Open Problems in Particle Astrophysics

Paolo Lipari
5th WAPP workshop
Ooty 15th december 2010

1. DARK MATTER

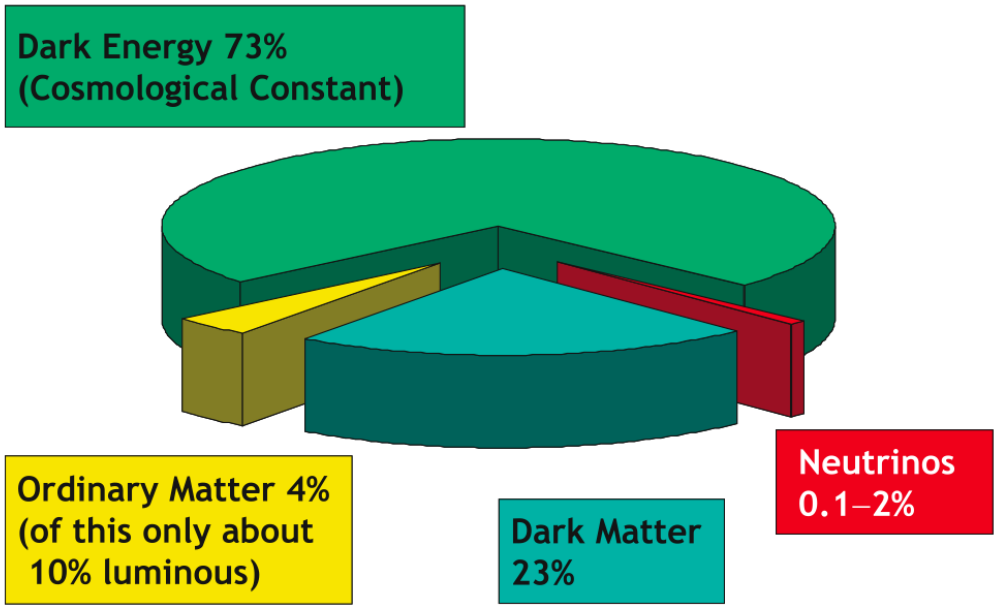
2. The sources of COSMIC RAYS

(the “High energy universe”)

Mysteries of the DARK UNIVERSE

DARK ENERGY :

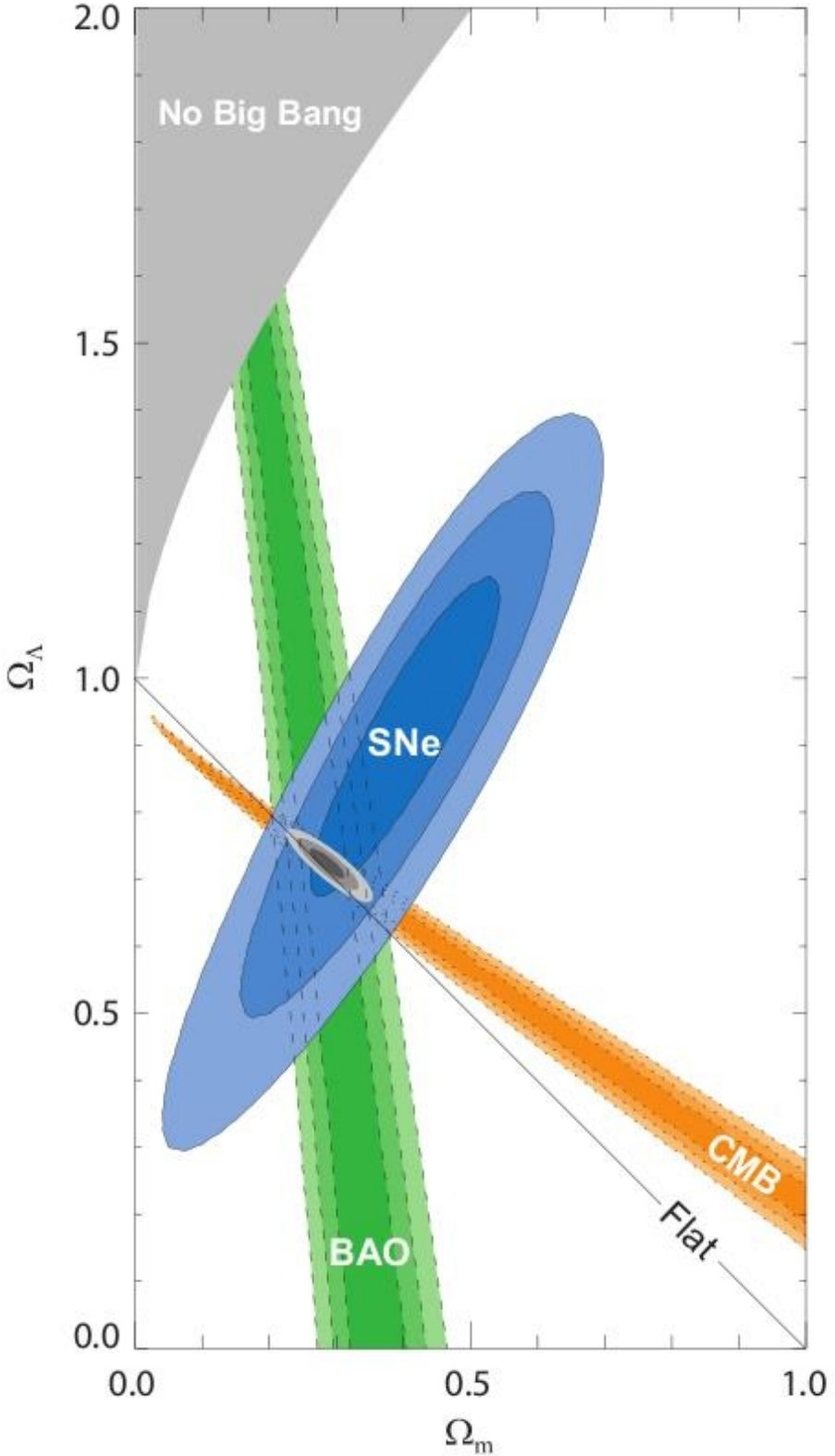
Drives apart galaxies
and other large scale structures
[The energy of vacuum itself ?]



DARK MATTER:

Holds together galaxies
and other large scale structures
[A new elementary particle ?]

Exist at different scales:
Entire Universe
Clusters of Galaxies
Galaxy

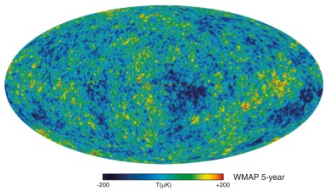


Determination of the density and "equation of state" of the Universe.

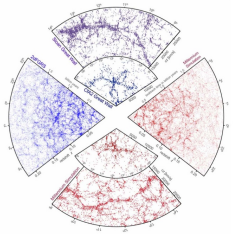
1. SN1a (standard candle) luminosity – redshift relation

$$a(t) \leftrightarrow \ell(z)$$

2. Cosmic Microwave Backround Radiation Anisotropies



3. Galaxy Distributions

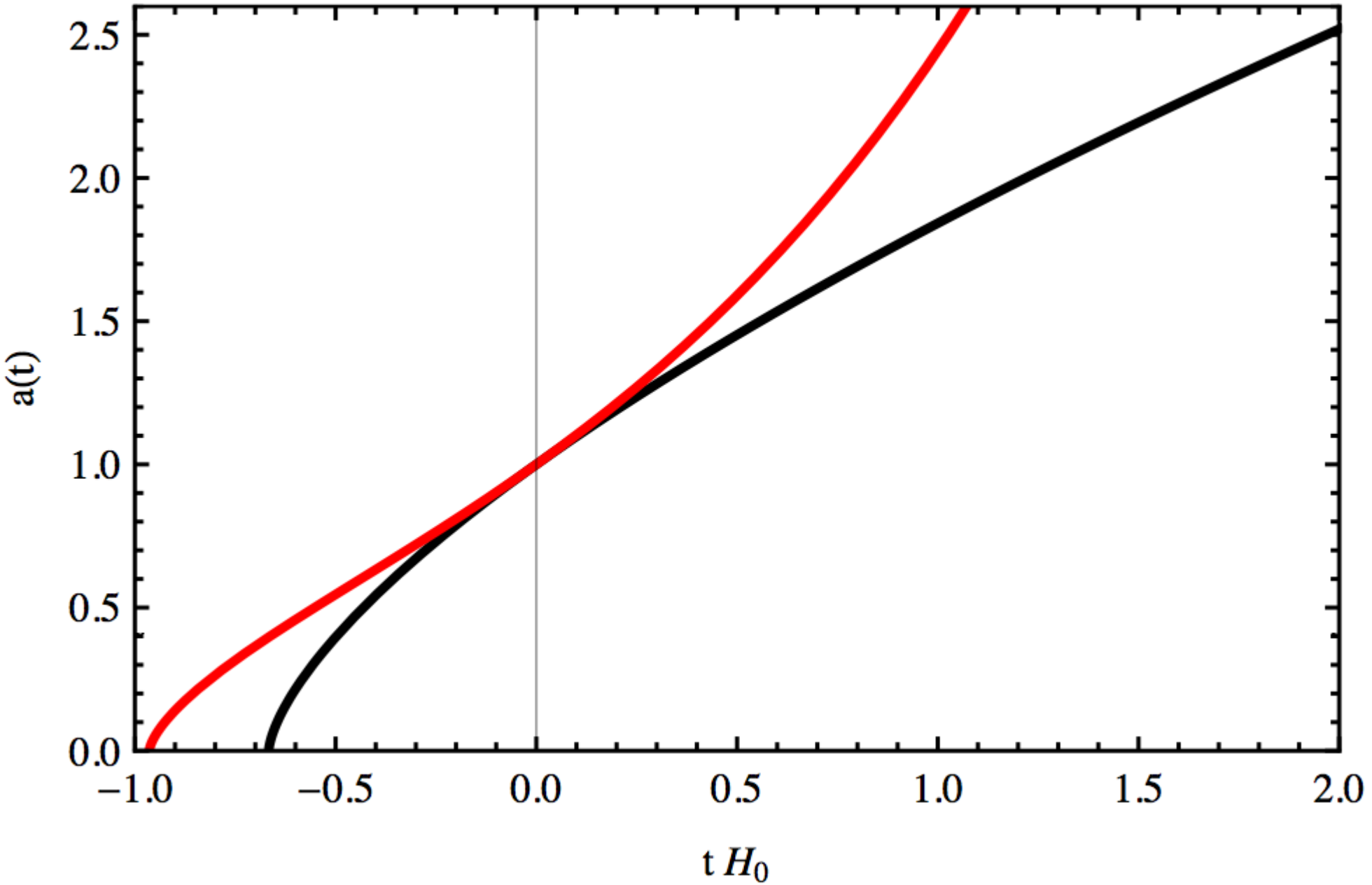


$\Omega_m = 1$

$\Omega_\Lambda = 0$

$\Omega_m = 0.3$

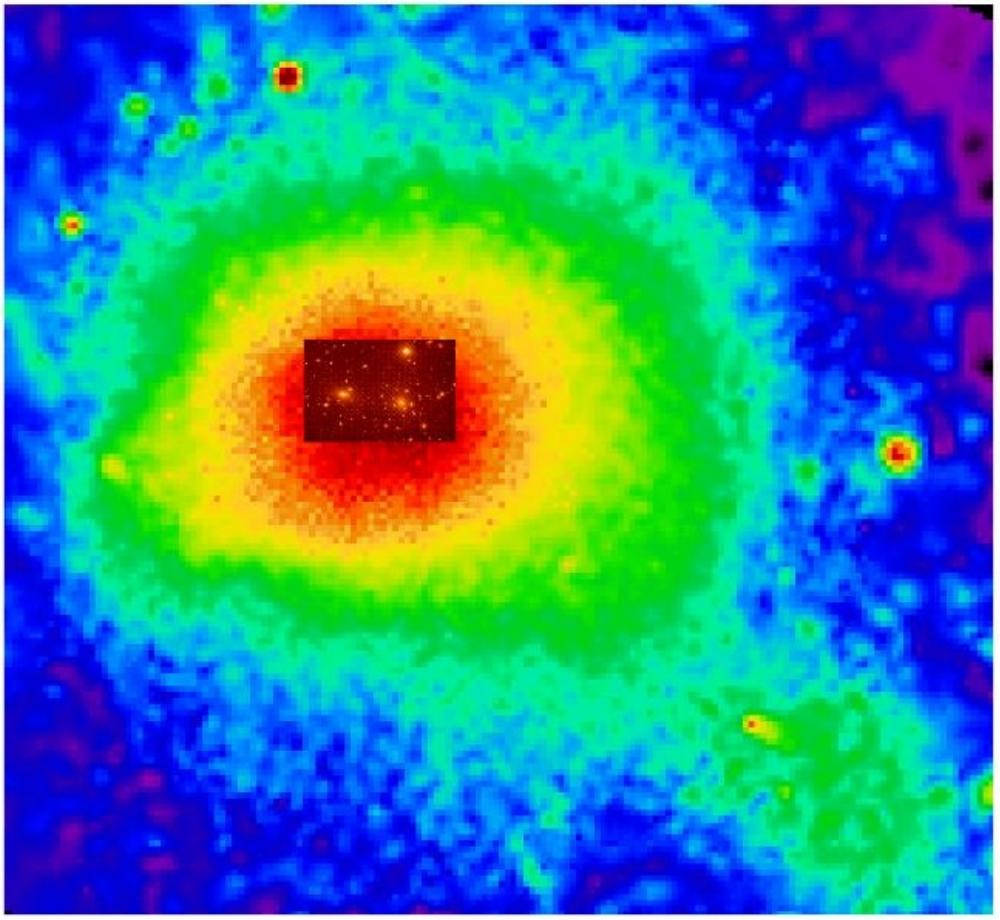
$\Omega_\Lambda = 0.7$



COMA Galaxy Cluster

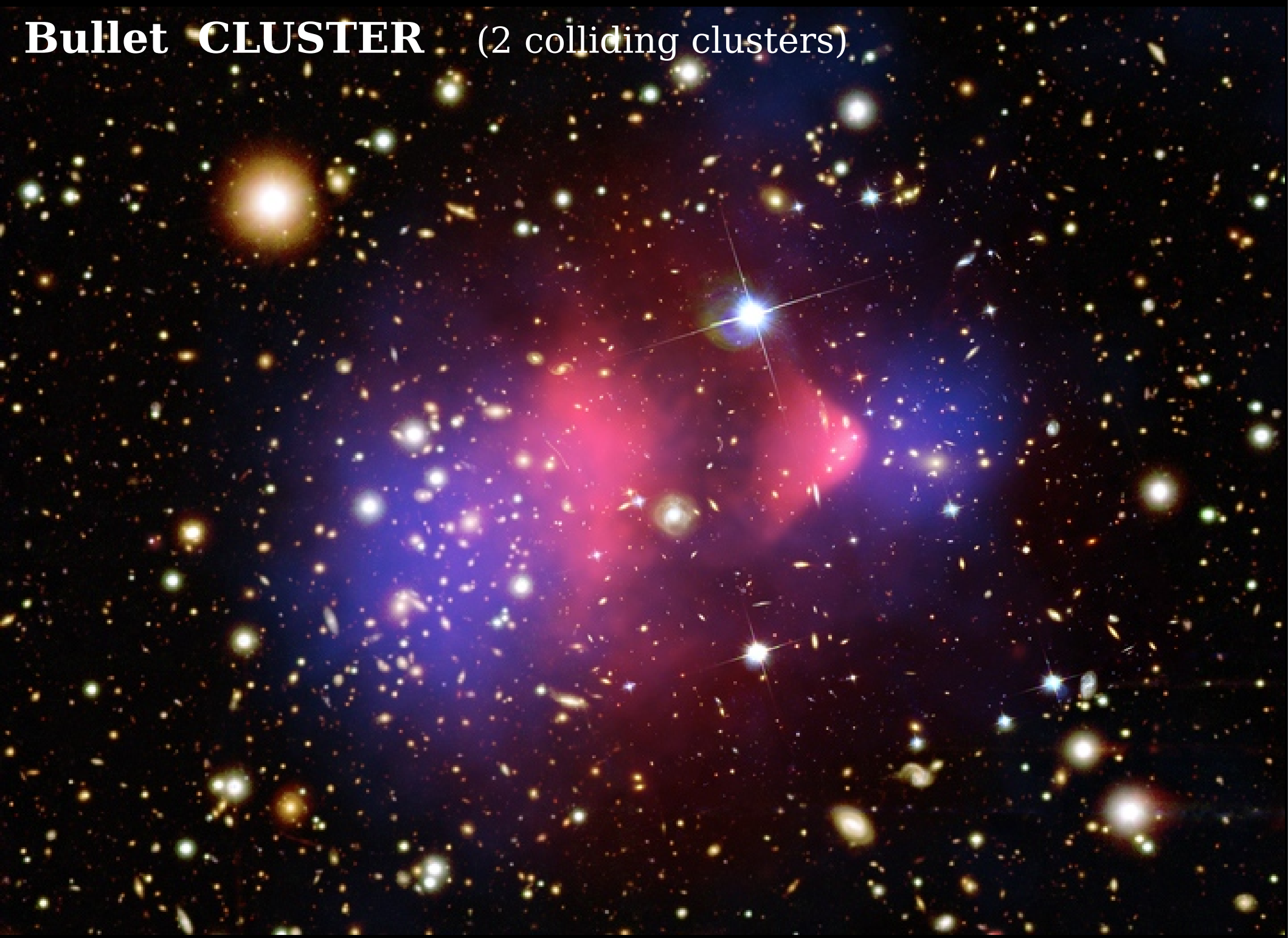
Optical

Fritz Zwicky 1933
First argument for Dark Matter

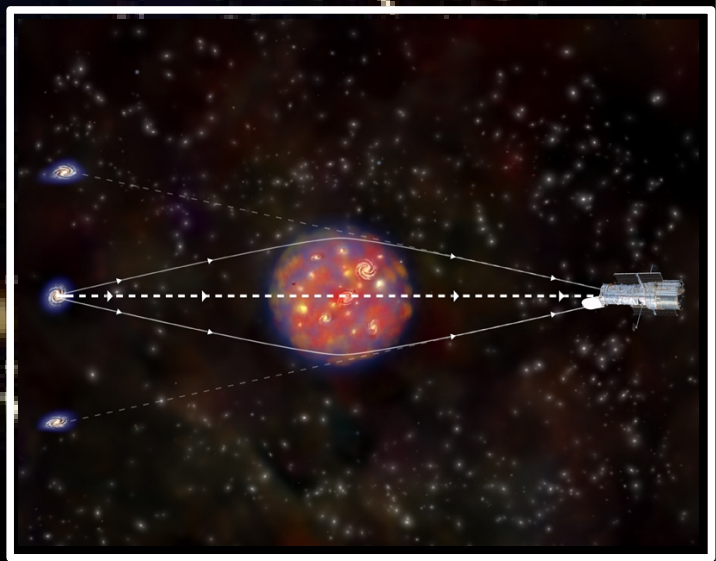


X-ray
[hot gas confined by
deep gravitational well]

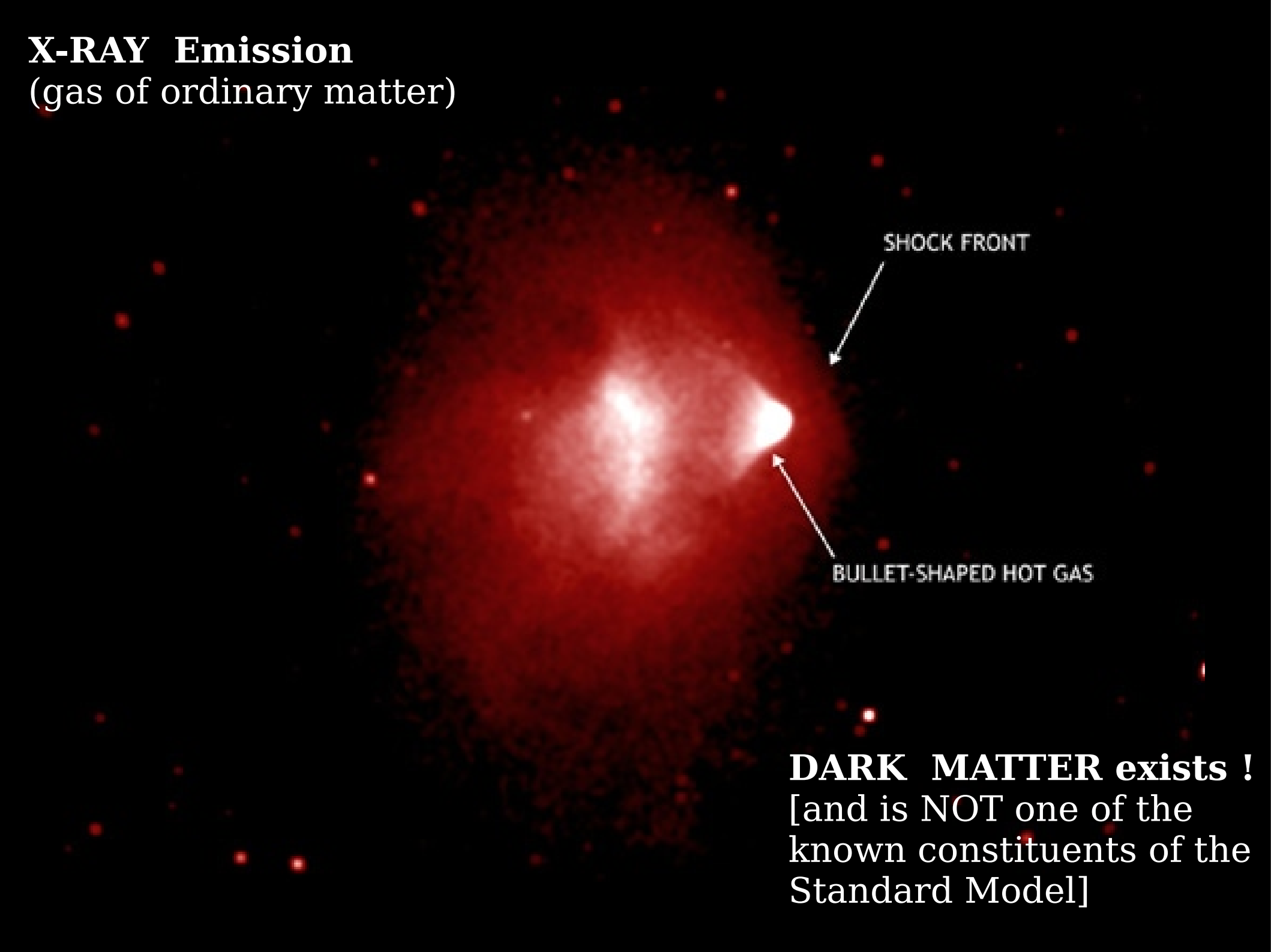
Virgo Cluster Intes Mk69@900mm St10XME L265min 300sec sub RGB 60/57/62min 200sec bin2x2 Gahberg 20080427/0507/0508 www.kerschhuber.astronomie.at


Bullet CLUSTER (2 colliding clusters)

MASS DISTRIBUTION
(from gravitational lensing)

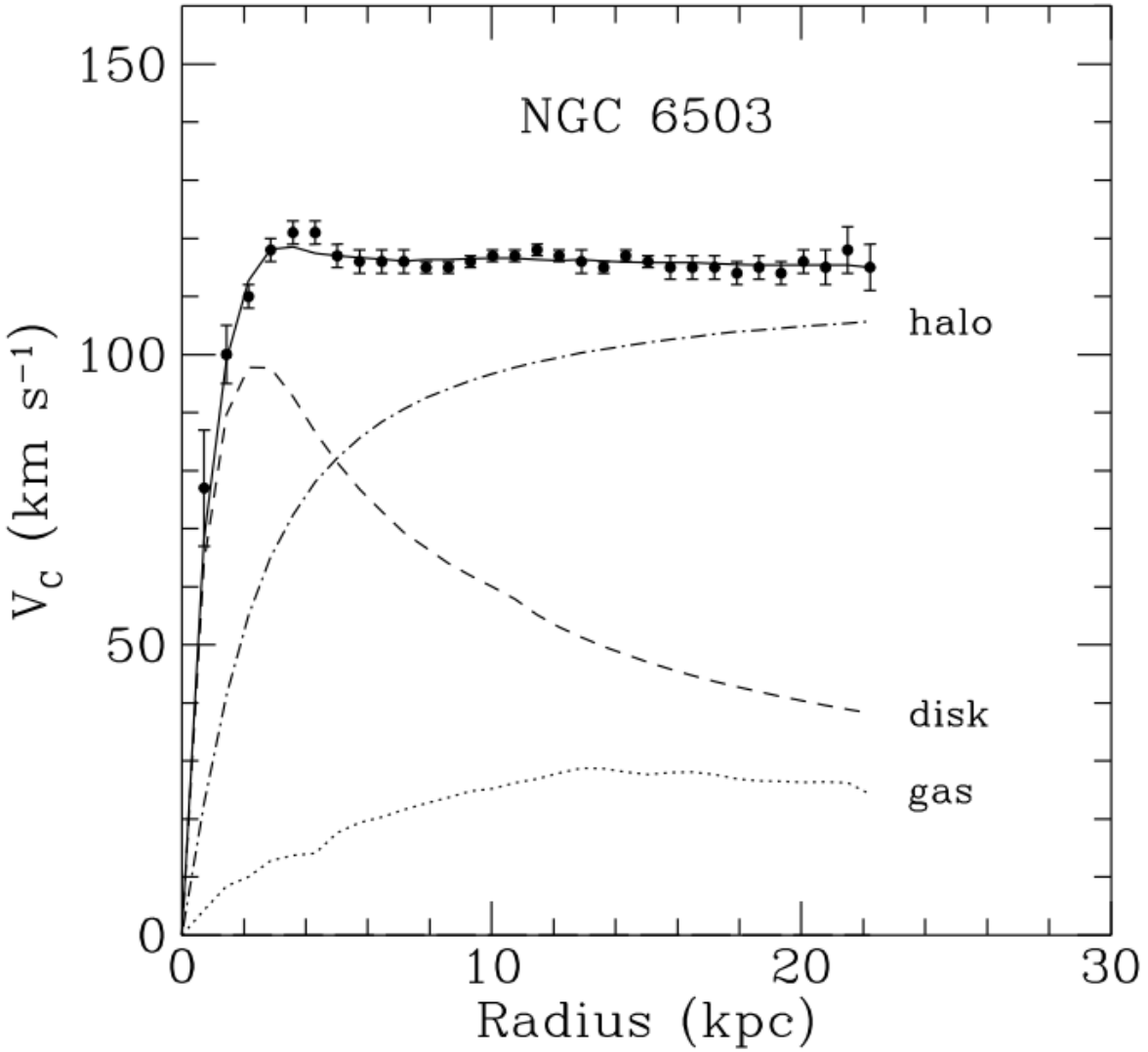


X-RAY Emission
(gas of ordinary matter)

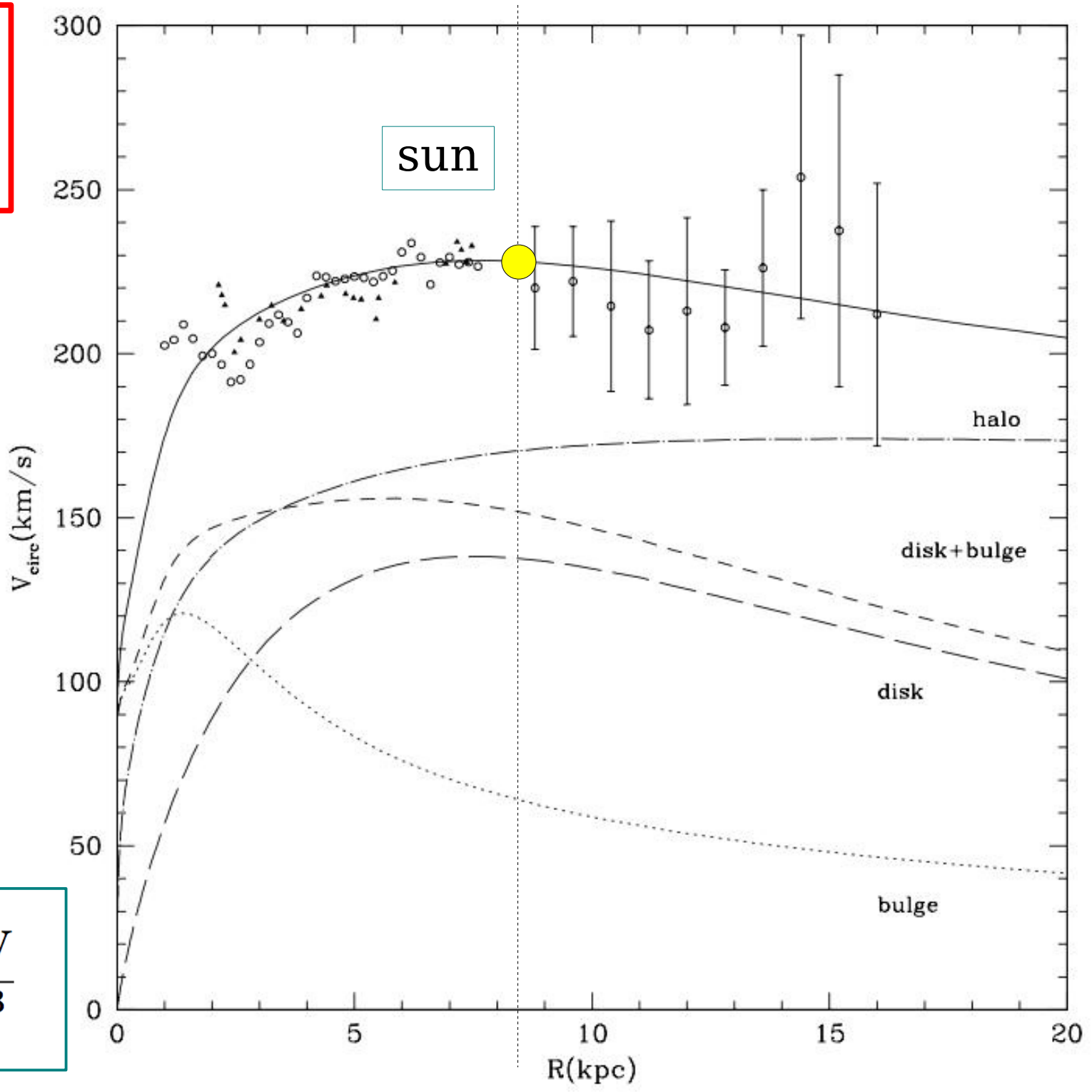


DARK MATTER exists !
[and is NOT one of the known constituents of the Standard Model]

DARK matter halos of spiral Galaxies

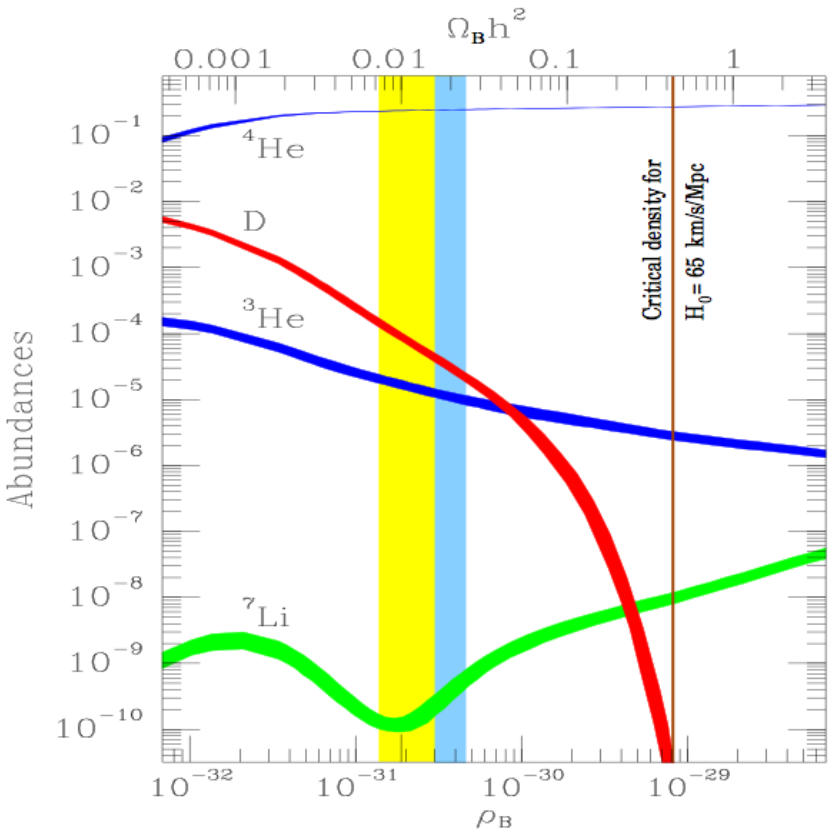


MILKY WAY



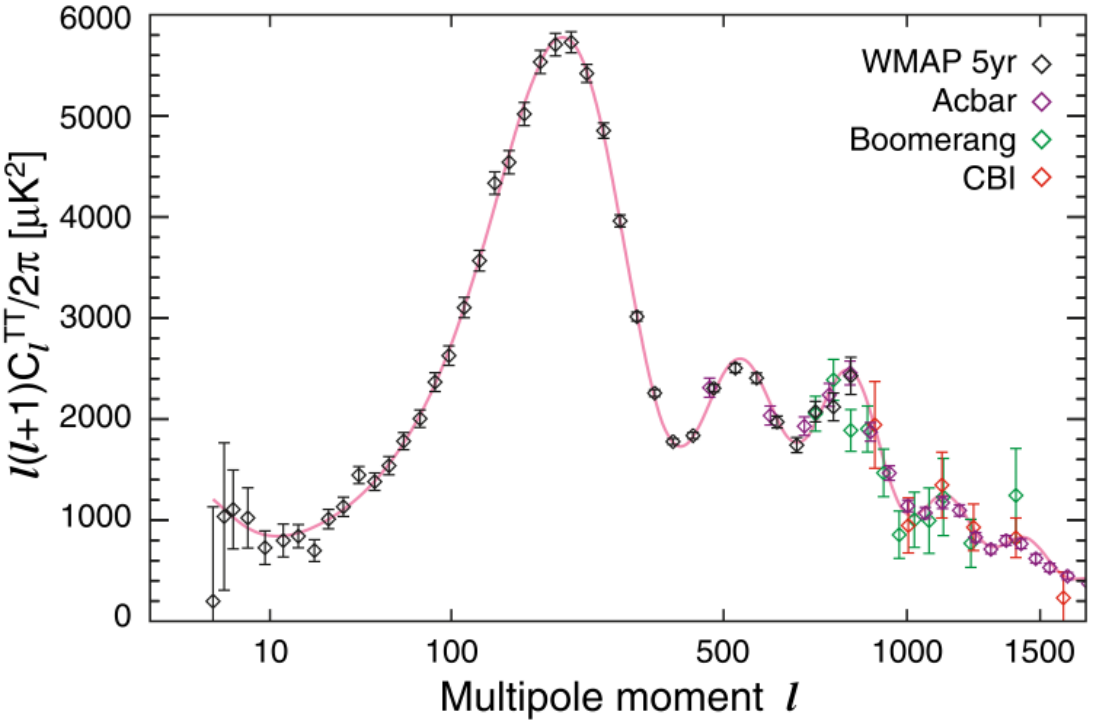
$$\rho_\oplus \simeq 0.3 \, \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

Nucleosynthesis constraints on ordinary ("baryonic") matter



DARK MATTER is NON BARYONIC

Power Spectrum of CMBR temperature fluctuations



DARK MATTER: we know a lot :

...but we
do NOT know
much more...

It exists (Serious difficulties for “modified gravity”)

Good estimate of the cosmological average (22%)

“Collisionless” and “Dissipationless”

Most of it is “cold”

Most of it is non baryonic

It cannot be explained by the Standard Model
in Particle Physics !!

What is the Dark Matter ?

Possible theoretical ideas

- Thermal Relic
- Axion
- Super-massive particles

[perhaps the best motivated]
[Offers the best chances of discovery]

$$\Omega_j^0 \simeq 0.3 \left[\frac{3 \times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma\, v \rangle} \right]$$

The "relic density" of a particle
Is determined by its annihilation cross section

(several complications are possible)

$$\sigma(\chi\chi \to \text{anything}) \simeq 10^{-36}\ \mathrm{cm}^2$$

$$\sigma \simeq \frac{\alpha^2}{M^2}\,(\hbar c)^2$$

Weak interaction mass scale

$$M \simeq 200\ \mathrm{GeV}$$

Dark Matter can be explained
With the existence of a stable “thermal relic”
Requirement on its annihilation cross sections.

Weakly (in the “technical” sense)
Interacting
Massive
Particle

the WIMP's “miracle”

“Killing two birds with a single stone”

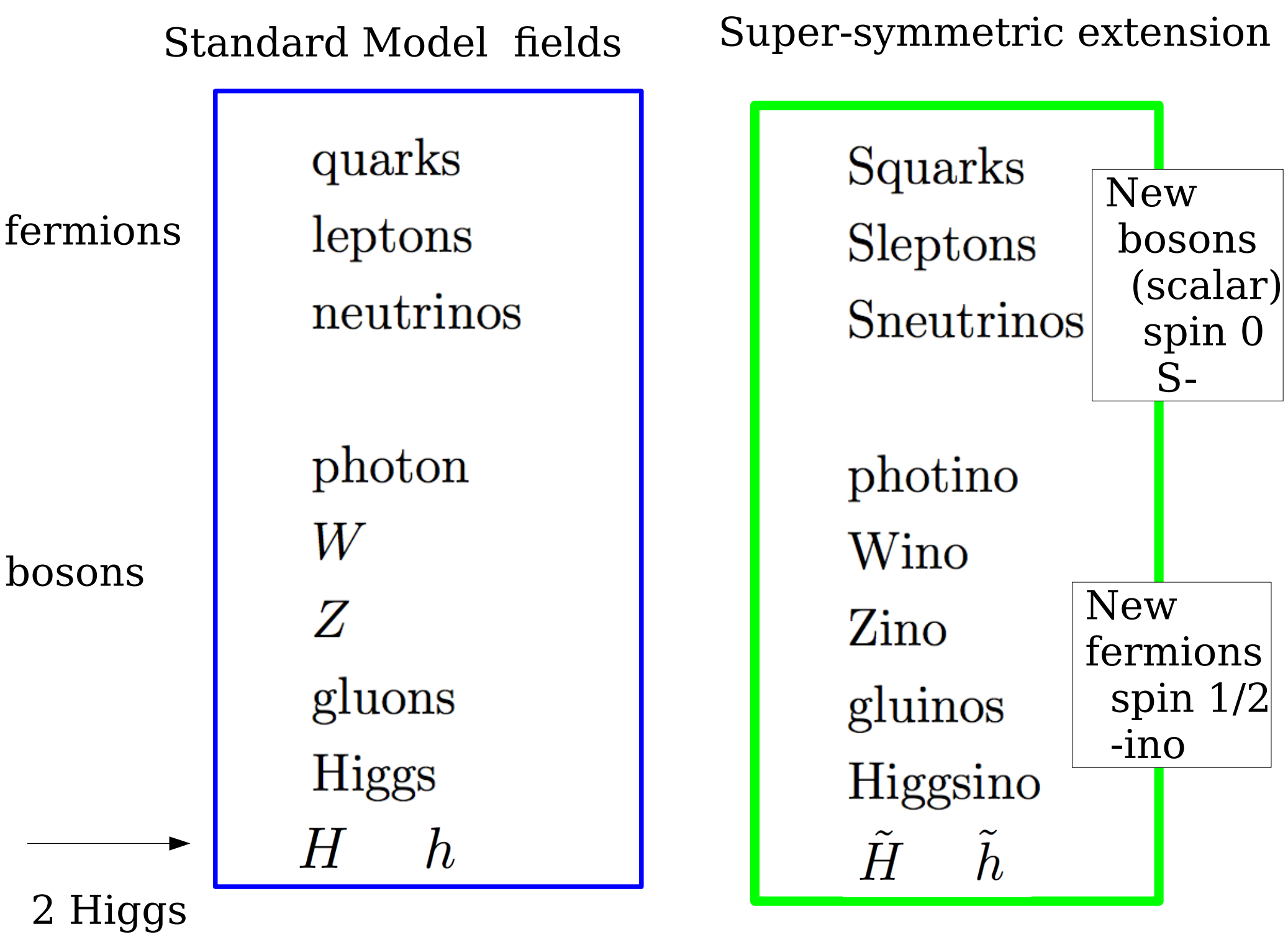
PHYSICS beyond the STANDARD MODEL is **REQUIRED** to explain Dark Matter !!

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

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

LHC/Dark Matter connection !!

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


Standard Model fields
Super-symmetric extension
fermions
bosons
quarks
leptons
neutrinos
photon
W
Z
gluons
Higgs
H h
2 Higgs
Squarks
Sleptons
Sneutrinos
photino
Wino
Zino
gluinos
Higgsino
H̃ h̃
New bosons (scalar) spin 0 S-
New fermions spin 1/2 -ino

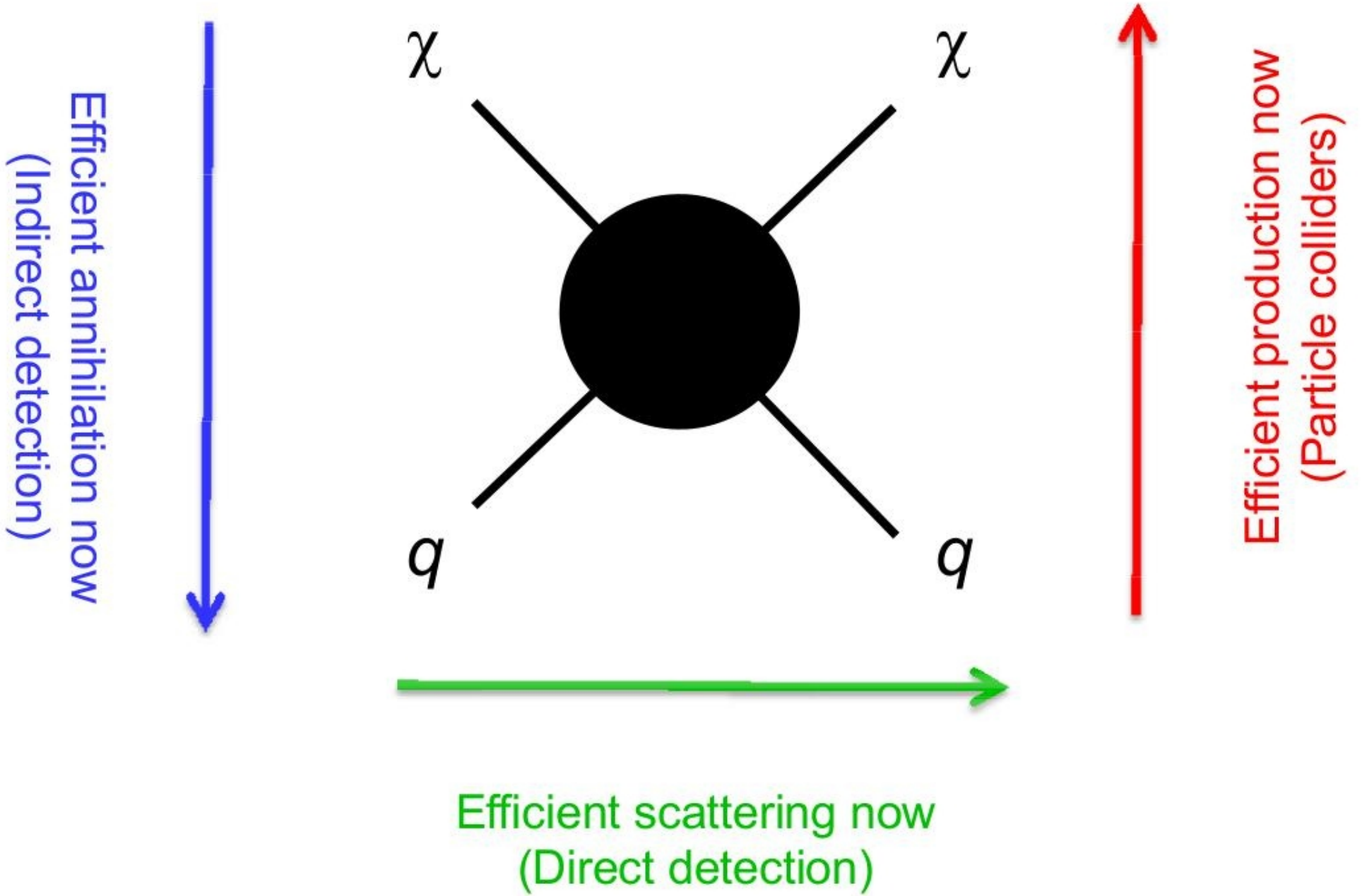
Stable supersymmetric particle

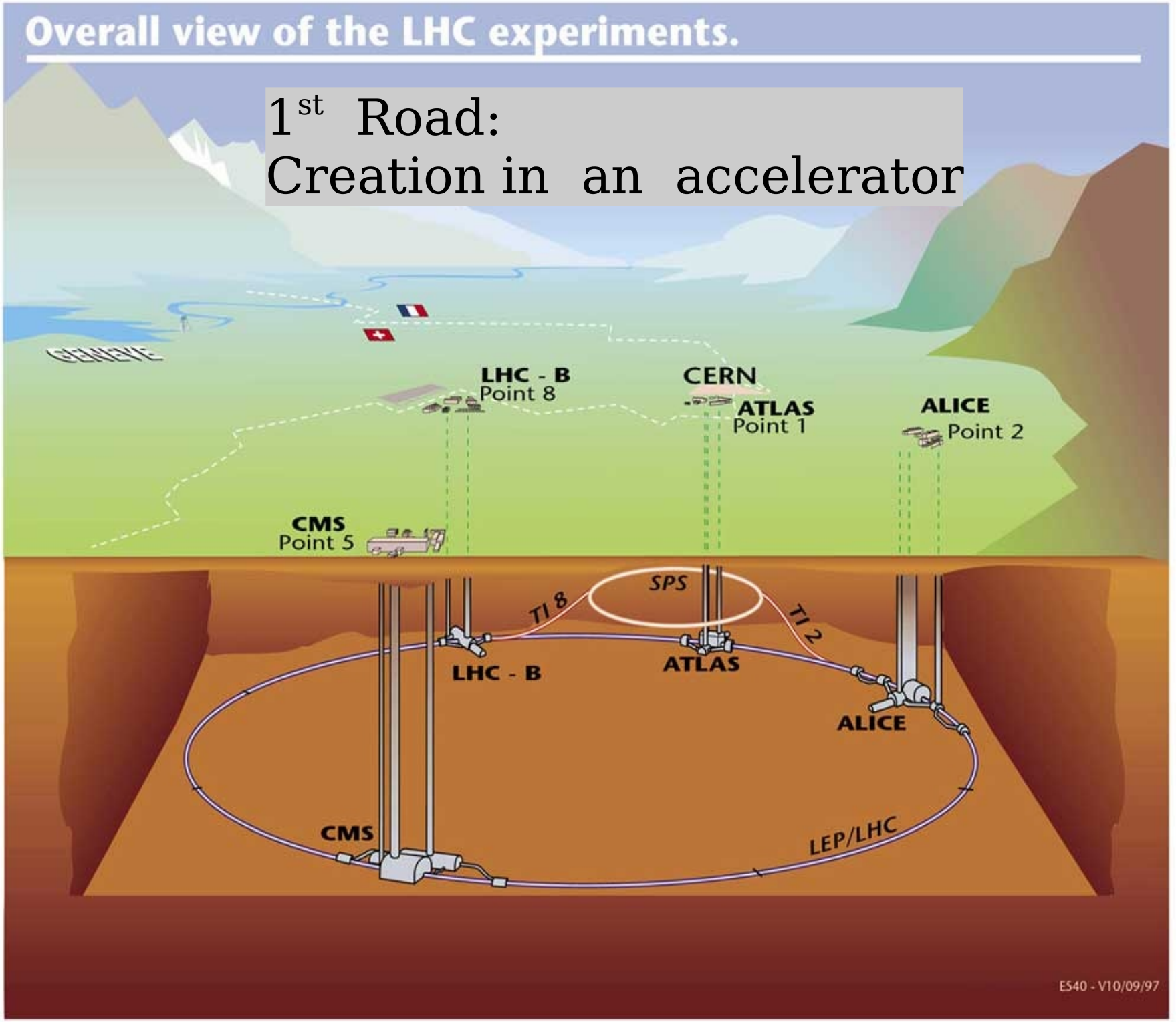
$$|\chi\rangle = c_1 \, |\tilde{\gamma}\rangle + c_2 \, |\tilde{z}\rangle + c_3 \, |\tilde{H}\rangle + c_4 \, |\tilde{h}\rangle$$

“Neutralino”

Note: the concept of Dark Matter
as a thermal relic is more general than the
“Minimal super-symmetric Model”

3 Roads for WIMP discovery



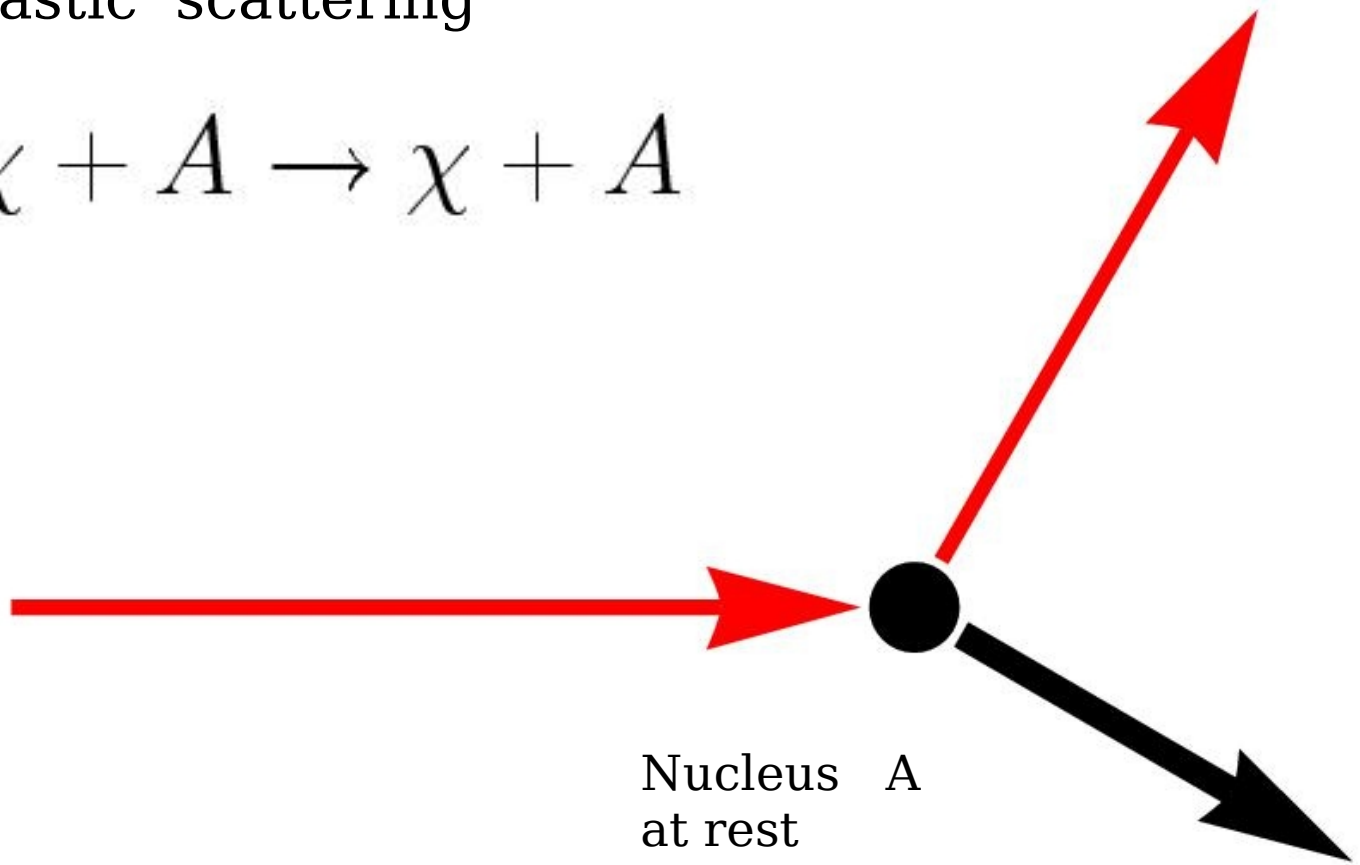

Overall view of the LHC experiments.
1st Road:
Creation in an accelerator
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
ES40 - V10/09/97

"Direct" Search for Dark Matter

2nd Road: Elastic Scattering in underground experiment

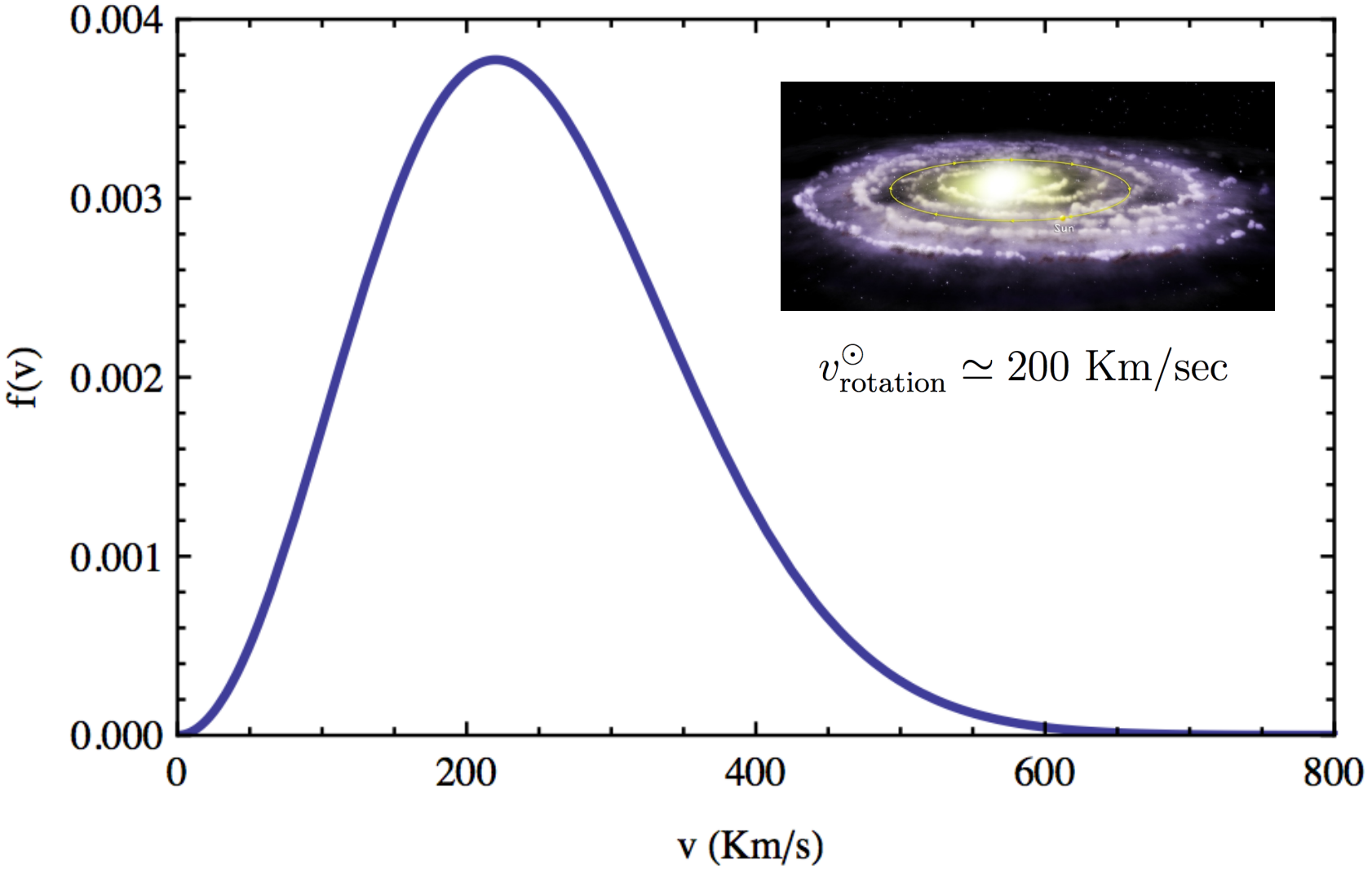
Elastic scattering

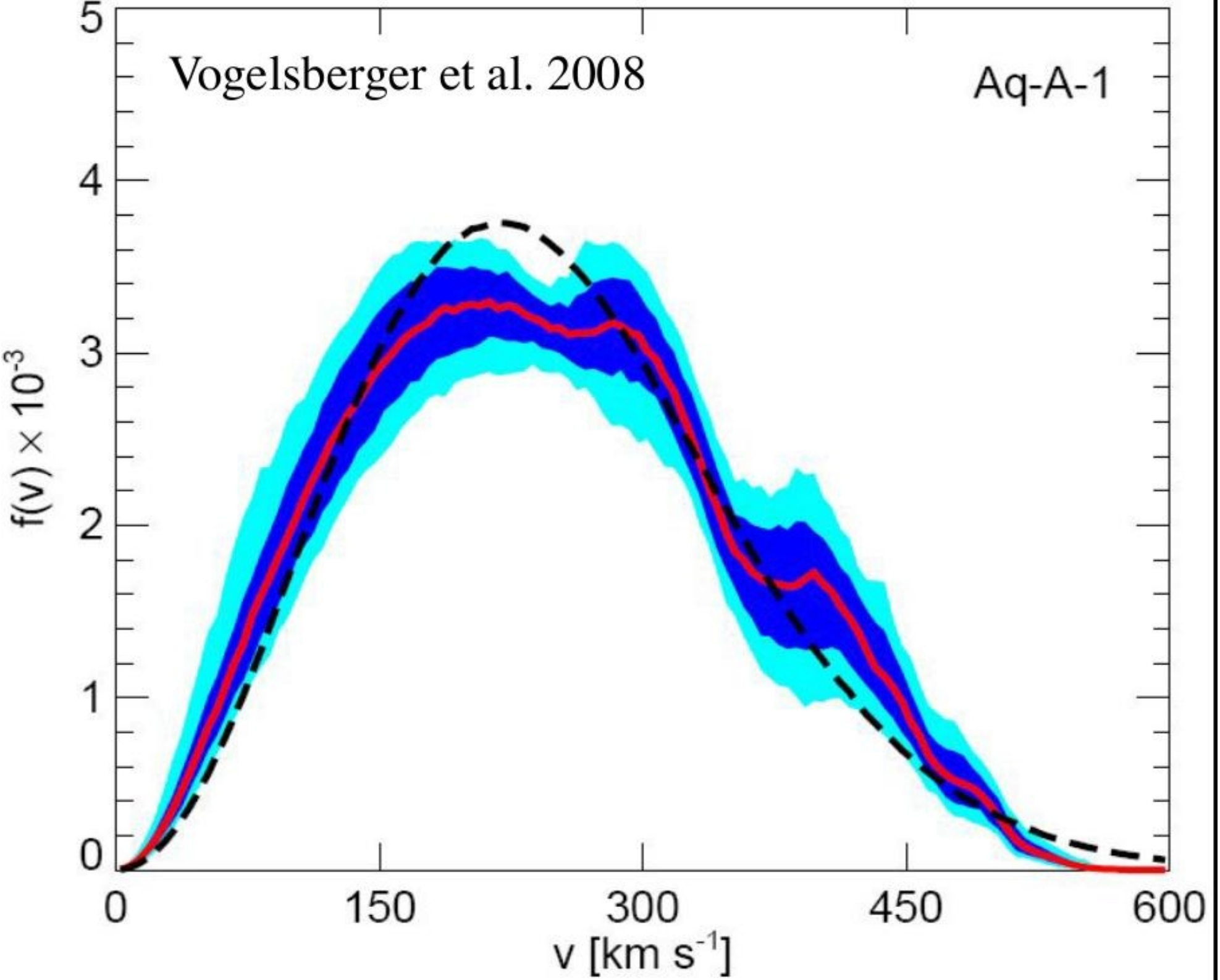
$$\chi + A \rightarrow \chi + A$$

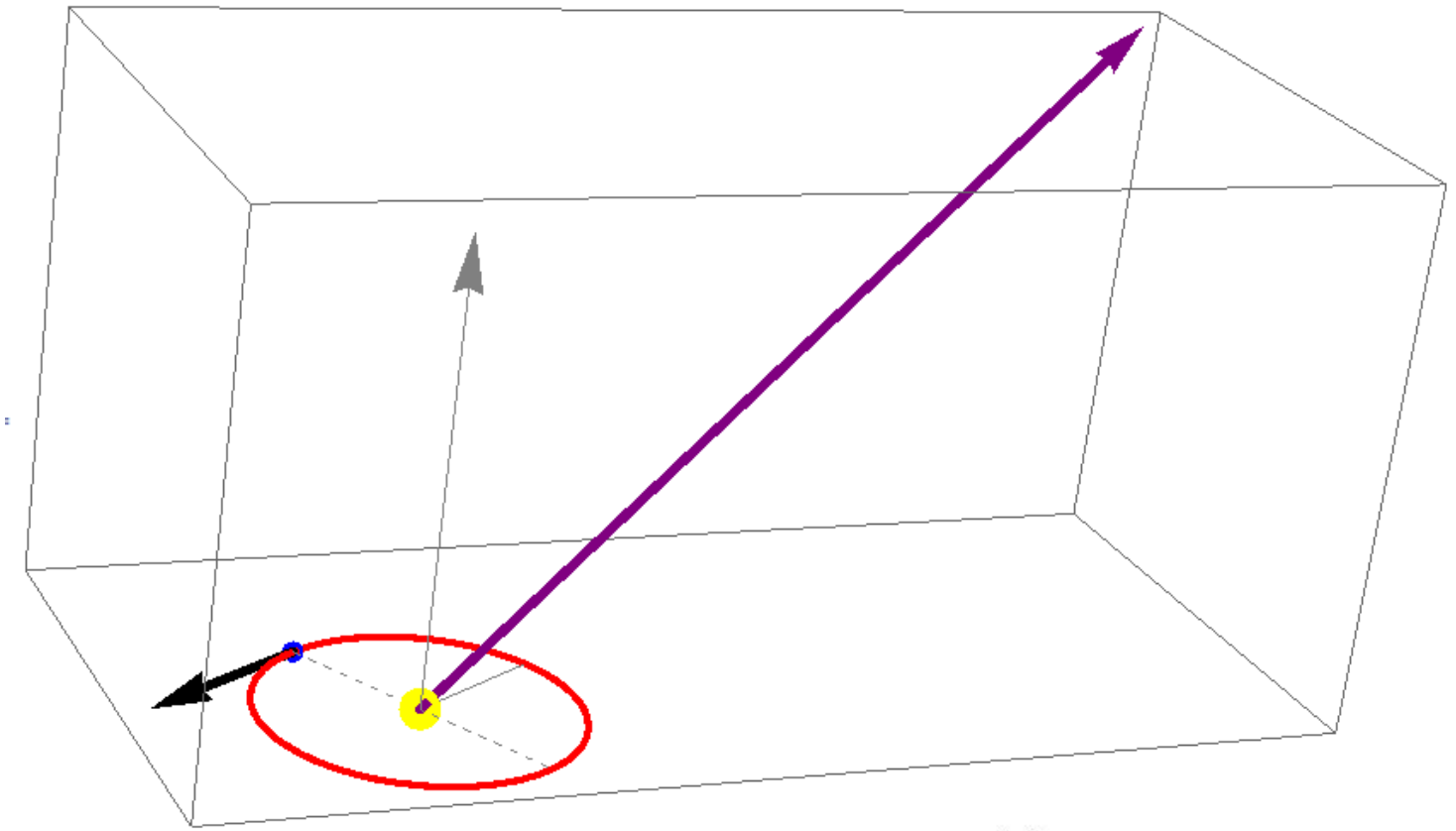


[Rita Bernabei
Gabriella Sartorelli
tuesday afternoon]

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




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



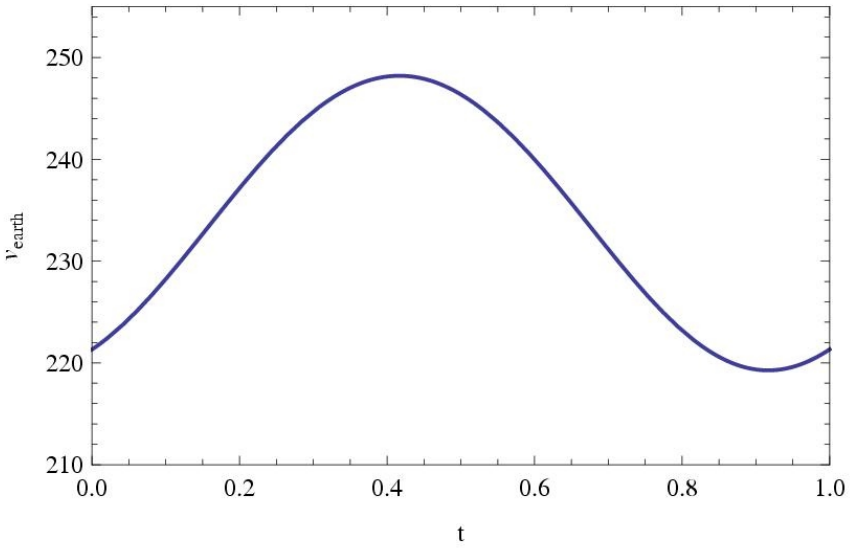
$$w_{\oplus}(t) \simeq w_{\odot} + \sin\gamma \; v_{\rm orbit} \;\; \cos\left[\omega(t - t_0)\right]$$

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

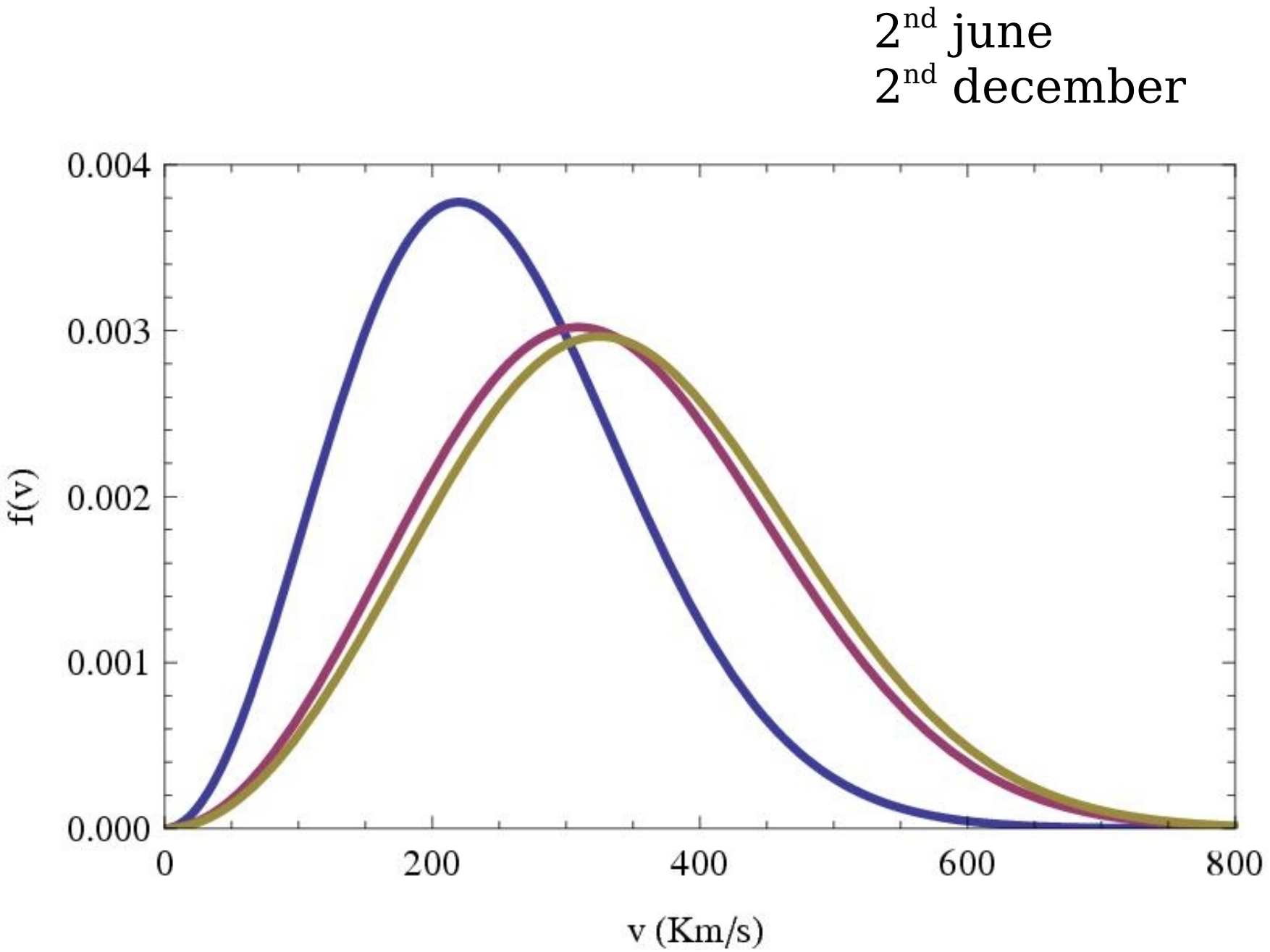
"Halo rest frame"

Velocity of Earth in the Halo rest frame

[Co-rotation ?]



Velocity distribution in the Earth Framexs



Expected flux of Dark Matter particles (here !) :

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

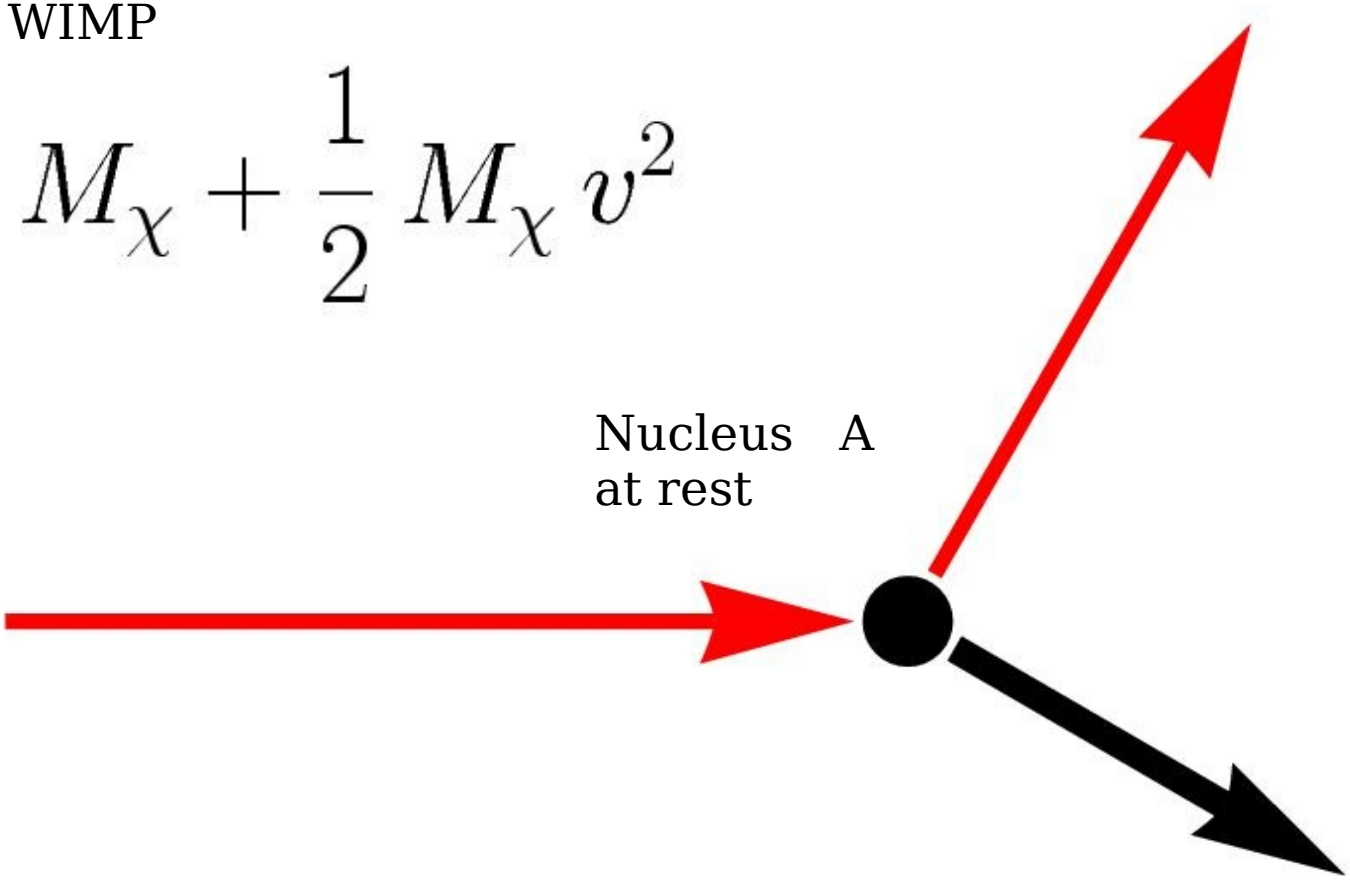
$$\simeq 1000 \left[\frac{100 \text{ GeV}}{m_\chi} \right] \quad (\text{cm}^2 \text{ s})^{-1}$$

"Direct" Search for Dark Matter

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

Non relativistic WIMP

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



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

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

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

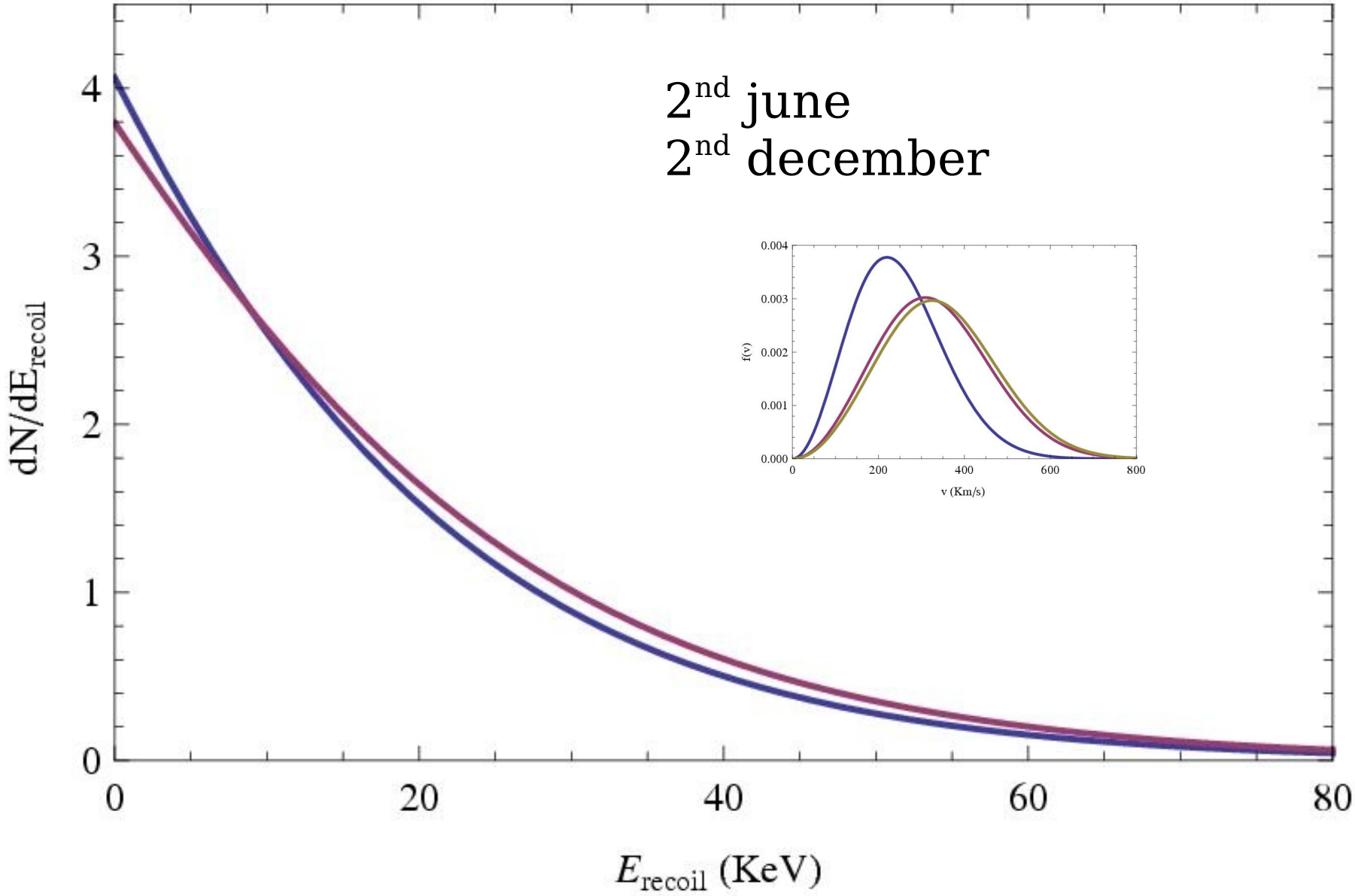
Nuclear Form Factor

Universal (A independent) function

Velocity Distribution

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

Quasi exponential distribution



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

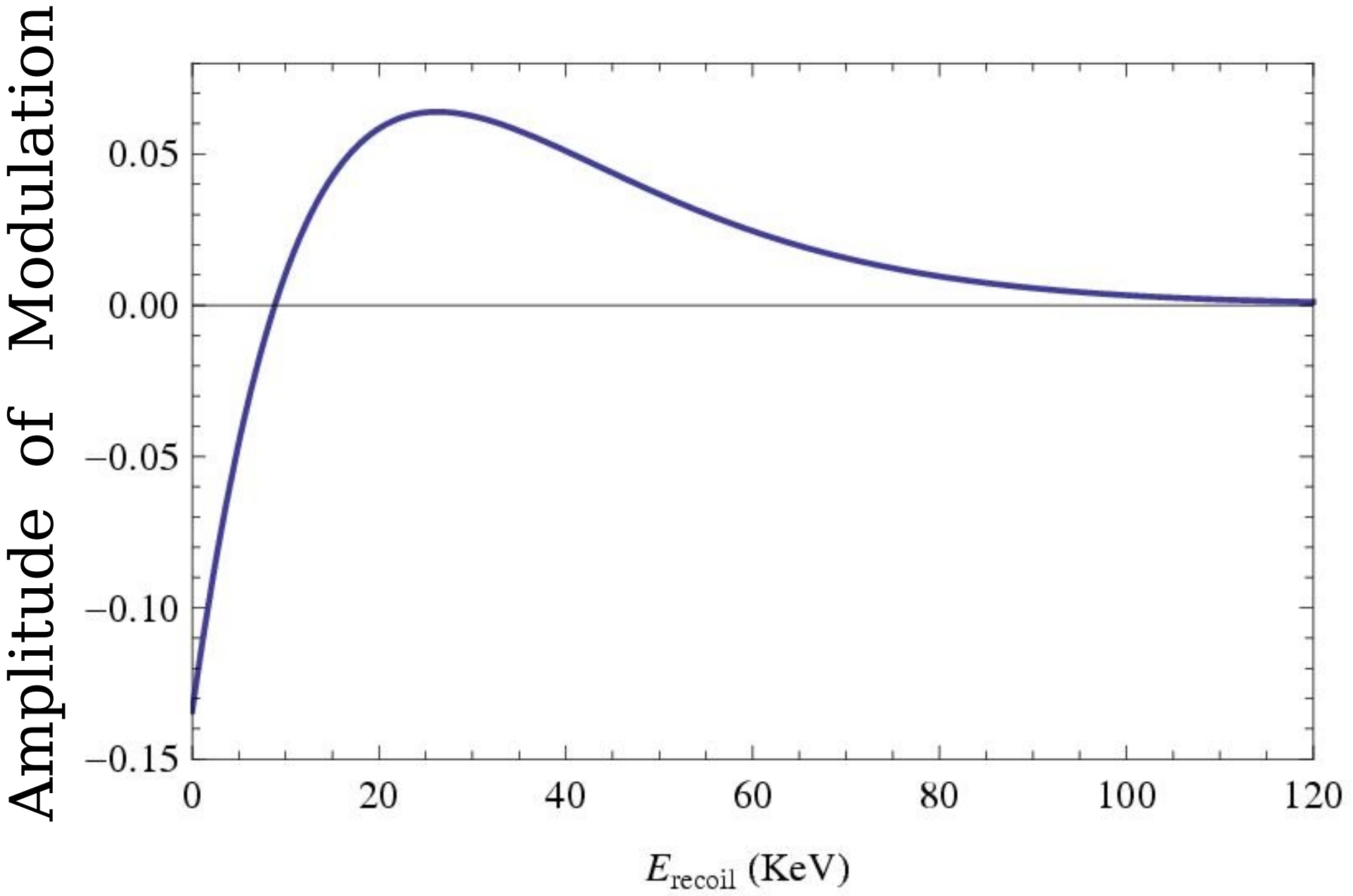
$$f(t) \simeq \cos\left[\frac{2\,\pi}{T_0}\,(t - t_0)\right]$$

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

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

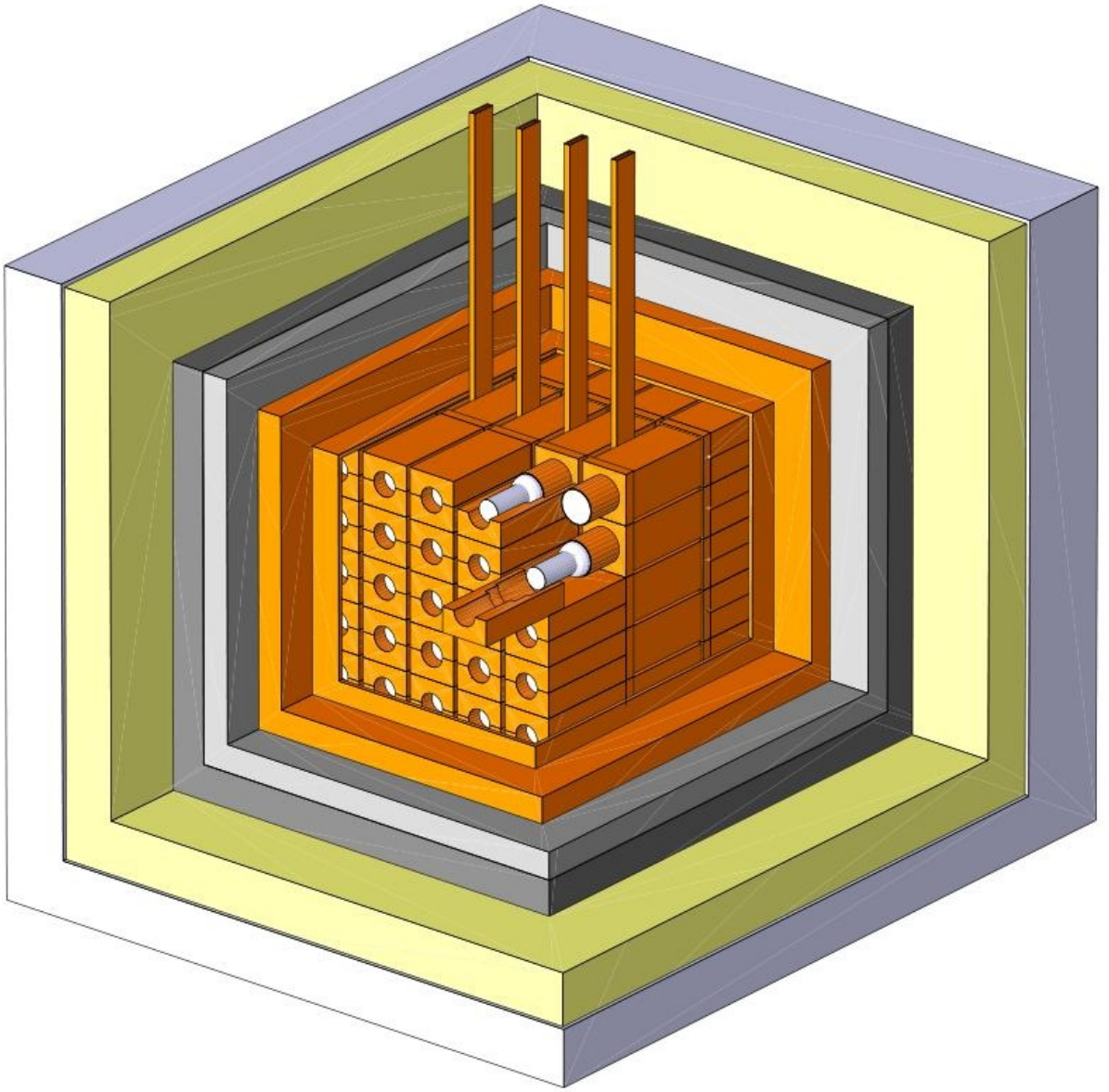
A = 127 (Iodium)

M_{wimp} = 50 GeV



DAMA-LIBRA (Gran Sasso underground Laboratory)

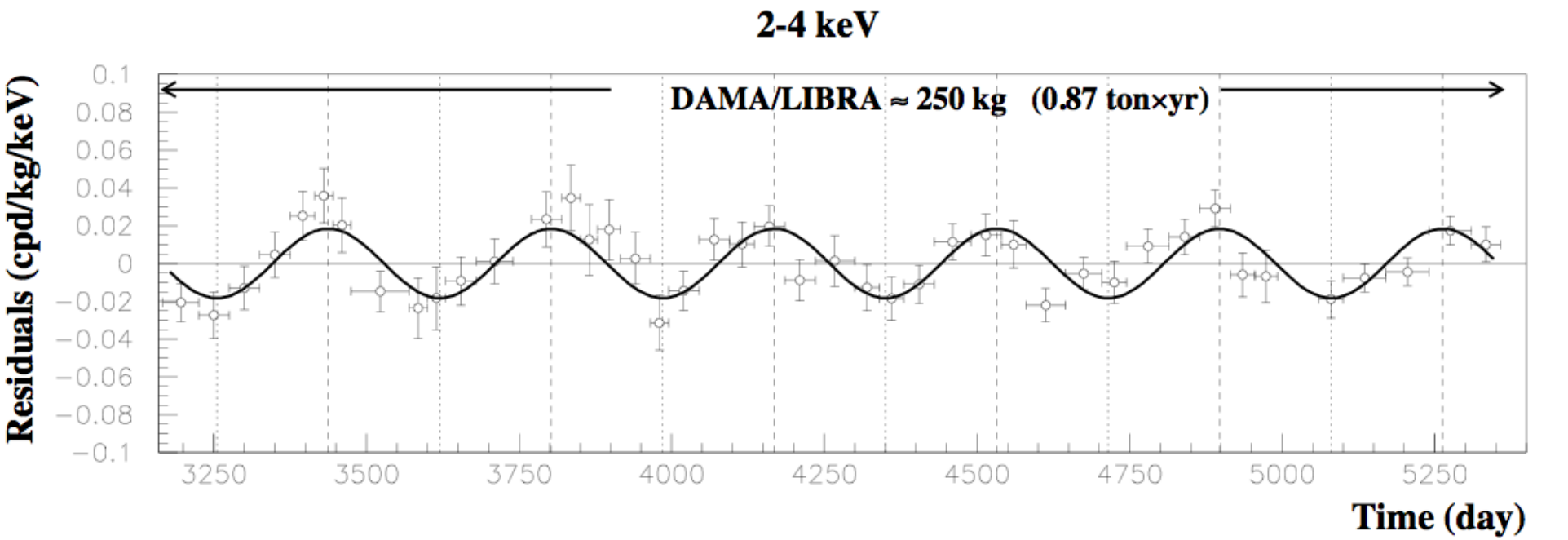
250 Kg NaI scintillator.

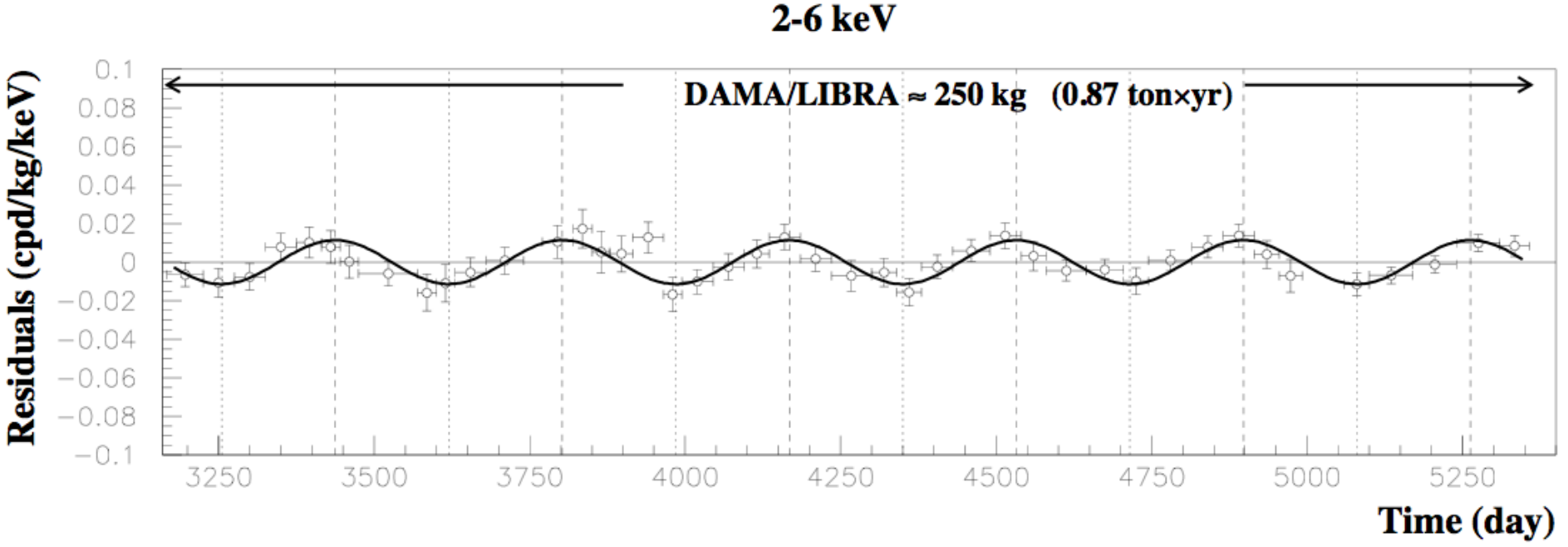


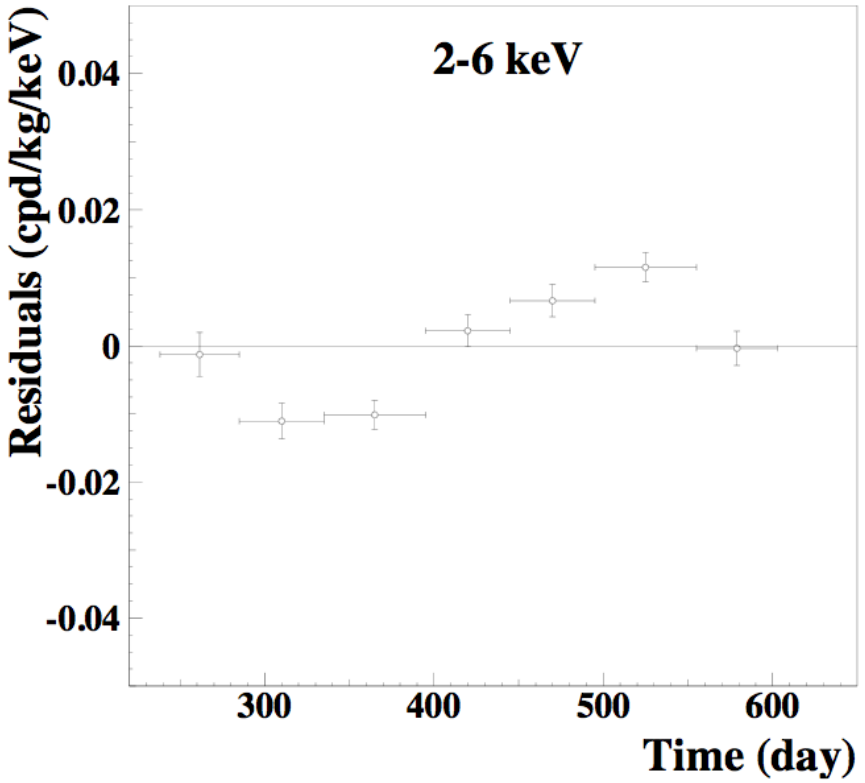
Observation
of sinusoidal
time-modulation of the
Energy Deposition Rate

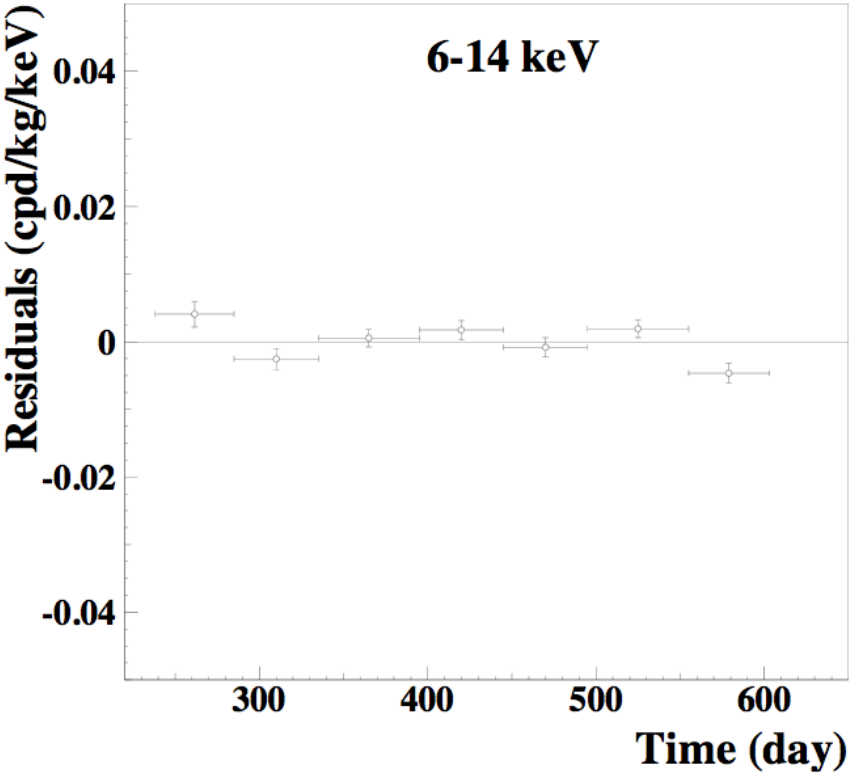
(controversial)
claim of evidence
of detection of
Galactic Dark Matter

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


2-4 keV
DAMA/LIBRA ≈ 250 kg (0.87 ton×yr)
Residuals (cpd/kg/keV)
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
Time (day)

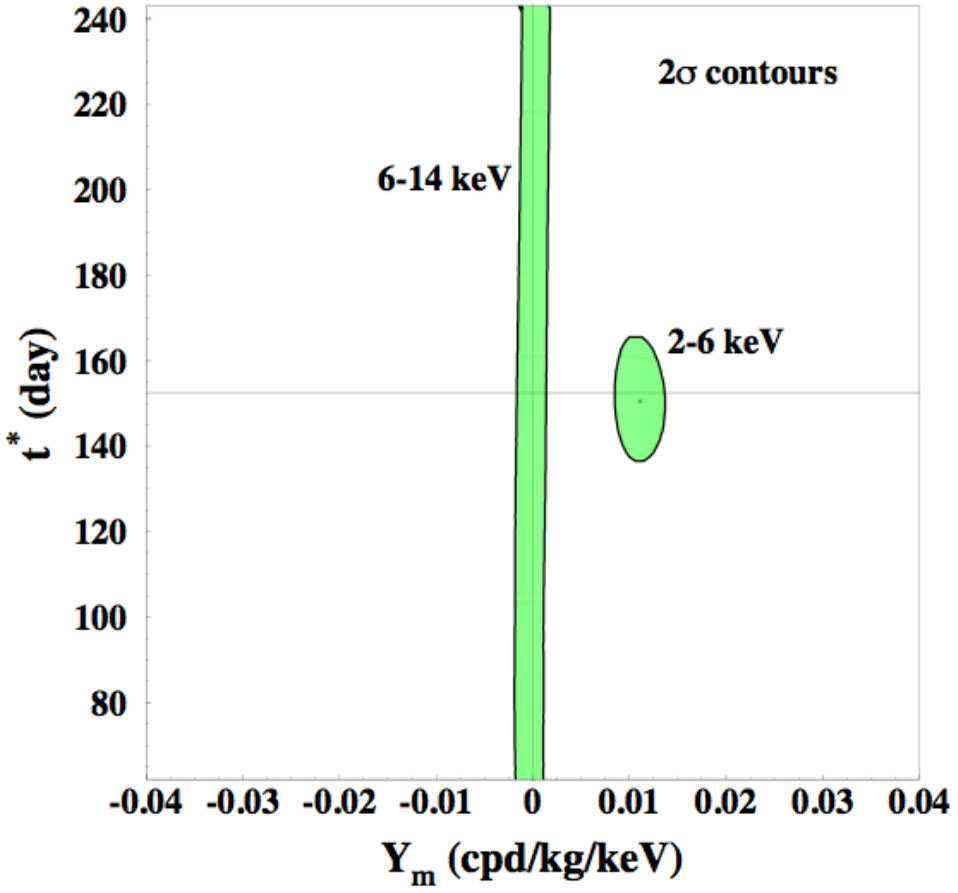

2-6 keV
DAMA/LIBRA ≈ 250 kg (0.87 ton×yr)
Residuals (cpd/kg/keV)
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
3250
3500
3750
4000
4250
4500
4750
5000
5250
Time (day)





Robust evidence for the existence of a
Sinusoidal time modulation of single hits signals:

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 $= 3.6 \times 10^{-5}$	χ^2/d.o.f. $= 147.4/80$ $\rightarrow$ P $= 6.8 \times 10^{-6}$
2-5	χ^2/d.o.f. $= 82.1/43$ $\rightarrow$ P $= 3.1 \times 10^{-4}$	χ^2/d.o.f. $= 135.2/80$ $\rightarrow$ P $= 1.1 \times 10^{-4}$
2-6	χ^2/d.o.f. $= 68.9/43$ $\rightarrow$ P $= 7.4 \times 10^{-3}$	χ^2/d.o.f. $= 139.5/80$ $\rightarrow$ P $= 4.3 \times 10^{-5}$



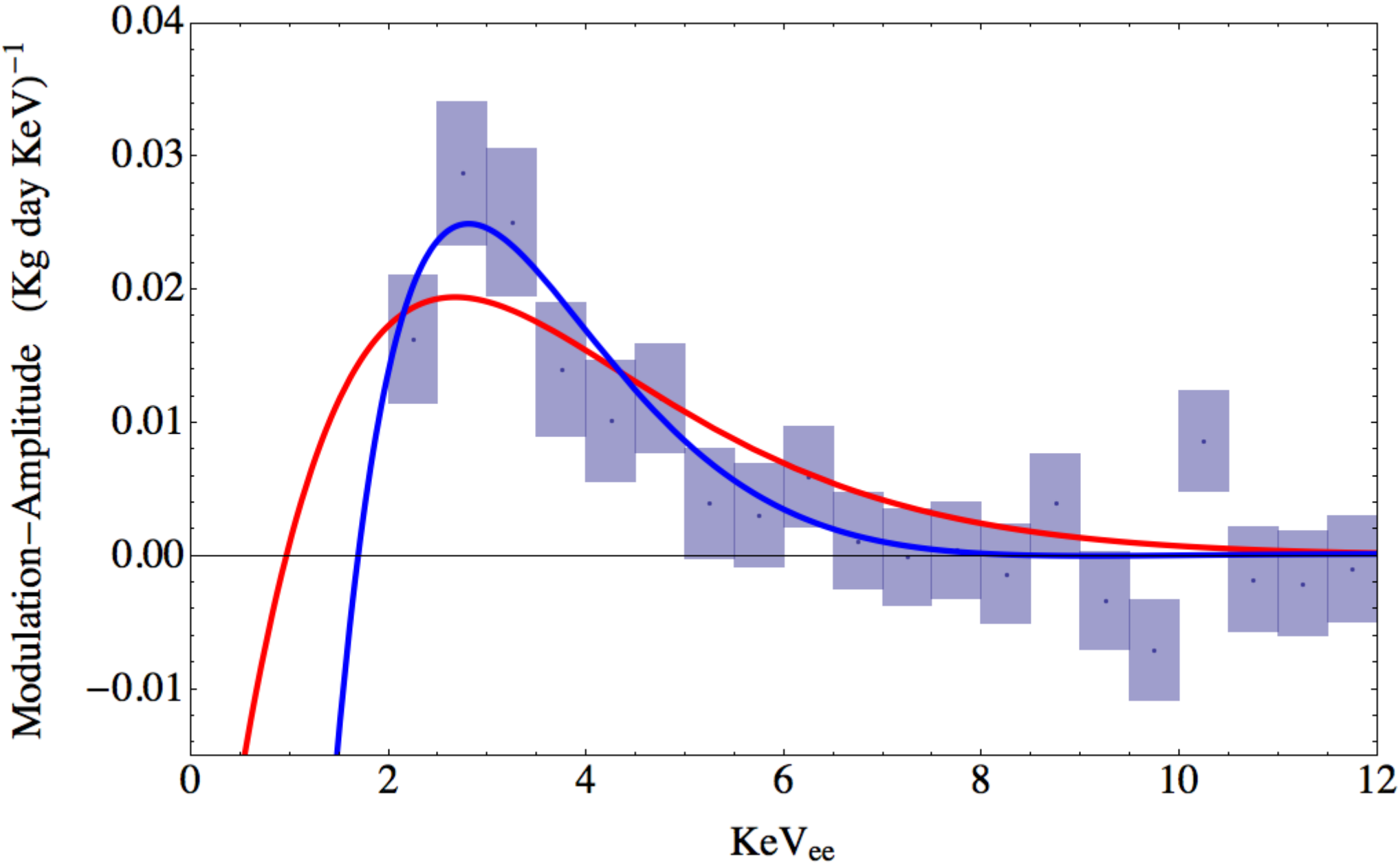
Period one year.
(… well obvious…)

"Phase"
Is centered
At the "right" value (!!)

Maximum
The 2nd june
day: (146 ± 7)

Fundamental discovery ?!

Unknown background
(with coincident phase) ?


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
KeVee

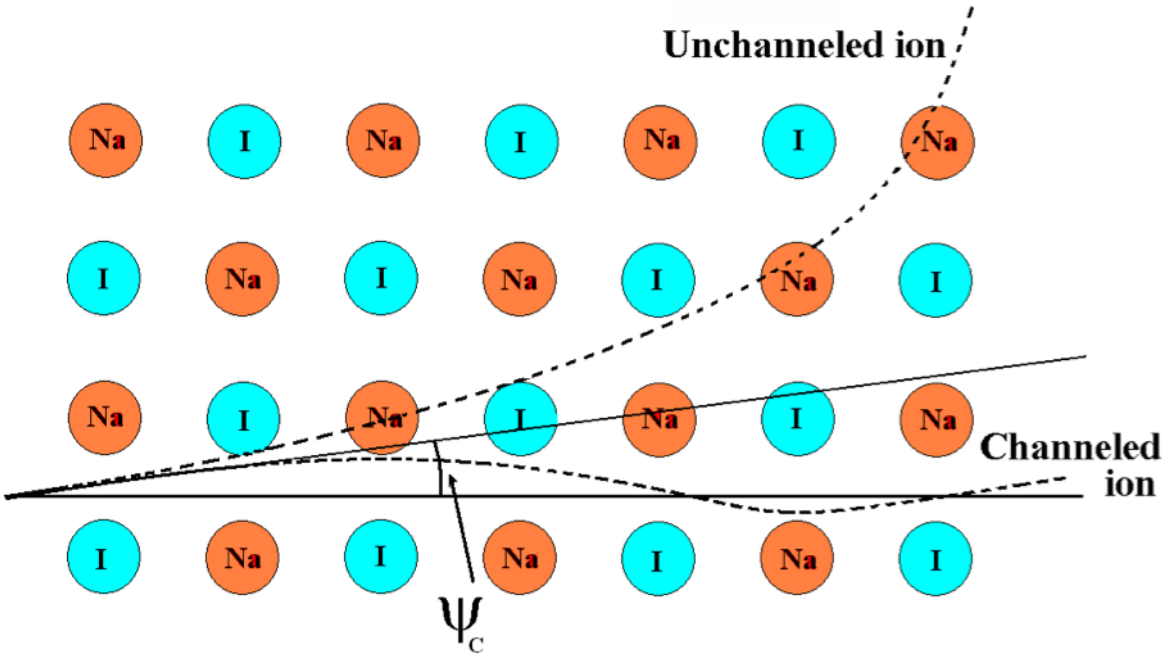
Relation between Light collected by PMT and E_{recoil}

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

In presence of “channeling”
Scattering in certain directions

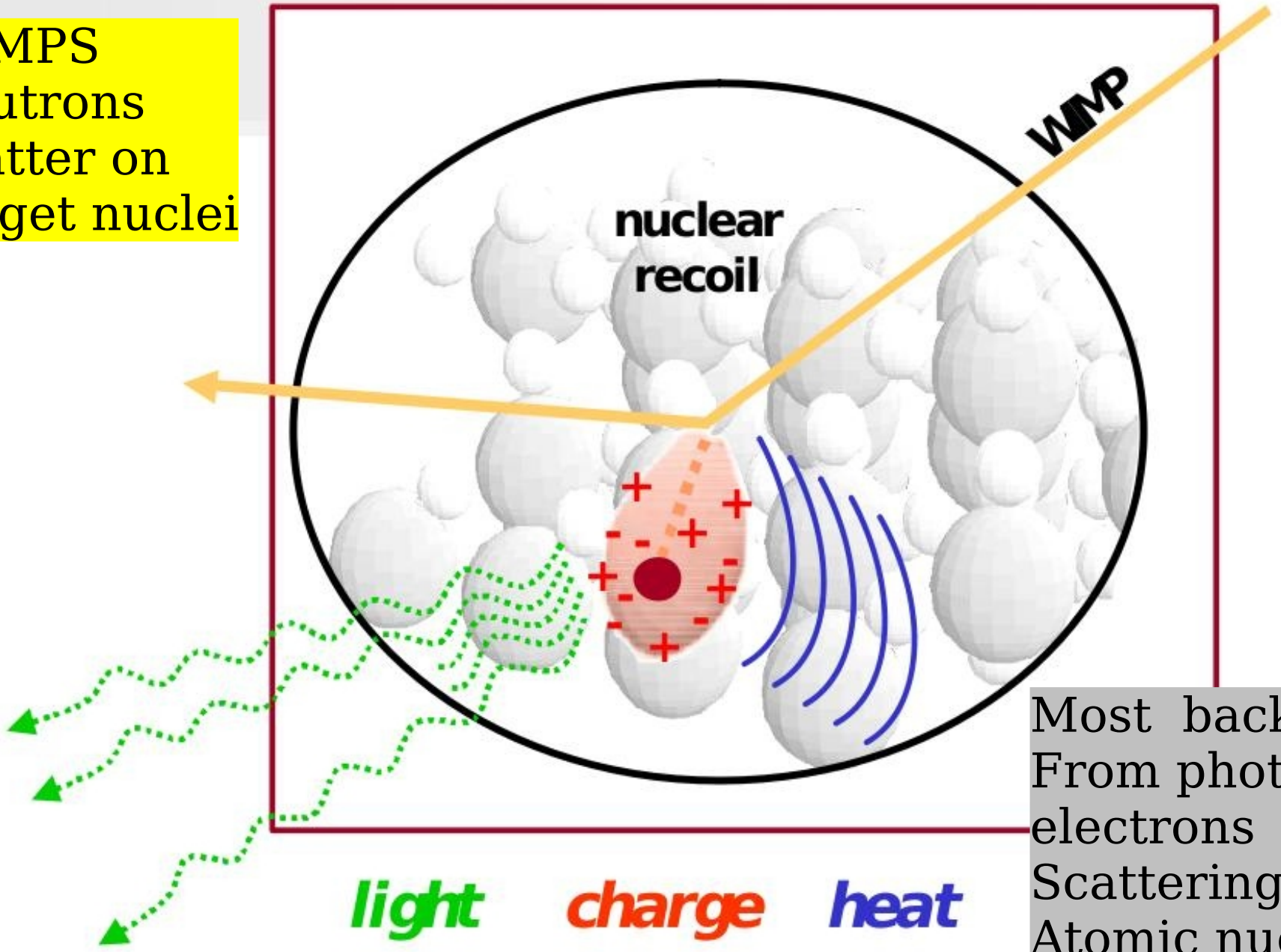
E(recoil) = 1.0 * E(electron-equivalent)

Important
Ambiguity
In the interpretation
Of the energy scale



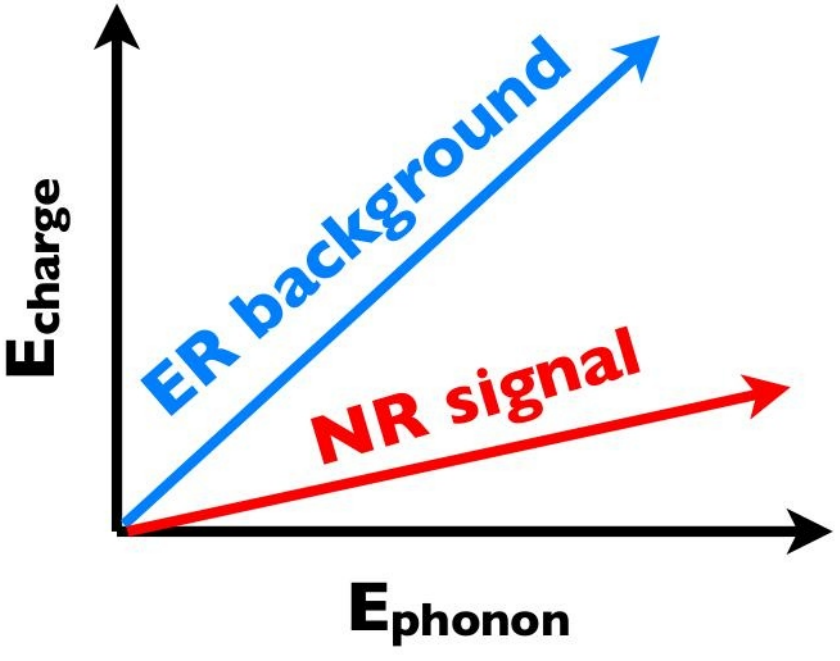
WIMP detection

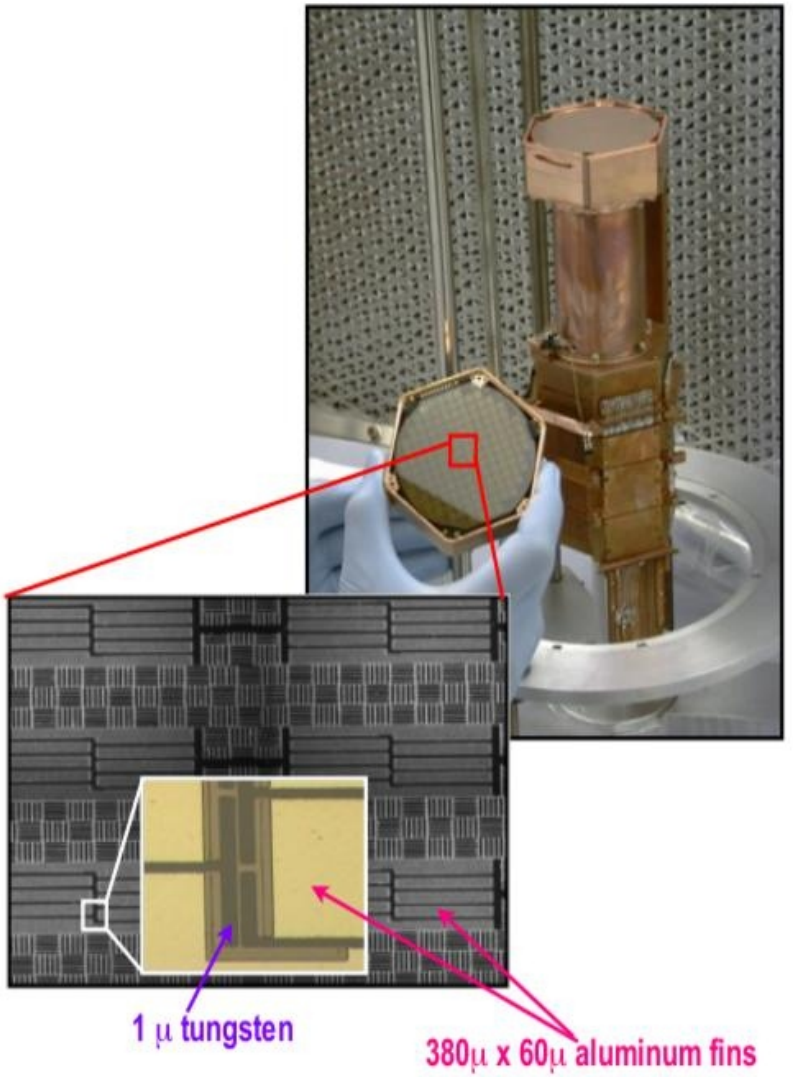
WIMPS
Neutrons
Scatter on
Target nuclei



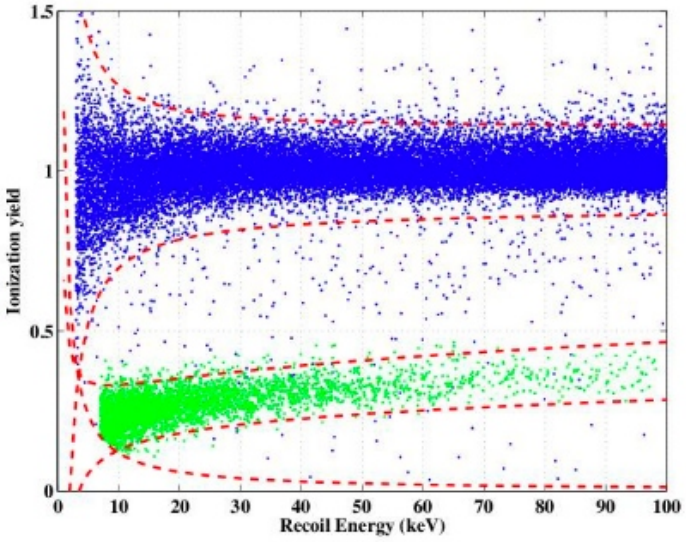
Most background
From photons and
electrons
Scattering on
Atomic nuclei

CDMS II ZIP Detectors



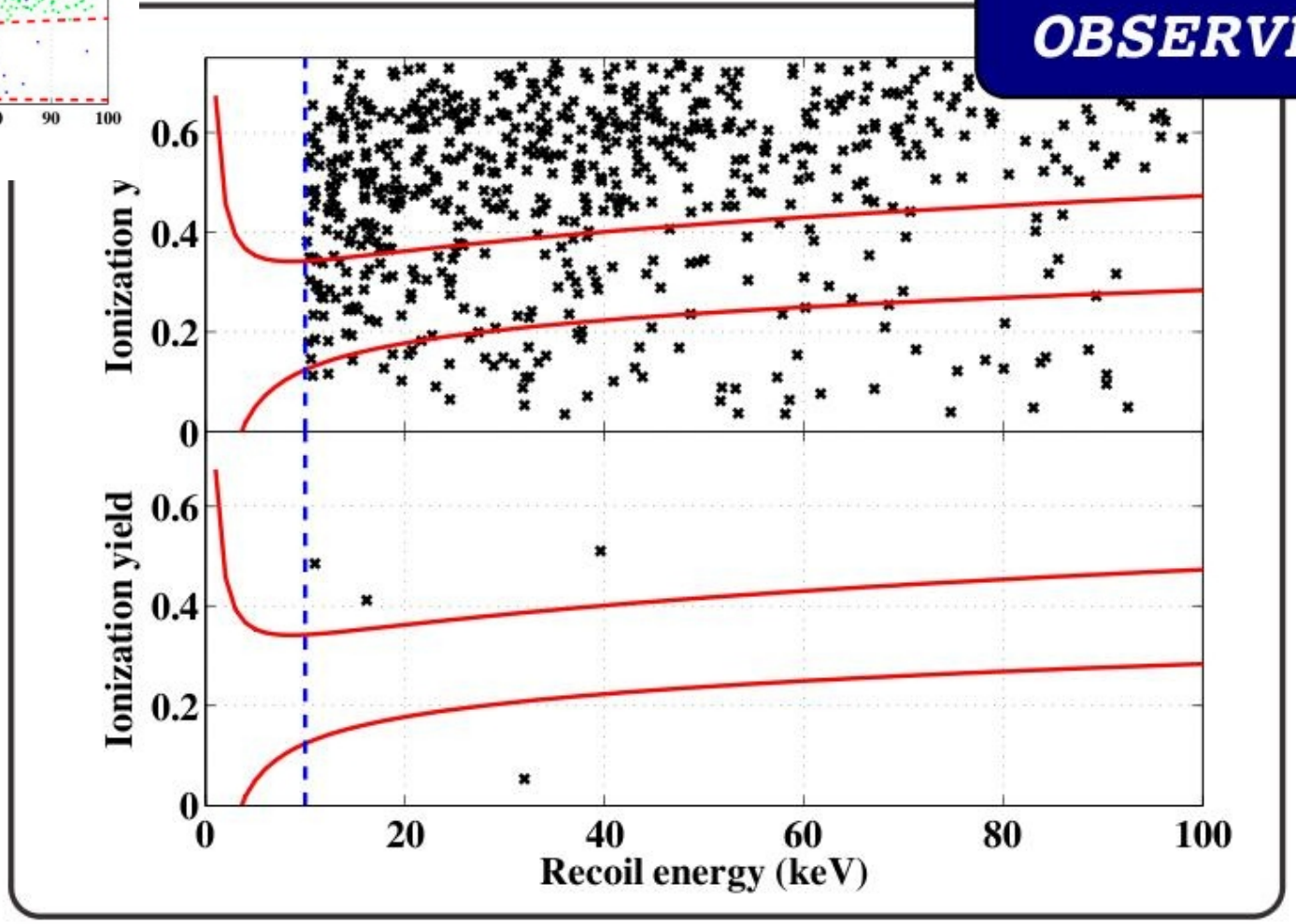


- surface rejection from pulse shapes
- 30 detectors stacked into 5 towers of 6 detectors



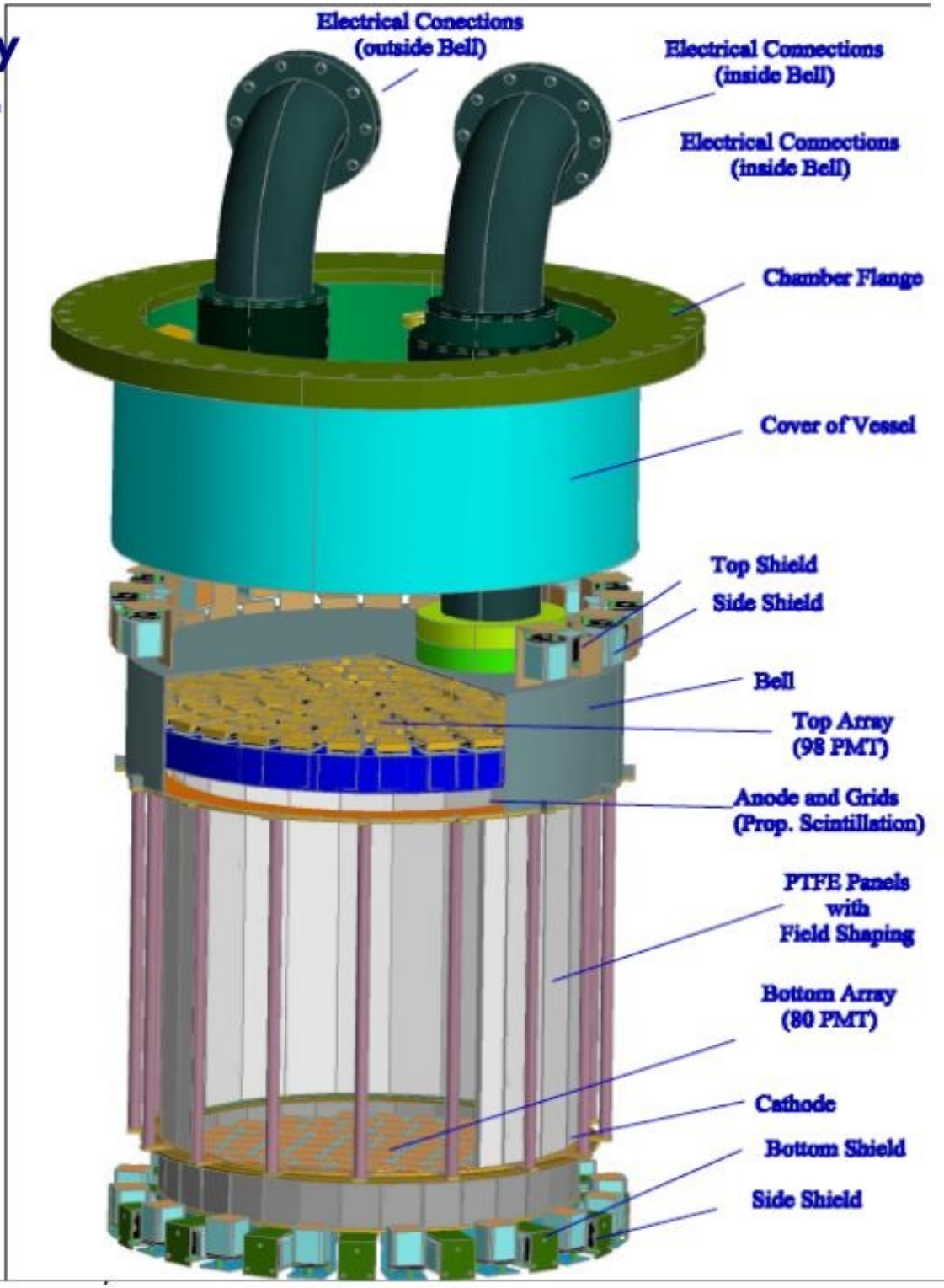
CDMS II Results

NO EVENTS OBSERVED!

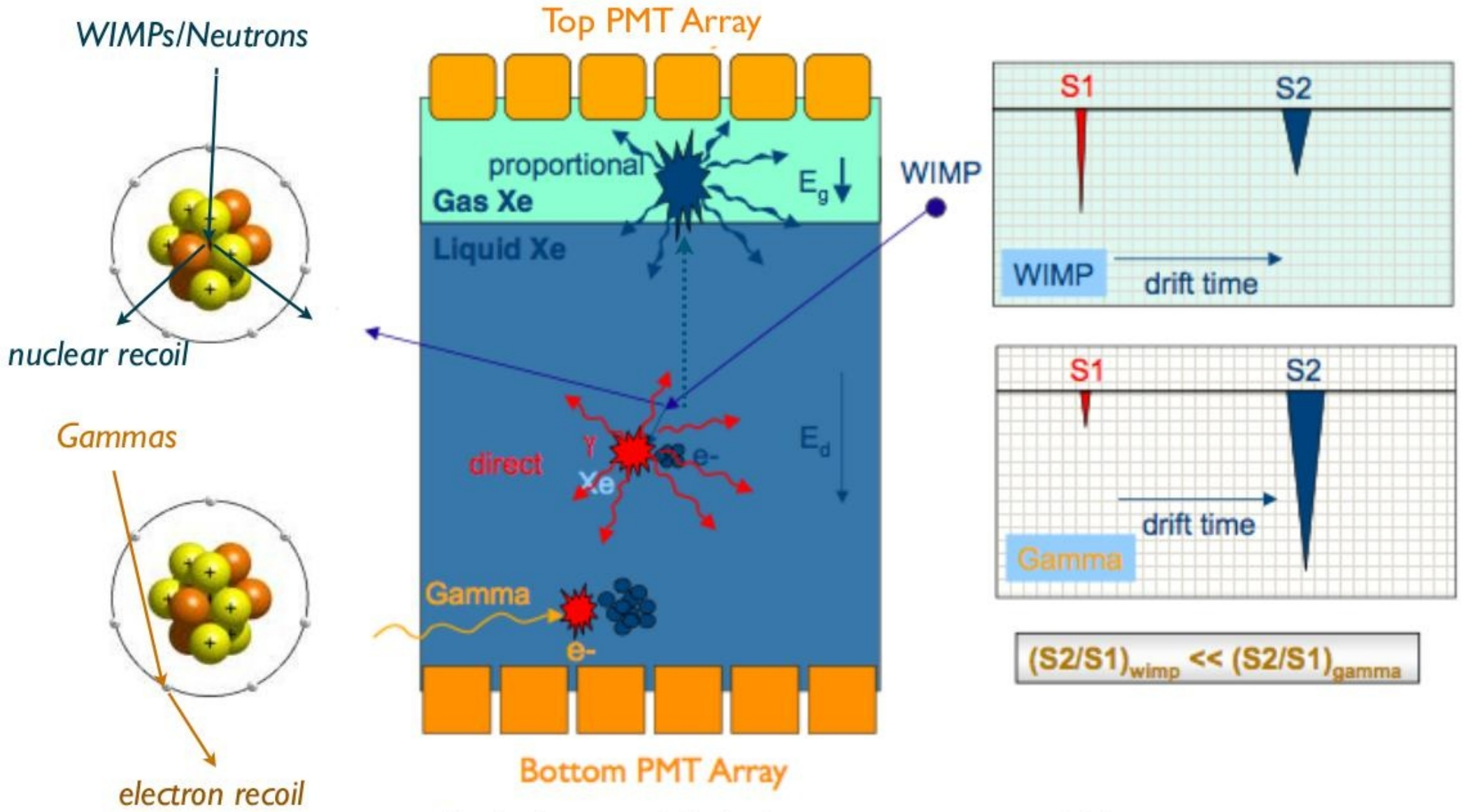


PRL 102, 011301 (2009)

XENON100: The TPC Assembly



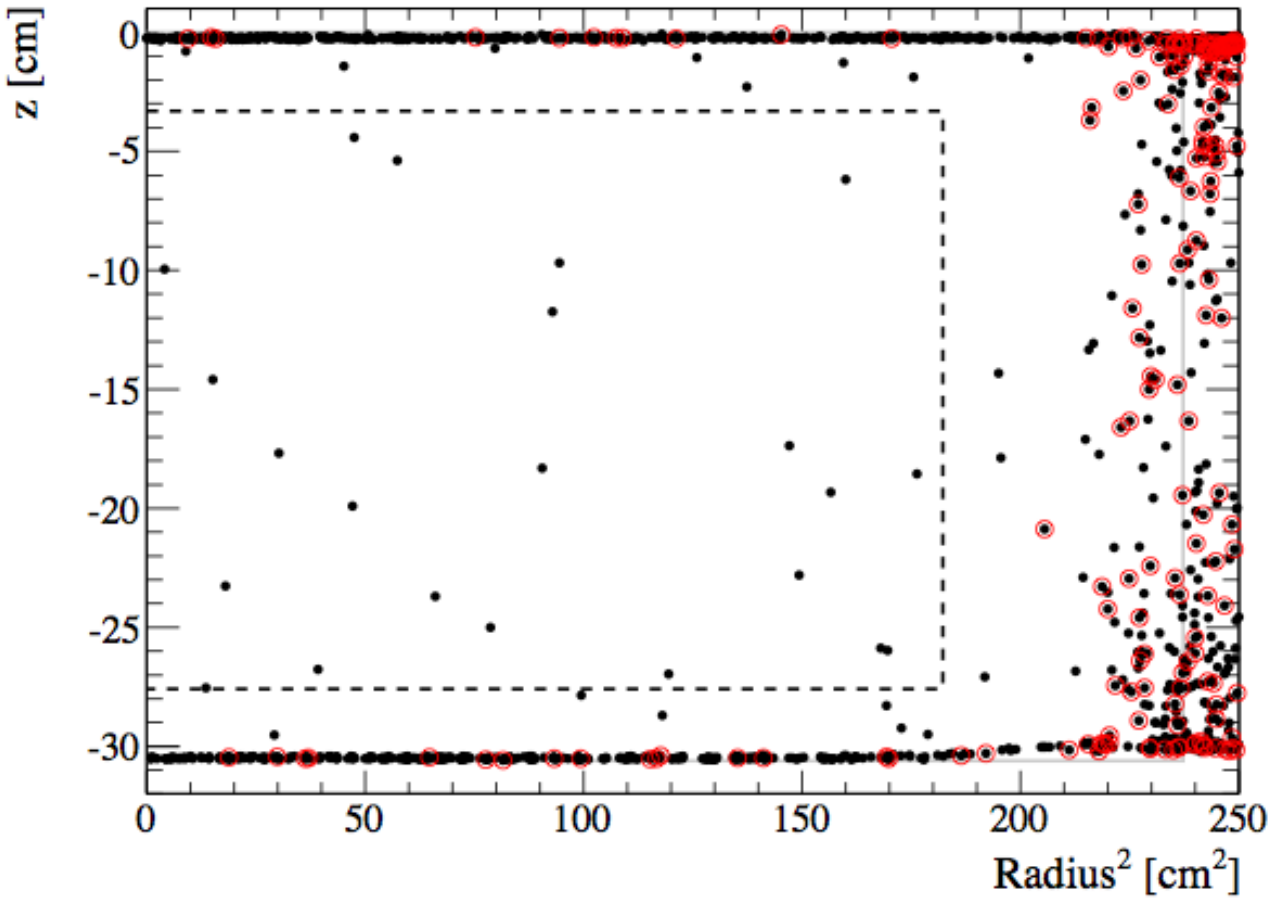
The XENON two-phase TPC



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

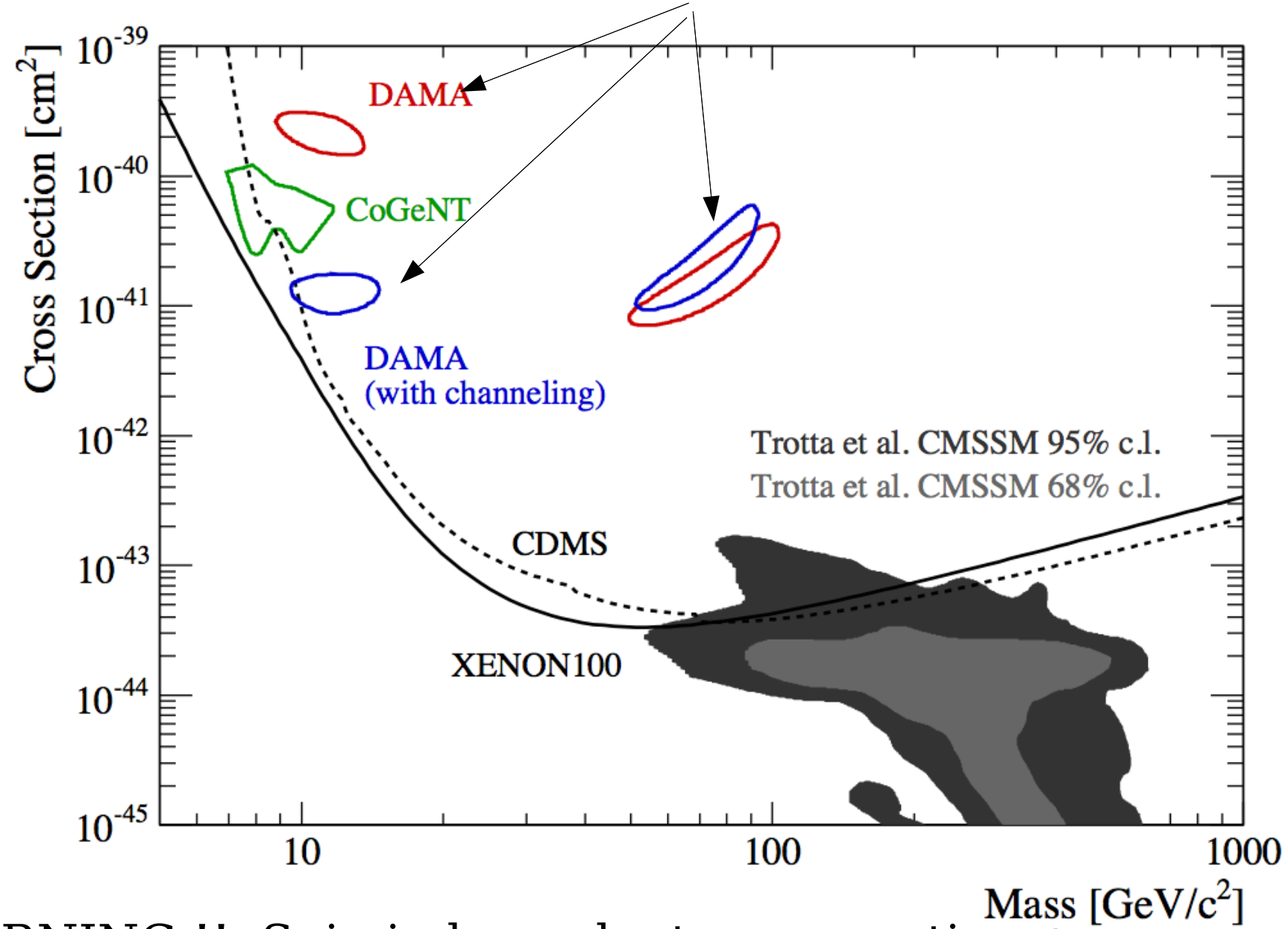
Xenon-100 (liters) results

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



[computed by Gelmini et al.]

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



WARNING !! Spin independent cross section +
A number of assumptions enter in this exclusion plot

Intense controversy around these results and their interpretation.

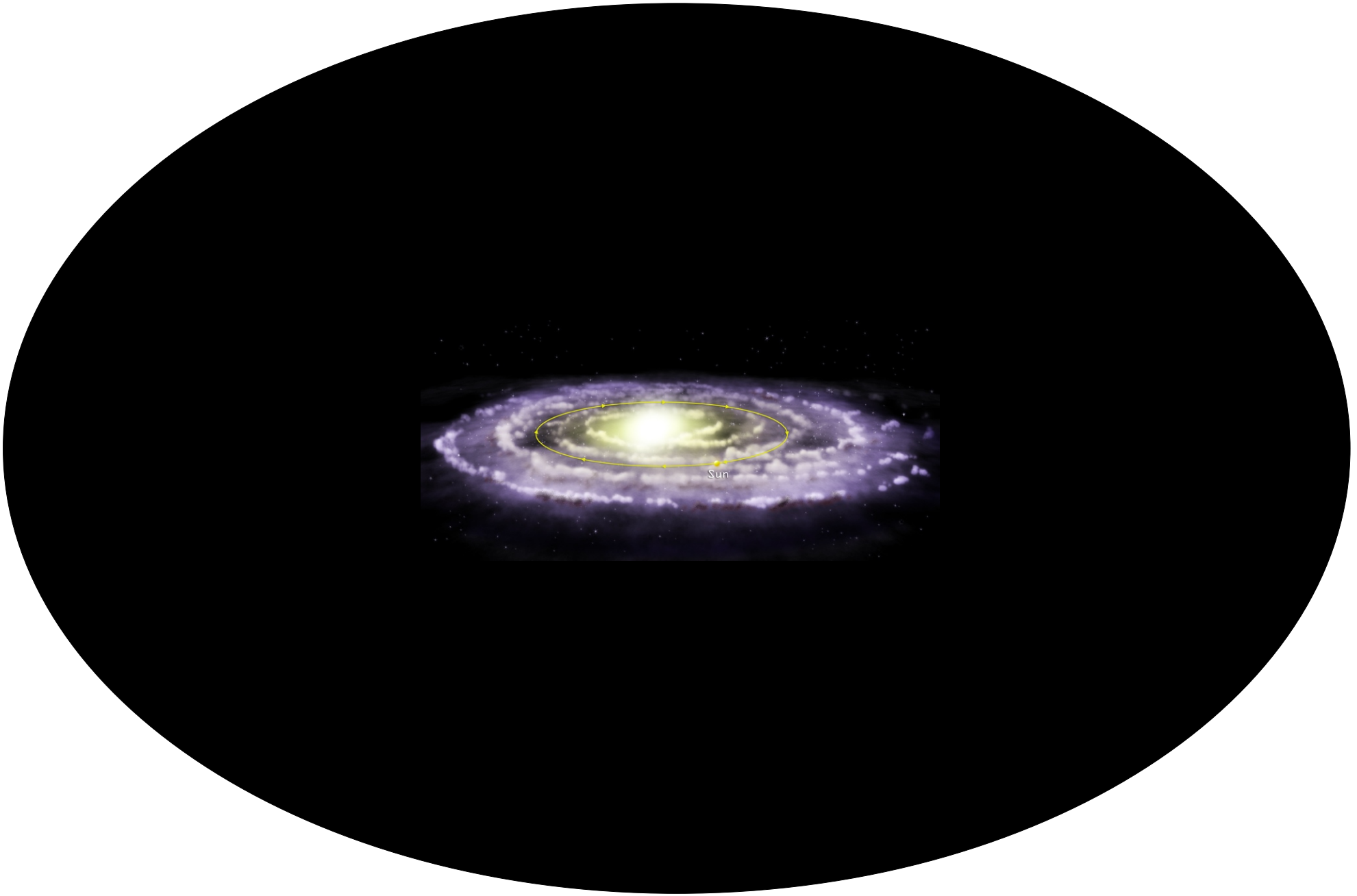
Is it possible that DAMA is detecting
a time dependent background
that by “coincidence” has the “right” features
that mimic Dark Matter ?
[Crucial test: repeat in different environment
(south hemisphere ?)]

If DAMA does see a DM signal:
why the other detector do not see a signal ?
Experimental problems ?!
Unexpected properties of DM particles ?!

Several other experiments are taking data
What should they see?

Indirect searches for DARK MATTER

3rd Road
To WIMP's Discovery



Power injection for Dark Matter annihilation

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

$$\chi + \chi \rightarrow \gamma \quad e^+ \quad \overline{p} \quad \nu_\alpha$$

Injection of energy because of DM annihilation in Our own galaxy.

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]

Astrophysical information

Dark Matter in the Milky Way

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

Dark Matter
density distribution

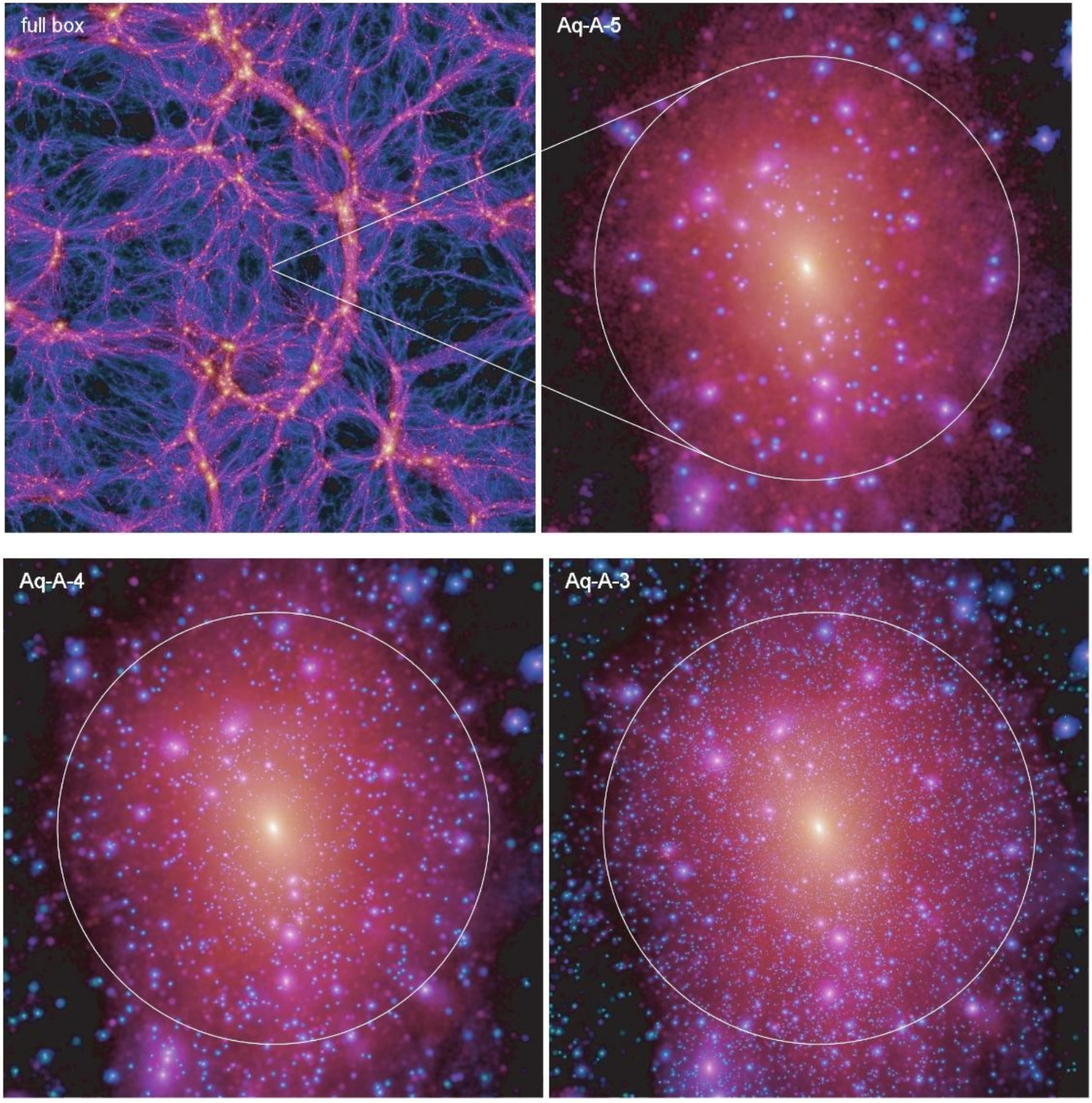
$$f_{\rm dm}(\vec{v},\vec{x})$$

Velocity distribution

[consistency requirement]

Problems:

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


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

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

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

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

  “Granularity” boosts the power output.

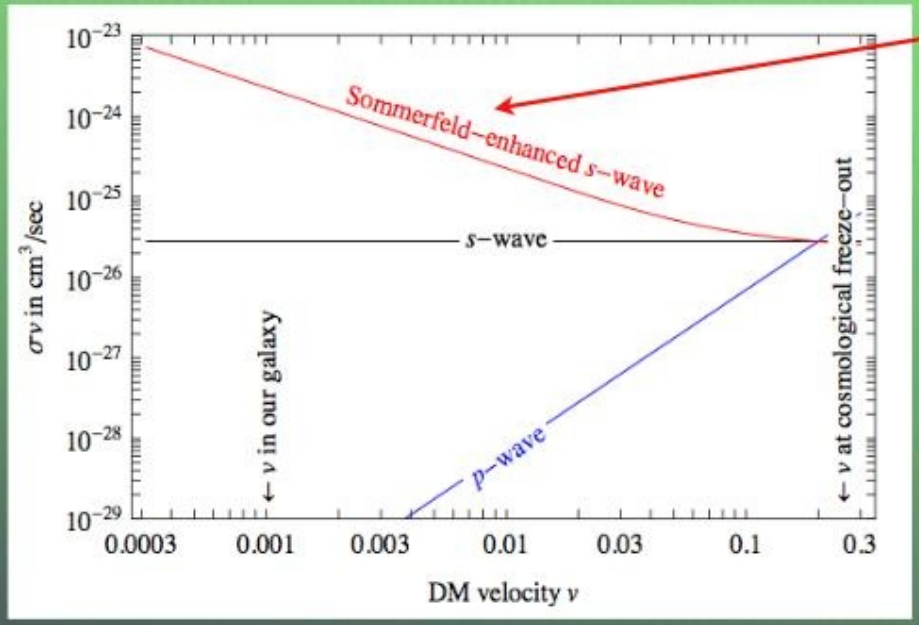
- The “WIMP miracle”

  $$v_{\rm freeze\ out} \simeq 0.2 \div 0.3$$

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

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

Annihilation cross section

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

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

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

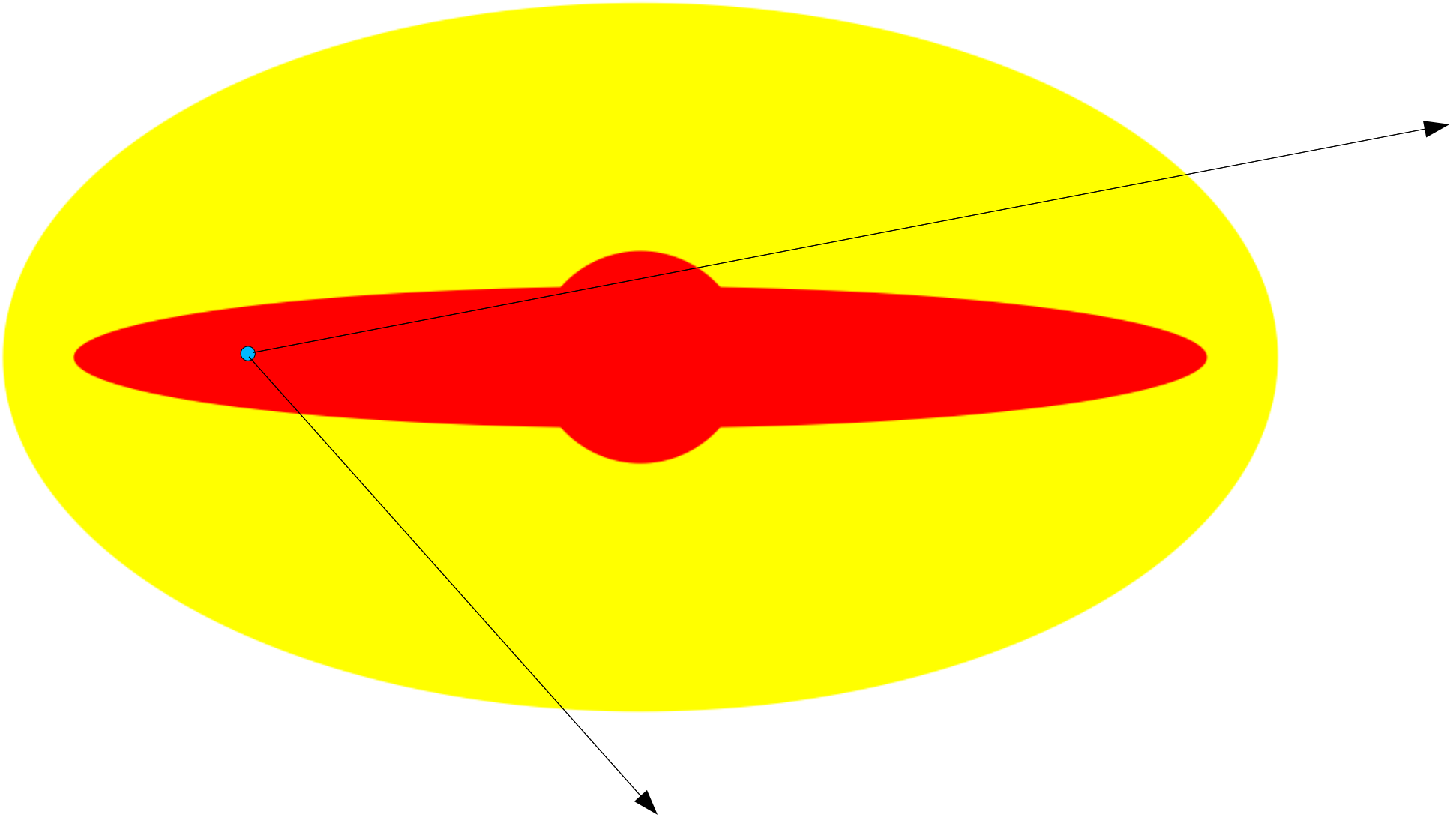
Inclusive spectra

In most models DM particle = Majorana particle

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

Branching Ratios in different final states F

Photon emission from DM annihilation



$$J(\Omega) = \frac{1}{R_\odot} \int d\ell \, \frac{\rho^2(\ell, \Omega)}{\rho_\odot^2}$$

Photons from Dark Matter

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

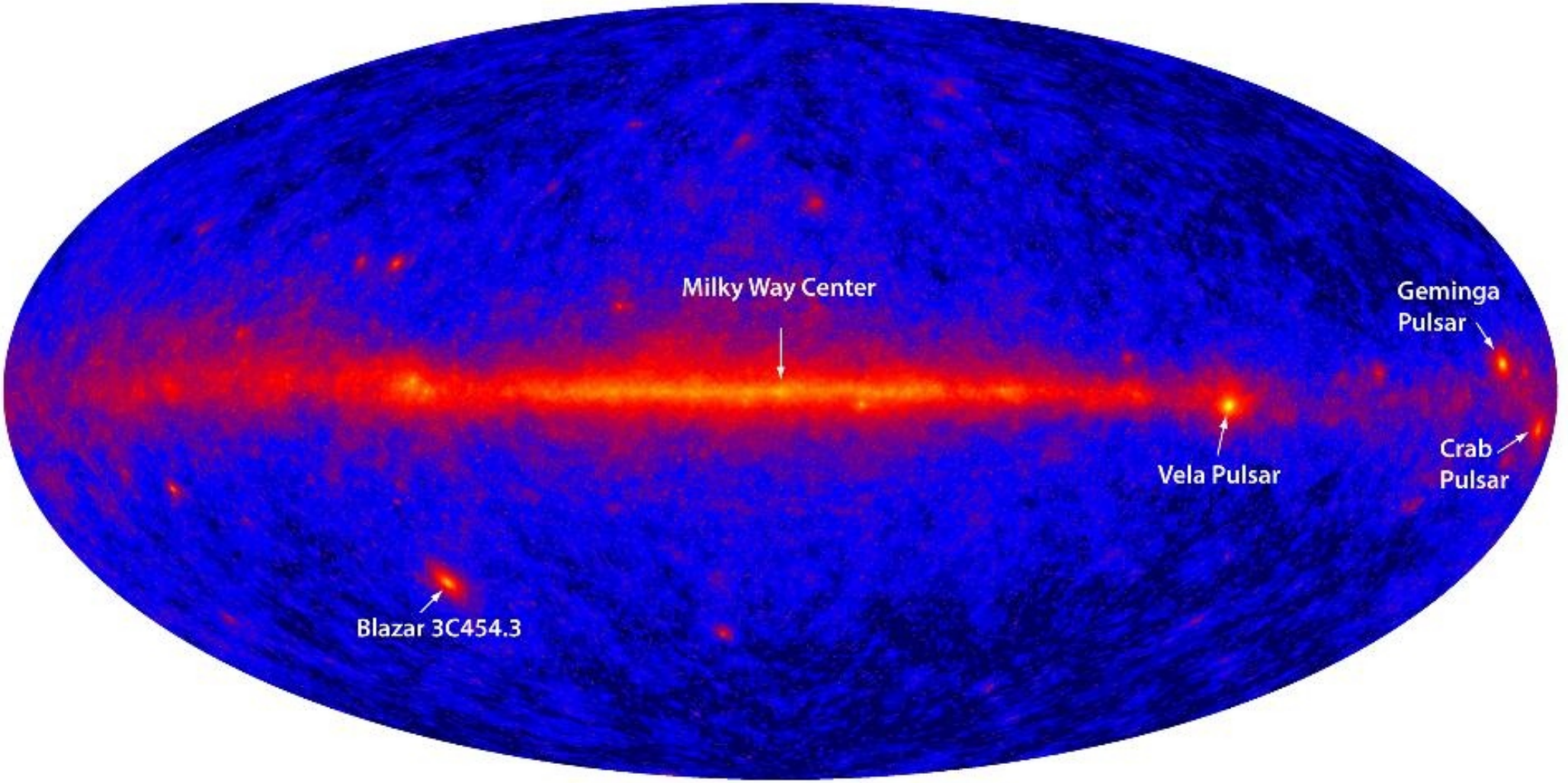
→ Spectrum

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

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

$$J(\Omega) = \frac{1}{R_\odot} \int d\ell \; \frac{\rho^2(\ell, \Omega)}{\rho_\odot^2}$$

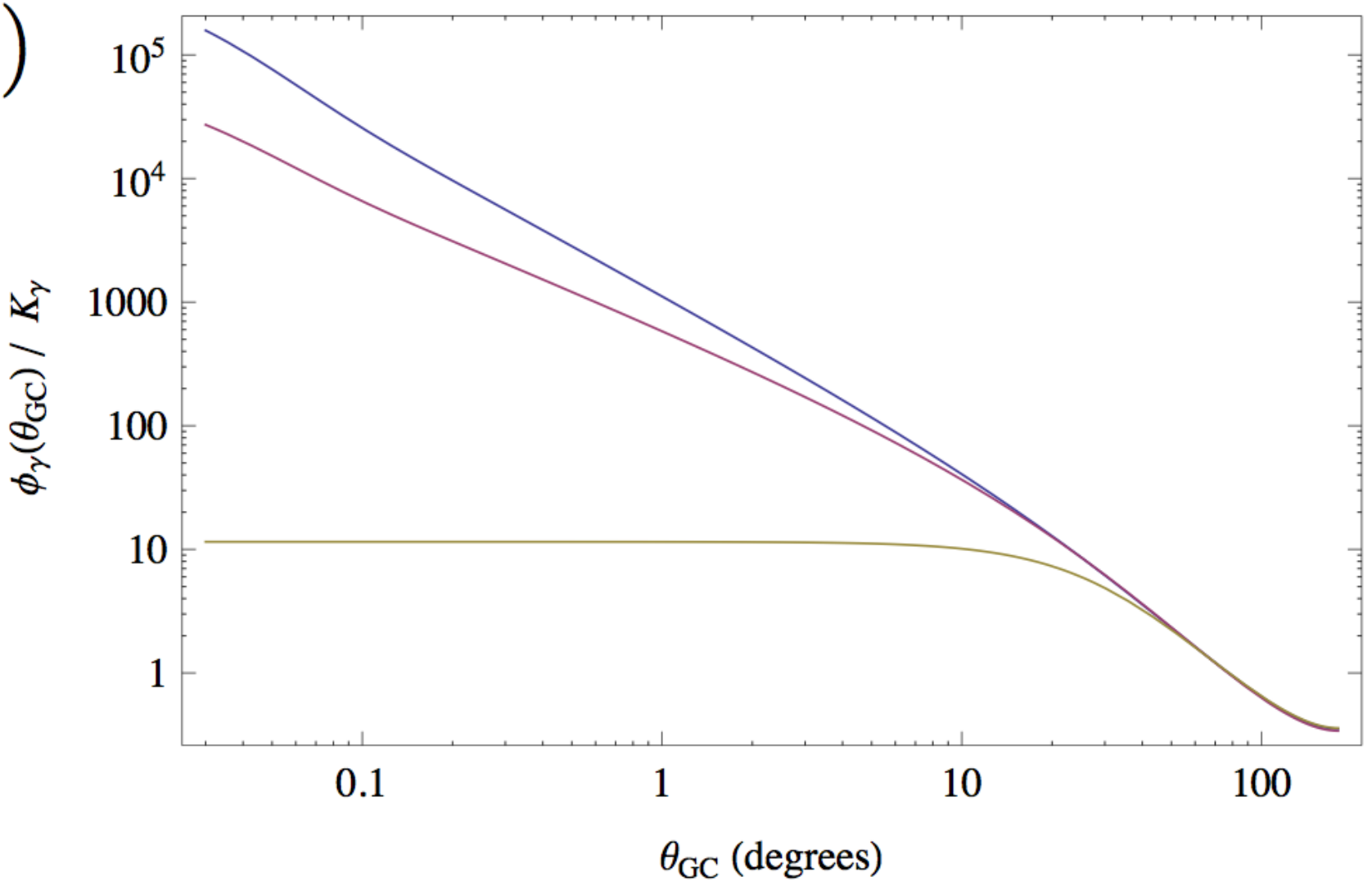
Adimensional
Angular factor

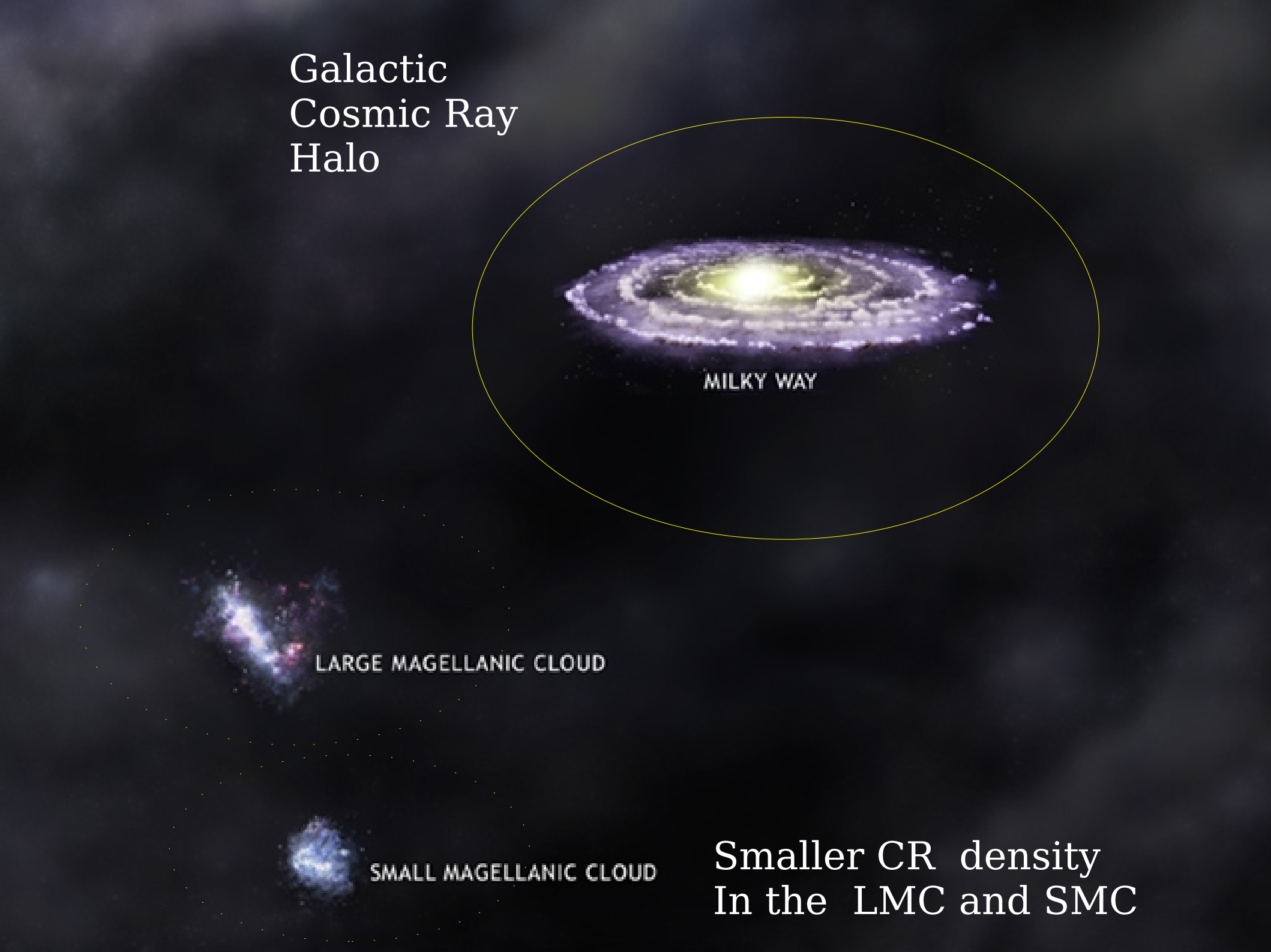


$E_\gamma > 100$ MeV

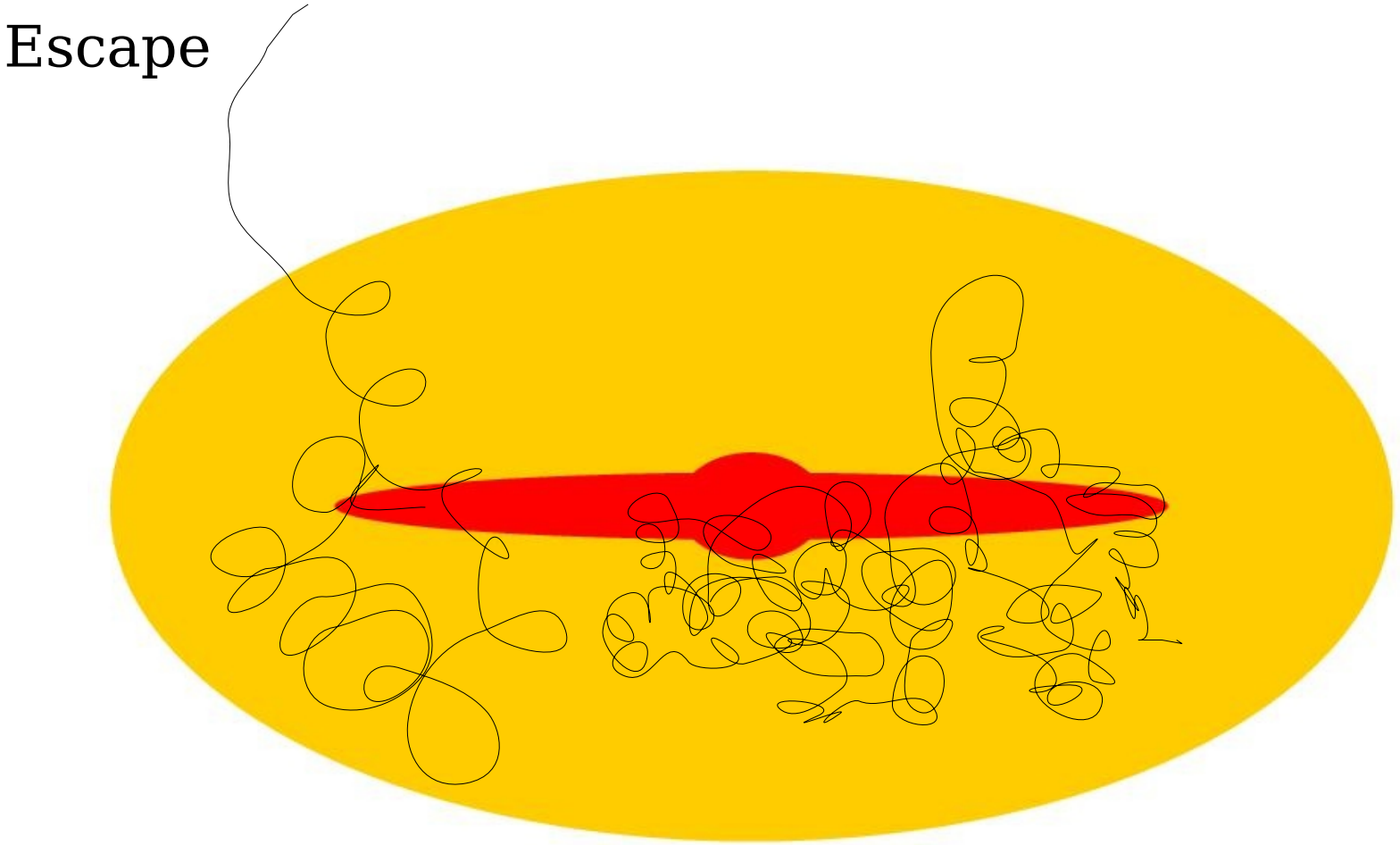
[Angular + Spectral features]

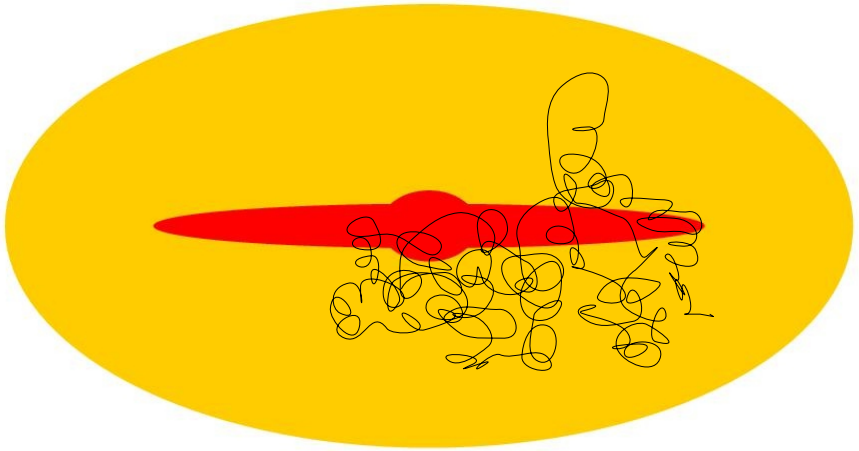
$J(\Omega)$



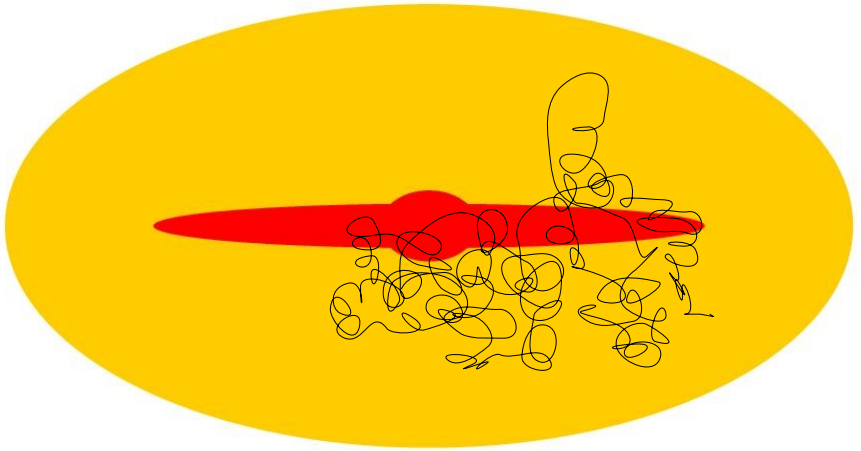

Galactic
Cosmic Ray
Halo
MILKY WAY
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD
Smaller CR density
In the LMC and SMC

Charged Particles: magnetic confinement





SOURCE(s) + Propagation $\rightarrow$ Observable Cosmic Rays



SOURCE(s) + Propagation → Observable Cosmic Rays

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

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

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

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

$$\chi + \chi \longrightarrow e^+ + \ldots$$

Possible
positron accelerators

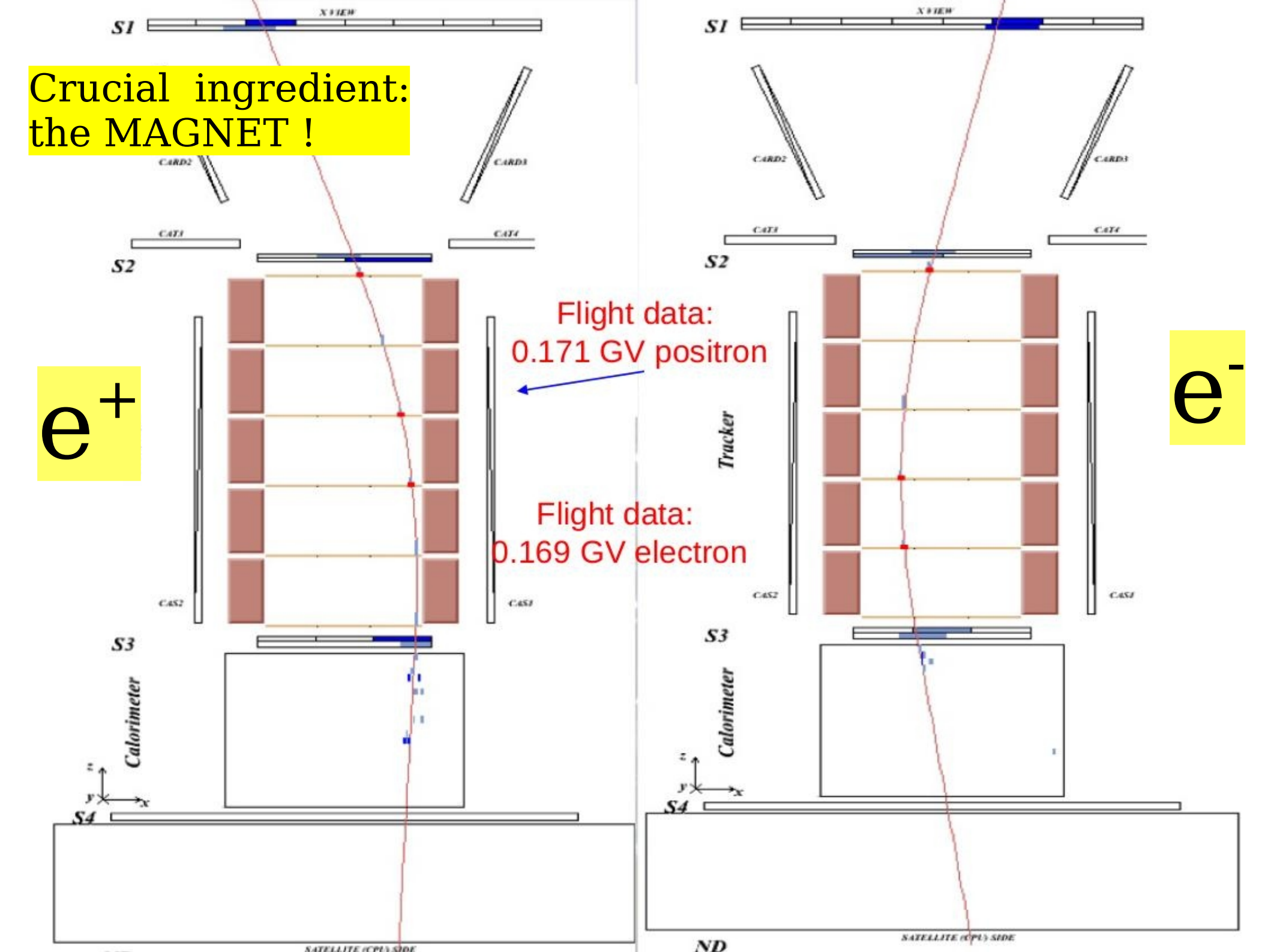
PAMELA

detector

Launch
15th june 2006

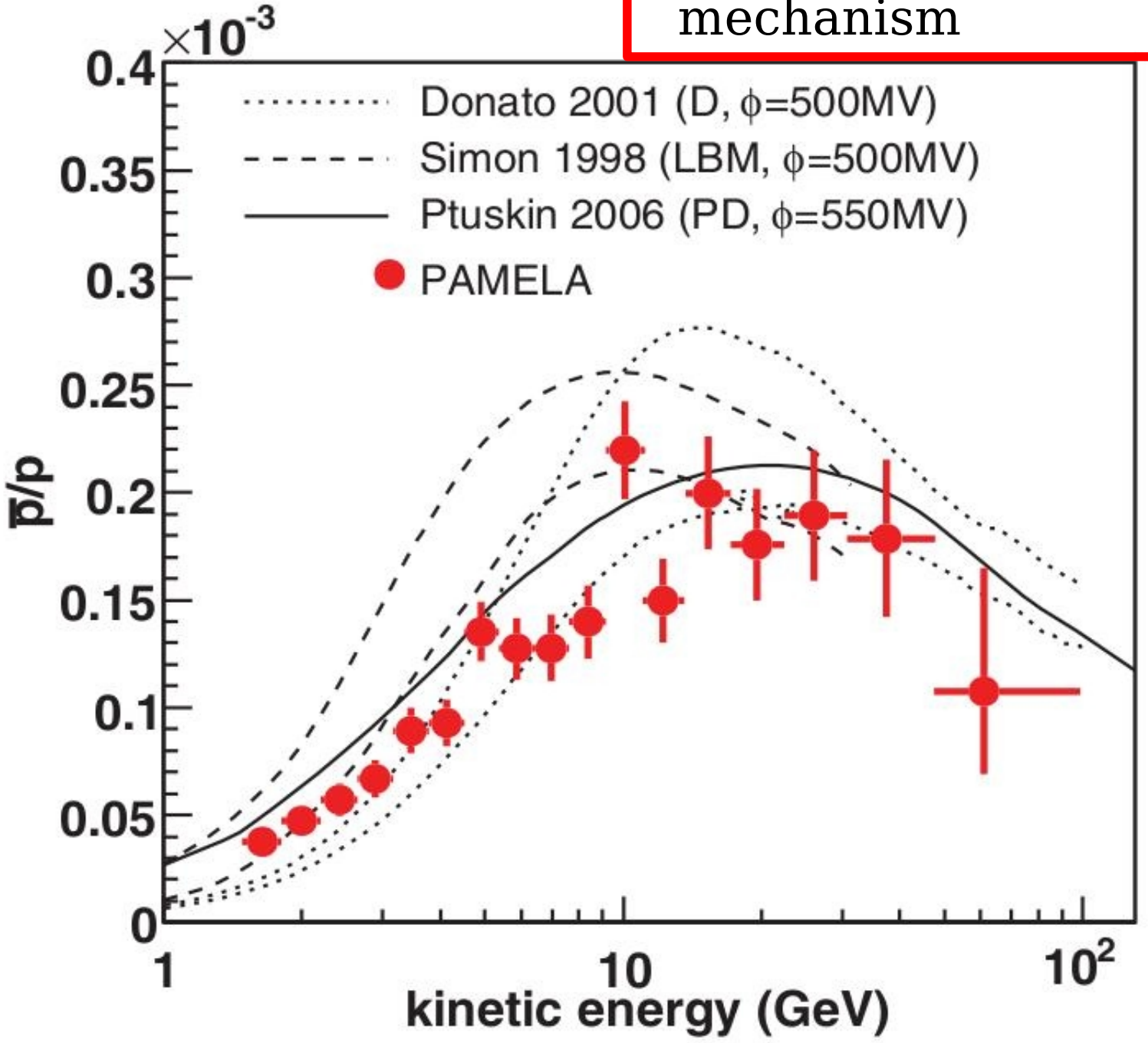
(4 years ago)

The “positron excess”:
Evidence for DM ??
or astrophysical effect ?

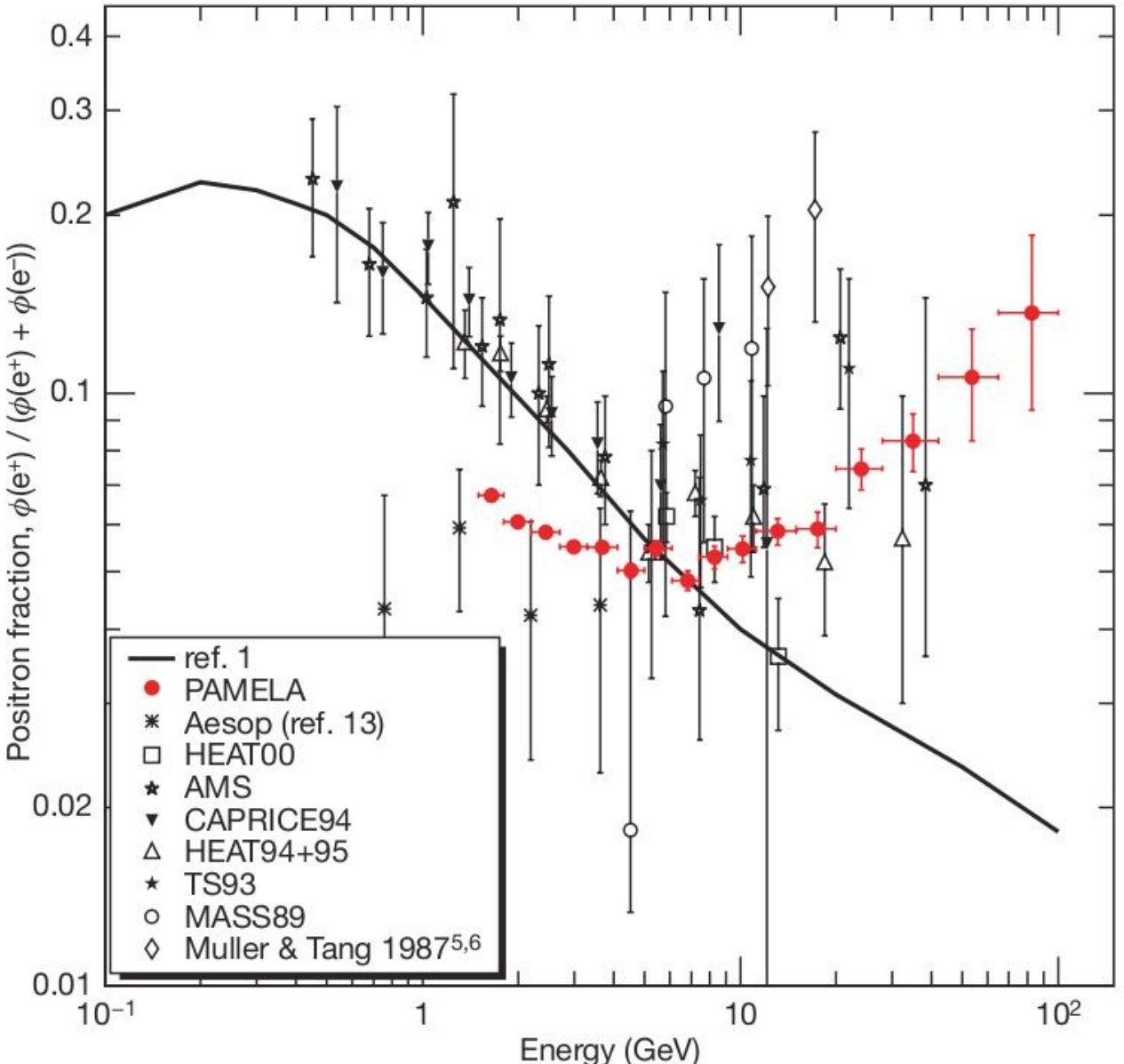

Crucial ingredient:
the MAGNET !
e+
e-
Flight data:
0.171 GV positron
Flight data:
0.169 GV electron
S1
S2
S3
S4
Tracker
Calorimeter
CARD2
CARD3
CAT3
CAT4
CAS2
CAS1
ND

Antiproton result

Agreement
With standard production mechanism



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



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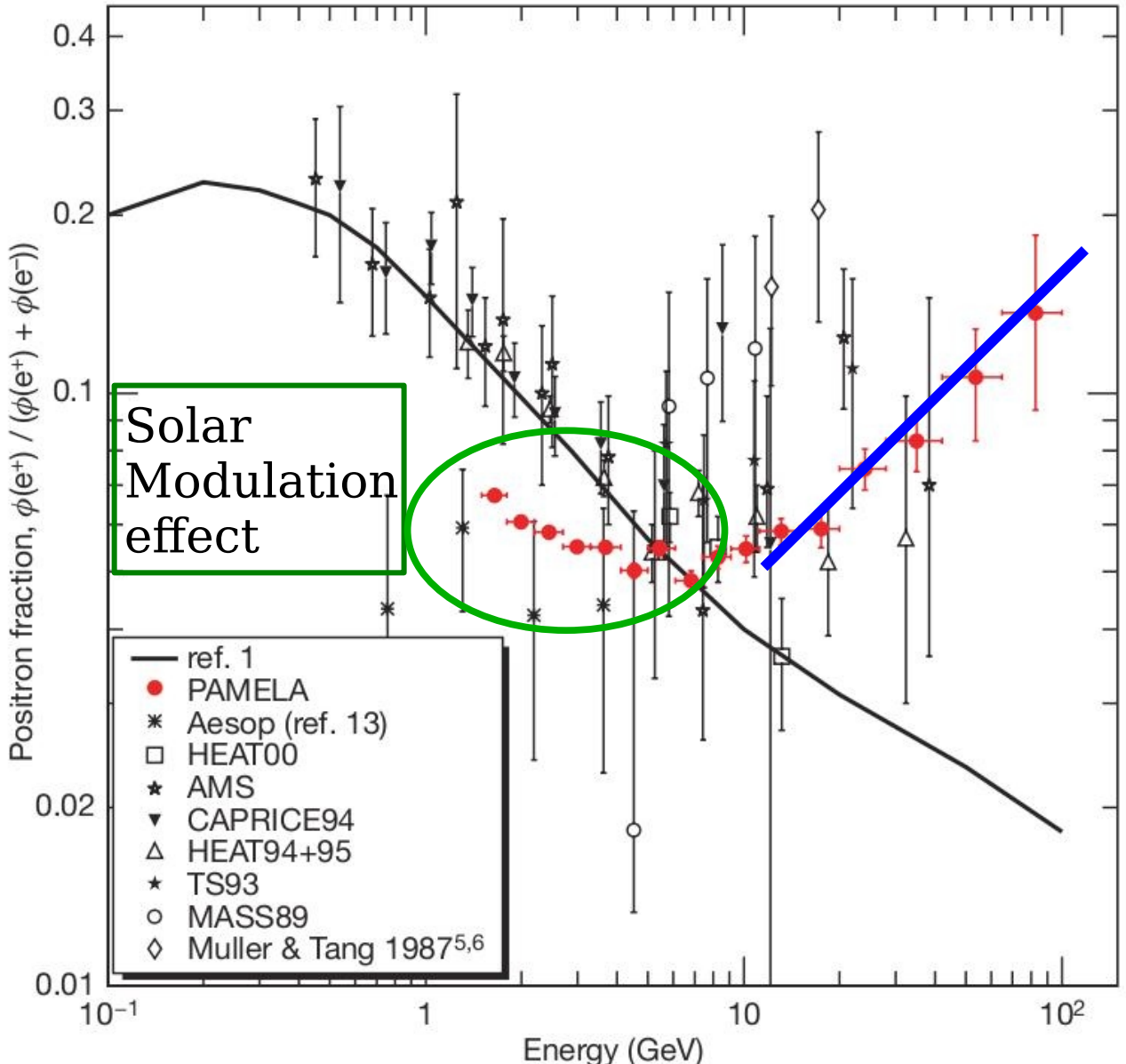


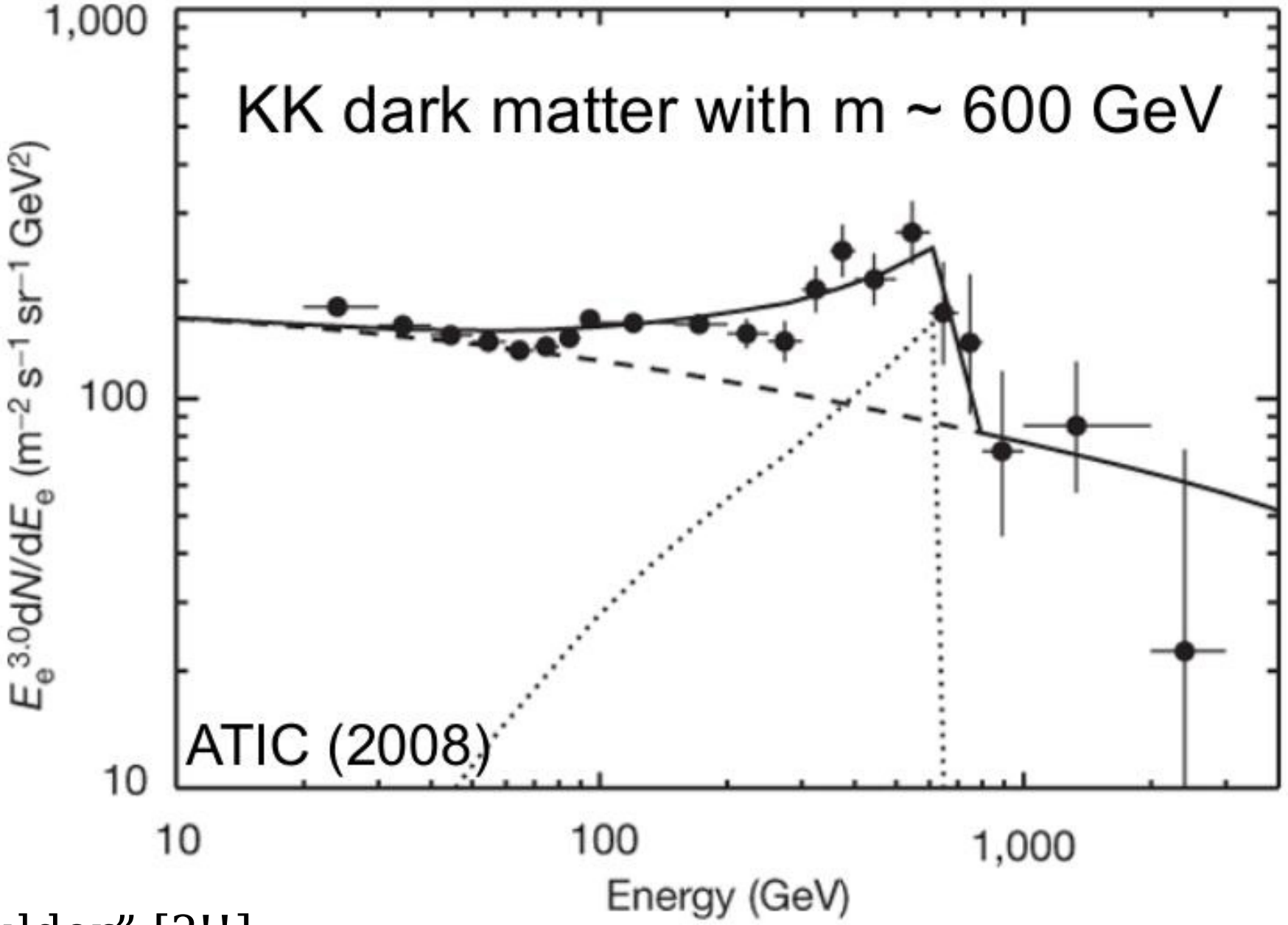
High energy: ratio e+/e- grow with E !!

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

Very unexpected result !

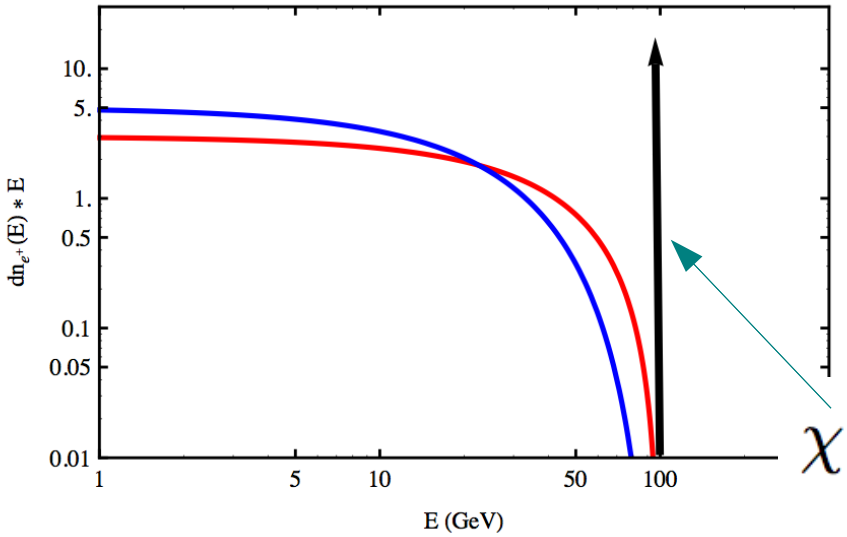
ATIC

Balloon experiment (electron + positron)



"Shoulder" [?!!]

Nature: October 2008



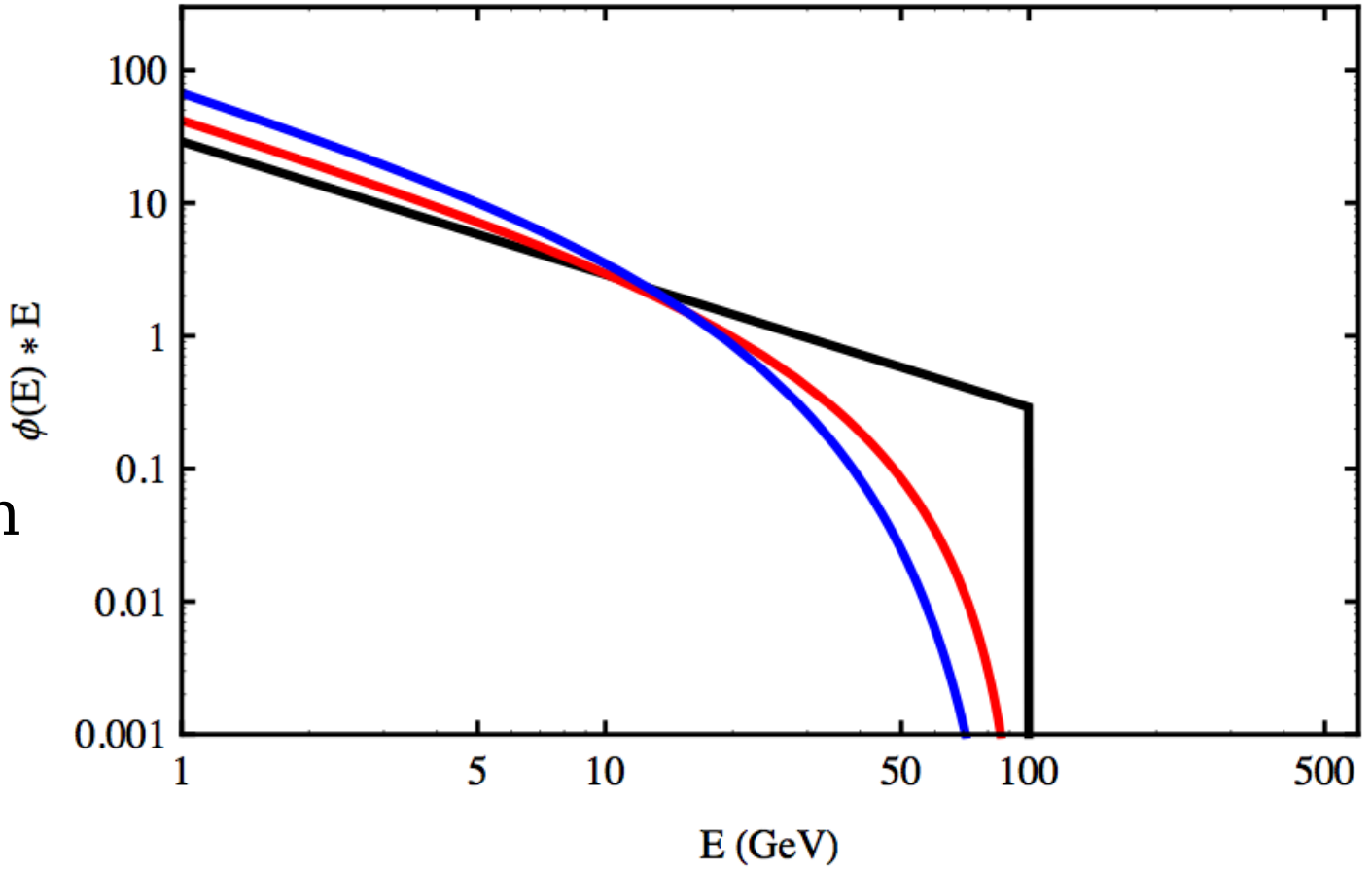
Annihilation of 2 Dark-Matter Particles. Produce particles with energy spectrum that extends to E = m

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

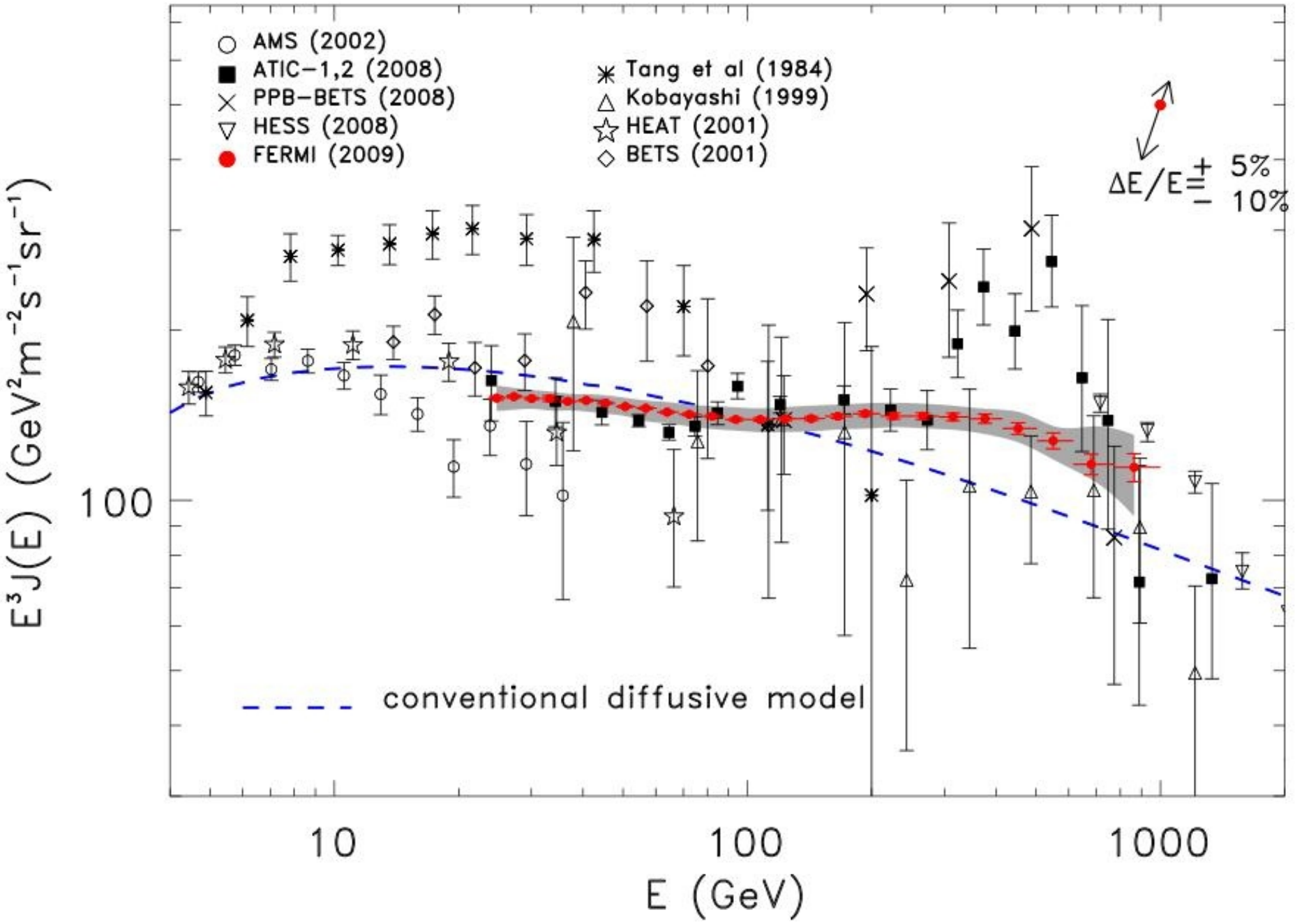
Injection spectrum

Observable Flux

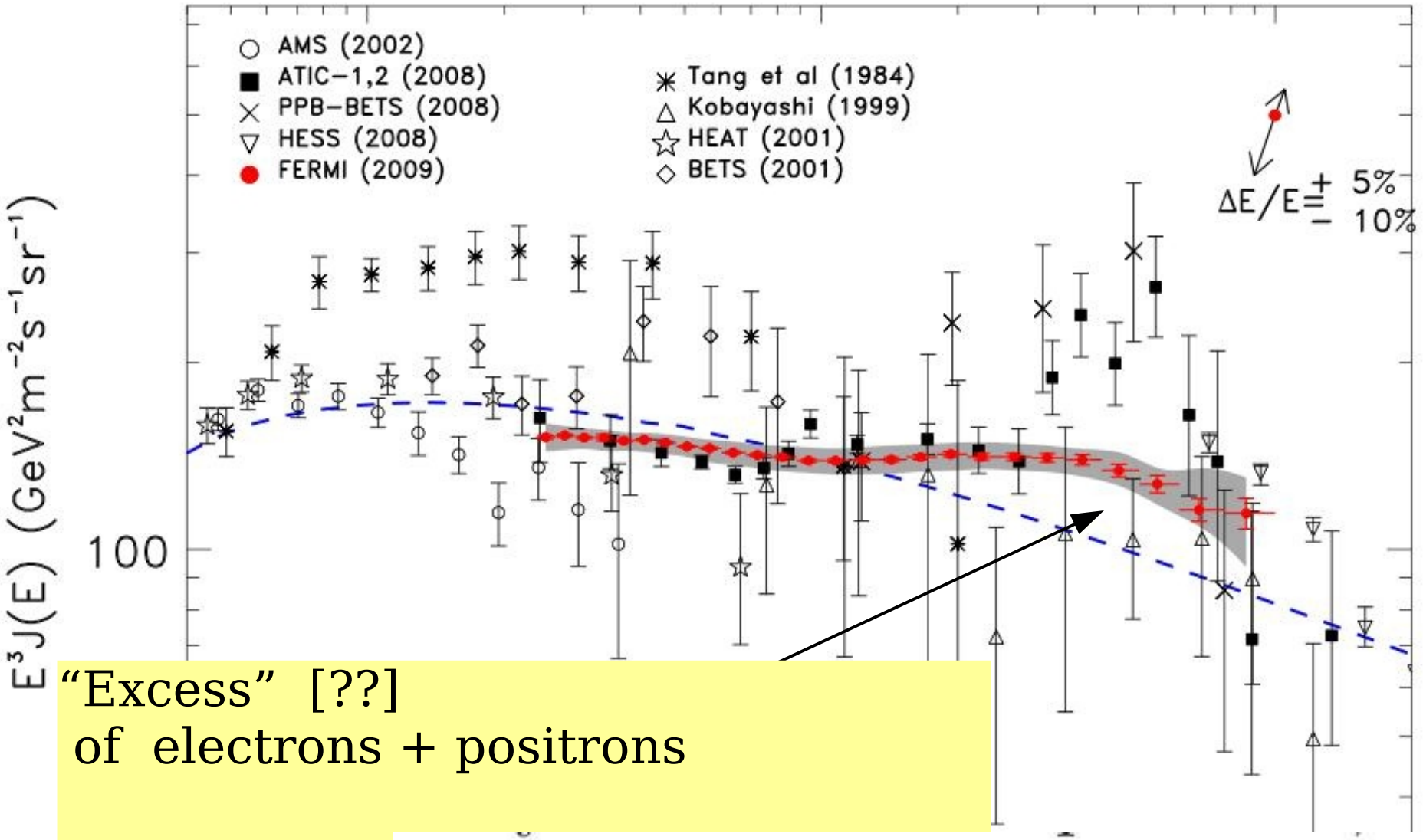
(after propagation + energy losses)



FERMI: electron + positron flux



FERMI: electron + positron flux

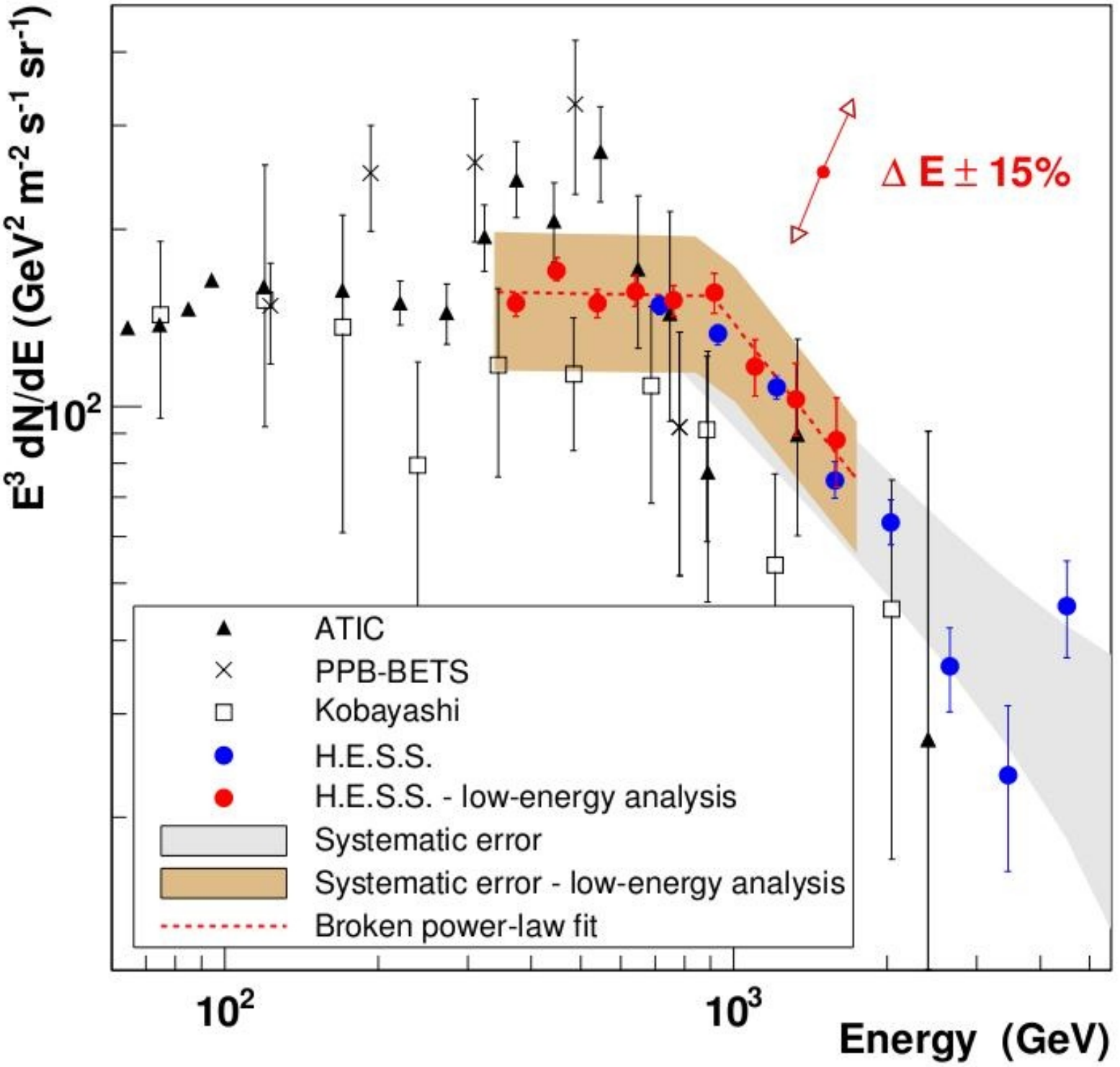


"Excess" [??]
of electrons + positrons

....
Possible...

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

but certainly not necessary


$E^3\ dN/dE\ (GeV^2\ m^{-2}\ s^{-1}\ sr^{-1})$
10^2
10^2
10^3
Energy (GeV)
$\Delta E \pm 15\%$
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

From : Cirelli

Results

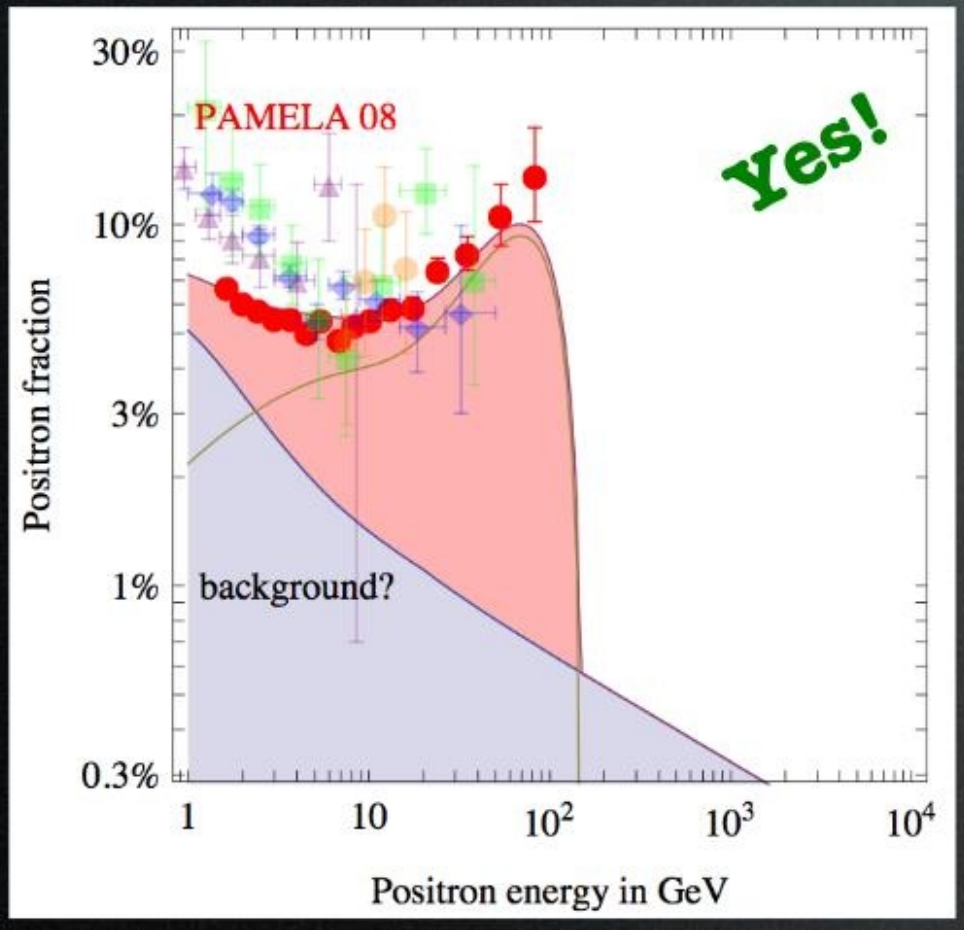
Which DM spectra can fit the data?

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

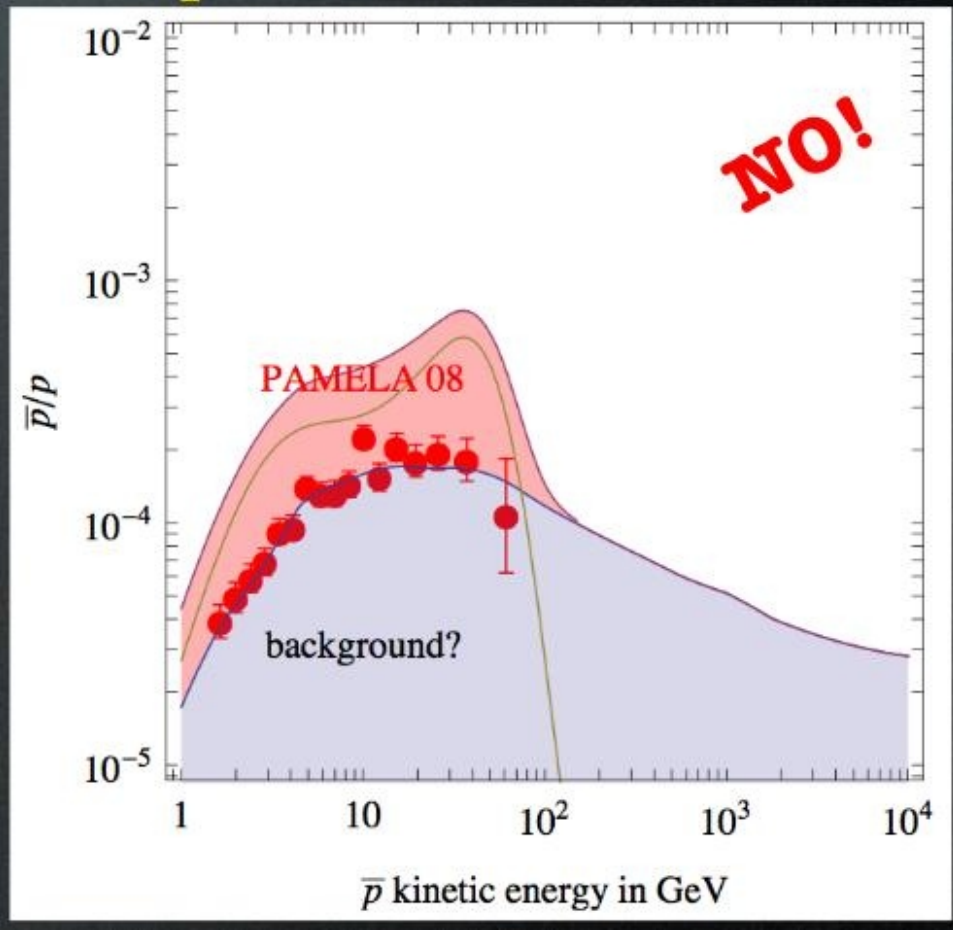
-annihilation $\mathrm{DM\ DM} \to W^+W^-$

(a possible SuperSymmetric candidate: wino)

Positrons:



Anti-protons:



Results

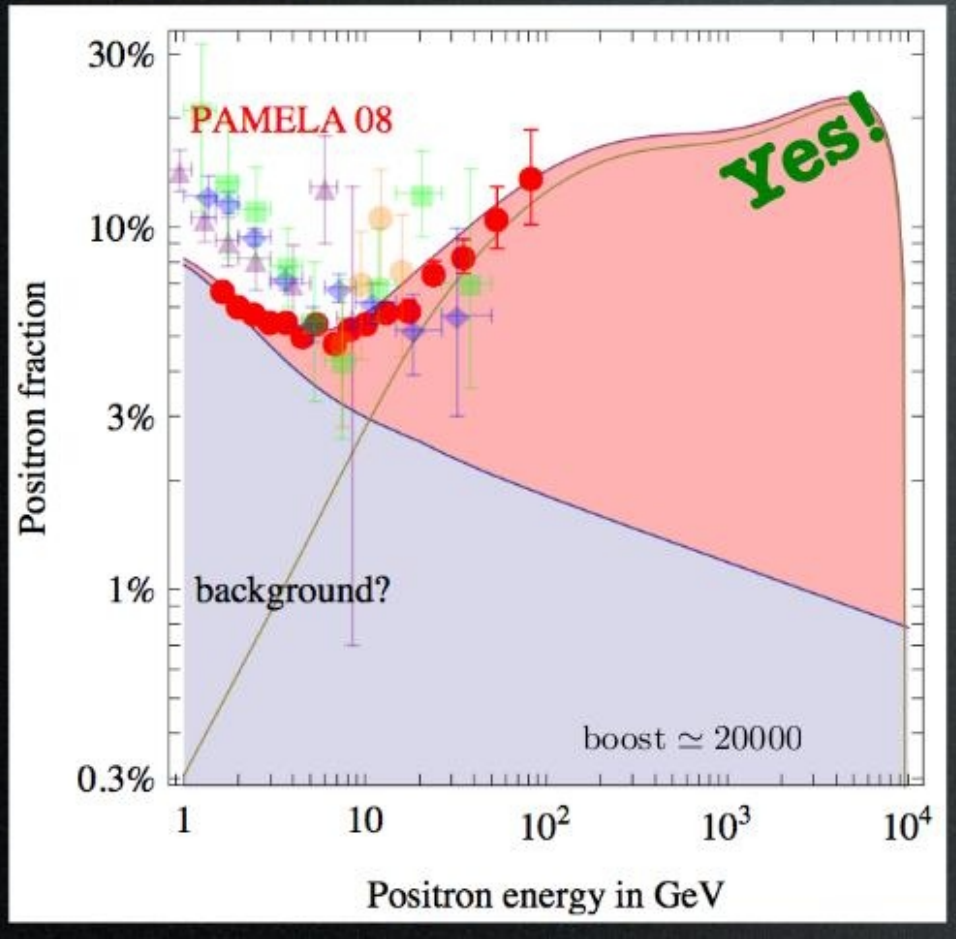
Which DM spectra can fit the data?

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

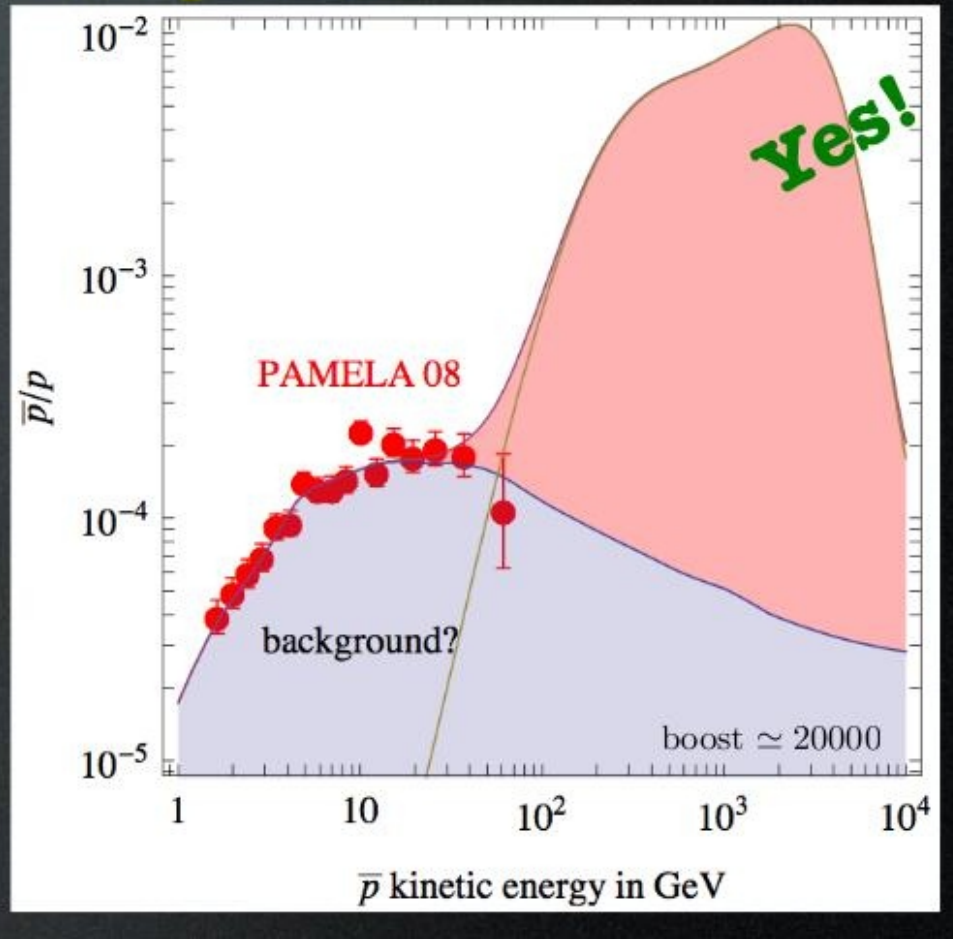
-annihilation $\mathrm{DM\ DM} \to W^+W^-$

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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"Pamela positron excess" in terms of the
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simplest, most natural version.

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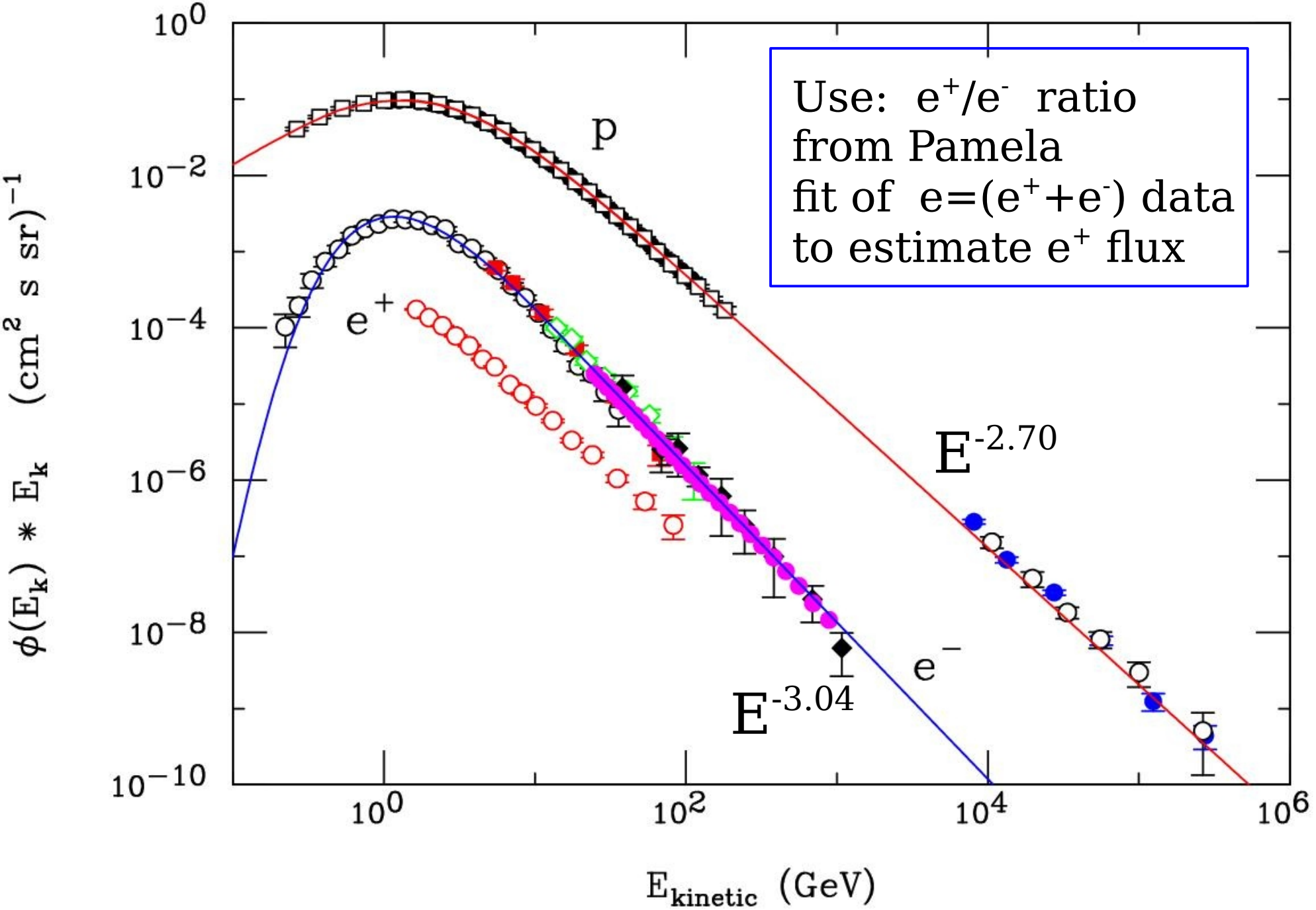
to increase the rate of the DM annihilations.
Very "clumpy" dark matter.
(very lucky in being close to a big clump)
"winning the jackpot" [?]

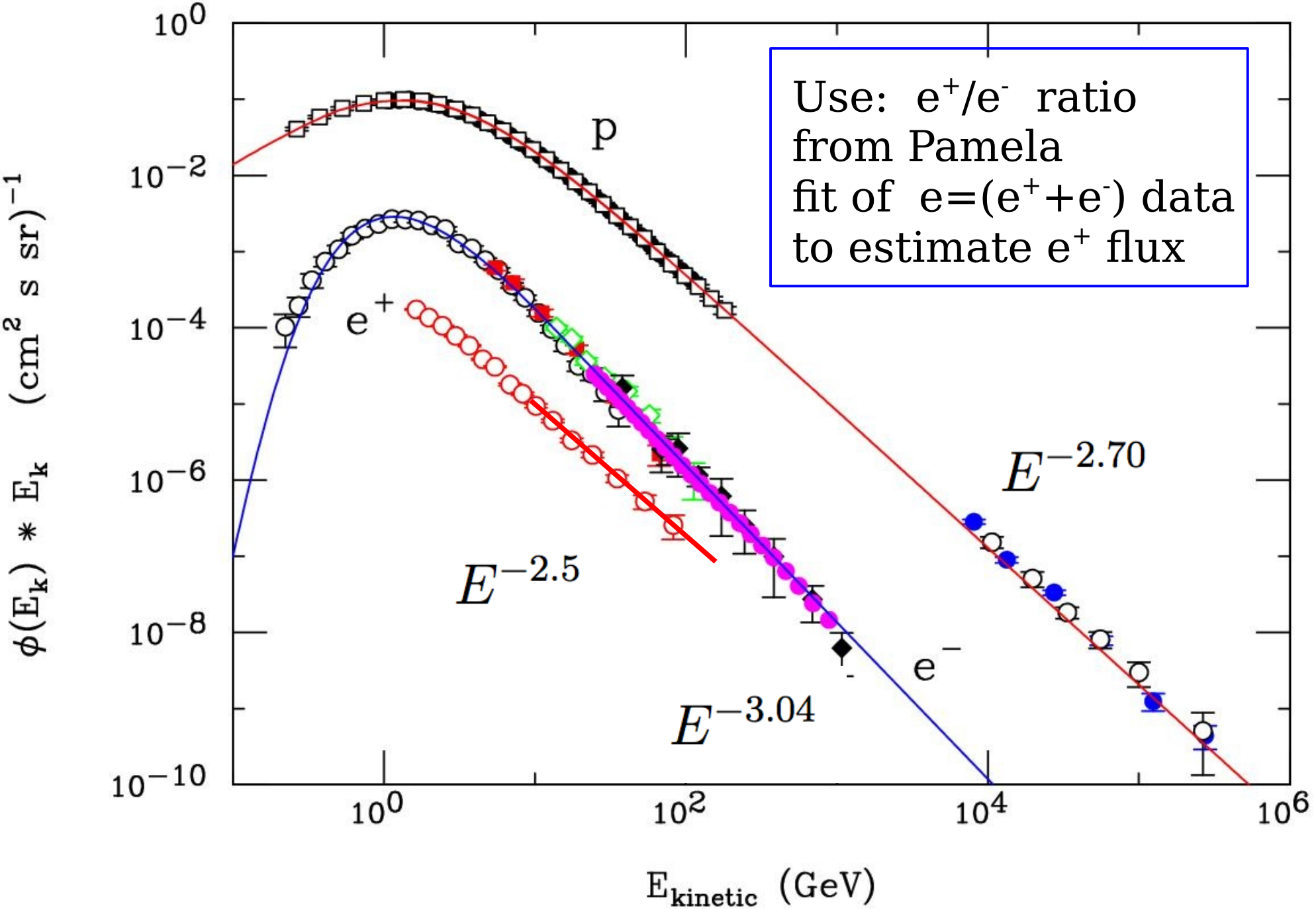
Is this "adding epicycles" to the wrong theory ?

Are there other possible interpretations for this result.

Proton and electron + Positron energy spectra



Proton and electron + Positron energy spectra

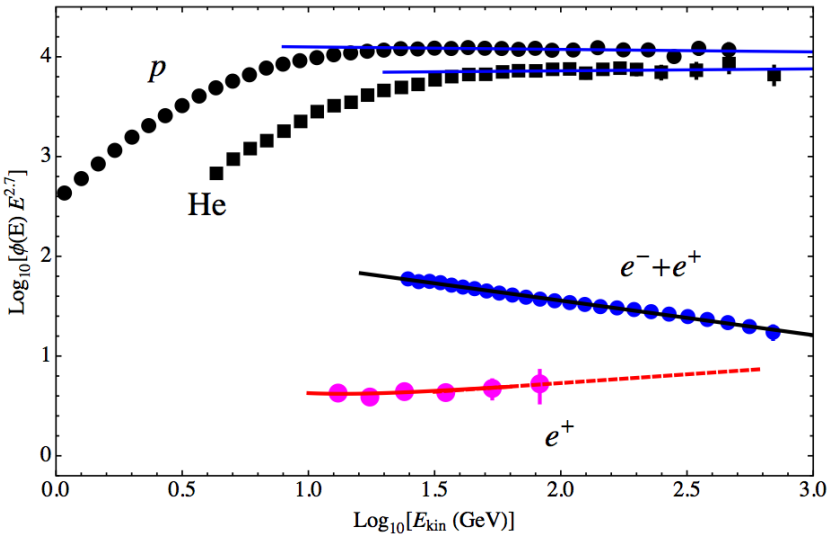


Spectra approximately of form:

protons $E^{-2.70}$

electrons $E^{-3.04}$

positrons $E^{-2.5}$

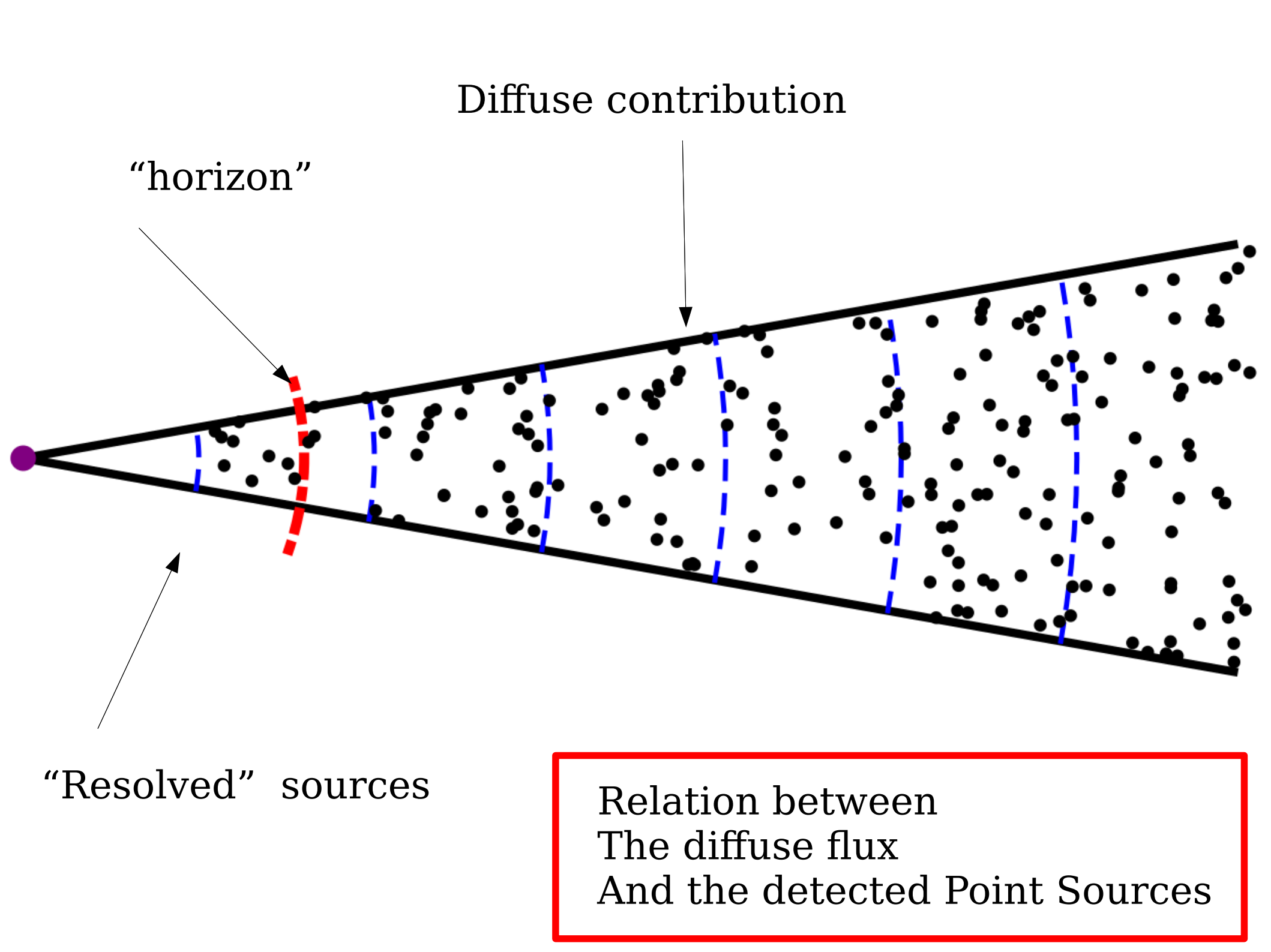


$E^{-3.1}$

$E^{-3.5}$

Completely unexpected result

Rough expectation
For the positron slope
SOFTER than electrons


Diffuse contribution
“horizon”
“Resolved” sources
Relation between
The diffuse flux
And the detected Point Sources

Expectations: (Homogeneous injection)

$$\alpha_p \simeq \alpha_0 + \delta$$

$$\alpha_{e-} \simeq \alpha_0 + 1$$

$$\alpha_{e+} \simeq \alpha_0 + \delta + 1$$

DATA

p	$E^{-2.70}$
e-	$E^{-3.04}$
e+	$E^{-2.5}$

(Planar injection)

$$\alpha_p \simeq \alpha_0 + \delta$$

$$\alpha_{e-} \simeq \alpha_0 + (1+\delta)/2$$

$$\alpha_{e+} \simeq \alpha_0 + \delta + (1+\delta)/2$$

NEW SOURCE of POSITRONS
seems NECESSARY

PULSARS

Proposed as possible Accelerators of e+ e-

CRAB Nebula

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

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

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

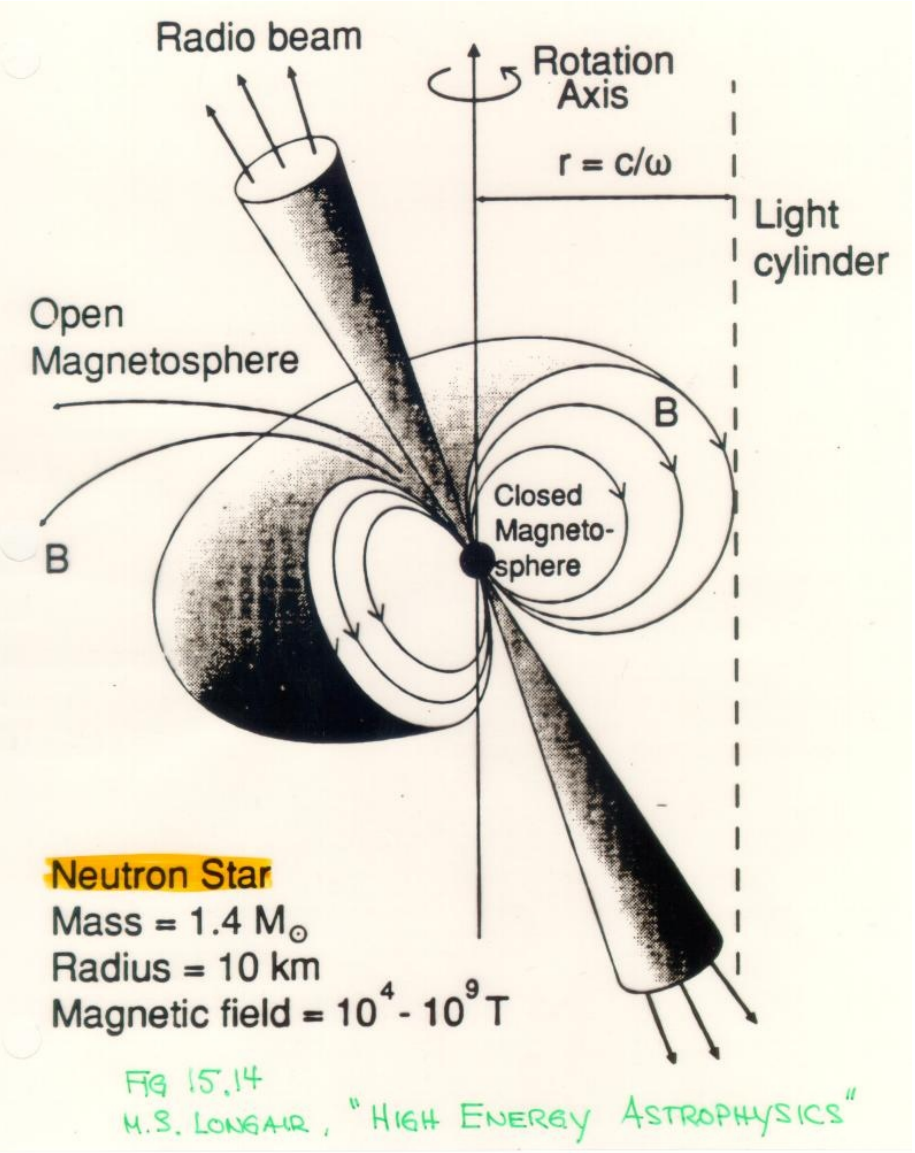
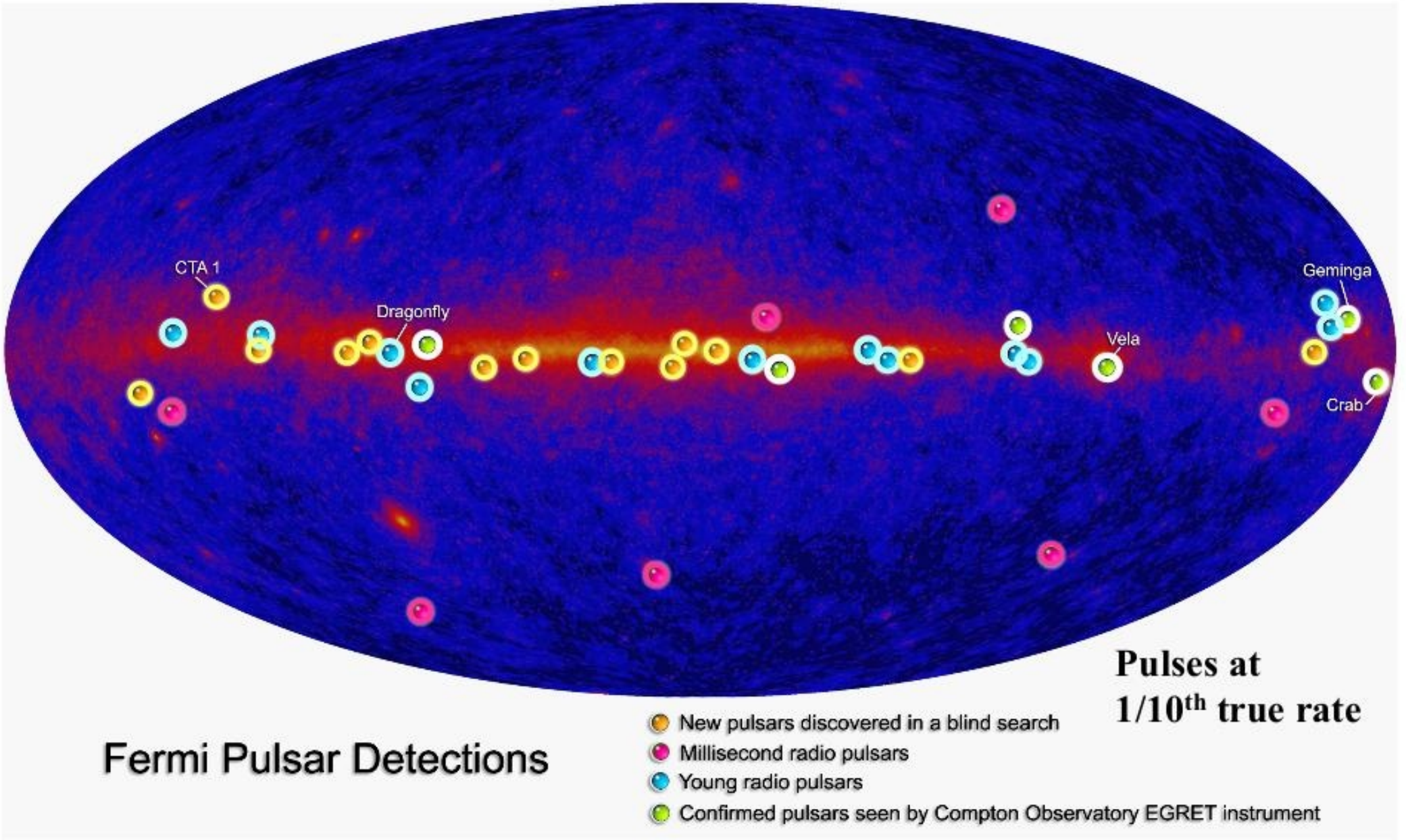


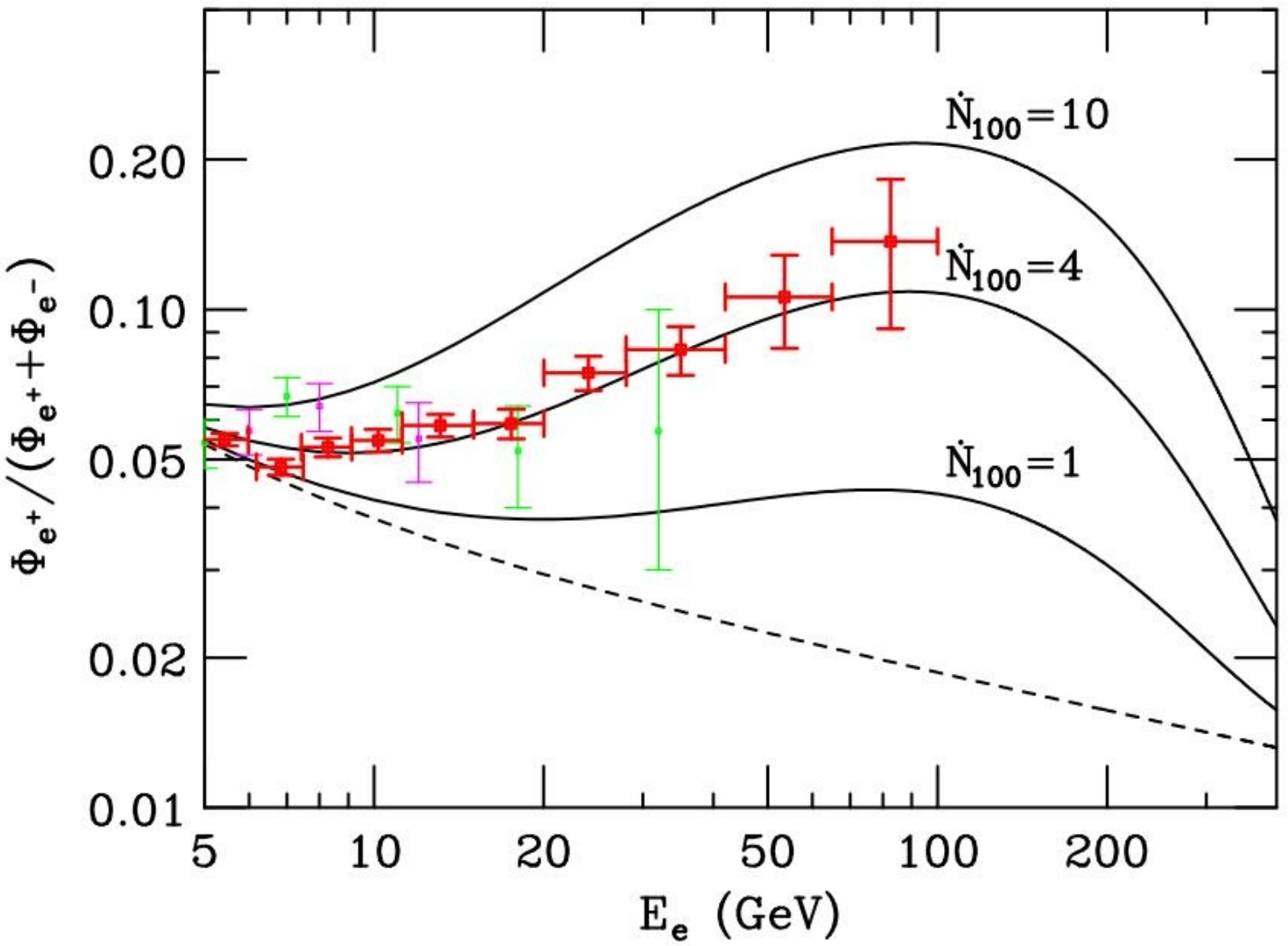
FIG 15.14
M.S. LONGAIR, "HIGH ENERGY ASTROPHYSICS"

Fermi Pulsar detection



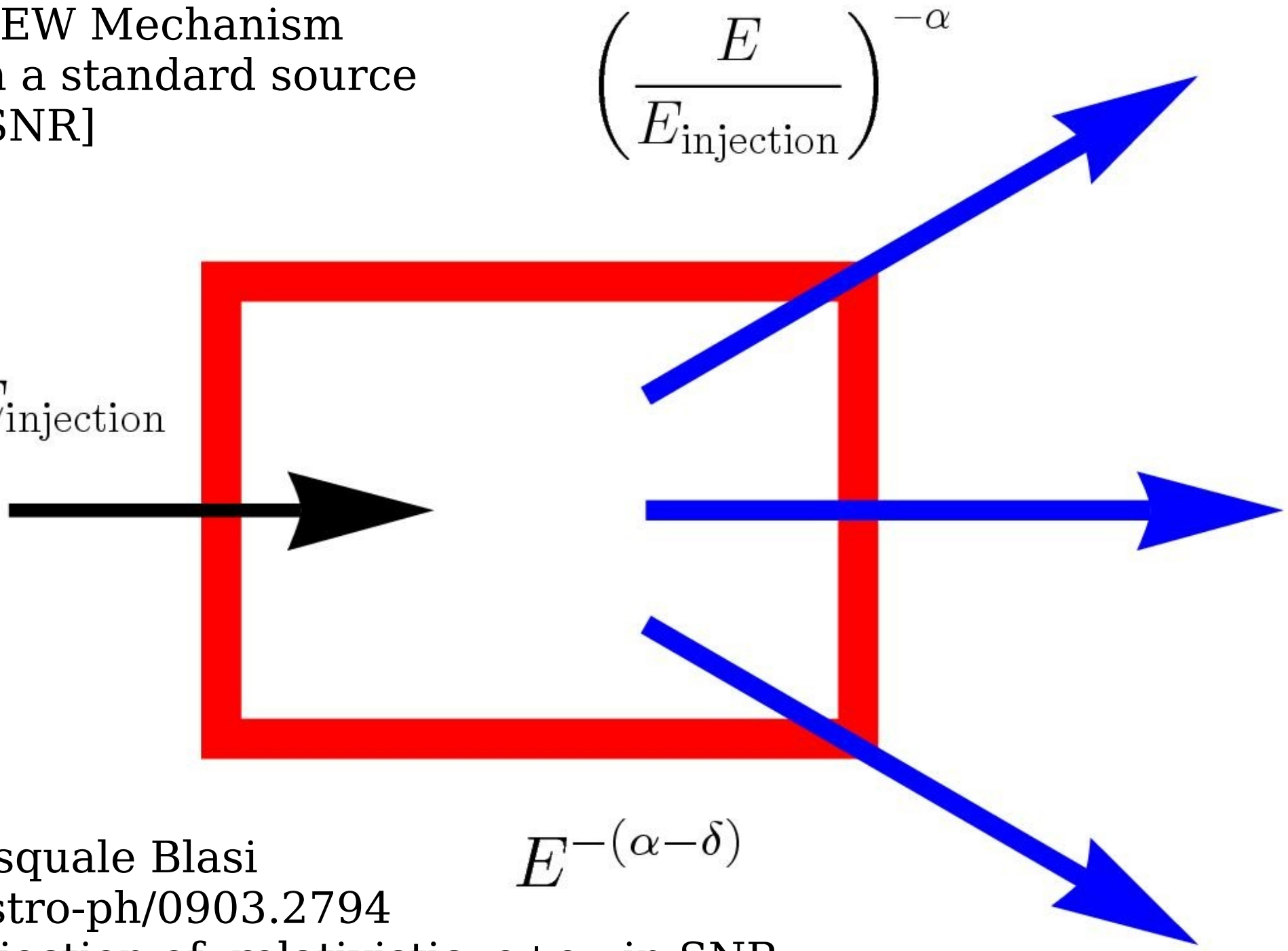
Hooper, Blasi, Serpico 2008

Contribution from all Pulsars

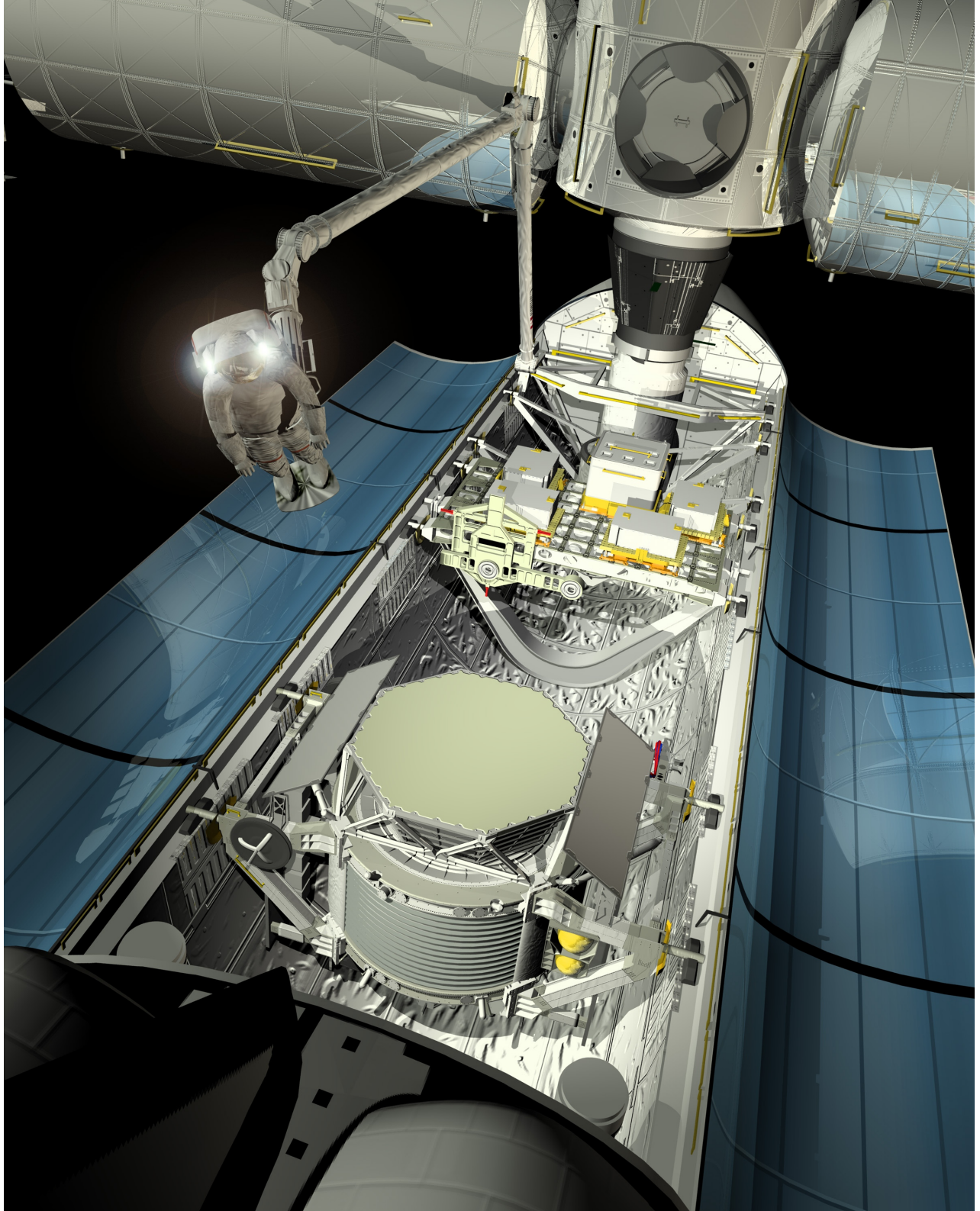


$$\frac{dN_e}{dE_e} \approx 8.6 \times 10^{38} \dot{N}_{100} \left(E_e/\mathrm{GeV}\right)^{-1.6} \exp\left(-E_e/80\,\mathrm{GeV}\right) \mathrm{GeV}^{-1}\,\mathrm{s}^{-1}$$

NEW Mechanism
In a standard source
[SNR]



Pasquale Blasi
Astro-ph/0903.2794
Injection of relativistic e+e- in SNR



Importance of

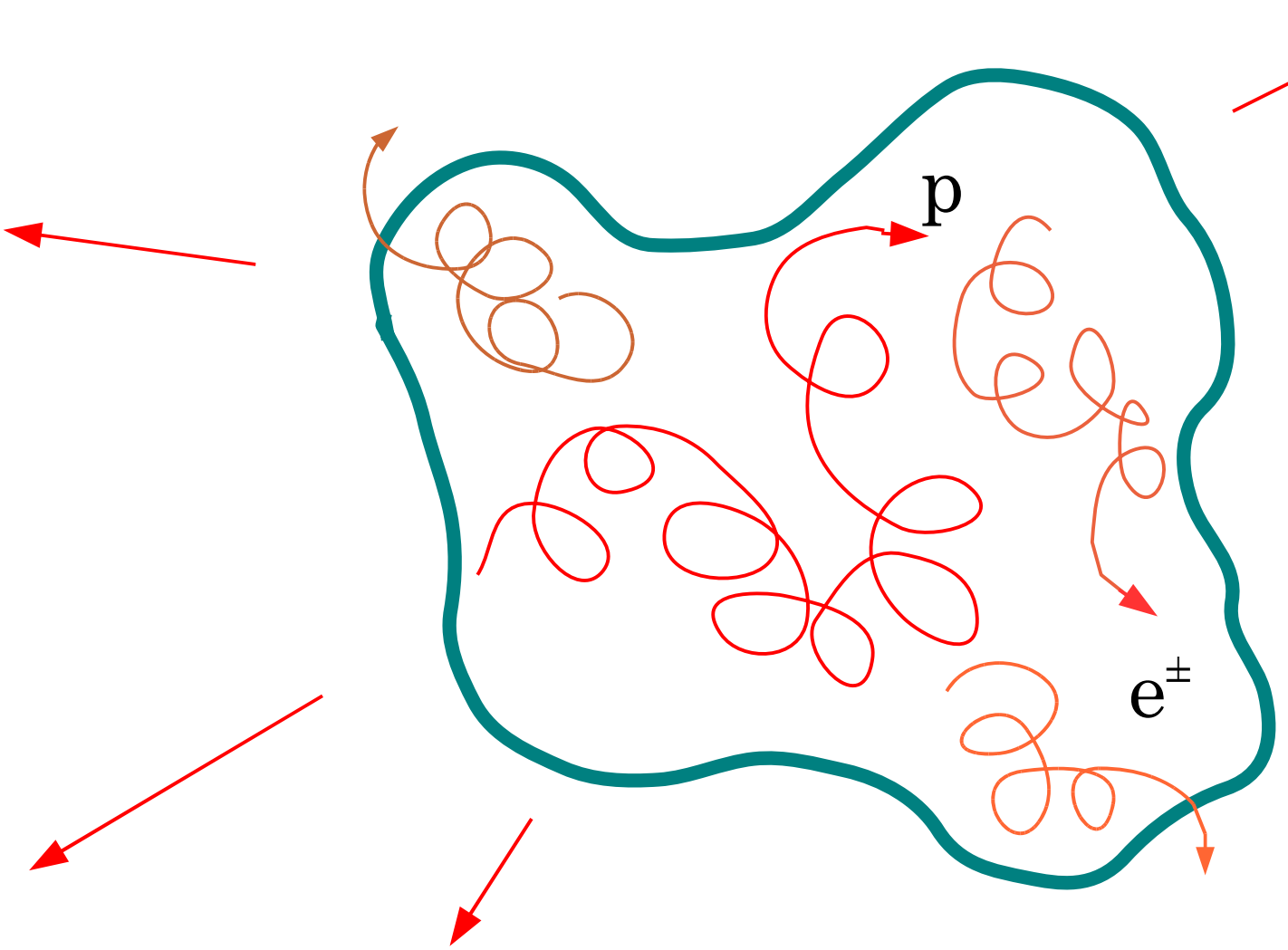
AMS

Mission.

Launch scheduled:
April 2011

High Energy Astrophysical Source:

Object (or an “event”) that produces
(and for some time contains)
relativistic particles



Unavoidable
Photon+
neutrino
emission !

Escaping
particles: CR

$$p + \text{target} \rightarrow \text{many particles}$$

$$\rightarrow p(n) + \pi^+ + \pi^- + \pi^\circ$$

$$\mu^+ + \nu_\mu \qquad \gamma + \gamma$$

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

"Hadronic Emission"

$$e^\mp + B \rightarrow e^\mp + \gamma_{\text{synchrotron}}$$

$$e^\mp + \gamma_{\text{soft}} \rightarrow e^\mp + \gamma_{\text{Inverse Compton}}$$

"Leptonic Emission"

Multi-messenger Astrophysics

COSMIC RAY physics

GAMMA Astronomy

NEUTRINO Astronomy

Accelerators associated with
Acceleration of astronomical masses.
Emission of Gravitational Waves

Multi-messenger Astrophysics

COSMIC RAY physics

GAMMA Astronomy

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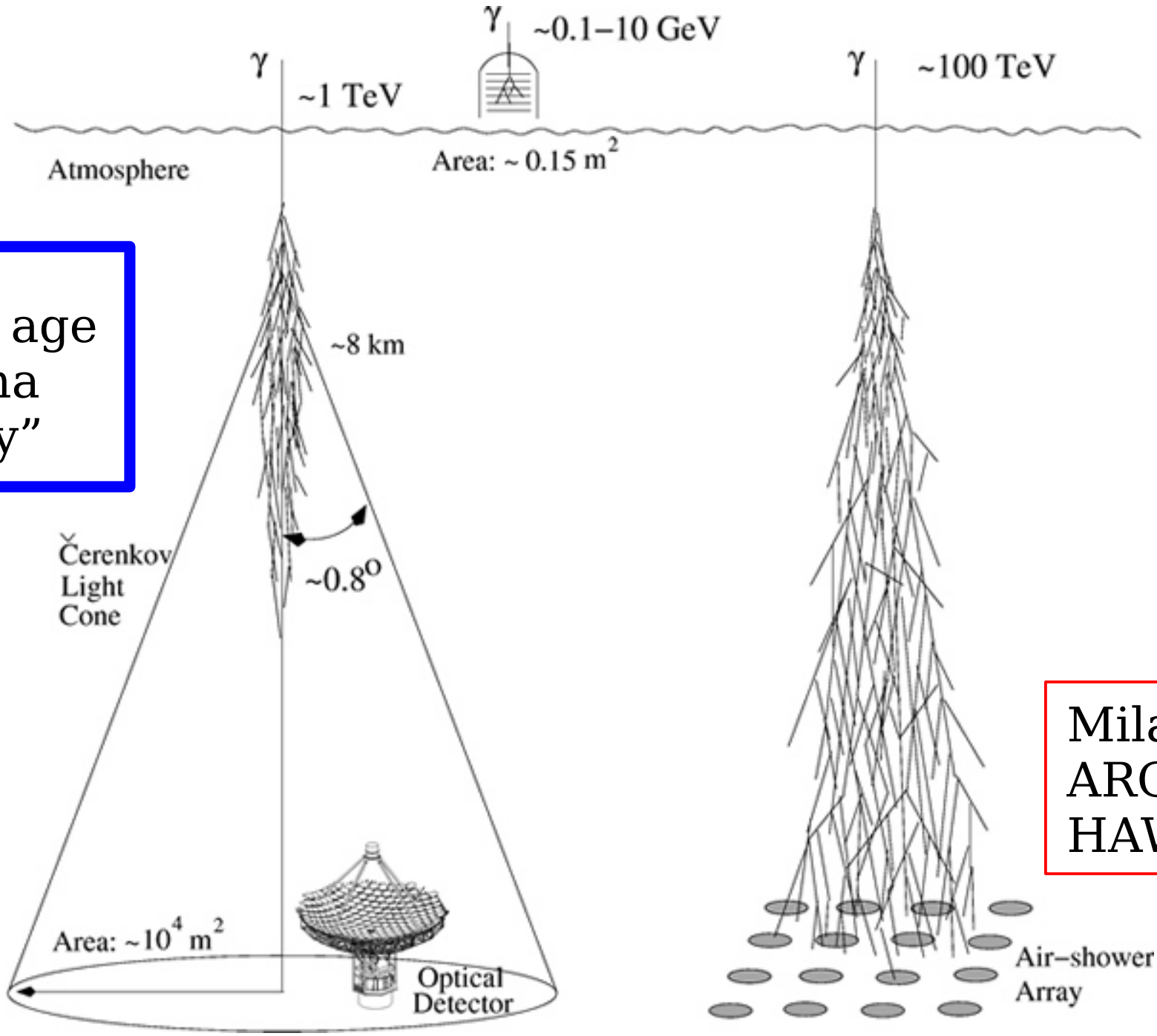
Accelerators associated with
Acceleration of astronomical masses.
Emission of Gravitational Waves

Egret
Agile
Fermi

"A golden age For Gamma Astronomy"

Hess
Magic
Veritas
CTA

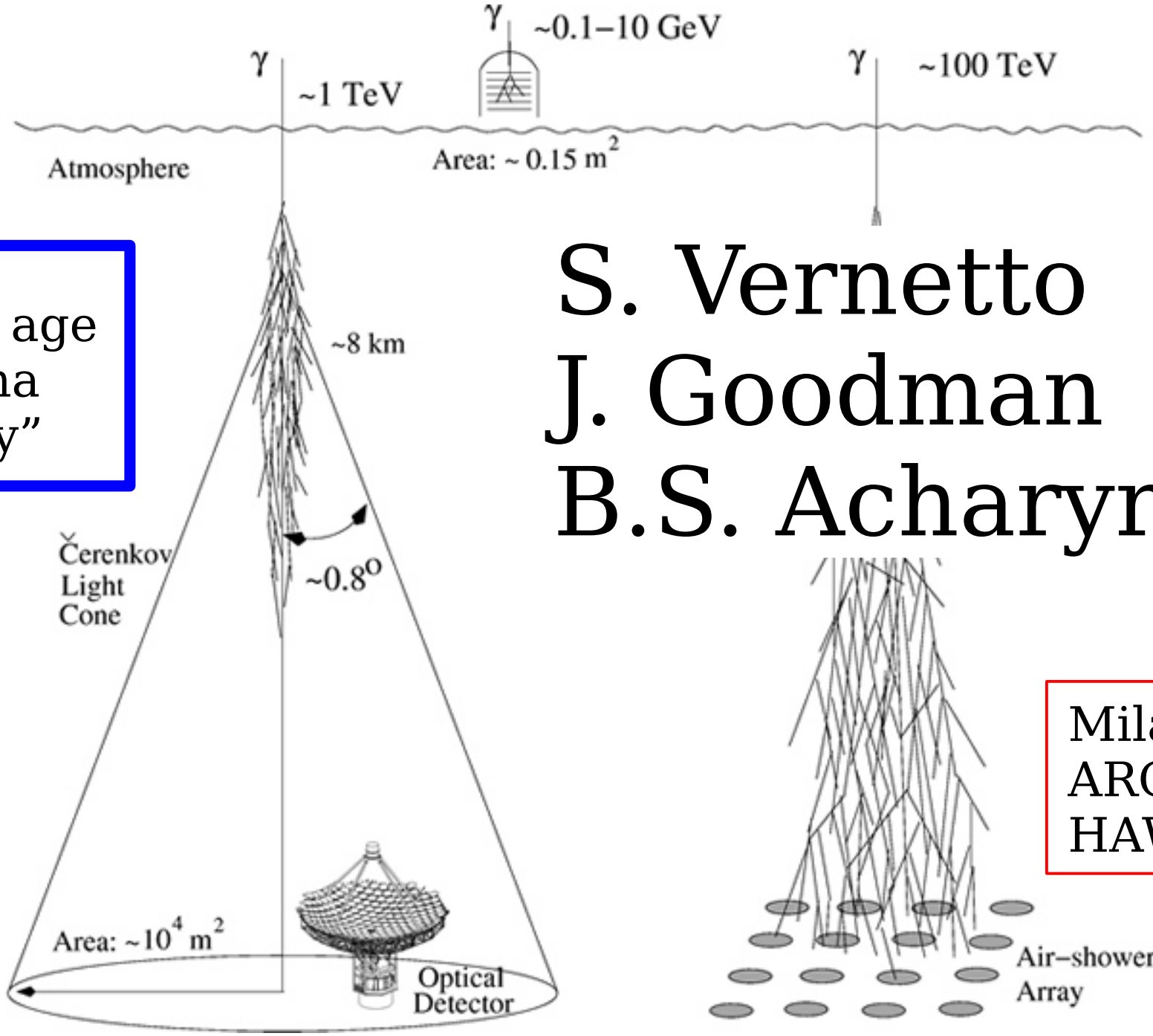


Milagro
ARGO
HAWC

Egret
Agile
Fermi

“A golden age
For Gamma
Astronomy”

Hess
Magic
Veritas
CTA



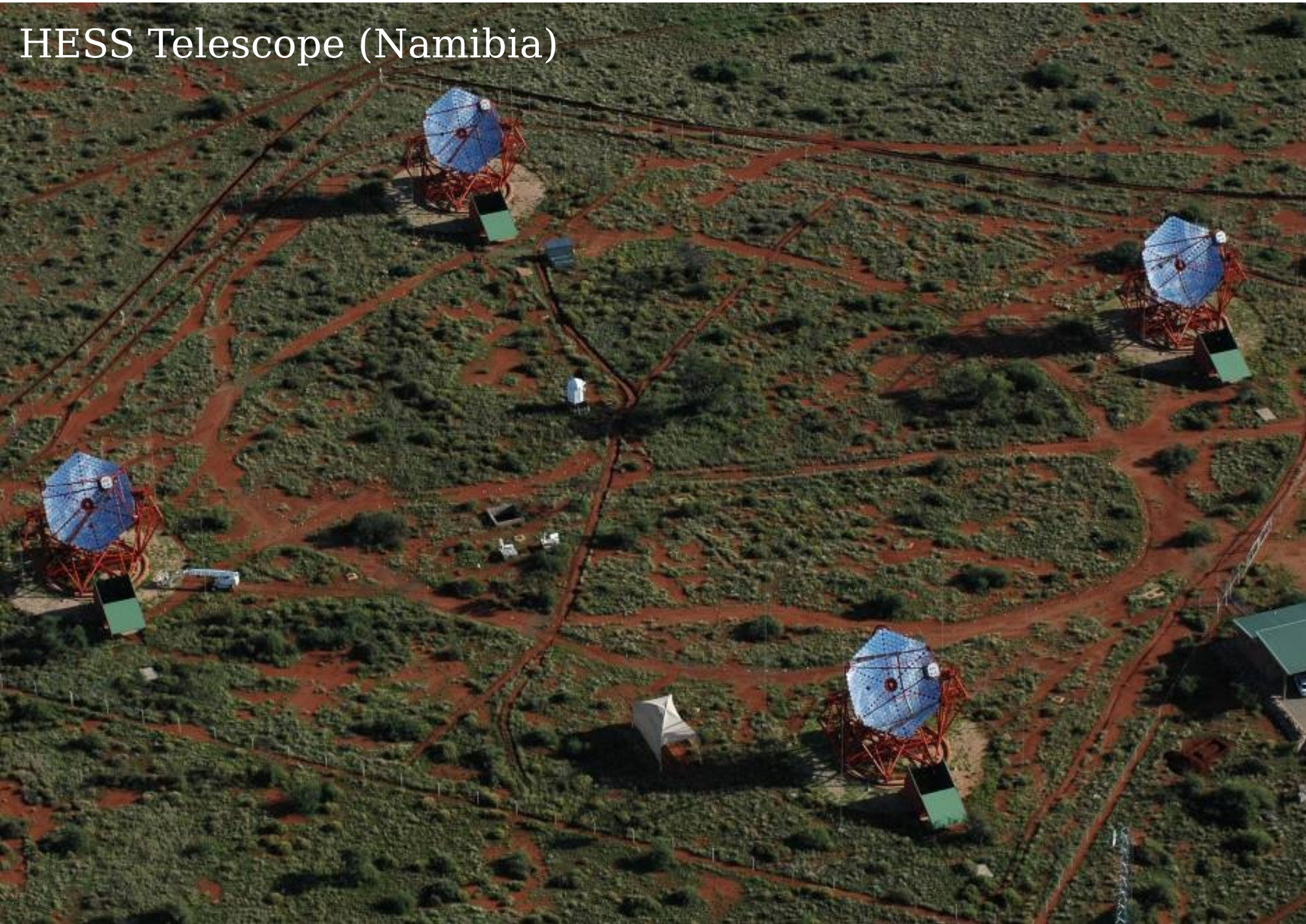
S. Vernetto
J. Goodman
B.S. Acharyra

Milagro
ARGO
HAWC

Launch of “GLAST” 11th june 2008

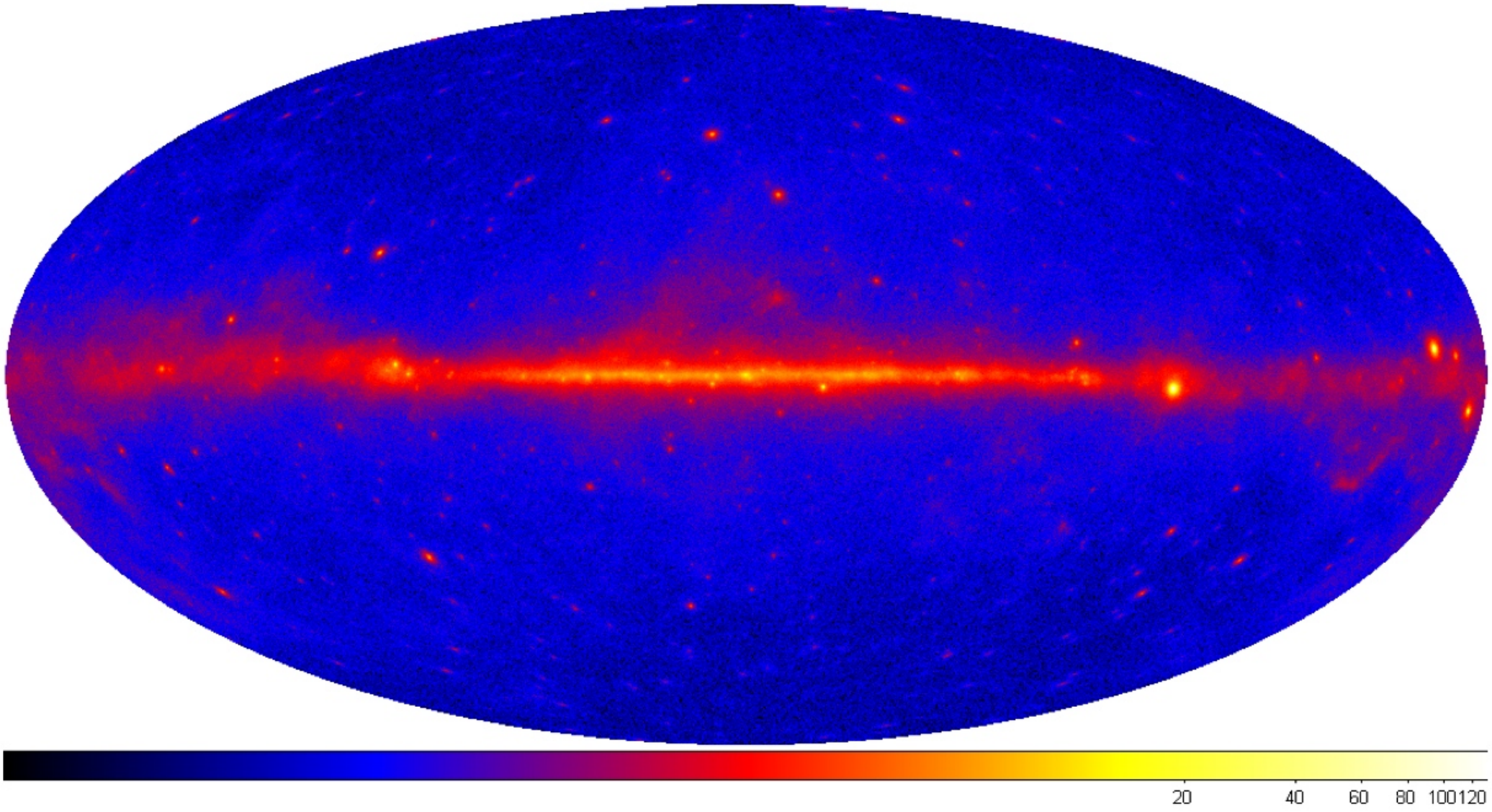
28th august satellite renamed FERMI


Cherenkov Imaging Telescopes
MAGIC
HESS
VERITAS


HESS Telescope (Namibia)

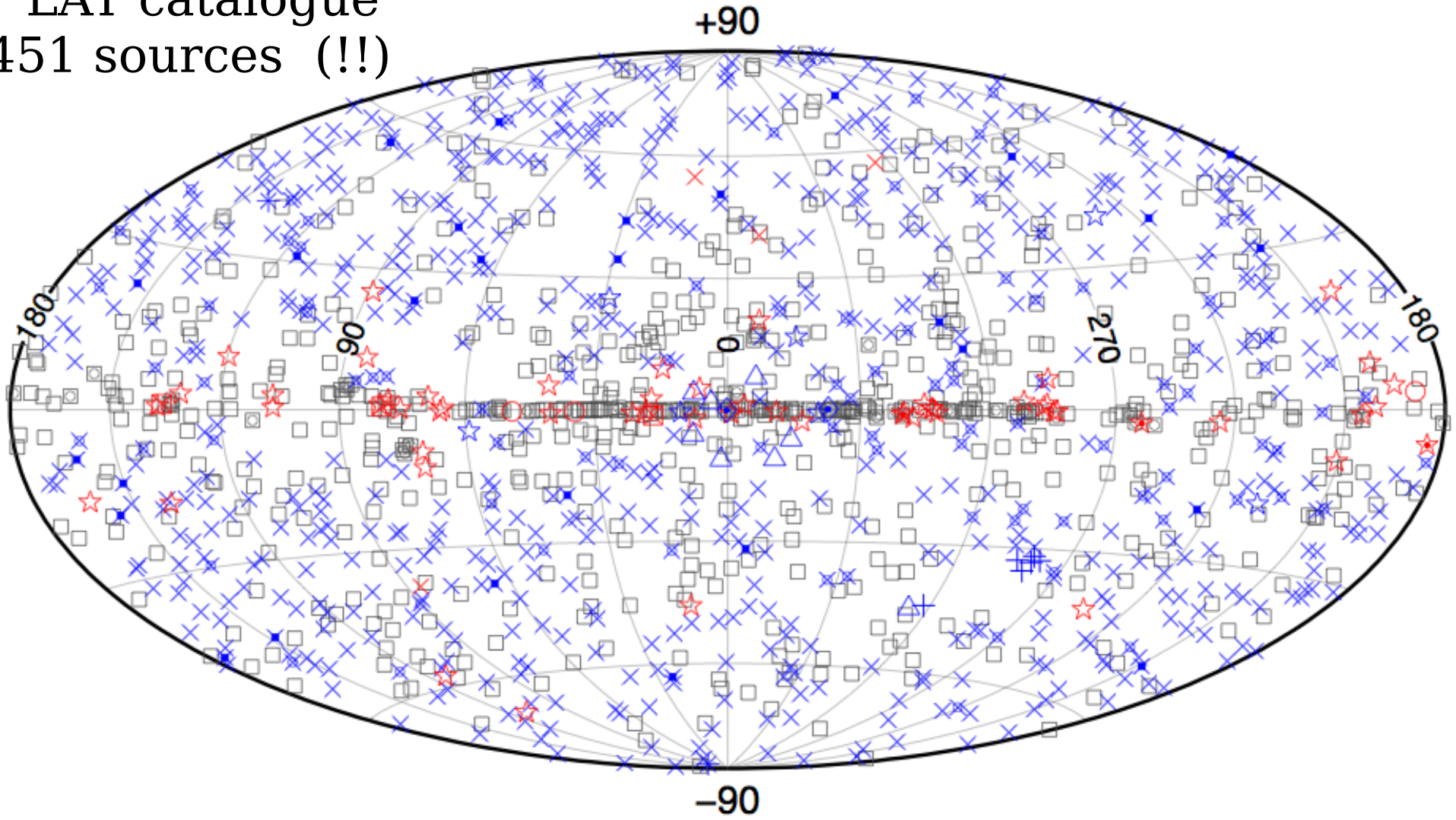

MAGIC 2 x 236 m²
2nd telescope : April 2009

The “RICHNESS” of TeV GAMMA ASTRONOMY”

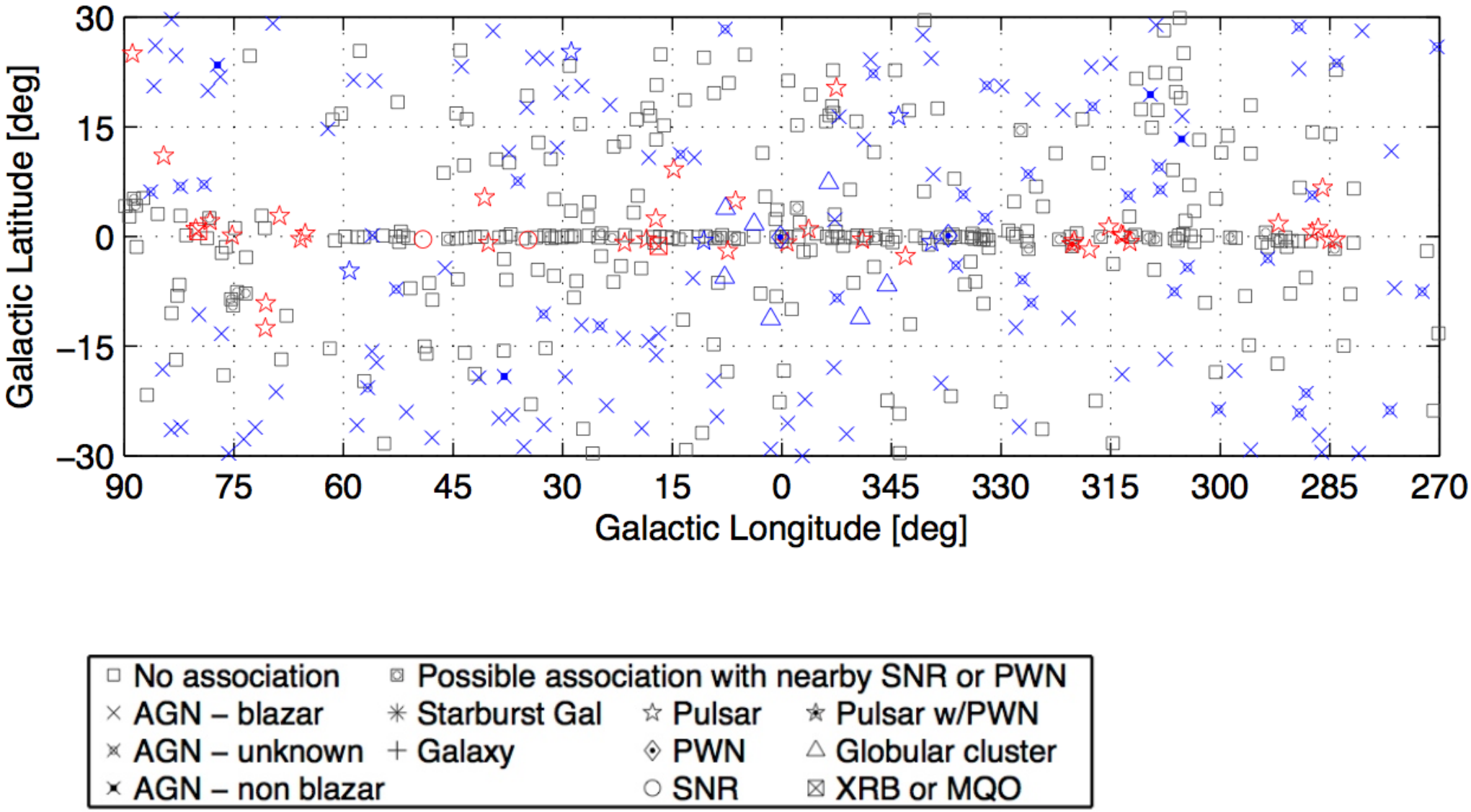


FERMI Sky

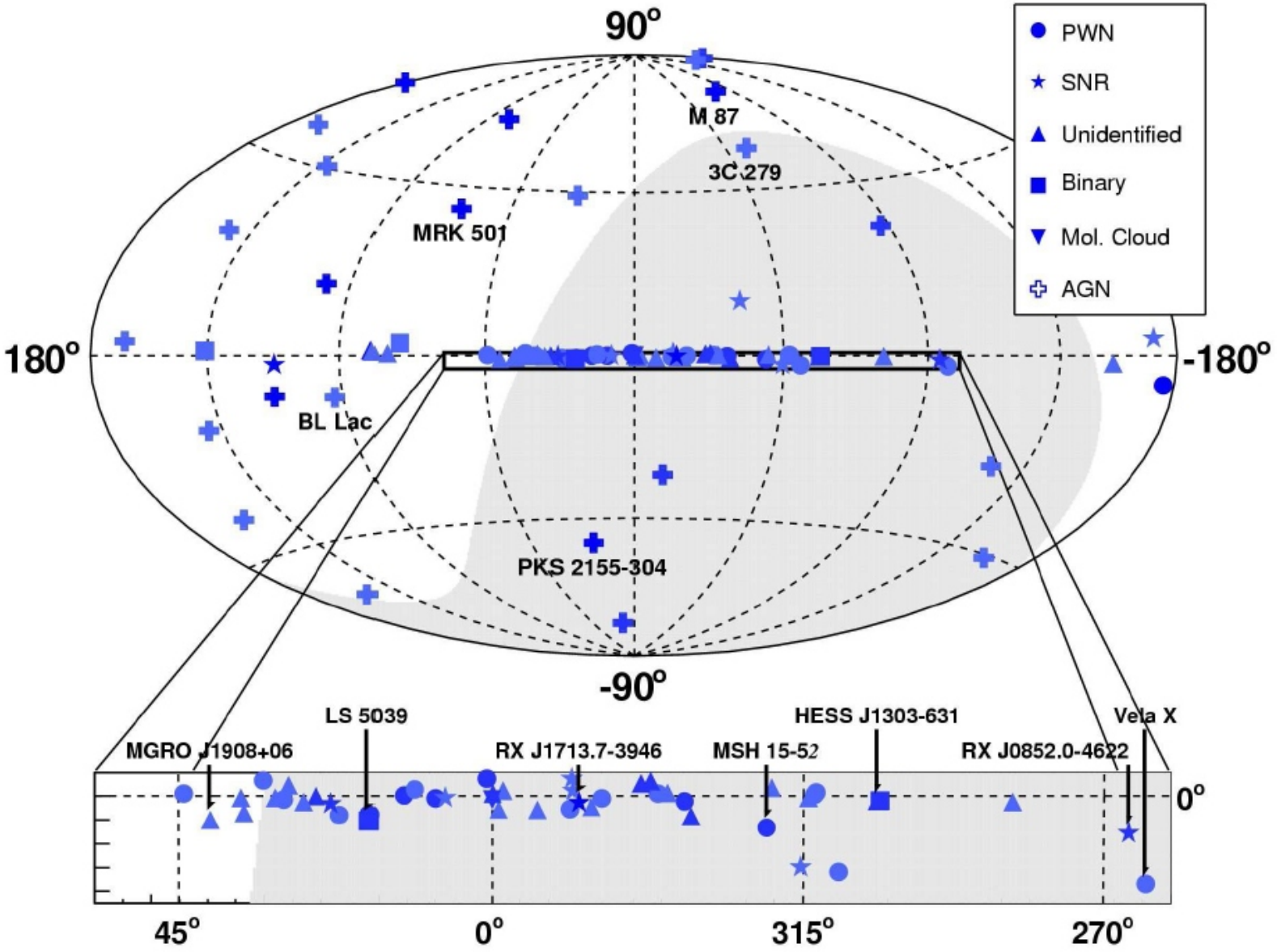
1st LAT catalogue
1451 sources (!!)



□ No association	▨ Possible association with nearby SNR or PWN		
× AGN – blazar	✳ Starburst Gal	☆ Pulsar	★ Pulsar w/PWN
⊗ AGN – unknown	+ Galaxy	◈ PWN	△ Globular cluster
✶ AGN – non blazar		○ SNR	⊠ XRB or MQO

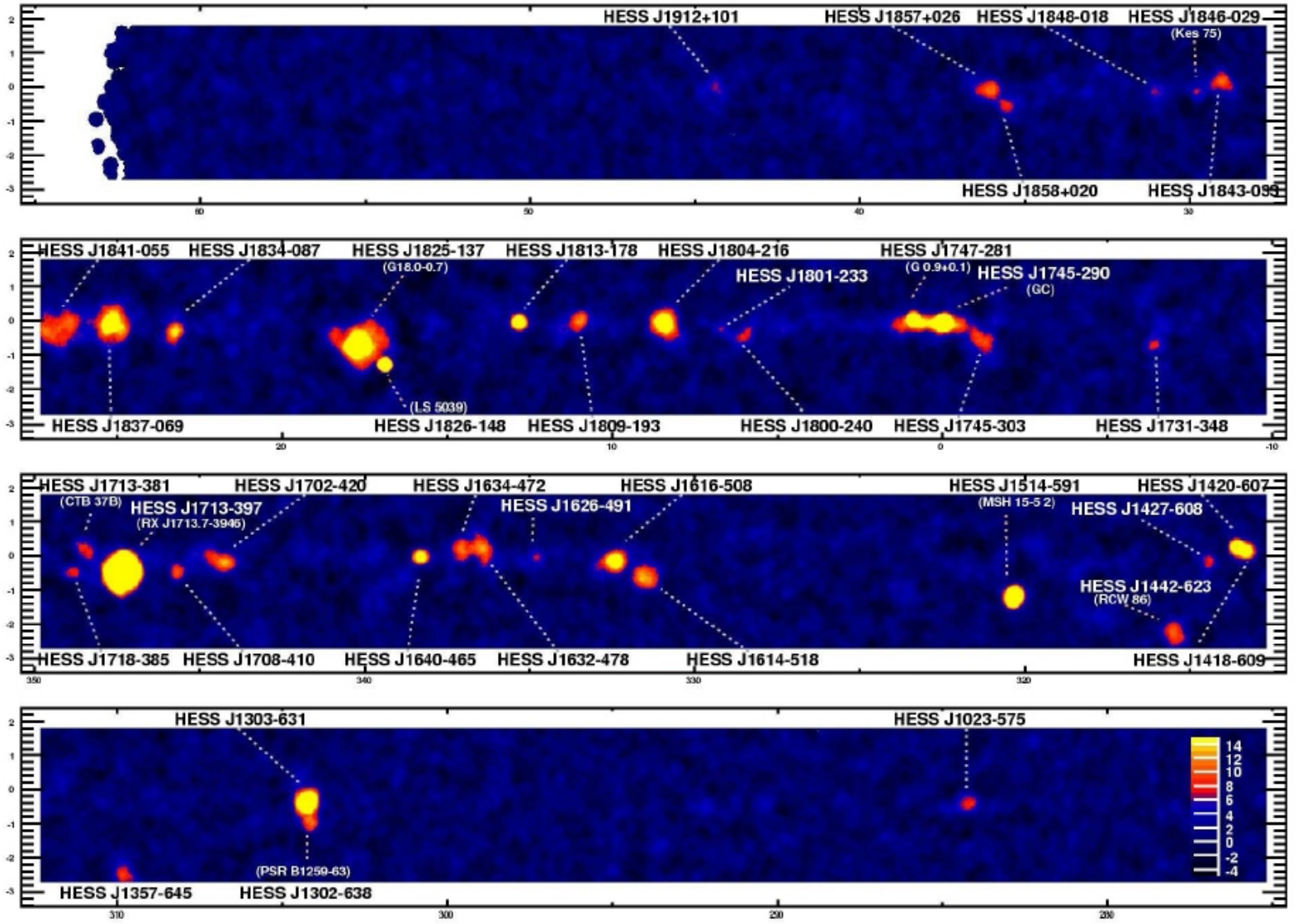

Galactic Latitude [deg]
30
15
0
−15
−30
90
75
60
45
30
15
0
345
330
315
300
285
270
Galactic Longitude [deg]
No association
Possible association with nearby SNR or PWN
AGN – blazar
Starburst Gal
Pulsar
Pulsar w/PWN
AGN – unknown
Galaxy
PWN
Globular cluster
AGN – non blazar
SNR
XRB or MQO

TEV SKY



The TeV sky is approaching 100 sources belonging to several different classes:

HESS scan of the Galactic plane



The “Richness of the High-Energy Sky”

Several astrophysical objects are capable
Of accelerating charged particles to relativistic energy.

- Pulsars
- SuperNova Remnants
- MicroQuasars
- Active Galactic Nuclei
- Gamma Ray Bursts.
- .....

The “Richness of the High-Energy Sky”

Several astrophysical objects are capable
Of accelerating charged particles to relativistic energy.

Pulsars

SuperNova Remnants

MicroQuasars

Active Galactic Nuclei

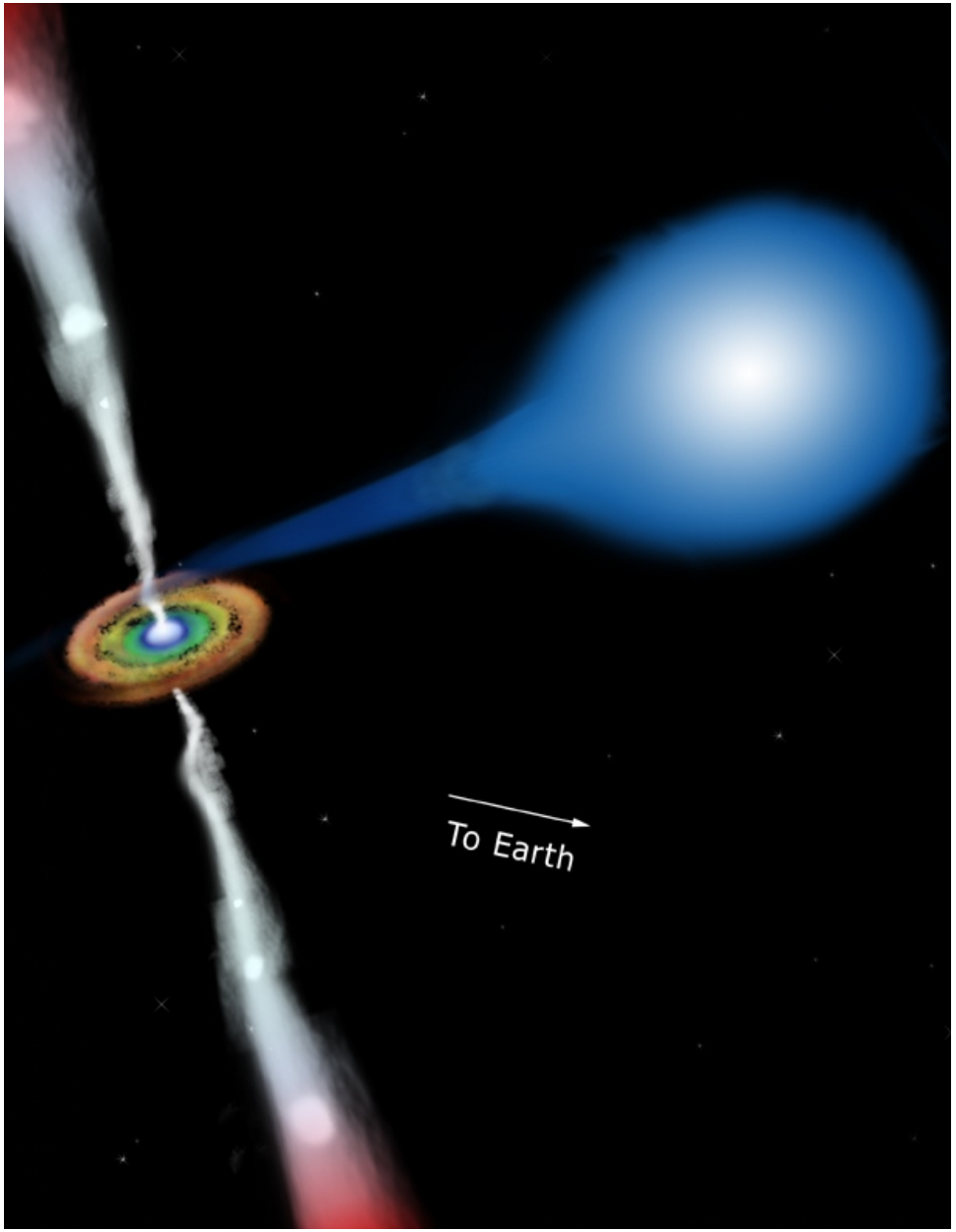
Gamma Ray Bursts.

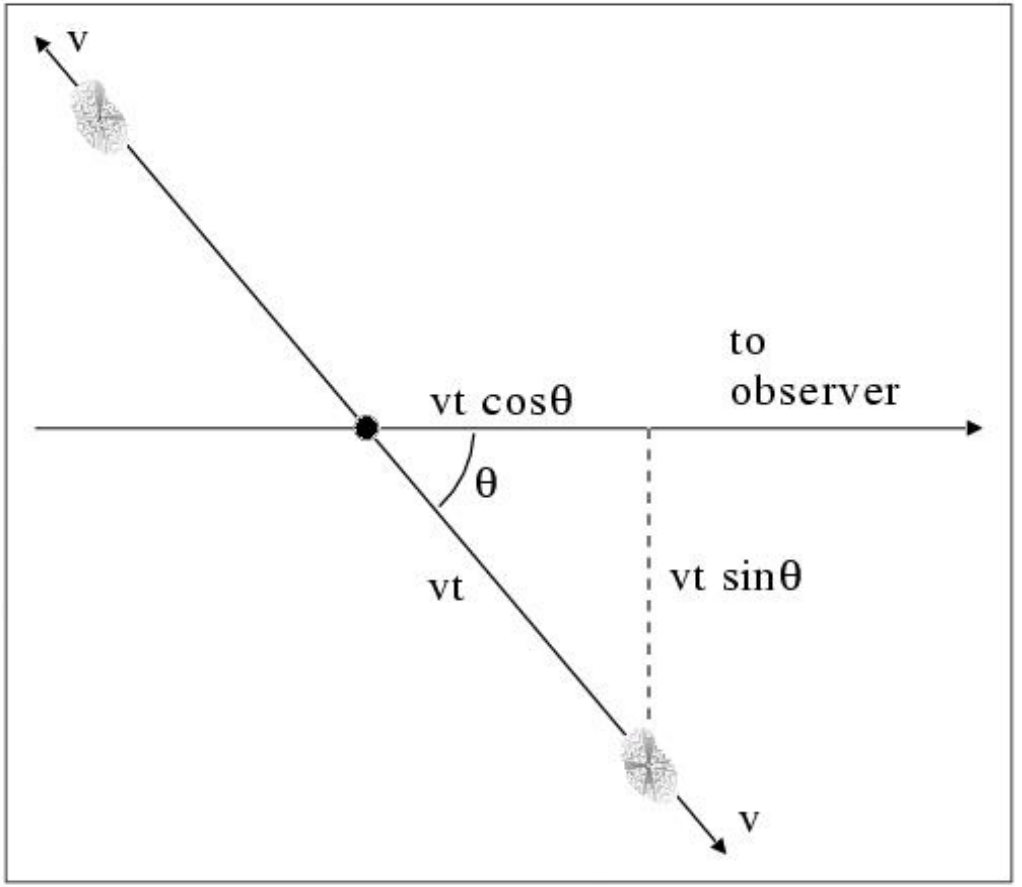
.....

Most of the observed
Relativistic Particles
are leptons.

Open Question:
Where are the observed
CR accelerated?

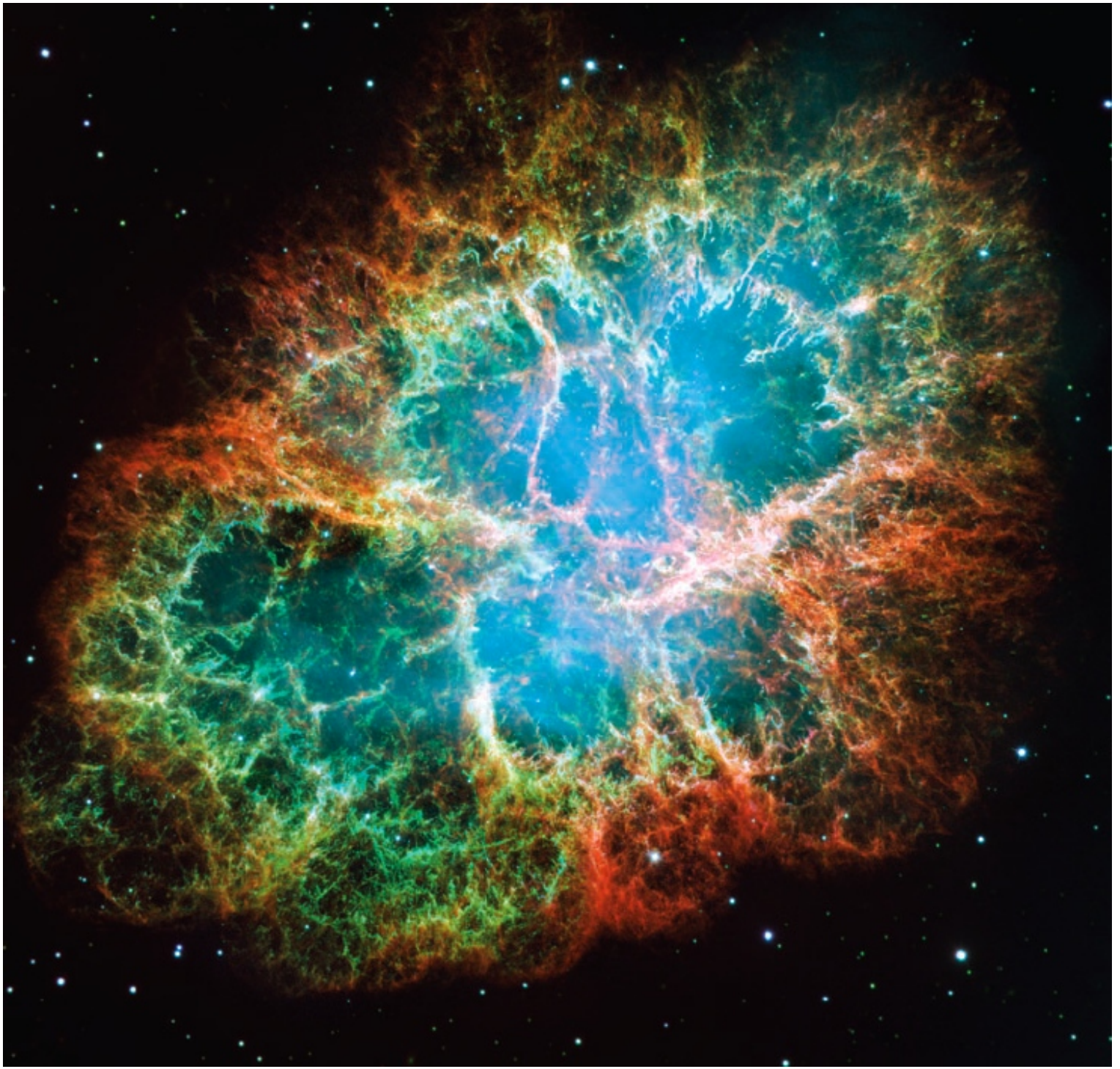
Geometry of the emission of the two jets

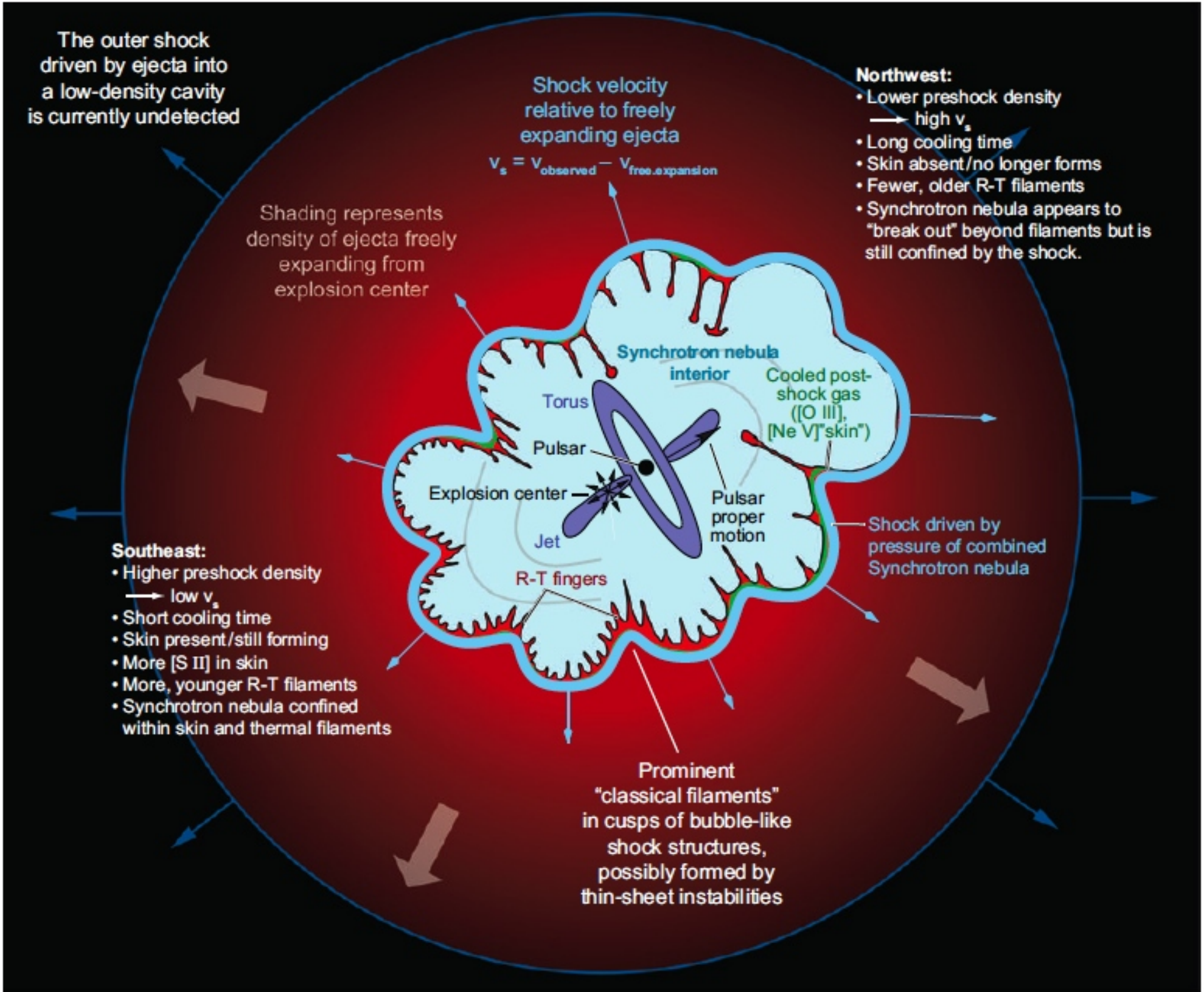




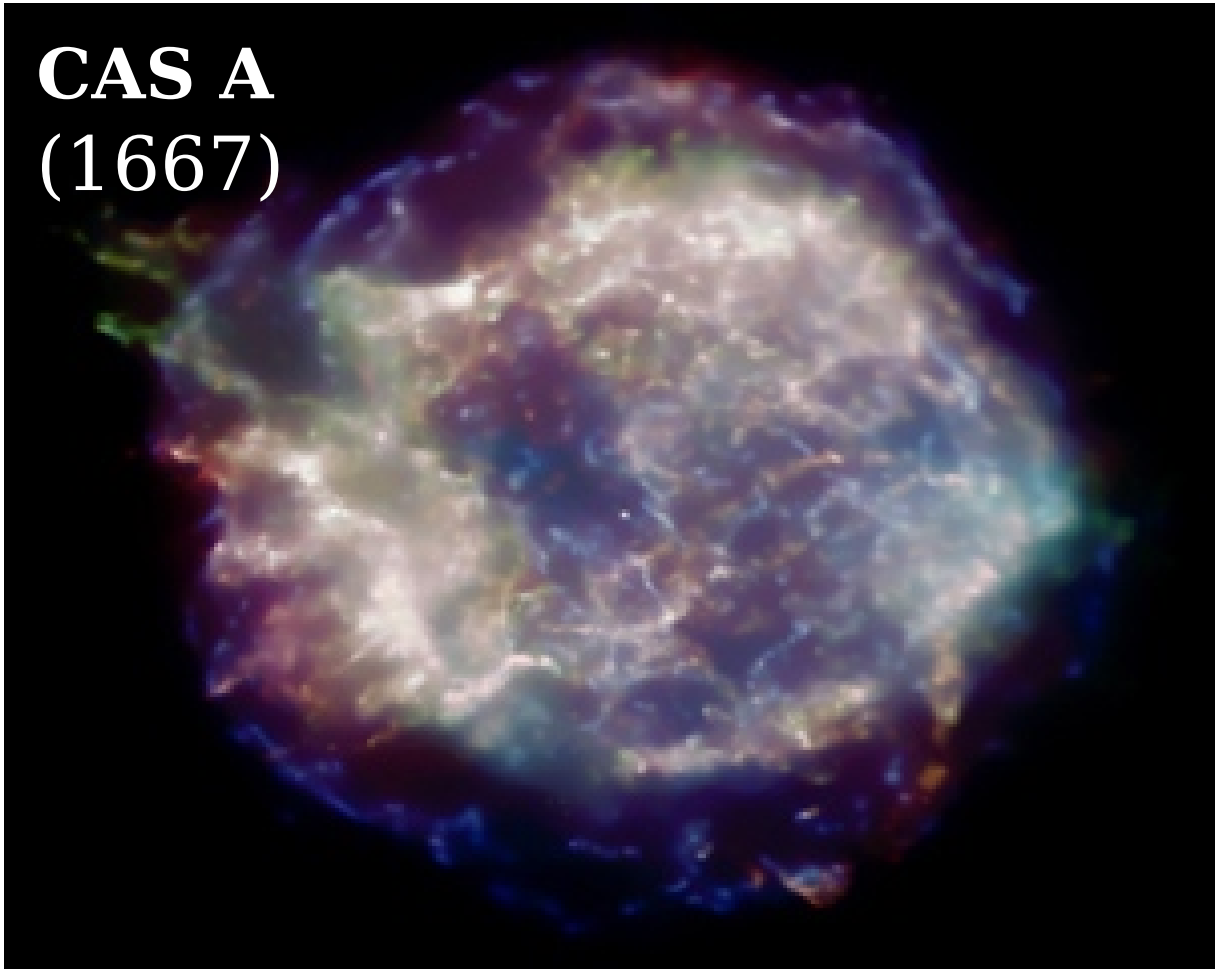
Intense radiation field
Of the companon star
Absorbs TeV photons [?]

CRAB
Nebula




The outer shock driven by ejecta into a low-density cavity is currently undetected
Shock velocity relative to freely expanding ejecta
$v_s = v_{observed} - v_{free.expansion}$
Shading represents density of ejecta freely expanding from explosion center
Northwest:
• Lower preshock density → high v_s
• Long cooling time
• Skin absent/no longer forms
• Fewer, older R-T filaments
• Synchrotron nebula appears to "break out" beyond filaments but is still confined by the shock.
Synchrotron nebula interior
Cooled post-shock gas ([O III], [Ne V]"skin")
Torus
Pulsar
Explosion center
Pulsar proper motion
Jet
R-T fingers
Shock driven by pressure of combined Synchrotron nebula
Southeast:
• Higher preshock density → low v_s
• Short cooling time
• Skin present/still forming
• More [S II] in skin
• More, younger R-T filaments
• Synchrotron nebula confined within skin and thermal filaments
Prominent "classical filaments" in cusps of bubble-like shock structures, possibly formed by thin-sheet instabilities

The SuperNova "Paradigm" for CR acceleration



Powering the galactic Cosmic Rays

$$L_{\rm cr}({\rm Milky\ Way}) \simeq \frac{\rho_{\rm cr}\, V_{\rm conf}}{T_{\rm conf}}$$

$$\simeq 2\times 10^{41}\left(\frac{\rm erg}{\rm s}\right)$$

$$\simeq 5\times 10^{7}\, L_{\odot}$$

- ENERGETICS
- DYNAMICS [Diffusive Shock acceleration]

$$L_{\text{SN kinetic}}^{\text{Milky Way}} \simeq E_{\text{SN}}^{\text{Kinetic}} \, f_{\text{SN}}$$

$$L_{\text{SN kinetic}}^{\text{Milky Way}} \simeq \left[1.6 \times 10^{51} \text{ erg}\right] \left[\frac{3}{\text{century}}\right]$$

$$M = 5 \, M_{\odot}$$

$$v \simeq 5000 \text{ Km/s}$$

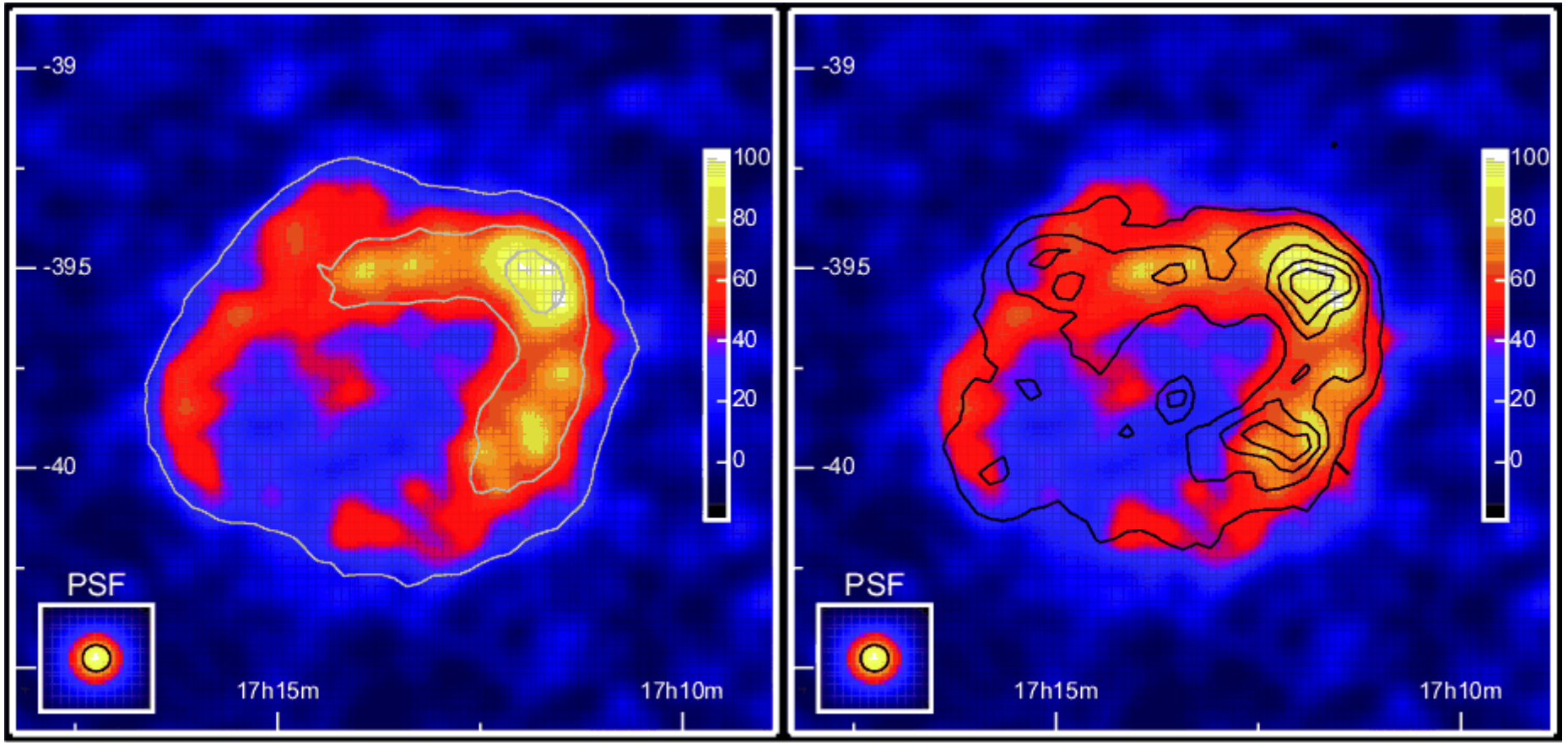
$$L_{\text{SN kinetic}}^{\text{Milky Way}} \simeq 1.5 \times 10^{42} \, \frac{\text{erg}}{\text{s}}$$

Power Provided by SN is sufficient
with a conversion efficiency of 15-20 %
in relativistic particles

HESS Telescope

Observations with TeV photons

SuperNova RX J1713.7-3946



Comparison with ROSAT observation

Have we proved that SNR are the source of the bulk of the Galactic Cosmic Rays ?

Have we proved that SNR are the source of the bulk of the Galactic Cosmic Rays ?

The evidence is accumulating.
Fermi, Hess results

Perhaps case not closed...
[different opinions]

Detection of Star-Burst Galaxies ....

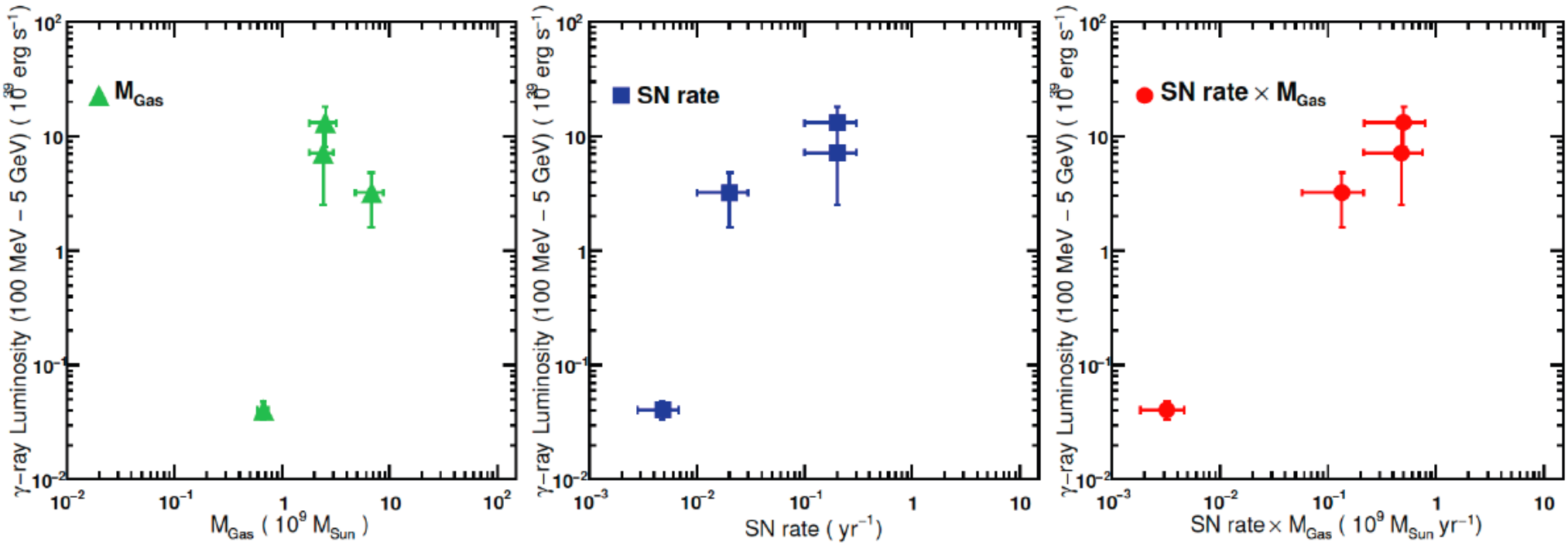
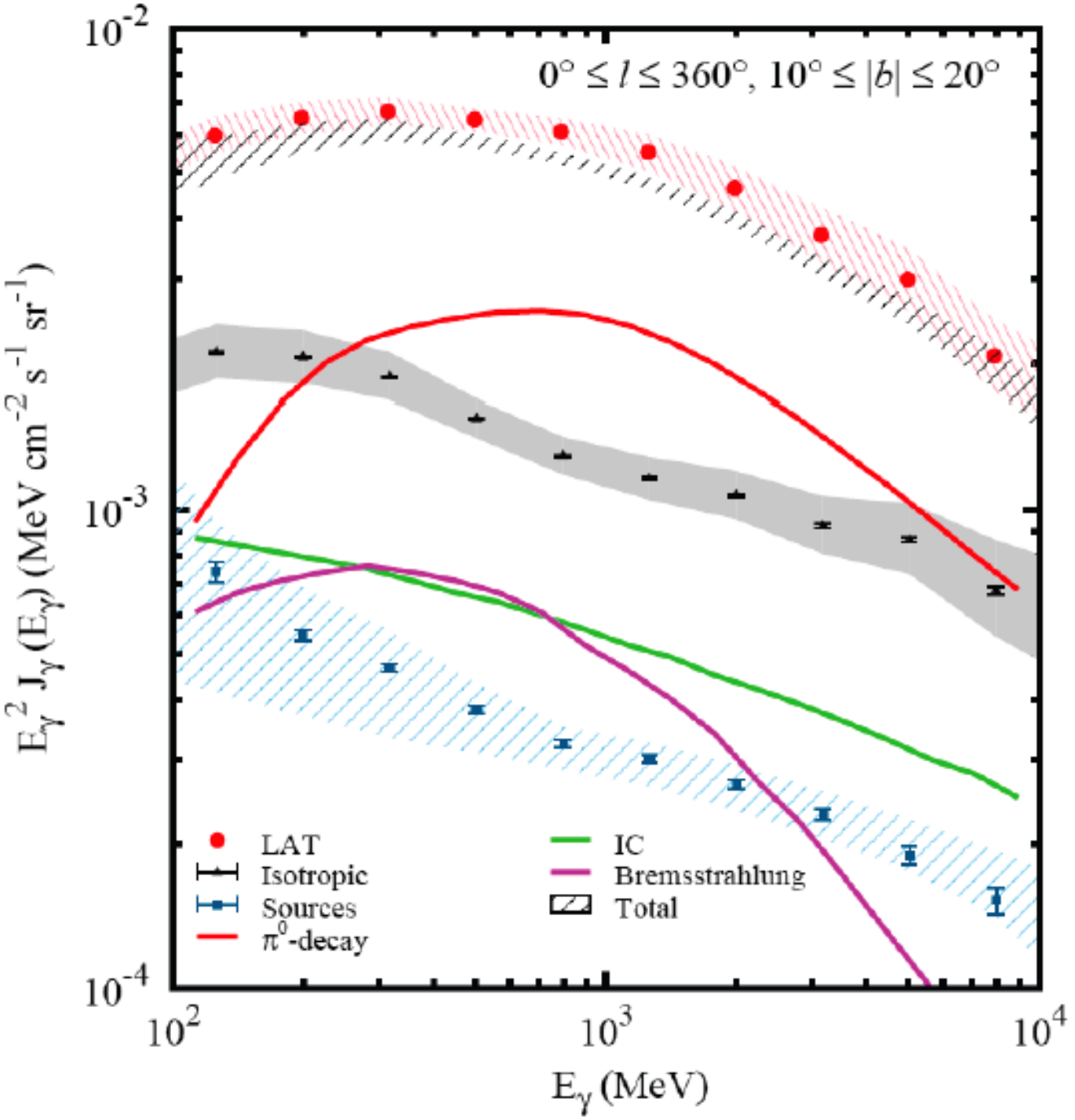


Table 2: Properties of γ-ray galaxies lacking active central nuclei.

Galaxy	d (Mpc)	R_{SN} (yr^{-1})	M_{Gas} (10^9 $M_\odot$)	$F_\gamma{}^a$ (10^{-8} ph cm^{-2} s^{-1})	$4\pi d^2 F_\gamma{}^a$ (10^{42} ph s^{-1})	$L_\gamma{}^a$ (10^{39} erg s^{-1})
LMC[b]	0.049 ± 0.001	0.005 ± 0.002	0.67 ± 0.08	26.3 ± 4.7	0.074 ± 0.013	0.041 ± 0.007
Milky Way[c]	1	0.02 ± 0.01	6.5 ± 2.0	4.6 ± 2.3	5.5 ± 2.8	3.2 ± 1.6
M82	3.6 ± 0.3	0.2 ± 0.1	2.5 ± 0.7	1.6 ± 0.5	25 ± 9	13 ± 5.0
NGC 253	3.9 ± 0.4	0.2 ± 0.1	2.5 ± 0.6	0.6 ± 0.4	11 ± 7	7.2 ± 4.7

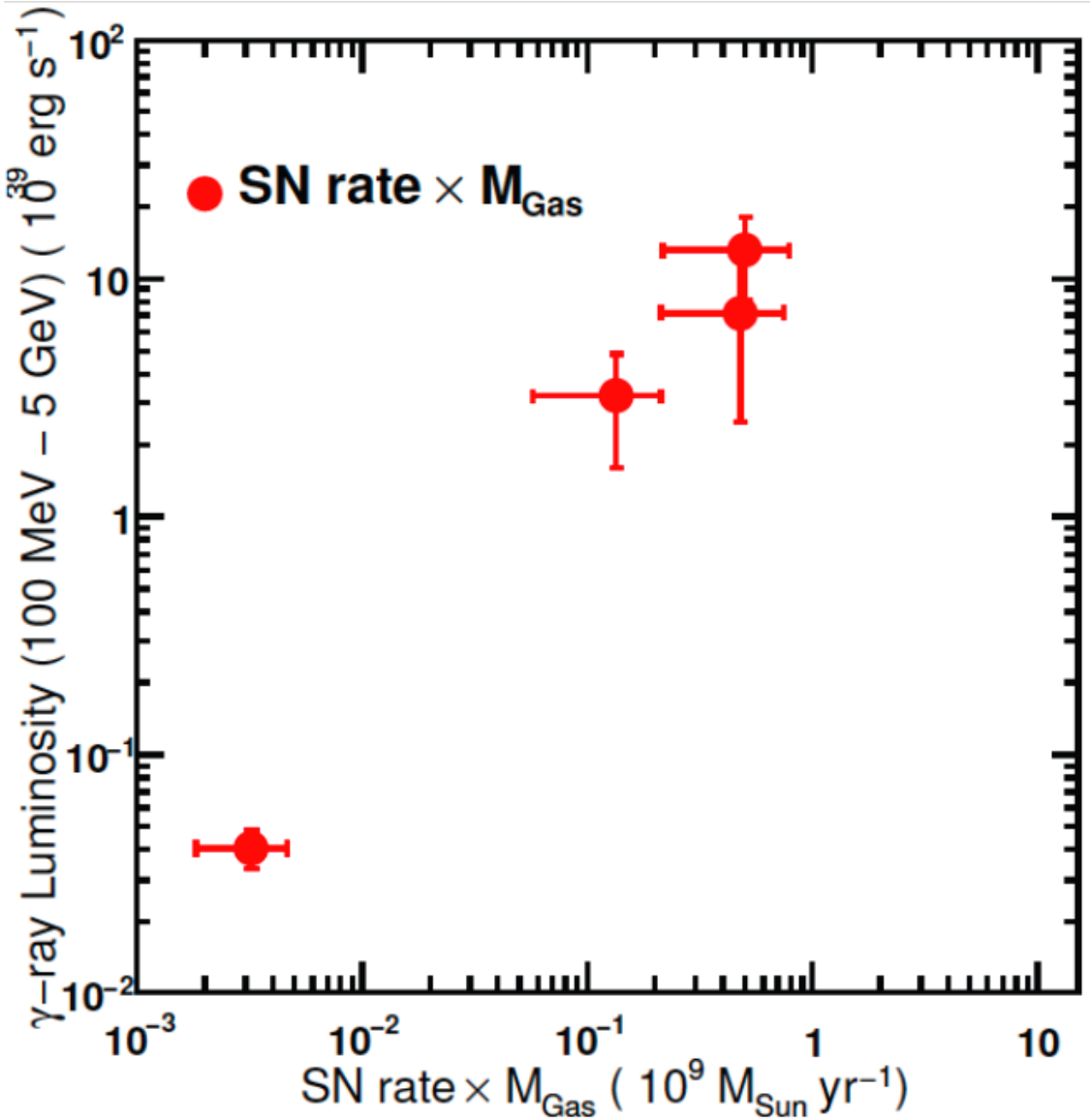
FERMI result



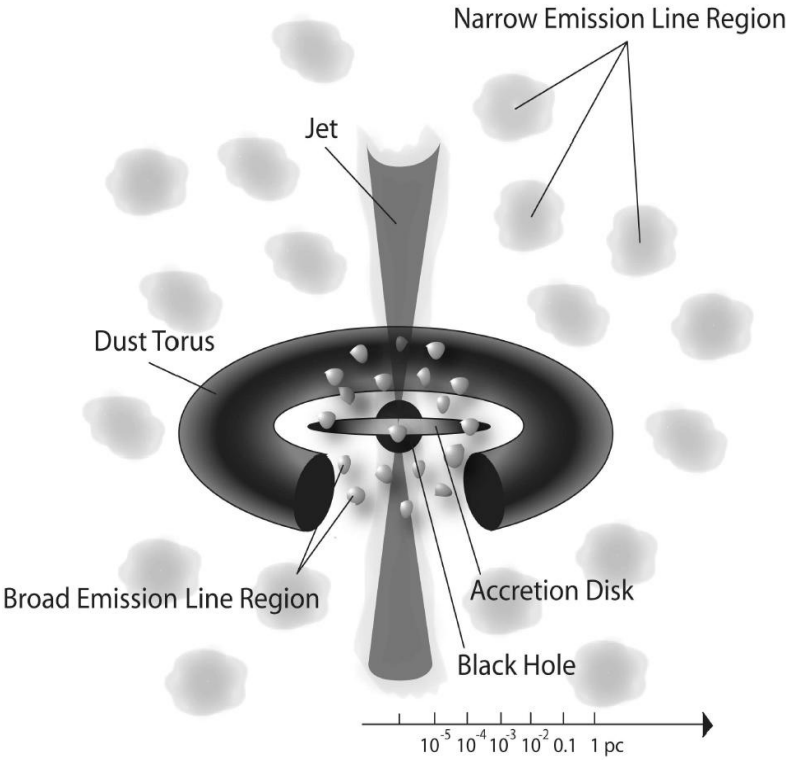
Galactic DiffuseFlux.

Consistent picture emerging

“EGRET GeV Excess” disappeared.


SN rate × M_Gas
γ−ray Luminosity (100 MeV – 5 GeV) (10^39 erg s^−1)
SN rate × M_Gas (10^9 M_Sun yr^−1)
10^2
10
1
10^−1
10^−2
10^−3
10^−2
10^−1
1
10

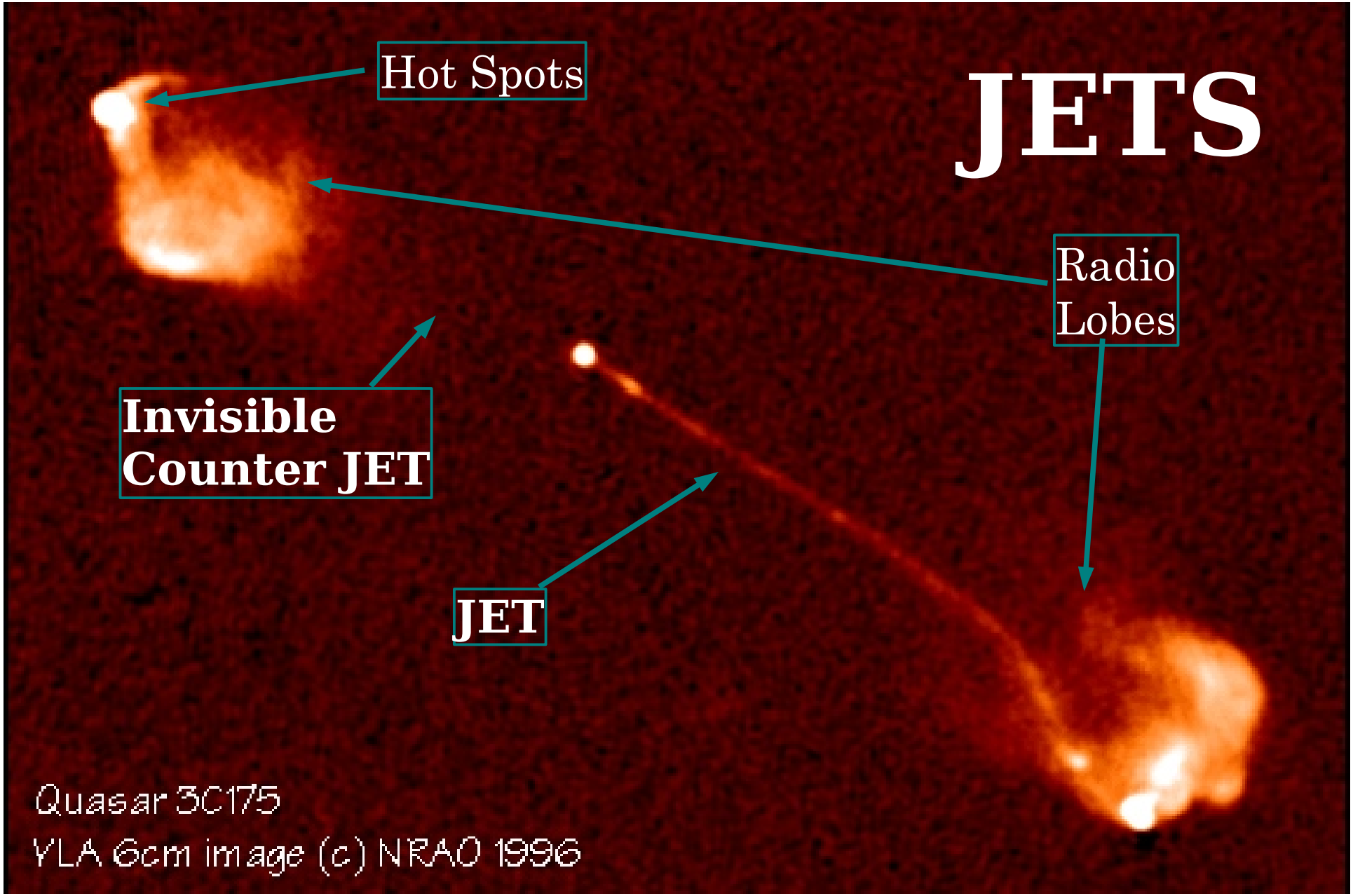
ACTIVE GALACTIC NUCLEI



Optical

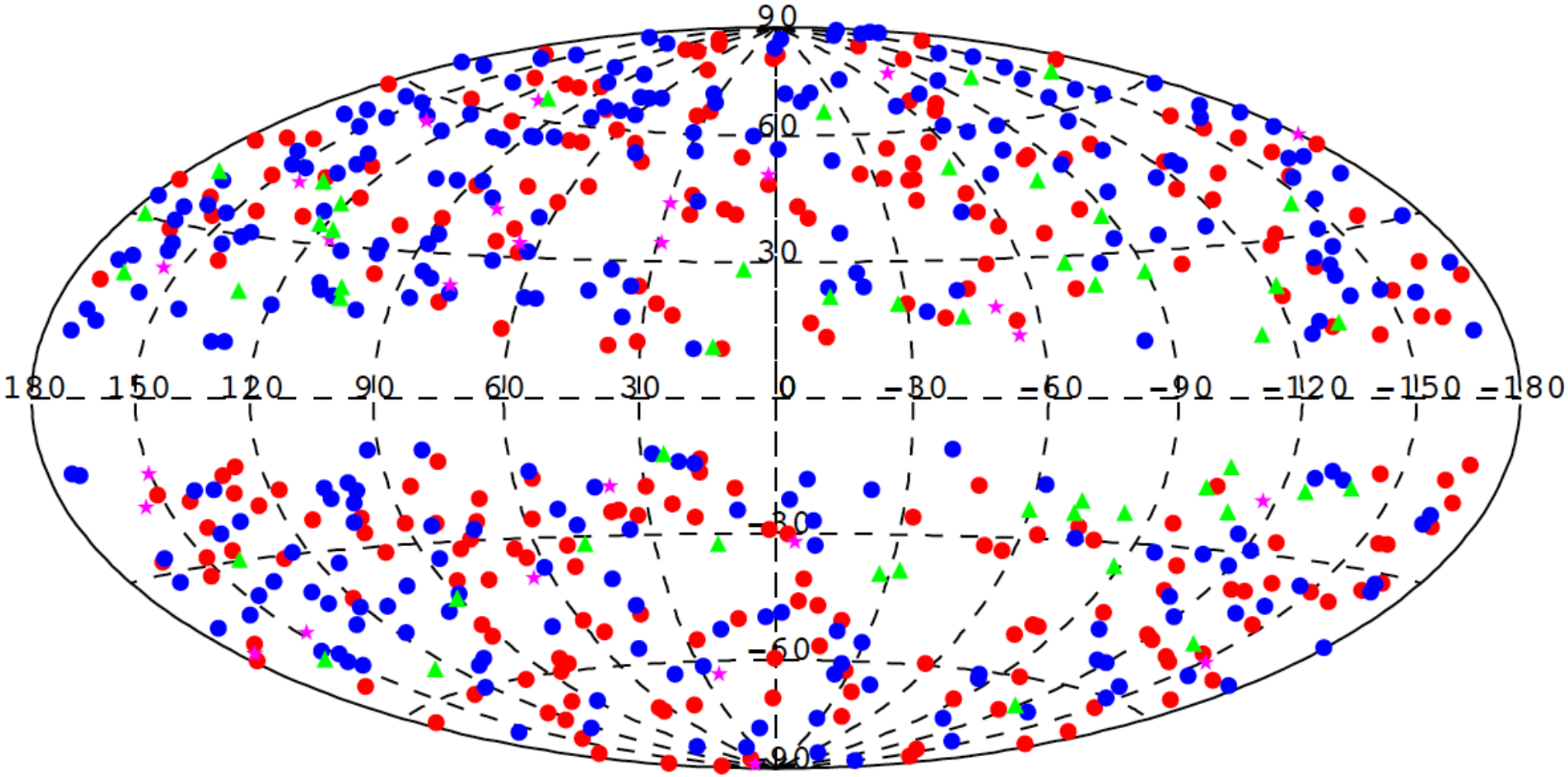
Radio

3C219


Hot Spots
JETS
Radio Lobes
Invisible Counter JET
JET
Quasar 3C175
VLA 6cm image (c) NRAO 1996

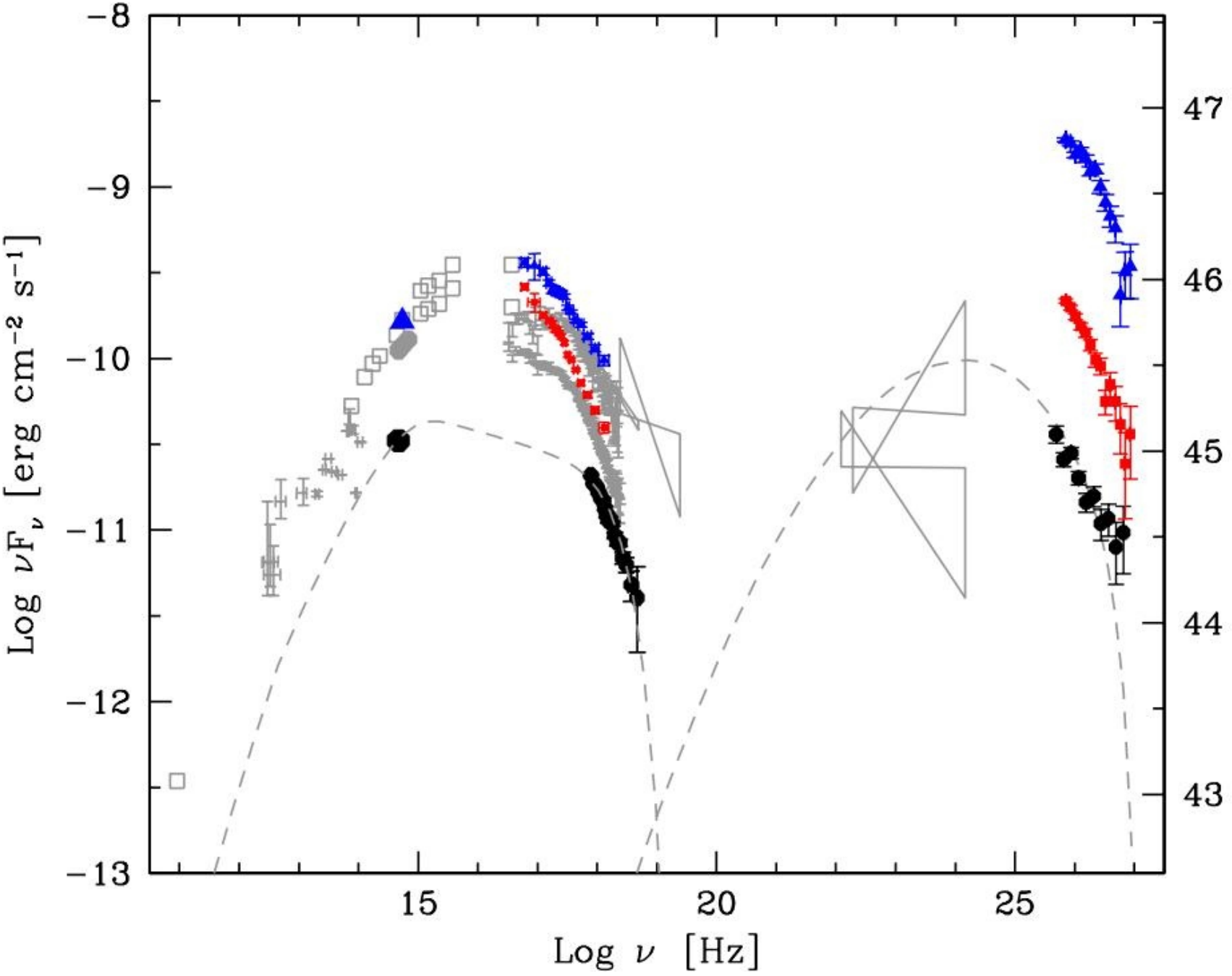
AGN observed by FERMI:

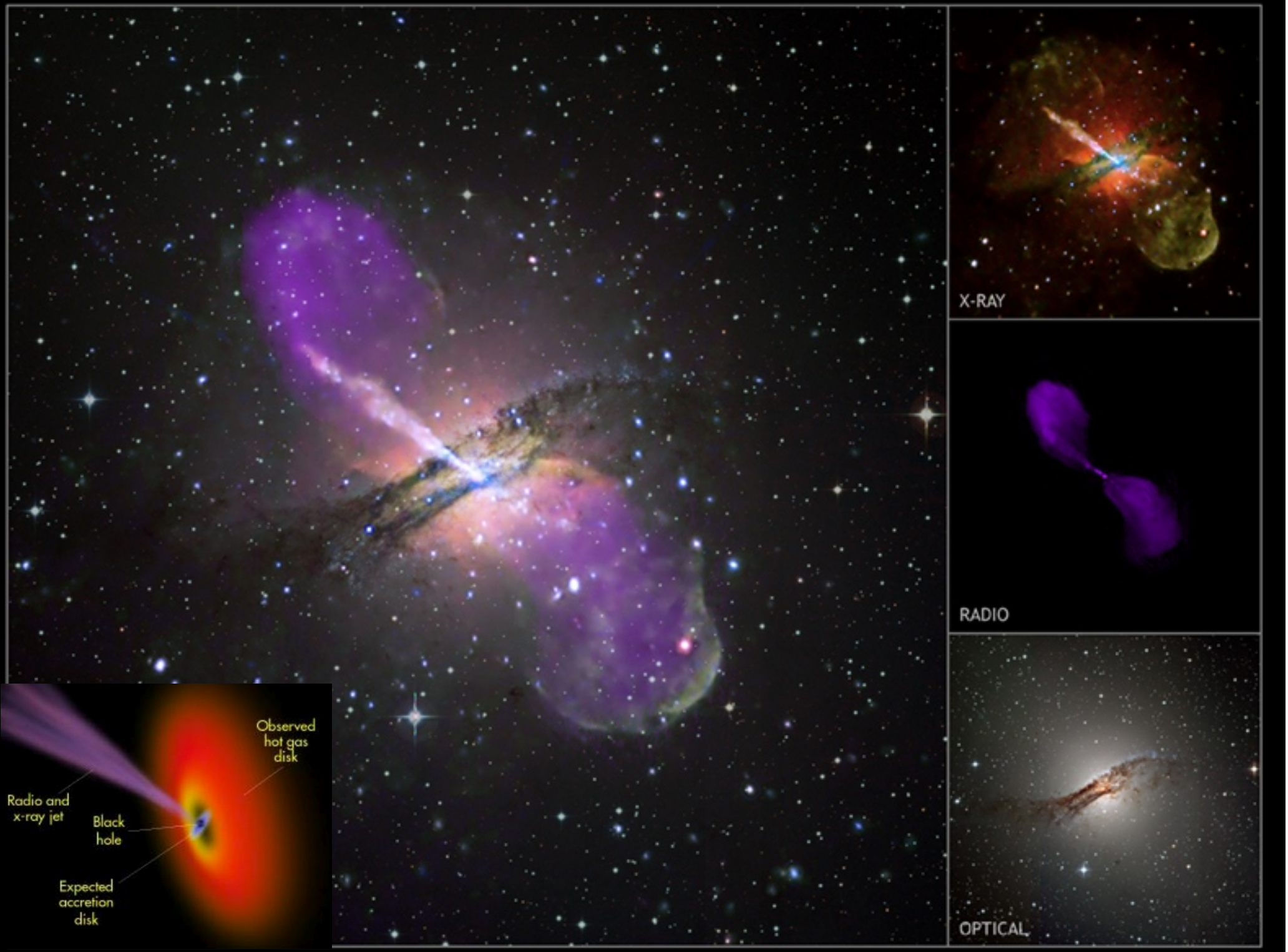
671 AGN's



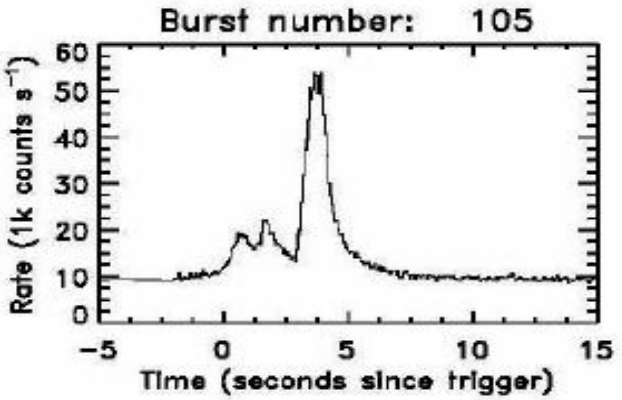
Red: FSRQ
Blue: Blac
Magenta: Radio Galaxies

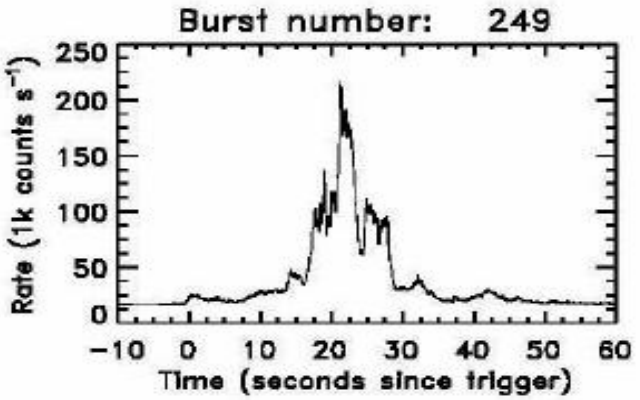
PKS 2155-304

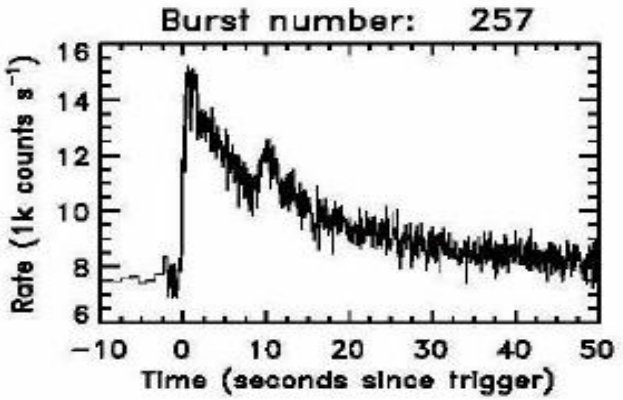


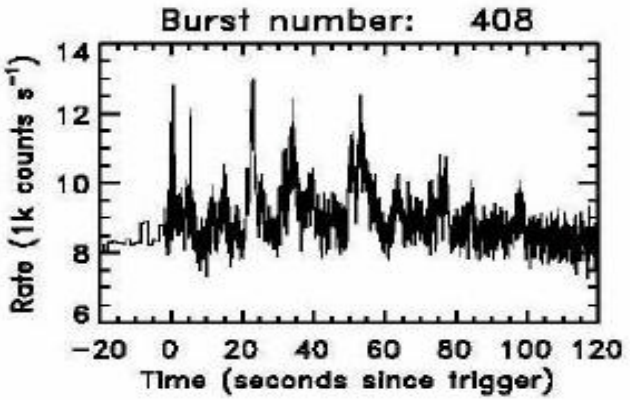

X-RAY
RADIO
OPTICAL
Observed hot gas disk
Radio and x-ray jet
Black hole
Expected accretion disk

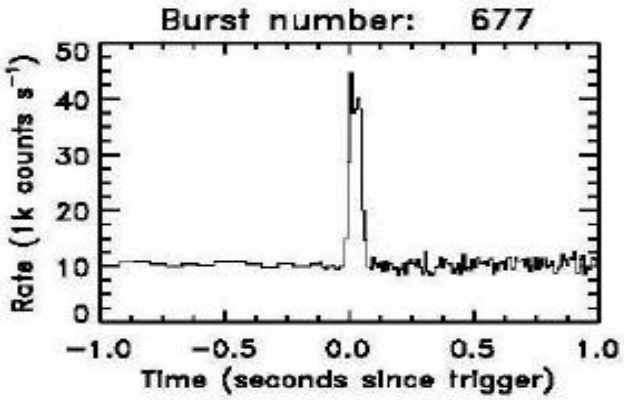
GAMMA RAY BURSTS (GRB's)

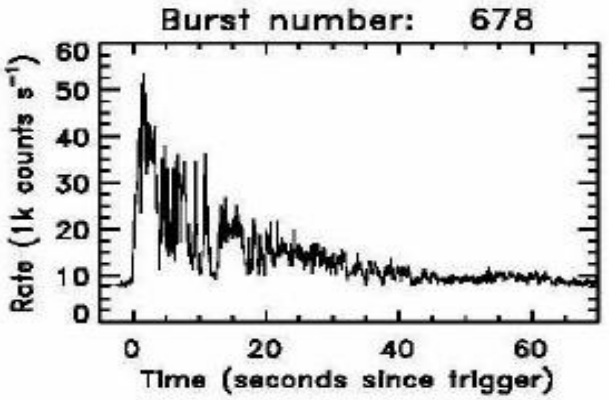






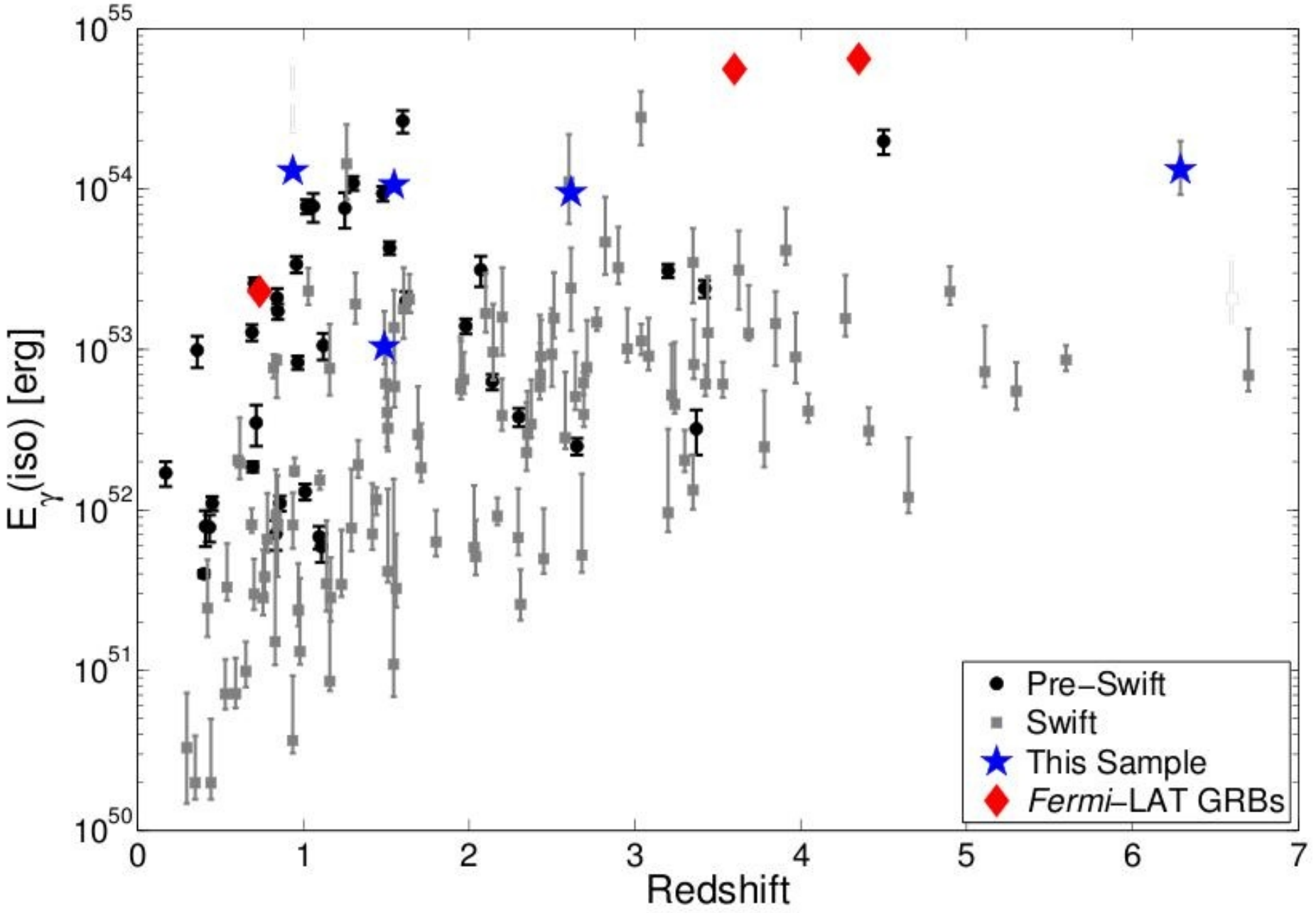


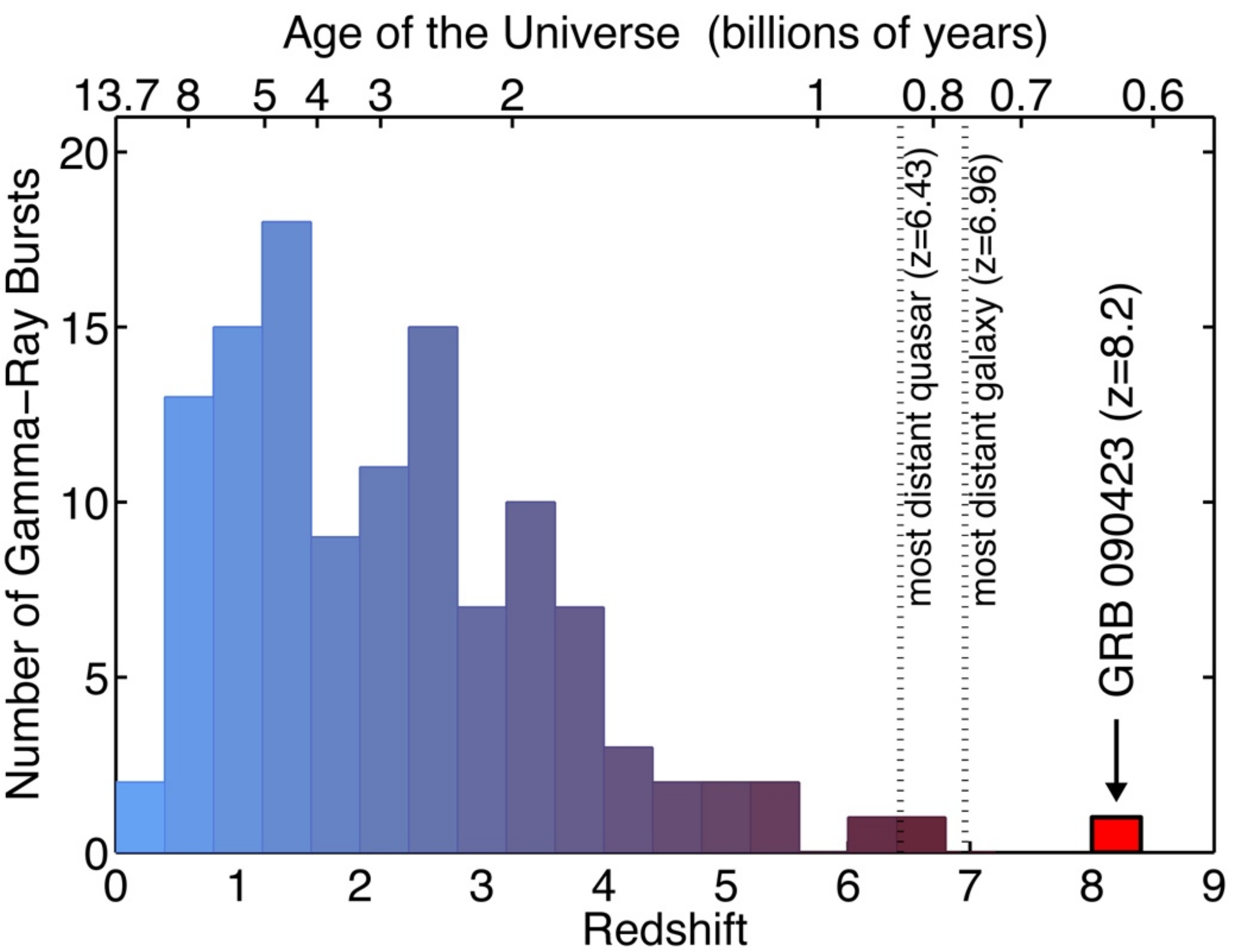


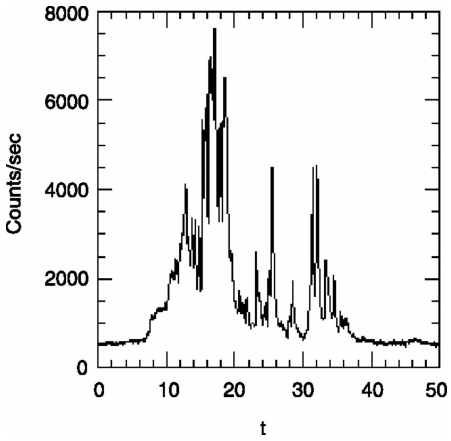


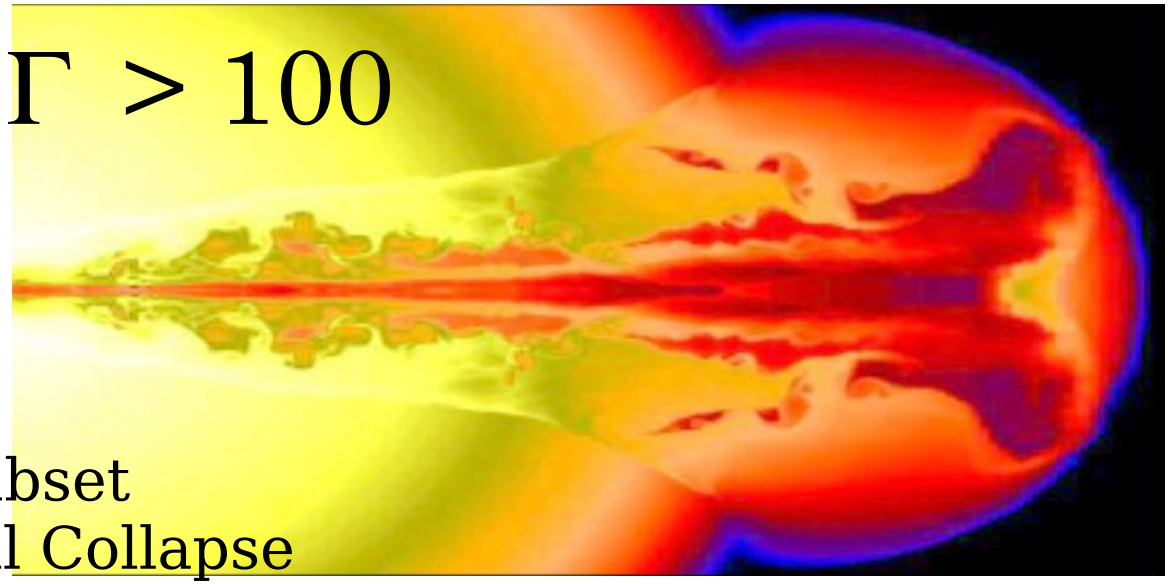
Proposed source
Of the CR

Extraordinary Large (beamed) Energy Output

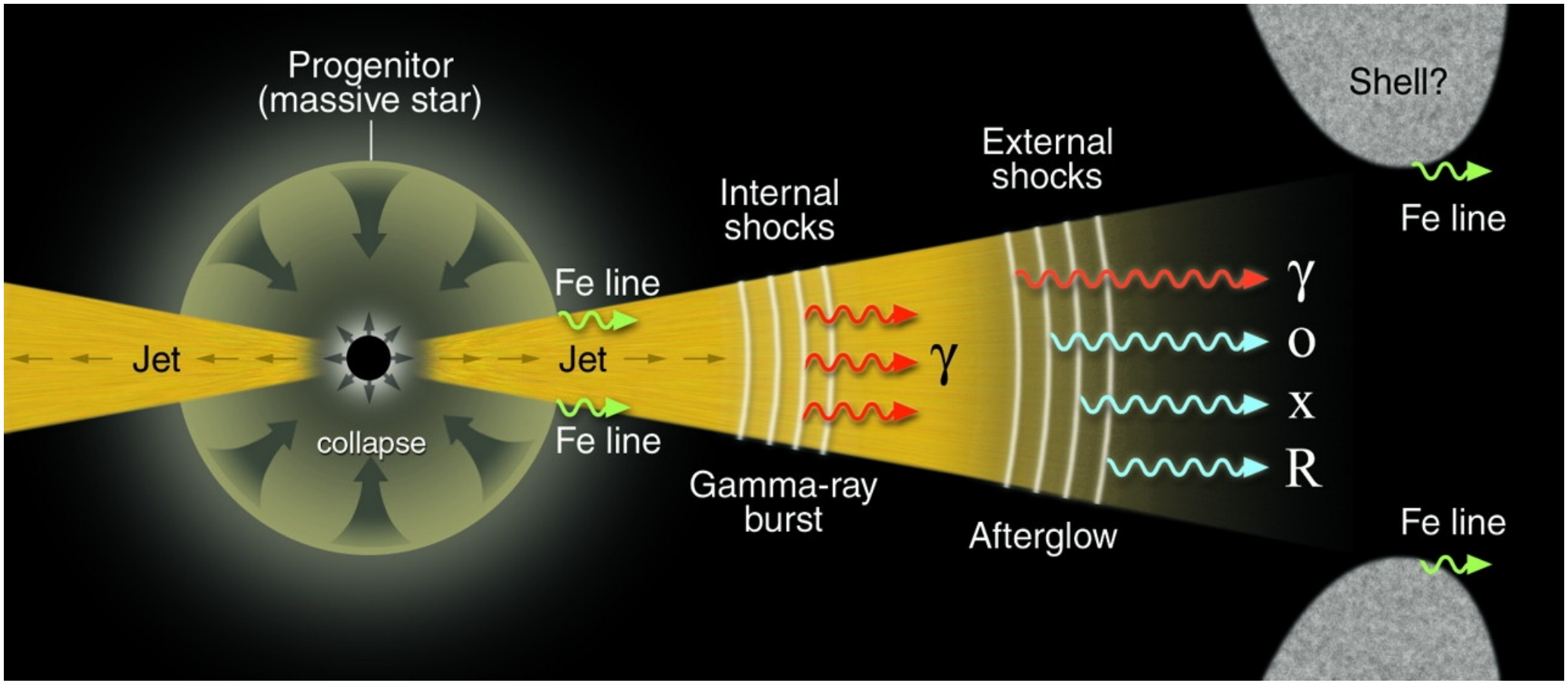



Age of the Universe (billions of years)
13.7
8
5
4
3
2
1
0.8
0.7
0.6
Number of Gamma−Ray Bursts
0
5
10
15
20
0
1
2
3
4
5
6
7
8
9
Redshift
most distant quasar (z=6.43)
most distant galaxy (z=6.96)
GRB 090423 (z=8.2)





GRB : associated with a subset
of SN Stellar Gravitational Collapse



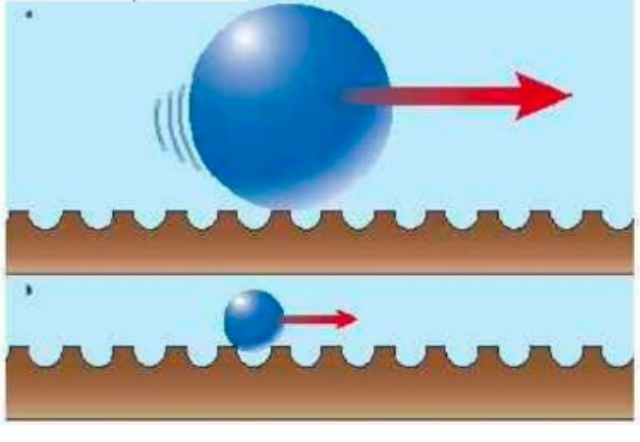
Short distance structure of space time

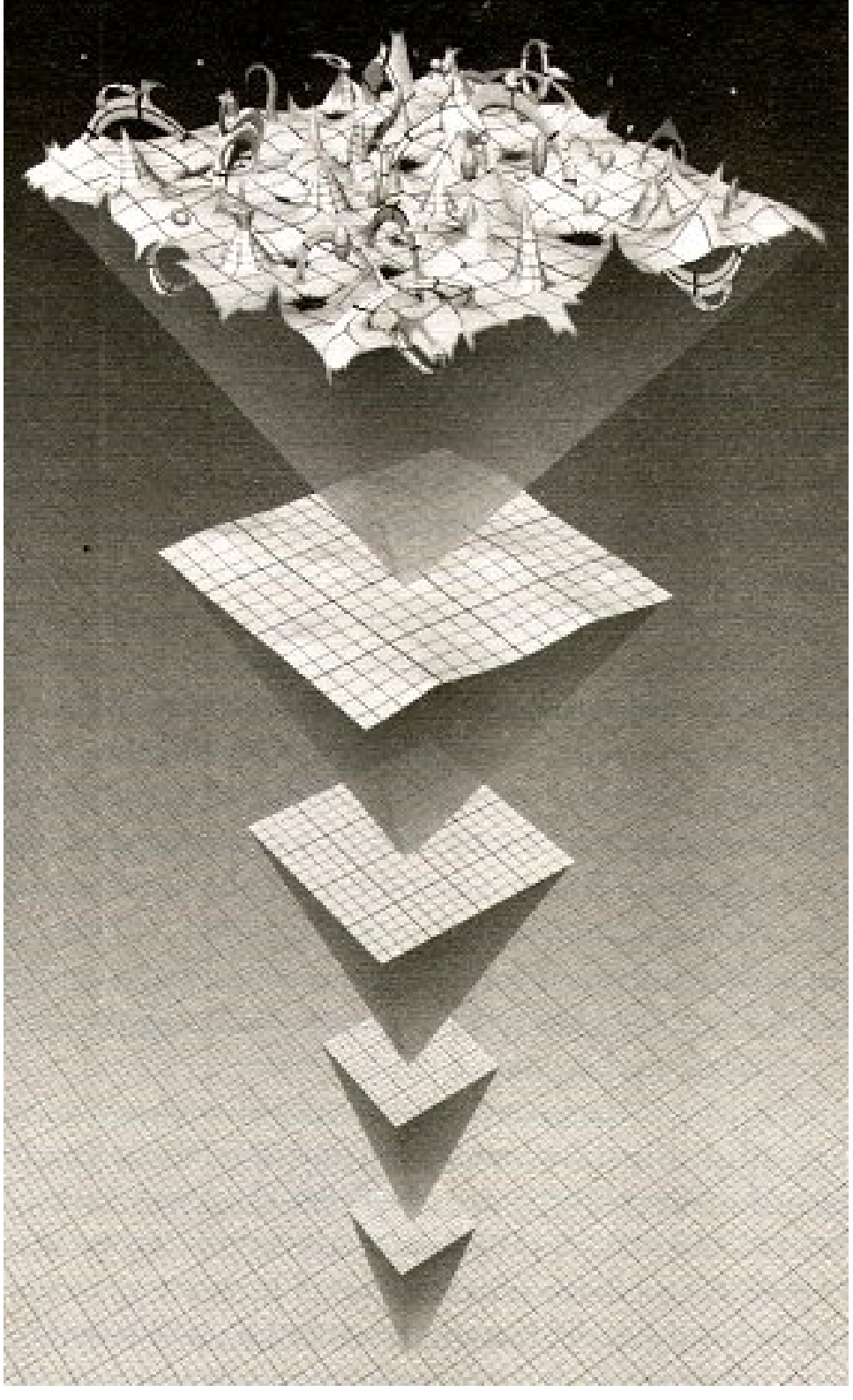
$$c(E) = c \times \left(1 - \xi \, \frac{E}{M_{\mathrm{Planck}}} + \ldots\right)$$

$$\Delta t \simeq \xi \, \frac{E}{M_{\mathrm{Planck}}} \, \frac{L}{c}$$

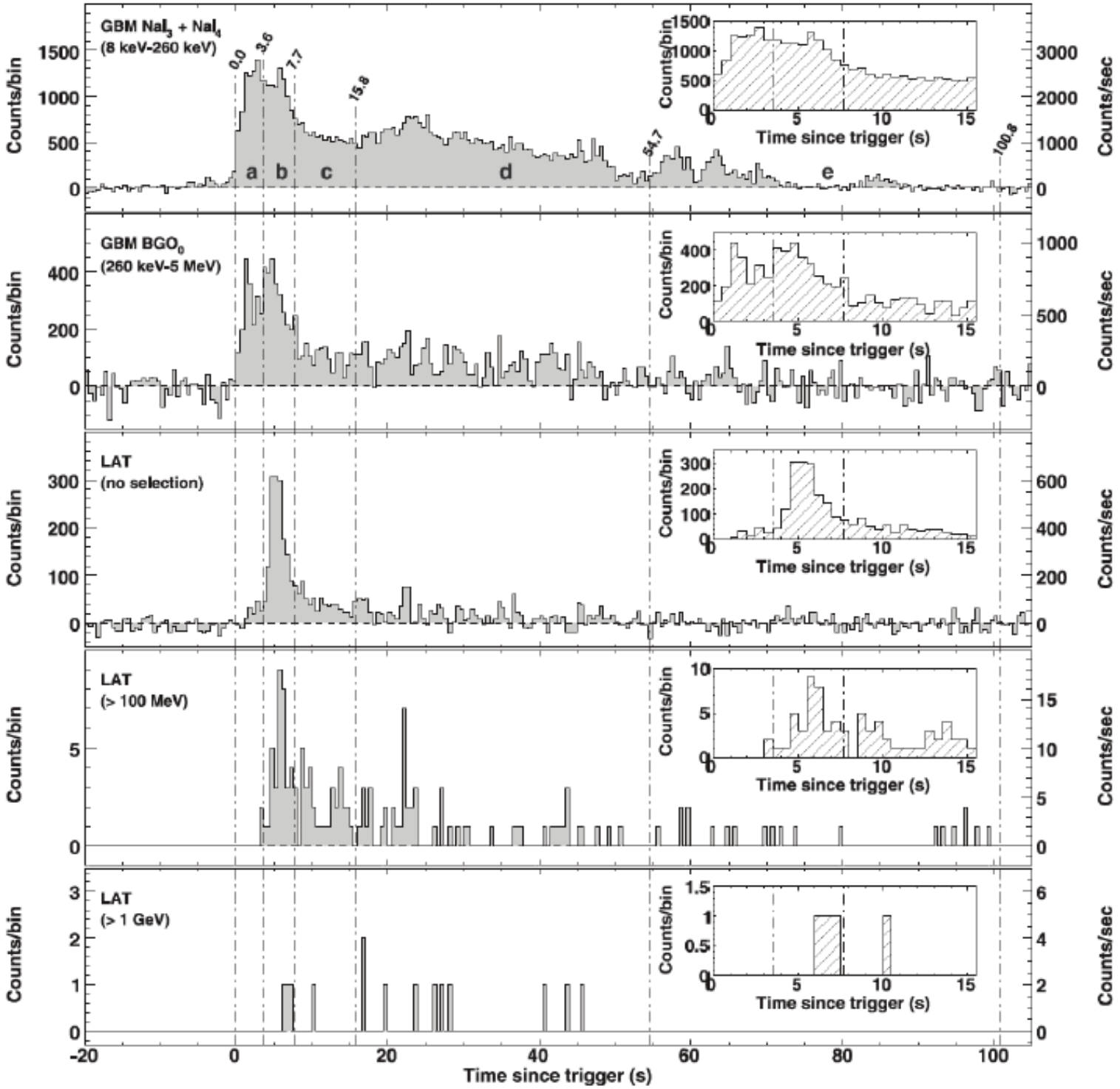
$$\Delta t \simeq 0.06 \, E_{\mathrm{GeV}} \; z$$

Delay of high energy photons



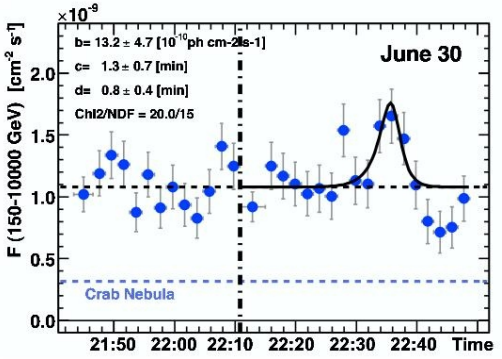


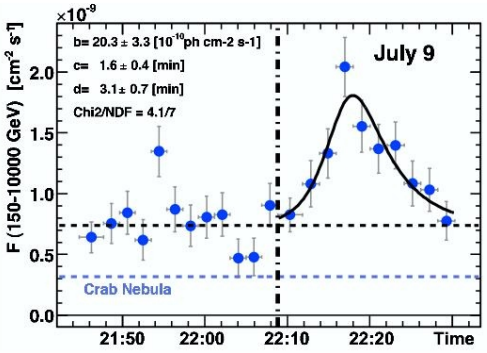
GRB 080916C
(Fermi)

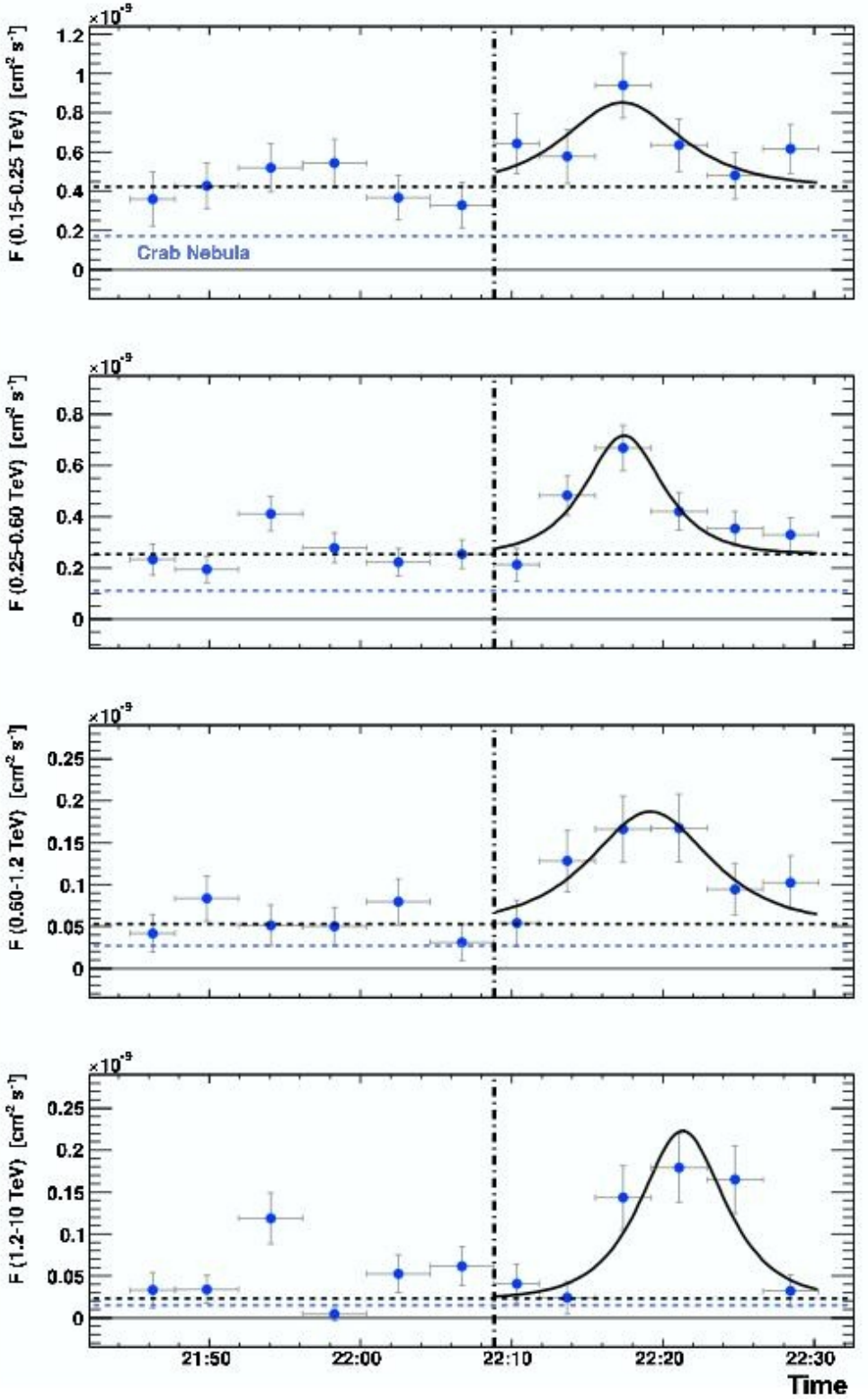


Markarian 501 (120 Mpc)

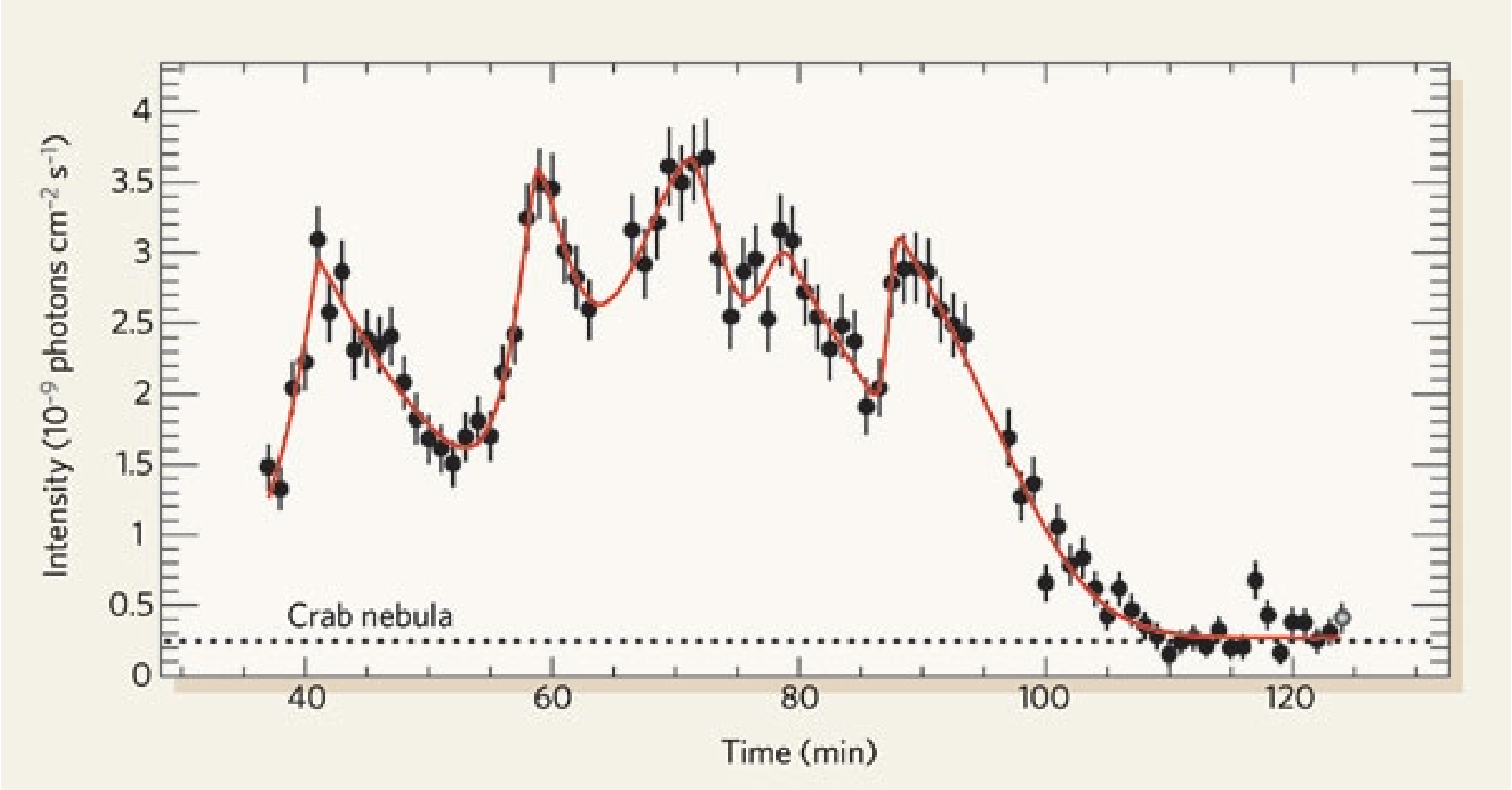
9 july 2005
2 minutes bins



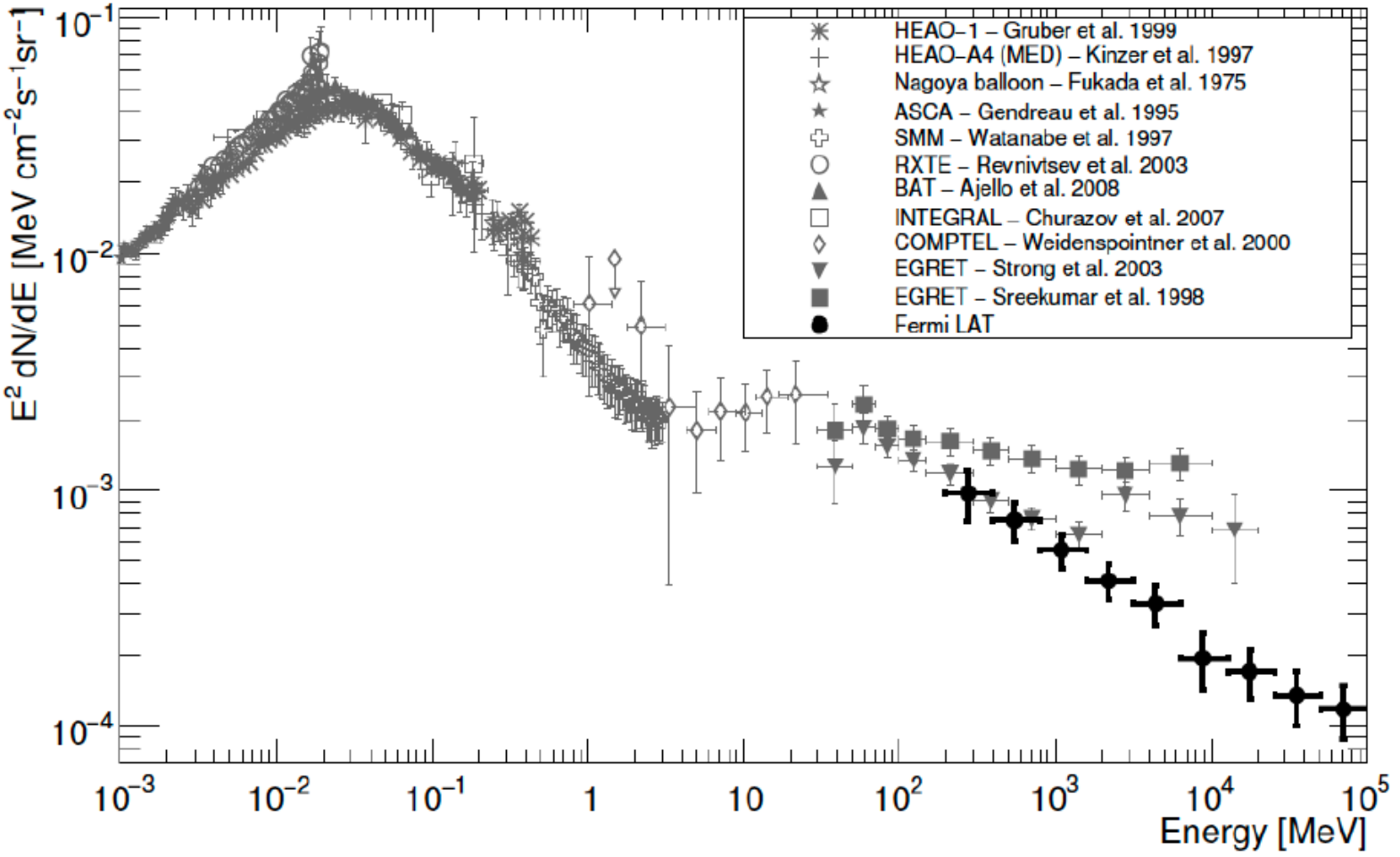




PKS 2155-304 (HESS measurements)



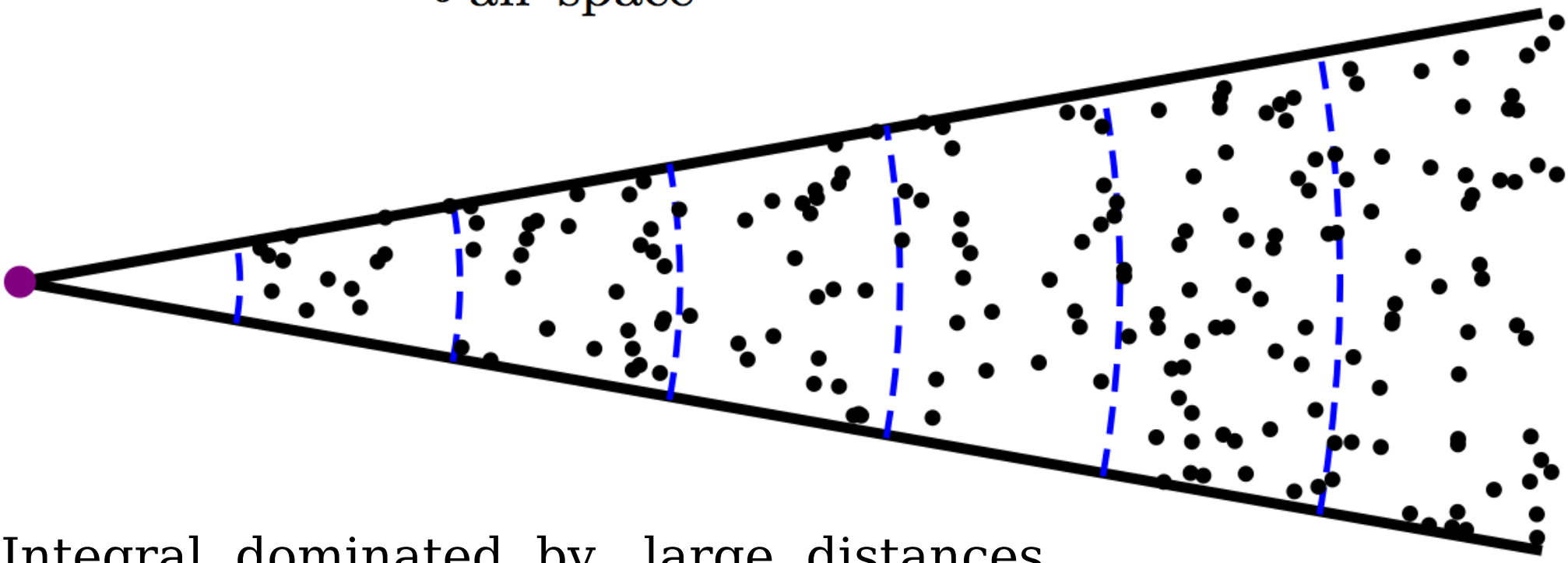
Extragalactic Background Light



INCLUSIVE Extra-Galactic Photon Flux

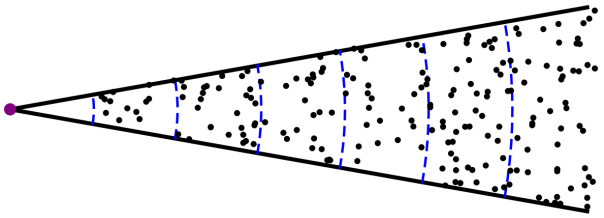
$$\phi_{\text{inclusive}} = \sum_{\text{all sources}} \phi_{\text{single source}}$$

$$\phi_{\text{inclusive}} = \int_{\text{all space}} d^3r \; \phi_{\text{source}}(\vec{r})$$



Integral dominated by large distances

Homogeneous Distribution of identical sources
In a static euclidean space:



$$\left.\frac{d\phi}{d\Omega}\right|_{\text{inclusive}} = \frac{1}{d\Omega}\int_0^\infty dr\ (d\Omega\, n_s\, r^2)\ \frac{q}{4\,\pi\, r^2}$$

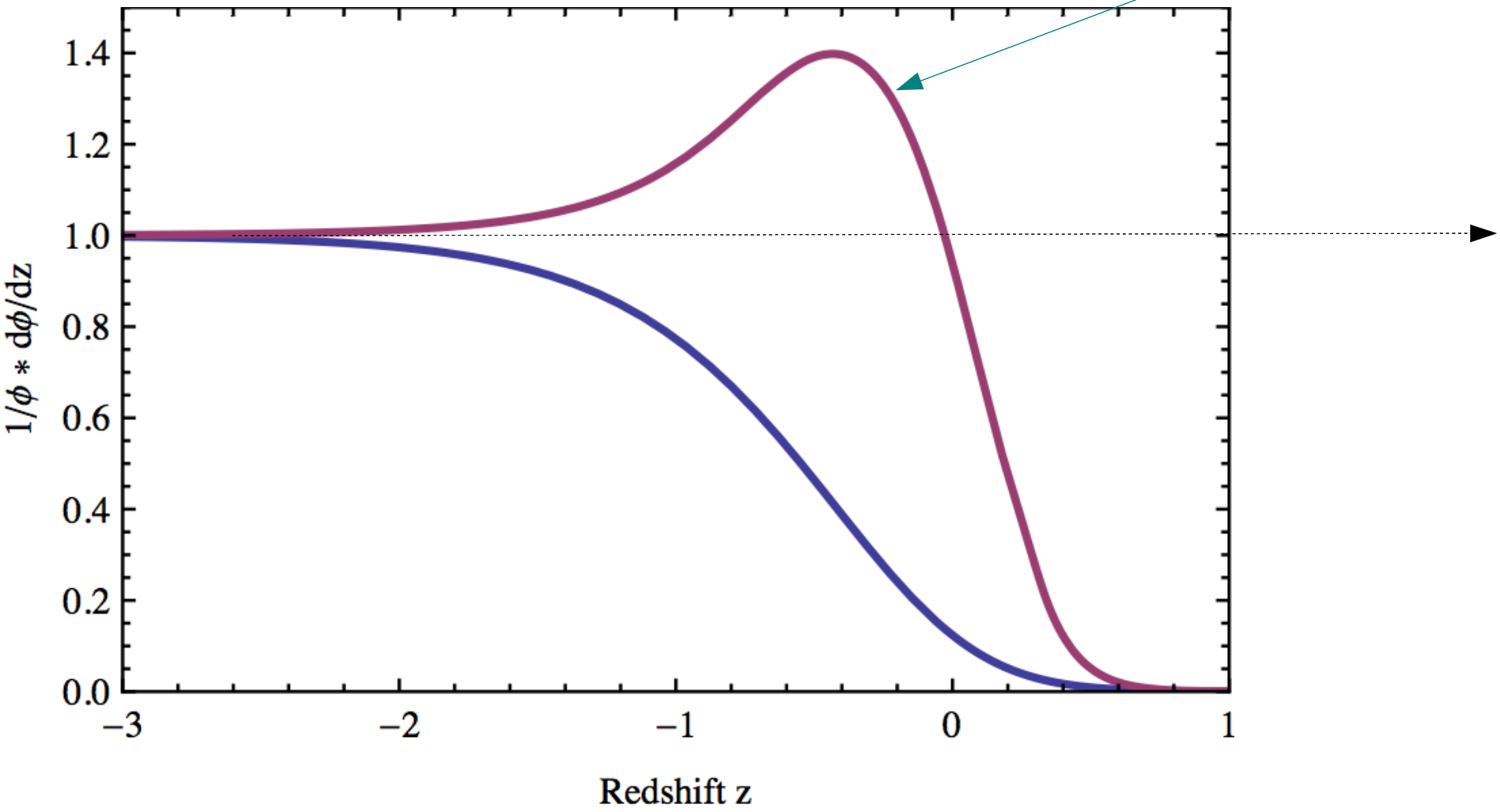
$$= \frac{n_s\, q}{4\,\pi}\int_0^\infty dr\ 1 \to \infty$$

Flux (static euclidean universe) is divergent !
Because of the contribution of Many far, faint sources.

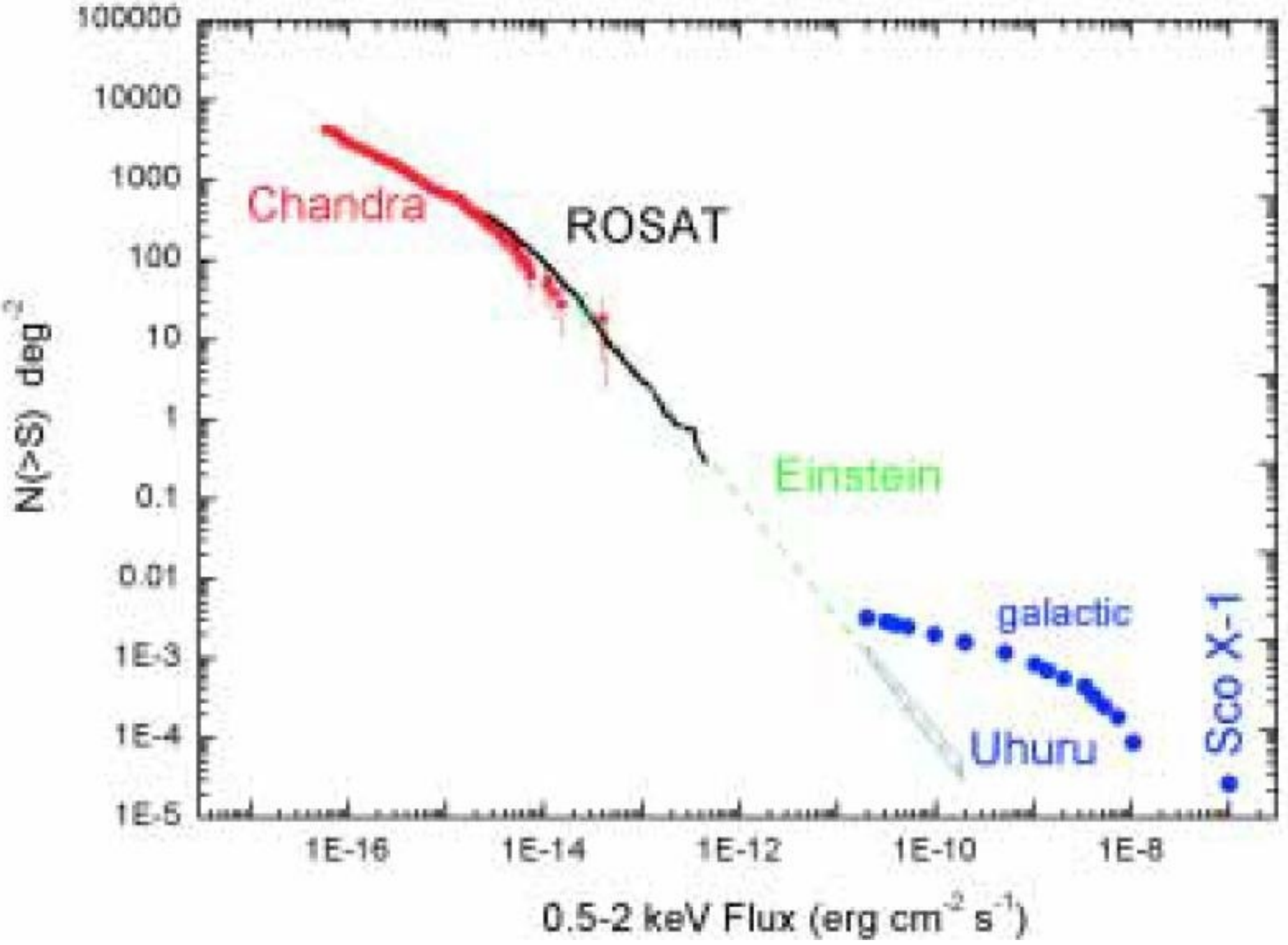
“The Olbers (Kepler) Paradox”: Why is the night sky dark ?

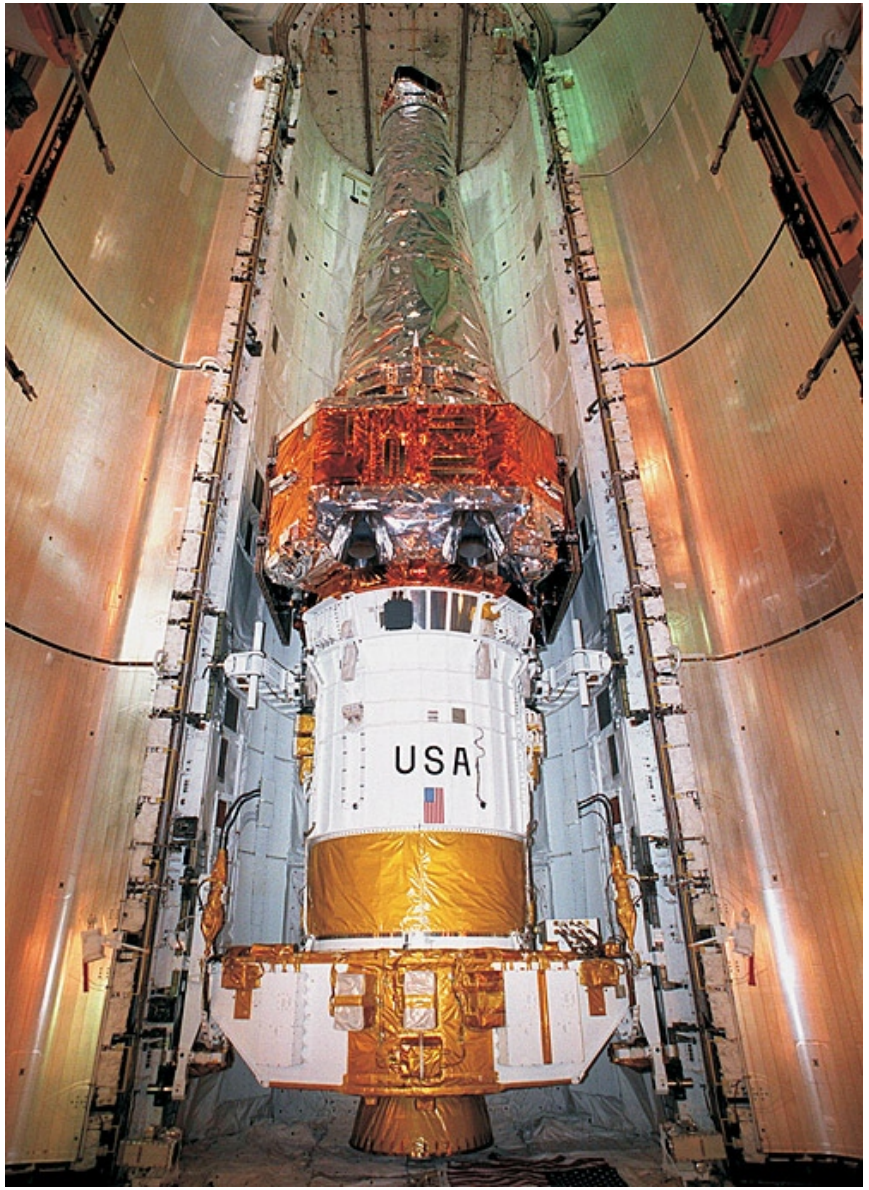
Solution of the Paradox:
The expansion of the universe !

Cosmological effects "cut" the integration
For $r > c/H_0$



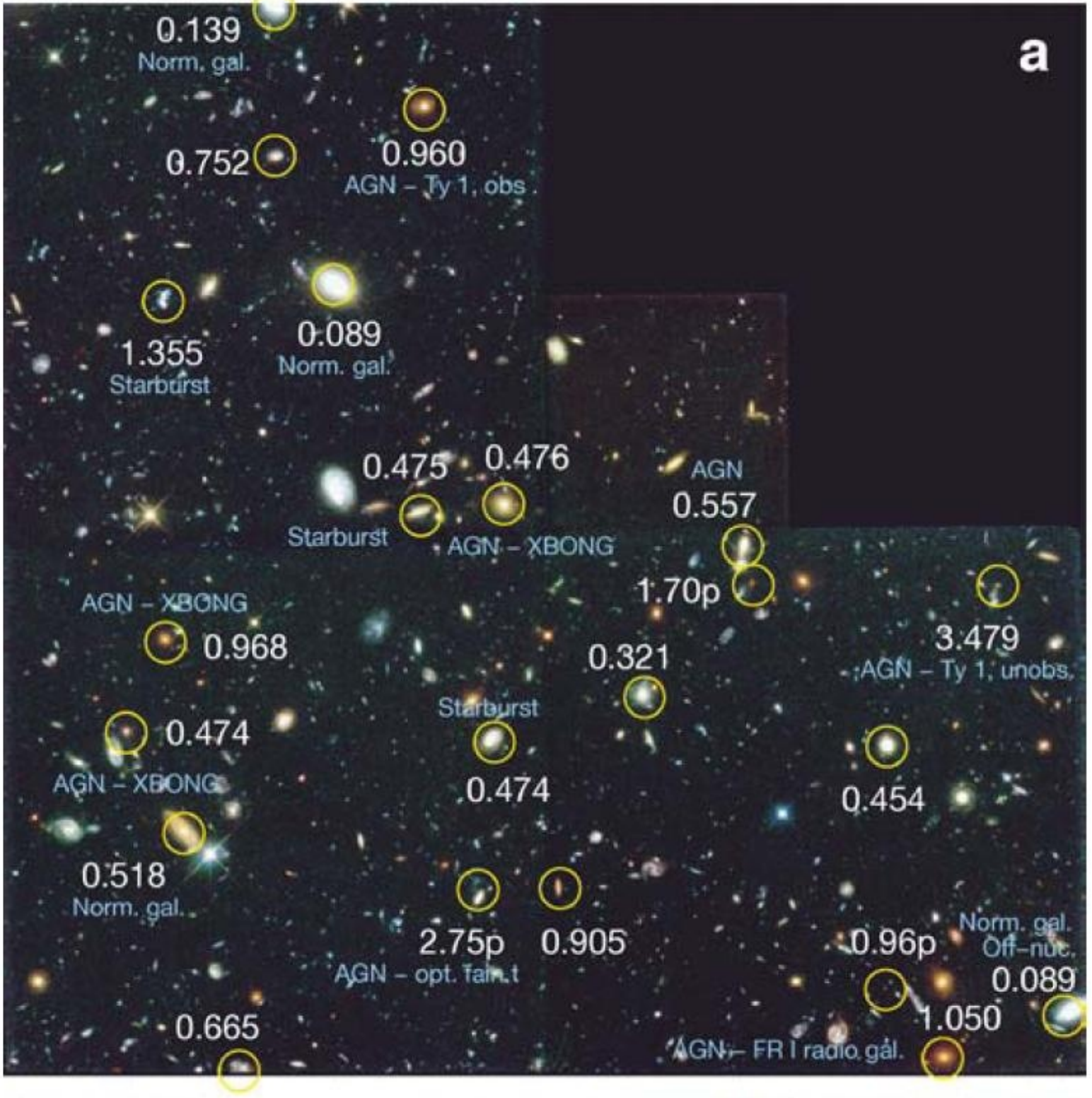
The X-ray SKY (Extra-galactic light has been resolved_



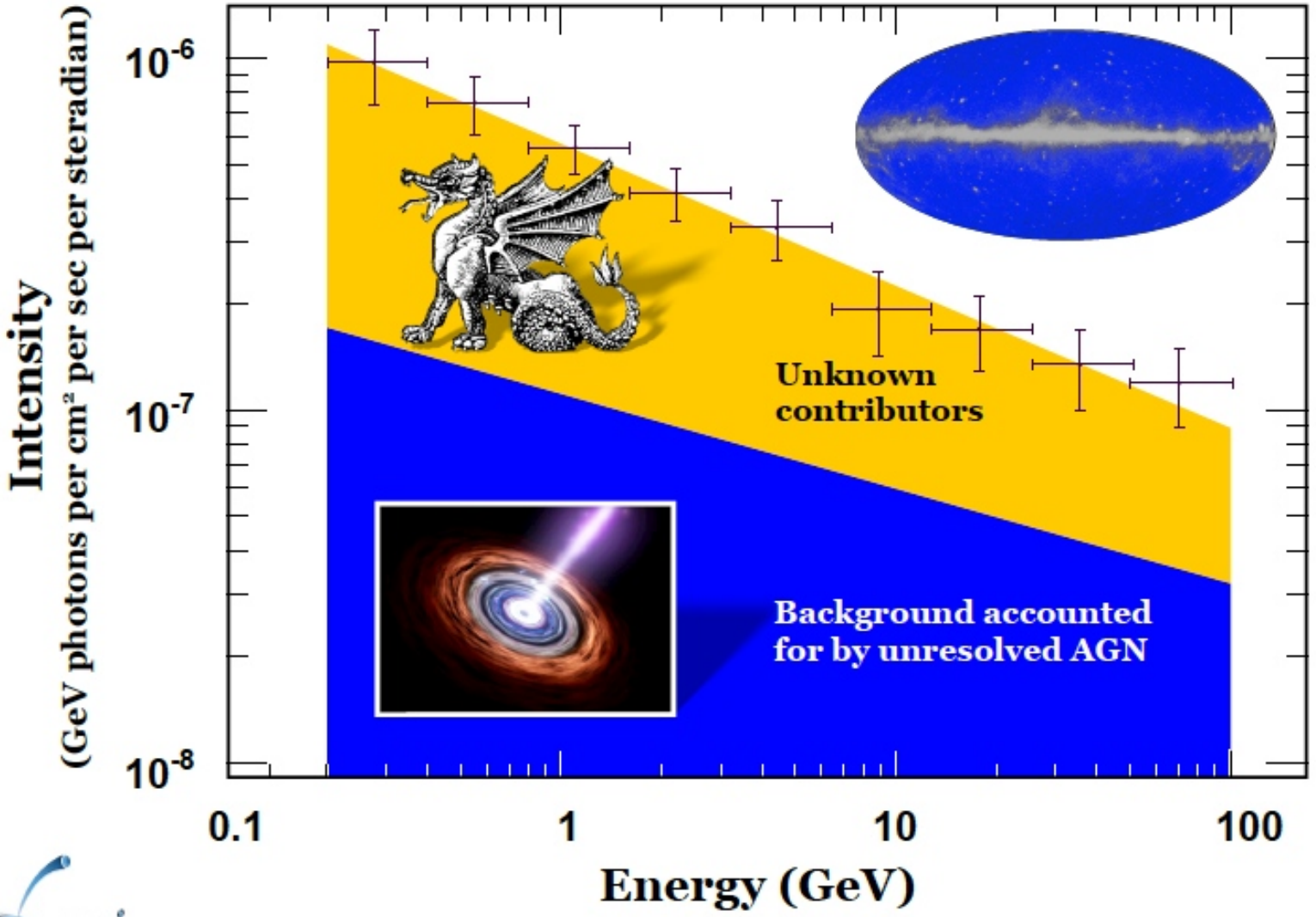

USA

CHANDRA

Deep
Field
North



Fermi LAT Extragalactic Gamma-ray Background



Fermi Gamma-ray Space Telescope

What about:

NEUTRINO

ASTRONOMY

The idea to observe the Universe using Neutrinos is profoundly fascinating.

The insights about Nature that are possible using this:

"New Way" to look at the Sky

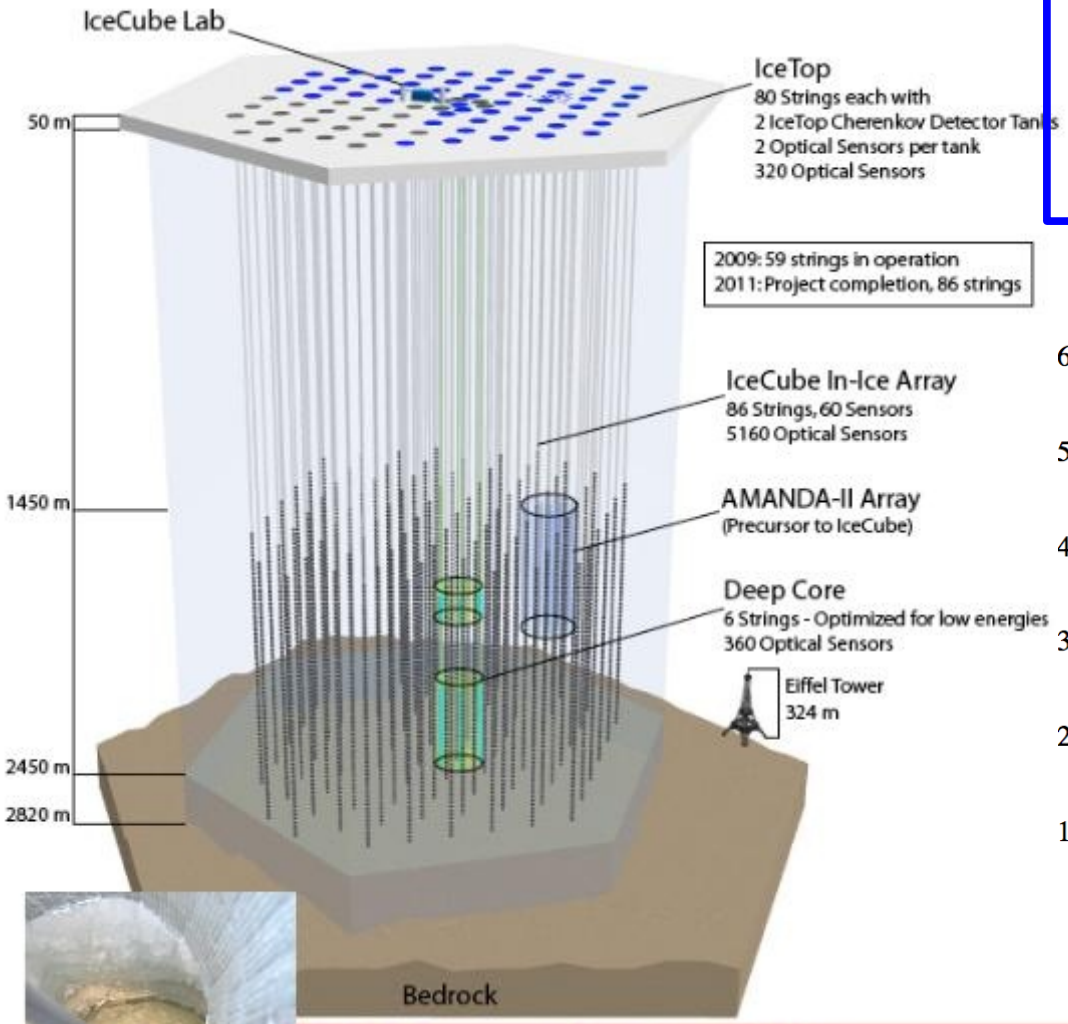
can be profound.

IceCube

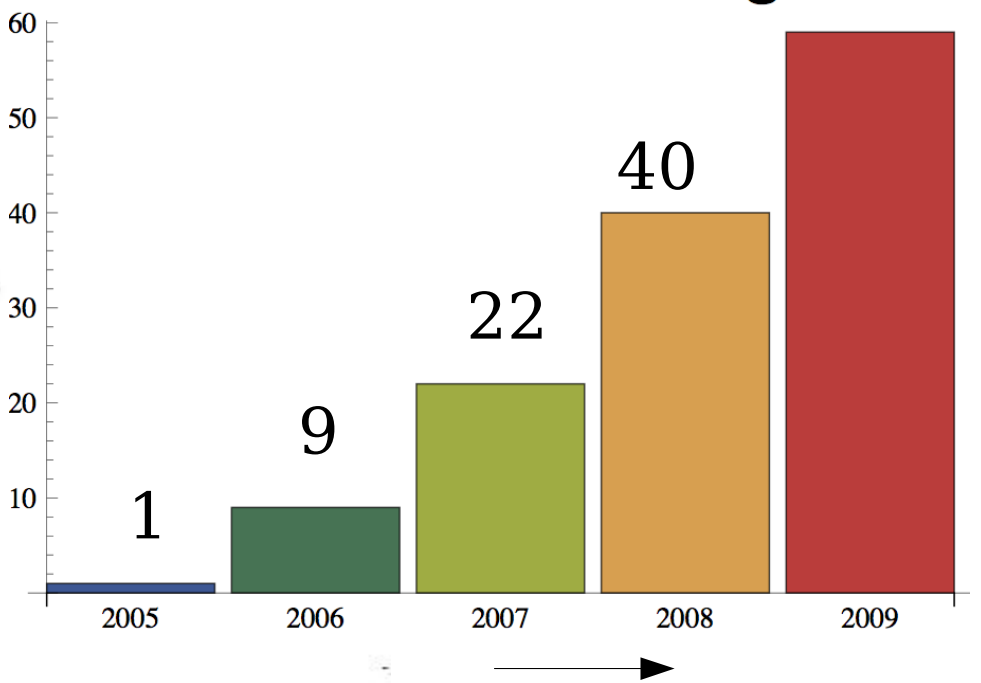
80 + 6 strings (125 m)

60 PMT / strings (17 m)

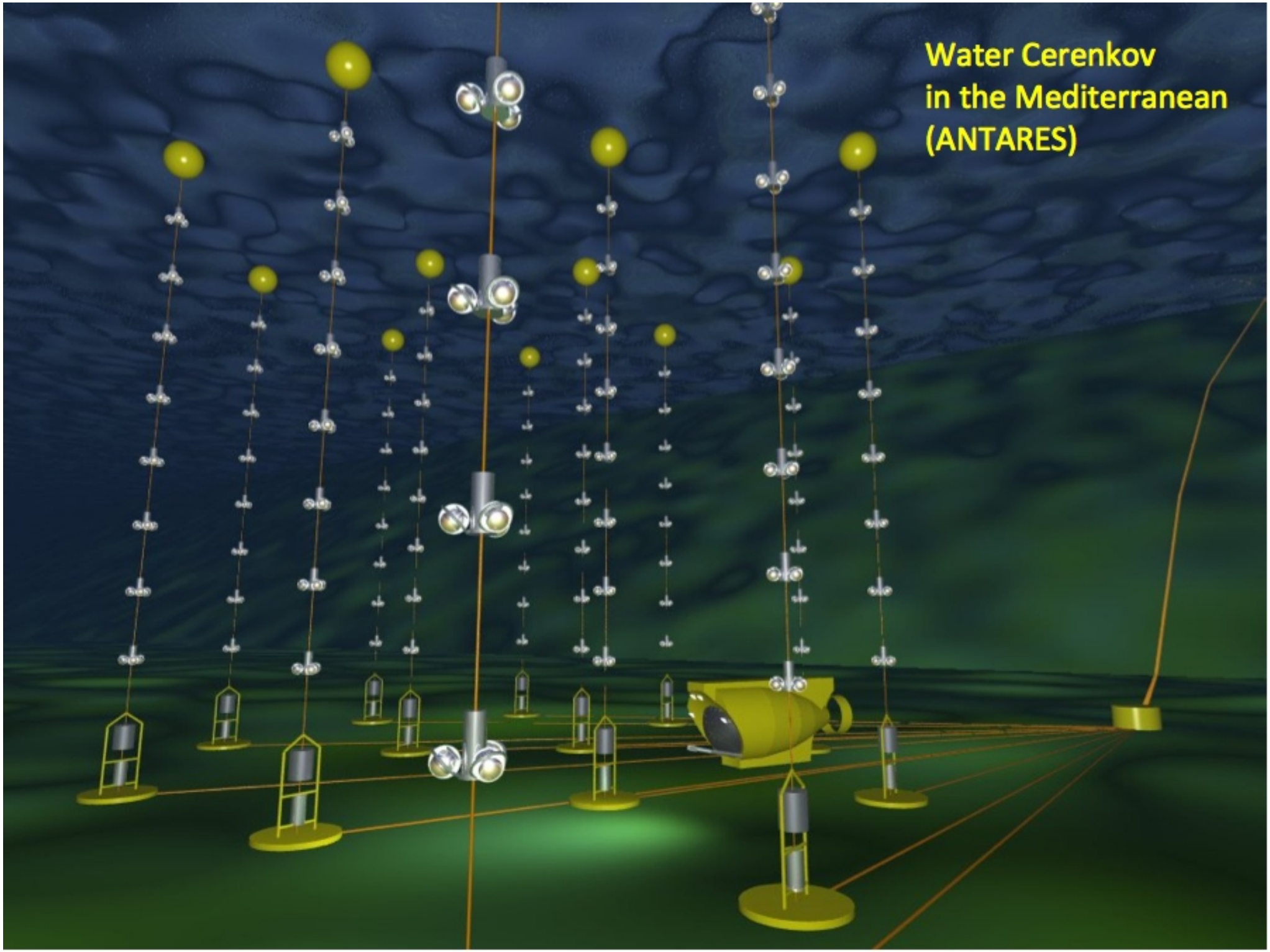
2400 PMT
+ surface array



85 strings, 60 OMs/string
17 m between OMs, 125 m between strings
IceTop: 80 stations of 2 tanks with 2 modules

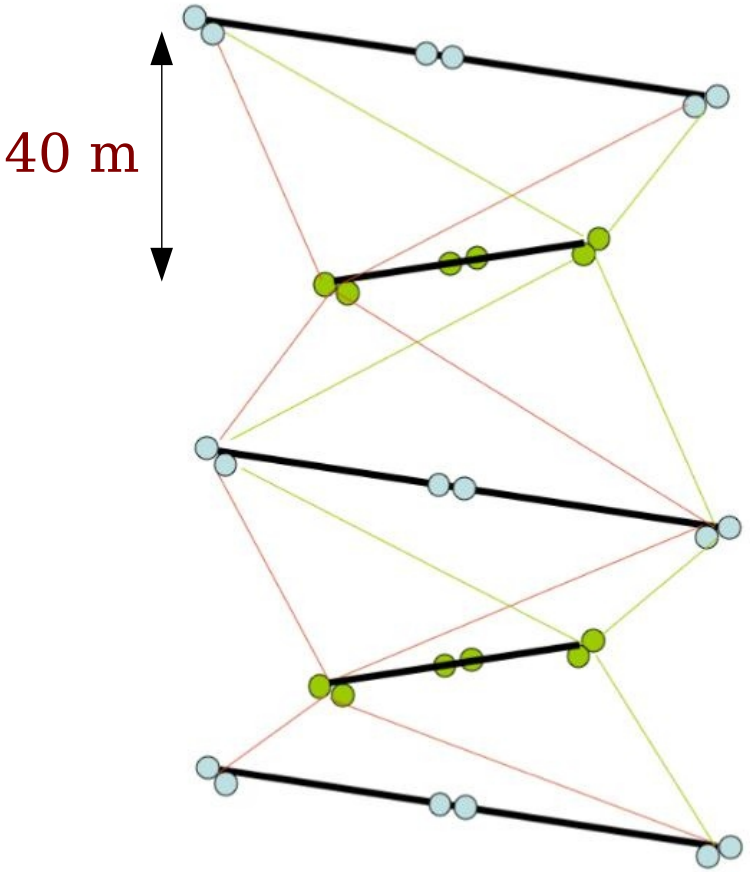


No SIGNAL
(yet)

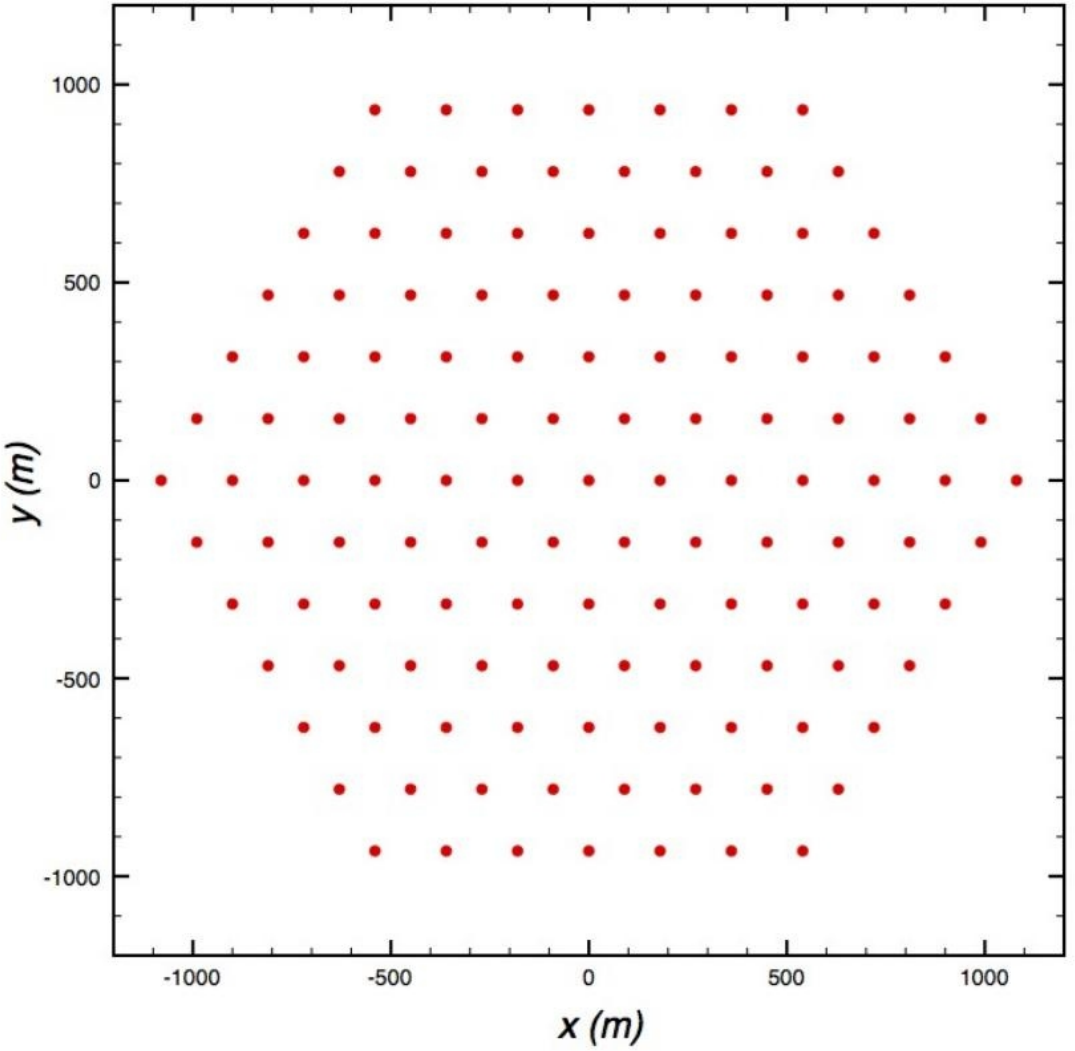

Water Cerenkov
in the Mediterranean
(ANTARES)

Possible structure of a “KM3” detector in the Mediterranean Sea:

“tower” [6 PMT's]



127 towers (180 m)



Detection Unit layout.

COSMIC RAYS

1. Below the Knee

2. The Knee

3. More knees ??

4. Galactic to Extragalactic transition

5. The “End” of the spectrum

Below the “Knee” Cosmic Rays

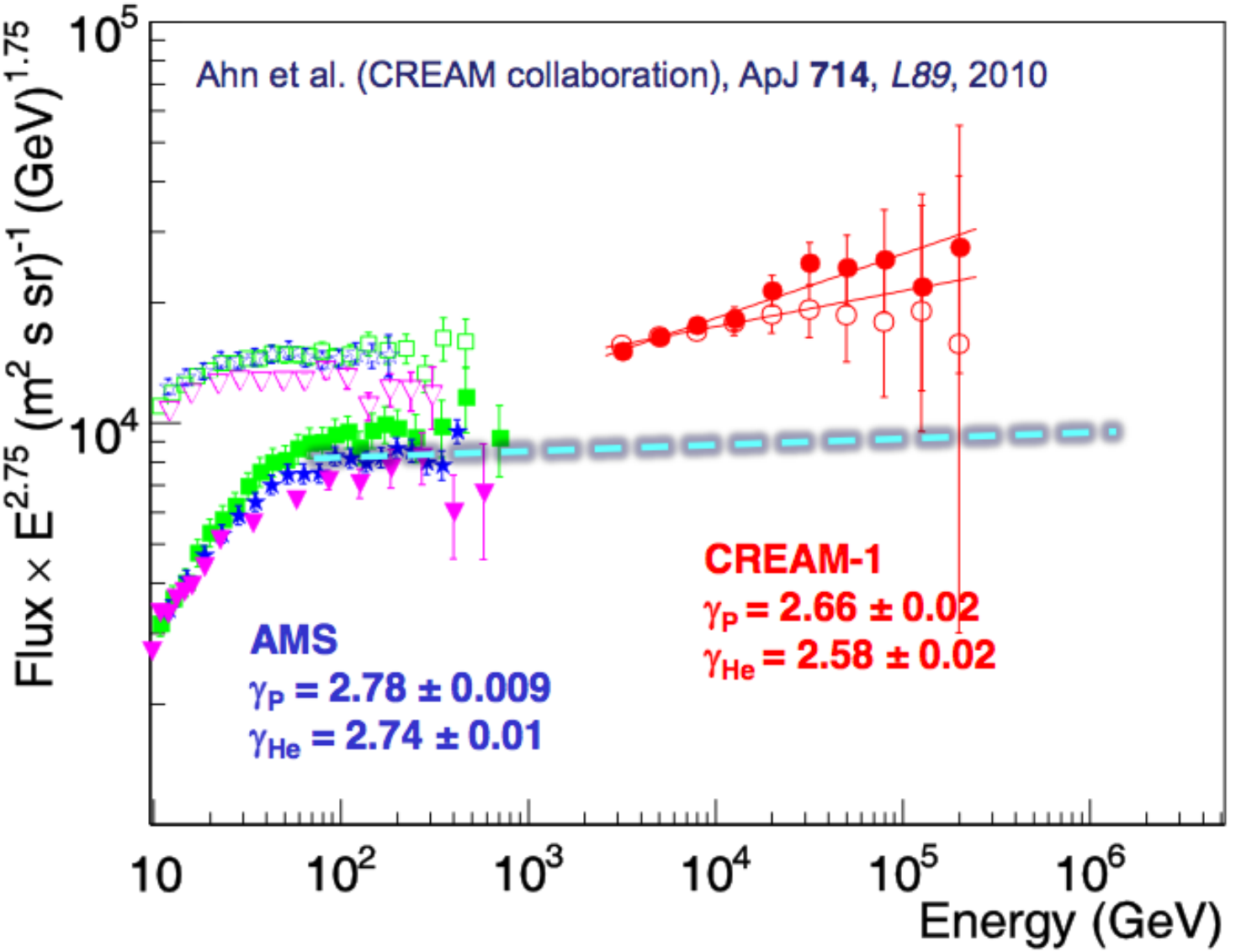
Several interesting problems:

Detailed shape of the spectra
(slope breaks indicated by CREAM)

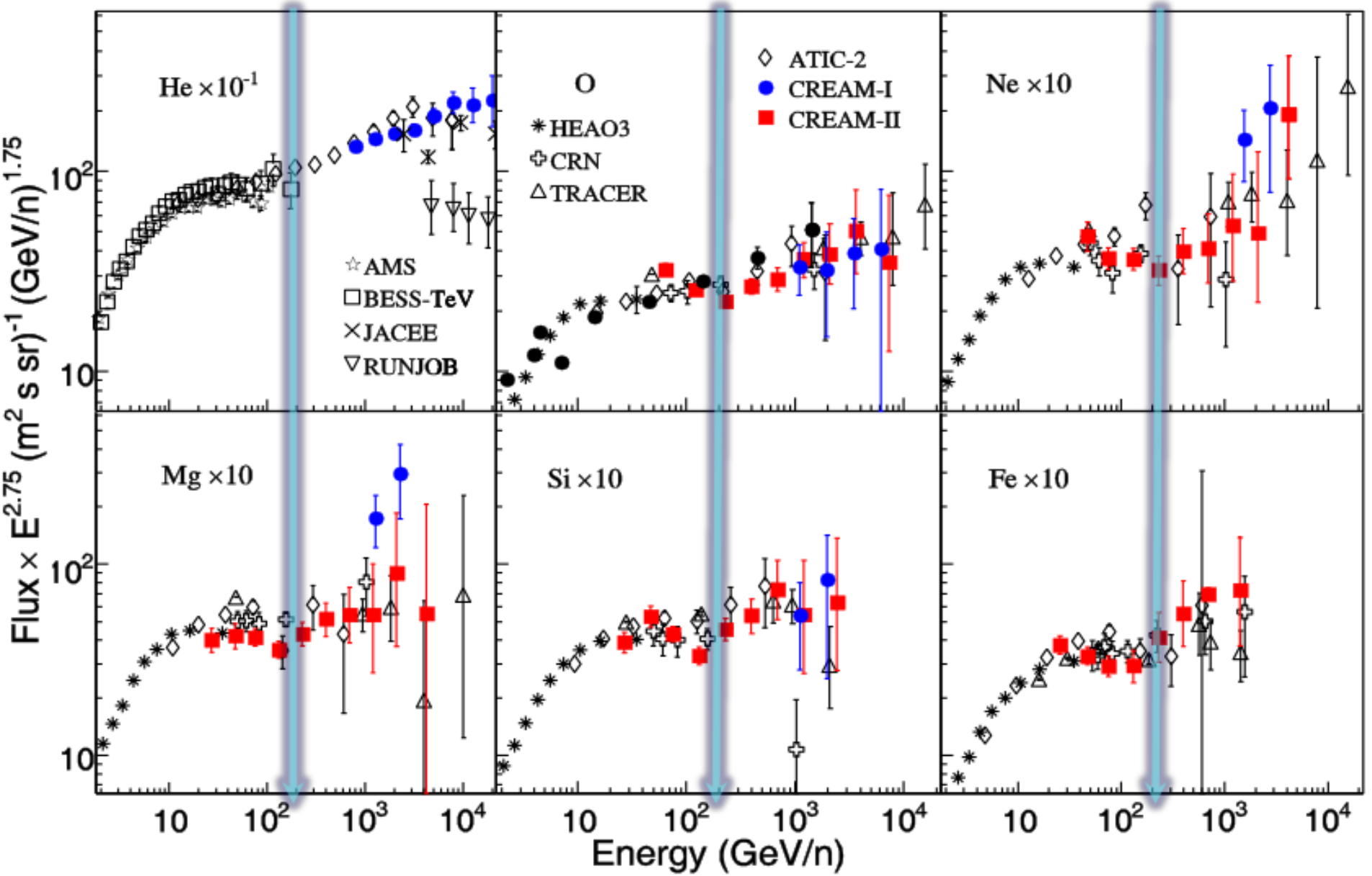
Anisotropies (“Milagro hot spots)

Study of the confinement time.

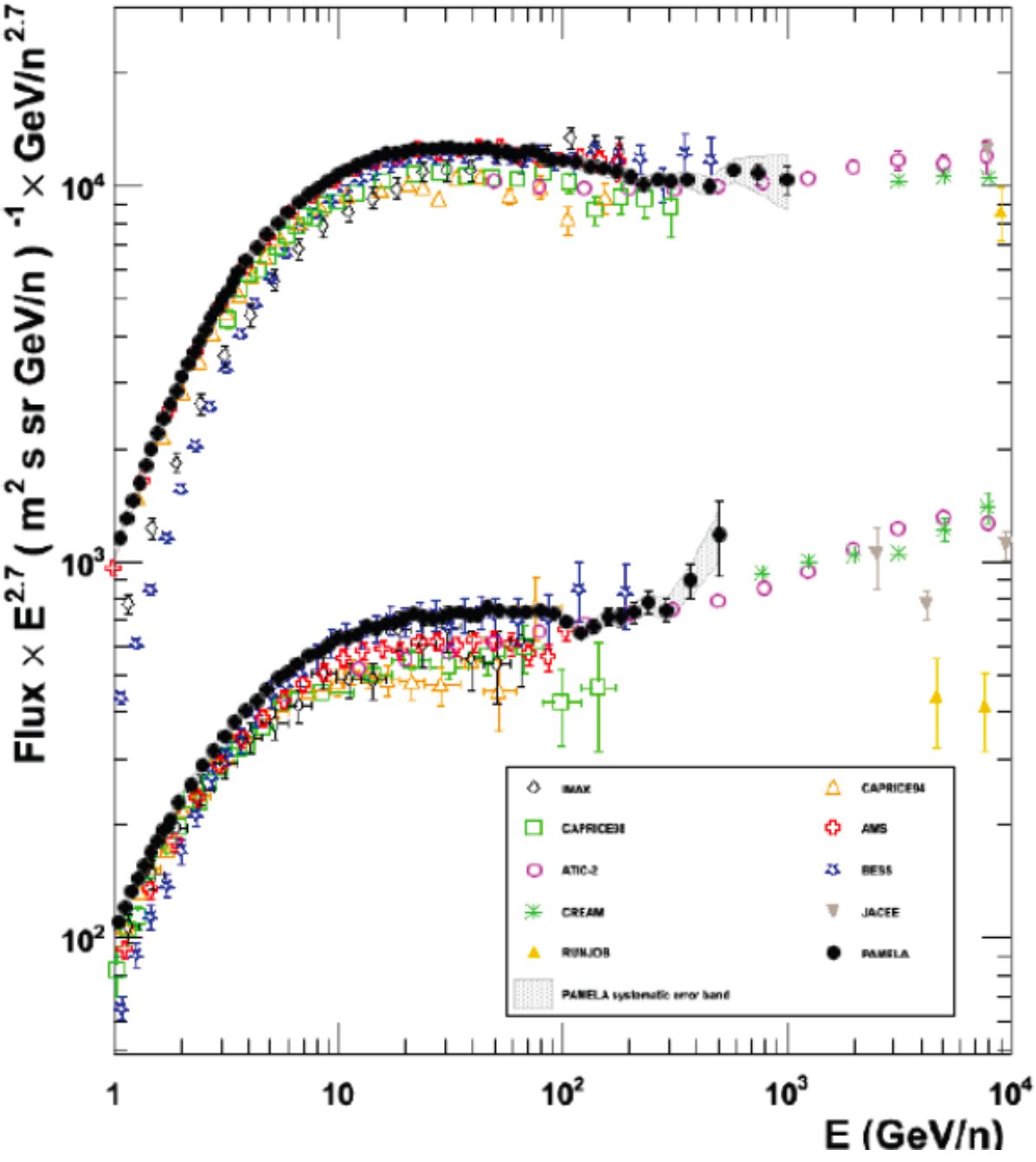
TeV spectra are harder than spectra < 200 GeV/n



Discrepant hardening



PAMELA PROTON AND HELIUM FLUX

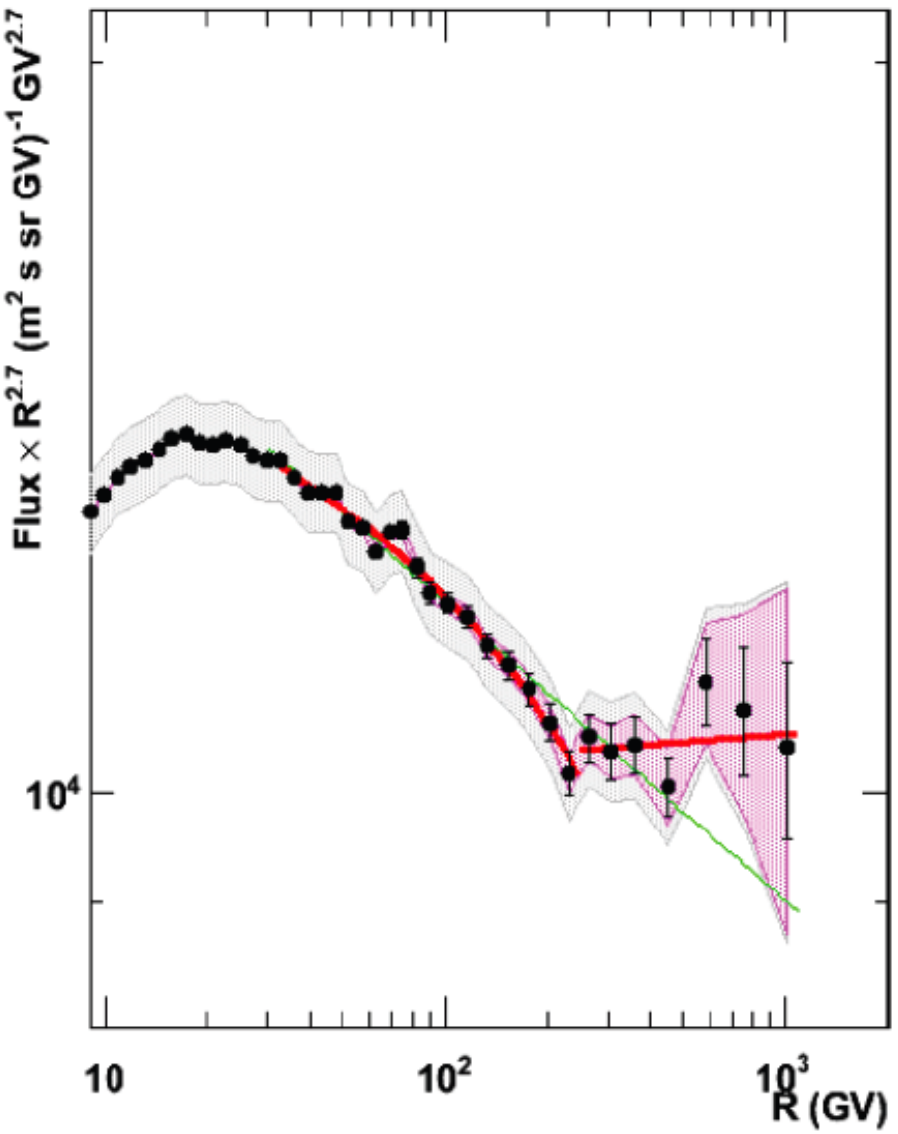


Accepted by SCIENCE
In press

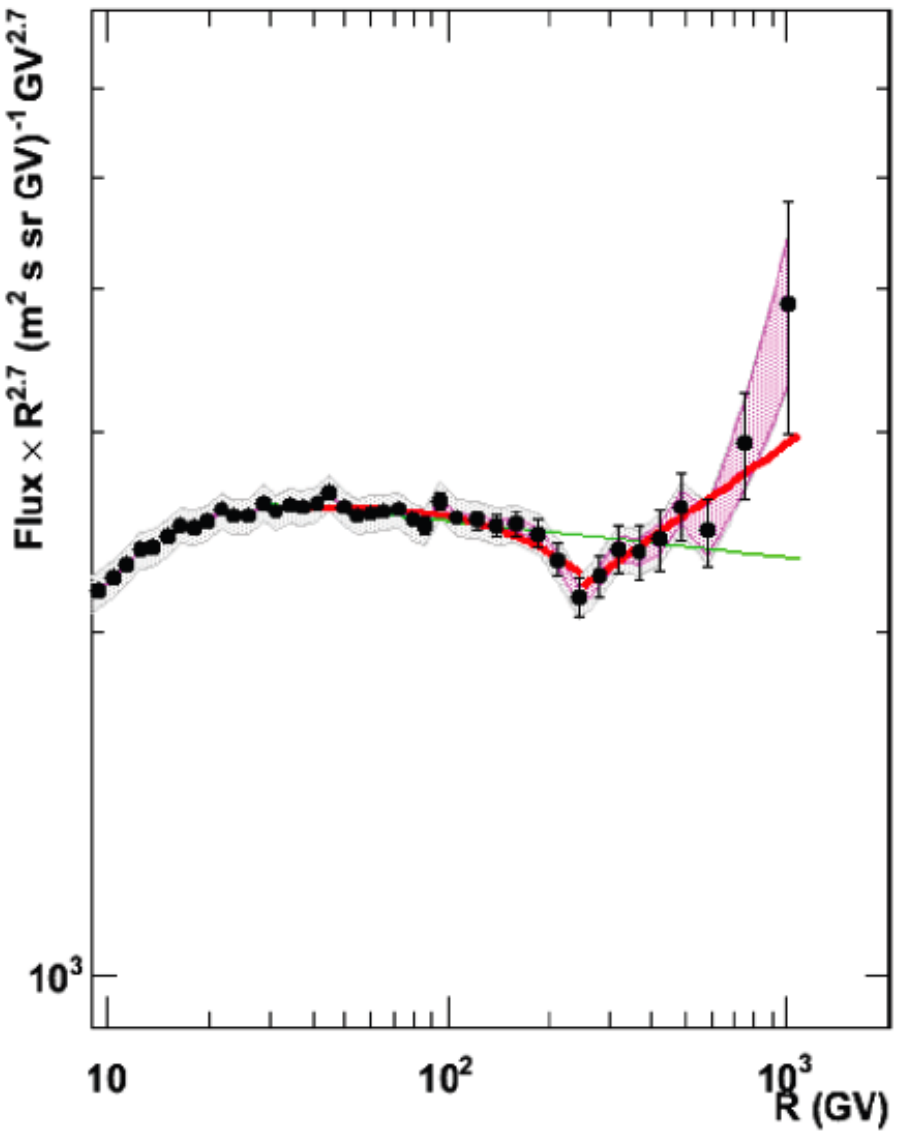
Hardening of the proton and helium spectra at 200 GV, corresponding to 200 GeV for p and 100 GeV/n for He

FIT WITH 2 SPECTRAL INDEXES

Proton



Helium



Cosmic Ray Nuclear Composition

Overabundance of Li, Be, B

Sub-iron elements

Spallation effect:

Column density
Confinement time

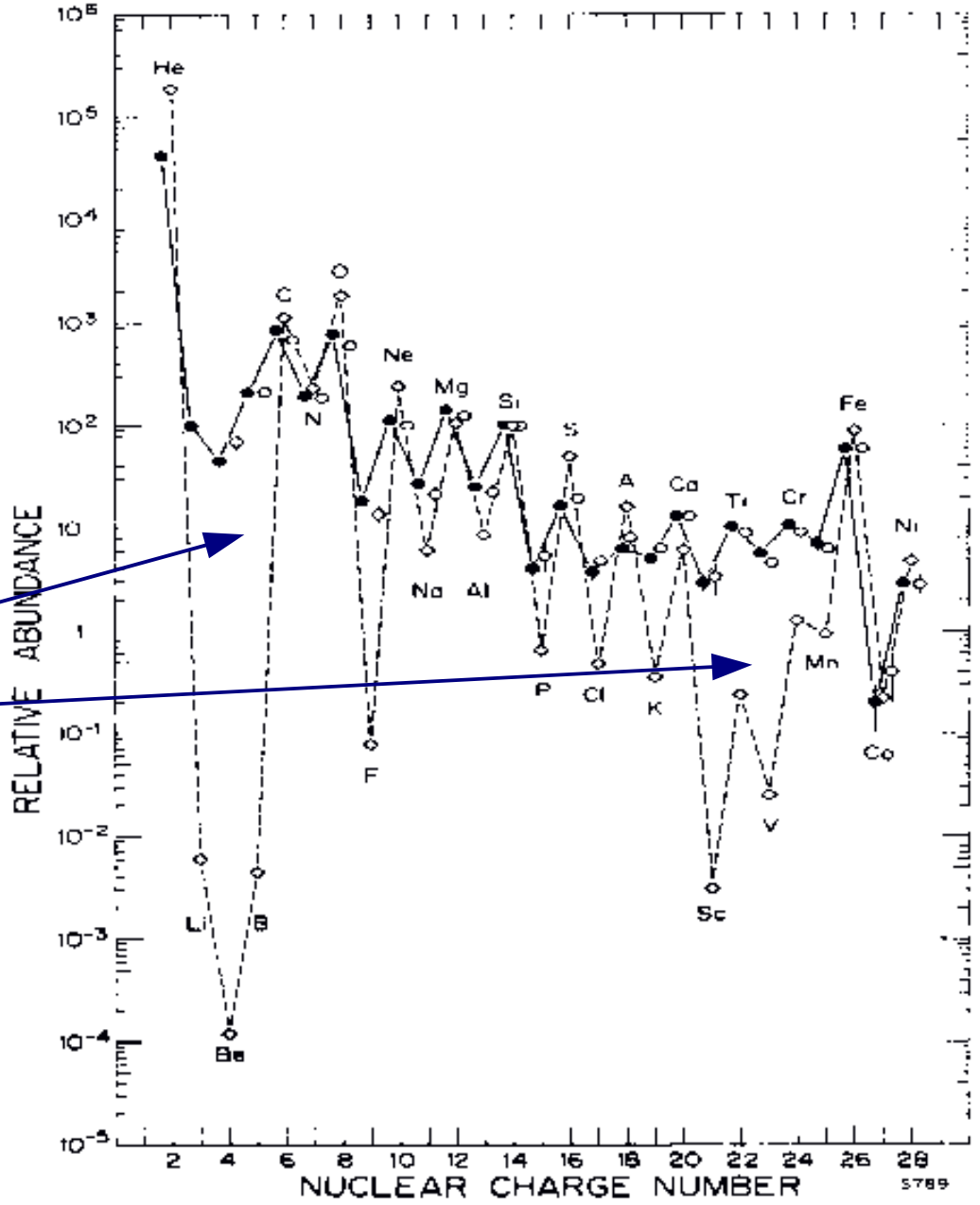
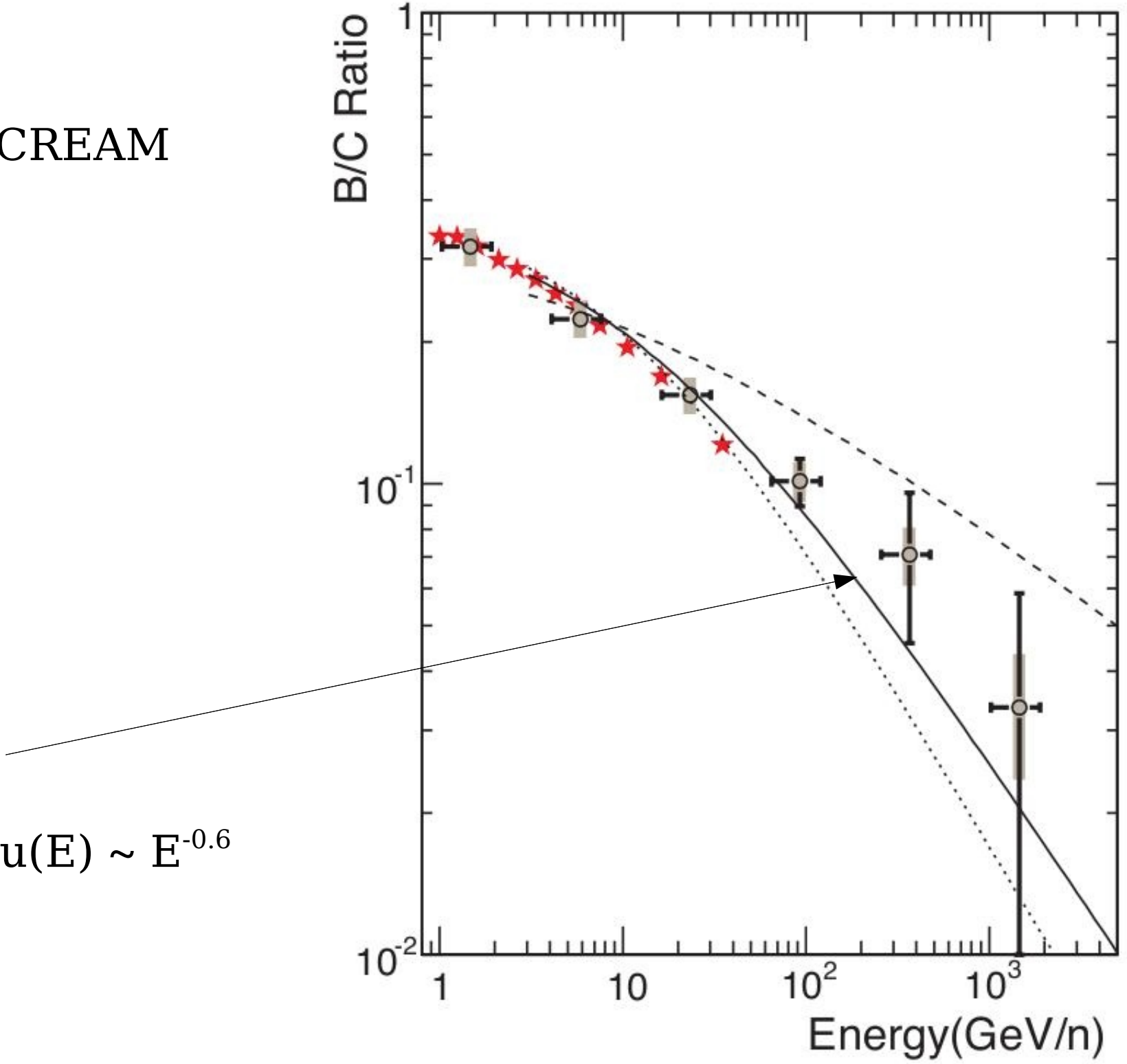


Figure 1. The relative abundance distribution of the elements in the cosmic radiation and in the solar system (normalized to Si = 100) from He to Ni (solid circles, 70–280 MeV per nucleon; open circles, 1000–2000 MeV per nucleon; open diamonds, solar system abundance distribution). [*Reproduced with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

From CREAM

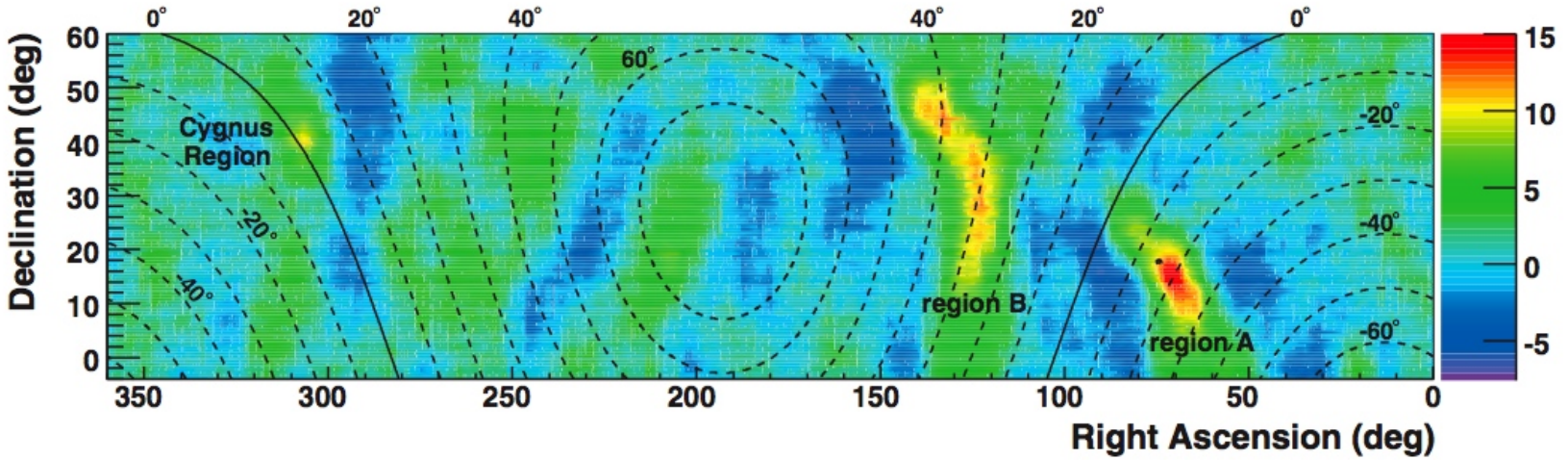


tau(E) ~ $E^{-0.6}$

Milagro collaboration

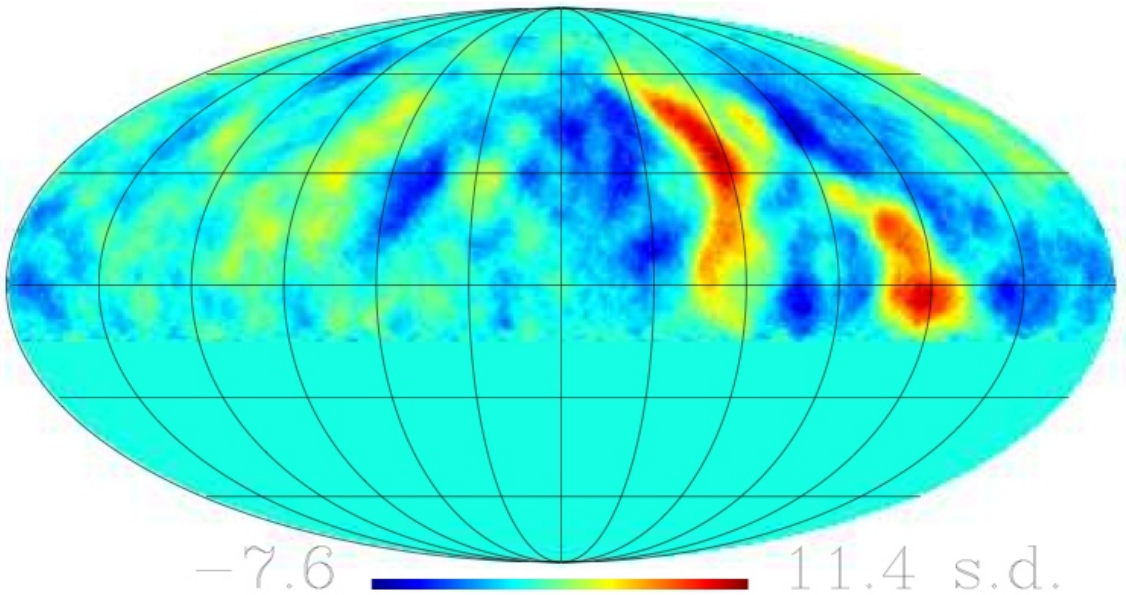
PRL 101, 221101 (2008)
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending
28 NOVEMBER 2008

Discovery of Localized Regions of Excess 10-TeV Cosmic Rays



ARGO

VERNETTO *et al.* SKY MONITORING WITH ARGO-YBJ



UHECR

1. Energy Spectrum

- Clear identification of a high energy suppression
  [the “END” (… well the “suppression”)
  of exotic/fundamental physics modeling for UHECR].
- Excellent agreement between experiments
  [“small” but important question about the energy scale].
- Physical interpretation strongly coupled to (2., 3.)
  (anisotropy + composition). [proton GZK ?]

UHECR

1. Energy Spectrum

2. Anisotropy

3. Composition

Significant Experimental Discrepancies

Auger/Hires

Confusing situation.

UHECR

1. Energy Spectrum

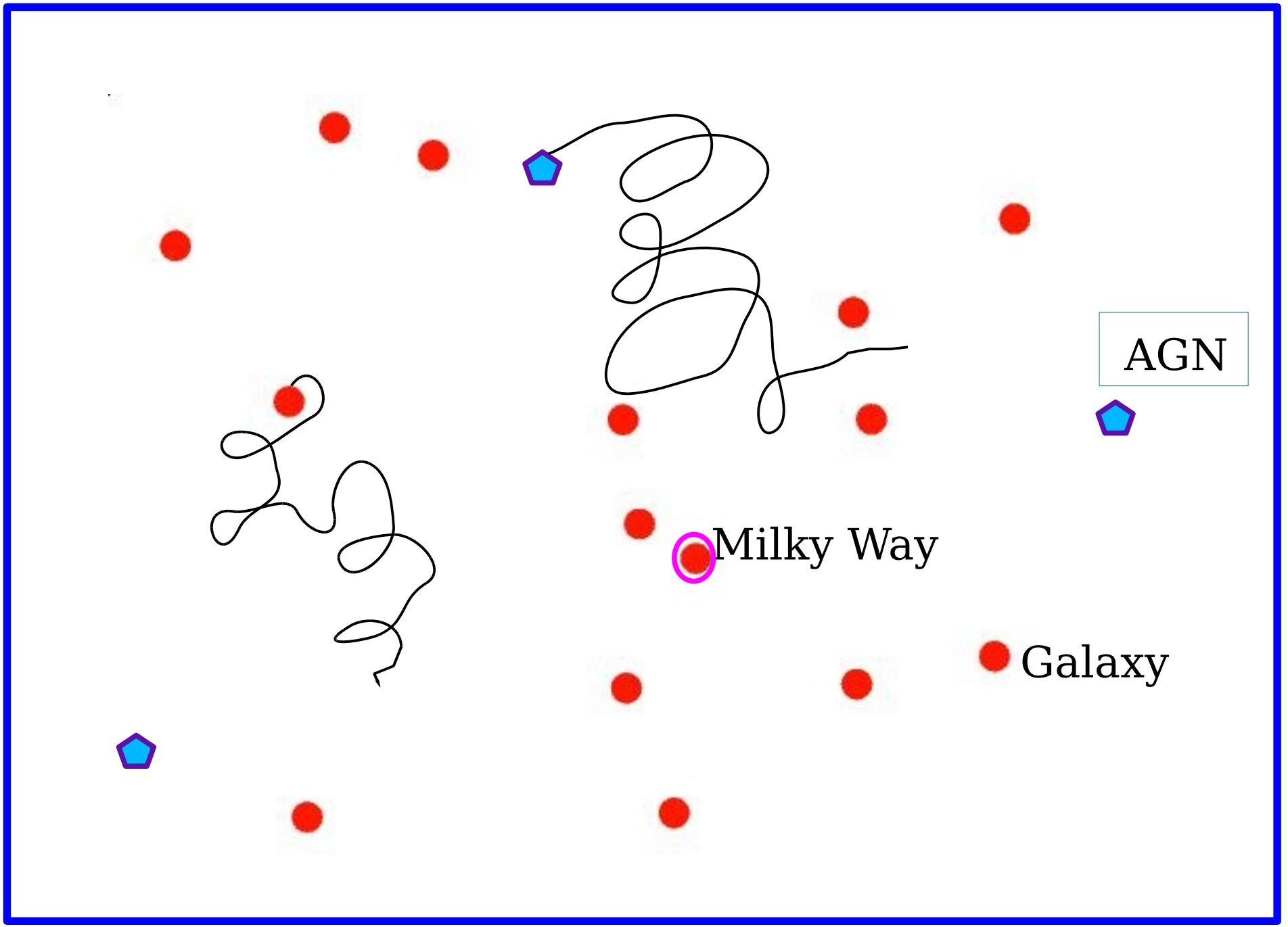
2. Anisotropy

3. Composition

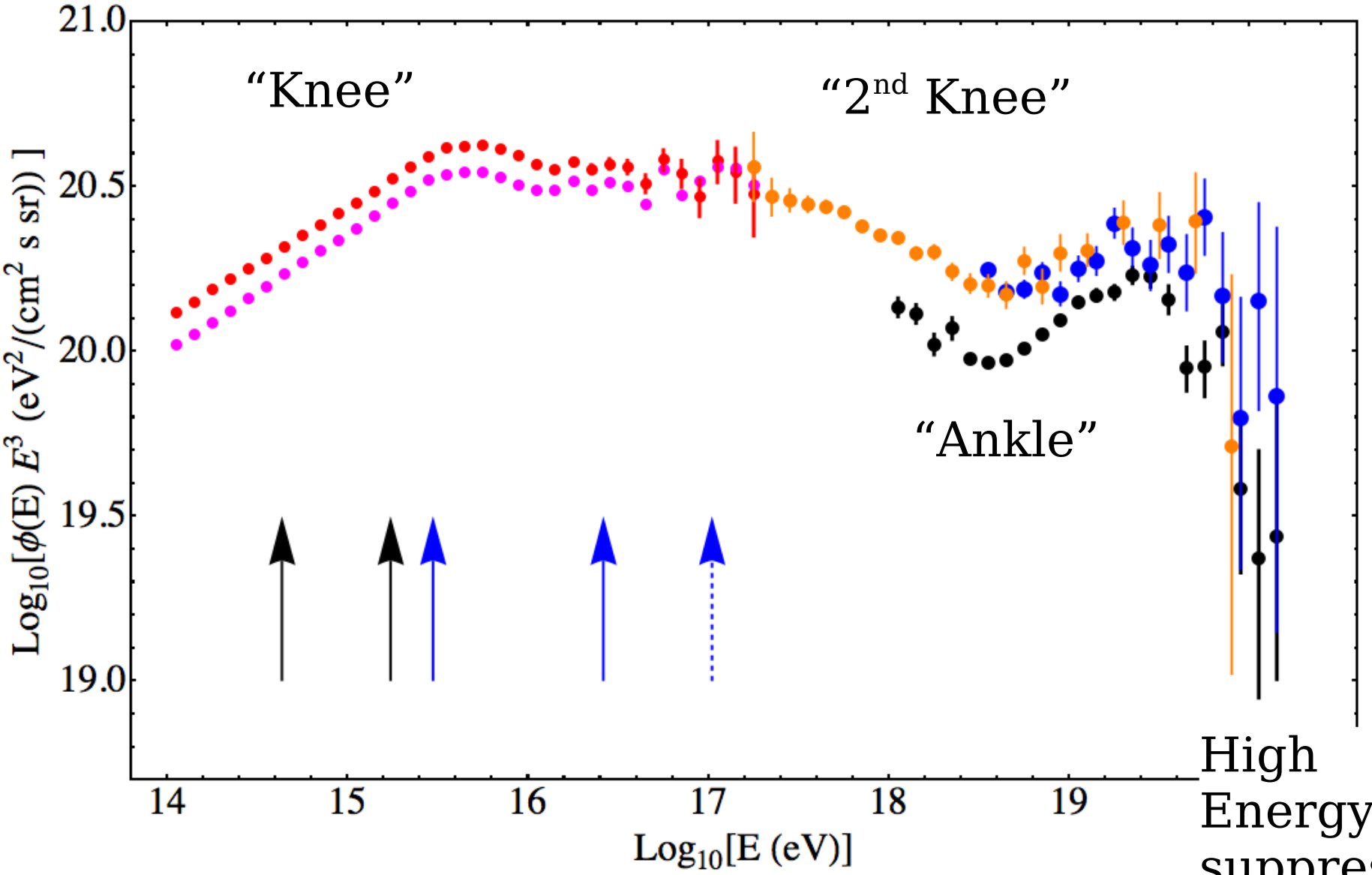
Consistent interpretation of AUGER results is problematic.

“CRISIS” (?)

Piece of extragalactic space: Non MilkyWay-like sources



Structure in the energy spectrum



High Energy suppression

UHECR

Crucial Problem:

Galactic Extragalactic Transition

Energy Spectrum "feature"

Composition change

Isotropy effect

1. Maximum Energy of Milky Way sources

2. Power of Extragalactic CR sources

3. Shape of injection spectrum of extragalactic CR

UHECR

Crucial Problem:

Galactic Extragalactic Transition

1. Maximum Energy of Milky Way sources

2. Power of Extragalactic CR sources

3. Shape of injection spectrum of extragalactic CR

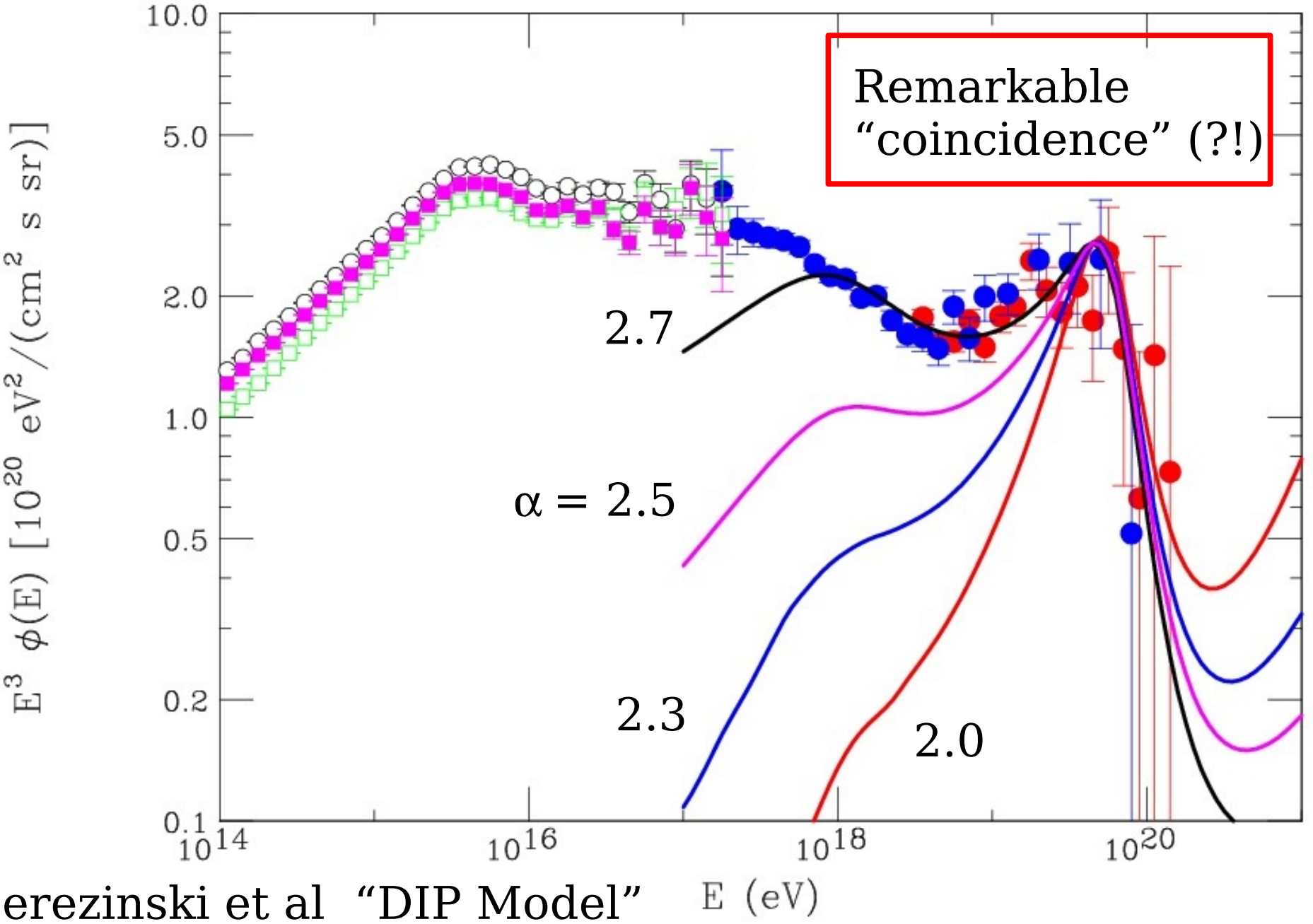
Energy Spectrum "feature"

Composition change

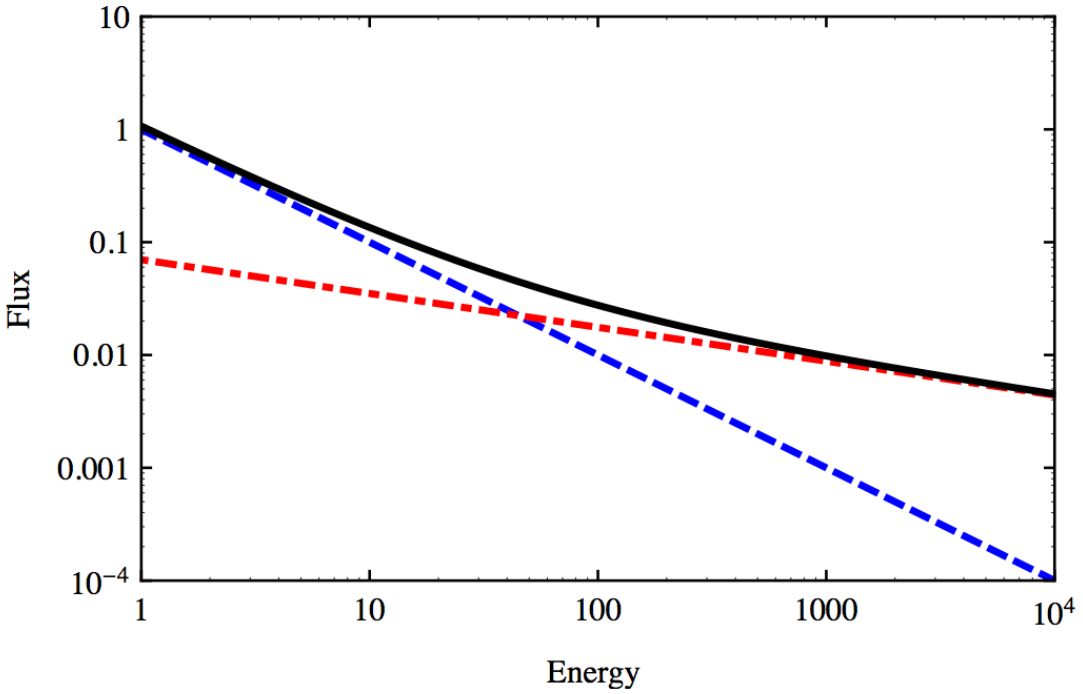
Isotropy effect

Not detected
Poorly predicted
MW large scale field

Power Law Injection (No Cosmic Evolution)

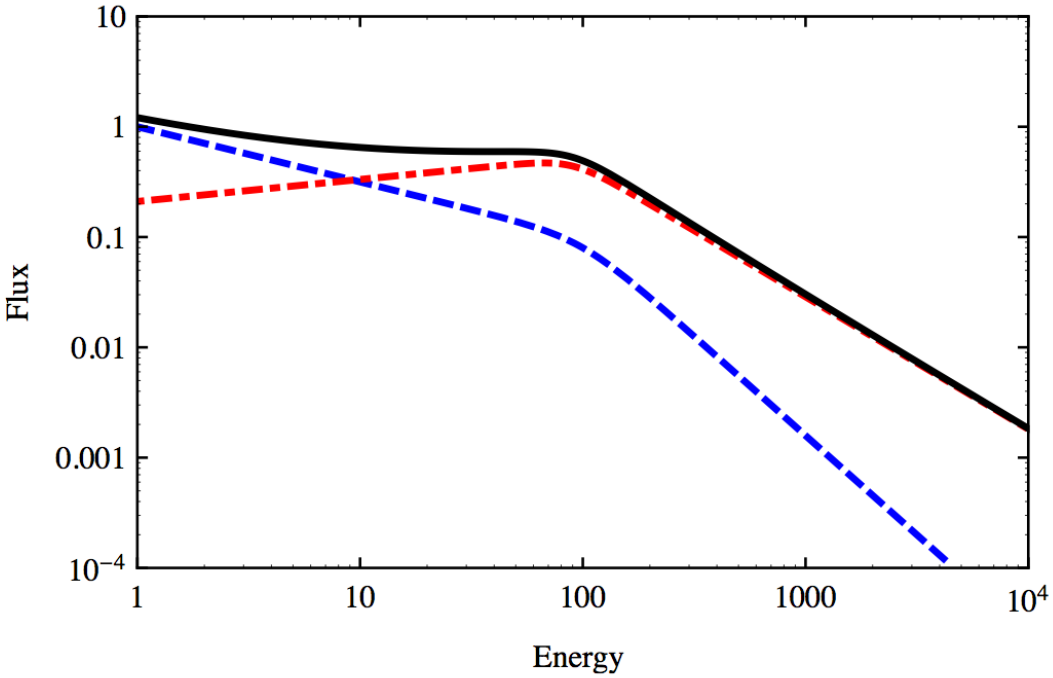


Berezinski et al “DIP Model”



"Ankle like" transition

"Knee like" transition



Power Density Requirements to Generate the Extra-Galactic Cosmic Rays:

α=2.0

$$\mathcal{L} \simeq 1.1 \times 10^{37} \left[1 - \ln\left(\frac{E_{\rm min}}{10^{18}\ {\rm eV}}\right)\right] \frac{\rm erg}{\rm s\ Mpc^3}$$

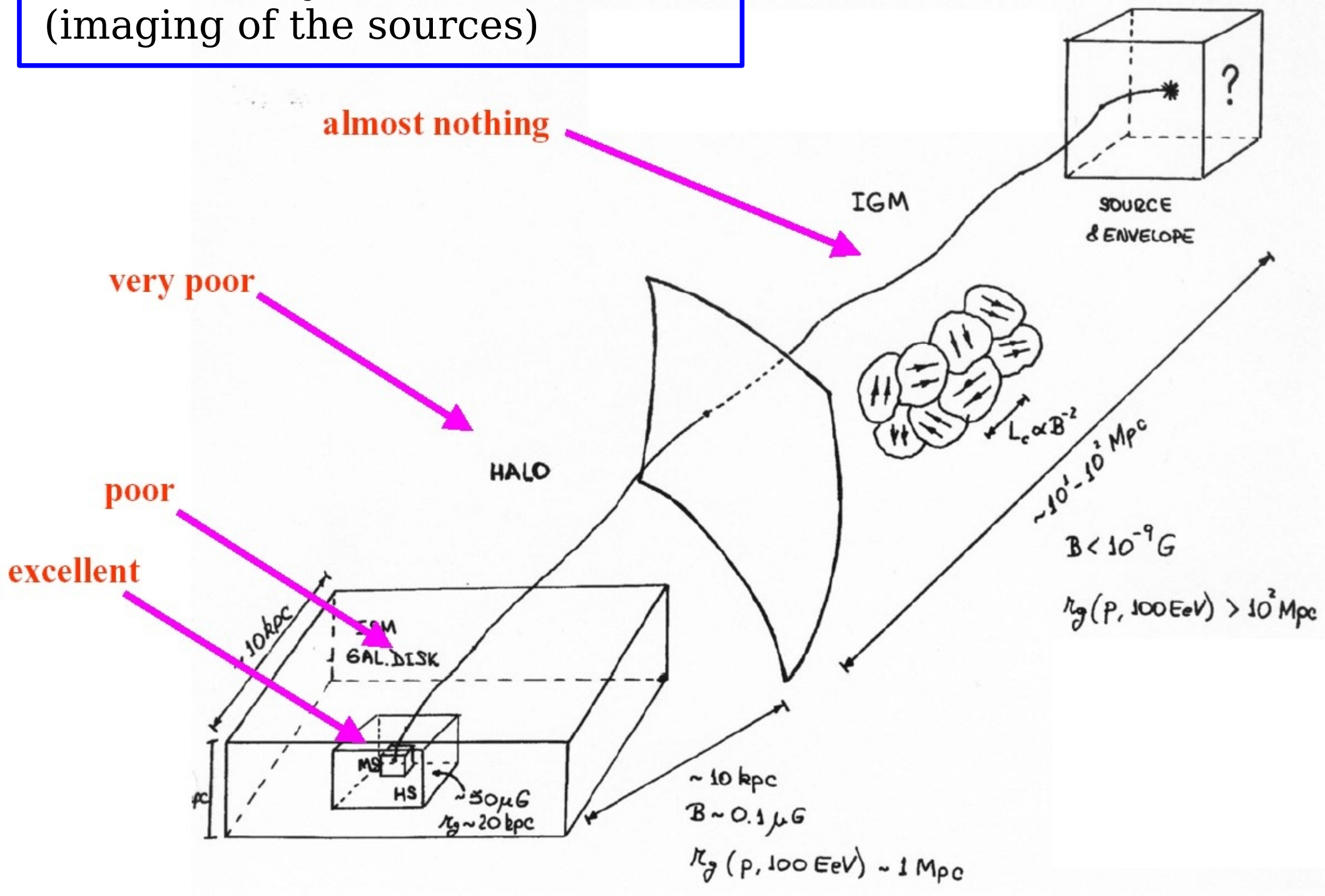
3000 Solar luminosities

α=2.7

$$\mathcal{L} \simeq 3.4 \times 10^{37} \left(\frac{E_{\rm min}}{10^{18}\ {\rm eV}}\right)^{-0.7} \frac{\rm erg}{\rm s\ Mpc^3}$$

9000 Solar luminosities

COSMIC Ray ASTRONOMY [?!]
(imaging of the sources)

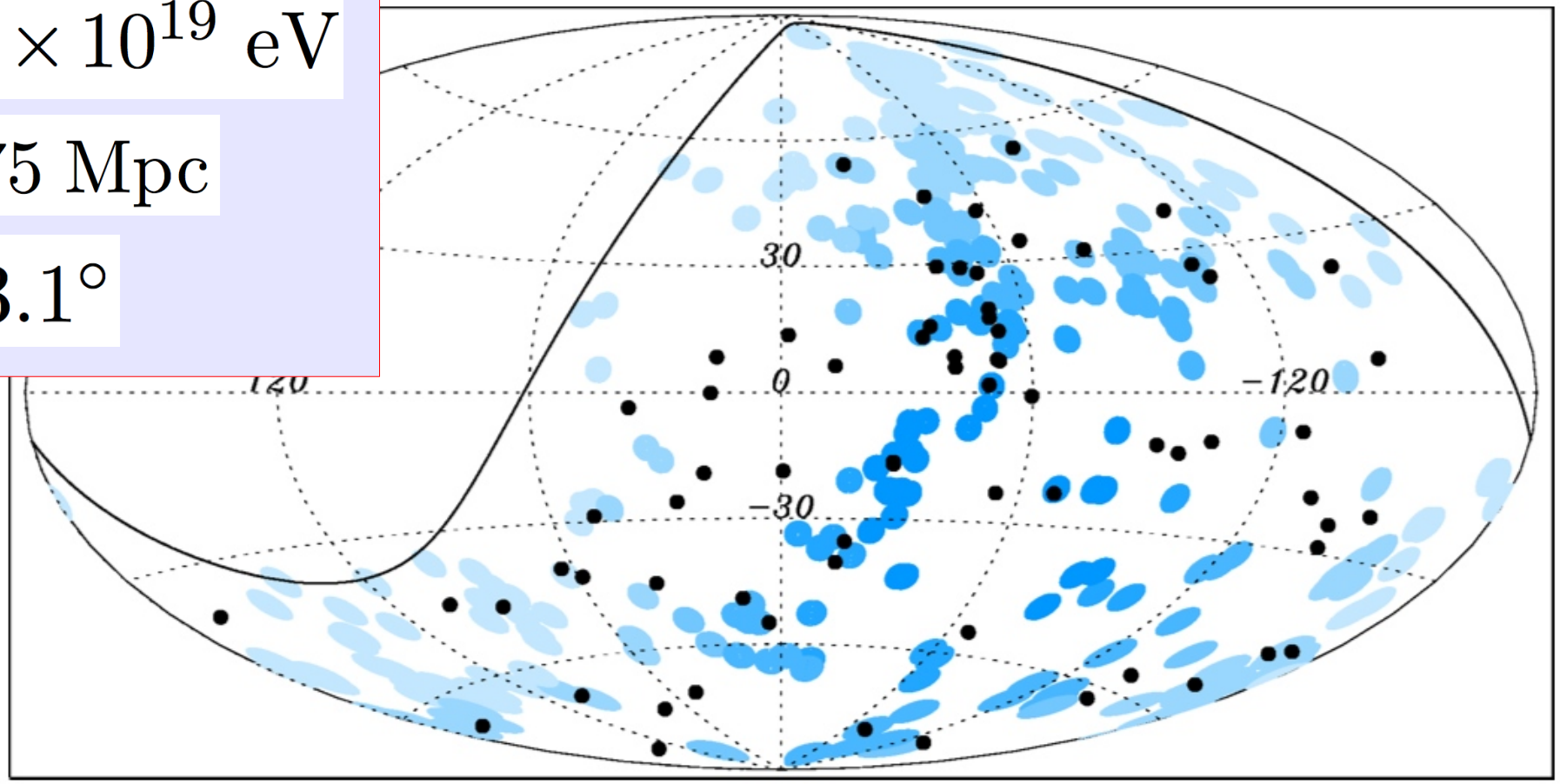


AUGER result on Correlations with the VCV AGN catalogue
November 2008. Update september 2010.

6×10^{19} eV

75 Mpc

3.1°

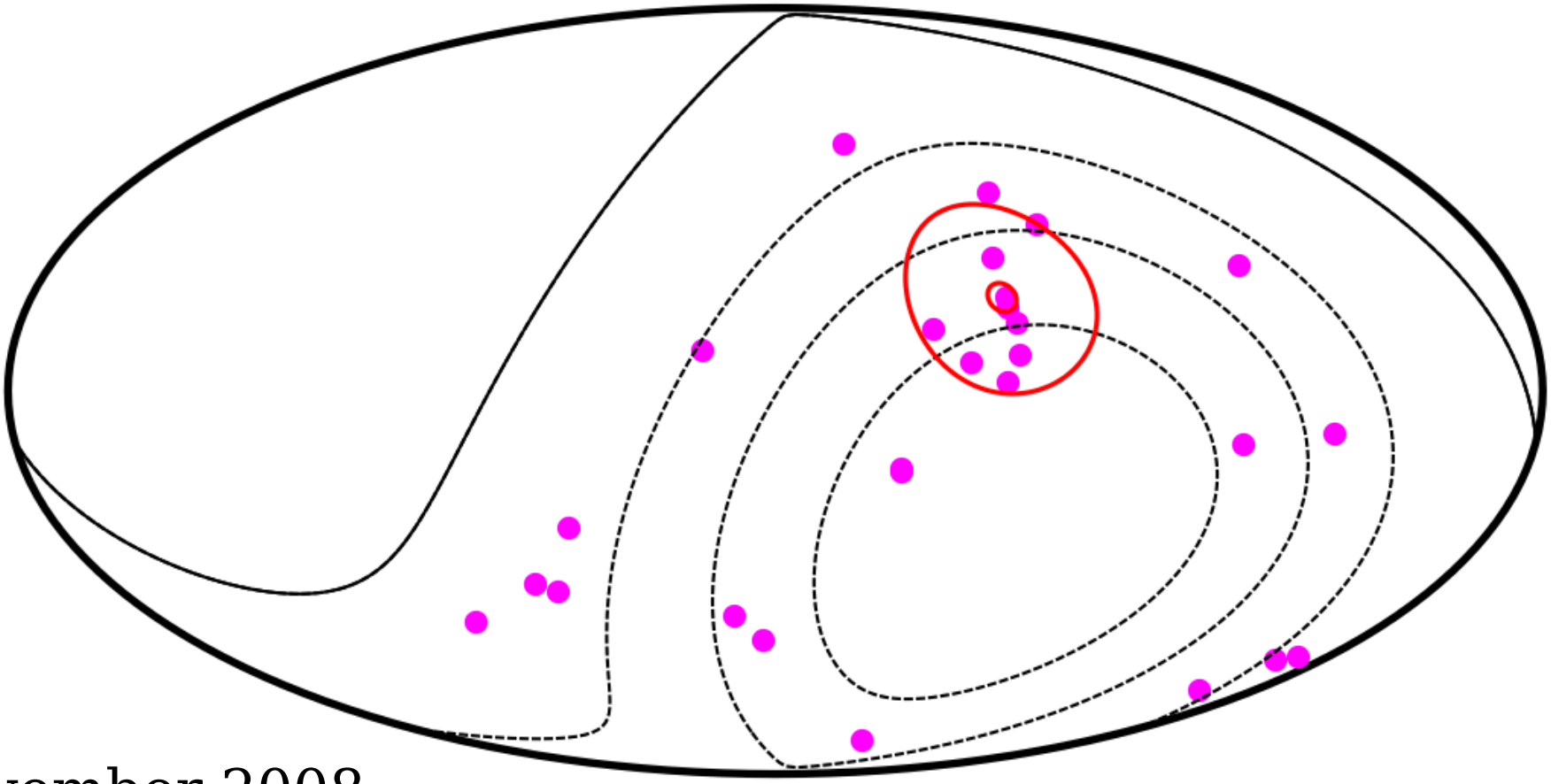


Significant dilution
[but not disappearance]
of the statistical significance

14 ev. 8 coincid. (2.9)
13 ev. 9 coincid. (2.7)
42 ev. 12 coincid.(8.8)

Discussion on CEN A
The AGN closest to us.

3 events within 3 degrees
8 events within 18 degrees



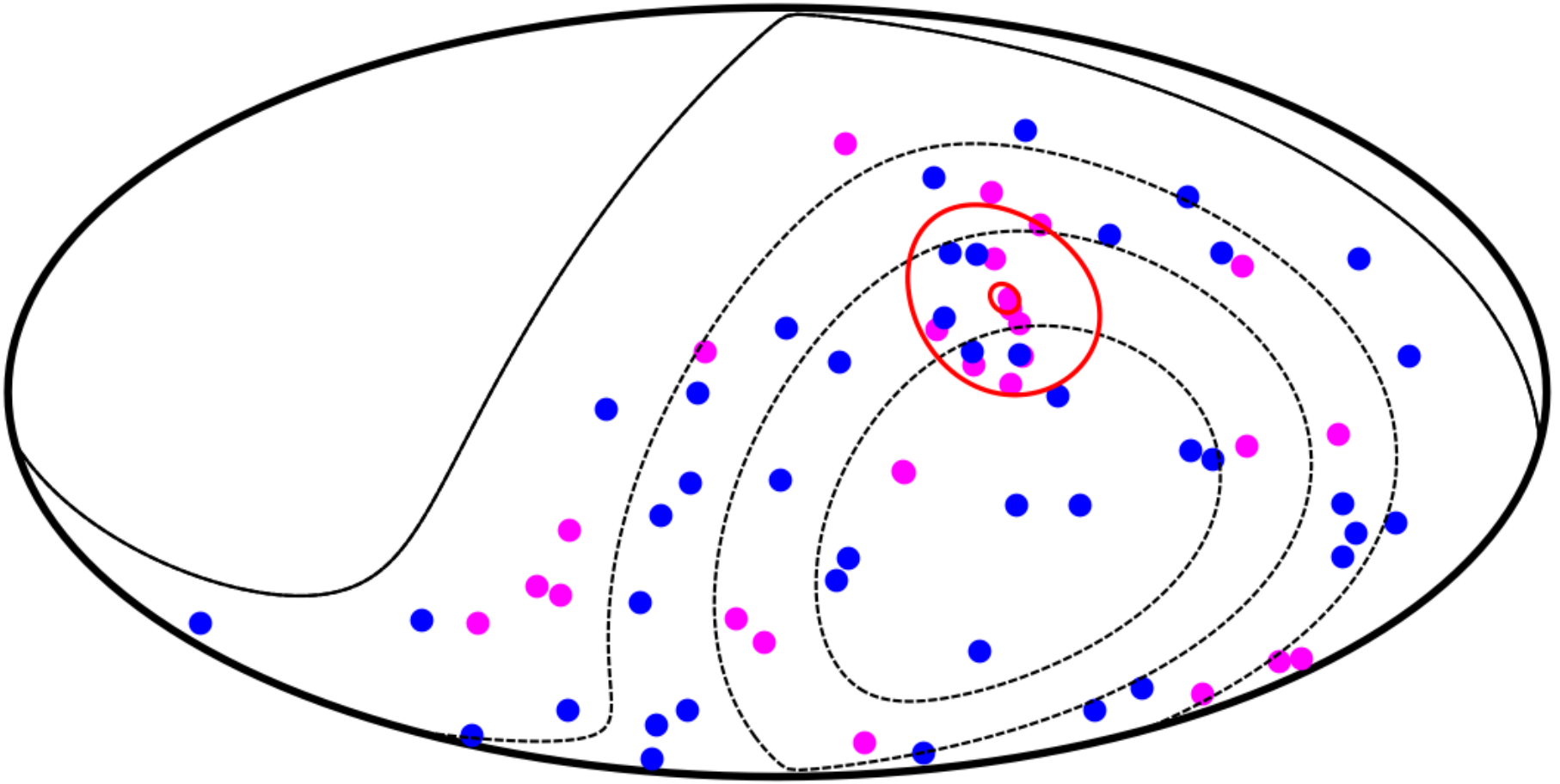
November 2008

3, 20 degrees circles

Discussion on CEN A
The AGN closest to us.

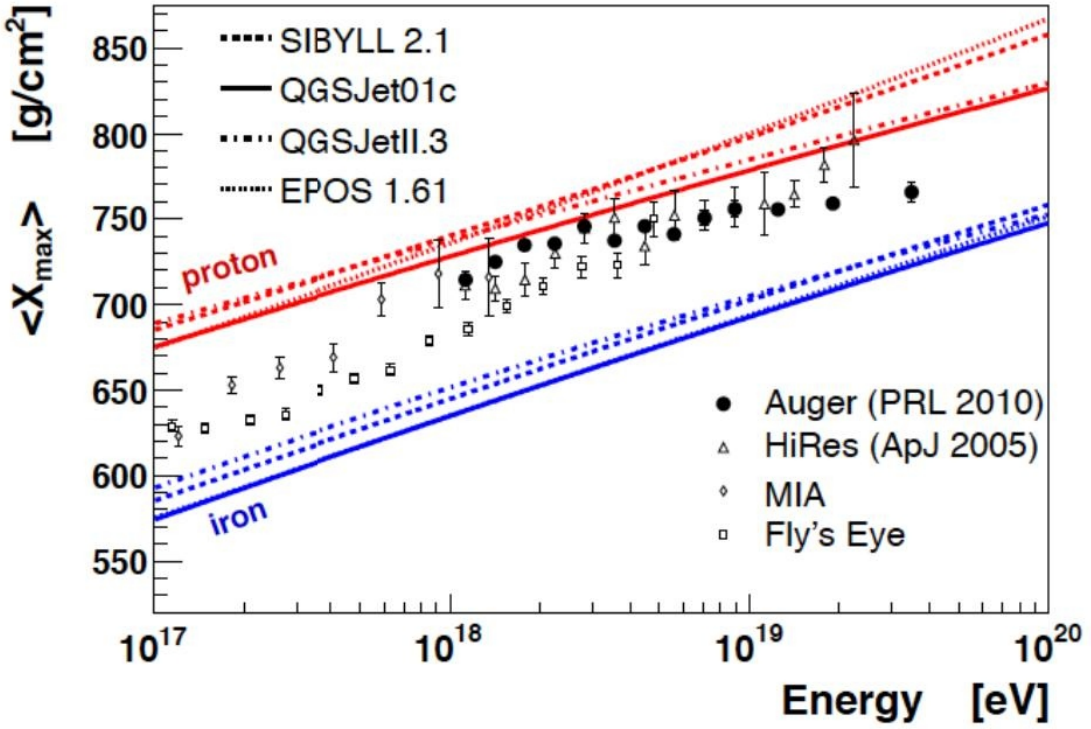
3 events within 3 degrees
8 events within 18 degrees

+0 events within 3 degrees
+5 events within 18 degrees



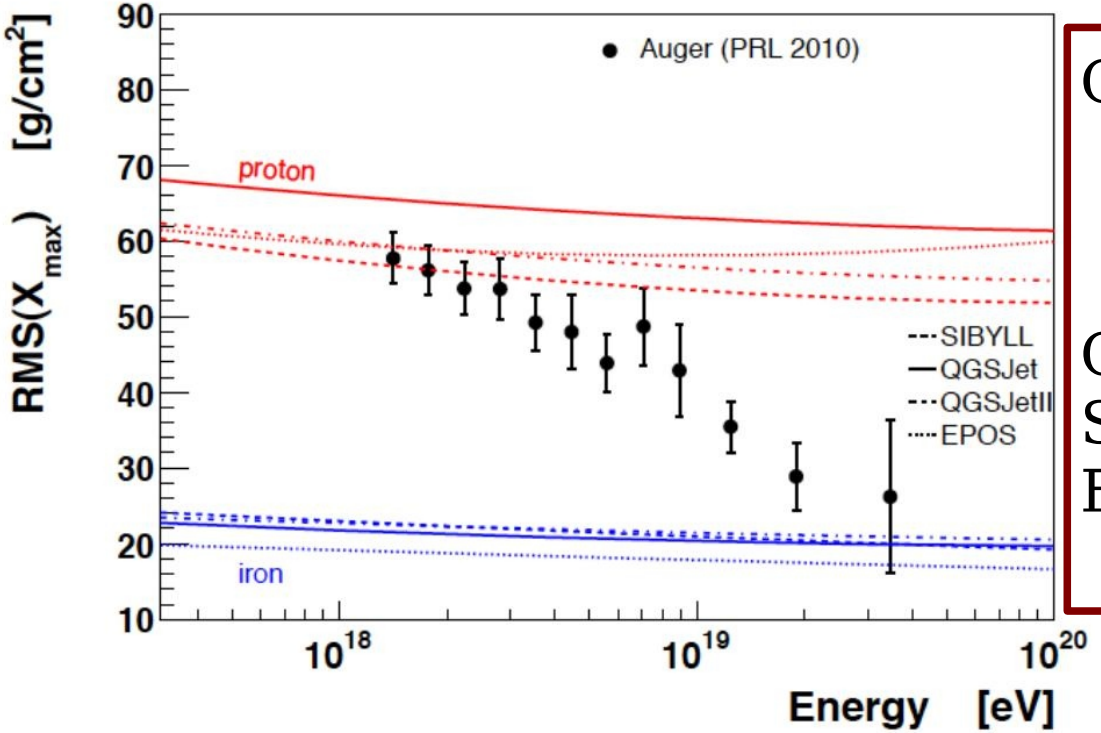
November 2008 (13 + 14 events)
Update september 2010 (+42 events)

3, 20 degrees circles



Mass Composition
becoming heavy ?
at very high energy ?

Significance would be
very important !
Constraints on the
structure and properties
of the astrophysical sources.



Observational controversy
NON confirmation
of HiRes

Correlation with sources
Small deviation in magnetic
Fields (Z < 3 ?)

J. Cronin: astro-ph/0911.47141

“If these trends persist to the
highest energies there would appear to be a conflict
between conclusions that can be drawn from
the anisotropy and the conclusions drawn
from the elongation rate measurement.”

“These results also demand a more careful review of
what seemed to be an obvious conclusion that iron nuclei
could not show an anisotropy because of galactic
and perhaps extragalactic magnetic fields.”

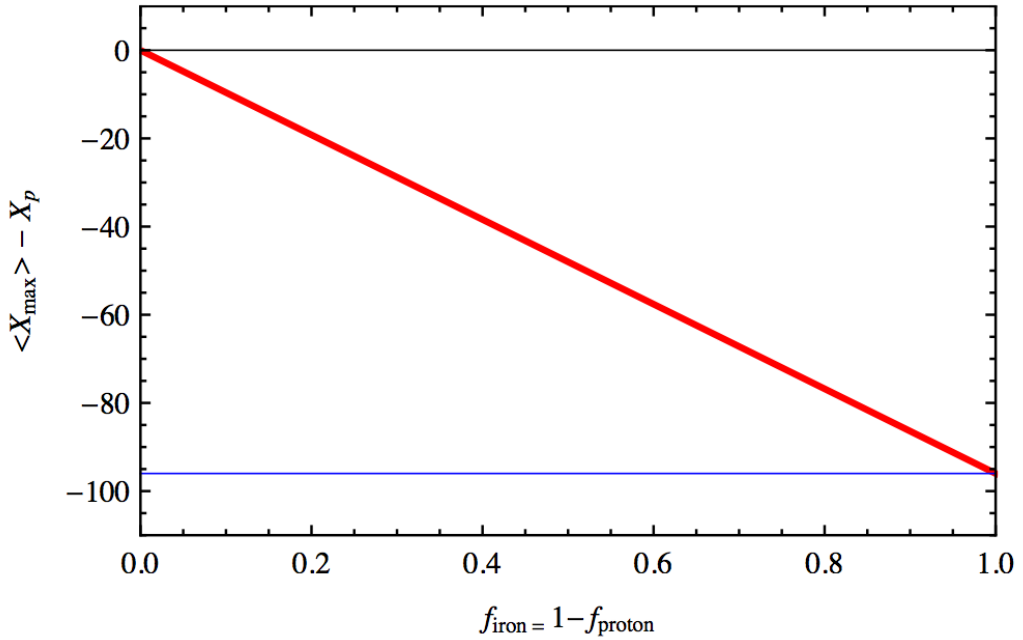
FLUCTUATIONS on $X_{\rm max}$

$$X_{\rm max} = X_{\rm 1st} + Y_{\rm max}$$

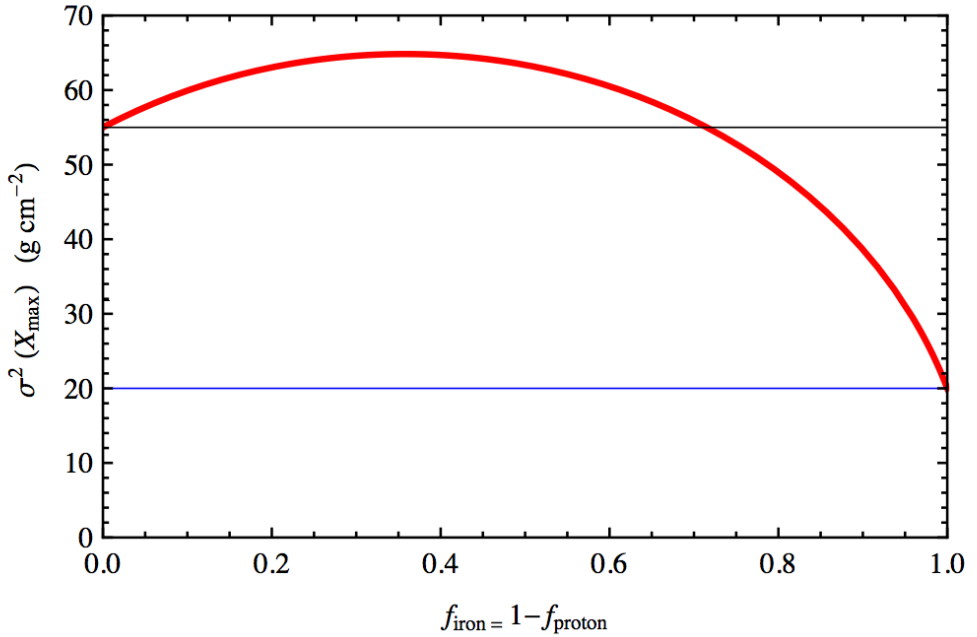
$$\sigma^2_{X_{\rm max}} = \sigma^2_{X_{\rm 1st}} + \sigma^2_{Y_{\rm max}}$$

$$\left(\sigma^{\rm proton}_{\langle X_{\rm max}\rangle}\right)^2 \simeq \lambda^2_p + \sigma^2_{Y_{\rm max}}$$

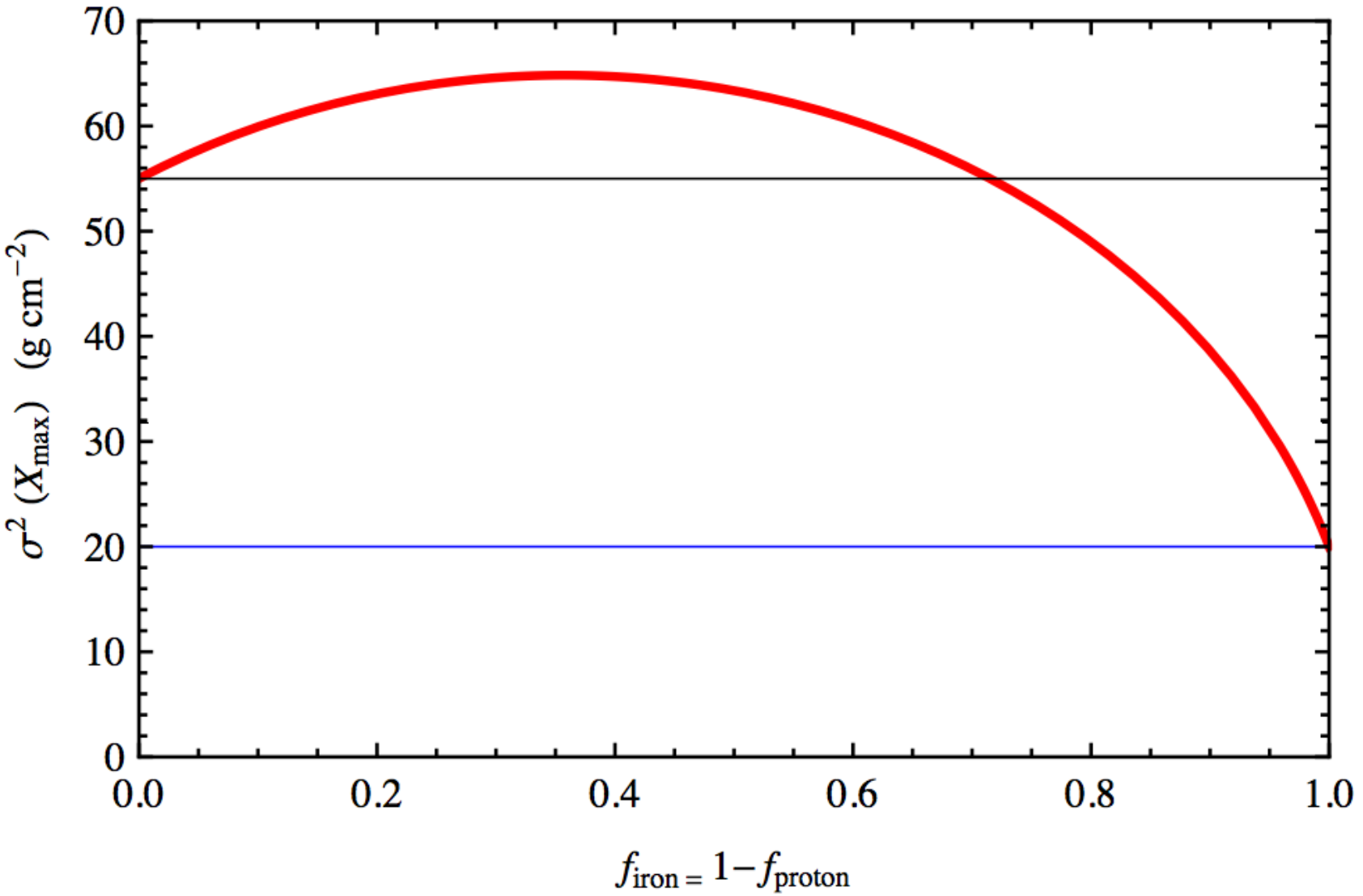
2 component model: Proton + Iron



$$\langle X_{\rm max}\rangle_{\rm obs} \simeq \langle X_p\rangle - D_p\,\langle \log A\rangle$$



$$\sigma^2_X = f_p\,\sigma^2_p + (1-f_p)\,\sigma^2_{\rm Fe} + f_p(1-f_p)\,\left(\langle X_p\rangle - \langle X_{\rm Fe}\rangle\right)^2$$


70
60
50
40
30
20
10
0
0.0
0.2
0.4
0.6
0.8
1.0
$\sigma^2\,(X_{max})$ (g cm^{-2})
$f_{iron} = 1 - f_{proton}$

Conclusions

1. Very exciting time for
   Cosmic Ray science and
   High Energy Astrophysics

2. Crucial moment for
   Particle Physics and accelerators.
   [Important connections with Astro-Particle Physics:
   Dark Matter, Hadronic interactions]

3. Many important open questions.
   [....which make life interesting....]