Particle Astrophysics

Status and Perspectives

Paolo Lipari
MAPSES workshop

Lecce 23rd - 25th november 2011

1. DARK MATTER

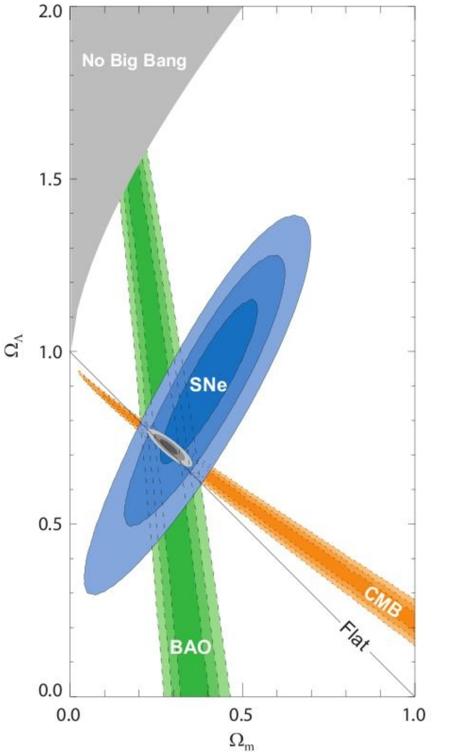
2. Sources of
   High Energy Particles

   (the “High energy universe”)

DARK

MATTER

Mysteries of the DARK UNIVERSE



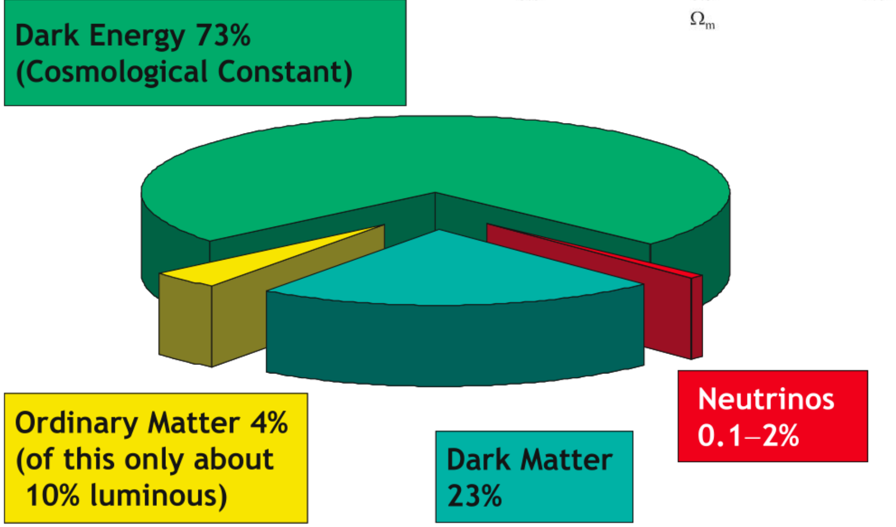
DARK ENERGY :

Drives apart galaxies
and other large scale structures
[The energy of vacuum itself ?]
[Alternatives ? See talk Ishak- Boushaki]

DARK MATTER:

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

Exist at different scales:
Entire Universe
Clusters of Galaxies
Galaxy



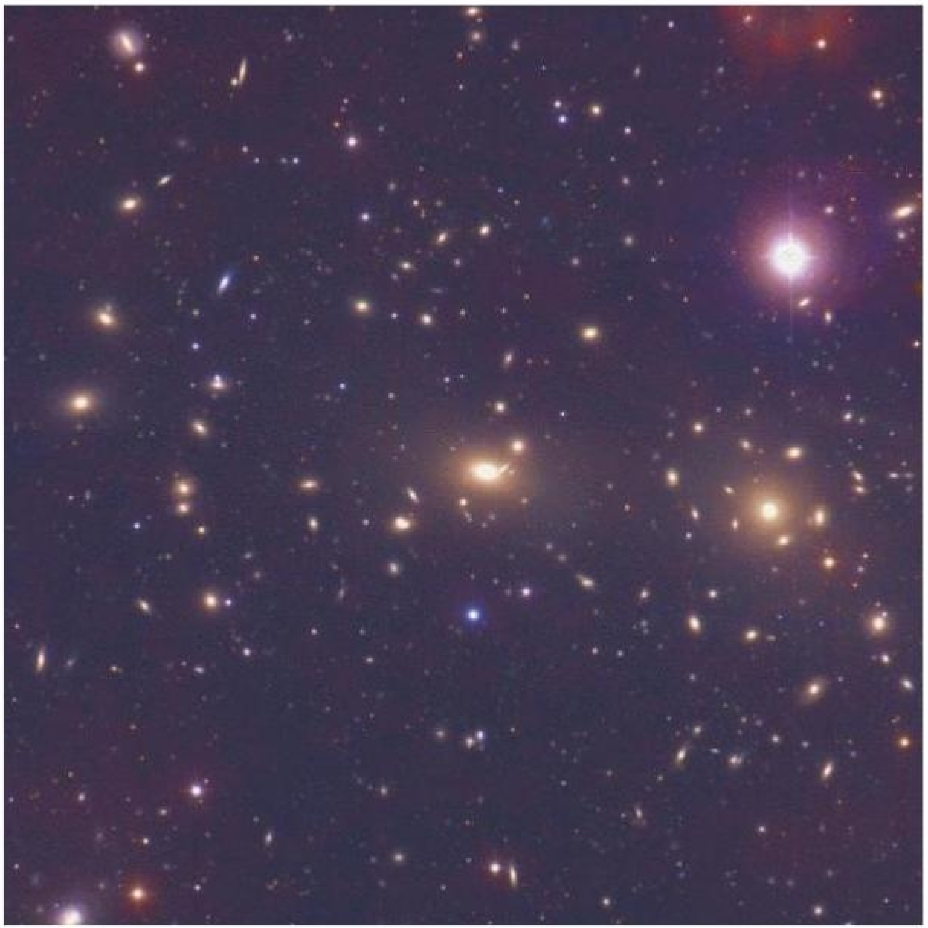
Dynamical Evidence for Dark Matter

- Galaxies
- Clusters of Galaxies
- The entire Universe

The Dark Matter is "non baryonic"
an "exotic" substance

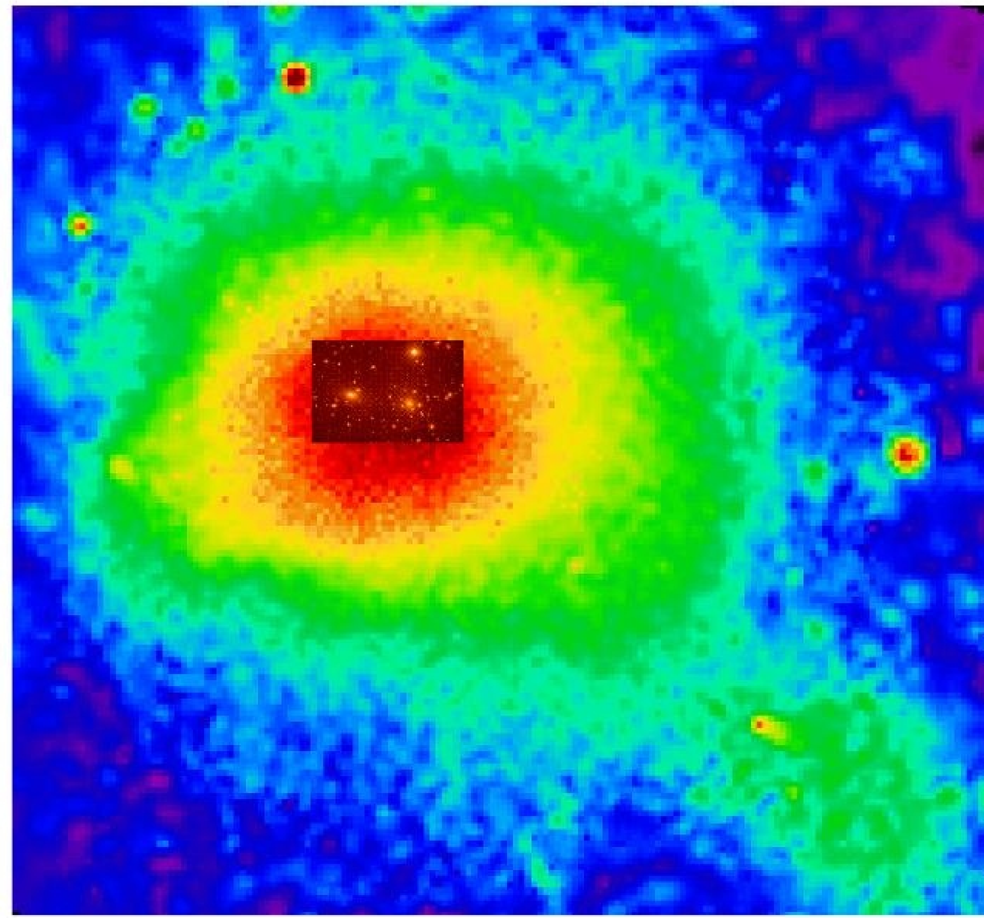
A field that is not contained
in the Standard Model of Particle Physics [!!]

COMA Galaxy Cluster



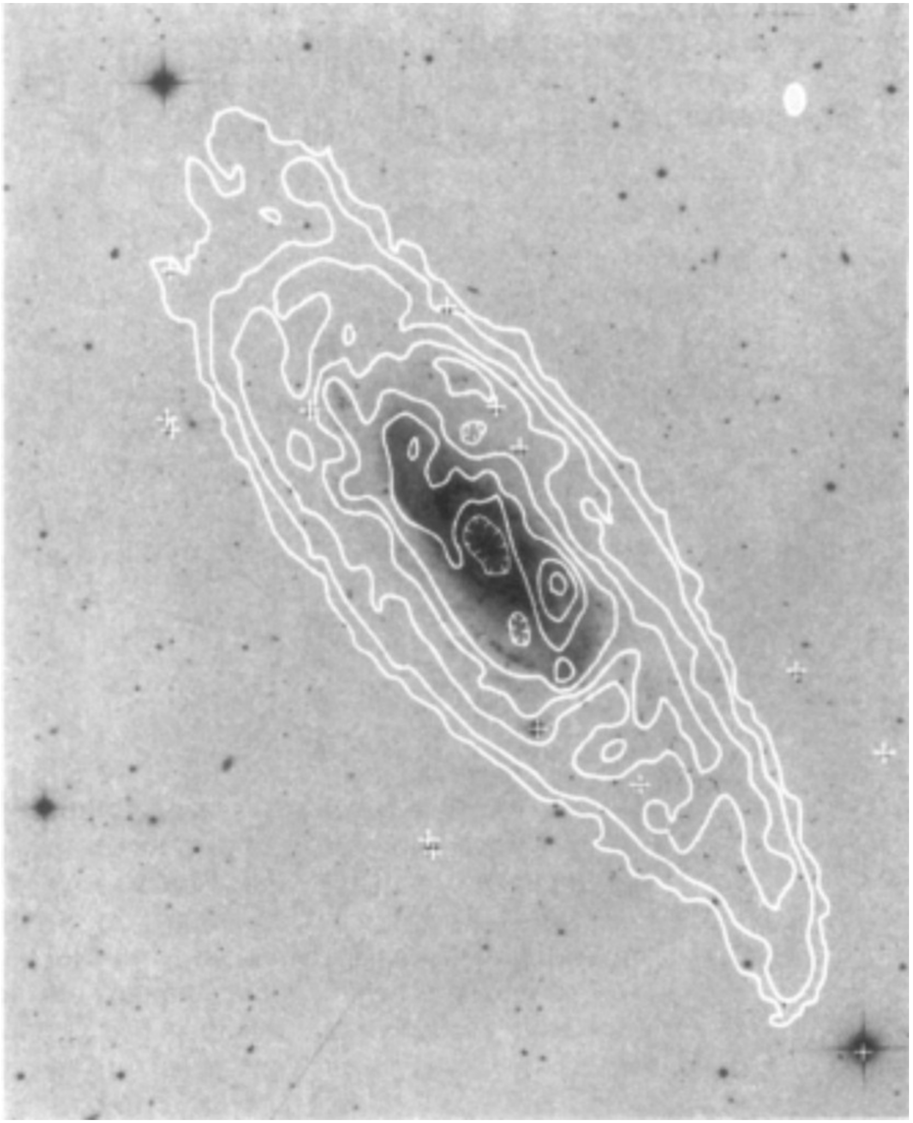
Optical

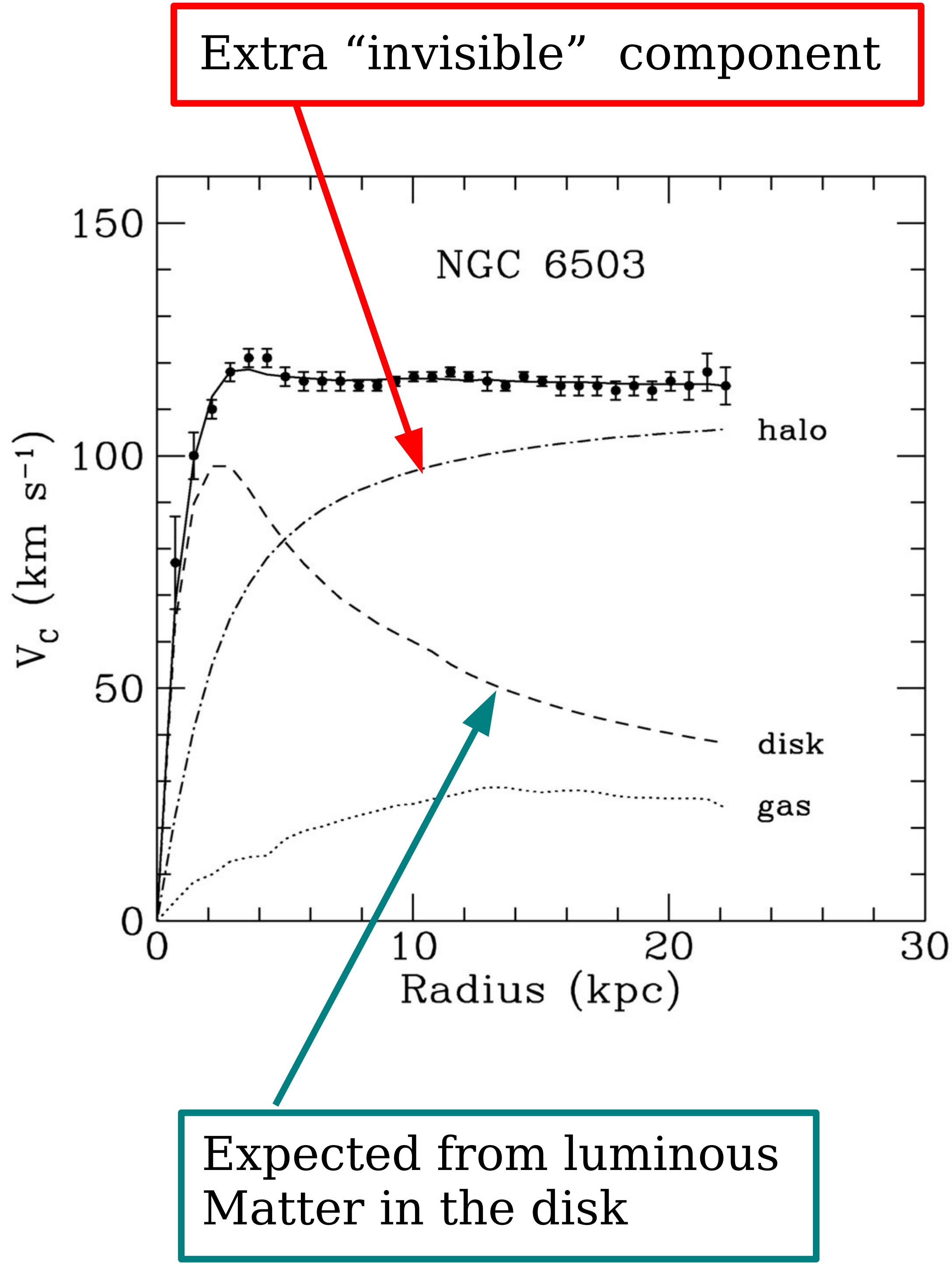
Fritz Zwicky 1933
First argument for Dark Matter



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

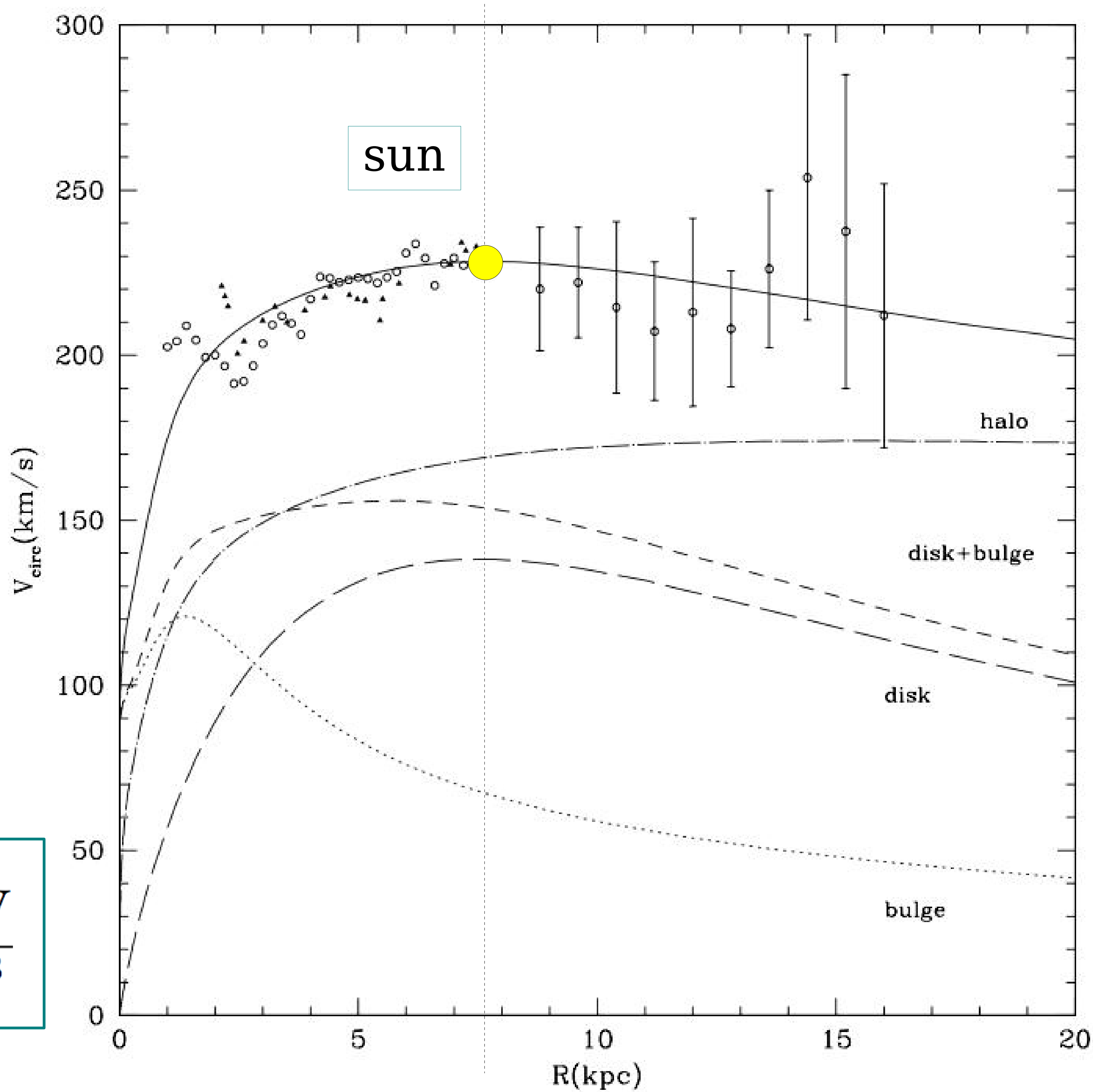
Virgo Cluster Intes Mk69@900mm St10XME L265min 300sec sub RGB 60/57/62min 200sec bin2x2 Gahberg 20080427/0507/0508 www.kerschhuber.astronomie.at





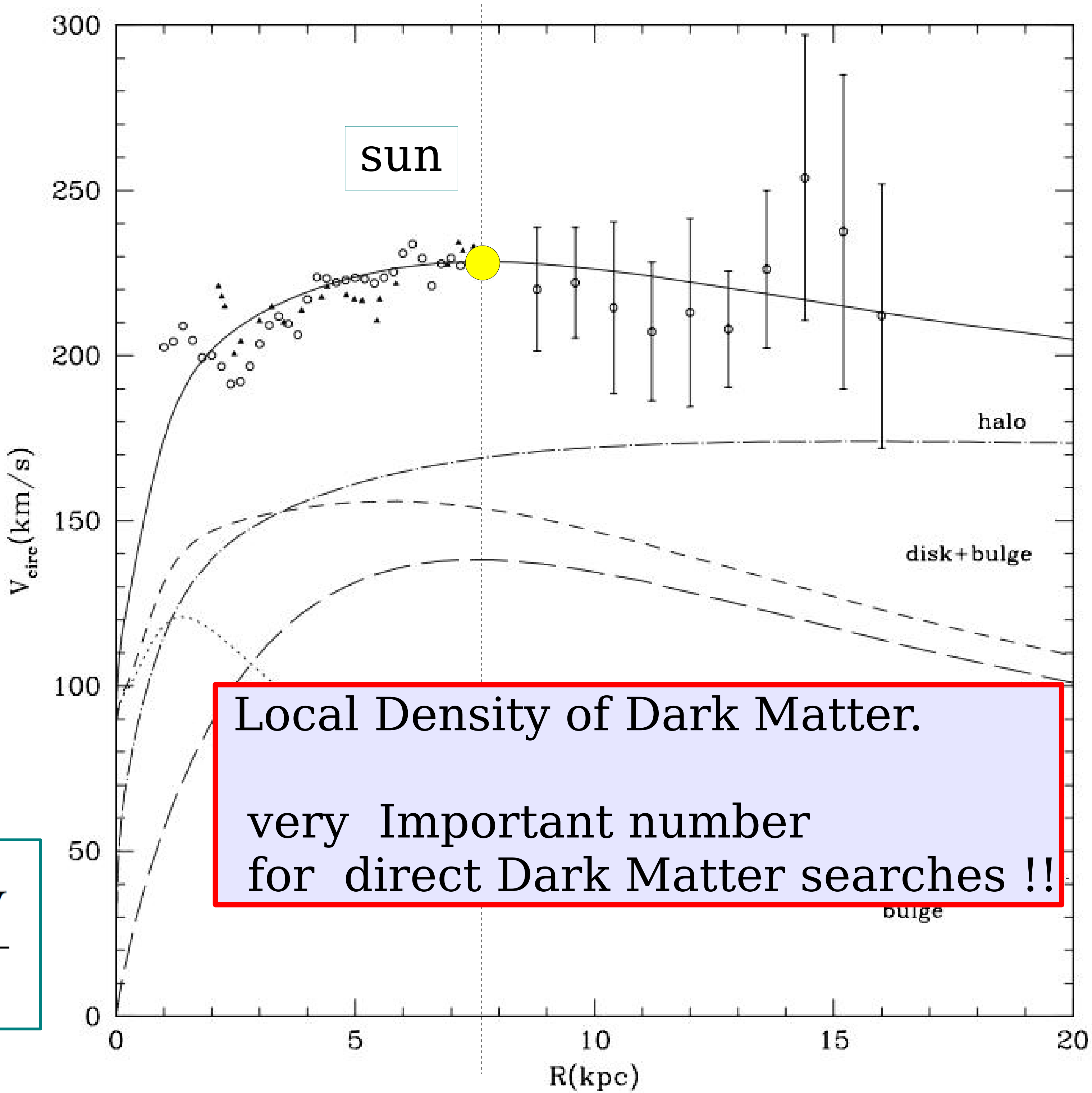
Spiral galaxy NGC 3198 overlaid with hydrogen column density [21 cm] [ApJ 295 (1905) 305

MILKY WAY



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

MILKY WAY

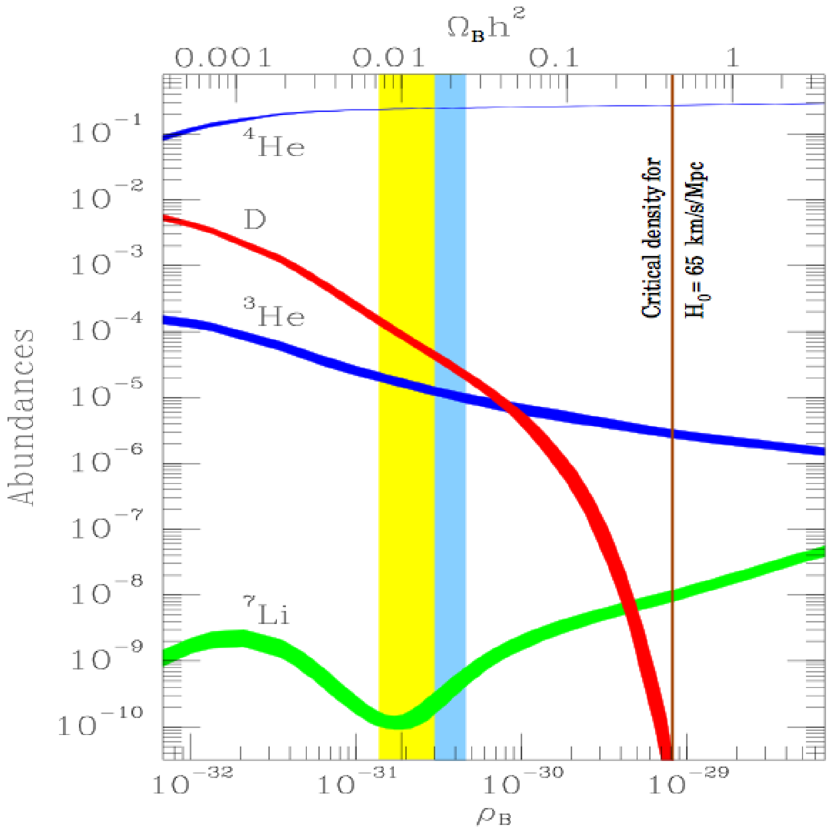


Local Density of Dark Matter.

very Important number
for direct Dark Matter searches !!

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

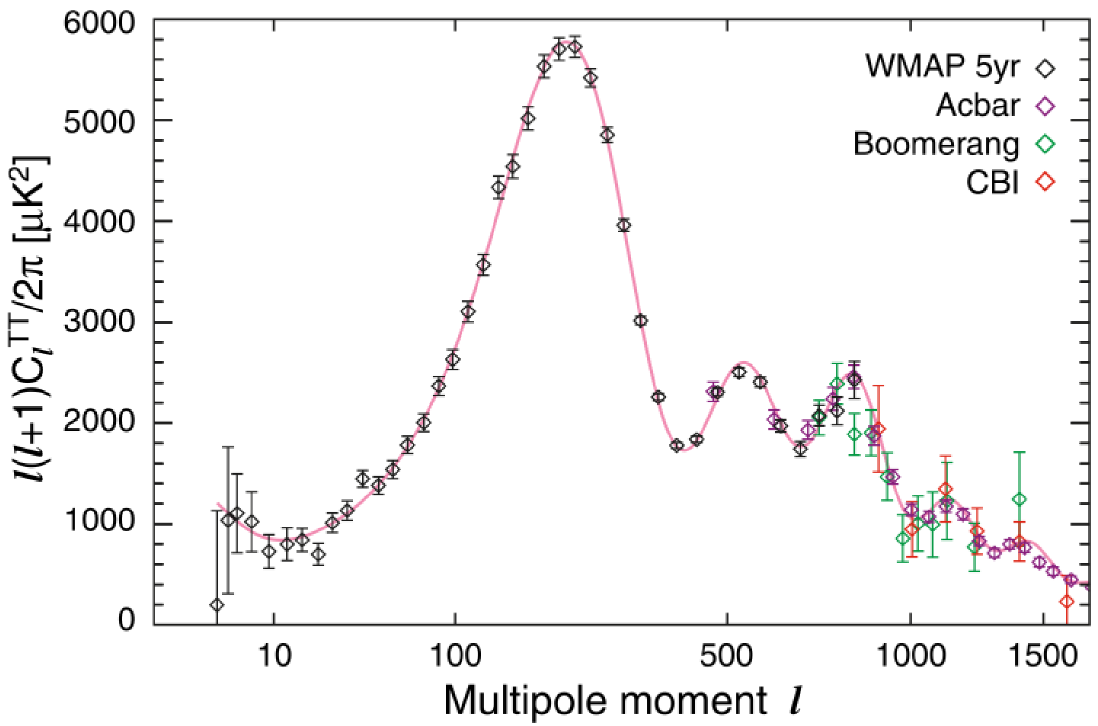
Nucleosynthesis constraints on ordinary ("baryonic") matter



DARK MATTER is NON BARYONIC

(2 main arguments)

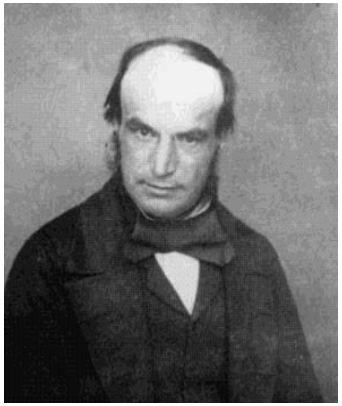
Power Spectrum of CMBR temperature fluctuations + Structure formation



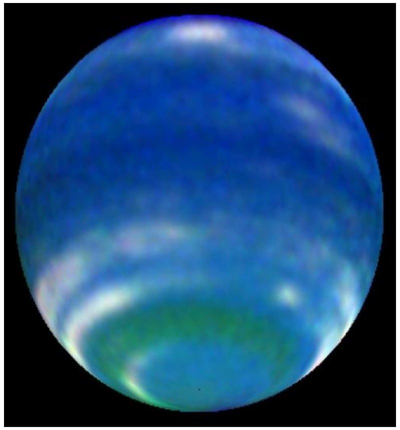
Uranus orbital anomalies

Prediction + Discovery of Neptune (23/24 september 1846)

Urbain Le Verrier

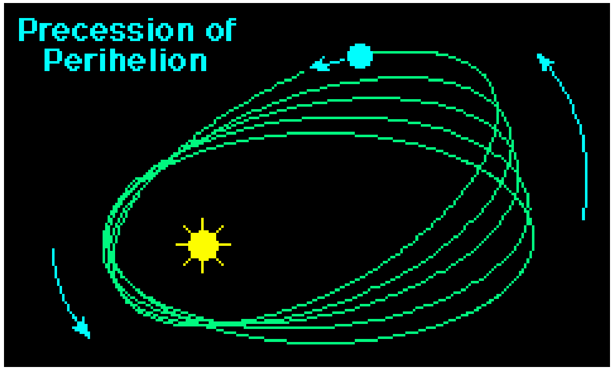


John Couch Adams

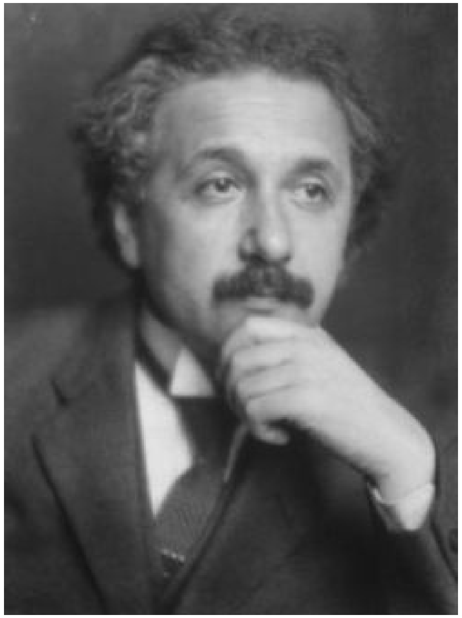


Mercury orbital anomalies

Extra 43''/century perihelion precession



New dynamics
General Relativity
(1916 Albert Einstein)



MOdified Newtonian Dynamics [MOND]

[Milgrom 1983]

$$a_0 \simeq 10^{-8}\ \mathrm{cm/s^2}$$

Fundamental acceleration

$$F_{\rm grav} = \begin{cases} ma & \text{for} \quad a \ll a_0 \\ m\,\dfrac{a^2}{a_0} & \text{for} \quad a \gg a_0 \end{cases}$$

$a_0 \simeq c\,H_0/5$

Coincidence?

$$\frac{G\,M}{r^2} = \frac{v^2}{r}$$

"Newtonian"

$v_{\rm rot}^2 \to GM/r$

$$\frac{G\,M}{r^2} = \left(\frac{v^2}{r}\right)^2 \frac{1}{a_0}$$

Modified Newtonian (small acceleration)

$v_{\rm rot}^4 \to GM\,a_0$

$v_{\rm rot} \propto M^{1/4} \propto L^{1/4}$

J. D. Bekenstein,
"Alternatives to dark matter: Modified gravity as an alternative to dark matter,"
arXiv:1001.3876 [astro-ph.CO].

1. Introduction

A look at the other papers in this volume will show the present one to be singular. Dark matter is a prevalent paradigm. So why do we need to discuss alternatives ? While observations seem to suggest that disk galaxies are embedded in giant halos of dark matter (DM), this is just an *inference* from accepted Newtonian gravitational theory. Thus if we are missing understanding about gravity on galactic scales, the mentioned inference may be deeply flawed. And then we must remember that, aside for some reports which always seem to contradict established bounds, DM is not seen directly. Finally, were we to put all our hope on the DM paradigm, we would be ignoring a great lesson from the history of science: accepted understanding of a phenomenon has usually come through confrontation of rather contrasting paradigms.

Why is "DARK MATTER" the "prevalent paradigm"

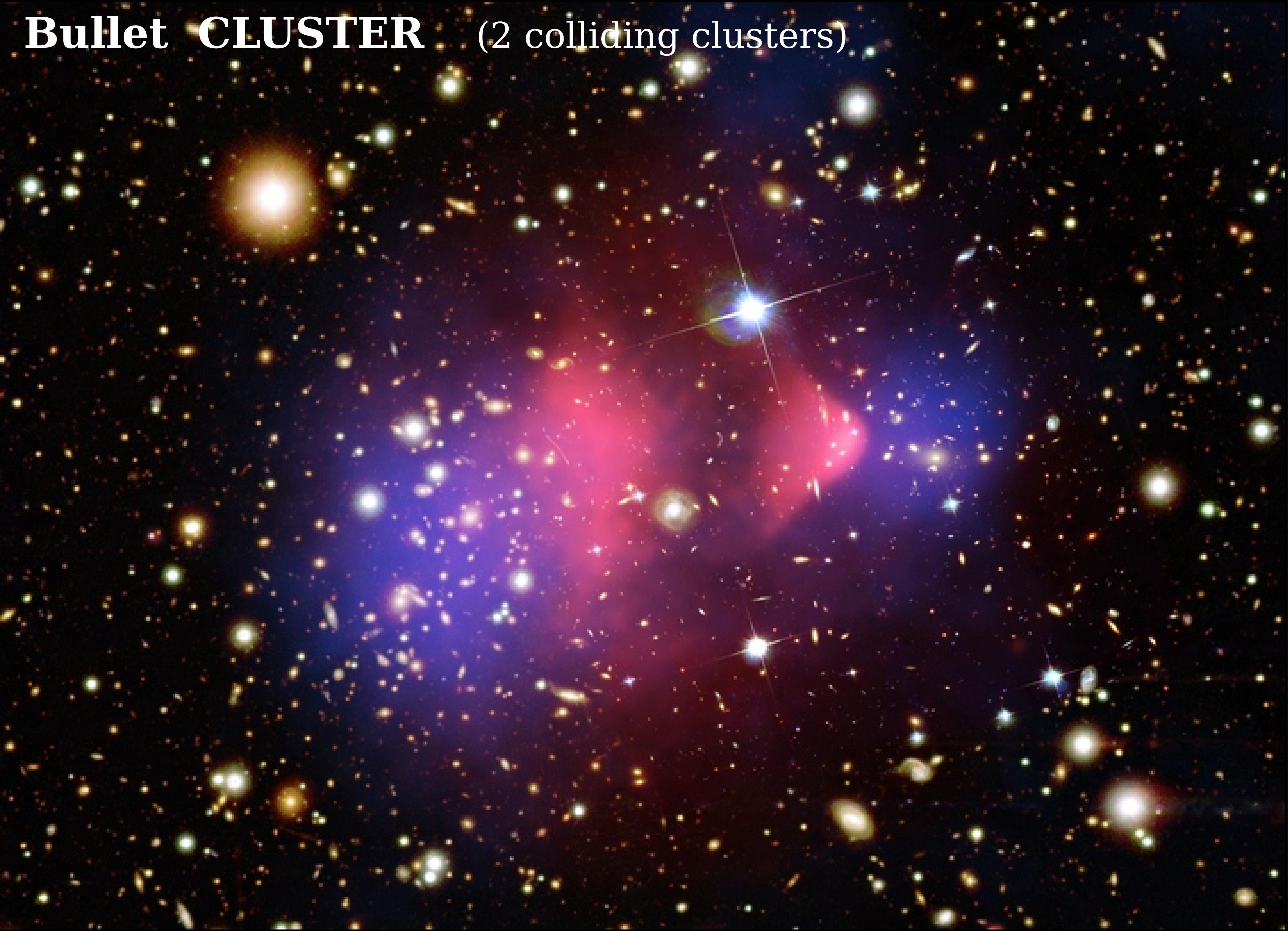
1. Theoretical Difficulties in constructing
   a consistent, covariant theory for a MOND.

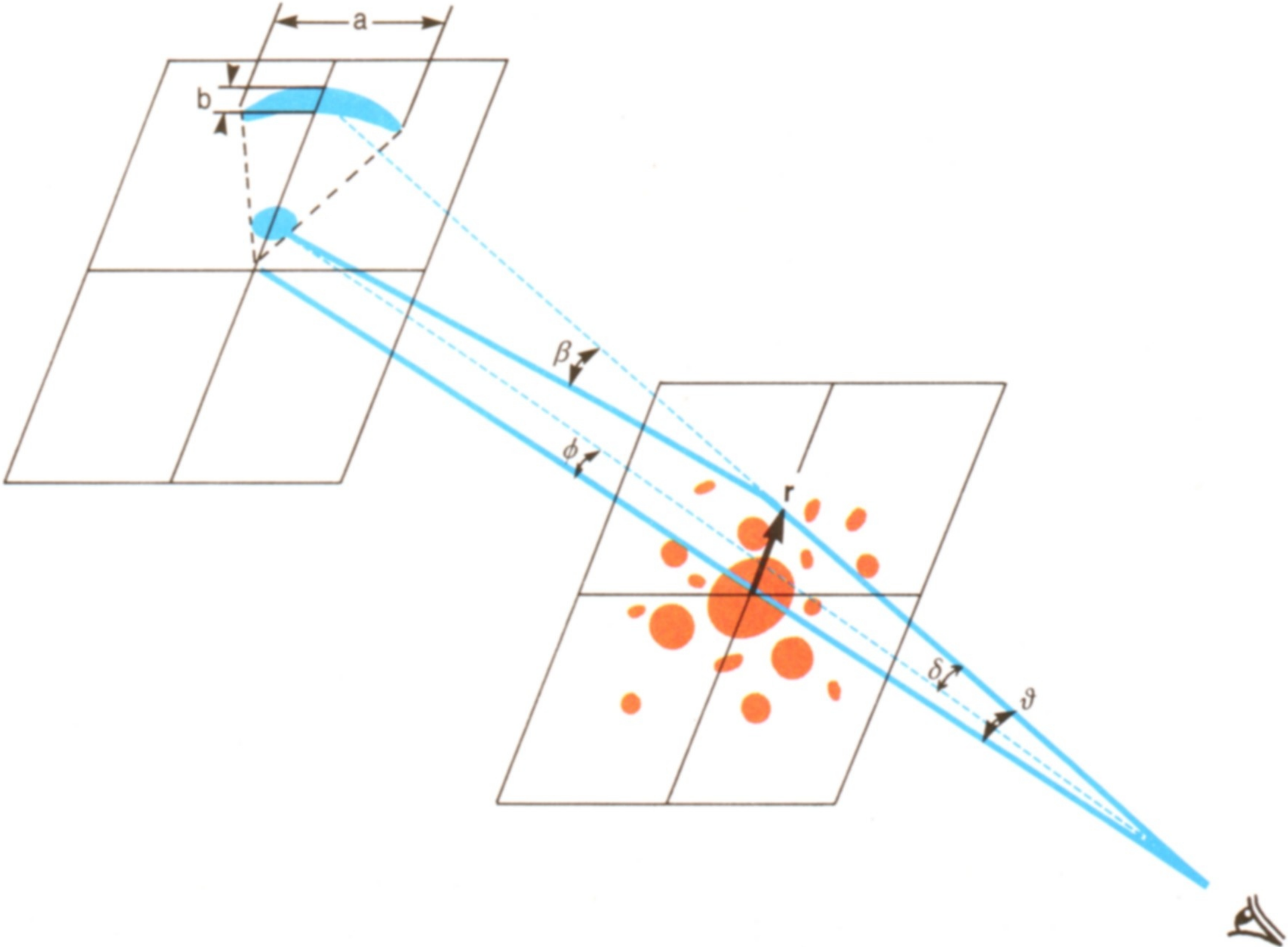
2. Remarkable success of the "Dark Matter" paradigm
   In describing the structure formation in our universe.
   Relation between the
   Large scale galaxy distribution.
   Anisotropies in the Cosmic Background Radiation.

3. The "BULLET CLUSTER"
   (Cluster 1E0657-558: 2 colliding clusters at z=0.296)
   Clear separation between Baryons and Mass.
   [other similar objects discovered (MACS J0025.4-1222)]

D. Clowe, M. Bradac, A. H. Gonzalez *et al.*,
"A direct empirical proof of the existence of dark matter,"
Astrophys. J. **648**, L109-L113 (2006). [astro-ph/0608407].

Bullet CLUSTER (2 colliding clusters)

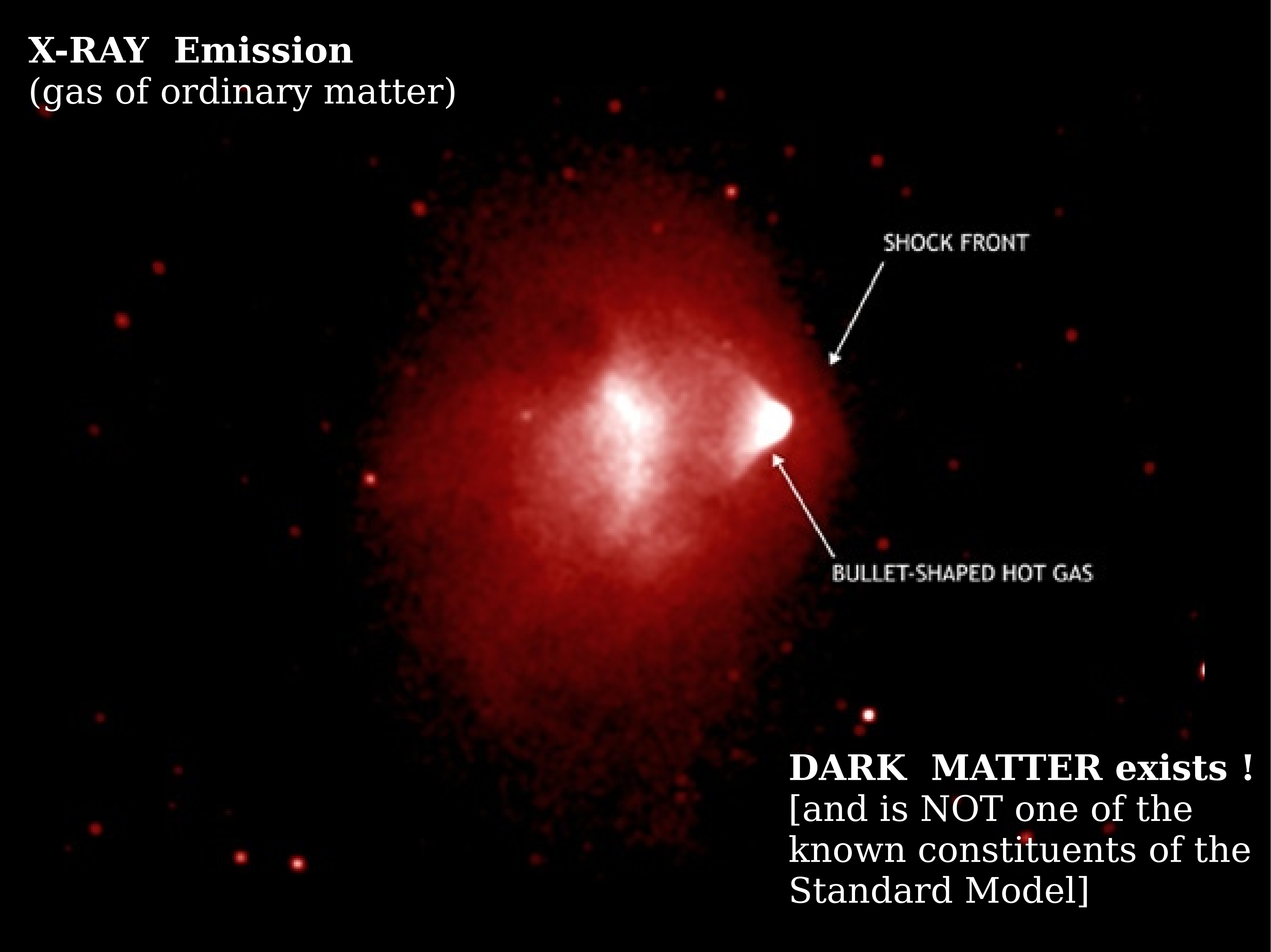




A.Tyson, Physics Today, 1992:6, pg.24

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: 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 !!

Artists And Dark Matter

Cold Dark Matter
(Tate Gallery. London)

Cornelia Parker




What is the Dark Matter ?

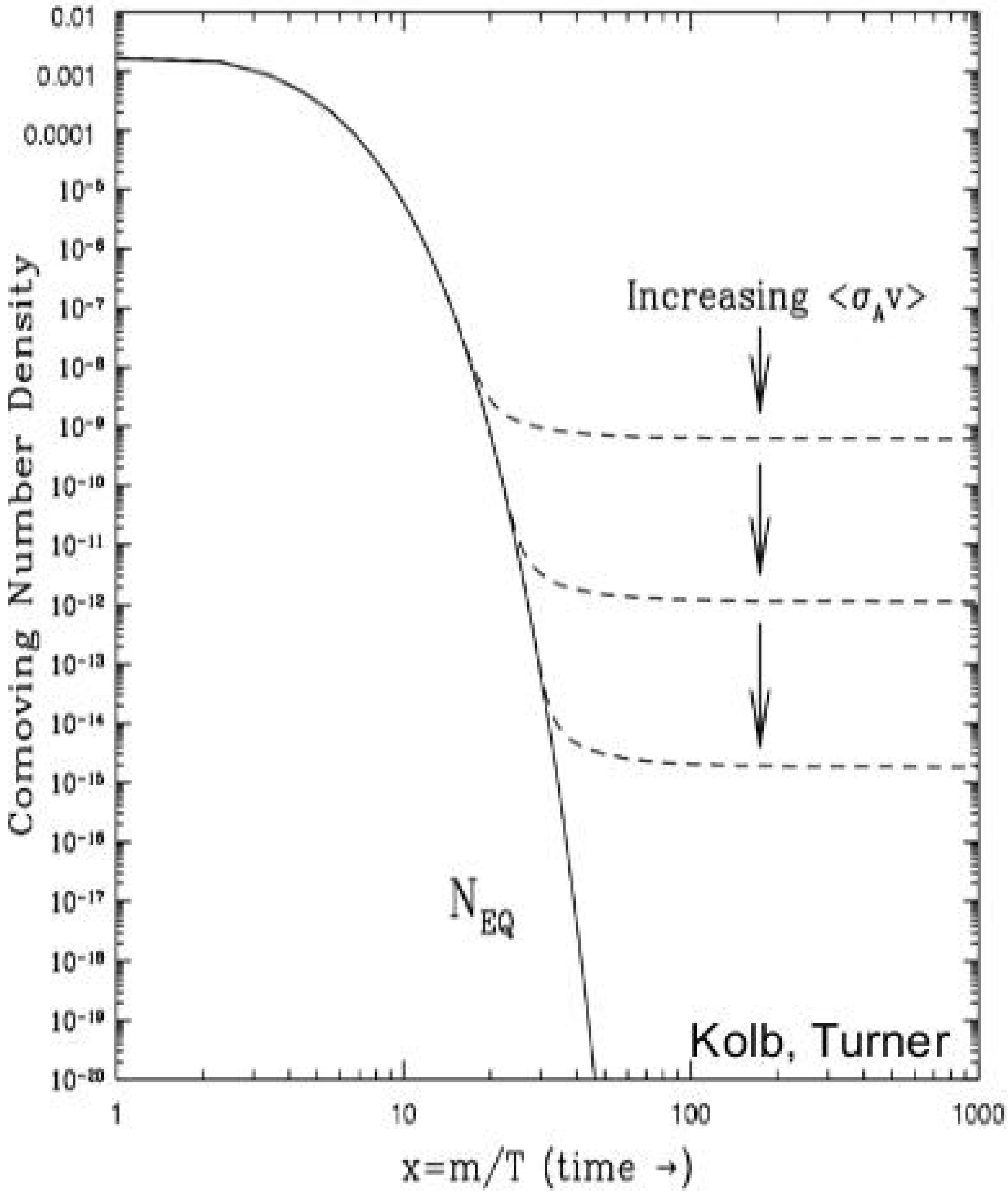
Possible theoretical ideas

Thermal Relic

Axion

Super-massive particles

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



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

Annihilation cross section
Determines the
"relic abundance"

$$\chi + \chi \leftarrow f + \overline{f}$$

$$\chi + \chi \rightarrow f + \overline{f}$$

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

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

(several complications are possible)

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

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

Weak interaction mass scale

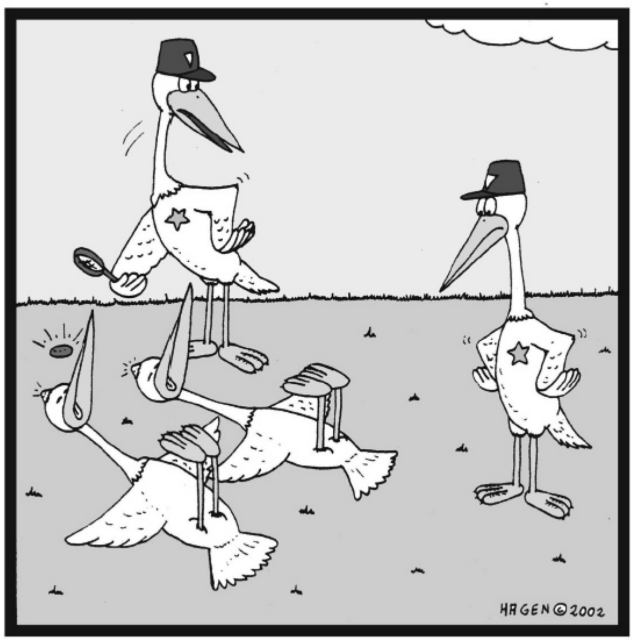
$$M \simeq 200\ \mathrm{GeV}$$

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”

the WIMP's “miracle”



Unbelievable! It looks like they've both been killed by the same stone...

“Killing two birds with a single stone”

“Dark Matter Particle”

“DM puzzle” = Best motivation for “New Particle Physics”

New particles
Required by “Unification”
(theory beyond the SM)

2 very different problems:
Direct observational puzzle
Much more indirect motivation for “New Physics”

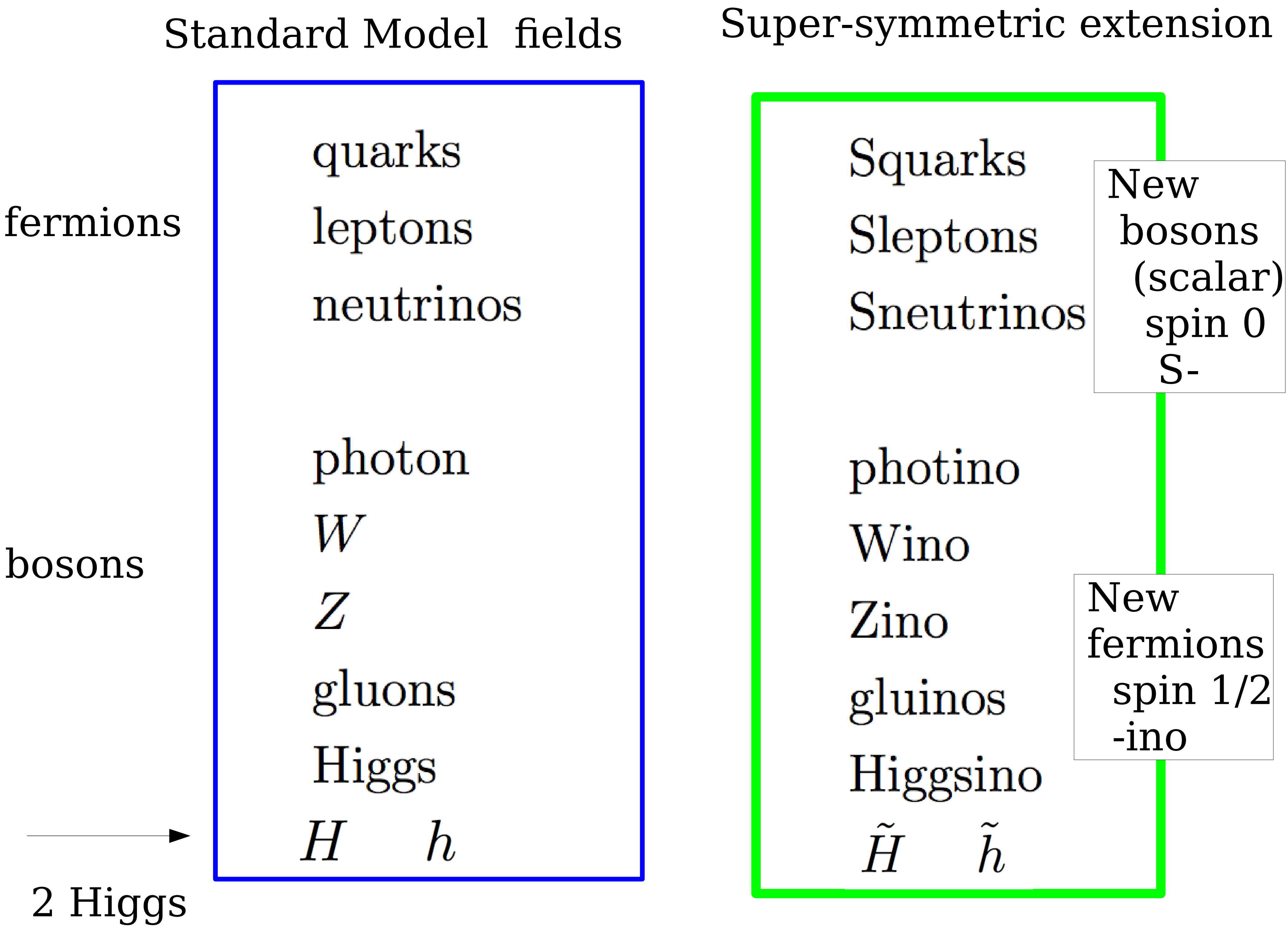
PHYSICS beyond the STANDARD MODEL
is **REQUIRED** to explain Dark Matter !!

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

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

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

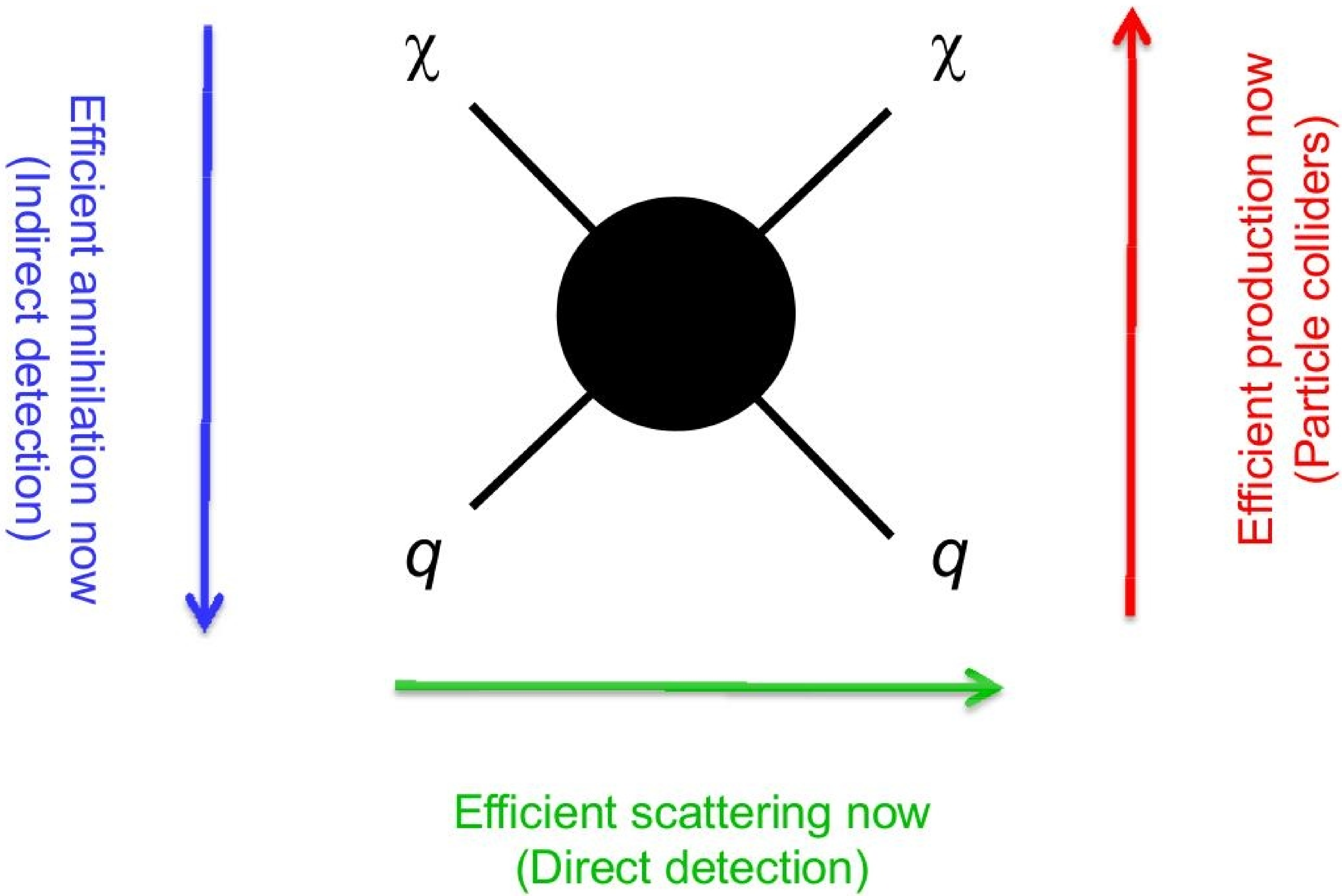
Stable supersymmetric particle

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

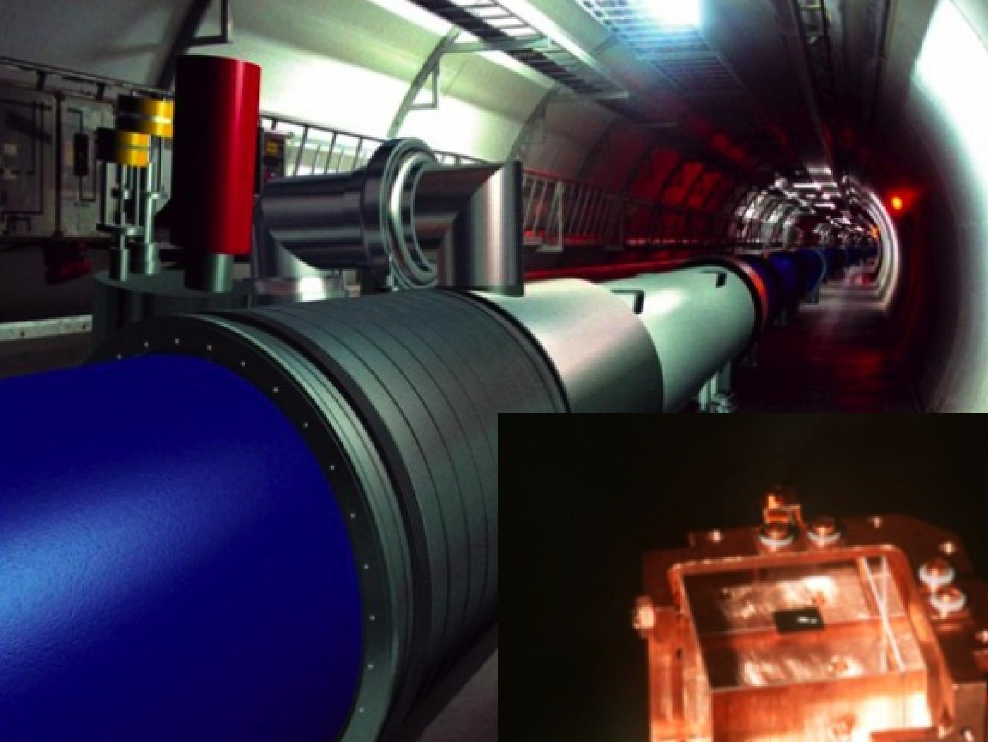
“Neutralino”

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

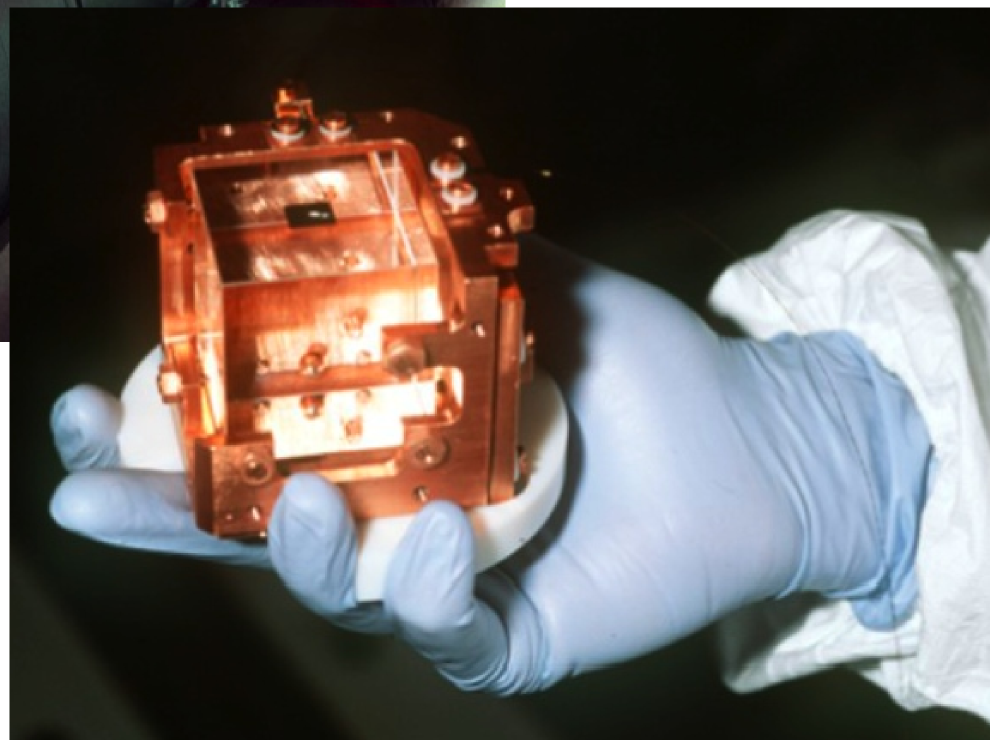
3 Roads for WIMP discovery



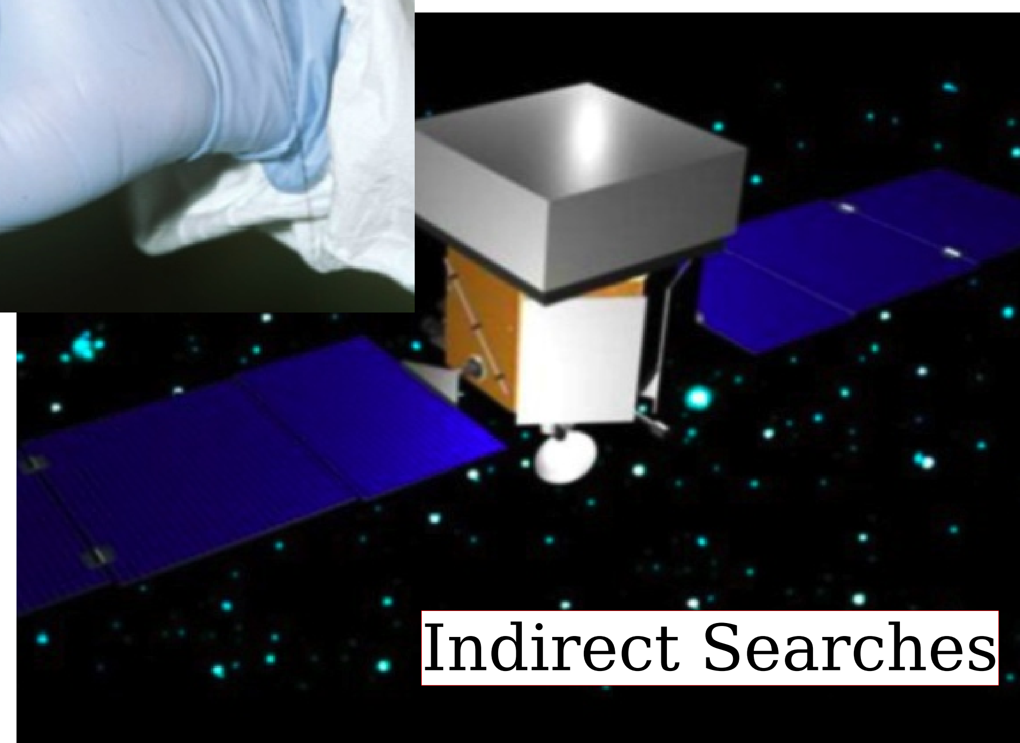
3 Roads to test the WIMP hypothesis



Accelerators

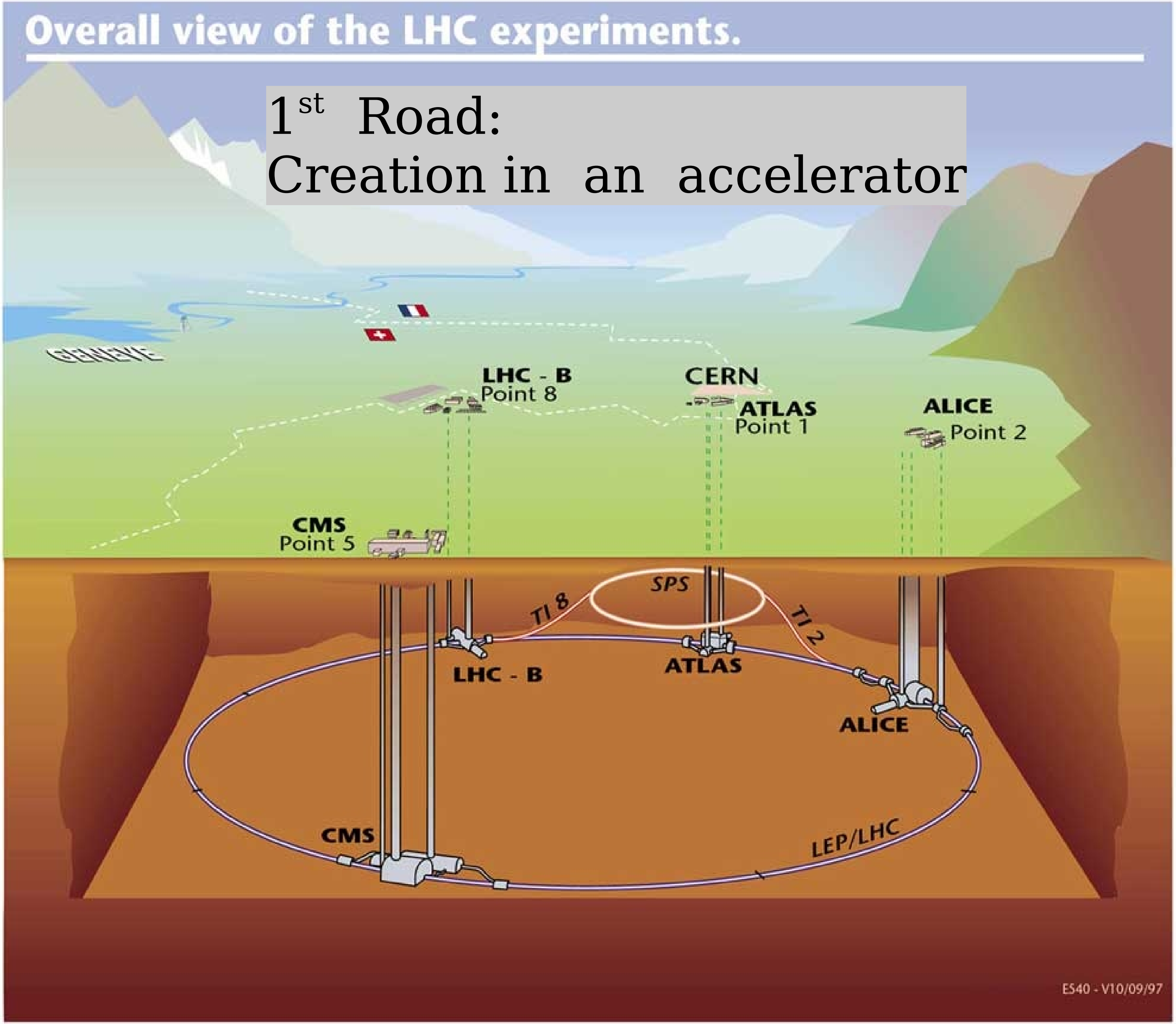


Direct Searches

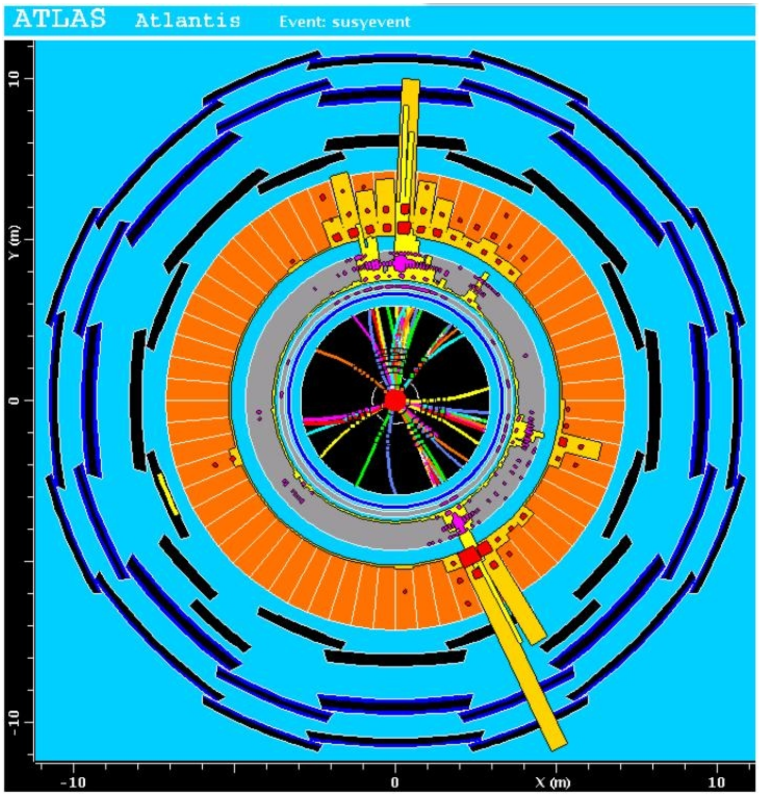


Indirect Searches

1st Road:
Creation in an accelerator

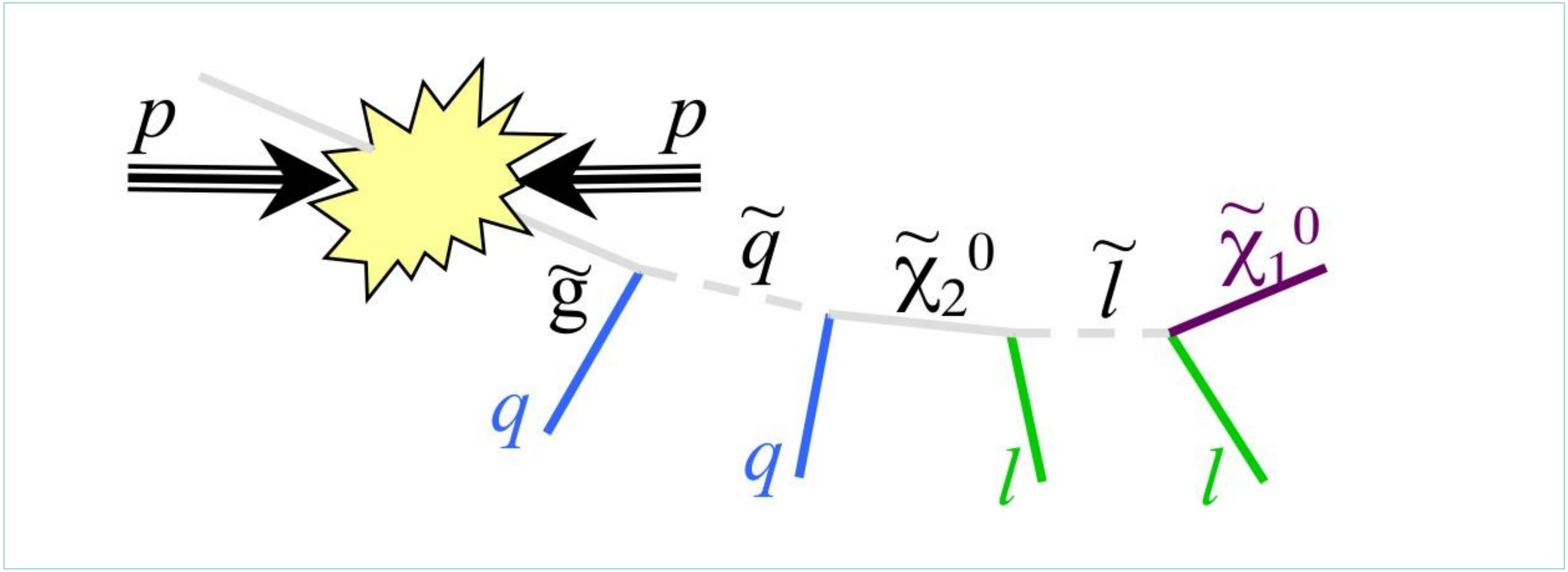


How would you “see” the Dark-Matter particle if it is produced at LHC ?



This particle interacts WEAKLY therefore (in practice always) it will Traverse the detector invisibly.

Detection via 4-momentum conservation ["Missing energy and (transverse) momentum"]

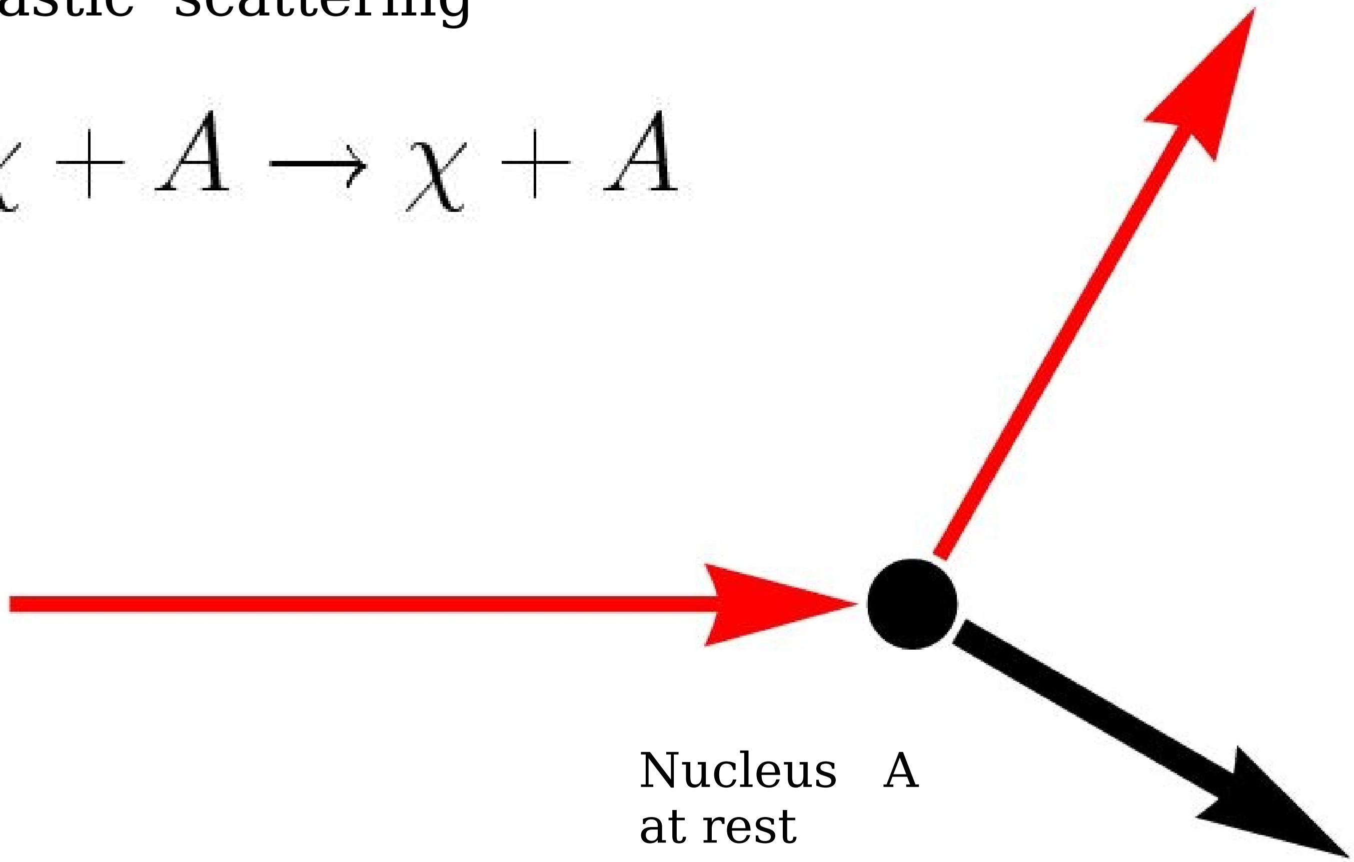


“Direct” Search for Dark Matter

2nd Road:
Elastic Scattering
in underground experiment

Elastic scattering

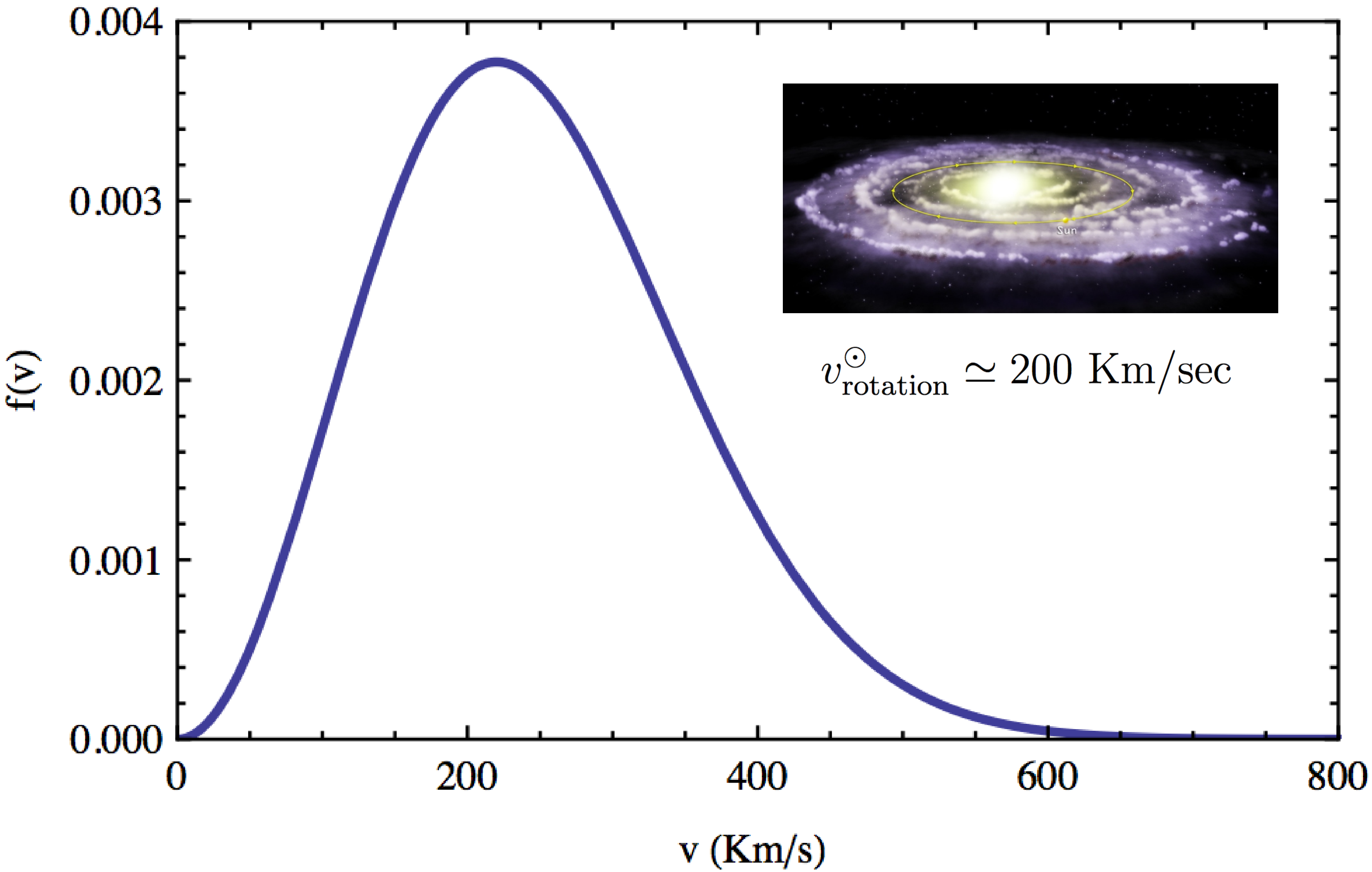
$$\chi + A \to \chi + A$$

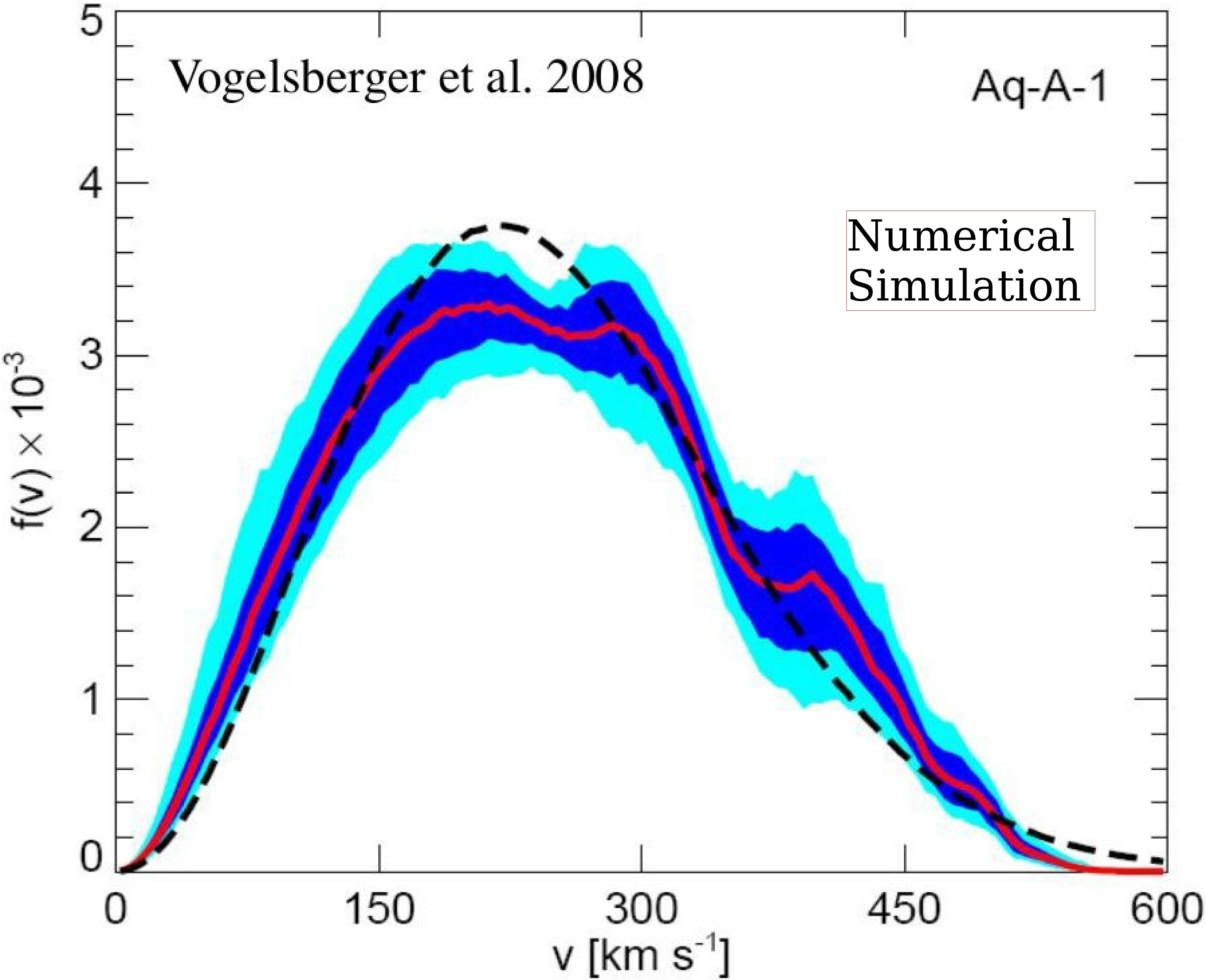


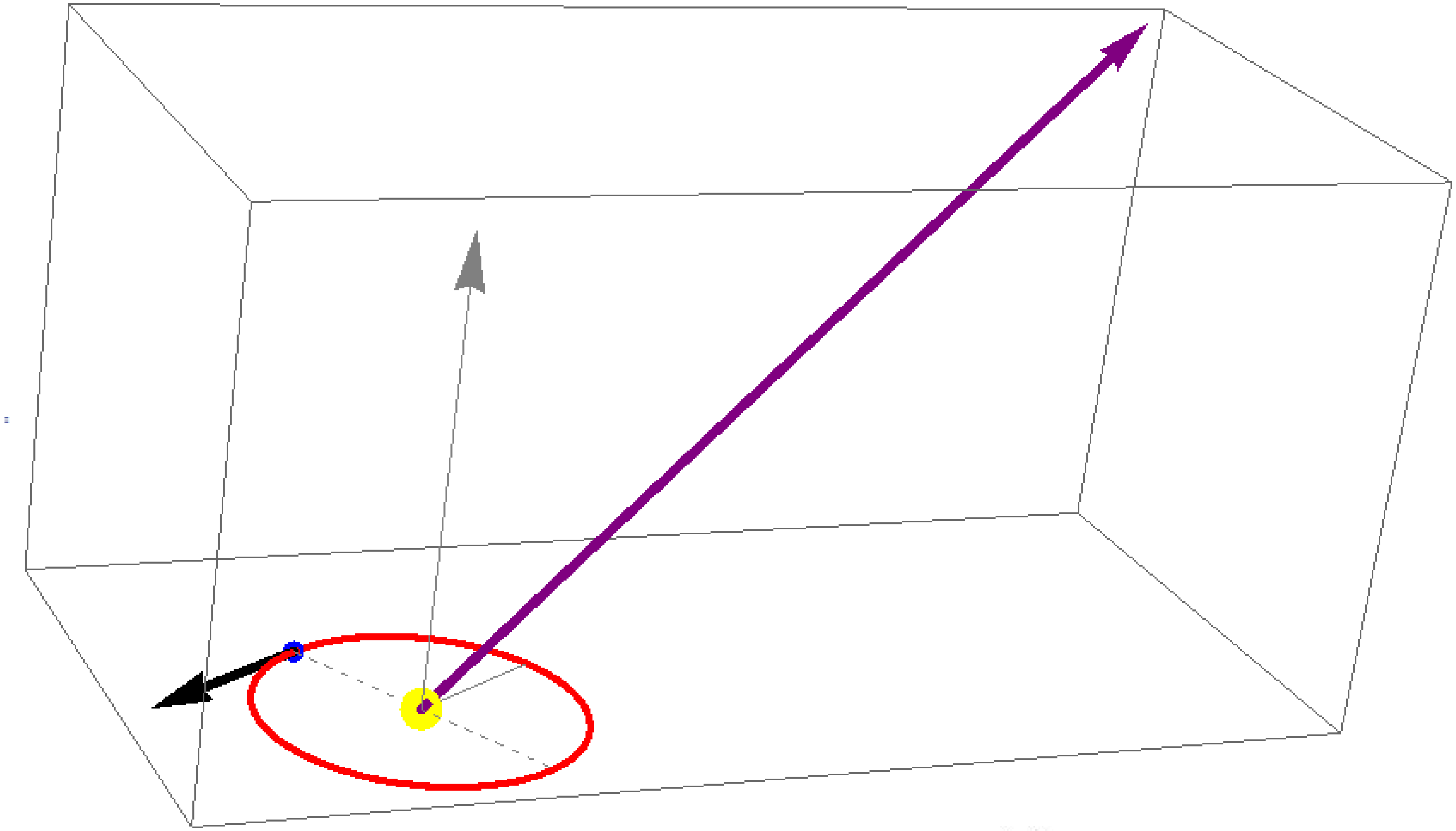
[Rita Bernabei
Gabriella Sartorelli
tuesday afternoon]

Predicted velocity distribution of DM particles
In the "Halo Frame"
Maxwellian form

$$\langle v_{\rm wimp} \rangle \simeq 250 \ {\rm km/sec}$$




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



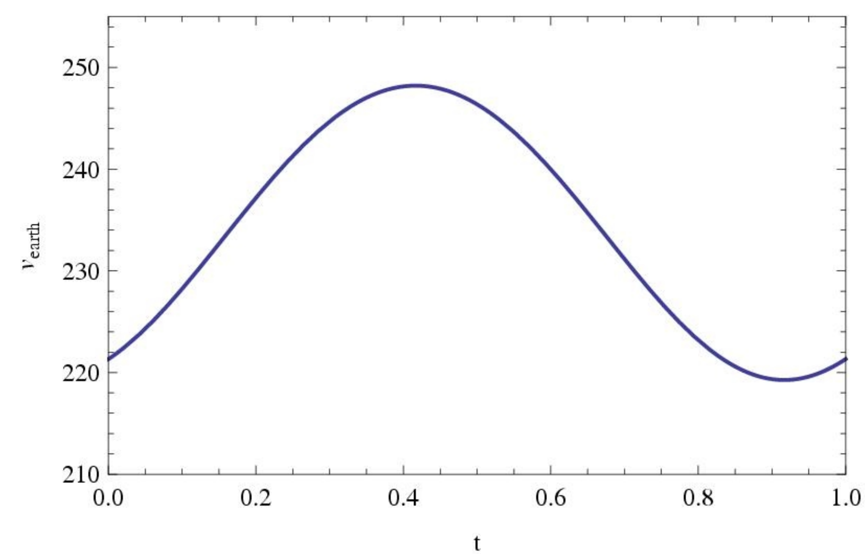
$$w_\oplus(t) \simeq w_\odot + \sin\gamma\ v_{\rm orbit}\ \cos[\omega(t-t_0)]$$

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

“Halo rest frame”

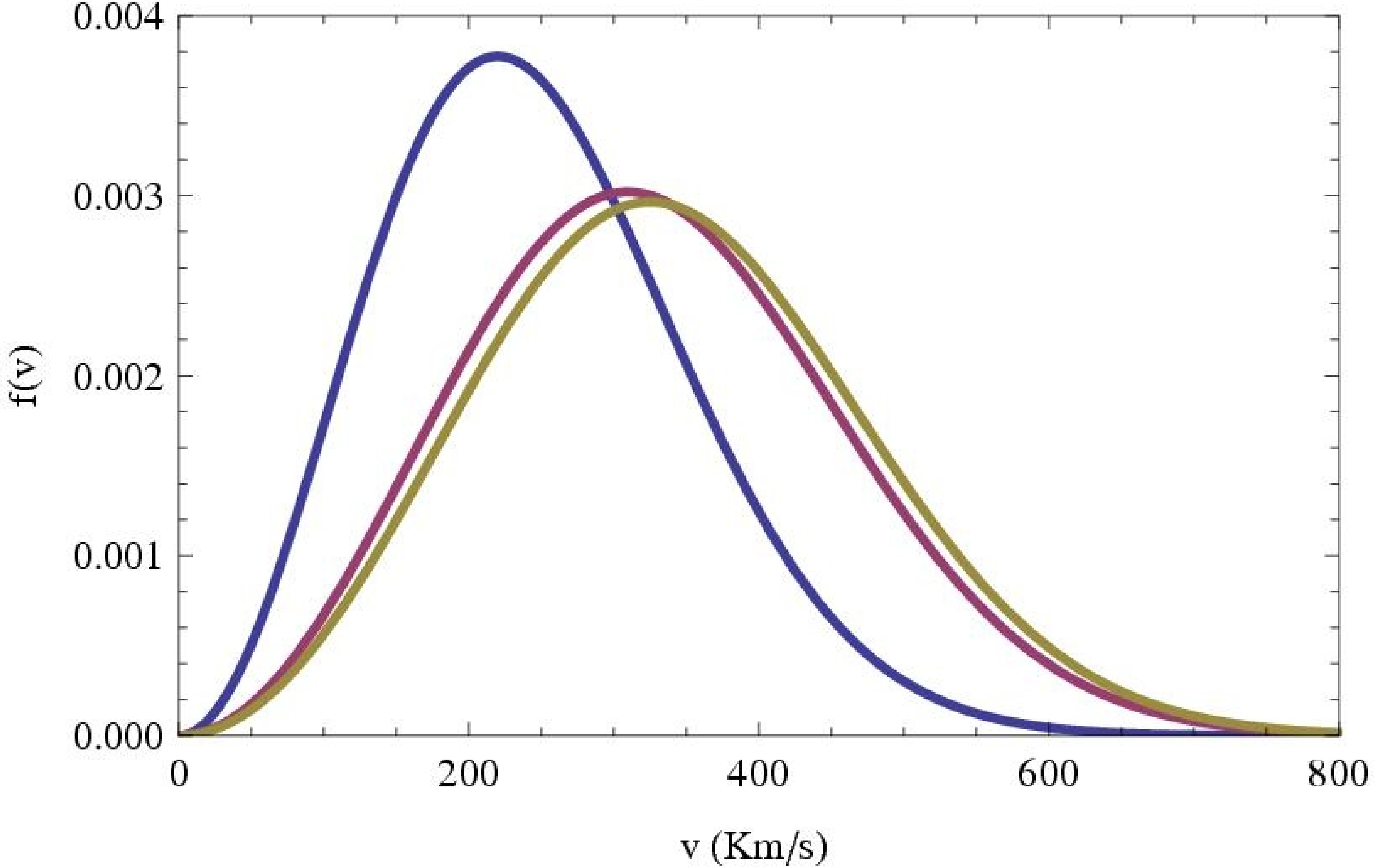
Velocity of Earth in the Halo rest frame

[Co-rotation ?]



Velocity distribution in the Earth Framexs

2nd june
2nd december



Expected flux of Dark Matter particles (here !) :

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

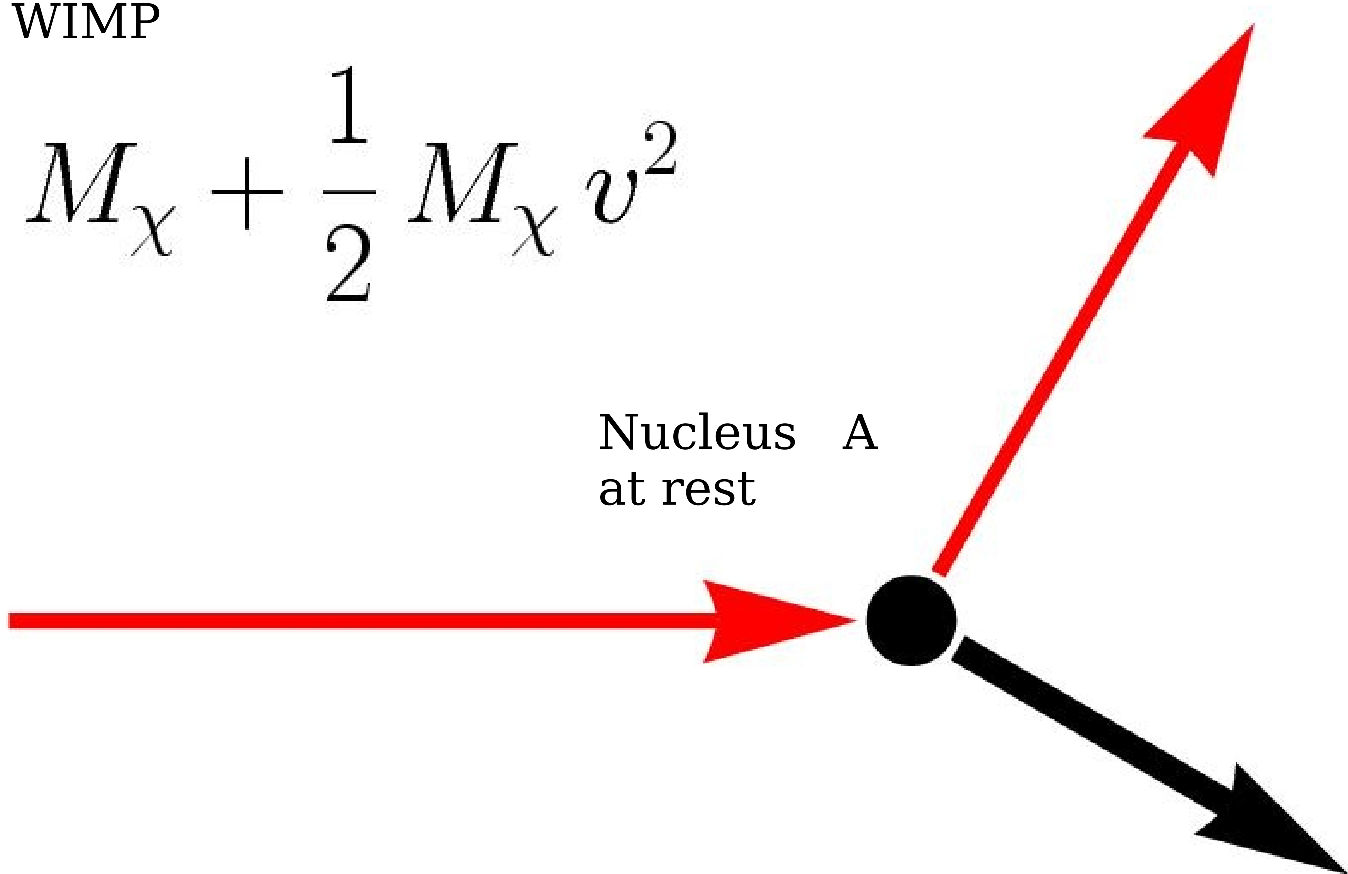
$$\simeq 1000 \left[\frac{100\ \mathrm{GeV}}{m_\chi}\right] \quad (\mathrm{cm}^2\ \mathrm{s})^{-1}$$

"Direct" Search for Dark Matter

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

Non relativistic WIMP

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

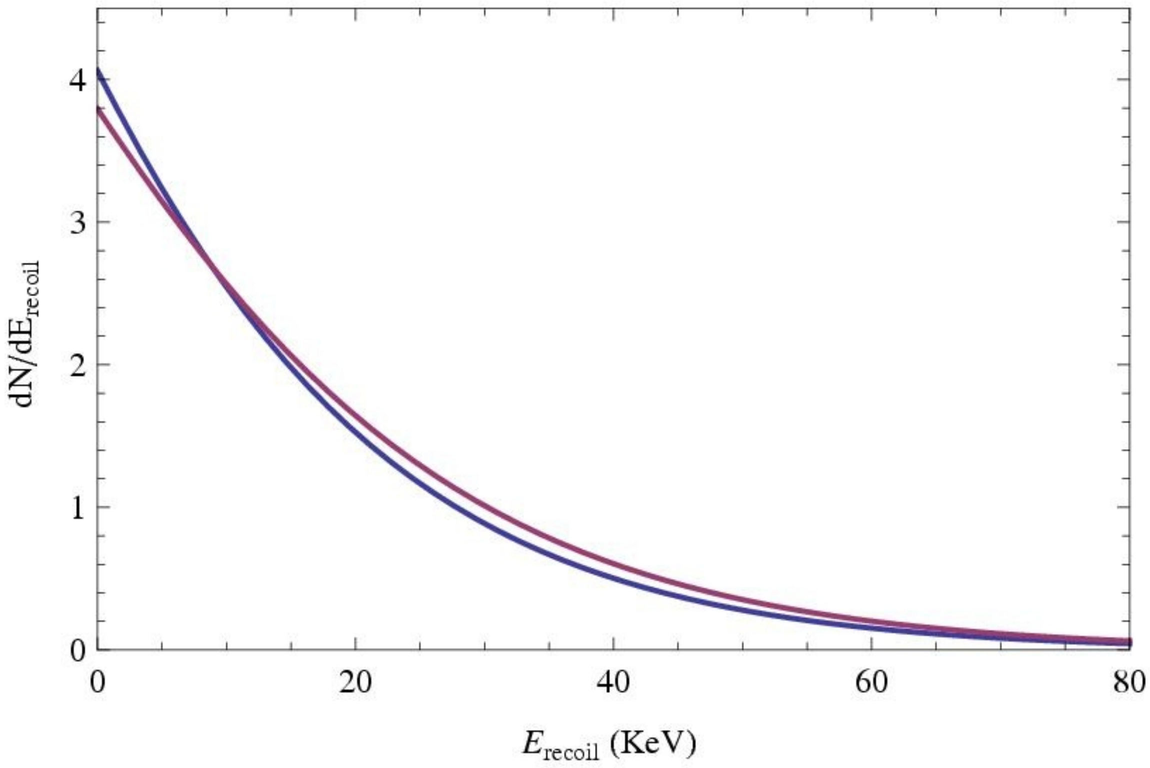


$$E_{\text{nucleus}} = M_A \quad + \quad \left[\frac{1}{2} M_\chi v^2\right] \frac{4 M_A M_\chi}{(M_A + M_\chi)^2} \left(\frac{1 - \cos\theta^*}{2}\right)$$

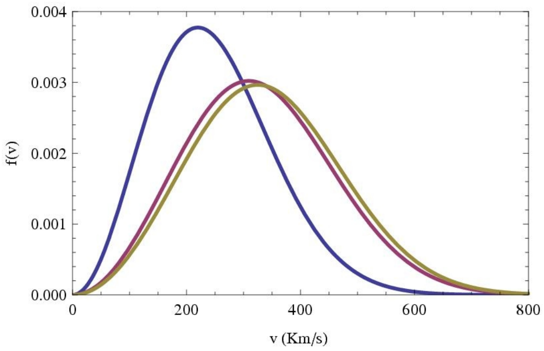
A = 127 (Iodium)
M_{wimp} = 50 GeV

Scattering RATE

Quasi exponential distribution



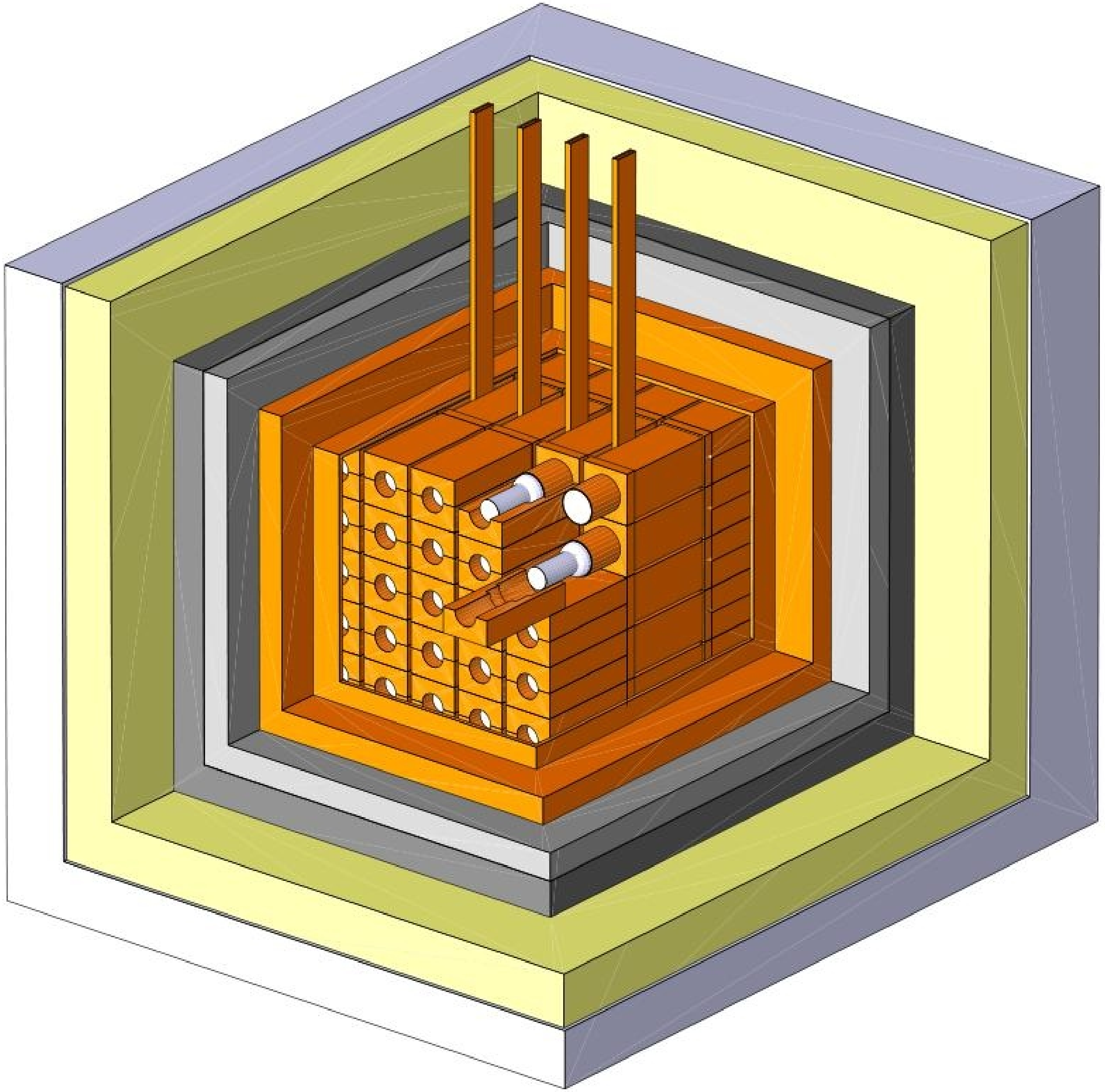
2nd june
2nd december



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

DAMA-LIBRA (Gran Sasso underground Laboratory)

250 Kg NaI scintillator.

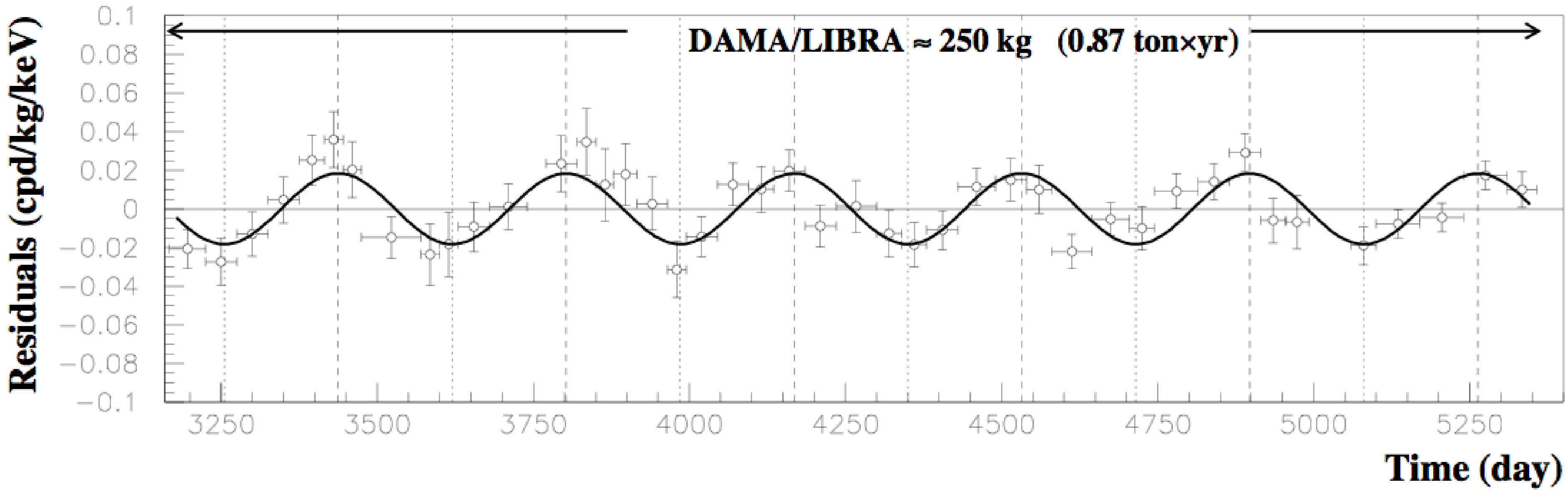


Observation
of sinusoidal
time-modulation of the
Energy Deposition Rate

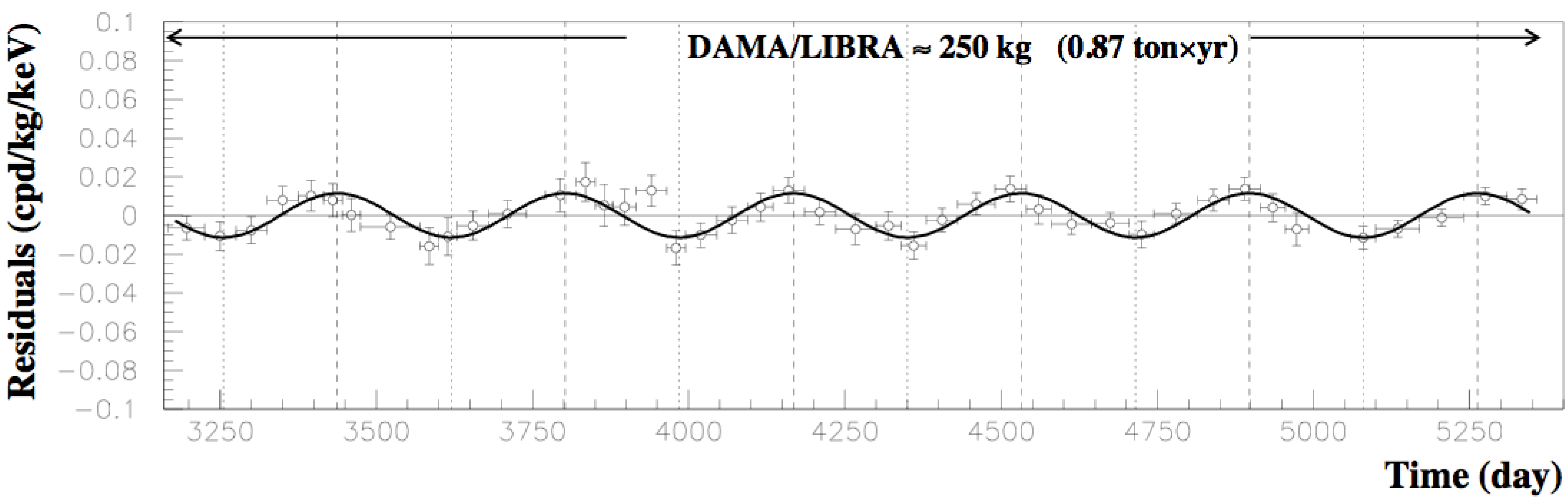
(controversial)
claim of evidence
of detection of
Galactic Dark Matter

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

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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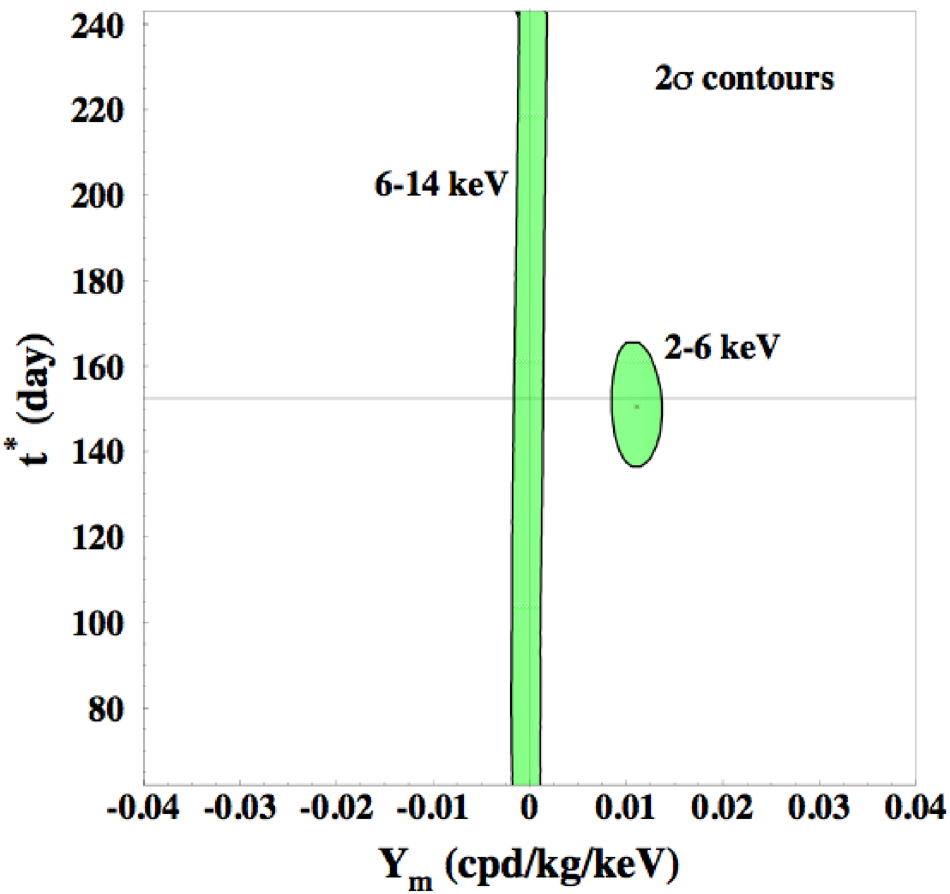
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
3250
3500
3750
4000
4250
4500
4750
5000
5250
Time (day)



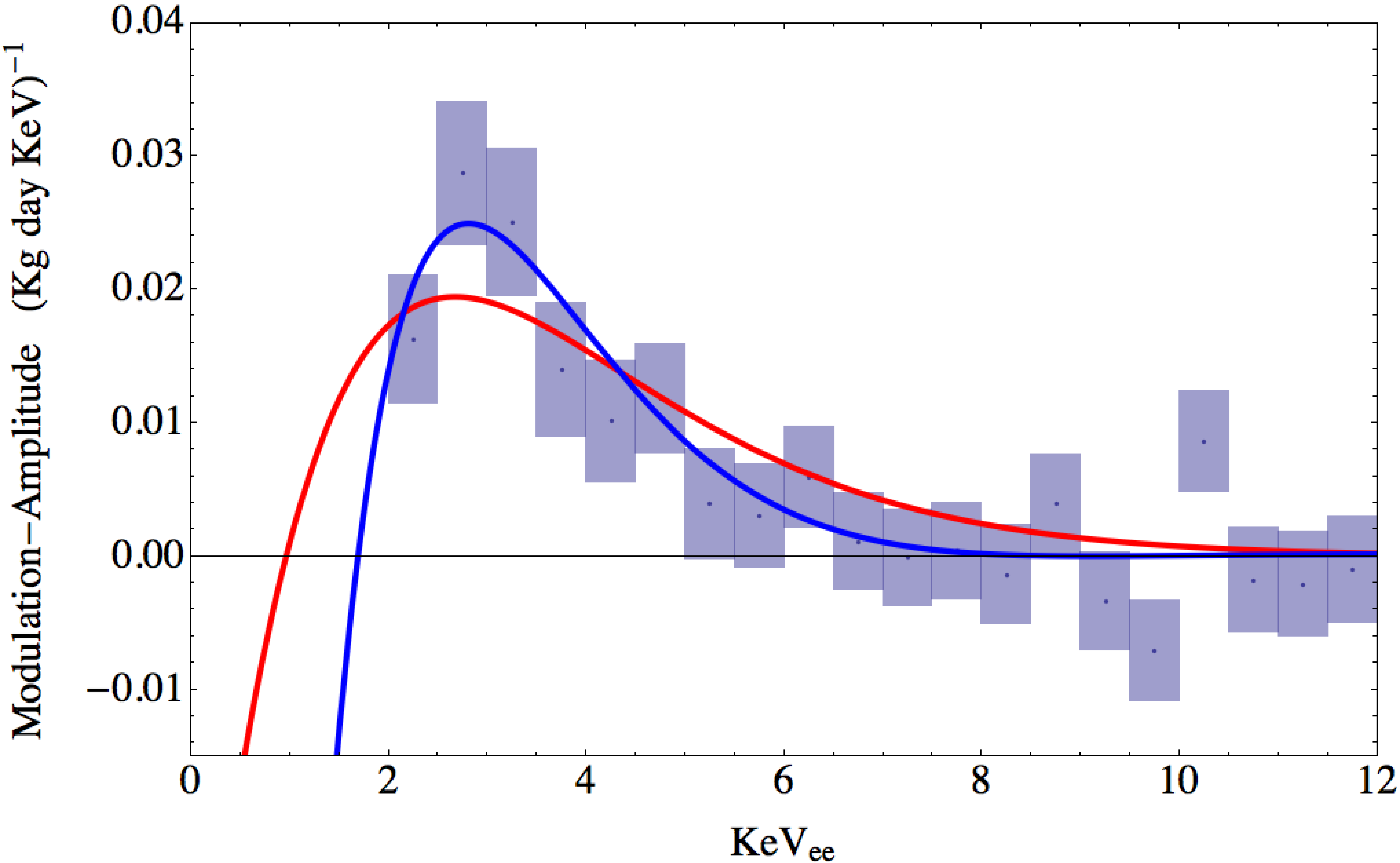
Period one year.
(… well obvious…)

"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
KeV$_{ee}$

0.82 ton yr of exposure of DAMA

First results from DAMA/LIBRA and the combined results with DAMA/NaI

Abstract

The highly radiopure $\simeq$ 250 kg NaI(Tl) DAMA/LIBRA set-up is running at the Gran Sasso National Laboratory of the I.N.F.N.. In this paper the first result obtained by exploiting the model independent annual modulation signature for Dark Matter (DM) particles is presented. It refers to an exposure of 0.53 ton$\times$yr. The collected DAMA/LIBRA data satisfy all the many peculiarities of the DM annual modulation signature. Neither systematic effects nor side reactions can account for the observed modulation amplitude and contemporaneously satisfy all the several requirements of this DM signature. Thus, the presence of Dark Matter particles in the galactic halo is supported also by DAMA/LIBRA and, considering the former DAMA/NaI and the present DAMA/LIBRA data all together (total exposure 0.82 ton$\times$yr), the presence of Dark Matter particles in the galactic halo is supported at 8.2 σ C.L..

1.17 ton yr of exposure of DAMA

Abstract

DAMA/LIBRA is running at the Gran Sasso National Laboratory of the I.N.F.N.. Here the results obtained with a further exposure of 0.34 ton $\times$ yr are presented. They refer to two further annual cycles collected one before and one after the first DAMA/LIBRA upgrade occurred on September/October 2008. The cumulative exposure with those previously released by the former DAMA/NaI and by DAMA/LIBRA is now 1.17 ton $\times$ yr, corresponding to 13 annual cycles. The data further confirm the model independent evidence of the presence of Dark Matter (DM) particles in the galactic halo on the basis of the DM annual modulation signature (8.9 σ C.L. for the cumulative exposure). In particular, with the cumulative exposure the modulation amplitude of the *single-hit* events in the $(2-6)$ keV energy interval measured in NaI(Tl) target is (0.0116 ± 0.0013) cpd/kg/keV; the measured phase is (146 ± 7) days and the measured period is (0.999 ± 0.002) yr, values well in agreement with those expected for the DM particles.

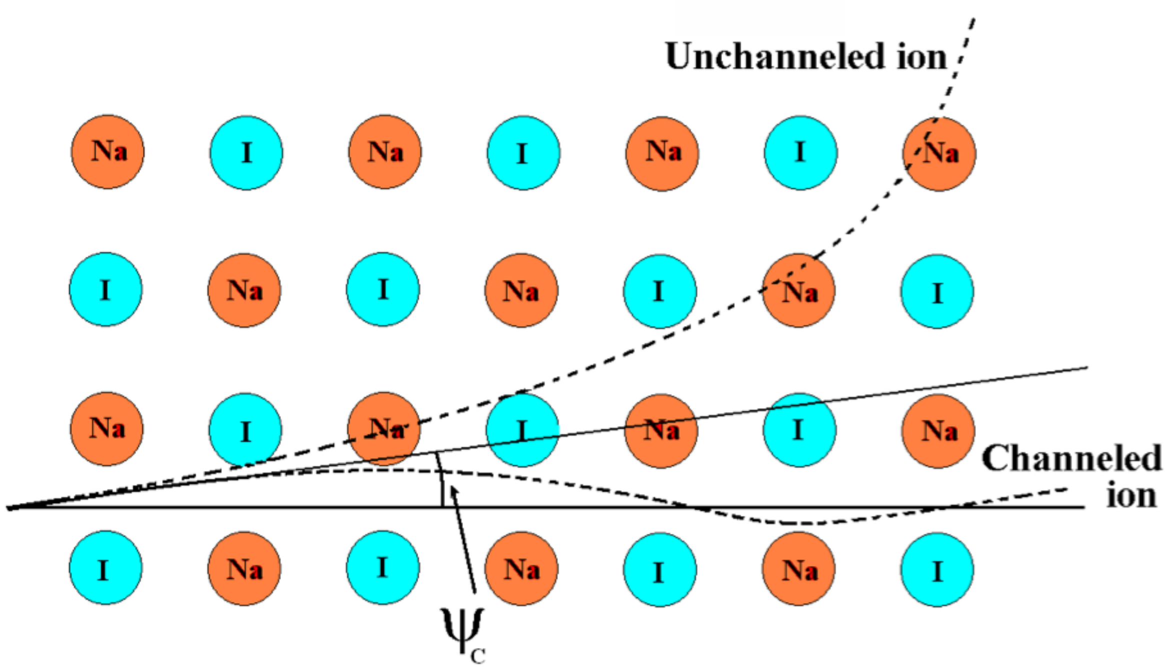
Relation between Light collected by PMT and E_{recoil}

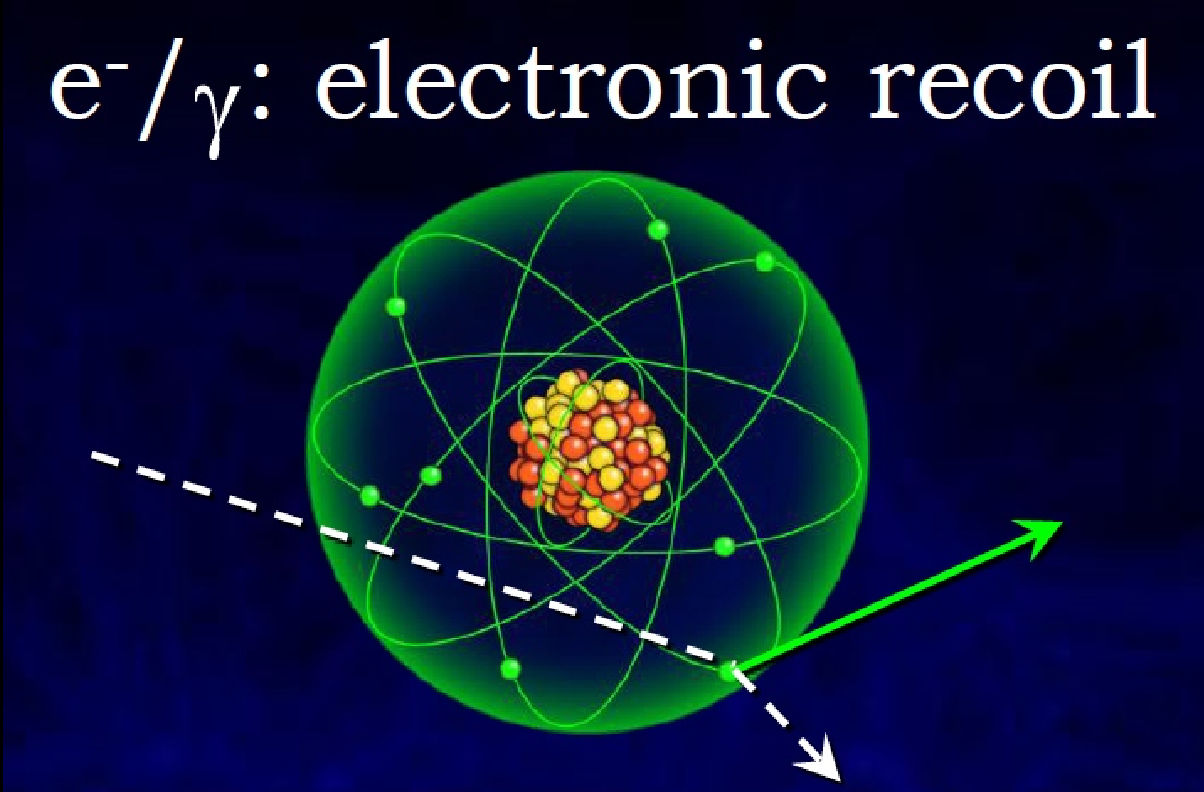
E(recoil) = 11.0 * E(electron-equivalent)

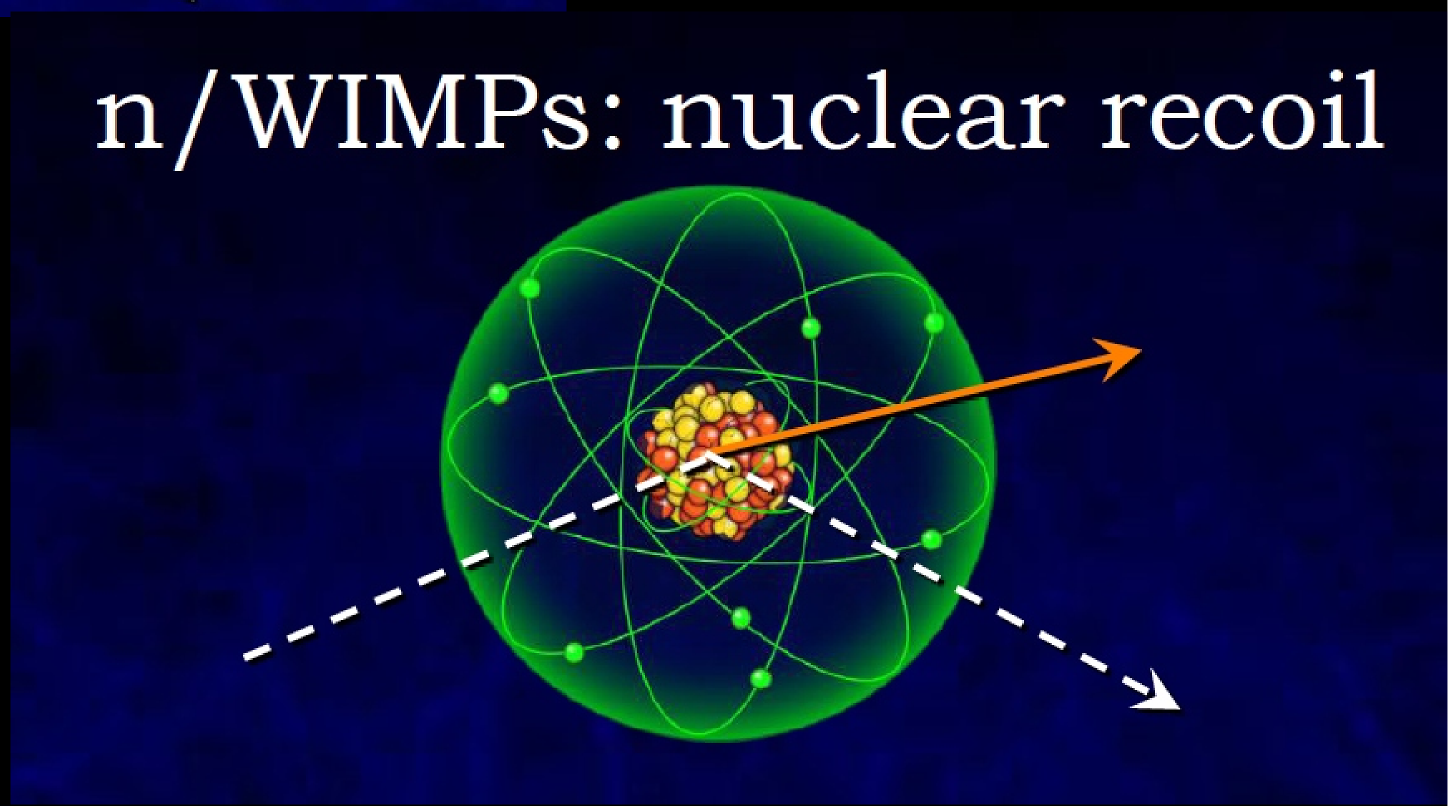
In presence of "channeling"
Scattering in certain directions

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

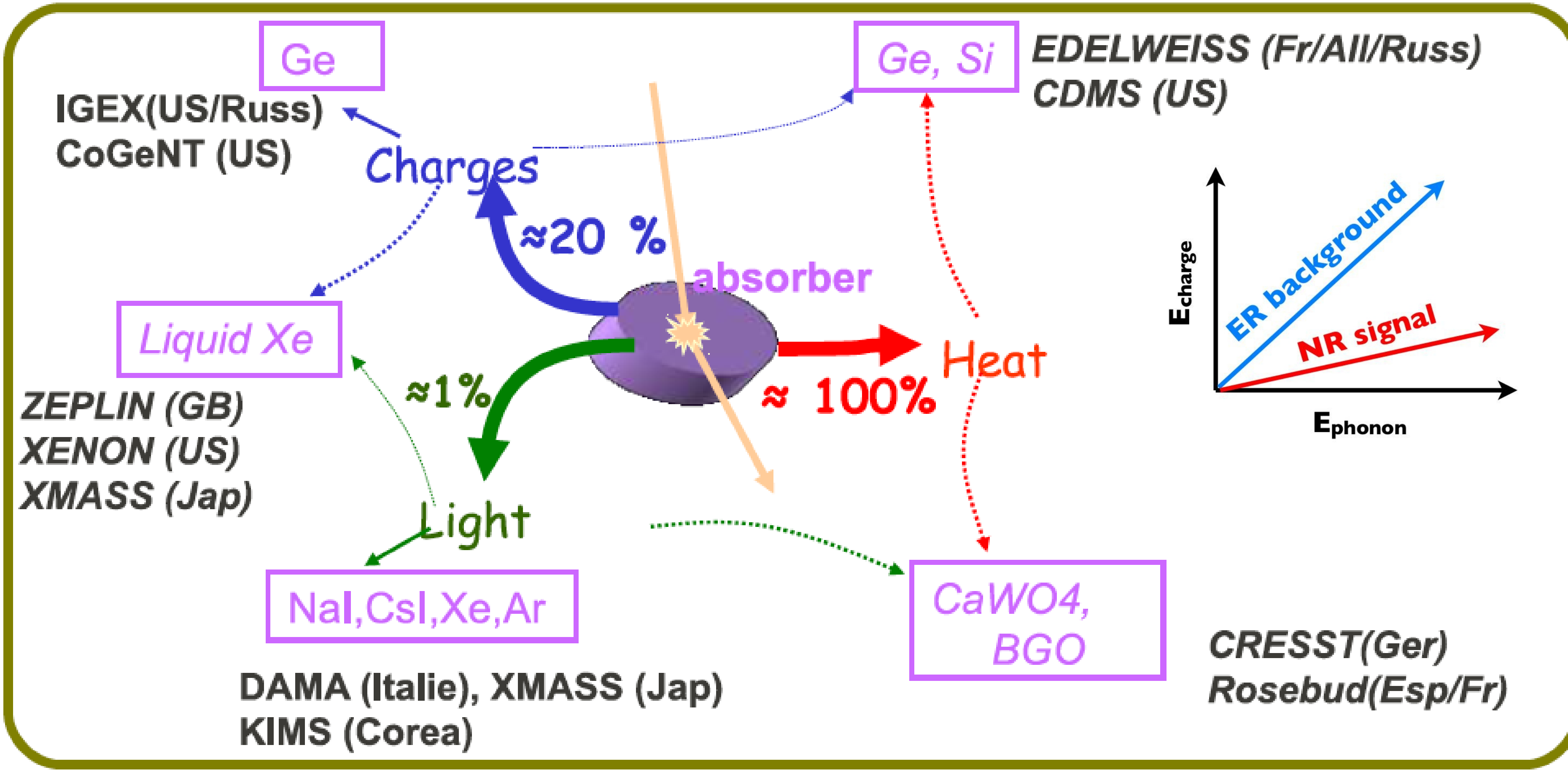
Important
Ambiguity
In the interpretation
Of the energy scale




e^-/γ: electronic recoil


n/WIMPs: nuclear recoil

WIMP detection: HEAT (total energy release)
LIGHT (scintillation)
CHARGE (ionization)



DISCRIMINATION, Quenching Factor

2 “POSITIVE HINTS”

COGENT
CRESST

1 NEGATIVE Result

XENON

Phys. Rev. Lett. 106, 131301 (2011) [4 pages]

COGENT collaboration

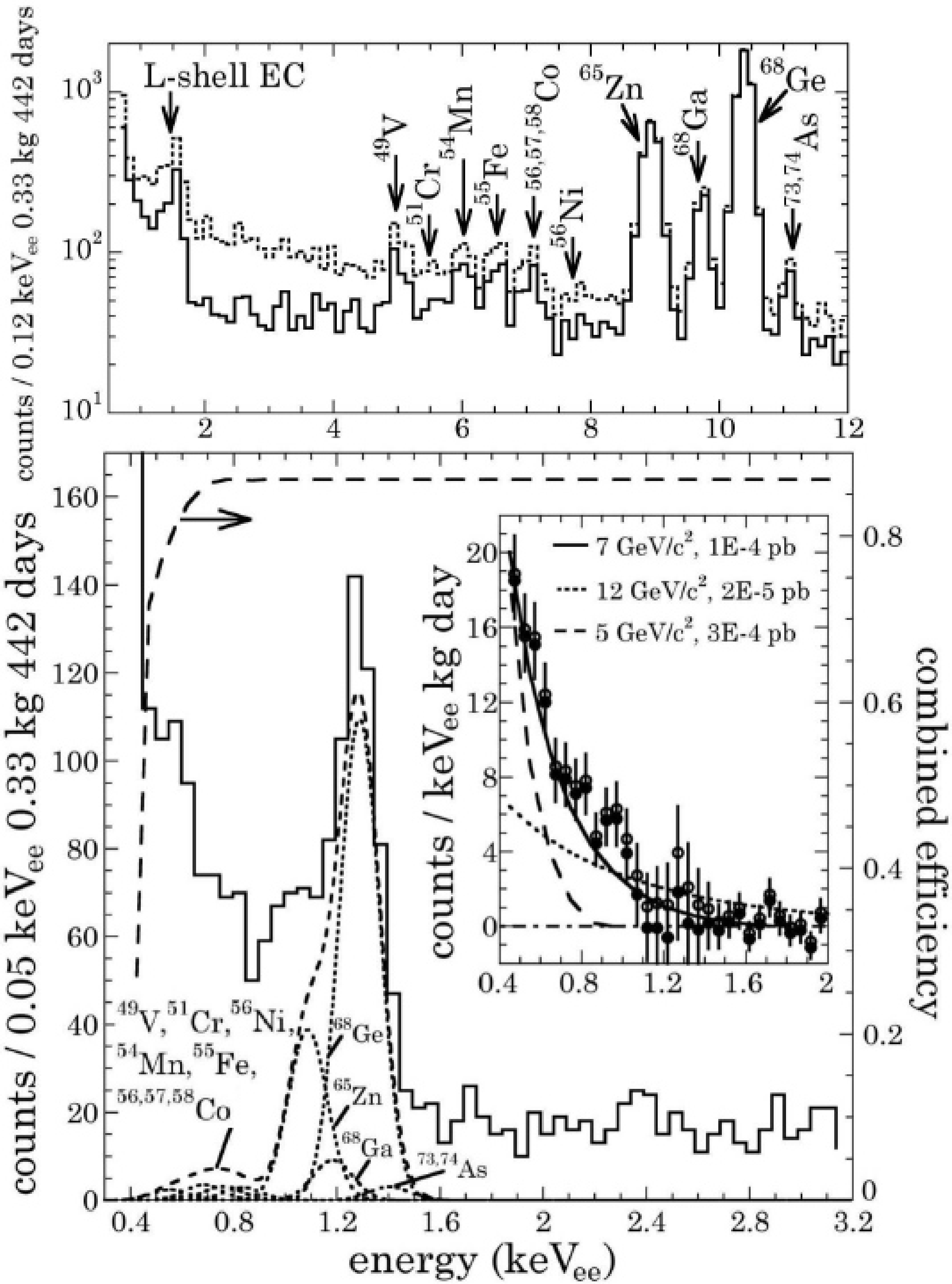
Results from a Search for Light-Mass Dark Matter with a *p*-Type Point Contact Germanium Detector

We report on several features in the energy spectrum from an ultralow-noise germanium detector operated deep underground. By implementing a new technique able to reject surface events, a number of cosmogenic peaks can be observed for the first time. We discuss an irreducible excess of bulklike events below 3 keV in ionization energy. These could be caused by unknown backgrounds, but also dark matter interactions consistent with DAMA/LIBRA. It is not yet possible to determine their origin. Improved constraints are placed on a cosmological origin for the DAMA/LIBRA effect.

Phys. Rev. Lett. 107, 141301 (2011) [5 pages]

Search for an Annual Modulation in a *p*-Type Point Contact Germanium Dark Matter Detector

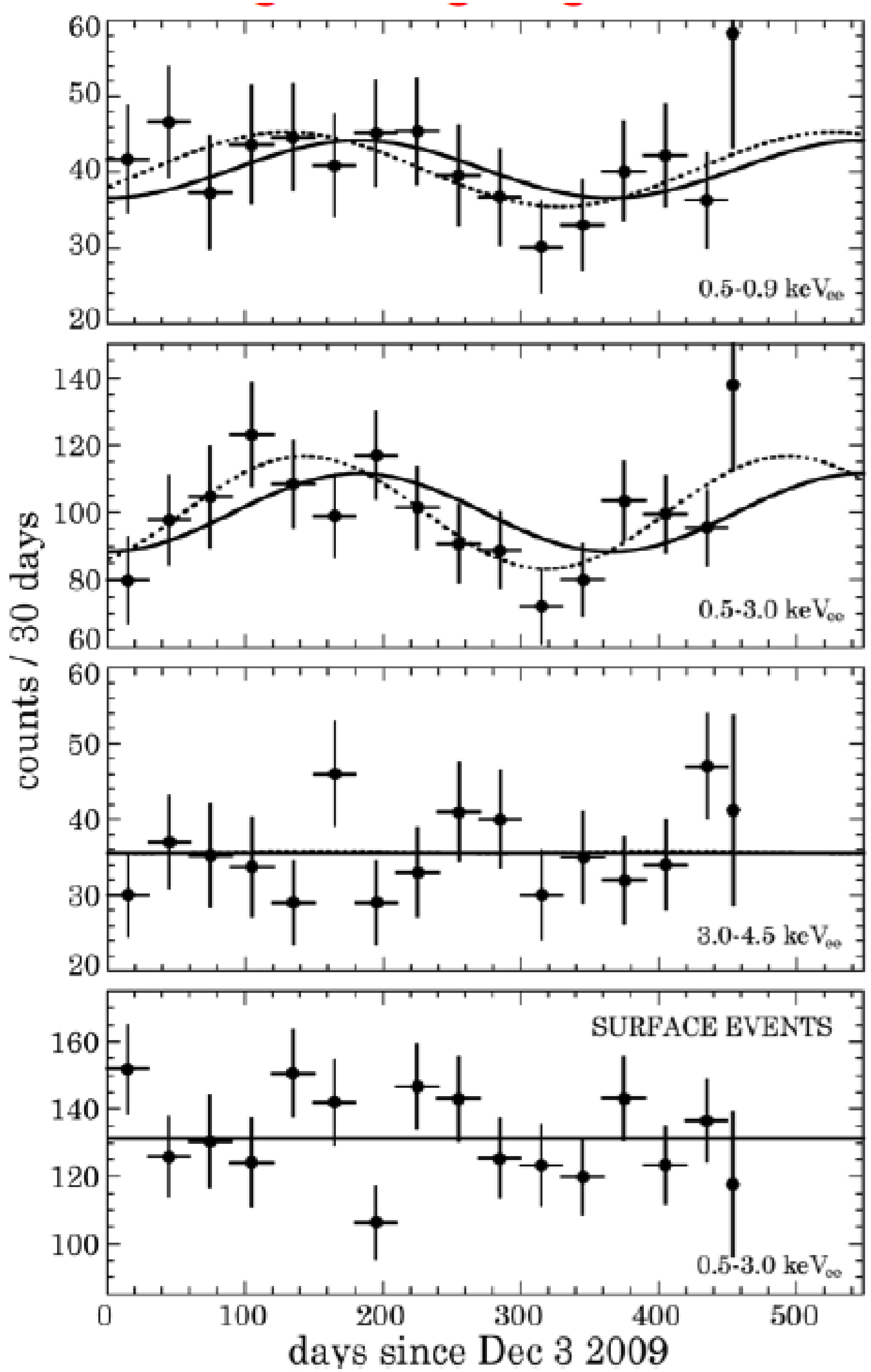
Fifteen months of cumulative CoGeNT data are examined for indications of an annual modulation, a predicted signature of weakly interacting massive particle (WIMP) interactions. Presently available data support the presence of a modulated component of unknown origin, with parameters *prima facie* compatible with a galactic halo composed of light-mass WIMPs. Unoptimized estimators yield a statistical significance for a modulation of ~2.8σ, limited by the short exposure.



COGENT
Energy spectrum

Evidence for
Dark Matter ??

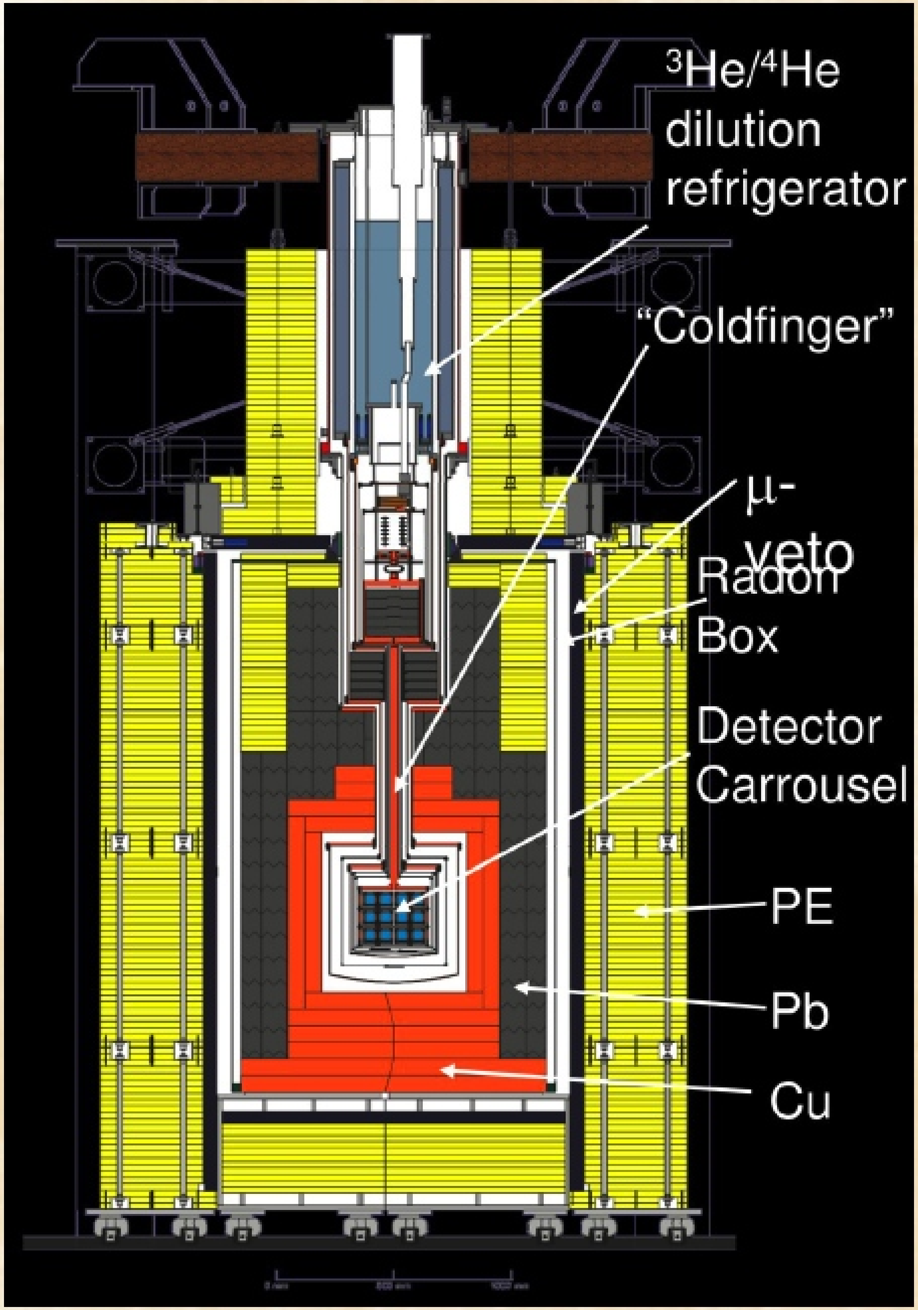
(No parameters)

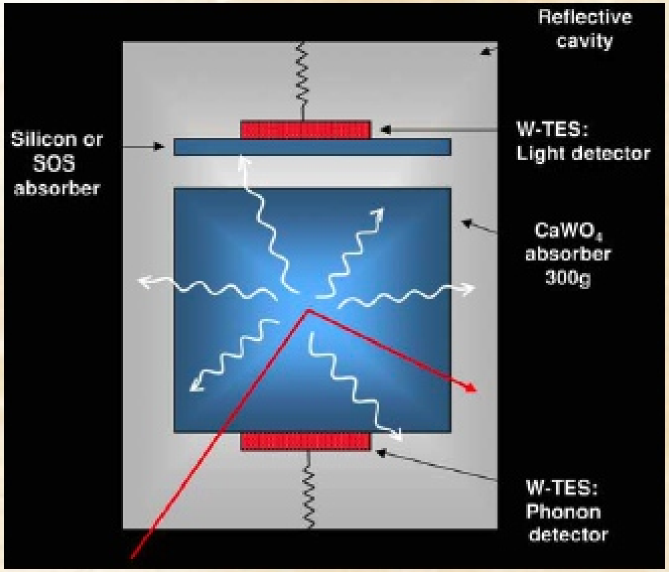


- No fancy estimators tried (several available). Two basic unoptimized methods point at ~2.8σ preference of a modulated rate over the null hypothesis.
- Compatible with WIMP hypothesis expectations (amplitude, phase, period).
- Spectral and temporal analysis are *prima facie* congruent with a light-WIMP hypothesis.
- Modulation absent for surface events and also at higher energies.
- Lots of independent interpretations via data-sharing, but a few are forgetting some basics. Hint: there must be reasons for the experimentalists to always include an exponential background in their models...

2.8 sigmas
Modulation effect

CRESST detector (Gran Sasso): Phonons + Light



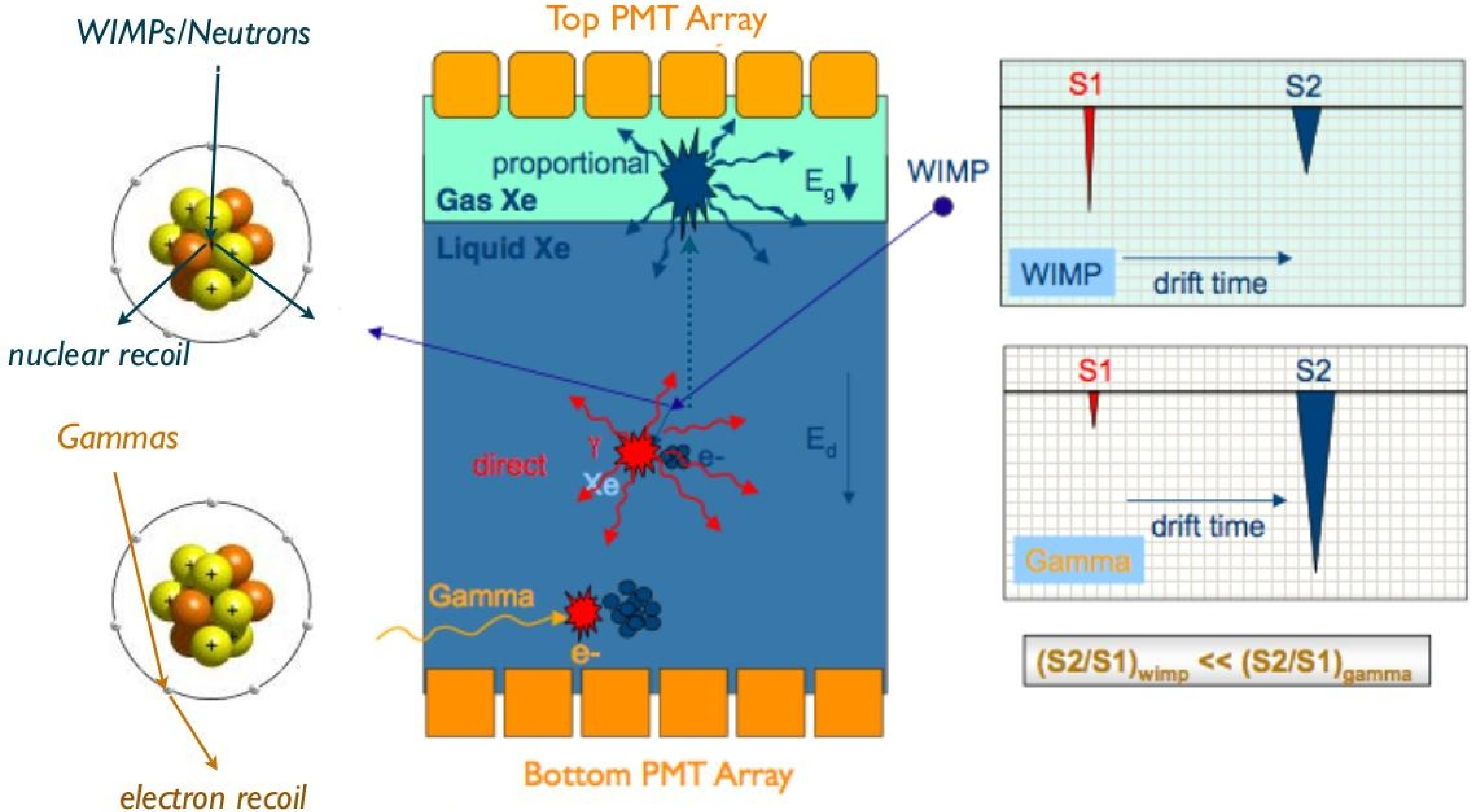


CRESST (submitted for publication)
730 Kg/day

Results from 730 kg days of the CRESST-II Dark Matter Search

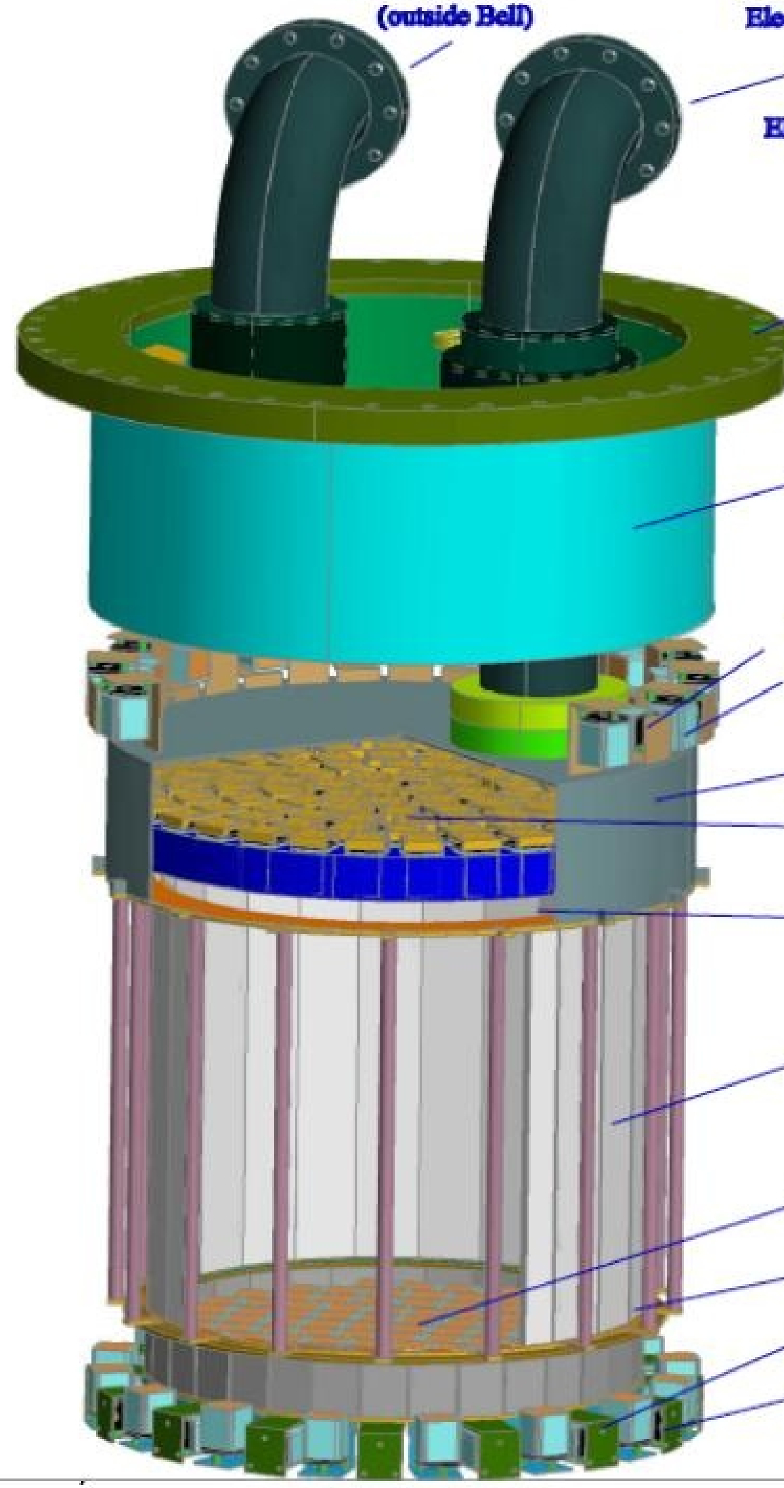
Abstract. The CRESST-II cryogenic Dark Matter search, aiming at detection of WIMPs via elastic scattering off nuclei in $CaWO_4$ crystals, completed 730 kg days of data taking in 2011. We present the data collected with eight detector modules, each with a two-channel readout; one for a phonon signal and the other for coincidently produced scintillation light. The former provides a precise measure of the energy deposited by an interaction, and the ratio of scintillation light to deposited energy can be used to discriminate different types of interacting particles and thus to distinguish possible signal events from the dominant backgrounds.
Sixty-seven events are found in the acceptance region where a WIMP signal in the form of low energy nuclear recoils would be expected. We estimate background contributions to this observation from four sources: 1) “leakage” from the e/γ-band 2) “leakage” from the α-particle band 3) neutrons and 4) ^{206}Pb recoils from ^{210}Po decay. Using a maximum likelihood analysis, we find, at a high statistical significance, that these sources alone are not sufficient to explain the data. The addition of a signal due to scattering of relatively light WIMPs could account for this discrepancy, and we determine the associated WIMP parameters.

The XENON two-phase TPC



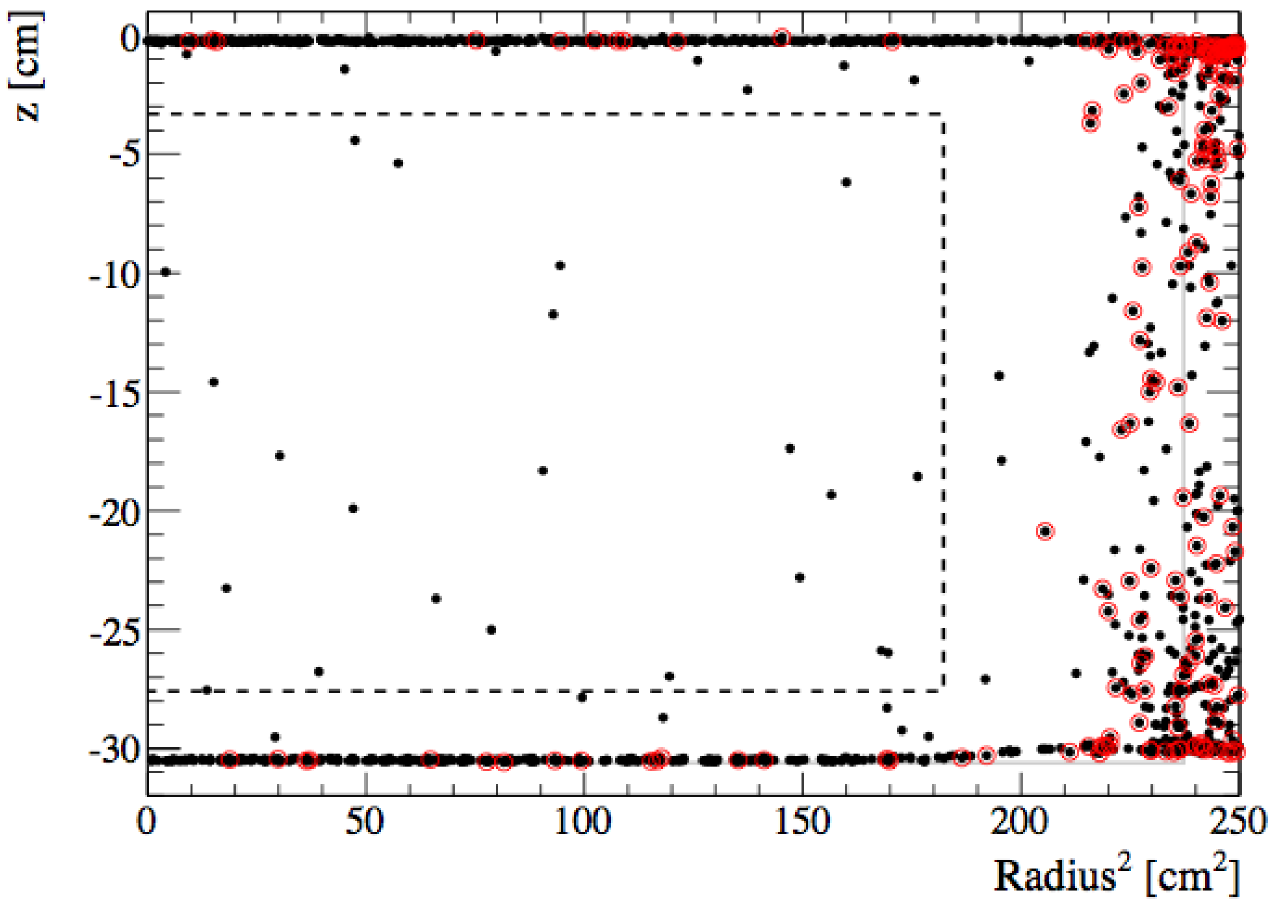
- Single electron and single photon measurement sensitivity
- > 99.5% ER rejection via Ionization/Scintillation ratio (S2/S1)

XENON100: The TPC Assembly



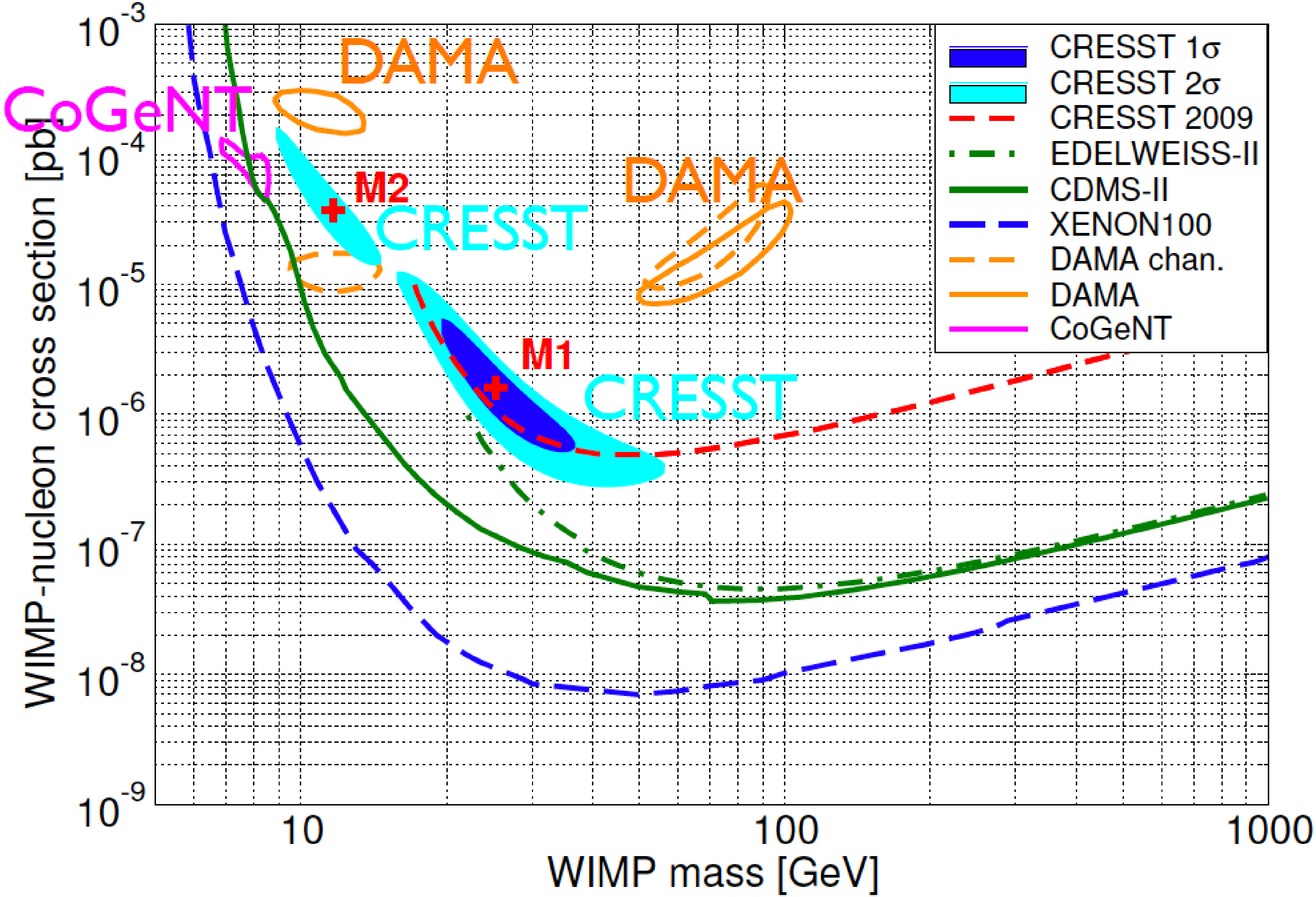
Xenon-100 (liters) results

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

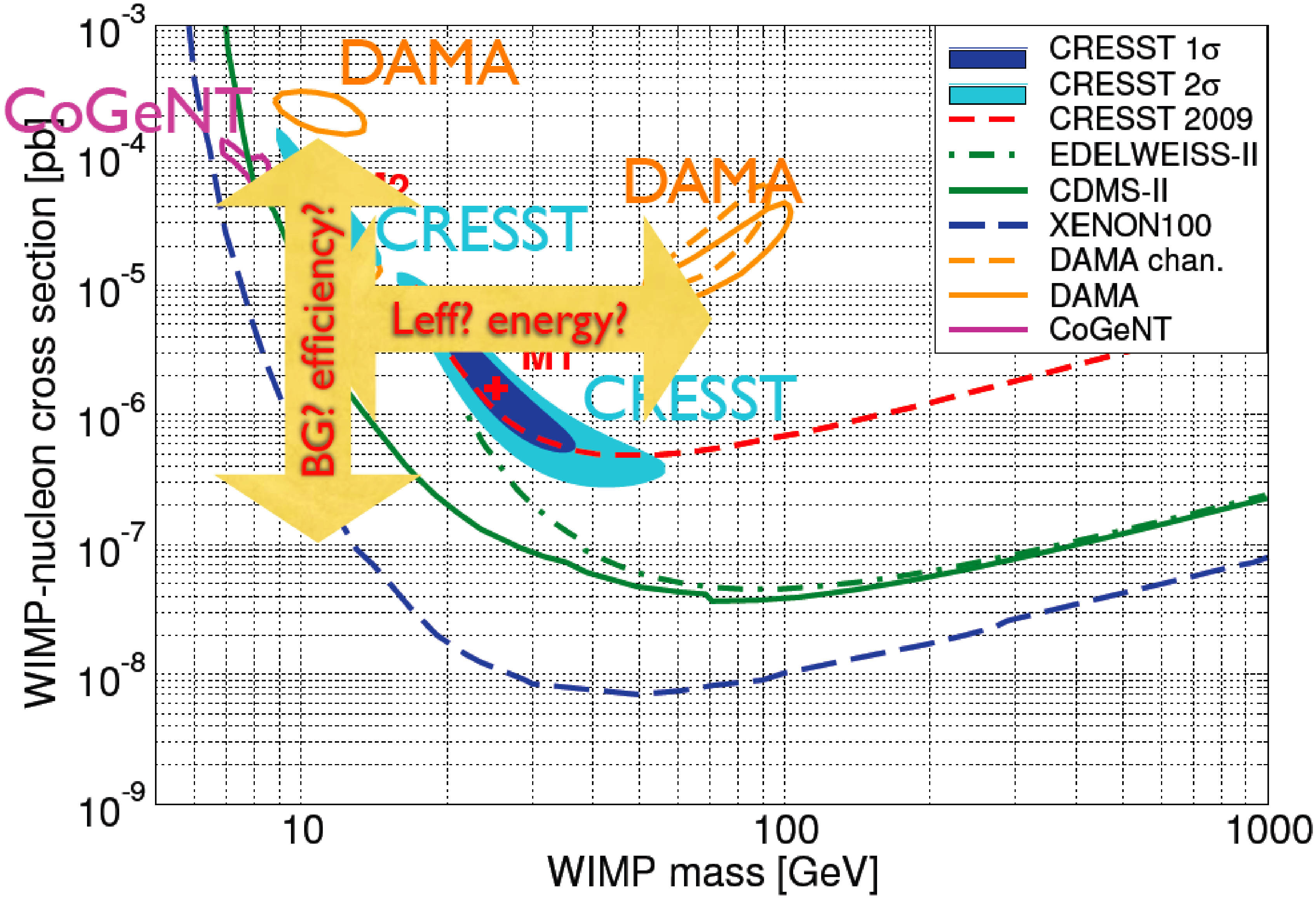


Intense controversy around these results and their interpretation.

How can they be reconciled ?



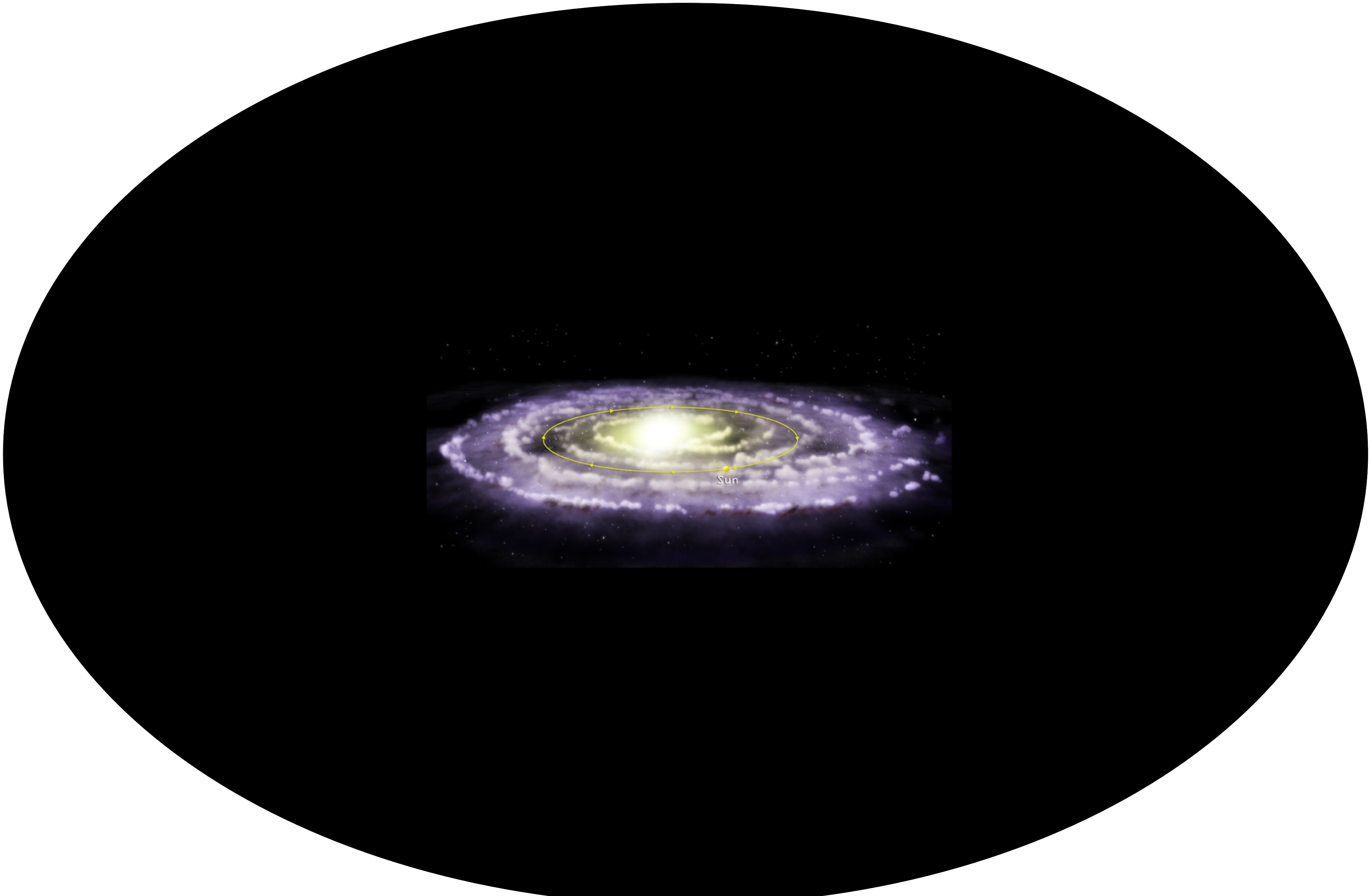
DAMA
CoGeNT
M2
CRESST
DAMA
M1
CRESST
CRESST 1σ
CRESST 2σ
CRESST 2009
EDELWEISS-II
CDMS-II
XENON100
DAMA chan.
DAMA
CoGeNT
WIMP-nucleon cross section [pb]
WIMP mass [GeV]
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10
100
1000



WIMP-nucleon cross section [pb]
WIMP mass [GeV]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10
100
1000
CRESST 1σ
CRESST 2σ
CRESST 2009
EDELWEISS-II
CDMS-II
XENON100
DAMA chan.
DAMA
CoGeNT
DAMA
CoGeNT
DAMA
CRESST
CRESST
BG? efficiency?
Leff? energy?

Indirect searches for DARK MATTER

3rd Road
To WIMP's Discovery



Power injection for Dark Matter annihilation

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

$$\chi + \chi \to \gamma \quad e^+ \quad \bar{p} \quad \nu_\alpha$$

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

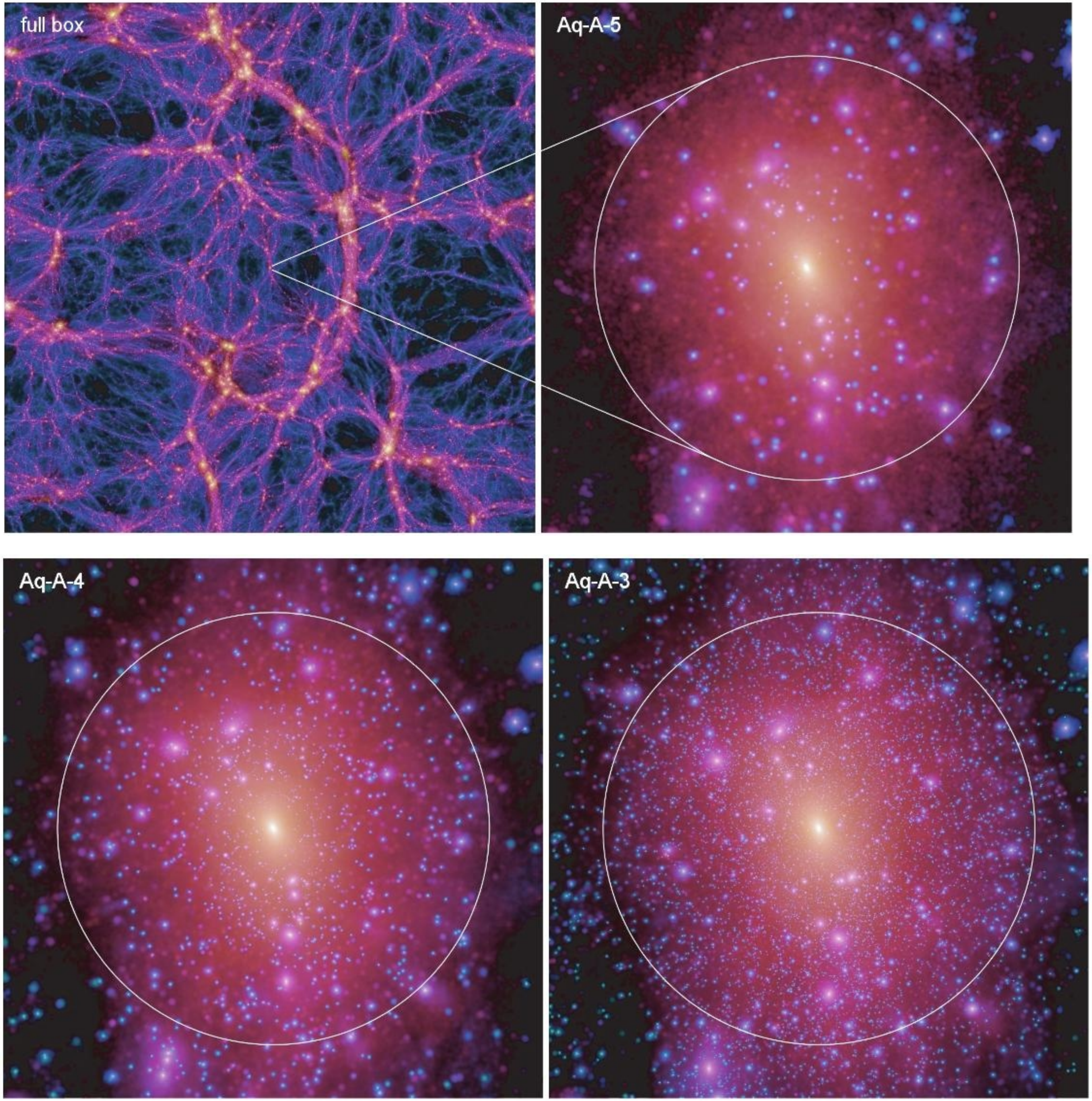
$$f_{\rm dm}(\vec{v}, \vec{x})$$

Velocity distribution

[consistency requirement]

Problems:

- "The CUSP" $\langle \rho(\vec{x})^2 \rangle \geq \langle \rho(\vec{x}) \rangle^2$
- "Granularity" [“the BOOST factor”]


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

Annihilation cross section

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

In most models
DM particle =
Majorana particle

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

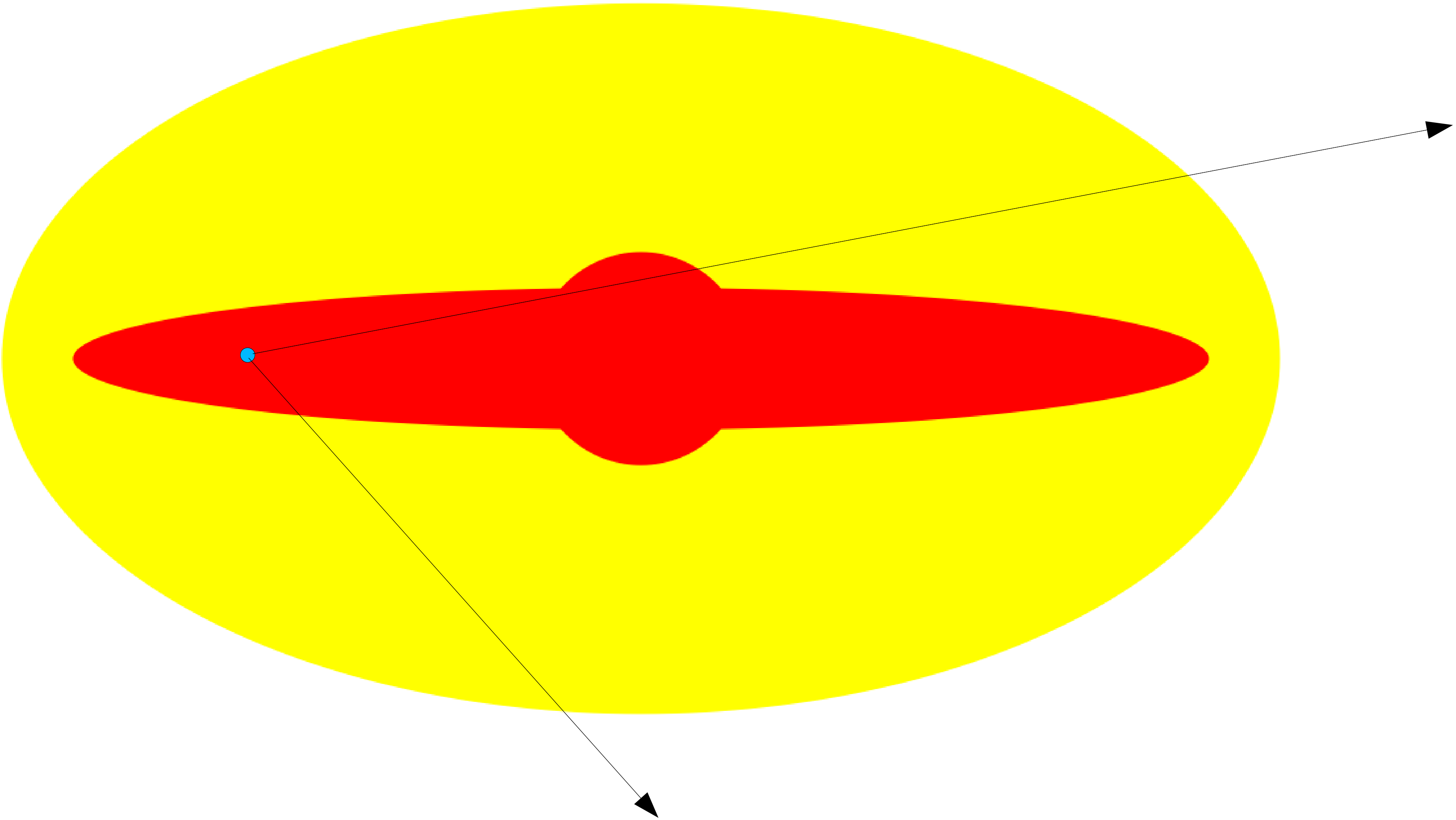
$$\left.\frac{dn}{dE}\right|_{(\chi+\chi\to\gamma,e^+,\overline{p},\nu_\alpha)}$$

Inclusive
spectra

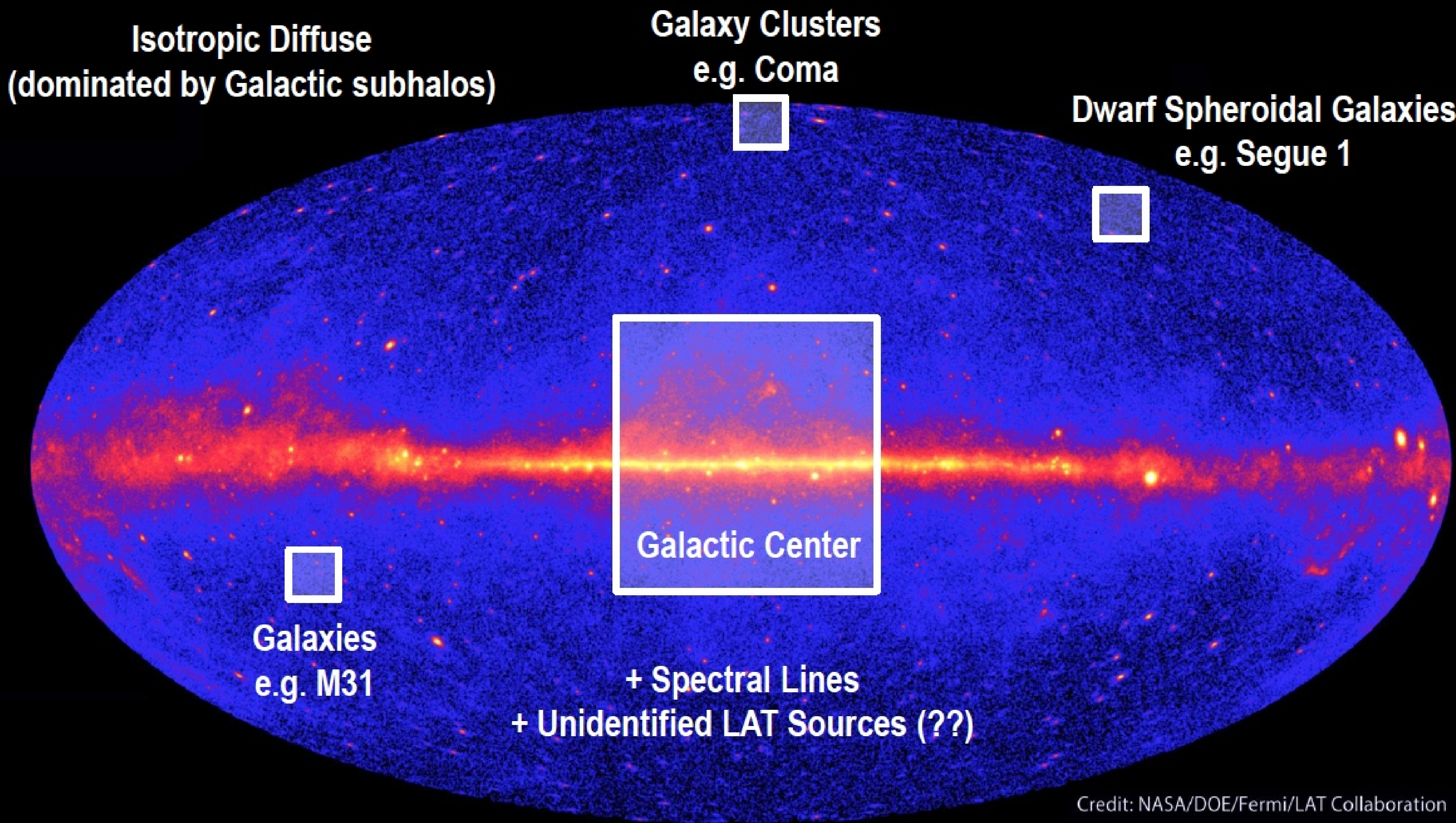
$$B(\chi + \overline{\chi} \to F)$$

Branching Ratios
in different final states F

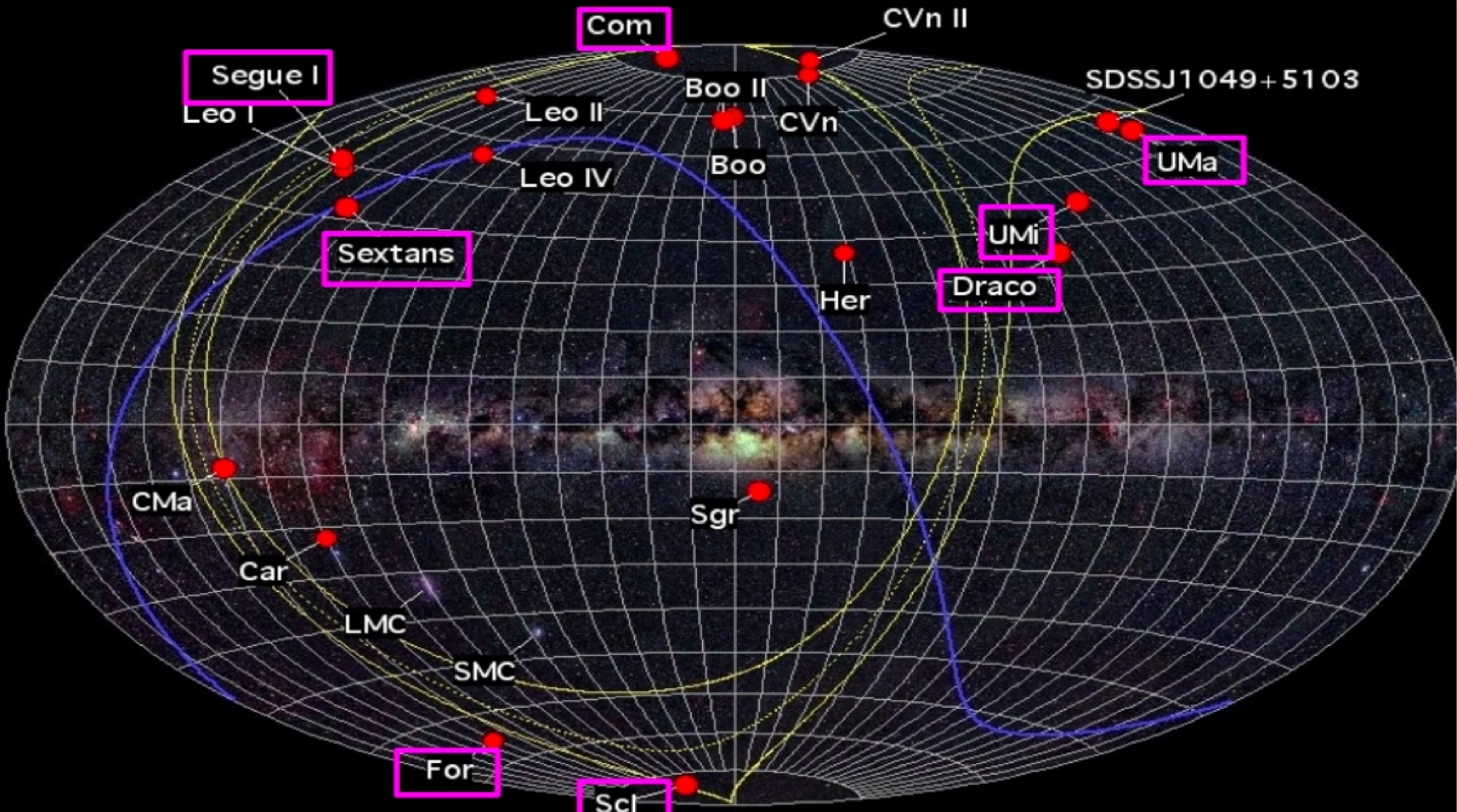
Photon emission from DM annihilation



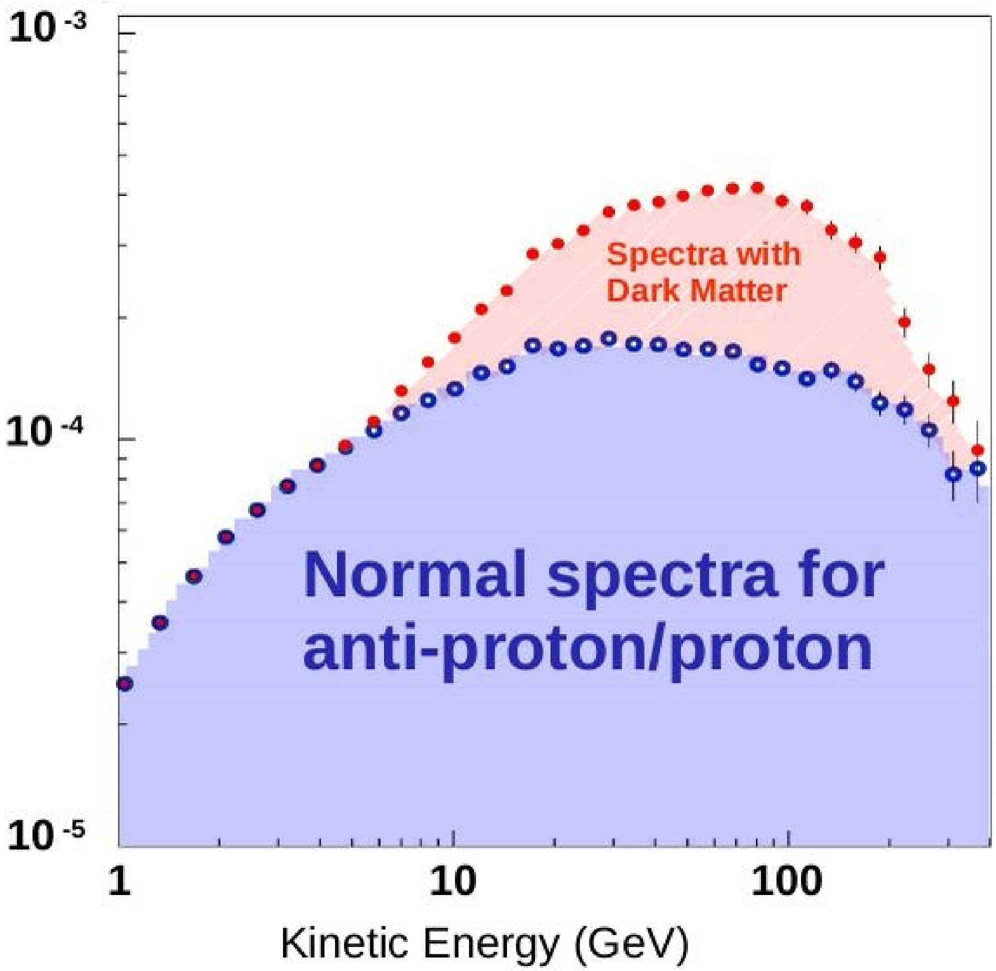
$$\phi_\gamma(E_\gamma,\Omega) = \frac{\langle \sigma v \rangle}{2\, m_\chi^2} \left(\int d\ell\, \rho^2(\ell,\Omega) \right) \left. \frac{dN_\gamma}{dE_\gamma} \right|_{\chi\chi\to\gamma}$$

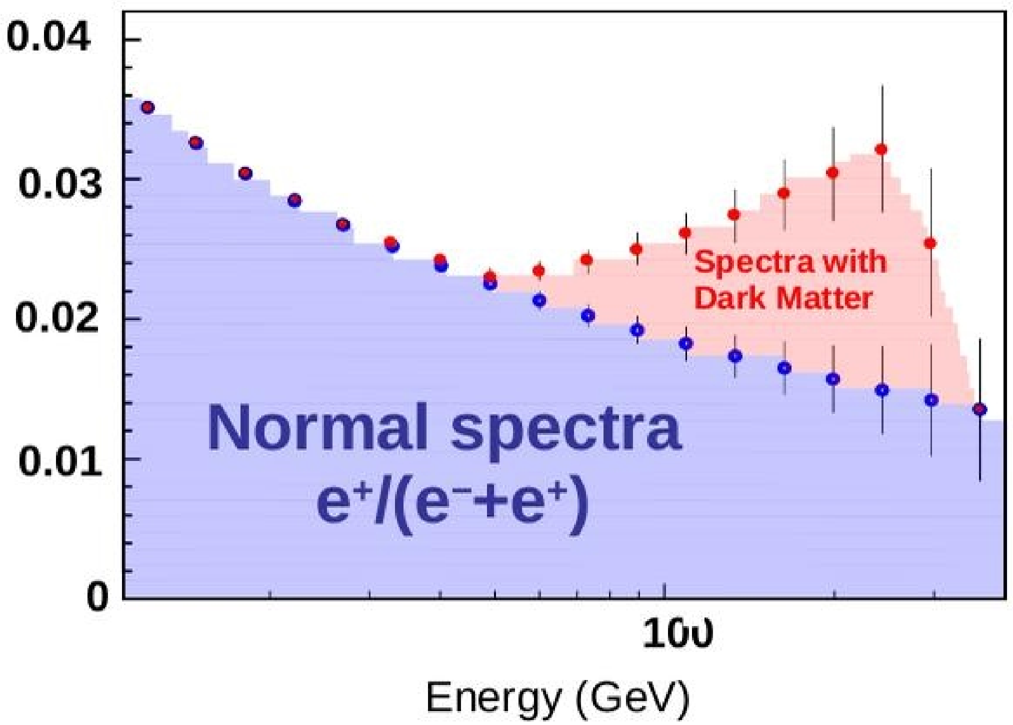


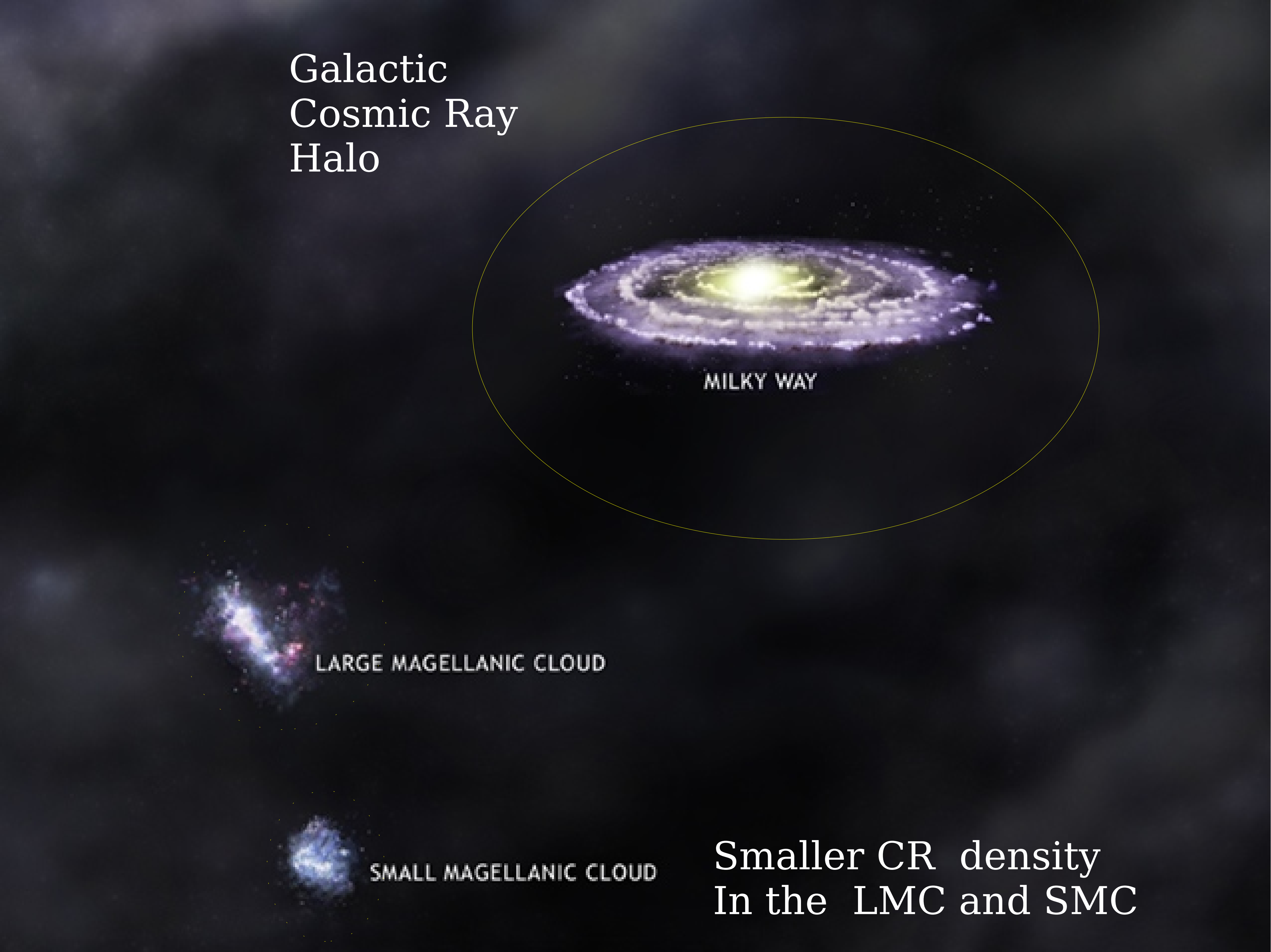
Trade-off between signal strength versus astrophysical background


Com
CVn II
Segue I
SDSSJ1049+5103
Leo II
Boo II
Leo I
CVn
UMa
Boo
Leo IV
UMi
Sextans
Draco
Her
CMa
Sgr
Car
LMC
SMC
For
Scl

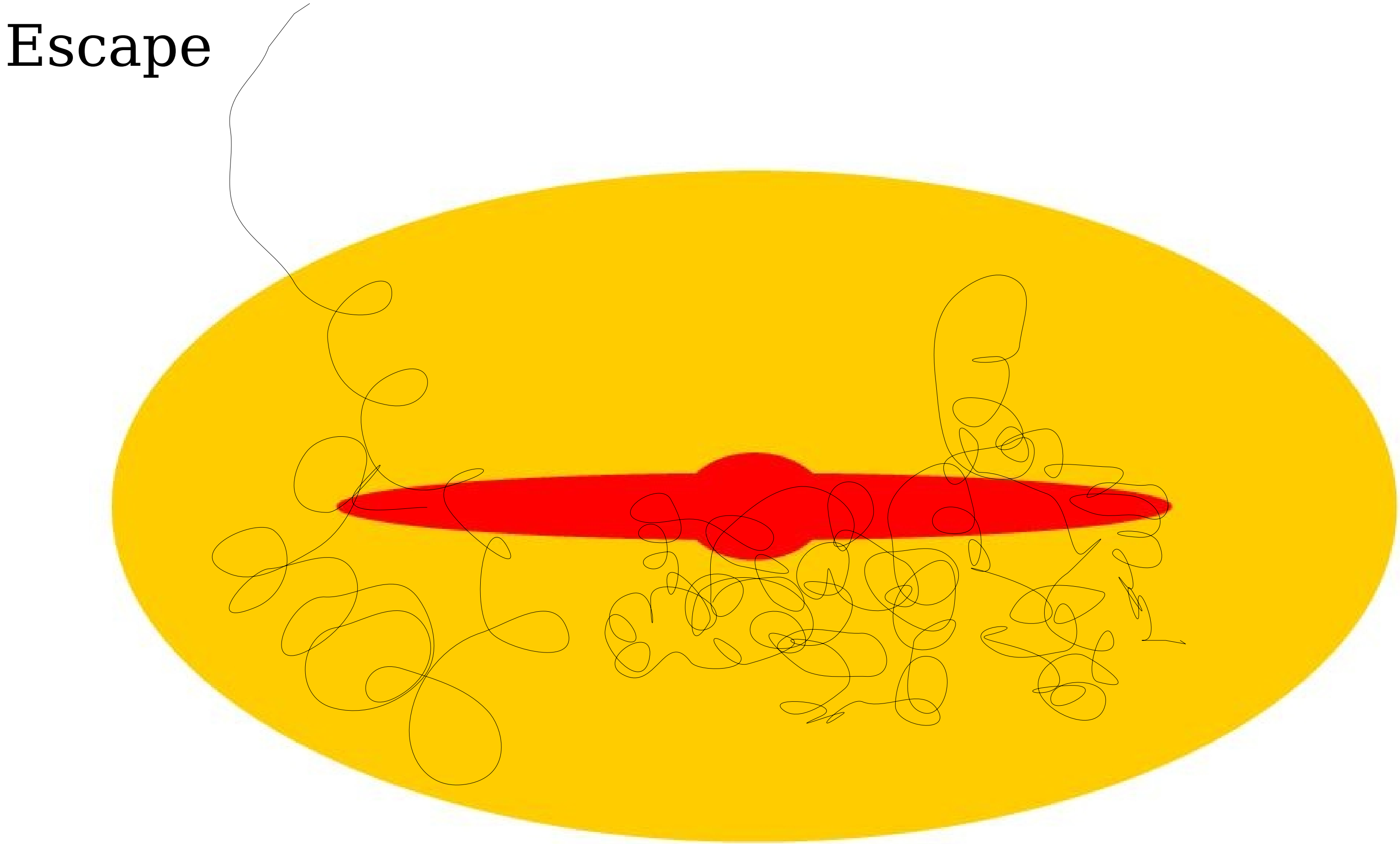
Antiprotons/Positrons from DM annihilation

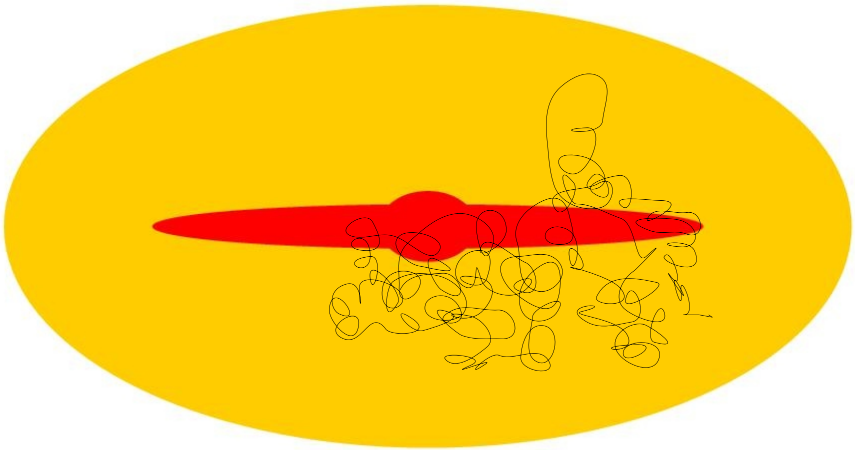





Galactic
Cosmic Ray
Halo
MILKY WAY
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD
Smaller CR density
In the LMC and SMC

Charged Particles: magnetic confinement





SOURCE(s) + Propagation → Observable Cosmic Rays

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

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

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

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

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

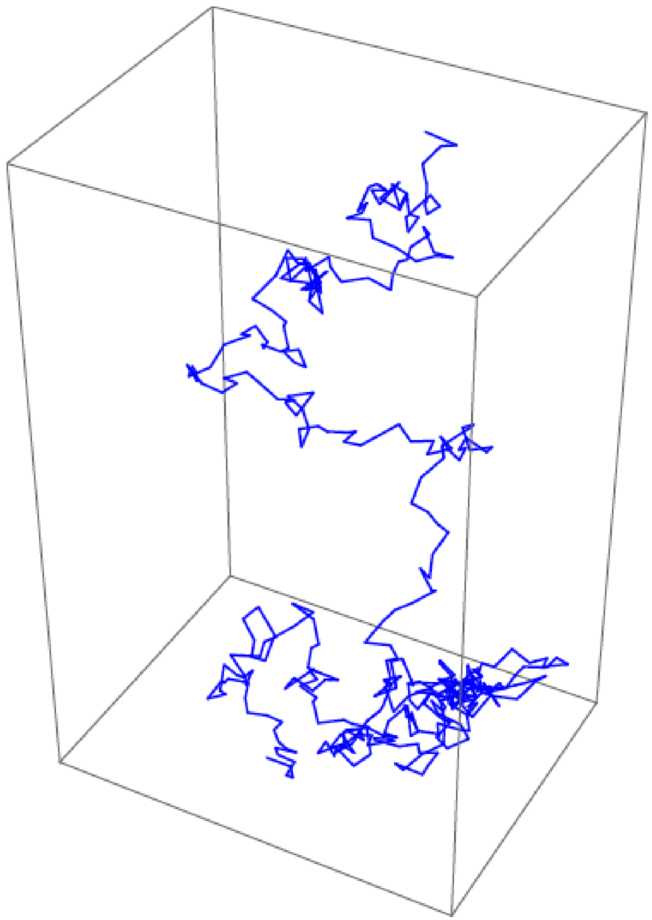
Possible
positron accelerators

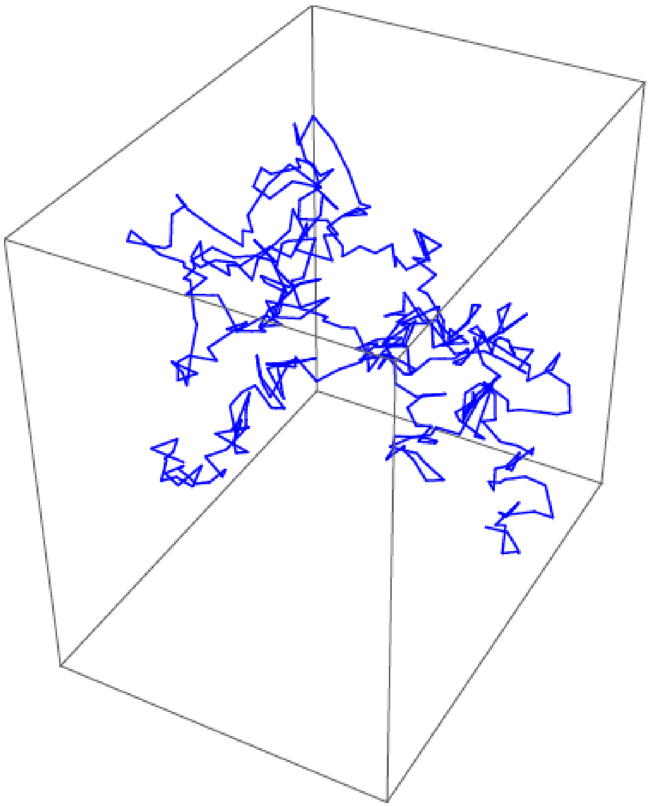
Diffusion

Random walk

Particle with velocity v
Steps and isotropic scattering

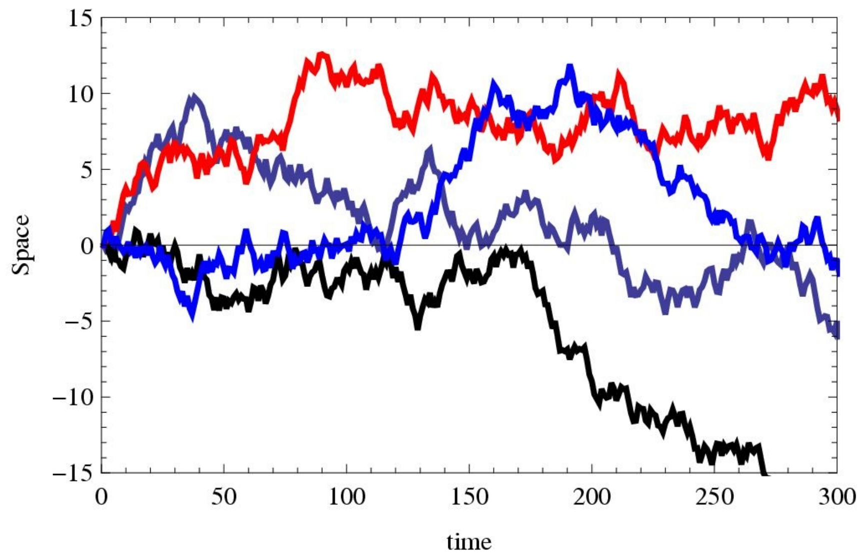
$$\vec{r}_j = \vec{r}_{j-1} + \ell_j \, \hat{n}_j$$

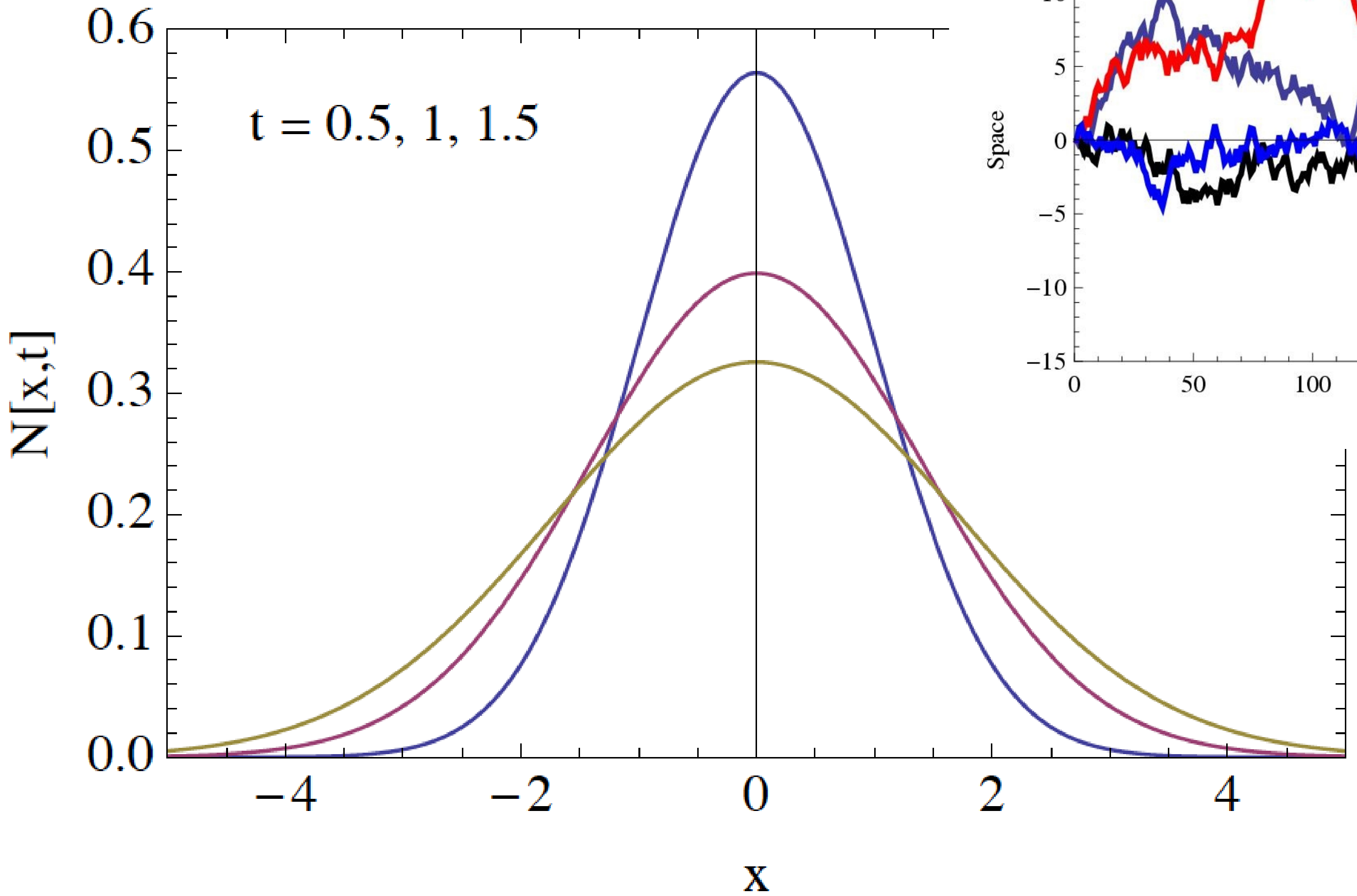




Ensemble of particles
starting from the same point
at time t=0

Spatial distribution at time t





$$n(\vec{r}, t) = \frac{1}{(4\pi\, D\, t)^{3/2}}\ \exp\left[-\frac{r^2}{4\, D\, t}\right]$$

Ensemble of particles
starting from the same point
at time t=0

Spatial distribution at time t

$$n(\vec{r},t) = \frac{1}{(4\pi\, D\, t)^{3/2}}\ \exp\left[-\frac{r^2}{4\, D\, t}\right]$$

$$\langle r^2(t)\rangle = 2\, D\, t$$

Gaussian of width
Increasing as sqrt[t]

Diffusion coefficient:

$$D = \frac{1}{6}\ \langle \ell \rangle\ v$$

Diffusion coefficient depends on the Rigidity of the particle

$$\text{Rigidity} = \frac{P}{q} = \frac{P}{Ze}$$

One example of an estimate of the Diffusion Coefficient For cosmic rays in the Milky Way

$$D(E) \simeq 0.059 \left(\frac{P/q}{\text{GV}}\right)^{0.6} \frac{\text{Kpc}^2}{\text{Myr}}$$

Absolute scale:
in principle POSITION dependent

+ Likely diffusion is not ISOTROPIC
But is a TENSOR
[propagation parallel and transverse to the regular field are very likely different.

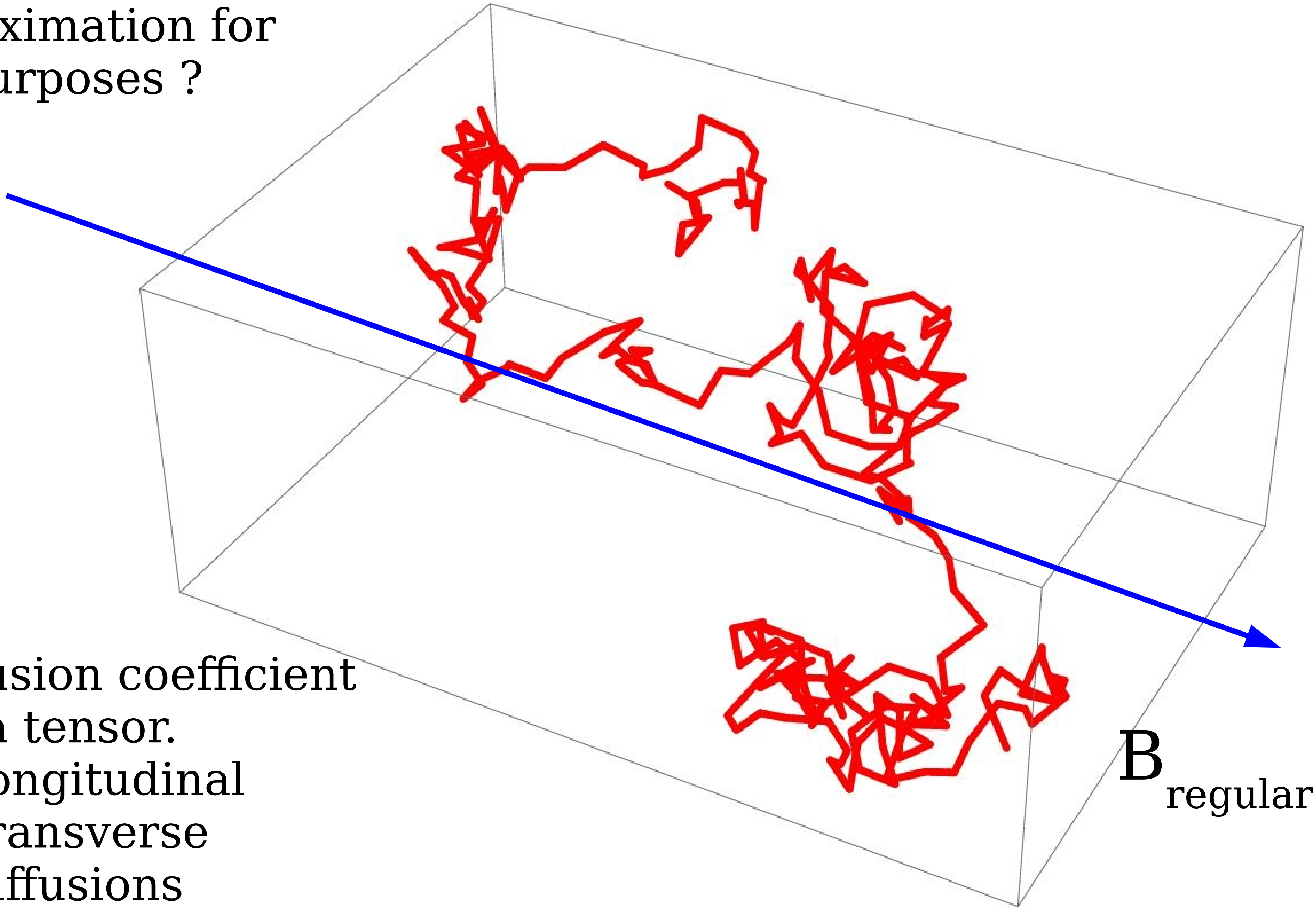
Rigidity dependence associated with the turbulence of the inter-stellar magnetic field.

Measurement of this Rigidity dependence very important

$$D(E) \simeq 0.059 \left(\frac{P/q}{\mathrm{GV}} \right)^{0.6} \frac{\mathrm{Kpc}^2}{\mathrm{Myr}}$$

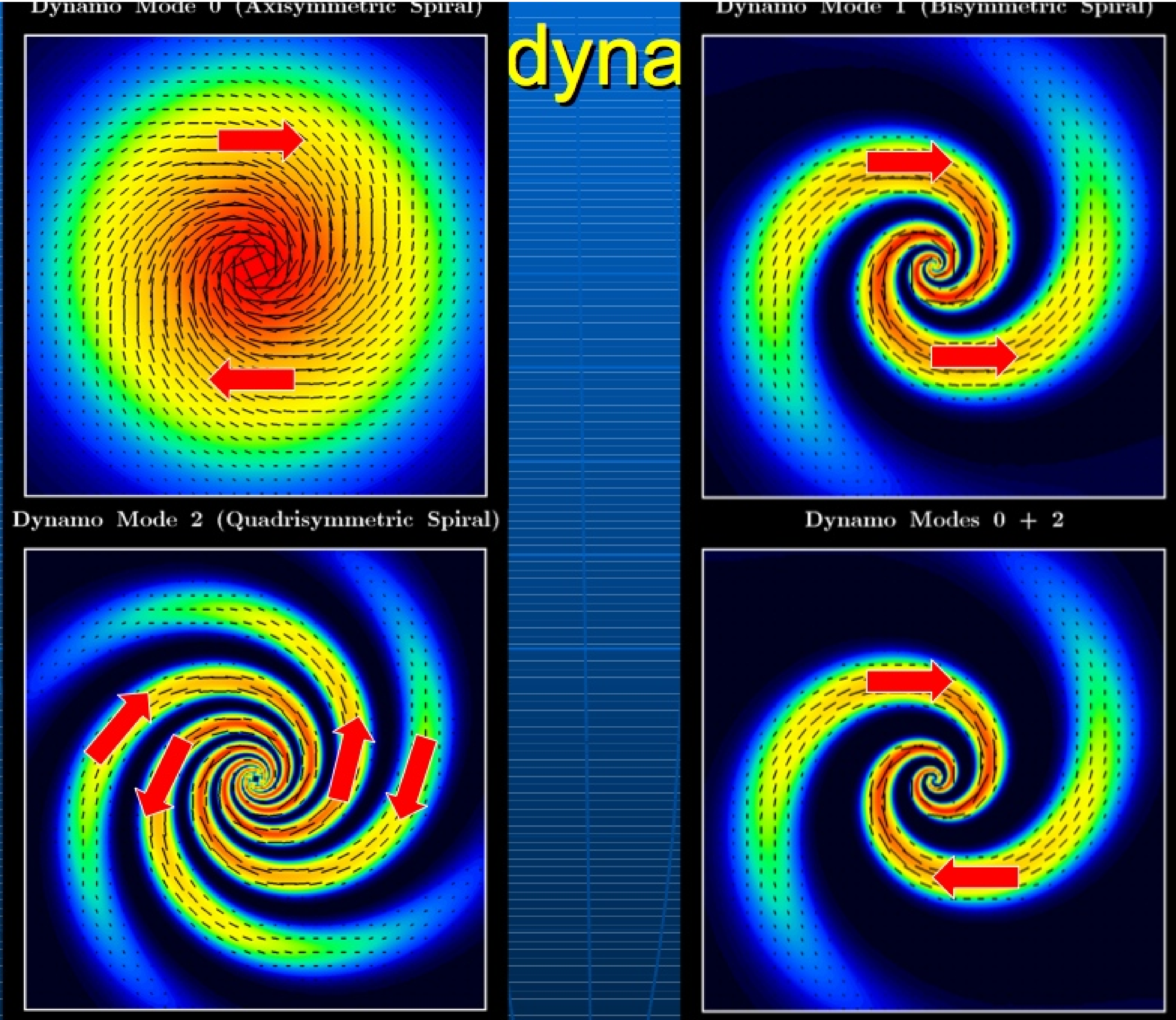
Propagation as homogeneous diffusion.

Is this a sufficiently good approximation for our purposes ?



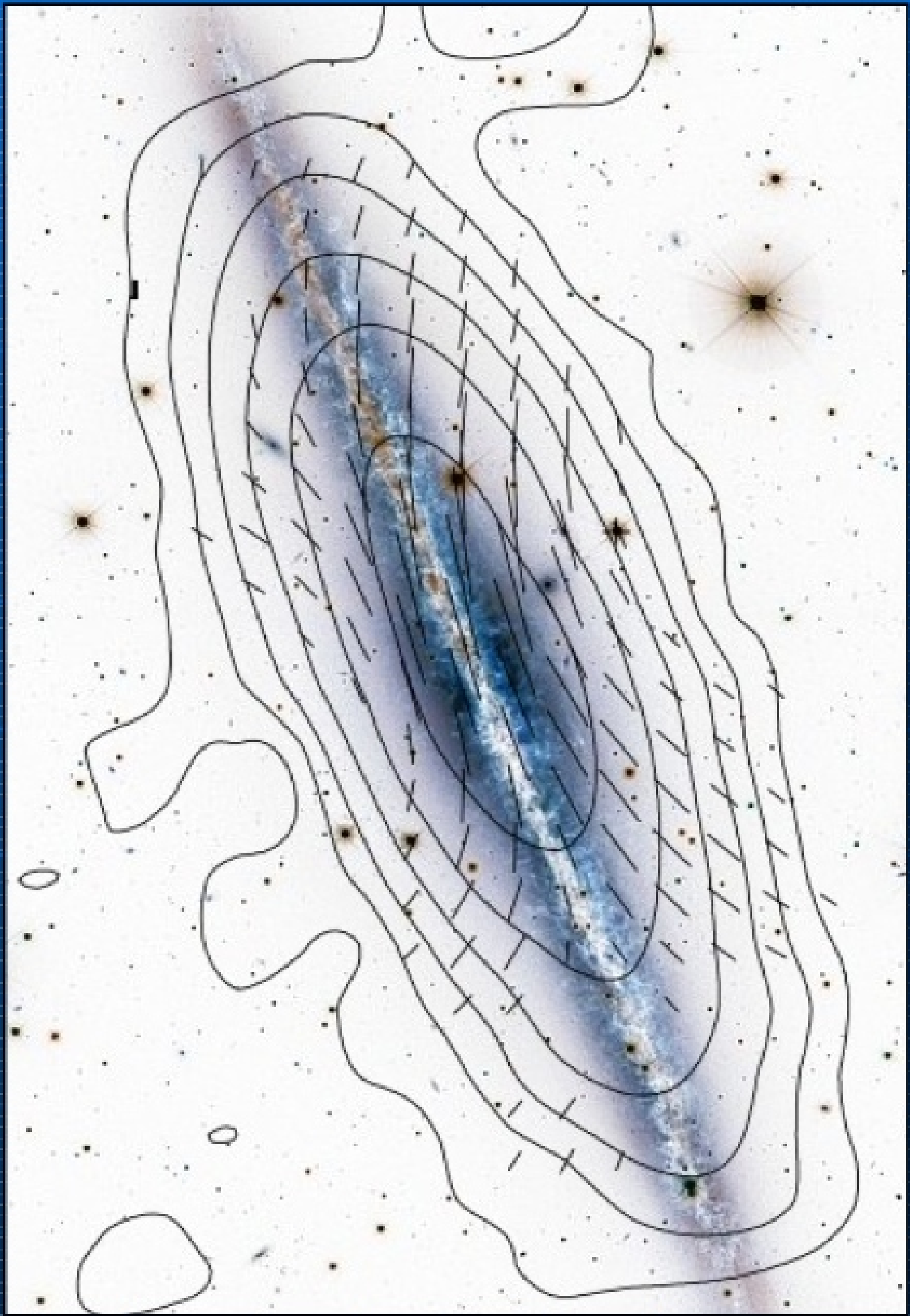
Diffusion coefficient
As a tensor.
Longitudinal
Transverse
Diffusions

dyna


Dynamo Mode 0 (Axisymmetric Spiral)
Dynamo Mode 1 (Bisymmetric Spiral)
Dynamo Mode 2 (Quadrisymmetric Spiral)
Dynamo Modes 0 + 2

NGC 891

3cm Effelsberg
Total intensity
+ B-vectors
(Krause 2007)



Similar to the Milky Way !

Bright radio halo with
X-shaped field pattern:

Vertical field increases
with increasing height

$$D(E) \simeq 0.059 \left(\frac{E}{\mathrm{GeV}}\right)^{0.6} \frac{\mathrm{Kpc}^2}{\mathrm{Myr}}$$

Diffusion coefficient is related to
The escape time from the Galaxy:

$$2\,D\,t \simeq L^2$$

L = Linear Size of Galaxy

$$T_{\mathrm{escape}} \simeq 8.5 \left(\frac{E}{\mathrm{GeV}}\right)^{-0.6} \left(\frac{L}{\mathrm{Kpc}}\right)^{2} \mathrm{Myr}$$

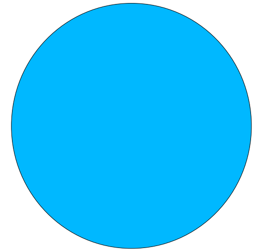
Escape Time

$$q(E) \propto E^{-\alpha}$$

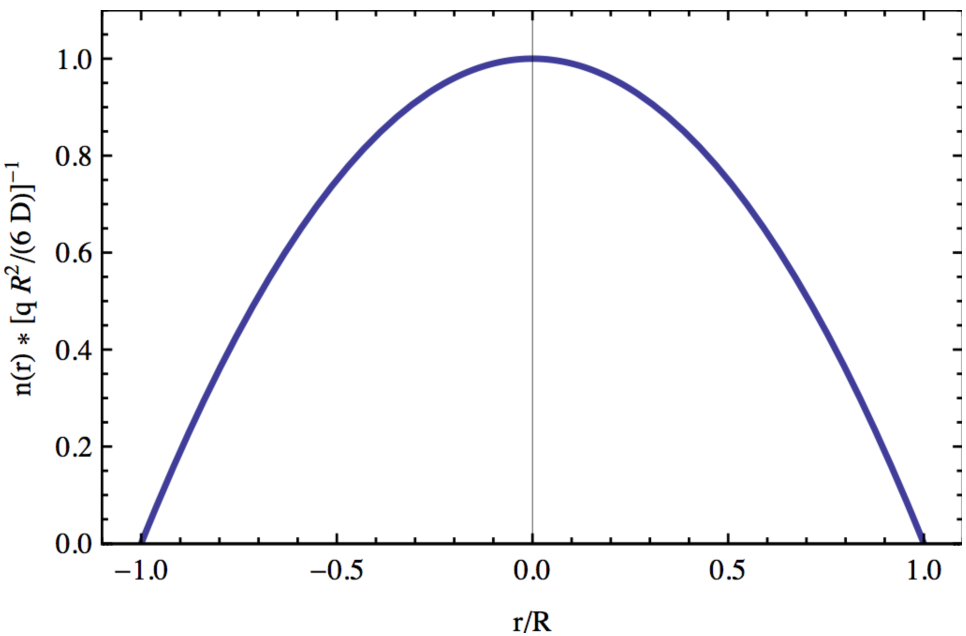
$$D(E) \propto E^{\delta}$$

$$n(E) \propto \frac{q(E)}{D(E)} \propto E^{-(\alpha+\delta)}$$

Toy Model:
“Spherical Galaxy” :



$$q(E,\vec{r}) = \begin{cases} q(E) & \text{for } r < R \\ 0 & \text{for } r \geq R \end{cases}$$

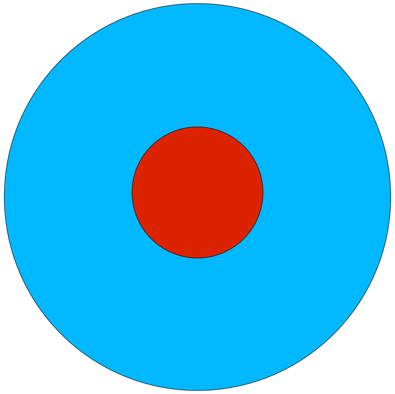


$$D(E,\vec{r}) = \begin{cases} D(E) & \text{for } r < R \\ \infty & \text{for } r \geq R \end{cases}$$

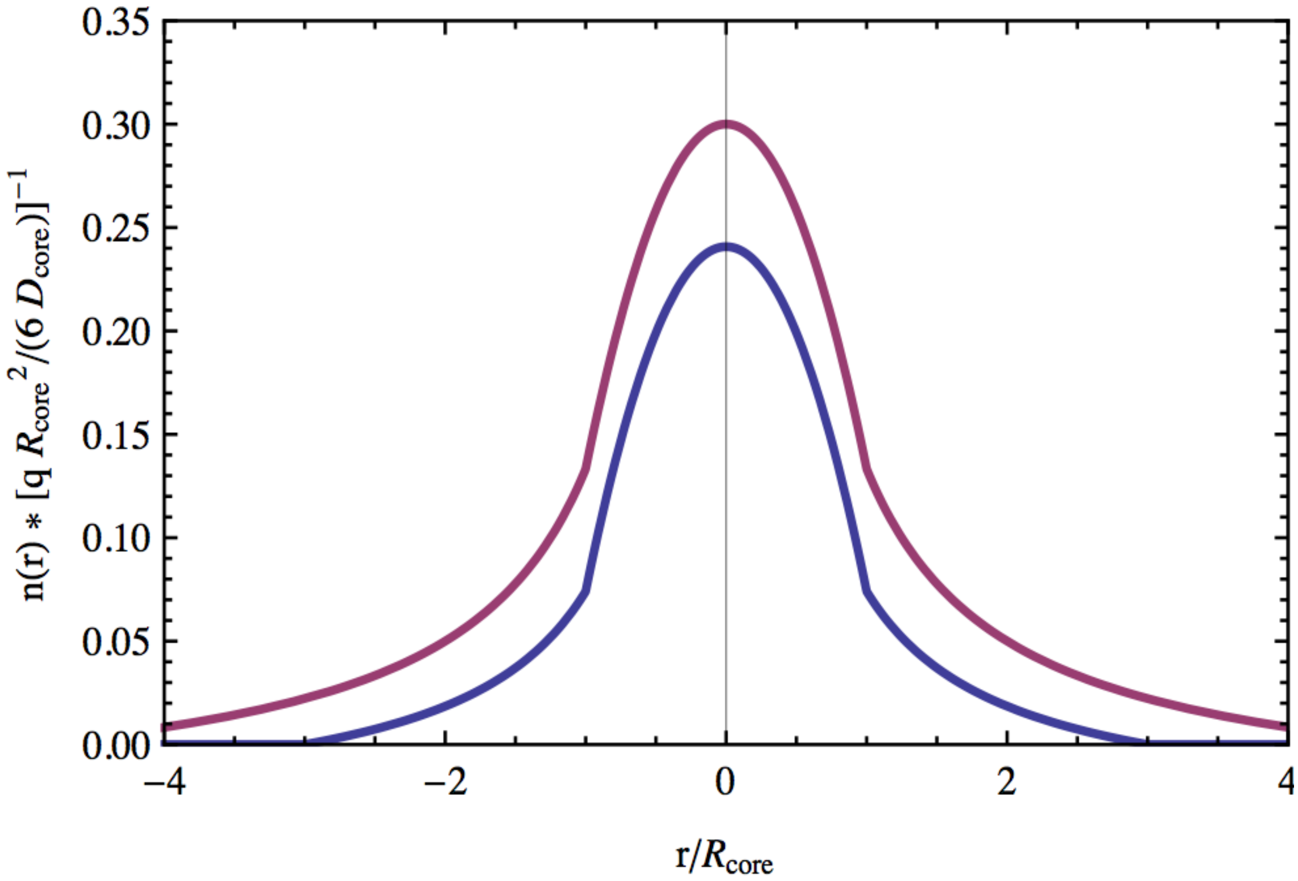
Exact solution :

$$n(E,r) = \frac{q(E)\,R^2}{D(E)} \left[1 - \frac{r^2}{R^2}\right]$$

“Concentrical spheres Galaxy”



$$D(E,\vec{r}) = \begin{cases} D_{\rm core}(E) & \text{for } r < R_{\rm core} \\ D_{\rm halo}(E) & \text{for } R_{\rm core} \le r < R_{\rm halo} \\ \infty & \text{for } r \ge R_{\rm halo} \end{cases}$$



Two models
Same CR injection

Larger/smaller
halo

Cosmic Ray Nuclear Composition

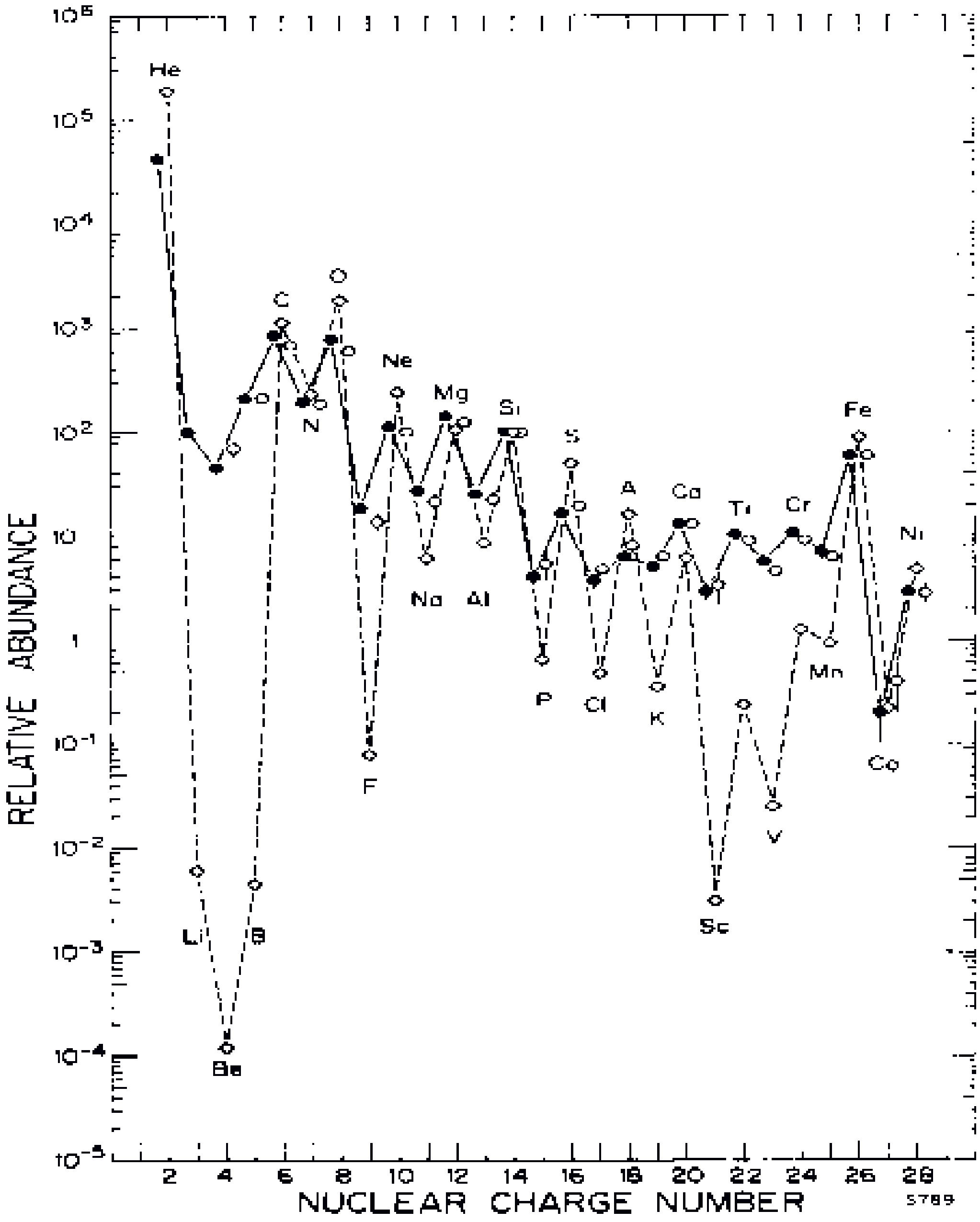


Figure 1. The relative abundance distribution of the elements in the cosmic radiation and in the solar system (normalized to Si = 100) from He to Ni (solid circles, 70–280 MeV per nucleon; open circles, 1000–2000 MeV per nucleon; open diamonds, solar system abundance distribution). [*Reproduced with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

Cosmic Ray Nuclear Composition

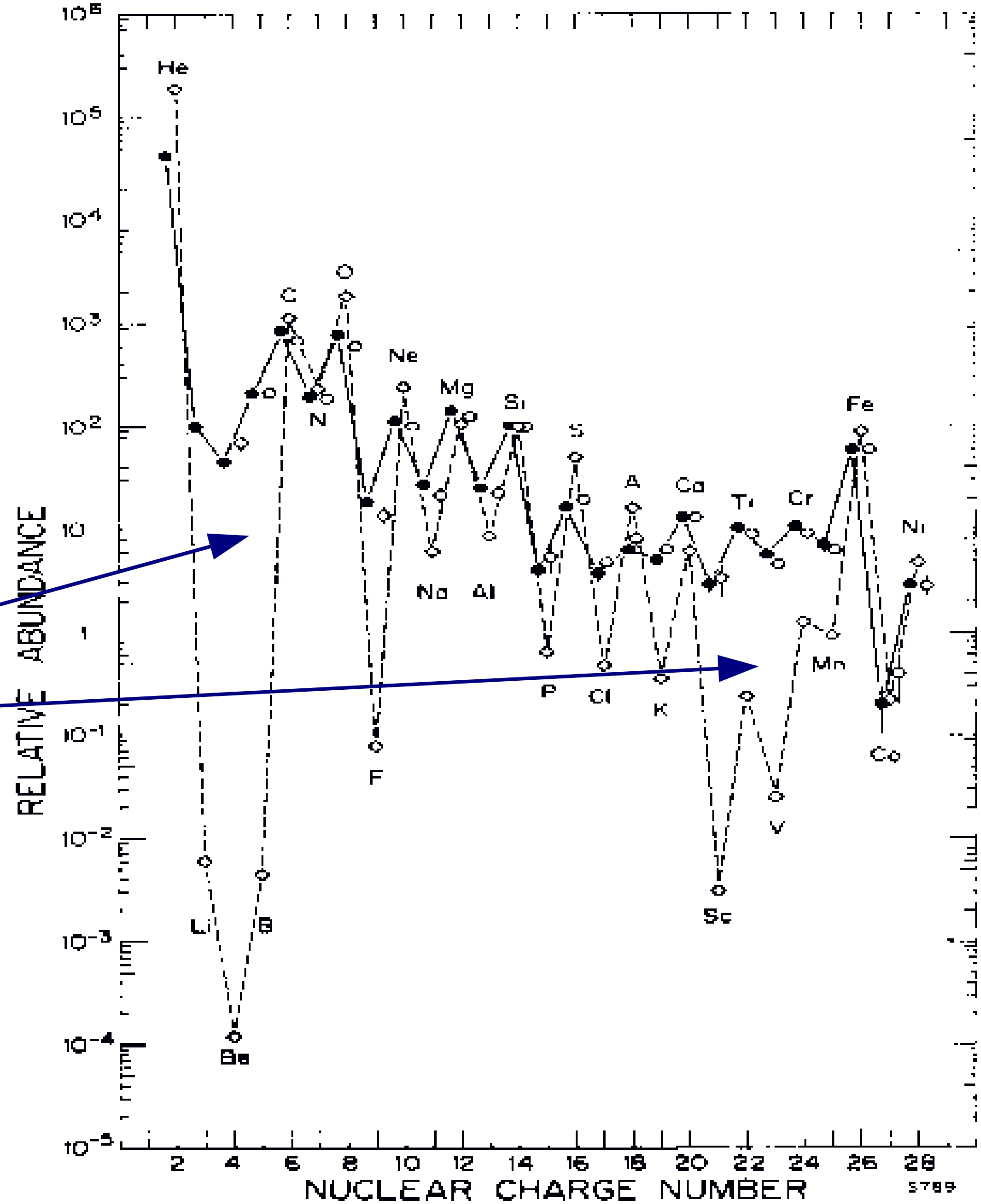


Figure 1. The relative abundance distribution of the elements in the cosmic radiation and in the solar system (normalized to Si = 100) from He to Ni (solid circles, 70–280 MeV per nucleon; open circles, 1000–2000 MeV per nucleon; open diamonds, solar system abundance distribution). [*Reproduced with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

Overabundance of Li, Be, B

Sub-iron elements

Spallation effect:

Column density
Confinement time

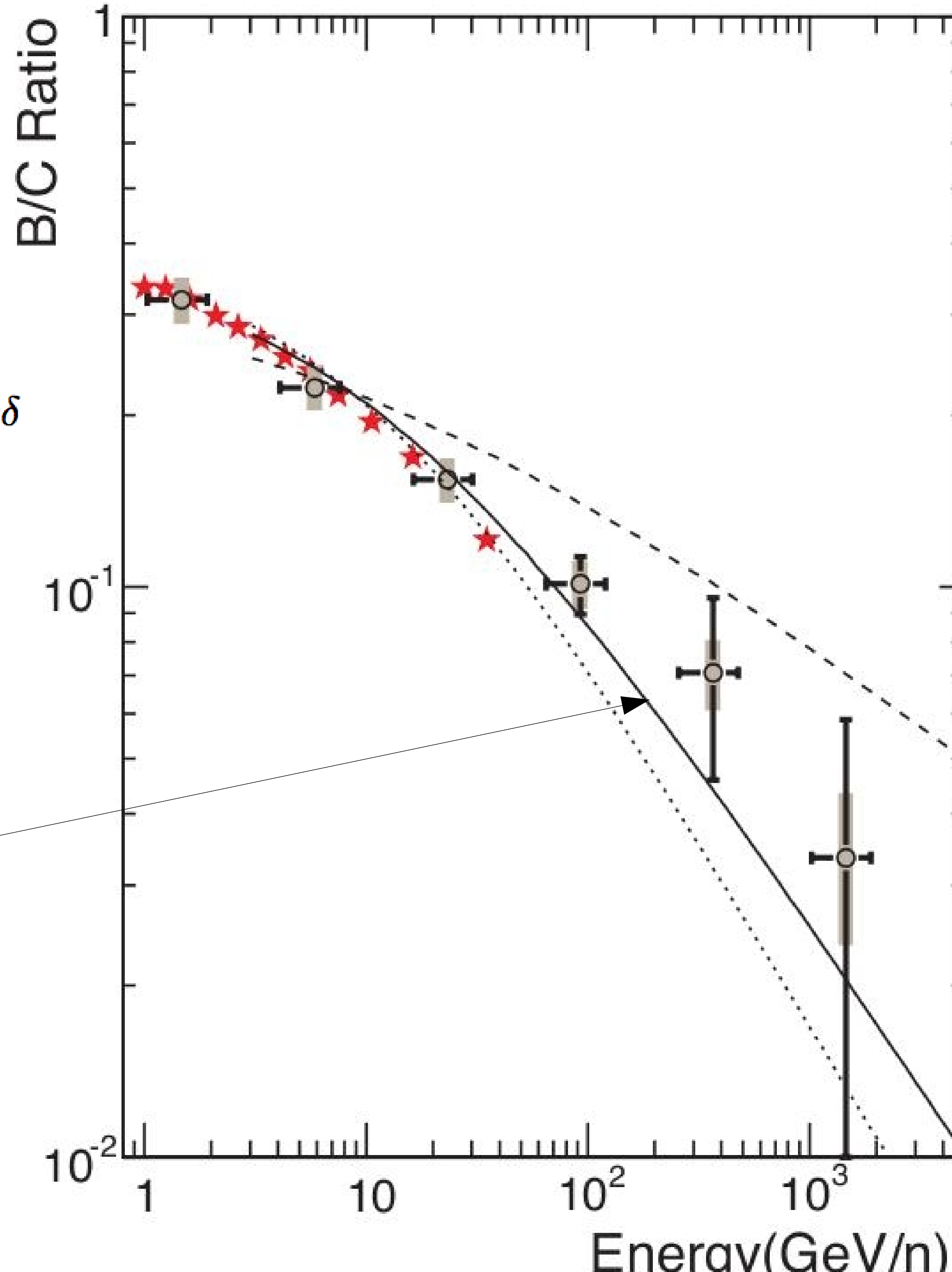
$$n_A(E) \propto \; E^{-(\alpha+\delta)}$$ Primary Nucleus

$$n_{A'}(E) \propto \langle n_{\rm ISM} \rangle \; E^{-(\alpha+2\,\delta)}$$ Secondary Nucleus

$$\frac{n_{A'}(E)}{n_A(E)} \propto \langle n_{\rm ISM} \rangle \; E^{-\delta}$$ Primary/Secondary

CREAM experiment:

$$\frac{n_{A'}(E)}{n_A(E)} \propto \langle n_{\mathrm{ISM}} \rangle \; E^{-\delta}$$



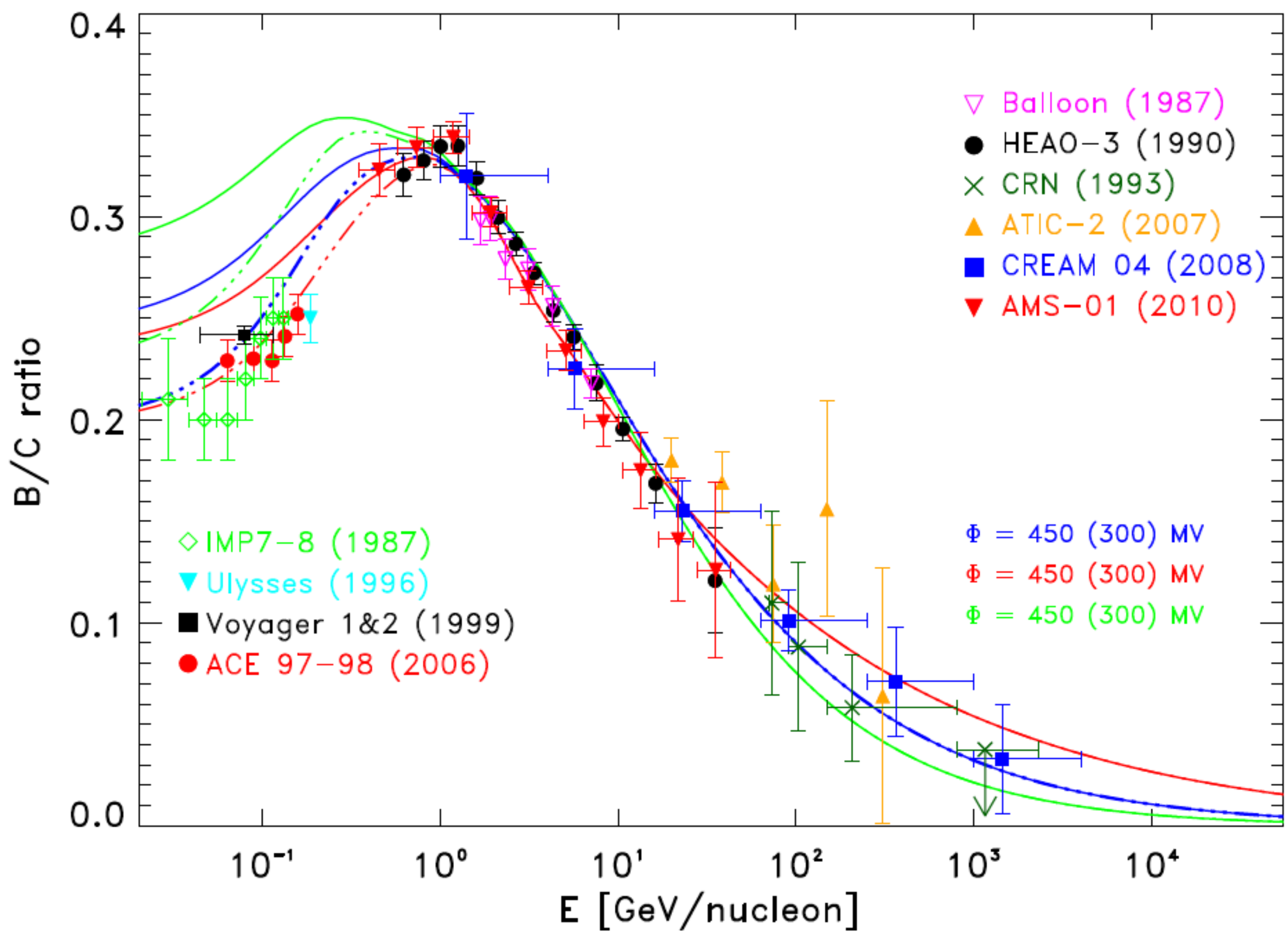
tau(E) ~ $E^{-0.6}$

Model	δ	D_0 ($cm^2 s^{-1}$)	z_h (kpc)	γ_p	v_A ($km\ s^{-1}$)	η
KOL	0.33	5.6×10^{28}	4	1.6/2.4	$v_A = 30$	1
KRA	0.5	3.0×10^{28}	4	2.25	$v_A = 15$	-0.4
PD	0.60	2.4×10^{28}	4	2.15	$v_A = 0$	-0.4

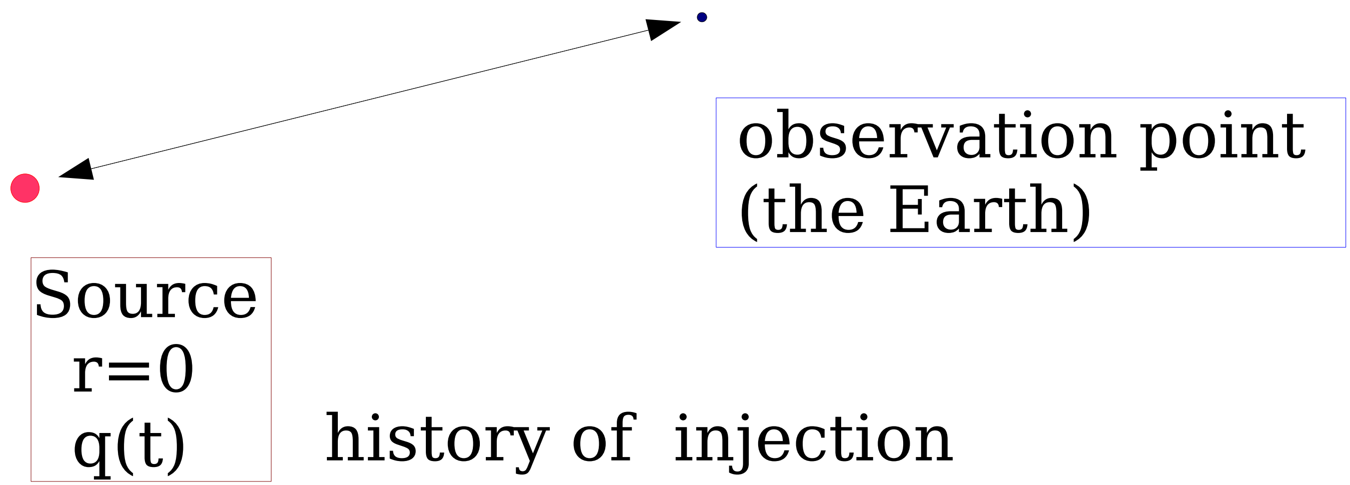
Implications of the Cosmic Ray Electron Spectrum and Anisotropy measured with Fermi-LAT

Giuseppe Di Bernardo[a], Carmelo Evoli[d], Daniele Gaggero[b,c], Dario Grasso[c,b,*], Luca Maccione[e], Mario Nicola Mazziotta[f]

arXiv:1010.0174



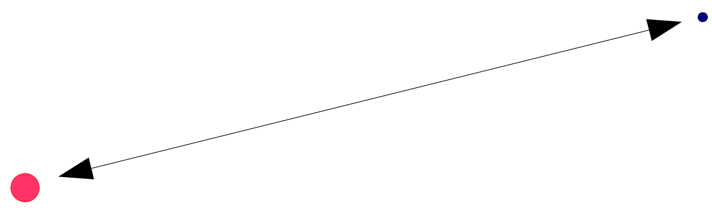
Diffusion and Anisotropies



Particle density at the observation point:

$$n(\vec{r}, t_{\rm obs}) = \int_{-\infty}^{t_{\rm obs}} dt \; q(t) \times \frac{1}{[4\pi\, D\,(t_{\rm obs} - t)]^{3/2}} \; e^{-r^2/[4D(t_{\rm obs} - t)]}$$

Diffusion and Anisotropies



observation point
(the Earth)

Source
r=0
q(t)

history of injection

Particle density at the observation point:

$$n(\vec{r}, t_{\rm obs}) = \int_{-\infty}^{t_{\rm obs}} dt\; q(t) \times \frac{1}{[4\pi\, D\,(t_{\rm obs} - t)]^{3/2}}\; e^{-r^2/[4D(t_{\rm obs}-t)]}$$

$$= \frac{q}{4\pi\, D\, r}$$

constant injection:
the integration gives simple result

Angular distribution of the particles

$$\int d\Omega \ \cos\theta \ \phi(\Omega) = D \ \vec{\nabla} n(\vec{r}) \cdot \hat{n}$$

Exact result in diffusion theory:
Net-flux across one surface =
gradient of the particle density * Diffusion coefficient.

Angular distribution of the particles

$$\int d\Omega \ \cos\theta \ \phi(\Omega) = D \ \vec{\nabla} n(\vec{r}) \cdot \hat{n}$$

Exact result in diffusion theory:
Net-flux across one surface =
gradient of the particle density * Diffusion coefficient.

$$\phi(\Omega) = \phi_0 + \phi_1 \ \cos\theta$$

First order expansion:
“monopole” + “dipole”

$$\phi_0 = \frac{4\pi}{c} \, n(\vec{r})$$

$$\phi_1 = \frac{4\pi}{3} \, D \, \left| \vec{\nabla} n(\vec{r}) \right|$$

Contribution of a single steady source

Identification of near sources ?

$$n(E,r) \simeq \frac{q(E)}{4\pi\, D(E)\, r}$$

$$\phi_0 = \frac{q\, c}{4\pi\, D\, r}$$

Monopole term 1/r

$$\phi_1 = \frac{3\, q}{4\pi r^2}$$

Dipole term $1/r^2$

$$\frac{\phi_1}{\phi_0} = \frac{3\, D}{c\, r}$$

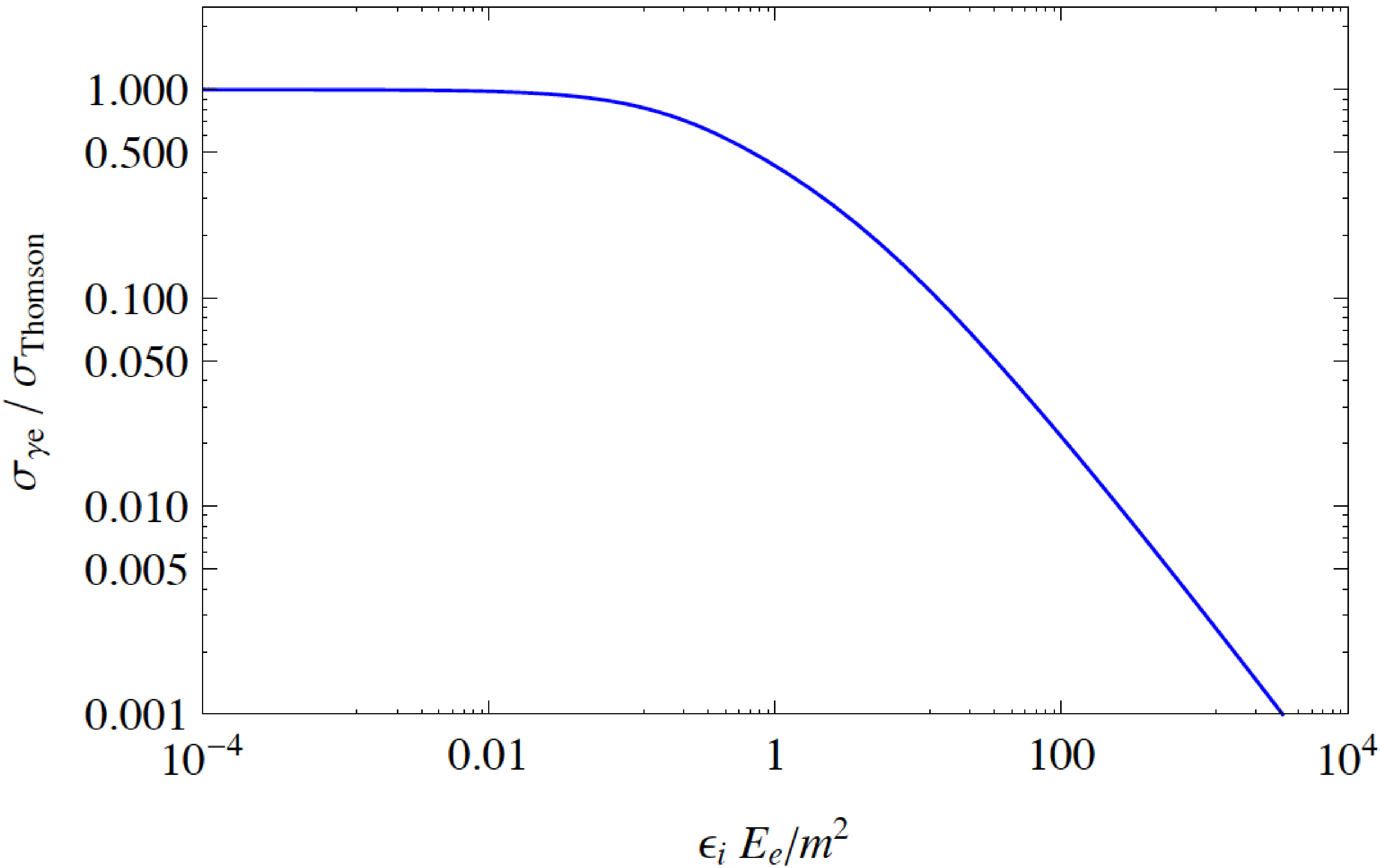
Radiation Mechanisms for Electrons and Positrons:

SYNCHROTRON

INVERSE COMPTON scattering

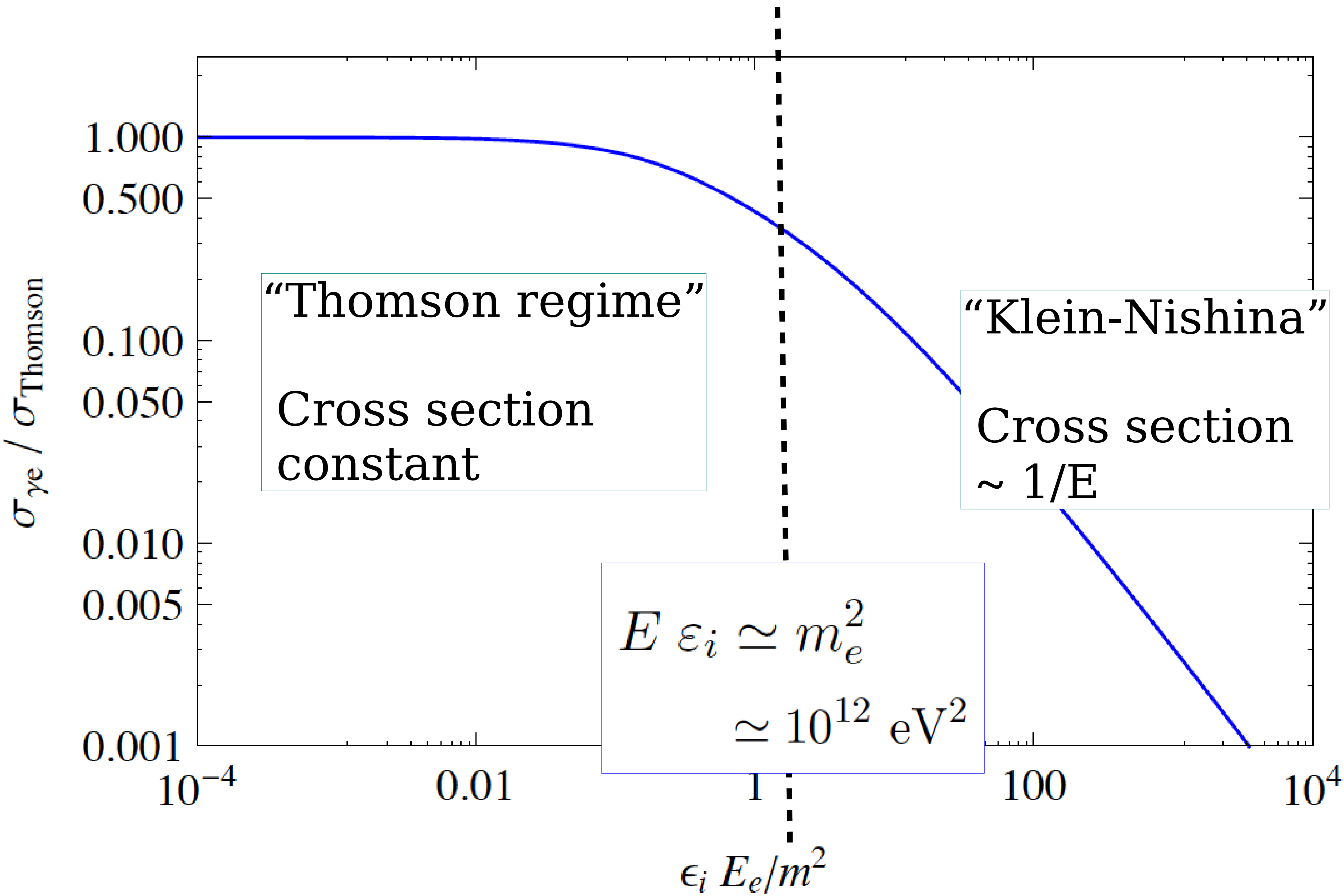
Cross section for electron-photon Compton scattering

$$e + \gamma \rightarrow e + \gamma$$



Cross section for electron-photon scattering

$$e + \gamma \rightarrow e + \gamma$$



$$\sigma_{\mathrm{Thomson}} = \frac{8\pi}{3}\,\frac{e^2}{(m_e\,c^2)^2} \quad = \frac{8\pi}{3}\,r_0^2$$

$$\simeq 6.65 \times 10^{-25}\ \mathrm{cm}^2$$

$$\sigma \propto \frac{1}{m^2}$$

Scattering process
Important only for electrons/positrons

Inverse Compton Scattering

Radiation Field: Density: $n_\gamma^{\rm target}$

Photon energy: ε_i

$$\dot{N}_\gamma^{[\rm Inv.Compt.]} = (\sigma_{\rm Th}\, c)\; n_\gamma^{\rm target}$$

Interaction rate

$$\langle \varepsilon_f \rangle = \frac{4}{3} \varepsilon_i\, \gamma^2 \qquad \gamma = E/m$$

Average energy of scattered photon

$$\left[\frac{dE}{dt}\right]_{\rm Inv.Compt.} = \dot{N}_\gamma\, \langle \varepsilon_f \rangle = \frac{4}{3}\, (\sigma_{\rm Th}\, c)\, (n_\gamma^{\rm target}\, \varepsilon_i)\, \gamma^2$$

Inverse Compton Scattering

Radiation Field: Density: n_γ^{target}

Photon energy: ε_i

$$\dot{N}_\gamma^{[\text{Inv.Compt.}]} = (\sigma_{\text{Th}}\, c)\ n$$

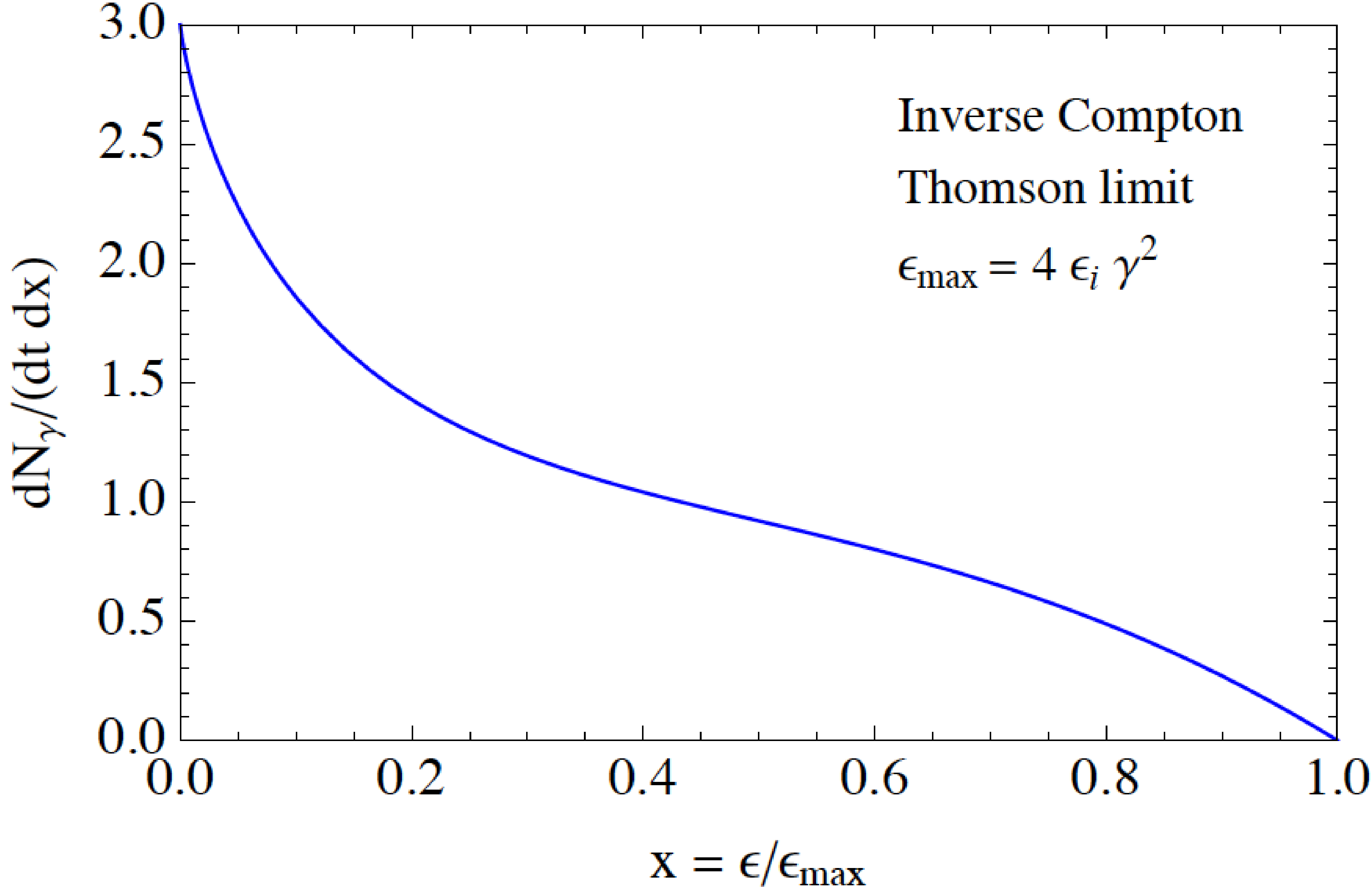
Quadratic Dependence

on

$$\langle \varepsilon_f \rangle = \frac{4}{3} \varepsilon_i \gamma^2 \qquad \gamma = E/m$$

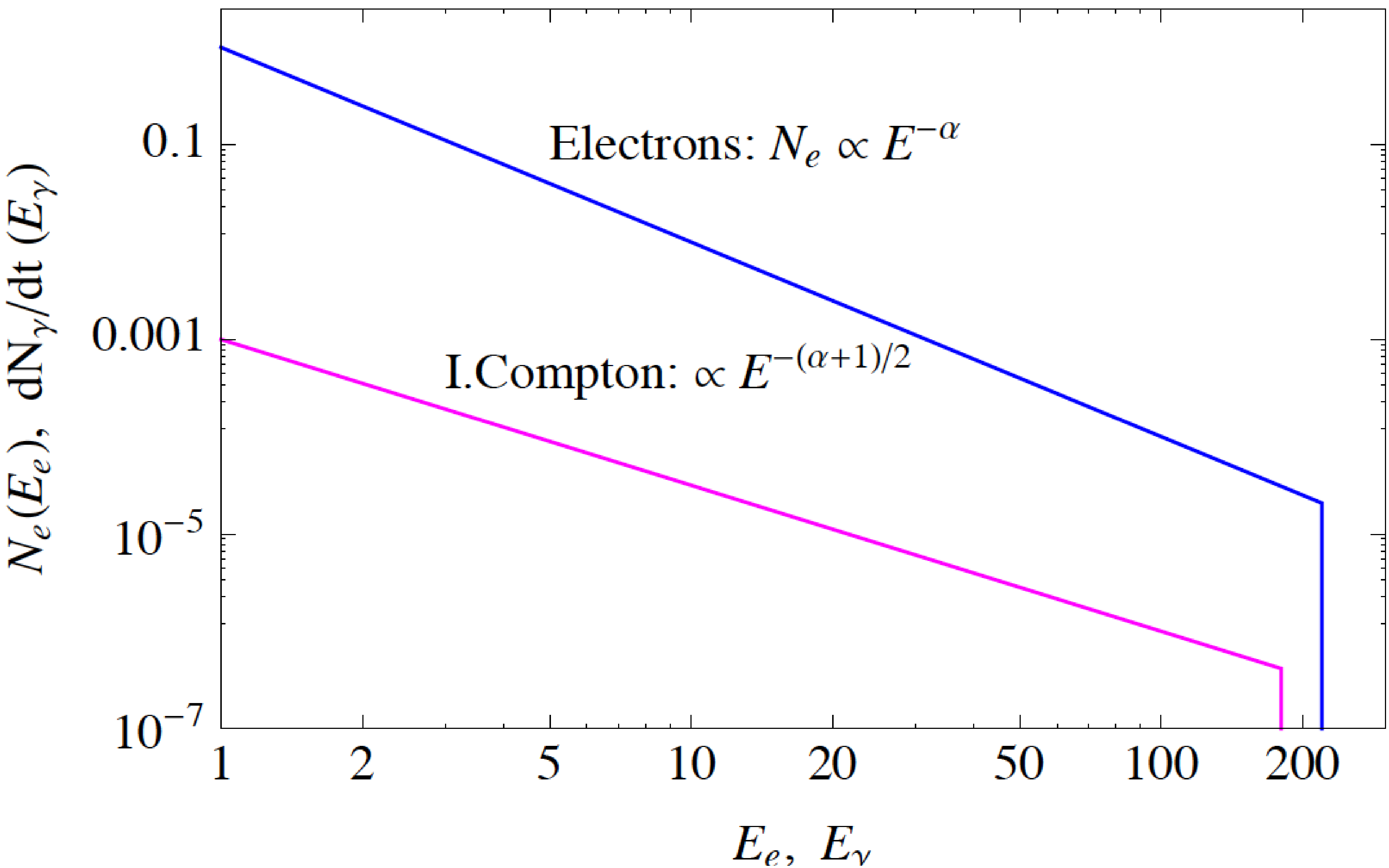
Average energy of scattered photon

$$\left[\frac{dE}{dt}\right]_{\text{Inv.Compt.}} = \dot{N}_\gamma \,\langle \varepsilon_f \rangle = \frac{4}{3}\,(\sigma_{\text{Th}}\, c)\,(n_\gamma^{\text{target}}\ \varepsilon_i)\,\gamma^2$$



$$\langle \varepsilon_f \rangle = \frac{\varepsilon_{\max}}{3} = \frac{4}{3} \varepsilon_i\, \gamma^2$$

$$\varepsilon_f^{\max} \simeq 4\, \varepsilon_i\, \gamma_{\max}^2$$



Electrons: $N_e \propto E^{-\alpha}$
I.Compton: $\propto E^{-(\alpha+1)/2}$
0.1
0.001
10^{-5}
10^{-7}
1
2
5
10
20
50
100
200
$N_e(E_e)$, $dN_\gamma/dt\,(E_\gamma)$
E_e, E_γ

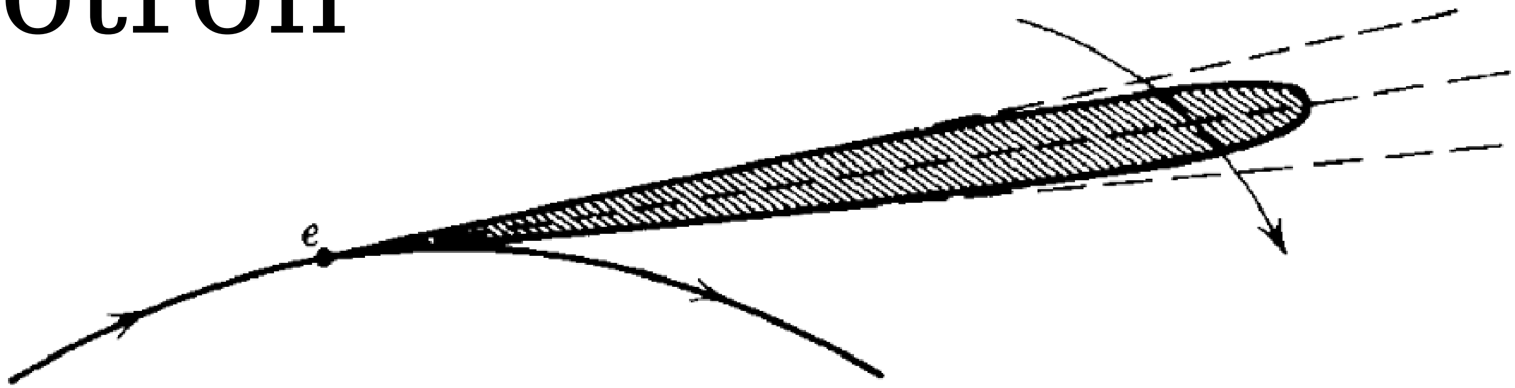
$$N_e(\gamma) = K_e\,\gamma^{-\alpha}$$

$$\frac{d\dot{N}_\gamma}{d\varepsilon_f} = K_\gamma\ \varepsilon_f^{-(\alpha+1)/2}$$

$$\frac{d\dot{N}_\gamma}{d\varepsilon_f} = \left[K_e\,a(\alpha)\ [\sigma_{Th}\,c\,n_\gamma^{\mathrm{target}}]\ \varepsilon_i^{(\alpha-1)/2}\right]\ \varepsilon_f^{-(\alpha+1)/2}$$

$$a(\alpha) = \frac{12(11+4\alpha+\alpha^2)}{(1+\alpha)(4+\alpha)(3+\alpha)^2}$$

Synchrotron



electron of Energy E
in a magnetic field of value B

Synchrotron Radiation

$$\dot{N}_\gamma = \frac{5}{2\sqrt{3}} \; \frac{e^3 \, B}{m \, c^2 \, \hbar} \; \sin\alpha$$

$$\langle \varepsilon_f \rangle = \frac{4}{5\sqrt{3}} \; \frac{\hbar c}{m \, c^2} \, e \, B \;\; \gamma^2 \; \sin\alpha$$

Synchrotron Radiation

$$\dot{N}_\gamma = \frac{5}{2\sqrt{3}} \frac{e^3 B}{m c^2 \hbar} \sin\alpha$$

$$\langle \varepsilon_f \rangle = \frac{4}{5\sqrt{3}} \frac{\hbar c}{m c^2} e B \; \gamma^2 \; \sin\alpha$$

Inverse Compton

$$(\sigma_{\mathrm{Th}} \, c) \; n_\gamma^{\mathrm{target}}$$

$$\frac{4}{3} \varepsilon_i \, \gamma^2$$

The magnetic field can be seen as an ensemble of virtual photons.

Synchrotron Radiation can be seen as the Inverse Compton scattering on these background photons

$$n_\gamma^{\rm target} \simeq \frac{5\sqrt{3}}{16\pi}\,\frac{mc^2}{\hbar c\, e} B \ \sin\alpha$$

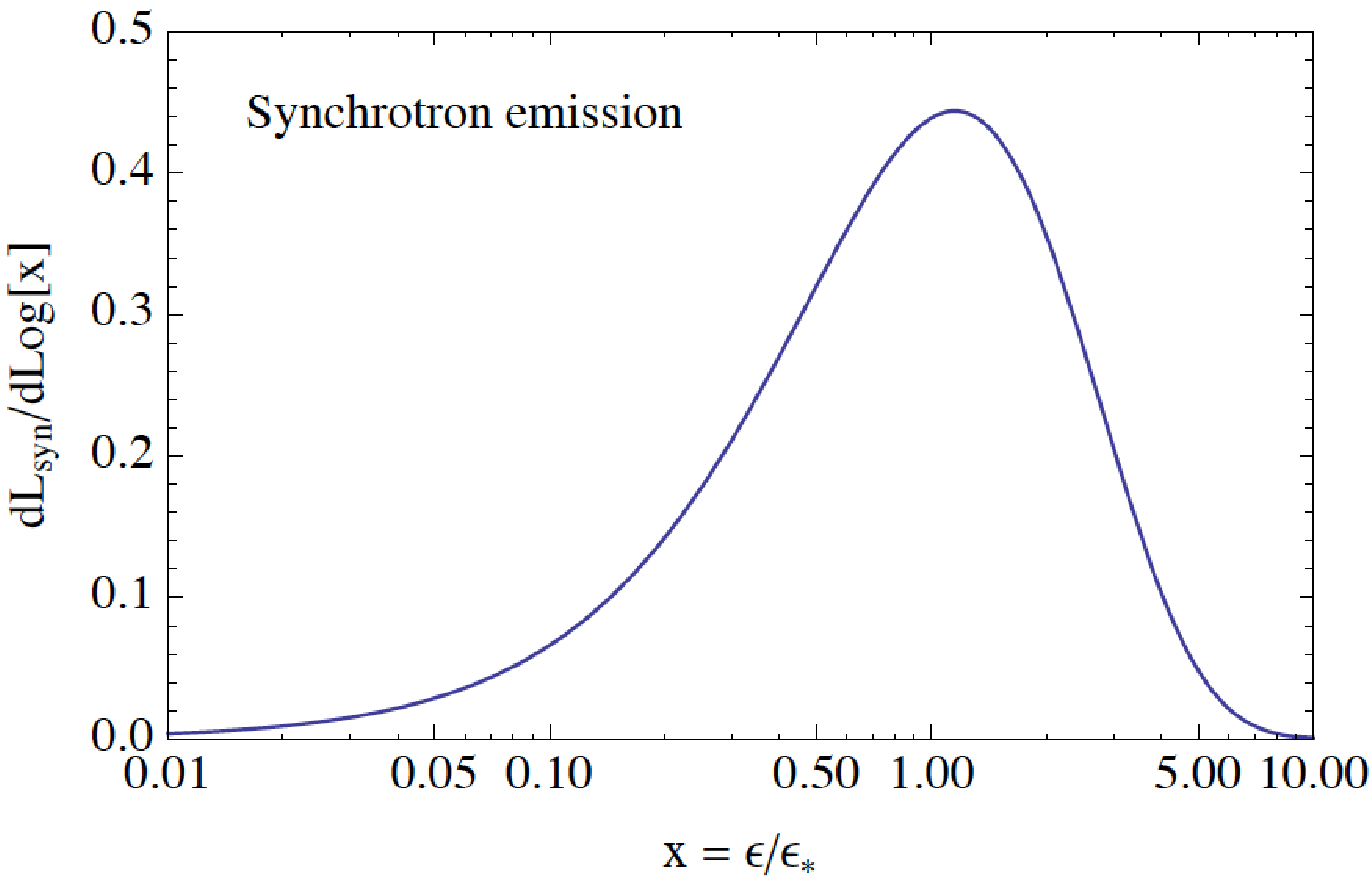
$$n_\gamma^{\rm target} \propto B$$

$$\langle \varepsilon_i \rangle \simeq \frac{4}{5\sqrt{3}}\,\frac{\hbar c}{mc^2} e\, B \ \sin\alpha$$

$$\langle \varepsilon_i \rangle \simeq\!\propto B$$

$$\rho_B = \frac{B^2}{8\pi}$$

Power Emitted in Synchrotron Radiation:



$$\varepsilon_* \simeq 0.0665 \left(\frac{B}{\mu\mathrm{G}}\right) \left(\frac{E}{\mathrm{TeV}}\right)^2 \mathrm{eV}$$

$$\varepsilon_* \simeq 0.0665 \left(\frac{B}{\mu\mathrm{G}}\right) \left(\frac{E}{\mathrm{TeV}}\right)^2 \mathrm{eV}$$

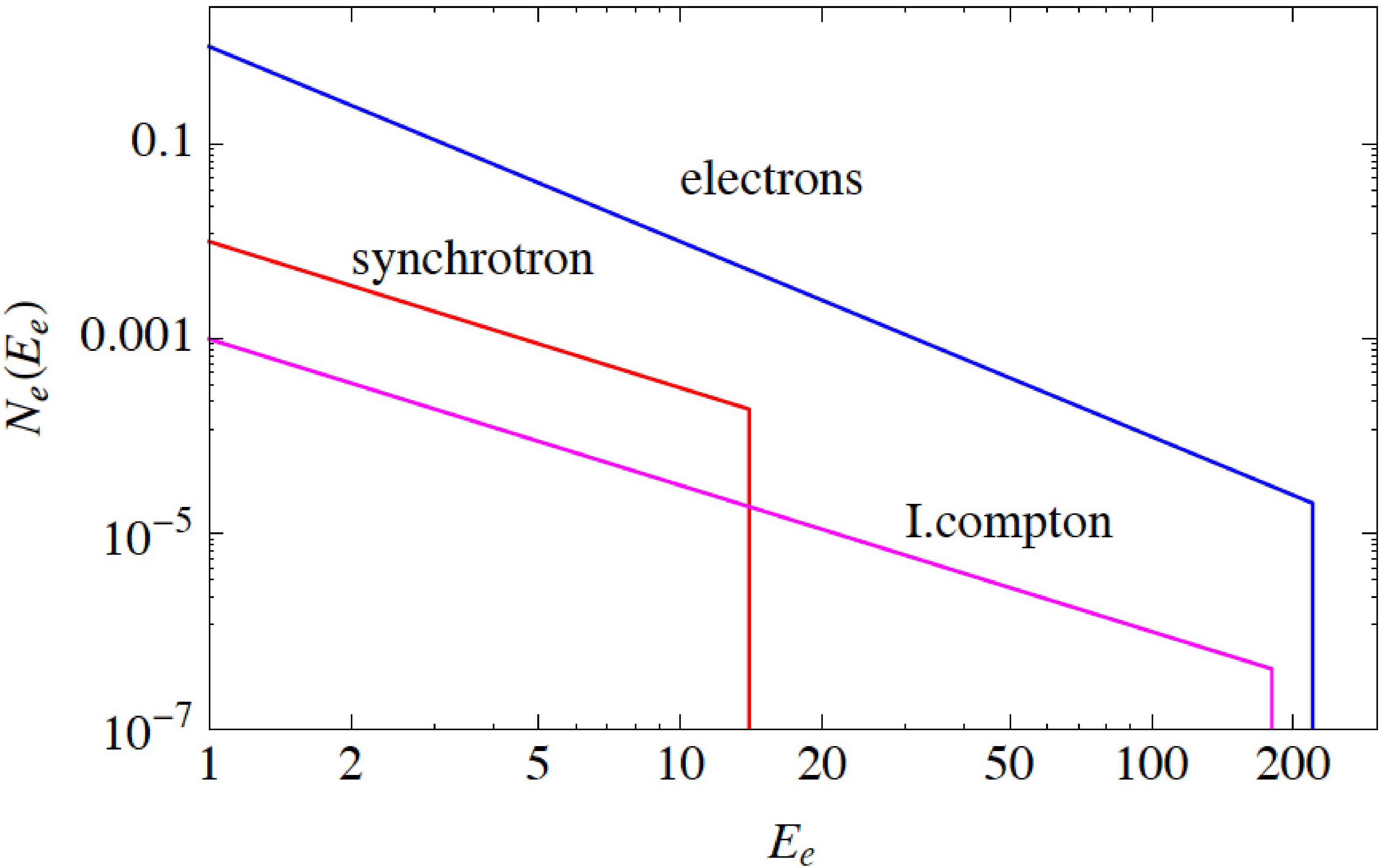
characteristic energy
for synchrotron emission

$$E_{\max} \simeq 3 \times 10^{15} \mathrm{eV}$$

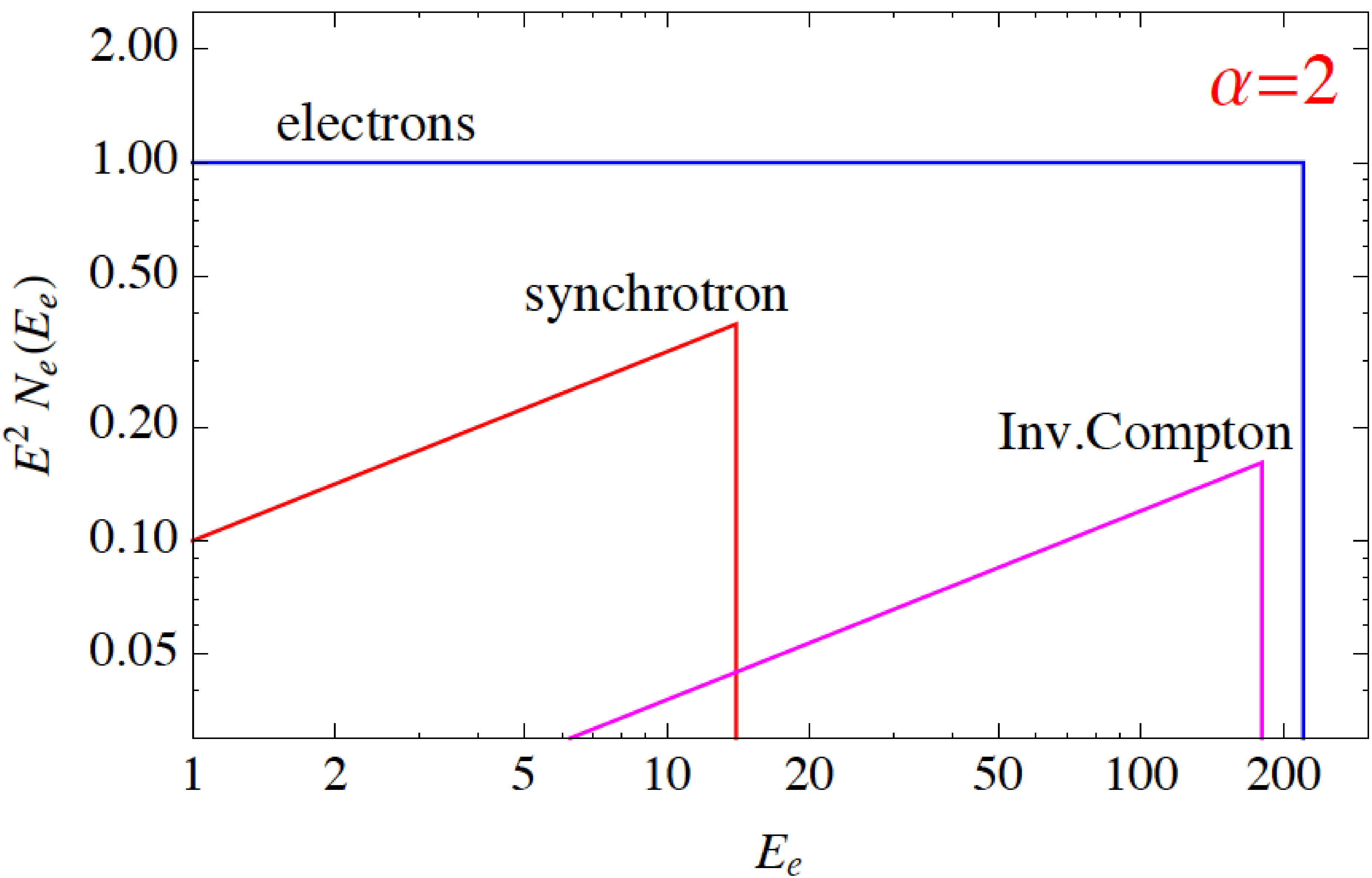
$$B_{\mathrm{Crab}} \simeq 120 \ \mu\mathrm{Gauss}$$

$$\varepsilon_{\mathrm{syn,max}} \simeq 70 \ \mathrm{MeV}$$

Example of
CRAB nebula

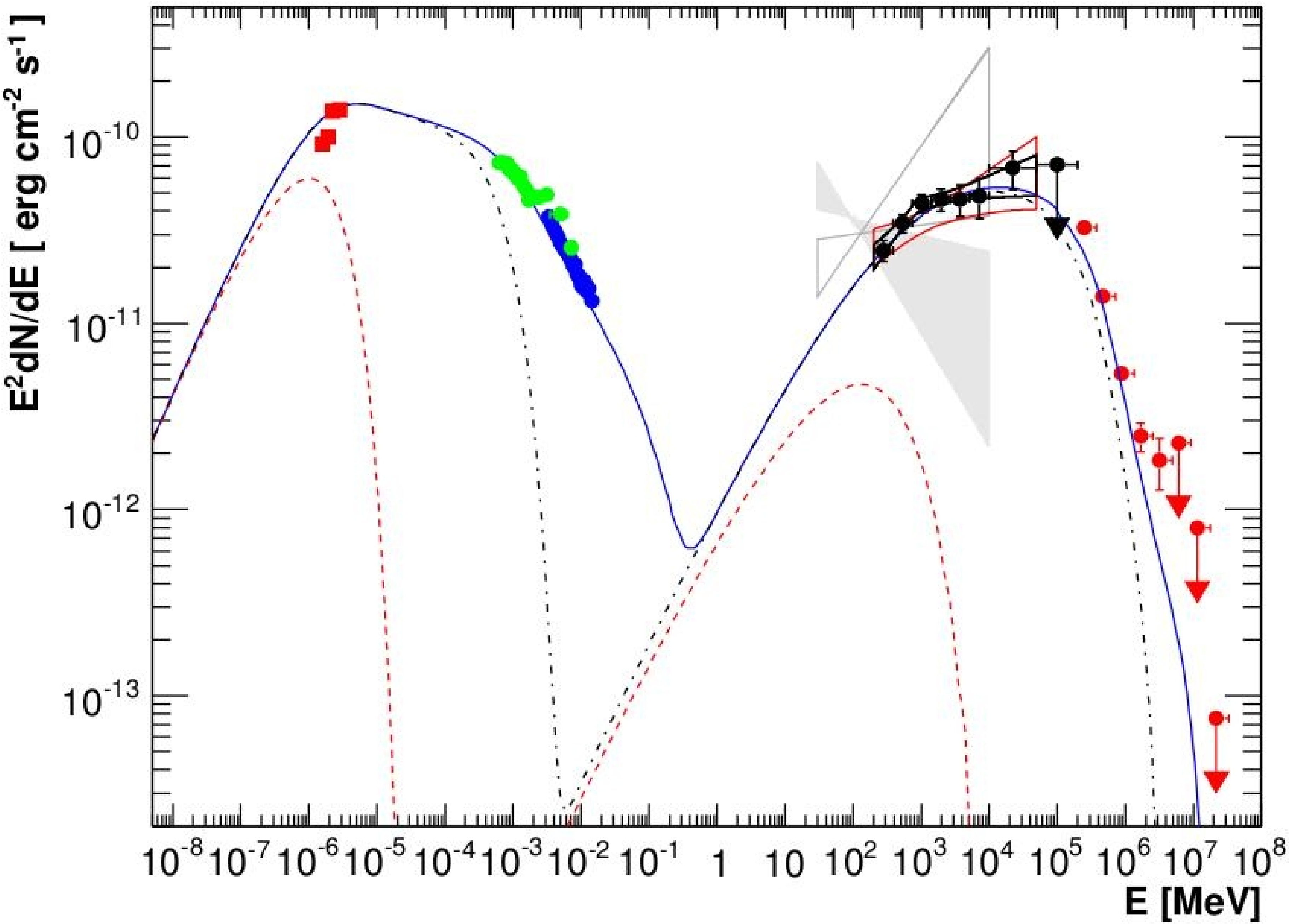


electrons
synchrotron
I.compton
$N_e(E_e)$
E_e
0.1
0.001
10^{-5}
10^{-7}
1
2
5
10
20
50
100
200

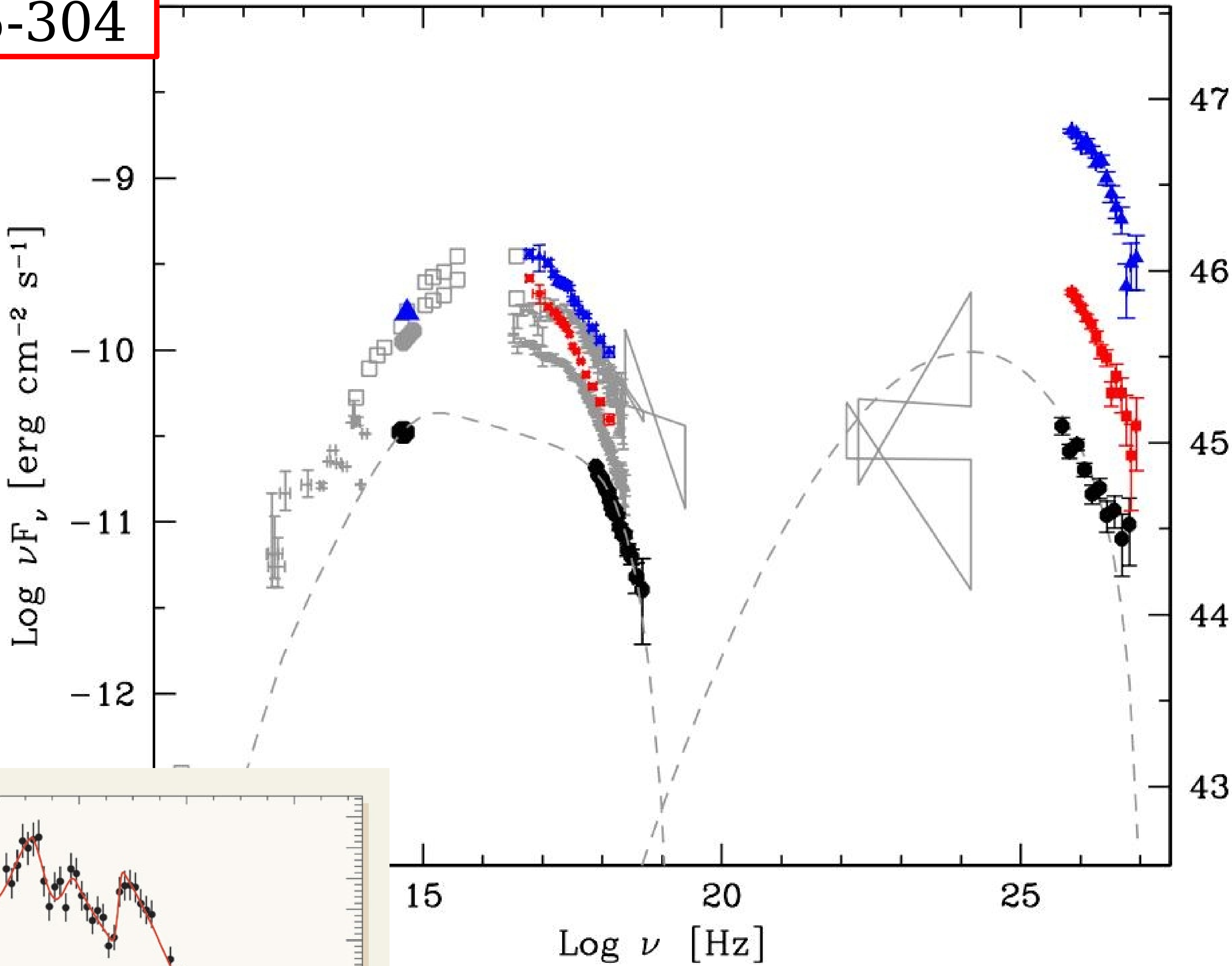


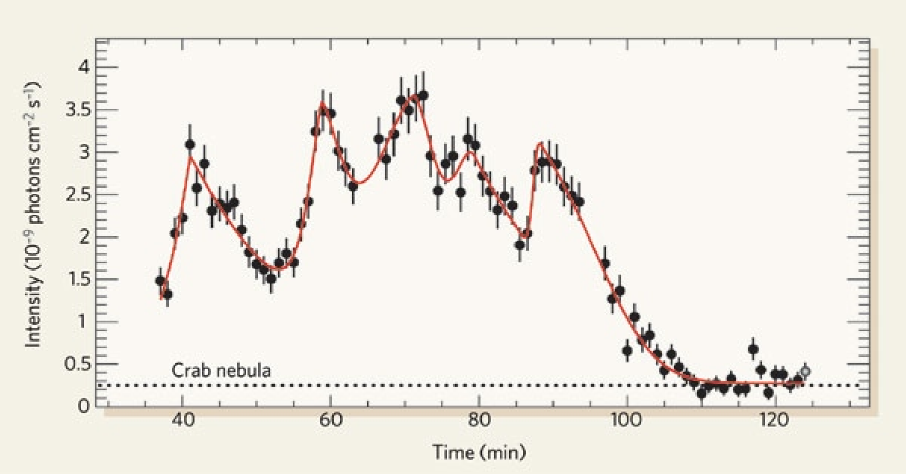
α=2
electrons
synchrotron
Inv.Compton
2.00
1.00
0.50
0.20
0.10
0.05
1
2
5
10
20
50
100
200
$E^2 N_e(E_e)$
E_e

PKS 2155-304


E²dN/dE [erg cm⁻² s⁻¹]
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻⁸ 10⁻⁷ 10⁻⁶ 10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10 10² 10³ 10⁴ 10⁵ 10⁶ 10⁷ 10⁸
E [MeV]

PKS 2155-304





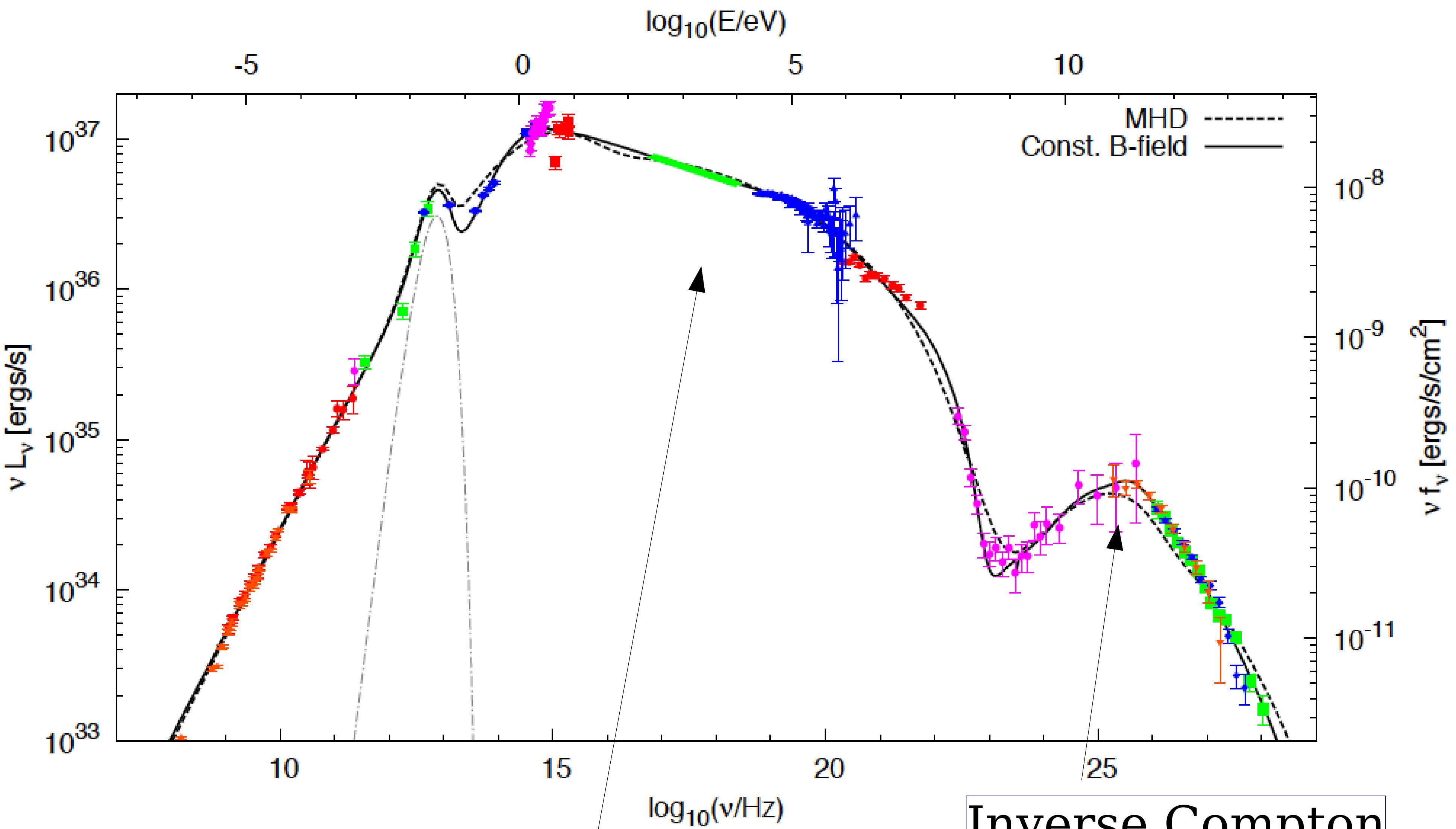
(Very rapid time variations)

The CRAB Nebula

1 minute = 0.58 pc
= $1.8 * 10^{18}$ cm

CRAB Nebula Energy Spectrum

SSC (Self Synchrotron Coompton) model emission



Synchrotron Radiation

Inverse Compton Scattering

CRAB emission, pulsed (from Pulsar)
From the Nebula

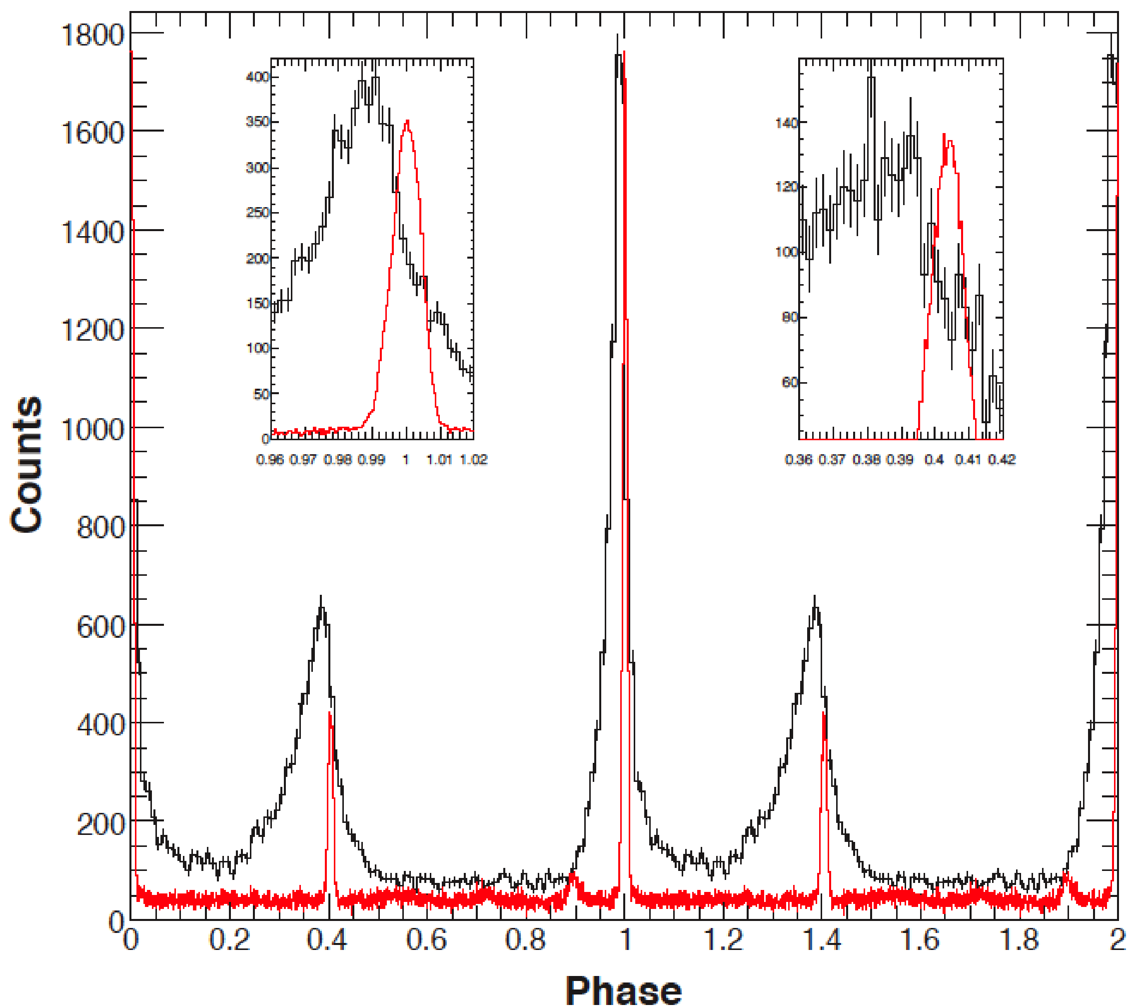
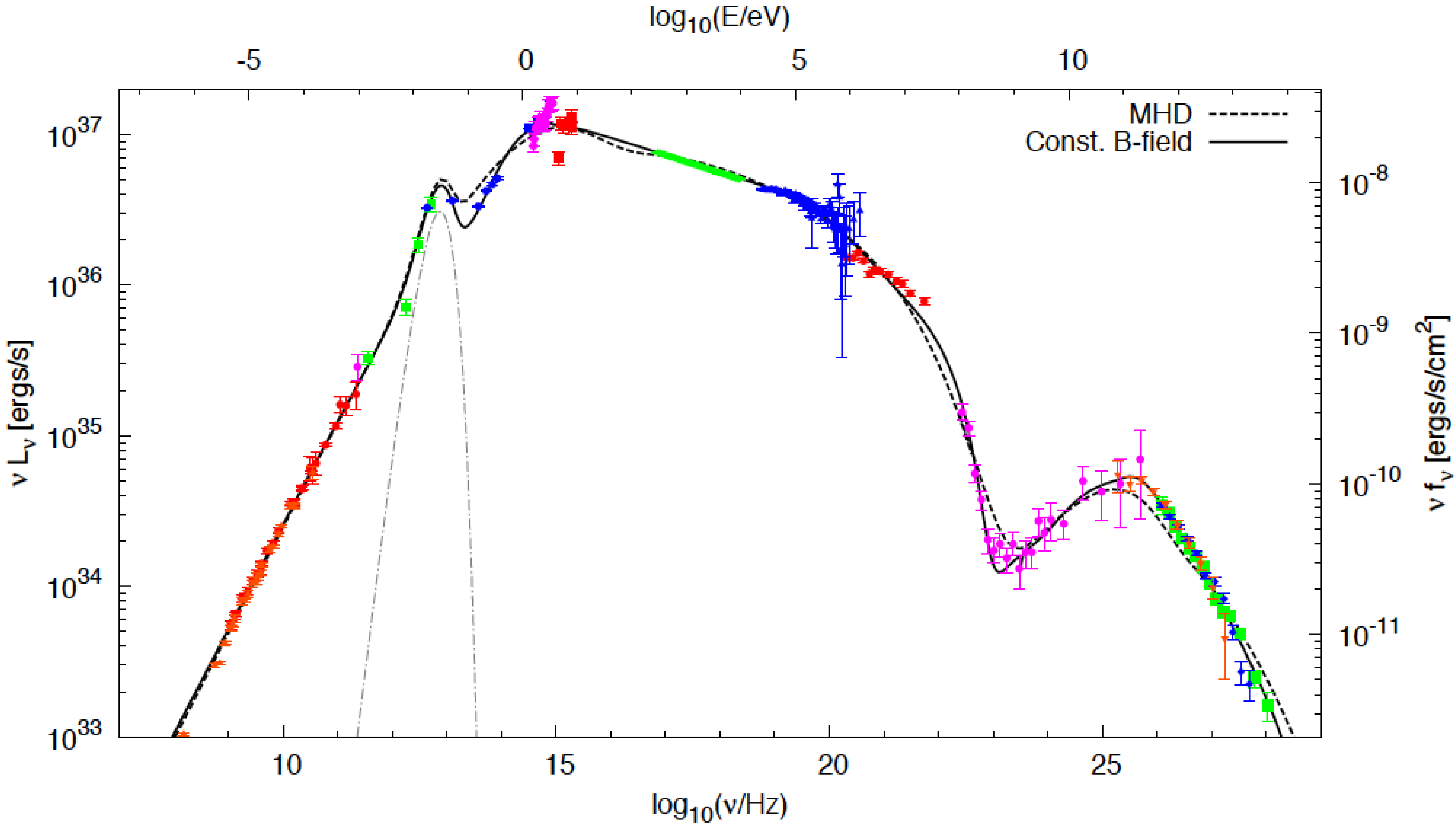


FIG. 1.— Light curve obtained with photons above 100 MeV within an energy-dependent circular region, as described in Section 4.1. The light curve profile is binned to 0.01 of pulsar phase. Insets show the pulse shapes near the peaks, binned to 0.002 in phase. The radio light curve (red line) is overlaid (arbitrary units). The main peak of the radio pulse seen at 1.4 GHz is at phase 0. Two cycles are shown.

Spectral Energy Distribution of the CRAB nebula



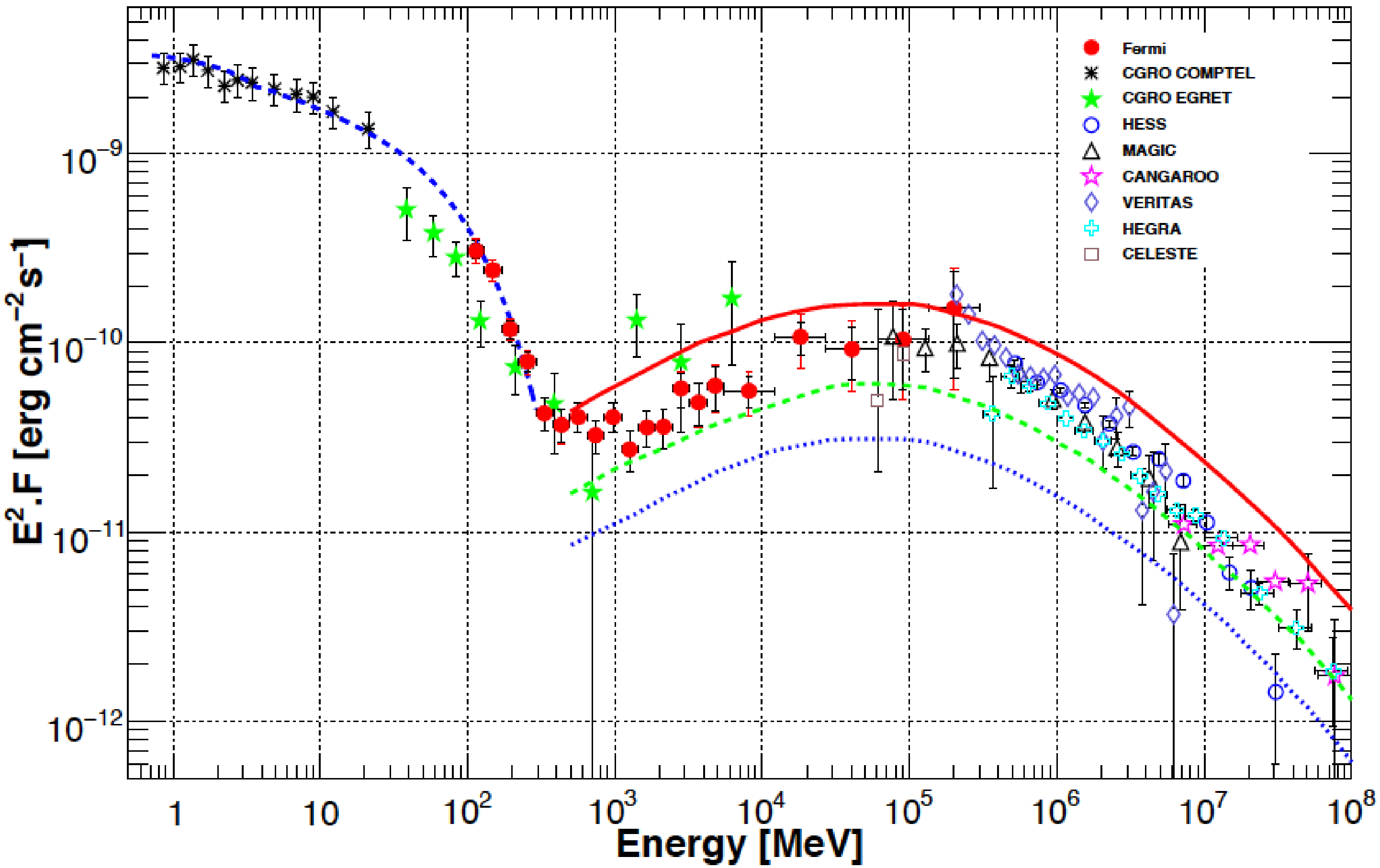


FIG. 9.— The spectral energy distribution of the Crab Nebula from soft to very high energy γ-rays. The fit of the synchrotron component, using COMPTEL and LAT data (blue dashed line), is overlaid. The predicted inverse Compton spectra from Atoyan and Aharonian (1996) are overlaid for three different values of the mean magnetic field: 100 μG (solid red line), 200 μG (dashed green line) and the canonical equipartition field of the Crab Nebula 300 μG (dotted blue line). References: CGRO COMPTEL and EGRET: Kuiper et al. (2001); MAGIC: Albert et al. (2008); HESS: Aharonian et al. (2006); CANGAROO: Tanimori et al. (1997); VERITAS: Celik (2007); **HEGRA: Aharonian et al. (2004); CELESTE: Smith et al. (2006)**

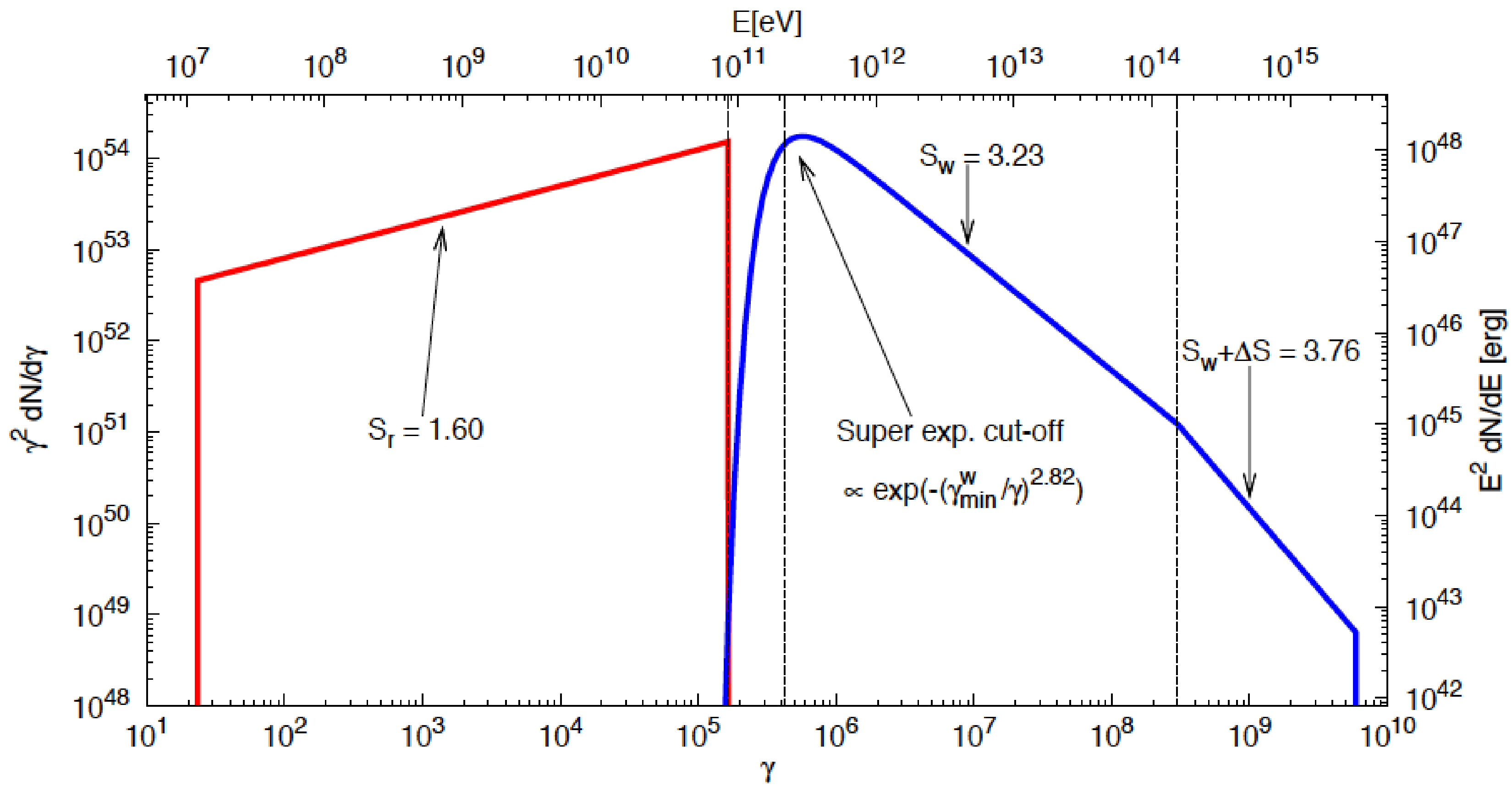
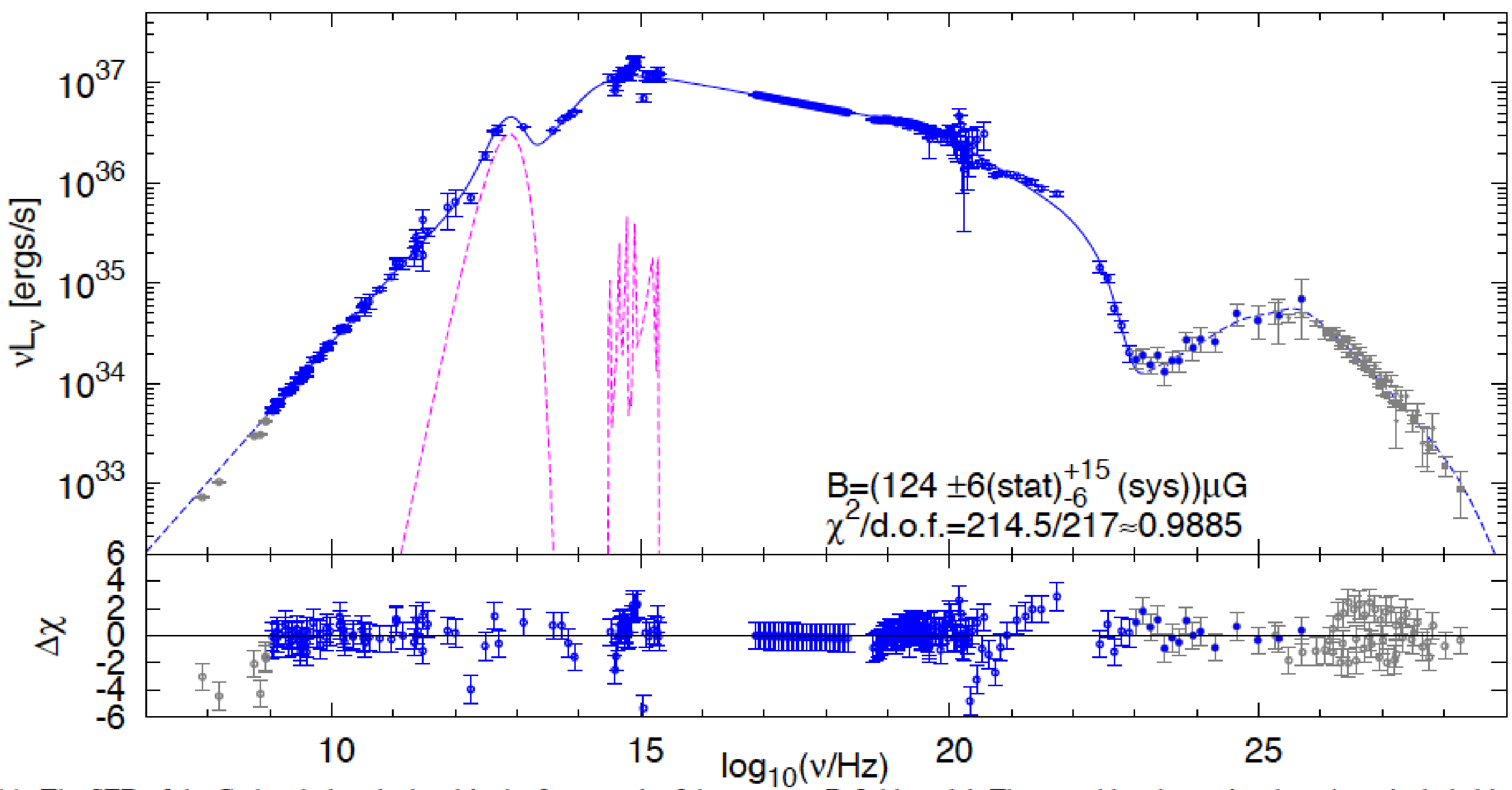
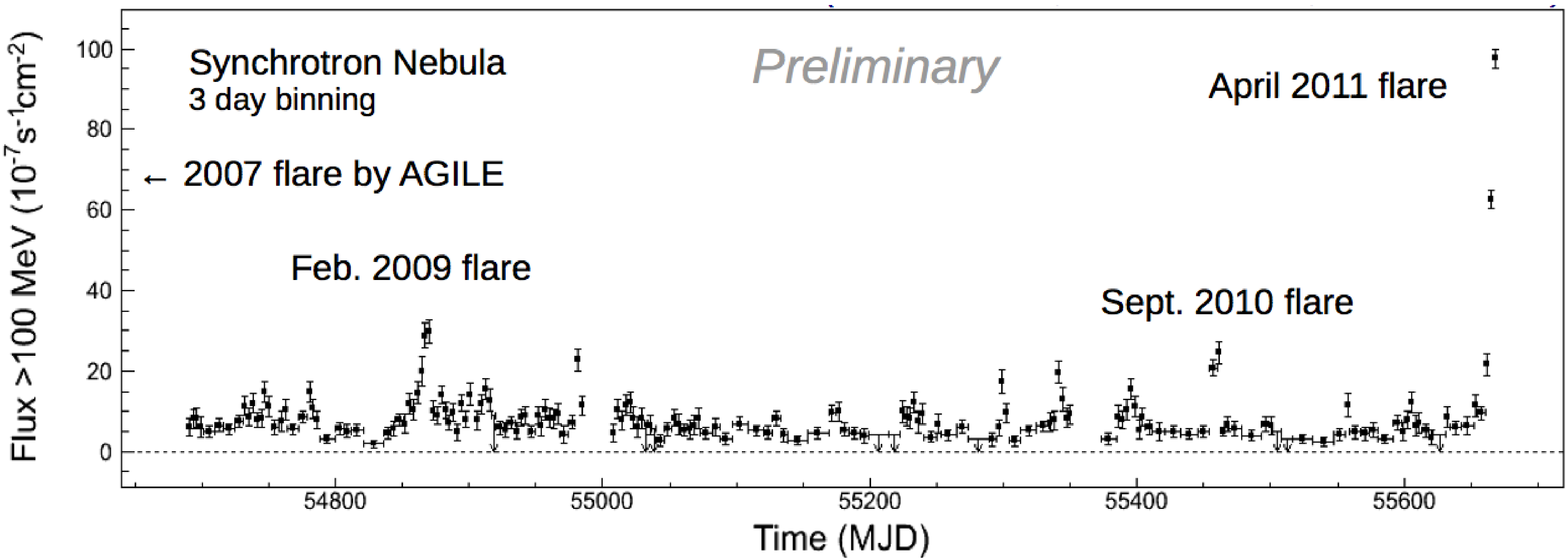


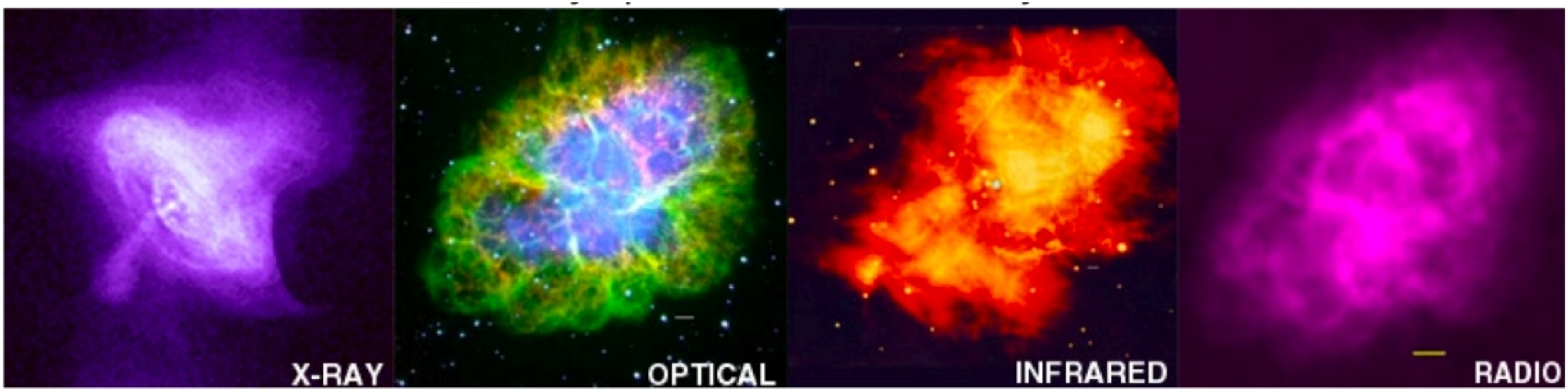
FIG. 4: The two components of the electron spectrum used to calculate the broad band emission of the Crab Nebula in the constant B-field model. Red solid line: radio electrons; blue solid line: wind electrons. The black dashed lines indicate the values fot the minimum, maximum, and break energies.



(a) The SED of the Crab nebula calculated in the framework of the constant B-field model. The open blue data points have been included in the fit for the synchrotron part and the filled blue points used to determine the best-fitting magnetic field.

CRAB NEBULA Flaring [!]



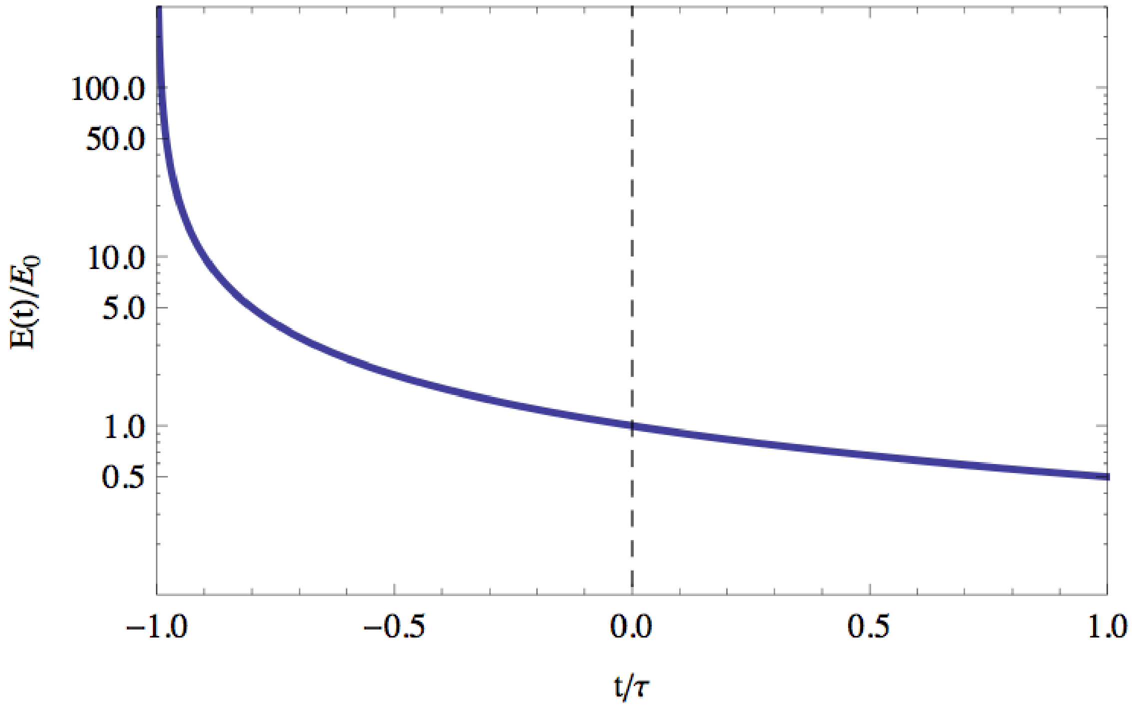


Electron/Positron propagation

$$-\frac{dE}{dt} \equiv \beta(E) \simeq b\ E^2$$

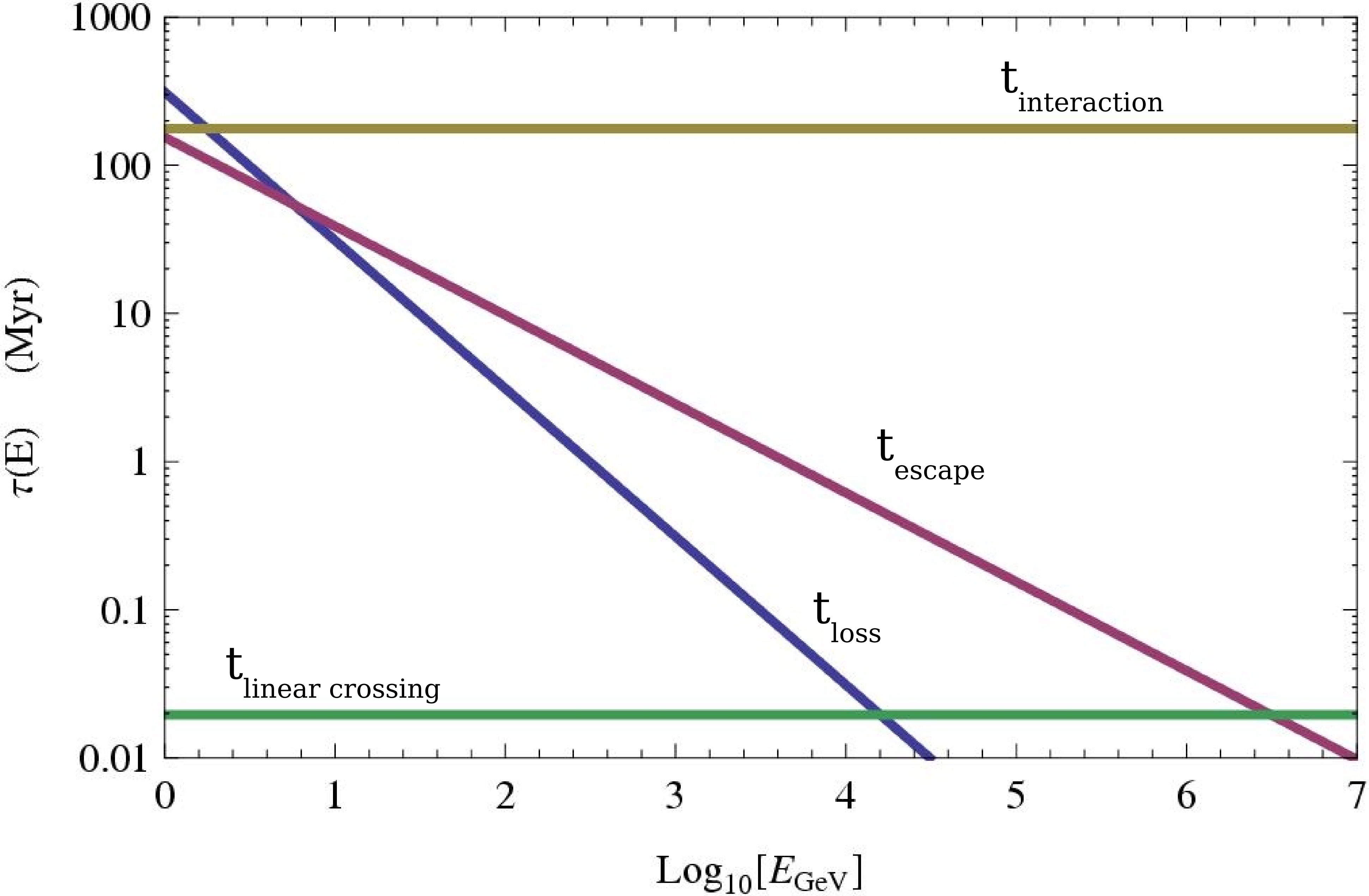
$$b = \frac{4}{3}\,\sigma_{\rm Thomson}\,c\ \left[\frac{B^2}{8\,\pi} + \rho_\gamma\right]\ \frac{1}{m^2}$$

$$E(E_0, t) = \frac{E_0}{1 + b\,E_0\,t}$$



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

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



1000
100
10
1
0.1
0.01
τ(E) (Myr)
0
1
2
3
4
5
6
7
Log10[E_GeV]
t_interaction
t_escape
t_loss
t_linear crossing

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

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

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

$$\alpha_0 \simeq 2.04$$

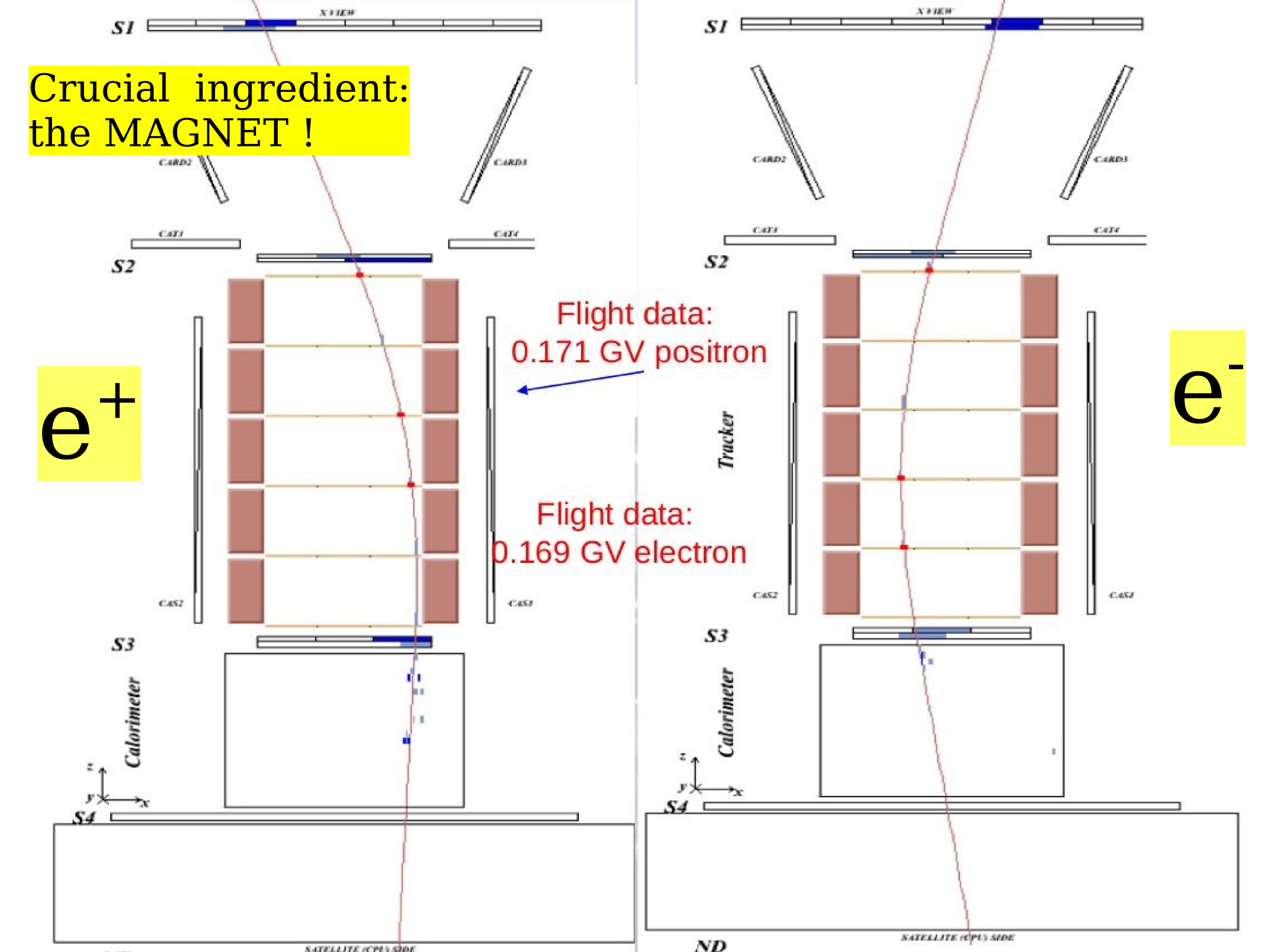
$$\delta \simeq 0.66$$

PAMELA

detector

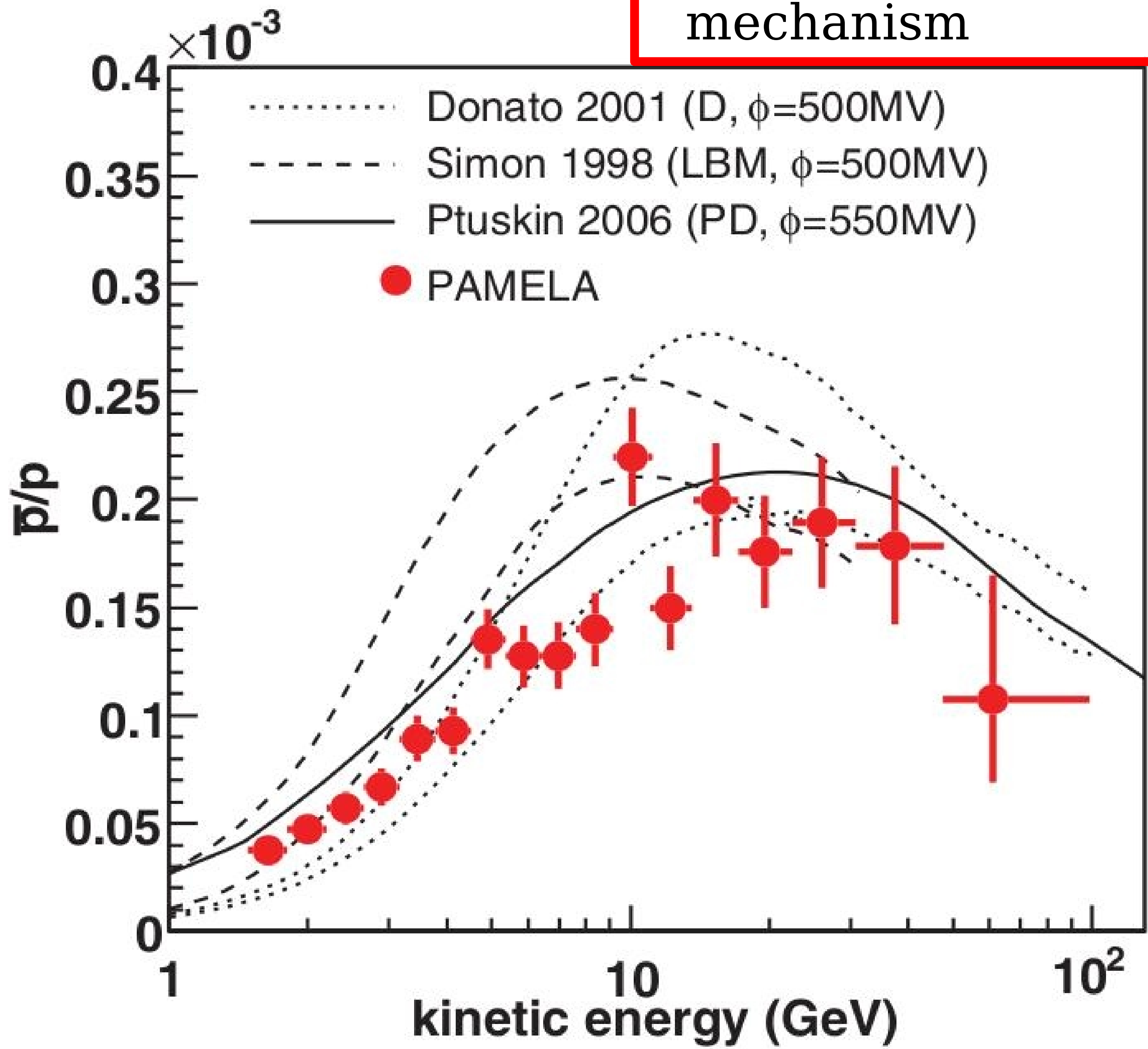
Launch
15th june 2006

The "positron excess":
Evidence for DM ??
or astrophysical effect ?

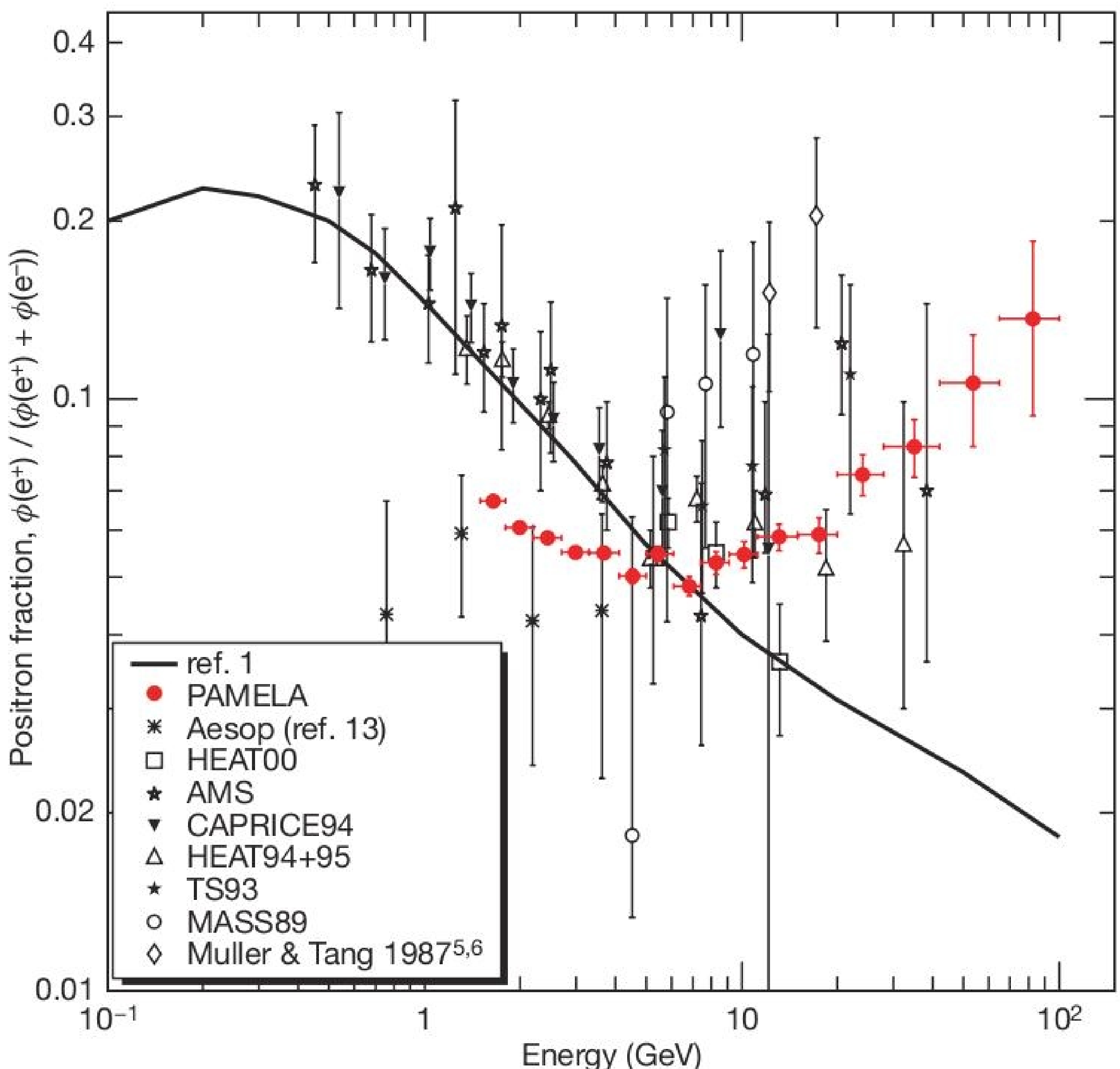

Crucial ingredient:
the MAGNET !
e^+
e^-
Flight data:
0.171 GV positron
Flight data:
0.169 GV electron
S1
S2
S3
S4
Tracker
Calorimeter
ND

Antiproton result

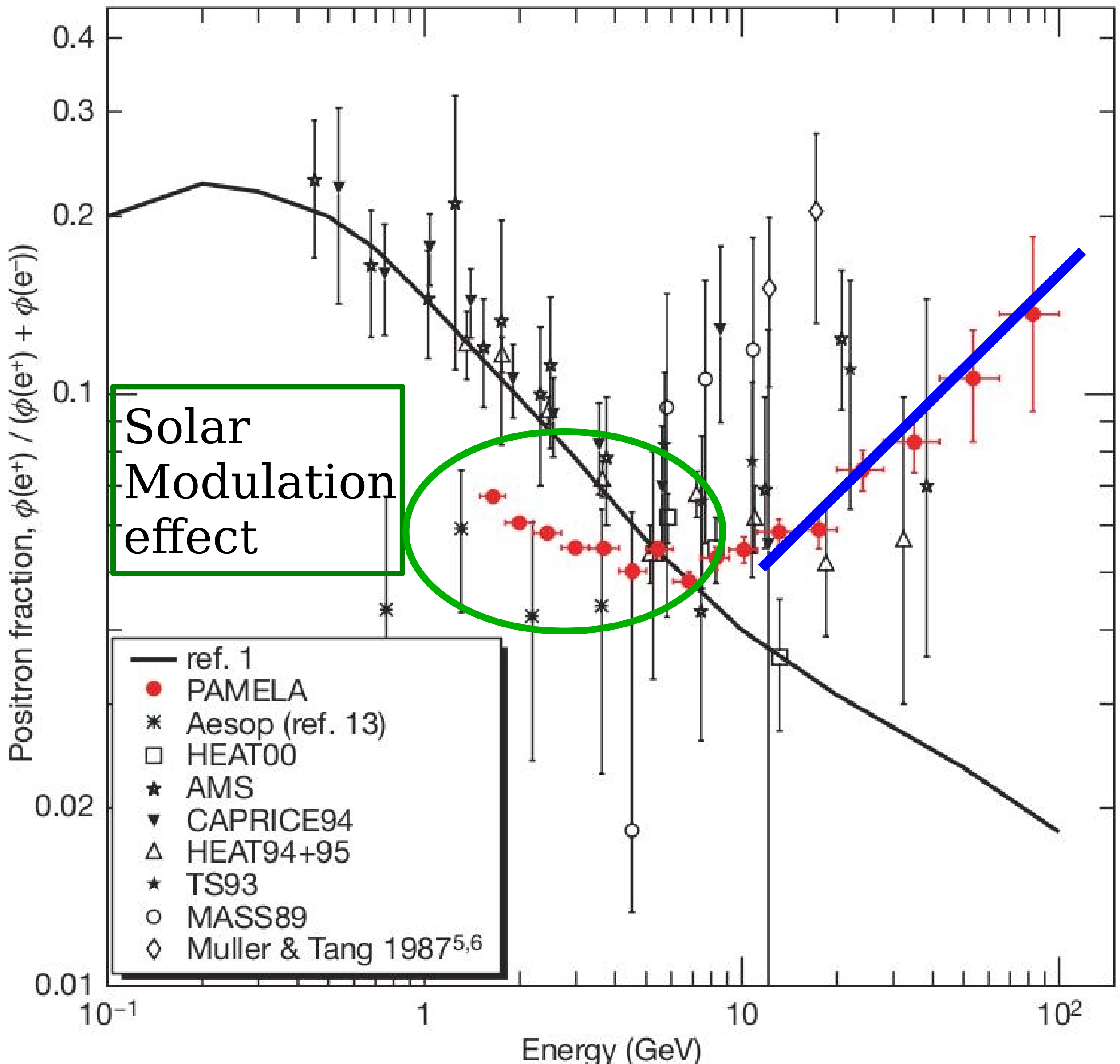
Agreement
With standard production mechanism



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



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

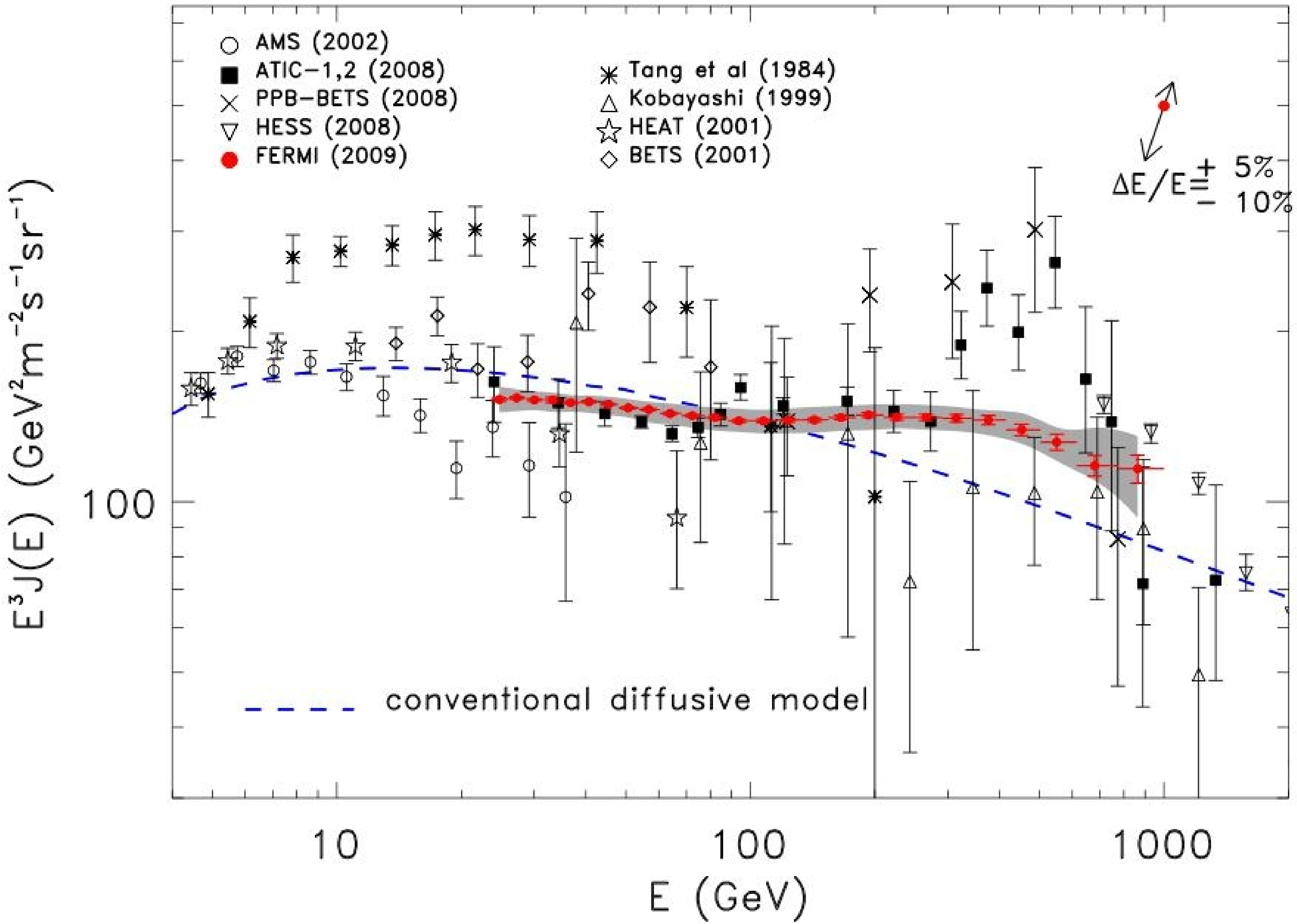


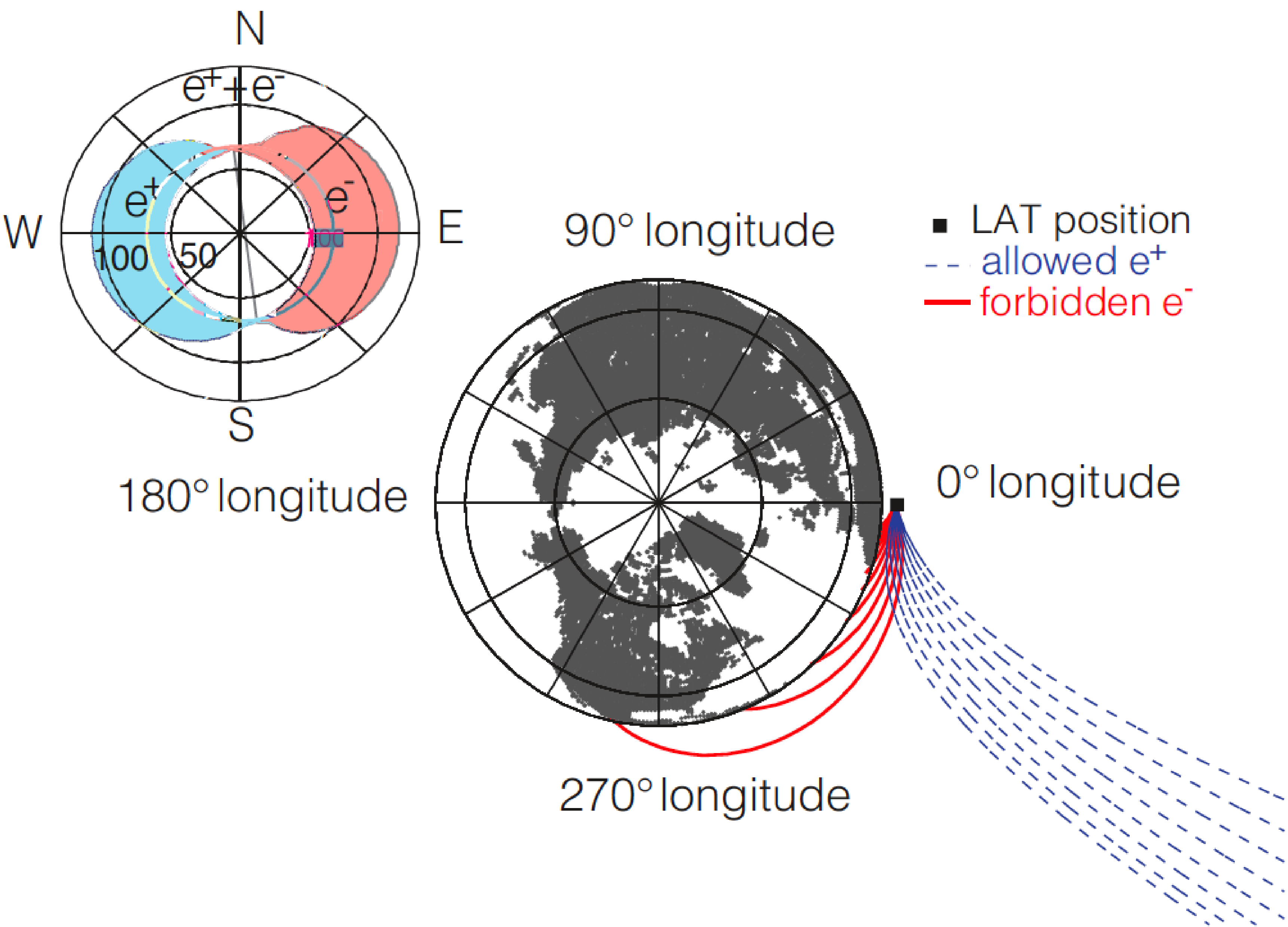
High energy: ratio e+/e- grow with E !!

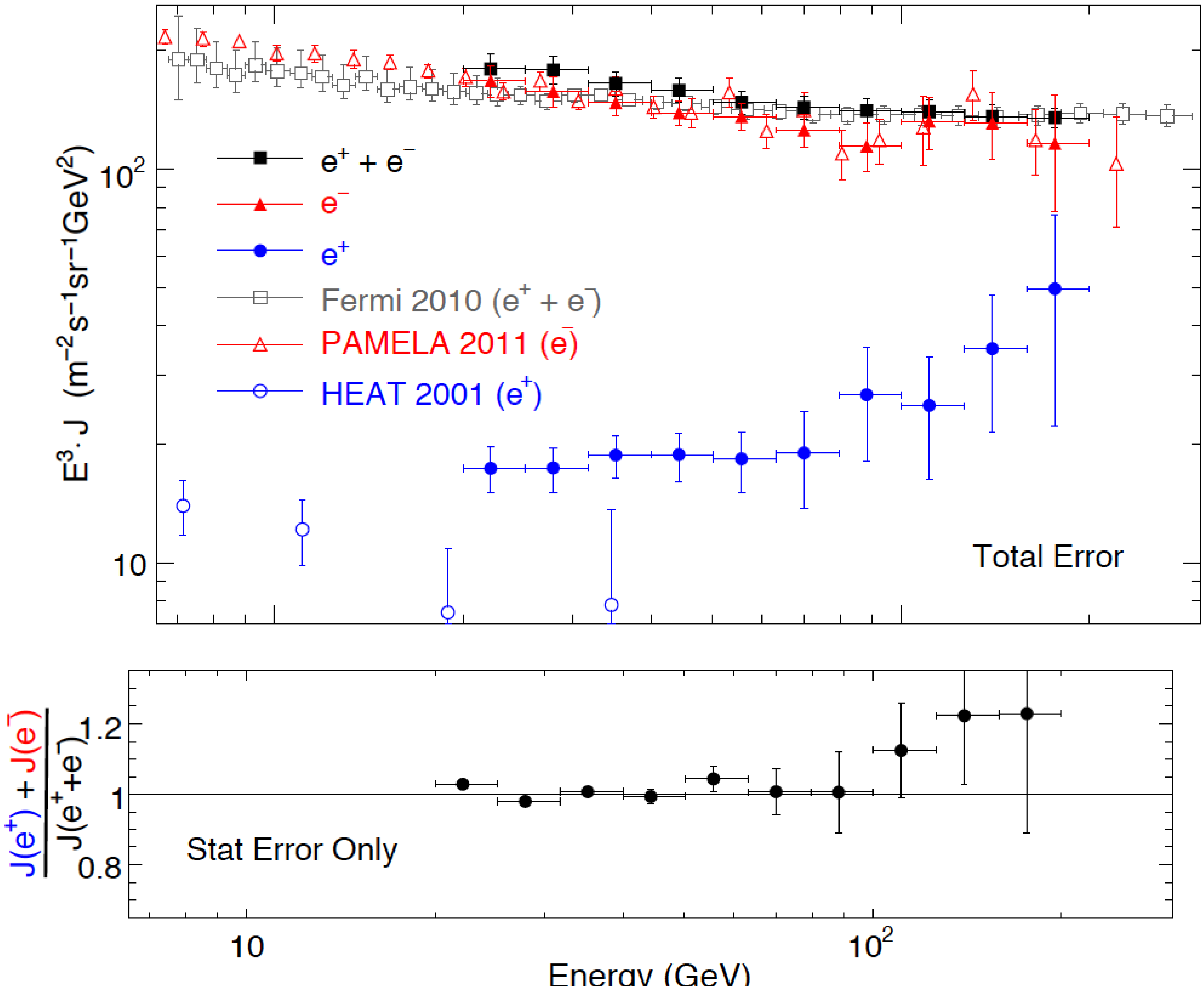
$$\frac{\phi_{e^+}}{\phi_{e^-}} \propto E^{0.52}$$

Very unexpected result !

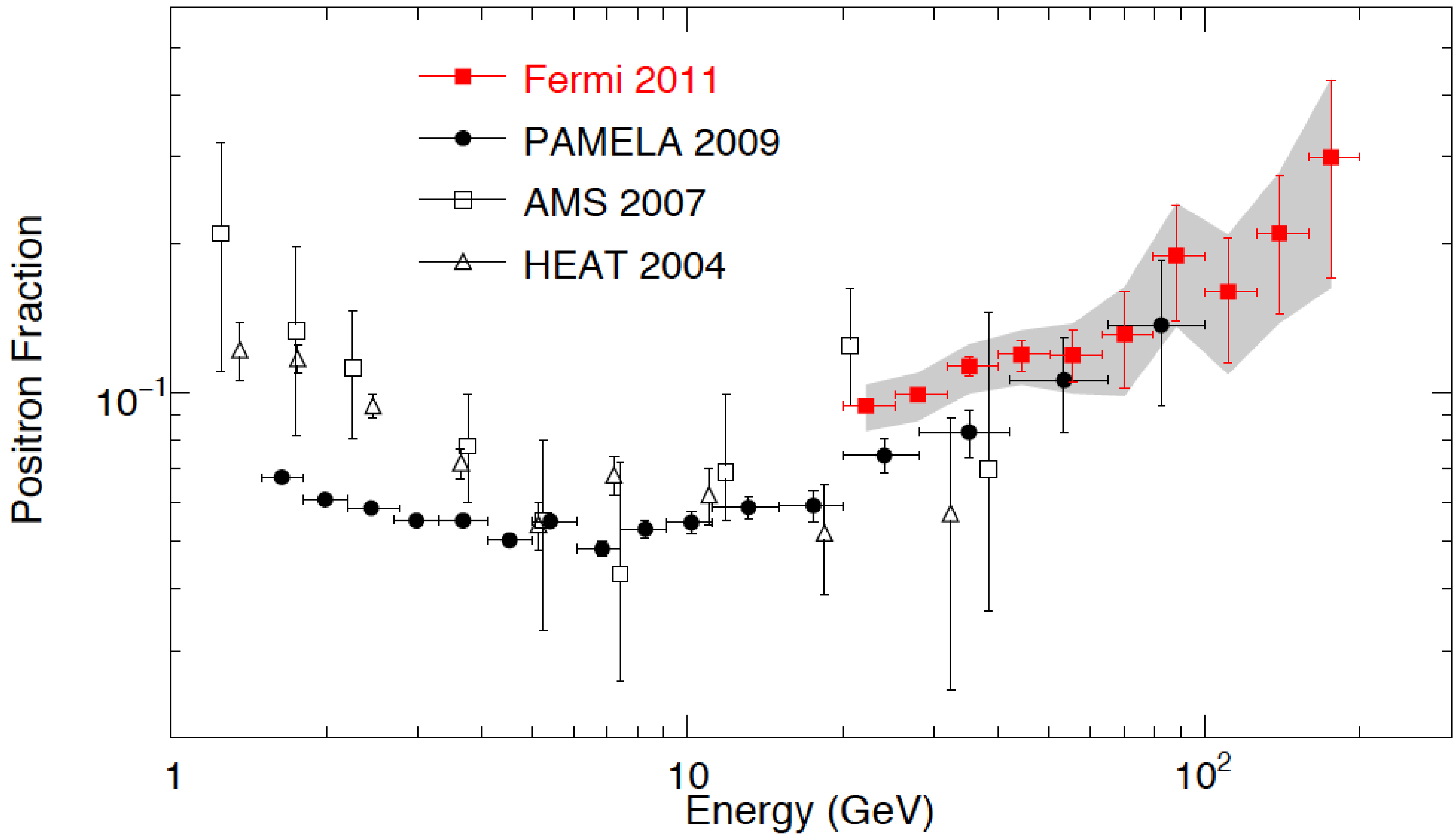
FERMI: electron + positron flux




N
e+ + e-
e+
e-
W
E
100
50
100
S
90° longitude
180° longitude
0° longitude
270° longitude
LAT position
allowed e+
forbidden e-



e+ + e−
e−
e+
Fermi 2010 (e+ + e−)
PAMELA 2011 (e−)
HEAT 2001 (e+)
Total Error
E3 · J (m−2s−1sr−1GeV2)
10
10^2
J(e+) + J(e−) / J(e+ + e−)
1.2
1
0.8
Stat Error Only
10
10^2
Energy (GeV)


Fermi 2011
PAMELA 2009
AMS 2007
HEAT 2004
Positron Fraction
10^{-1}
1
10
10^2
Energy (GeV)

From : Cirelli

Results

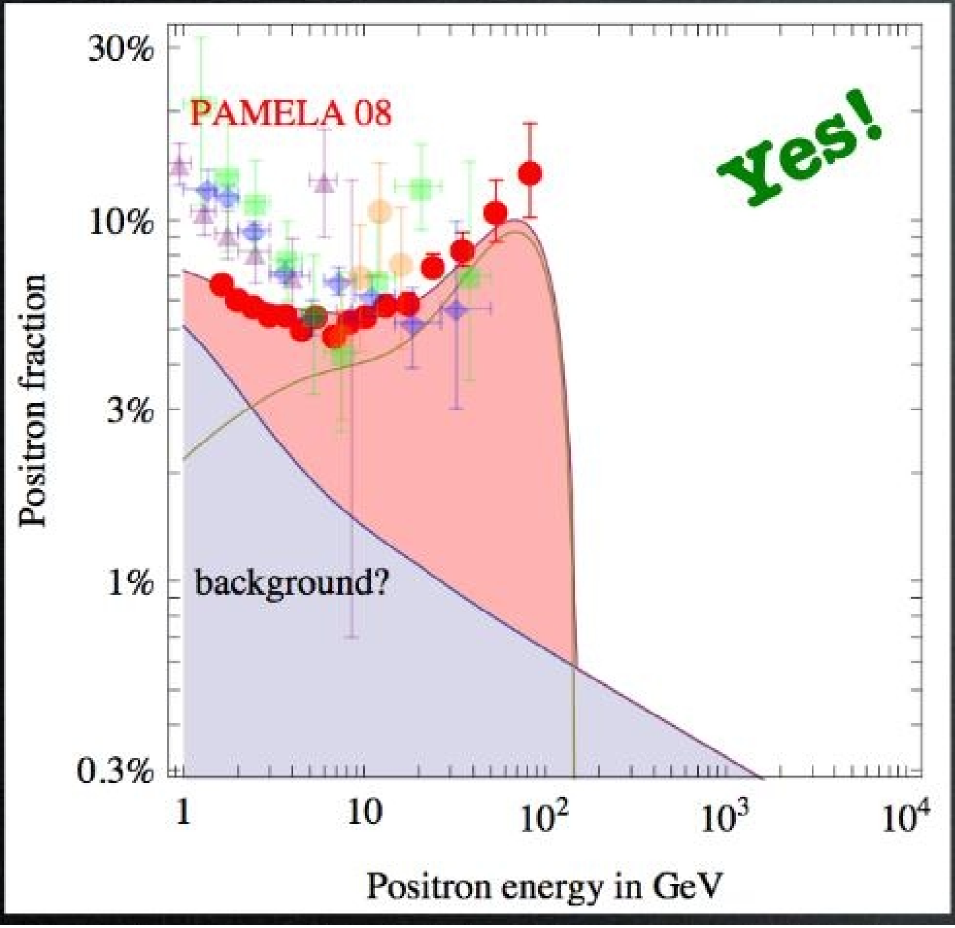
Which DM spectra can fit the data?

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

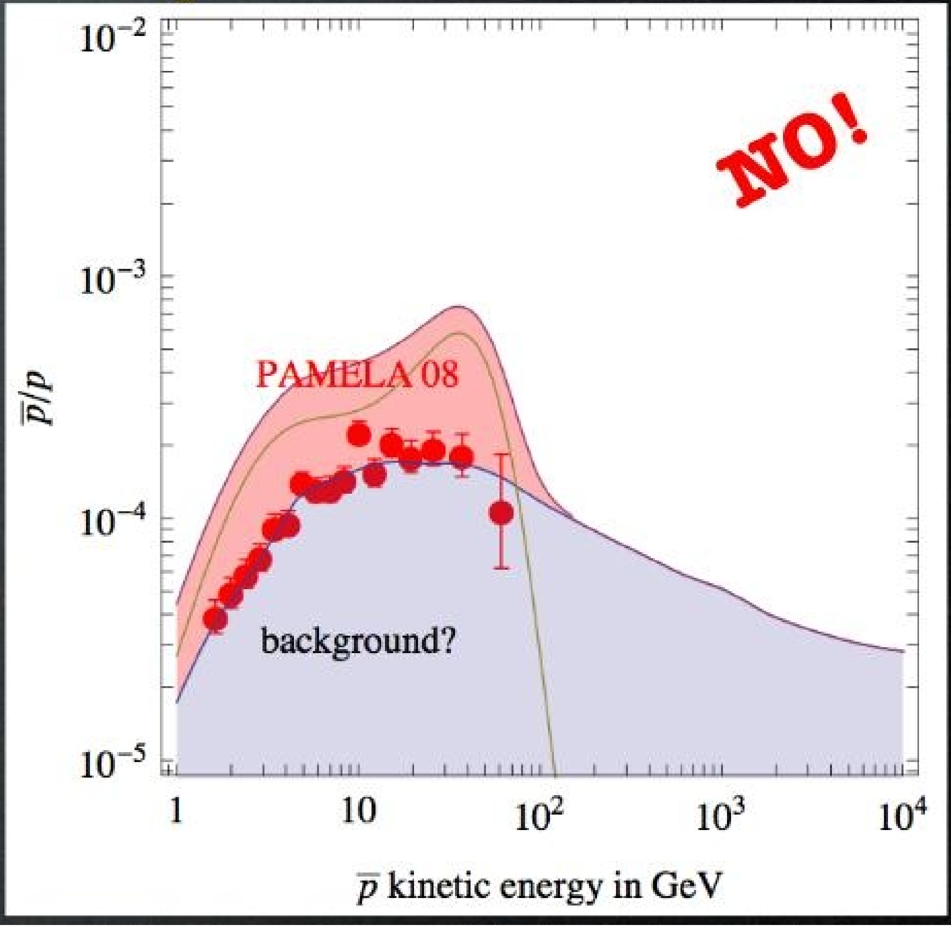
-annihilation $\text{DM DM} \to W^+W^-$

(a possible SuperSymmetric candidate: wino)

Positrons:



Anti-protons:



Results

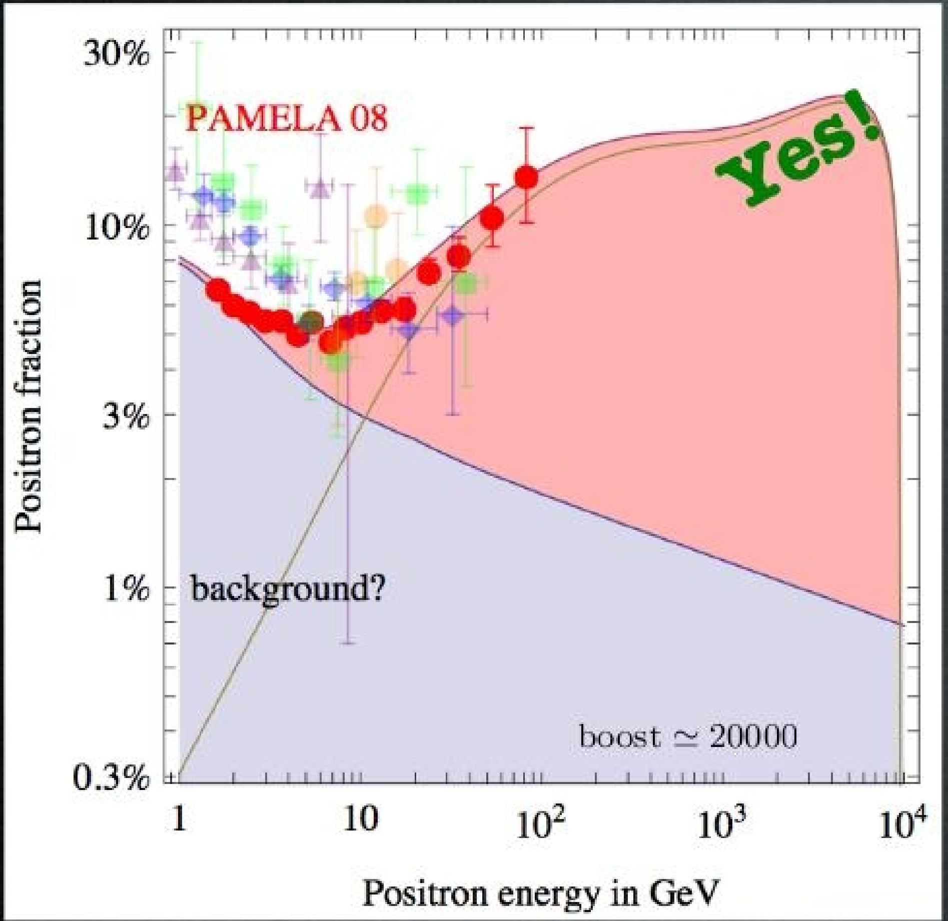
Which DM spectra can fit the data?

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

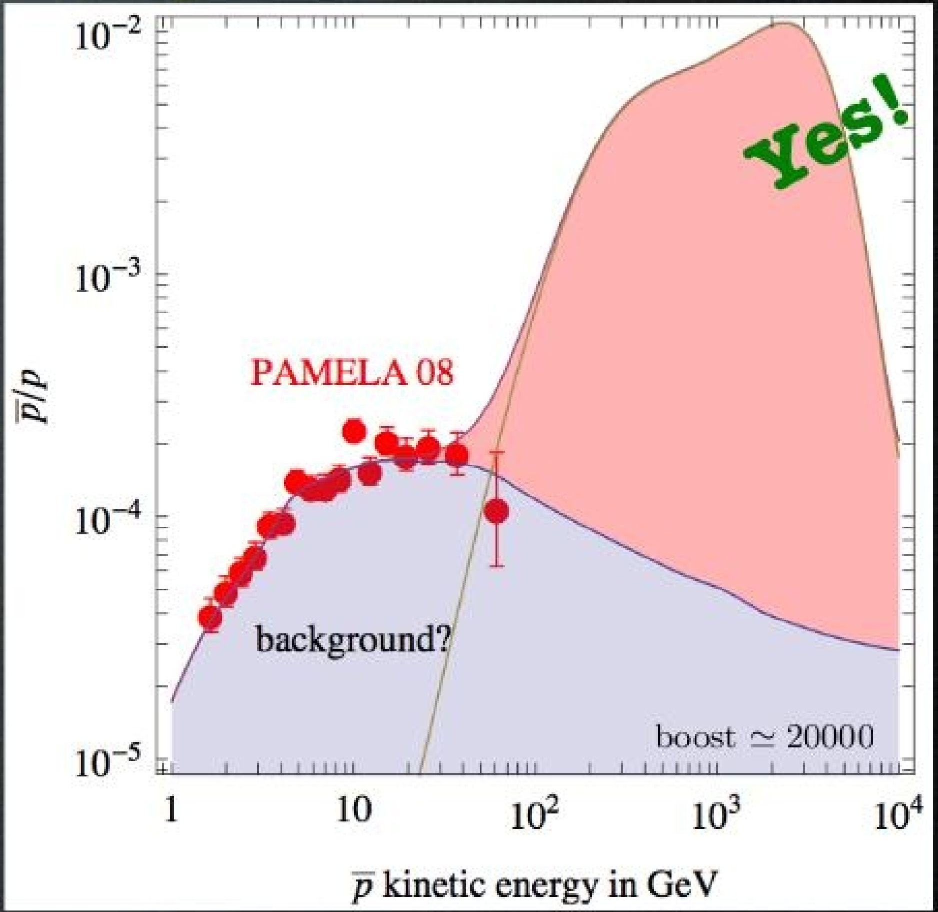
-annihilation $\rm DM\ DM \to W^+W^-$

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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Very "clumpy" dark matter.
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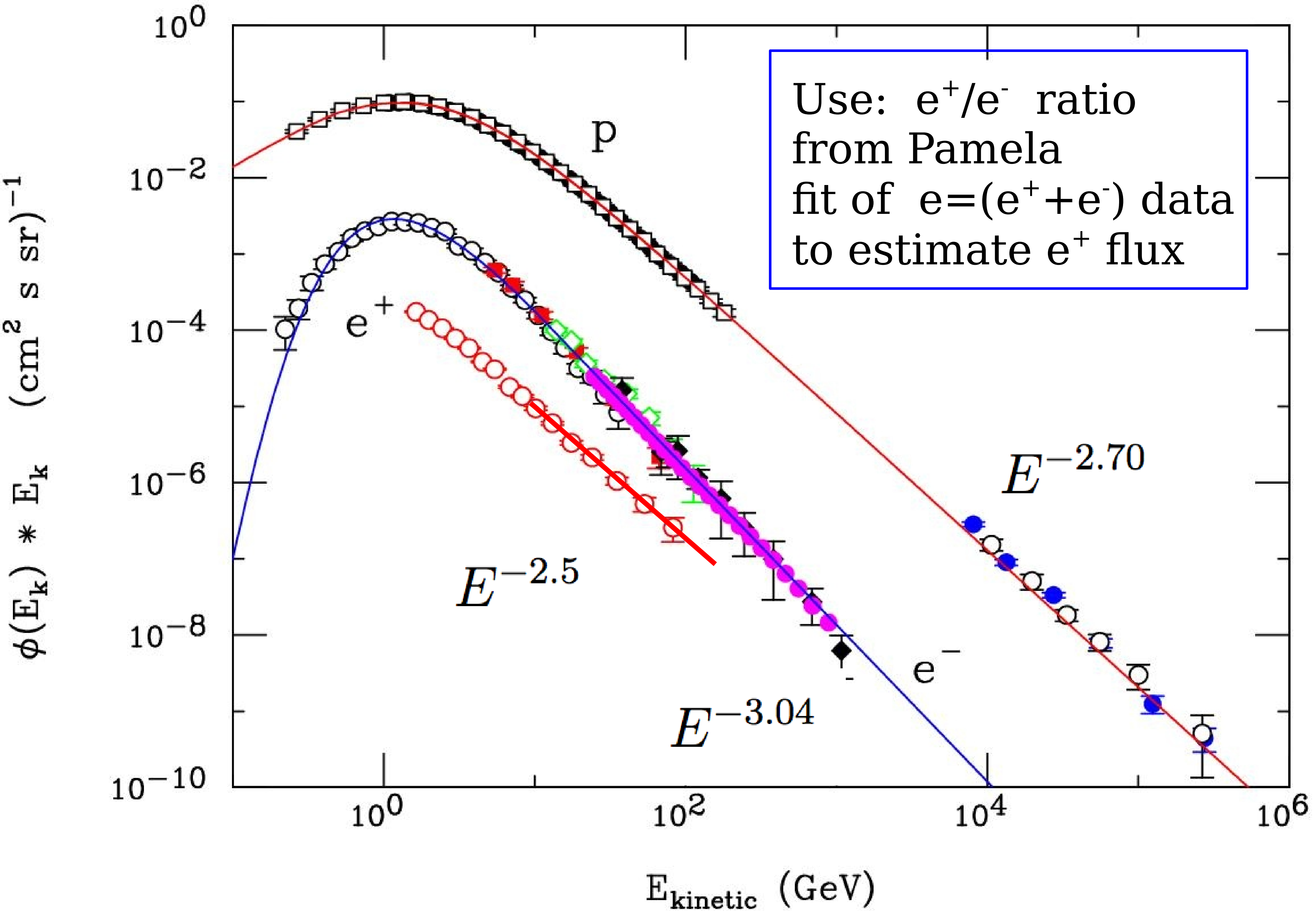
"winning the jackpot" [?]

Is this "adding epicycles" to the wrong theory ?

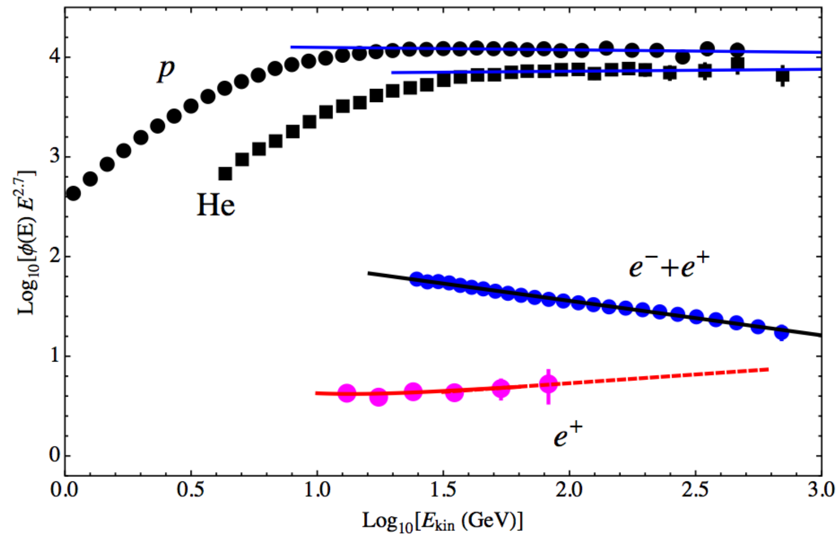
Are there other possible interpretations for this result.

Proton and electron + Positron energy spectra



Spectra approximately of form:

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



$E^{-3.1}$

$E^{-3.5}$

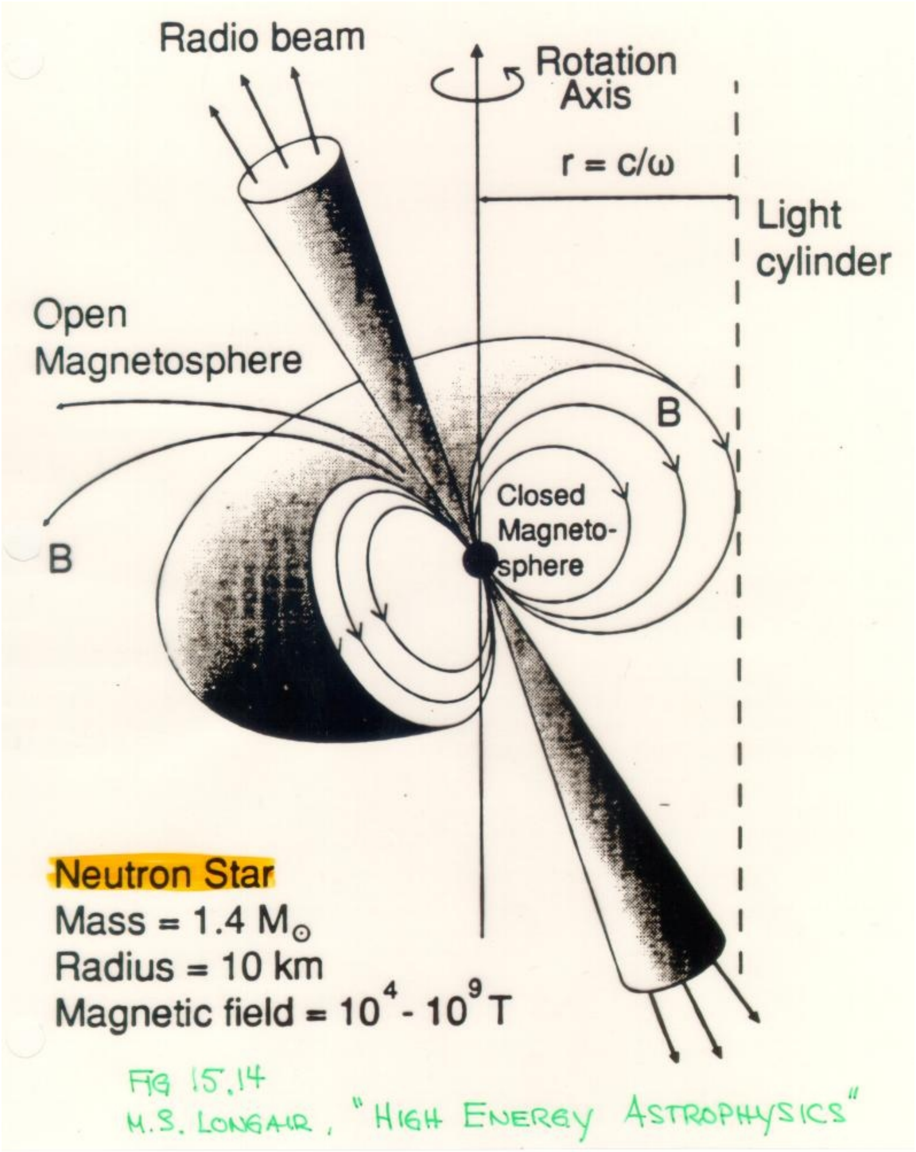
Completely unexpected result

Rough expectation
For the positron slope
SOFTER than electrons

NEW SOURCE of POSITRONS
seems NECESSARY

PULSARS

Proposed as possible Accelerators of e+ e-



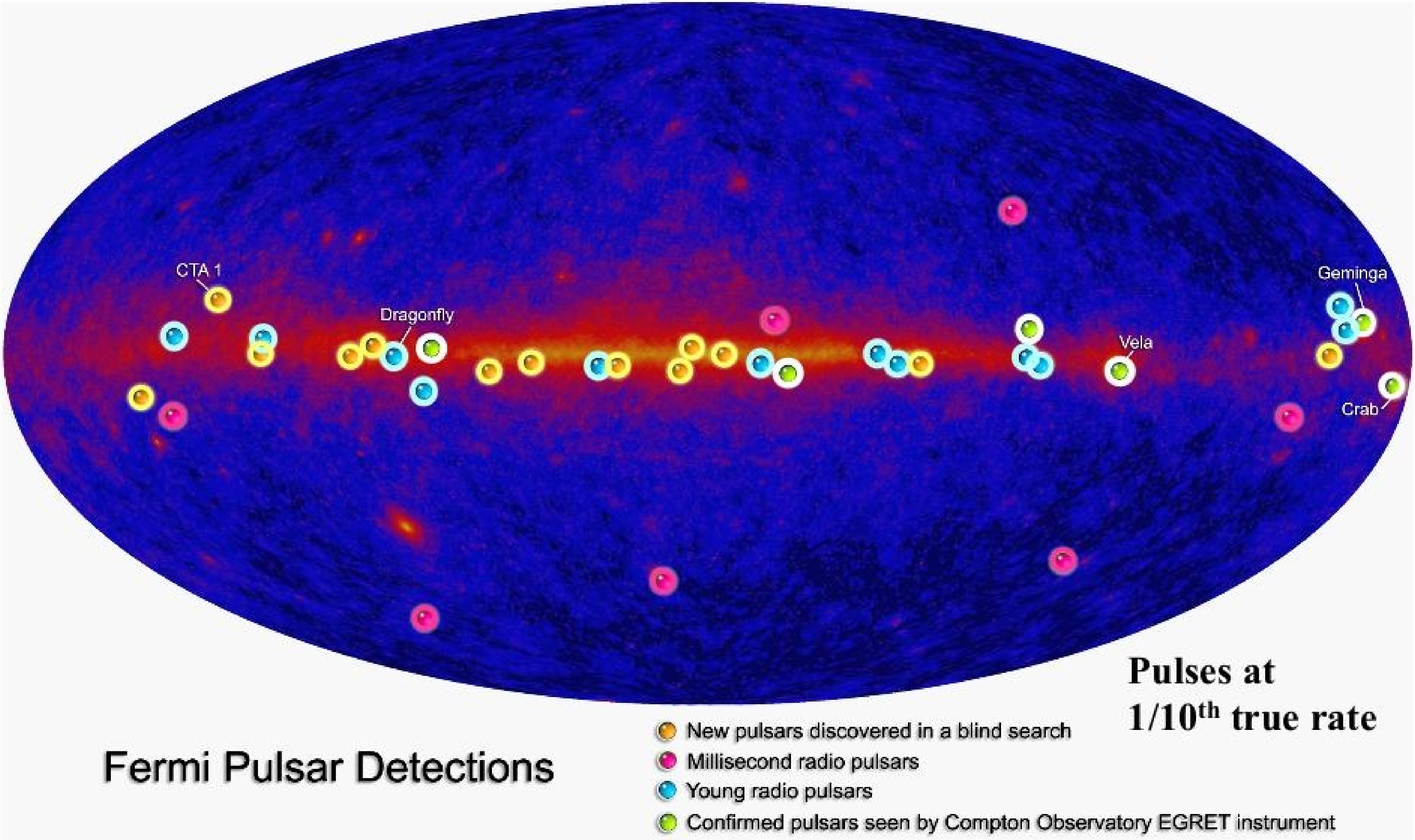
CRAB Nebula

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

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

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

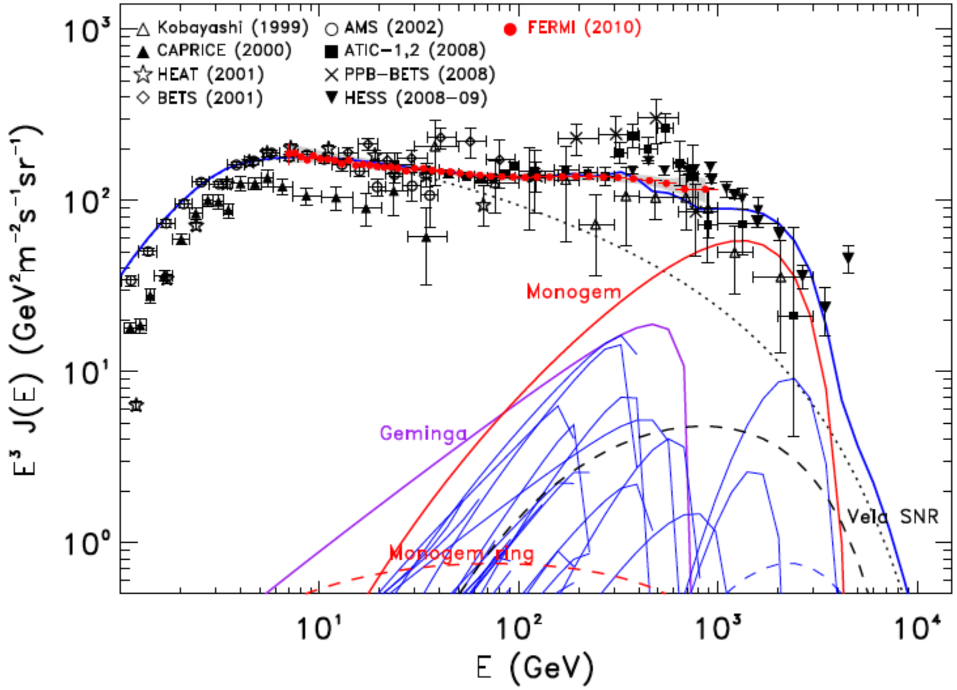
Fermi Pulsar detection

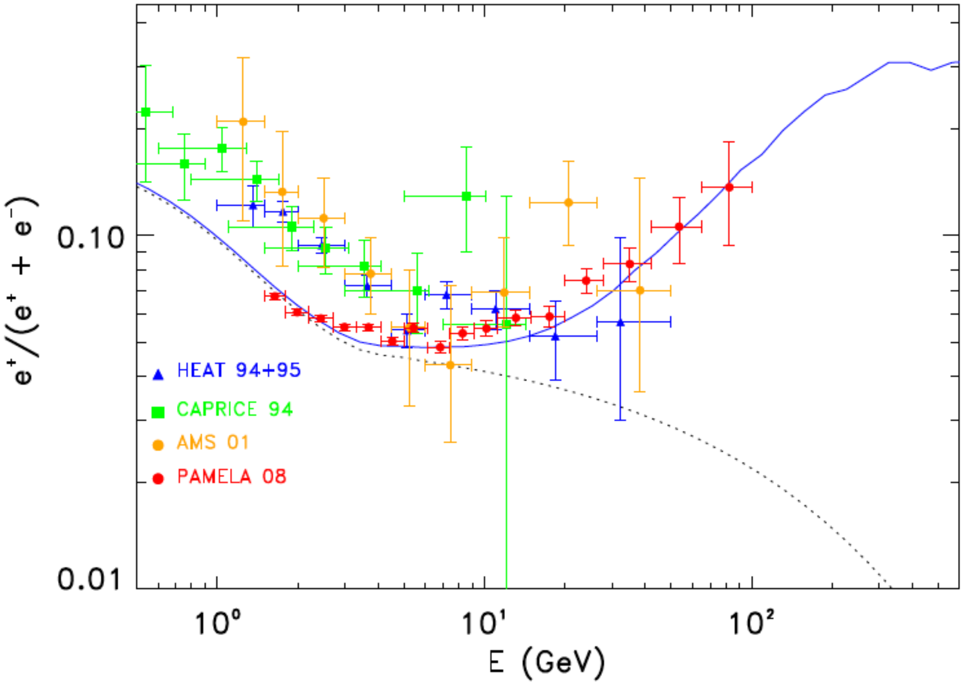


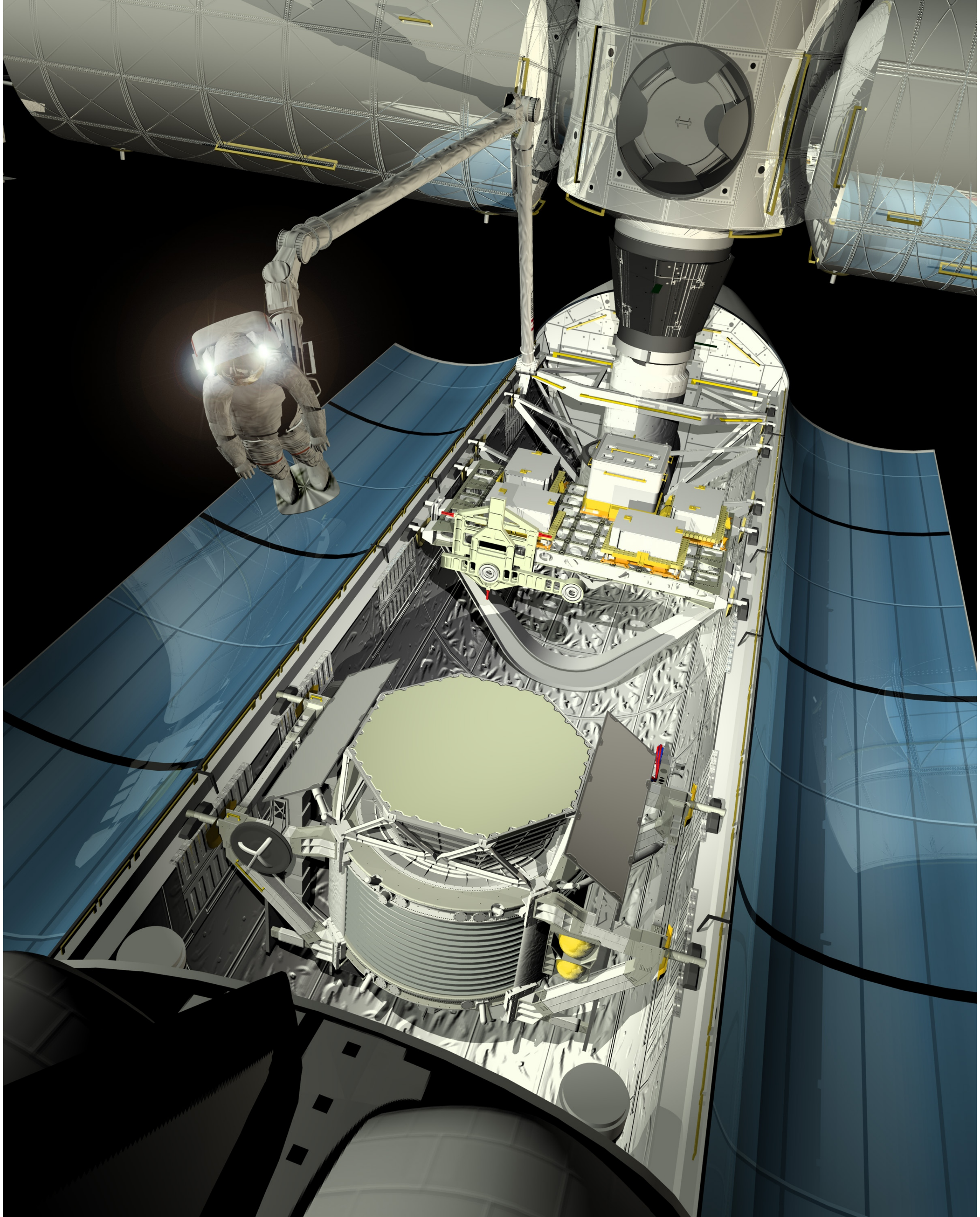
Implications of the Cosmic Ray Electron Spectrum and Anisotropy measured with Fermi-LAT

Giuseppe Di Bernardo[a], Carmelo Evoli[d], Daniele Gaggero[b,c], Dario Grasso[c,b,*], Luca Maccione[e], Mario Nicola Mazziotta[f]

arXiv:1010.0174







Importance of

AMS

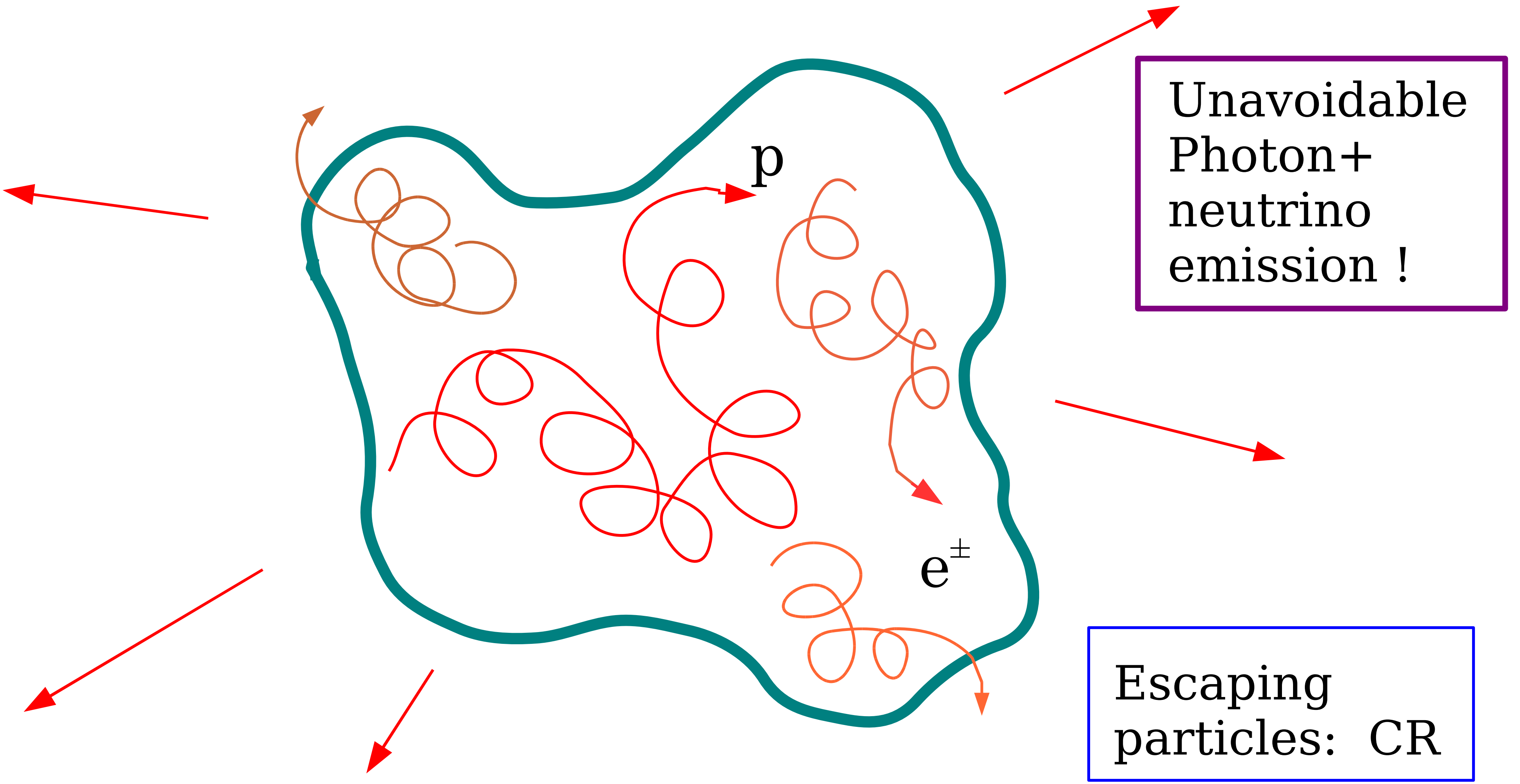
Mission.

Launch May 2011


+00 00 31

High Energy Astrophysical Source:

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



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

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

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

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

$$\pi^{\circ} \rightarrow \gamma + \gamma$$

"Hadronic Emission"

"Leptonic Emission"

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

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

Multi-messenger Astrophysics

COSMIC RAY physics

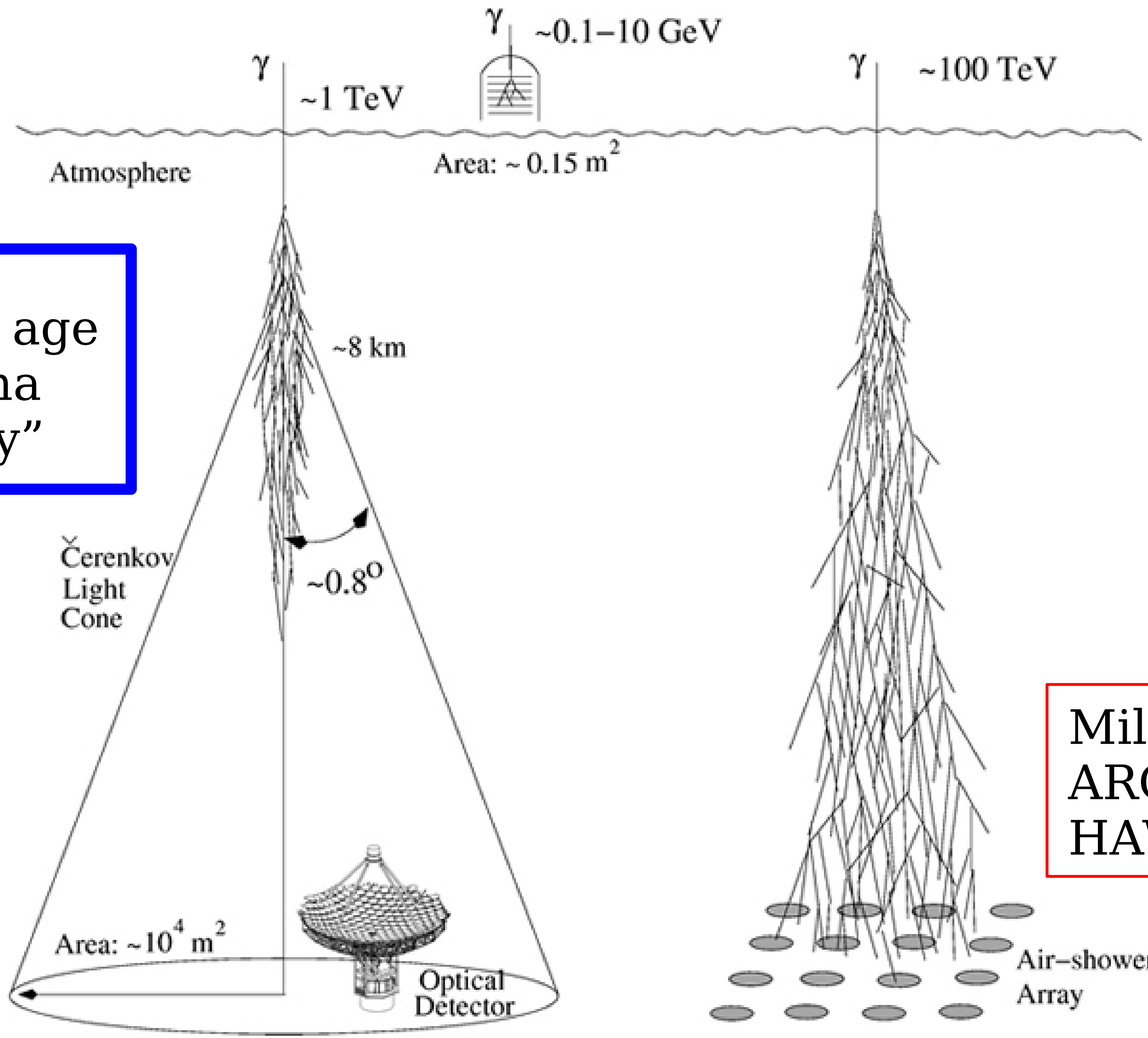
GAMMA Astronomy

NEUTRINO Astronomy

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

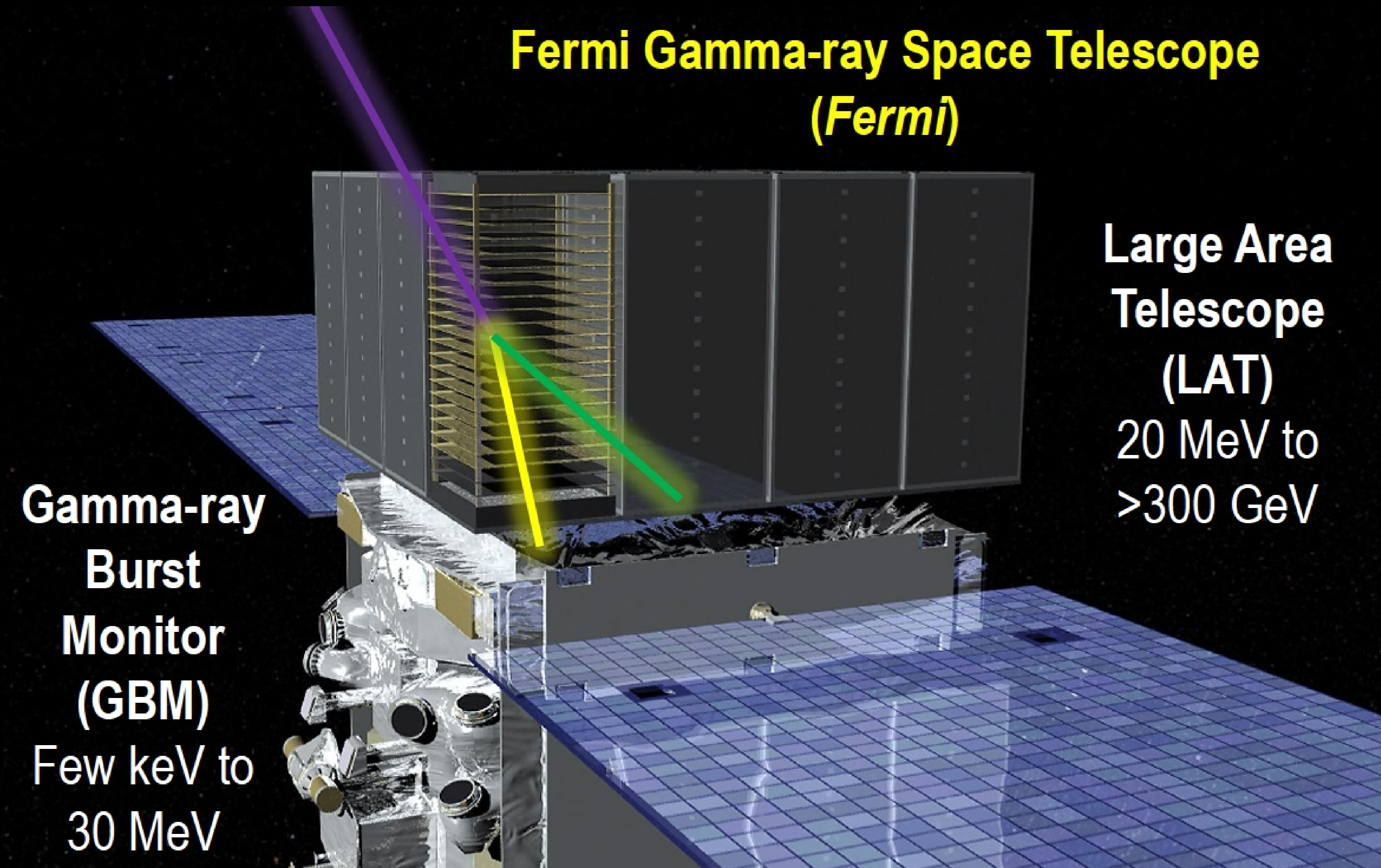
Egret
Agile
Fermi

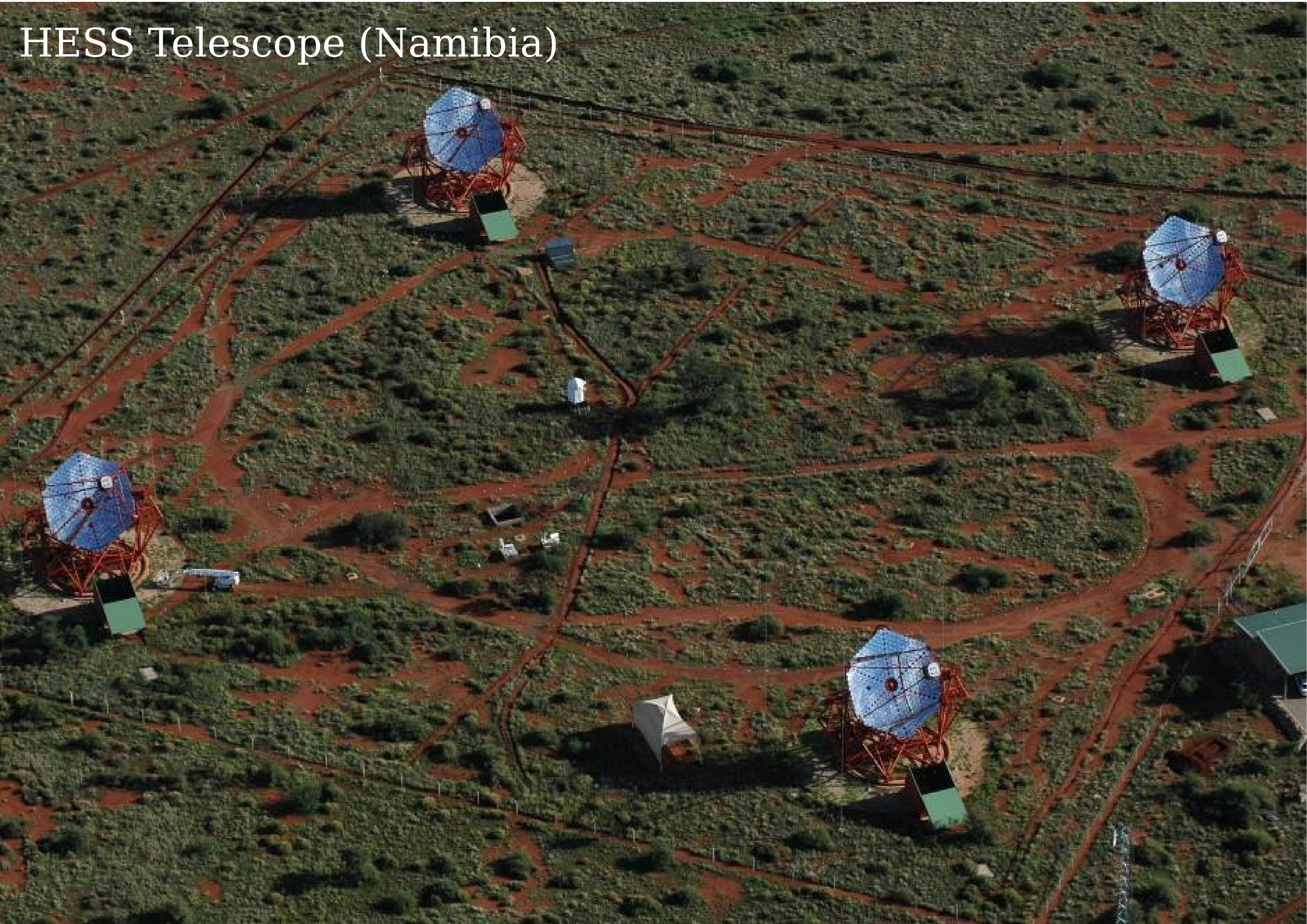
“A golden age
For Gamma
Astronomy”



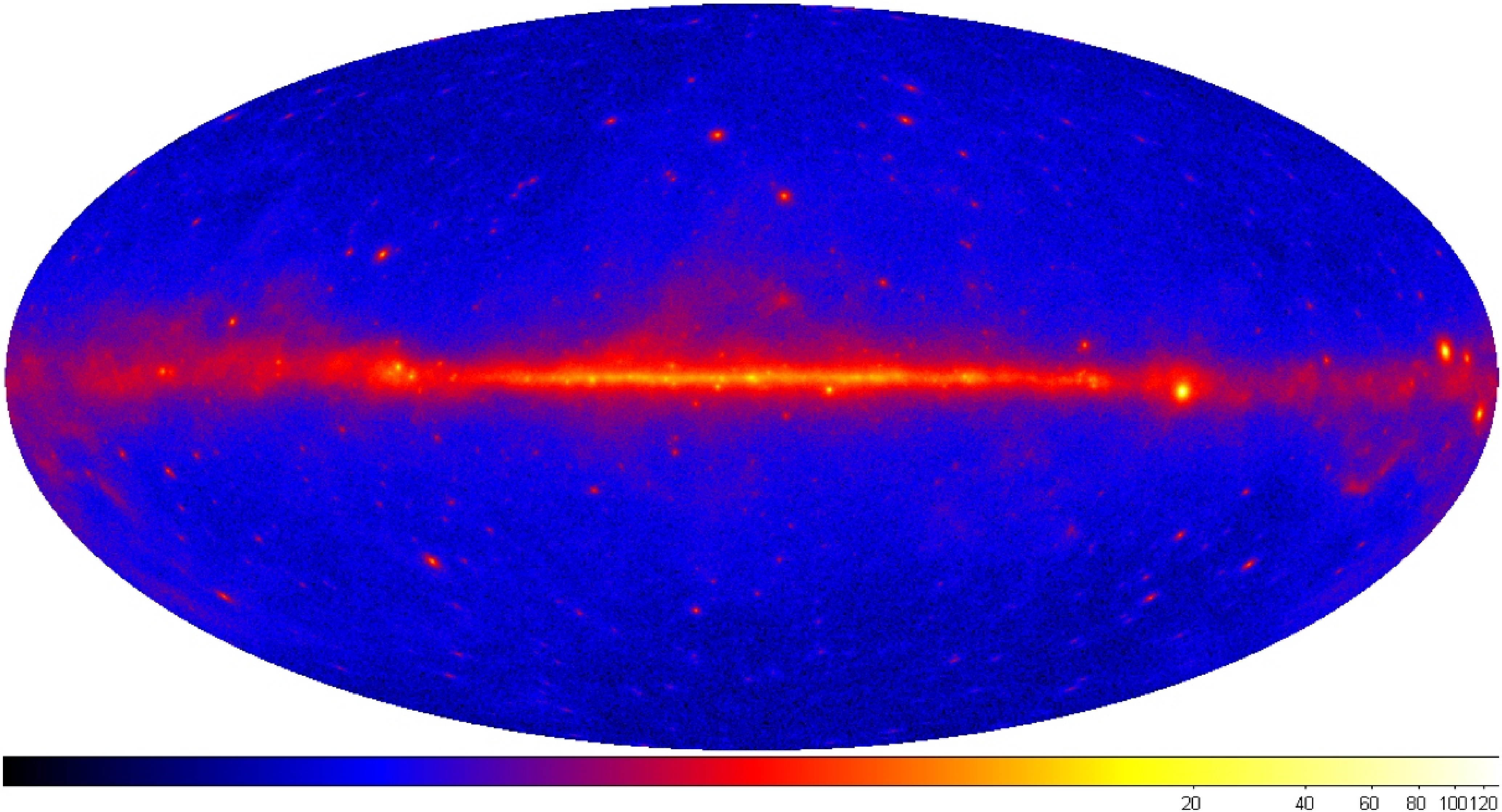
Milagro
ARGO
HAWC

Hess
Magic
Veritas
CTA


Fermi Gamma-ray Space Telescope
(*Fermi*)
Large Area
Telescope
(LAT)
20 MeV to
>300 GeV
Gamma-ray
Burst
Monitor
(GBM)
Few keV to
30 MeV

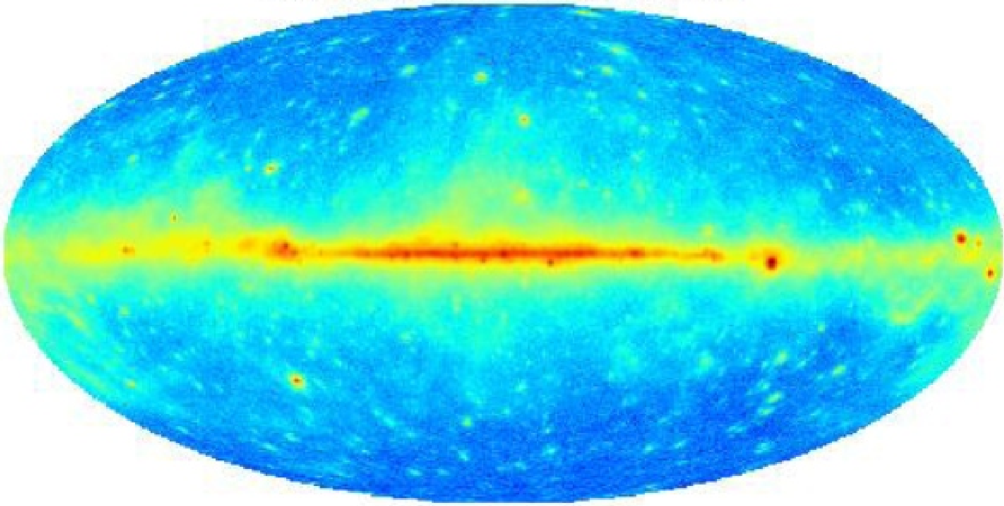

HESS Telescope (Namibia)

The “RICHNESS” of GAMMA ASTRONOMY”

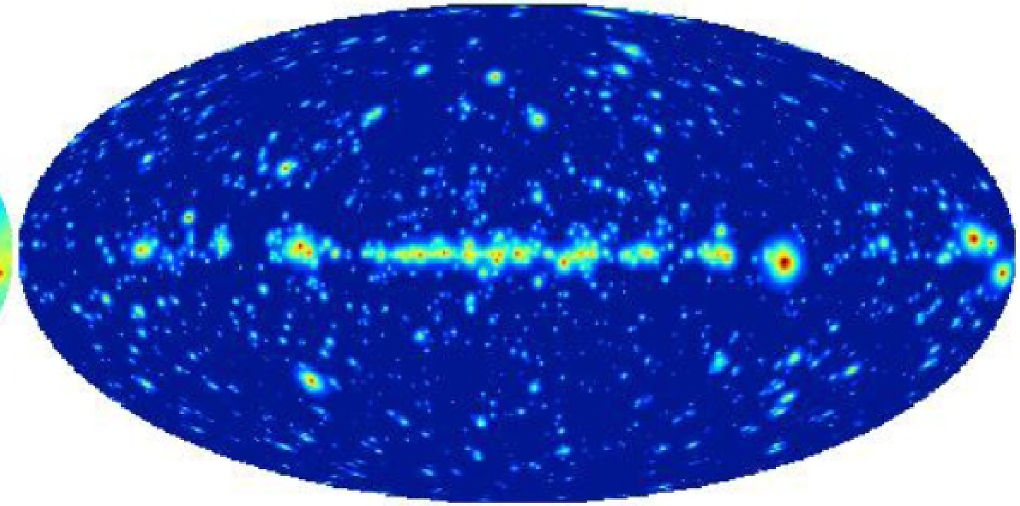


FERMI Sky

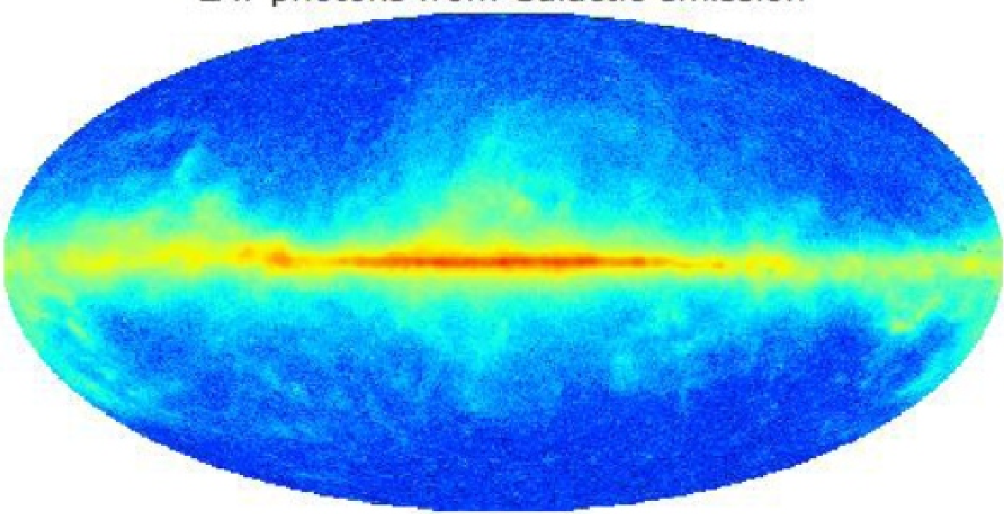
LAT photons above 300 MeV

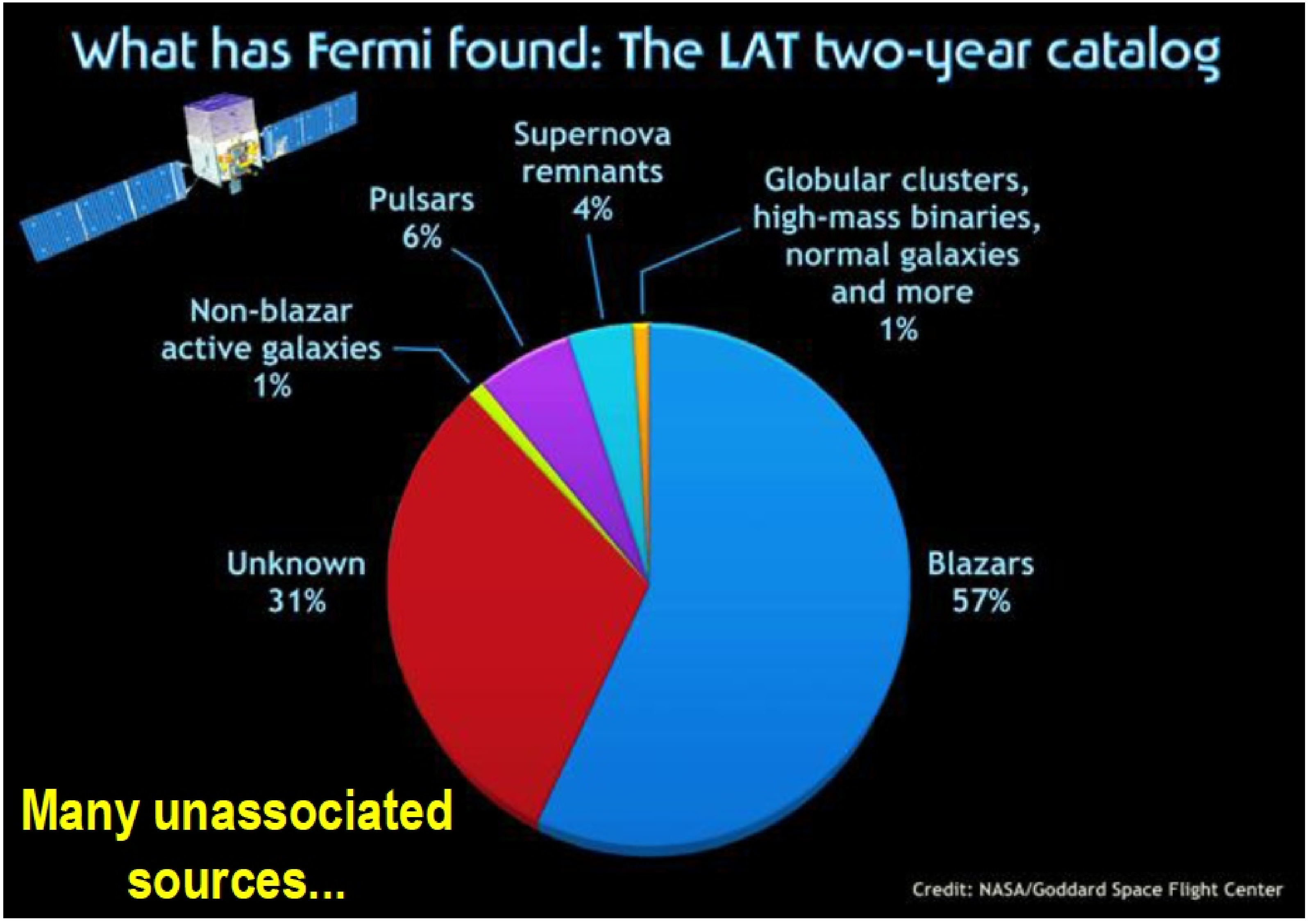


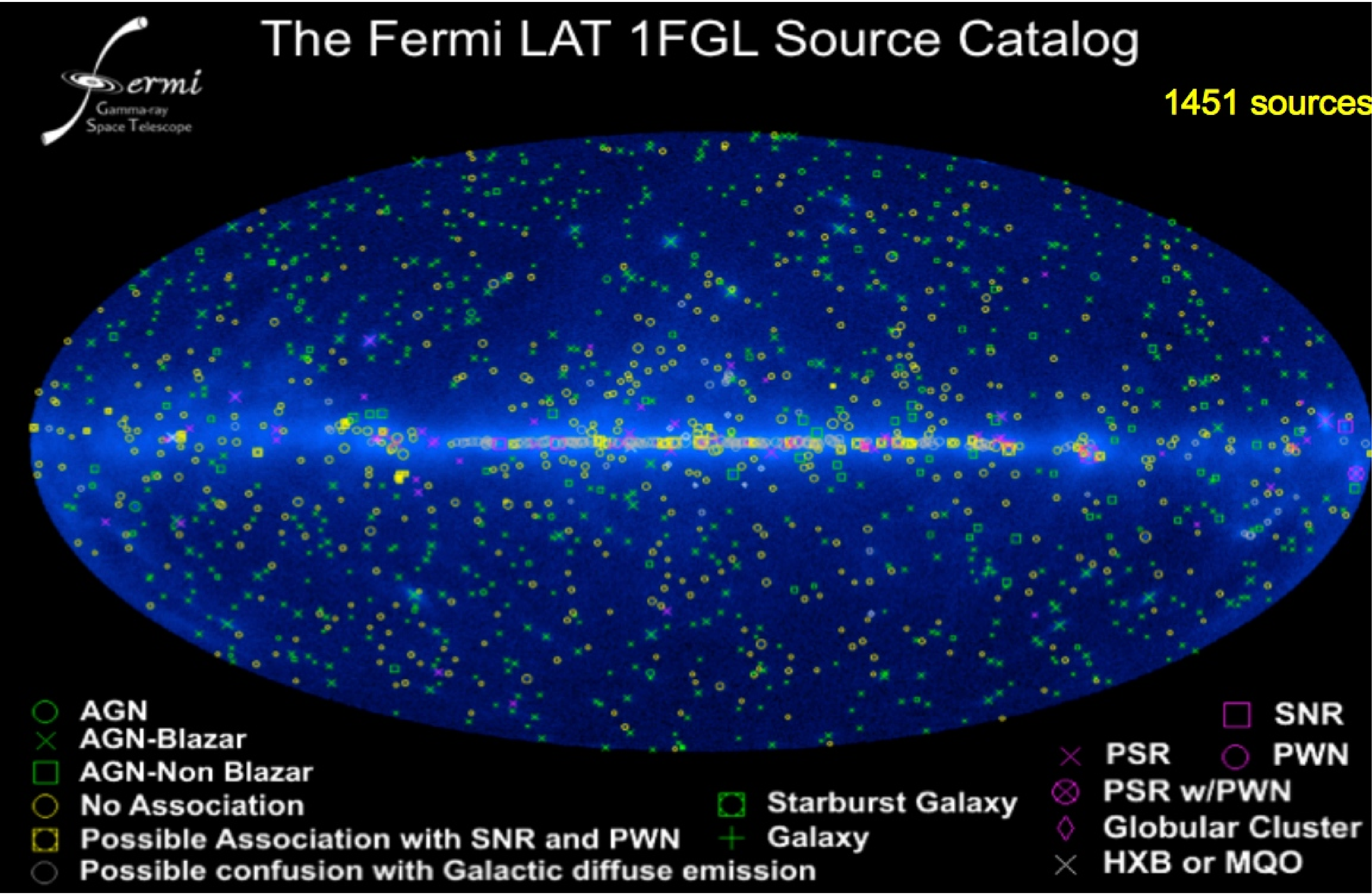
Point Sources

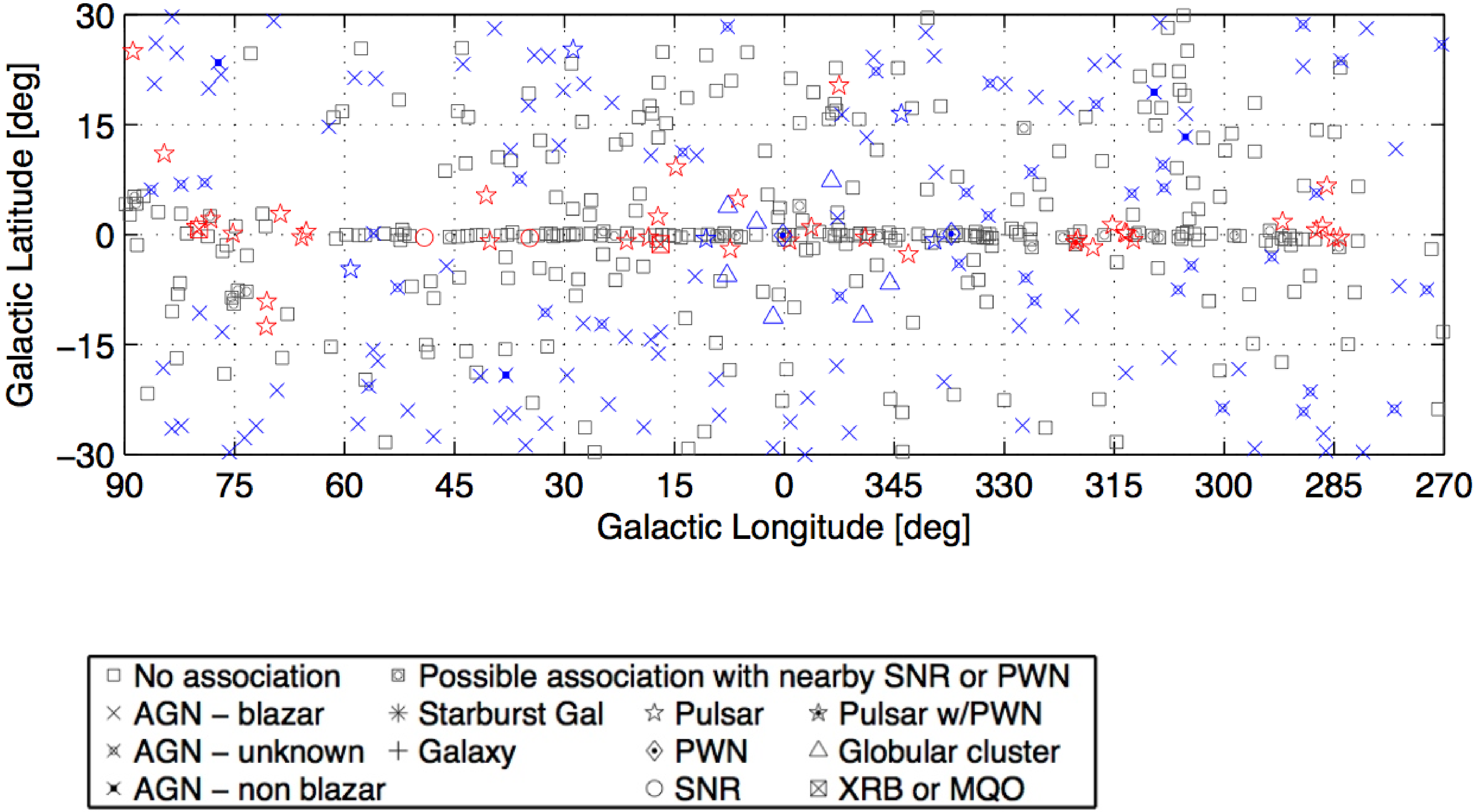


LAT photons from Galactic emission



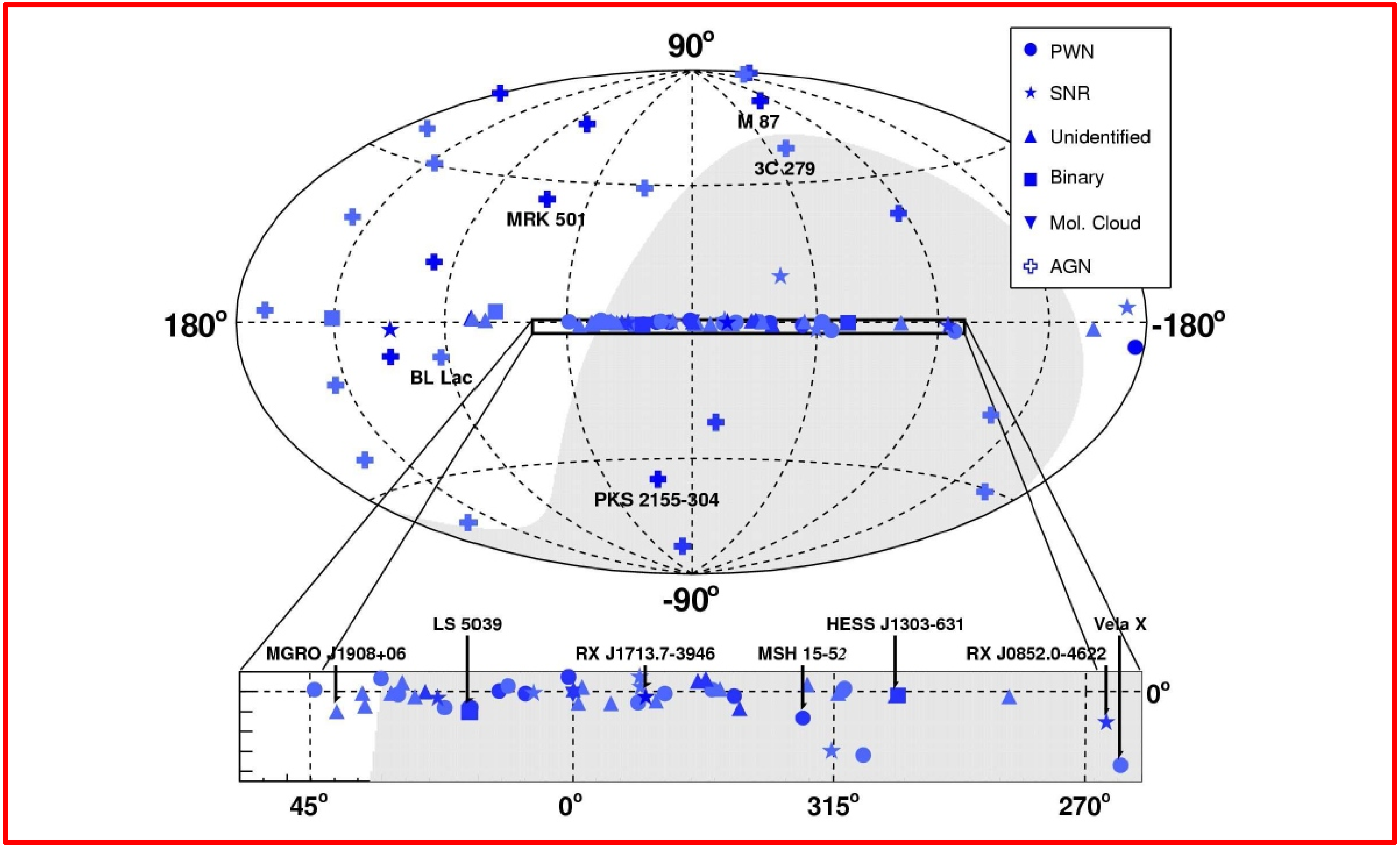

What has Fermi found: The LAT two-year catalog
Supernova remnants 4%
Globular clusters, high-mass binaries, normal galaxies and more 1%
Pulsars 6%
Non-blazar active galaxies 1%
Unknown 31%
Blazars 57%
Many unassociated sources...
Credit: NASA/Goddard Space Flight Center


The Fermi LAT 1FGL Source Catalog
fermi
Gamma-ray
Space Telescope
1451 sources
AGN
AGN-Blazar
AGN-Non Blazar
No Association
Possible Association with SNR and PWN
Possible confusion with Galactic diffuse emission
Starburst Galaxy
Galaxy
SNR
PSR
PWN
PSR w/PWN
Globular Cluster
HXB or MQO



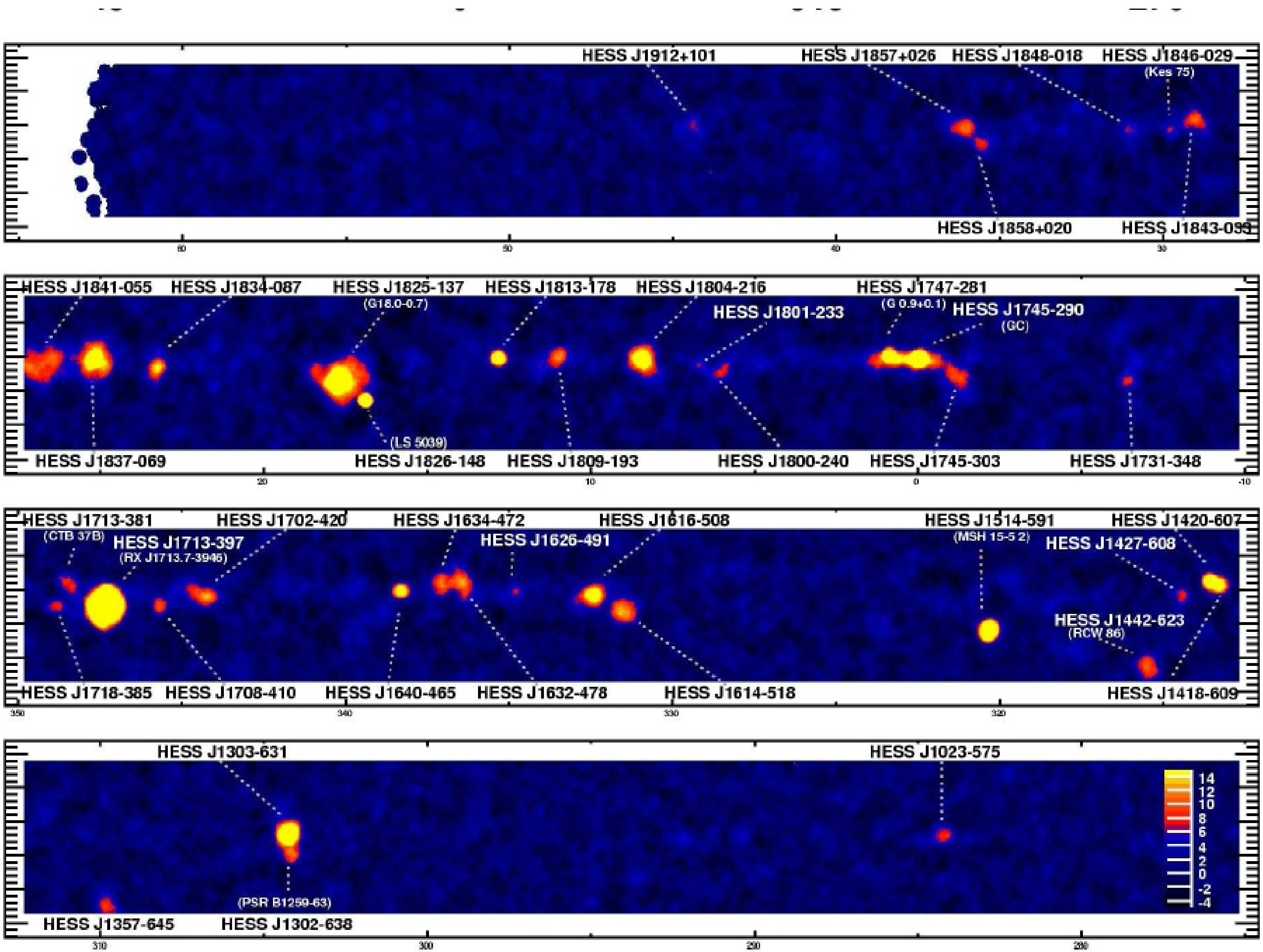
30
15
0
−15
−30
Galactic Latitude [deg]
90
75
60
45
30
15
0
345
330
315
300
285
270
Galactic Longitude [deg]
No association
Possible association with nearby SNR or PWN
AGN – blazar
Starburst Gal
Pulsar
Pulsar w/PWN
AGN – unknown
Galaxy
PWN
Globular cluster
AGN – non blazar
SNR
XRB or MQO

TEV SKY



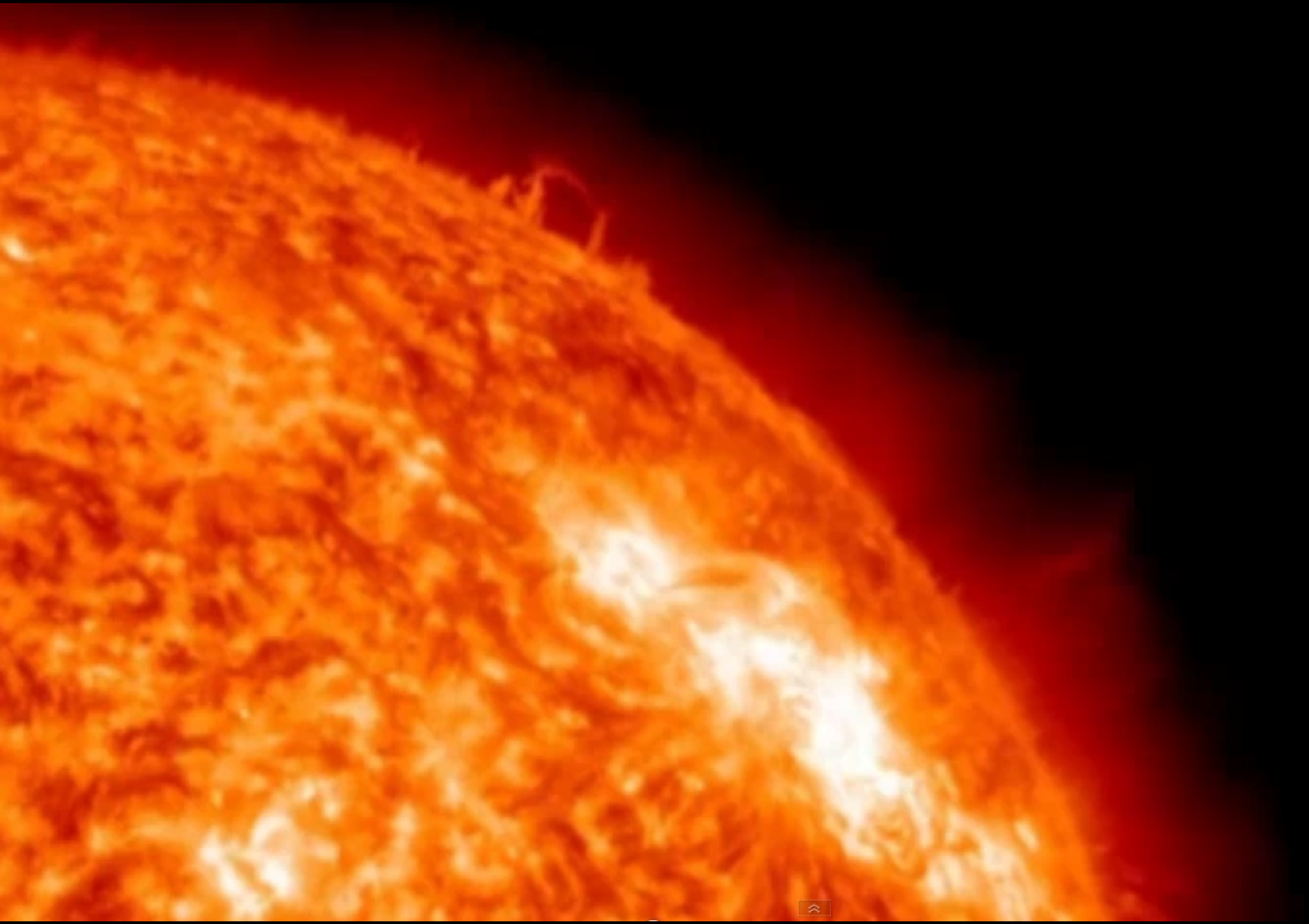
The TeV sky is approaching 100 sources belonging to several different classes:

HESS scan of the Galactic plane

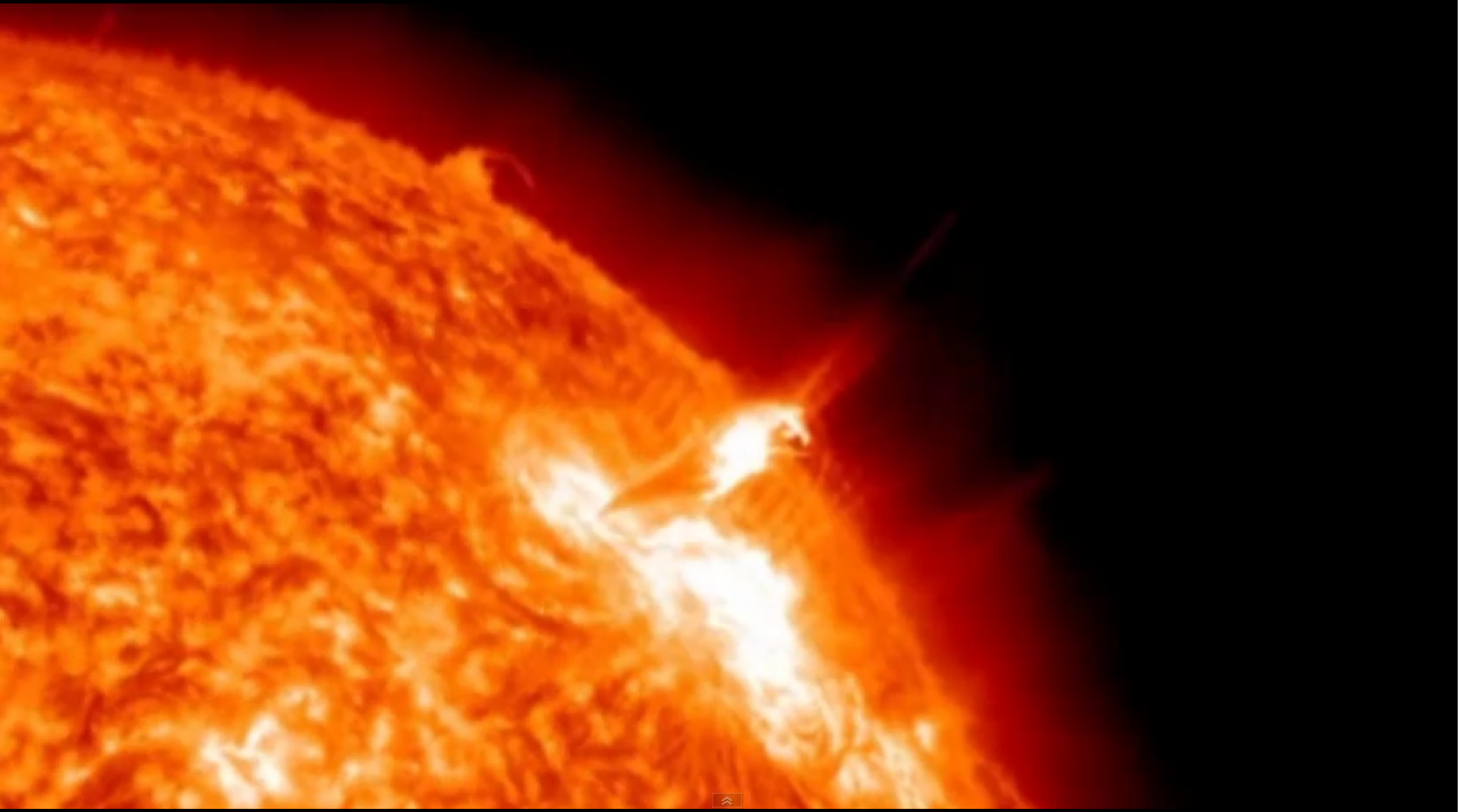


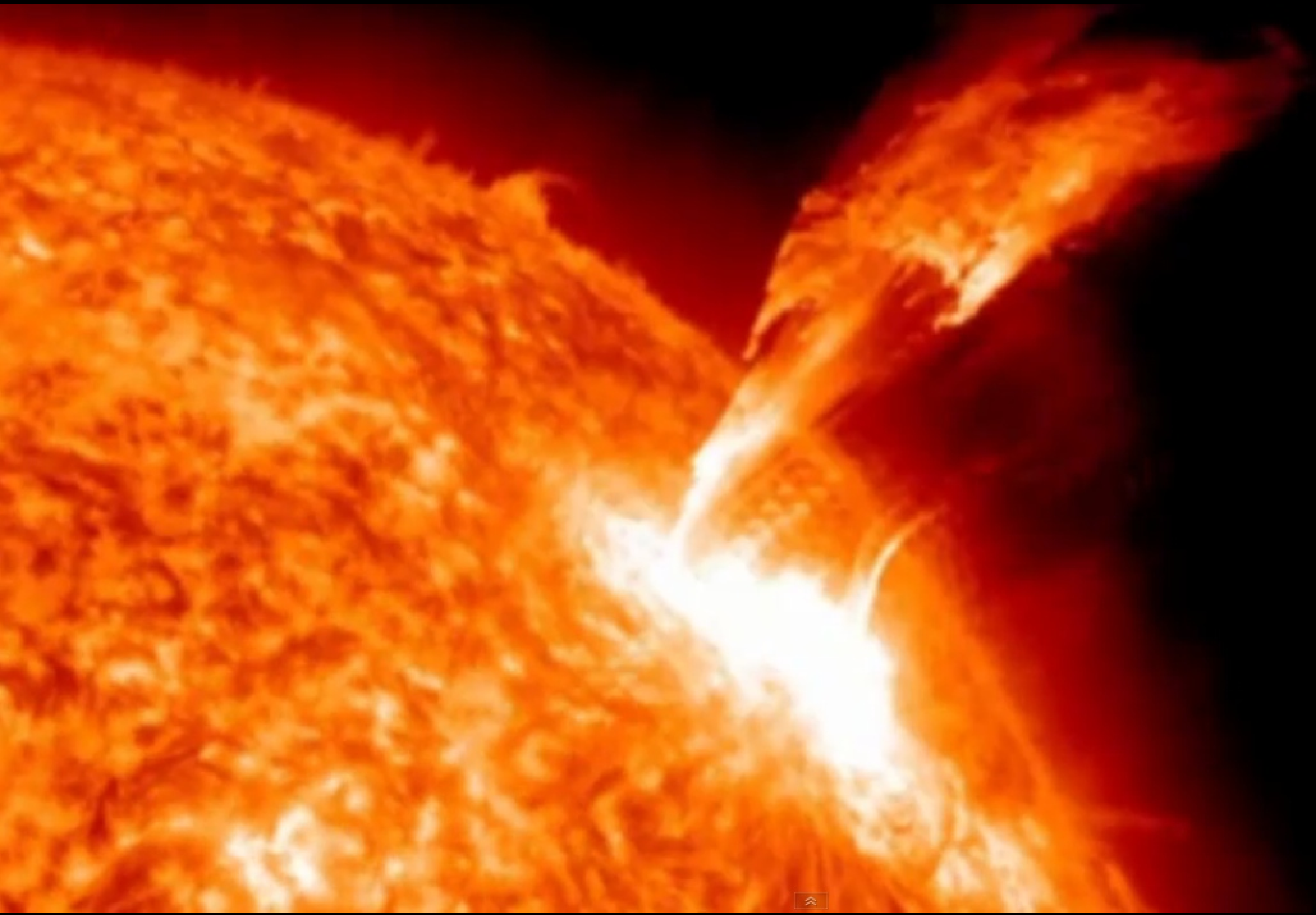
The SUN

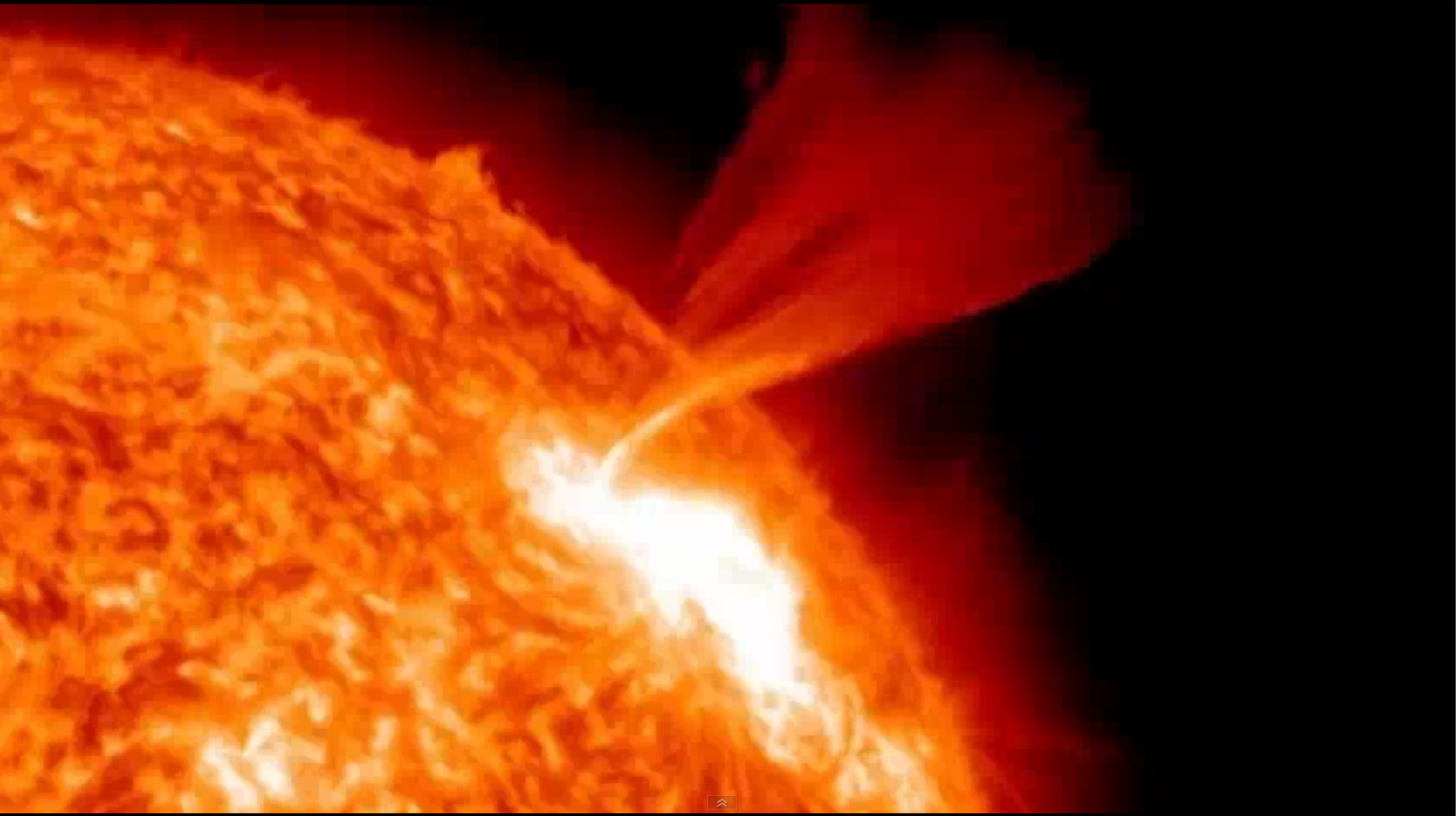
as a “laboratory”
for CR Acceleration
and Transport

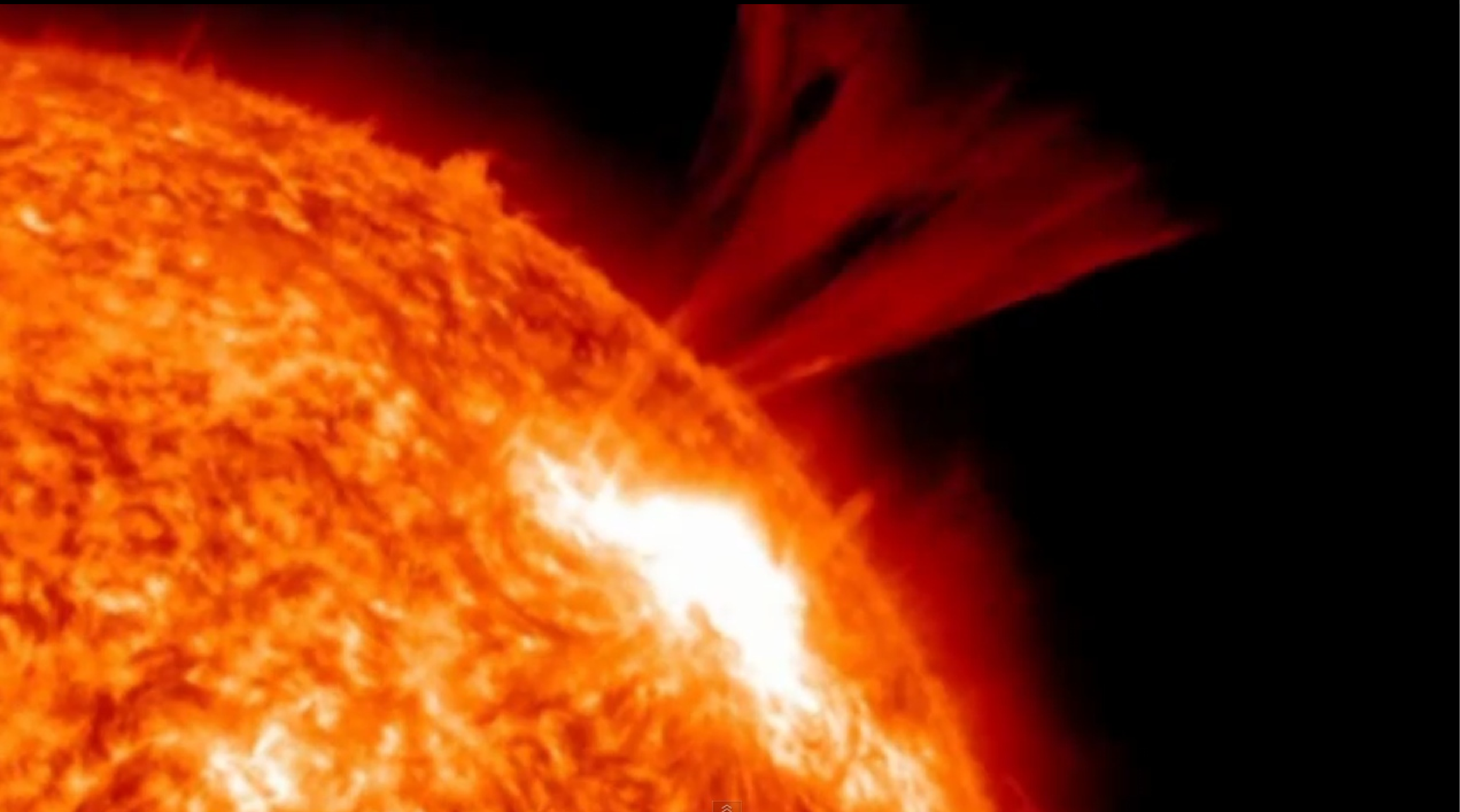


7th march 2011. 20:02 UT



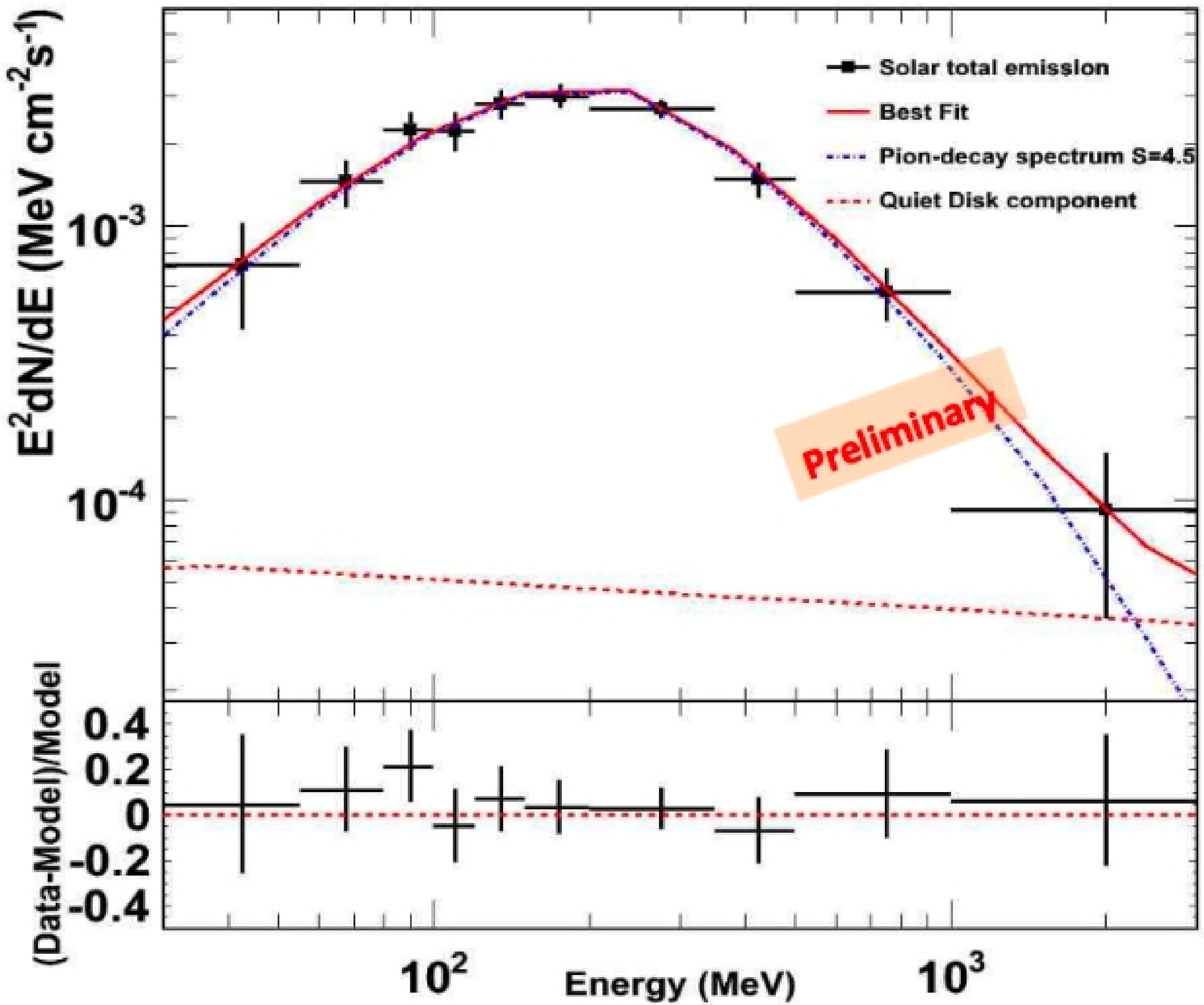






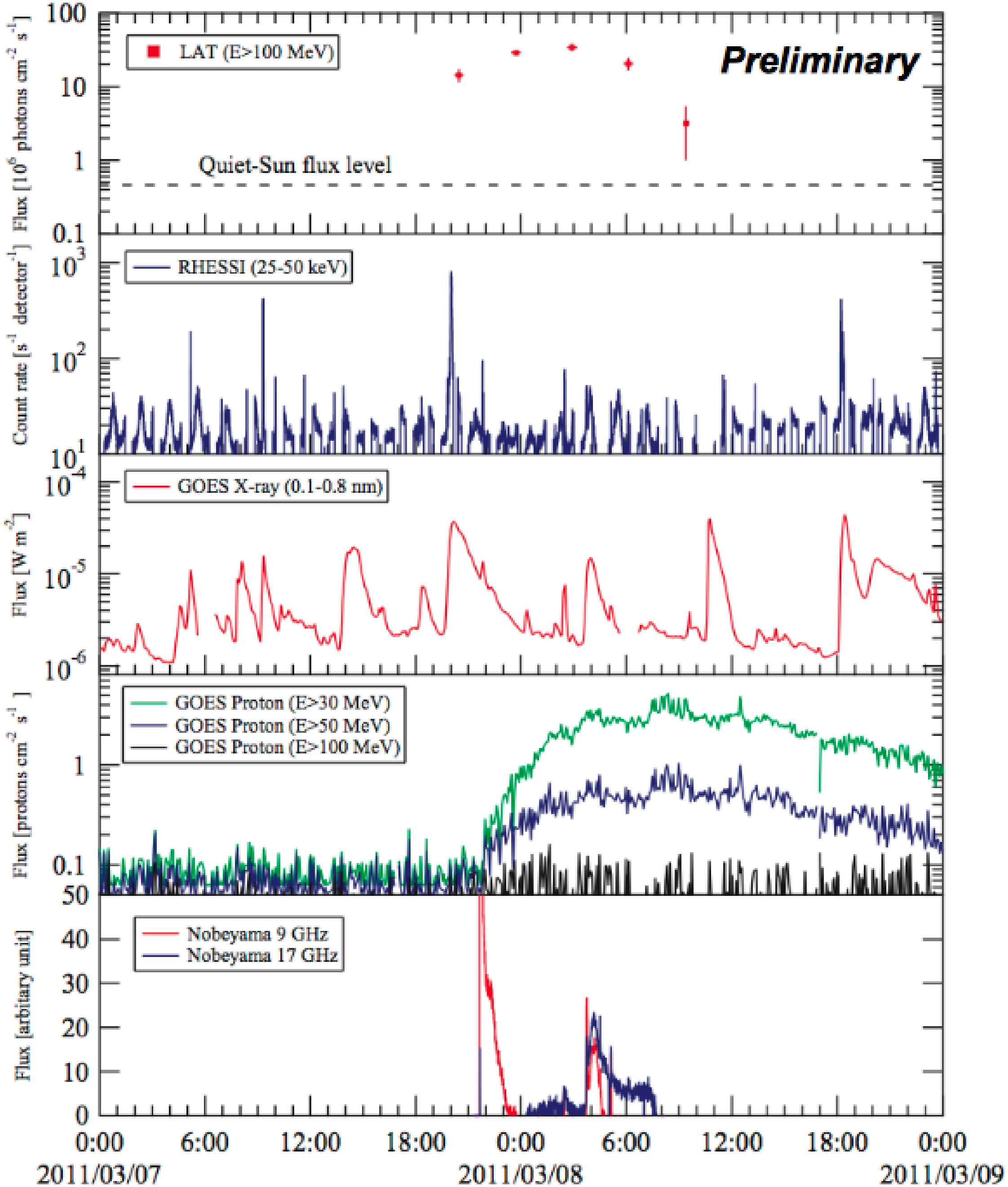

This aurora image was taken on March 10, 2011 by Zoltan Kenwell near Edmonton, Alberta, Canada.
©2011 Zoltan Kenwell

LAT spectrum



- The LAT data are accumulated for the whole flare duration
- The LAT spectrum showed clear turn over around 200 MeV

Multi-wavelength light curve



- **Following M3.7 flare at ~20 UT on March 7, Fermi-LAT detected long-lasting HE emission over ~12 hours**
- **LAT flux showed clear rising profile**
- **No corresponding long-lasting enhancements were seen in hard X-ray (RHESSI), soft X-ray (GOES), and radio (Nobeyama) bands**
- **GOES proton monitor at 1AU detected solar energetic protons above 50 MeV, suggesting that CME-driven shock indeed accelerated protons**

The “Richness of the High-Energy Sky”

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

Pulsars

SuperNova Remnants

MicroQuasars

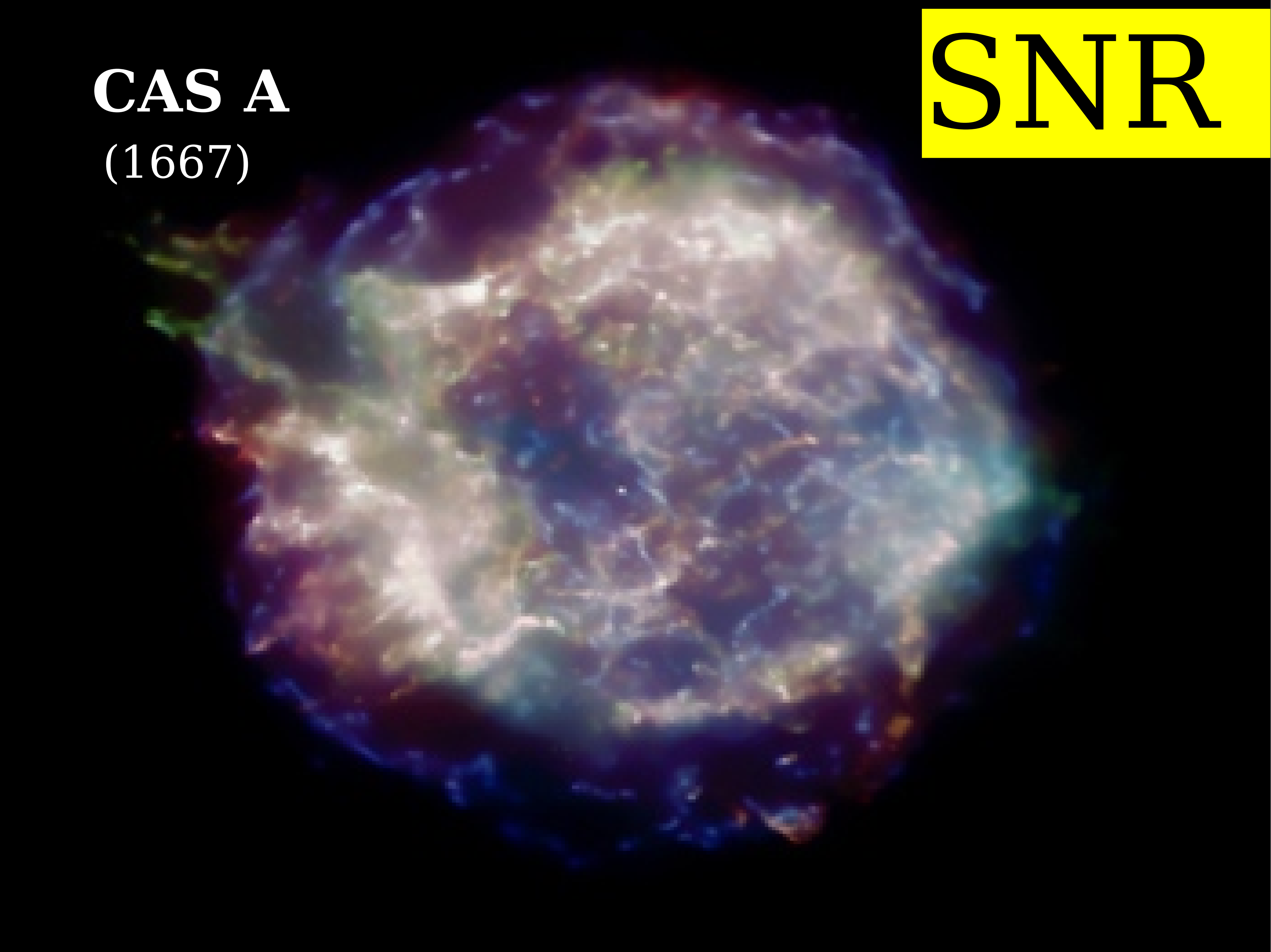
Active Galactic Nuclei

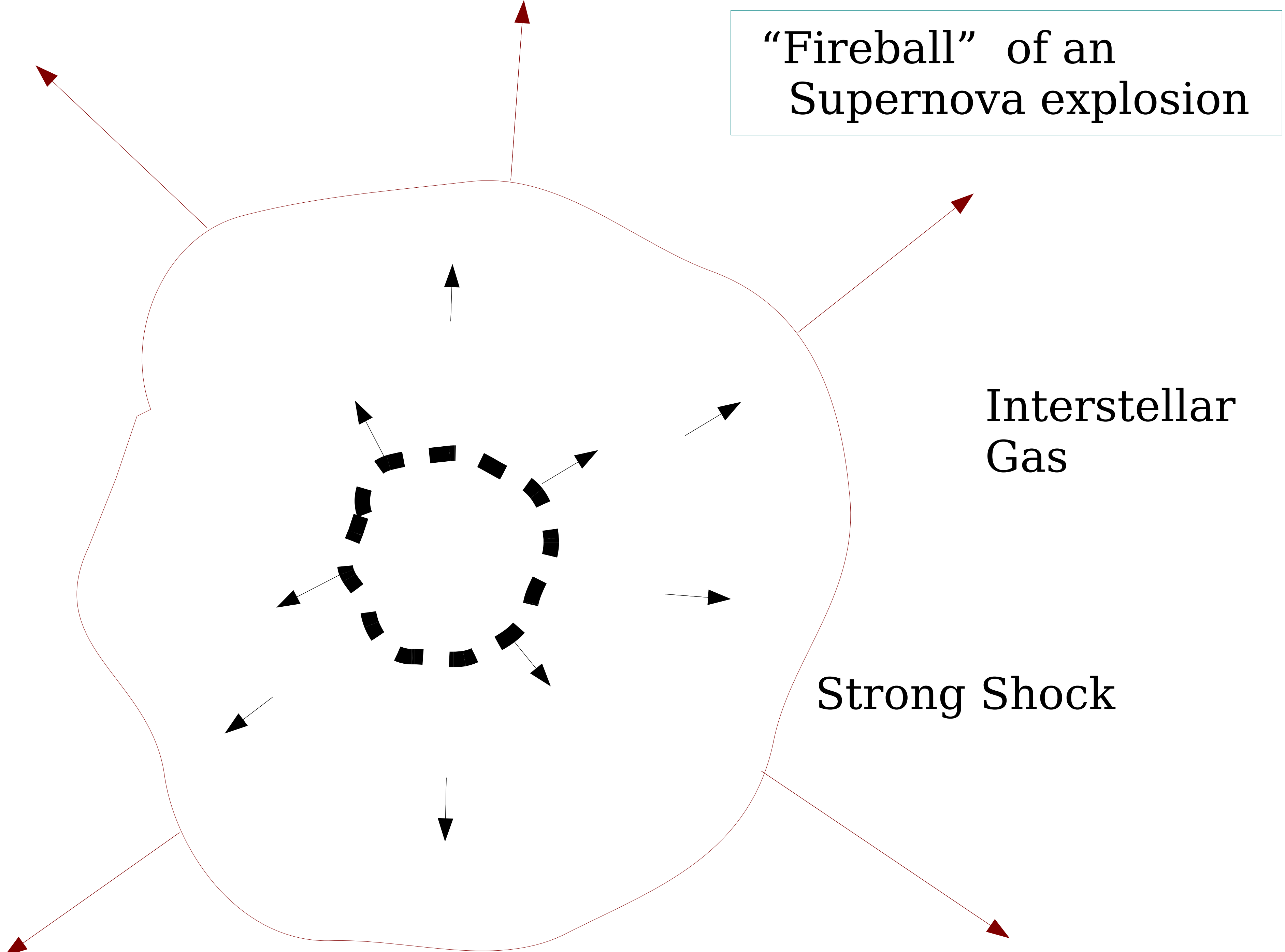
Gamma Ray Bursts.

....

Most of the observed
Relativistic Particles
are leptons.

Open Question:
Where are the observed
CR accelerated?

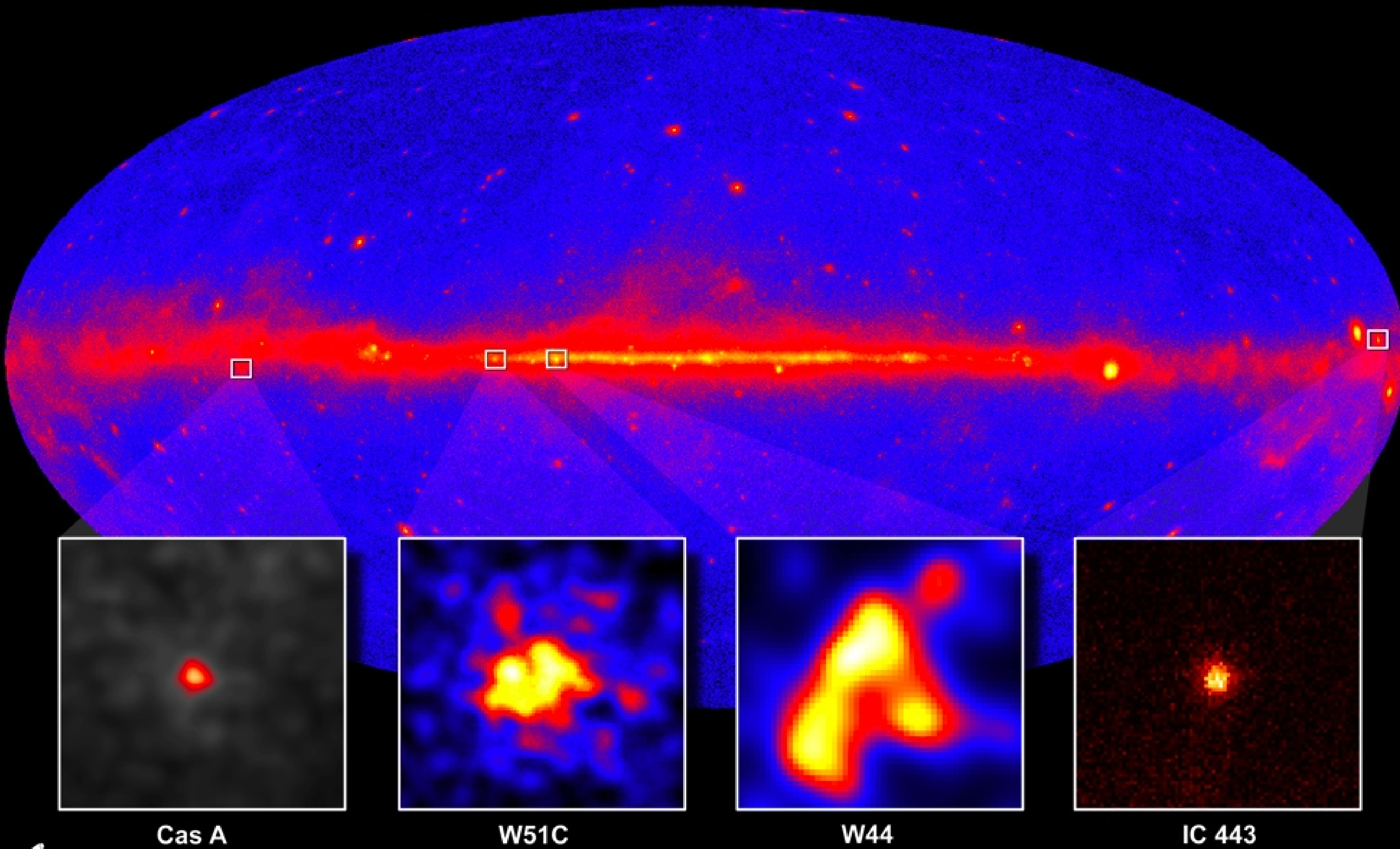

CAS A
(1667)
SNR



Fermi 1st order acceleration

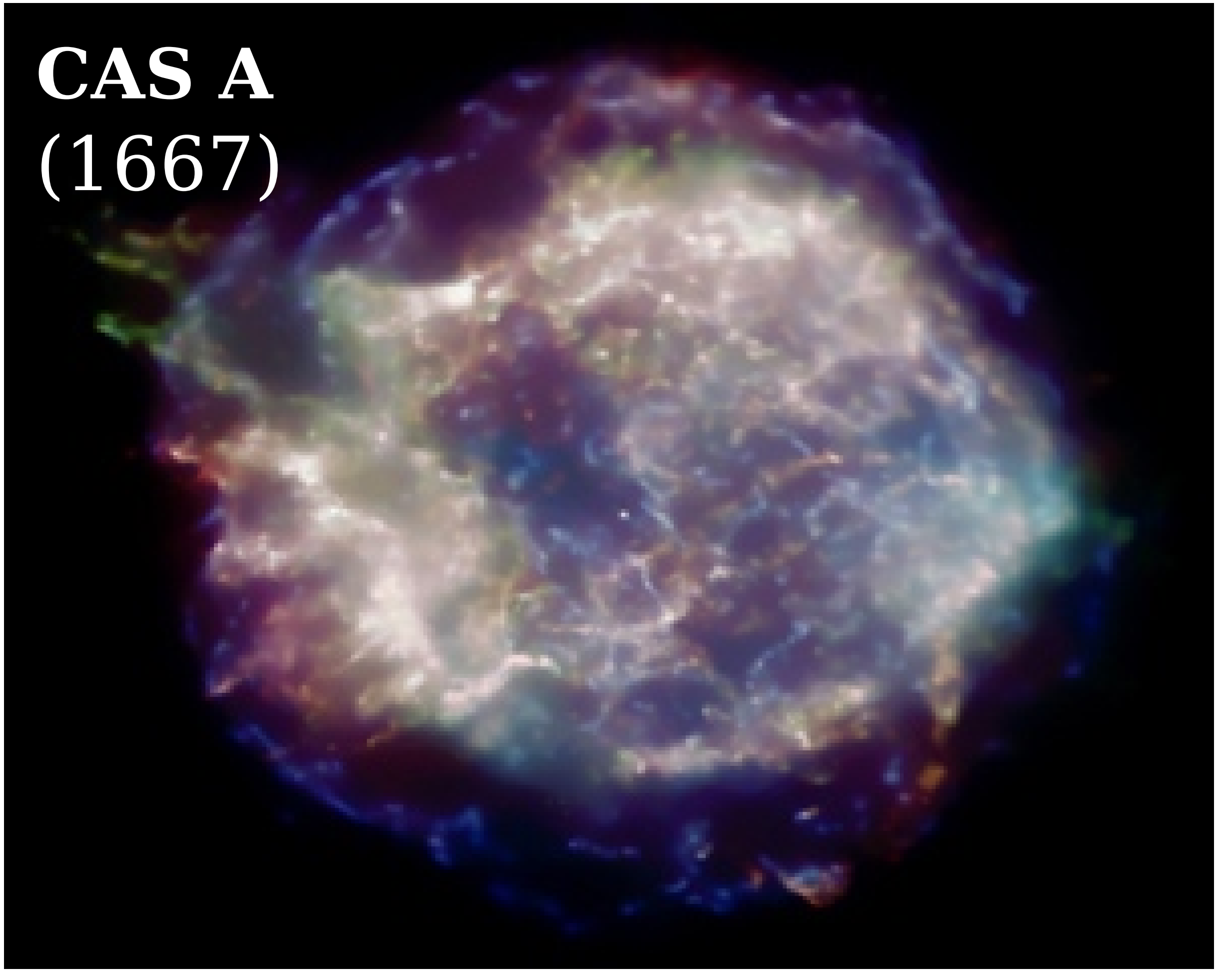
$$q(E) \propto E^{-(2+\varepsilon)}$$

NASA's Fermi telescope resolves supernova remnants at GeV energies



W49B

The SuperNova "Paradigm" for CR acceleration



Powering the galactic Cosmic Rays

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

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

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

- ENERGETICS
- DYNAMICS [Diffusive Shock acceleration]

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

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

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

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

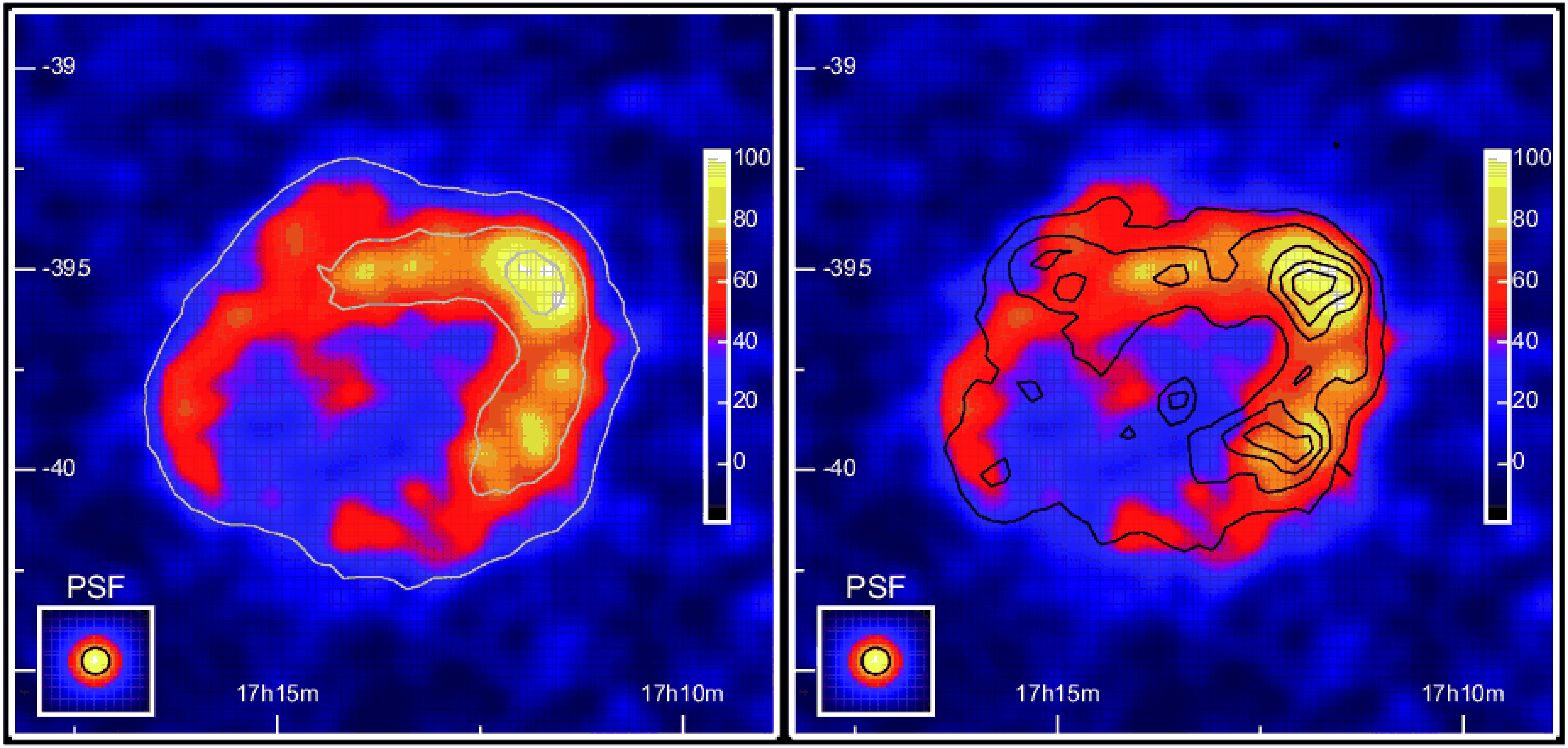
$$L_{\rm SN\ kinetic}^{\rm Milky\ Way} \simeq 1.5 \times 10^{42}\ \frac{\rm erg}{\rm s}$$

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

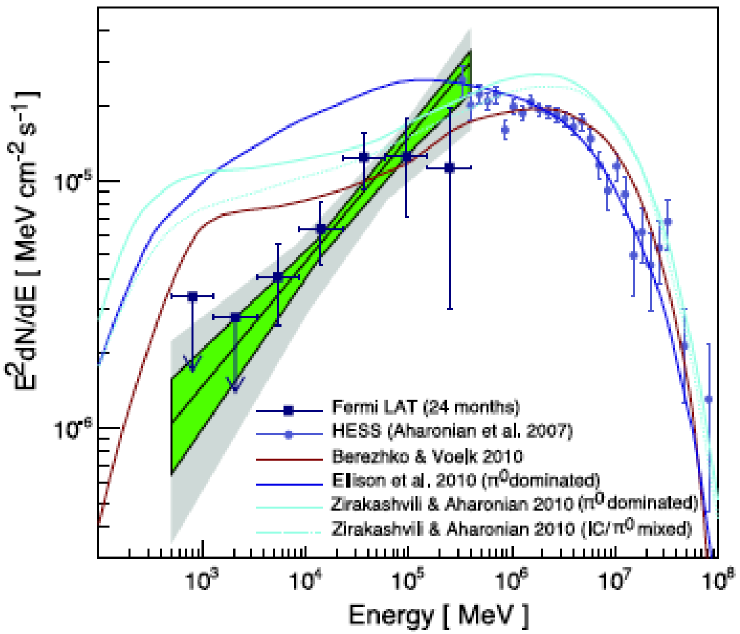


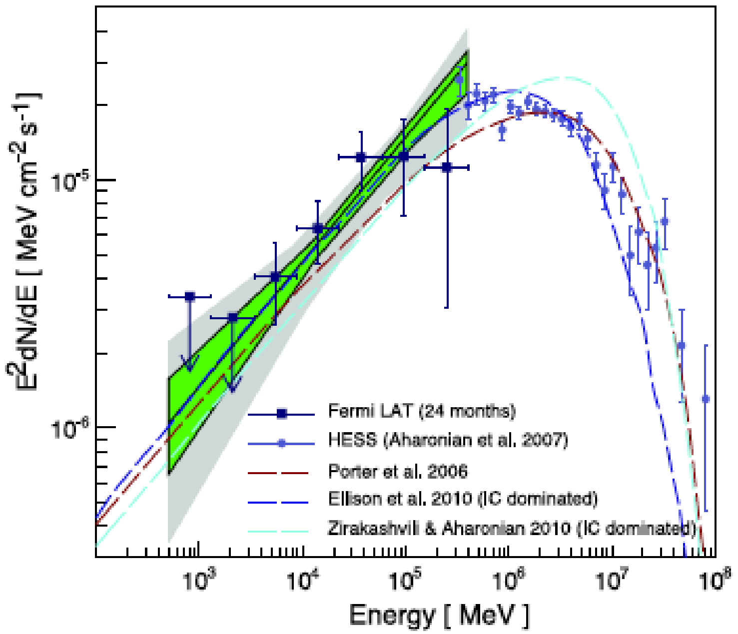
Comparison with ROSAT observation

Observations of the young Supernova remnant RX J1713.7−3946 with the *Fermi* Large Area Telescope

astro-ph/1103.5727.
29th march 2011

Favors
leptonic interpretation.





Identification of the sources of (hadronic) Cosmic Rays

Association of the cosmic Rays with

The STAR FORMATION RATE

Detection of Galaxies in the local group

Detection of Star-Burst Galaxies ....

From FERMI:

Table 1. Properties and gamma-ray characteristics of Local Group and nearby starburst galaxies (see text).

Galaxy	d kpc	M_{HI} 10^8 $M_\odot$	$M_{\mathrm{H_2}}$ 10^8 $M_\odot$	SFR $M_\odot$ yr^{-1}	F_γ 10^{-8} ph cm^{-2} s^{-1}	L_γ 10^{41} ph s^{-1}	$\bar{q}_\gamma$ 10^{-25} ph s^{-1} H-atom^{-1}
MW	...	35 ± 4[7]	14 ± 2[7]	1 – 3[19]	...	11.8 ± 3.4[28]	2.0 ± 0.6
M31	780 ± 33[1]	73 ± 22[8]	3.6 ± 1.8[14]	0.35 – 1[19]	0.9 ± 0.2	6.6 ± 1.4	0.7 ± 0.3
M33	847 ± 60[2]	19 ± 8[9]	3.3 ± 0.4[9]	0.26 – 0.7[20]	< 0.5	< 5.0	< 2.9
LMC	50 ± 2[3]	4.8 ± 0.2[10]	0.5 ± 0.1[15]	0.20 – 0.25[21]	26.3 ± 2.0[25]	0.78 ± 0.08	1.2 ± 0.1
SMC	61 ± 3[4]	4.2 ± 0.4[11]	0.25 ± 0.15[16]	0.04 – 0.08[22]	3.7 ± 0.7[26]	0.16 ± 0.04	0.31 ± 0.07
M82	3630 ± 340[5]	8.8 ± 2.9[12]	5 ± 4[17]	13 – 33[23]	1.6 ± 0.5[27]	252 ± 91	158 ± 75
NGC253	3940 ± 370[6]	64 ± 14[13]	40 ± 8[18]	3.5 – 10.4[24]	0.6 ± 0.4[27]	112 ± 78	9 ± 6


M82 , M83

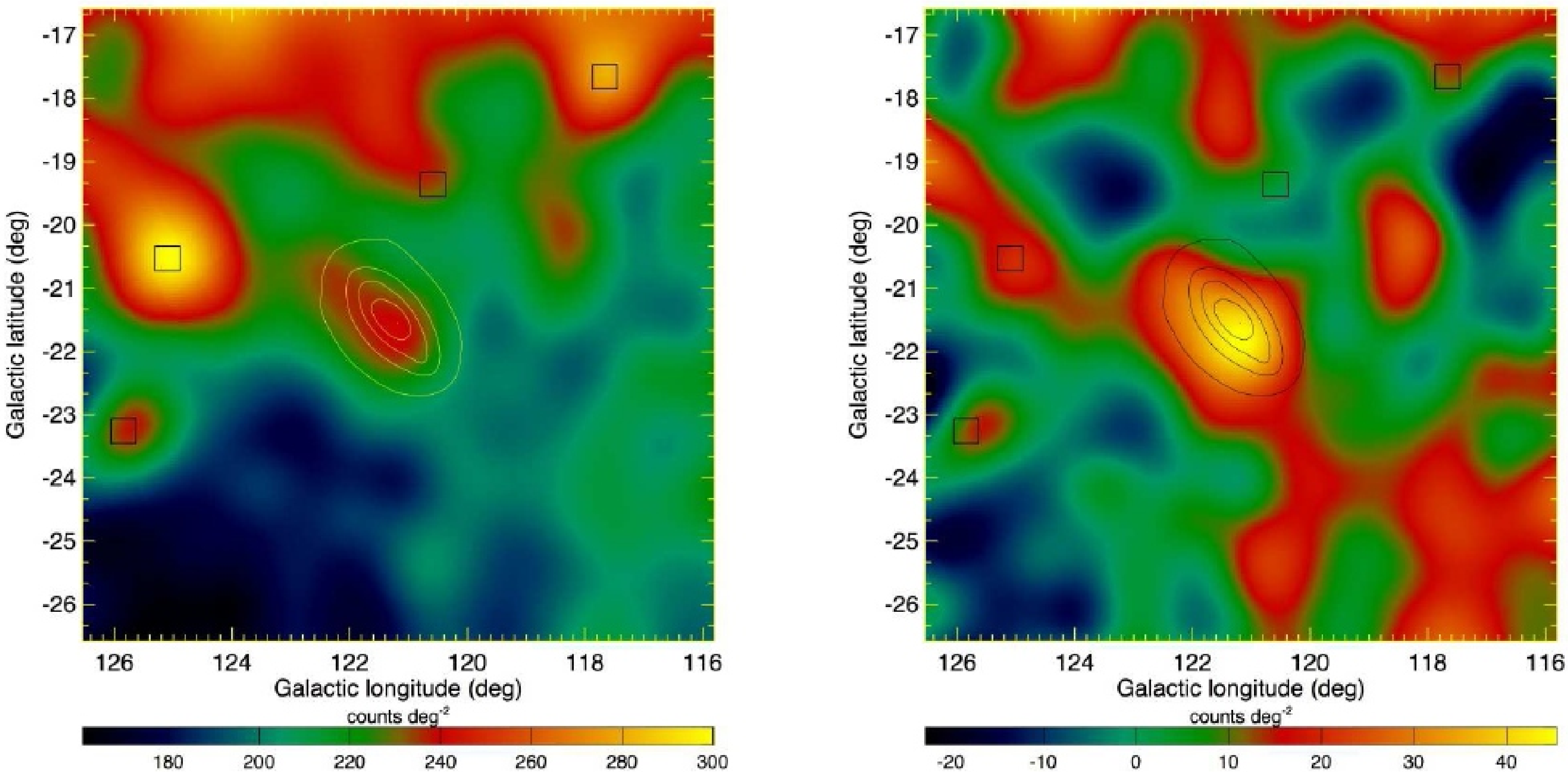
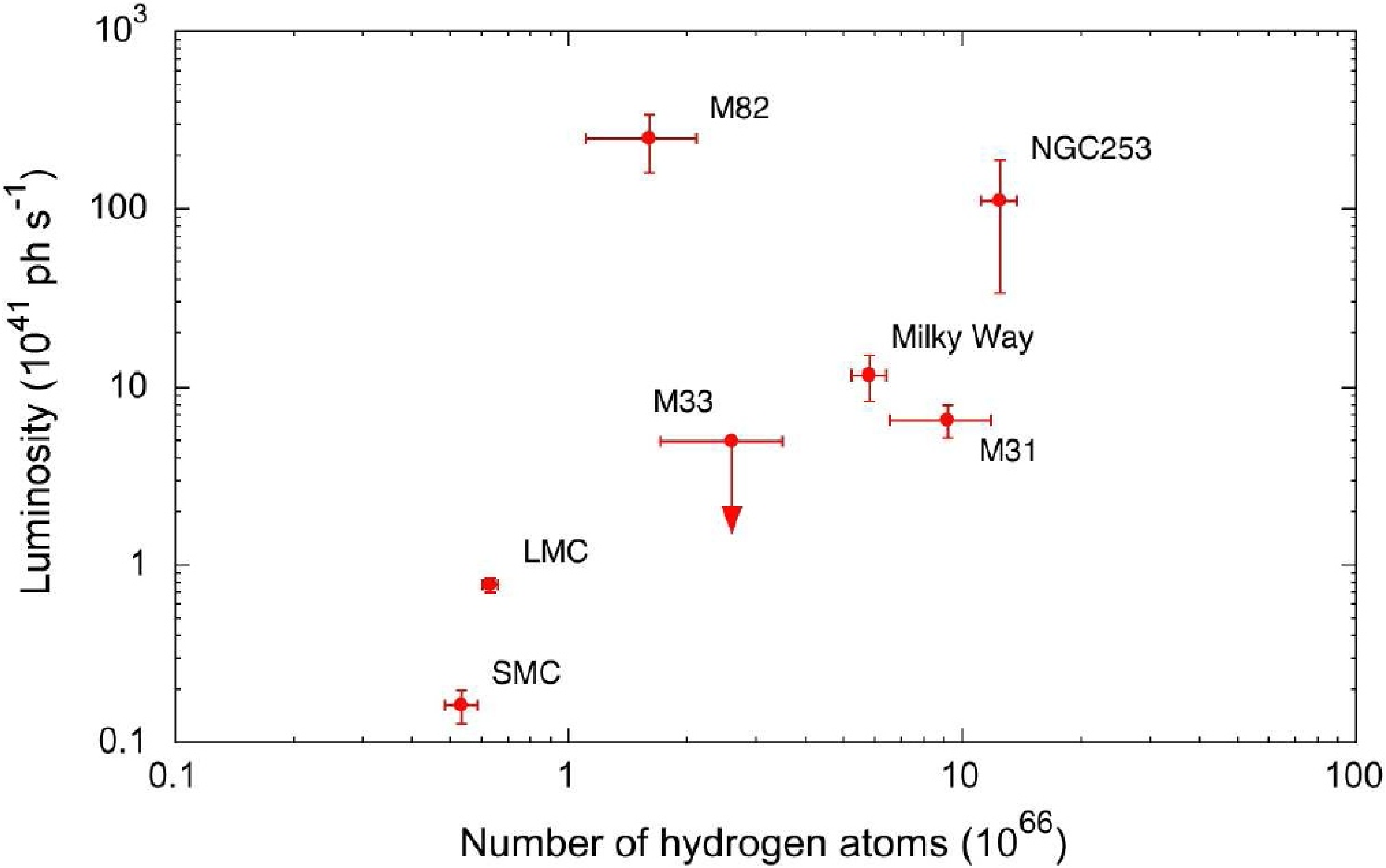
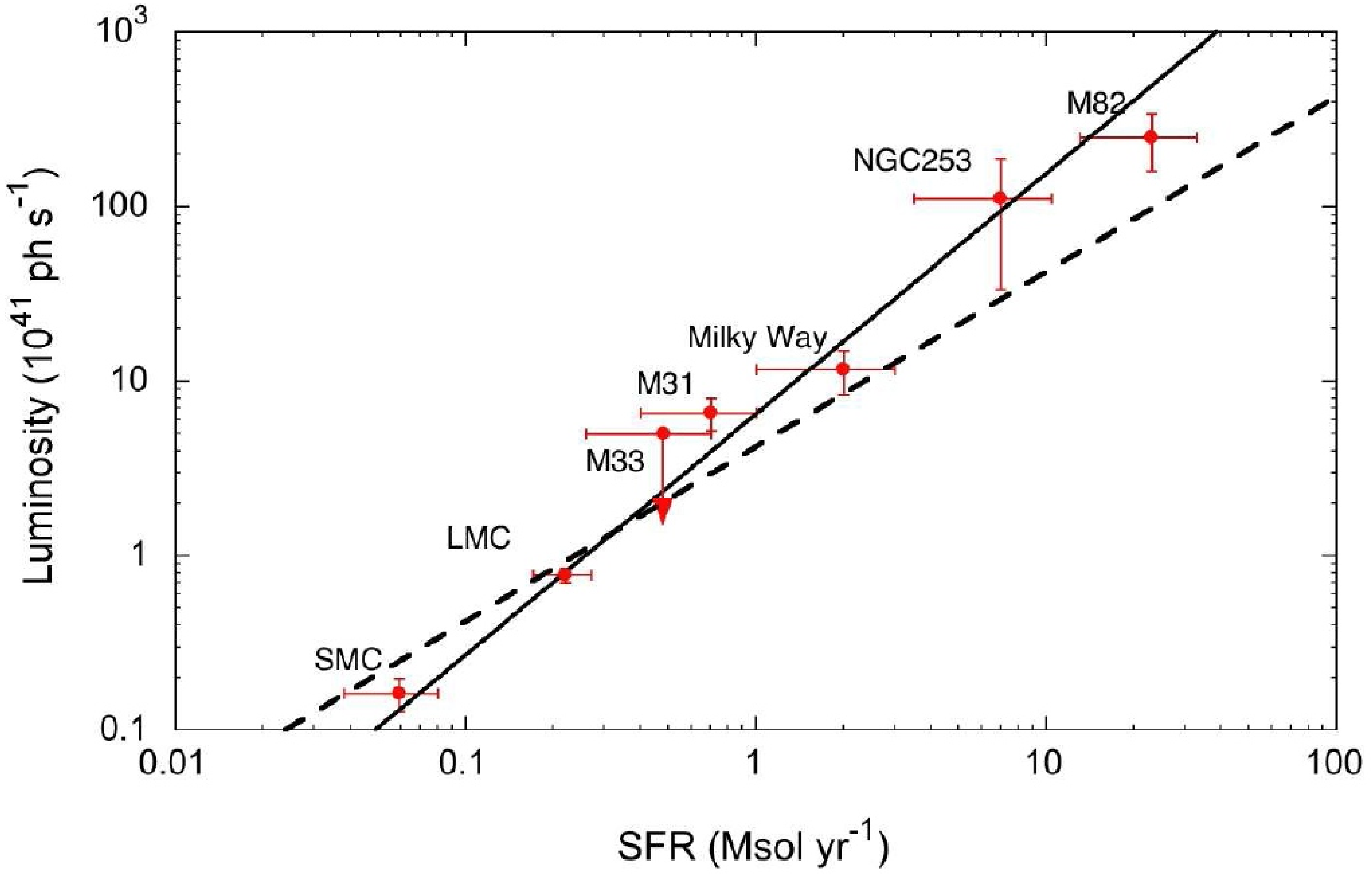


Fig. 1. Gaussian kernel ($\sigma = 0.5°$) smoothed counts maps of the region of interest (ROI) in a true local projection before (left) and after subtraction of the background model (right) for the energy range 200 MeV – 20 GeV and for a pixel size of $0.05° \times 0.05°$. Overlaid are IRIS 100 μm contours of M31 convolved with the LAT point spread function to indicate the extent and shape of the galaxy. The boxes show the locations of the 4 point sources that have been included in the background model.



Luminosity (E >100 MeV) versus Number of atoms.
Local Group galaxies (SMC, LMC, M31)
2 starburs galaxies (M82, NGC253)



Luminosity (E >100 MeV) versus star formation rate (SFR).
Dashed line: Linear relation
Solid line : Power law best fit

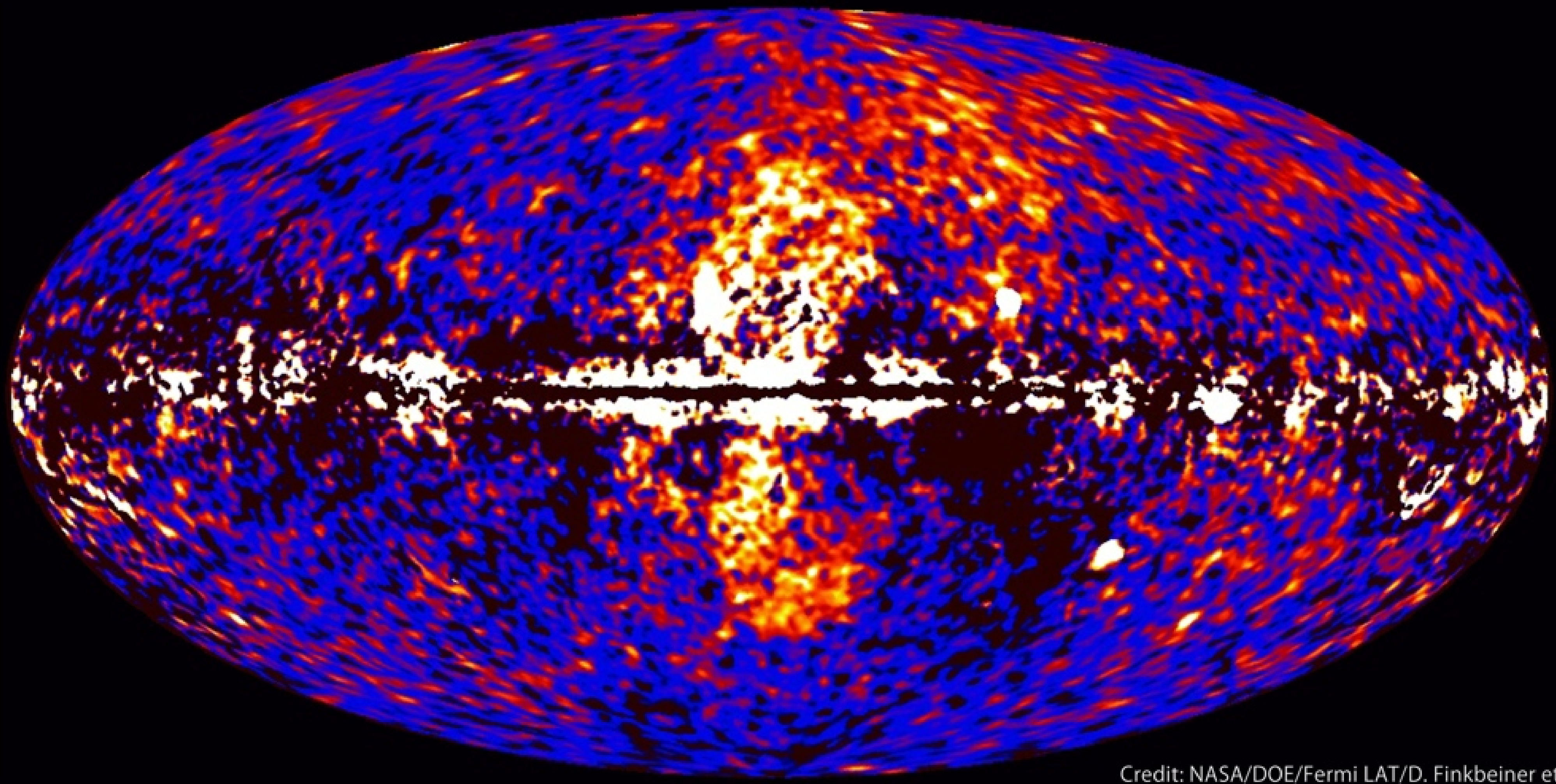
The

“FERMI BUBBLES”

“hidden in plain sight (!)”

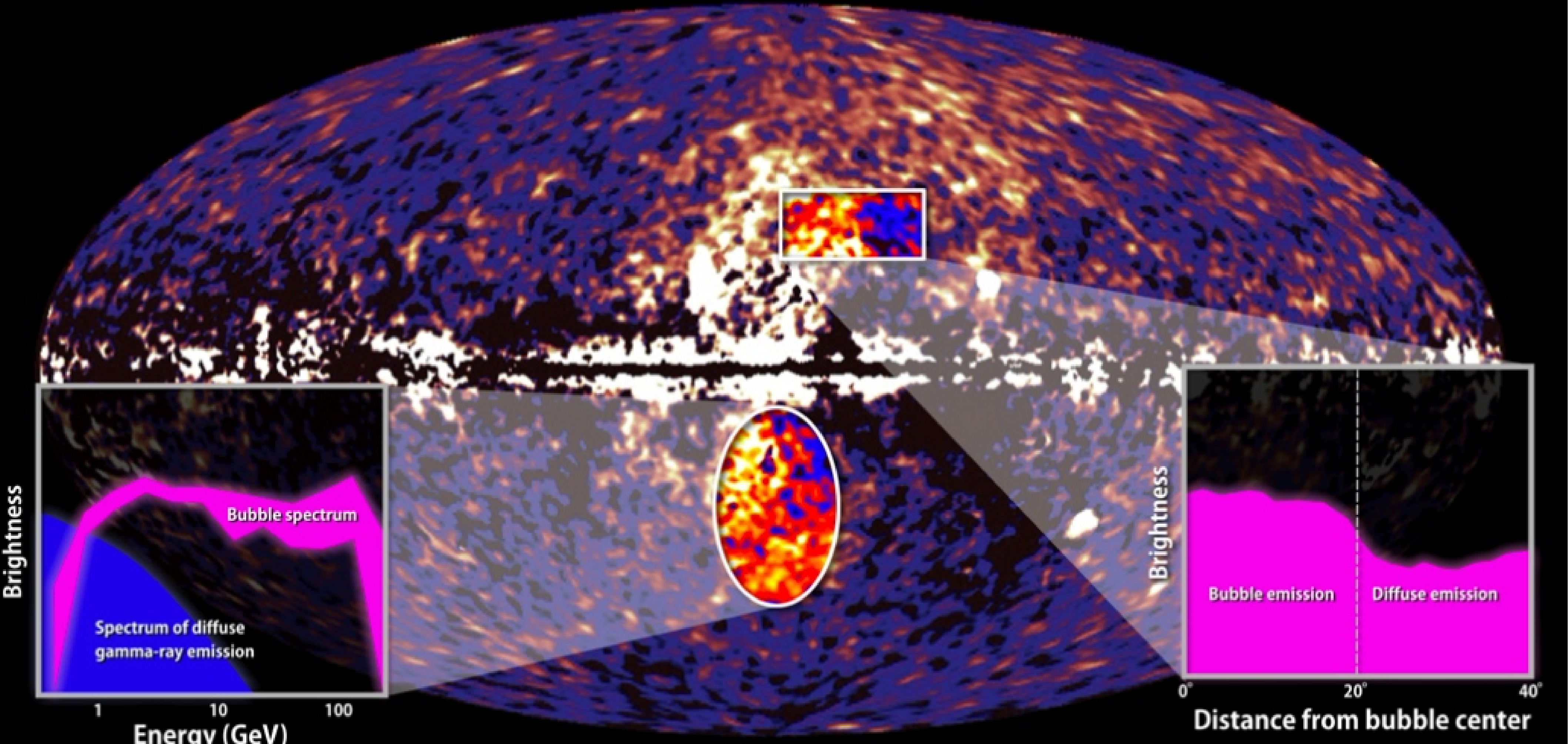
Scientific American news. Title:

Hidden in Plain Sight: Researchers Find Galaxy-Scale Bubbles Extending from the Milky Way

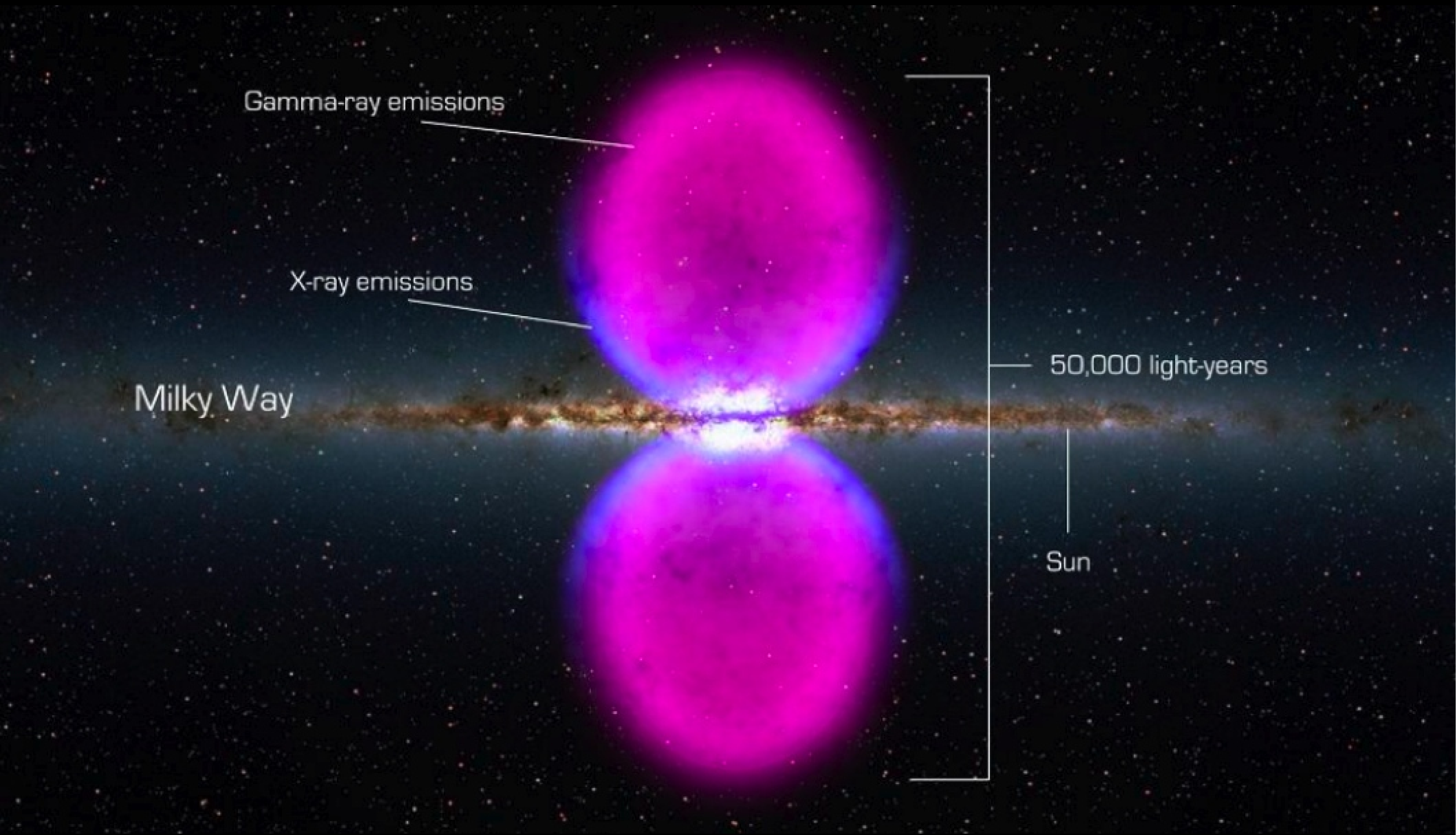


M. Su, T. R. Slatyer, D. P. Finkbeiner,
"Giant Gamma-ray Bubbles from Fermi-LAT: AGN Activity or Bipolar Galactic Wind?,"
Astrophys. J. **724**, 1044-1082 (2010). [arXiv:1005.5480 [astro-ph.HE]].

Bubbles show energetic spectrum and sharp edges

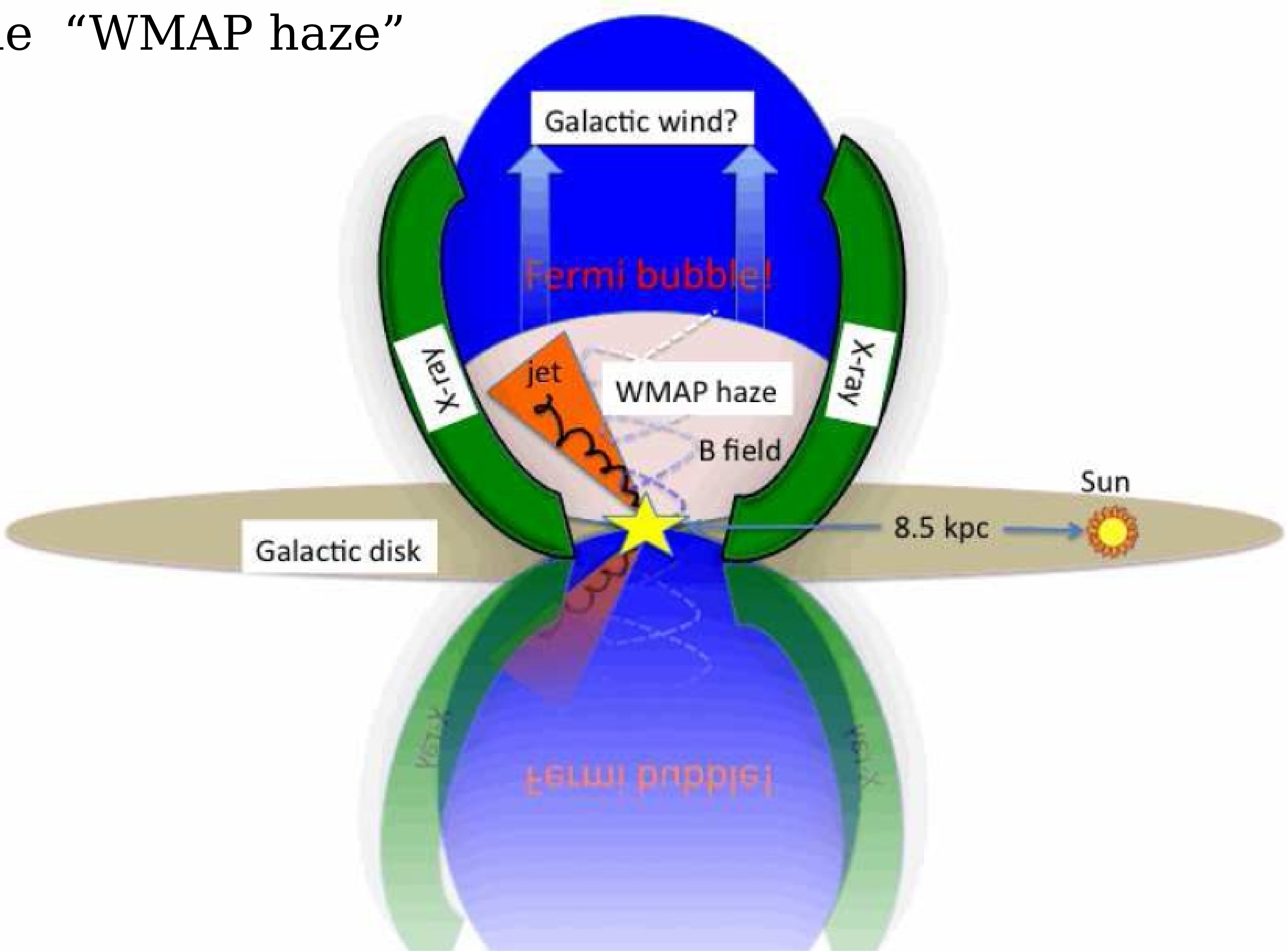


Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.



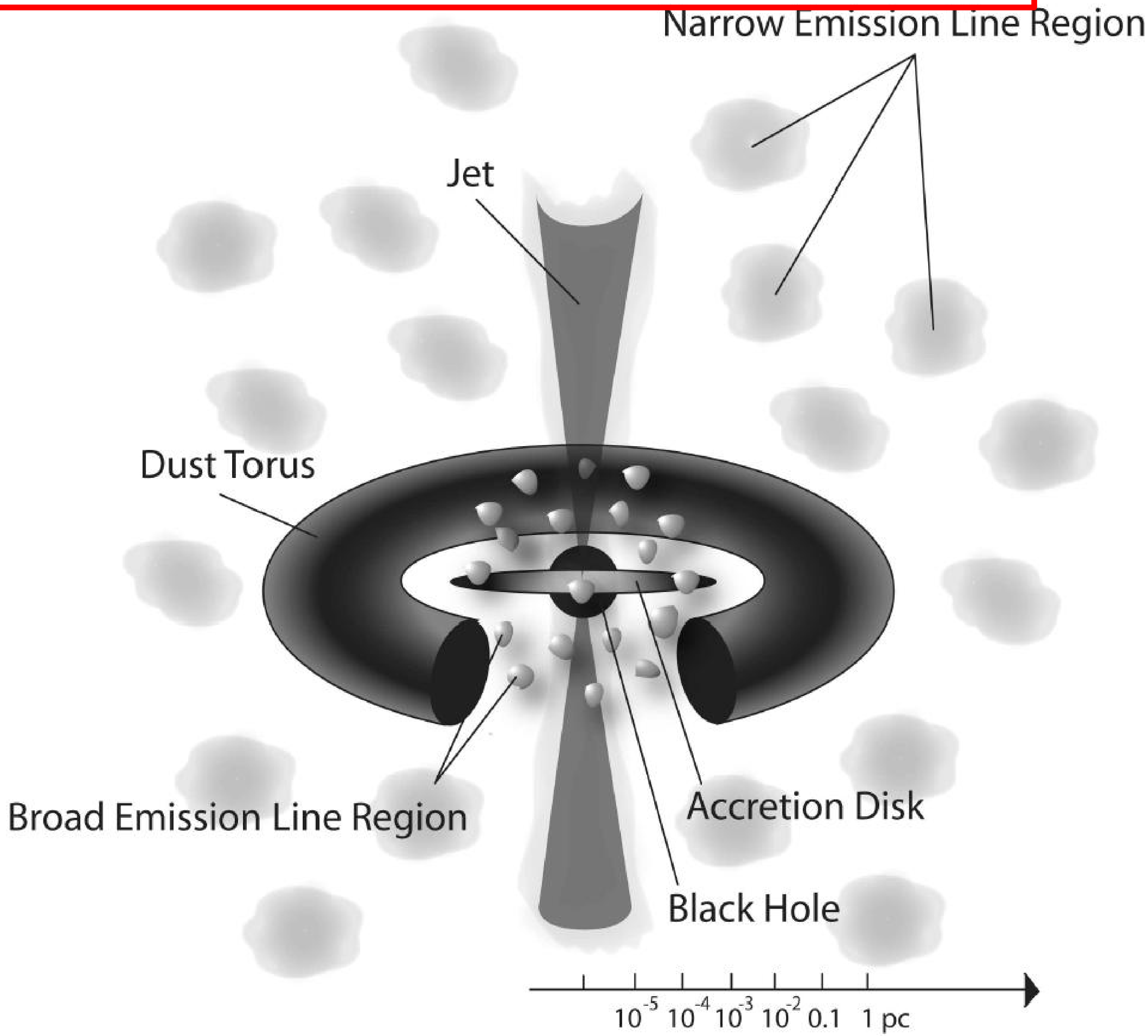
R. M. Crocker, F. Aharonian,
"The Fermi Bubbles: Giant, Multi-Billion-Year-Old Reservoirs of Galactic Center Cosmic Rays,"
[arXiv:1008.2658 [astro-ph.GA]].

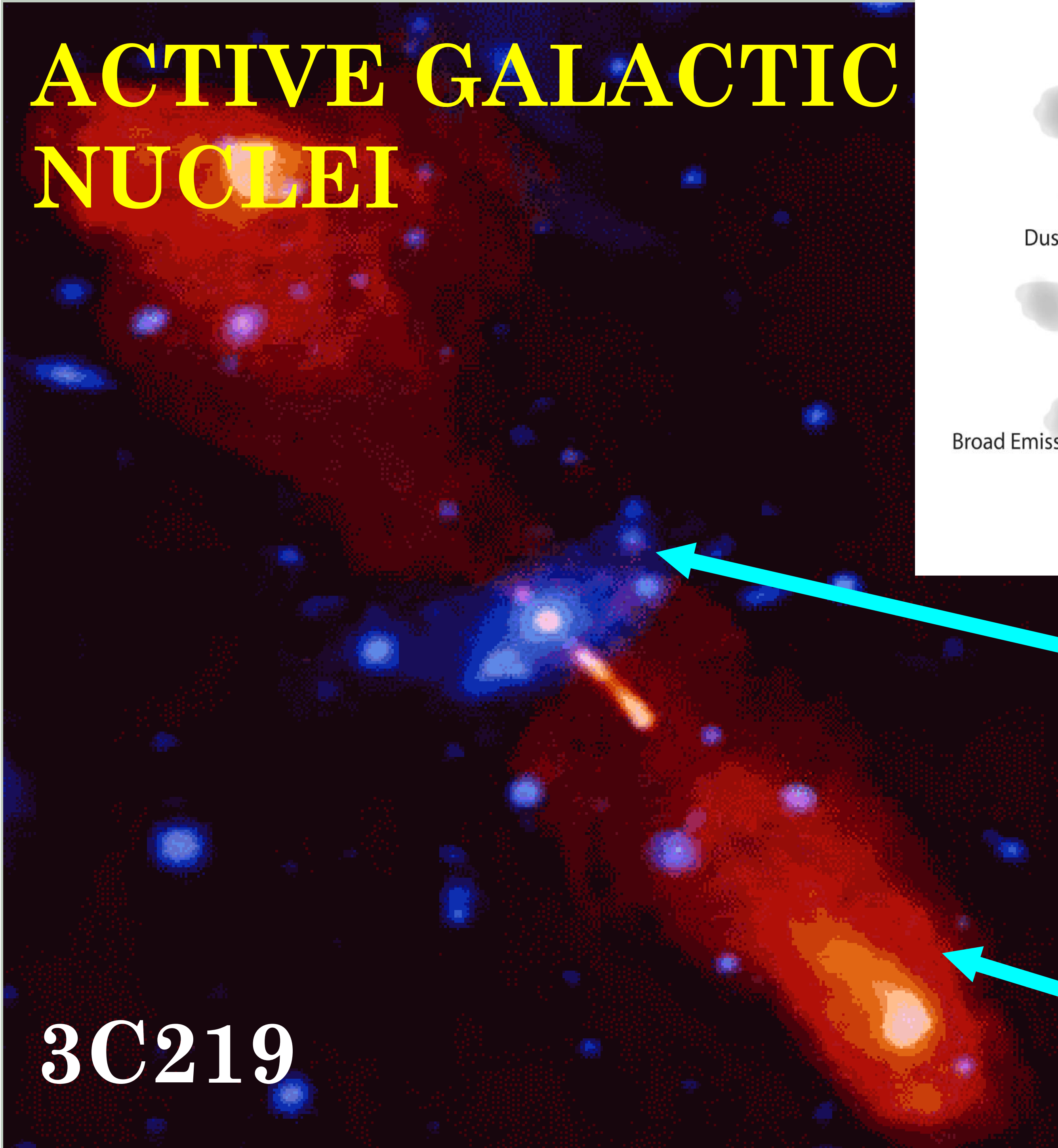
Connection with
The "WMAP haze"

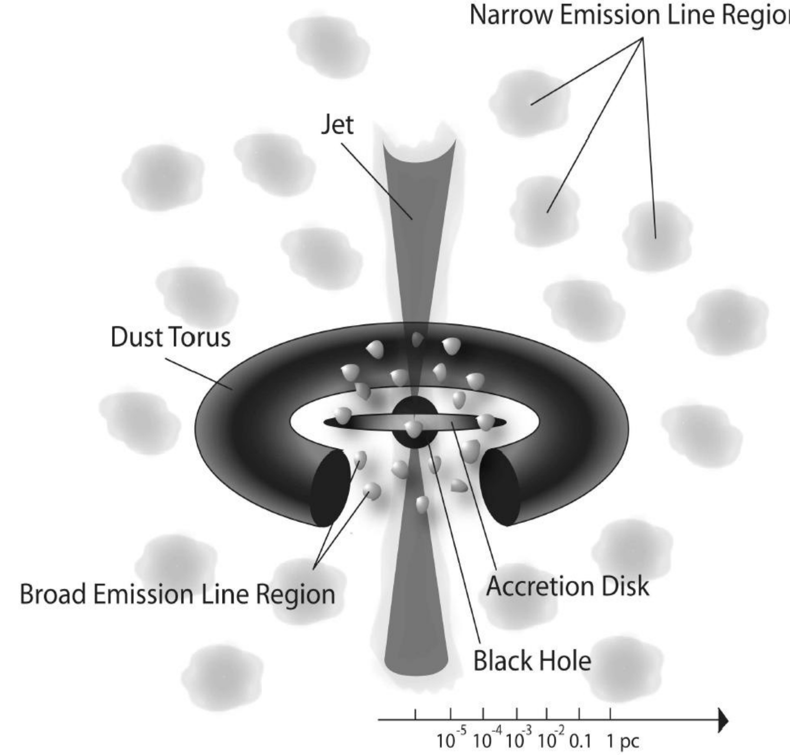


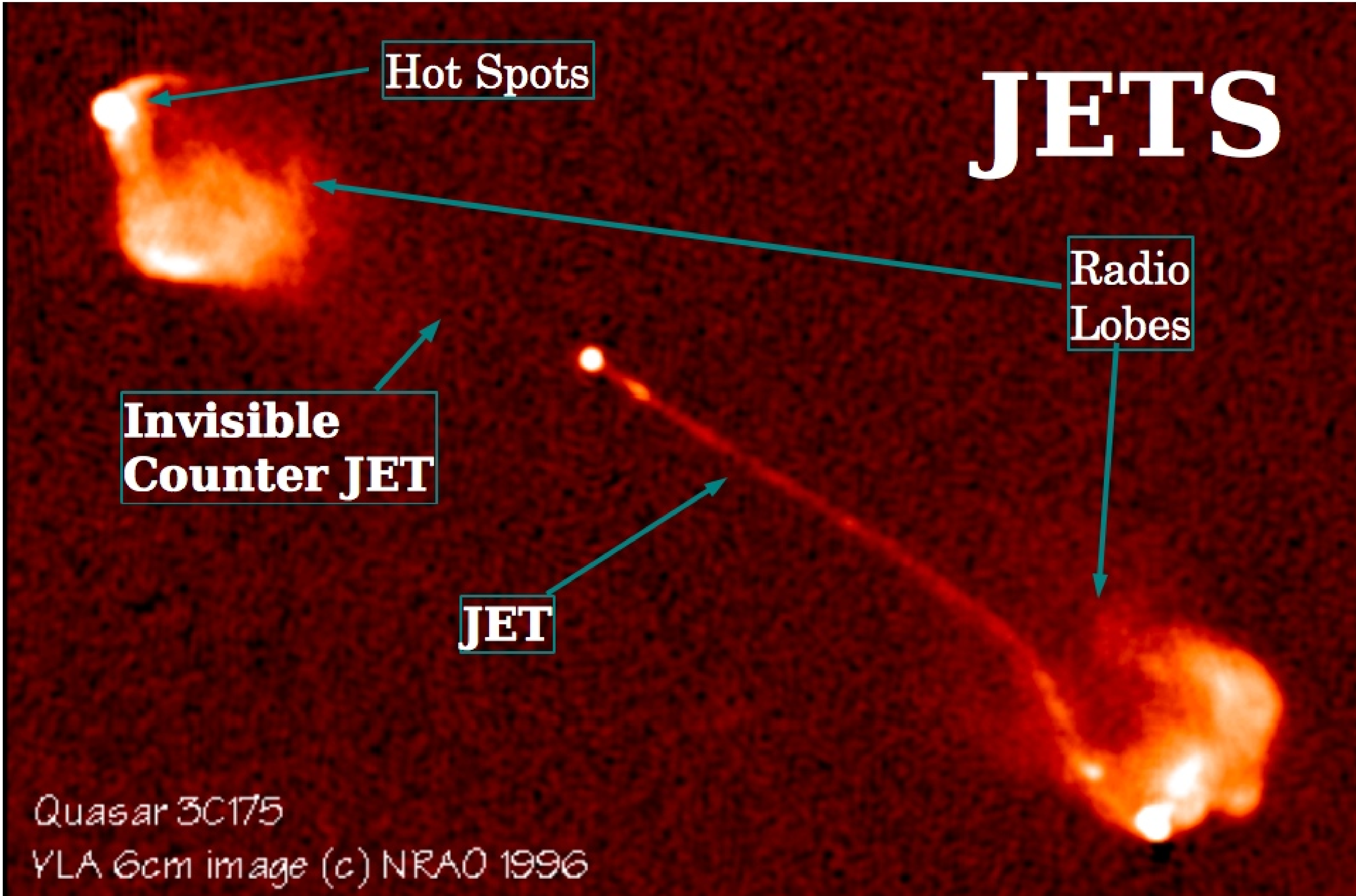
“Wild at Heart” the Galactic center!

ACTIVE GALACTIC NUCLEI




ACTIVE GALACTIC NUCLEI
3C219
Optical
Radio

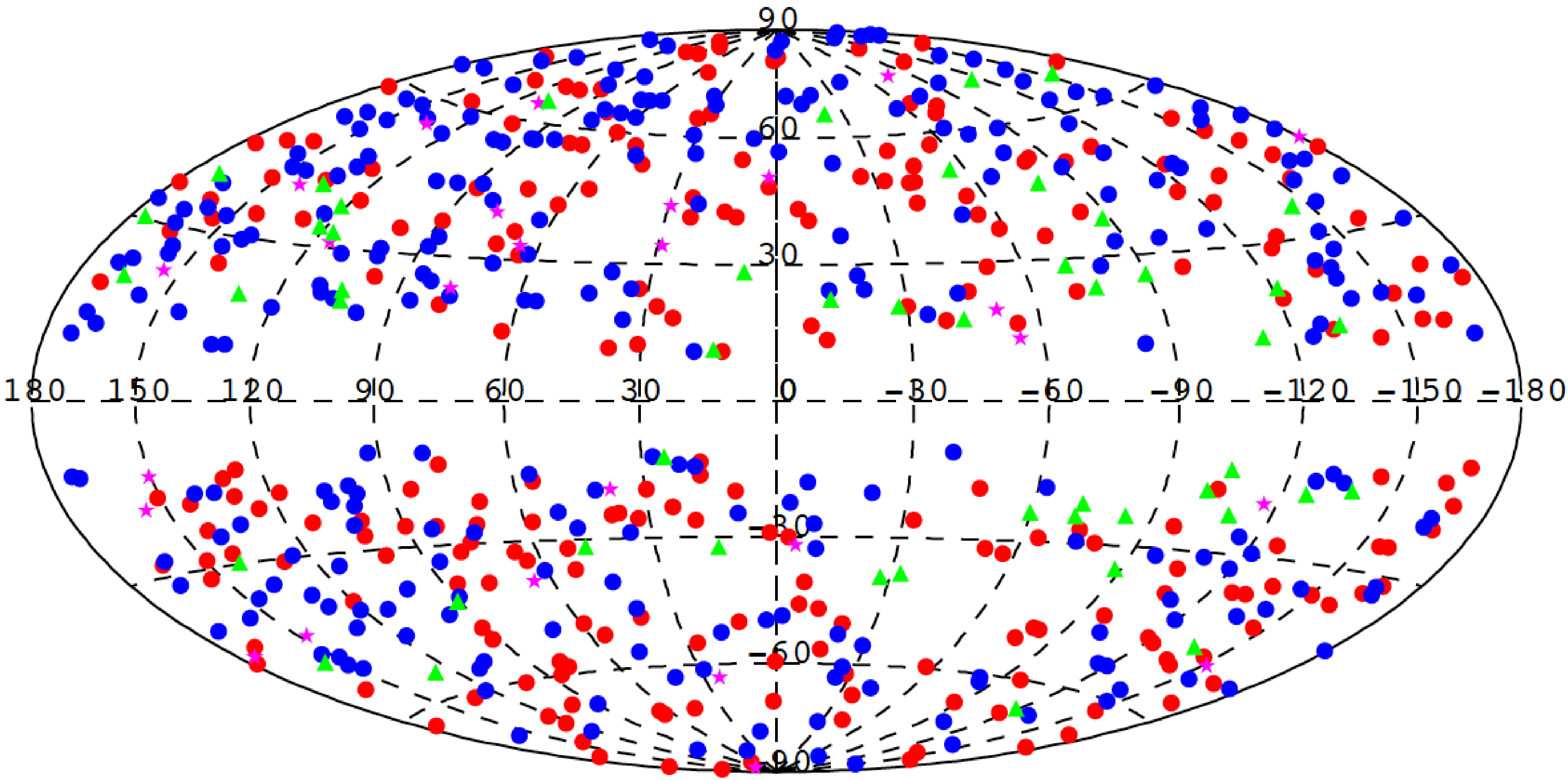

Narrow Emission Line Region
Jet
Dust Torus
Broad Emission Line Region
Accretion Disk
Black Hole
10^{-5} 10^{-4} 10^{-3} 10^{-2} 0.1 1 pc



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

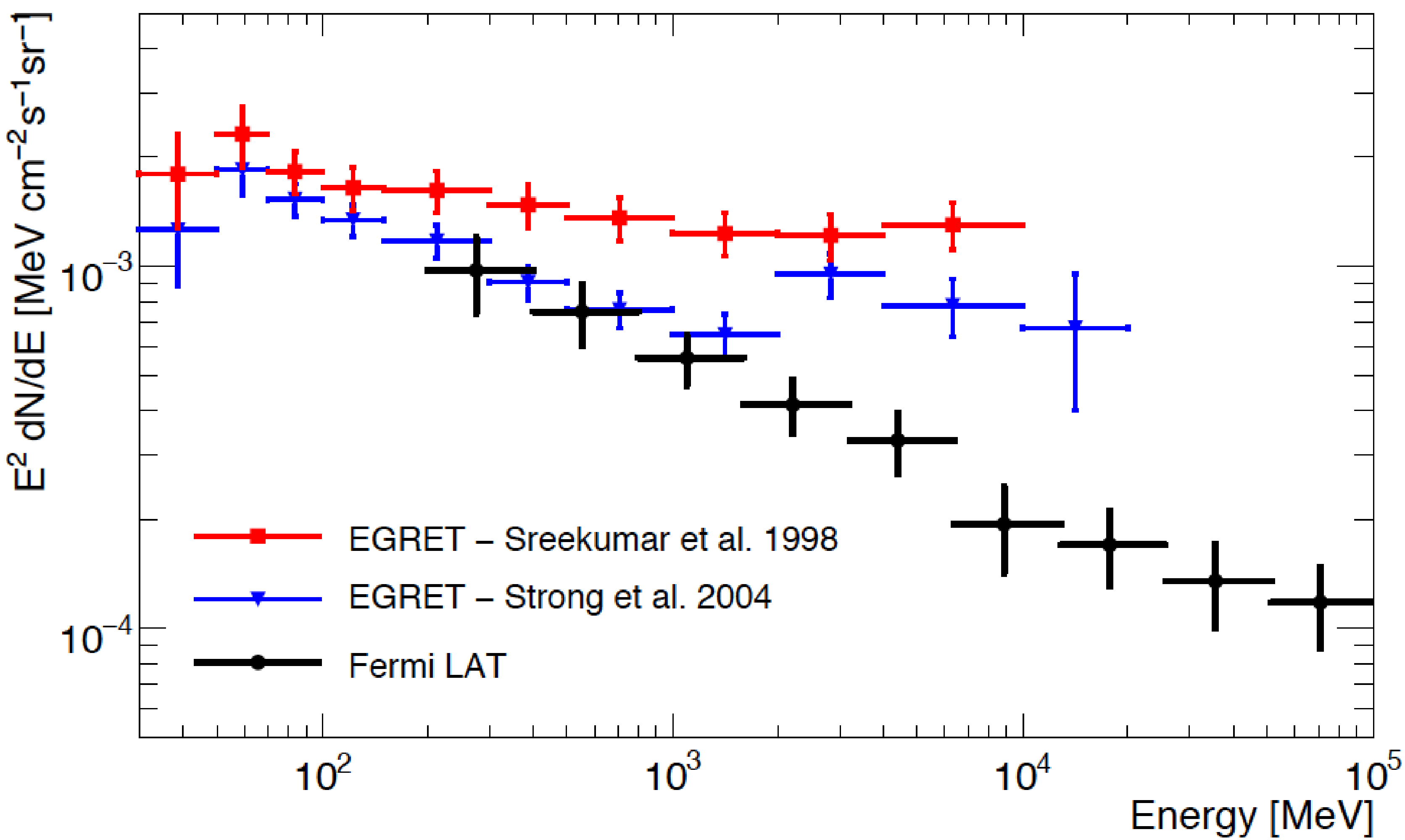
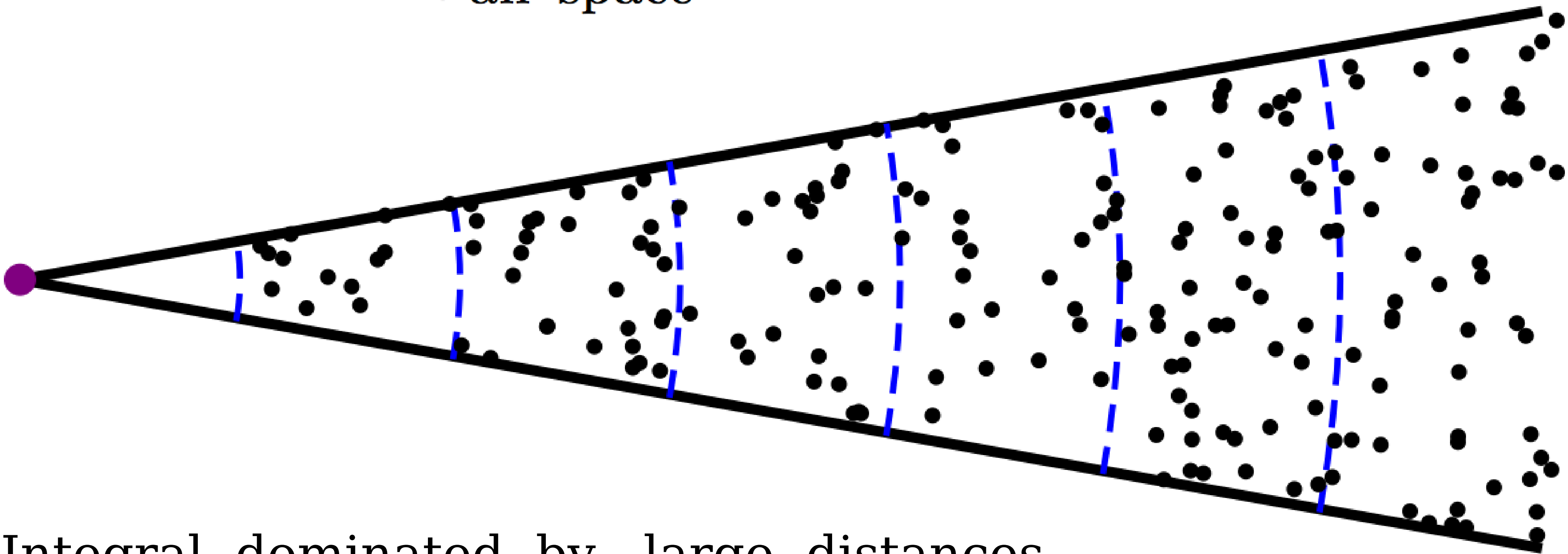


FIG. 4: EGB intensity derived in this work compared with EGRET-derived intensities taken from table 1 in [2] and table 3 in [24]. Our derived spectrum is compatible with a simple power-law with index $\gamma = 2.41 \pm 0.05$ and intensity $I(> 100\,\mathrm{MeV}) = (1.03 \pm 0.17) \times 10^{-5}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$ where the uncertainties are systematics dominated.

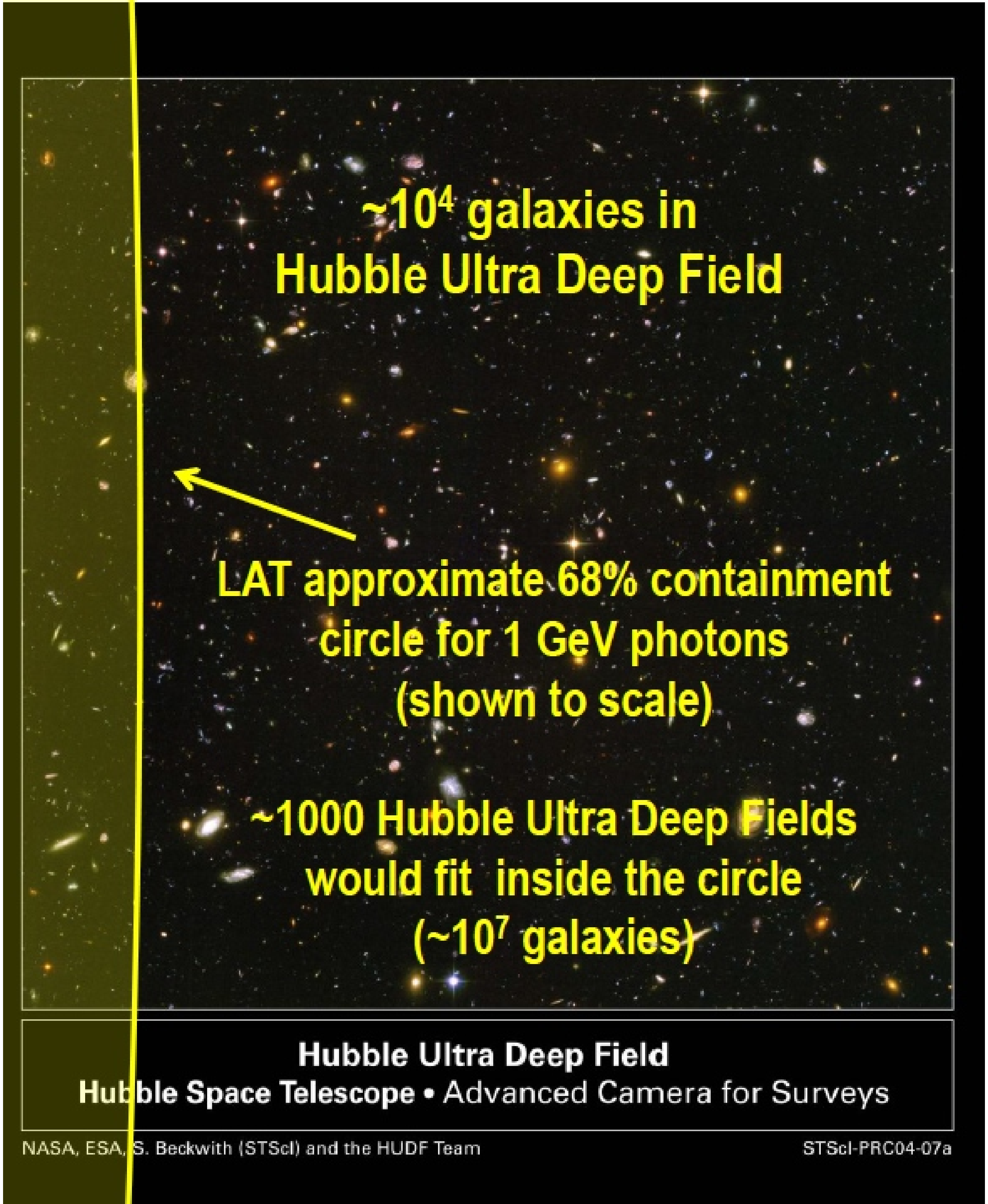
INCLUSIVE Extra-Galactic Photon Flux

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

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



Integral dominated by large distances


~10^4 galaxies in
Hubble Ultra Deep Field
LAT approximate 68% containment
circle for 1 GeV photons
(shown to scale)
~1000 Hubble Ultra Deep Fields
would fit inside the circle
(~10^7 galaxies)
Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys
NASA, ESA, S. Beckwith (STScI) and the HUDF Team
STScI-PRC04-07a

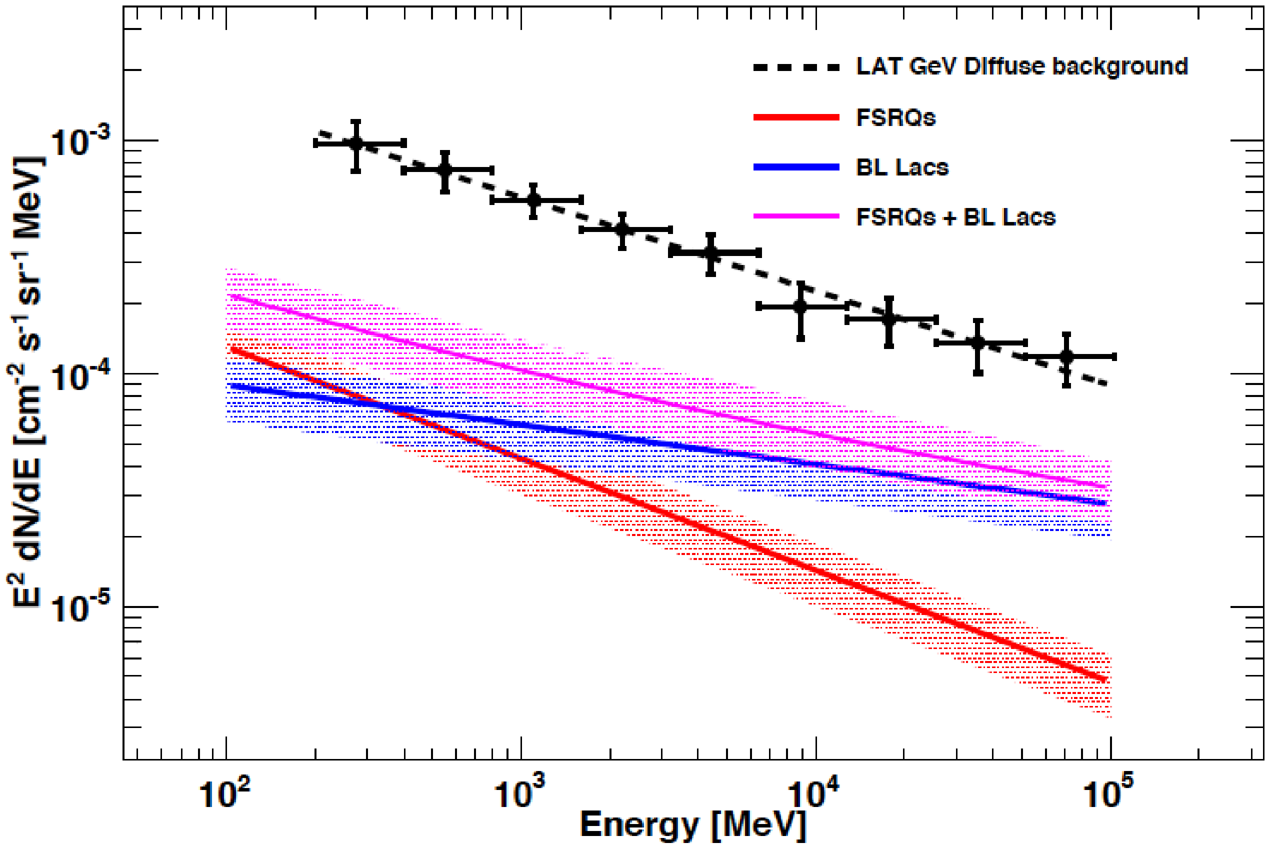
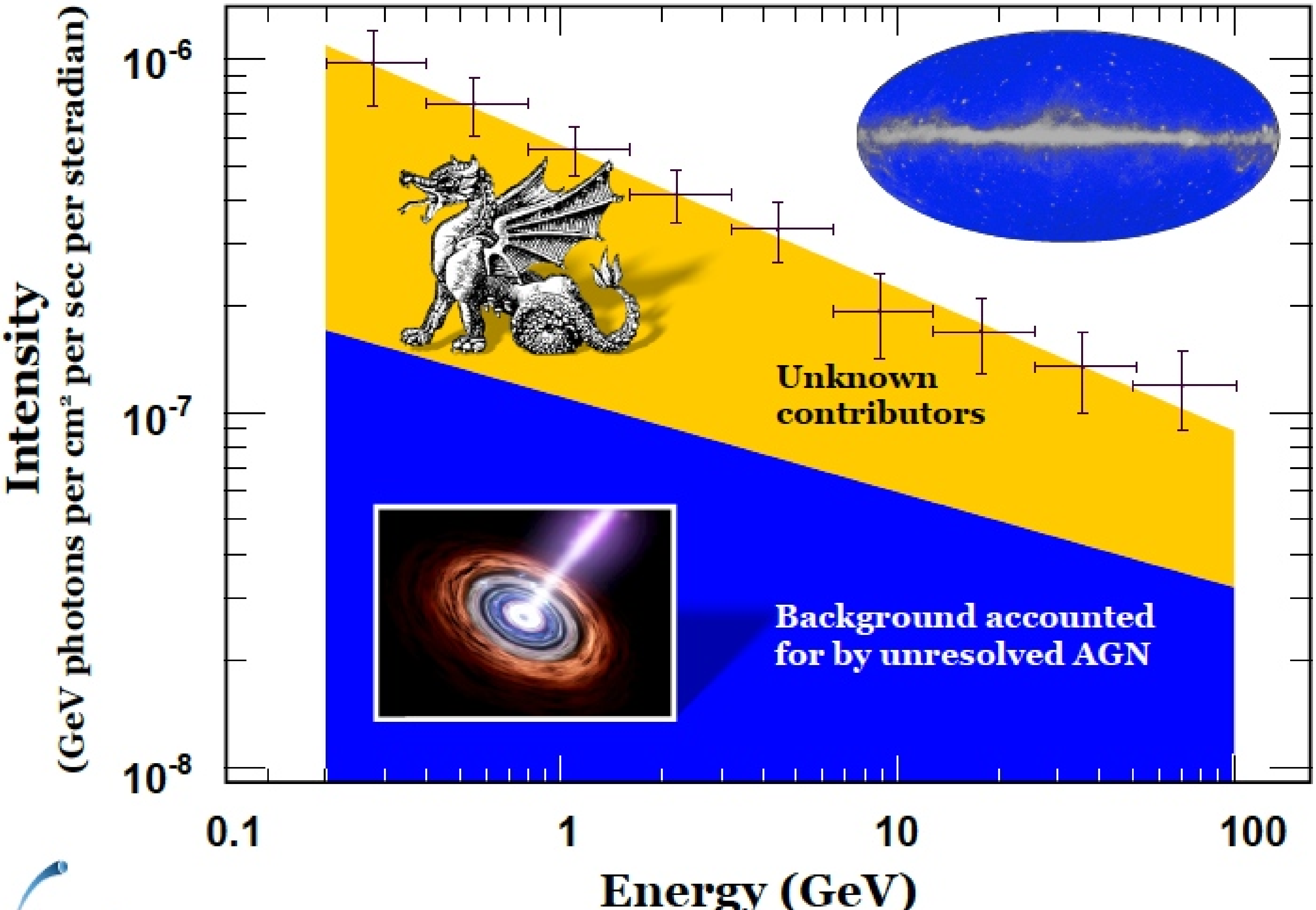
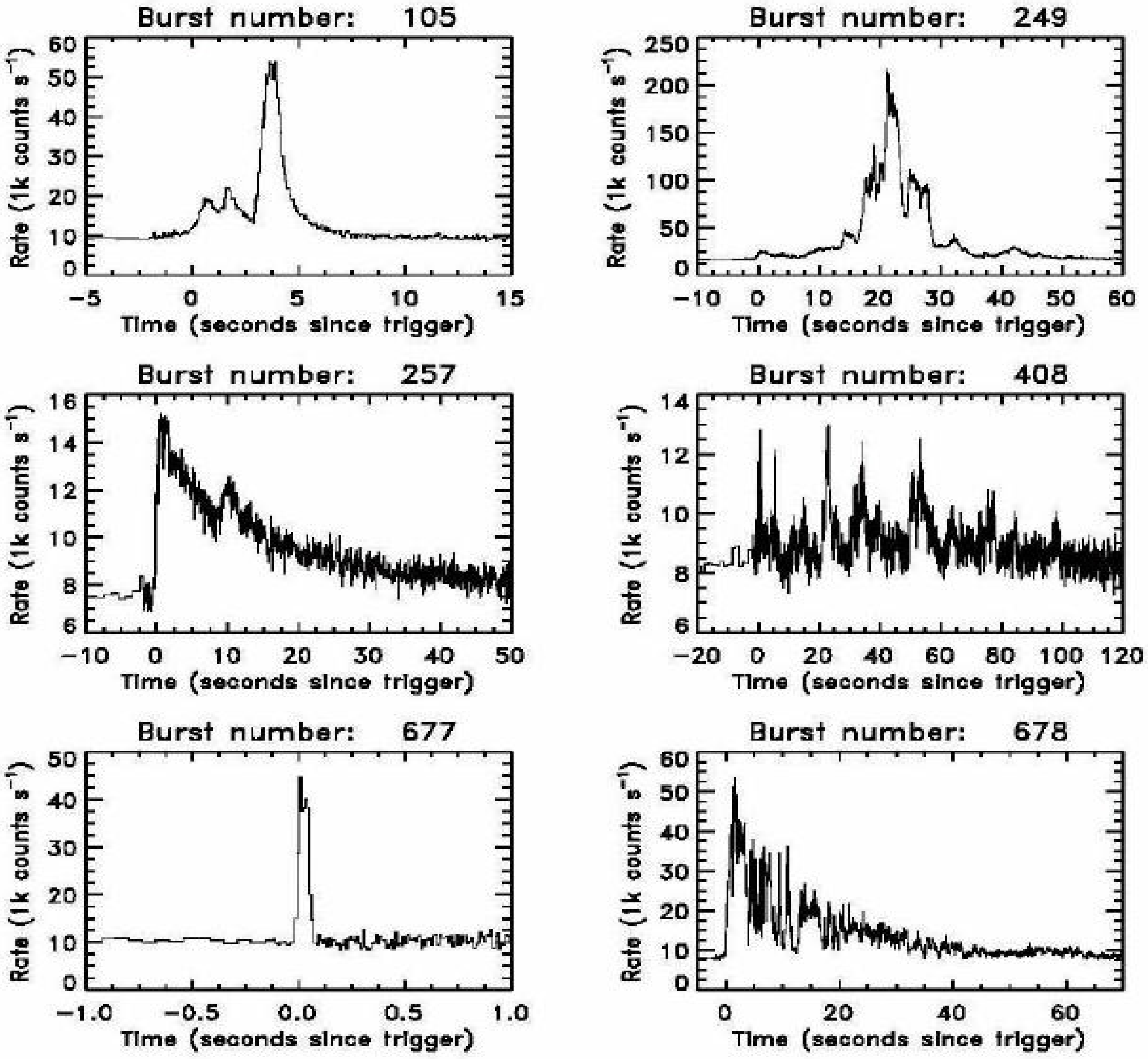


Fig. 20.— Contributions of different classes of blazars to the diffuse GeV background obtained by integrating the log N–log S. The red and the blues solid lines show the contribution of FSRQs and BL Lacs respectively, while the pink solid line shows the sum of the two. The bands around each line show the total (statistical plus systematic) uncertainty.

Fermi LAT Extragalactic Gamma-ray Background

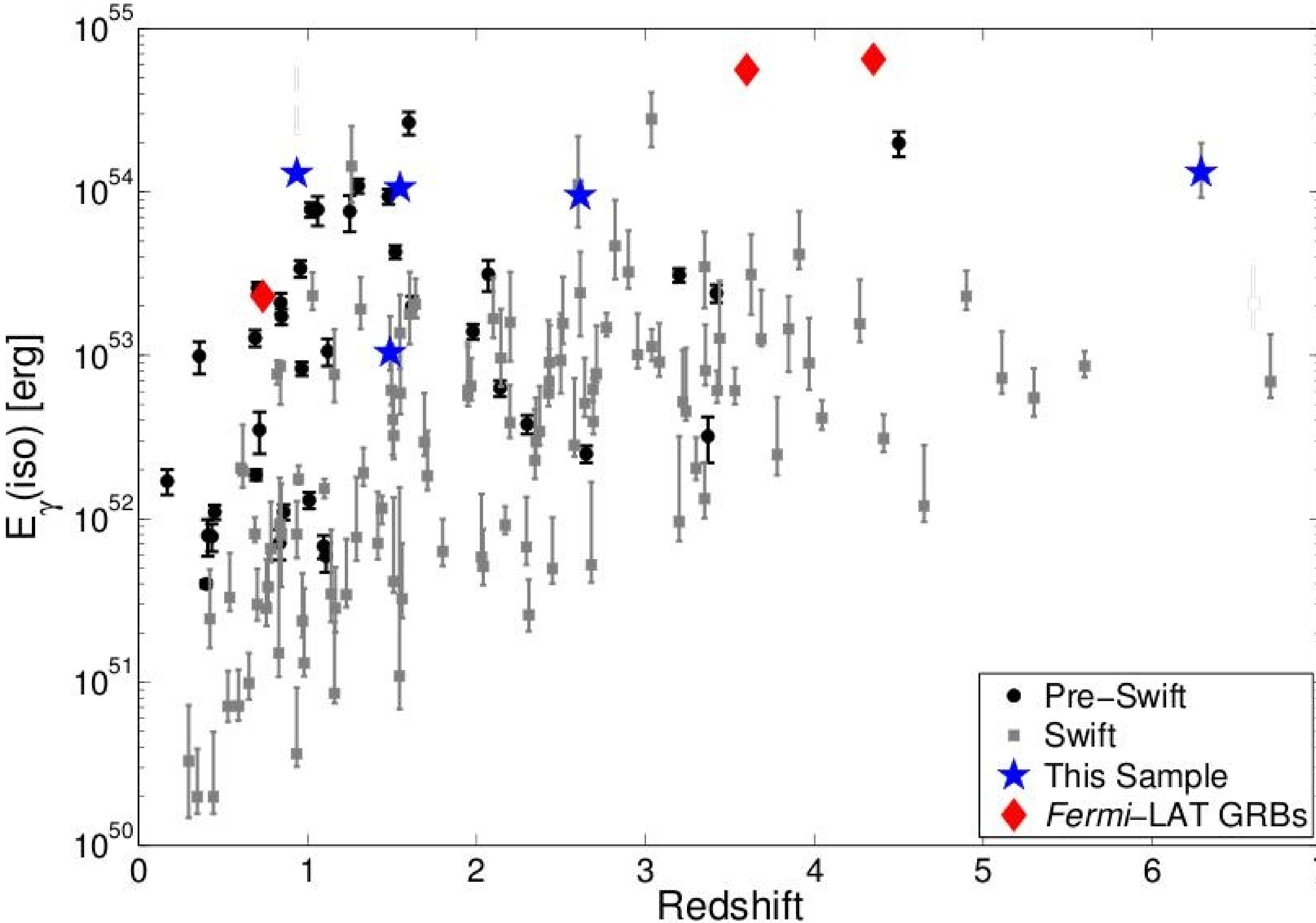


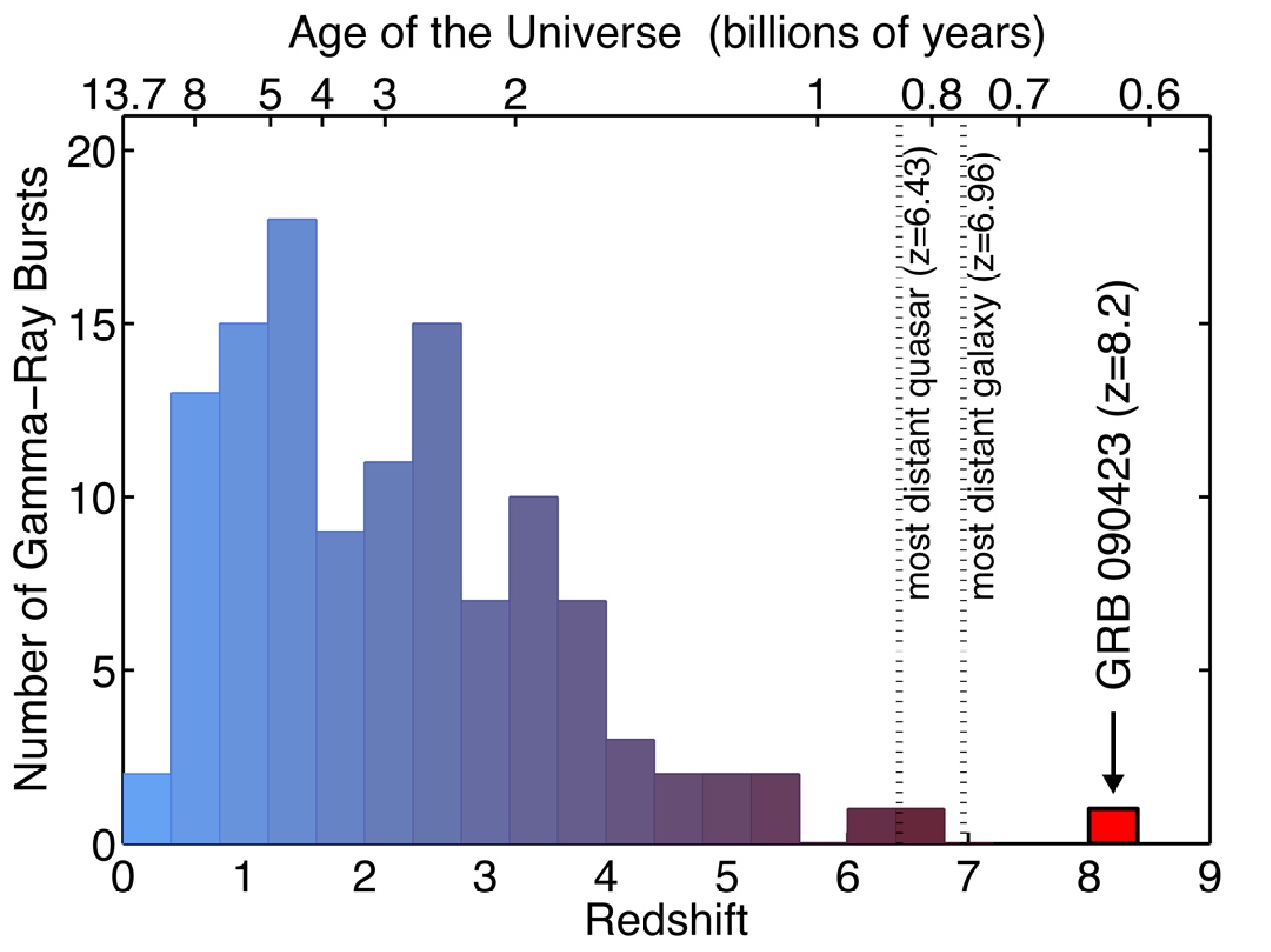
GAMMA RAY BURSTS (GRB's)



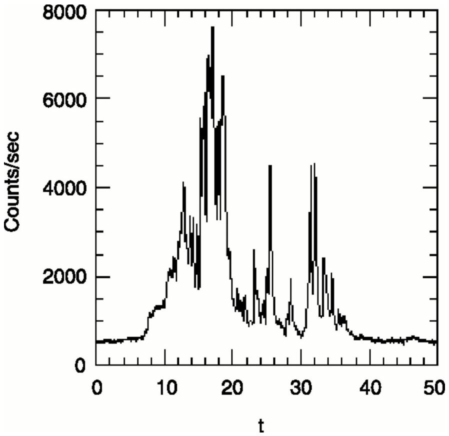
Proposed source
Of the CR

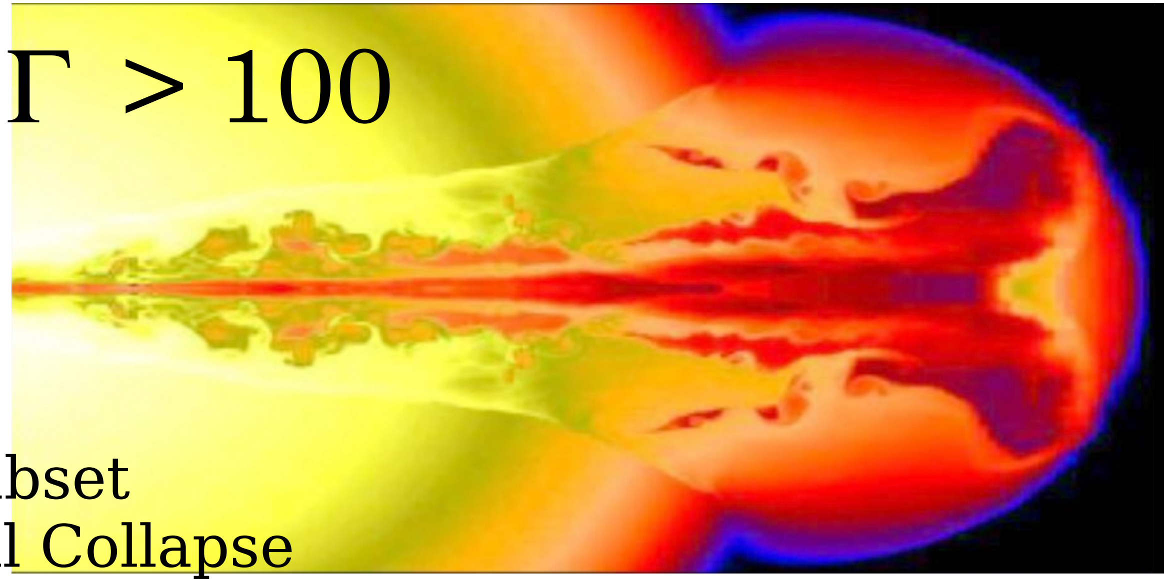
Extraordinary Large (beamed) Energy Output



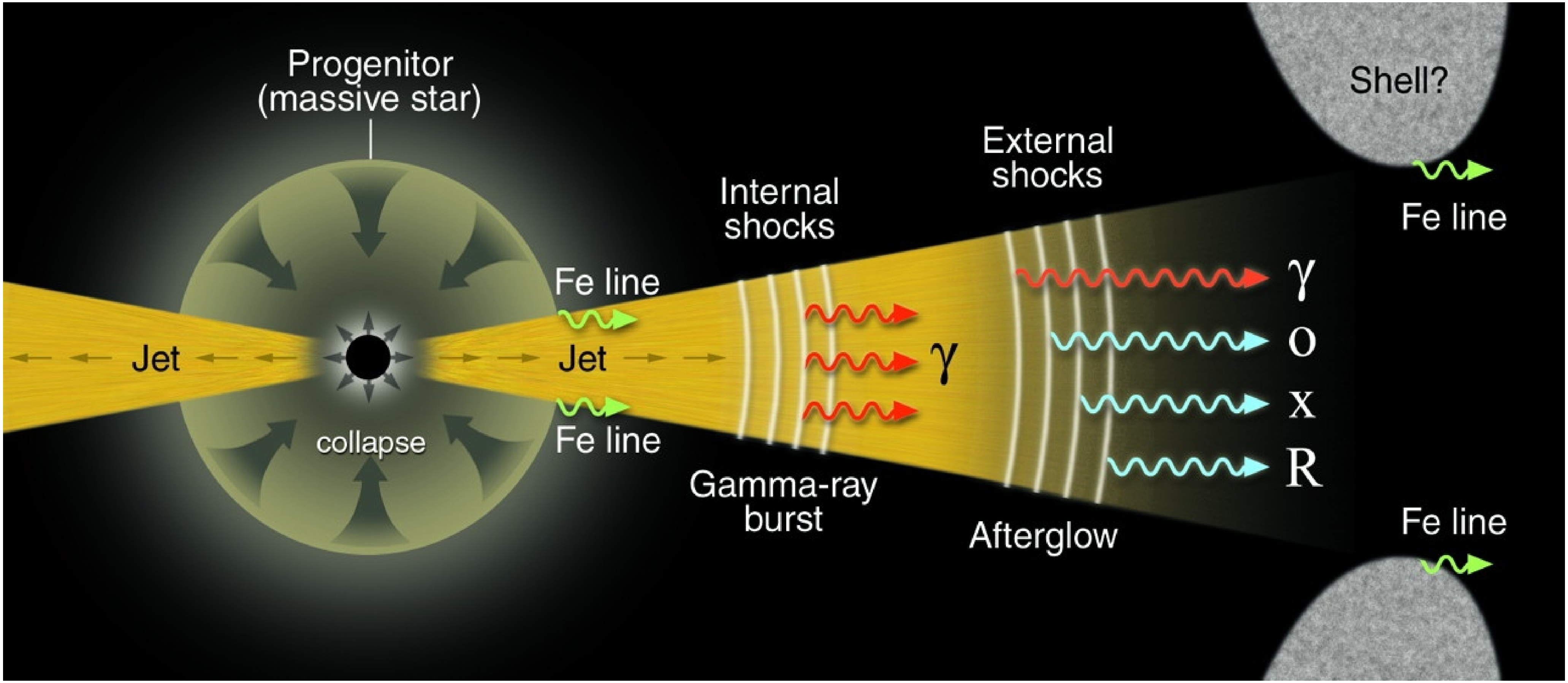


Age of the Universe (billions of years)
13.7
8
5
4
3
2
1
0.8
0.7
0.6
Number of Gamma–Ray Bursts
0
5
10
15
20
most distant quasar (z=6.43)
most distant galaxy (z=6.96)
GRB 090423 (z=8.2)
0
1
2
3
4
5
6
7
8
9
Redshift





GRB : associated with a subset
of SN Stellar Gravitational Collapse



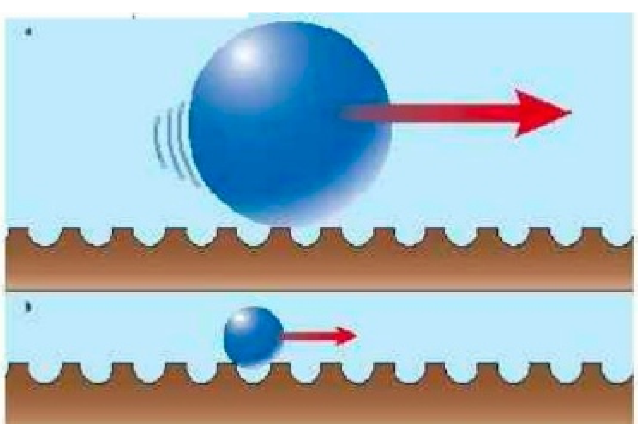
Short distance structure
of space time

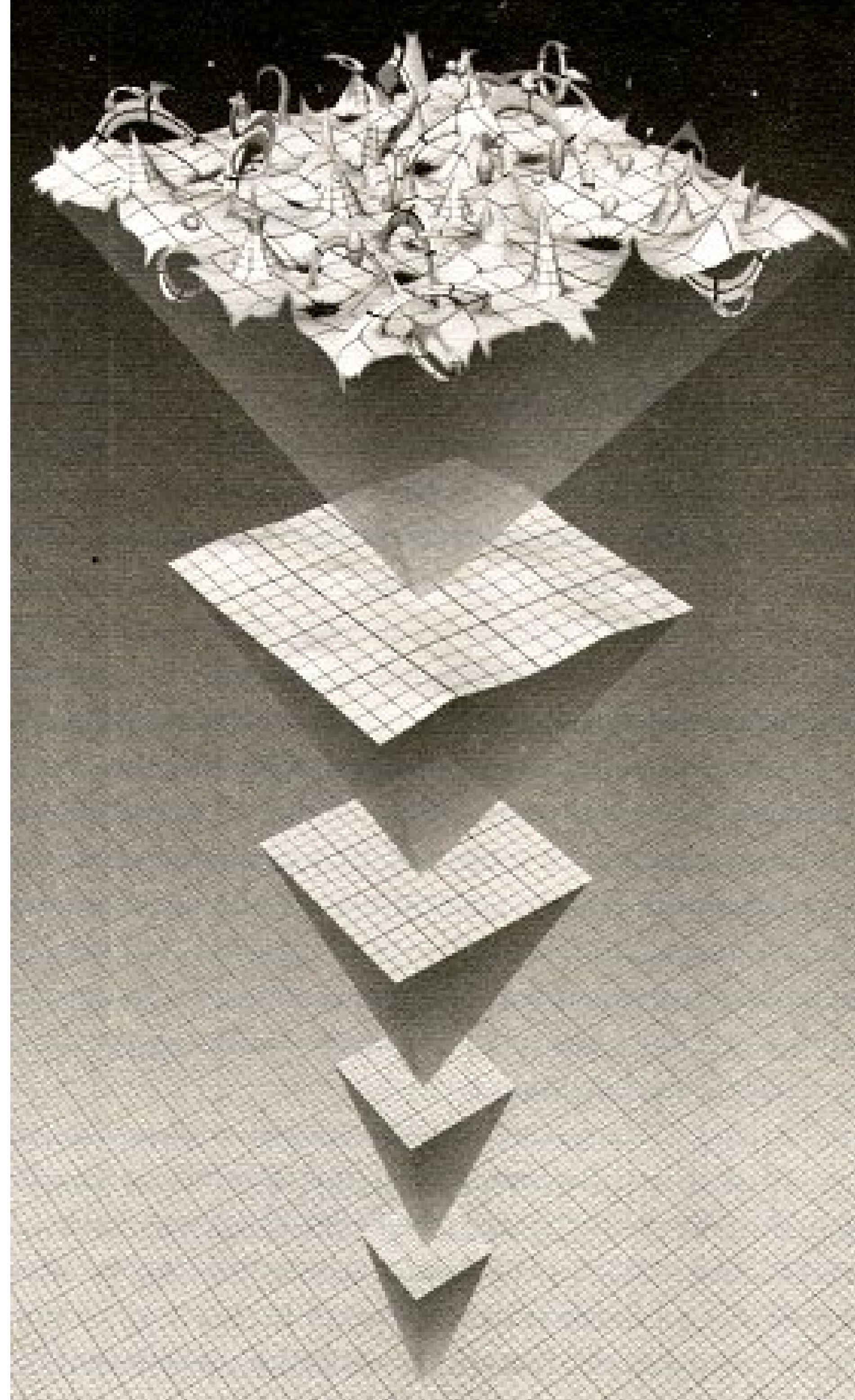
$$c(E) = c \times \left(1 - \xi \, \frac{E}{M_{\rm Planck}} + \ldots\right)$$

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

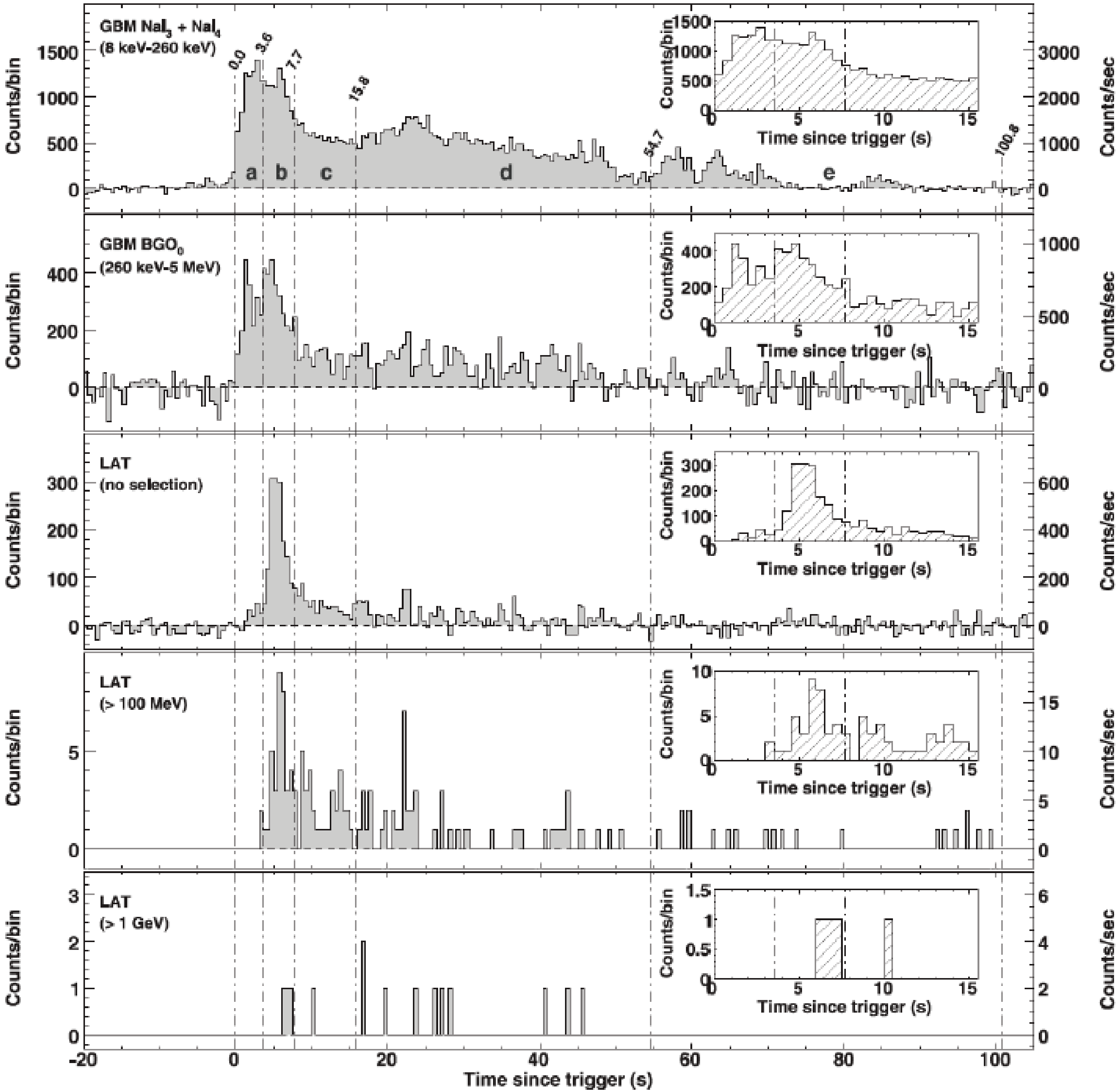
$$\Delta t \simeq 0.06 \, E_{\rm GeV} \, z$$

Delay of high energy photons



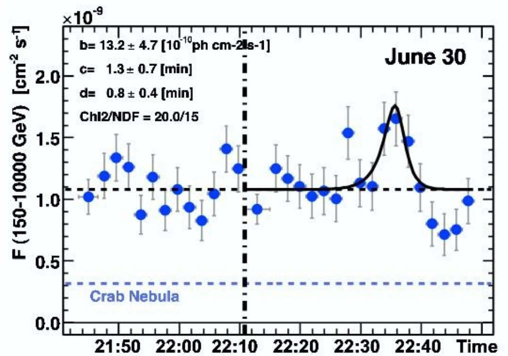


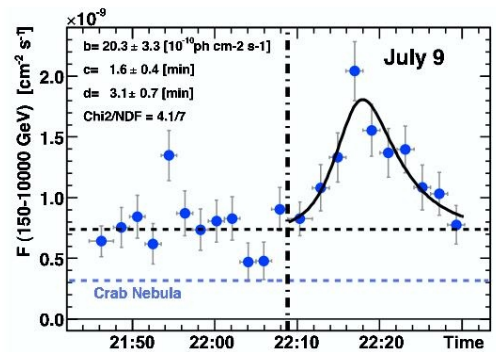
GRB 080916C
(Fermi)

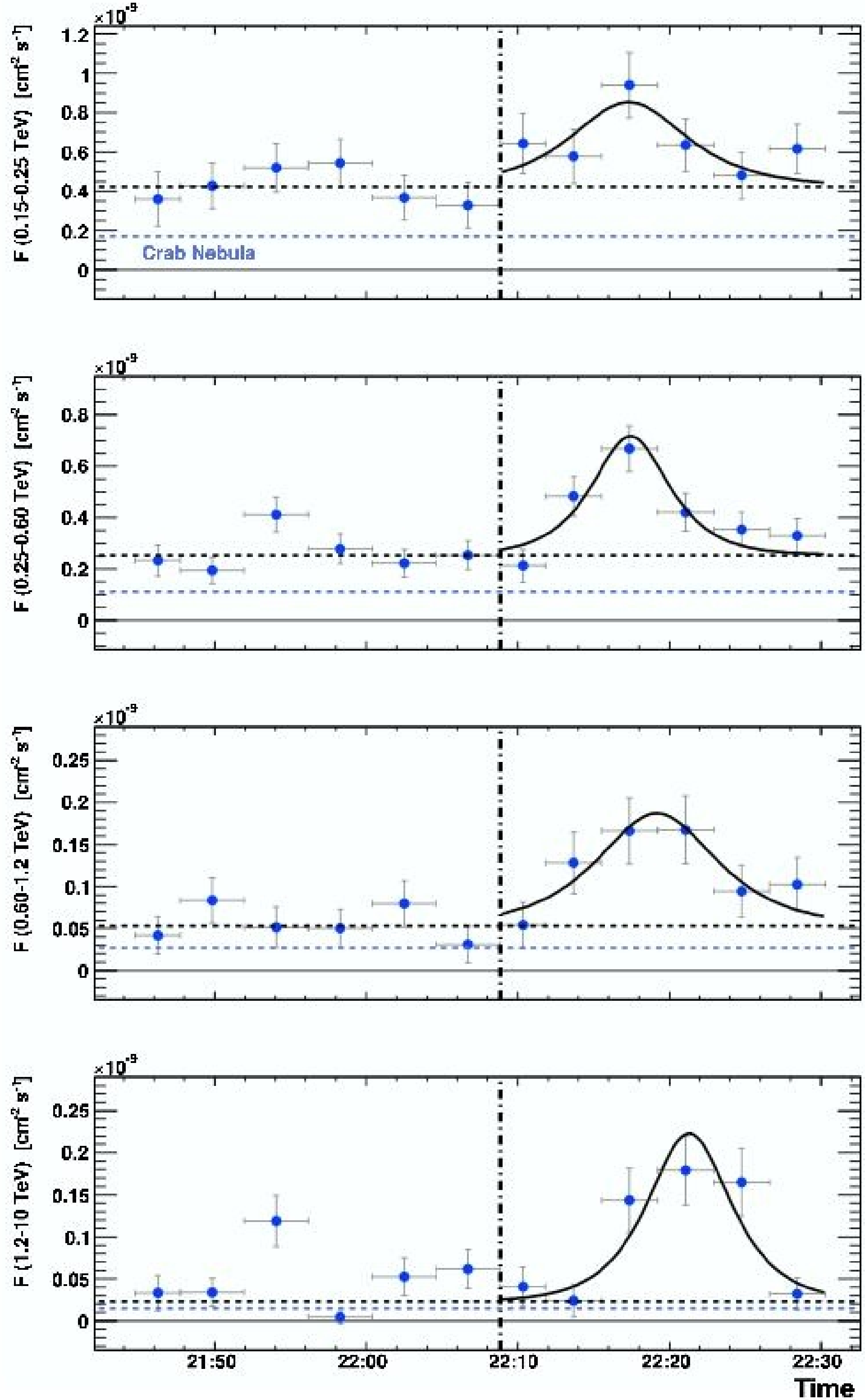


Markarian 501
(120 Mpc)

9 july 2005
2 minutes bins







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

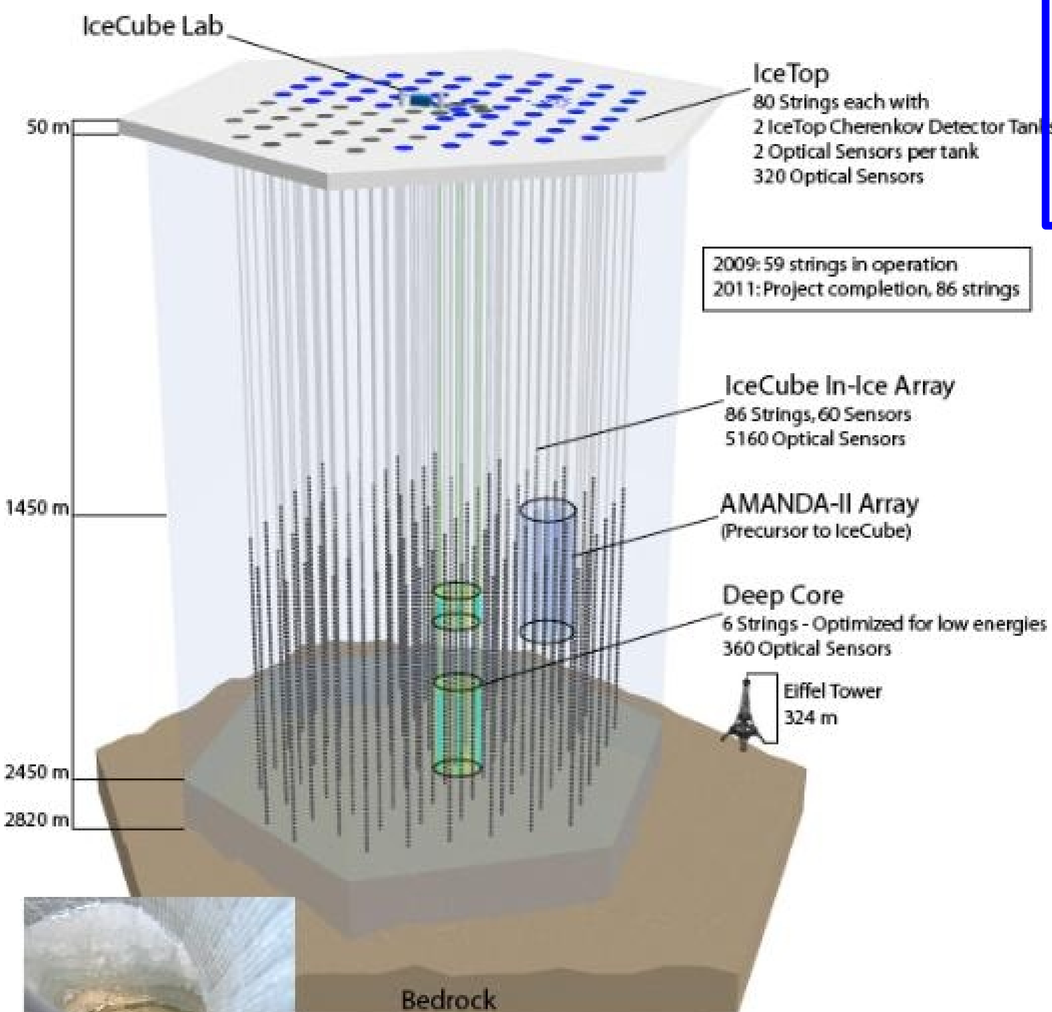
can be profound.

IceCube

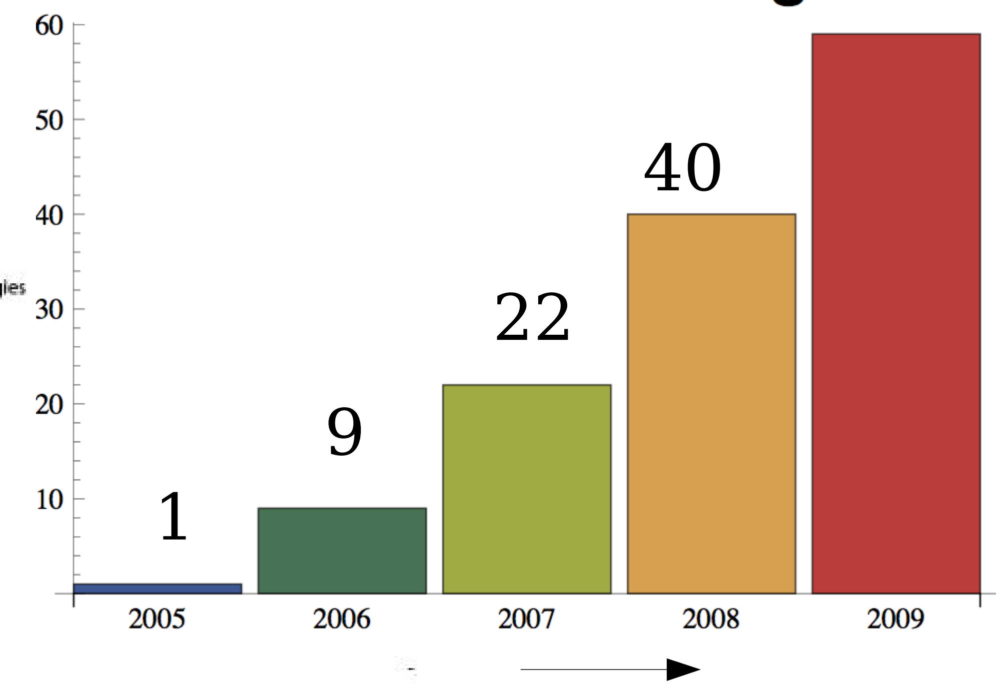
80 + 6 strings (125 m)

60 PMT / strings (17 m)

2400 PMT
+ surface array

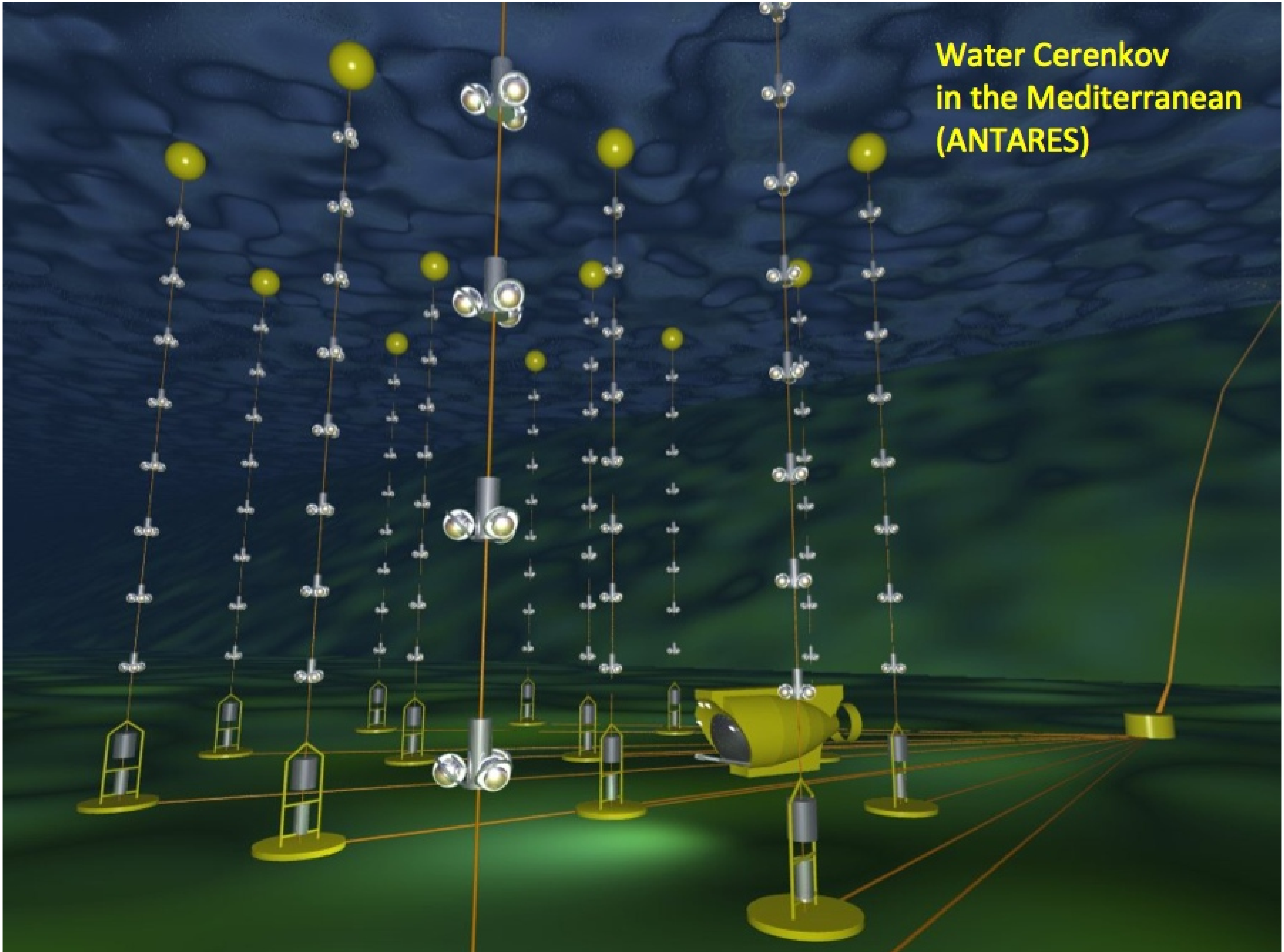


IceCube total strings 59



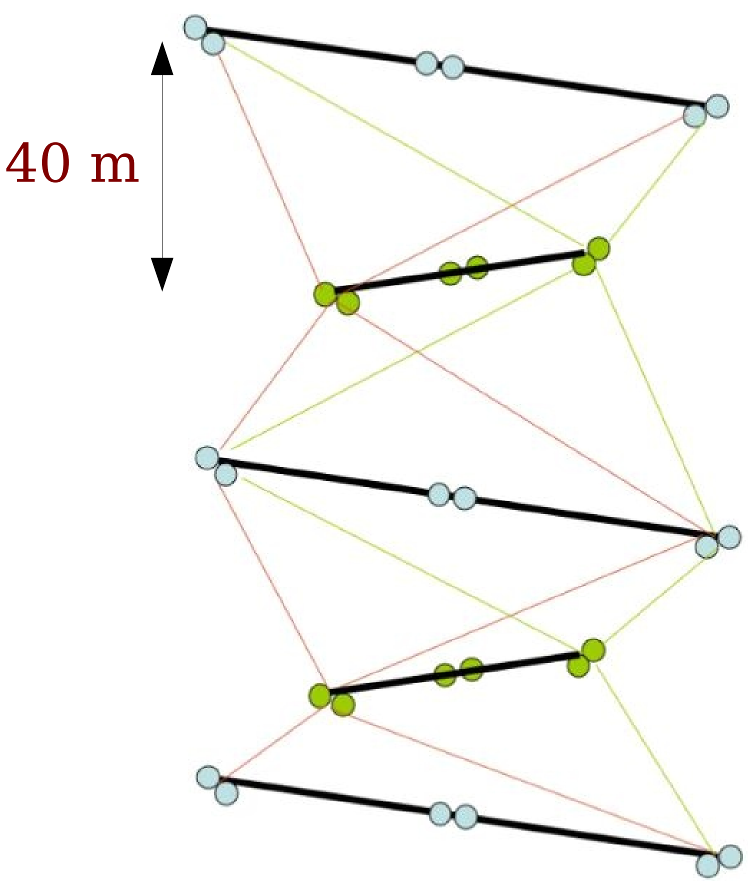
85 strings, 60 OMs/string
17 m between OMs, 125 m between strings
IceTop: 80 stations of 2 tanks with 2 modules

No SIGNAL
(yet)


Water Cerenkov
in the Mediterranean
(ANTARES)

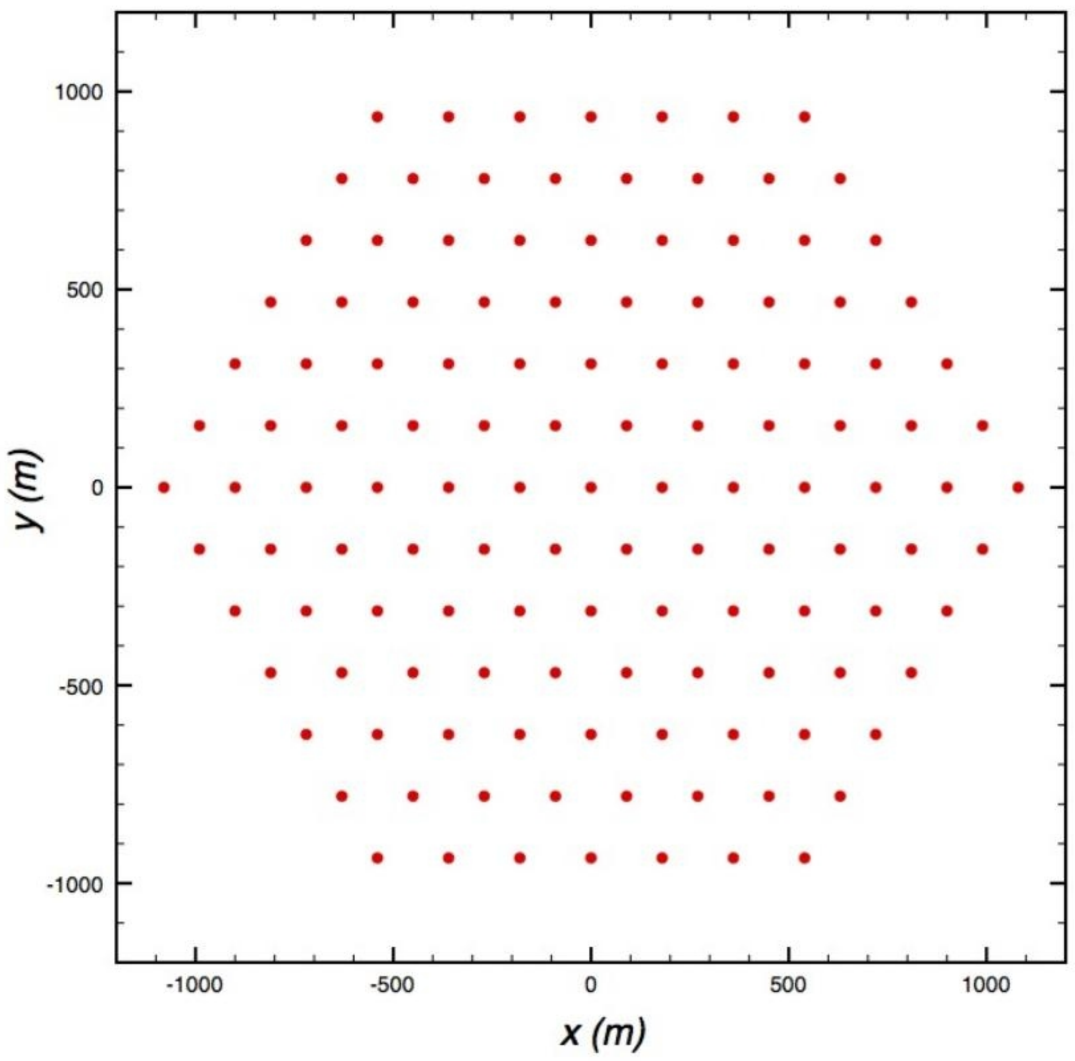
Possible structure of a "KM3" detector in the Mediterranean Sea:

"tower" [6 PMT's]



Detection Unit layout.

127 towers (180 m)



COSMIC RAYS

1. Below the Knee

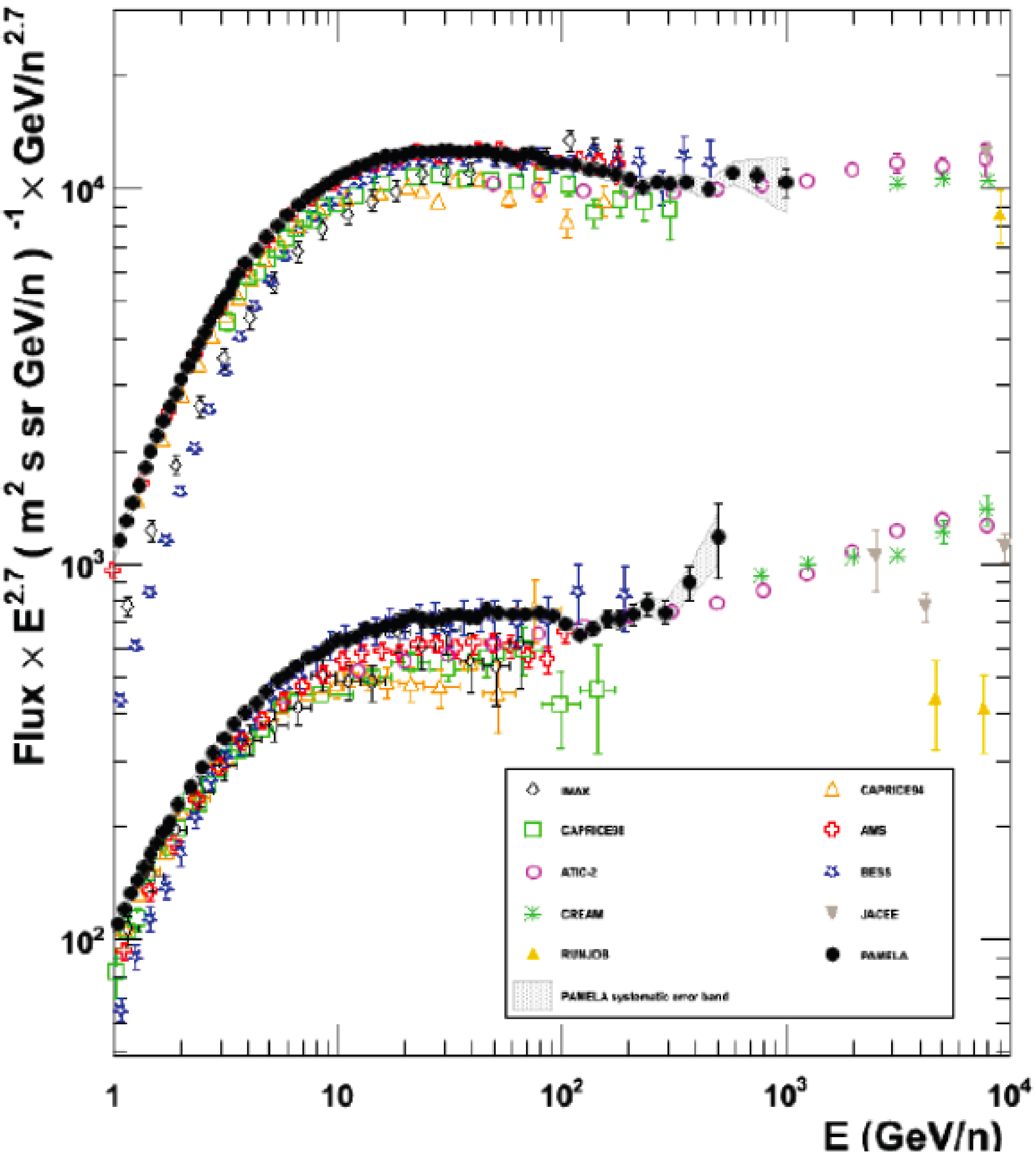
2. The Knee

3. More knees ??

4. Galactic to Extragalactic transition

5. The “End” of the spectrum

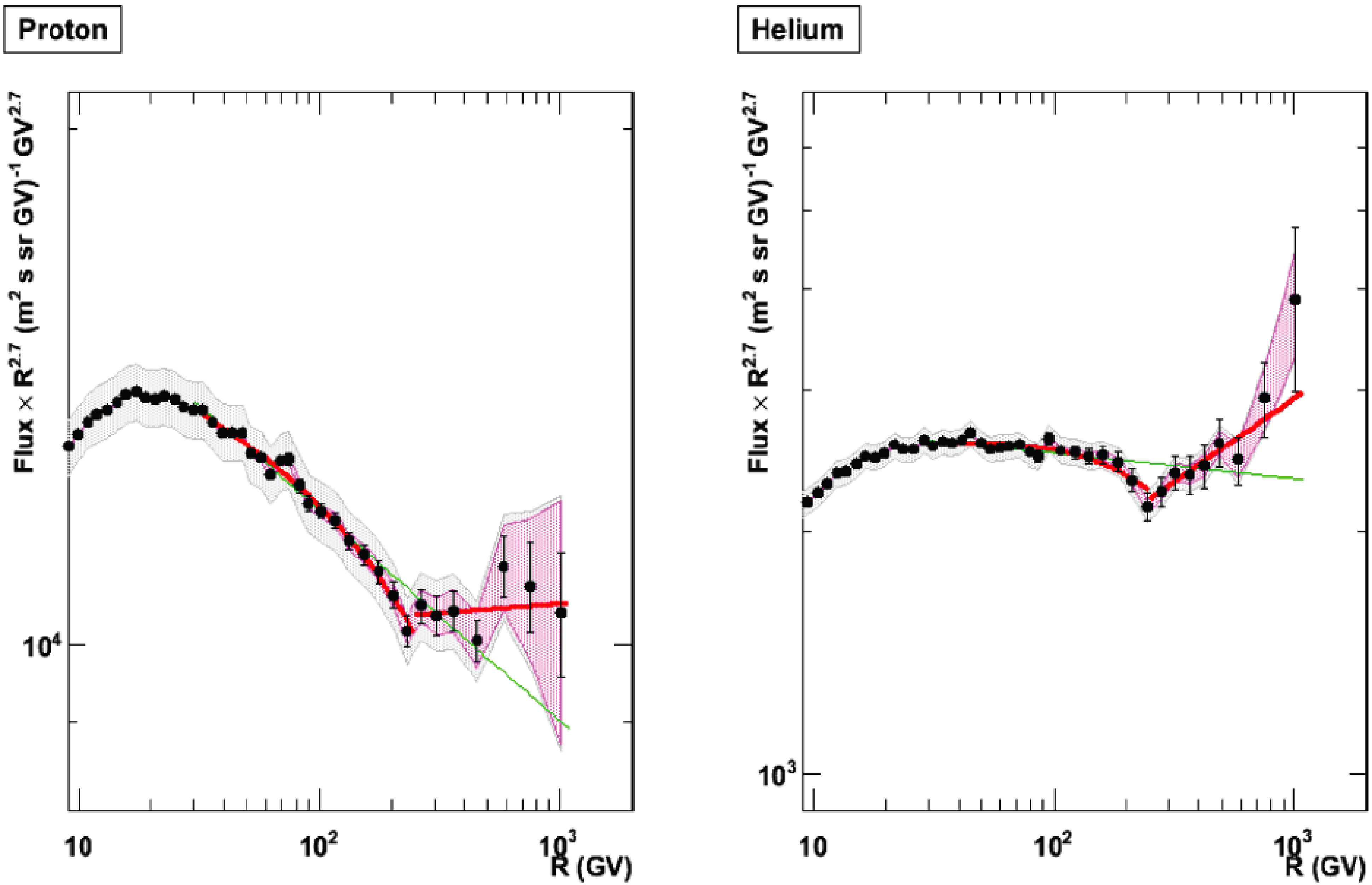
PAMELA Proton and Helium flux

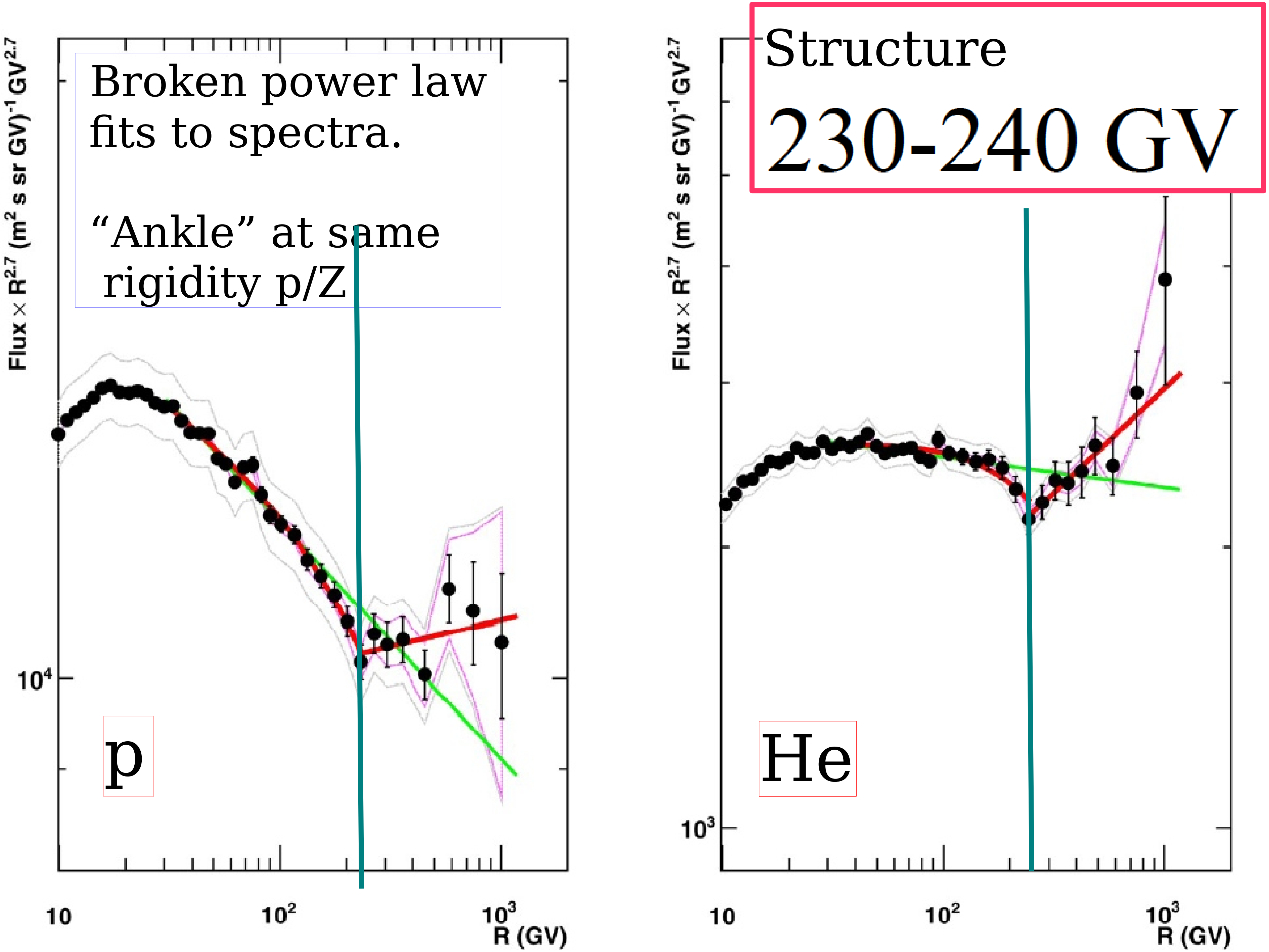


Accepted by SCIENCE
In press

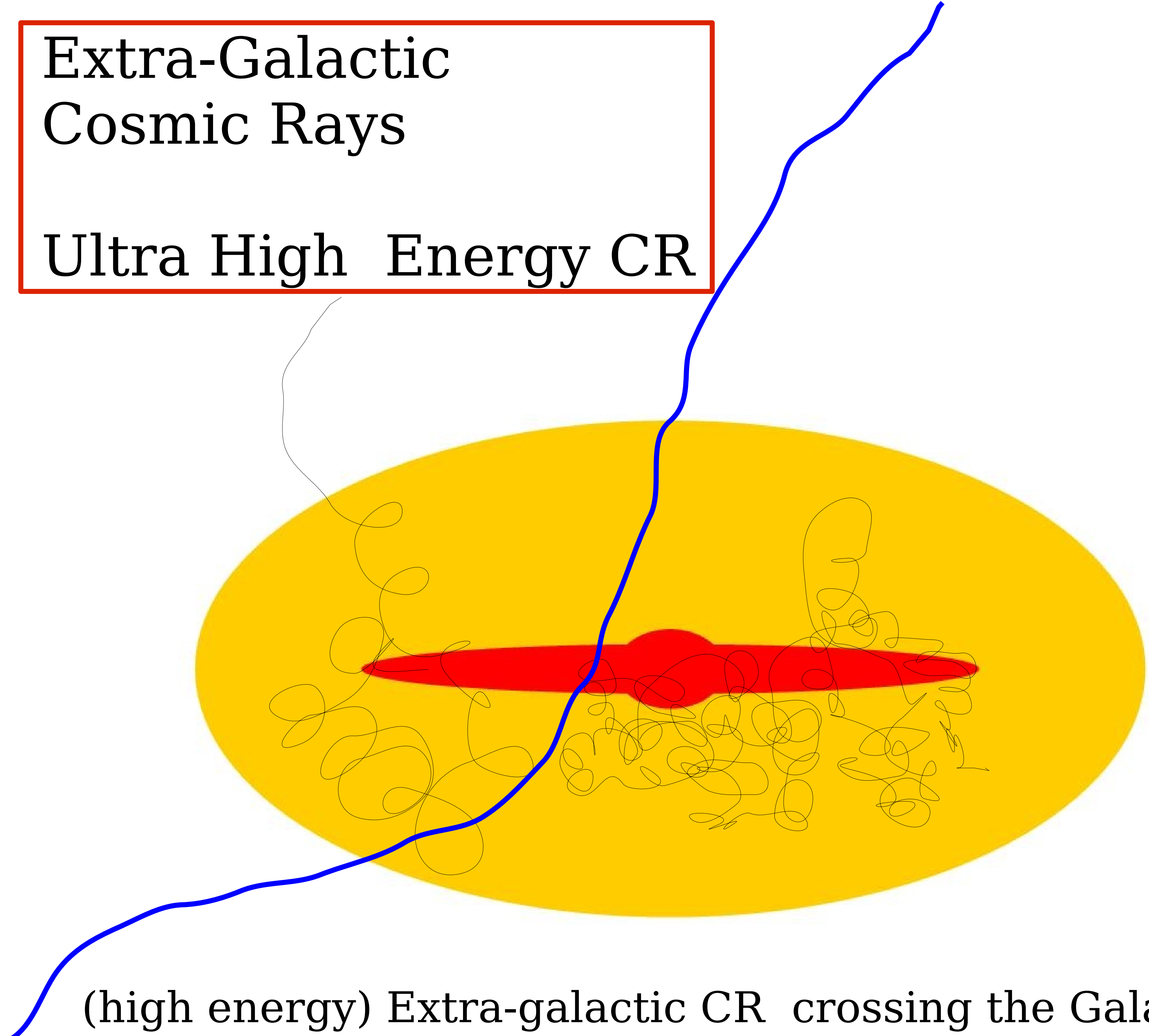
Hardening of the proton and helium spectra at 200 GV, corresponding to 200 GeV for p and 100 GeV/n for He

FIT WITH 2 SPECTRAL INDEXES



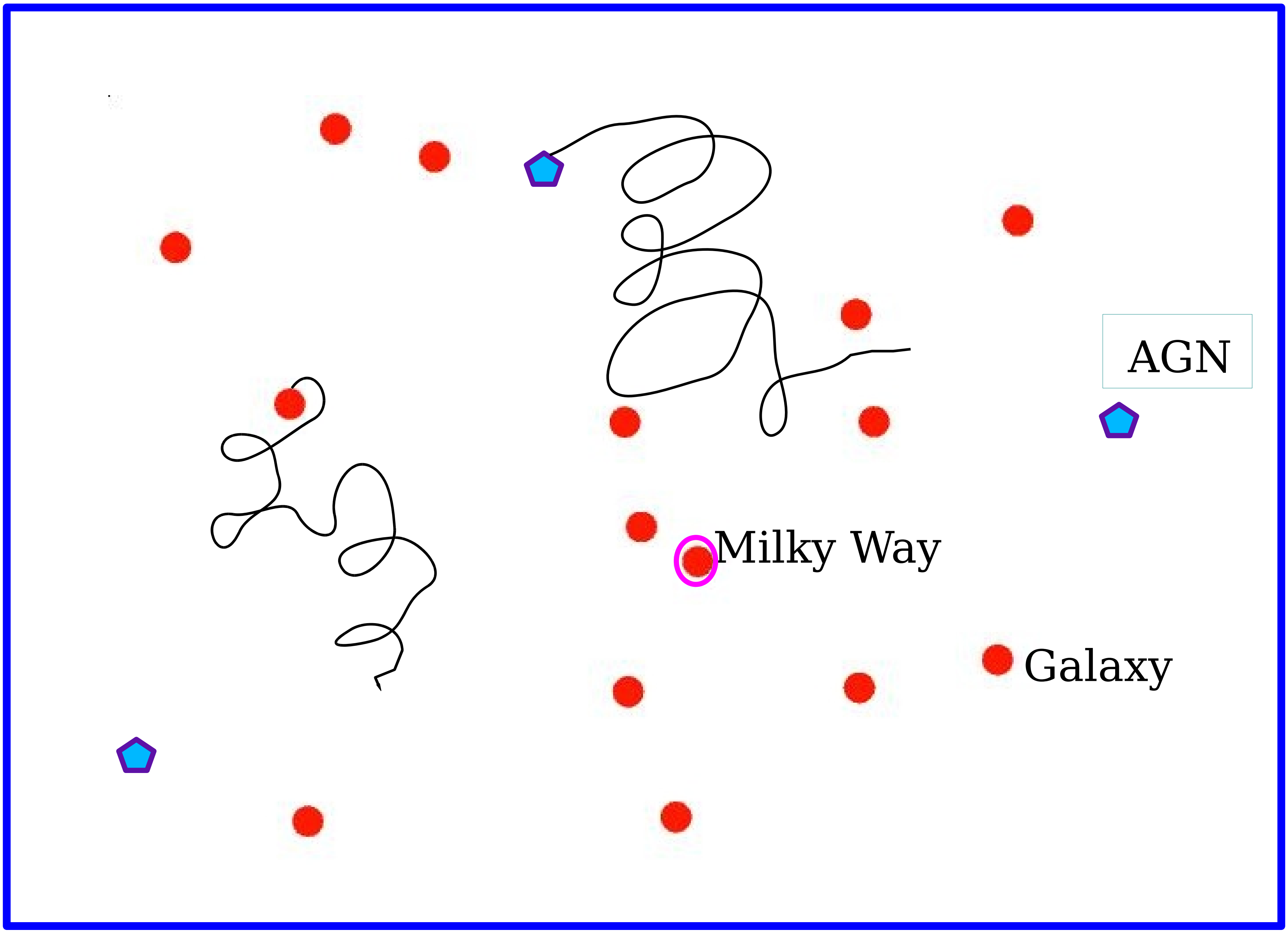


Surprising and important result.



(high energy) Extra-galactic CR crossing the Galaxy.

Piece of extragalactic space: Non MilkyWay-like sources



UHECR

1. Energy Spectrum

2. Anisotropy

3. Composition

Significant
Experimental
Discrepancies

Auger/Hires

Confusing
situation.

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

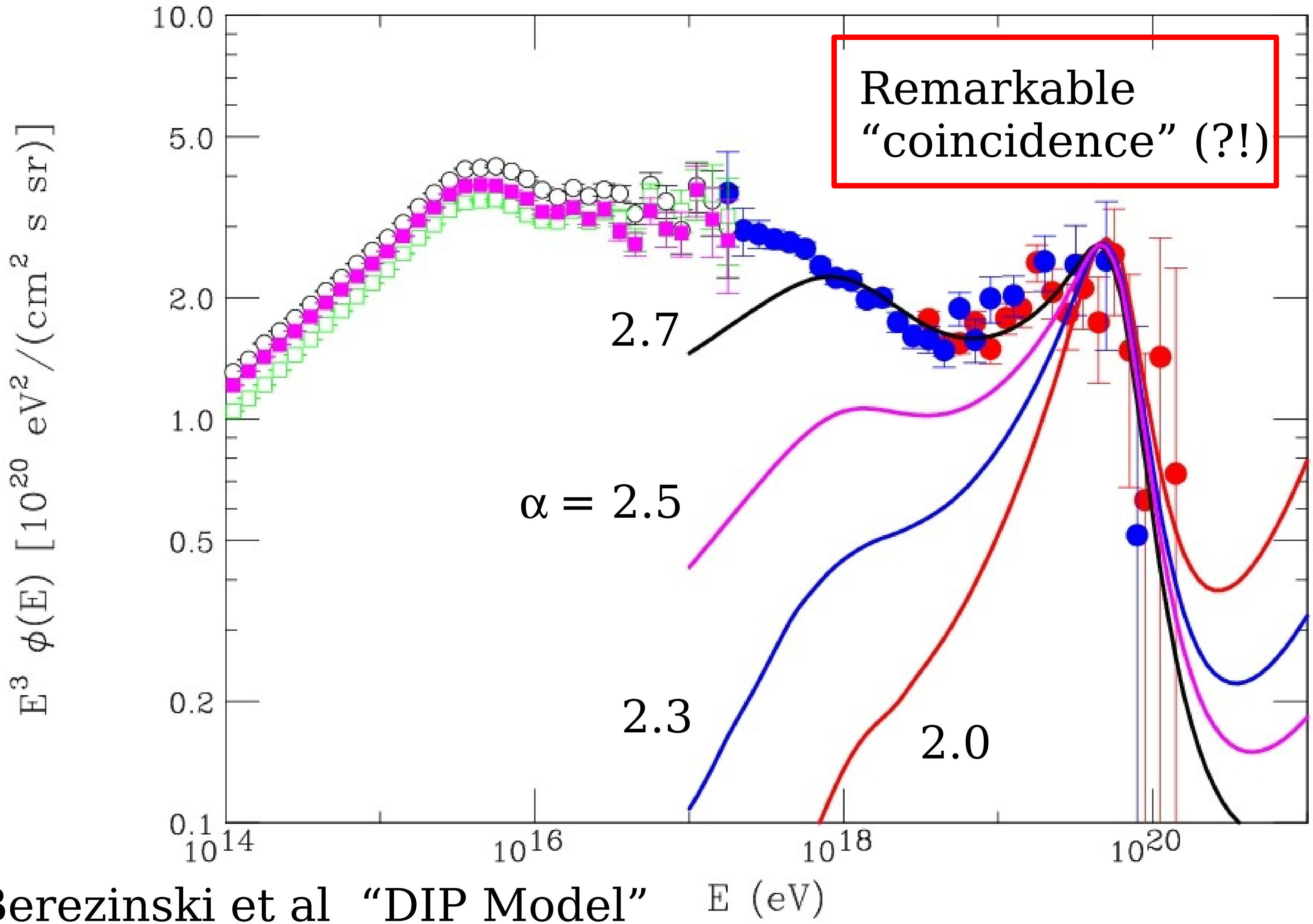
3. Composition

Significant
Experimental
Discrepancies

Auger/Hires

Confusing
situation.

Power Law Injection (No Cosmic Evolution)



Berezinski et al "DIP Model"

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

α=2.0

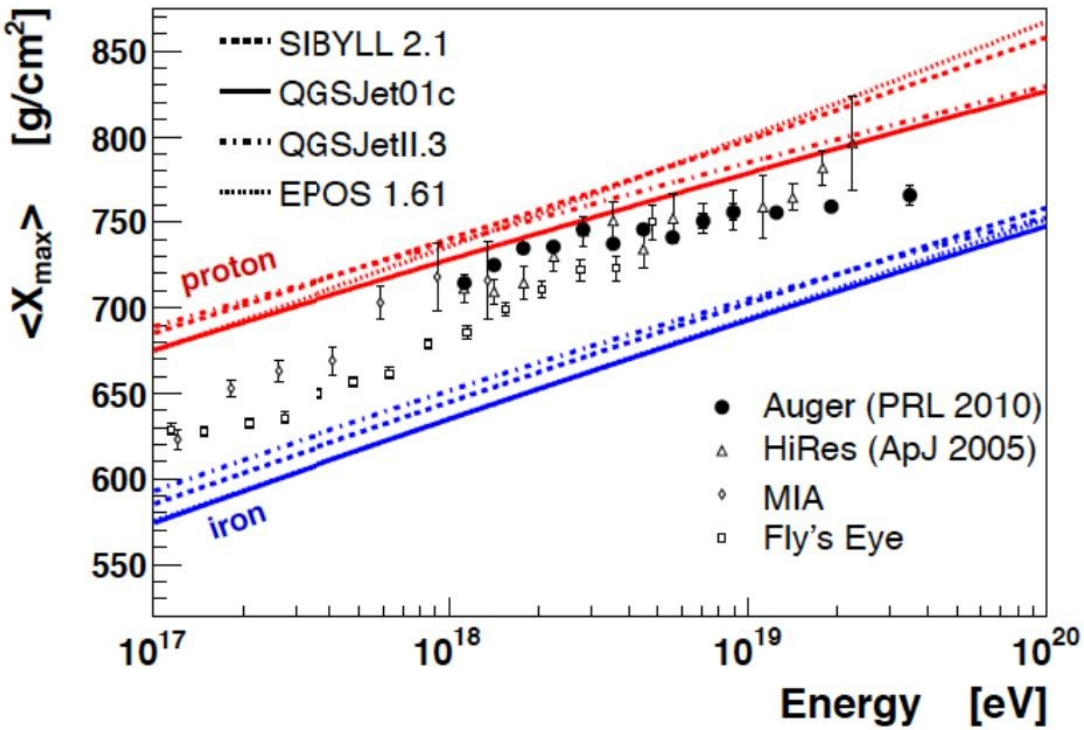
$$\mathcal{L} \simeq 1.1 \times 10^{37} \left[1 - \ln\left(\frac{E_{\rm min}}{10^{18}\ {\rm eV}}\right)\right] \frac{\rm erg}{\rm s\ Mpc^3}$$

3000 Solar luminosities

α=2.7

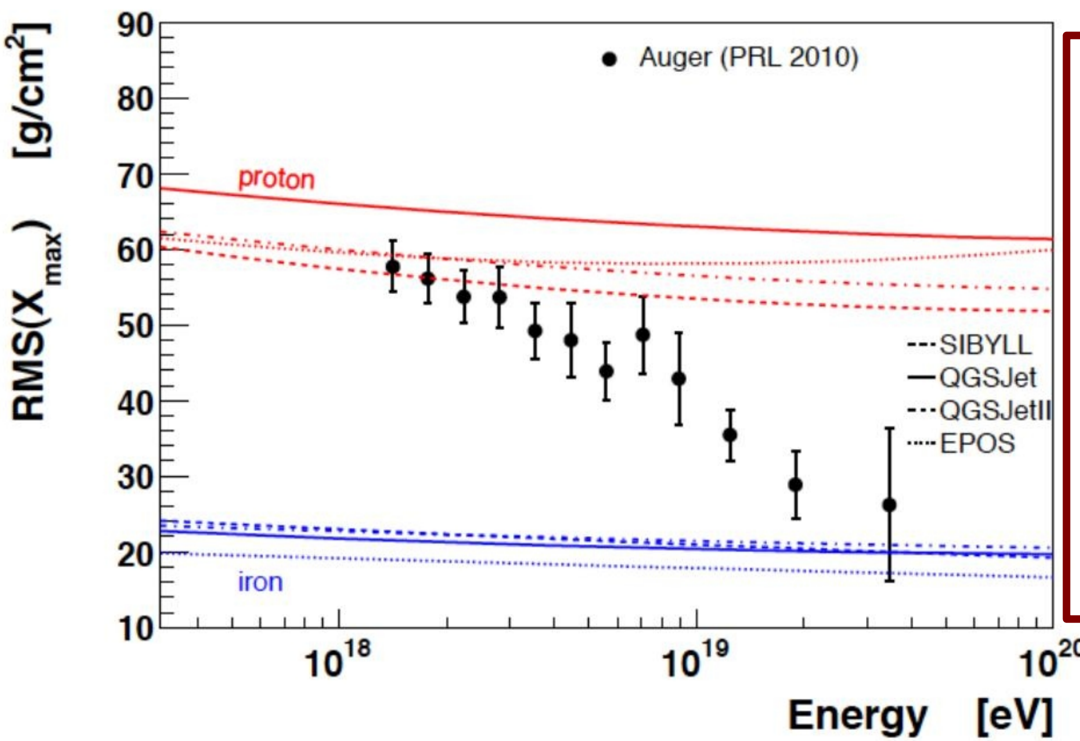
$$\mathcal{L} \simeq 3.4 \times 10^{37} \left(\frac{E_{\rm min}}{10^{18}\ {\rm eV}}\right)^{-0.7} \frac{\rm erg}{\rm s\ Mpc^3}$$

9000 Solar luminosities



Mass Composition
becoming heavy ?
at very high energy ?

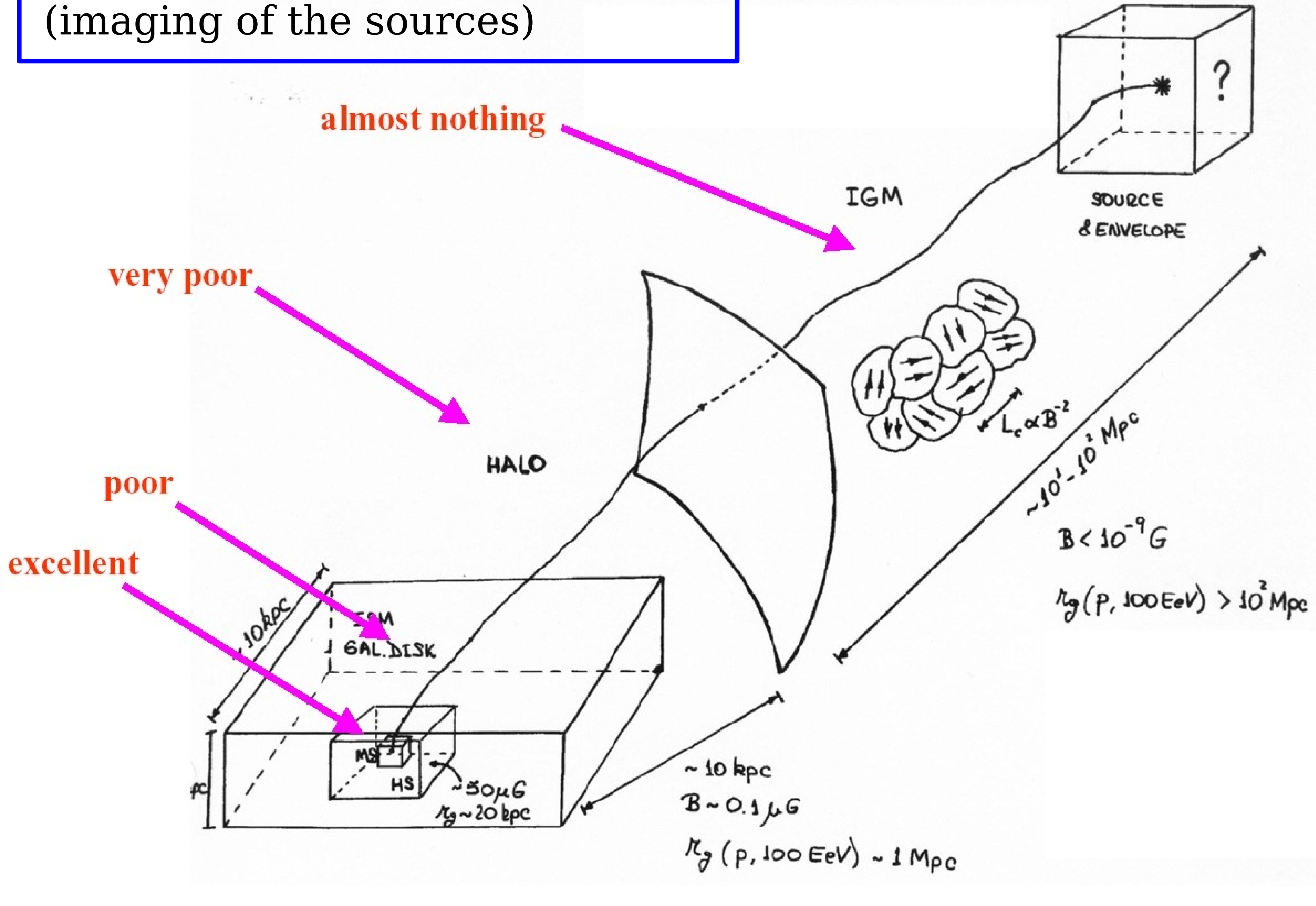
Significance would be
very important !
Constraints on the
structure and properties
of the astrophysical sources.



Observational controversy
NON confirmation
of HiRes

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

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

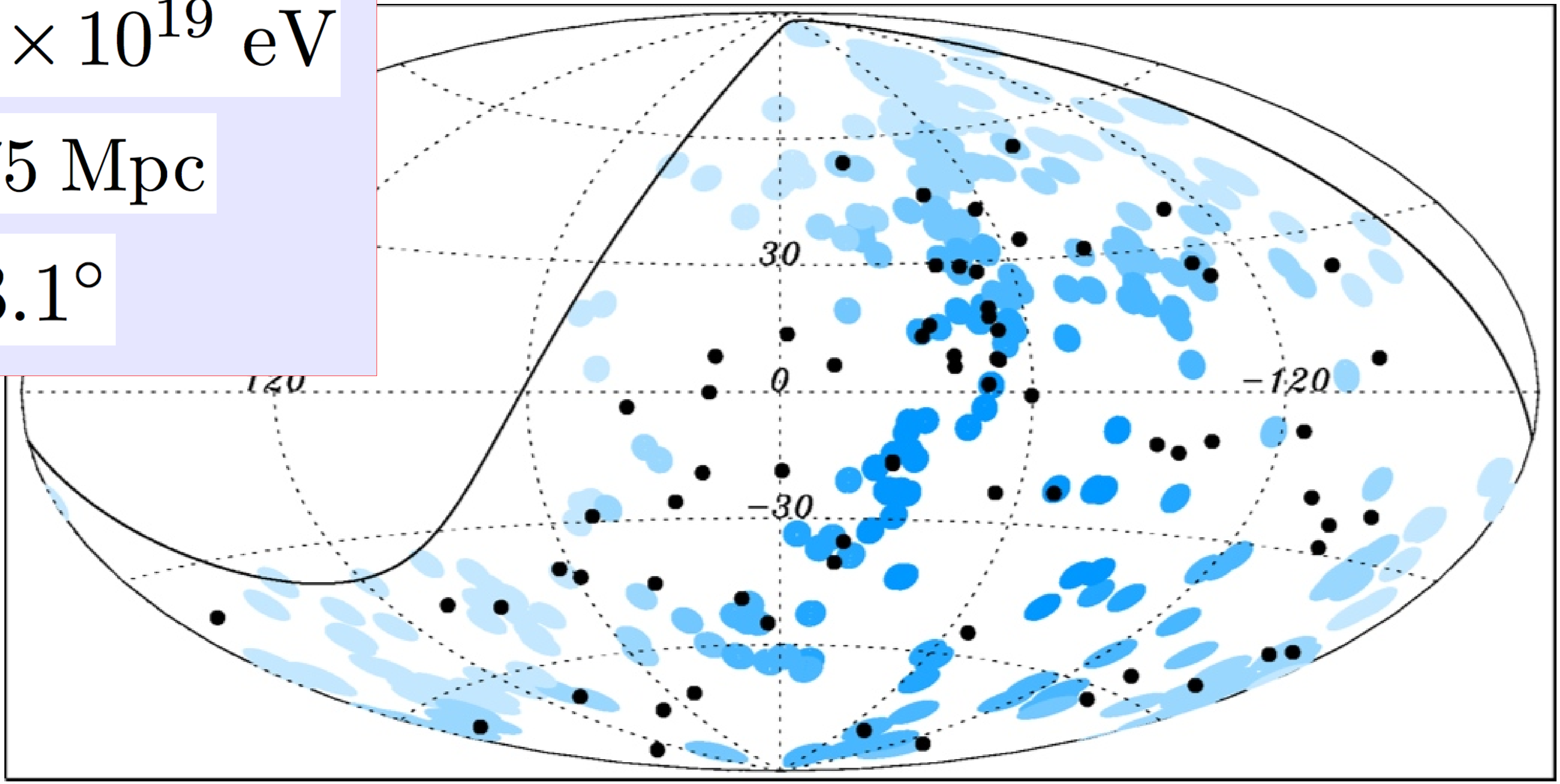


AUGER result on Correlations with the VCV AGN catalogue
November 2008. Update september 2010.

6×10^{19} eV

75 Mpc

3.1°



Significant dilution
[but not disappearance]
of the statistical significance

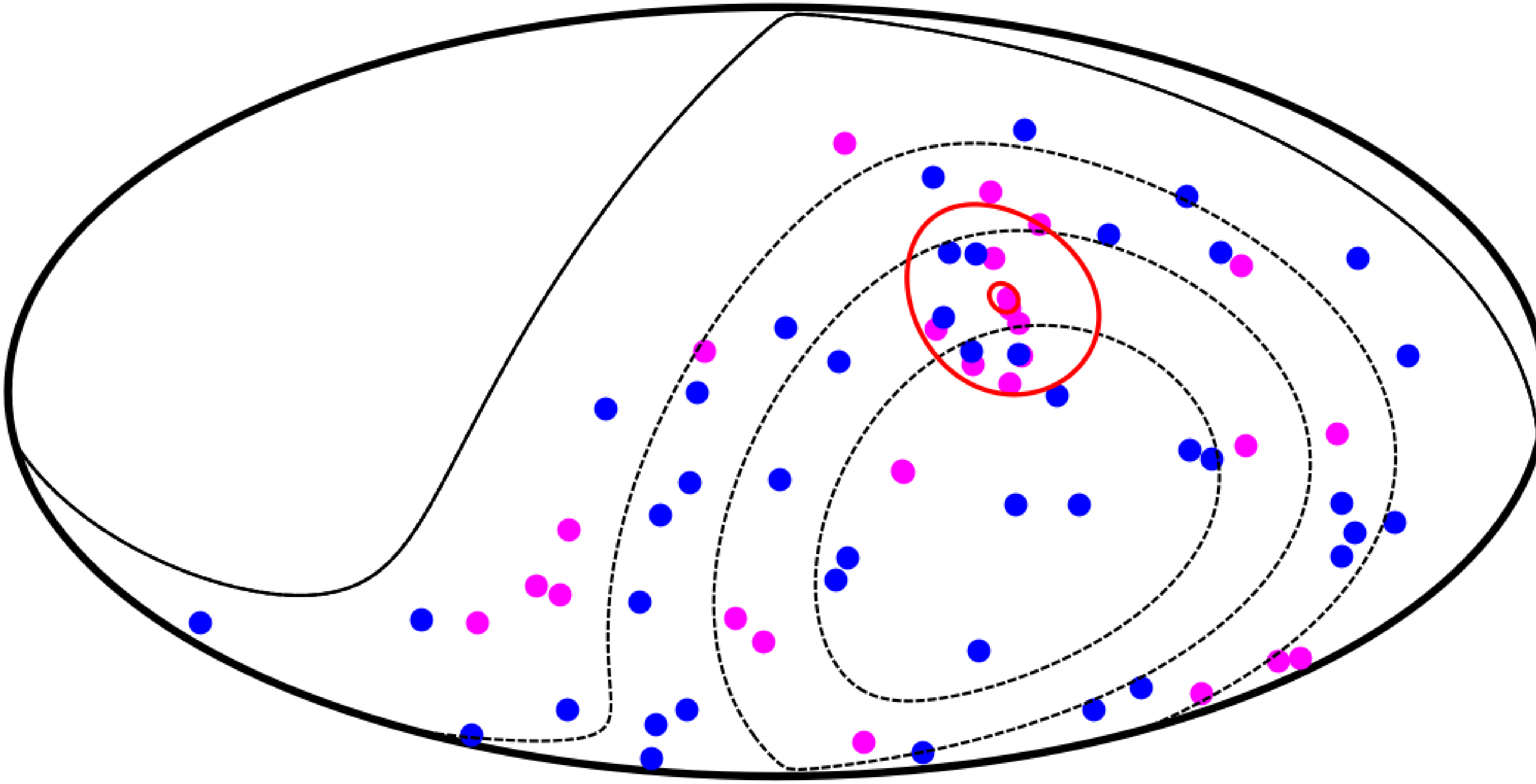
14 ev. 8 coincid. (2.9)
13 ev. 9 coincid. (2.7)
42 ev. 12 coincid.(8.8)

Discussion on CEN A

The AGN closest to us.

3 events within 3 degrees
8 events within 18 degrees

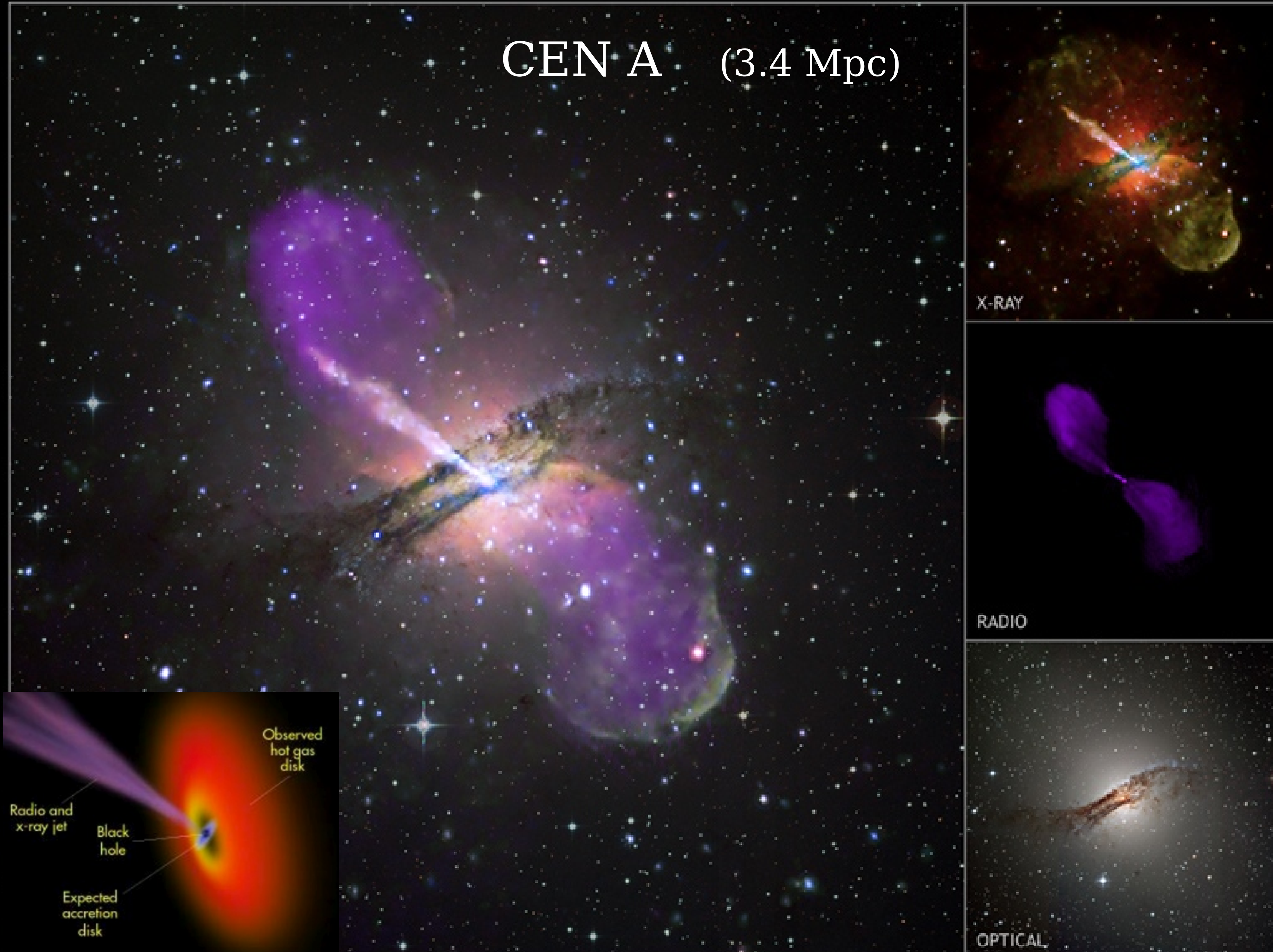
+0 events within 3 degrees
+5 events within 18 degrees



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

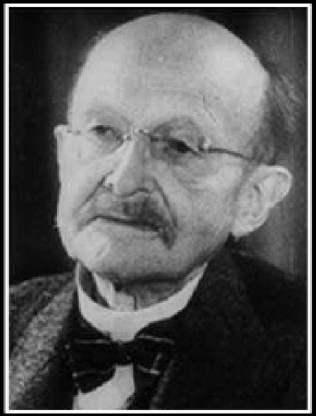
3, 20 degrees circles

CEN A (3.4 Mpc)


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

«Those who have reached the stage of no longer being able to marvel at anything simply show that they have lost the art of reasoning and reflection.»

Max Planck



Final Remarks

- The "Dark Matter problem" is one of the deepest and most fundamental questions in physics.

  The "WIMP" (thermal relic) paradigm can be explored in depth with a "3-roads" approach [LHC/Direct/Indirect methods].

  [Perhaps Nature is more "subtle"
  "Dark Matter" could be something else
  (Axions, super-massive particles, ...)
  We should also be ready for alternative paradigms.]

- The efforts to understand the objects and the mechanisms that generate high energy relativistic particles in our Galaxy and in the universe form a vibrant field with continuous surprises and new discoveries.
  [Multi-Messenger studies are essential]