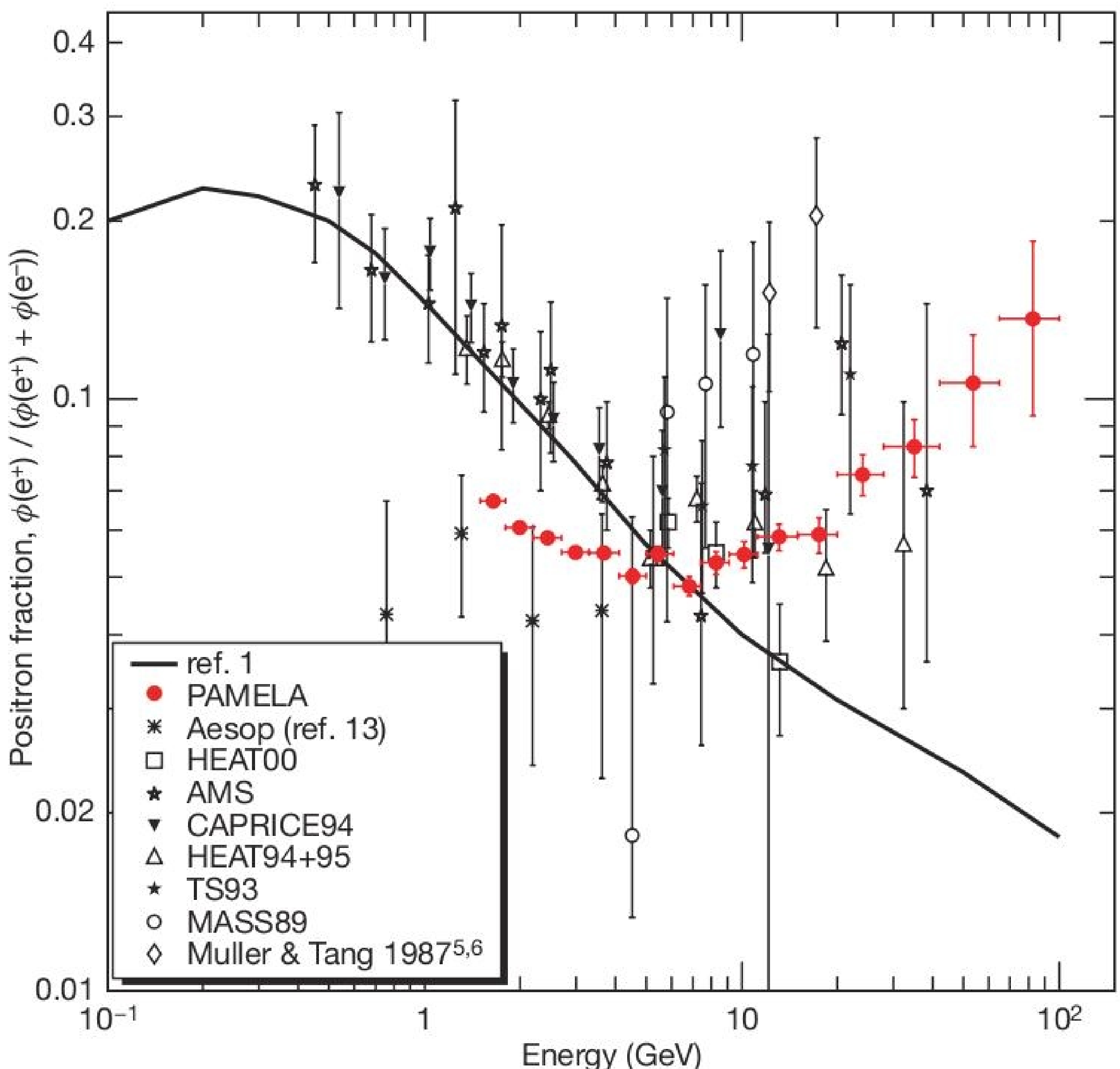
Crucial ingredient:
the MAGNET !
e^+
e^-
Flight data:
0.171 GV positron
Flight data:
0.169 GV electron
S1
S2
S3
S4
X VIEW
CARD2
CARD3
CAT3
CAT4
CAS2
CAS3
Tracker
Calorimeter
ND
SATELLITE (CPU) SIDE
z
y
x

Antiproton result

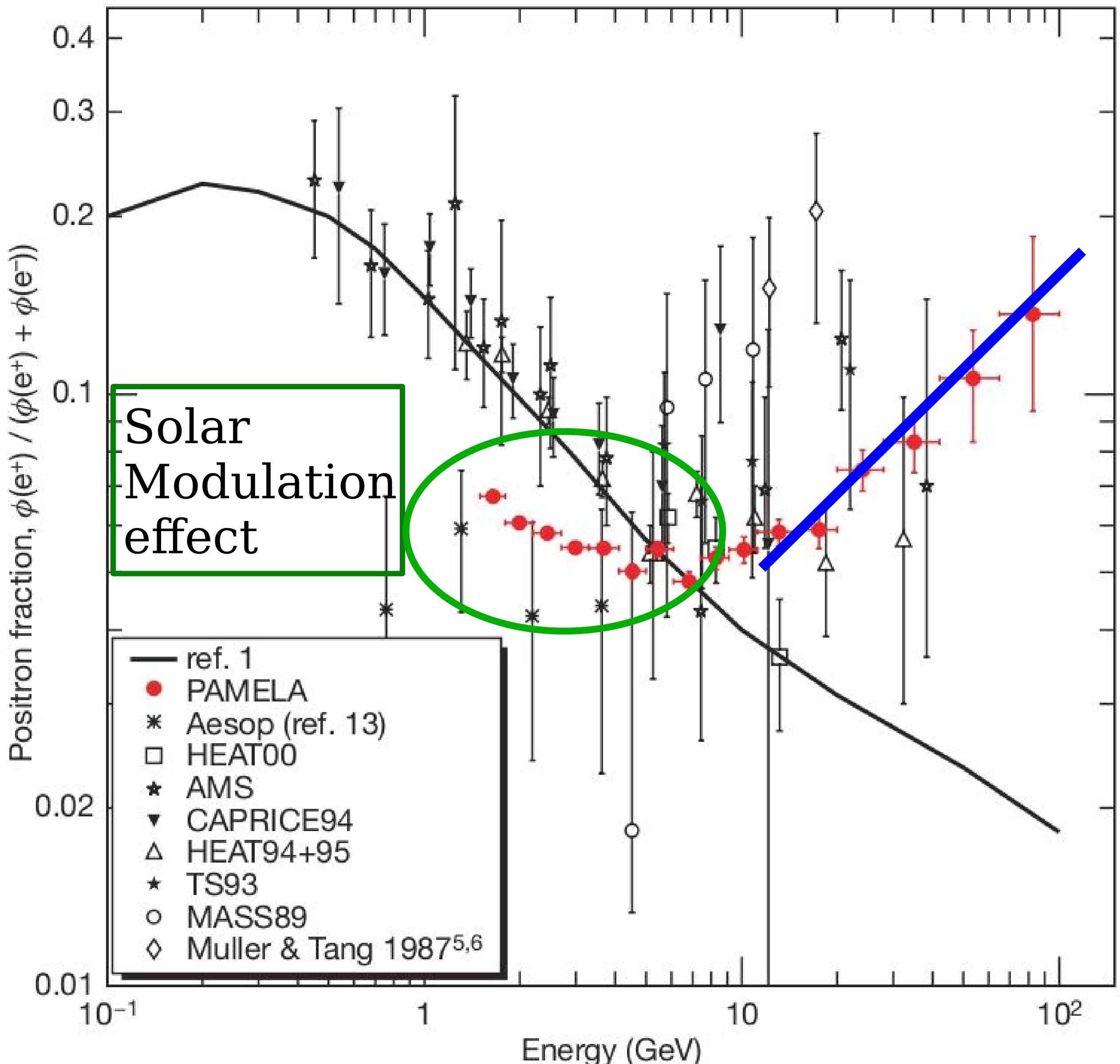
Agreement
With standard production
mechanism



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



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

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

Very unexpected result !

From : Cirelli

Results

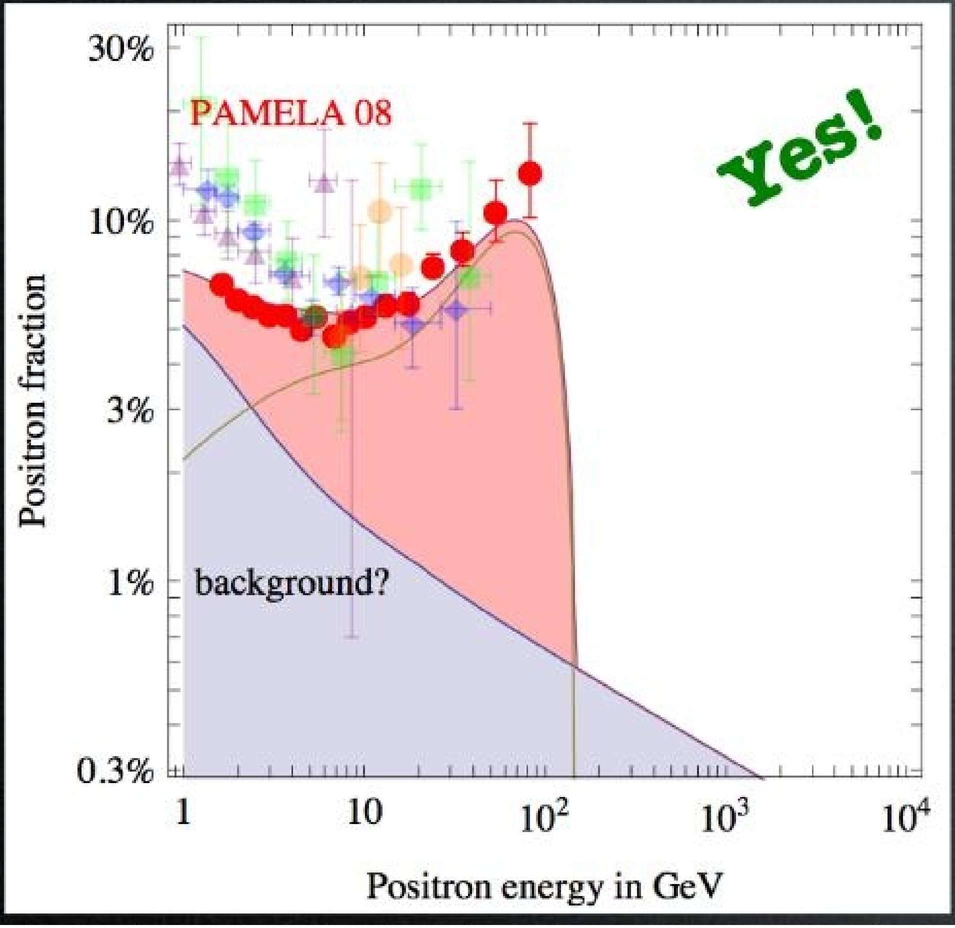
Which DM spectra can fit the data?

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

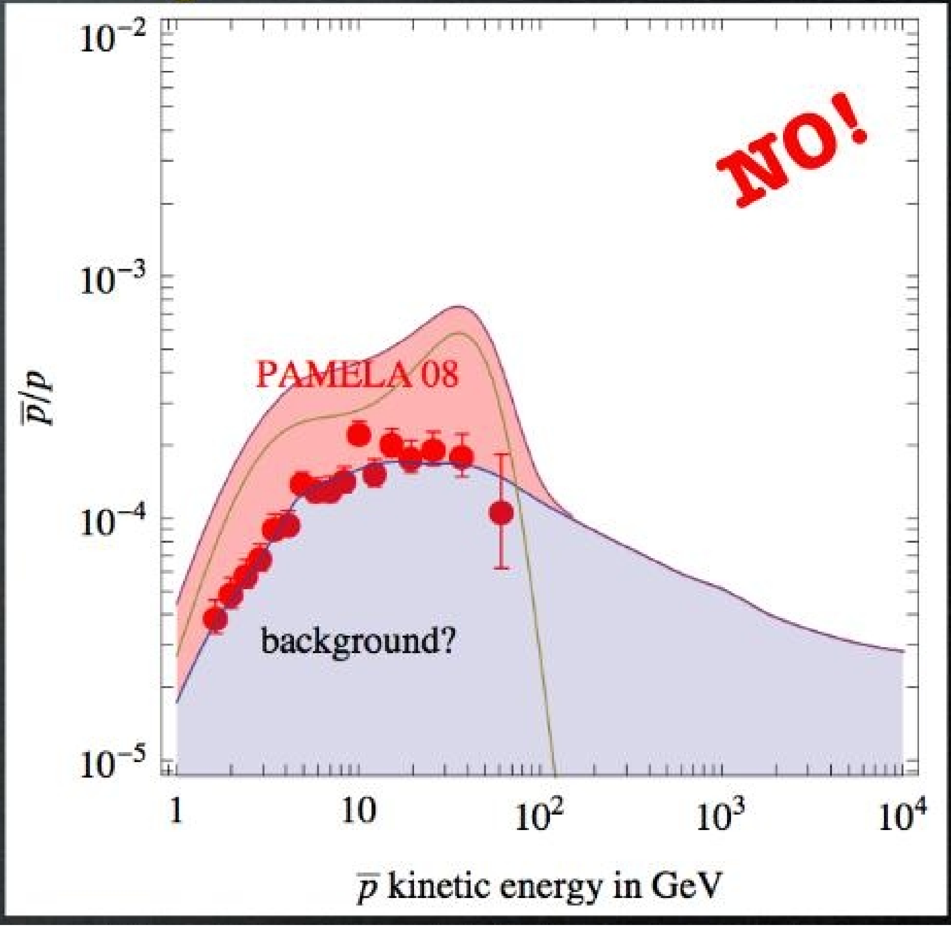
-annihilation $\text{DM DM} \to W^+W^-$

(a possible SuperSymmetric candidate: wino)

Positrons:



Anti-protons:



Results

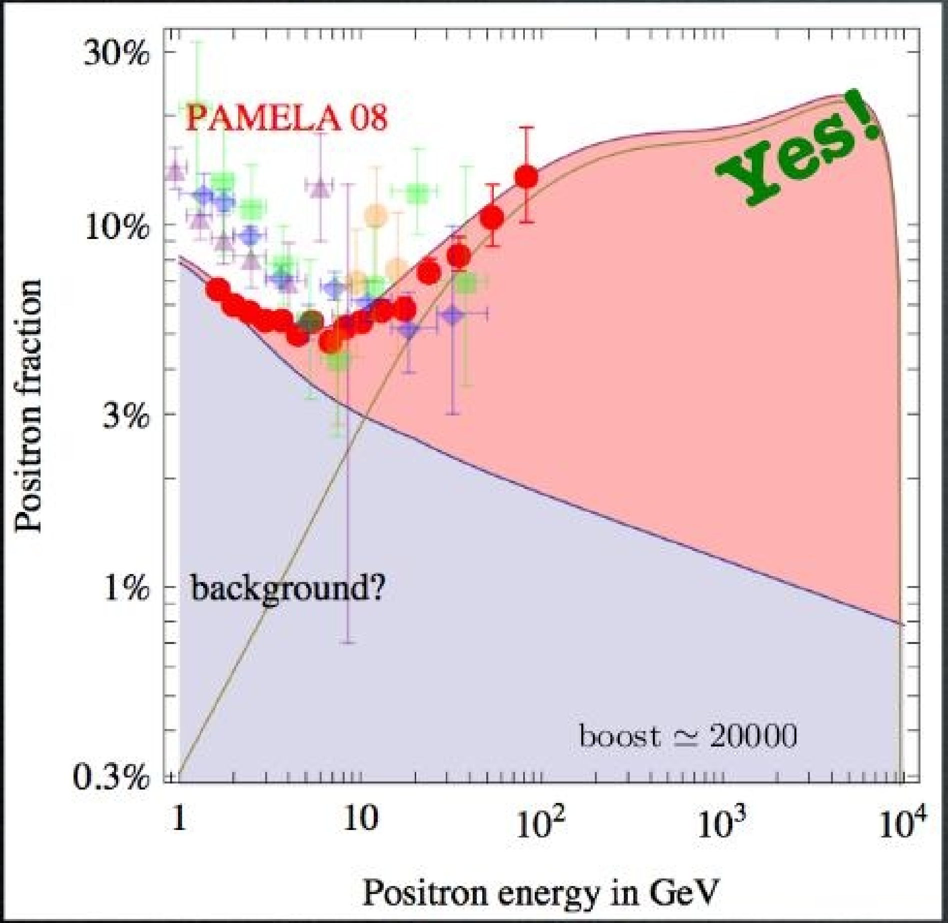
Which DM spectra can fit the data?

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

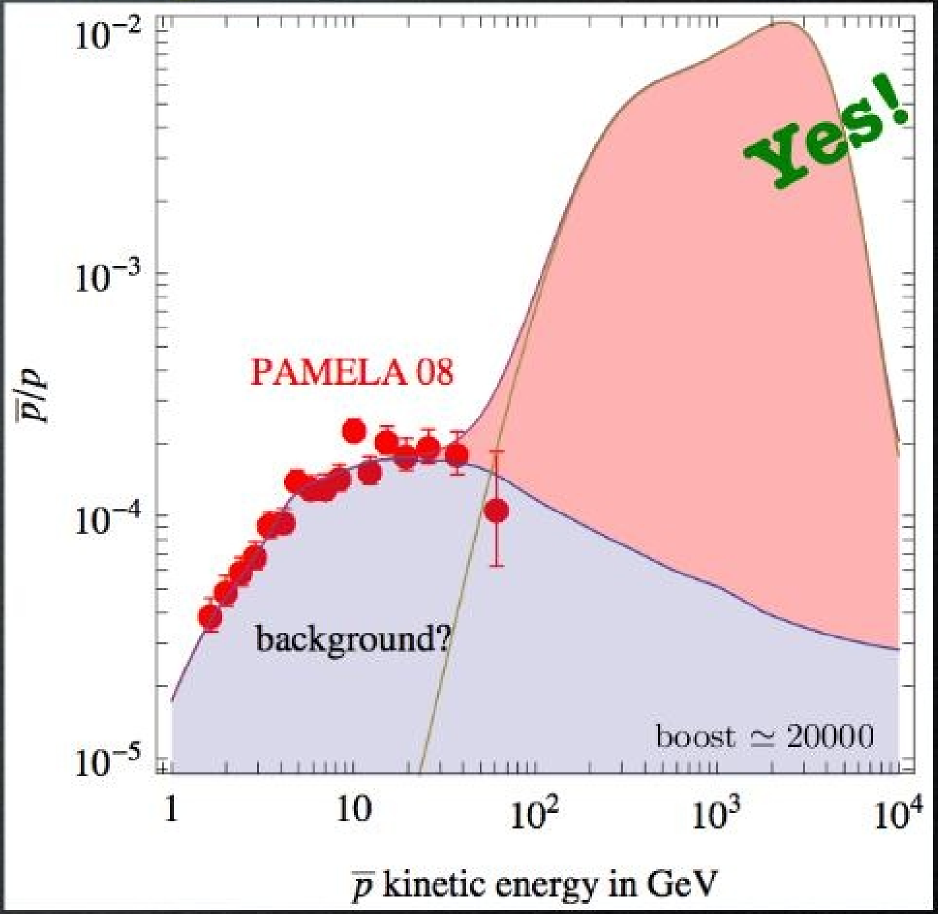
-annihilation $\mathrm{DM\ DM} \to W^+W^-$

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

Positrons:



Anti-protons:



Dark Matter explanation of the
"Pamela positron excess" in terms of the
"WIMP" model is possible, but not in its
Simplest, most natural version.

[1.] The DM annihilation does not produce antiprotons
"Leptophilic" Dark Matter [?]
(no convincing dynamical explanation)

[2.] Include a large "Boost factor"
to increase the rate of the DM annihilations.
Very "clumpy" dark matter.
(very lucky in being close to a big DM clump)
"winning the jackpot" [?]

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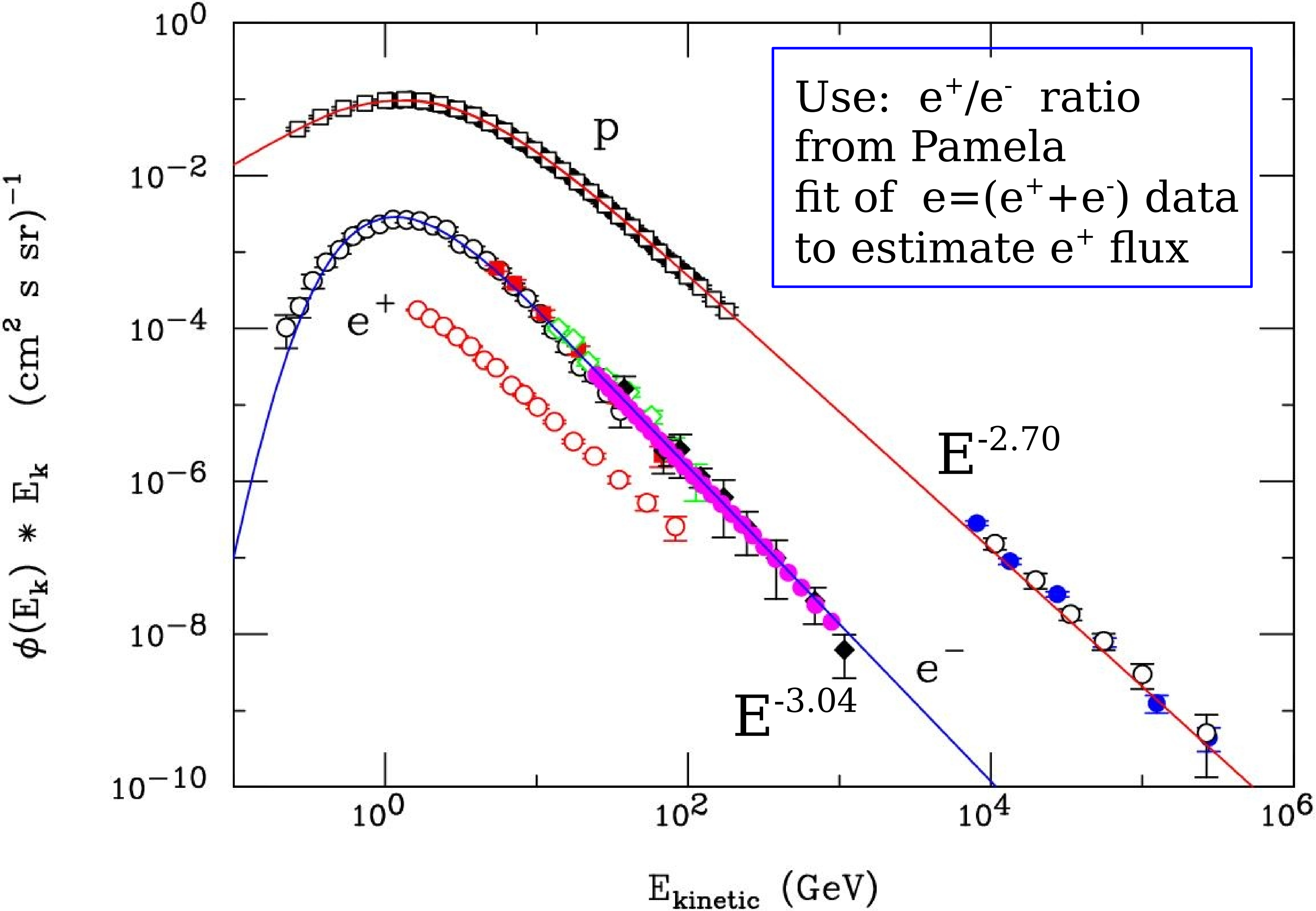
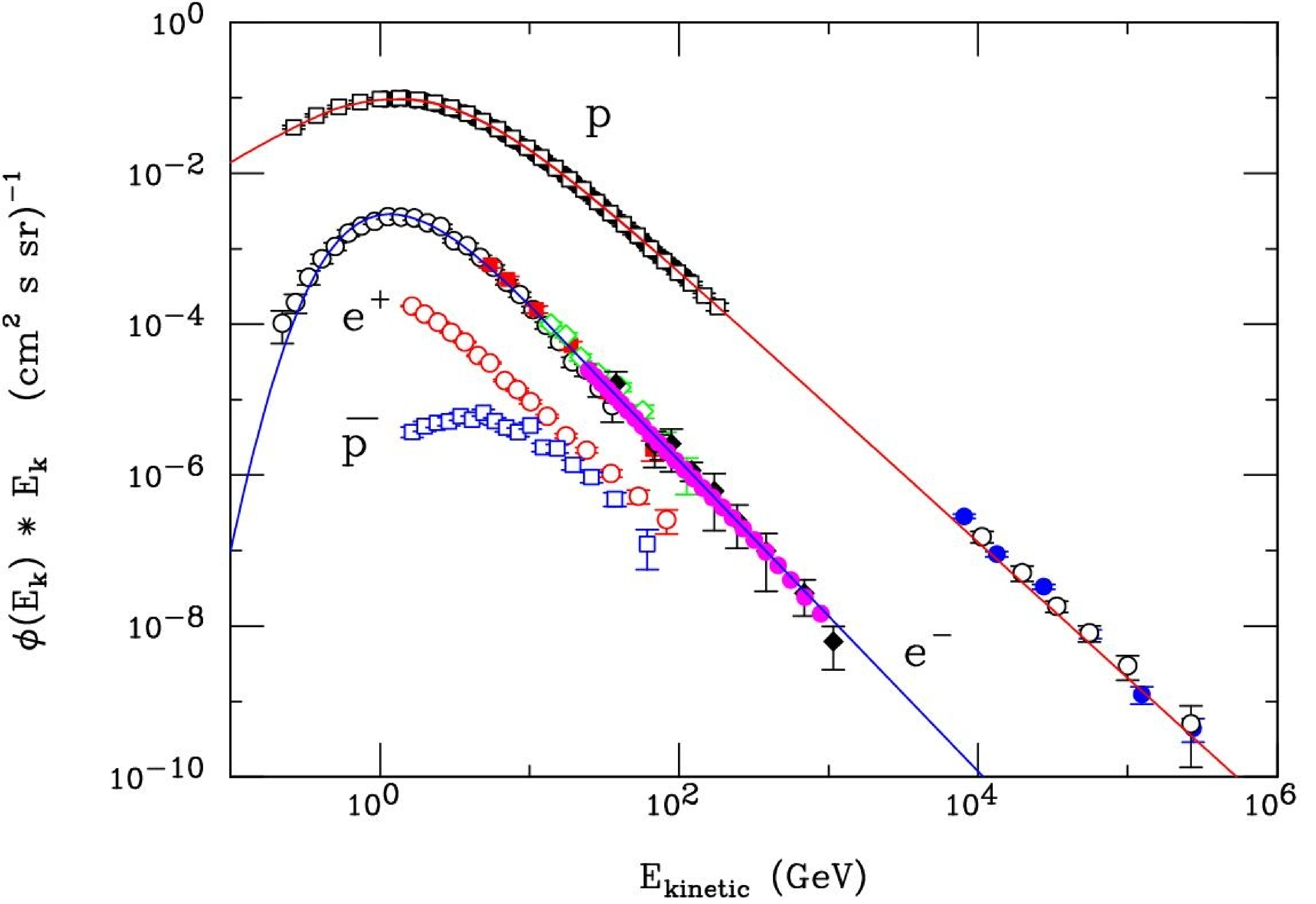
"winning the jackpot" [?]

Is this "adding epicycles" to the wrong theory ?

Are there other possible interpretations for this result.

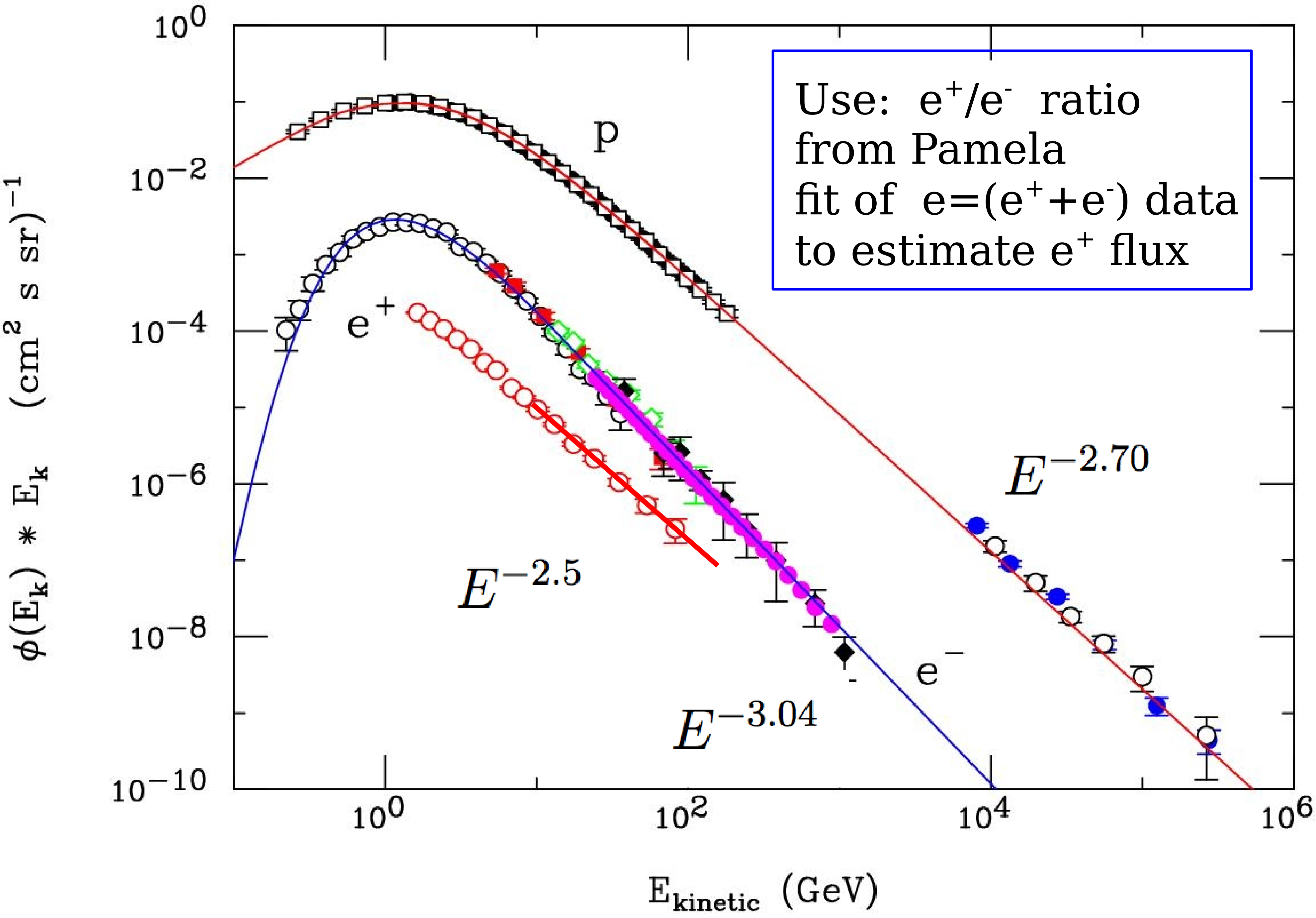
Proton and electron + Positron energy spectra





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

Proton and electron + Positron energy spectra



Spectra of approximately form:

protons	$E^{-2.70}$
electrons	$E^{-3.04}$
positrons	$E^{-2.5}$

$E^{-3.1}$

$E^{-3.5}$

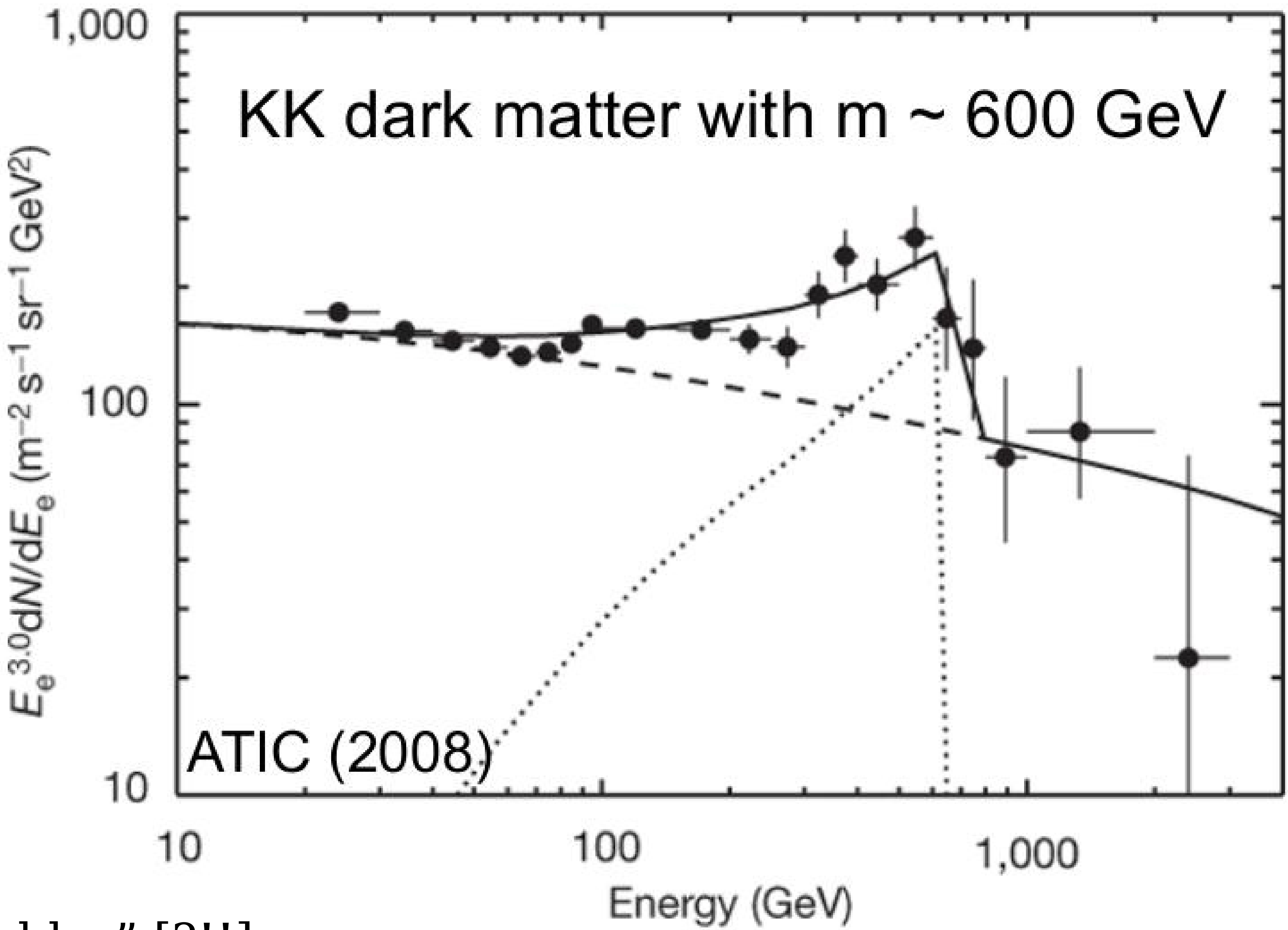
Completely unexpected result

Rough expectation
For the positron slope
SOFTER than electrons

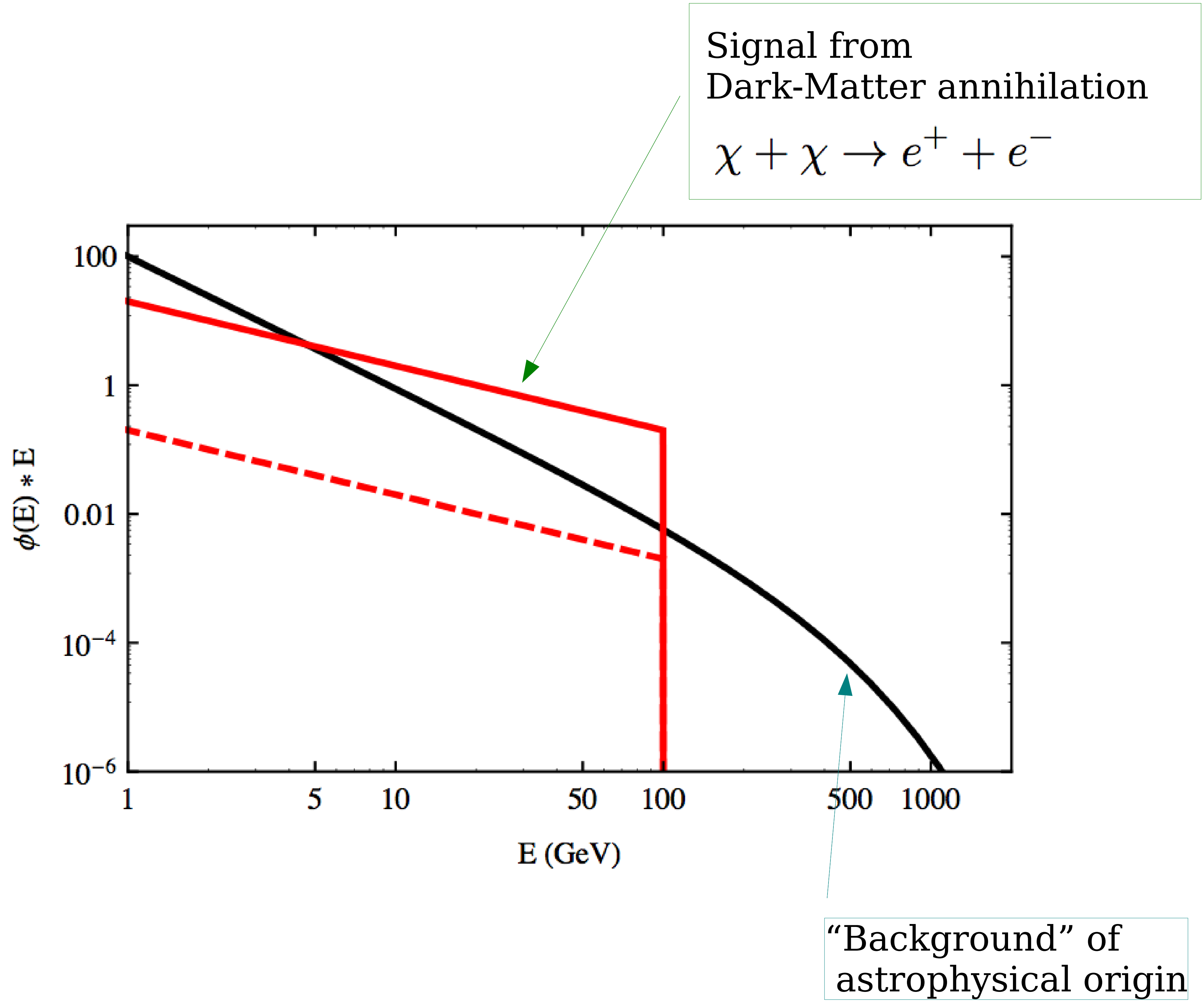
Another very surprising result that has generated a lot of discussion
The balloon calorimeter ATIC

ATIC

Balloon experiment (electron + positron)

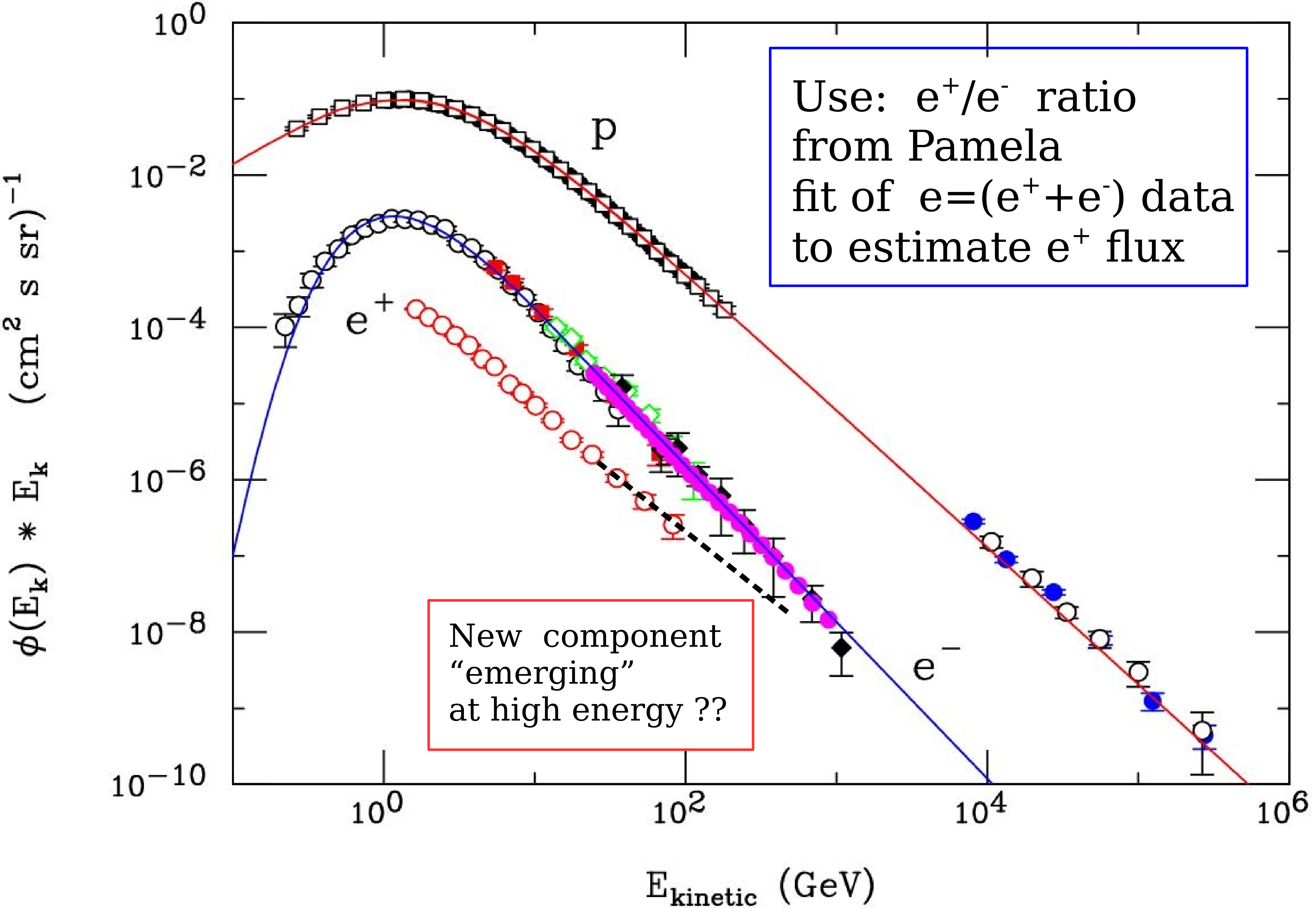


“Shoulder” [?!!]

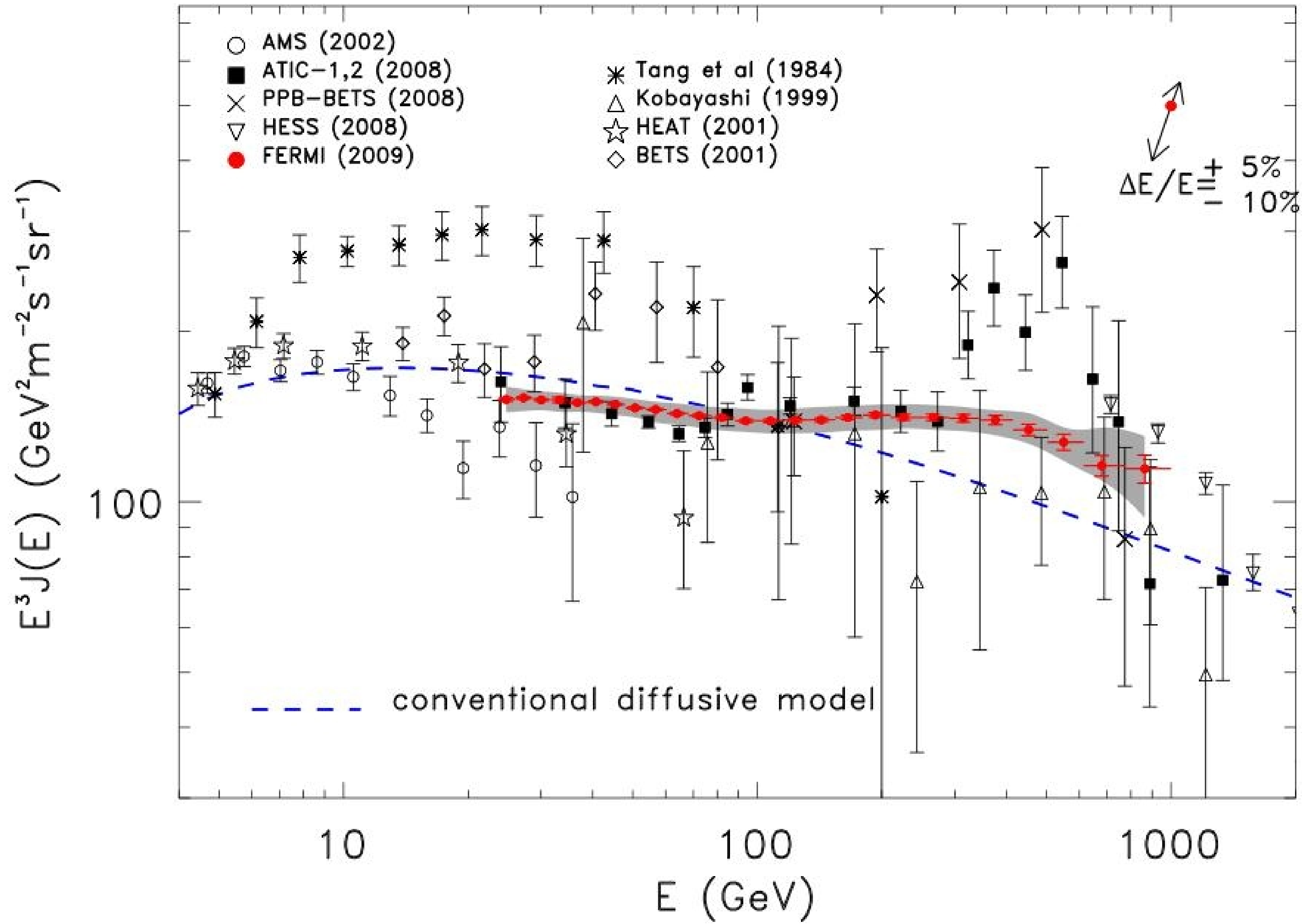


Signal from
Dark-Matter annihilation
$\chi + \chi \to e^+ + e^-$
100
1
0.01
10^{-4}
10^{-6}
$\phi(E) * E$
1
5
10
50
100
500
1000
E (GeV)
"Background" of
astrophysical origin

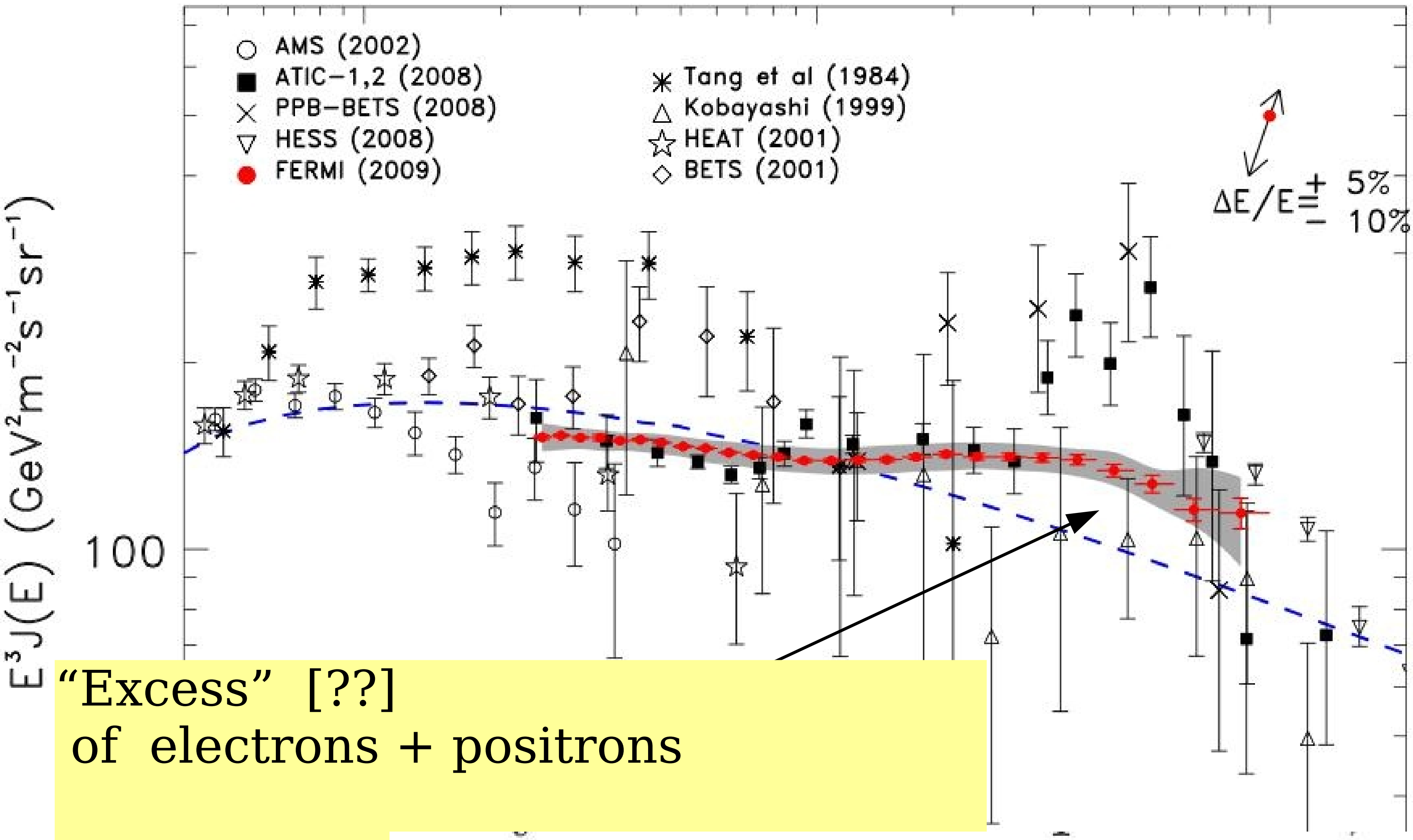
Proton and electron + Positron energy spectra



FERMI: electron + positron flux



FERMI: electron + positron flux



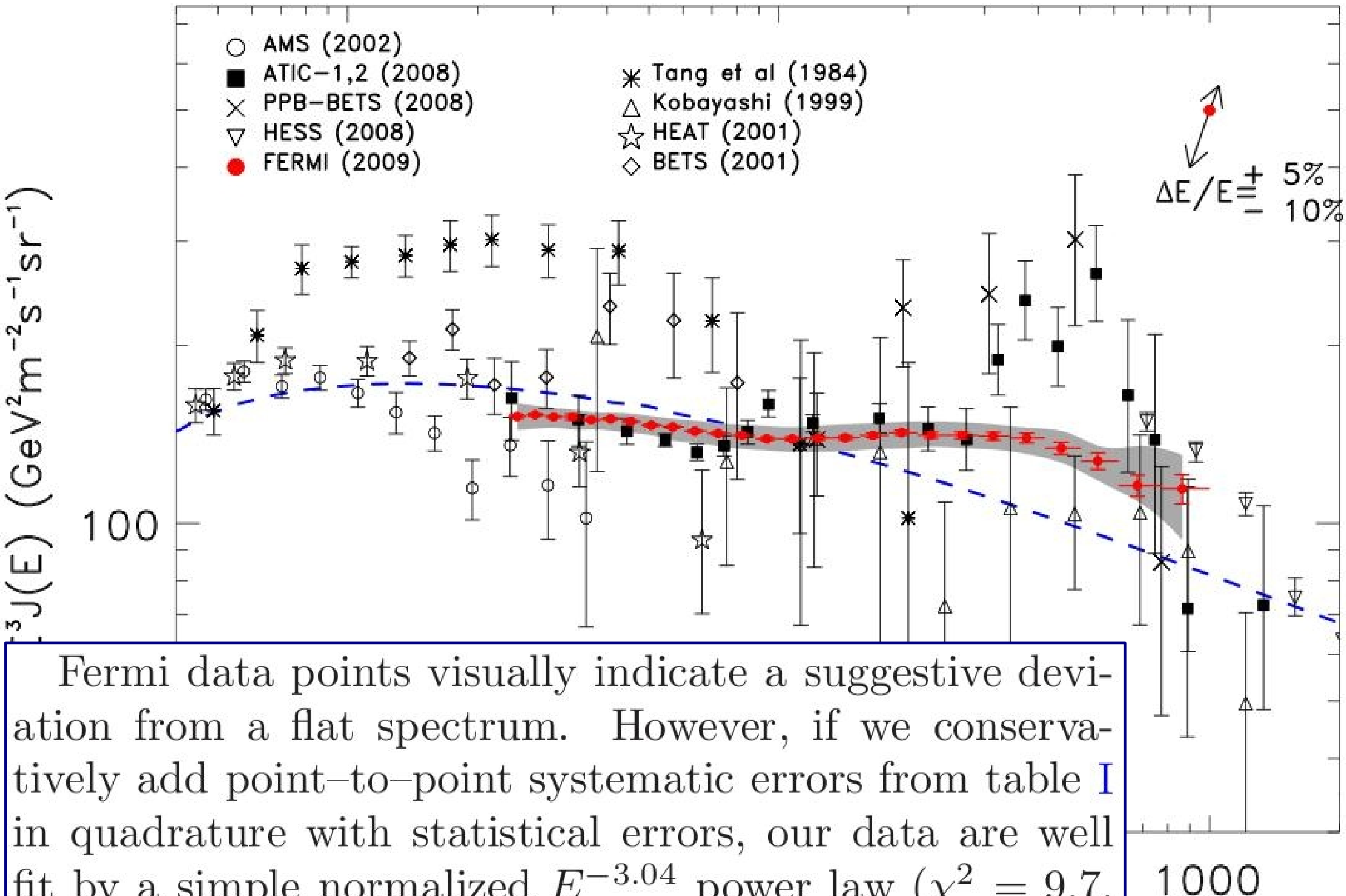
"Excess" [??]
of electrons + positrons

....
Possible...

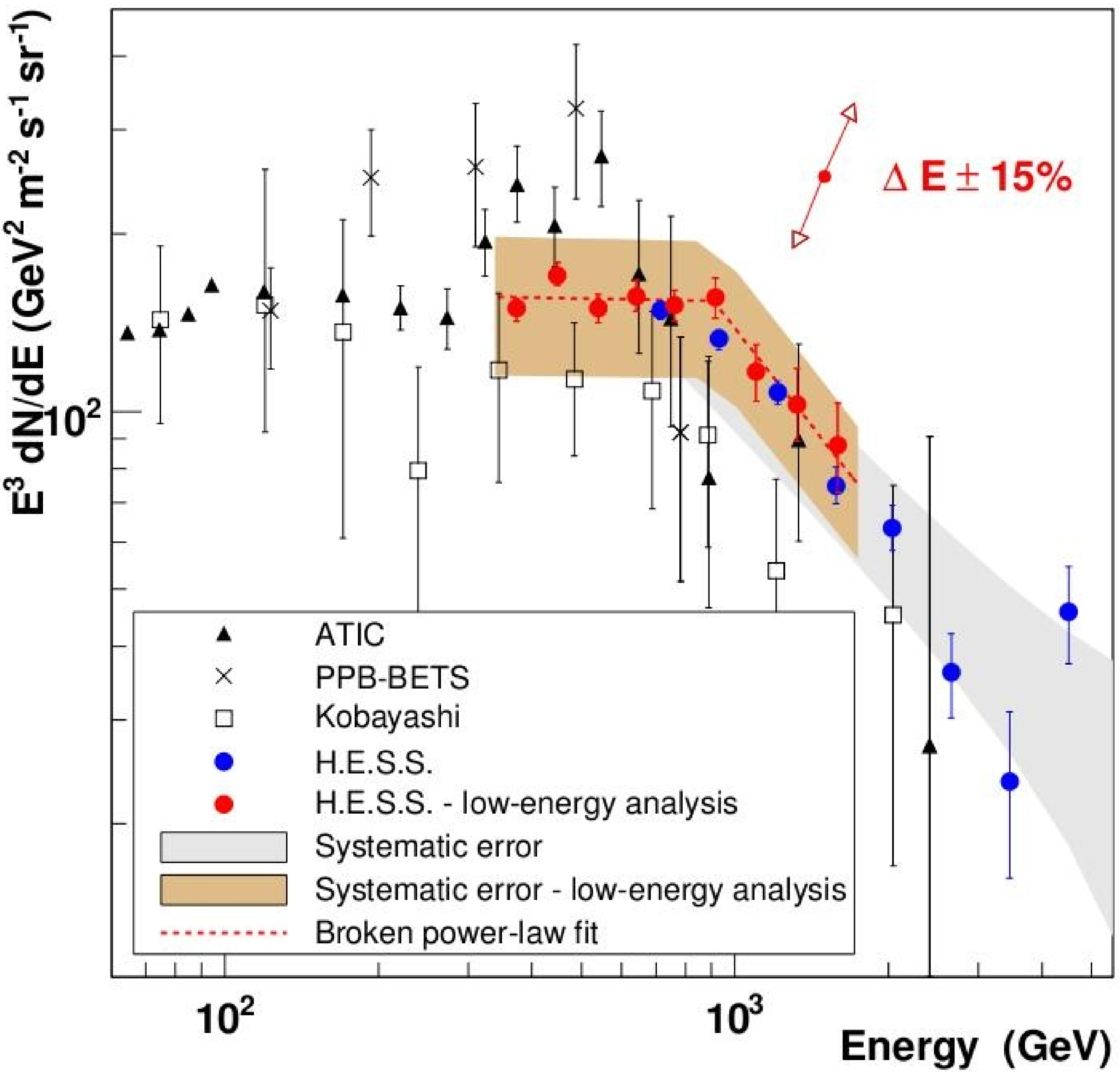
$$J_{\rm extra}(E) \;\propto\; E^{-\gamma_e} \exp\{-E/E_{\rm cut}\}$$

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).



E^3 dN/dE (GeV^2 m^{-2} s^{-1} sr^{-1})
10^2
10^3
Energy (GeV)
Δ E ± 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

Astrophysical Solutions
for the PAMELA positron excess

protons	$E^{-2.70}$
electrons	$E^{-3.04}$
positrons	$E^{-2.5}$

New source of electrons and positrons
that accelerate particles with
a very hard source spectrum $E^{-1.6}$ $E^{-1.7}$

Injection from a plane

$$\alpha_p = \alpha_0 + \delta \simeq 2.70$$

$$\alpha_e = \alpha_0 + \frac{\delta}{2} + \frac{1}{2} \simeq 3.04$$

$$\alpha_0 \simeq 2.38$$

$$\delta \simeq 0.32$$

Homogeneous injection

$$\alpha_p = \alpha_0 + \delta \simeq 2.70$$

$$\alpha_e = \alpha_0 + 1 \simeq 3.04$$

$$\alpha_0 \simeq 2.04$$

$$\delta \simeq 0.66$$

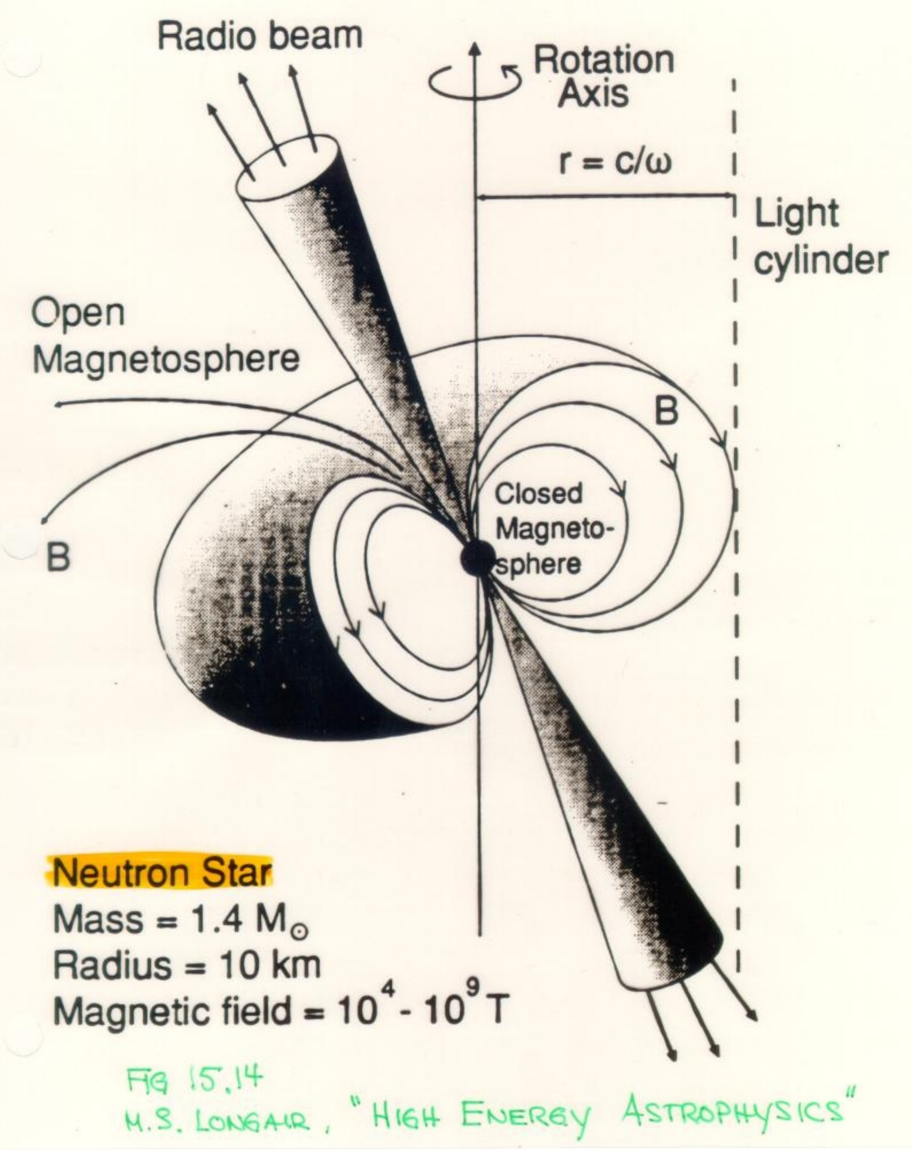
PULSARS

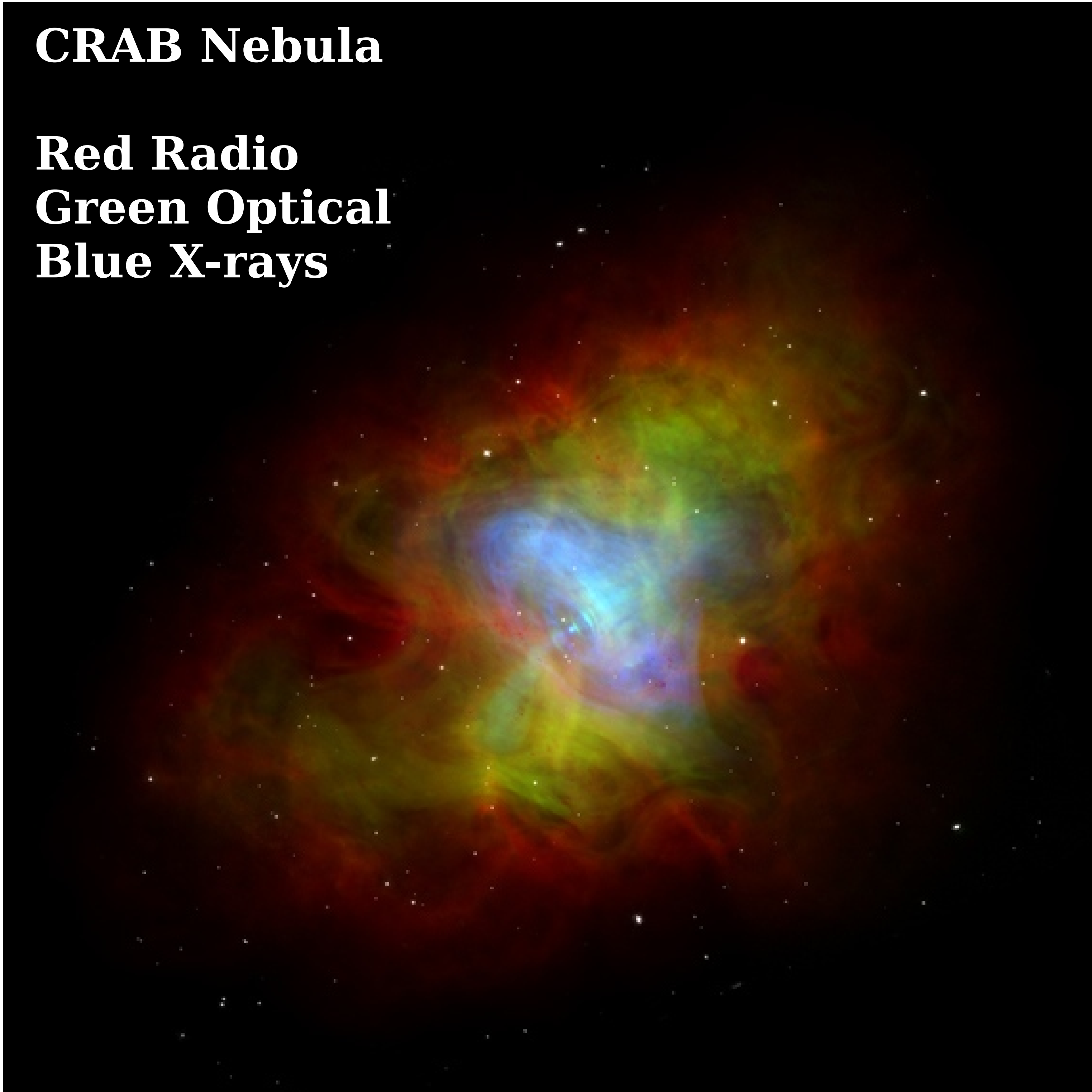
CRAB Nebula

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

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

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




CRAB Nebula
Red Radio
Green Optical
Blue X-rays

Pulsars as the Sources of High Energy Cosmic Ray Positrons

Hooper, Blasi, Serpico 2008

Energy is available

Dynamics of particle production?

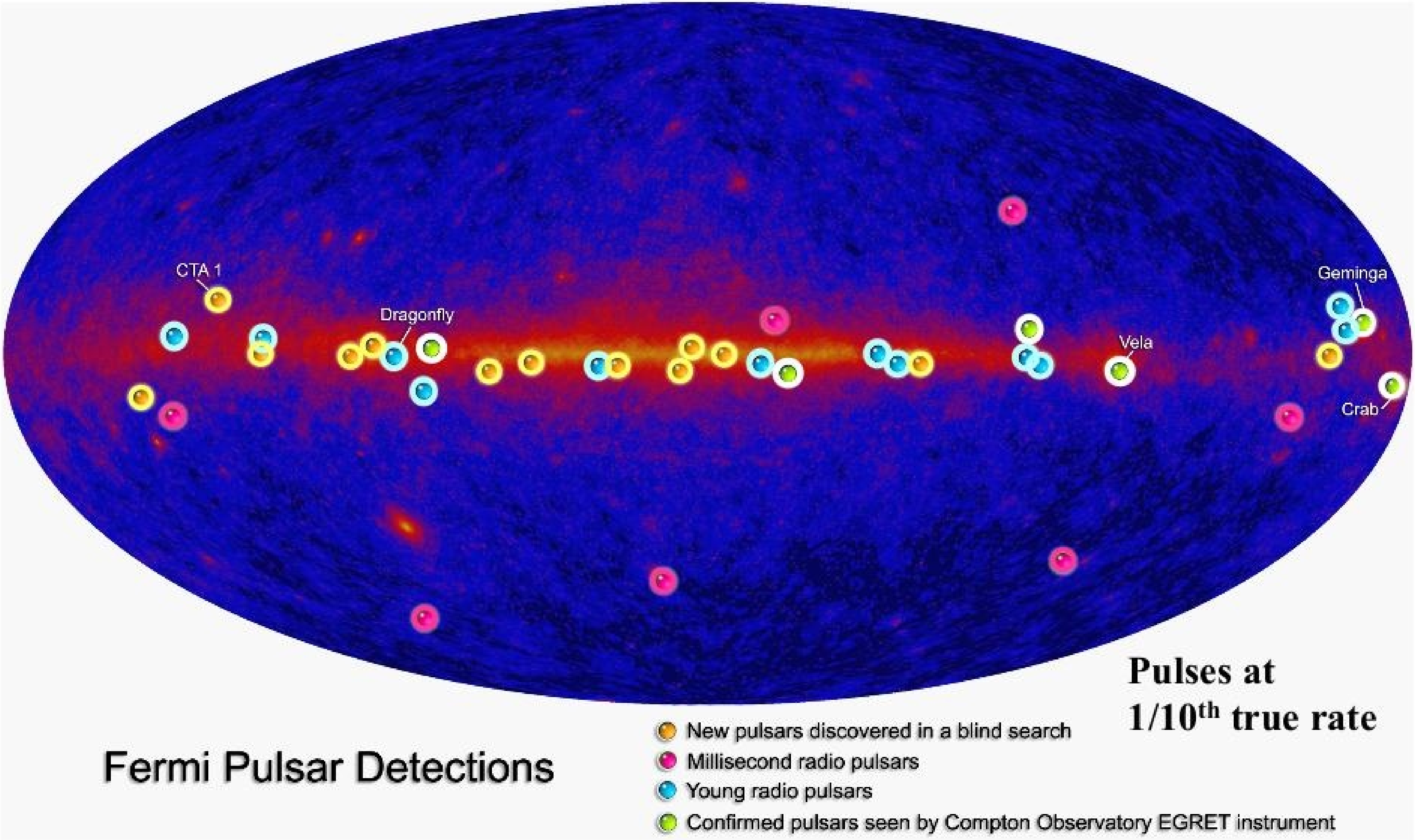
$$\frac{dN_e}{dE_e} \approx 8.6 \times 10^{38}\, \dot{N}_{100}\, (E_e/\mathrm{GeV})^{-1.6} \exp\left(-E_e/80\,\mathrm{GeV}\right) \mathrm{GeV}^{-1}\,\mathrm{s}^{-1}$$

$$-\frac{dE}{dt} = \frac{2}{3\,c^3}\,\left|\ddot{M}\right|^2$$

$$|\ddot{\vec{M}}|^2 = \frac{B_p^2 R^6}{4}\Omega^4\,\sin^2\alpha;$$

$$\frac{dE}{dt} = \frac{d}{dt}\left[\frac{1}{2}\,\Omega^2\right] = I\,\Omega\,\dot{\Omega}$$

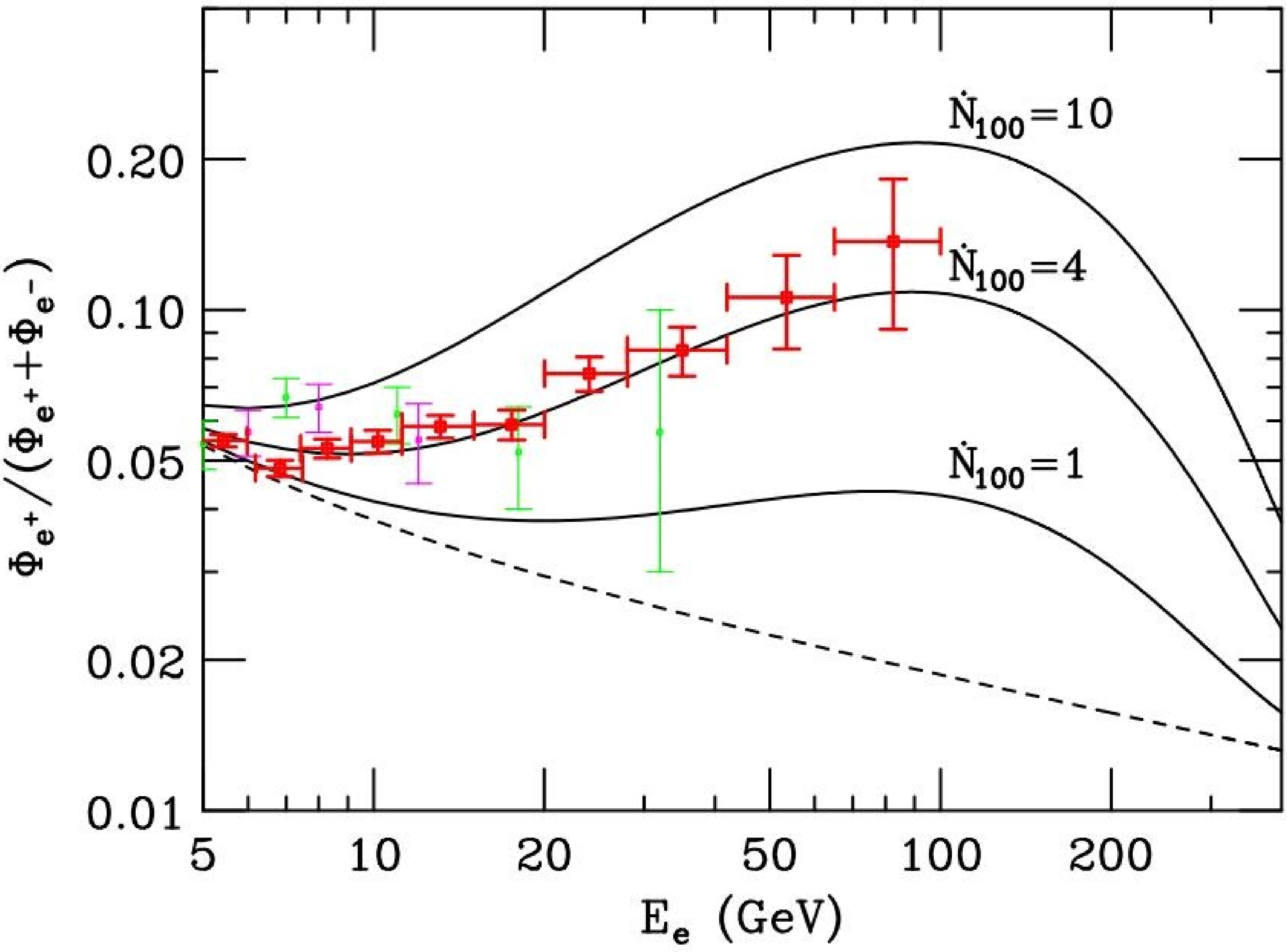
Fermi Pulsar detection



Pulses at $1/10^{th}$ true rate

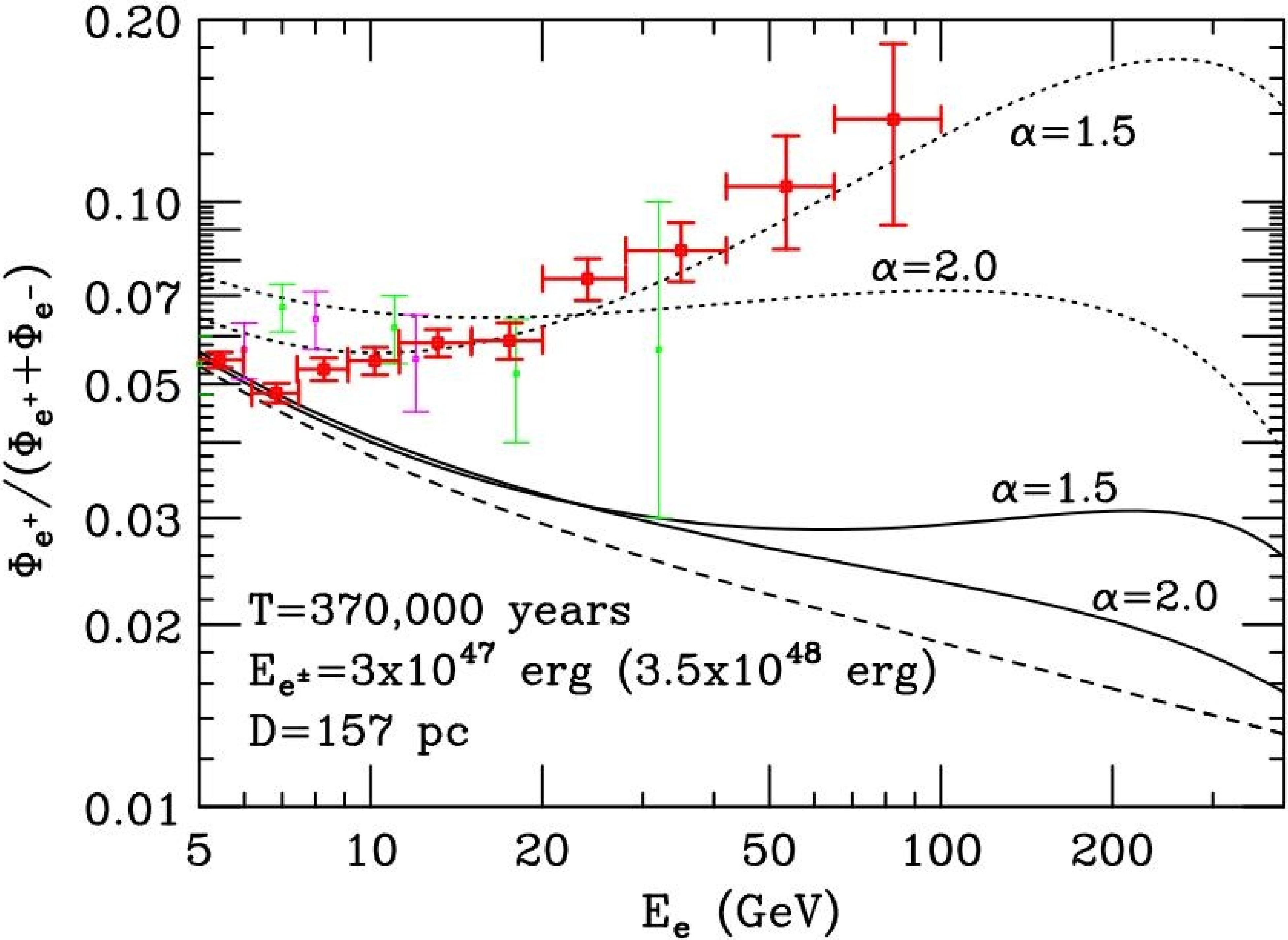
Hooper, Blasi, Serpico 2008

Contribution from all Pulsars



Hooper, Blasi, Serpico 2008

Contribution from single close Pulsar



The origin of the positron excess in cosmic rays

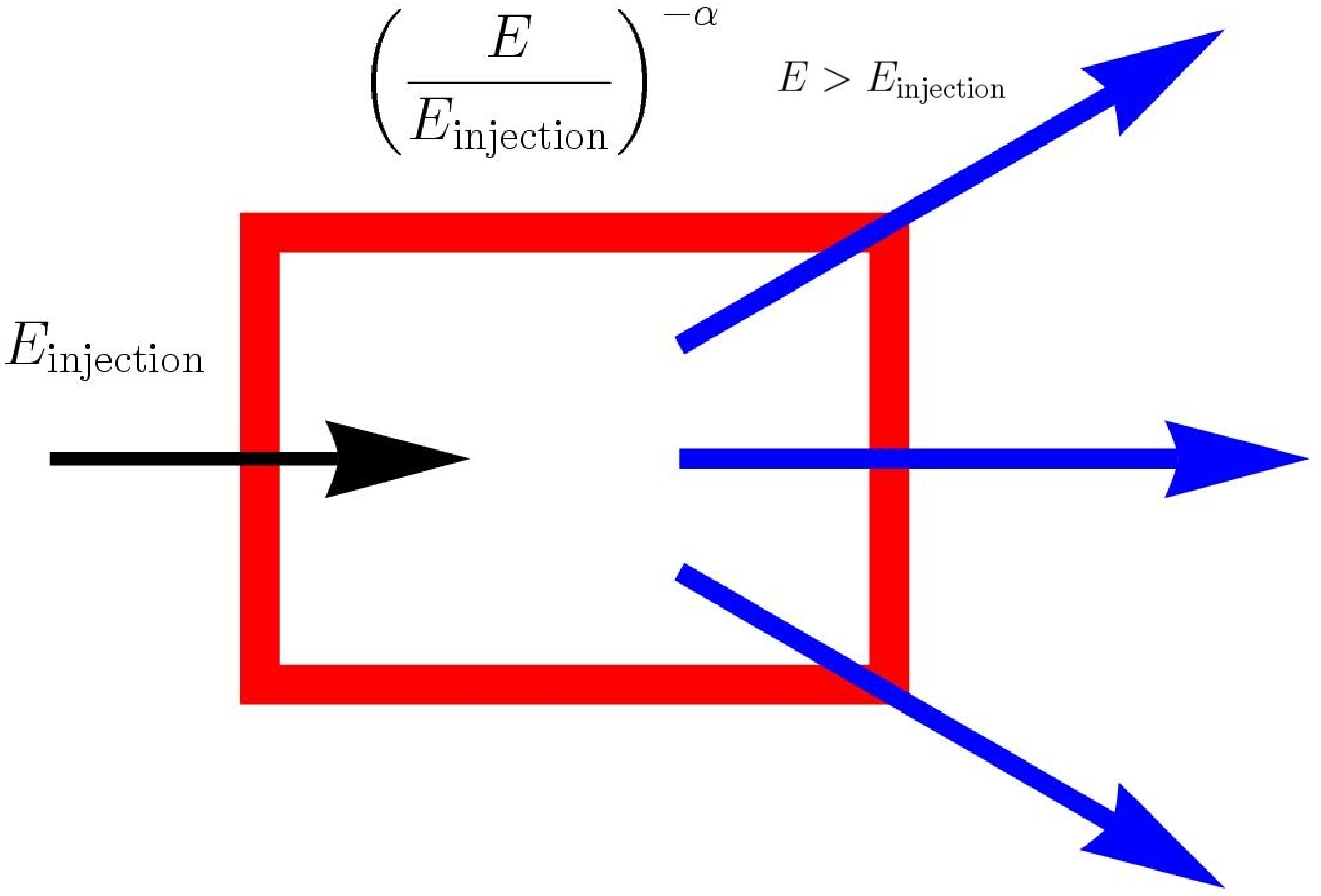
Pasquale Blasi

astro-ph/0903.2794

New mechanism in
“standard Supernova acceleration” scenario

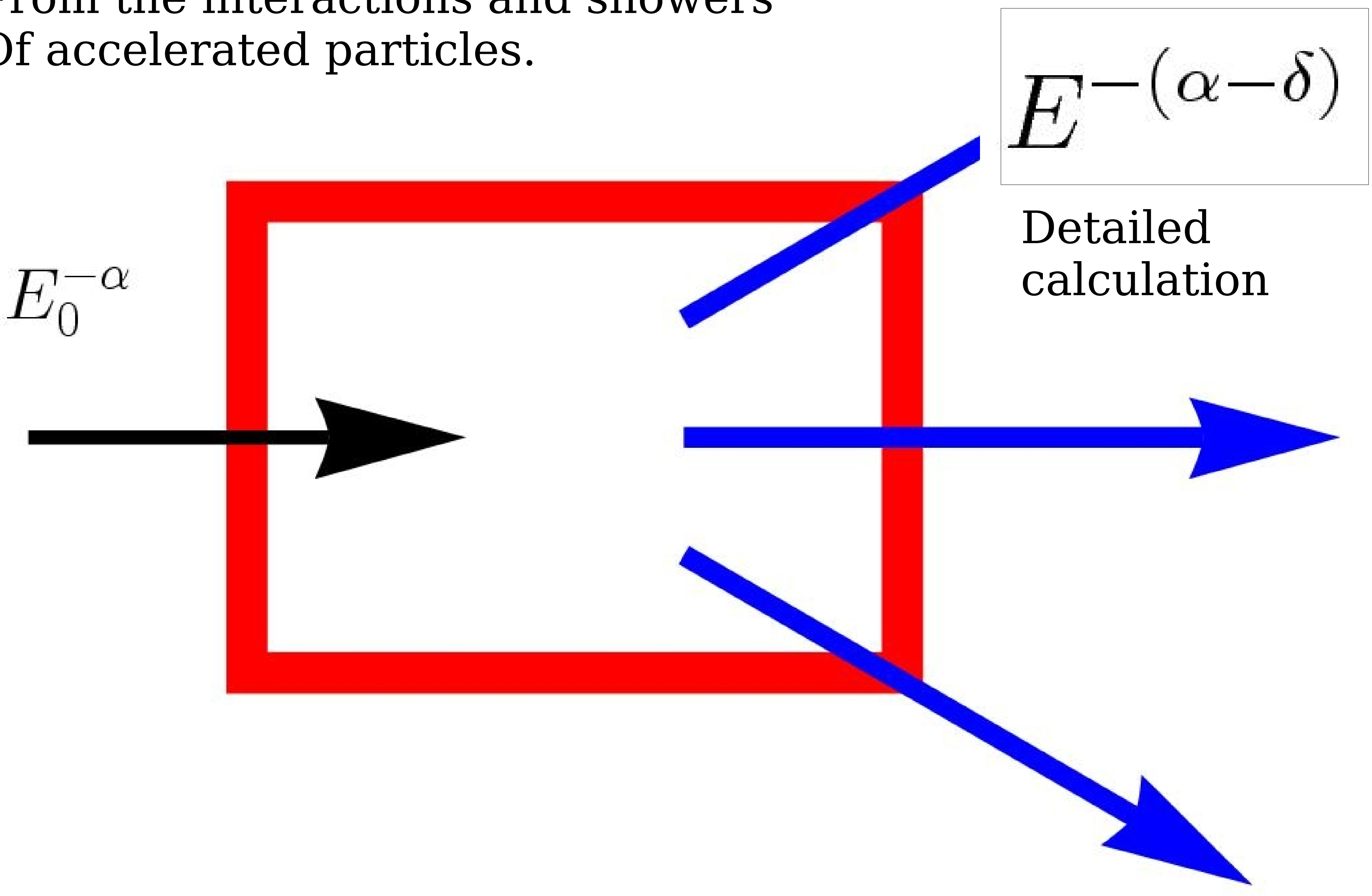
INJECTION of e+e- pairs
from accelerated particles at the source

Crucial problems:
- Normalization
- Spectrum



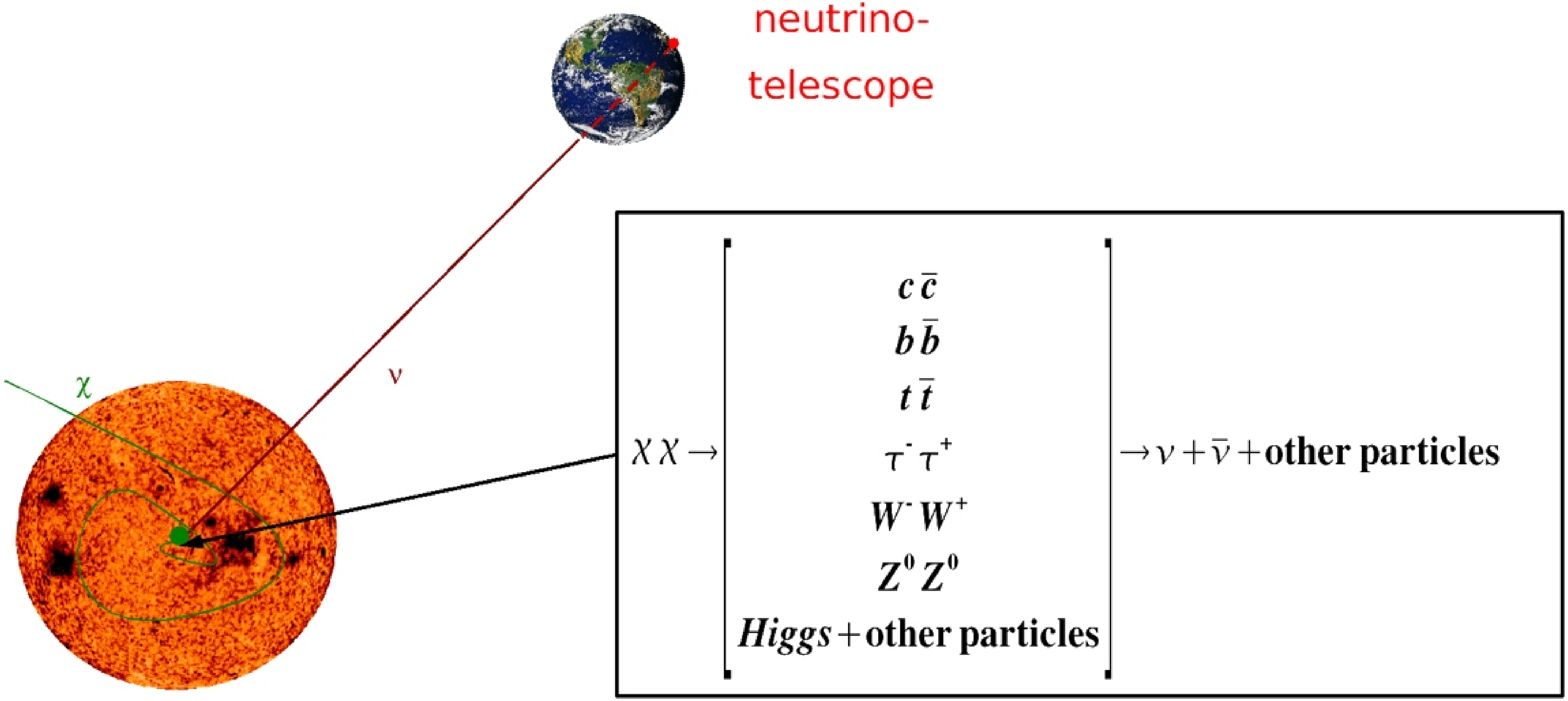
$\left(\frac{E}{E_{\rm injection}}\right)^{-\alpha}$
$E > E_{\rm injection}$
$E_{\rm injection}$

Injections of relativistic particles
From the interactions and showers
Of accelerated particles.



Detailed
calculation

Dark Matter detection with neutrino telescopes.



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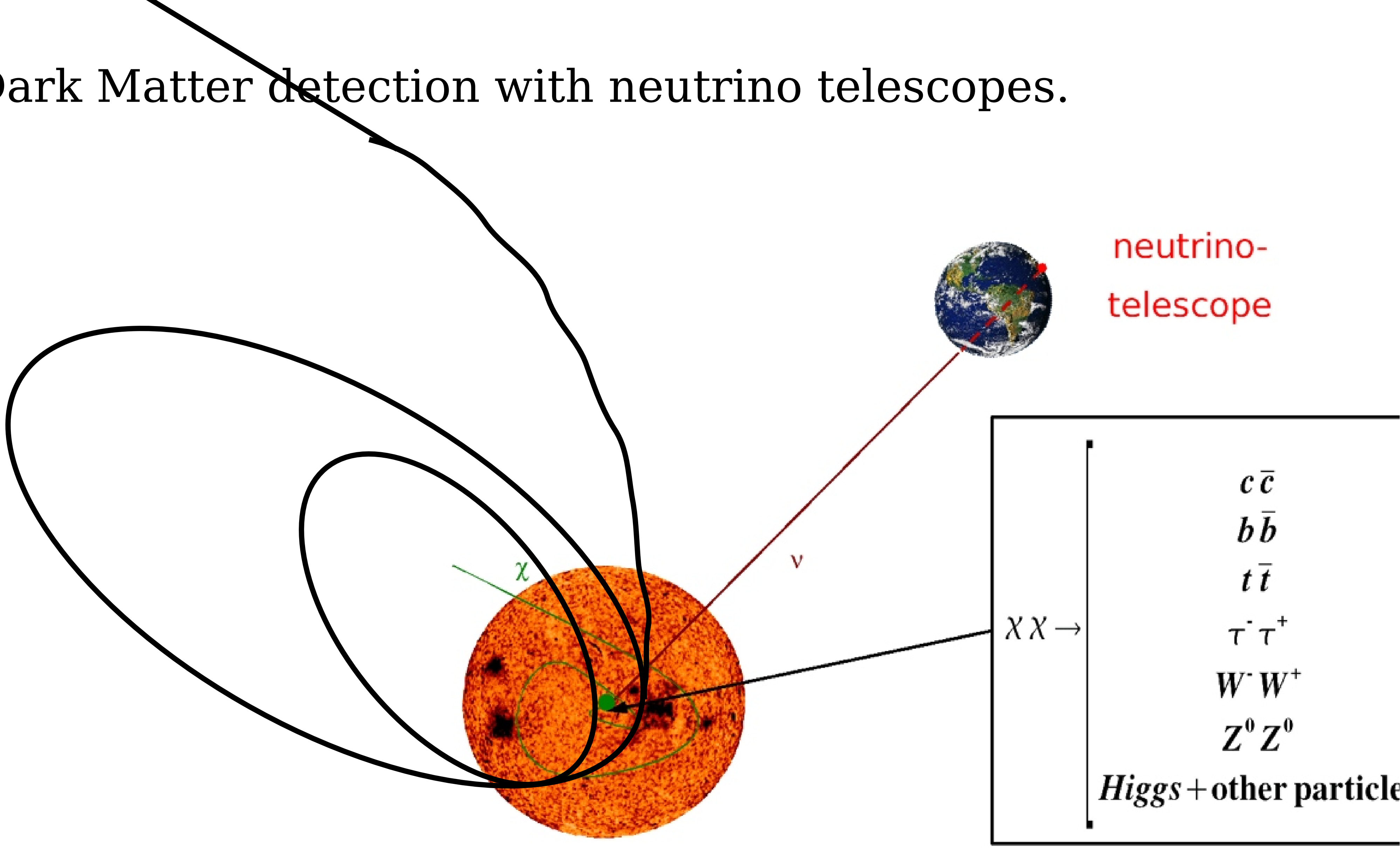
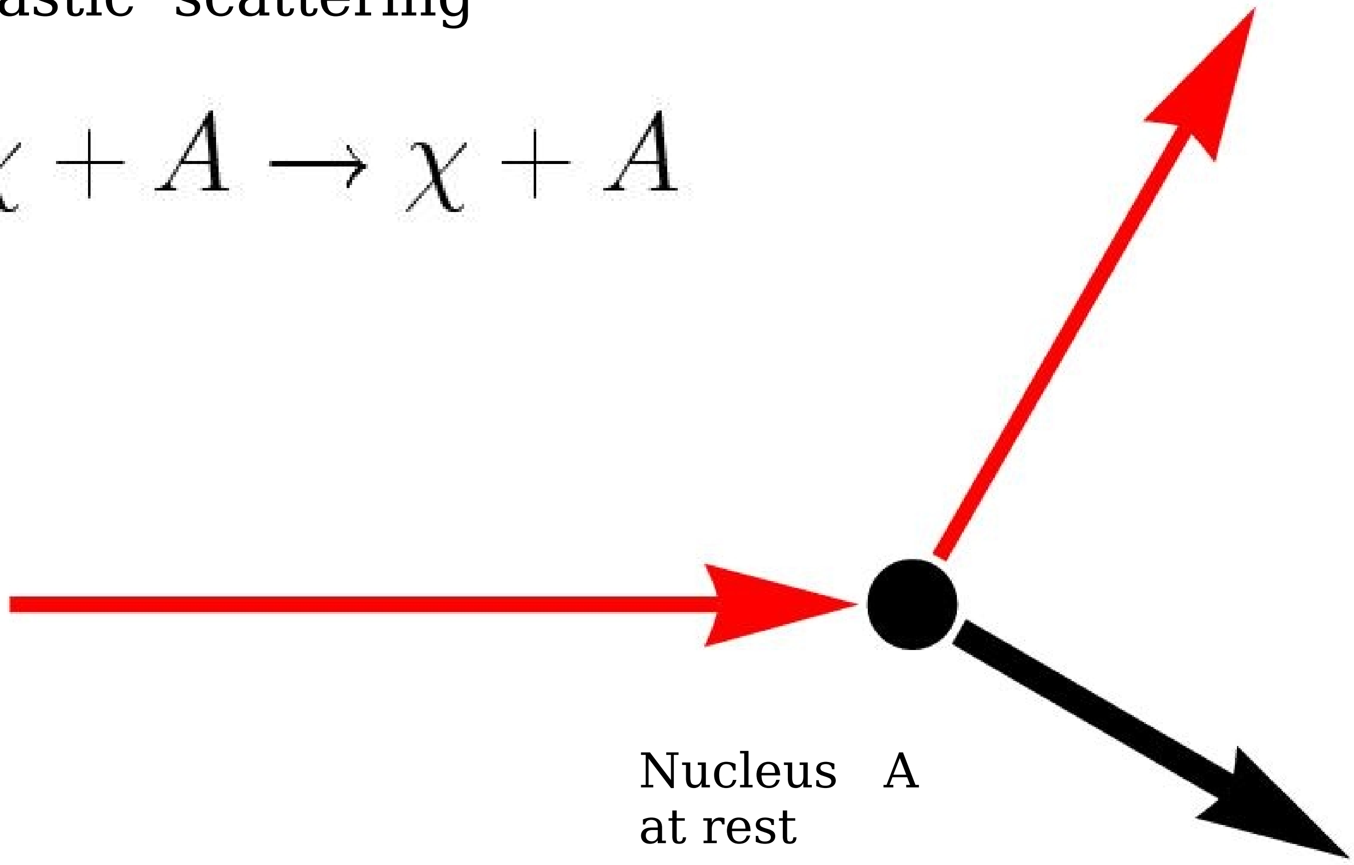


"Direct" Search for Dark Matter

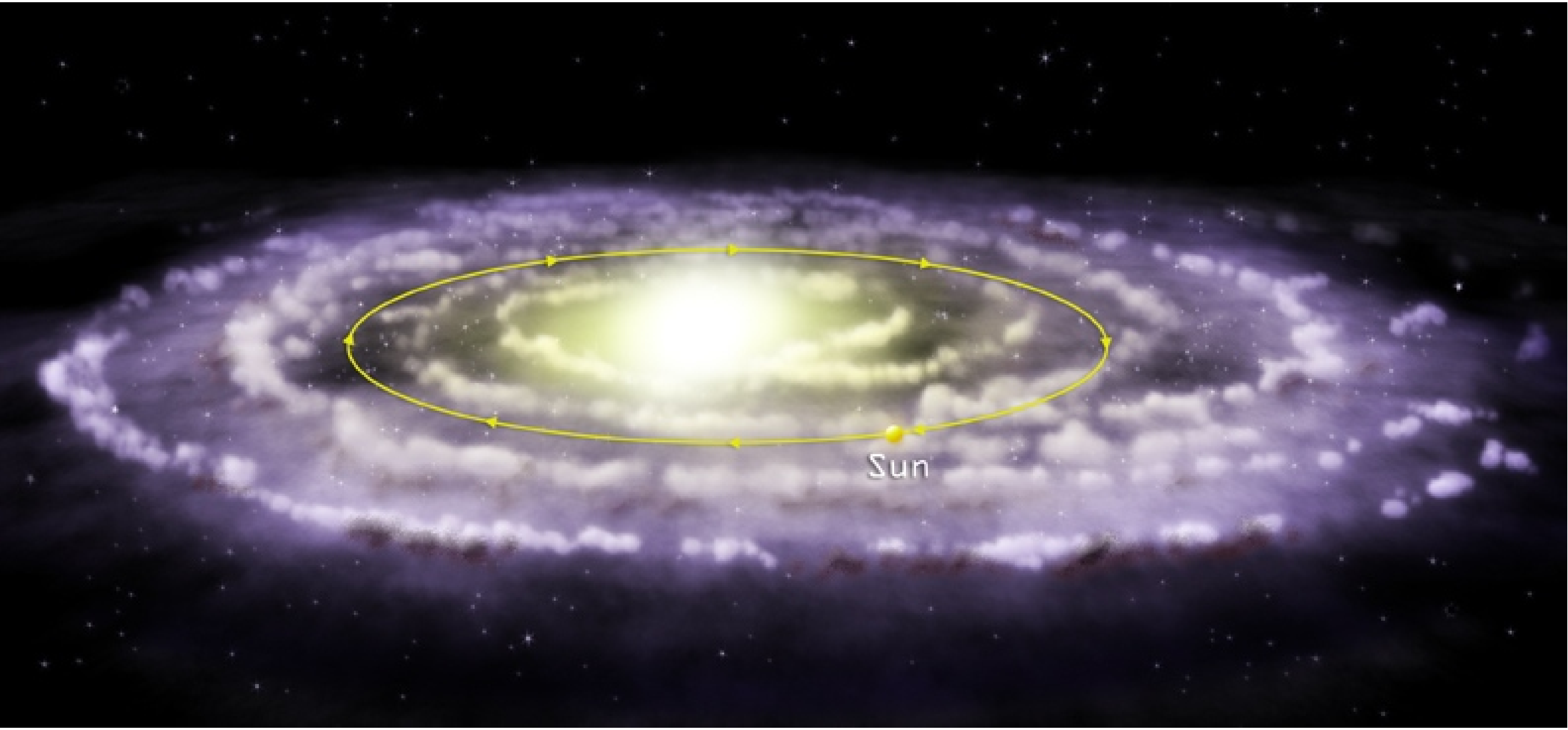
Elastic scattering

$$\chi + A \rightarrow \chi + A$$

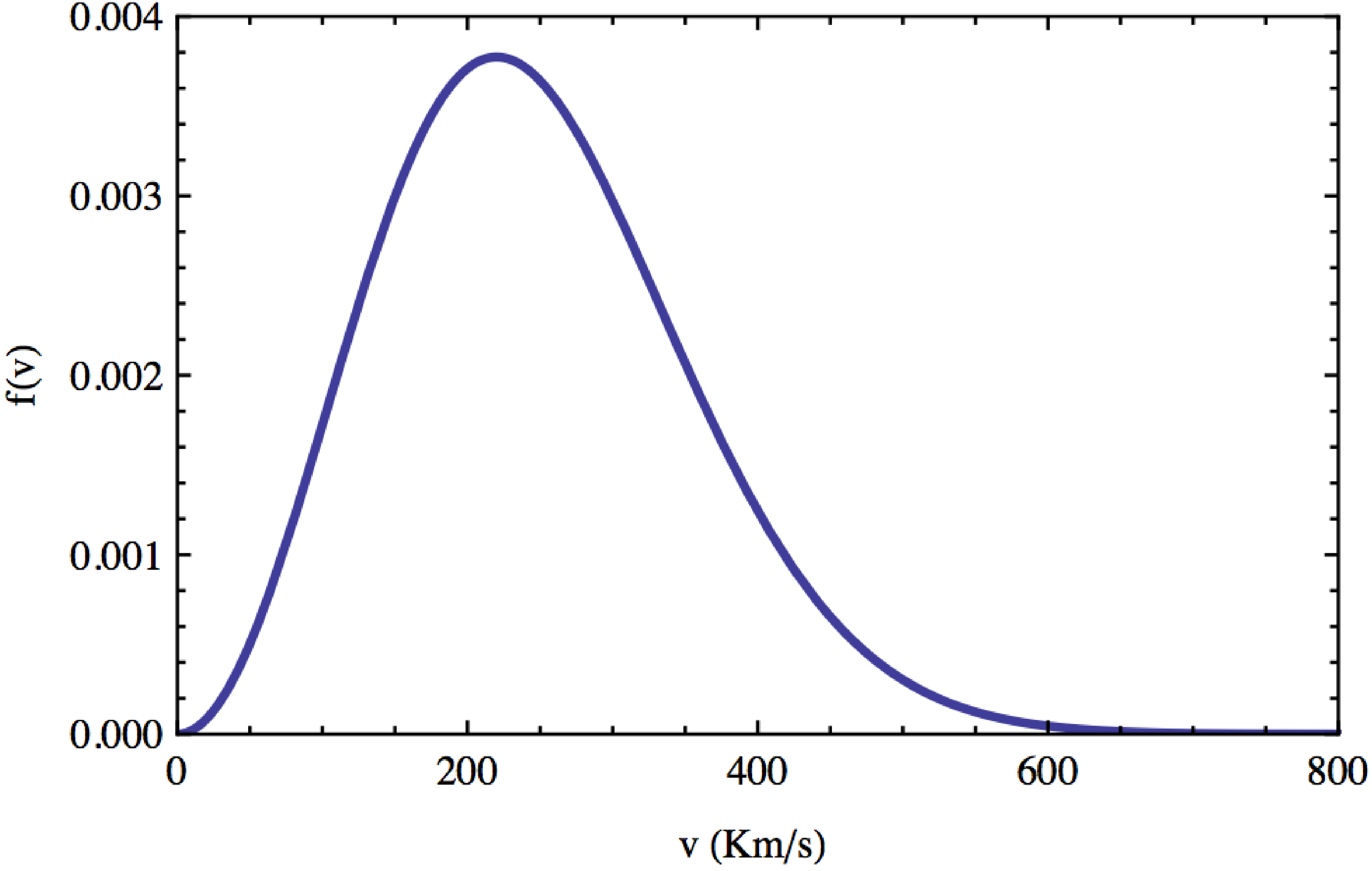


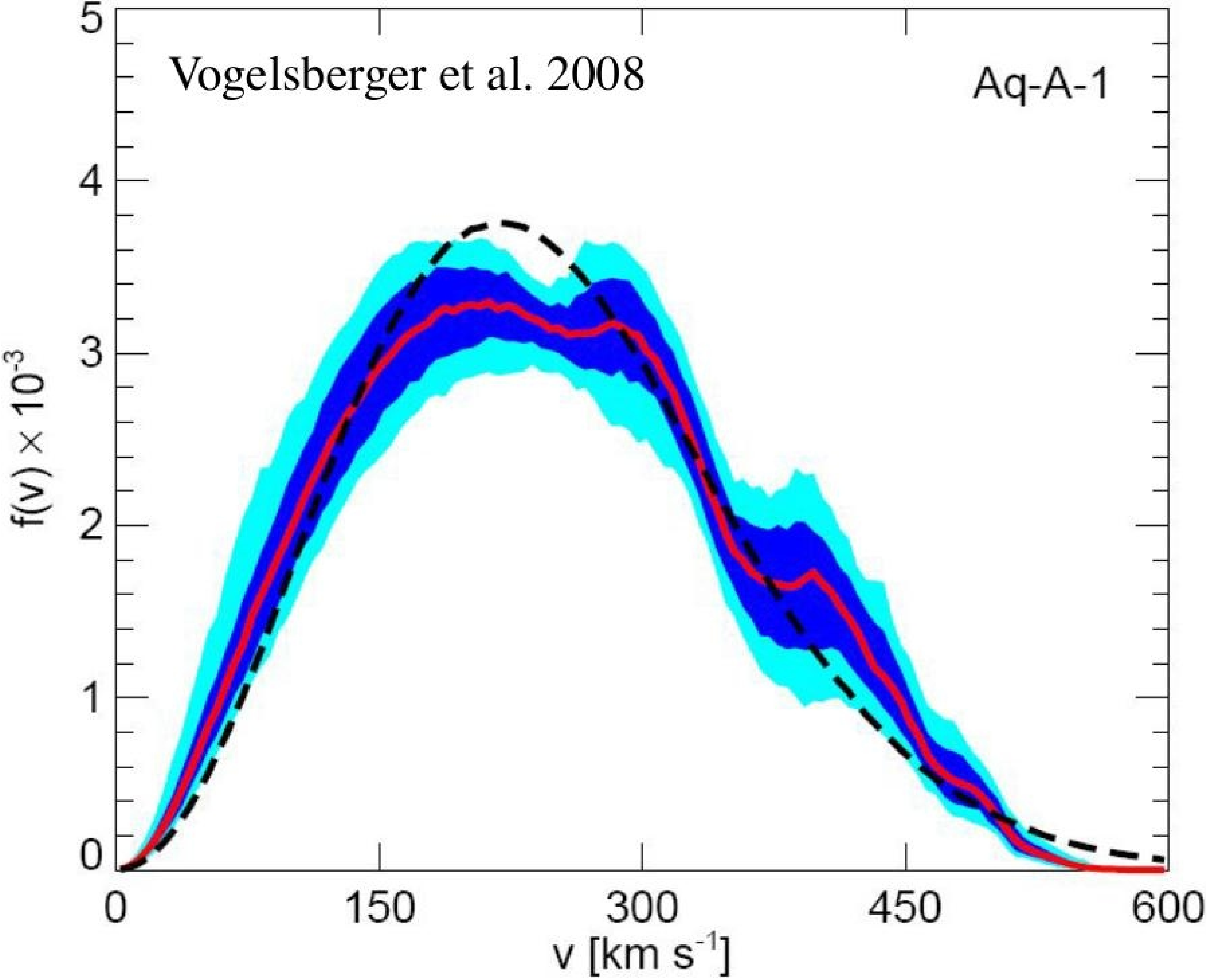
SUN – rotation around the galactic center.

$$v^{\odot}_{\rm rotation} \simeq 200\ {\rm Km/sec}$$

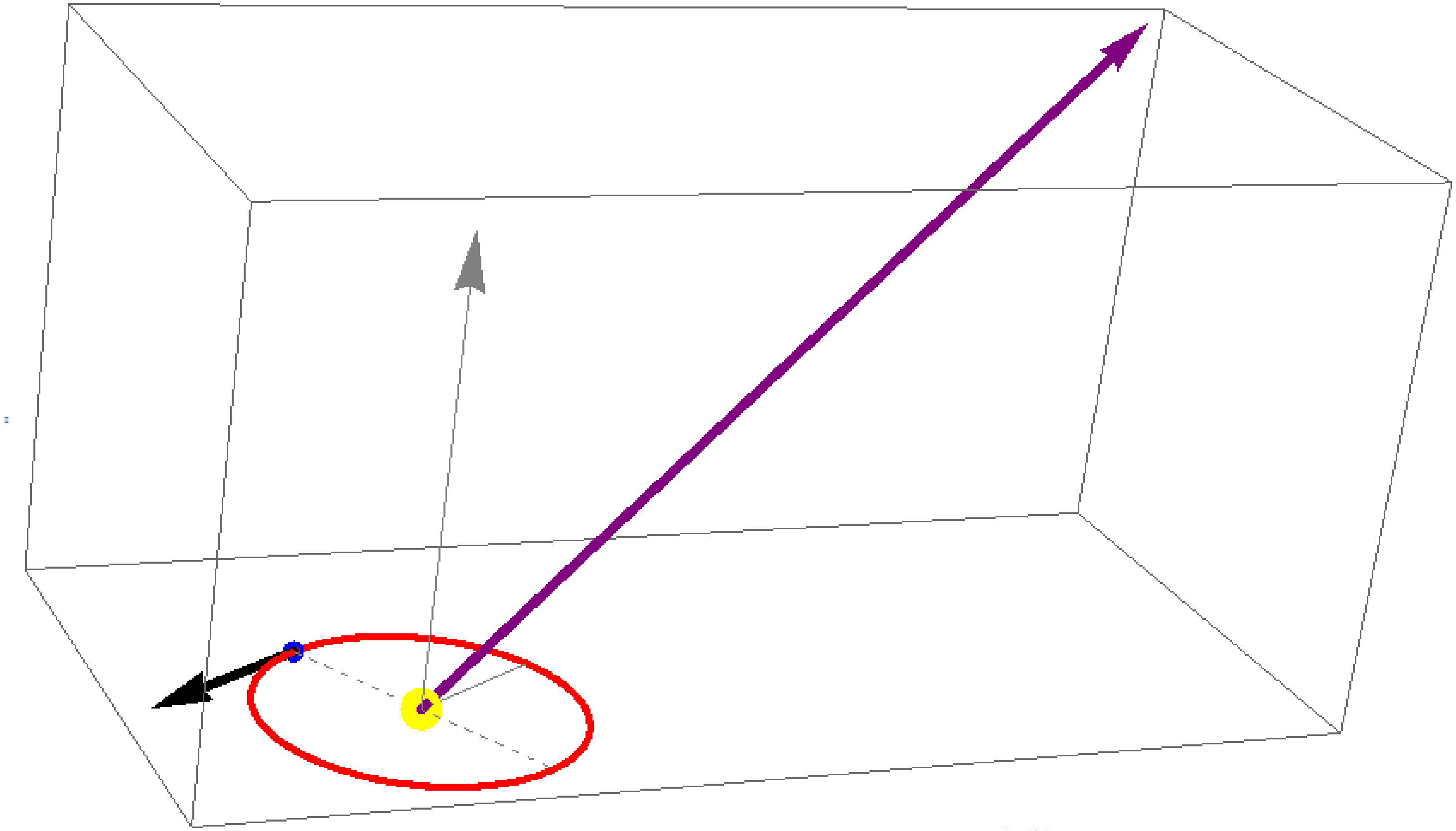


Predicted velocity distribution of DM particles
In the "Halo Frame"
Maxwellian form $\langle v_{\rm wimp} \rangle \simeq 250 \text{ km/sec}$





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



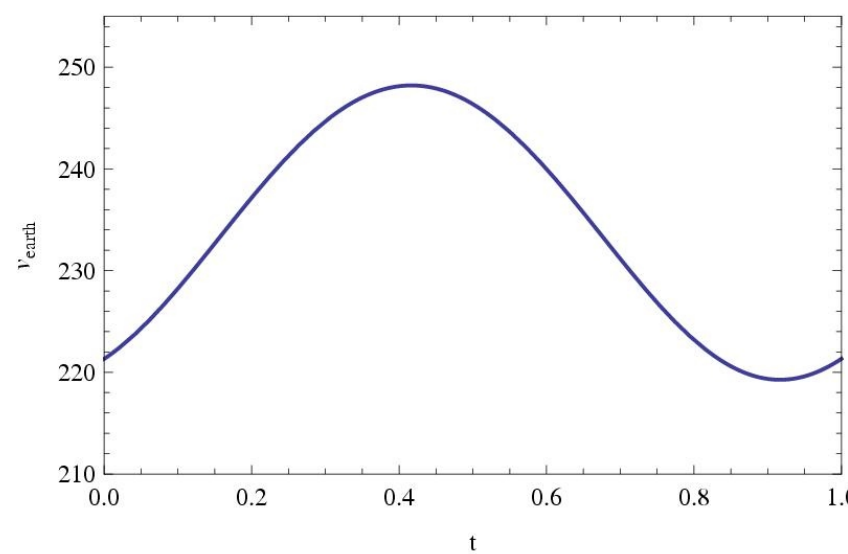
$$w_\oplus(t) \simeq w_\odot + \sin\gamma \; v_{\rm orbit} \;\; \cos[\omega(t-t_0)]$$

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

"Halo rest frame"

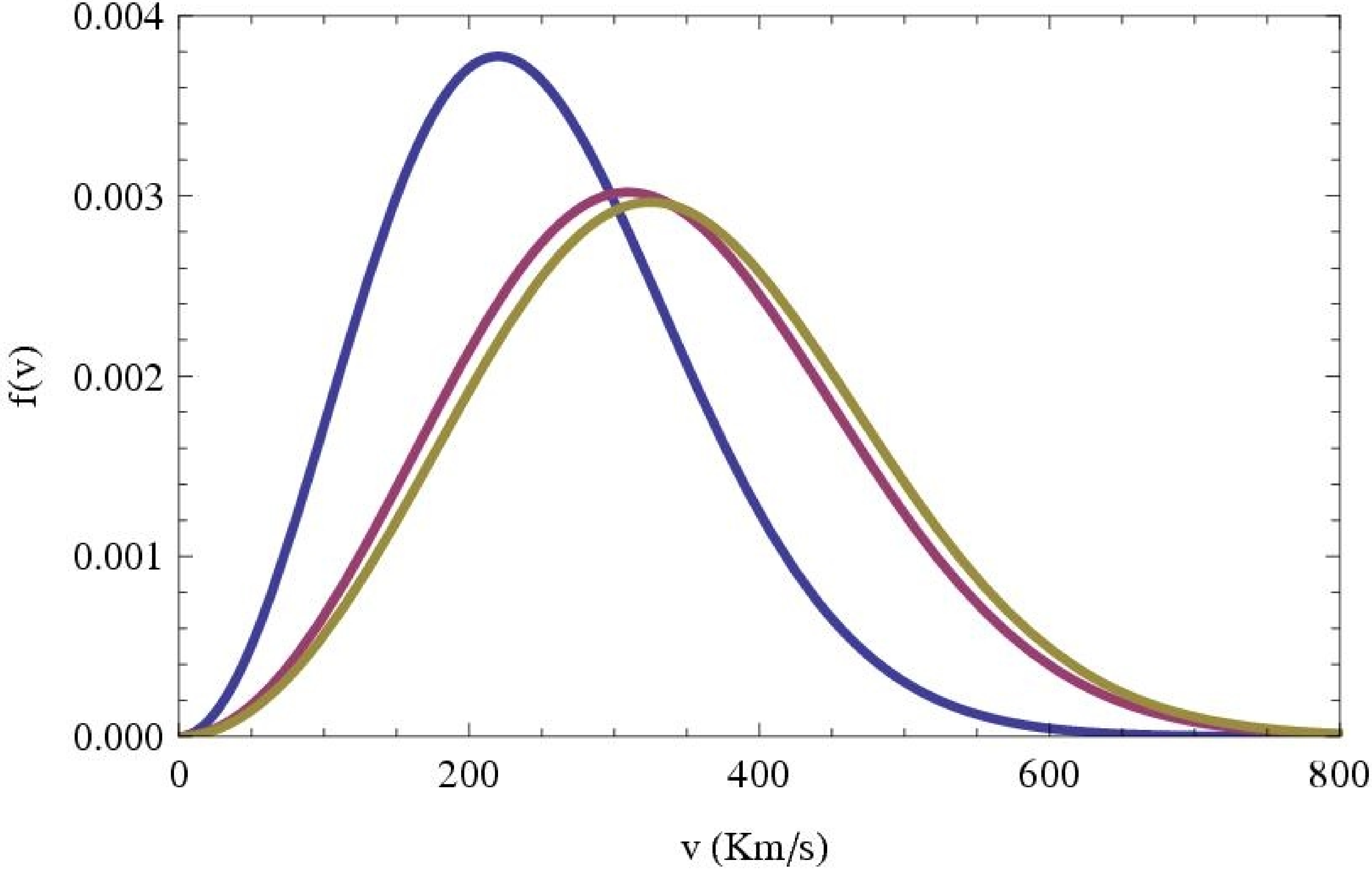
Velocity of Earth in the Halo rest frame

[Co-rotation ?]



Velocity distribution in the Earth Framexs

2^{nd} june
2^{nd} december



Flux of Dark Matter particles:

$$\phi_\chi = \frac{\rho_\chi}{m_\chi} \langle v_\chi \rangle$$

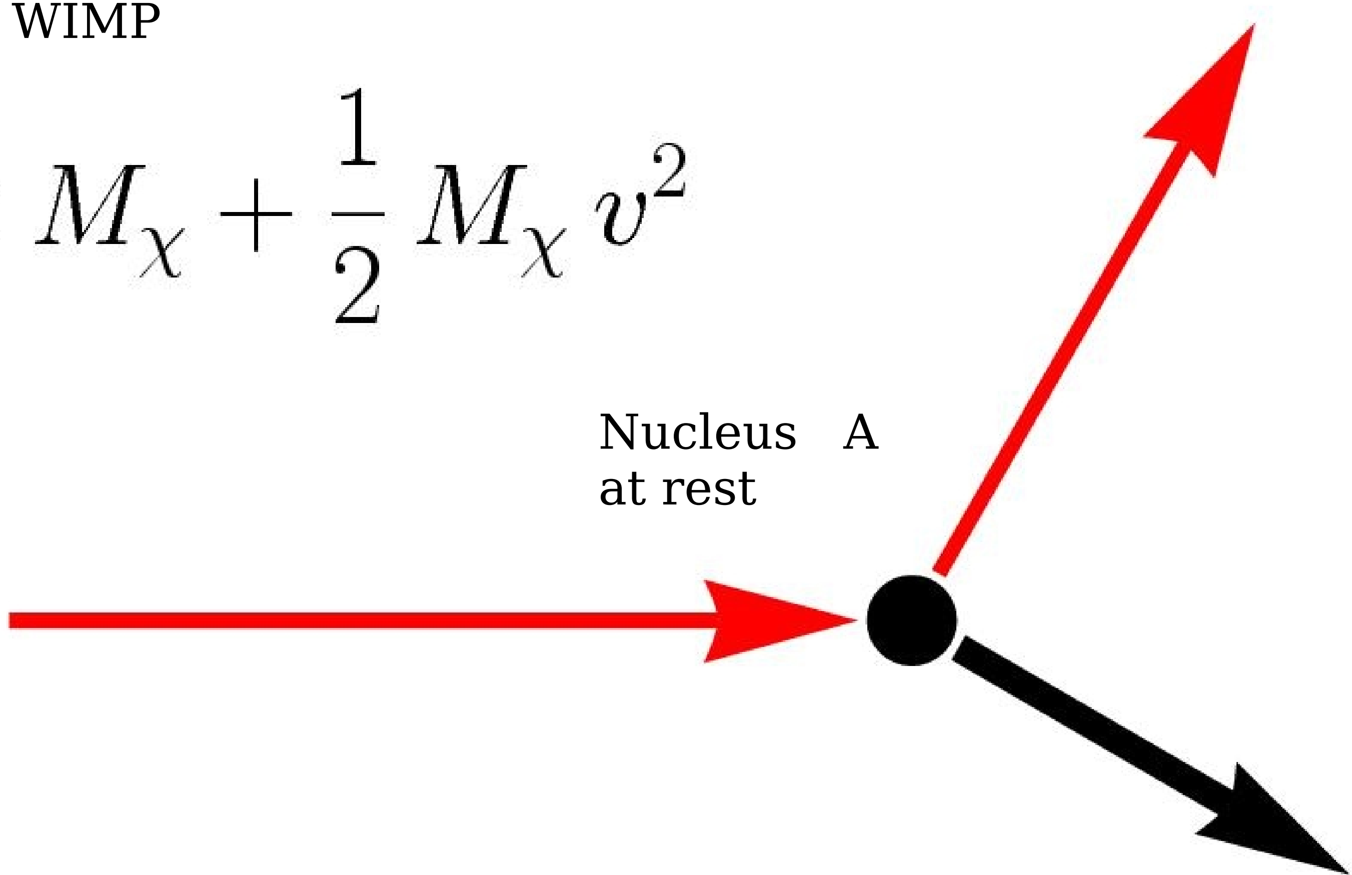
$$\simeq 1000 \left[\frac{100 \text{ GeV}}{m_\chi} \right] \quad (\text{cm}^2 \text{ s})^{-1}$$

"Direct" Search for Dark Matter

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

Non relativistic WIMP

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



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

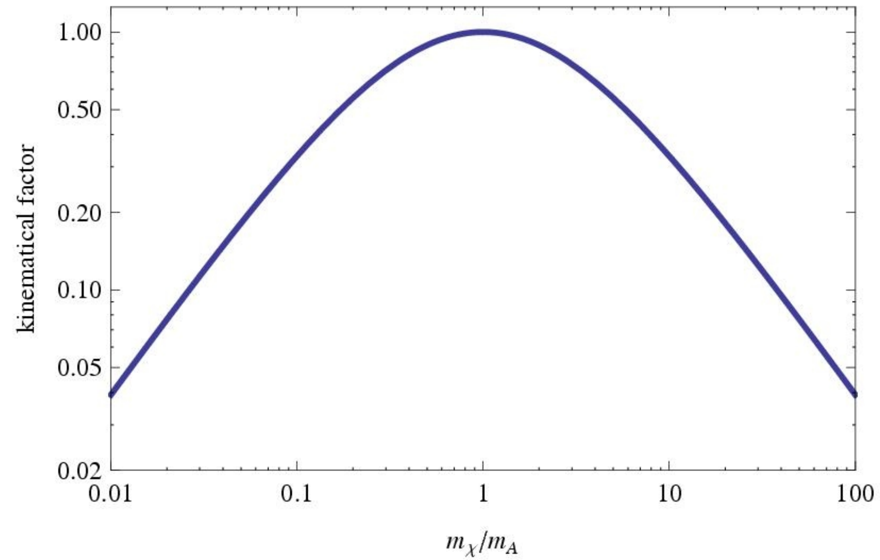
$$E_{\text{nucleus}} = M_A + \left[\frac{1}{2} M_\chi v^2\right] \frac{4 M_A M_\chi}{(M_A + M_\chi)^2} \left(\frac{1 - \cos\theta^*}{2}\right)$$

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

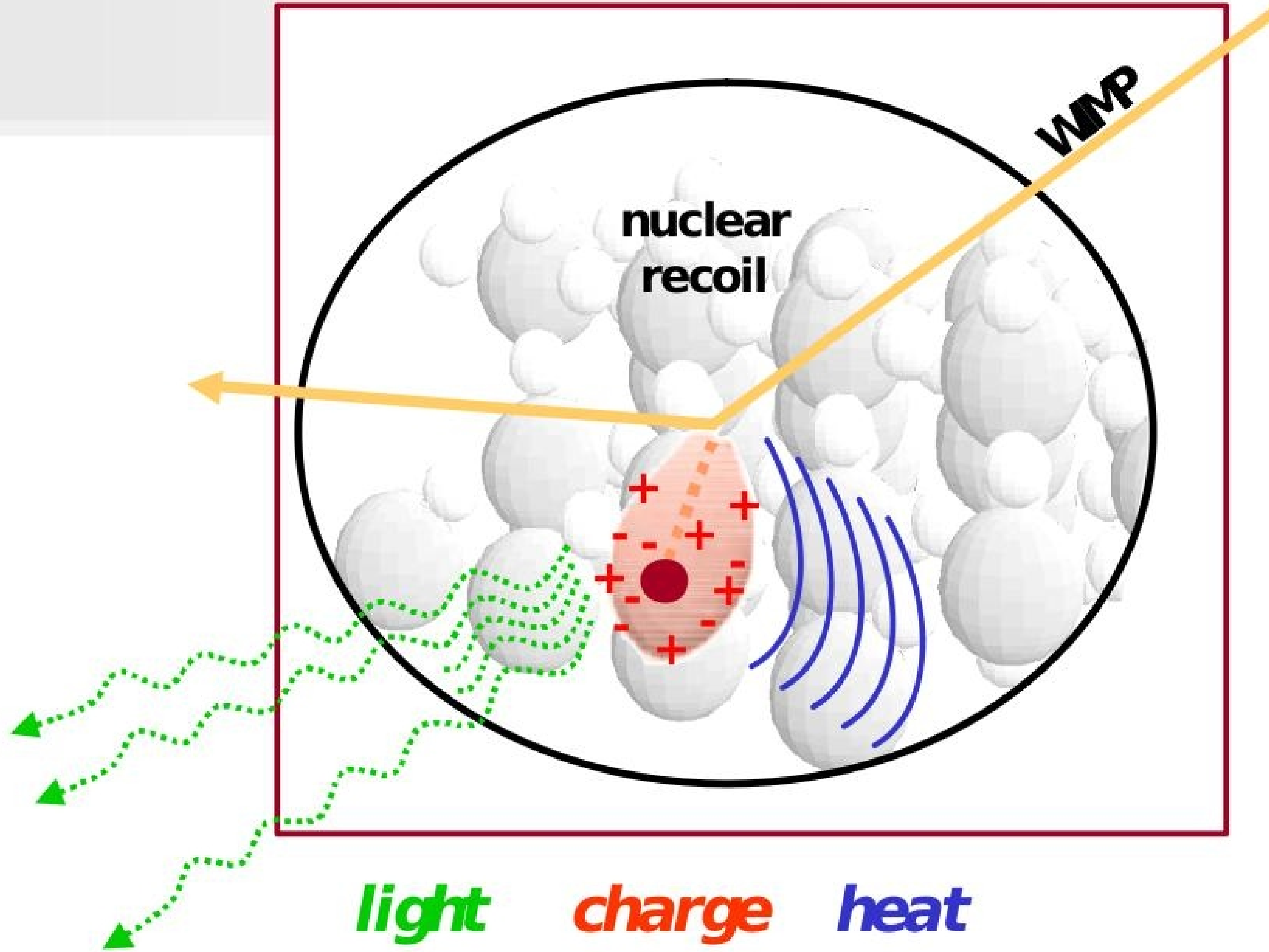
$$E^*_{\text{recoil}} \simeq 39 \text{ KeV} \left[\frac{M_\chi}{100 \text{ GeV}}\right] \left[\frac{v_0}{220 \text{ km s}^{-1}}\right]^2 r$$

Kinematical factor r

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



WIMP detection



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

Target not point-like:
Form Factor

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

$$\frac{d\sigma_p}{d\cos\theta^*} = \frac{\sigma_p}{2}\, F_p(Q^2)$$

$$\sigma_p \propto \left(\frac{M_\chi\, M_p}{M_\chi + M_p}\right)^2$$

$$\frac{d\sigma_A}{d\cos\theta^*} = \frac{\sigma_A}{2}\, F_A(Q^2)$$

$$\sigma_A \propto \left(\frac{M_\chi\, M_A}{M_\chi + M_A}\right)^2$$

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

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

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

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

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

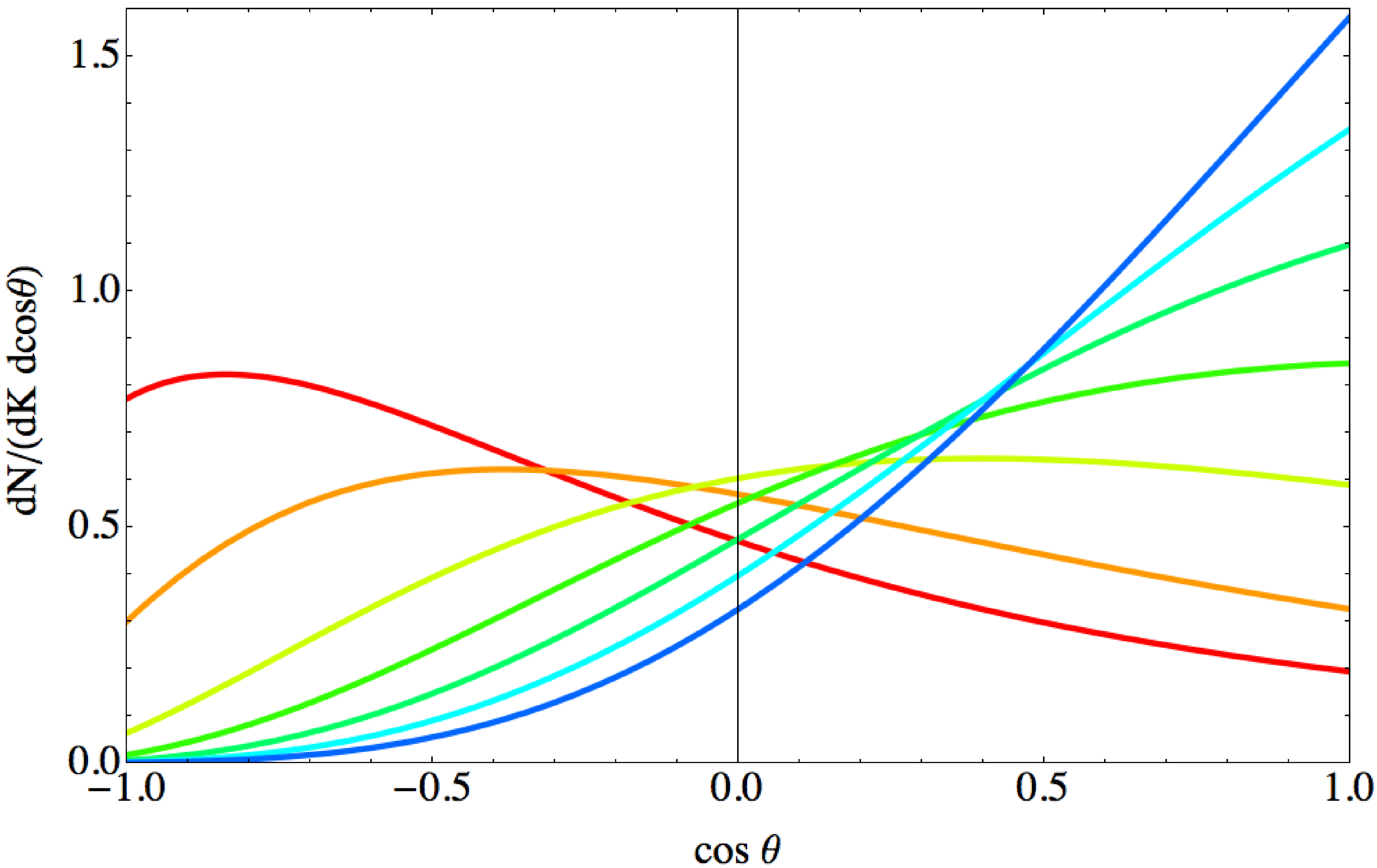
Velocity Distribution

Directional Response

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

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

$A = 127$



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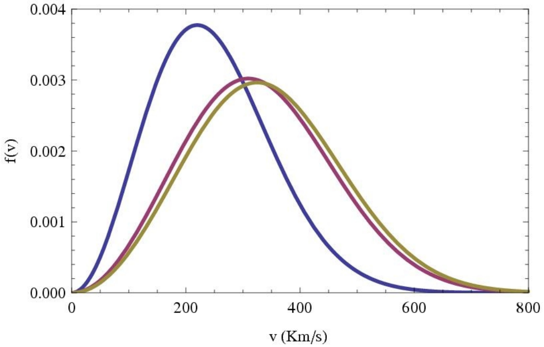
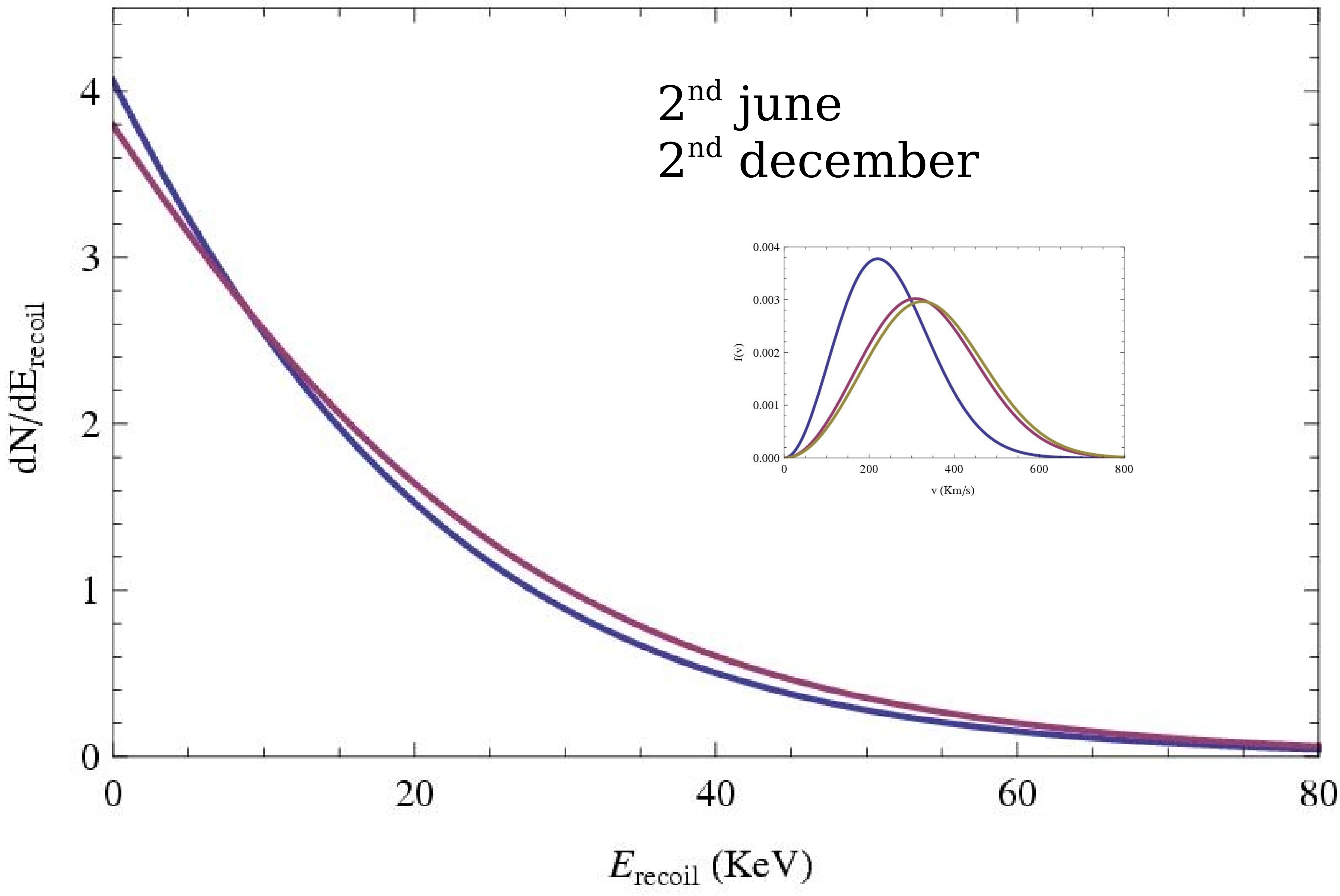


$$F\left(\frac{K}{K^*}, w_\oplus(t)\right) = \frac{1}{v_0} \int_{\text{vmin}(K)}^{\infty} dv\; \frac{f(v,t)}{v}$$

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

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

Quasi exponential distribution

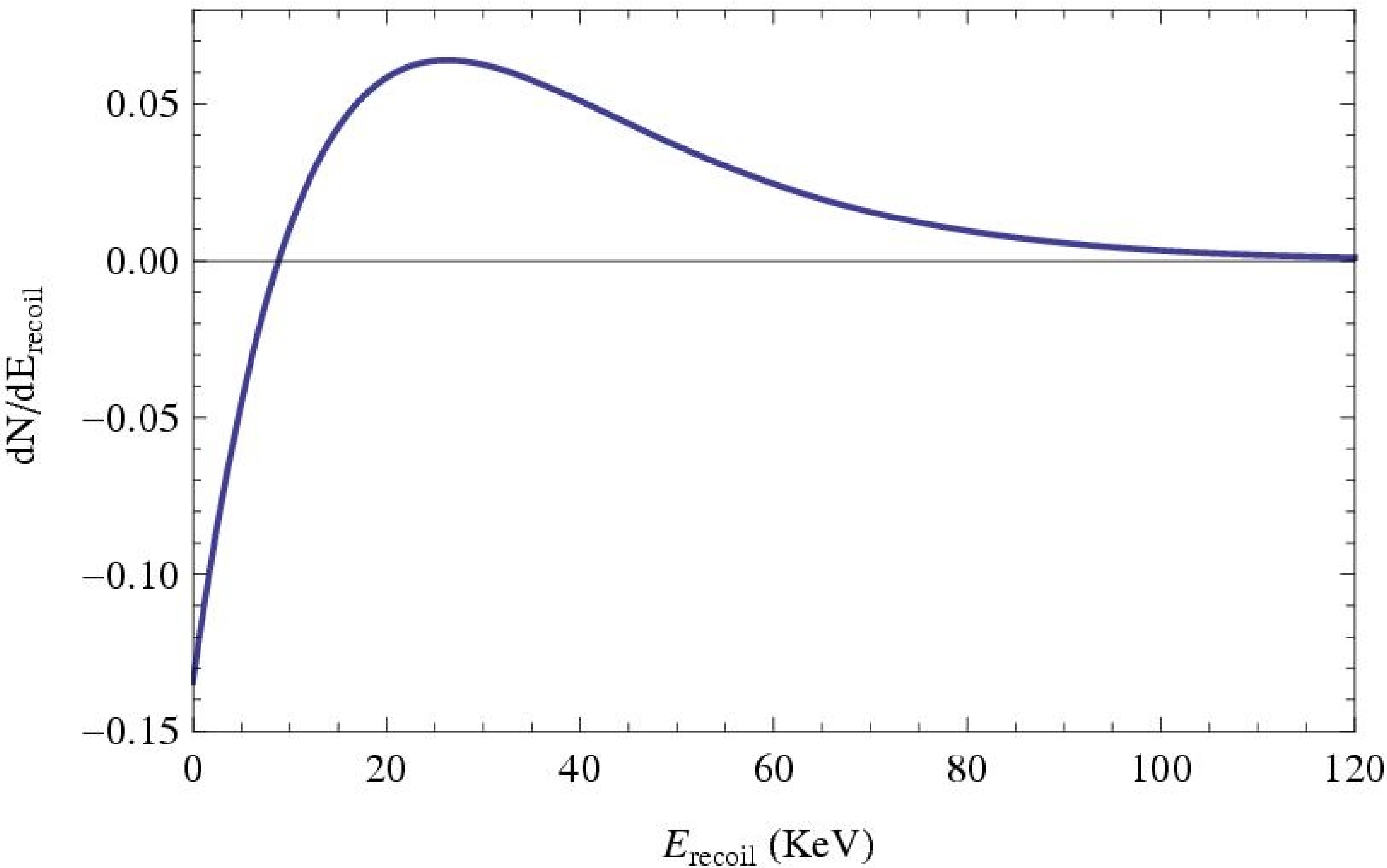


$$\frac{dR}{dE_{\rm recoil}}(E_{\rm recoil}, t) = R_0(E_{\rm recoil}) + A(E_{\rm recoil})\ f(t)$$

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

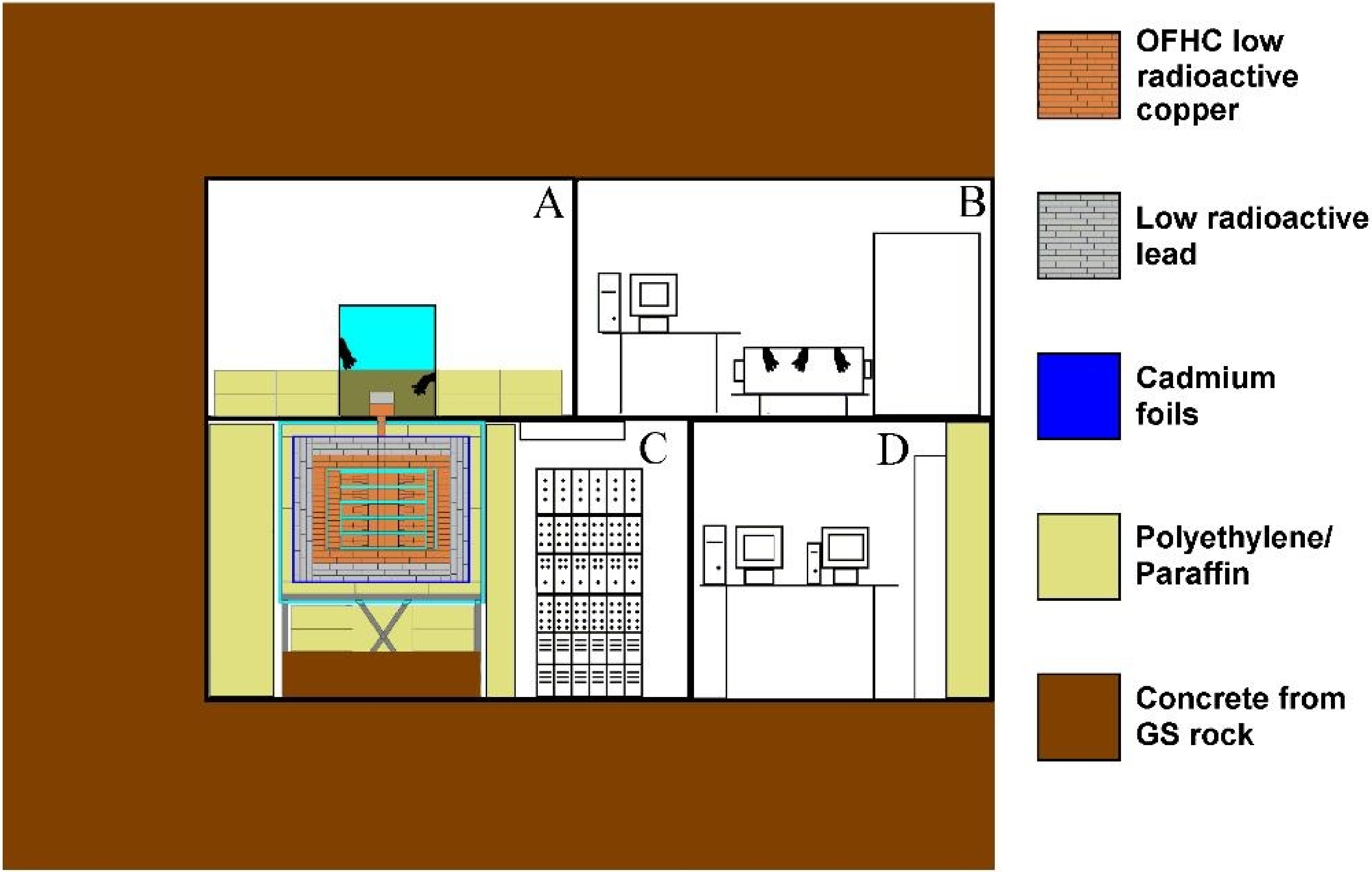
$$A(K) = \left[\frac{\rho_\chi}{M_\chi\, M_A}\,\sigma_A\right]\ [\sin\gamma\ v_{\rm orbit}]\ F_A^2(2\,M_A\,K)\ \left\{\frac{1}{K^*} G\left(\frac{K}{K^*}\right)\right\}$$

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



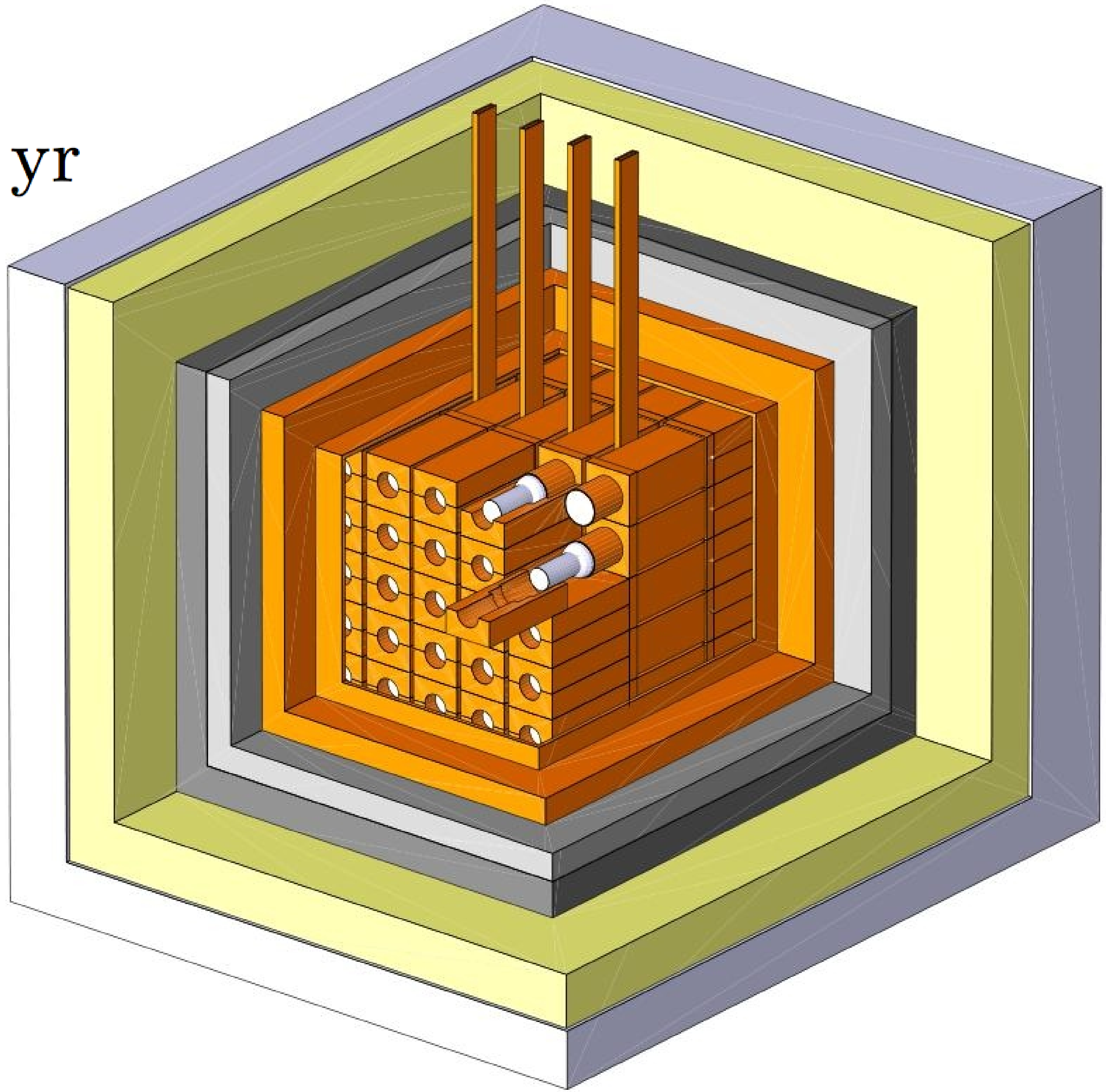
0.05
0.00
−0.05
−0.10
−0.15
dN/dE$_{recoil}$
0
20
40
60
80
100
120
E_{recoil} (KeV)

DAMA-LIBRA (Gran Sasso)

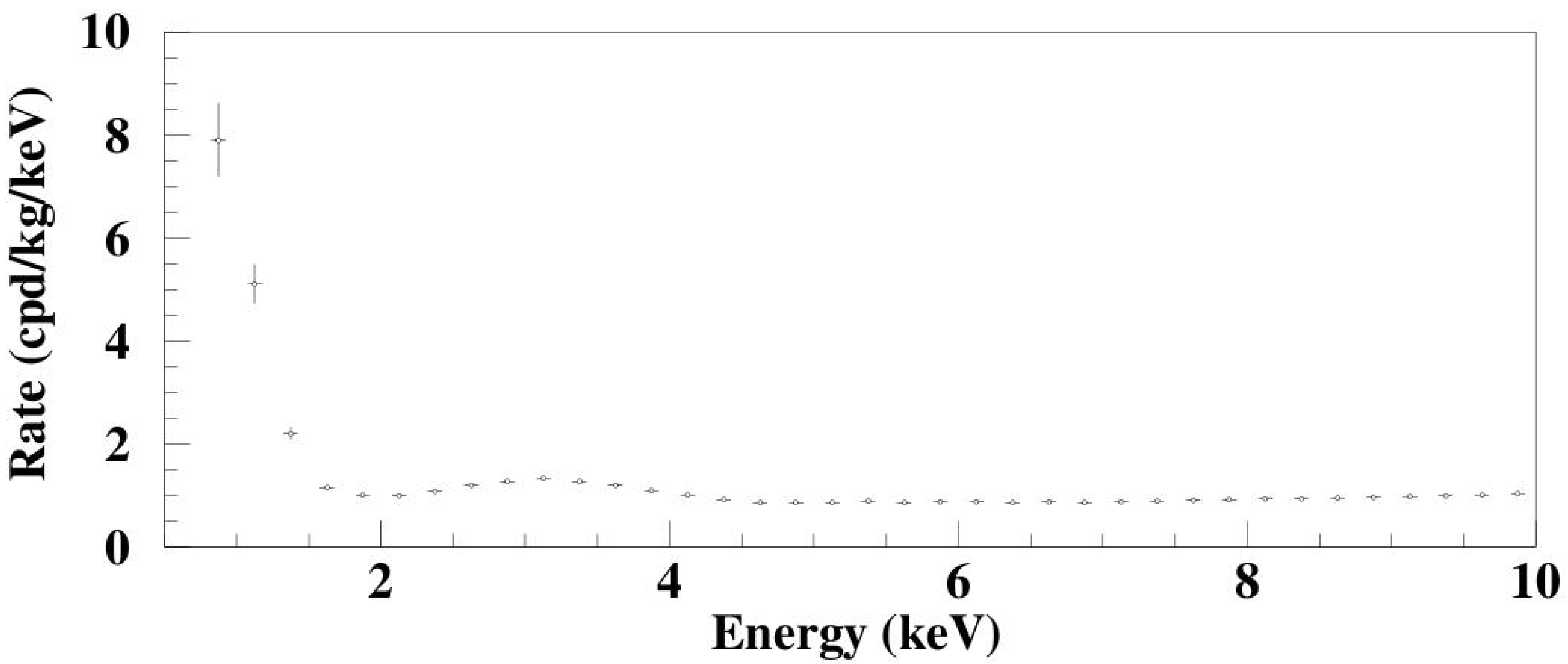


Dama-Libra
250 Kg NaI

$1.17\ \text{ton} \times \text{yr}$



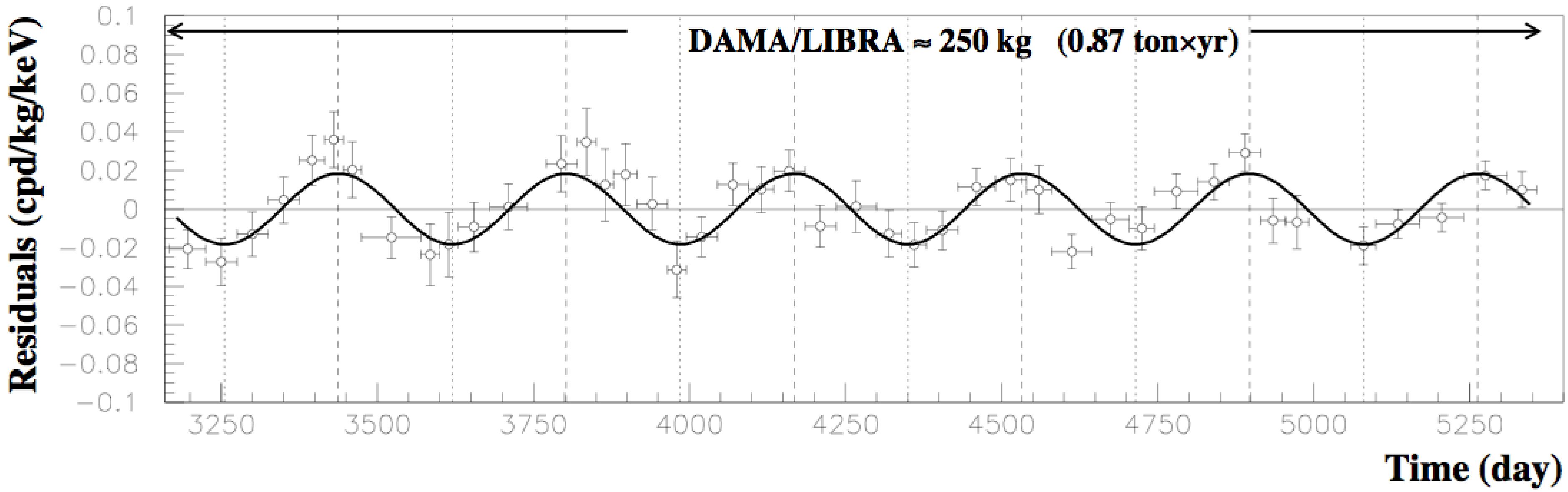
Dama average Counting Rate



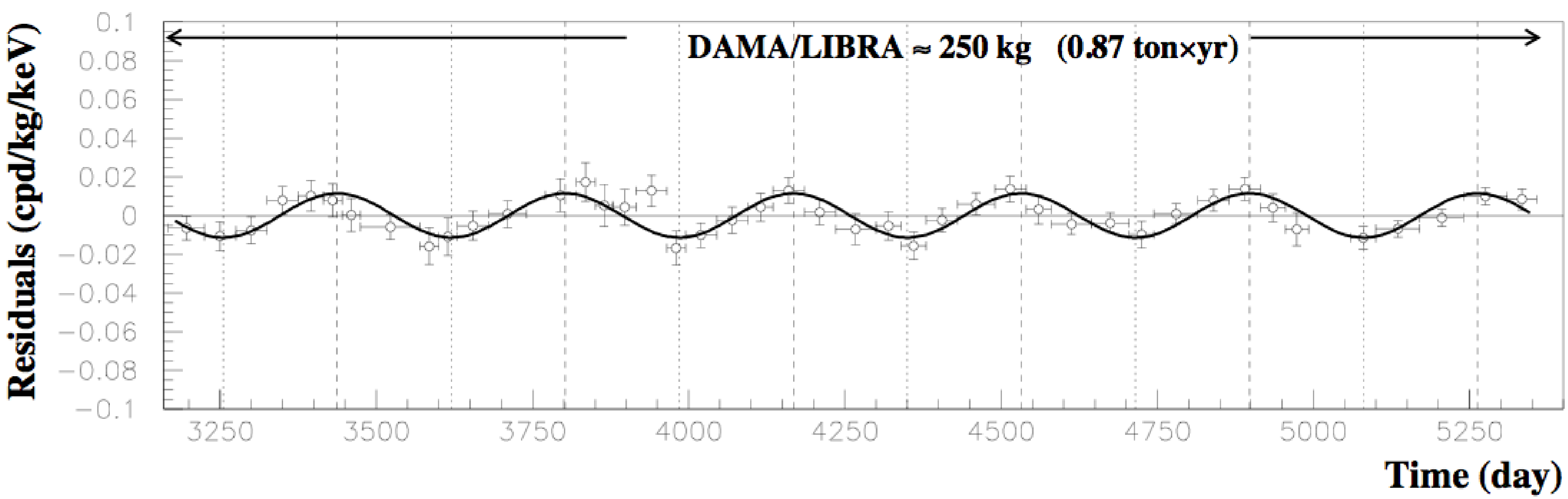
$$1 \text{ KeV}_{ee} \simeq 11 \text{ KeV}_{\text{recoil}}$$

ee [electron equivalent]

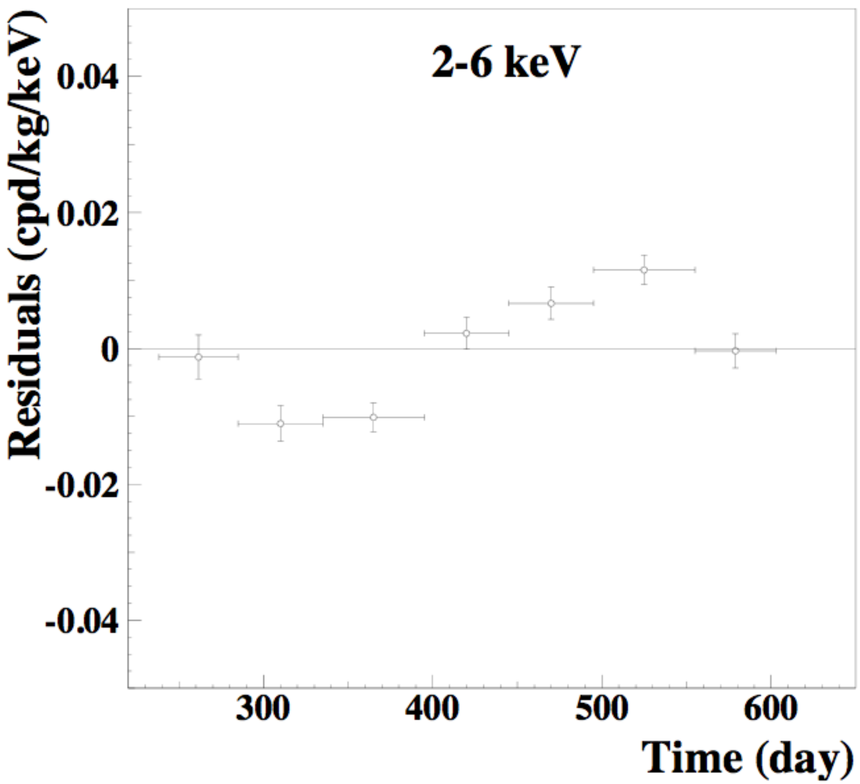
2-4 keV


DAMA/LIBRA ≈ 250 kg (0.87 ton×yr)
Residuals (cpd/kg/keV)
Time (day)
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
3250
3500
3750
4000
4250
4500
4750
5000
5250

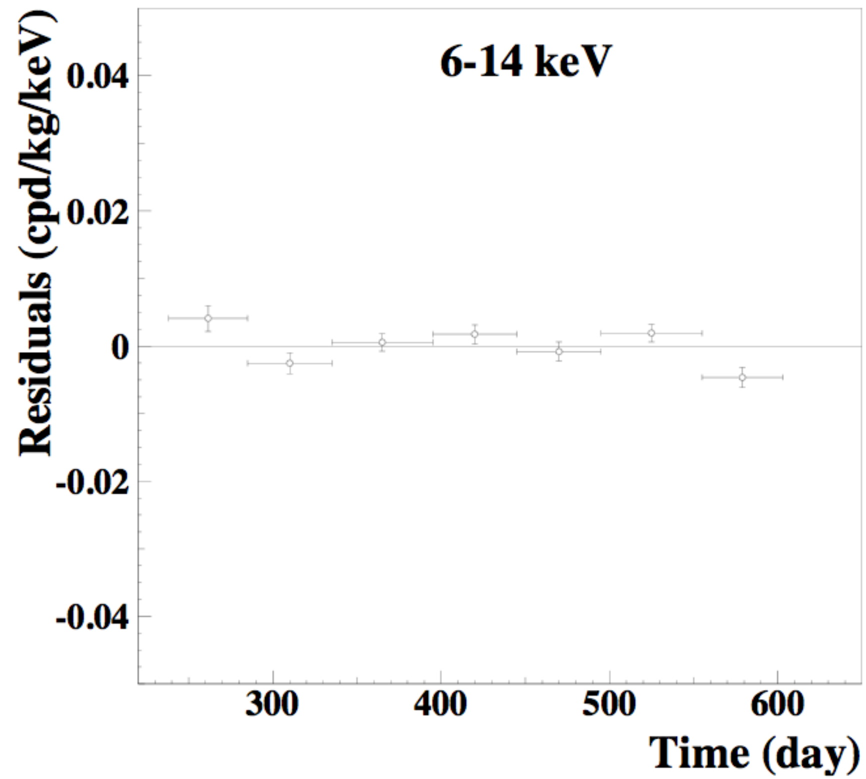
2-6 keV


DAMA/LIBRA ≈ 250 kg (0.87 ton×yr)
Residuals (cpd/kg/keV)
Time (day)
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
3250
3500
3750
4000
4250
4500
4750
5000
5250

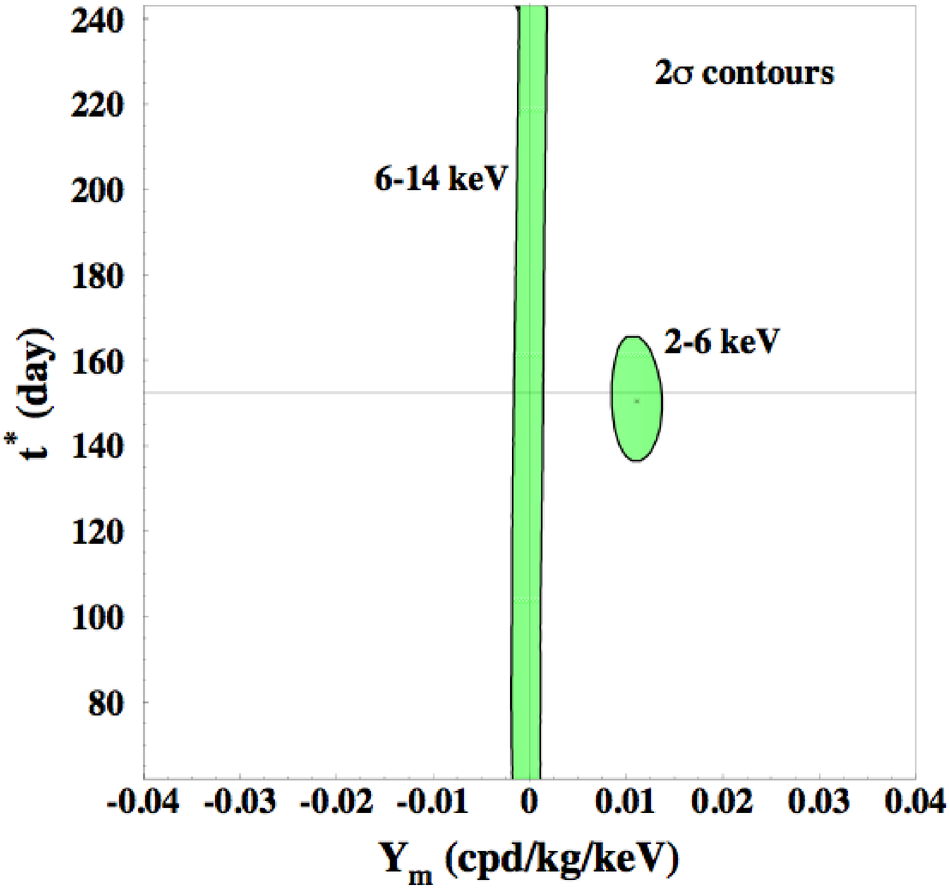
Energy interval (keV)	DAMA/LIBRA (6 annual cycles)	DAMA/NaI & DAMA/LIBRA (7+6 annual cycles)
2-4	χ^2/d.o.f. = 90.0/43 $\rightarrow$ P = 3.6×10^{-5}	χ^2/d.o.f. = 147.4/80 $\rightarrow$ P = 6.8×10^{-6}
2-5	χ^2/d.o.f. = 82.1/43 $\rightarrow$ P = 3.1×10^{-4}	χ^2/d.o.f. = 135.2/80 $\rightarrow$ P = 1.1×10^{-4}
2-6	χ^2/d.o.f. = 68.9/43 $\rightarrow$ P = 7.4×10^{-3}	χ^2/d.o.f. = 139.5/80 $\rightarrow$ P = 4.3×10^{-5}



2-6 keV
Residuals (cpd/kg/keV)
0.04
0.02
0
-0.02
-0.04
300
400
500
600
Time (day)



6-14 keV
Residuals (cpd/kg/keV)
0.04
0.02
0
-0.02
-0.04
300
400
500
600
Time (day)

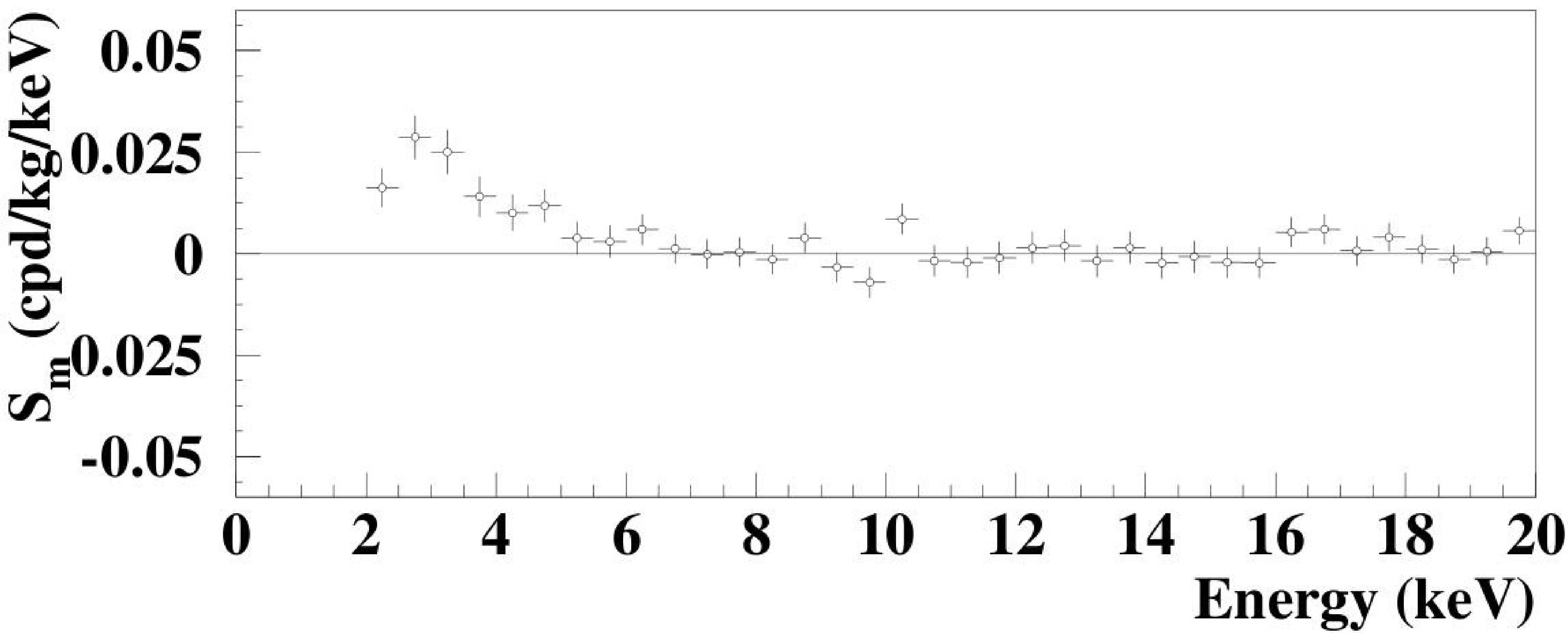


Period one year.

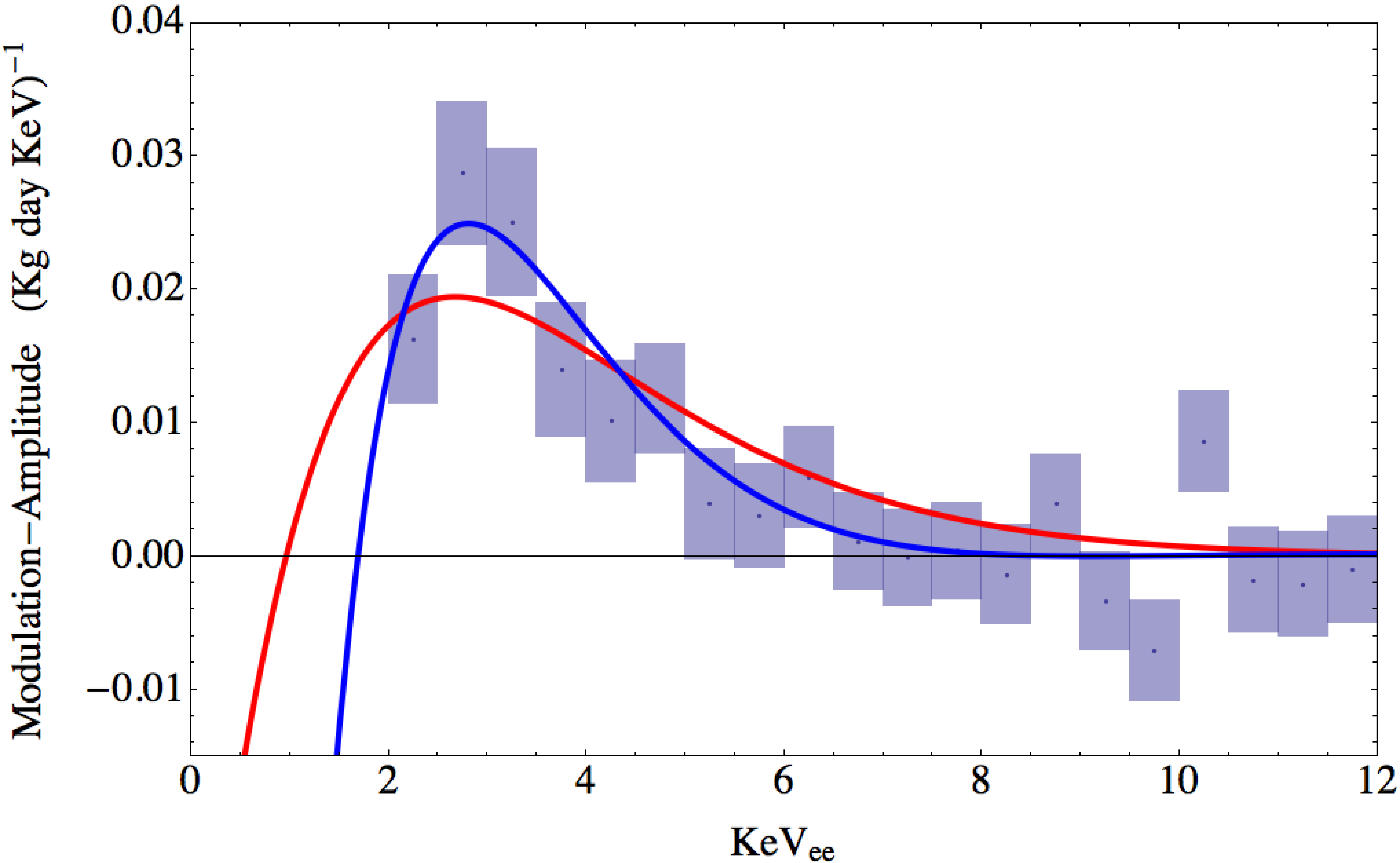
"Phase"
Is centered
At the "right" value

Maximum
The 2nd june.
(146 ± 7)

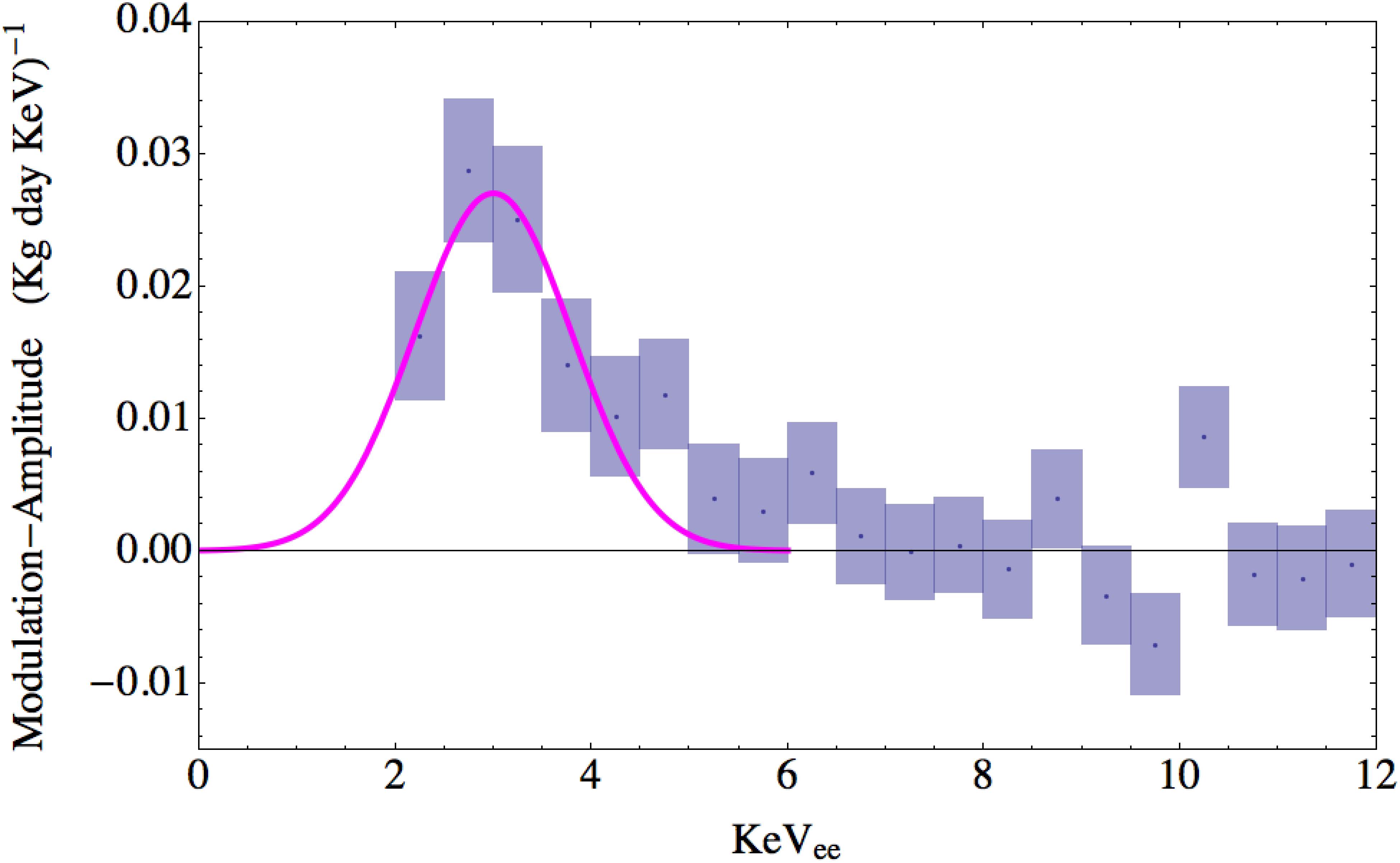
Coincidence ?



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)



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



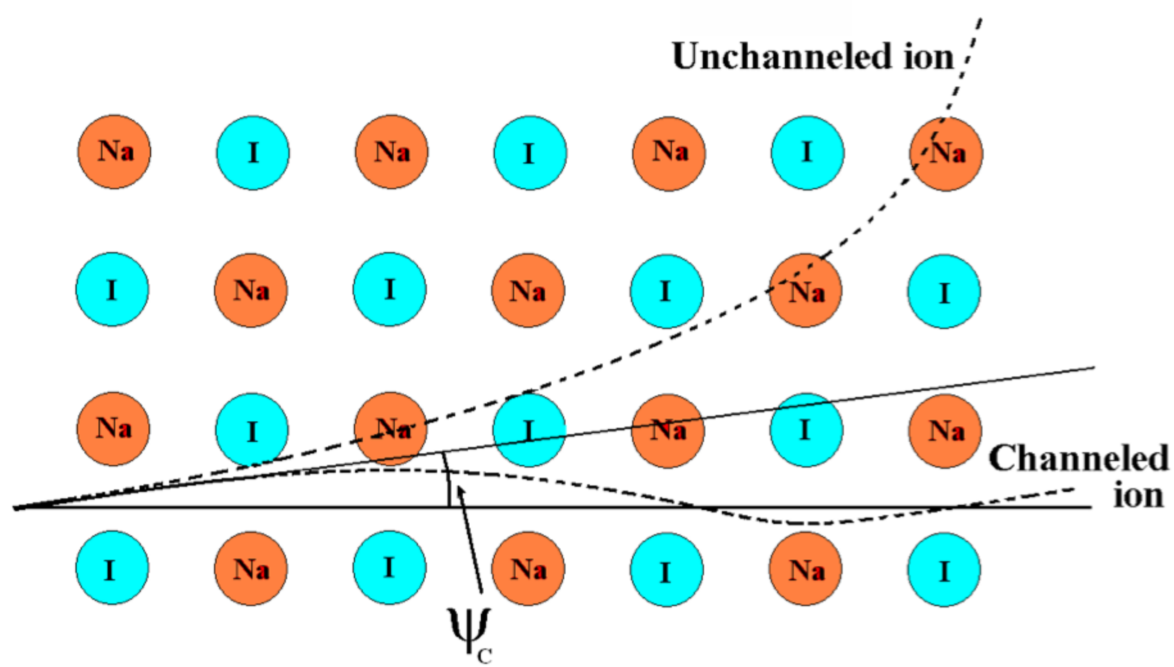
Gaussian with detector resolution

Relation between Light collected by PMT and E_{recoil}

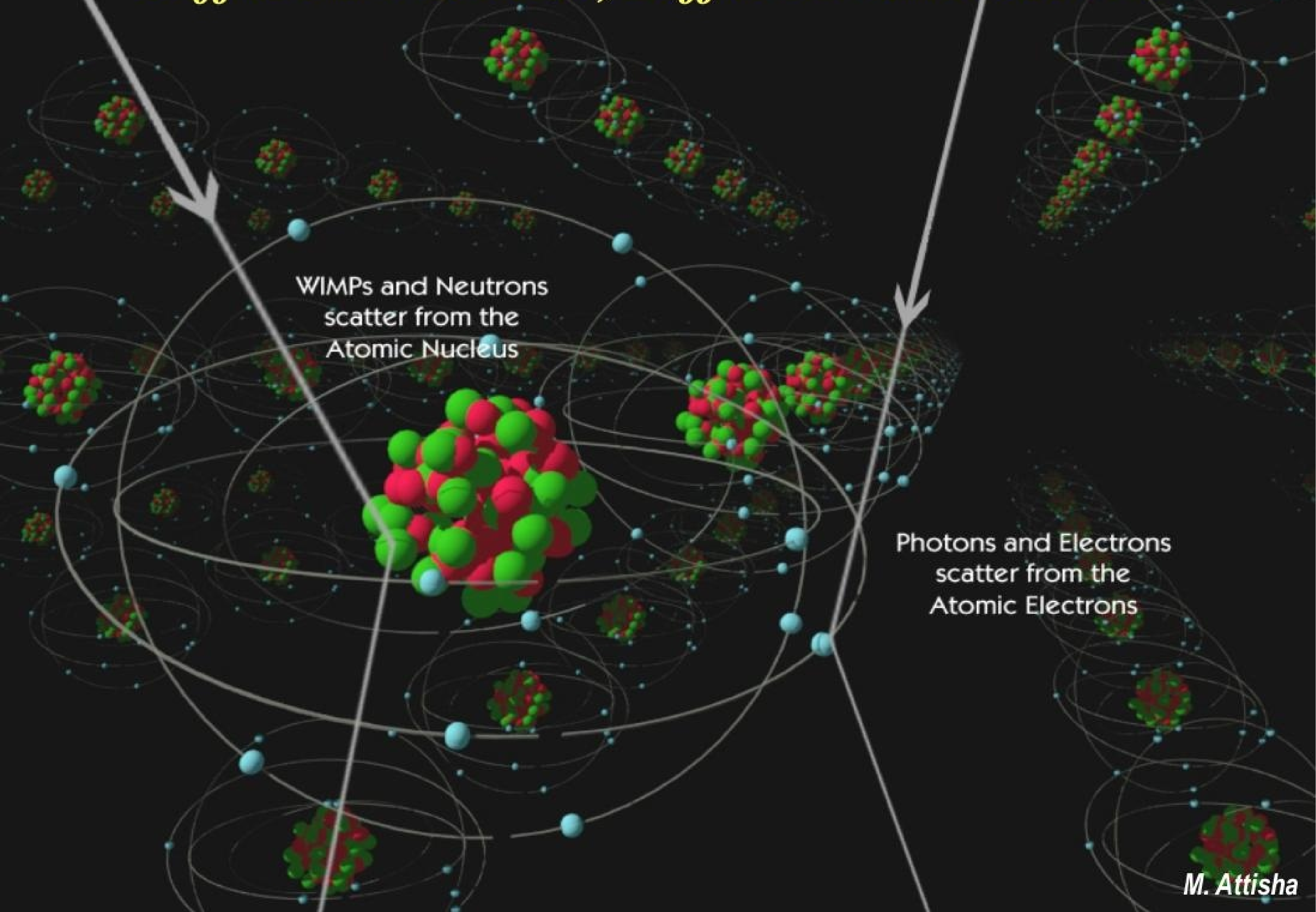
E(recoil) = 11.0 * E(electron-equivalent)

In presence of "channeling"
Scattering in certain directions

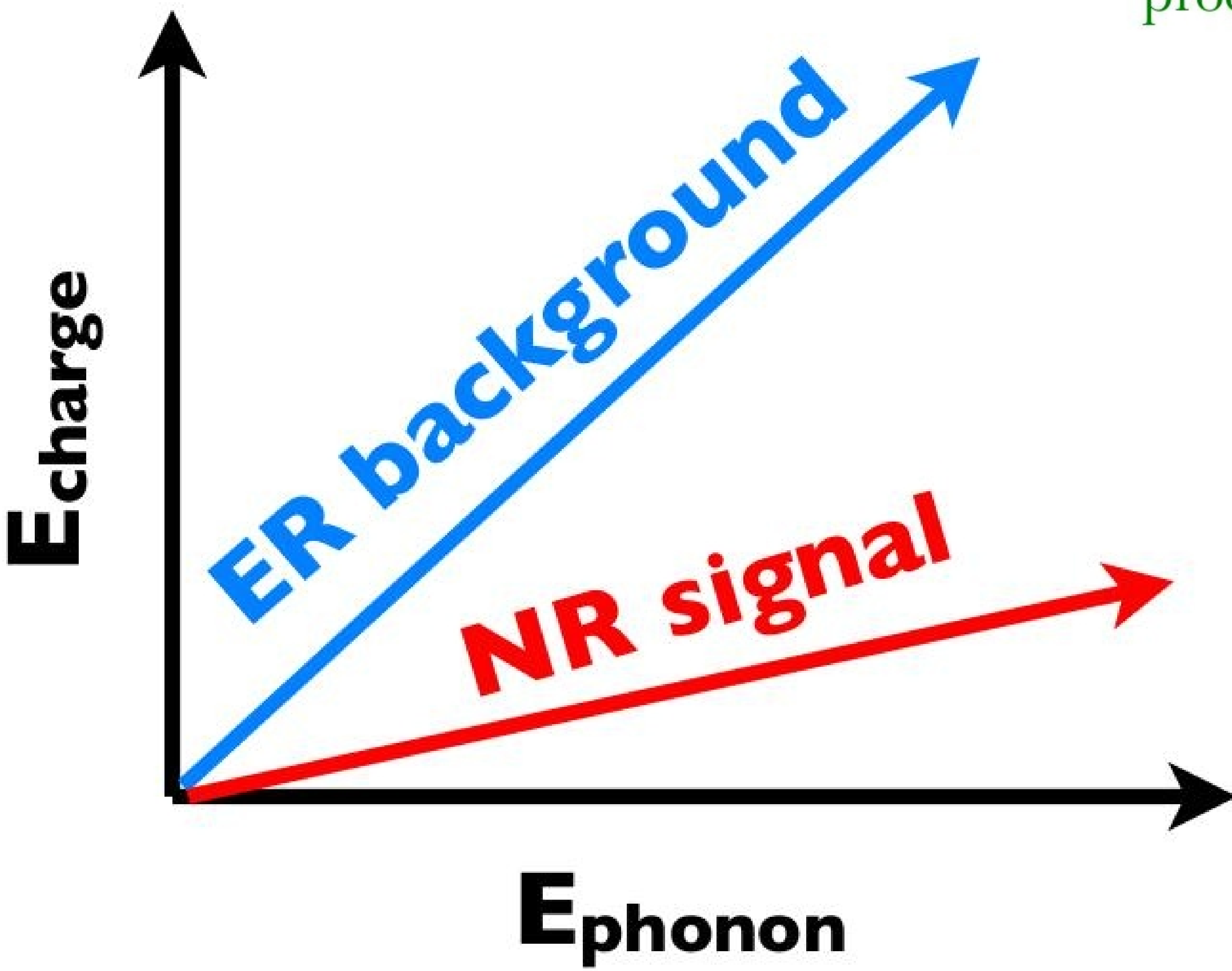
E(recoil) = 1.0 * E(electron-equivalent)



Different Particles, Different Interactions

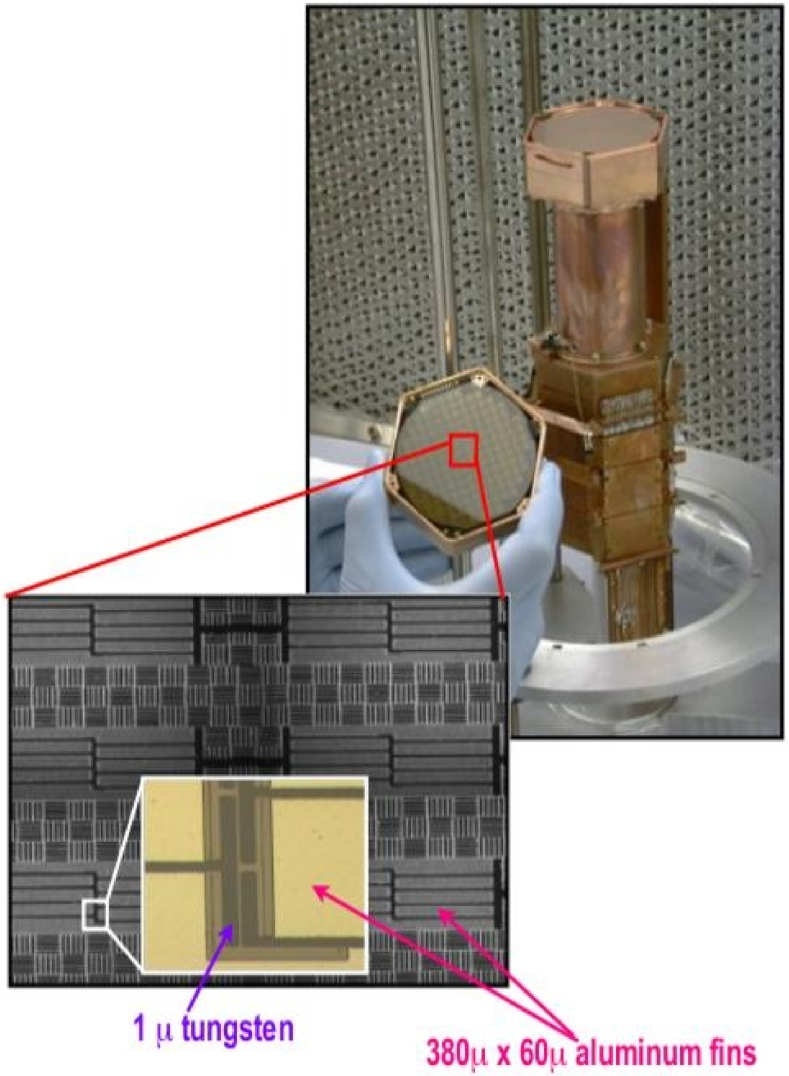


- Most backgrounds (e, γ) produce electron recoils
- WIMPS and neutrons produce nuclear recoils.

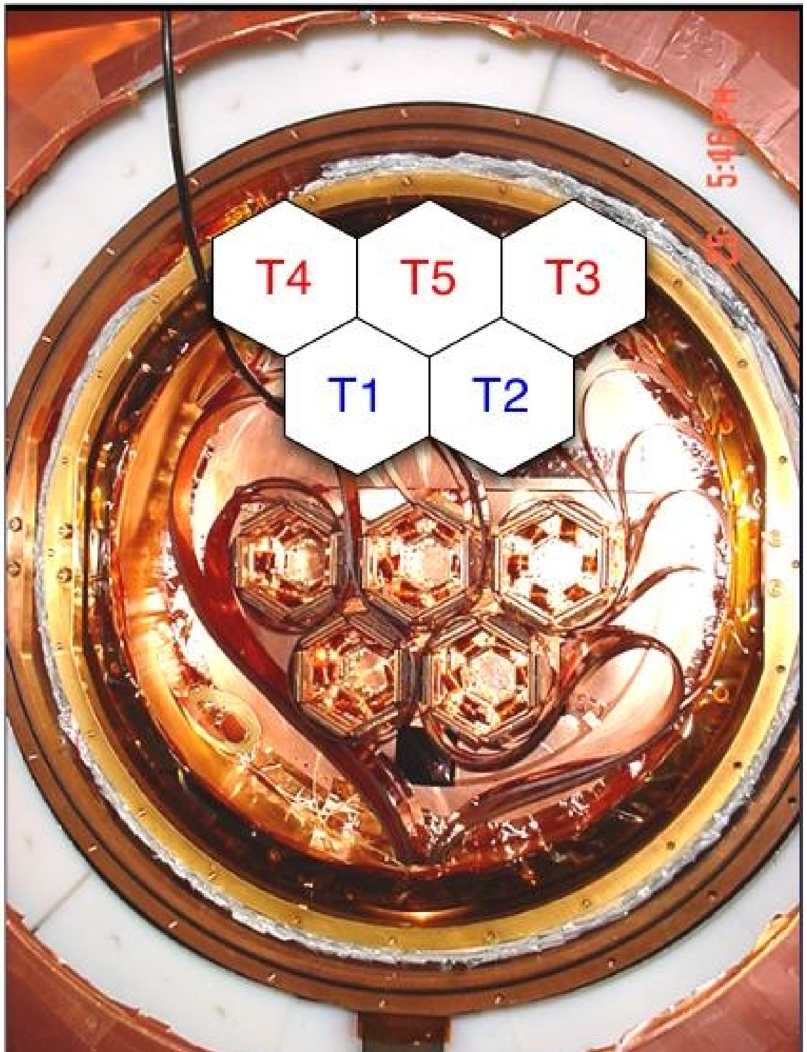


CDMS II ZIP Detectors

- 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

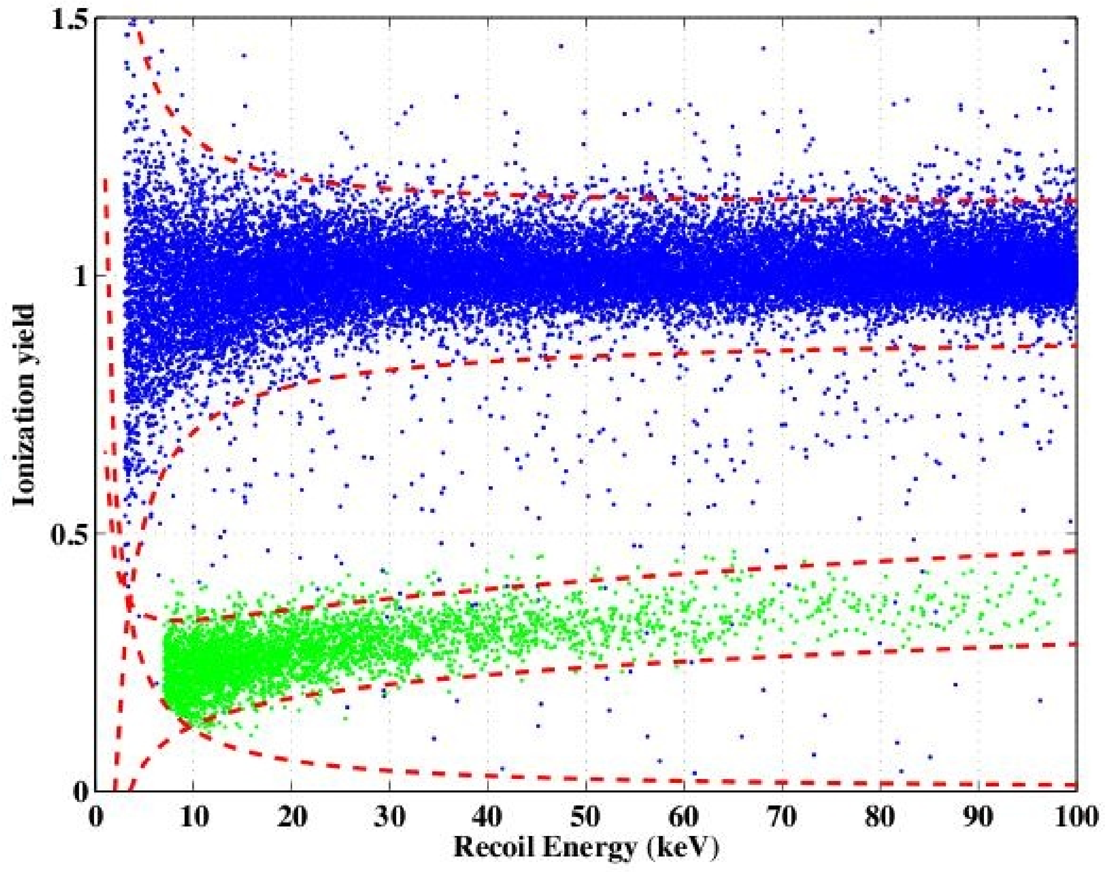


- 30 detectors installed and operating in Soudan since June 06.
  - 4.75 kg of Ge, 1.1 kg of Si
- Seven Total Data Runs:
  - R123 - R124:
    - taken: (10/06 - 3/07) (4/07 - 7/07)
    - exposure: ~400 kg-d (Ge "raw")
    - PRL 102, 011301 (2009)
  - R125 - R128
    - taken: (7/07 - 1/08) (1/08 - 4/08)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

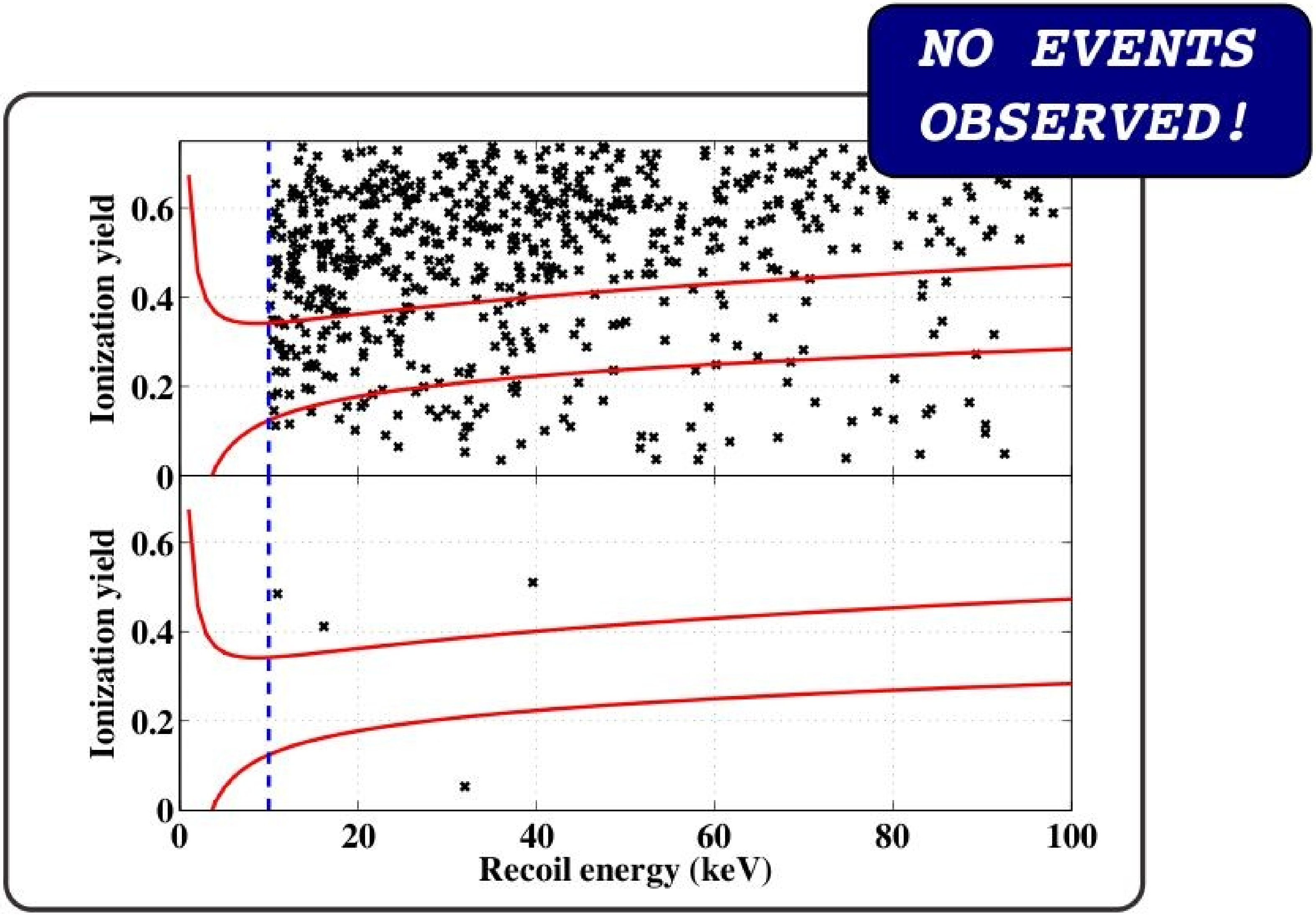
Jodi Cooley - Stanford University

Background Rejection

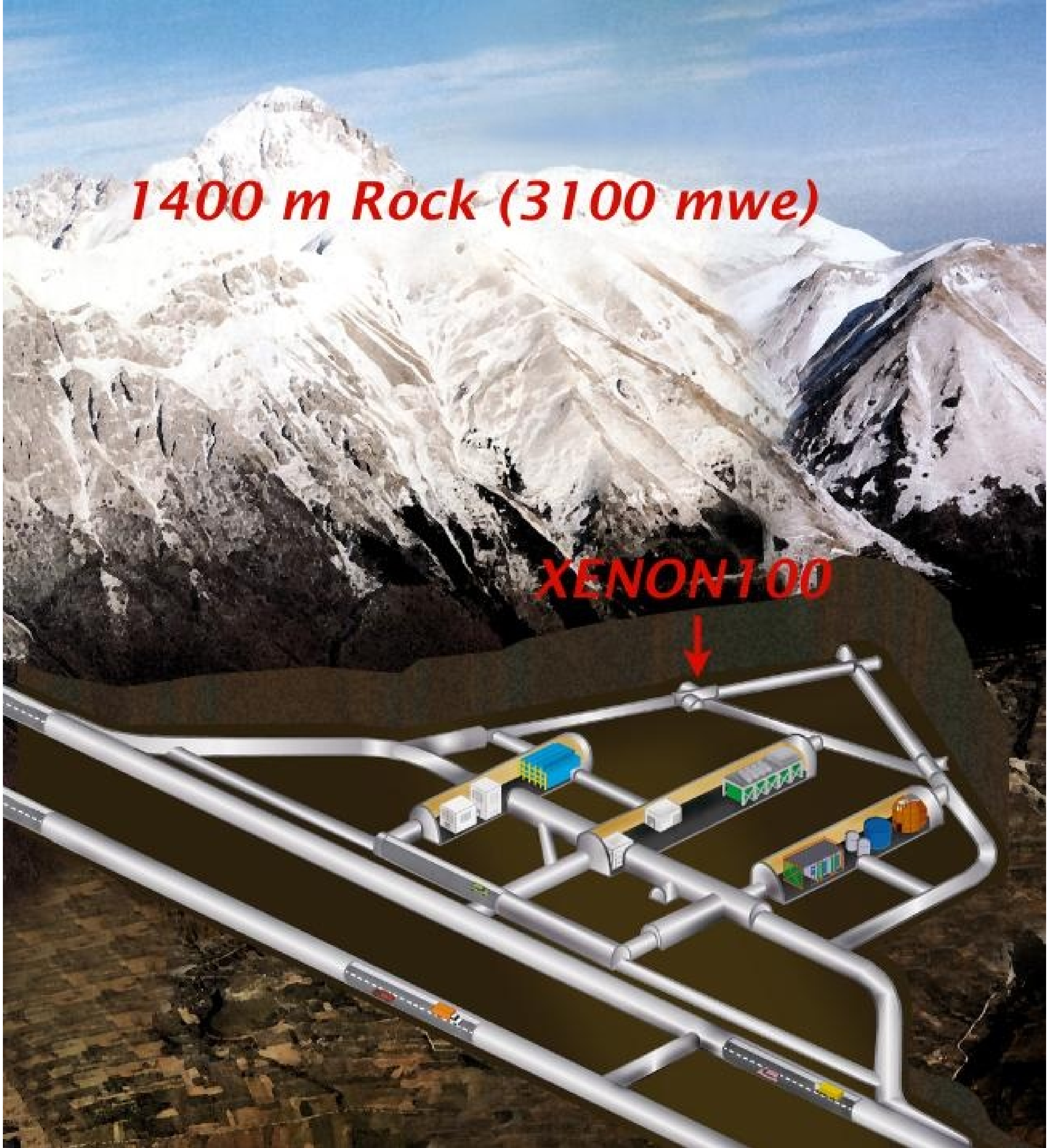
- Most backgrounds (e, γ) produce electron recoils
- WIMPS and neutrons produce nuclear recoils.
- Ionization yield (ionization energy per unit phonon energy) strongly depends on particle type.



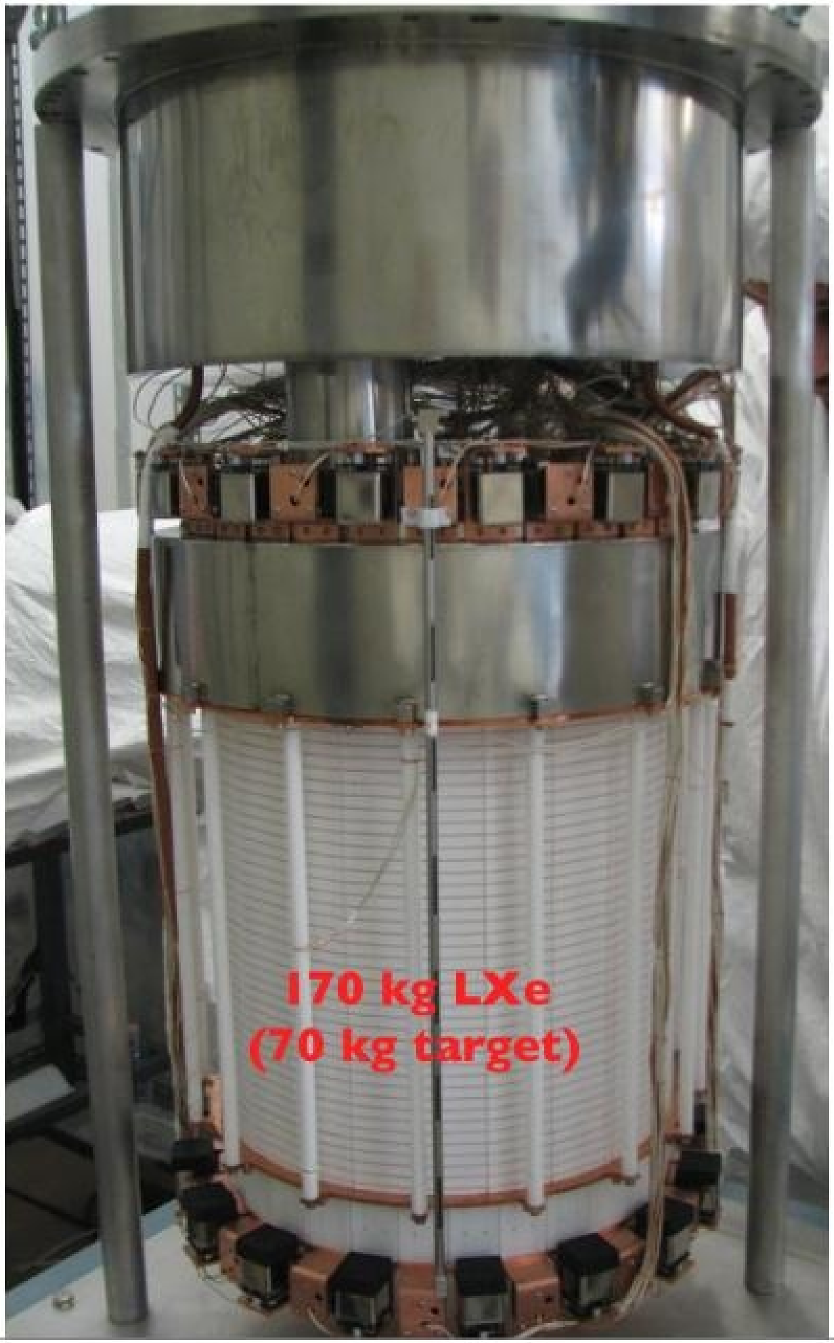
CDMS II Results

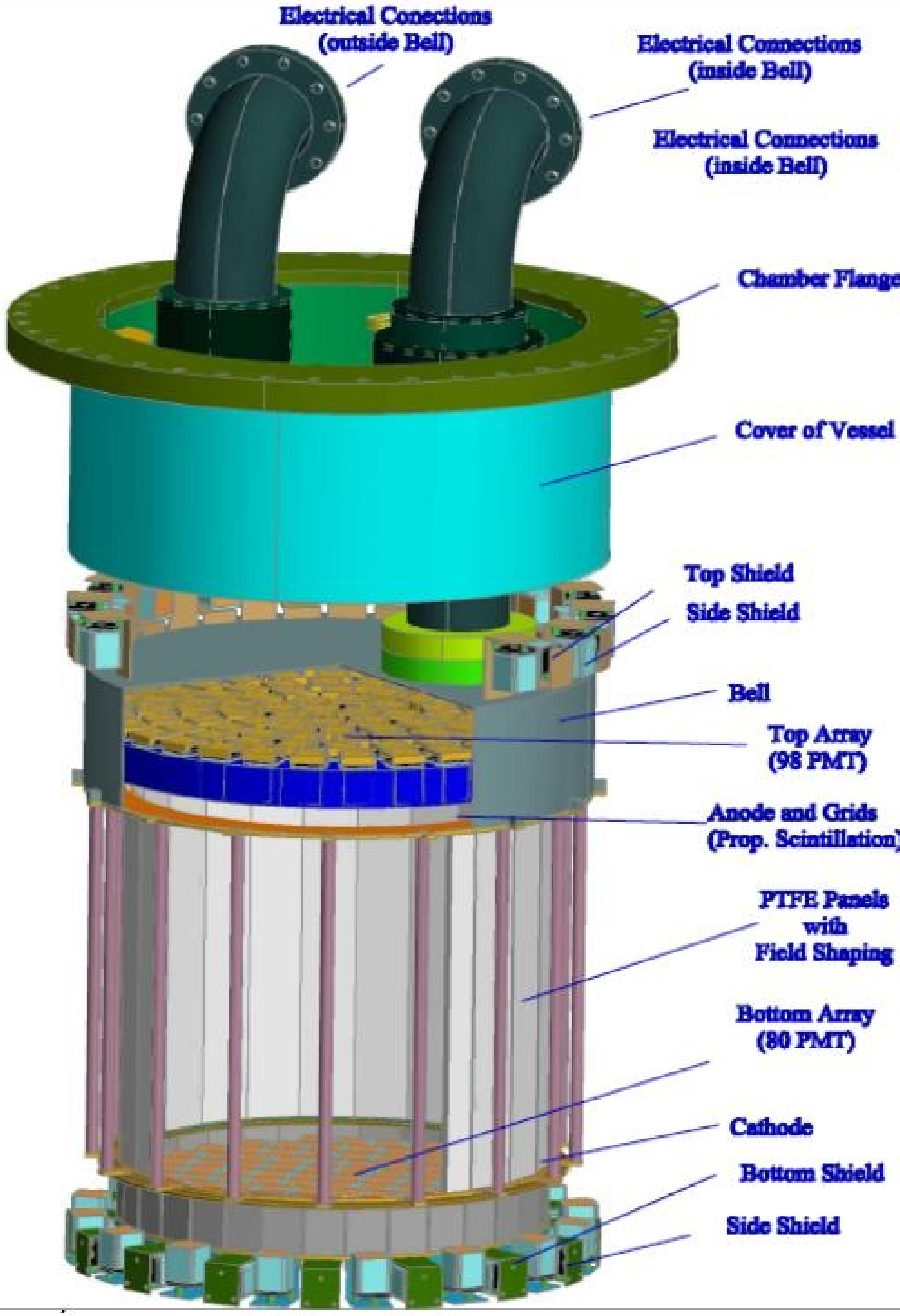


PRL 102, 011301 (2009)

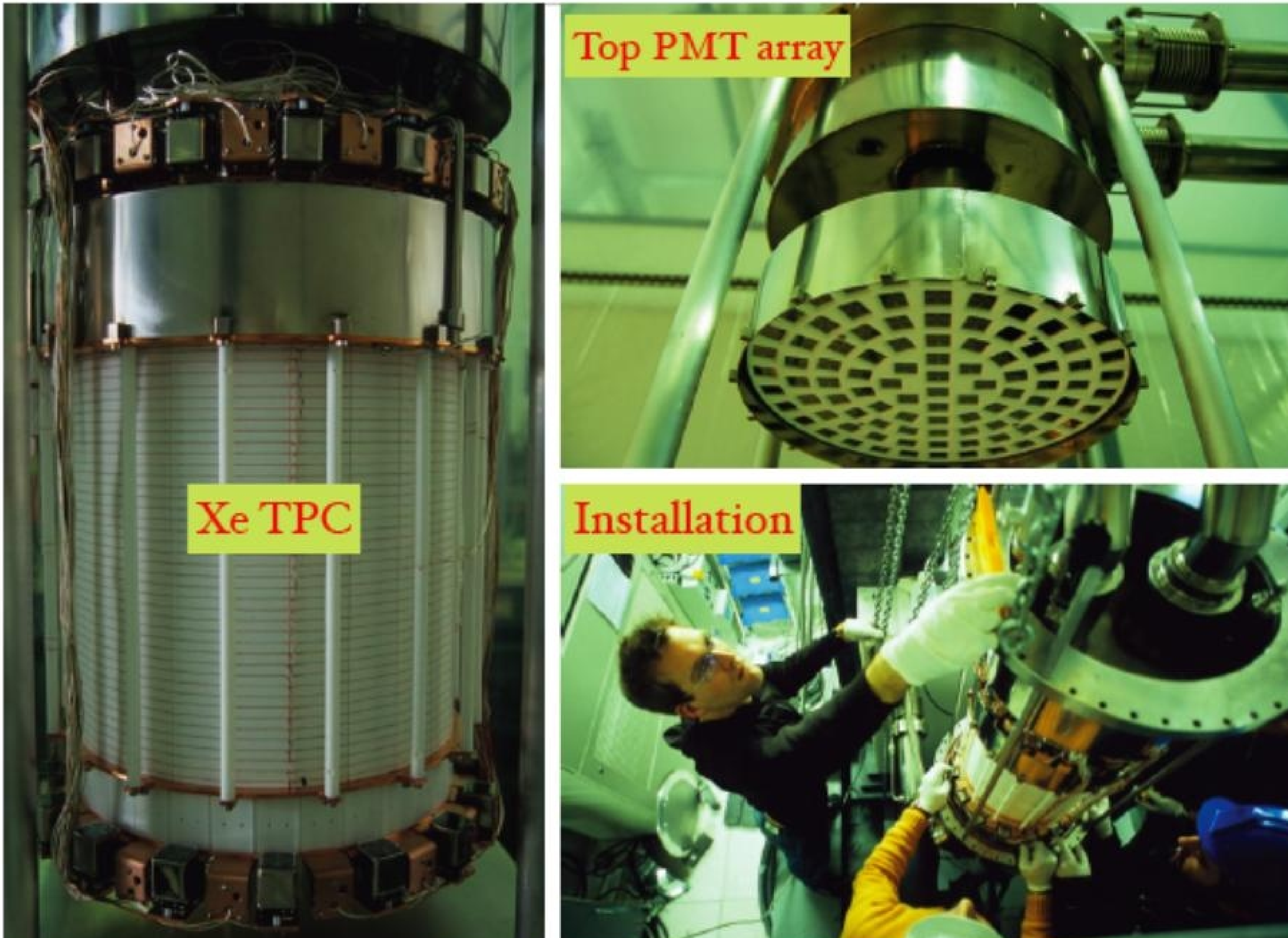

1400 m Rock (3100 mwe)
XENON100

XENON100: The TPC Assembly

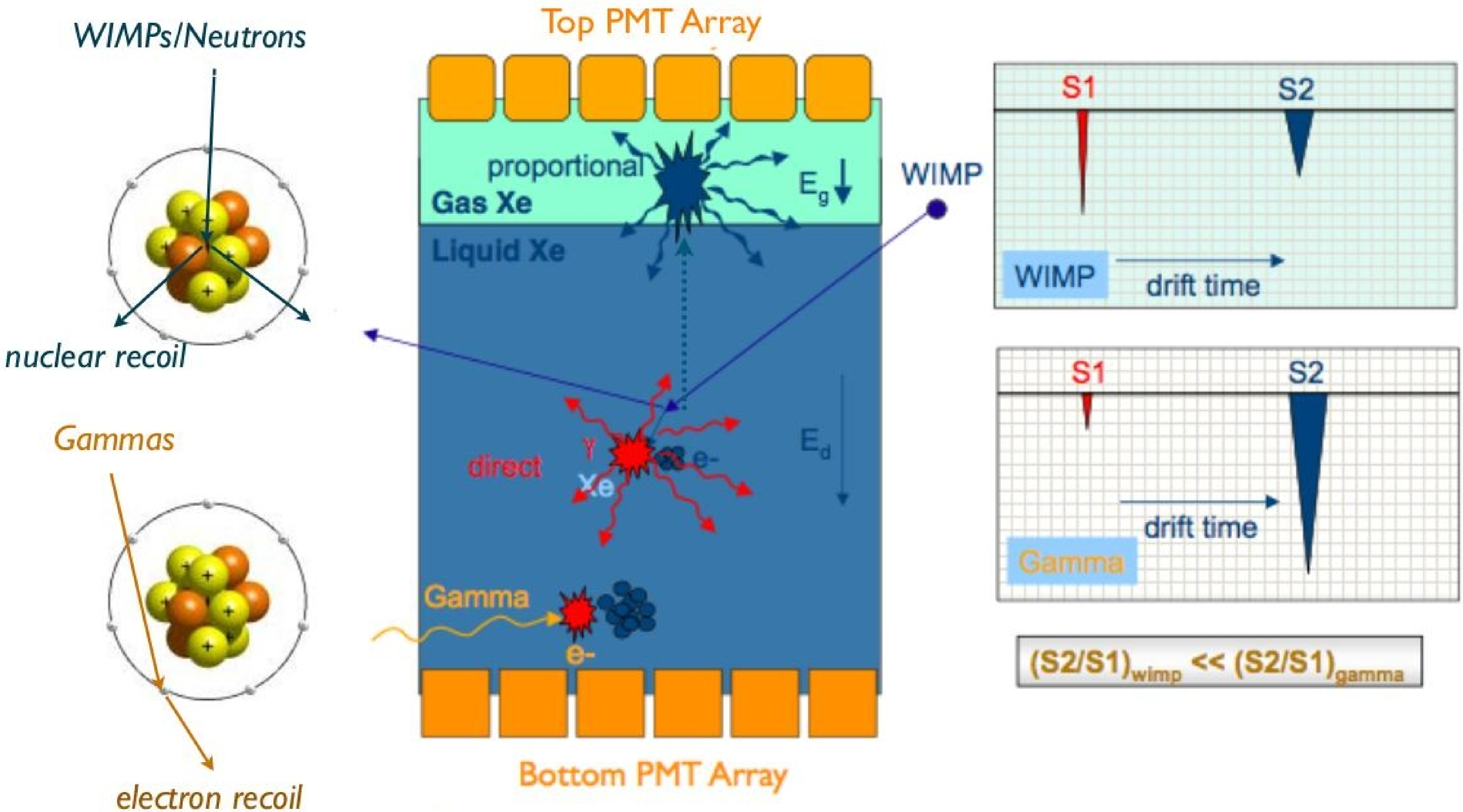




more detector photos at:
http://xenon.astro.columbia.edu/



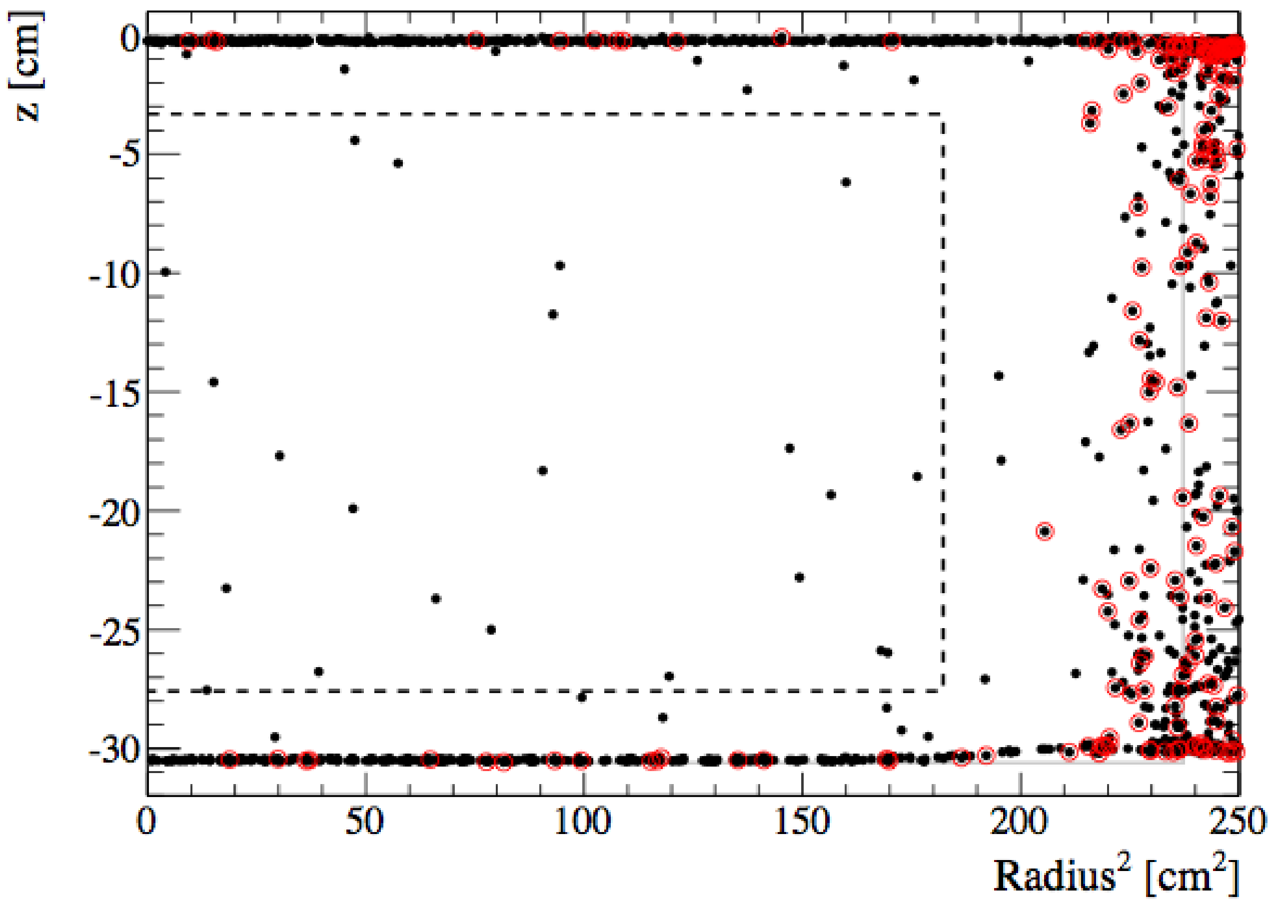
The XENON two-phase TPC

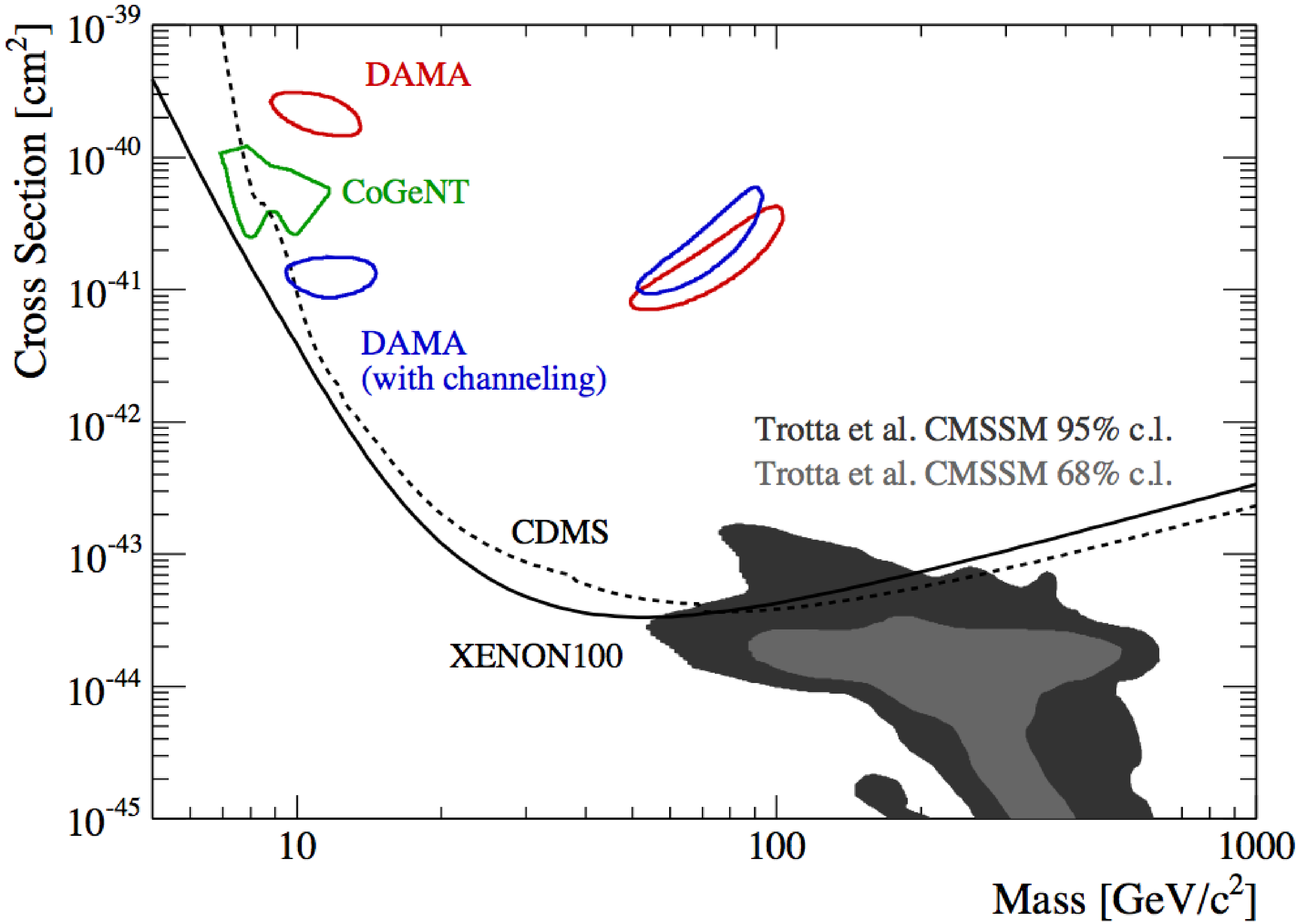


- Single electron and single photon measurement sensitivity
- > 99.5% ER rejection via Ionization/Scintillation ratio (S2/S1)

Xenon-100 (liters) results

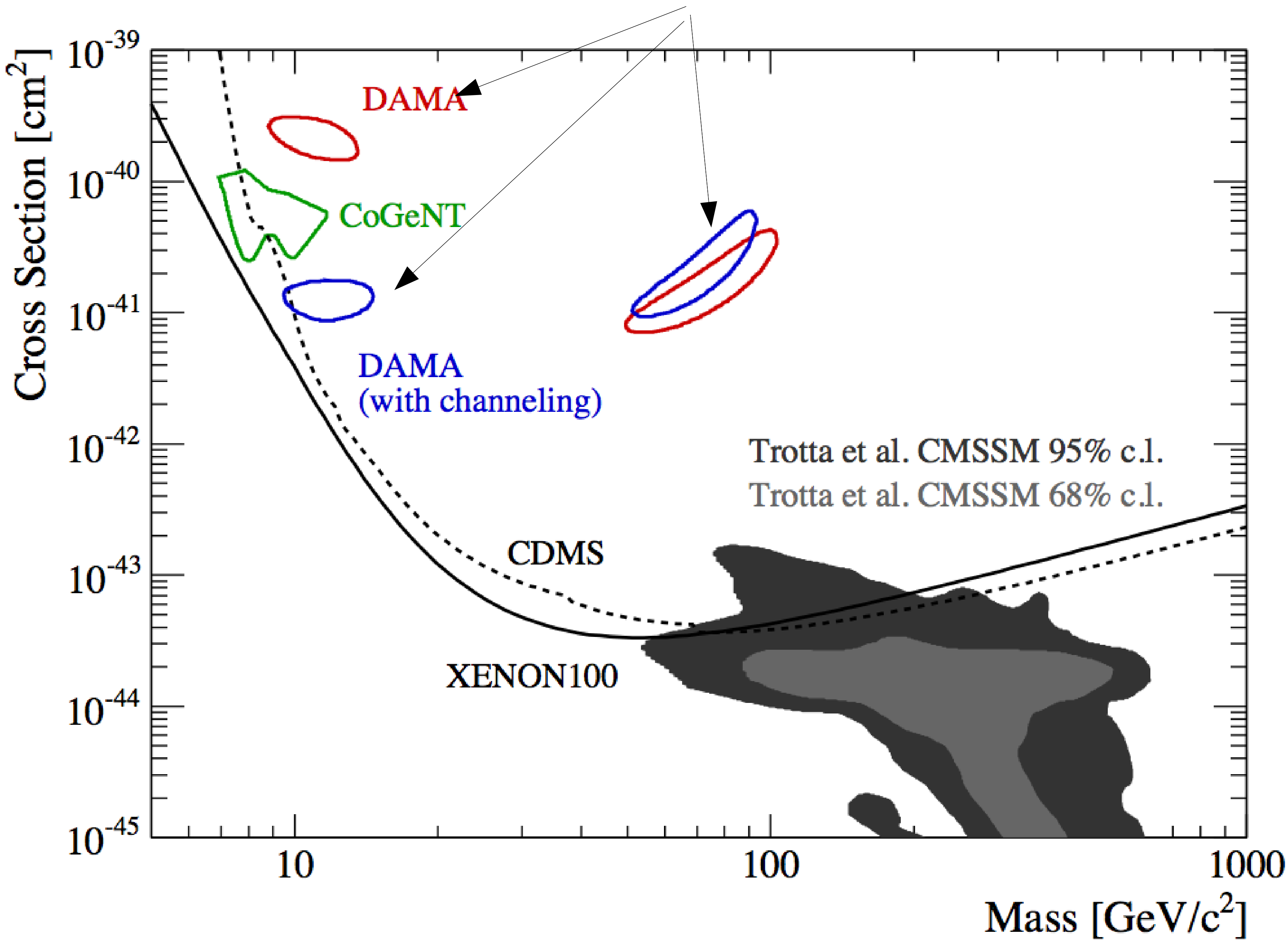
40 Kg of fiducial mass
11.17 days of data taking   [1/1000 the DAMA exposure]
0 candidates





Cross Section [cm^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
DAMA
CoGeNT
DAMA
(with channeling)
Trotta et al. CMSSM 95% c.l.
Trotta et al. CMSSM 68% c.l.
CDMS
XENON100
10
100
1000
Mass [GeV/c^2]

4 “allowed regions for DAMA”
[Dominant Na, I] * [“channelling”]



Intense controversy around these results
and their interpretation.

For DAMA: is it possible they are detecting
a seasonal effect in the background rate
That by “coincidence” has the “right” features
That mimic Dark Matter ?
[Crucial test: repeat in the South hemisphere ?]

If DAMA does see a DM signal, then
why the other detector do not see a signal ?

Conclusions - Perspectives

3 remarks

Conclusions - Perspectives

The DARK MATTER problem is one of the key problems for modern Science in the 21st century. [Good luck to you, for finding the solution !!!]

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

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The PAMELA "positron excess" is a very interesting phenomenon, that is very likely to involve some new interesting high energy astrophysics idea.
[And high energy astrophysics is a very exciting Vibrant field, with continuos surprises an developments.]

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[And high energy astrophysics is a very exciting
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GOOD LUCK TO YOU also in this field !!!