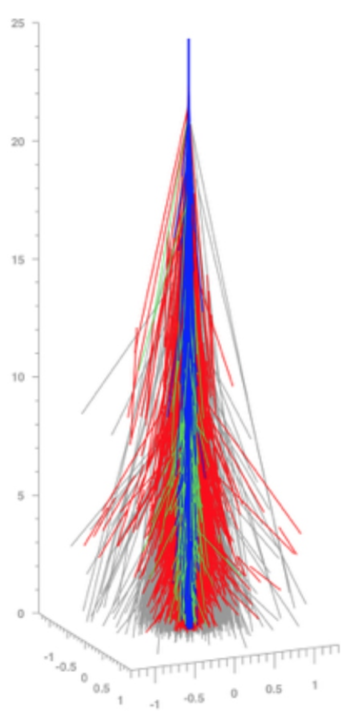
Hadronic Interactions
and
Astroparticle Physics



Paolo Lipari, INFN Roma “Sapienza”

Terzo Incontro di Fisica Nucleare

Frascati 16th november 2016

Intimate (and "multiform") relationship

between

Particle Physics
(hadronic interactions)

and

"High Energy Astrophysics"
[multi messenger astrophysics]

1. Introduction

2. Dark Matter

3. Antimatter (e^+ and $\overline{p}$) in Cosmic Rays.

4. Very High Energy Cosmic Rays

5. Outlook

104 years of Cosmic Rays

Discovery of Cosmic Rays
Ballon flight of
Viktor Hess (1912)

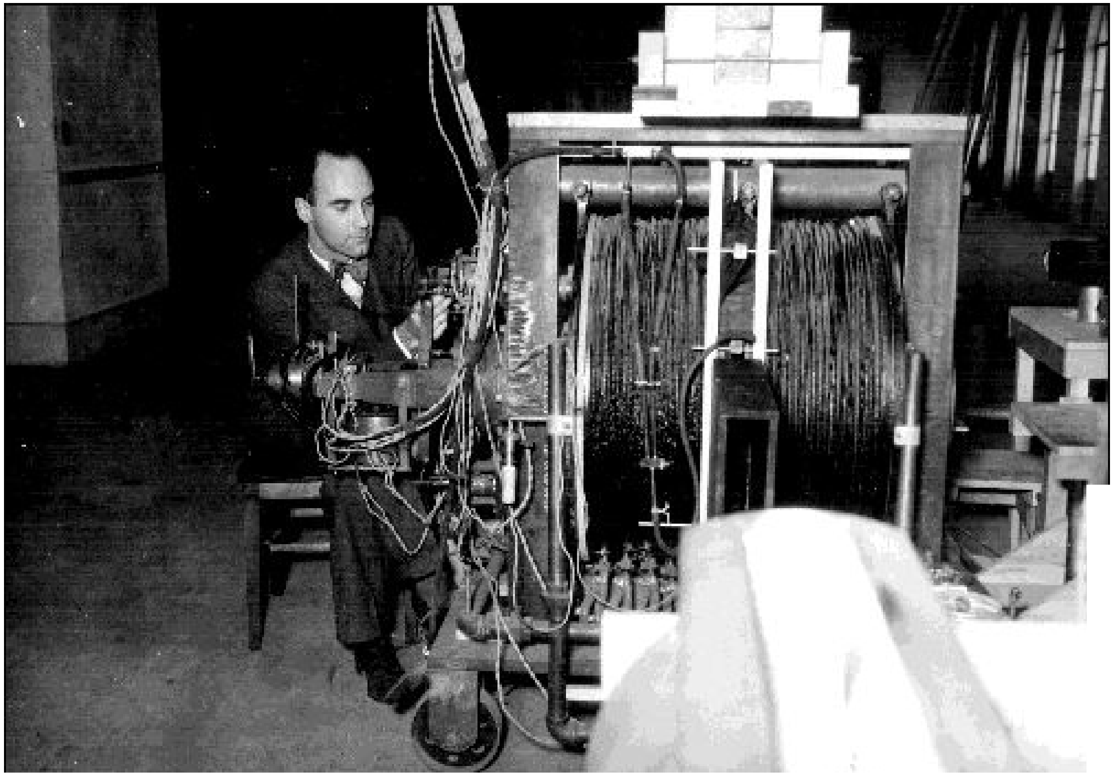
birth of

"High energy astrophysics"

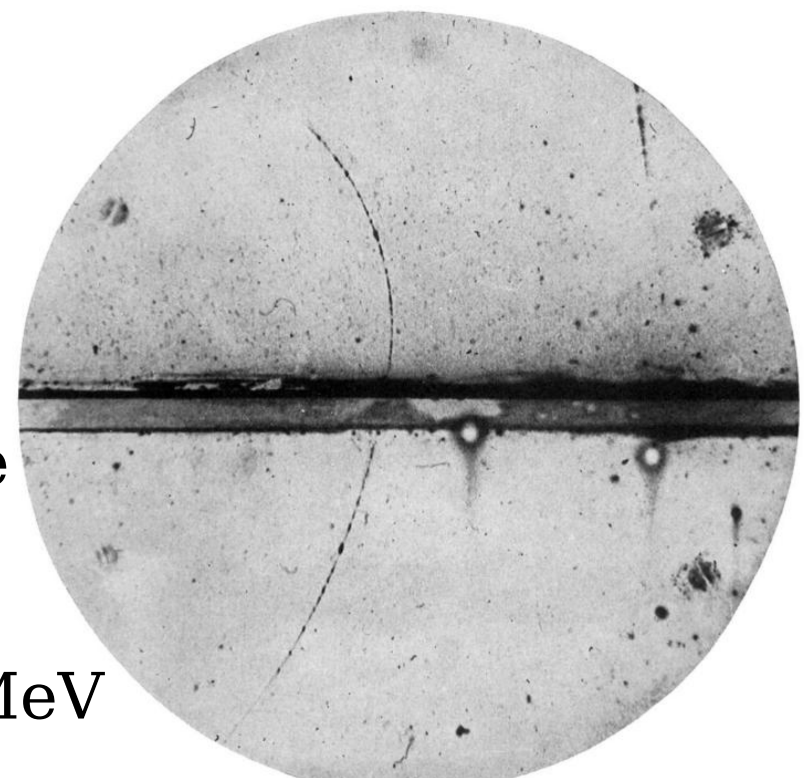
and of

Particle Physics

Nobel prize (1936) divided between
Viktor Hess and Carl Anderson (discovery of positron)



23 MeV

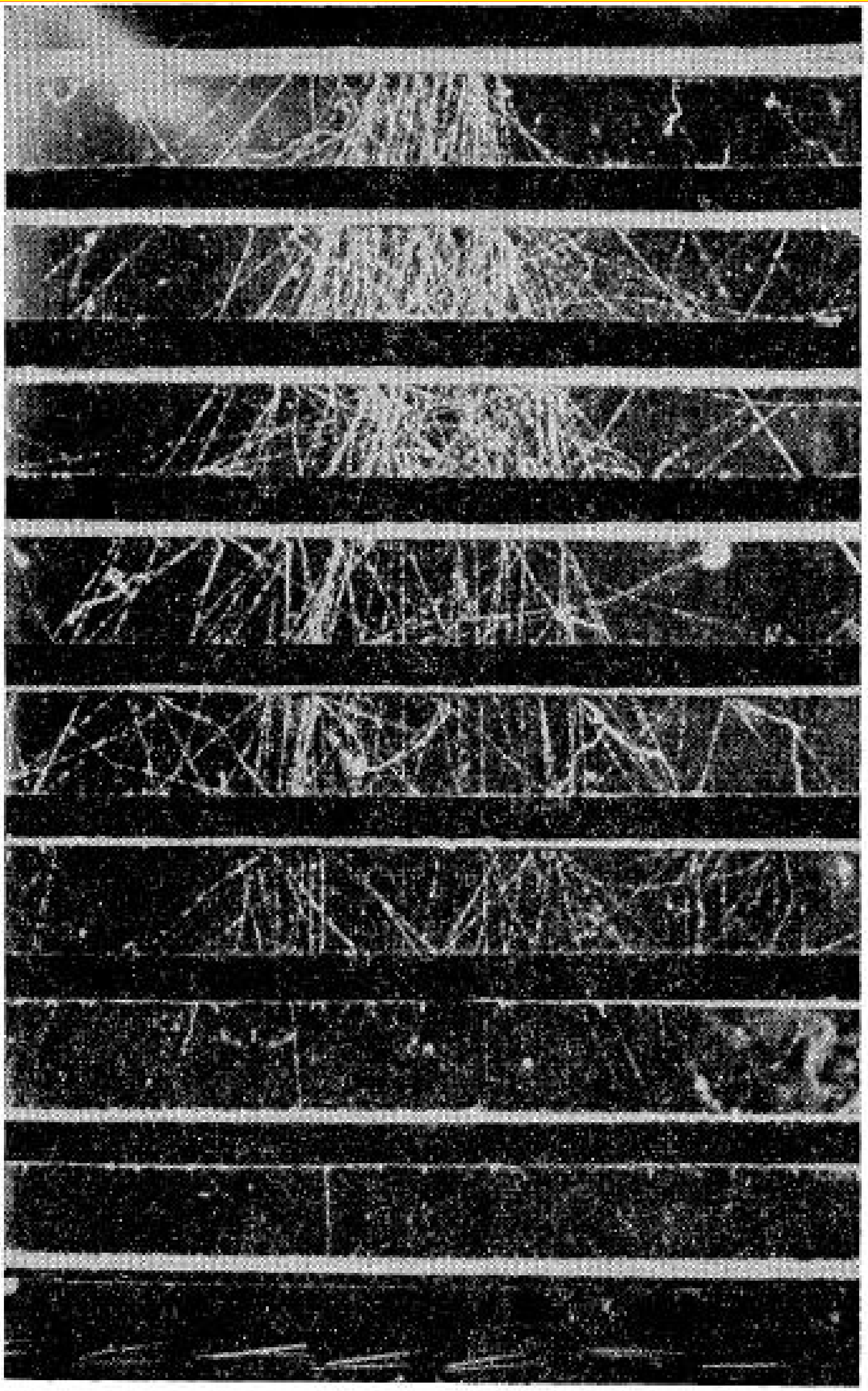


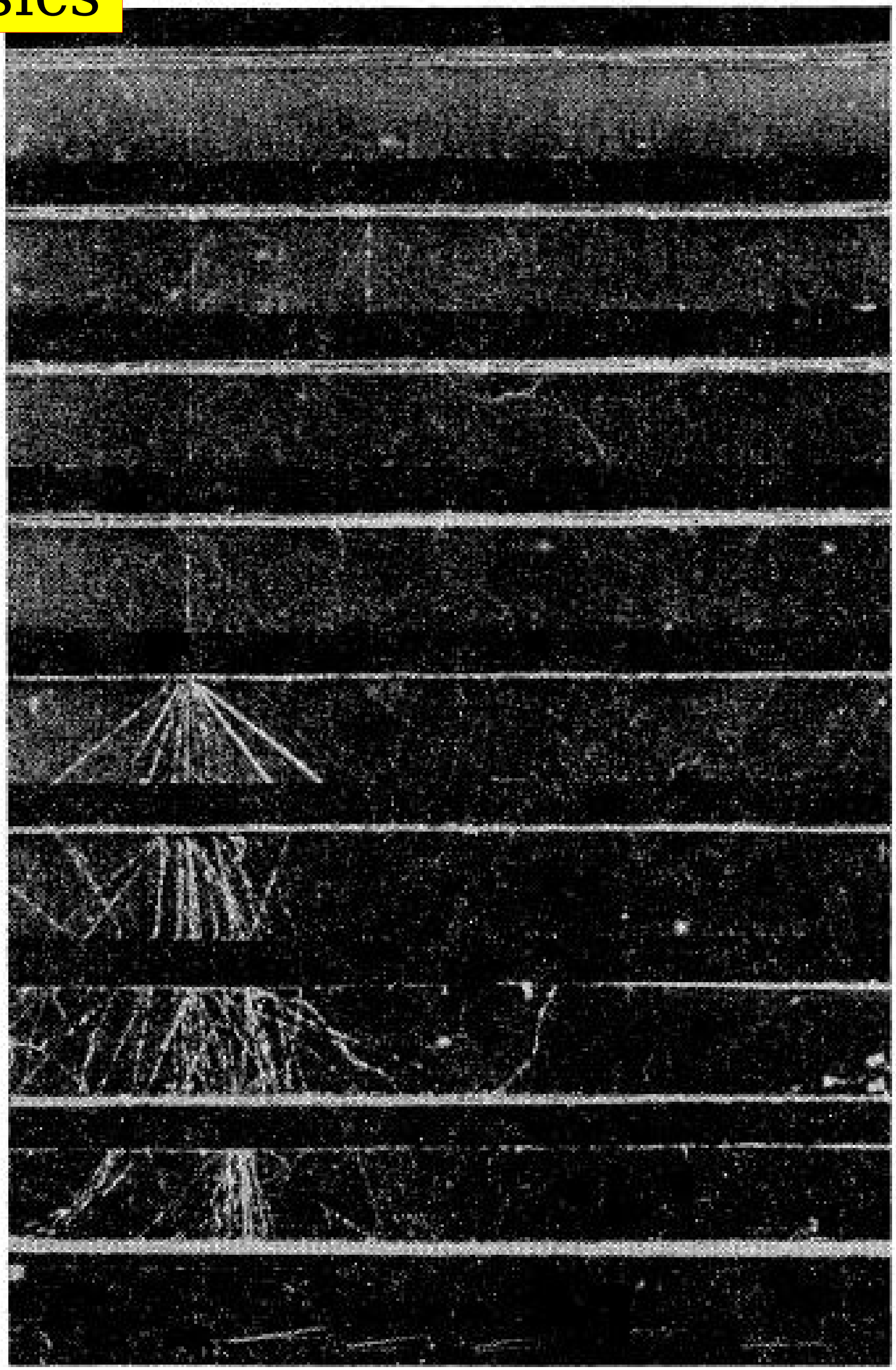
6 mm
Lead plate

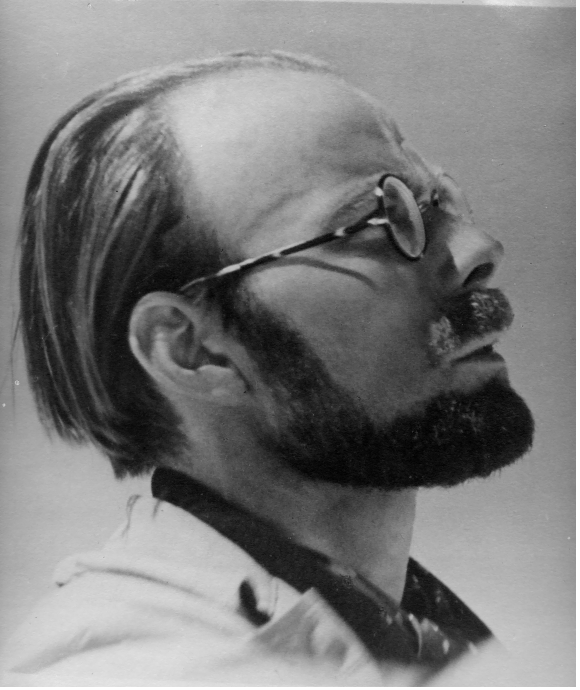
63 MeV

Phys. Rev. 15th march 1933

Cosmic Rays and Particle Physics







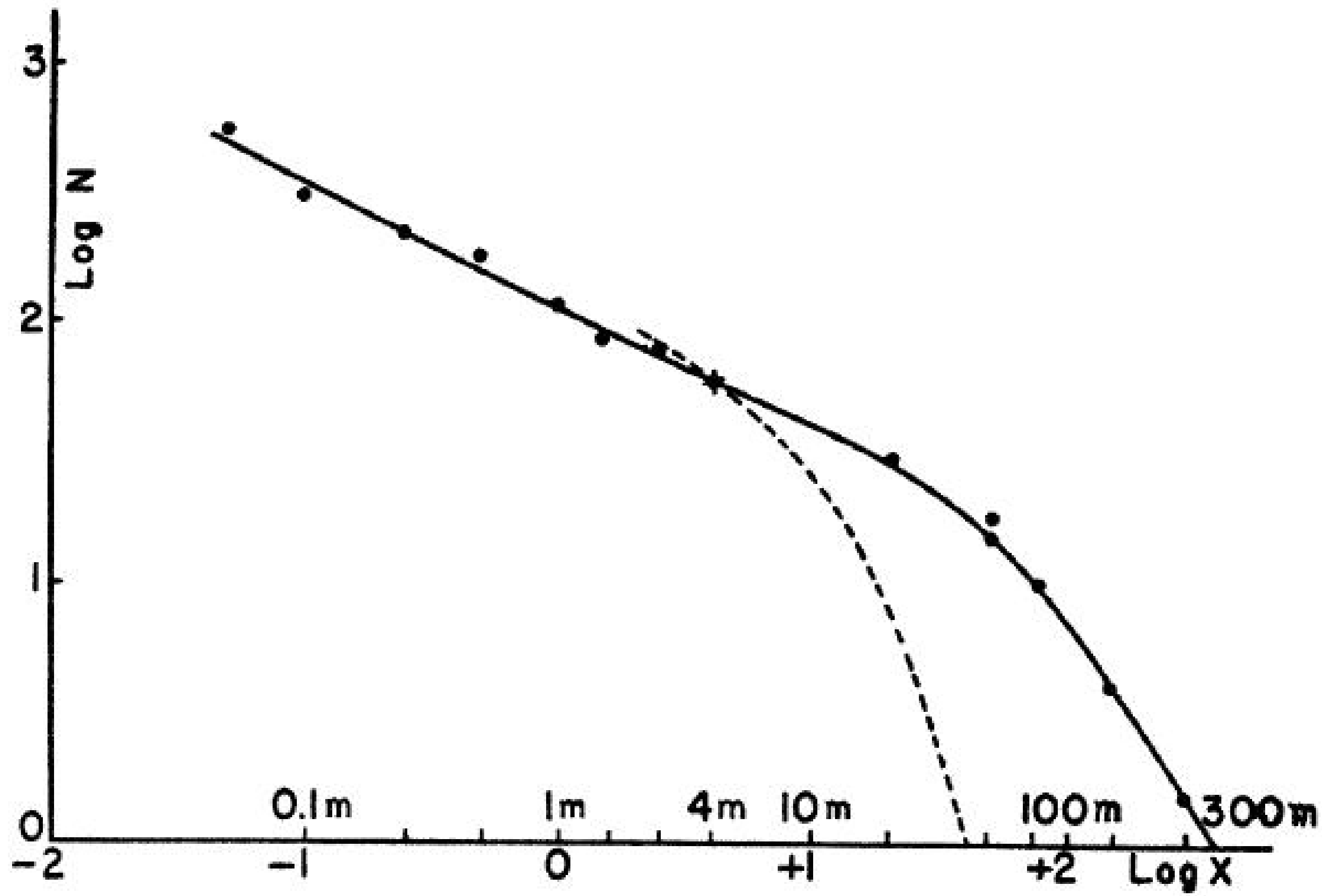
Pierre Auger

Extensive
Air
Showers

JULY–OCTOBER, 1939 REVIEWS OF MODERN PHYSICS

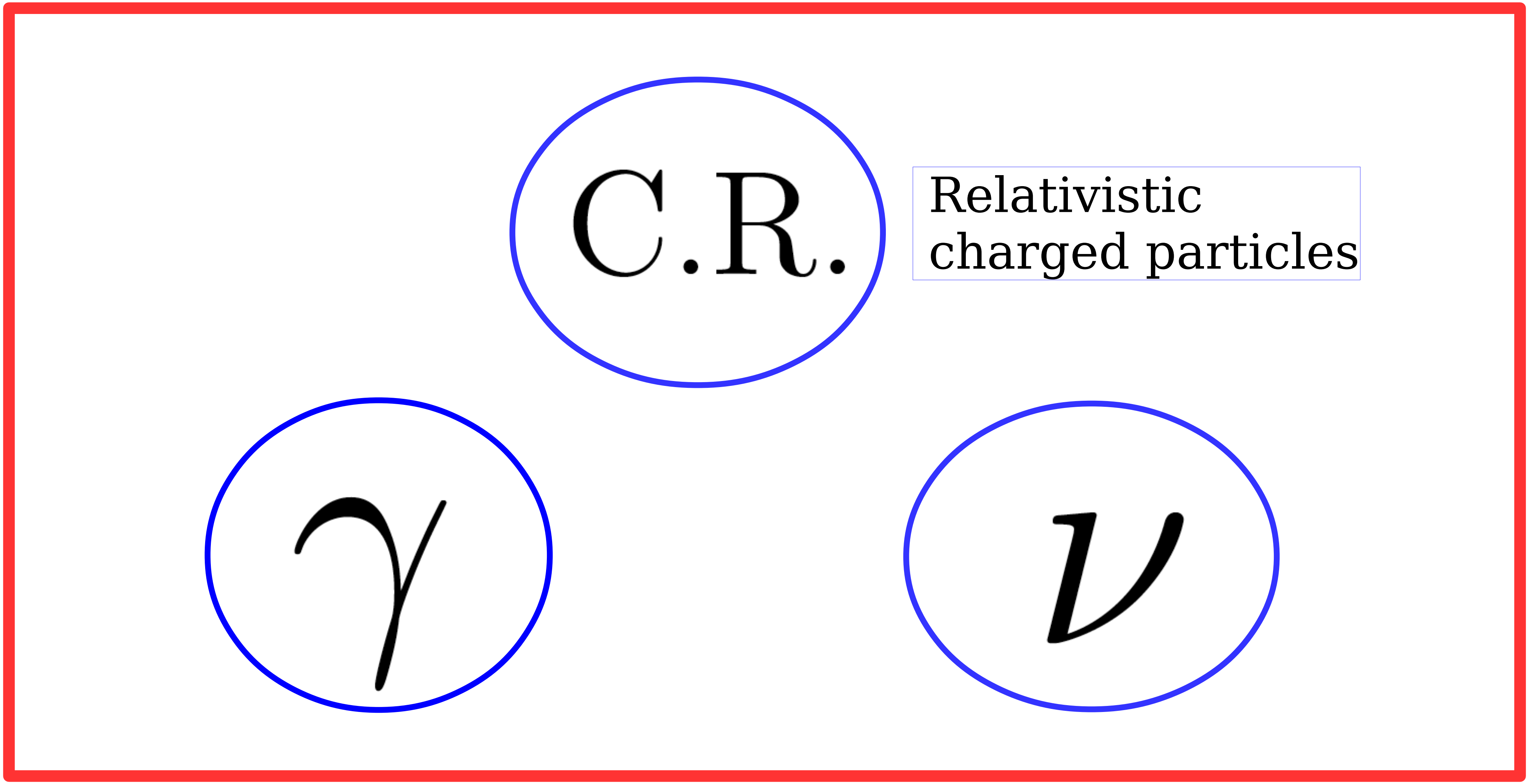
Extensive Cosmic-Ray Showers

PIERRE AUGER
In collaboration with
P. EHRENFEST, R. MAZE, J. DAUDIN, ROBLEY, A. FRÉON
Paris, France



Log[distance between particle detectors]

Three messengers are “inextricably” tied together
[Cosmic Rays, Gamma Rays, High Energy Neutrinos
can really be considered as three probes that study the same underlying physical phenomena]



Fundamental Mechanism:

Acceleration of Charged Particles

to Very High Energy ("non thermal processes")
in astrophysical objects (or better "events").

Creation of Gamma Rays and Neutrinos
via the interactions of these relativistic charged particles.

"Hadronic "

$$p + \mathrm{X} \to \pi^+ \; \pi^- \; \pi^\circ \; \ldots$$

$$\pi^\circ \to \gamma \; \gamma$$

$$\pi^+ \to \mu^+ \; \nu_\mu$$

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

"Leptonic "

$$e^\pm \; \gamma_{\rm soft} \to e^\pm \; \gamma$$

$$e^\pm \; Z \to e^\pm \; \gamma \; Z$$

$$e^\pm \; \vec{B} \to e^\pm \; \gamma_{\rm syn}$$

Non accelerator sources

Dark Matter

(in form of WIMP's
self annihilation or decay)

Super Massive Particles

[Very High mass scales]

Production of high energy particles
of all types $\gamma\ ,\ \nu\ ,\ e^+\ ,\ e^-\ ,\ p\ ,\ \ldots$

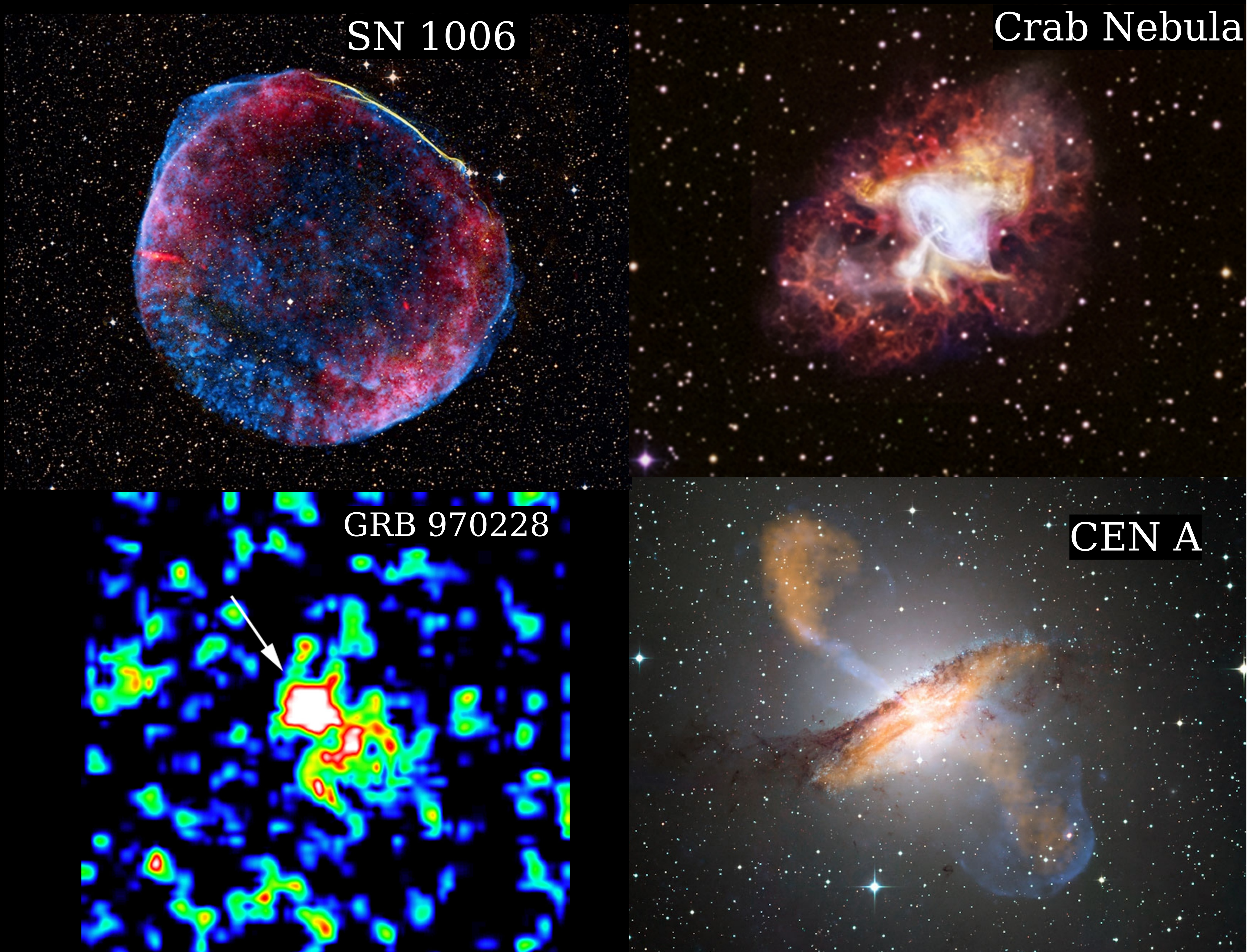
Gamma Astronomy has revealed a
a *very rich, fascinating landscape*

- Many sources have been identified
  [GeV , TeV ranges]

- Several classes of objects
  [SNR, Pulsars, PWN, AGN, GRB, ...]

- Probably different acceleration mechanisms.

Still developing an understanding
many questions remain open


SN 1006
Crab Nebula
GRB 970228
CEN A

Sources are transients

[with a variety of time scales
from a small fraction of a second to thousands of years]

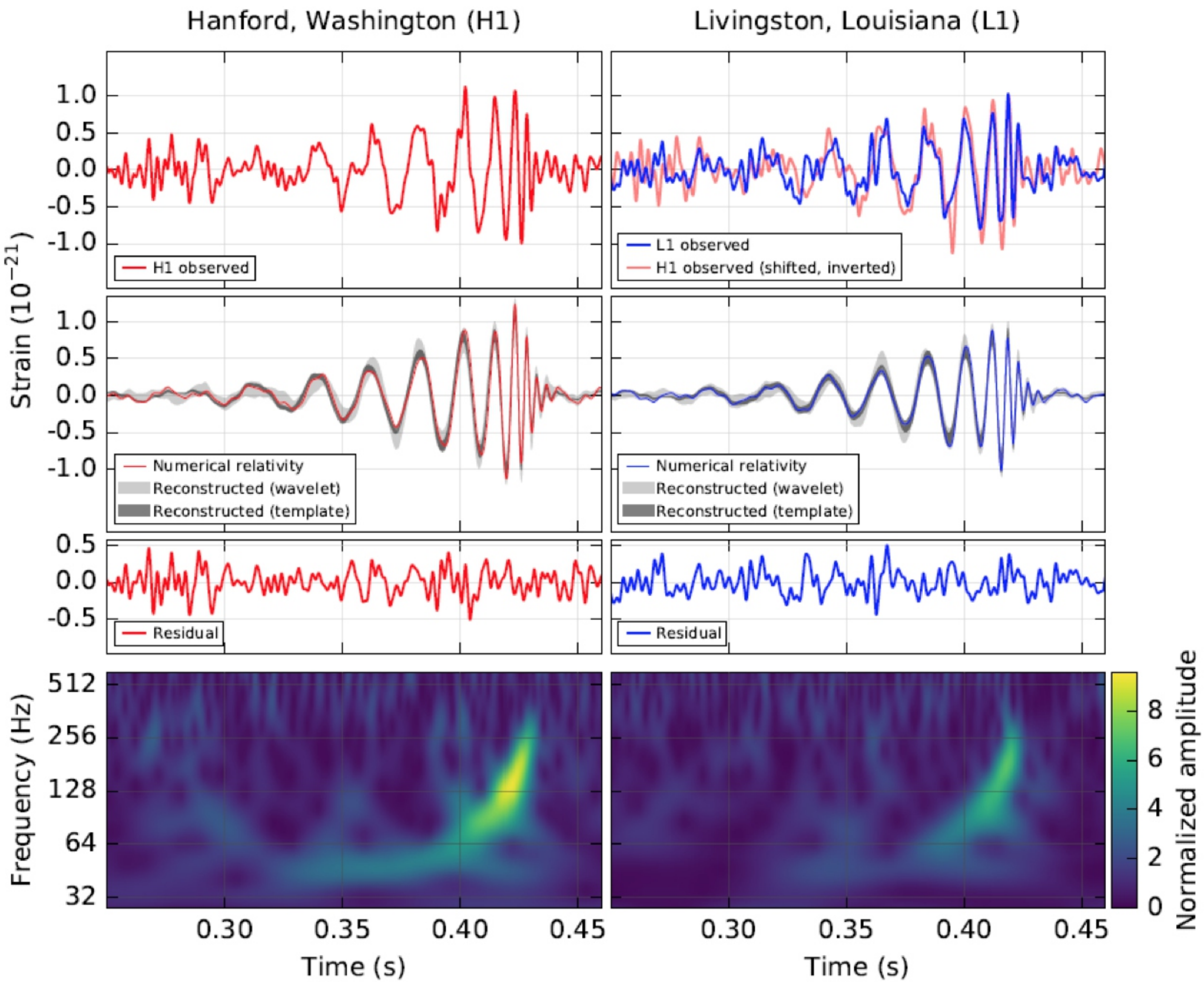
Associated to Compact Objects

Neutron stars,
Black Holes (stellar and Supermassive)

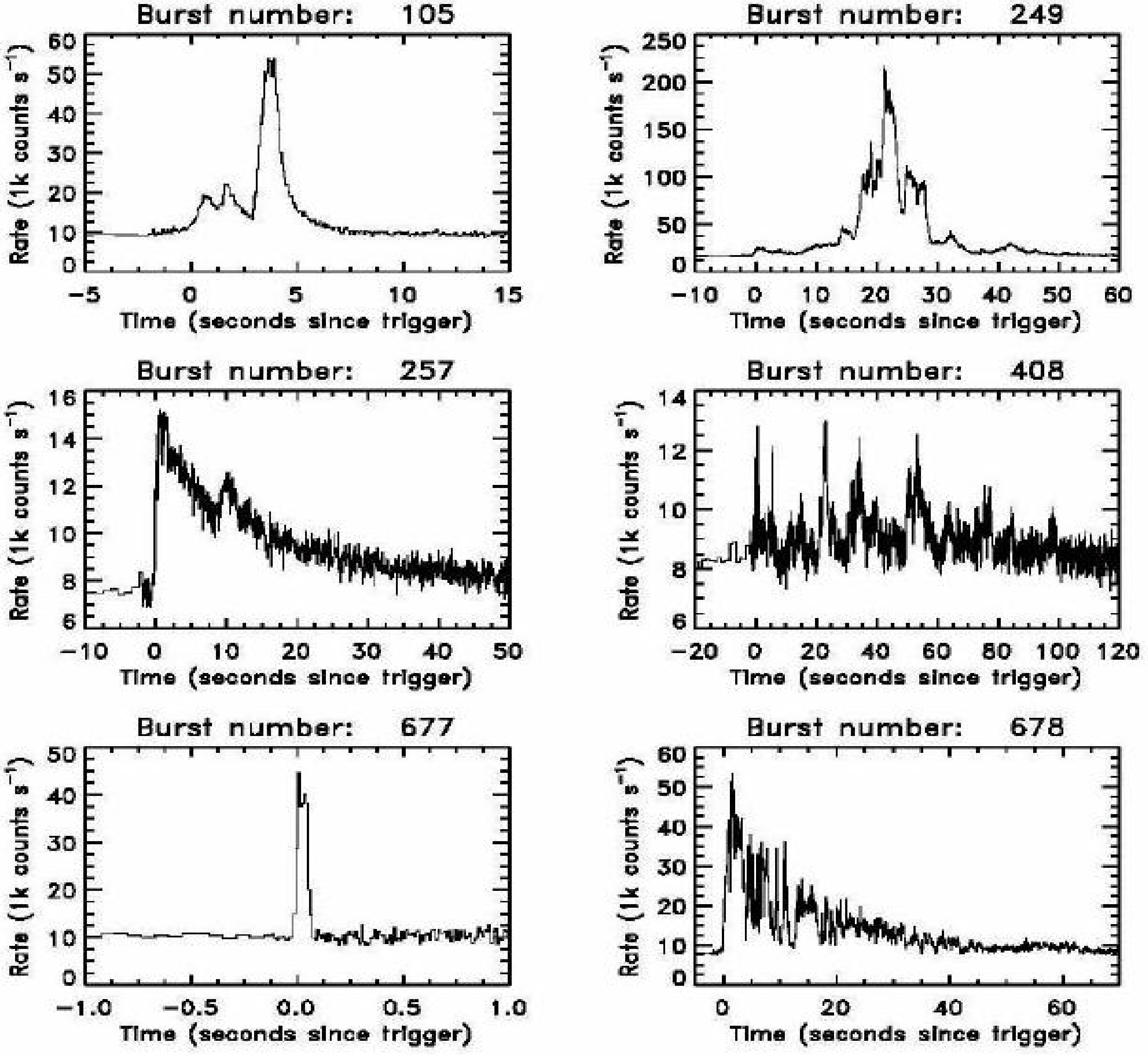
FORMATION of Compact Objects
(very large acceleration of very large masses)

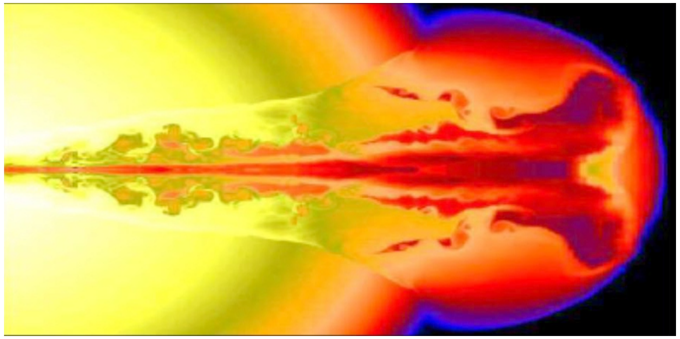
Natural connection to **Gravitational Waves**

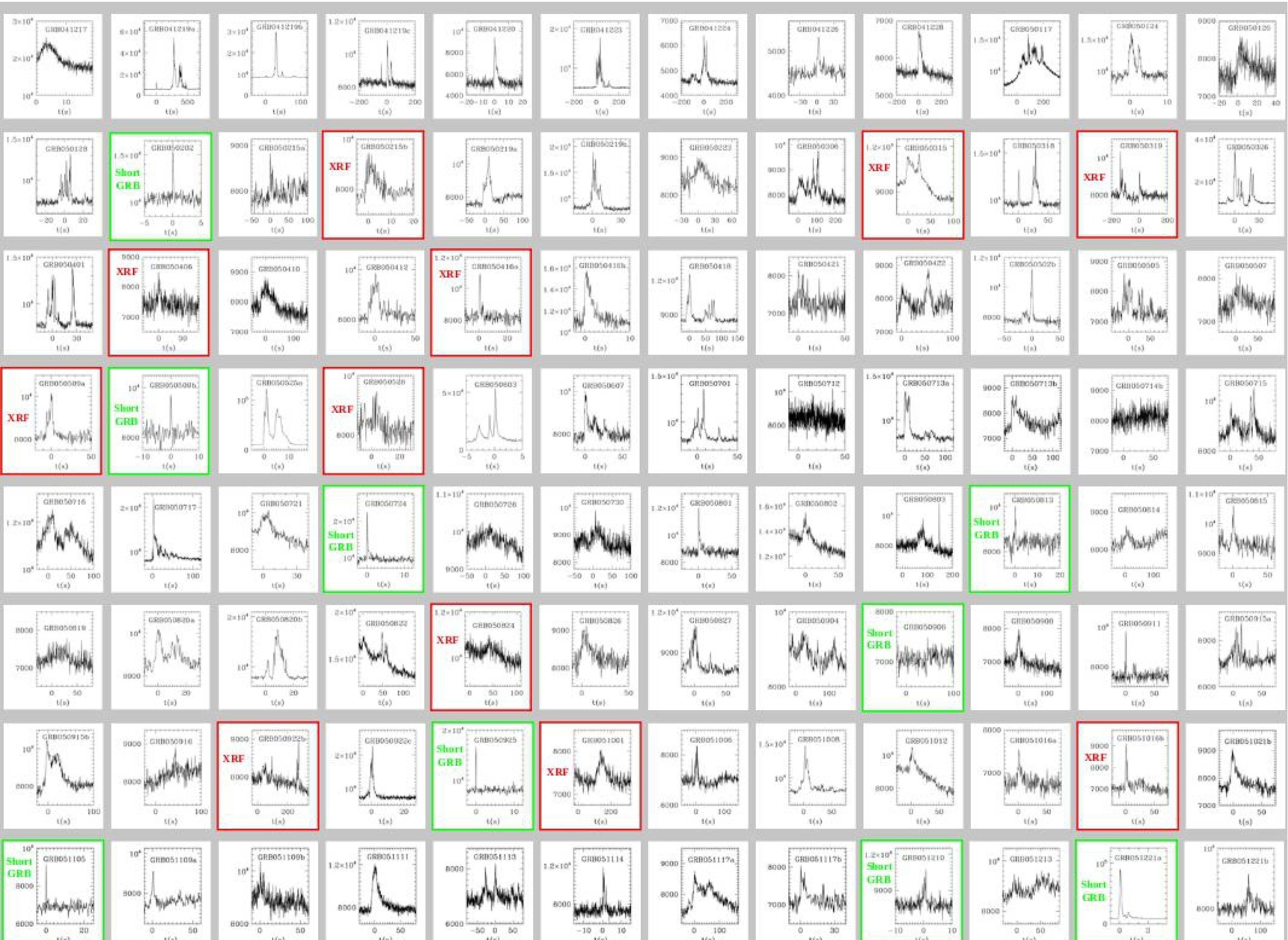
September 14th, 2015 at 09:50:45 UTC



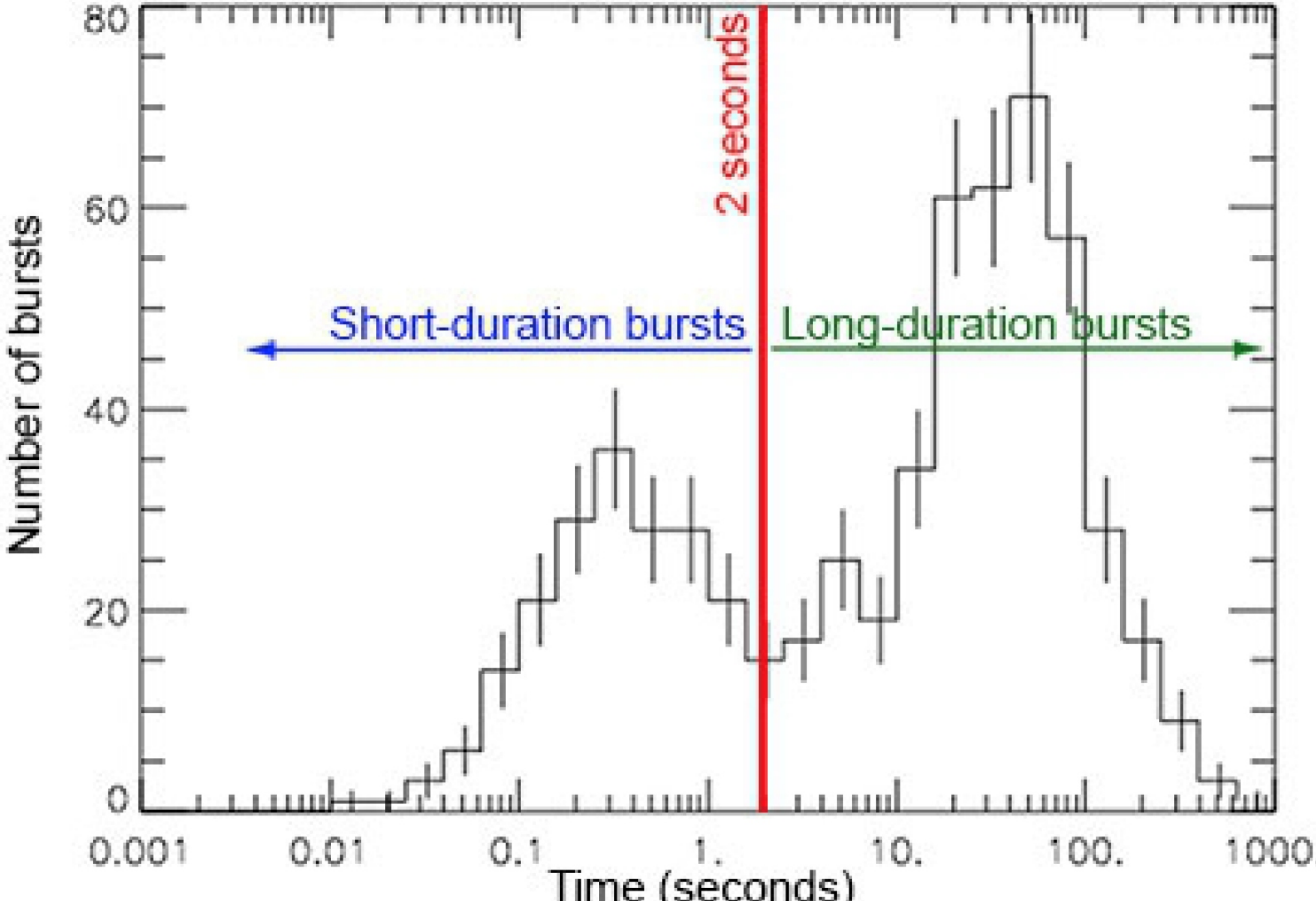
GAMMA RAY BURSTS (GRB's)





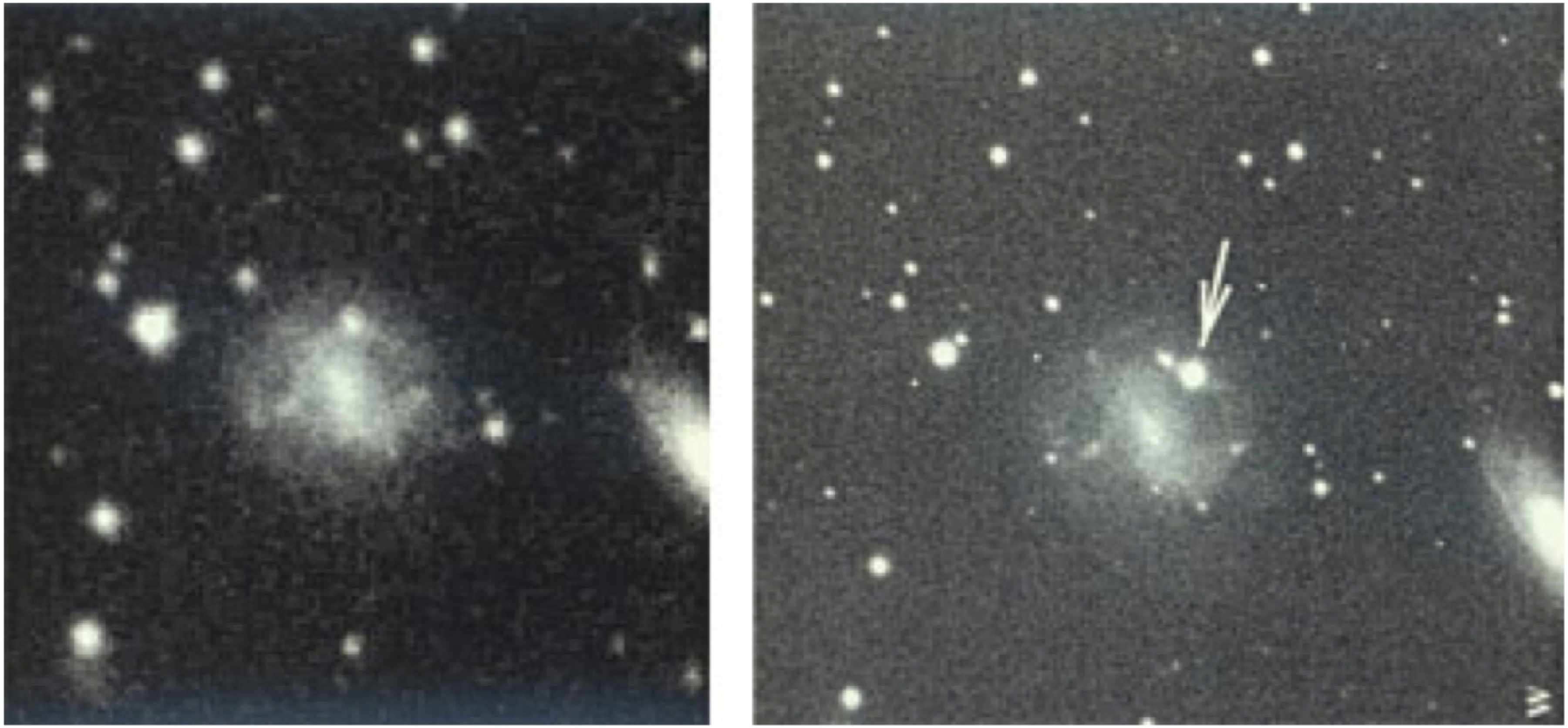


[From N. Gehrels]

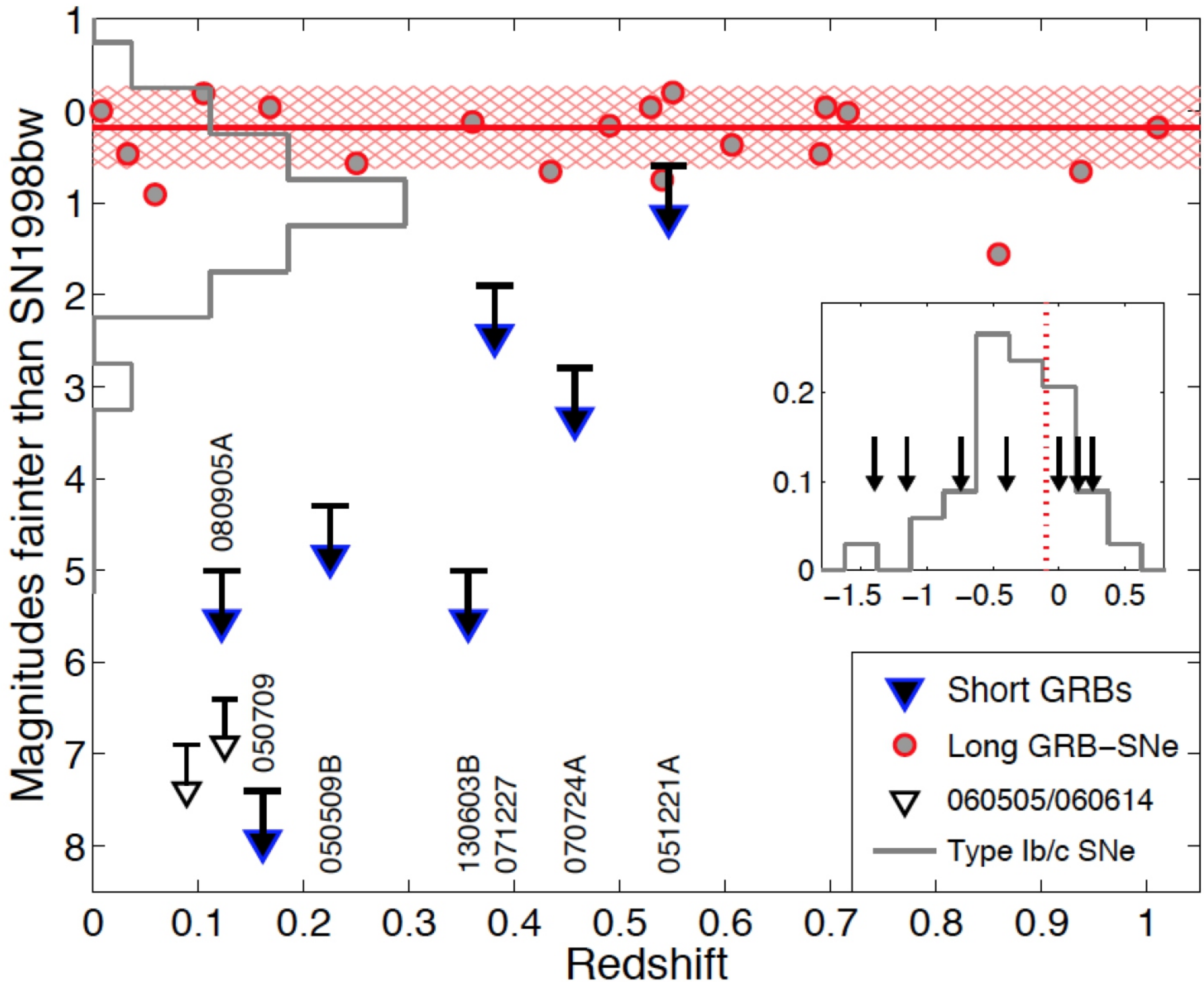


80
60
40
20
0
Number of bursts
2 seconds
Short-duration bursts
Long-duration bursts
0.001
0.01
0.1
1.
10.
100.
1000.
Time (seconds)

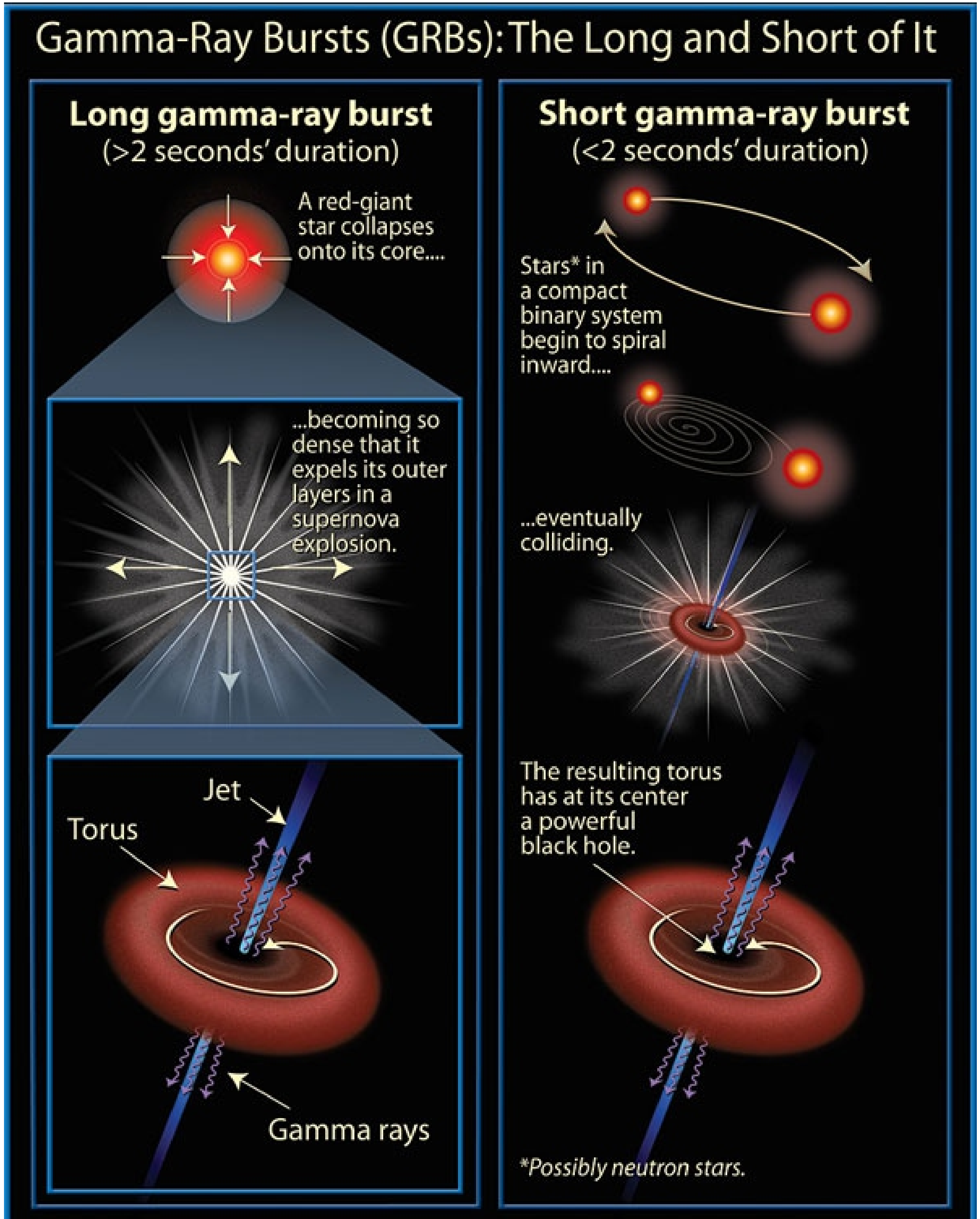
Long GRB associated with SuperNova explosions



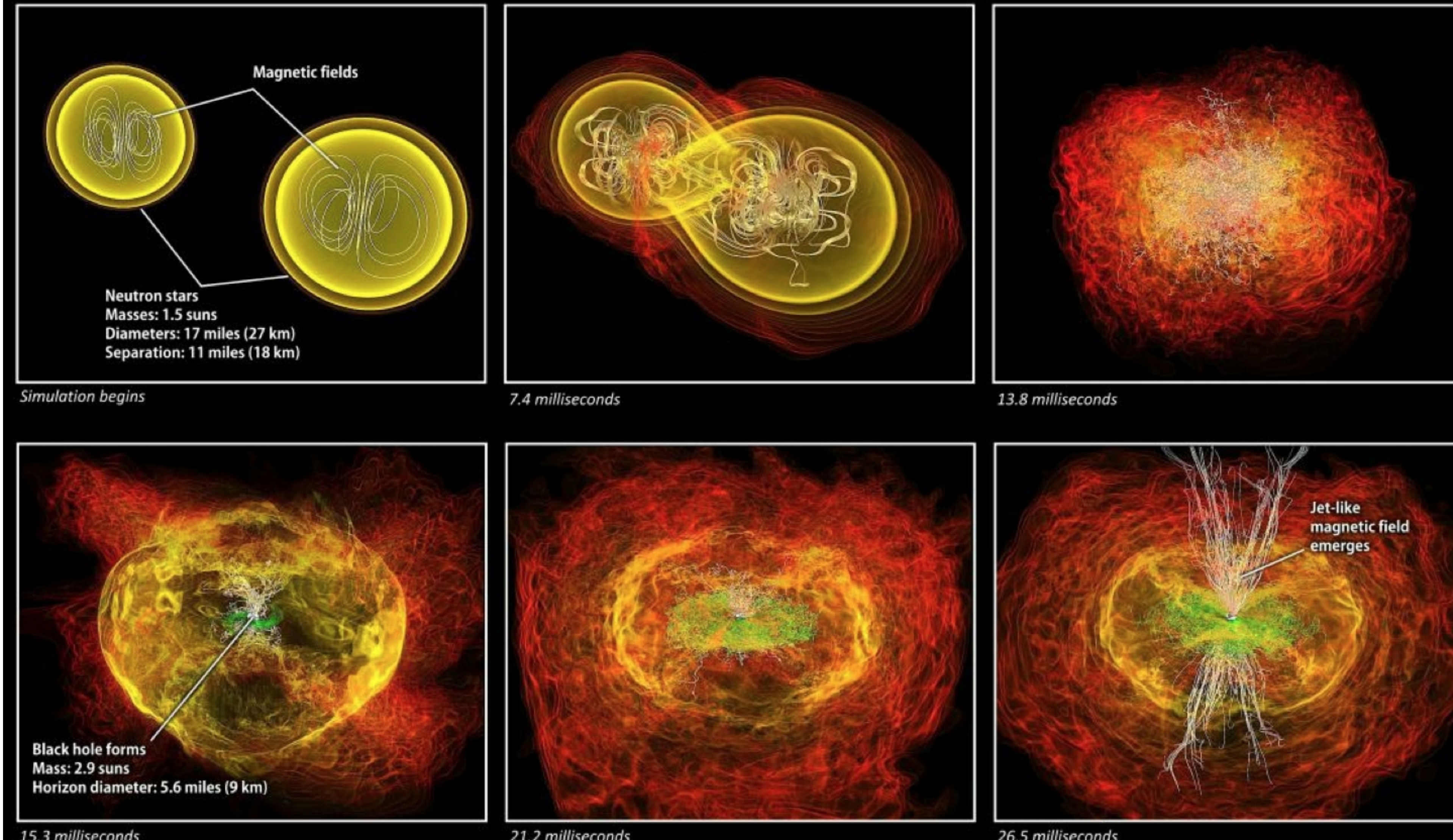
Images: A 1998 supernova (*SN 1998bw*, left) and the corresponding gamma-ray burst on April 25, 1998 (*GRB 980425*, right). Courtesy of Dr. Kulkarni.



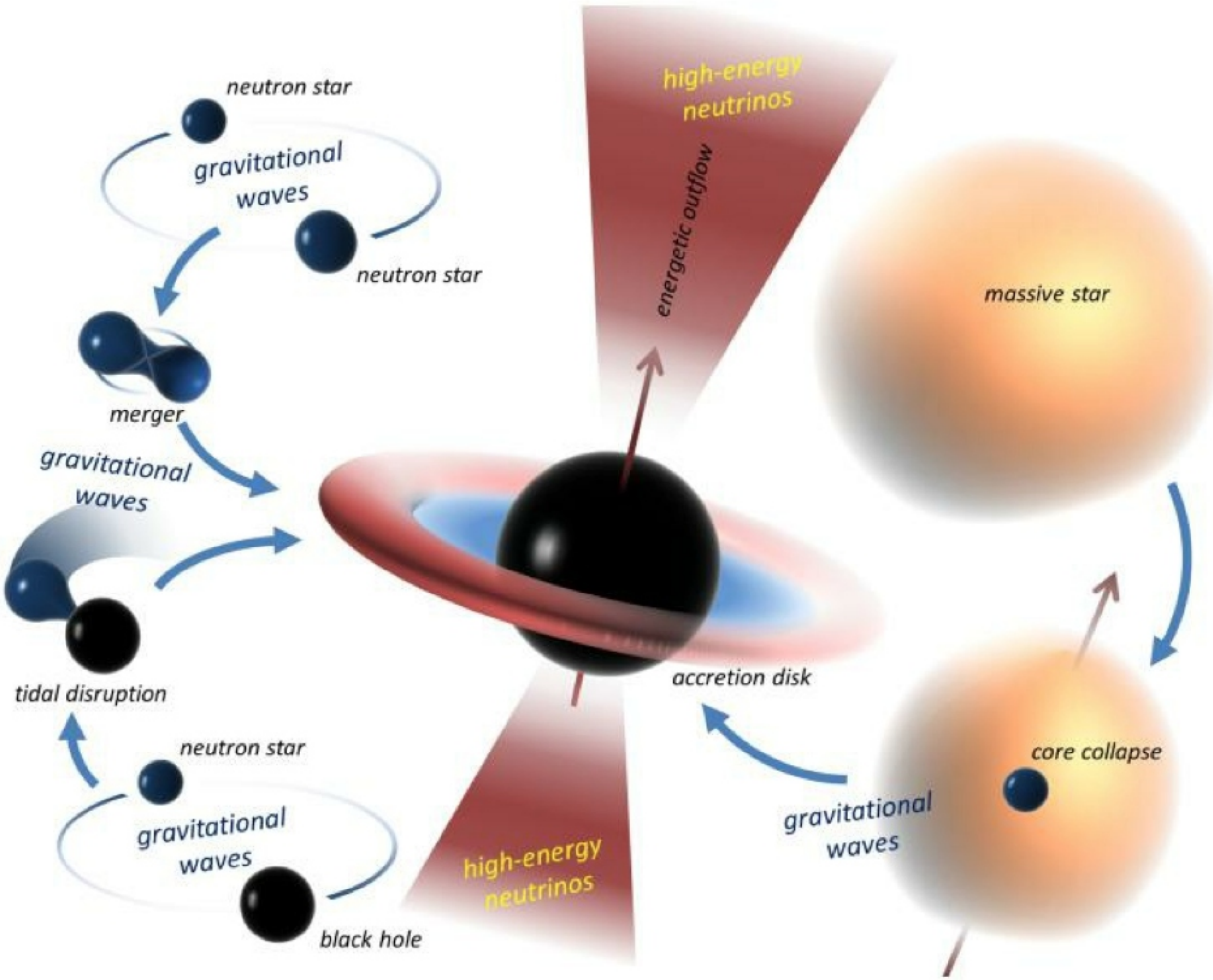
Magnitudes fainter than SN1998bw
Redshift
080905A
050709
050509B
130603B
071227
070724A
051221A
Short GRBs
Long GRB–SNe
060505/060614
Type Ib/c SNe


Gamma-Ray Bursts (GRBs): The Long and Short of It
Long gamma-ray burst
(>2 seconds' duration)
A red-giant star collapses onto its core....
...becoming so dense that it expels its outer layers in a supernova explosion.
Jet
Torus
Gamma rays
Short gamma-ray burst
(<2 seconds' duration)
Stars* in a compact binary system begin to spiral inward....
...eventually colliding.
The resulting torus has at its center a powerful black hole.
*Possibly neutron stars.

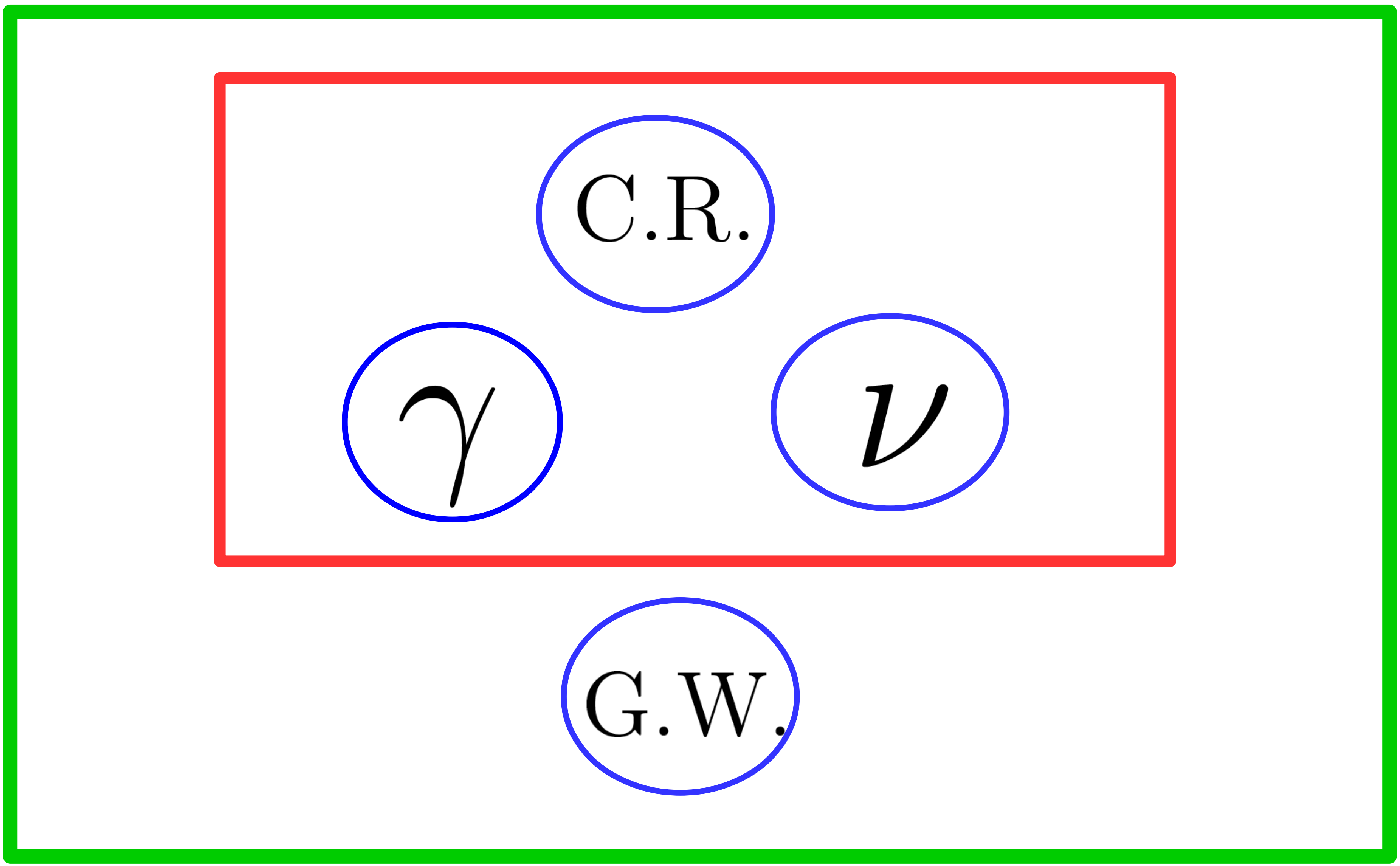
Crashing neutron stars can make gamma-ray burst jets



Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla


neutron star
gravitational waves
neutron star
merger
gravitational waves
tidal disruption
neutron star
gravitational waves
black hole
high-energy neutrinos
energetic outflow
accretion disk
high-energy neutrinos
massive star
core collapse
gravitational waves

Gravitational Waves Studies
Entering a new exciting era with LIGO/VIRGO



2. Dark Matter

- Dynamical Evidence
- The “WIMP” hypothesis
- Three Roads to explore the WIMP hypothesis

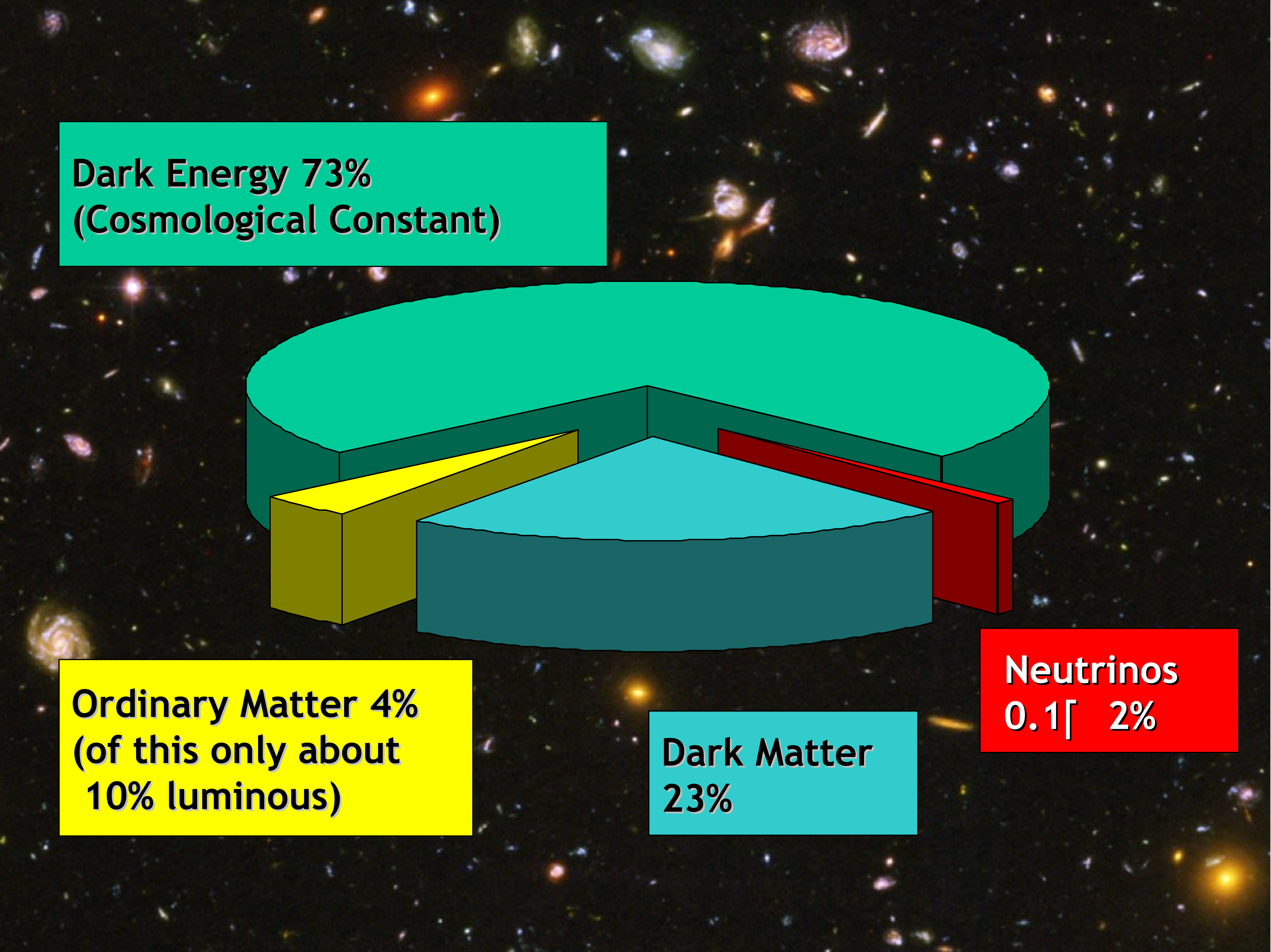
DARK MATTER

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 [!]


Dark Energy 73%
(Cosmological Constant)
Ordinary Matter 4%
(of this only about
10% luminous)
Dark Matter
23%
Neutrinos
0.1⌈ 2%

$$\Omega_{\rm b} = 0.0458 \pm 0.0016$$

$$\Omega_{\rm cold} = 0.229 \pm 0.015$$

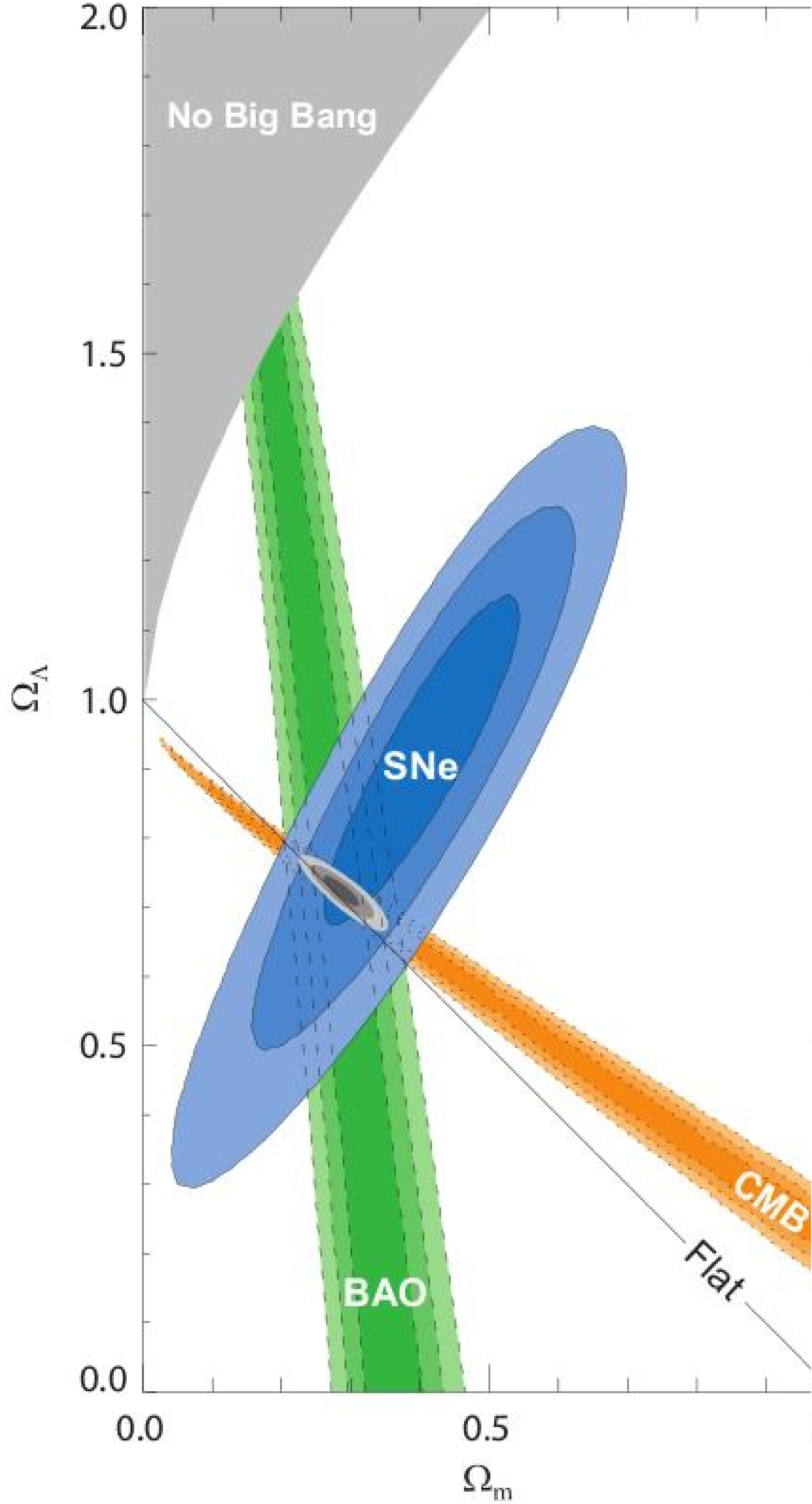
$$\Omega_{\Lambda} = 0.725 \pm 0.016$$

$$\Omega_k = 1 - \Omega_{\rm total} \;\; = -\frac{c^2}{H_0^2 \; R_0^2}$$

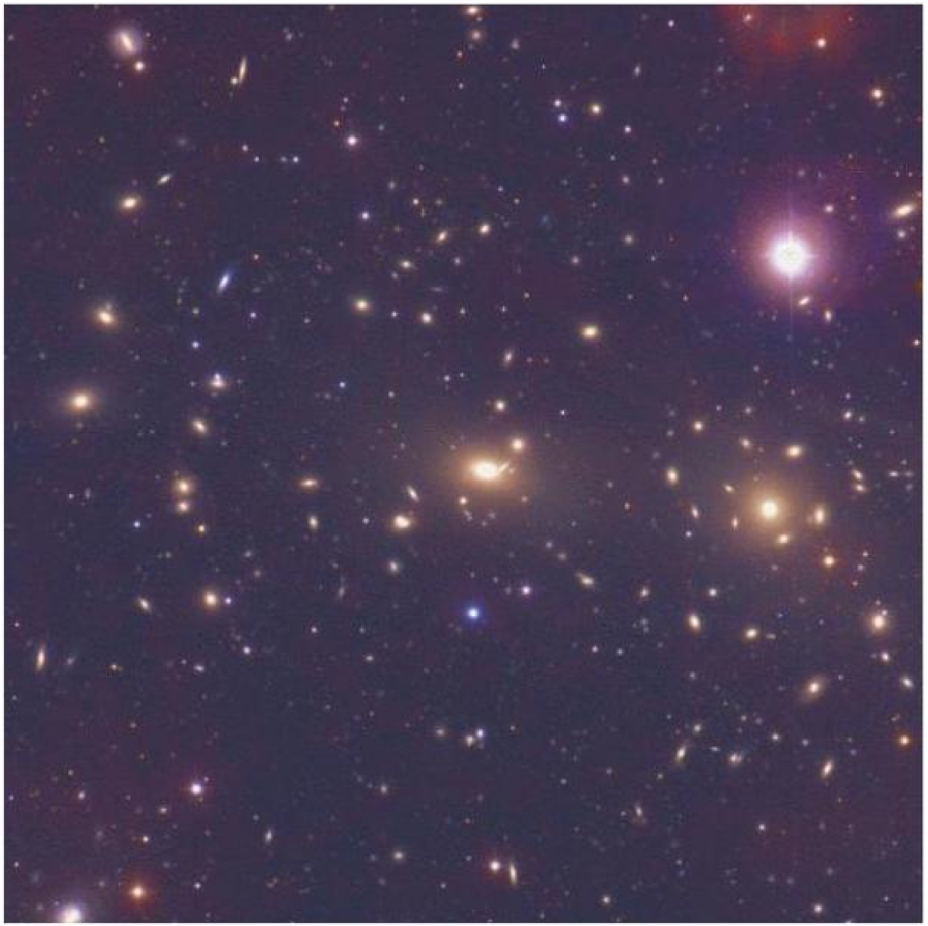
$$-0.0133 \leq \Omega_k \leq 0.0084$$

$$|R_0| > 37 \text{ Gpc}$$

The Universe is FLAT

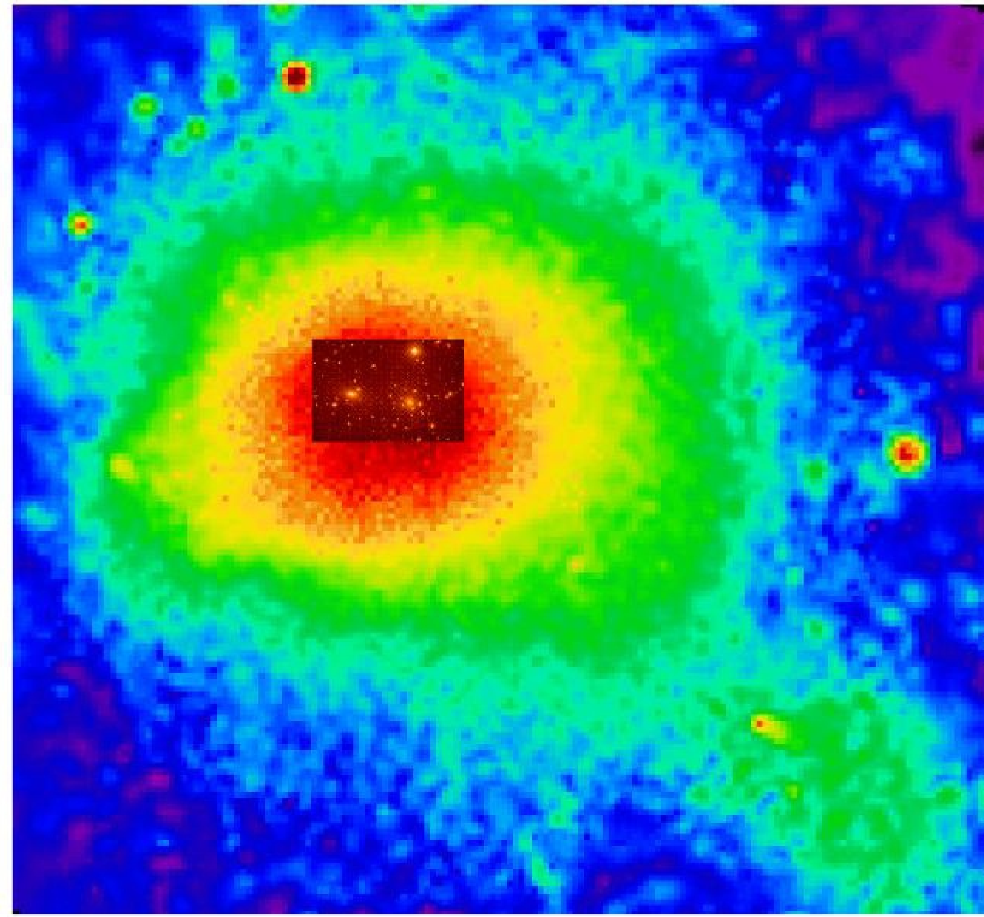


COMA Galaxy Cluster



Optical

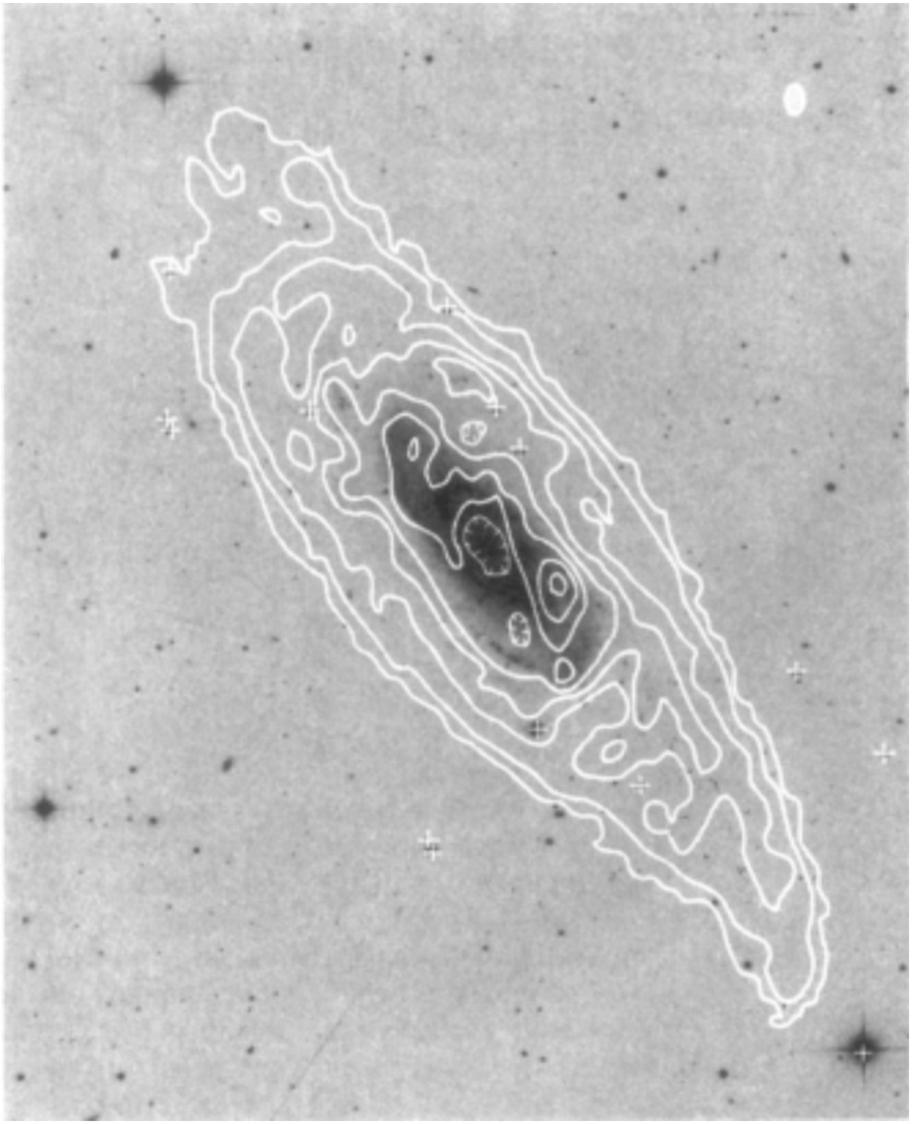
Fritz Zwicky 1933
First argument for Dark Matter
Virial theorem



X-ray

[hot gas confined by
deep gravitational well]

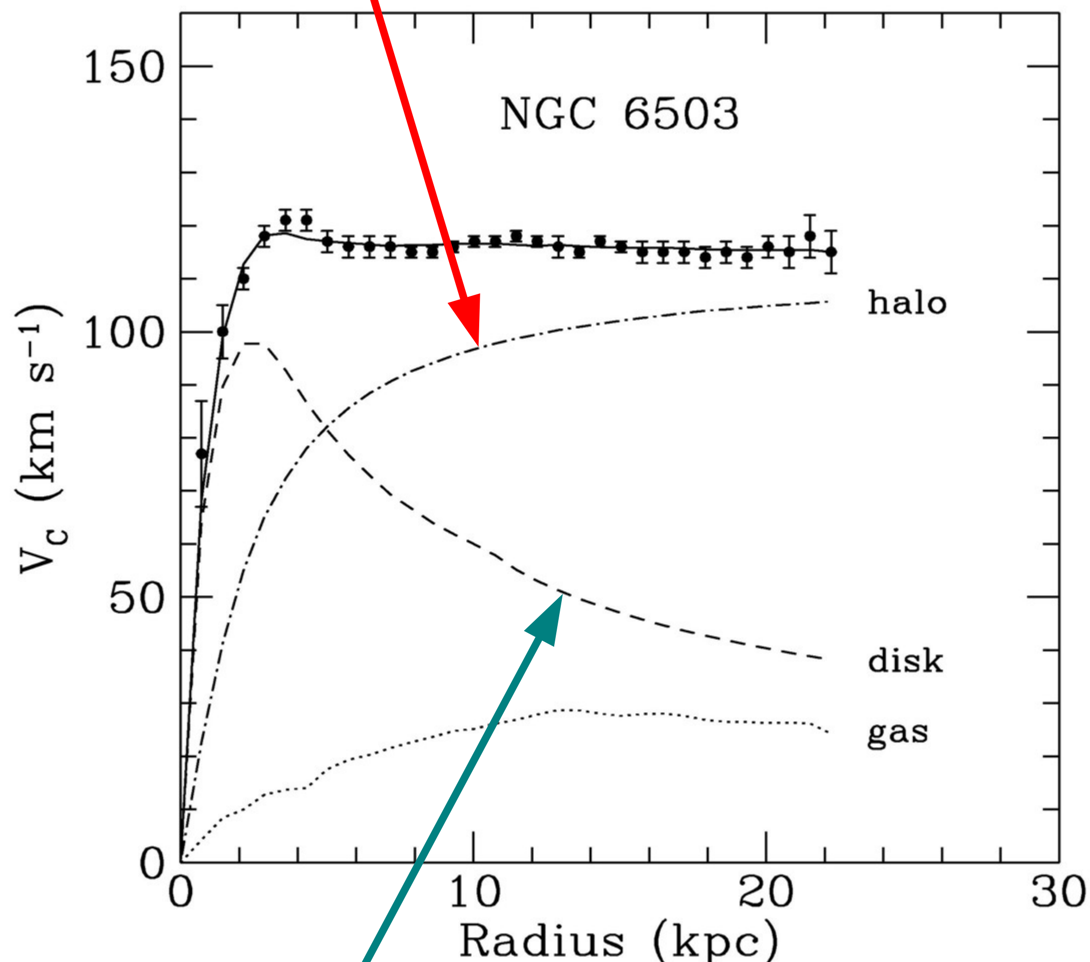
Galaxy Dark Matter Halos



Spiral galaxy NGC 3198
overlaid with hydrogen
column density [21 cm]

[ApJ 295 (1905) 305

Extra “invisible” component

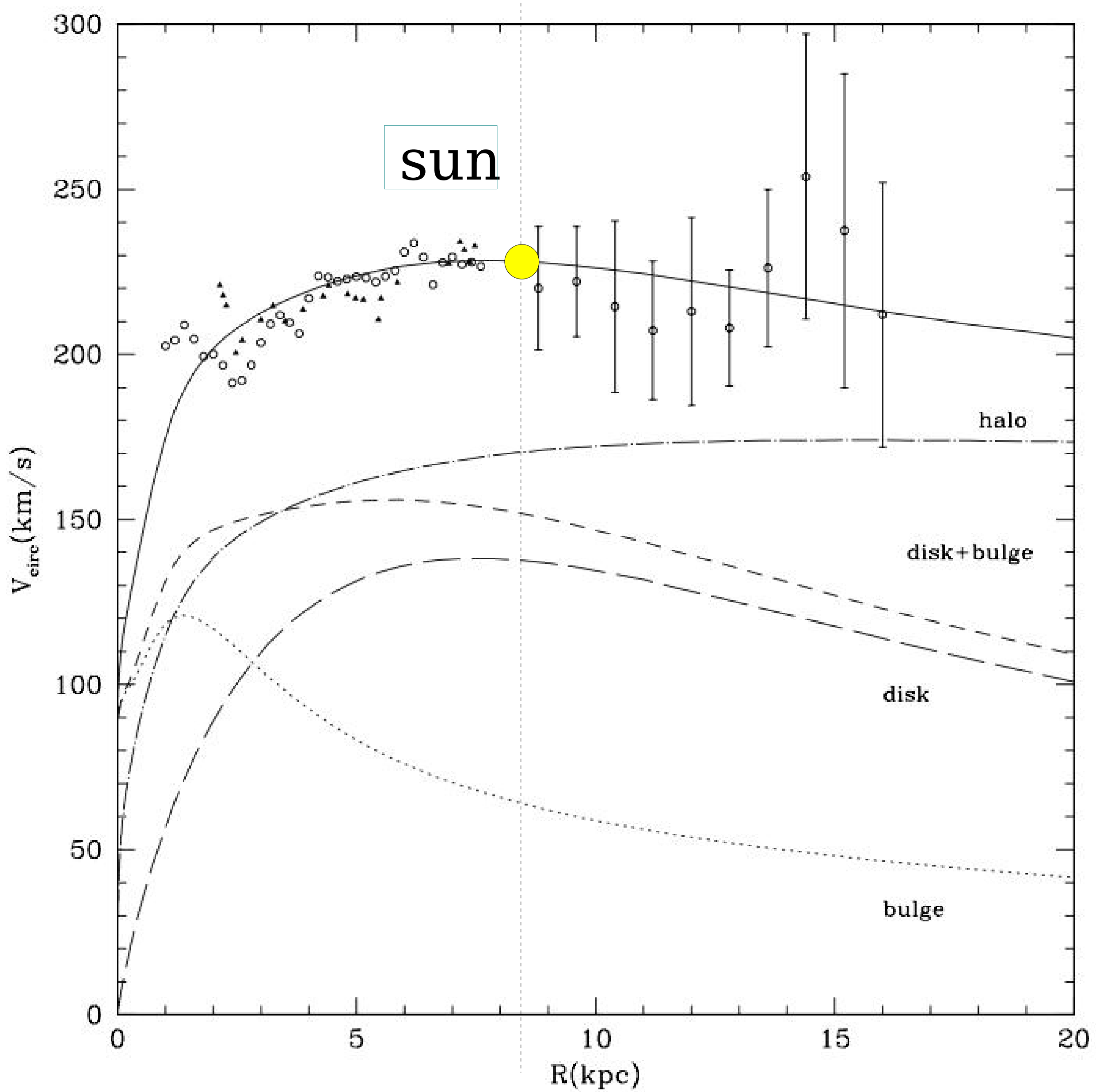


Expected from luminous
Matter in the disk

MILKY WAY DM Halo

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

DM Density
at the Sun



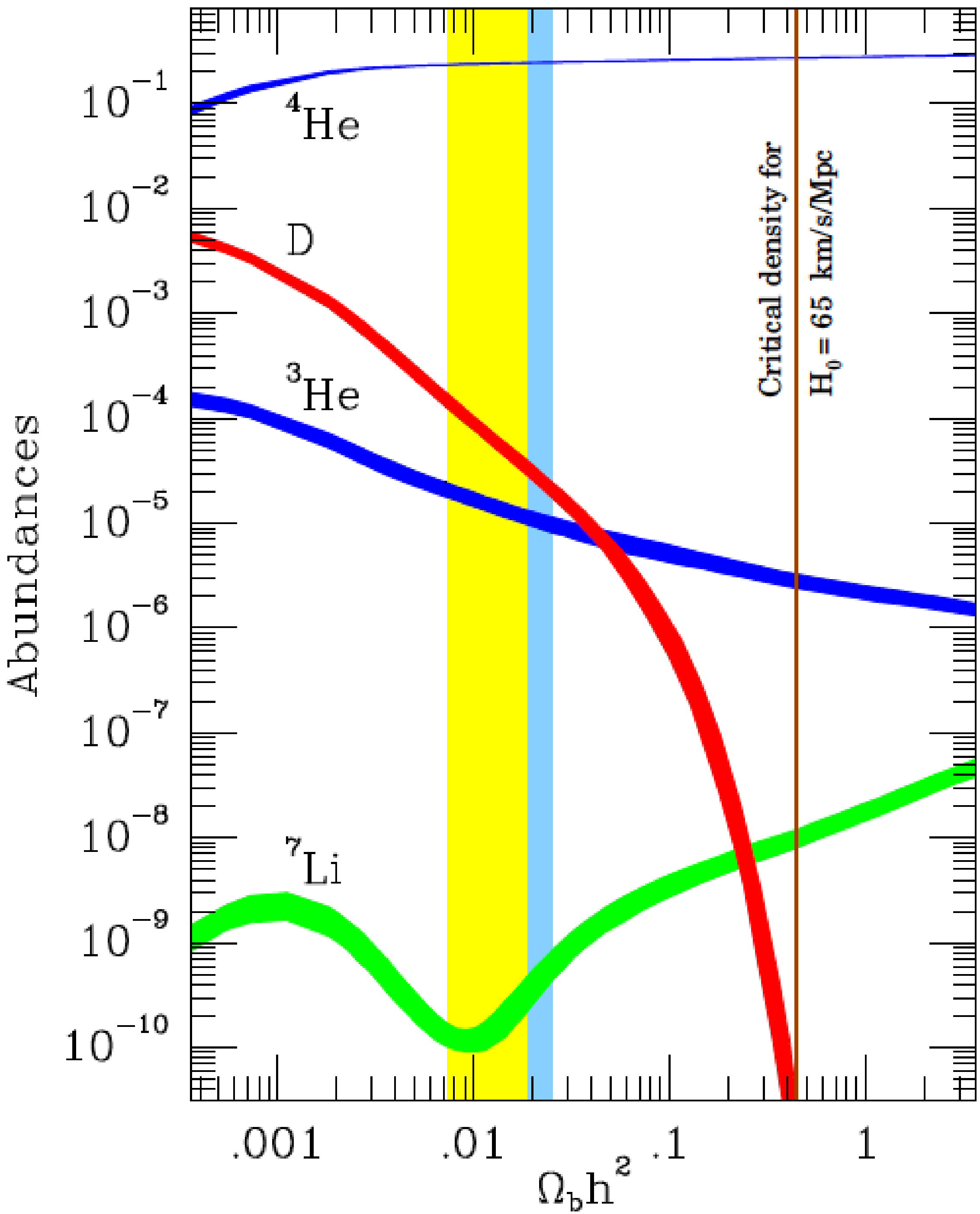
The DARK MATTER is “Non Baryonic”

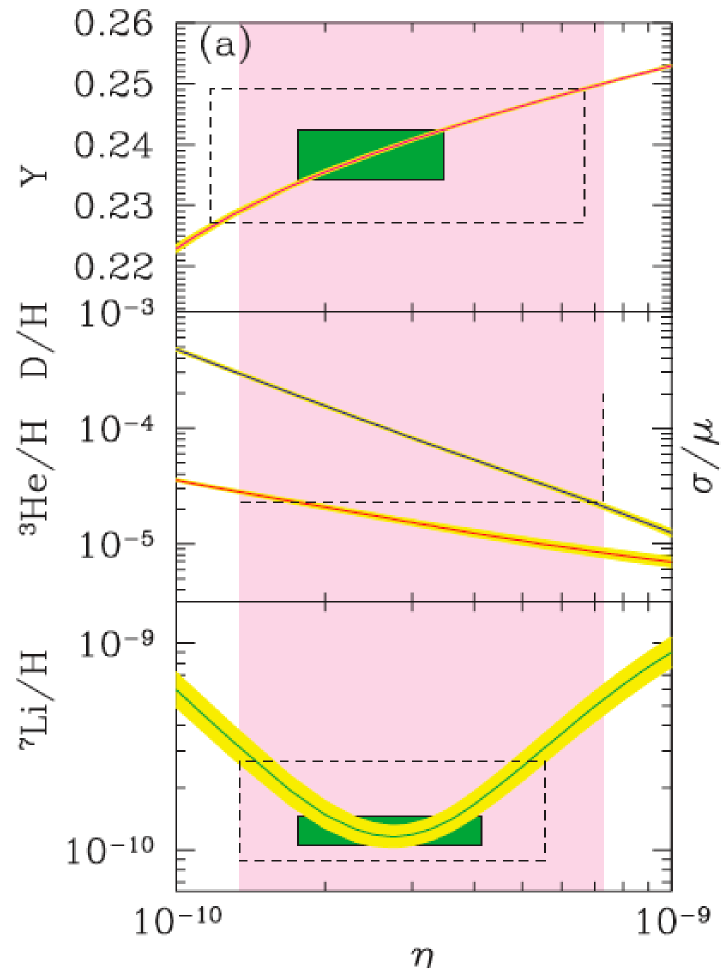
Nucleosynthesis

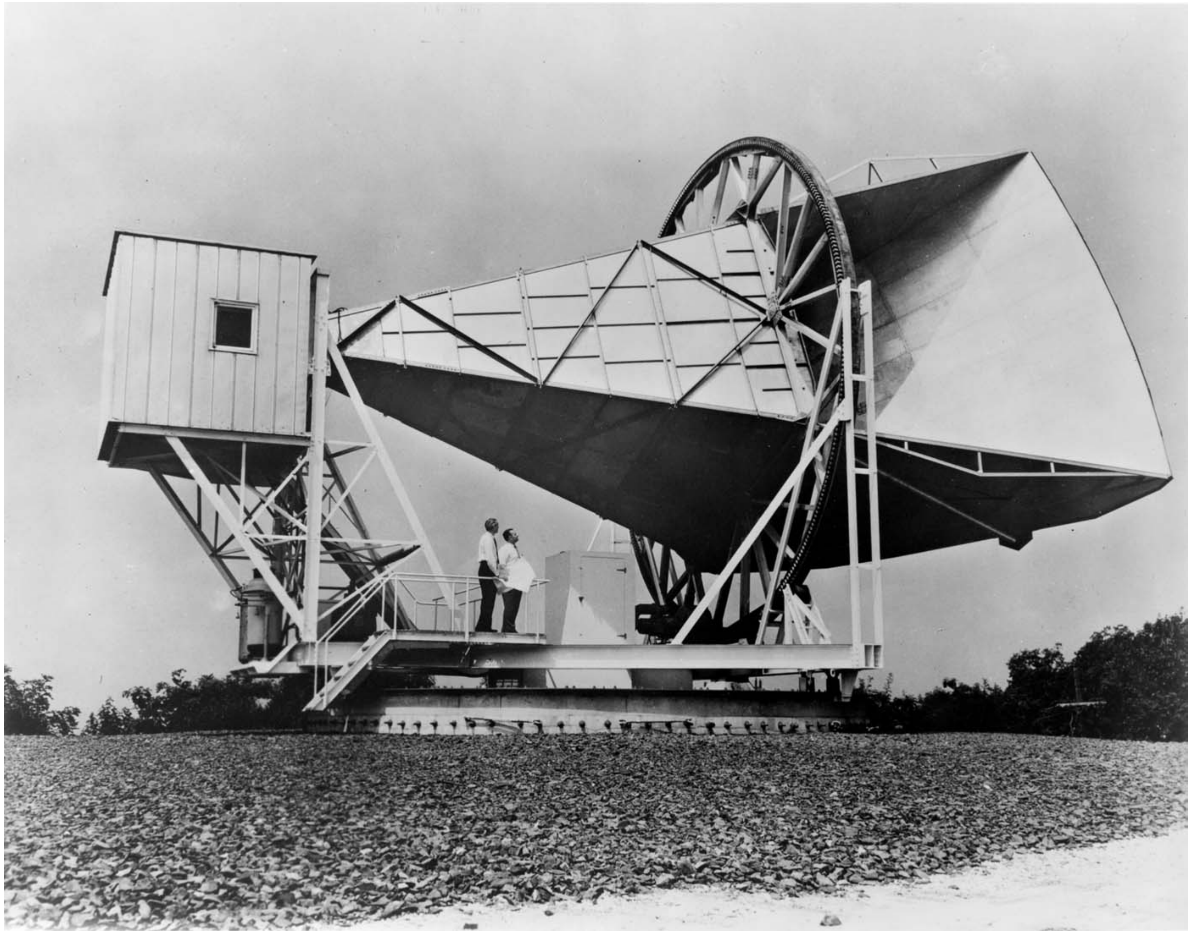
Structure Formation

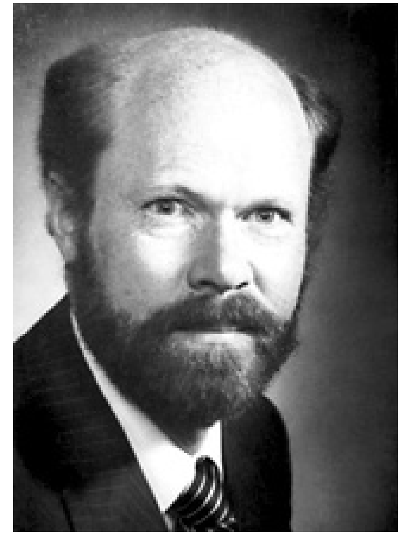
BigBang Nucleosynthesis constraints

on ordinary ("baryonic") matter





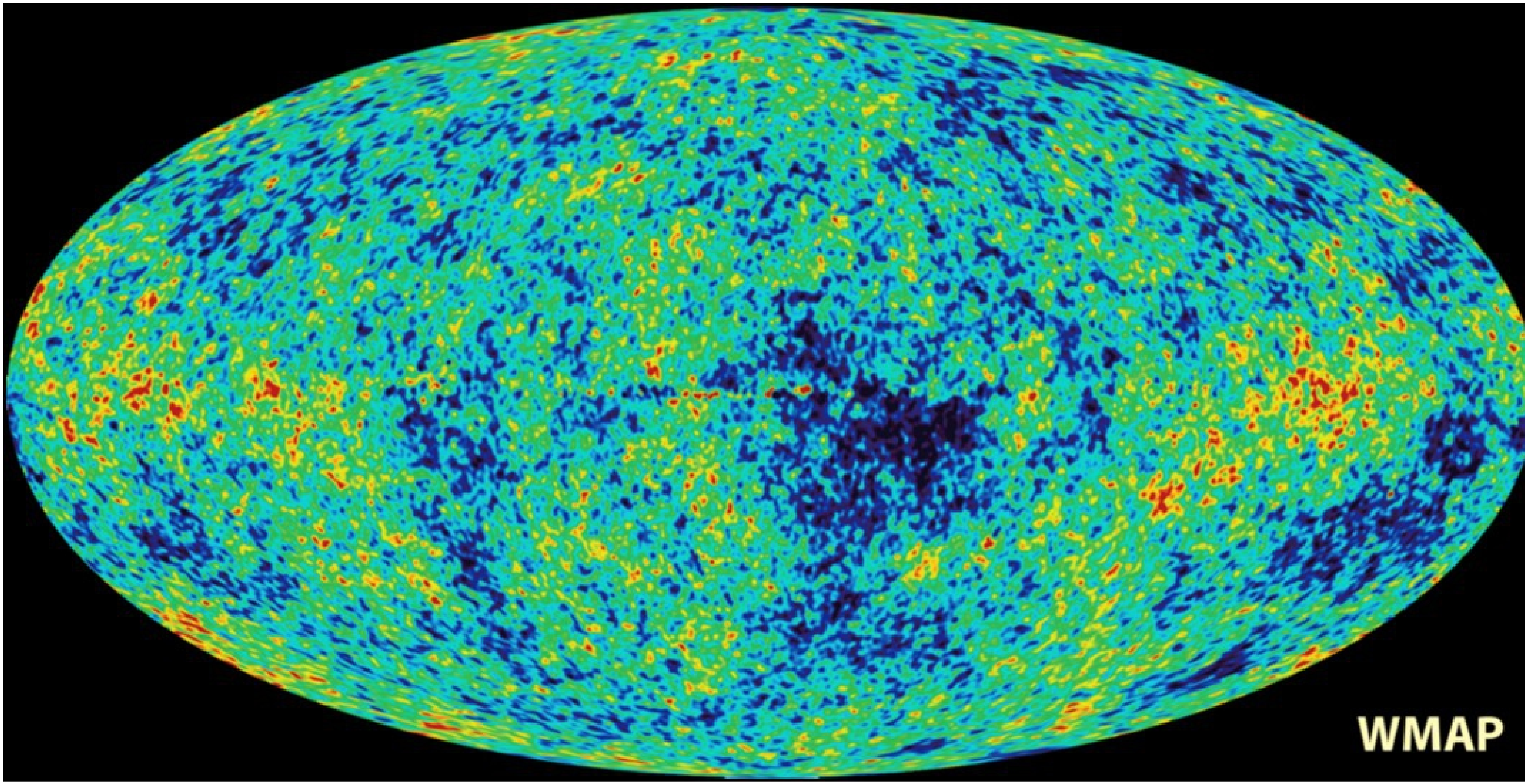




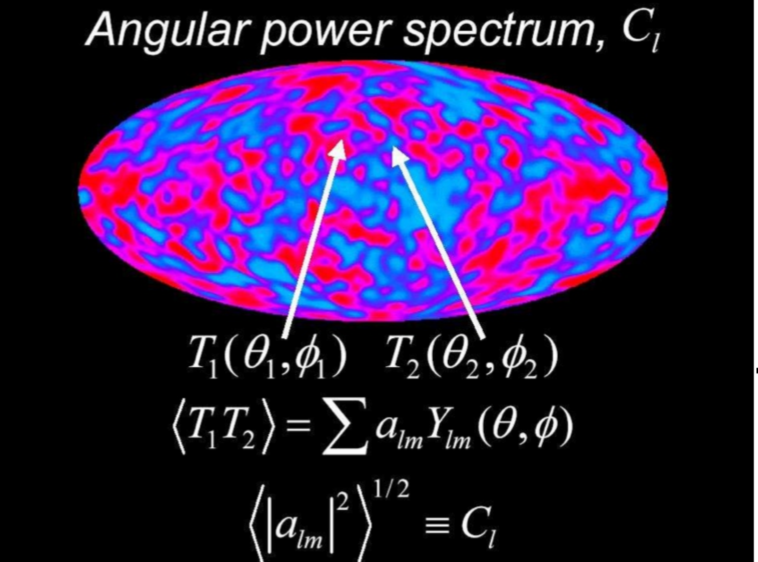
Robert W. Wilson

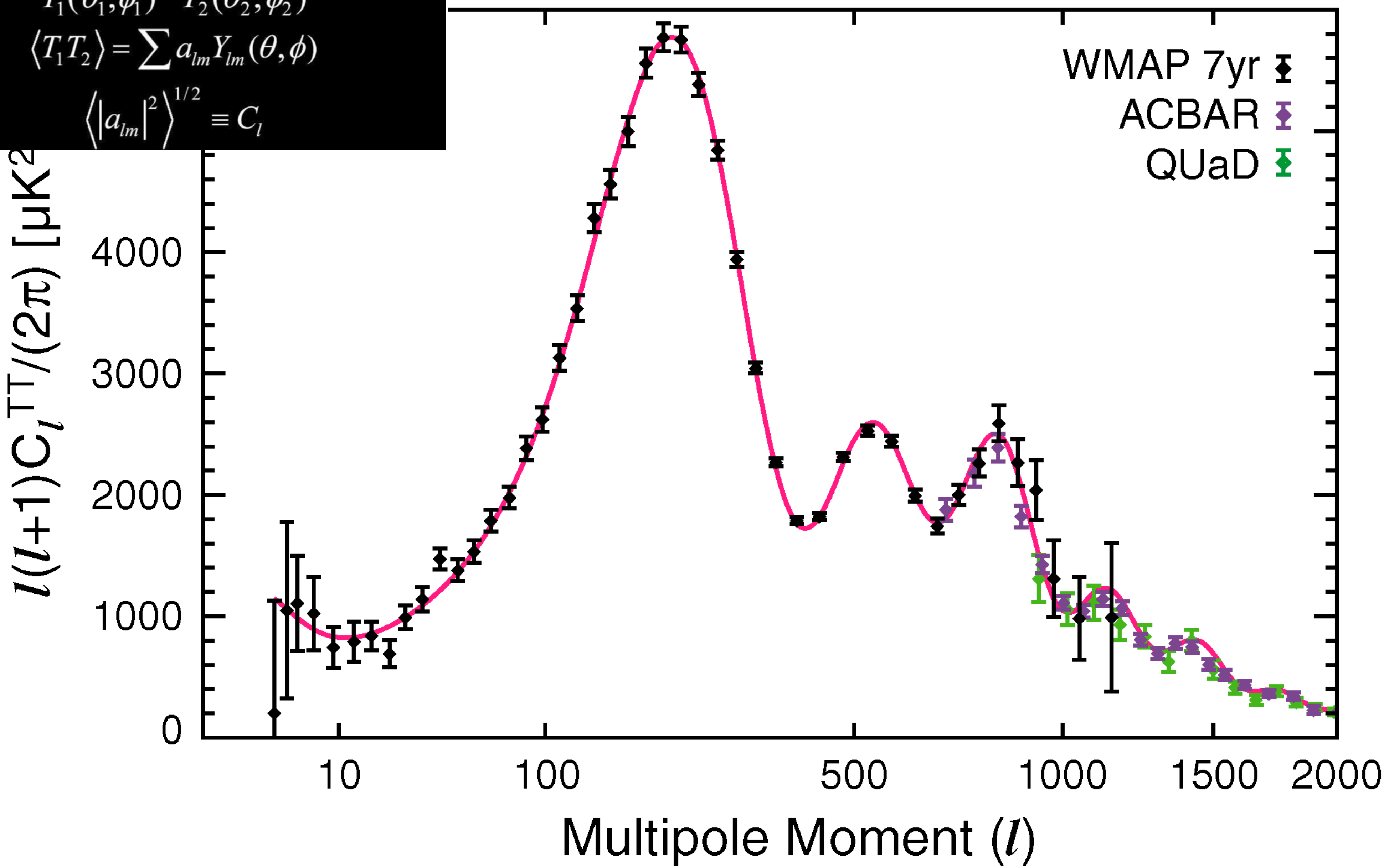
Arno.A. Penzias

Discovery of the 2.7 Kelvin
Cosmic Microwave Background Radiation
By Penzias and Wilson (1965), [Nobel 1978]


WMAP

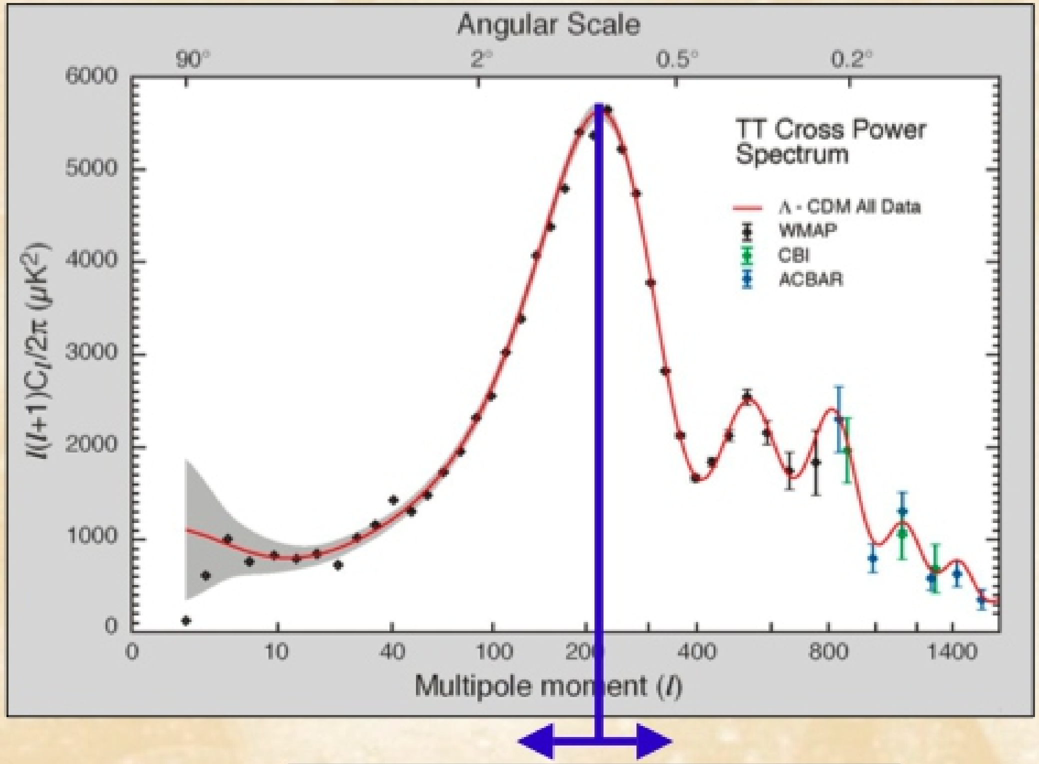
The “Rosetta stone”
of the Early Universe





Flat Universe from CMBR Angular Fluctuations

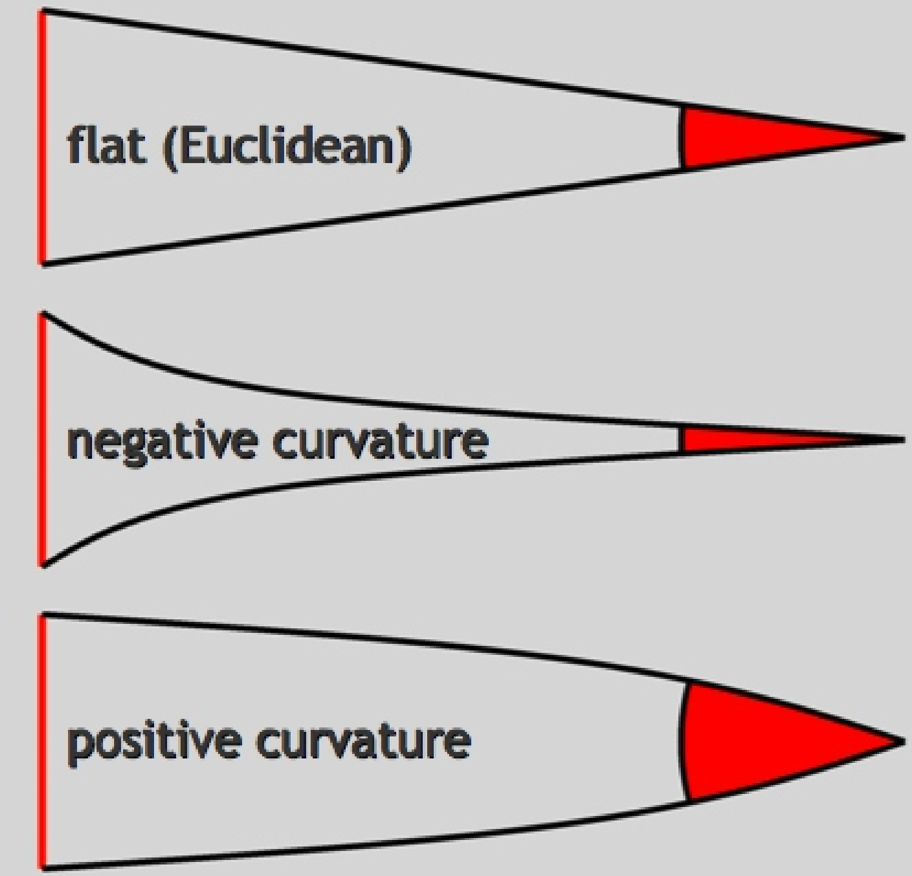
Spergel et al. (WMAP Collaboration)
astro-ph/0302209



$$\ell_{\max} \approx 200 / \sqrt{\Omega_{\mathrm{tot}}}$$

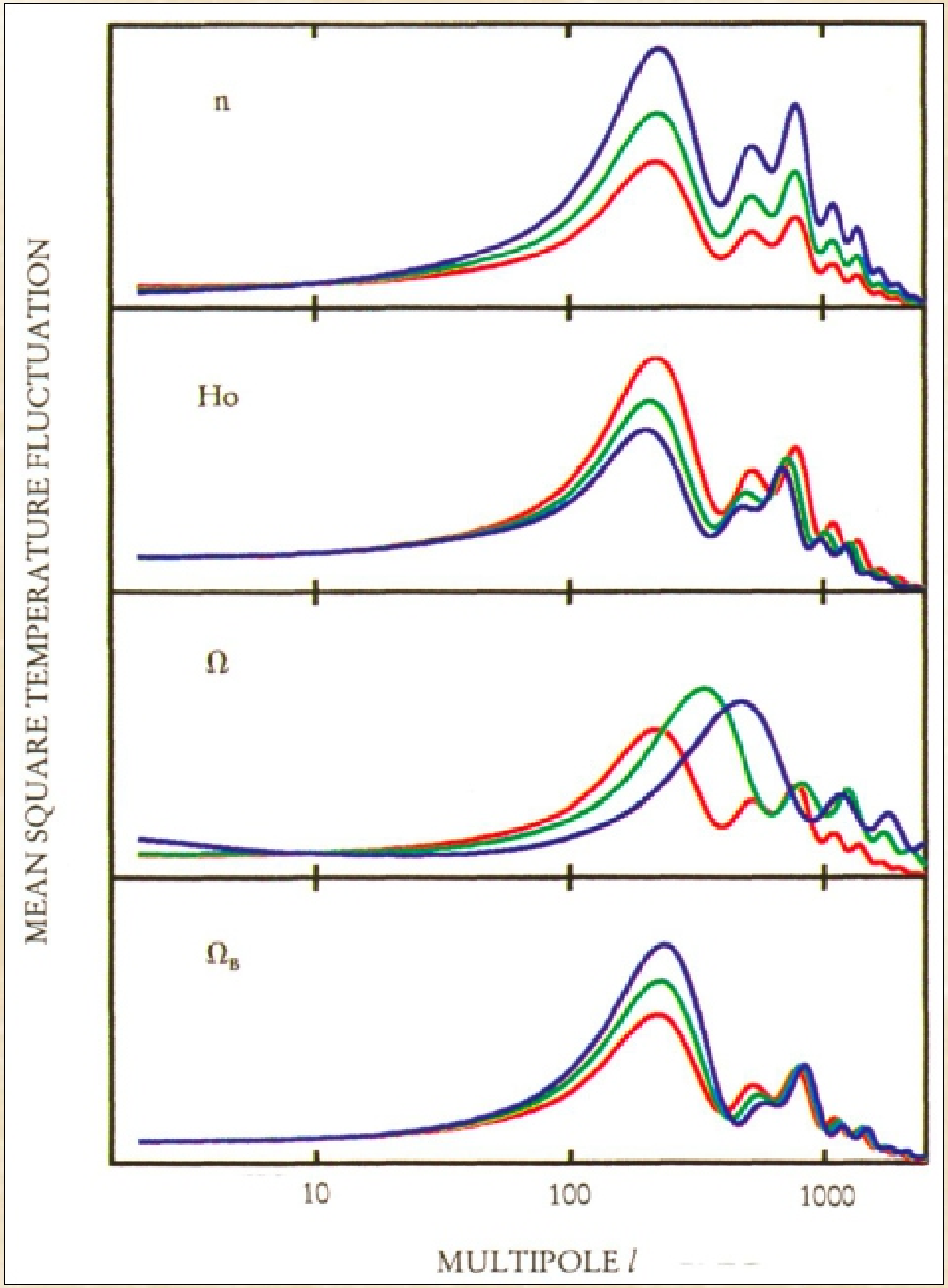
$$\Omega_{\mathrm{tot}} = 1.02 \pm 0.02$$

Triangulation with acoustic peak



Known physical size of acoustic peak at decoupling ($z \approx 1100$)

Measured angular size today ($z = 0$)



Power-law index (tilt)
$n = 1.0, 1.1, 1.2$

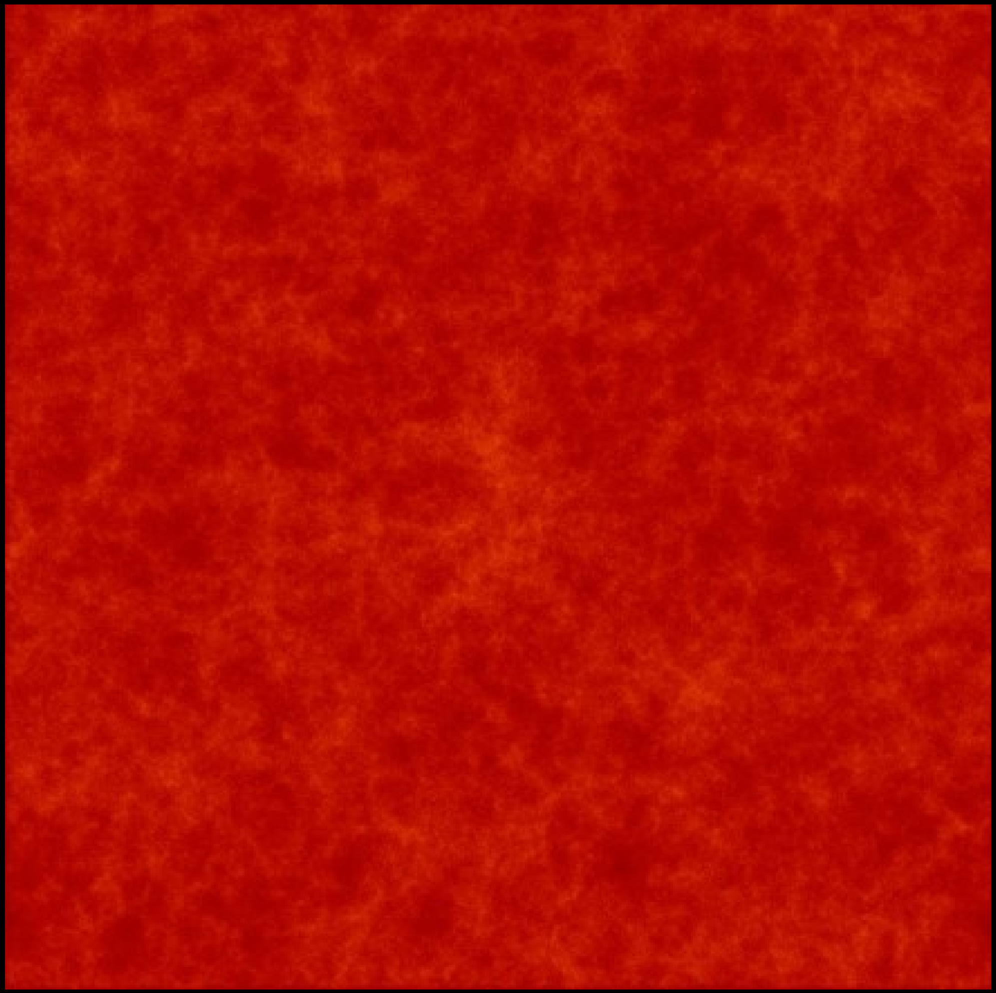
Hubble constant
$H_0 = 50, 60, 70$

Total density
$\Omega_{tot} = 1.0, 0.5, 0.3$

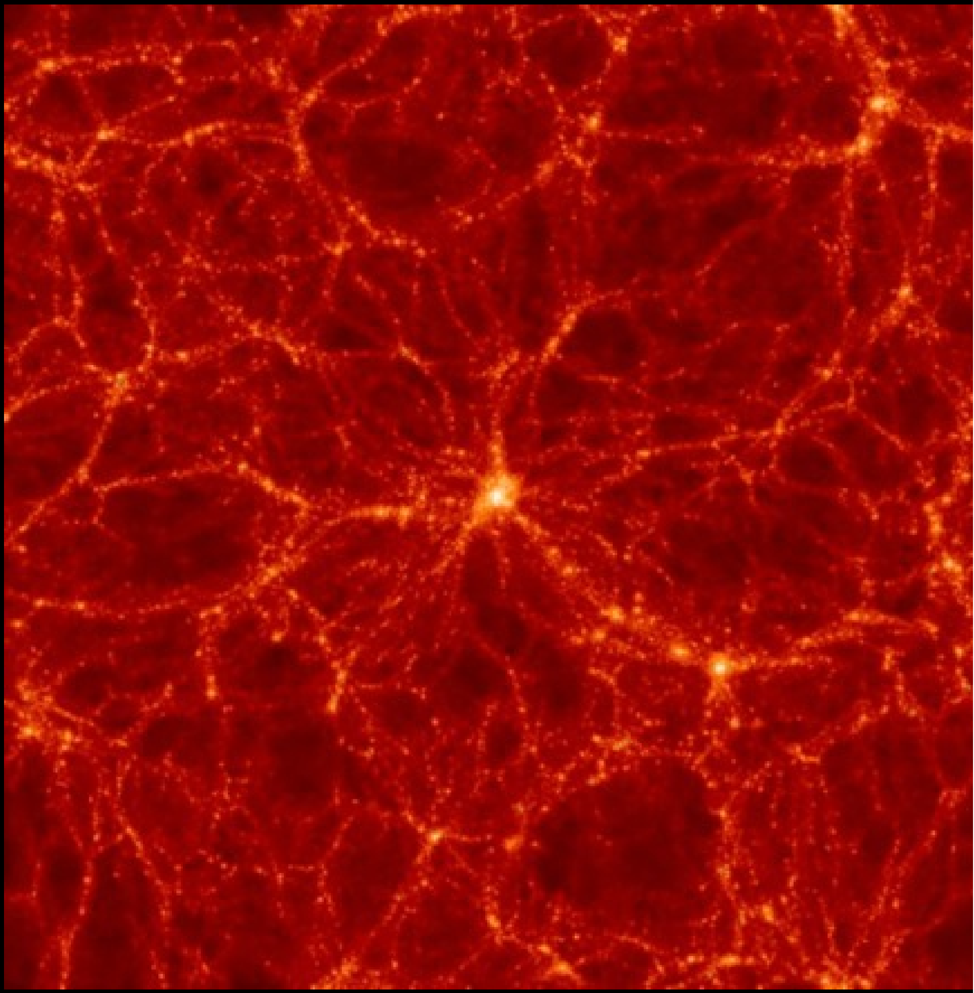
Baryon density
$\Omega_B = 5, 7.5, 10 \times 10^{-3}$

Physics Today 1997:11, 32

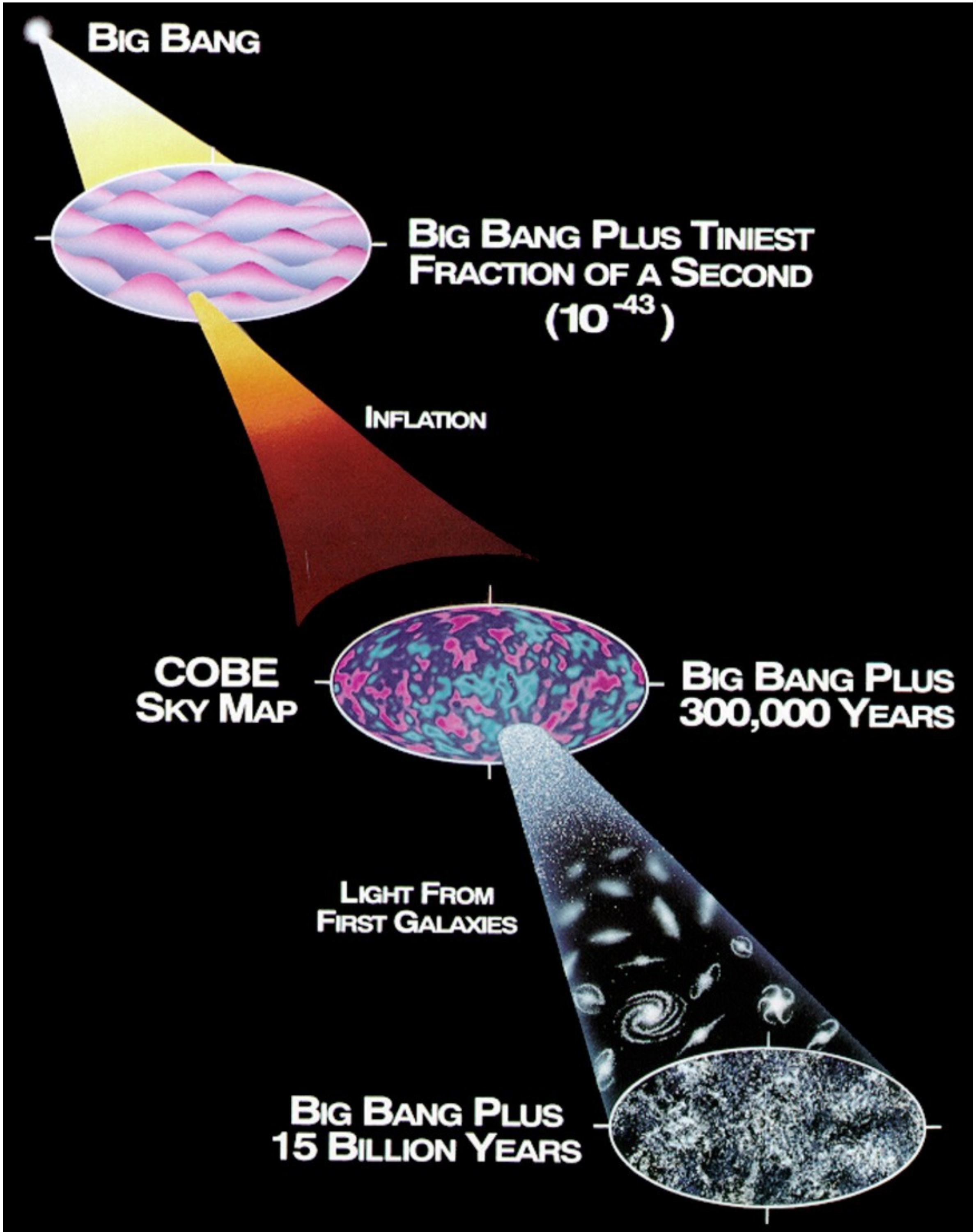
GRAVITATIONAL INSTABILITY



Smooth

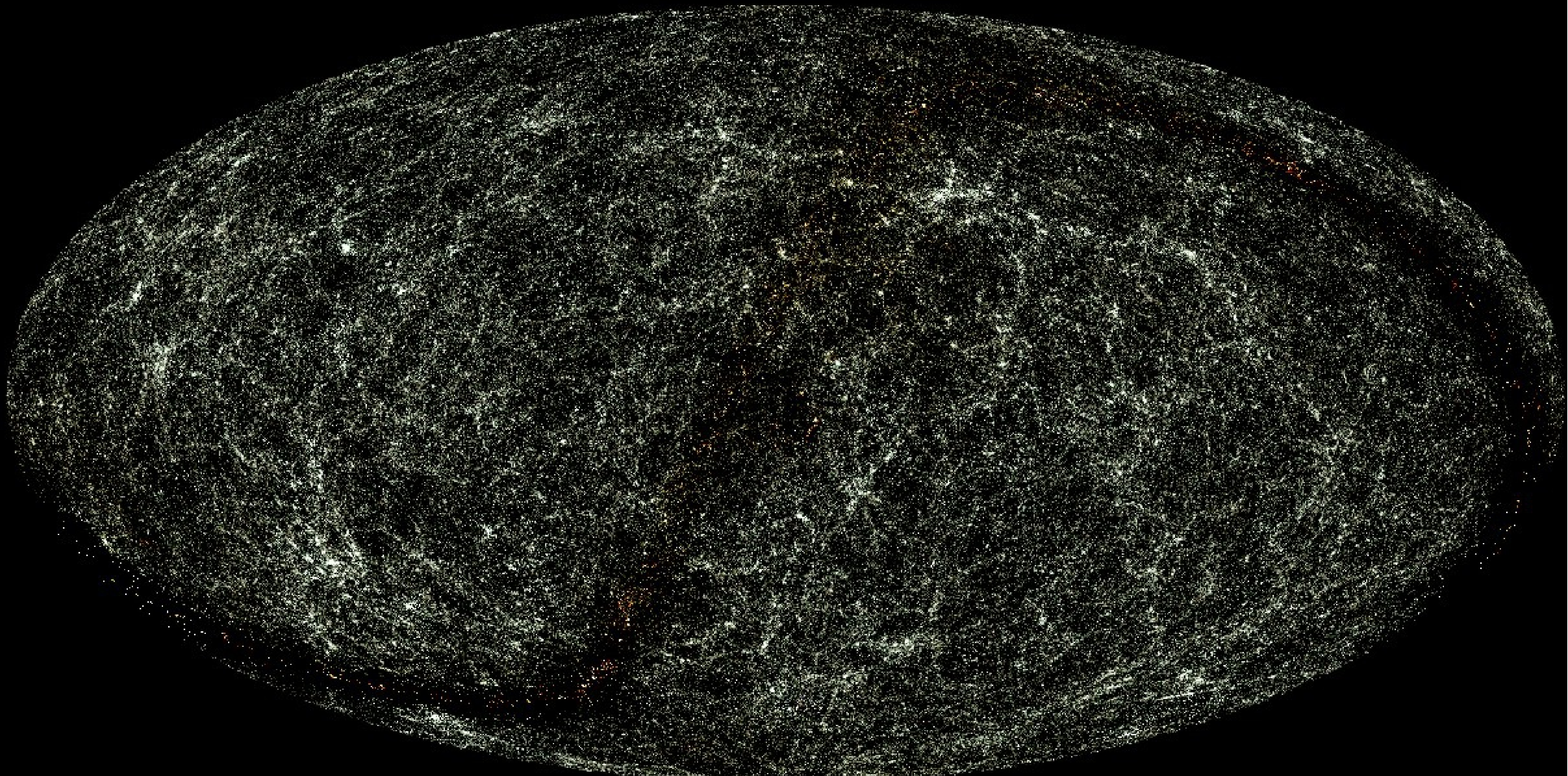


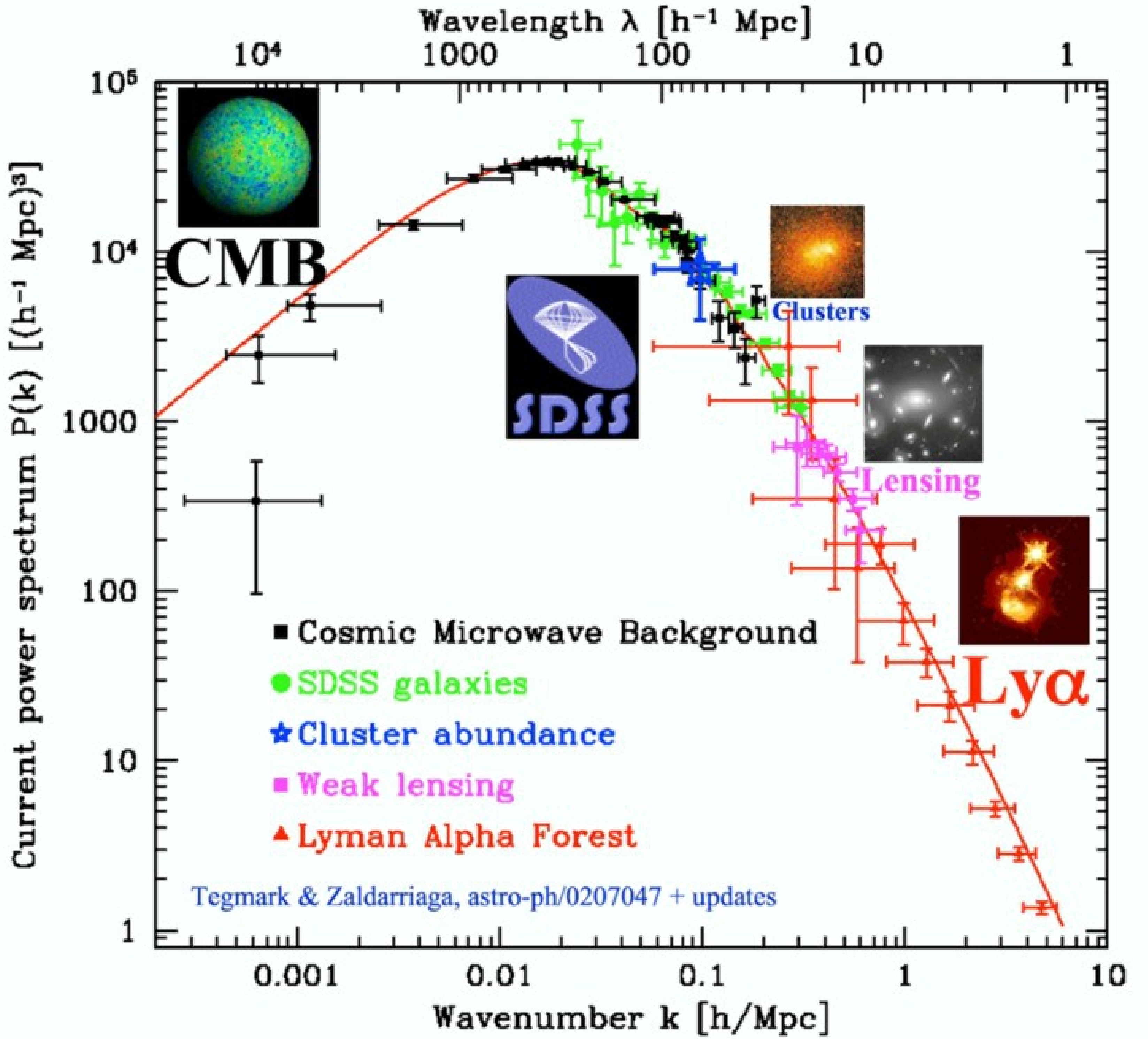
Structured



BIG BANG
BIG BANG PLUS TINIEST FRACTION OF A SECOND (10^{-43})
INFLATION
COBE SKY MAP
BIG BANG PLUS 300,000 YEARS
LIGHT FROM FIRST GALAXIES
BIG BANG PLUS 15 BILLION YEARS

Distribution of Galaxies in the SKY (XMASS)





Max Tegmark
Univ. of Pennsylvania
max@physics.upenn.edu
TAUP 2003
September 5, 2003

DARK MATTER: we know a lot :

It (very likely) exists
("modified gravity" models strongly disfavored)

Good estimate of the cosmological average (~23%)

Reasonably good estimate of "local" density

Most of it is non baryonic

Most of it is "cold"

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

DARK MATTER: we know a lot :

It (very likely) exists
("modified gravity" models strongly disfavored)

Good estimate of the cosmological average (~23%)

Reasonably good estimate of "local" density

Most of it is non baryonic

Most of it is "cold"

… but we
do NOT what it
is made of ….

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

Cold Dark Matter
(Tate Gallery. London)

Artists and Dark Matter

Cornelia Parker




What is the Dark Matter ?

Possible theoretical ideas

Thermal Relic (“WIMP” hypothesis)

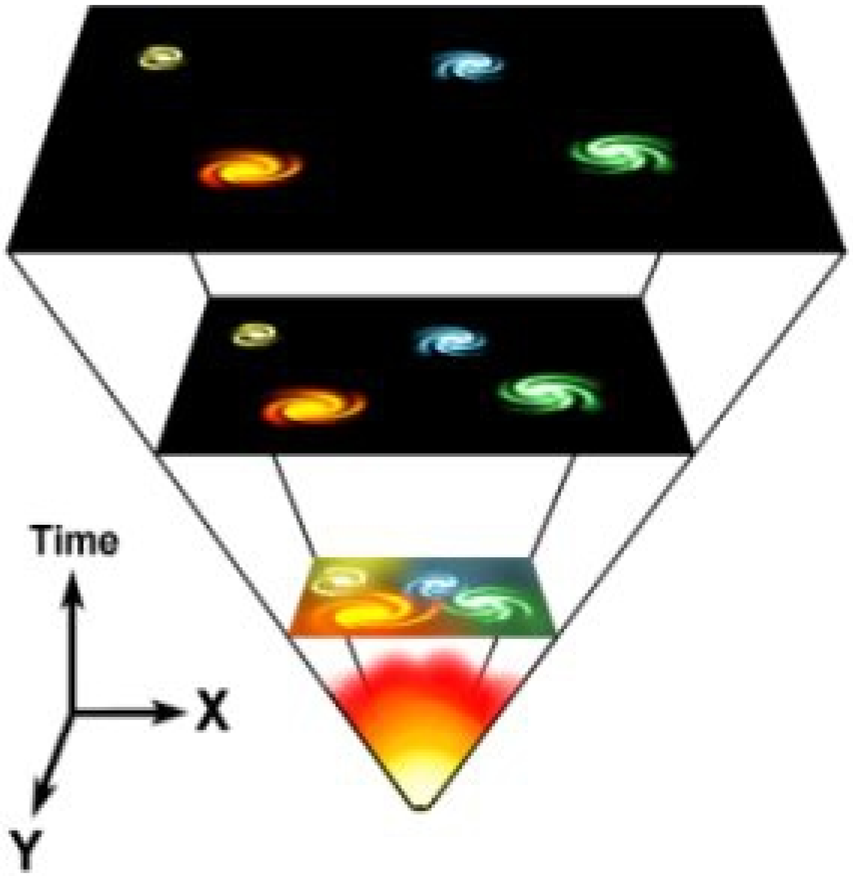
Axion

Super-massive particles

……….

WIMP = “Weakly Interacting Massive particle”
Perhaps the most natural idea.
Offers good possibility to be tested experimentally.

Early Hot Universe



Particles in
Thermal equilibrium

$$\boxed{a + b \leftrightarrow c + d}$$

"COSMIC SOUP"

$$n(T) = \int d^3p \, \frac{dN}{d^3x \; d^3p}$$

Number (mass) density of a particle in thermal equilibrium at temperature T

$$\rho(T) = \int d^3p \; E(p) \; \frac{dN}{d^3x \; d^3p}$$

High Temperature

$$T \gg m_\chi$$

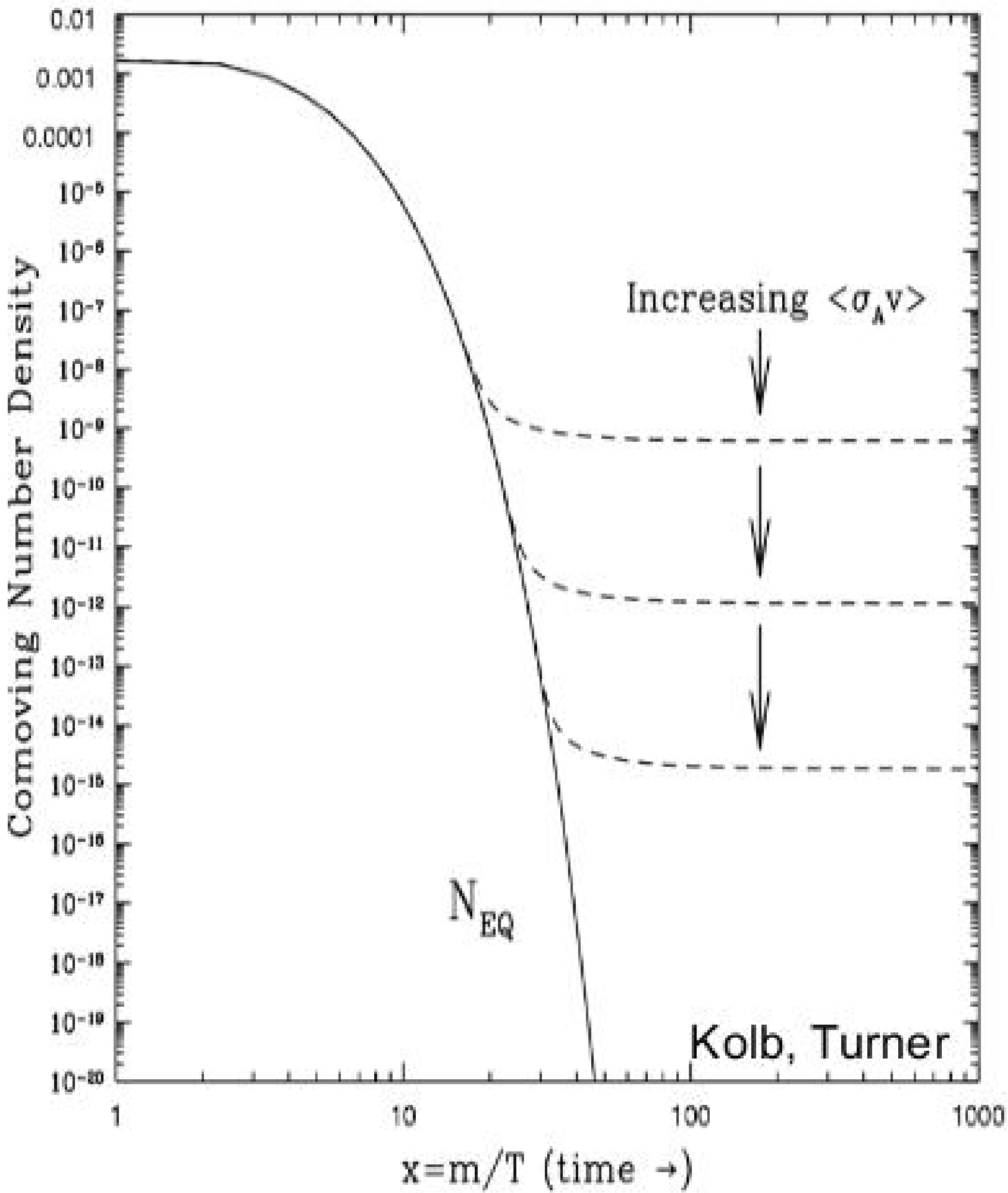
$$n_{\rm boson}(T) = g \, \frac{\zeta(3)}{\pi^2} \, T^3$$

$$n_{\rm fermion}(T) = g \, \frac{\zeta(3)}{\pi^2} \, T^3 \times \frac{3}{4}$$

$$\rho_{\rm boson}(T) = g \, \frac{\pi^2}{30} \, T^4$$

$$\rho_{\rm fermion}(T) = g \, \frac{\pi^2}{30} \, T^4 \times \frac{7}{8}$$

g = number of spin degrees of freedom



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

Annihilation cross section
Determines the
"relic abundance"

$$\Omega_\chi \simeq \left(\frac{16\,\pi^{5/2}}{9\,\sqrt{\pi}}\right)\ \frac{G^{3/2}\,T_0^3}{H_0^2\,(\hbar c)^{3/2}\,c^3}\ \frac{\sqrt{g_{\mathrm{eff}}}}{\langle \sigma\, v\rangle}$$

$$\Omega_\chi^{\mathrm{analytic}} = 0.173\ \left(\frac{3\times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma\, v\rangle_{\mathrm{f}}}\right)\ \sqrt{\frac{g_{\mathrm{eff}}}{106.75}}$$

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

$$n(T) = g\,\frac{e^{-m/T}\ (m\,T)^{3/2}}{2\sqrt{2}\,\pi^{3/2}}$$ Thermal equilibrium

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

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

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

(several complications are possible)

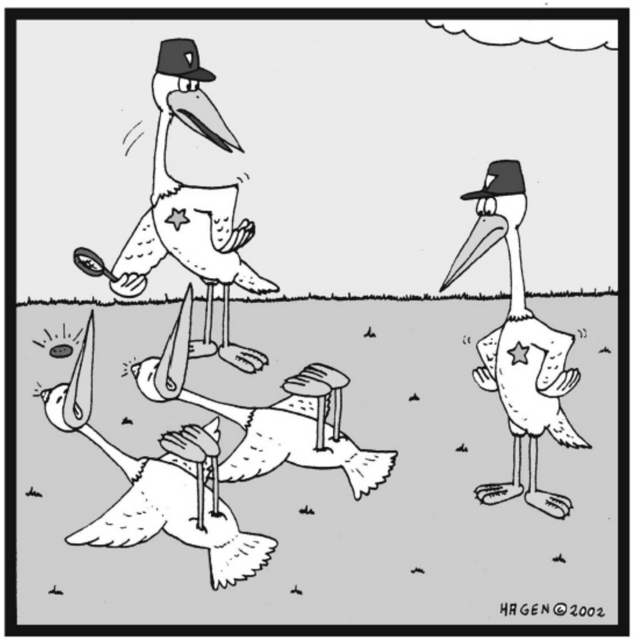
$$\sigma(\chi\chi \to \mathrm{anything}) \simeq 10^{-36}\ \mathrm{cm}^2$$

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

Weak interaction mass scale

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

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"

Direct observational puzzle

New particles are predicted in "beyond the Standard Model" theories, (in particular Supersymmetry) that have the DM particle properties.

Theoretical motivations (hierarchy problem)

Supersymmetry

Fermionic degrees of freedom

Bosonic degrees Of freedom

All “internal quantum numbers” (charge, color,...) must be identical

$q \quad \tilde{q}$ squark

$e^{\pm} \quad \tilde{e}^{\pm}$ selectron

$g \quad \tilde{g}$ gluino

....

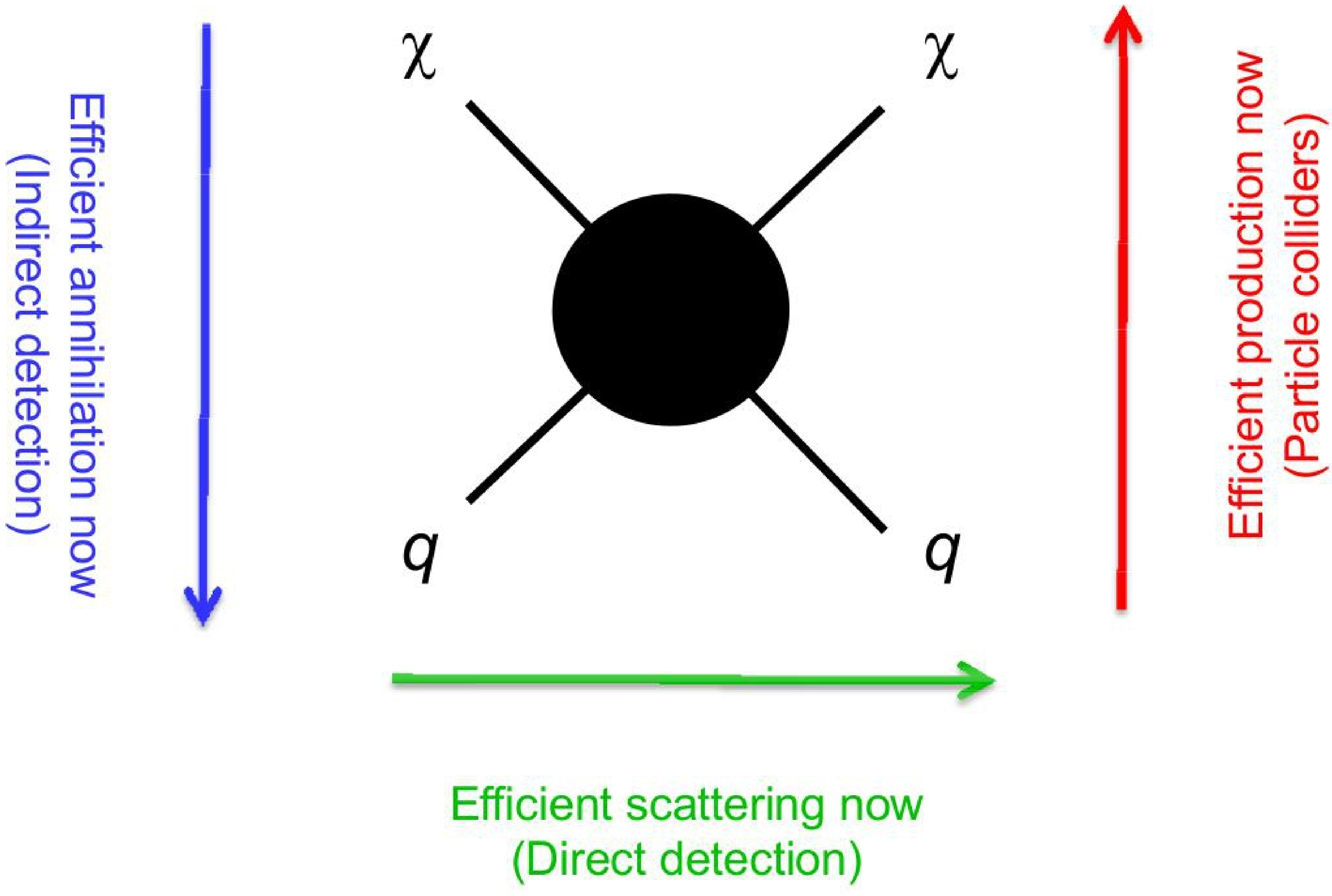
	Standard Model fields	Super-symmetric extension	
fermions	quarks	Squarks	New bosons (scalar) spin 0 S-
	leptons	Sleptons	
	neutrinos	Sneutrinos	
bosons	photon	photino	New fermions spin 1/2 -ino
	W	Wino	
	Z	Zino	
	gluons	gluinos	
	Higgs	Higgsino	
2 Higgs →	H h	$\tilde{H}$ $\tilde{h}$	

Weak (~100 GeV) Mass scale ?

1 stable New Particle (R-parity conserved)

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

Three roads to study of the "WIMP hypothesis"



“Three Roads to the Study of the “WIMP hypothesis”

$$\chi + \chi \to q + \overline{q}$$

Annihilation

[estimated from Cosmology]

$$q + \overline{q} \to \chi + \chi$$

Creation

Time reversal

$$\chi + q \to \chi + q$$

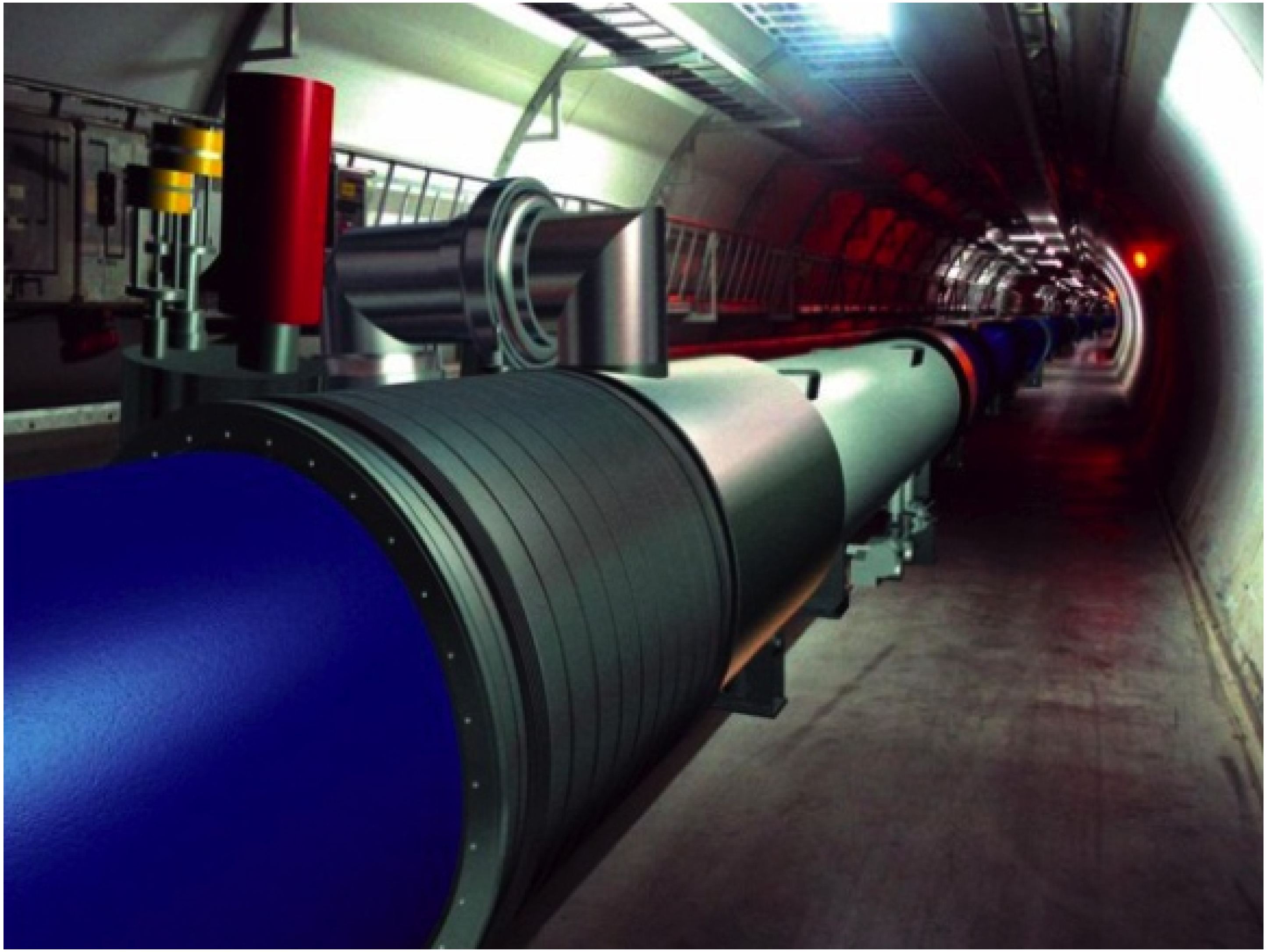
Elastic

Crossing symmetry

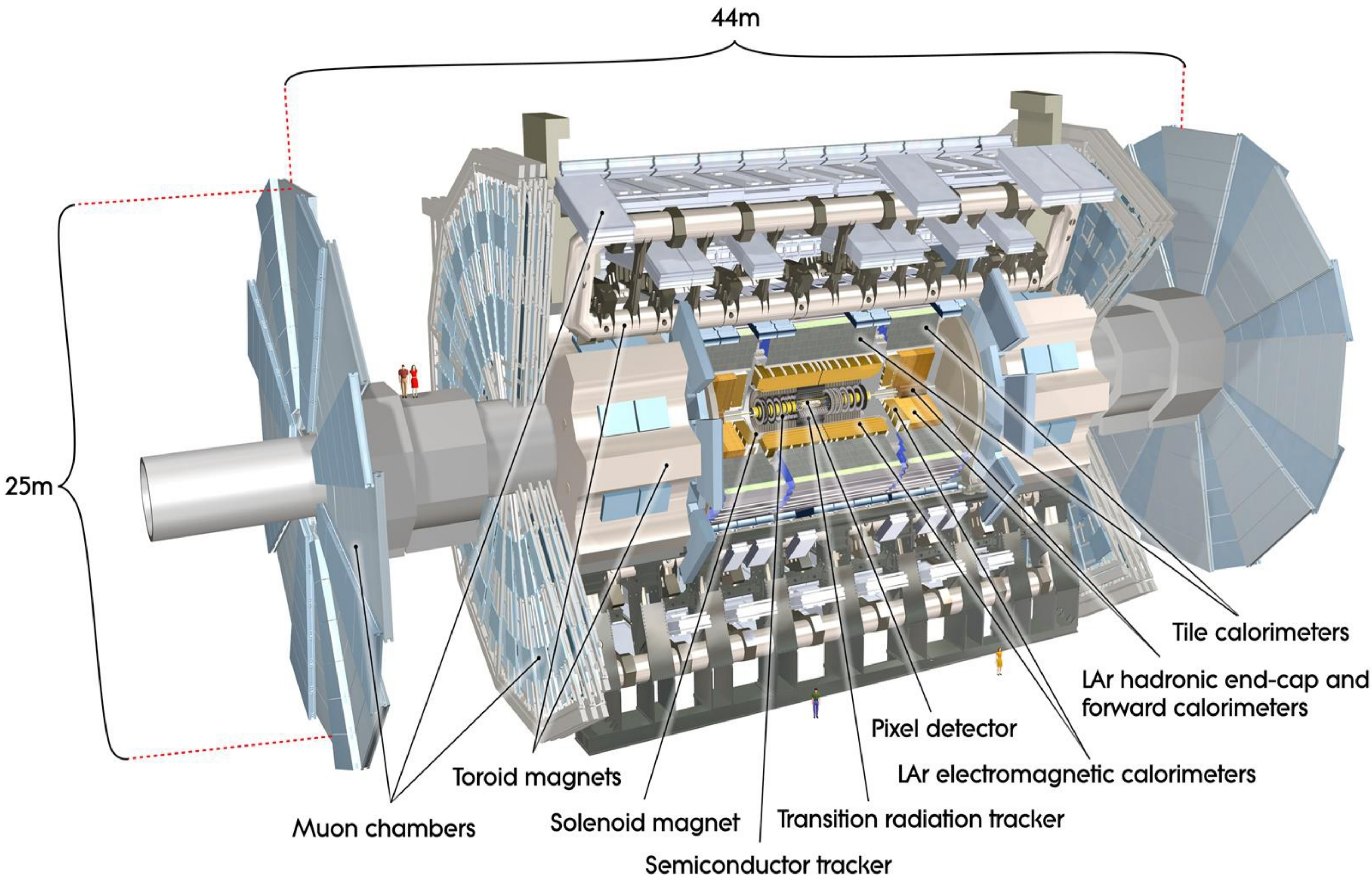
1^{st} Road to DARK Matter

[in the form of "WIMPs"]

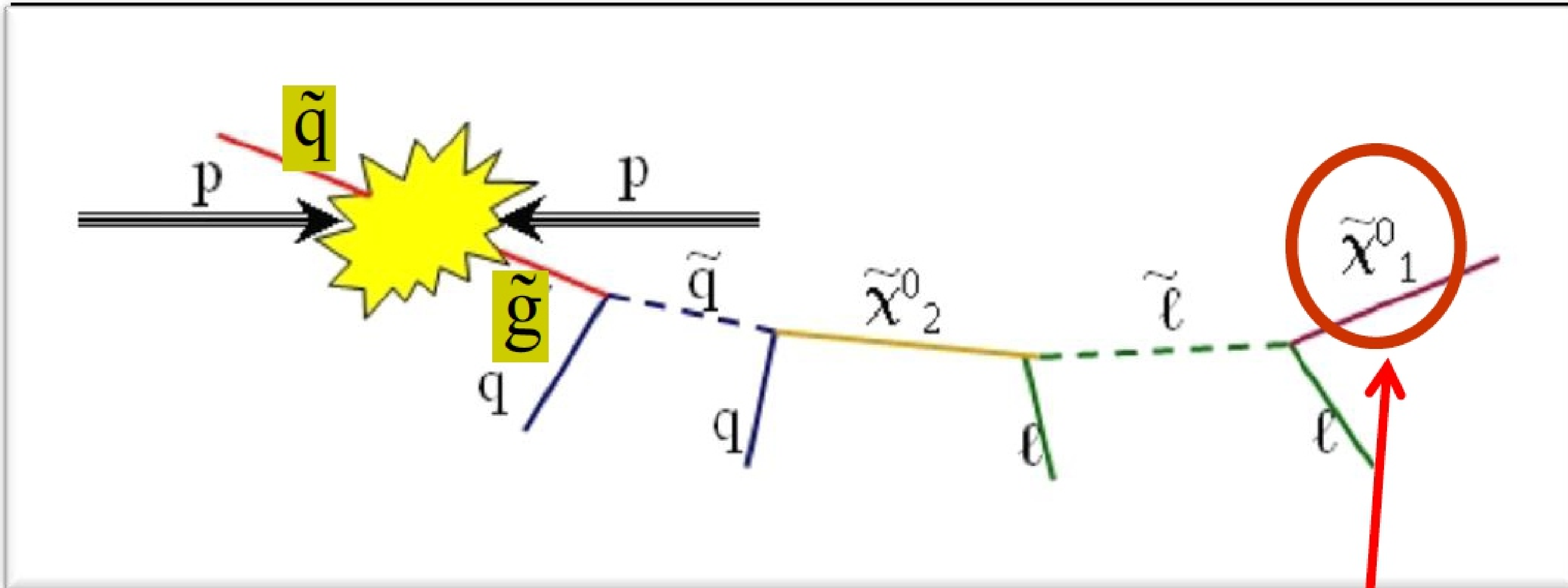
Production
in accelerators



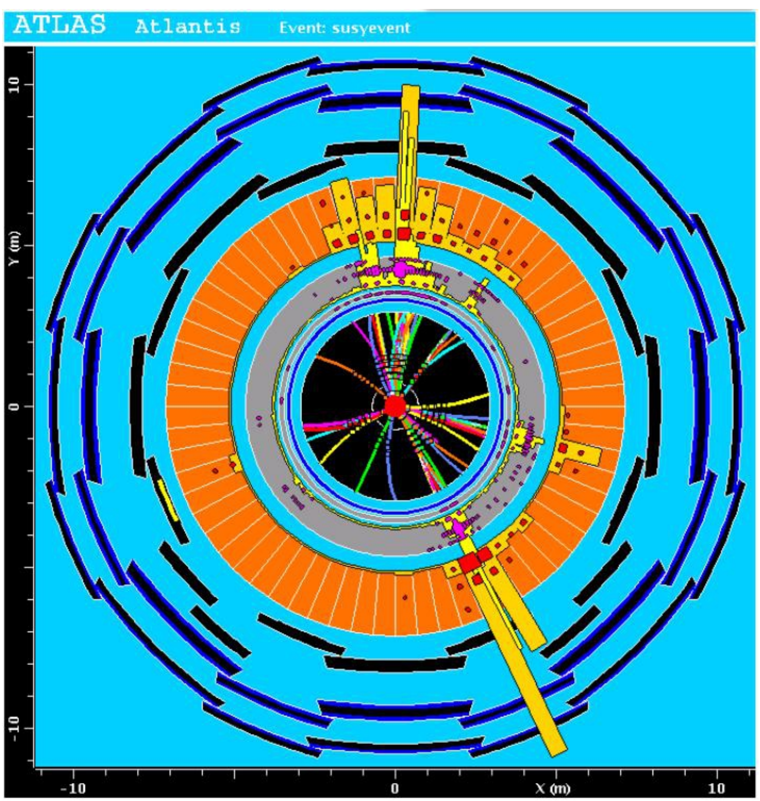
ATLAS detector at LHC



How do you see a Dark Matter (therefore invisible) particle ?



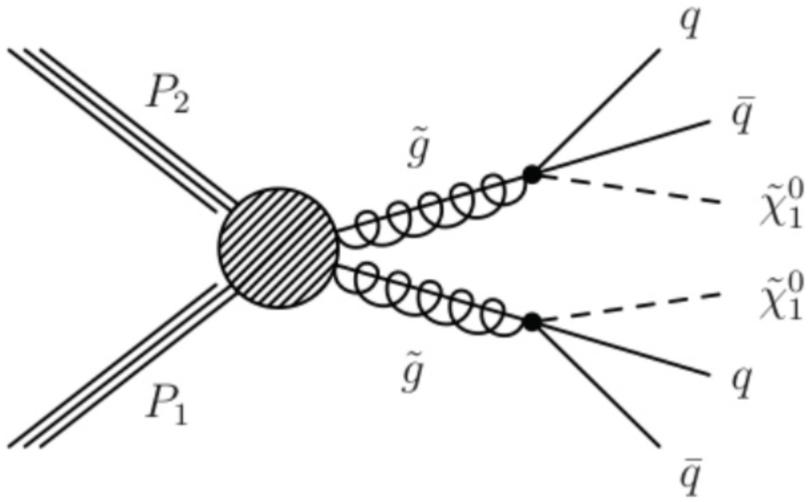
Lowest mass,
Stable,
(super-symmetric)
Particle [LSP]

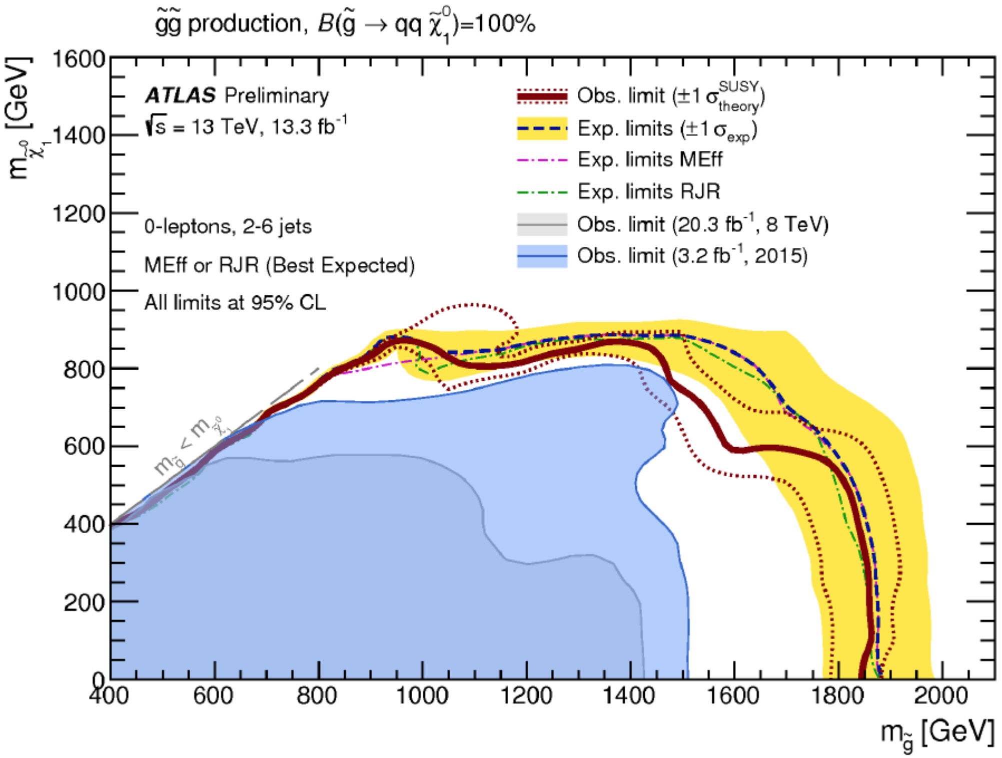


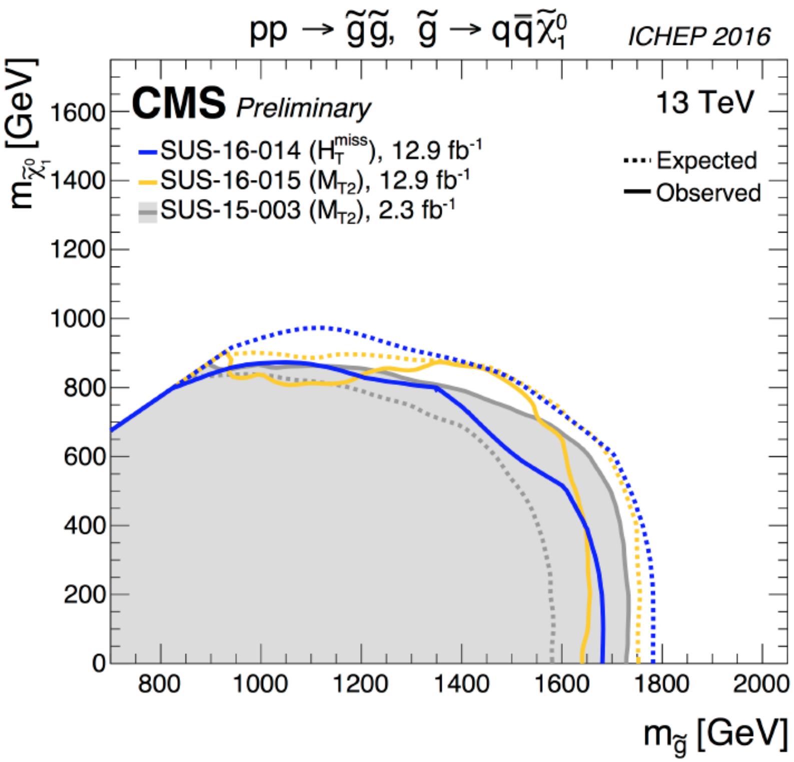
This particle interacts WEAKLY therefore (in practice always) it will traverse the detector invisibly.

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

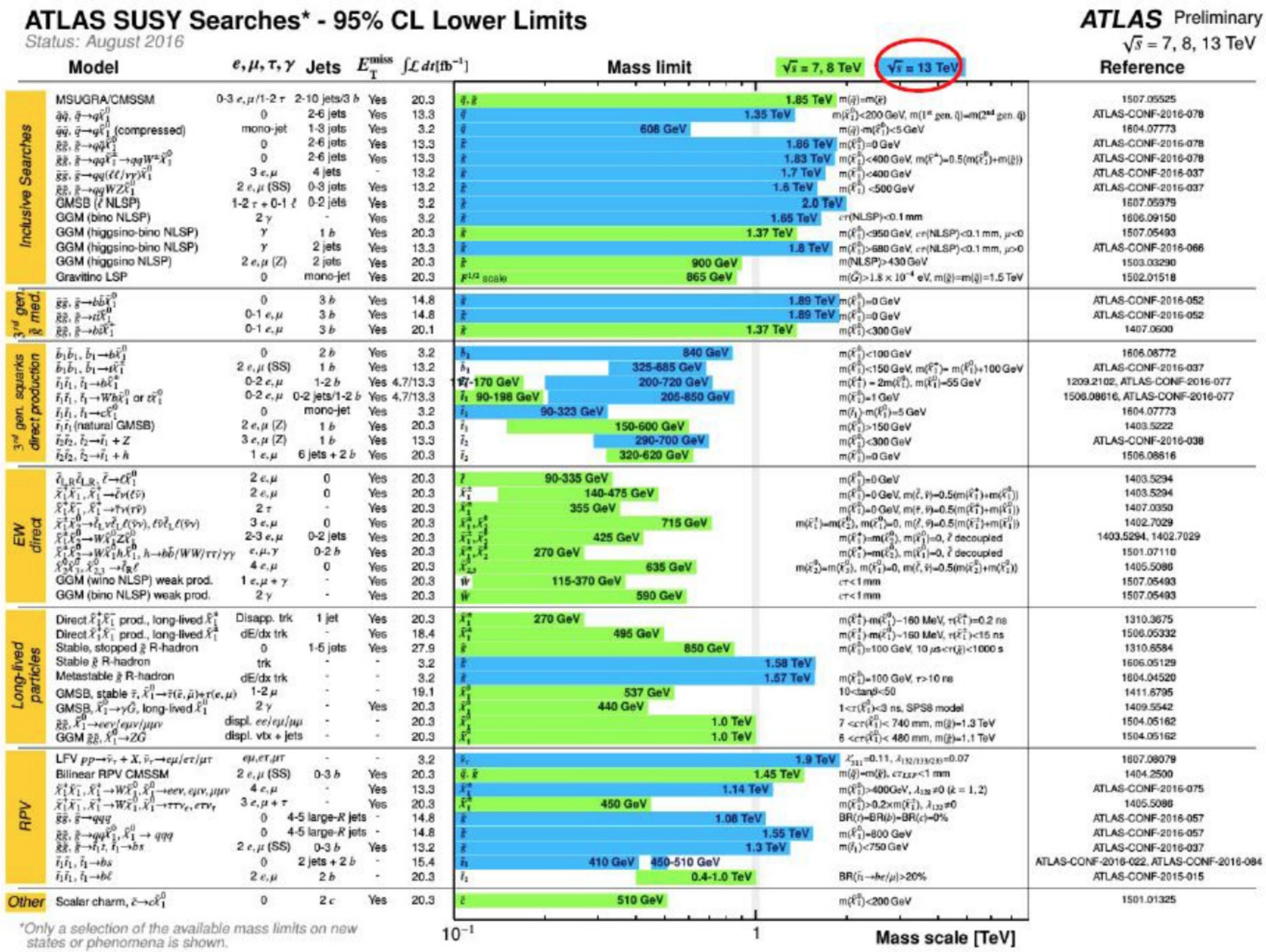
Limits obtained at LHC (ICHEP 2016) [example]







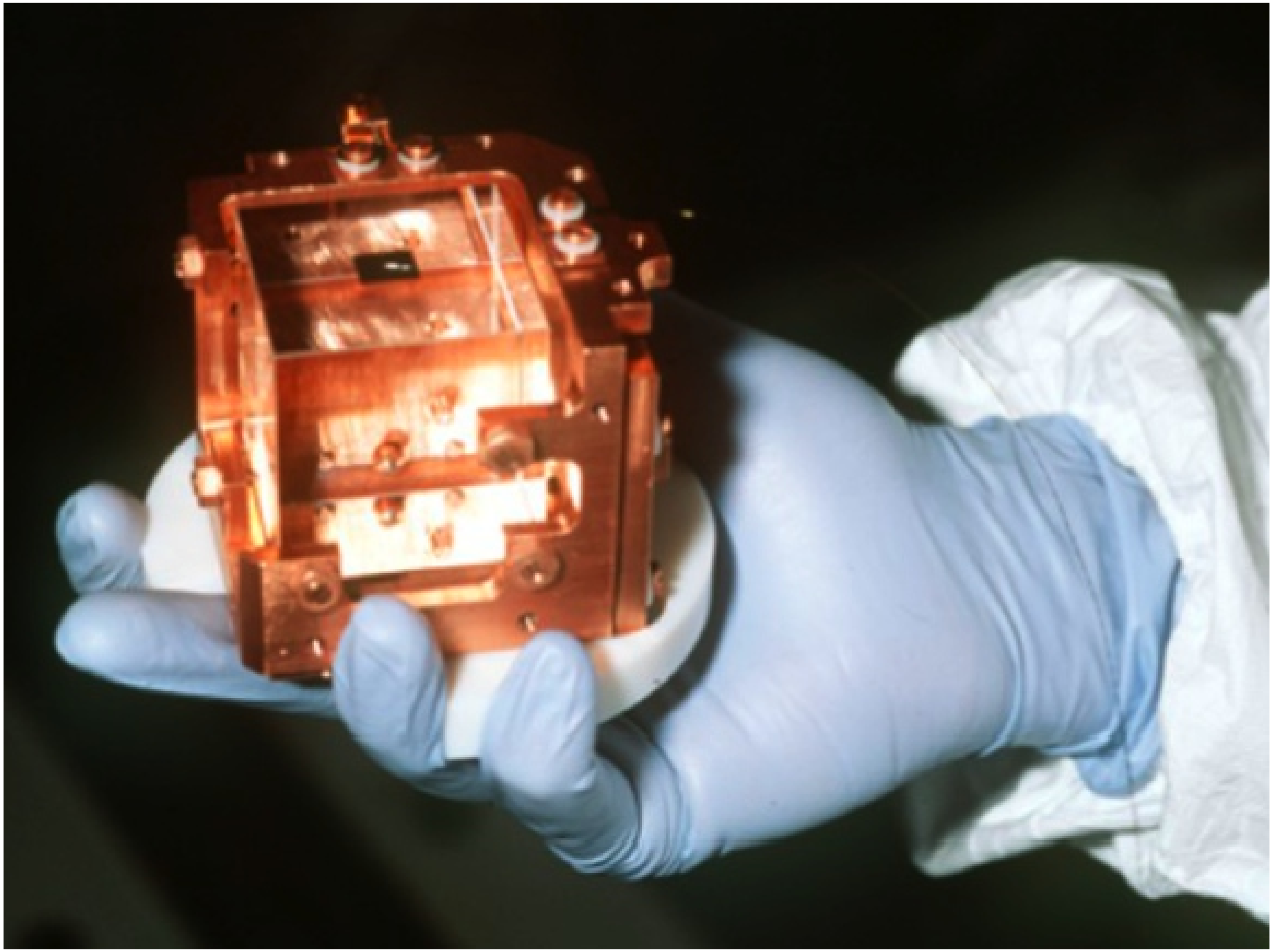
Searches for SuperSymmetry at LHC



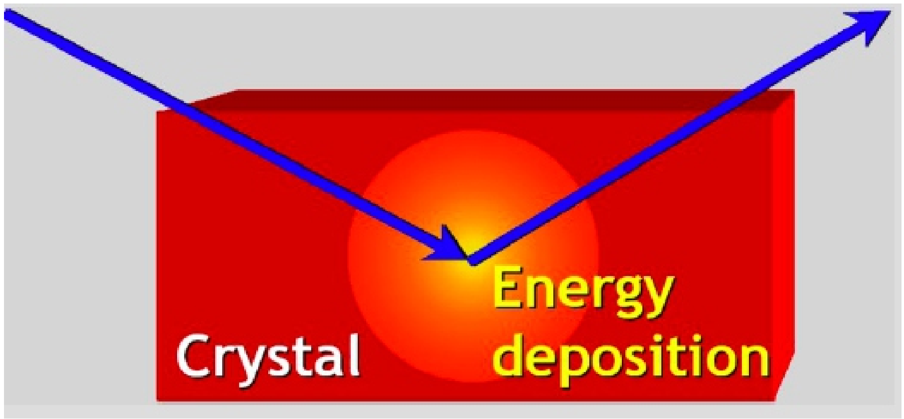
2nd Road to DARK Matter

[in the form of “WIMPs”]

Direct searches



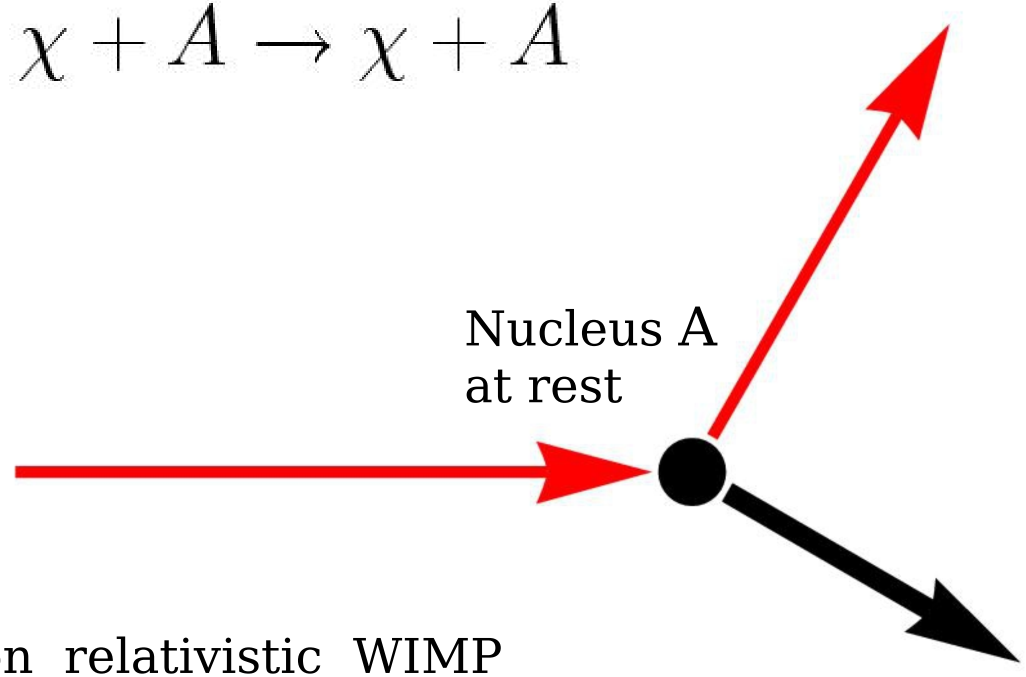
"Direct" Search for Dark Matter



Elastic scattering

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

Nucleus A
at rest



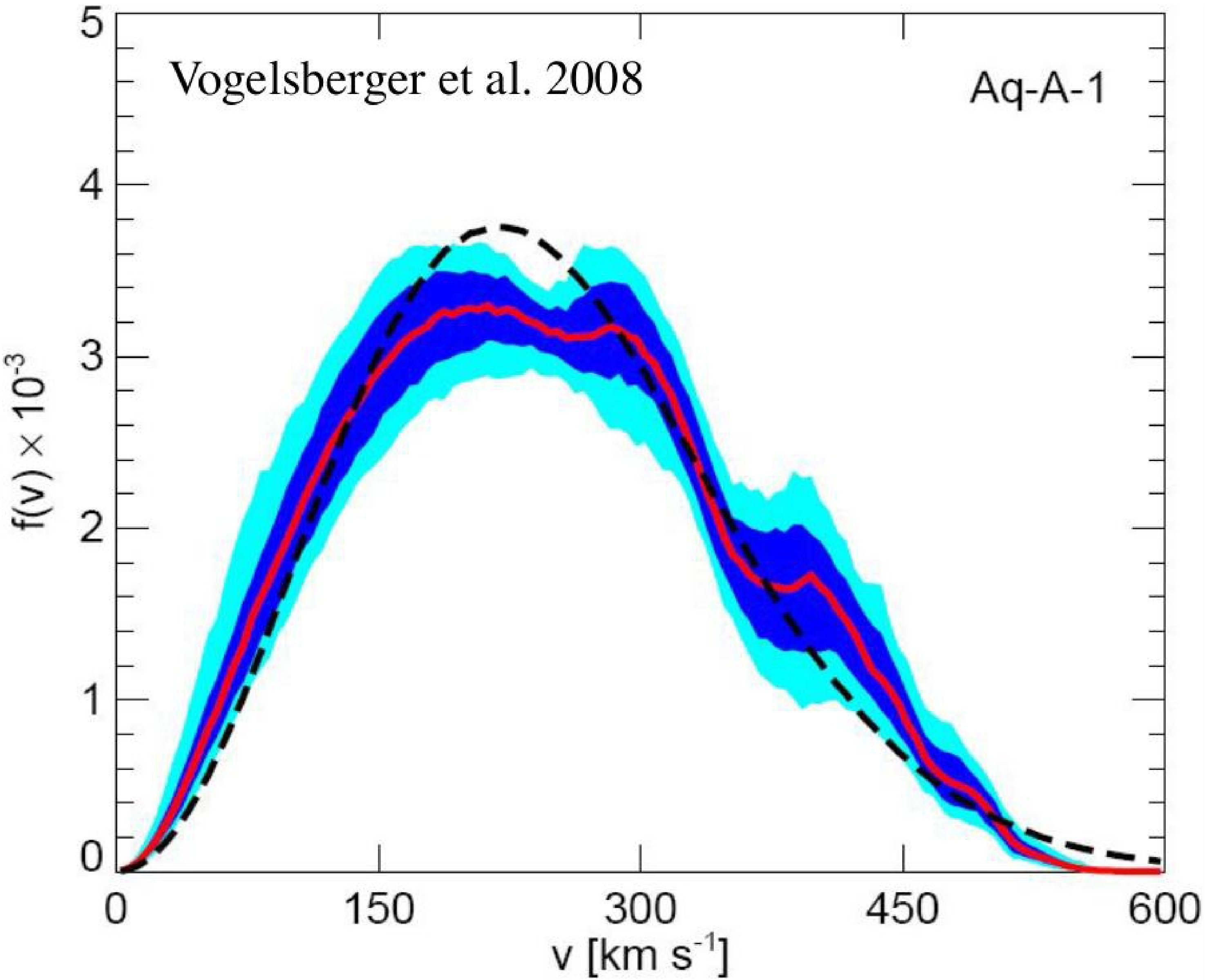
Non relativistic WIMP

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

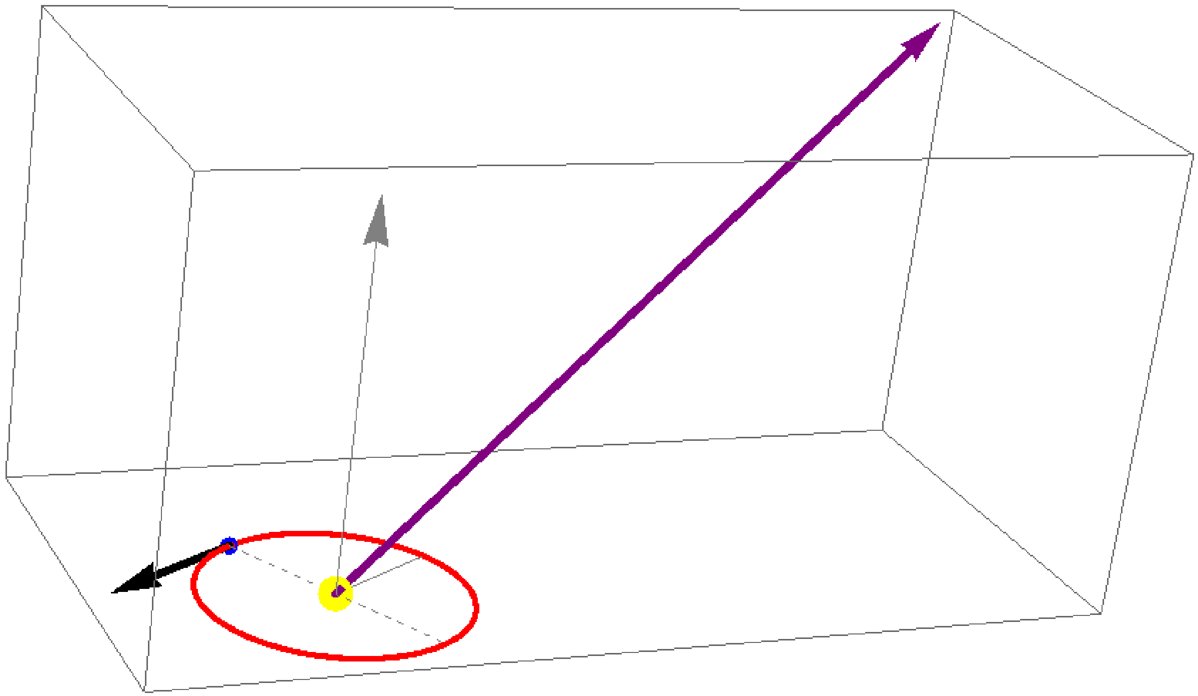
$$E_{\rm nucleus} = M_A \quad + \quad \left[\frac{1}{2} M_\chi \, v^2\right] \; \frac{4 \, M_A \, M_\chi}{(M_A + M_\chi)^2} \; \left(\frac{1 - \cos\theta^*}{2}\right)$$

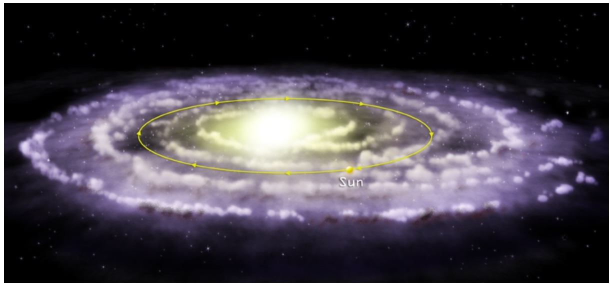
Predicted *velocity distribution* of DM particles in the "Halo Frame".

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



Numerical Simulation





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

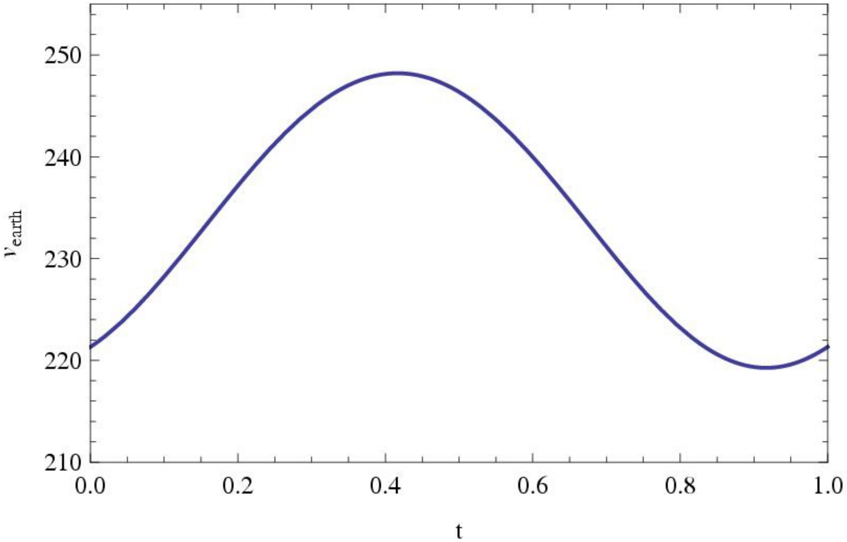
$$w_{\oplus}(t) \simeq w_{\odot} + \sin\gamma \; v_{\text{orbit}} \; \cos[\omega(t - t_0)]$$

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

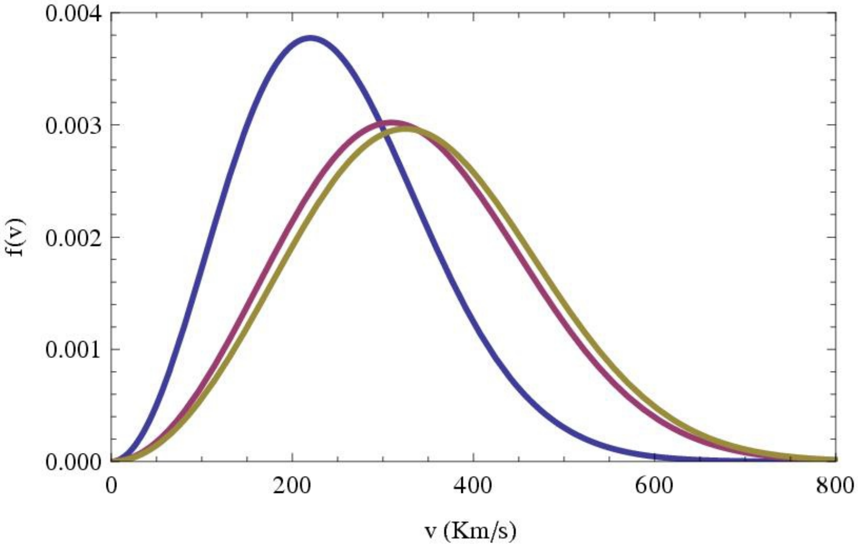
"Halo rest frame"

Velocity of Earth in the Halo rest frame

[Co-rotation ?]



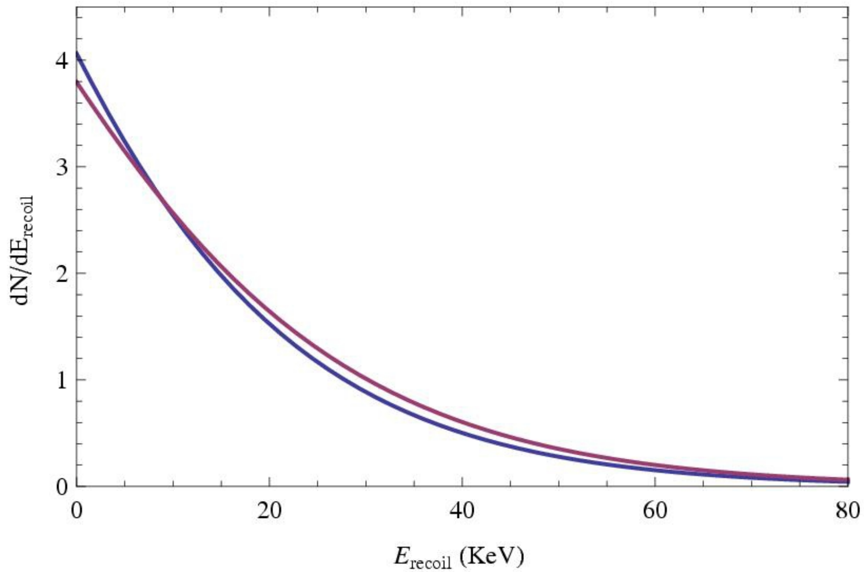
Velocity distribution of DM particles in the Earth Frame



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

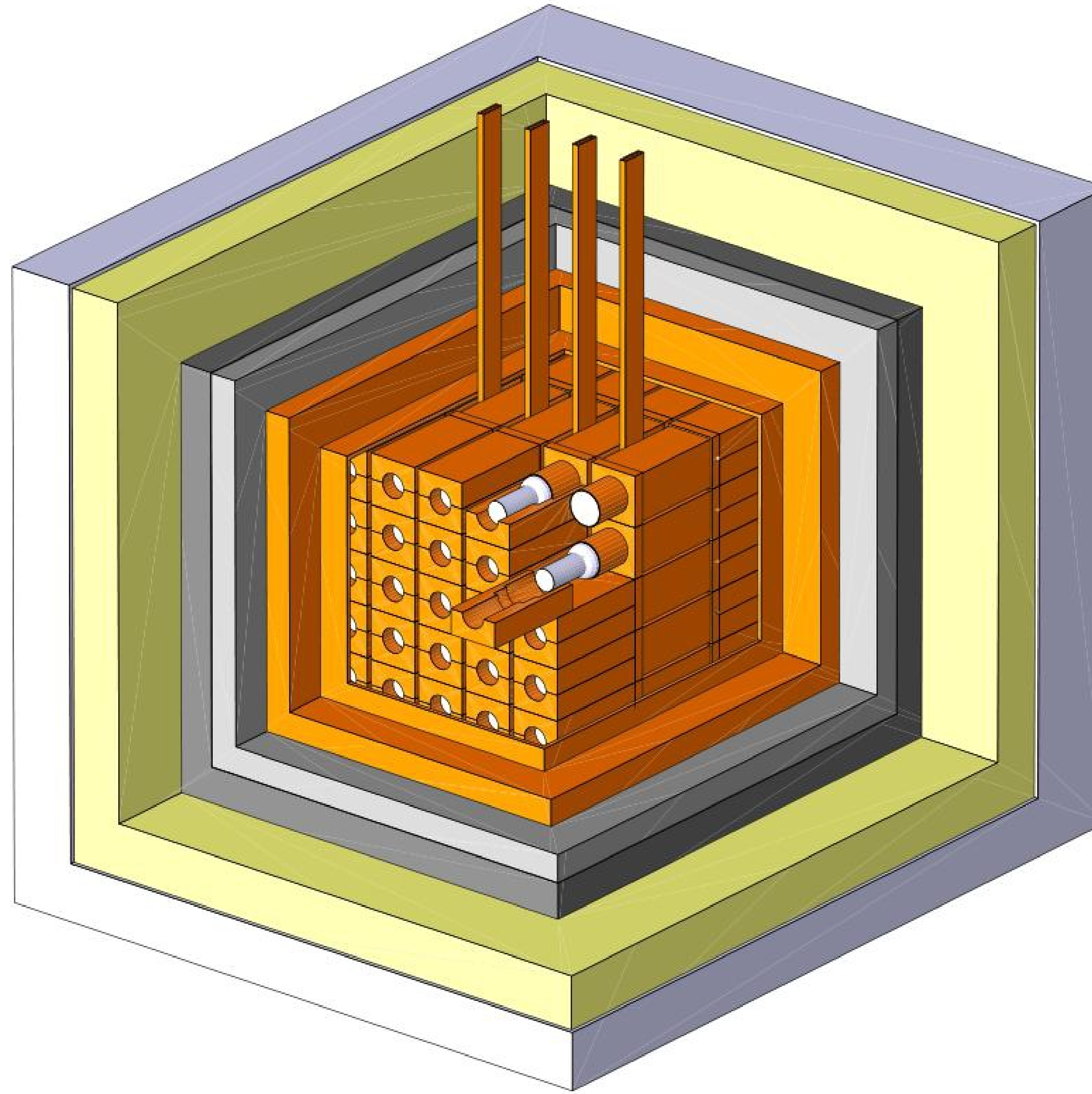
Scattering Rate:

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



DAMA-LIBRA (Gran Sasso underground Laboratory)

250 Kg NaI scintillator.

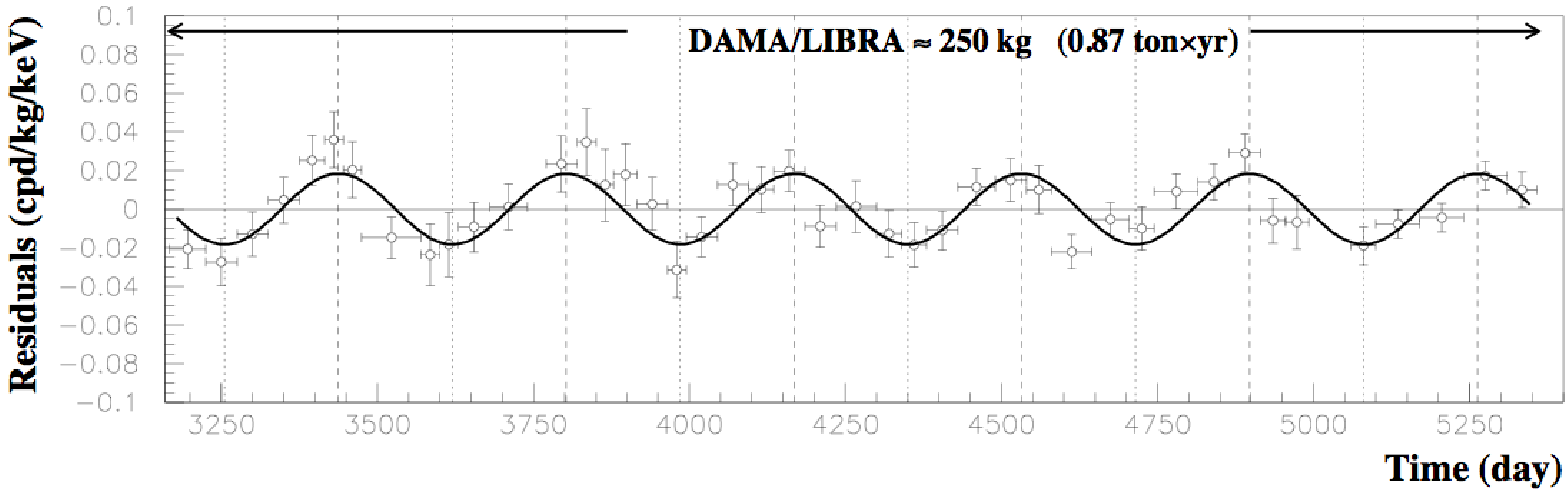


Observation
of sinusoidal
time-modulation of the
Energy Deposition Rate

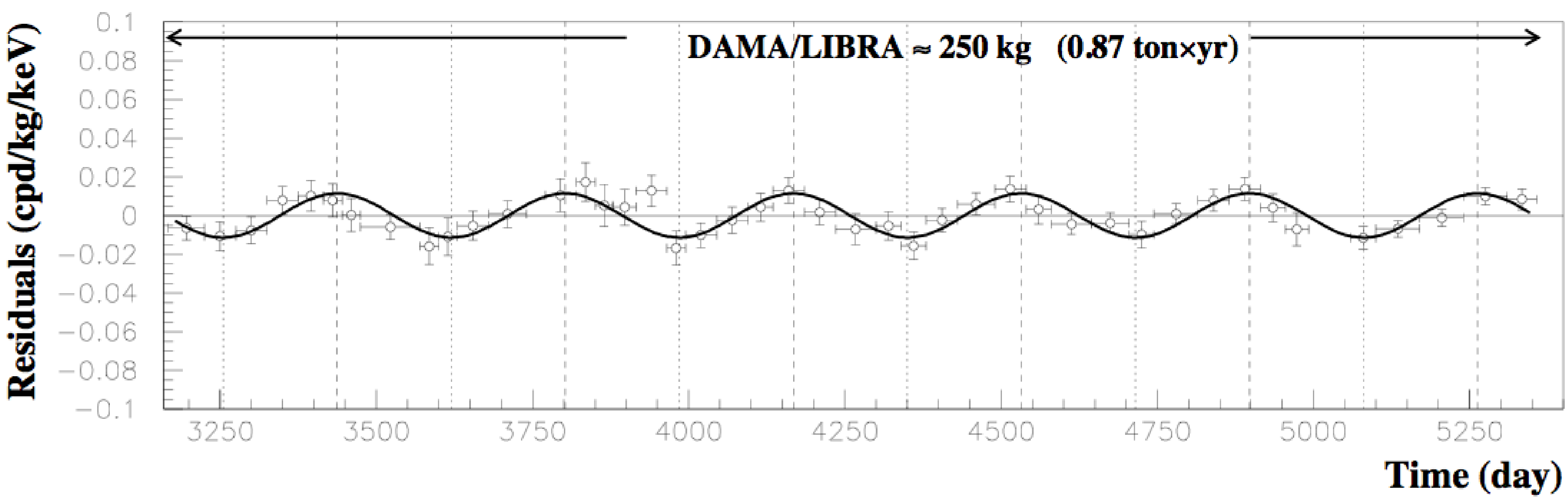
(controversial)
claim of evidence
of detection of
Galactic Dark Matter

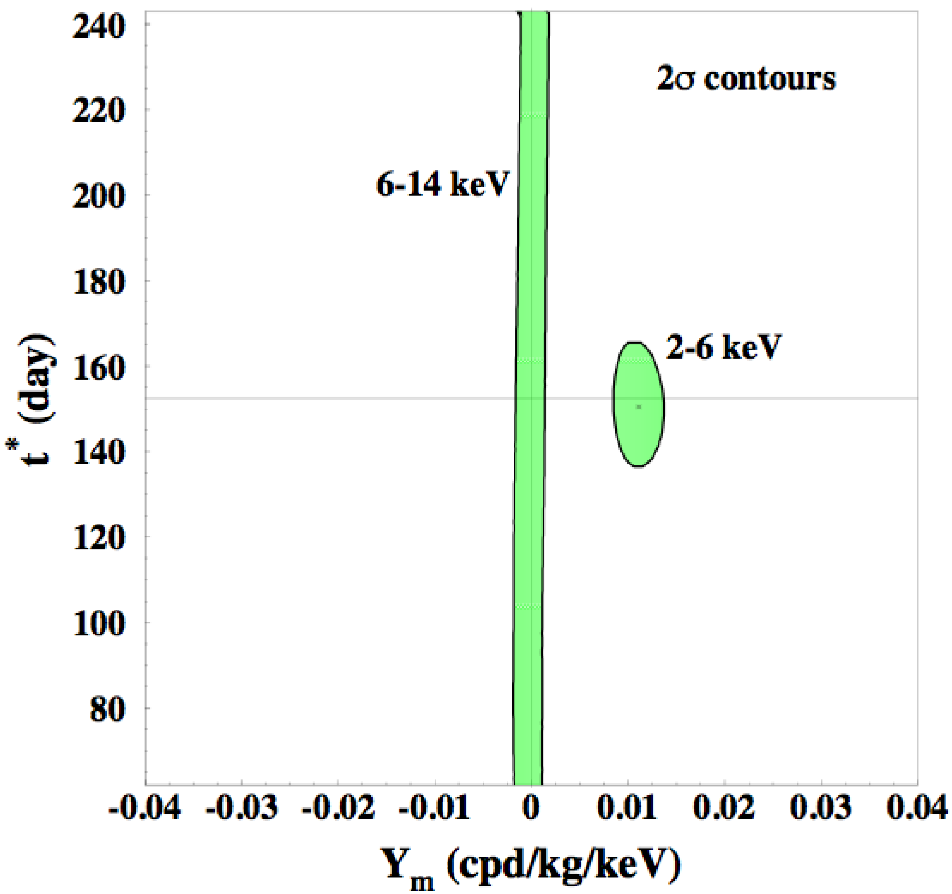
$$\boxed{1.17 \text{ ton} \times \text{yr}}$$

2-4 keV


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

2-6 keV


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



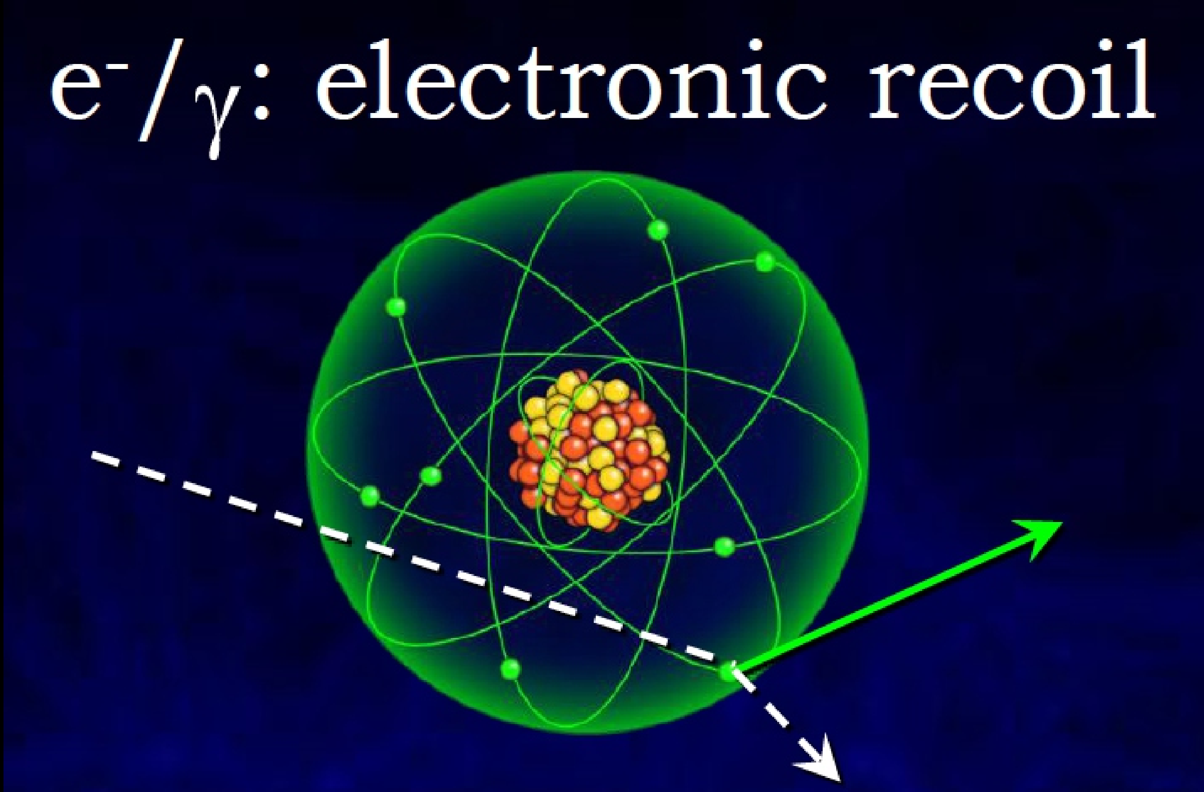
Period one year.
(… well obvious…)

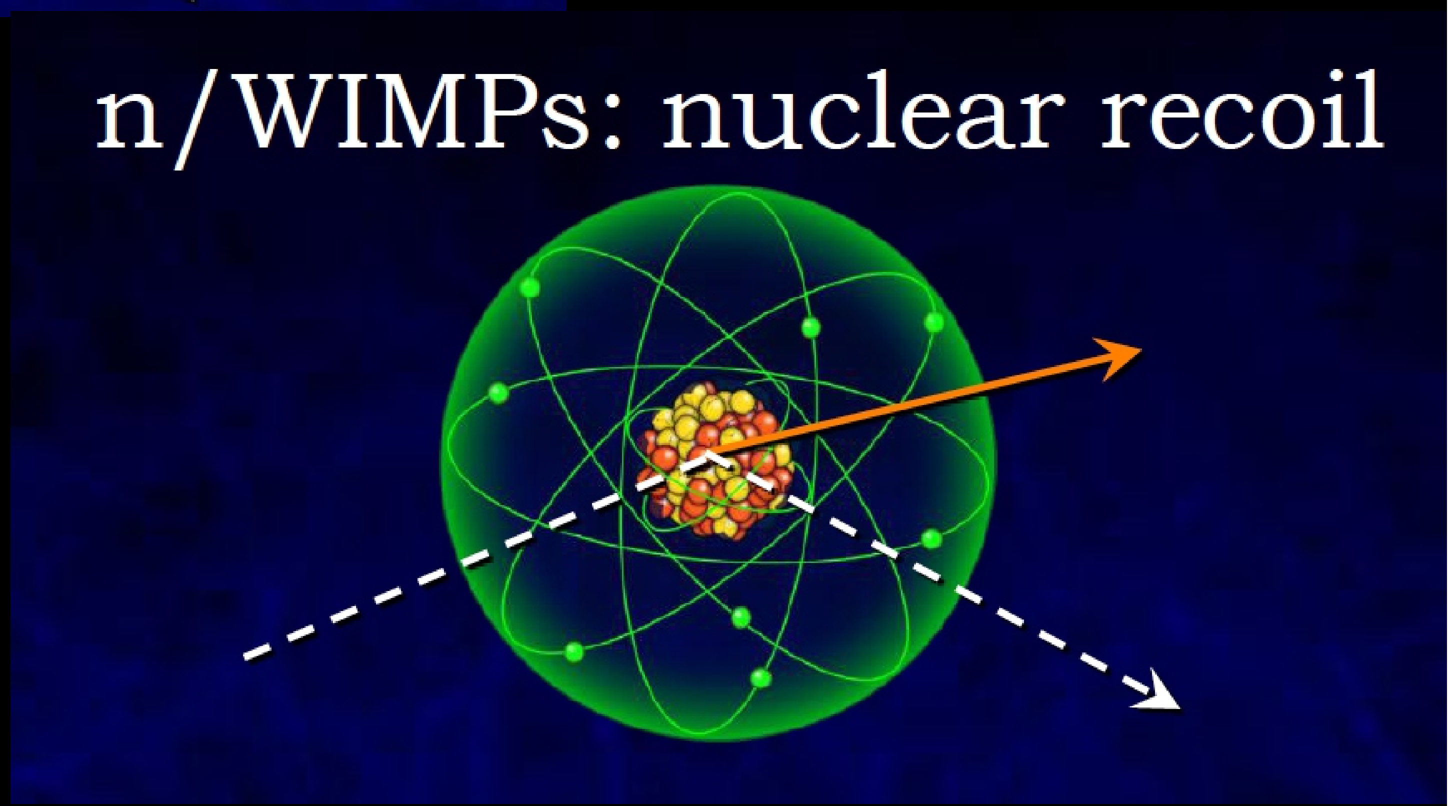
"Phase"
Is centered
At the "right" value (!)

Maximum
The 2nd june
day: (146 ± 7)

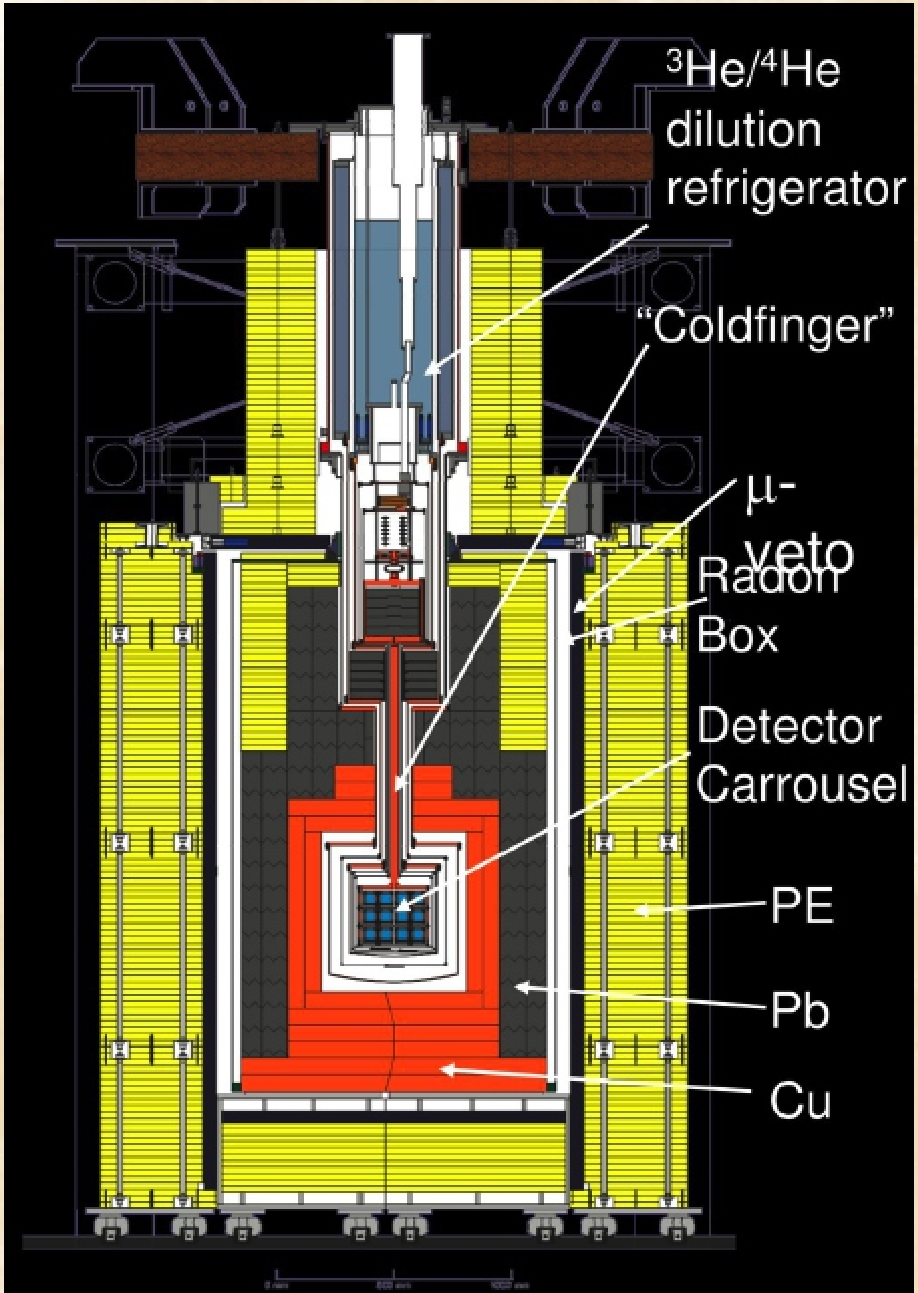
Fundamental discovery ?!

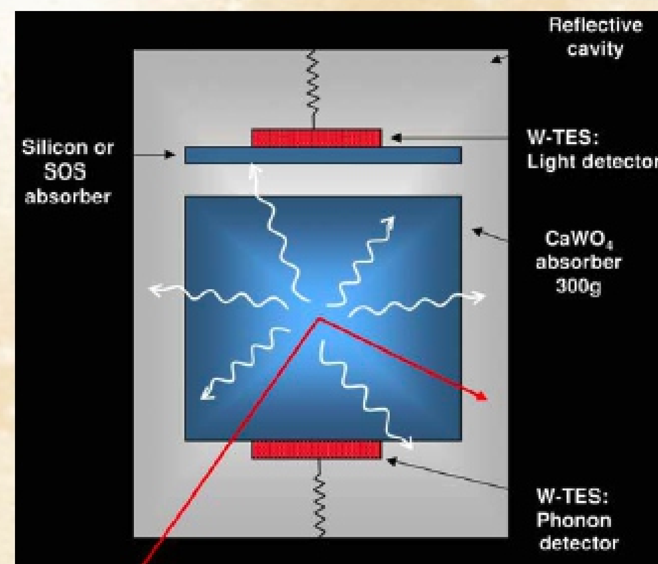
Unknown background
(with coincident phase) ?


e⁻/γ: electronic recoil

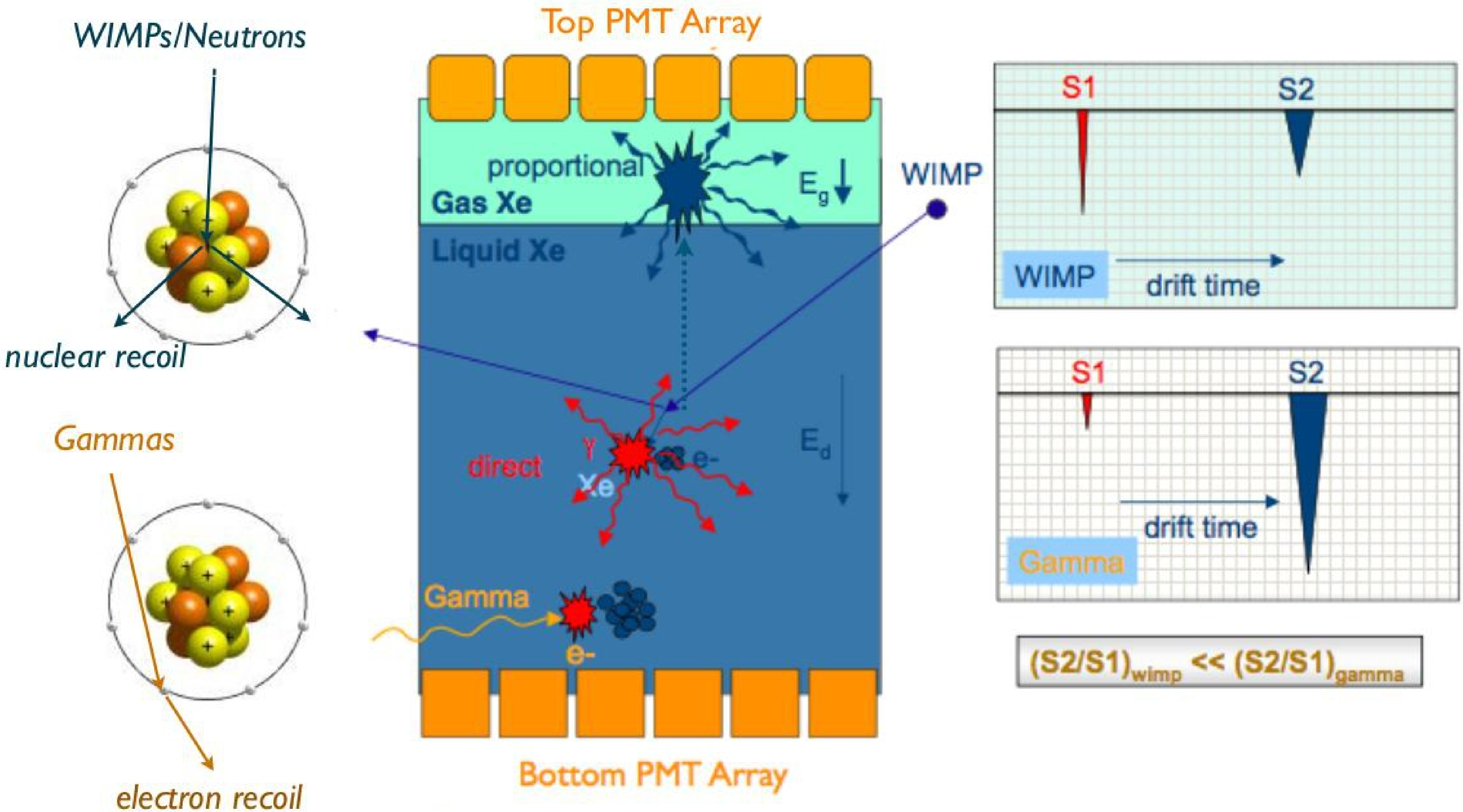

n/WIMPs: nuclear recoil

CRESST detector (Gran Sasso): Phonons + Light

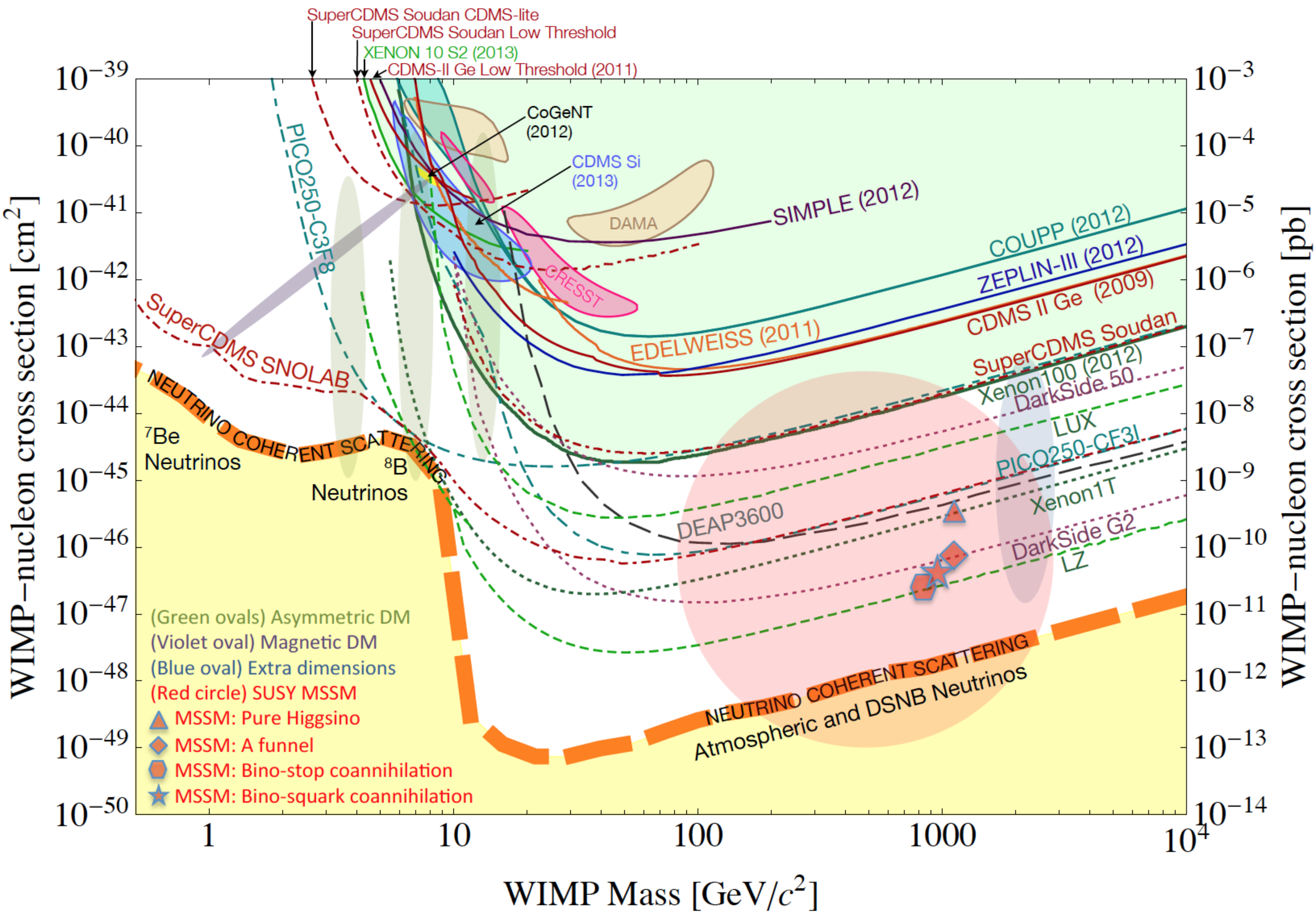




The XENON two-phase TPC



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

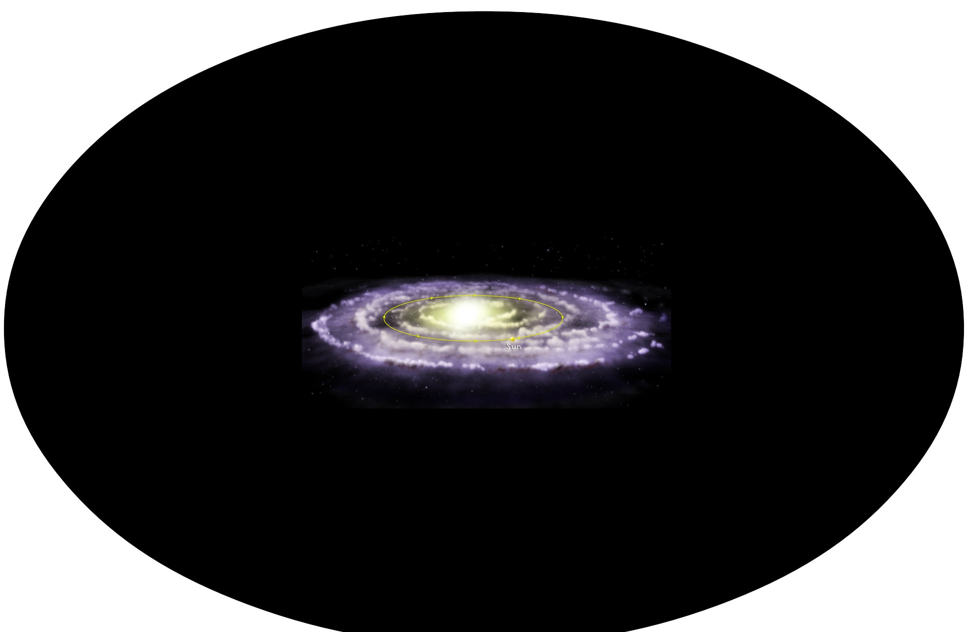


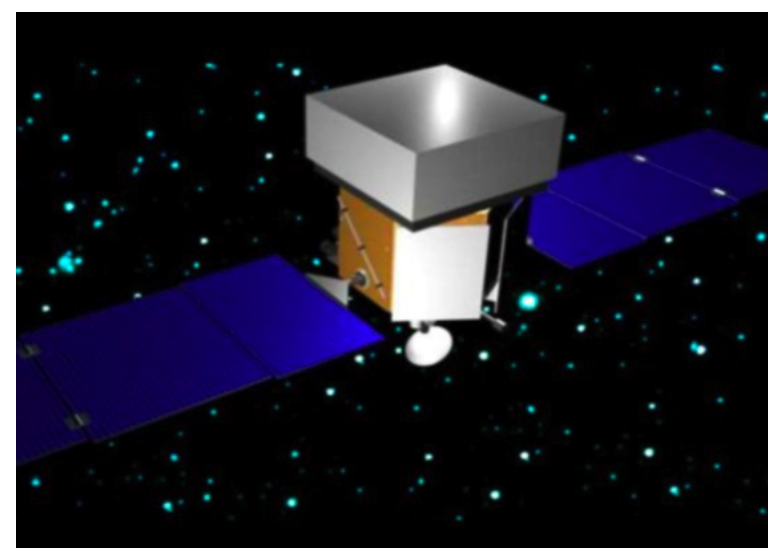
SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
CRESST
PICO250-C3F8
SuperCDMS SNOLAB
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DEAP3600
DarkSide G2
LZ
NEUTRINO COHERENT SCATTERING
7Be Neutrinos
8B Neutrinos
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c2]

3rd Road to DARK Matter

[in the form of “WIMPs”]

Indirect
searches
in Cosmic Rays





In the "WIMP paradigm" Dark Matter is NOT really dark

Point in the Milky Way halo.

$$n_\chi(\vec{x}) = \frac{\rho_\chi(\vec{x})}{m_\chi}$$

Number density
of Dark Matter particles

$$\frac{dN_{\chi\chi\to X}}{d^3x\,dt} = \frac{1}{2}\,n_\chi^2(\vec{x})\ \langle\sigma\,v\rangle$$

Number of annihilations
per unit time and unit volume

$$\frac{dL_{\rm DM}}{d^3x}(\vec{x}) = \frac{\rho^2(\vec{x})}{m_\chi}\ \langle\sigma\,v\rangle$$

Luminosity
per unit volume

What is the energy output of the Milky Way in DM annihilations?

$$\frac{dL_{\rm DM}}{d^3x}(\vec{x}) = \frac{\rho^2(\vec{x})}{m_\chi}\langle\sigma\, v\rangle$$

We know
(more or less)
from cosmology

Astrophysical observations
(rotation velocity)
+ Modeling of galaxy formation
for the central part of the Galaxy

Power injection from Dark Matter annihilation

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

Injection of energy because of DM annihilation

$$L_{\rm DM} \simeq 3 \times 10^{37} \text{ erg s}^{-1} \left[\frac{\langle \sigma \, v \rangle}{3 \times 10^{-26} \, (\text{cm}^3 \text{s})^{-1}} \right] \left[\frac{100 \text{ GeV}}{m_\chi} \right]$$

For comparison,
for Cosmic Ray protons

$$L_p \simeq 10^{41} \; \frac{\text{erg}}{\text{s}}$$

What is the final state of DM annihilations ?

… well we do not know, we have to build a model (for example supersymmetry).

But it is plausible that the Dark Matter particle will (or could) produce all particles (and anti-particles) that we know.

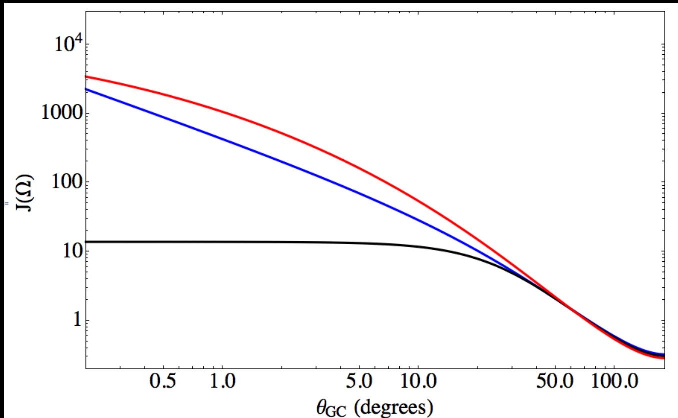
Most promising for detection:

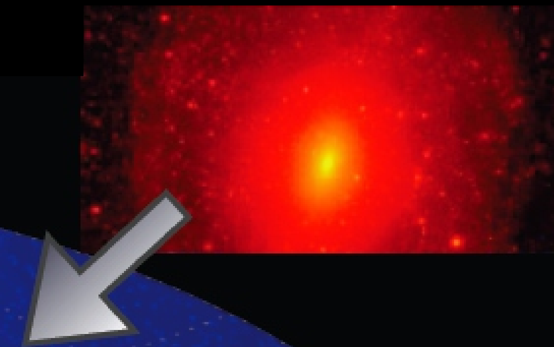
$$\chi + \chi \rightarrow \boxed{\gamma} \quad \boxed{e^+ \qquad \bar{p}} \quad \boxed{\nu_\alpha}$$

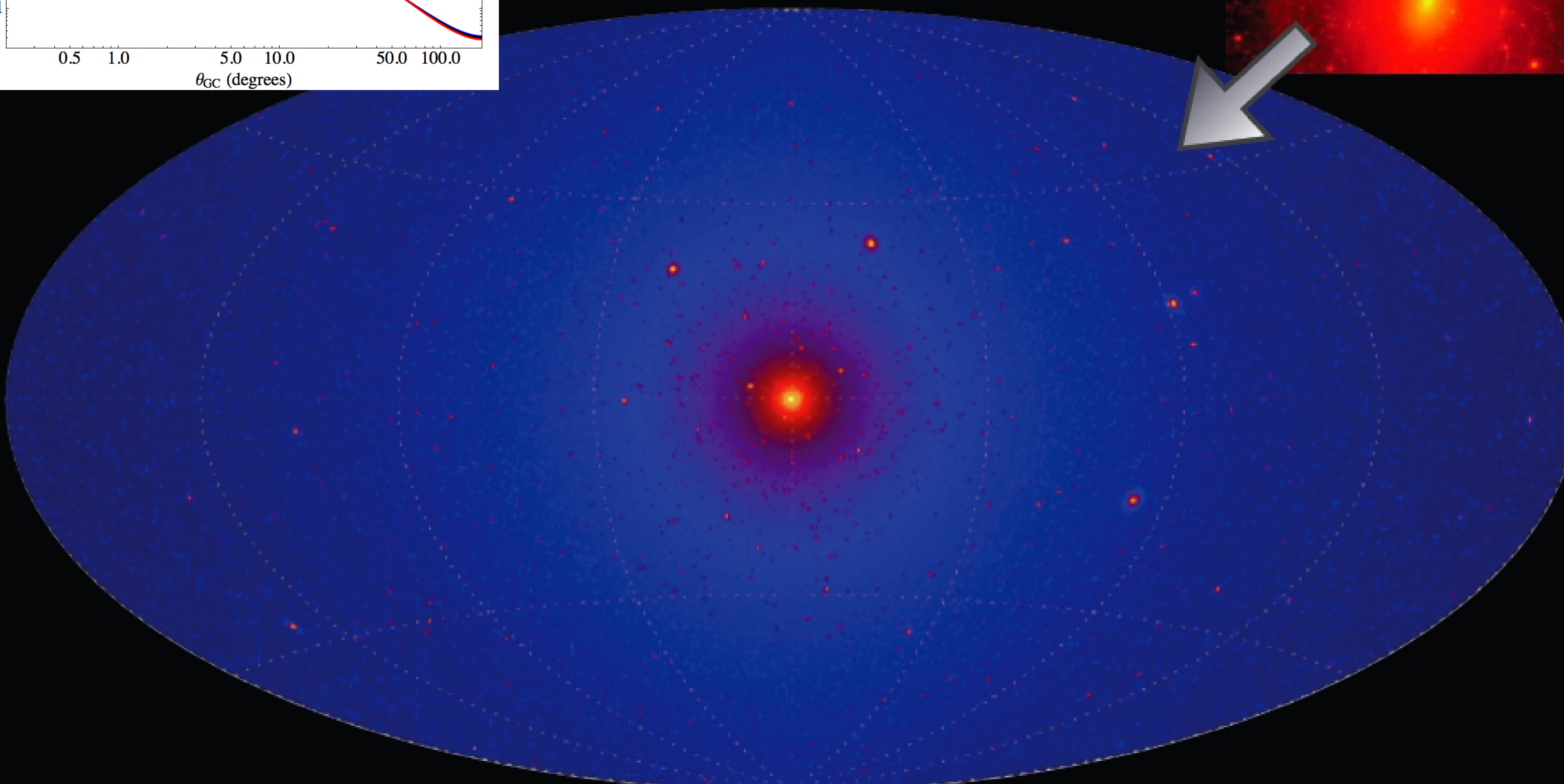
photons

Charged (anti)particles

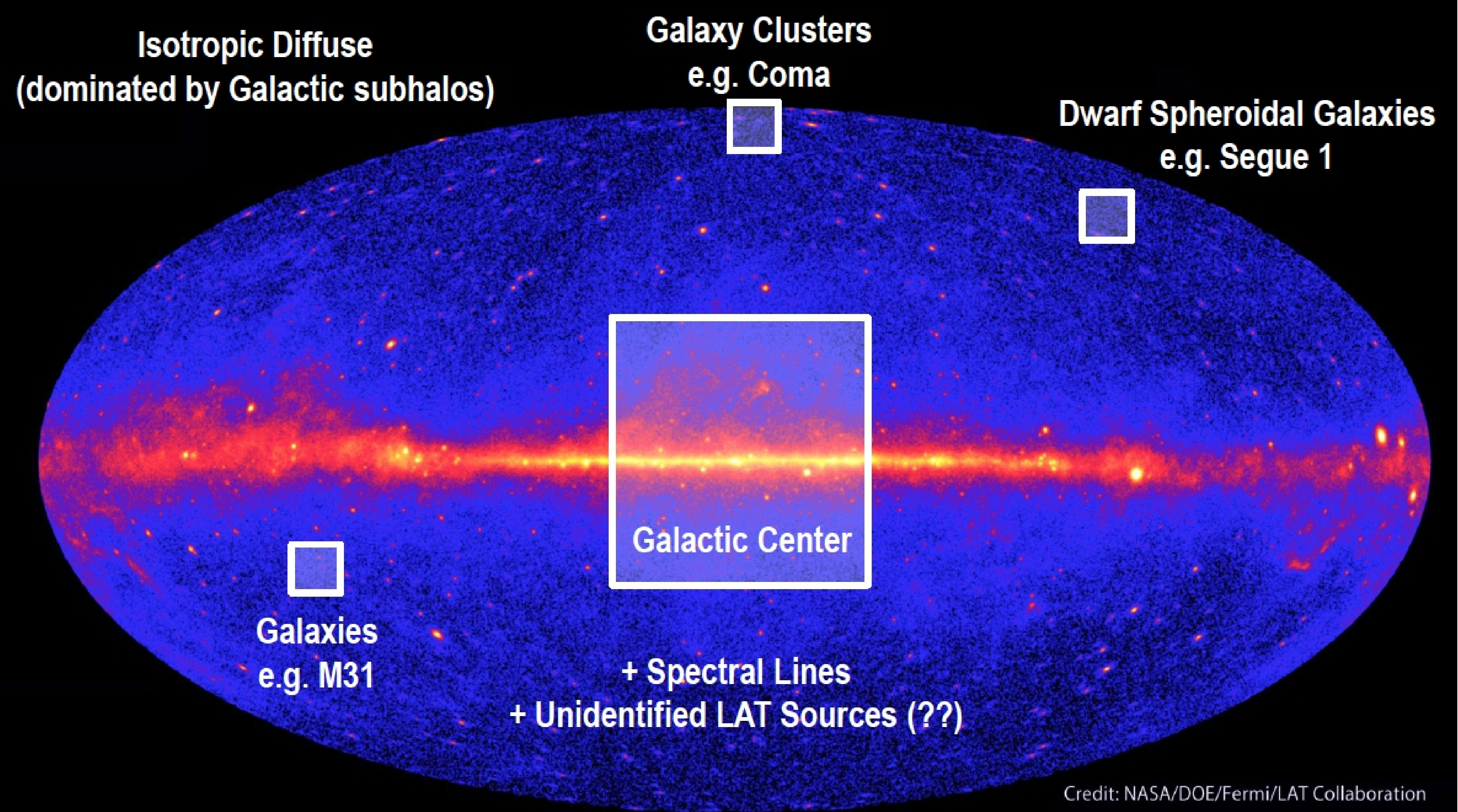
Neutrinos



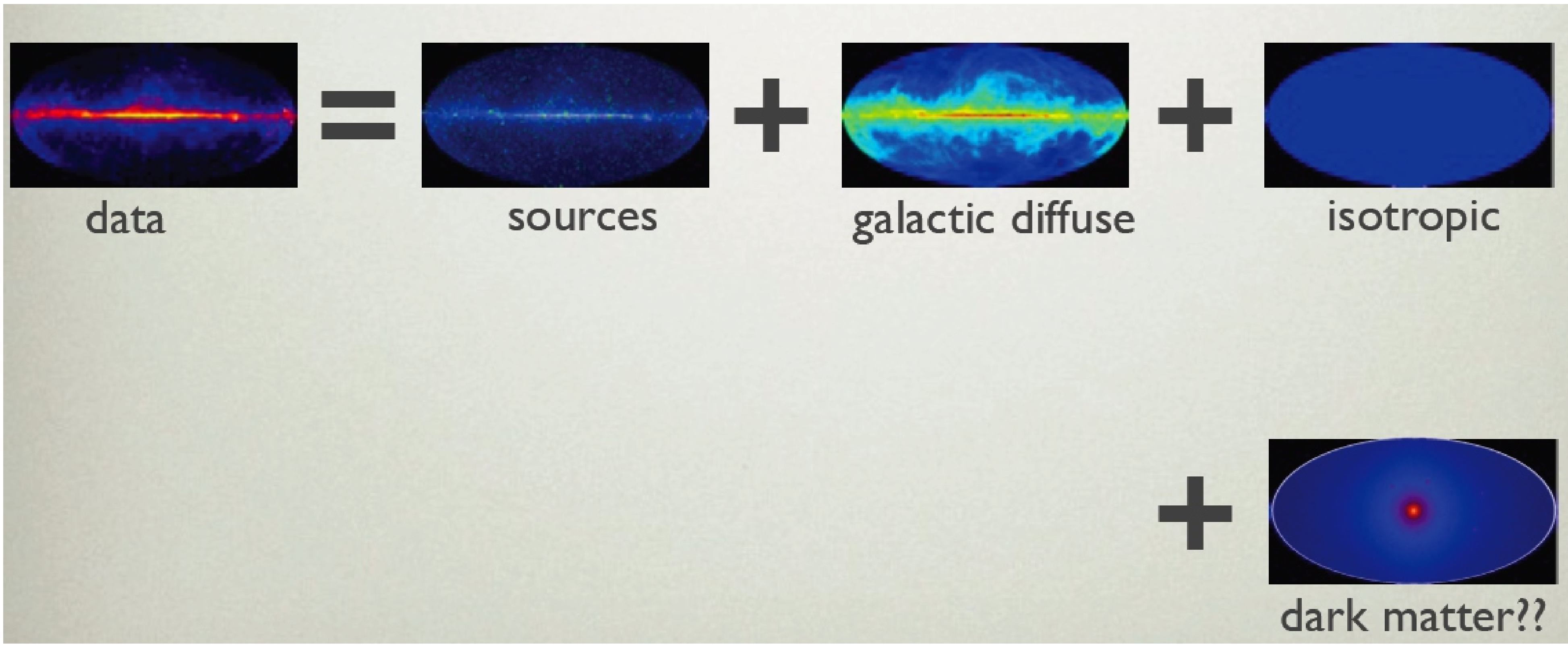




arXiv:0908.0195



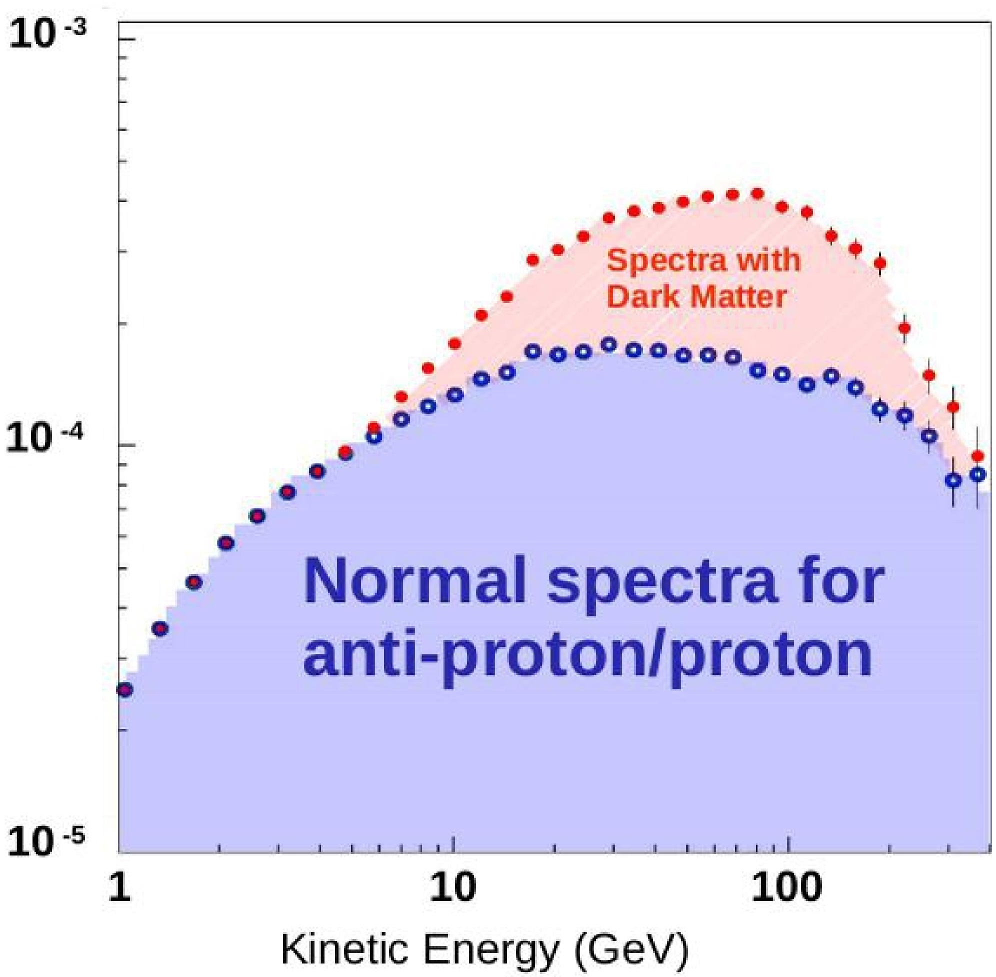
Trade-off between signal strength versus astrophysical background

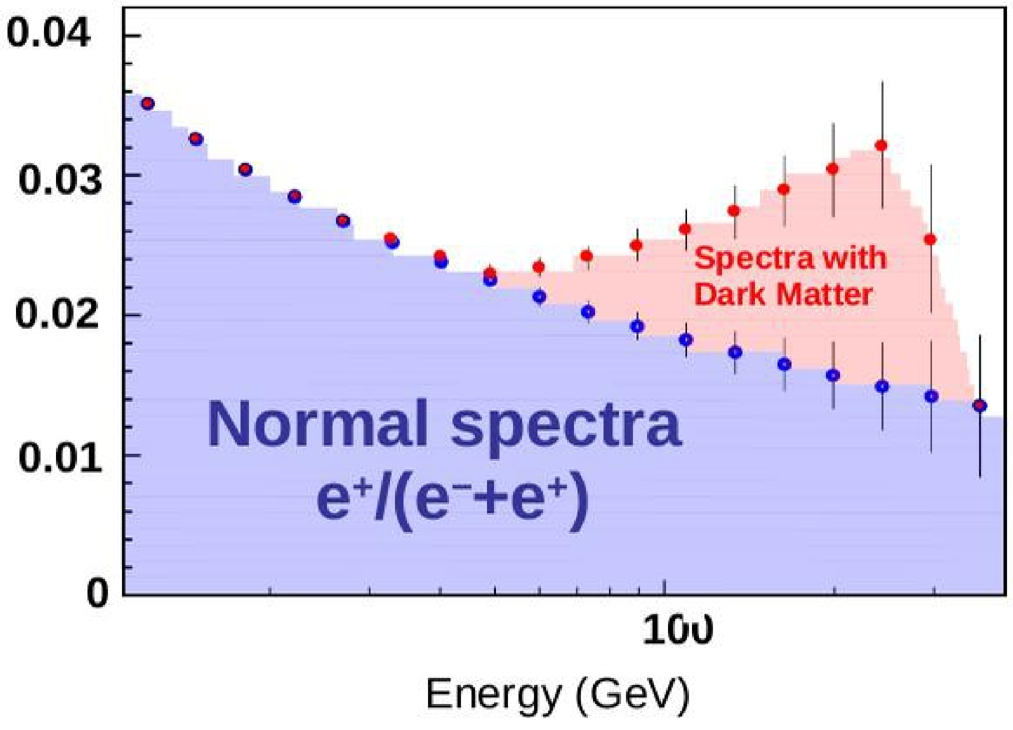

data
sources
galactic diffuse
isotropic
dark matter??

Charged particles:
positrons and
anti-protons

Trapped by the
Galactic magnetic field

Extra contribution to
the cosmic ray fluxes





3. Antimatter (e^+ and $\overline{p}$) in Cosmic Rays.

- Secondary production of e^+ and $\overline{p}$
- Formation of the CR spectra
- Production of anti-deuterium.
- (Nuclear Fragmentation Cross sections)
- (γ ray production in CR sources)

Formation of the
Cosmic Ray Spectra

$$\phi = \frac{4\,\pi}{\beta\,c}\,n$$

Cosmic Ray Density
at the Sun position

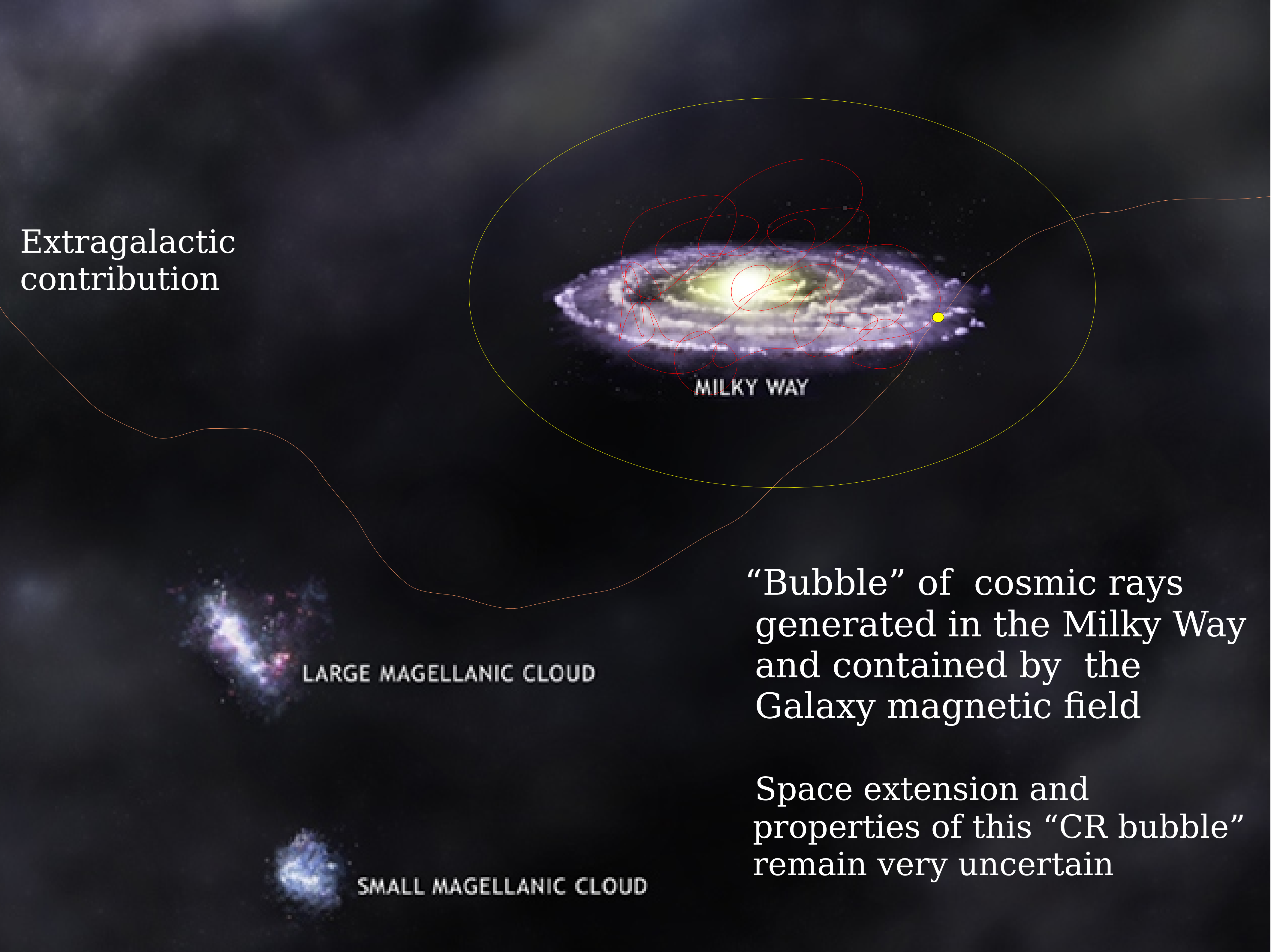
=

"Release"
in Interstellar
Medium

[Injection]

$\otimes$

Propagation
from source to Sun



Extragalactic contribution
MILKY WAY
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD
"Bubble" of cosmic rays generated in the Milky Way and contained by the Galaxy magnetic field
Space extension and properties of this "CR bubble" remain very uncertain

Formation of the (proton) Cosmic Ray Spectrum

$$n_p(E, \vec{x}_\odot, t_{\rm now}) =$$

Instellar Injection (or “release”) function

$$\int_{-\infty}^{t_{\rm now}} dt \int d^3x \int dE_i \quad \boxed{q_p(E_i, \vec{x}, t)} \times$$

$$\boxed{P_p(E, \vec{x}_\odot, t_{\rm now};\ E_i, \vec{x}, t)}$$

Propagation effects

[*General*, explicit (but “formal”) expression]

Galactic Cosmic Rays

$$\boxed{N_j(E) = Q_j(E) \times T_j(E)}$$

Different particles

$p, \quad \mathrm{nuclei}(Z, A)$

$\overline{p}, \quad e^-, \quad e^+$

Injection of cosmic rays

Containment time

$$N_j(E) = \int d^3x \; n_j(E, \vec{x})$$

$$\phi_j(E) = \frac{c}{4\,\pi} \, n_j(E)$$

Primary particles:
(protons, electrons, Helium nuclei, ...)

Accelerated in Astrophysical Sources

"Release" = Injection in the acceleration process $\otimes$ Acceleration $\otimes$ Source Ejection (escape from accelerator)

Secondary particles:

positrons, antiprotons

[in the "conventional picture" :

no DM, no antimatter accelerators)]

Rare Nuclei (Li, Be, B, ...)

"born relativistic"

"Release" = $\boxed{\text{Creation in the interaction of a higher energy particle}}$

"Conventional mechanism"
for the production of positrons and antiprotons:

Creation of secondaries in the inelastic hadronic interactions of cosmic rays in the interstellar medium

$$pp \to \overline{p} + \ldots$$

Injections of positrons and anti-protons are intimately connected

$$pp \to \pi^+ + \ldots$$

$$\hookrightarrow \mu^+ + \nu_\mu$$

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

Dominant source of positrons:

$$\pi^+ \to \mu^+ + \nu_\mu \to [e^+ \; \nu_e \; \overline{\nu}_\mu] + \nu_\mu$$

Additional sources [kaon decay]

$$K^+ \to e^+ + \nu_e + \pi^\circ$$

$$K^+ \to \mu^+ + \nu_\mu \to [e^+ \; \nu_e \; \overline{\nu}_\mu] + \nu_\mu$$

$$K^+ \to \mu^+ + \nu_\mu + \pi^\circ \to [e^+ \; \nu_e \; \overline{\nu}_\mu] + \nu_\mu + \pi^\circ$$

$$K^+ \to \pi^+ + \pi^\circ \to \nu_\mu \to e^+$$

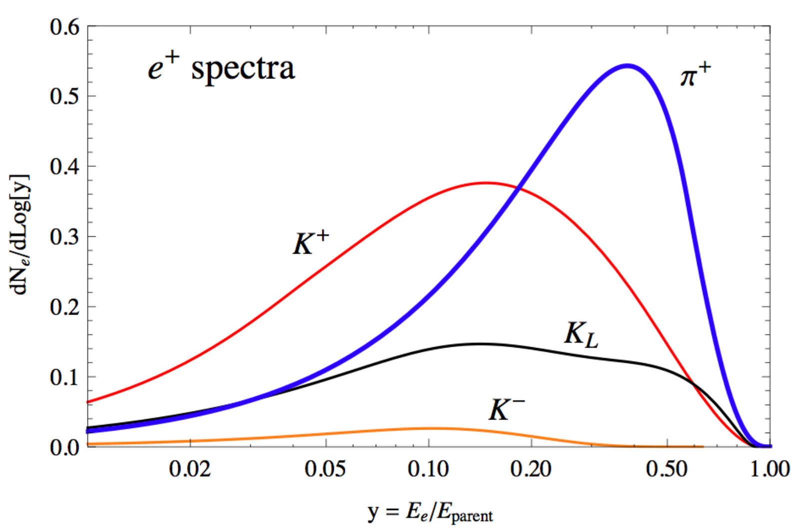
$$K^+ \to \pi^+ + \pi^\circ + \pi^\circ \to e^+ + \ldots$$

$$K^+ \to \pi^+ + \pi^+ + \pi^- \to e^+ + \ldots$$

$$K_L \to \pi^- + e^+ + \nu_e$$

$$K_L \to \pi^- + \mu^+ + \nu_\mu \to \pi^- + [e^+ \; \nu_e \; \overline{\nu}_\mu] + \nu_\mu$$

$$K_L \to \pi^+ + \pi^\circ + \pi^\circ \to e^+ + \ldots$$



Calculation of the "Local injection" of secondaries by the *"conventional mechanism"*

$$q_{\overline{p}}^{\rm loc}(E) = \phi_p(E) \otimes n_{\rm ism}(\vec{x}_\odot) \otimes \sigma_{\rm hadronic}[pp \to \overline{p} + \ldots]$$

$$q_{e^+}^{\rm loc}(E) = \phi_p(E) \otimes n_{\rm ism}(\vec{x}_\odot) \otimes \sigma_{\rm hadronic}[pp \to e^+ + \ldots]$$

Step 1: Measure the spectra of CR near the Earth.

Step 2: Correct for Solar Modulation effects
to obtain the spectra in interstellar space

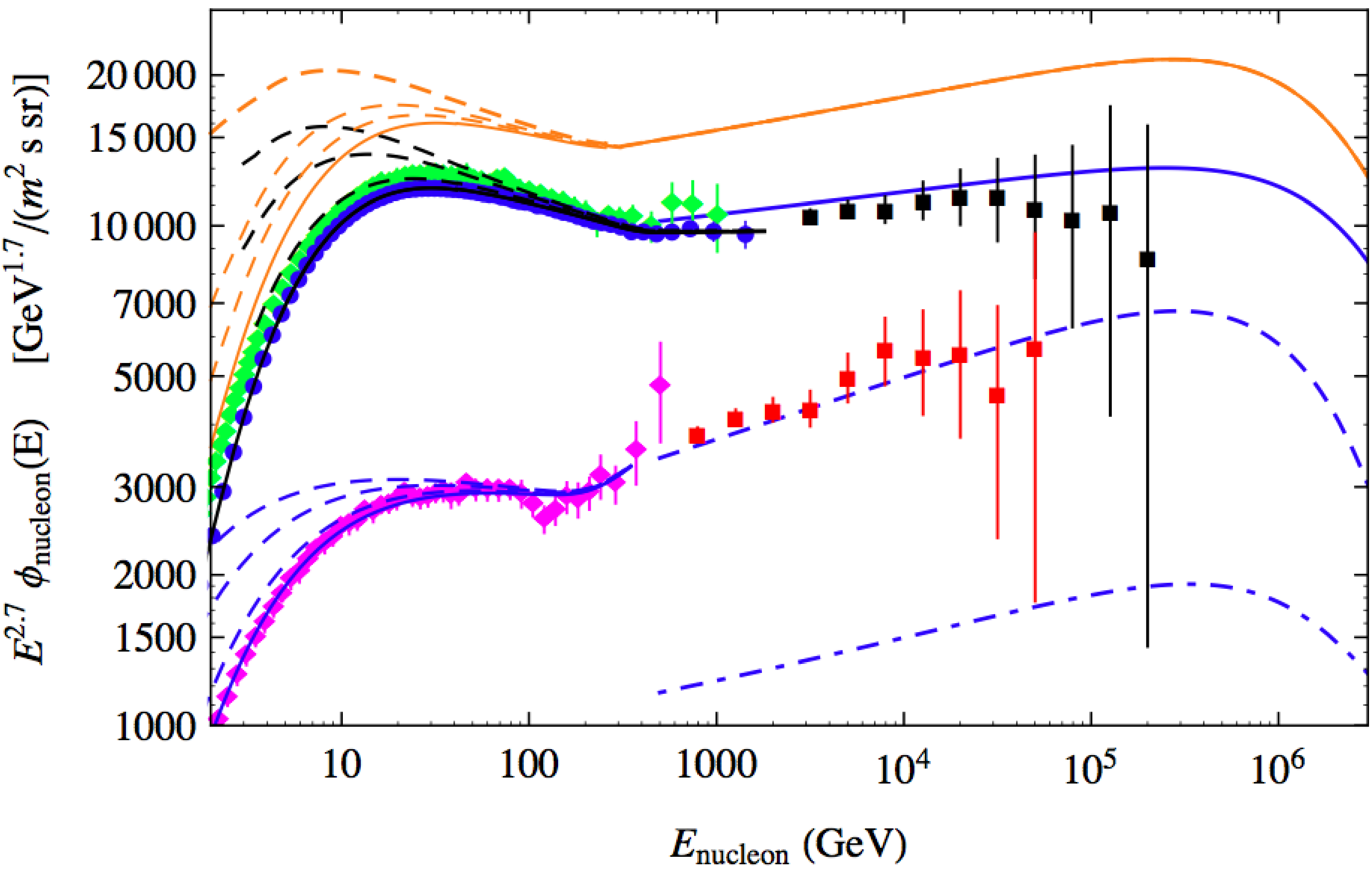
Step 4: Model the interaction to compute
injection spectra of positrons + anti-protons.

$$q_j^{\rm loc}(E) = n_{\rm ism}(\vec{x}_\odot)\, f_p \int dE_0\; n_p^{\rm loc}(E_0)\,(\beta\, c)\, \sigma_{pp}(E_0)\, \frac{dN_{pp\to j}}{dE}(E, E_0)$$

$$+ (p + {\rm He}) + ({\rm He} + p) + ({\rm He} + {\rm He}) + \ldots$$

Nucleon Fluxes

Pamela, AMS02, CREAM
HEA0 (for nuclei)



p

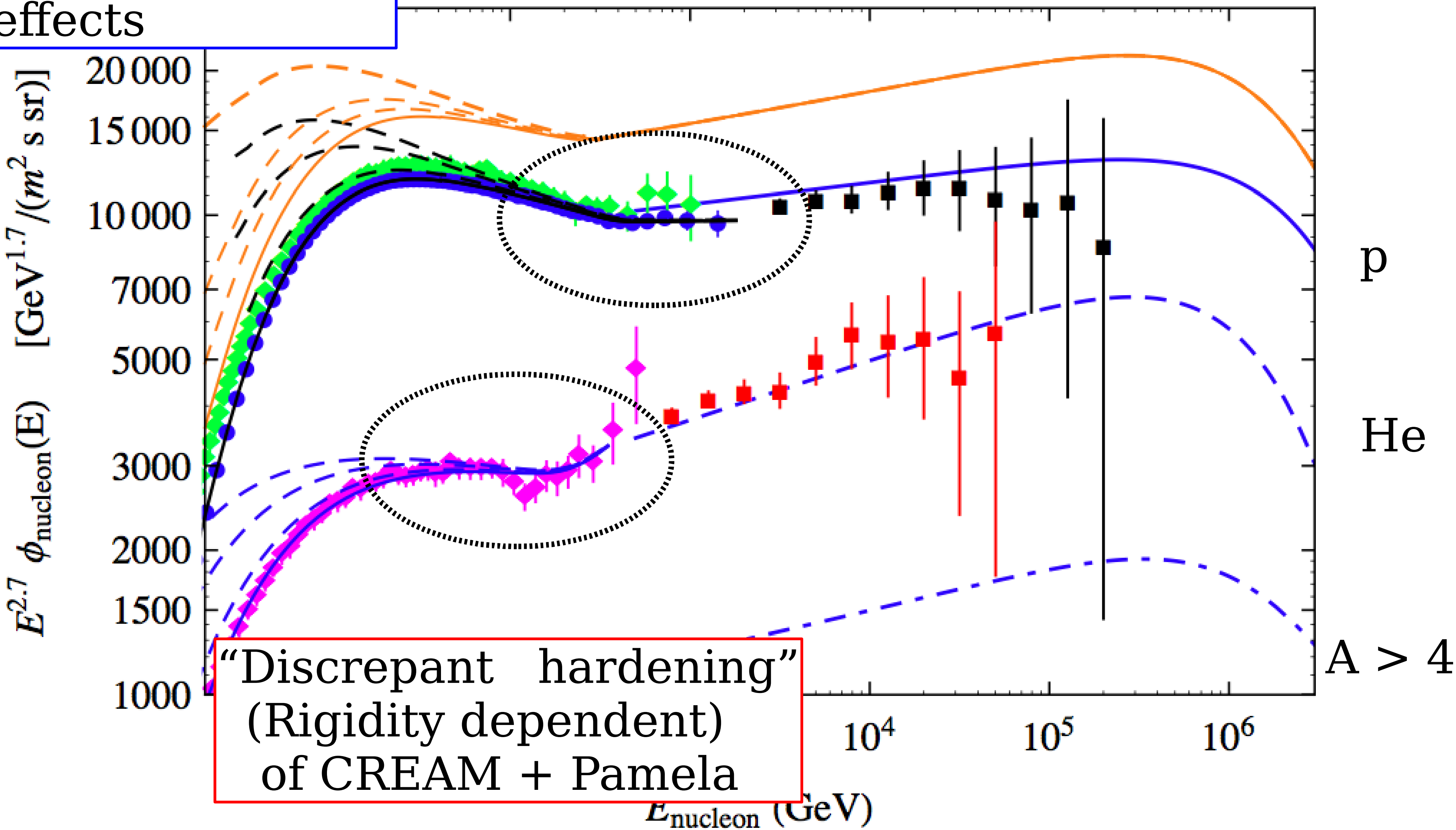
He

A > 4

Nucleon Fluxes

Pamela, AMS02, CREAM
HEA0 (for nuclei)

“unfold”
Solar Modulation
effects



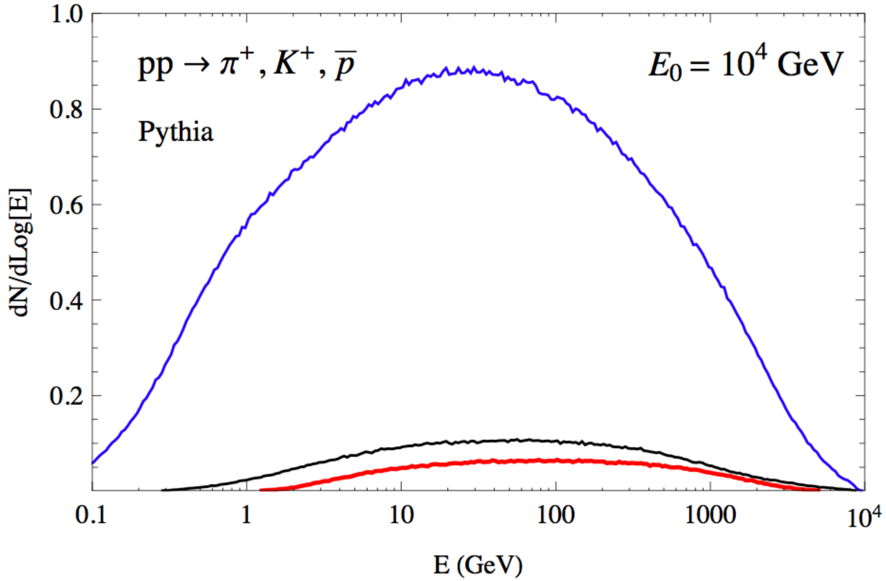
“Discrepant hardening”
(Rigidity dependent)
of CREAM + Pamela

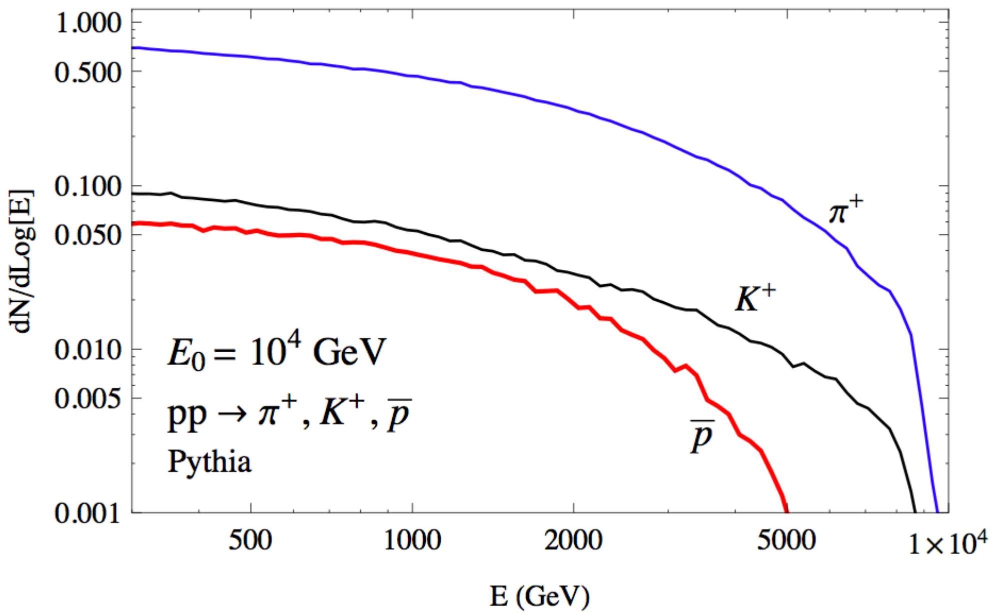
Particle production in hadronic collisions

$$pp \to \pi^+, \quad K^+, \quad \overline{p}, \quad \ldots$$

$$E_0 = 10^4 \text{ GeV}$$

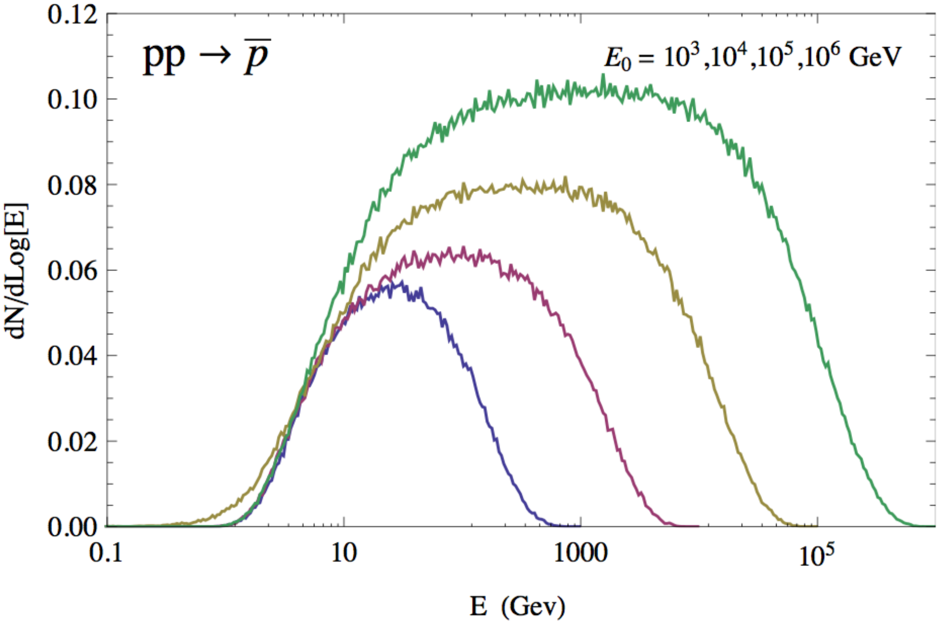
Example of a Montecarlo calculation with Pythia

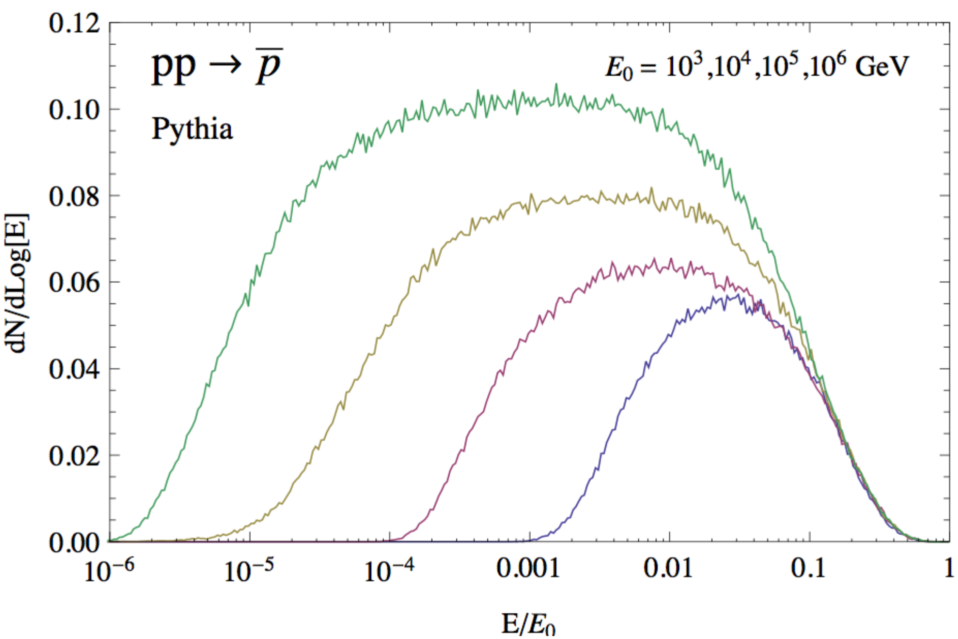


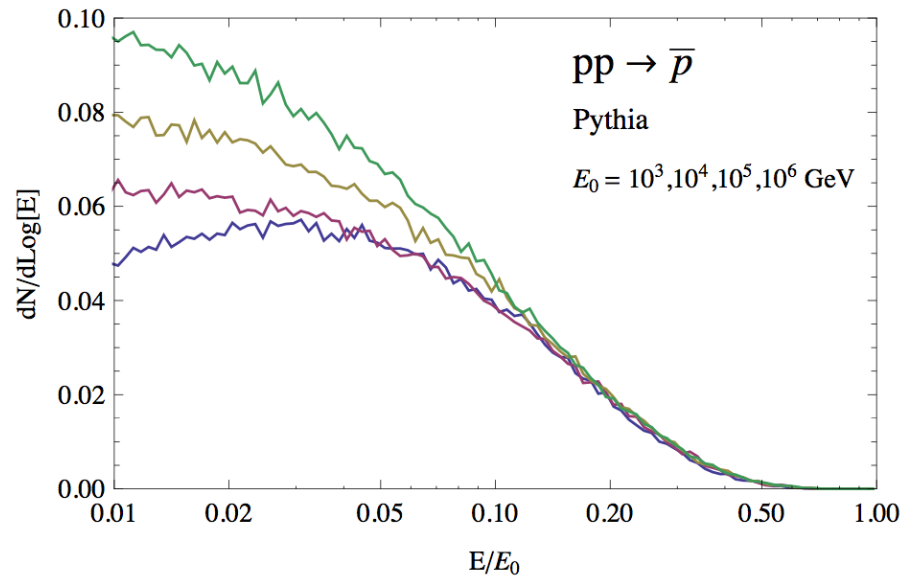


Pythia Montecarlo

$$pp \to \overline{p} + \ldots$$







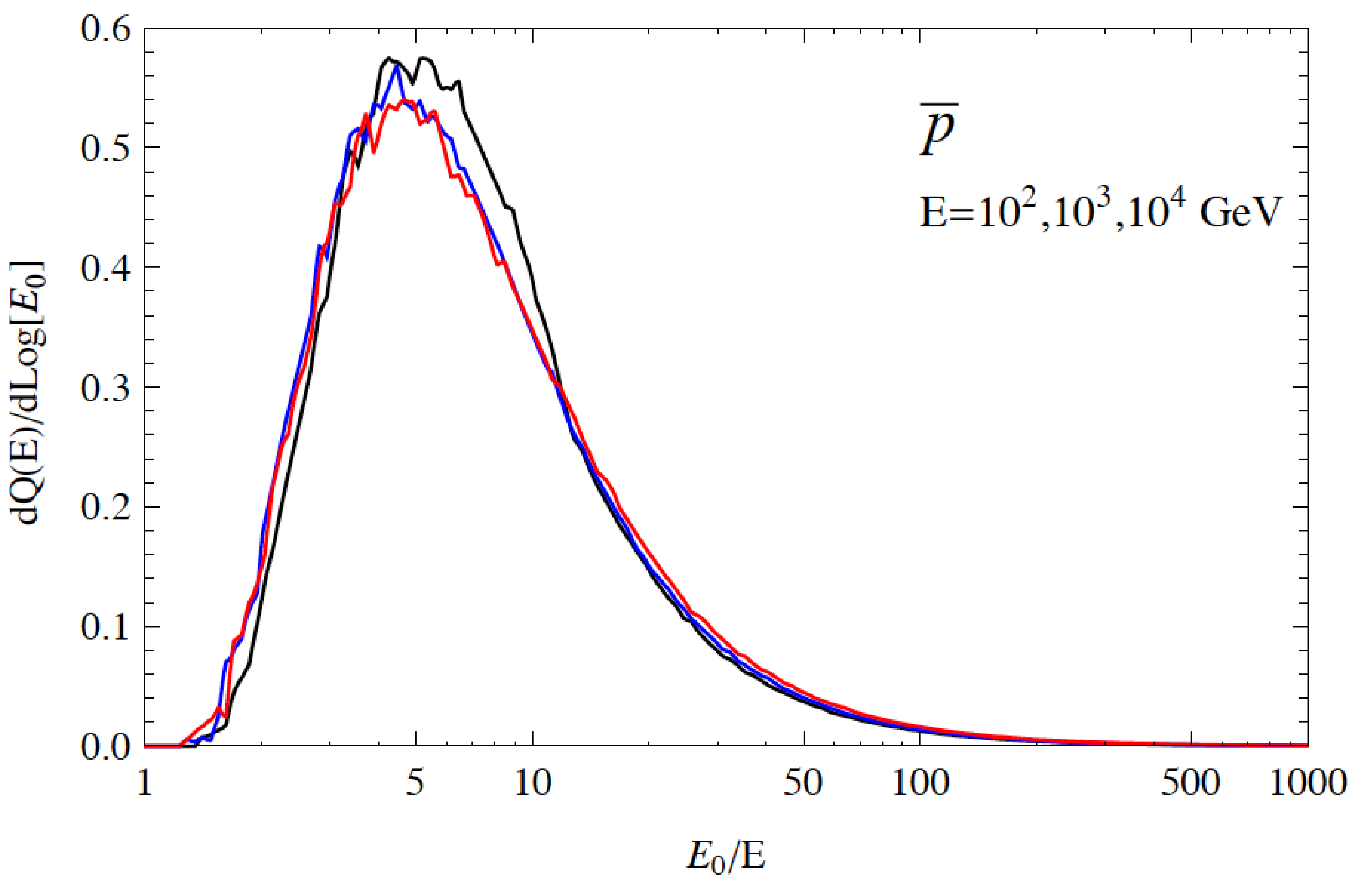
Note: approximate "scaling" of cross section

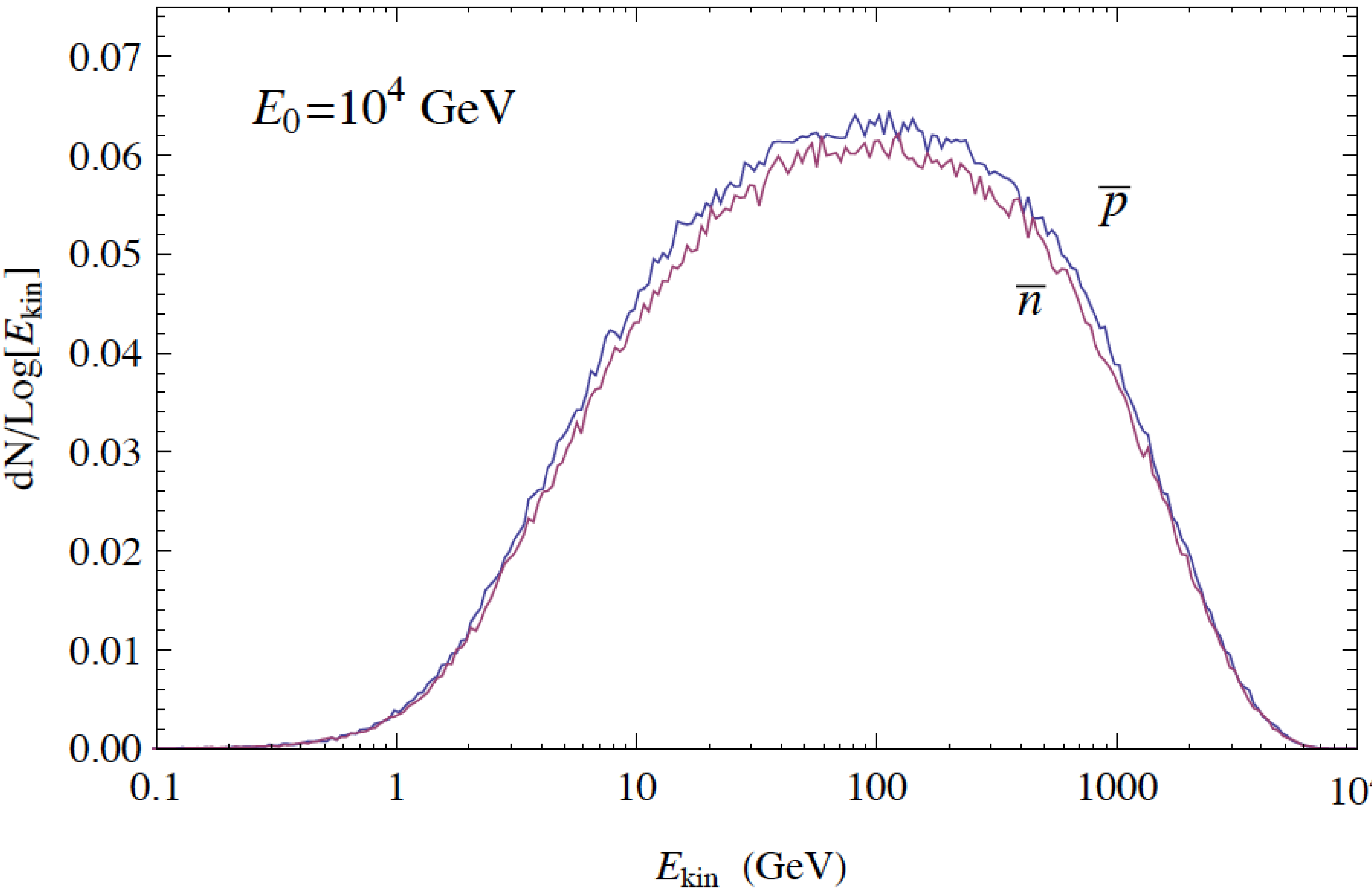
Power Law for projectiles

Power law for secondaries

Response function for anti-proton production.
[Primary particle energy that contributes
to the flux at energy E]

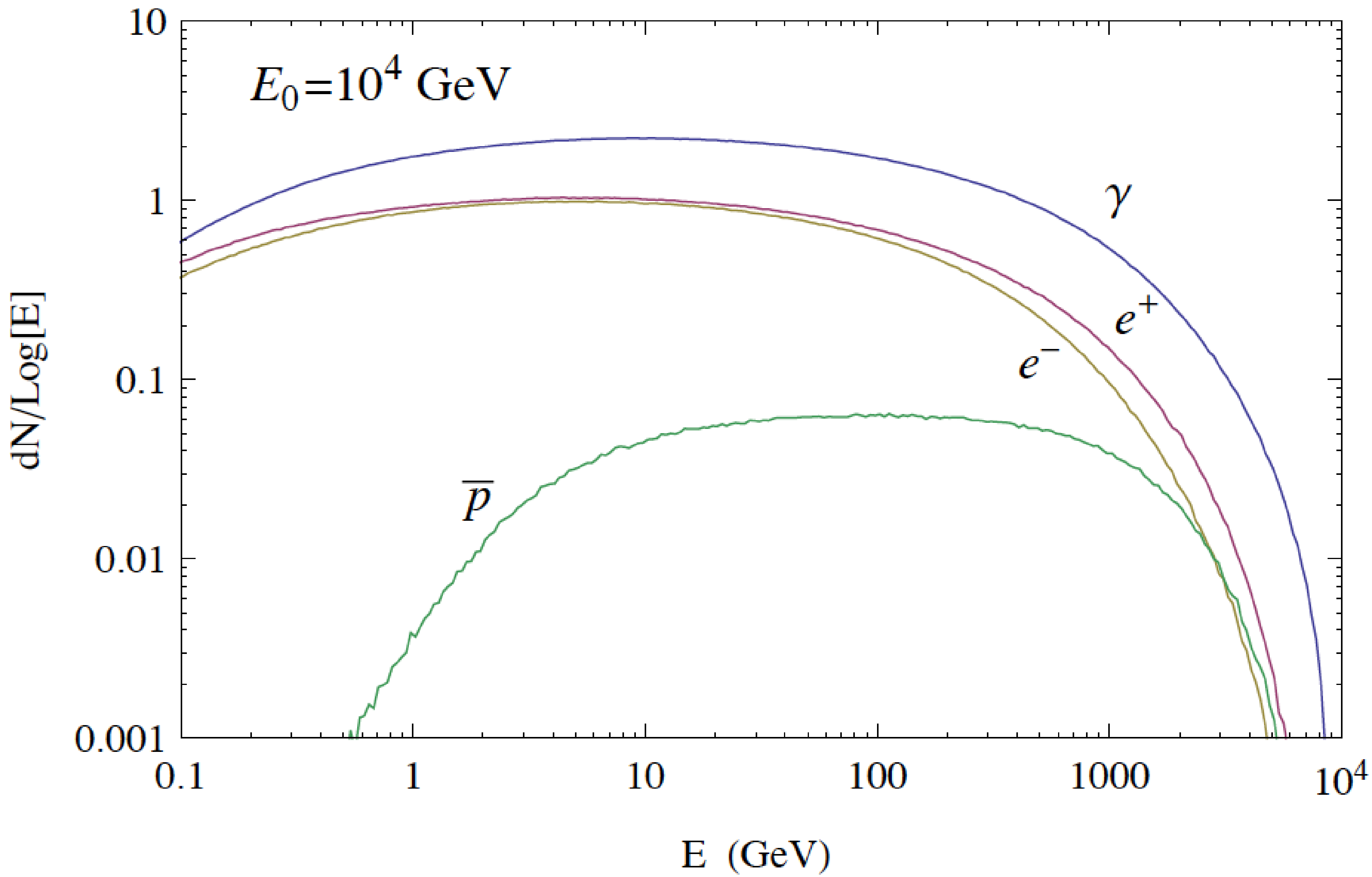
$$q_j^{(\mathrm{ism})}(E,\vec{x},t) = \sum_A \int dE_0 \; n_A(E_0,\vec{x},t) \; n_{\mathrm{ism}}(\vec{x}) \, \beta c \, \frac{d\sigma_{A\to j}}{dE}(E,E_0)$$



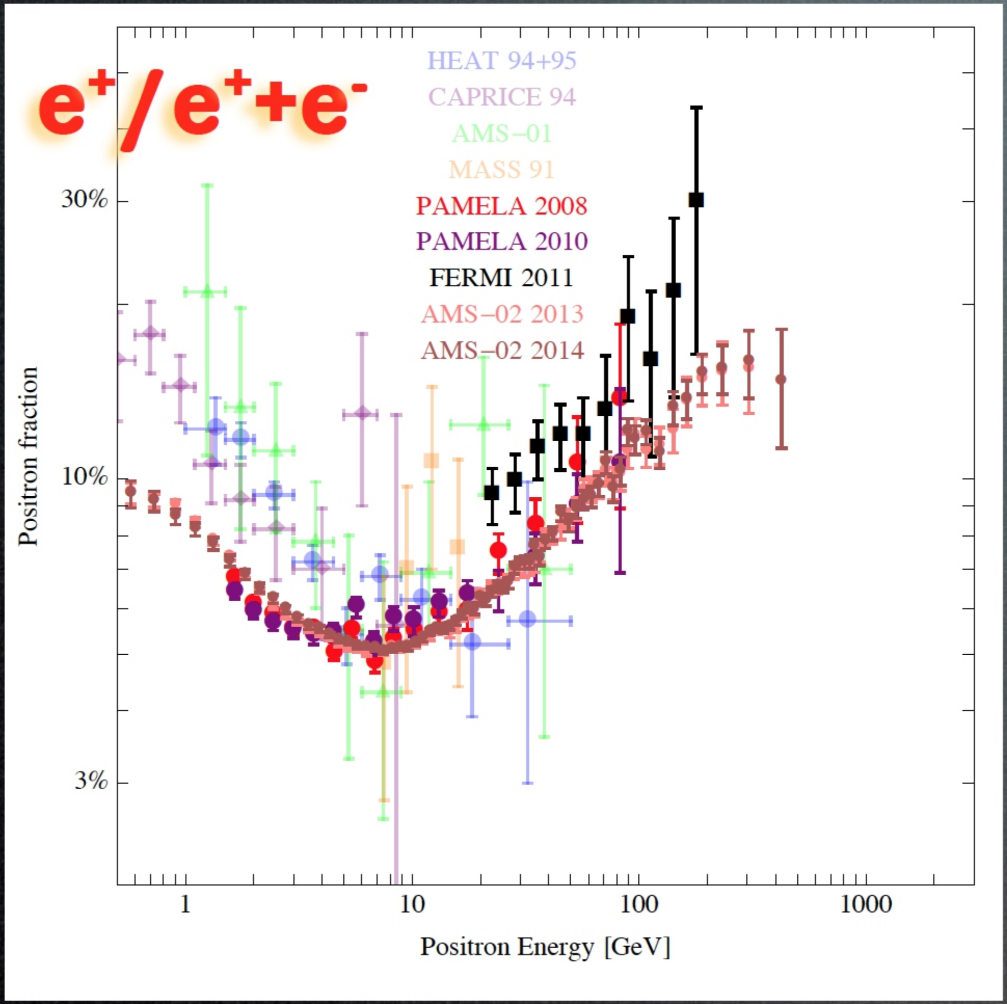


$E_0 = 10^4$ GeV
$\overline{p}$
$\overline{n}$
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
dN/Log[$E_{\rm kin}$]
0.1
1
10
100
1000
10^4
$E_{\rm kin}$ (GeV)

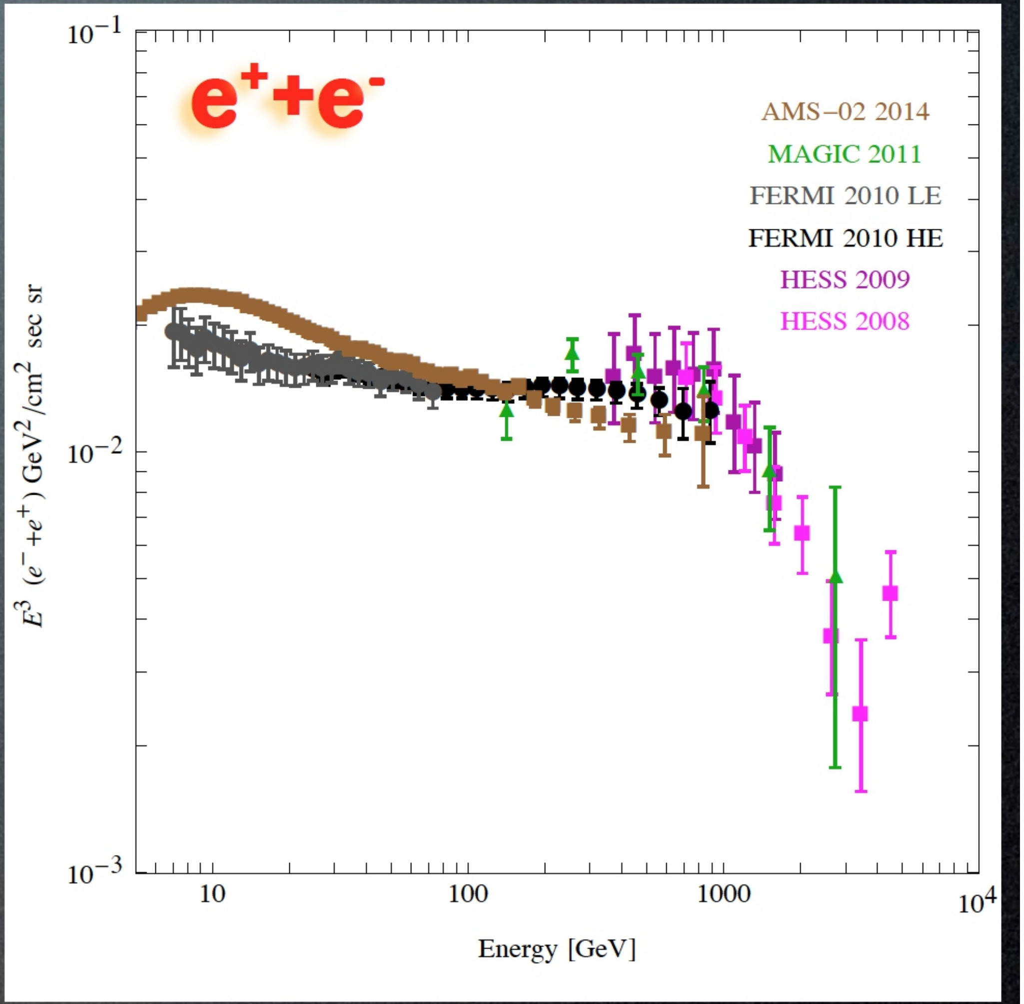
Production of different particles



Data on Positrons

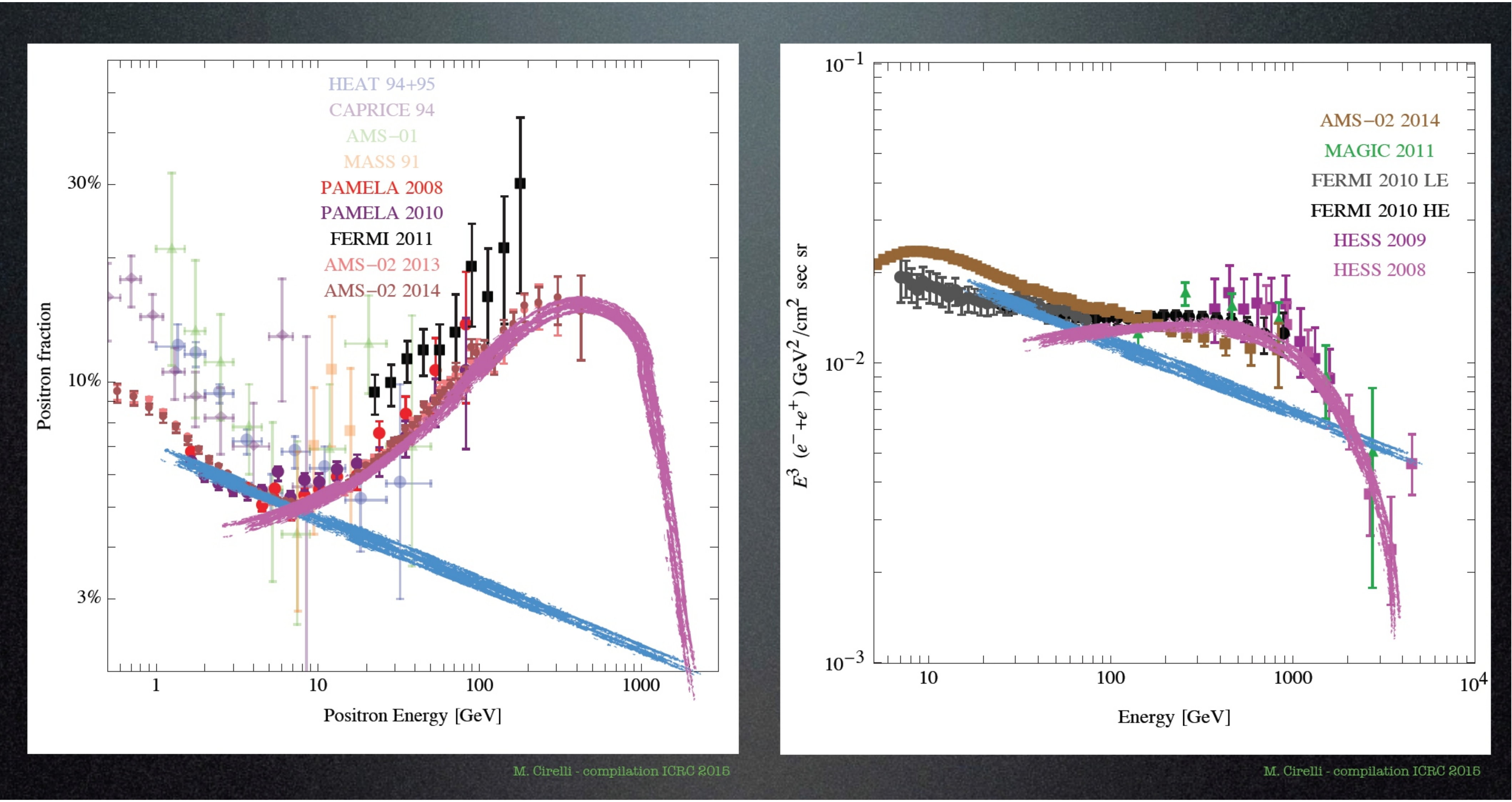


M. Cirelli - compilation ICRC 2015

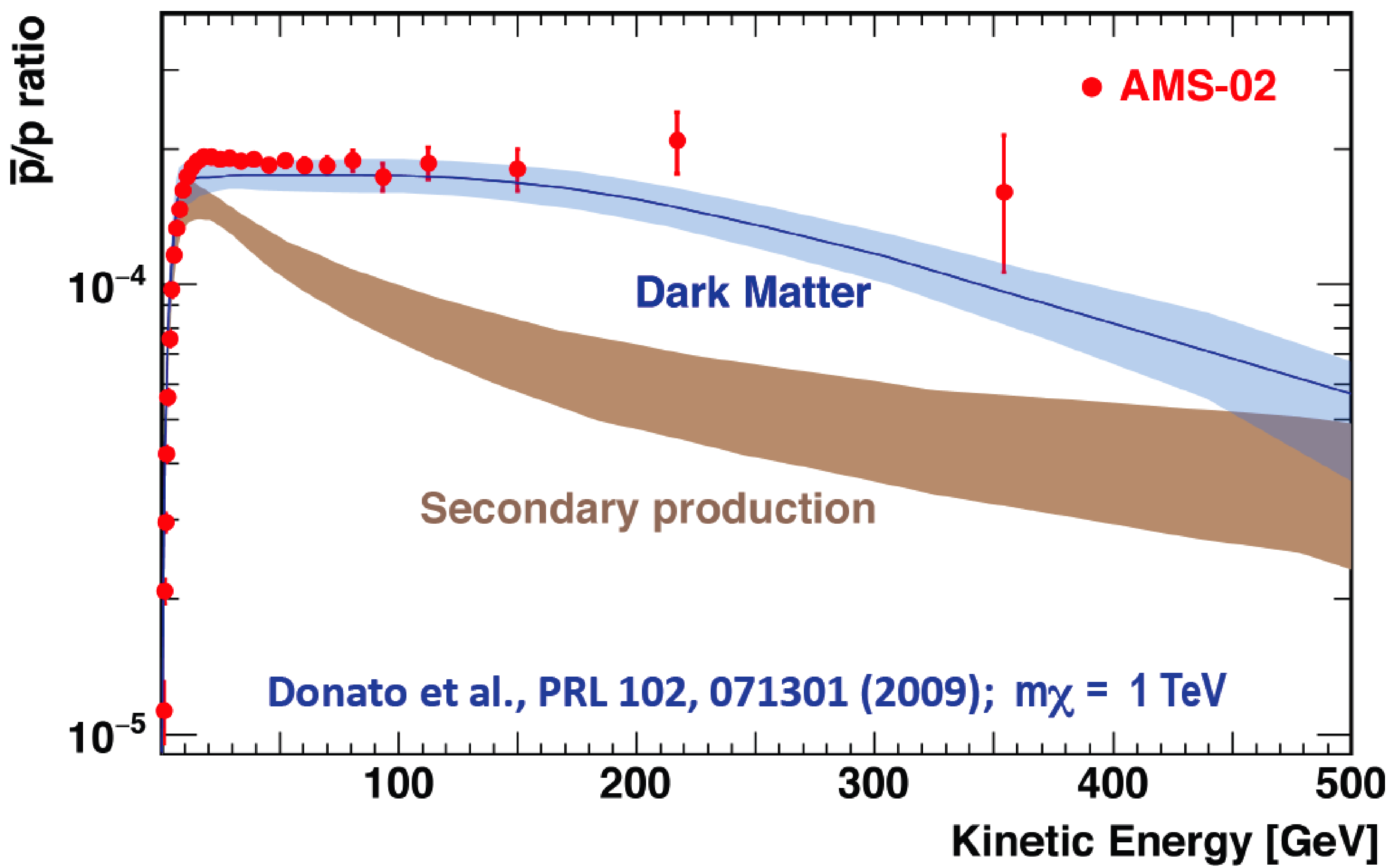


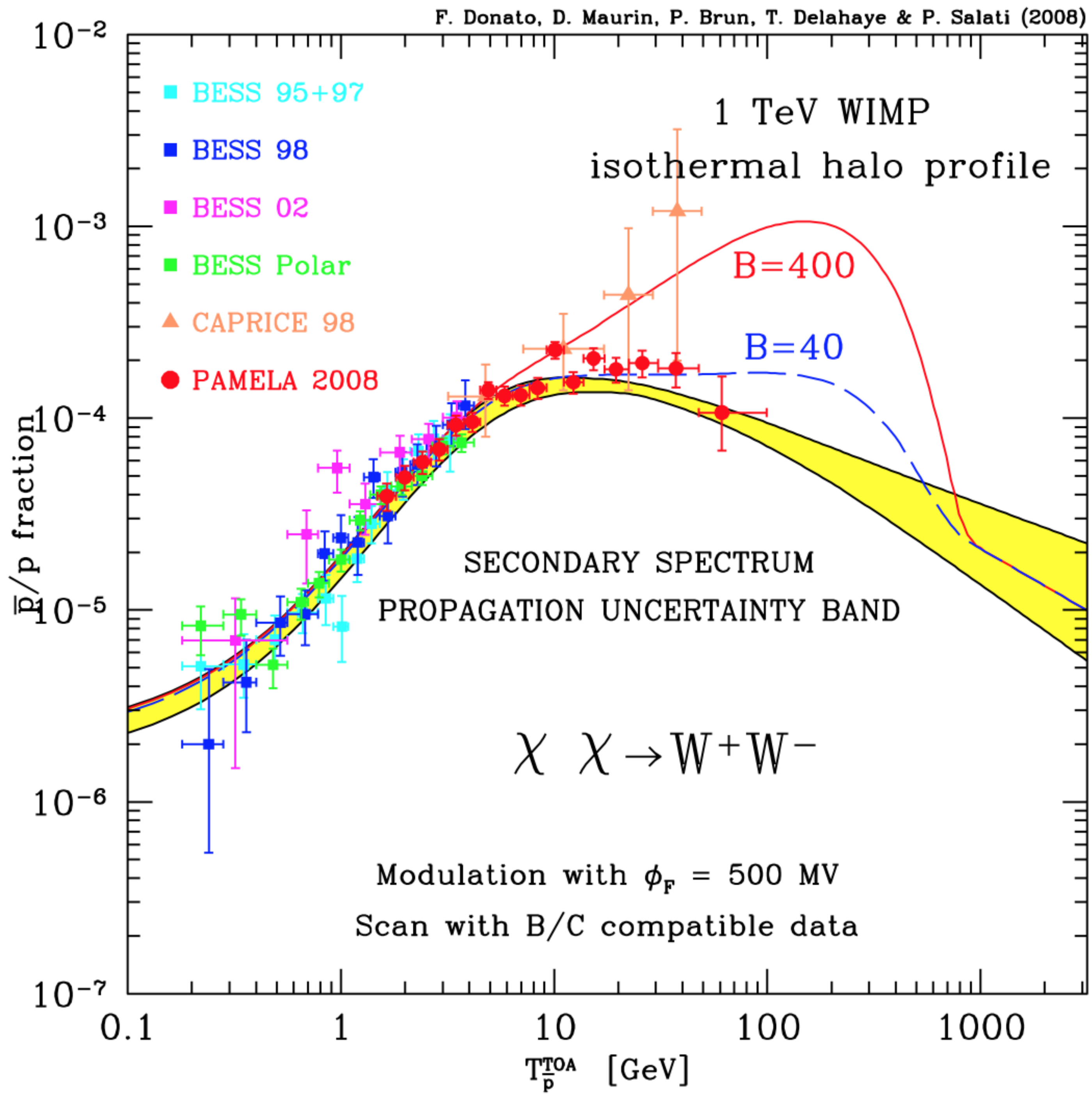
M. Cirelli - compilation ICRC 2015

Data on Positrons

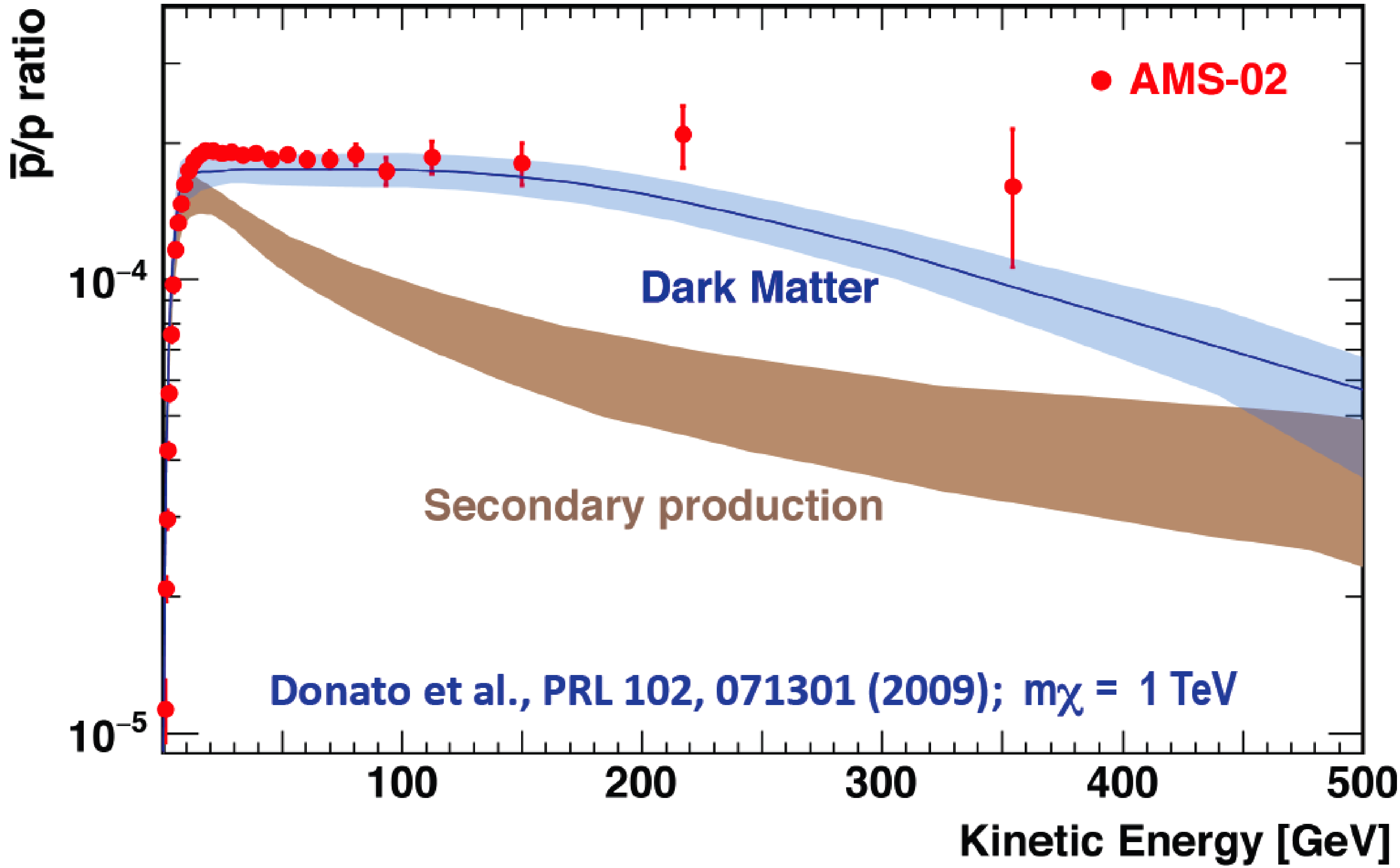


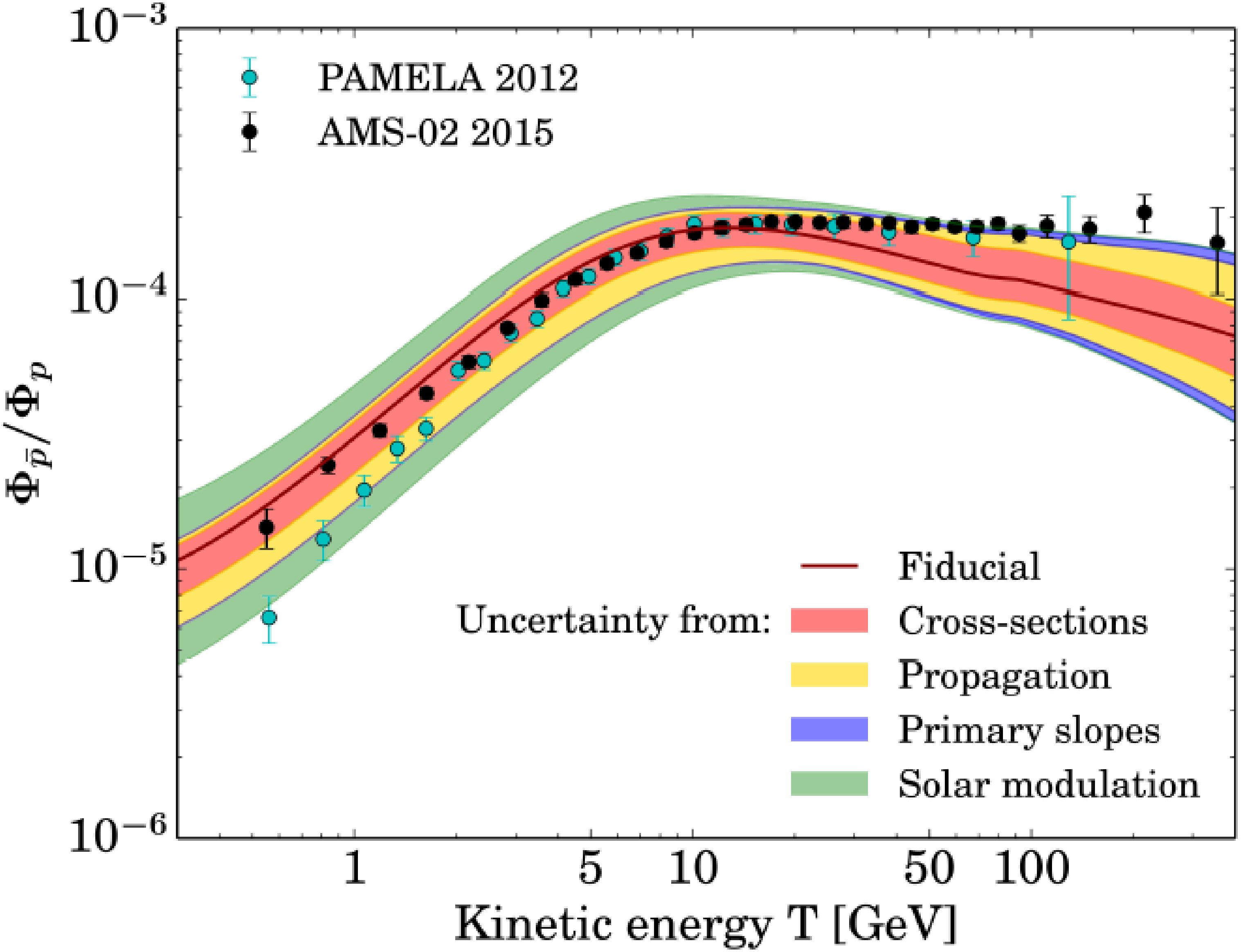
AMS $\bar{p}/p$ results and modeling




F. Donato, D. Maurin, P. Brun, T. Delahaye & P. Salati (2008)
BESS 95+97
BESS 98
BESS 02
BESS Polar
CAPRICE 98
PAMELA 2008
1 TeV WIMP
isothermal halo profile
B=400
B=40
SECONDARY SPECTRUM
PROPAGATION UNCERTAINTY BAND
$\chi\ \chi \rightarrow W^+W^-$
Modulation with ϕ_F = 500 MV
Scan with B/C compatible data
$\bar{p}/p$ fraction
$T_{\bar{p}}^{TOA}$ [GeV]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.1
1
10
100
1000

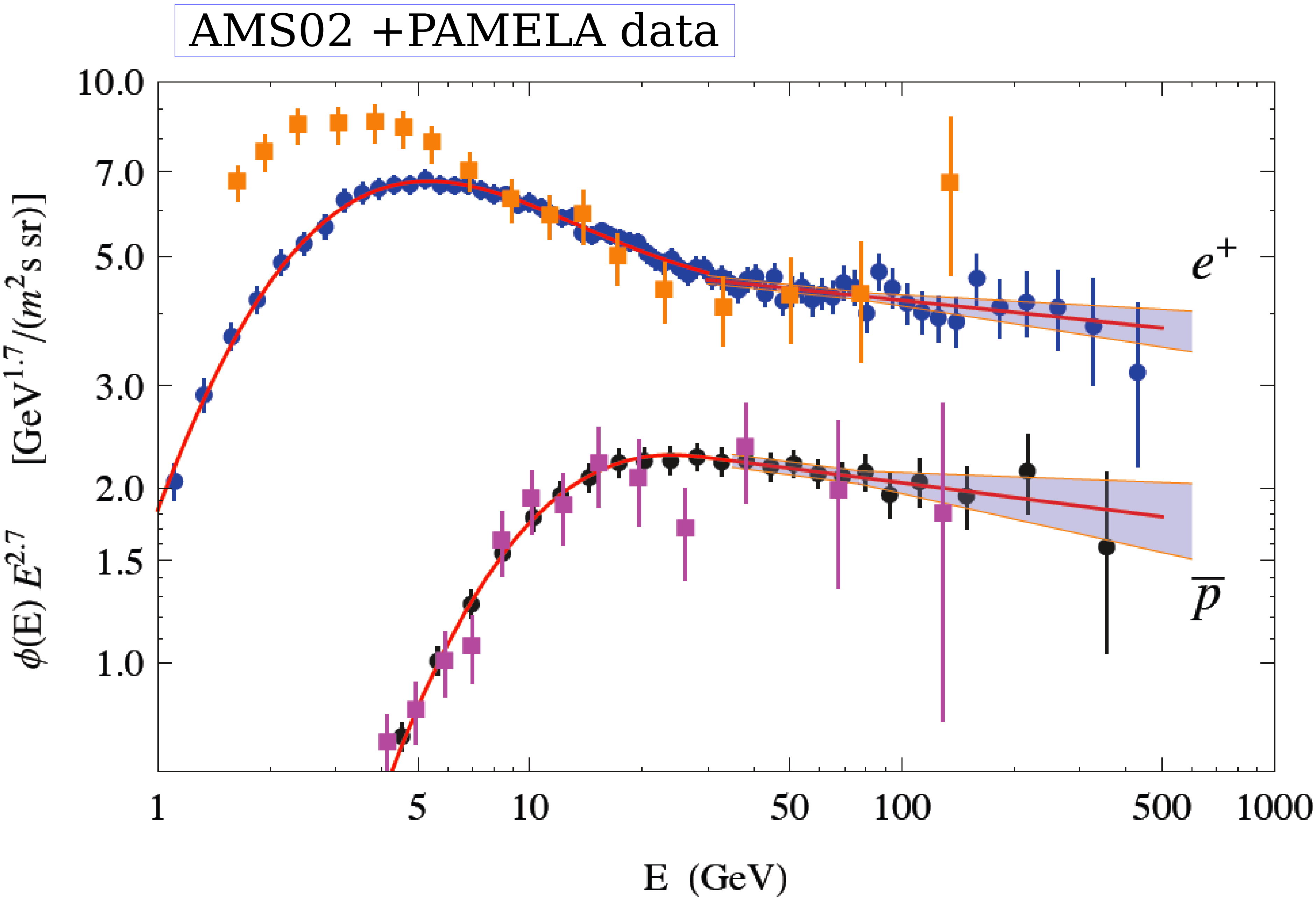
AMS $\bar{p}/p$ results and modeling





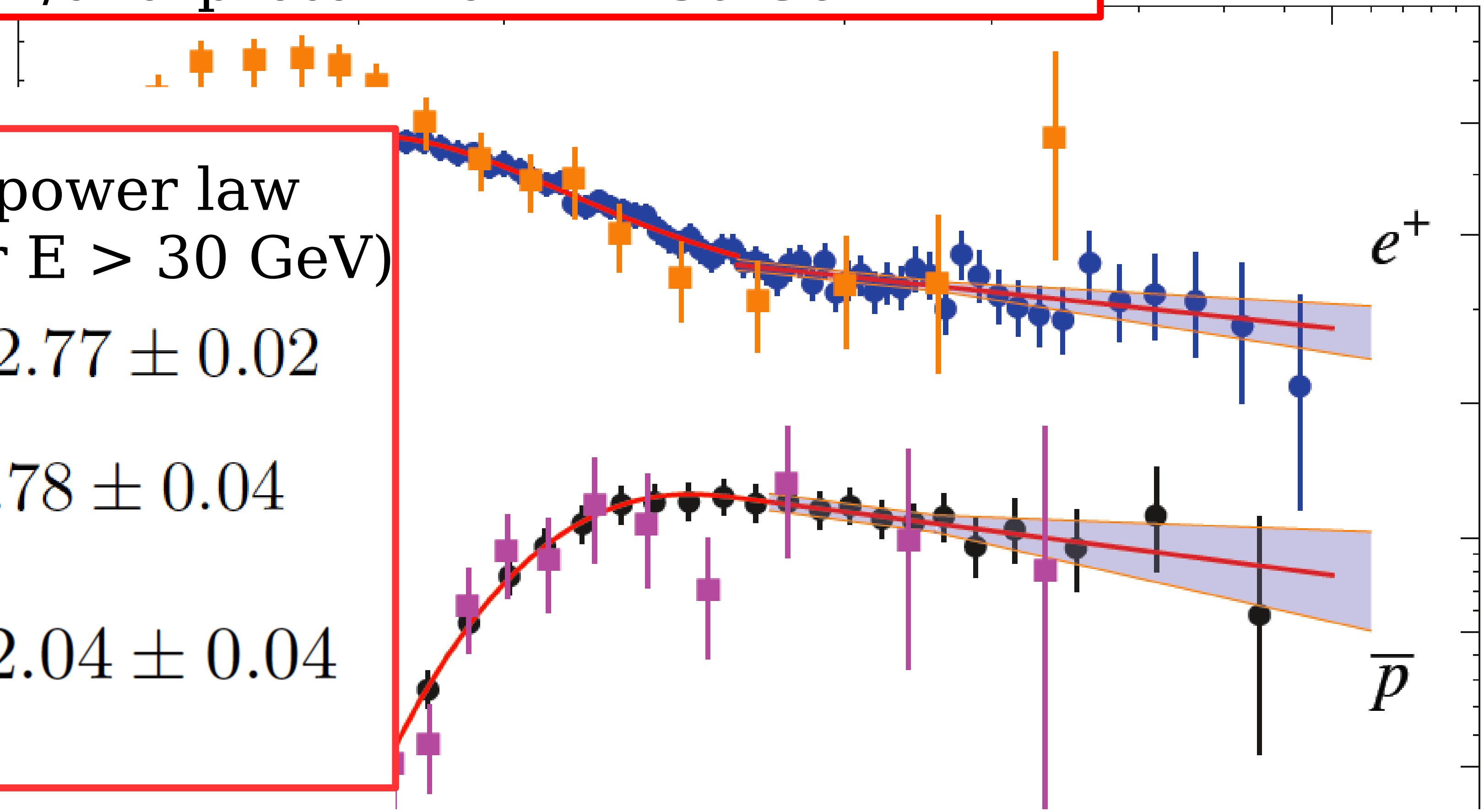
Giesen, Boudaud, Génolini, Poulin, Cirelli, Salati, Serpico
1504.04276

New precision measurements (by AMS02) of anti-matter Cosmic Rays. e^+ $\overline{p}$



New precision measurements (by AMS02) of anti-matter Cosmic Rays. e^+ $\overline{p}$

Approximately constant value for the ratio positron/anti-proton for E > 30 GeV



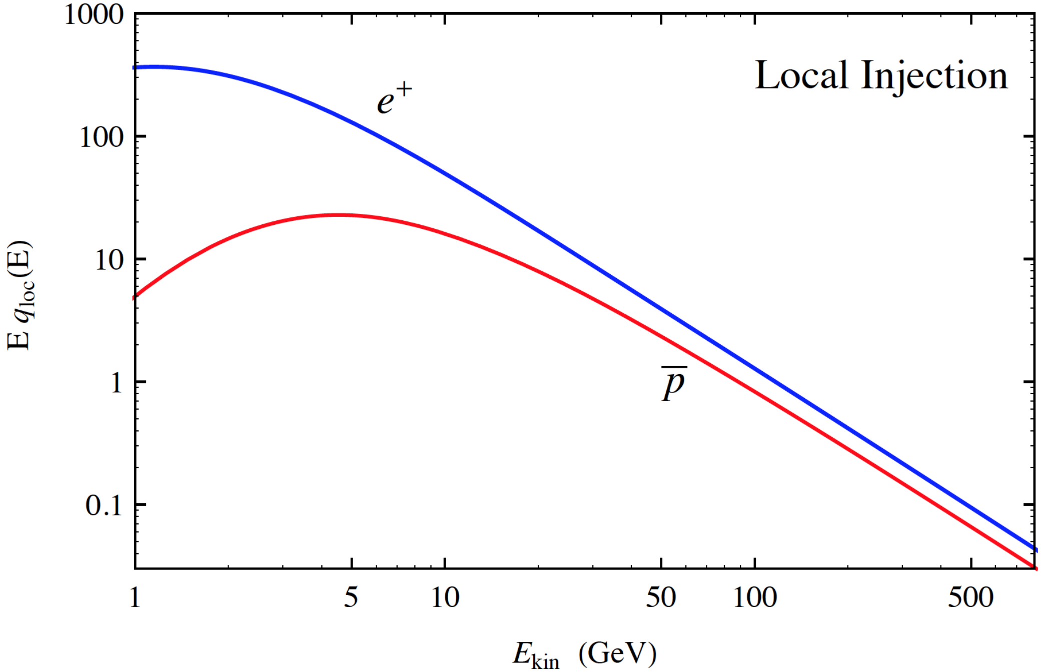
Simple power law Fits (for E > 30 GeV)

$$\gamma_{e^+} = 2.77 \pm 0.02$$

$$\gamma_{\overline{p}} = 2.78 \pm 0.04$$

$$\frac{e^+}{\overline{p}} \simeq 2.04 \pm 0.04$$

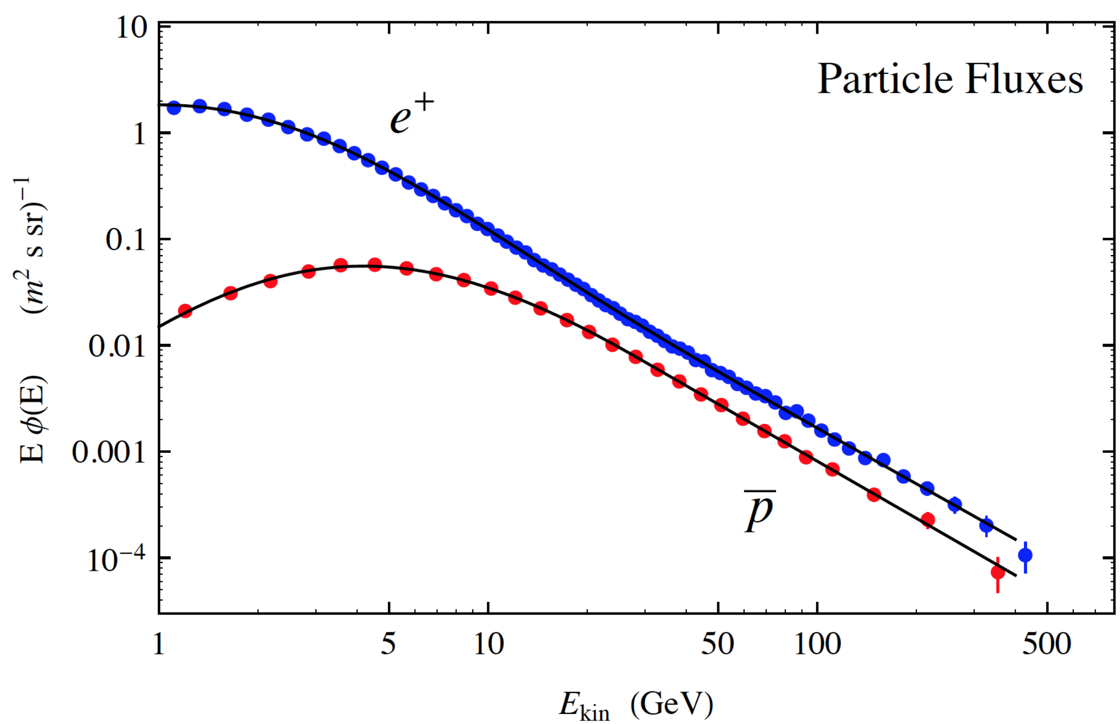
$$\left.\frac{\phi_{e+}(E)}{\phi_{\overline{p}}(E)}\right|_{E\in[30,400]\ \mathrm{GeV}} \simeq (2.04 \pm 0.04) \times \left(\frac{E}{50\ \mathrm{GeV}}\right)^{0.015\pm0.045}$$

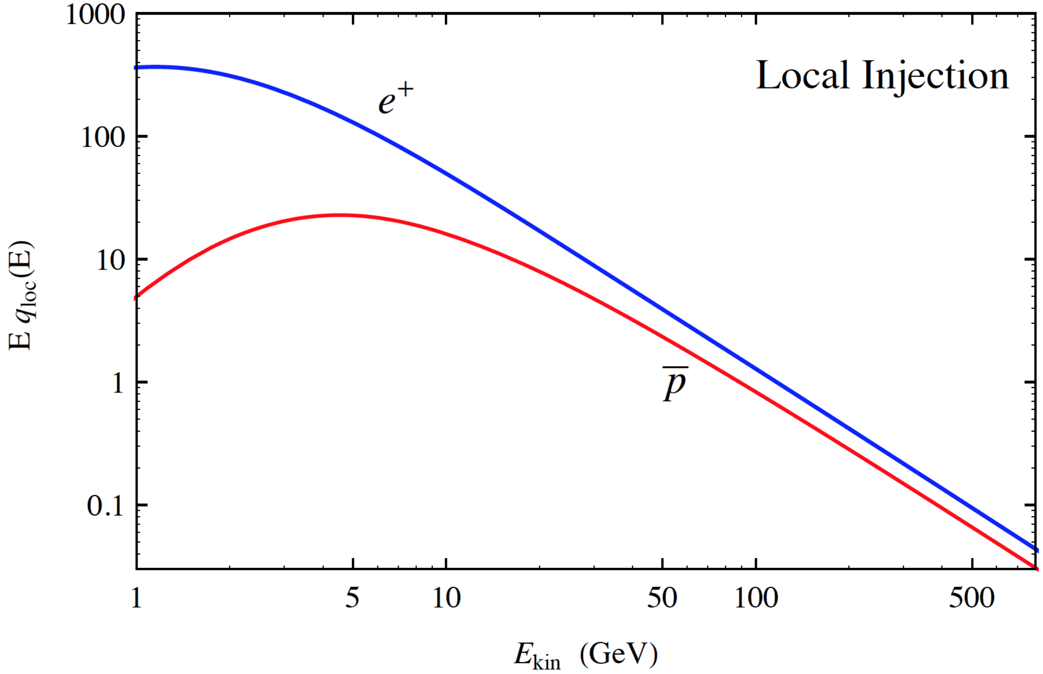


Injection

Observed Fluxes

“Striking” similarity





Injection of positrons and antiprotons

At *high energy*
approximately constant ratio
(consequence of scaling)

$$\frac{q_{\overline{p}}}{q_{e^+}} \simeq 1.80 \pm 0.5$$

$$\left.\frac{\phi_{e+}(E)}{\phi_{\overline{p}}(E)}\right|_{E\in[30,350]\ \text{GeV}} \simeq 2.04 \pm 0.04$$

$$p + p \to p + p + p + \overline{p}$$

$$E_{i,\text{threshold}} = 7\ m_p$$

$$E_{f,\text{threshold}} = 2\ m_p$$

Low energy:
kinematical suppression of antiproton production

Production of anti-deuteron
and anti-helium in Dark Matter annihilation

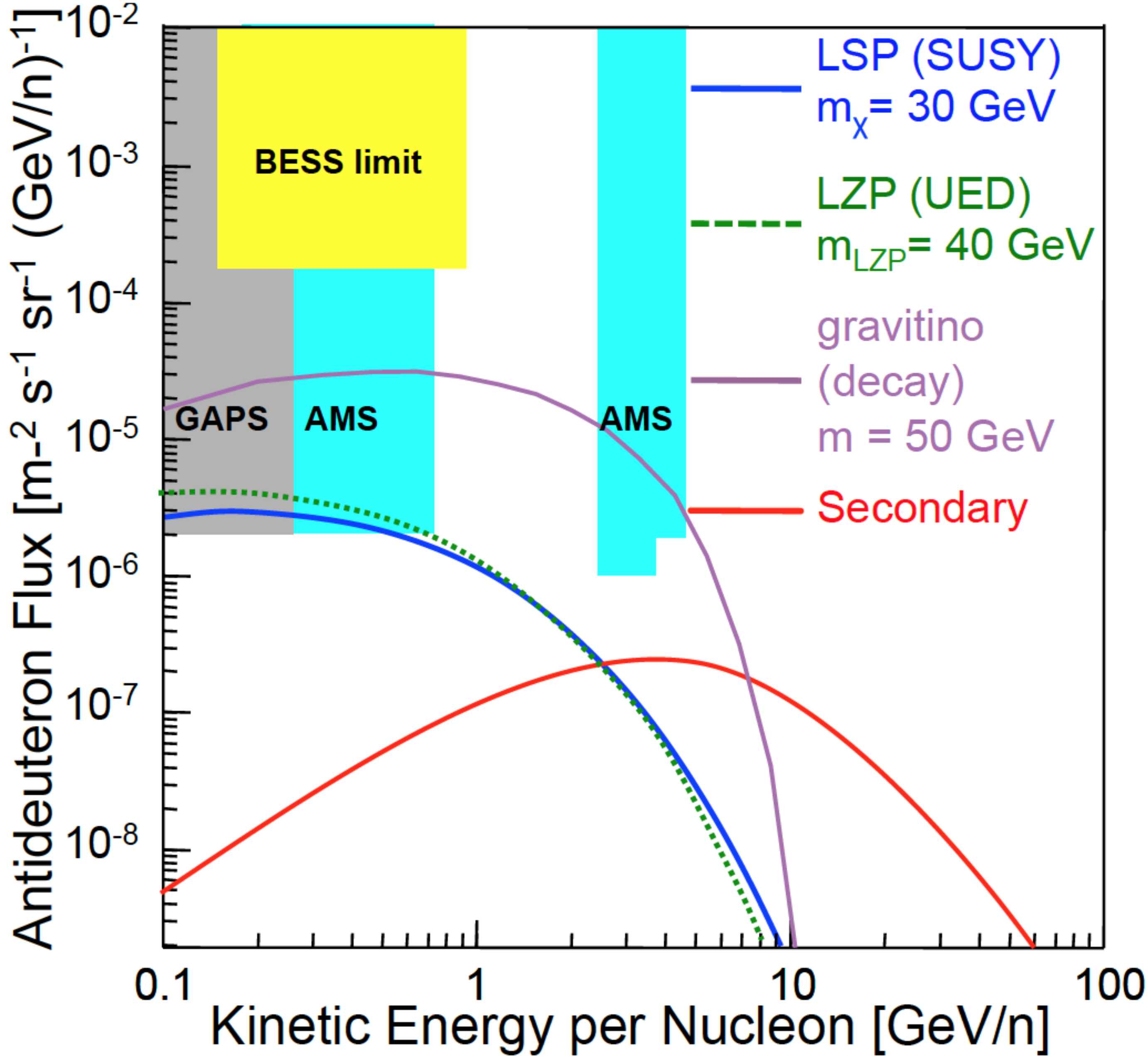
Background suppressed for
kinematical reasons

$$p + p \to p + p + \mathrm{A} + \overline{\mathrm{A}}$$

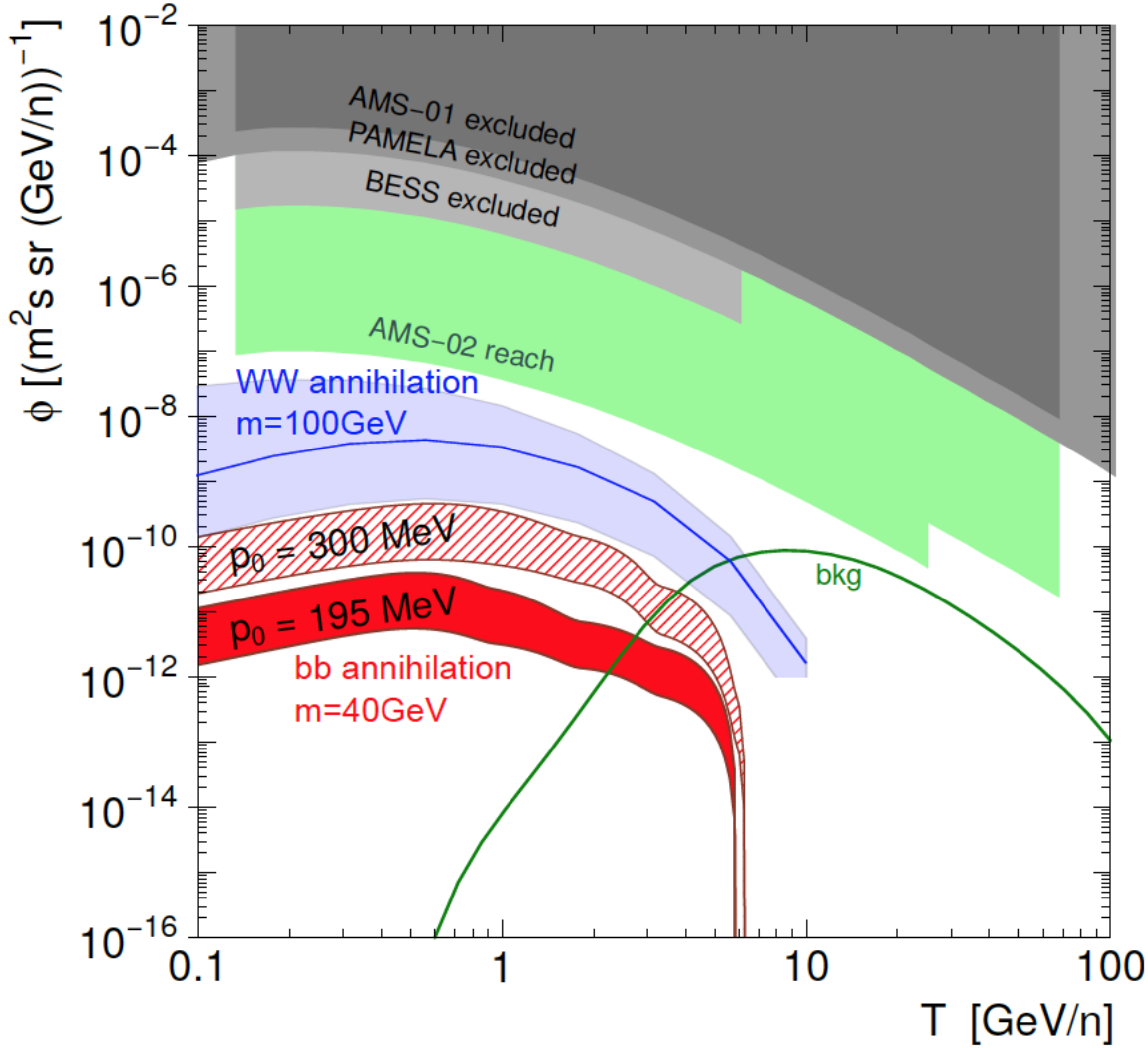
$$2\,m_p^2 + 2\,m_p\,E \gtrsim [2\,(\mathrm{A}+1)]^2\,m_p^2$$

$$E_p^{\mathrm{th}}(\overline{\mathrm{A}}) = [2\,(\mathrm{A}+1)^2 - 1]\,m_p$$

$$E(\overline{\mathrm{A}}) = (\mathrm{A}^2 + \mathrm{A})\,m_p$$



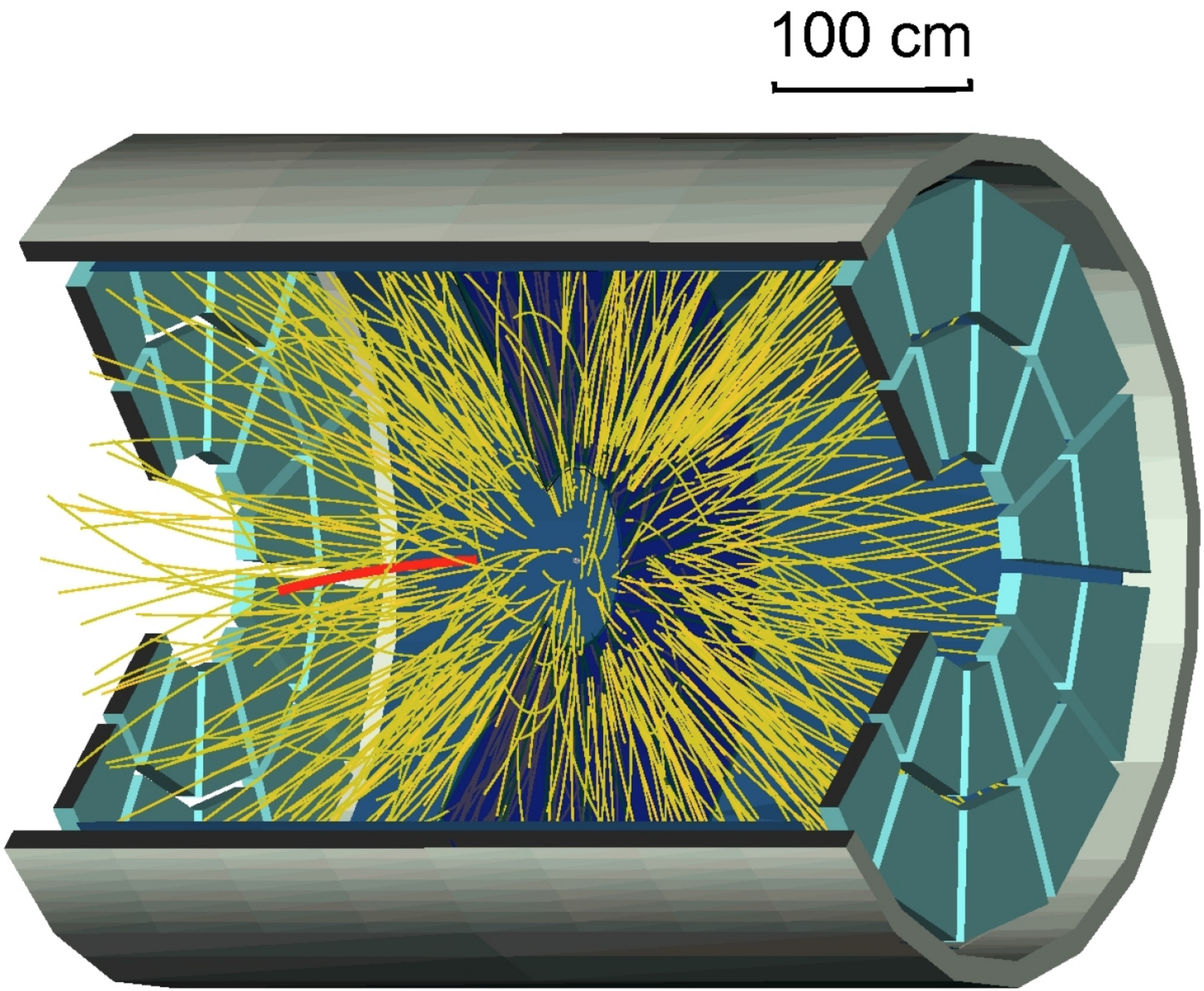
Antideuteron Flux [m-2 s-1 sr-1 (GeV/n)-1]
10-2
10-3
10-4
10-5
10-6
10-7
10-8
0.1
1
10
100
Kinetic Energy per Nucleon [GeV/n]
BESS limit
GAPS
AMS
AMS
LSP (SUSY)
mχ= 30 GeV
LZP (UED)
mLZP= 40 GeV
gravitino
(decay)
m = 50 GeV
Secondary

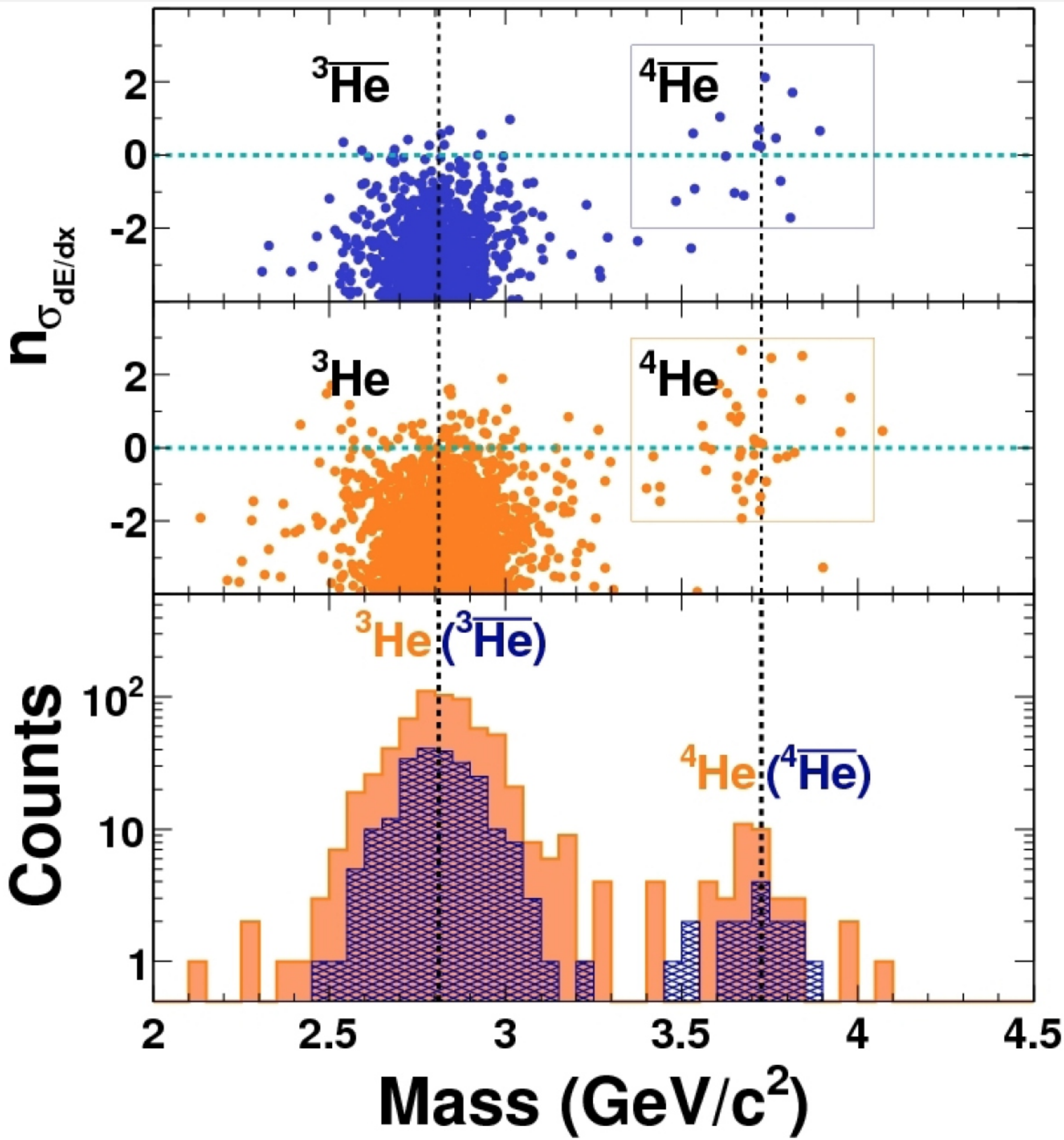


AMS−01 excluded
PAMELA excluded
BESS excluded
AMS−02 reach
WW annihilation
m=100GeV
p0 = 300 MeV
p0 = 195 MeV
bb annihilation
m=40GeV
bkg
φ [(m2s sr (GeV/n))−1]
T [GeV/n]
10−2
10−4
10−6
10−8
10−10
10−12
10−14
10−16
0.1
1
10
100

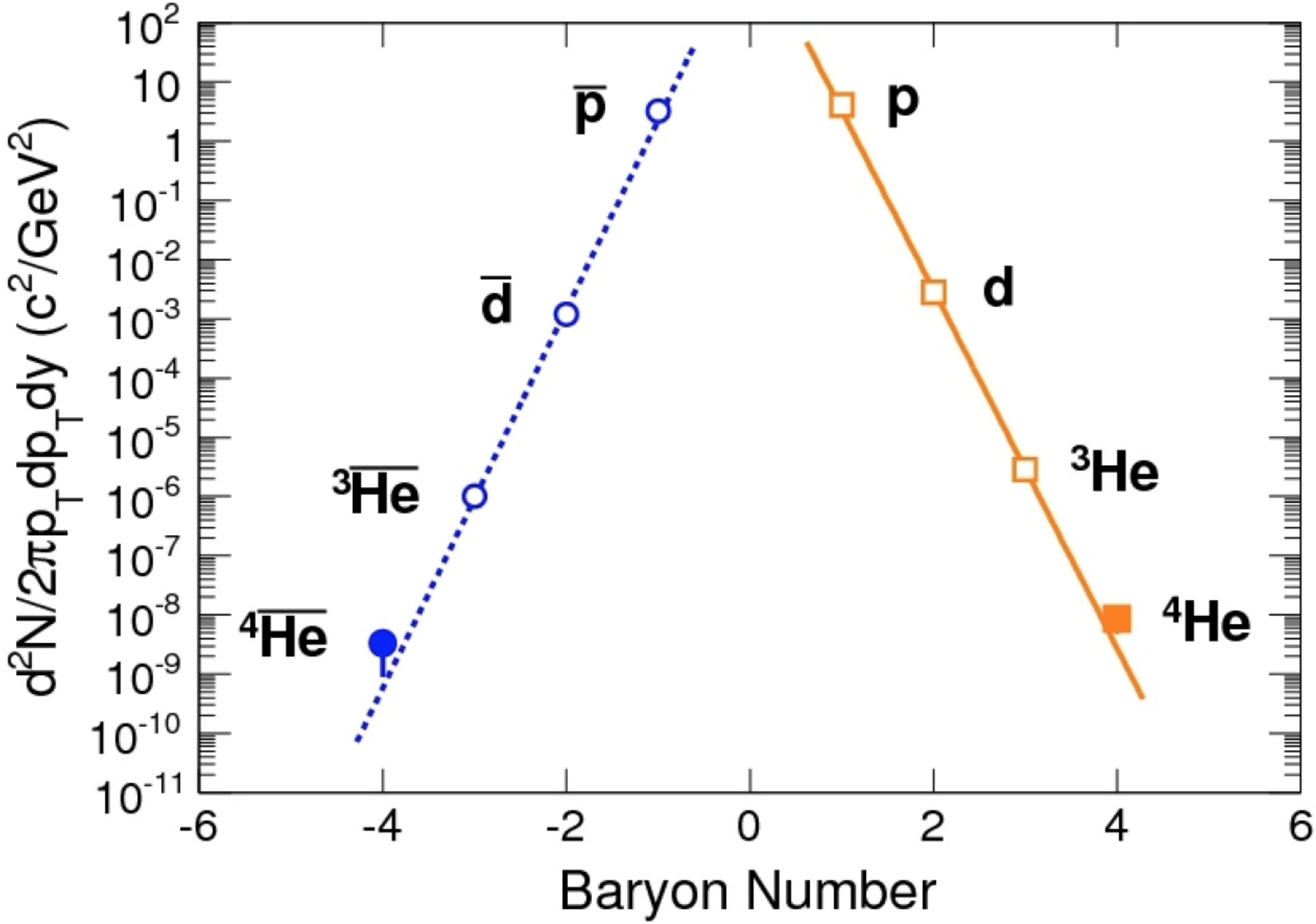
$^{4}\overline{\mathrm{He}}$

Event in STAR detector at RHIC
(200 GeV Gold – Gold collisions)



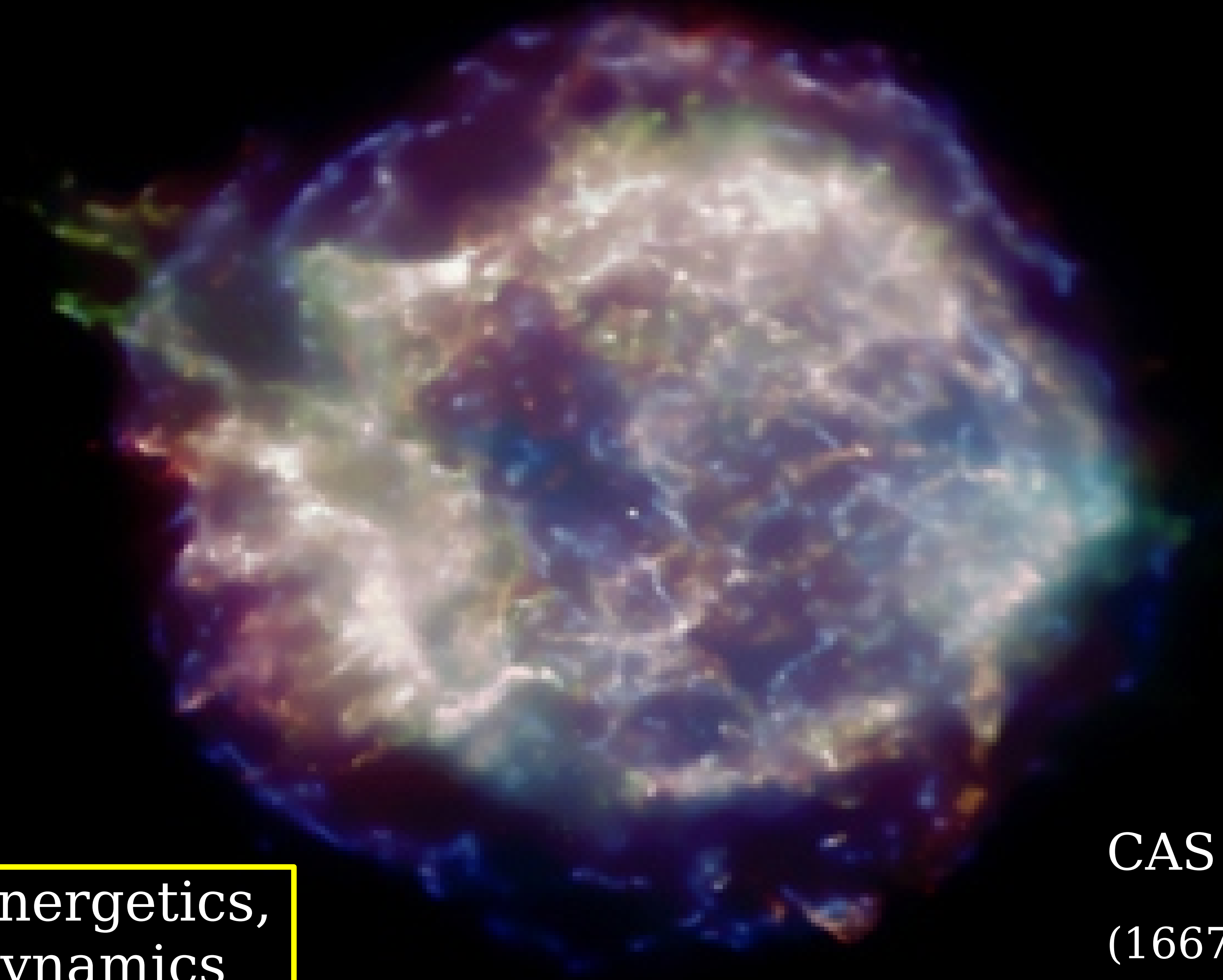


$^{3}\overline{He}$
$^{4}\overline{He}$
^{3}He
^{4}He
^{3}He ($^{3}\overline{He}$)
^{4}He ($^{4}\overline{He}$)
$n_{\sigma_{dE/dx}}$
Counts
2
0
-2
10^2
10
1
2
2.5
3
3.5
4
4.5
Mass (GeV/c^2)



10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$d^2N/2\pi p_T dp_T dy$ (c^2/GeV^2)
-6
-4
-2
0
2
4
6
Baryon Number
$\bar{p}$
$\bar{d}$
$^3\overline{He}$
$^4\overline{He}$
p
d
^3He
^4He

The SuperNova “Paradigm” for CR acceleration



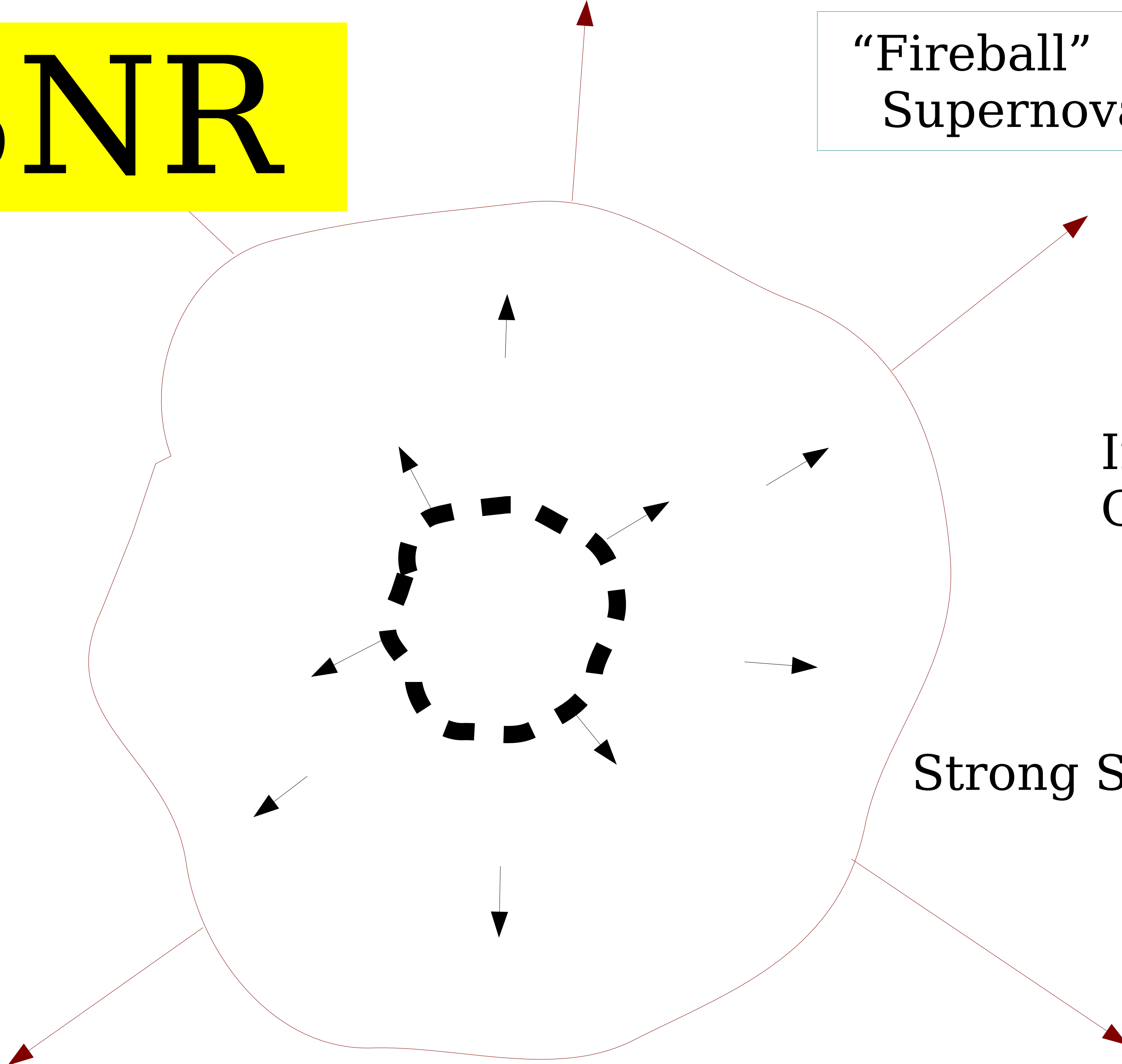
Energetics,
Dynamics

CAS A

(1667)

SNR

“Fireball” of an Supernova explosion



Interstellar Gas

Strong Shock

Fermi 1st order acceleration

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

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

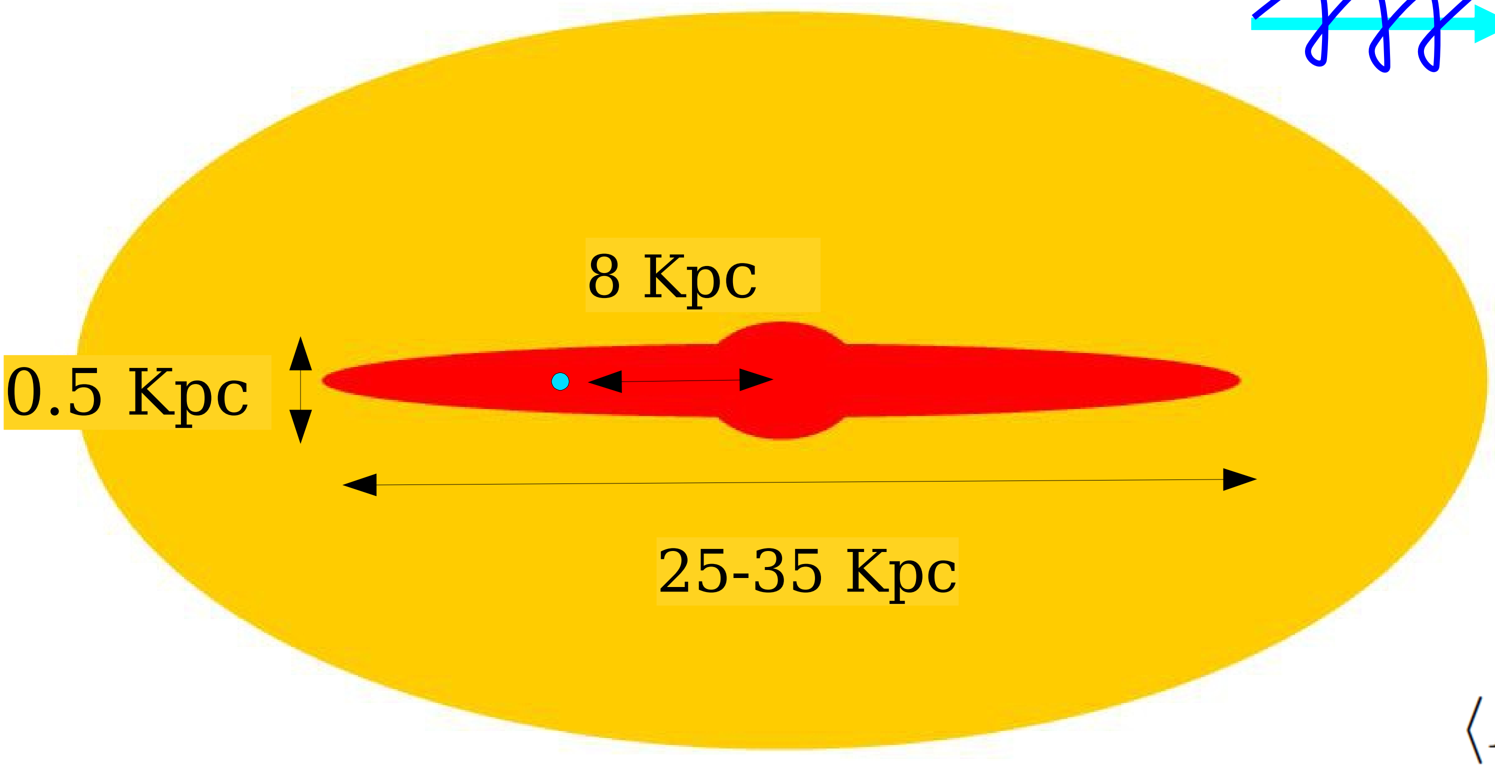
$$L_{\rm SN\ kinetic}^{\rm Milky\ Way} \simeq \left[1.6 \times 10^{51}\ {\rm erg}\right] \ \left[\frac{3}{\rm century}\right]$$

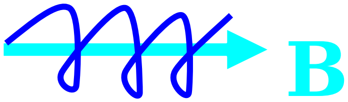
$$M = 5\ M_\odot$$

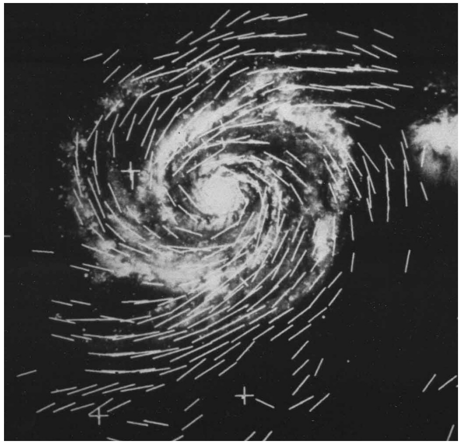
$$v \simeq 5000\ {\rm Km/s}$$

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

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







$$r_L = \frac{p_\perp\, c}{q\, B}$$

$$\langle B_{\rm MW} \rangle \simeq 3\ \mu\text{Gauss}$$

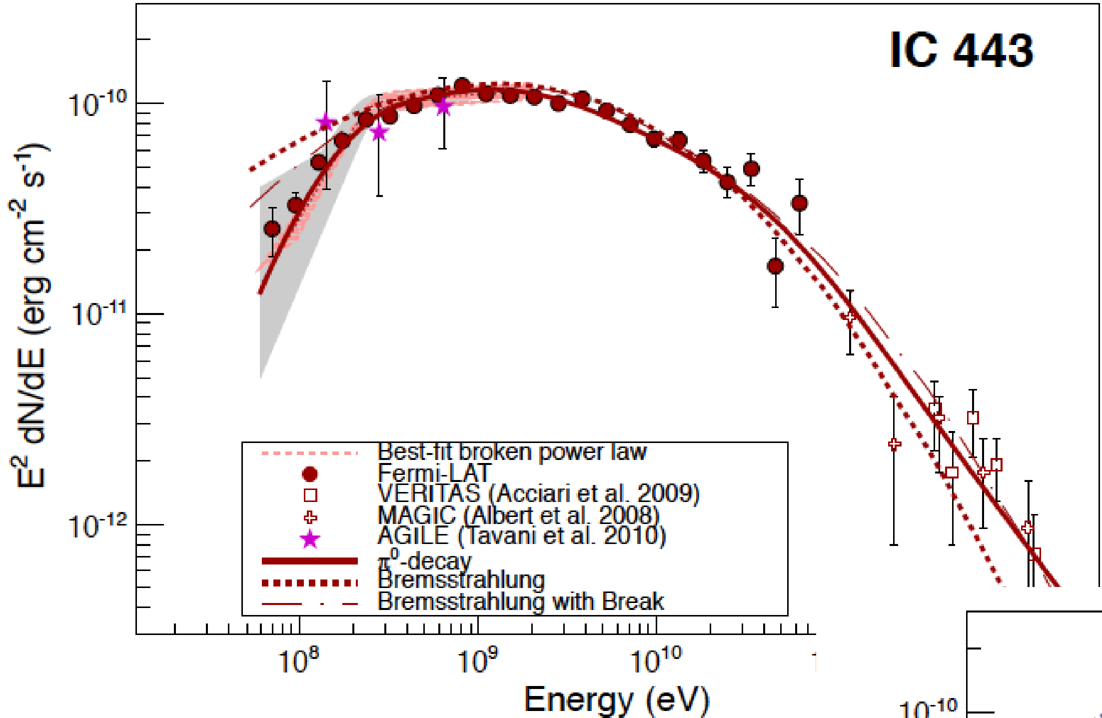
$$r_L = \frac{1.08\ \text{Kpc}}{Z} \left[\frac{E}{10^{18}\,\text{eV}}\right] \left[\frac{\mu\text{Gauss}}{B}\right]$$

$$r^{p}_{\rm Larmor}(100\ \text{GeV}) \simeq 3.6 \times 10^{-8}\ \text{Kpc}$$

$$r^{p}_{\rm Larmor}(10^{20}\ \text{eV}) \simeq 36\ \text{Kpc}$$

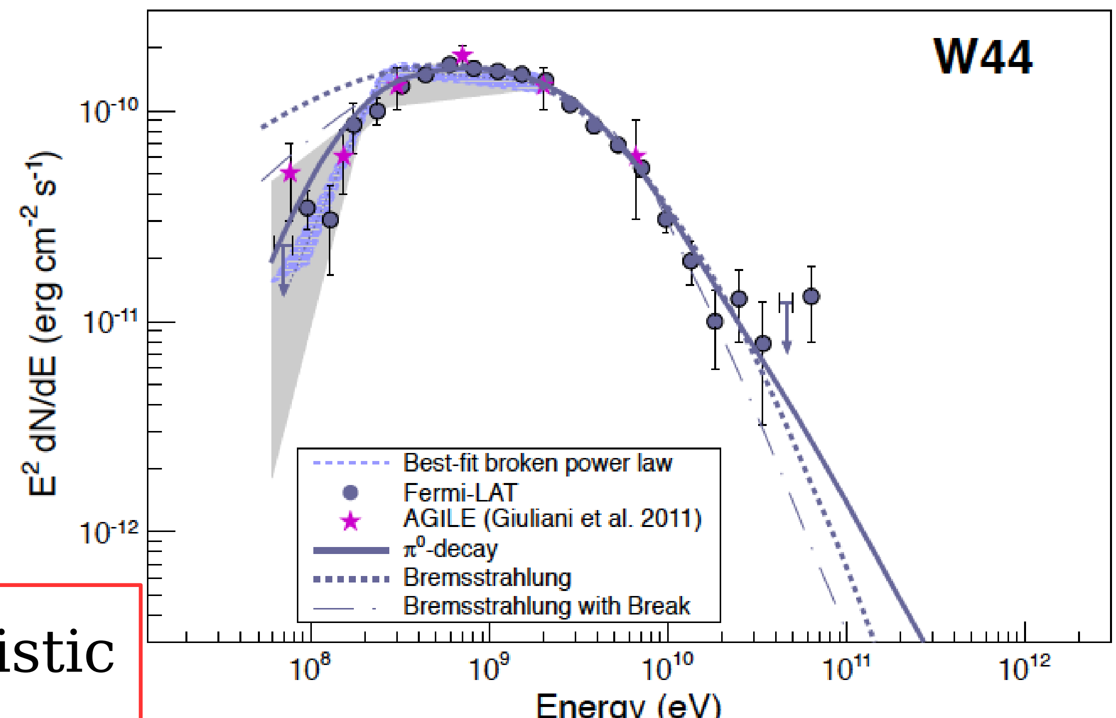
$$r^{\rm Fe}_{\rm Larmor}(10^{20}\ \text{eV}) \simeq 1.4\ \text{Kpc}$$

- Diffusion approximation
- Maximum energy for containment



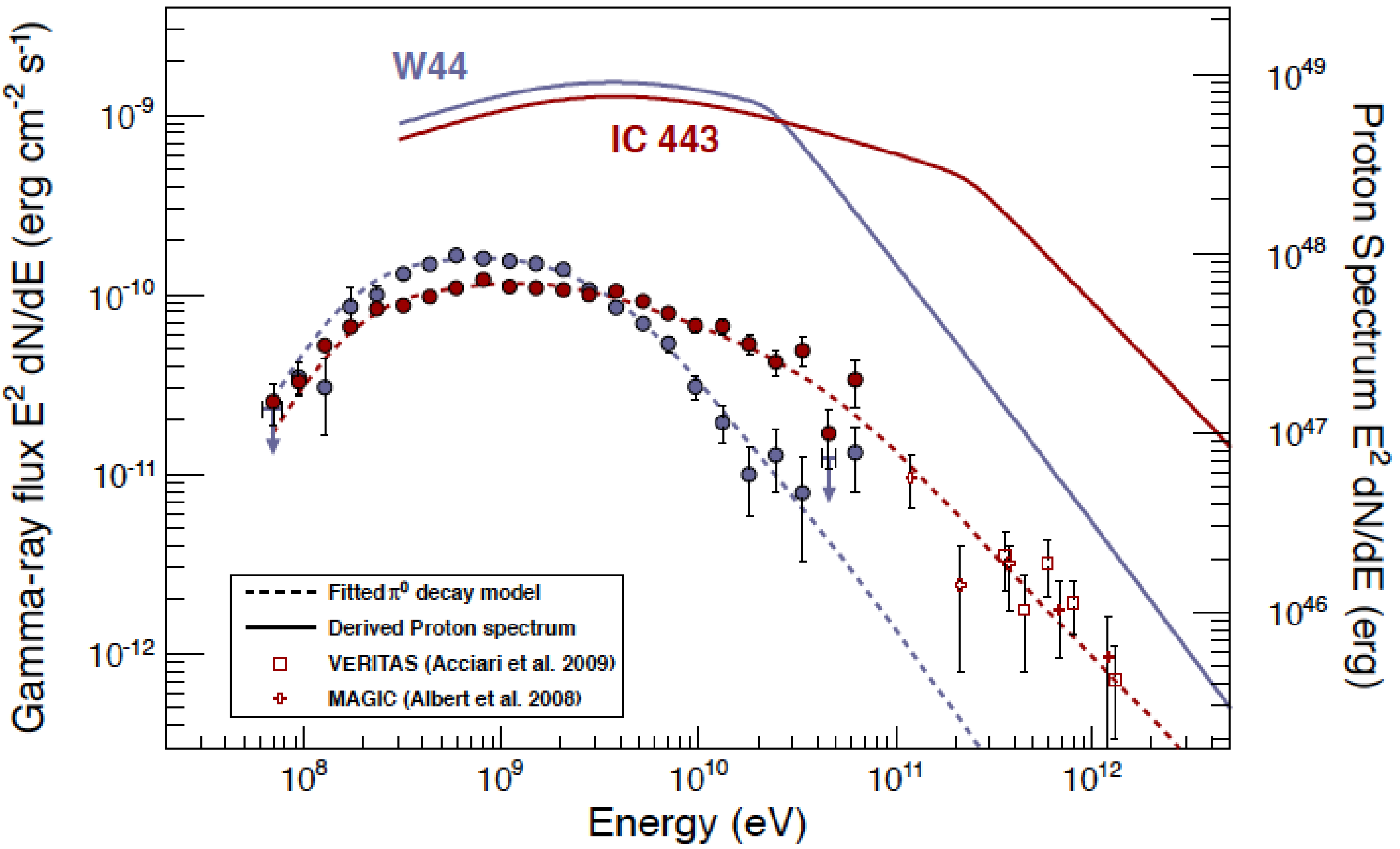
Result of the
FERMI collaboration

SCIENCE feb. 2013

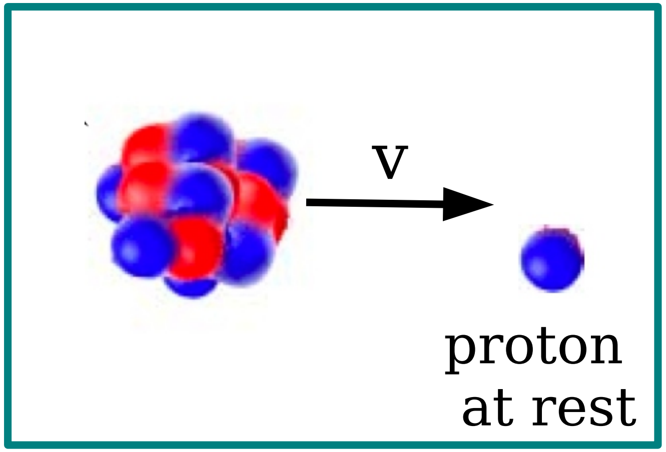


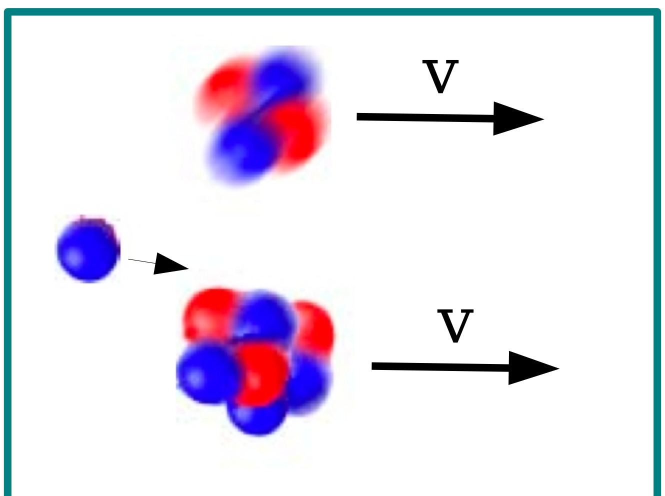
“Detection of the characteristic
Pion-decay signature in
Supernova Remnants”

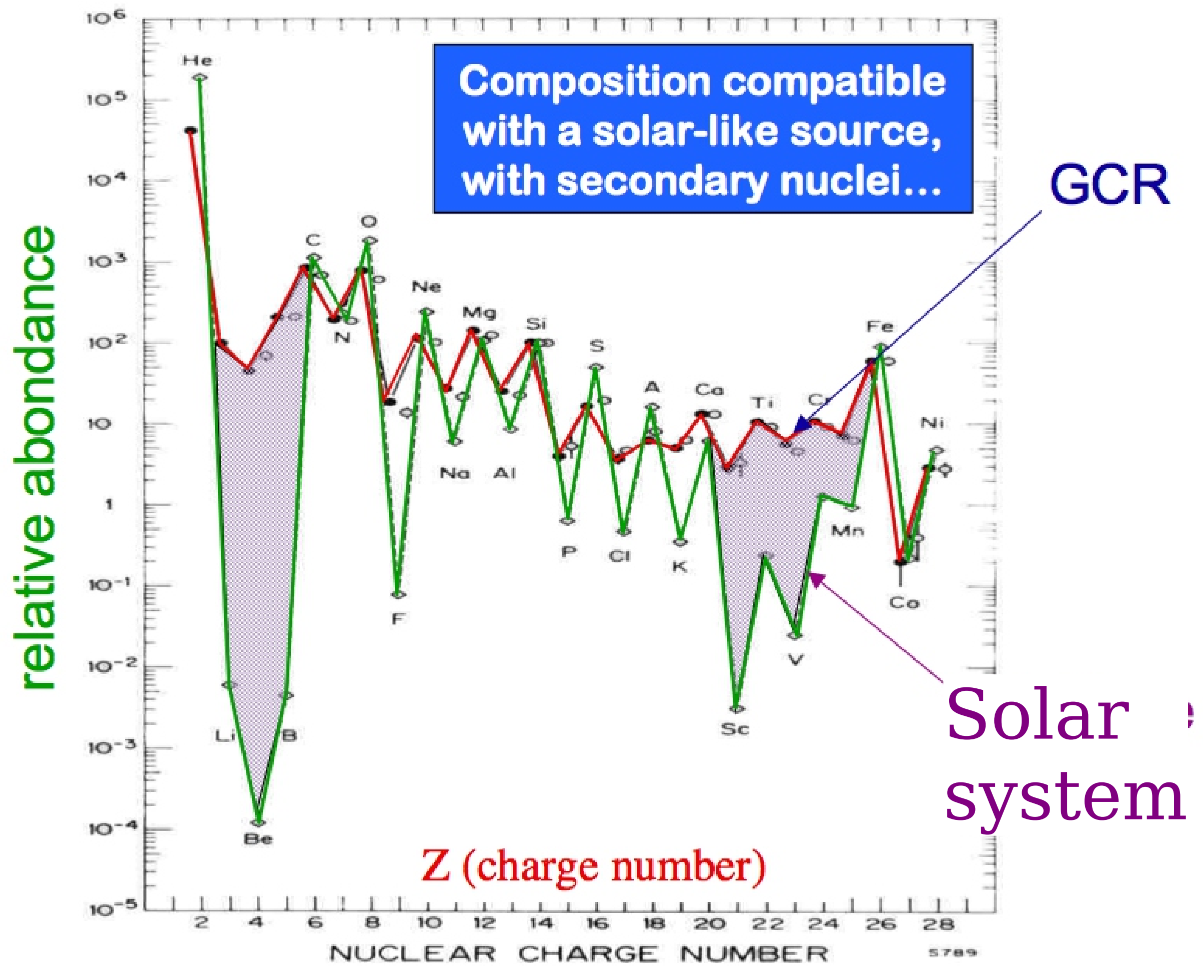
Reconstruction of the Proton population
Inside the two SuperNova shells

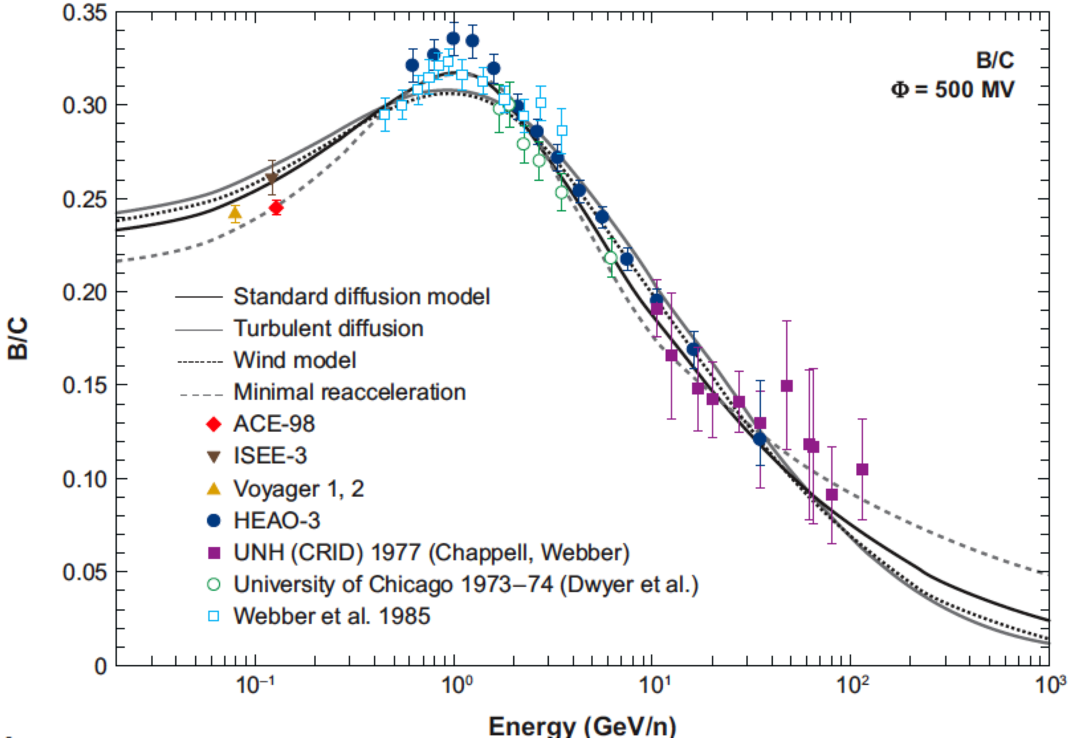


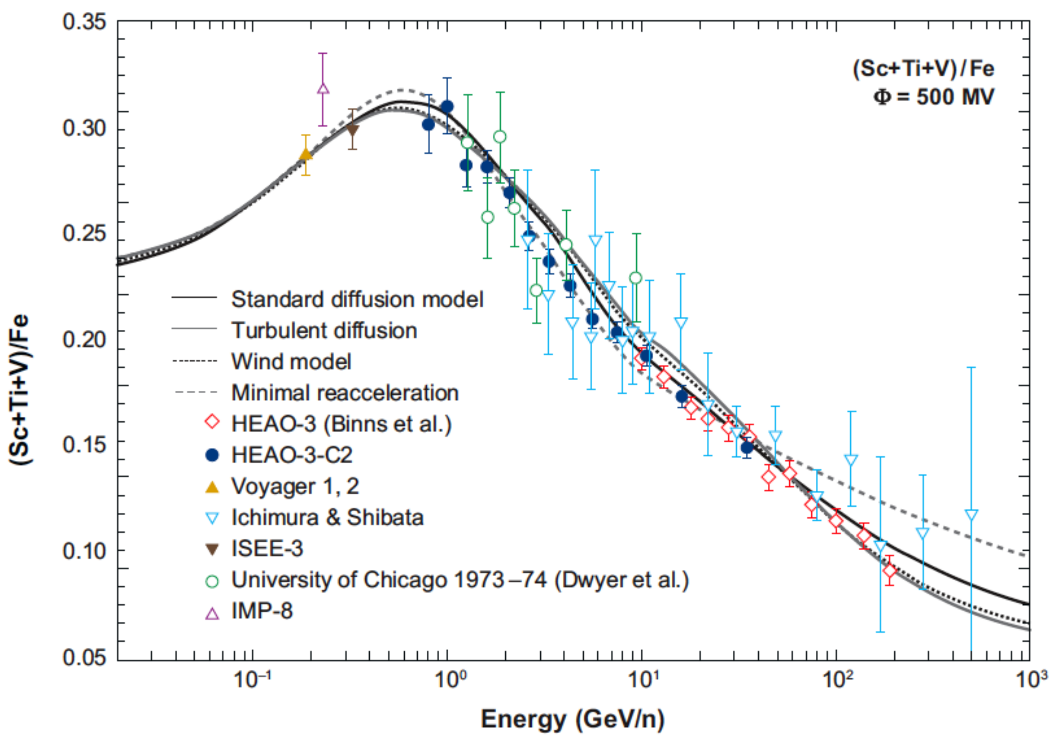
Nuclear Fragmentation
(collisions with the Inter Stellar Medium)











Column density

$$\boxed{X(E) = \langle\rho\rangle\, T(E)}$$

Escape faster at higher E

$$X(E) \propto E^{-\delta}$$

$$\delta \simeq 0.4 \div 0.6$$

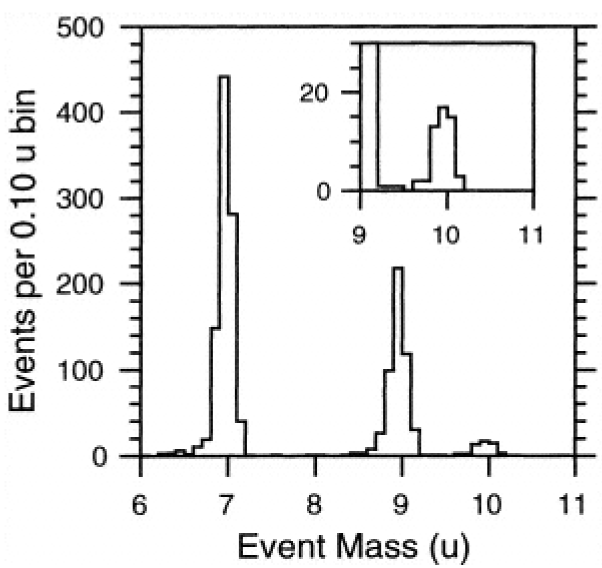
$$\frac{\langle\rho\rangle}{m_p} \simeq 0.2\ \mathrm{cm}^{-3}$$

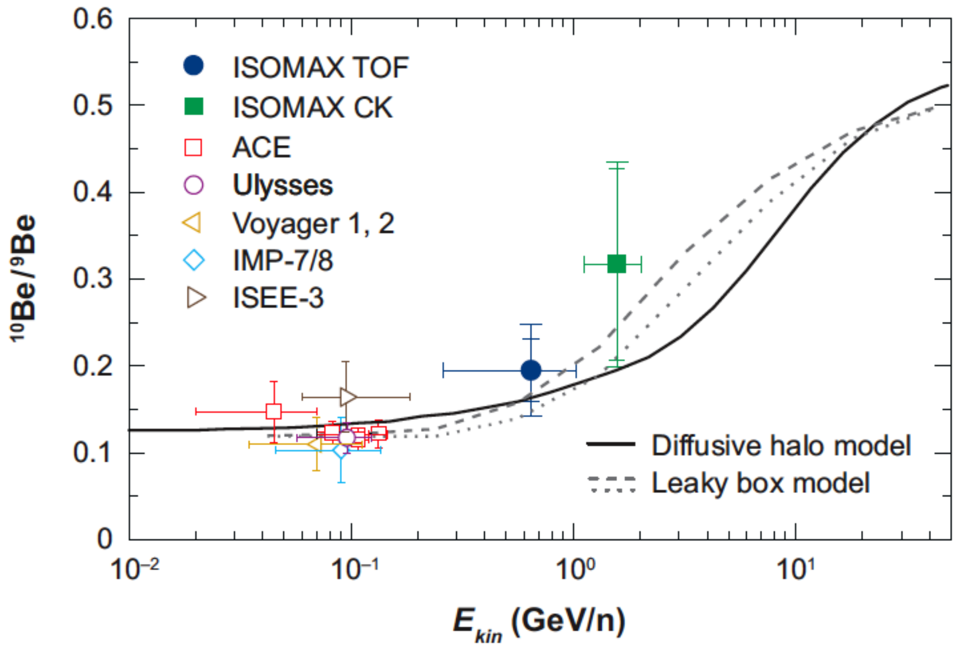
(extended halo)

Determination of the “confinement time” T(p/Z)

“Cosmic clock” (Beryllium-10)

$$T_{1/2}\left[{}^{10}\mathrm{Be}\right] = 1.39 \times 10^{6} \text{ years}$$





$$\boxed{T \simeq 10 \text{ Myr}}$$

4. Very High Energy Cosmic Rays

- Extensive Air Showers
- Longitudinal Development
- Muons and Electromagnetic components

Cosmic Ray Energy Spectrum

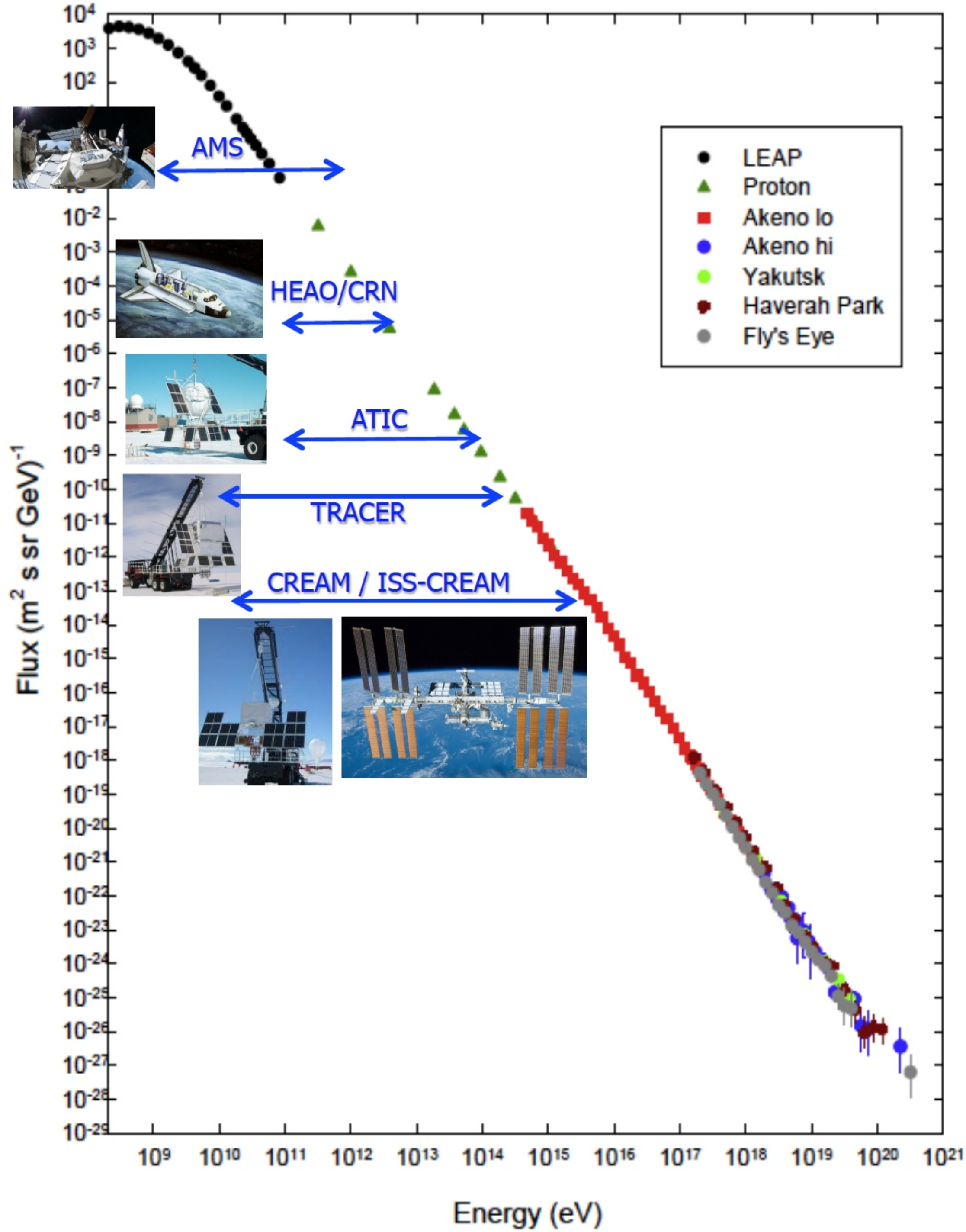
Great extension
in energy

[rapidly decreasing flux]

“Direct”

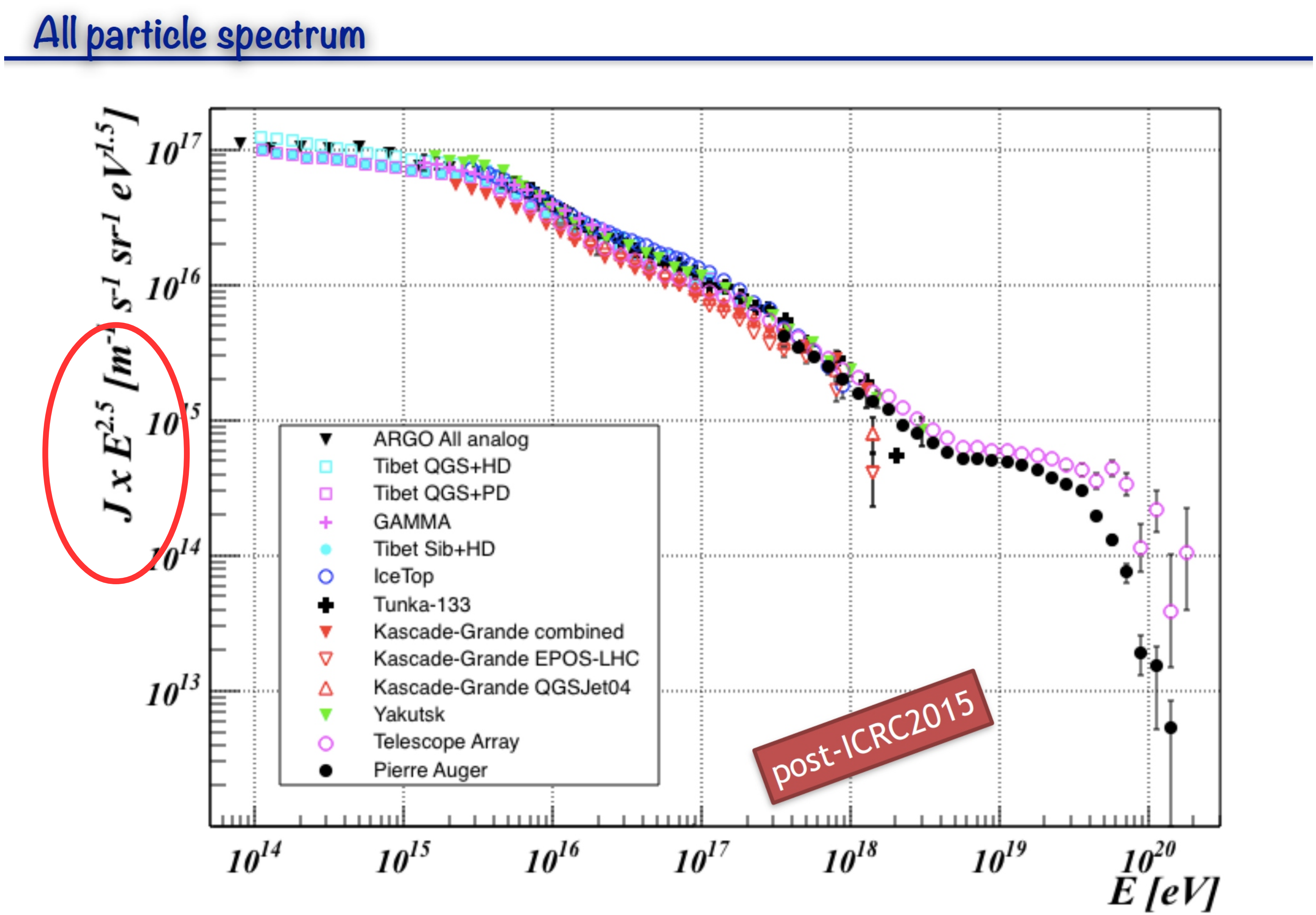
“Indirect”
[Shower properties]
observations

Detection



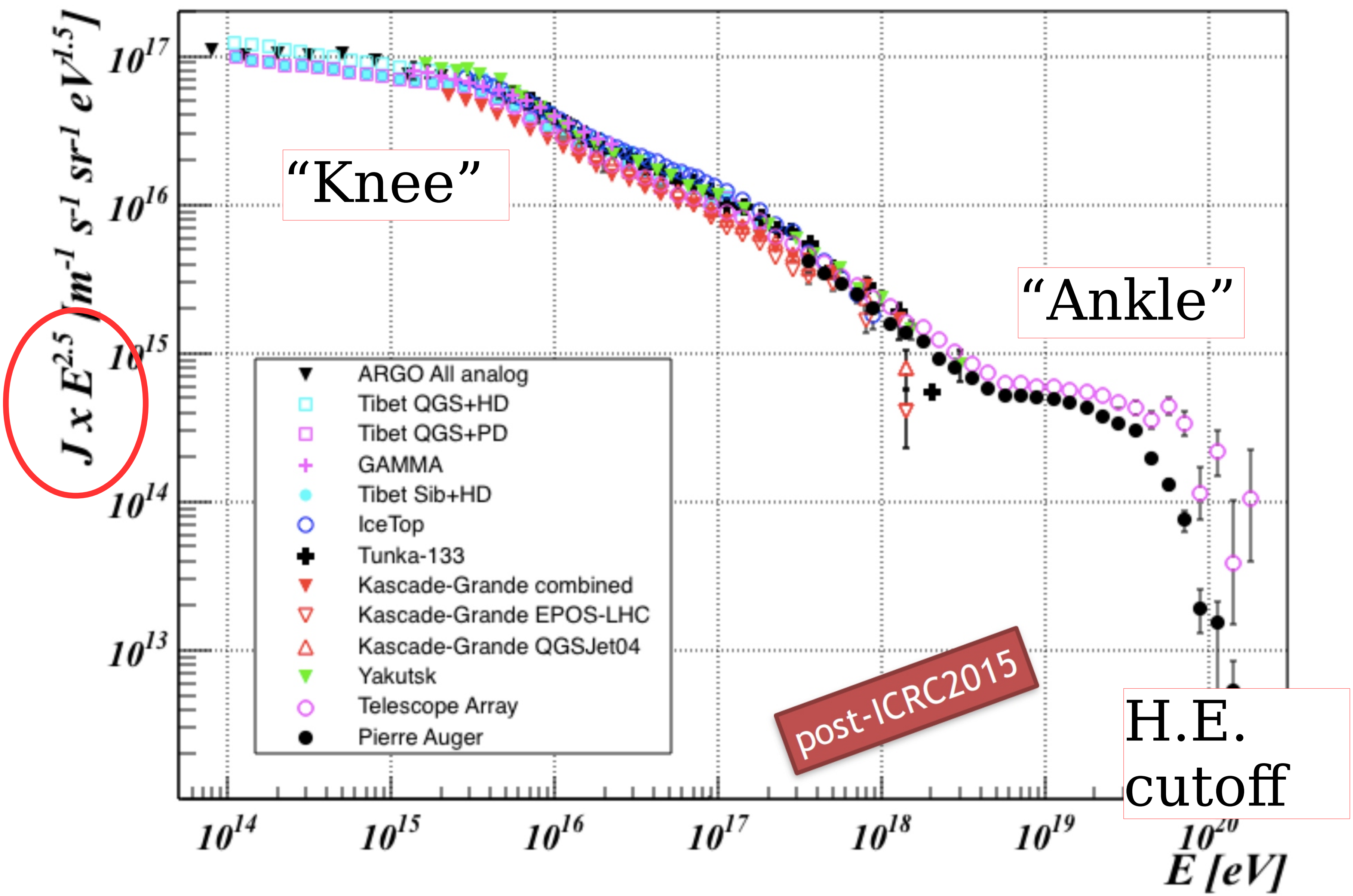
Spectrum of high energy Cosmic Rays
"All particle Spectrum"

$$\phi(E) \times E^{2.5}$$



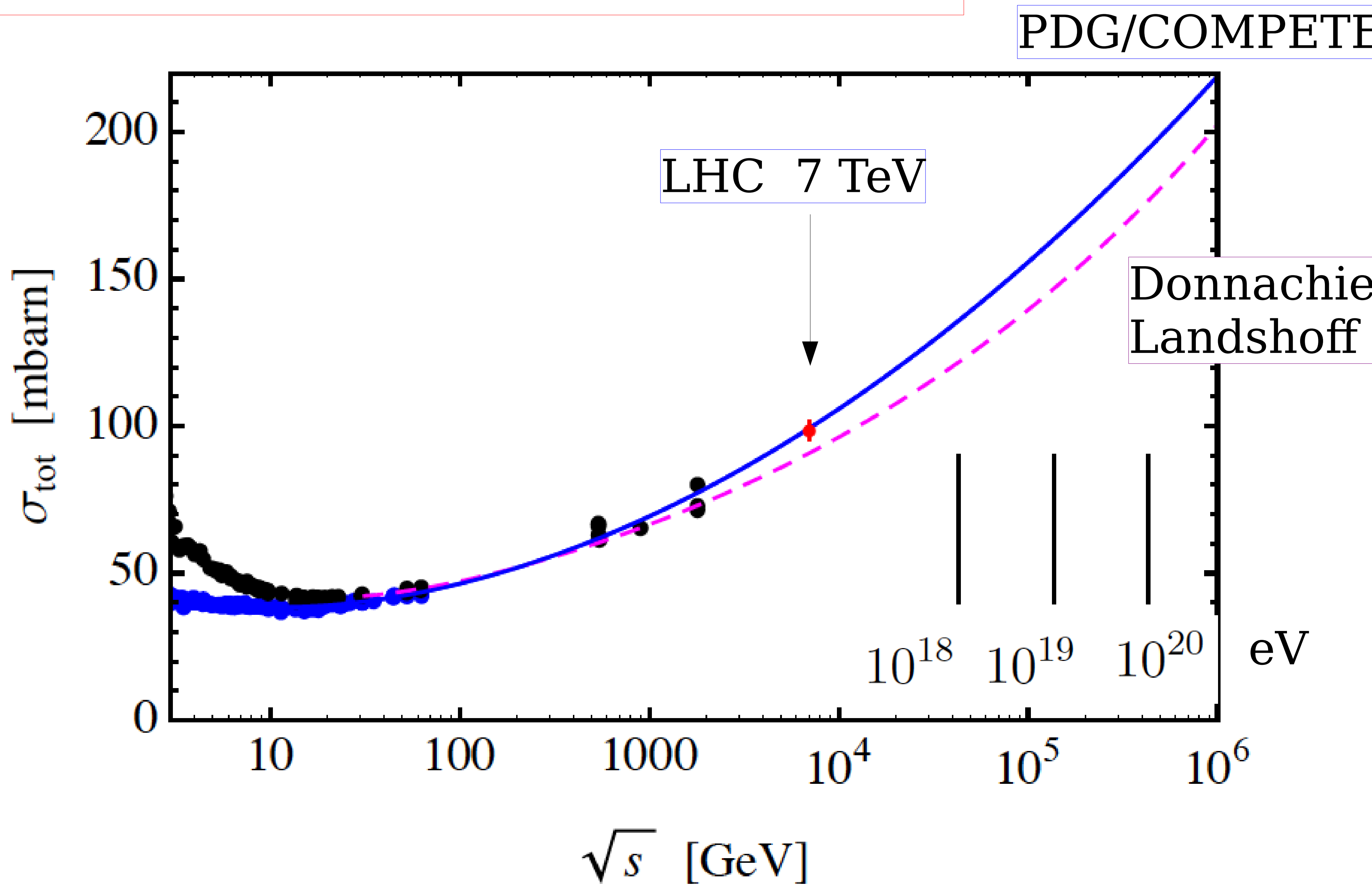
Spectrum of high energy Cosmic Rays $\phi(E) \times E^{2.5}$

All particle spectrum

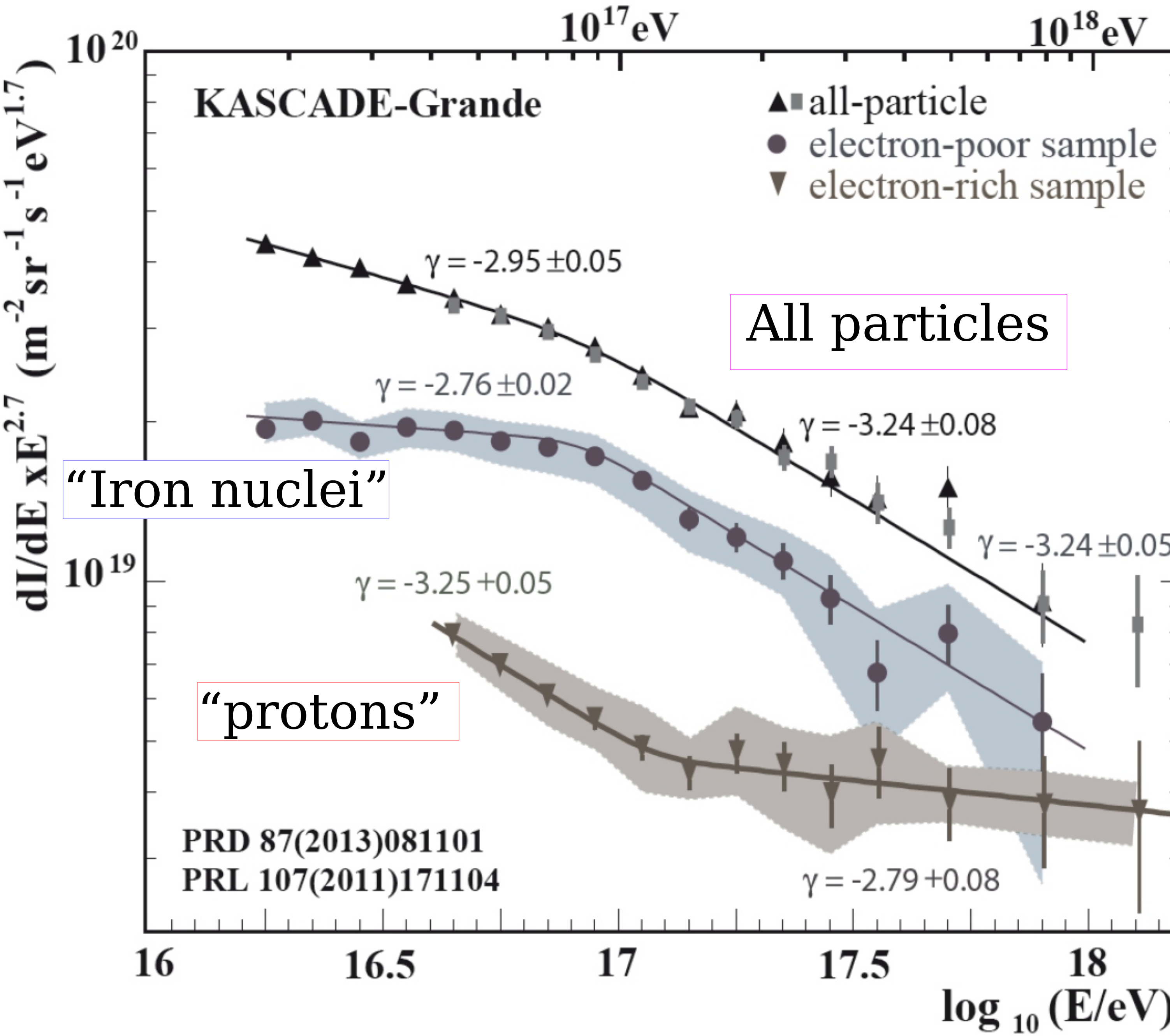


Proton laboratory energy	Nucleon-nucleon c.m. energy
$E_0 \simeq 3 \times 10^{15}$ eV	$\sqrt{s} \simeq 2.37$ TeV
$E_0 \simeq 10^{17}$ eV	$\sqrt{s} \simeq 13.7$ TeV
$E_0 \simeq 10^{18}$ eV	$\sqrt{s} \simeq 43.3$ TeV
$E_0 \simeq 10^{19}$ eV	$\sqrt{s} \simeq 137$ TeV
$E_0 \simeq 10^{20}$ eV	$\sqrt{s} \simeq 433$ TeV

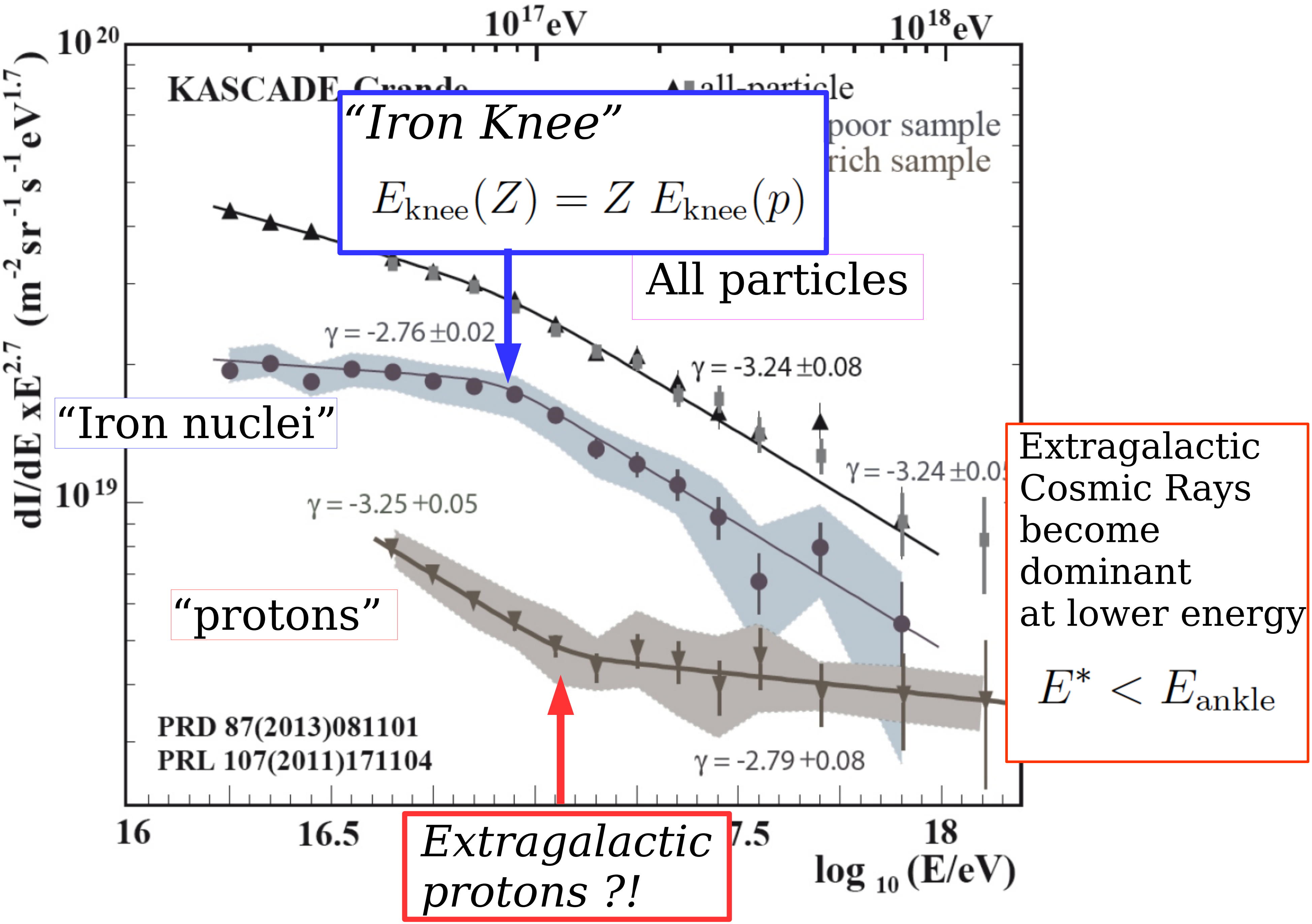
$$E_{\rm lab} = 10^{20}\ \text{eV} \longleftrightarrow \sqrt{s} = 433\ \text{TeV}$$



Kascade-Grande results

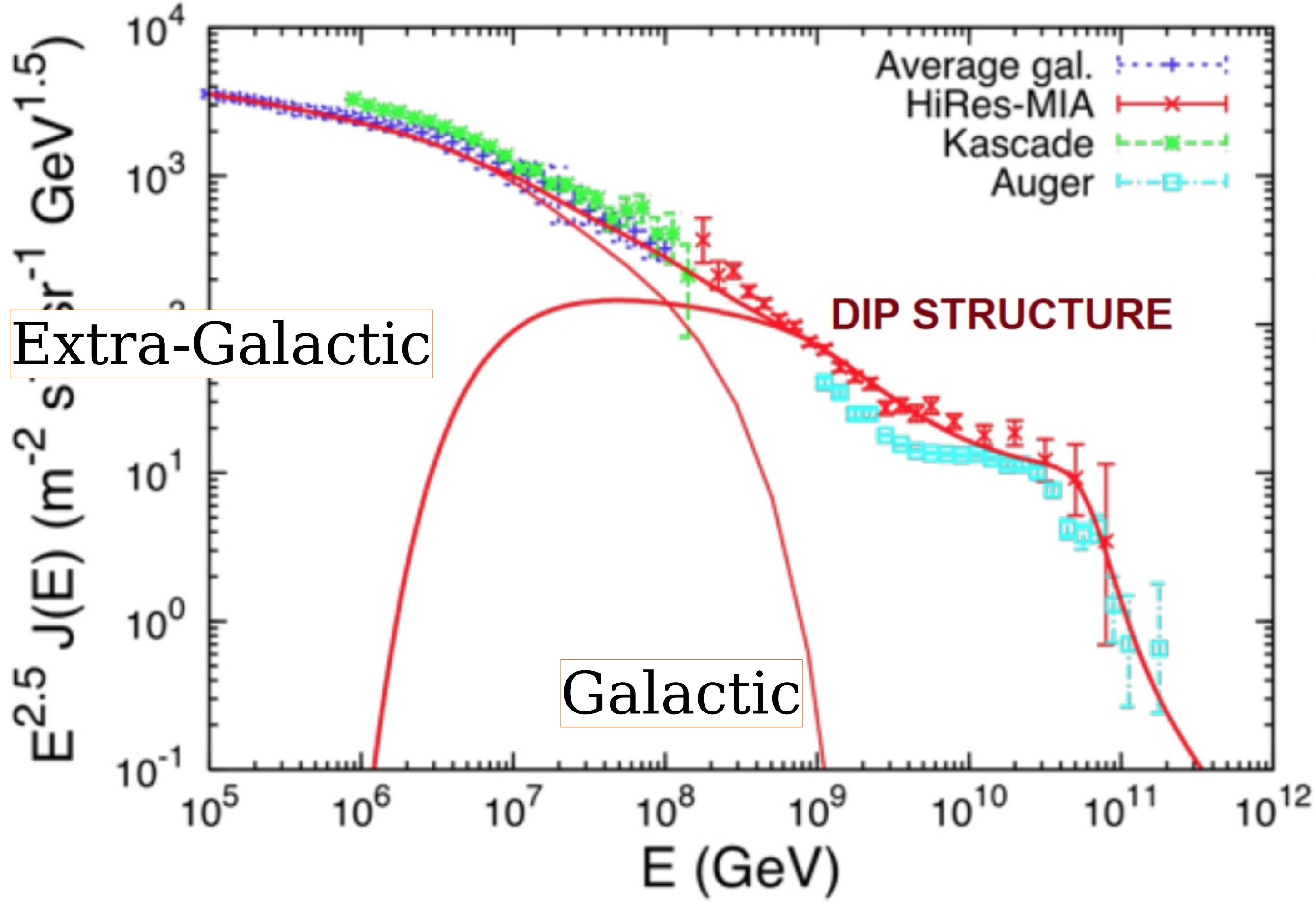


Kascade-Grande results



Interpretation of the Ankle as the “DIP”

$$p + \gamma_{\rm cmbr} \to p + e^+ e^-$$



Interpretation of the Ankle as the "DIP"

$$p + \gamma_{\rm cmbr} \to p + e^+ e^-$$

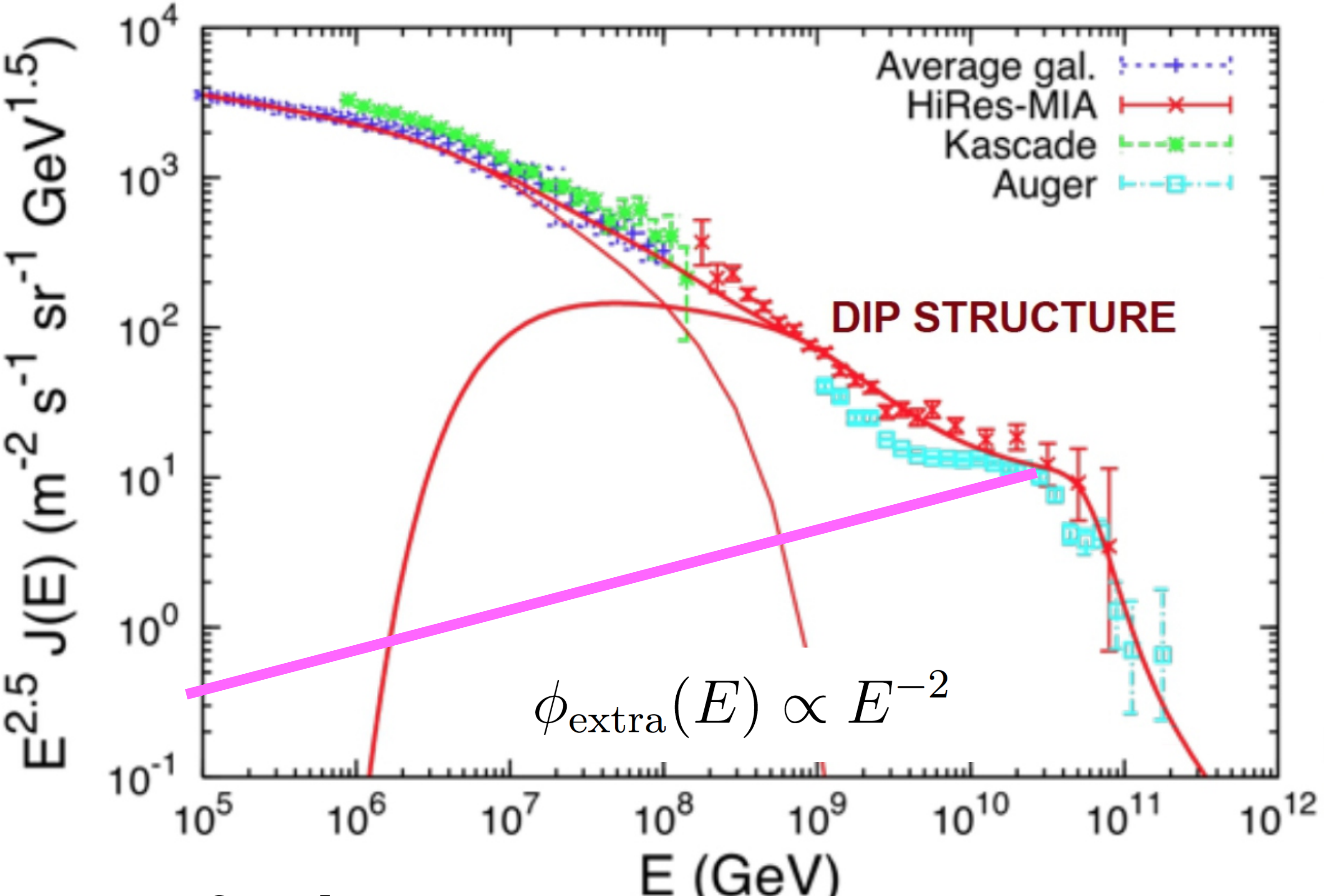
V.Berezinsky, P. Blasi

"ANKLE models"
versus
"DIP Models"

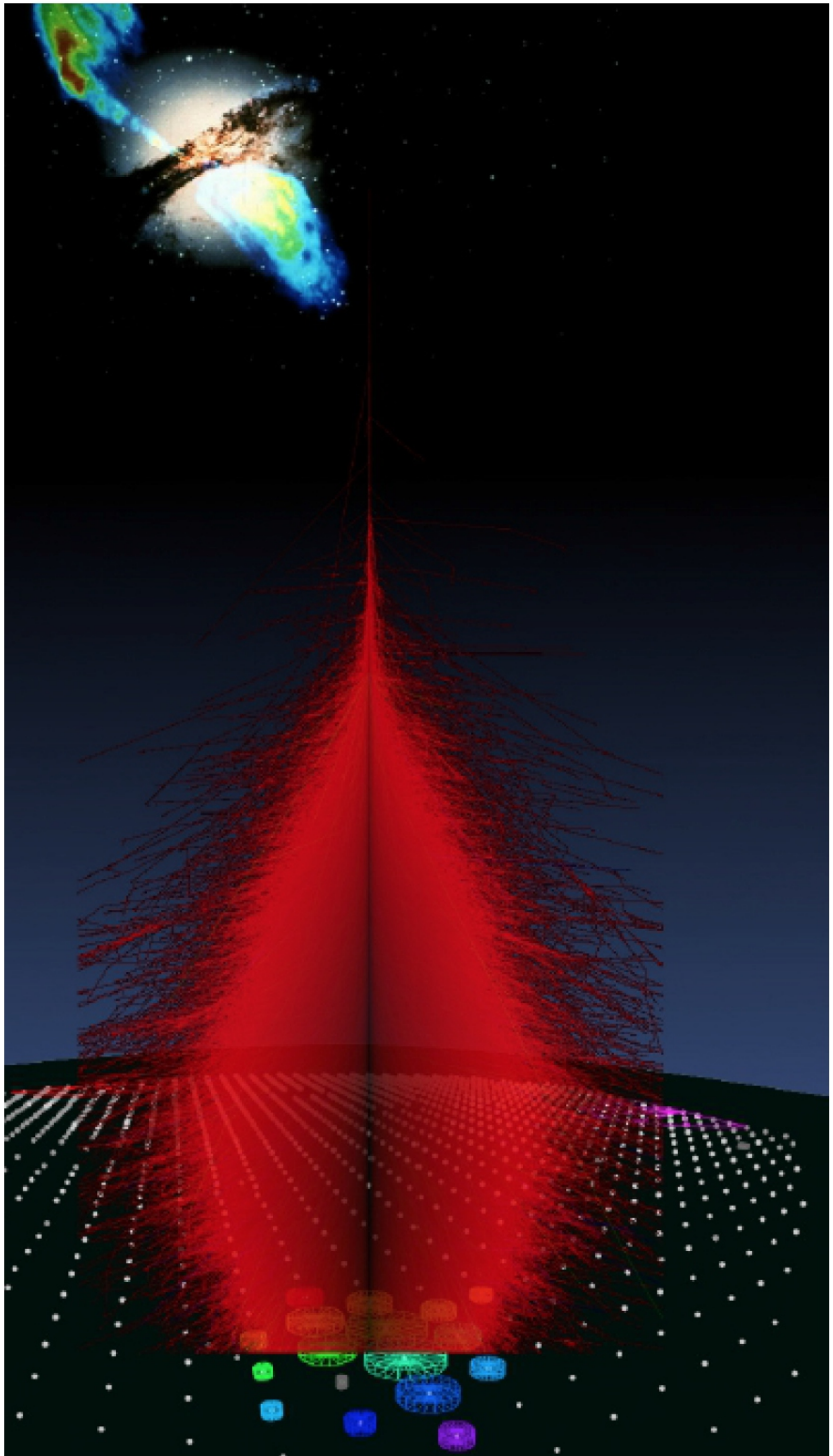
Different
Transition energy

Different
spectral shape

Different Power
requirement



Very important constraints for the sources



the Source

the Shower

[The estimate of the Energy and Mass
of the shower requires the
detailed modeling of shower
development]

the Data

Observations of Cosmic Rays at
Very High energy (Extensive Air Showers)

Two techniques:

1. "Surface Detector"

[A single layer of the shower]
Measure the particles that reach the ground, separating if possible the difference components [*Muon component* + *electromagnetic component*]

2. Fluorescence Light Telescopes

Measure the *Longitudinal development* of an Air shower

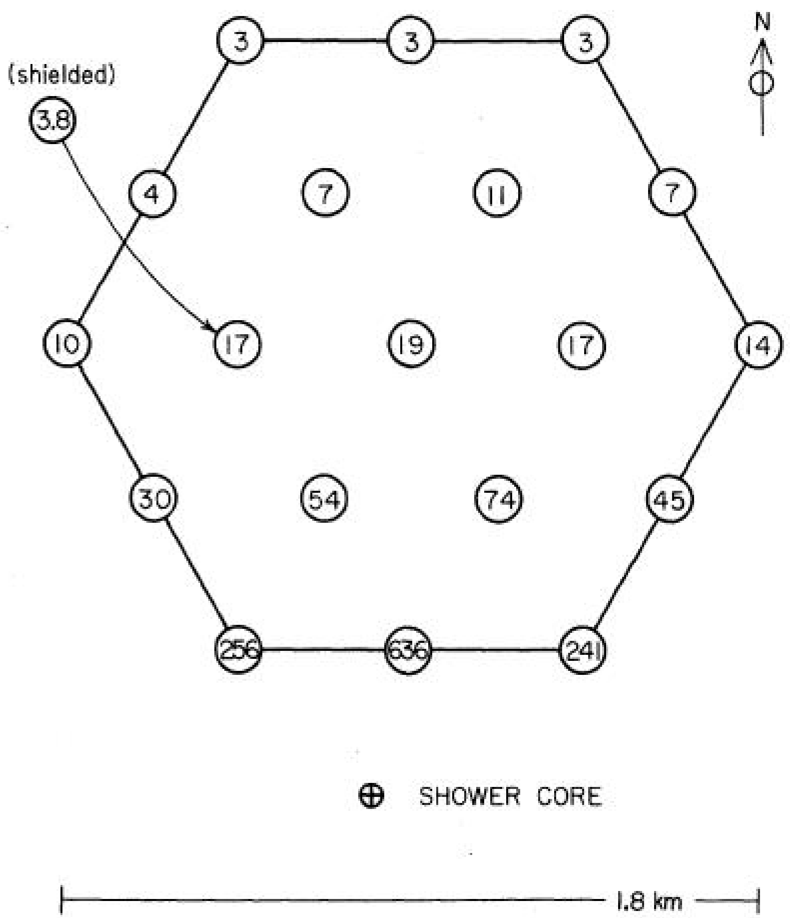
PHYSICAL REVIEW LETTERS

~60 years of UHECR

EXTREMELY ENERGETIC COSMIC-RAY EVENT*

John Linsley, Livio Scarsi,† and Bruno Rossi
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received April 12, 1961)

Energy

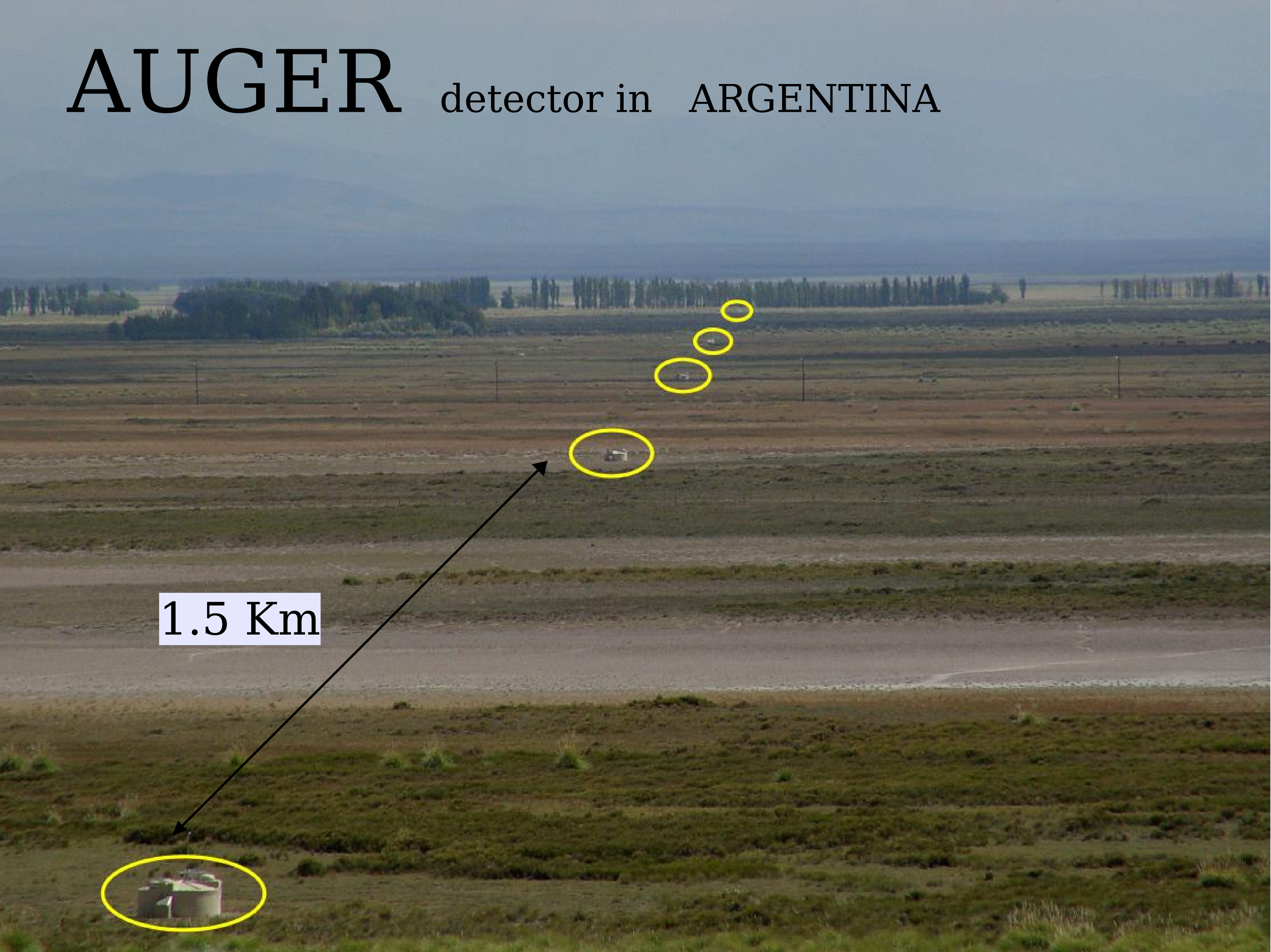


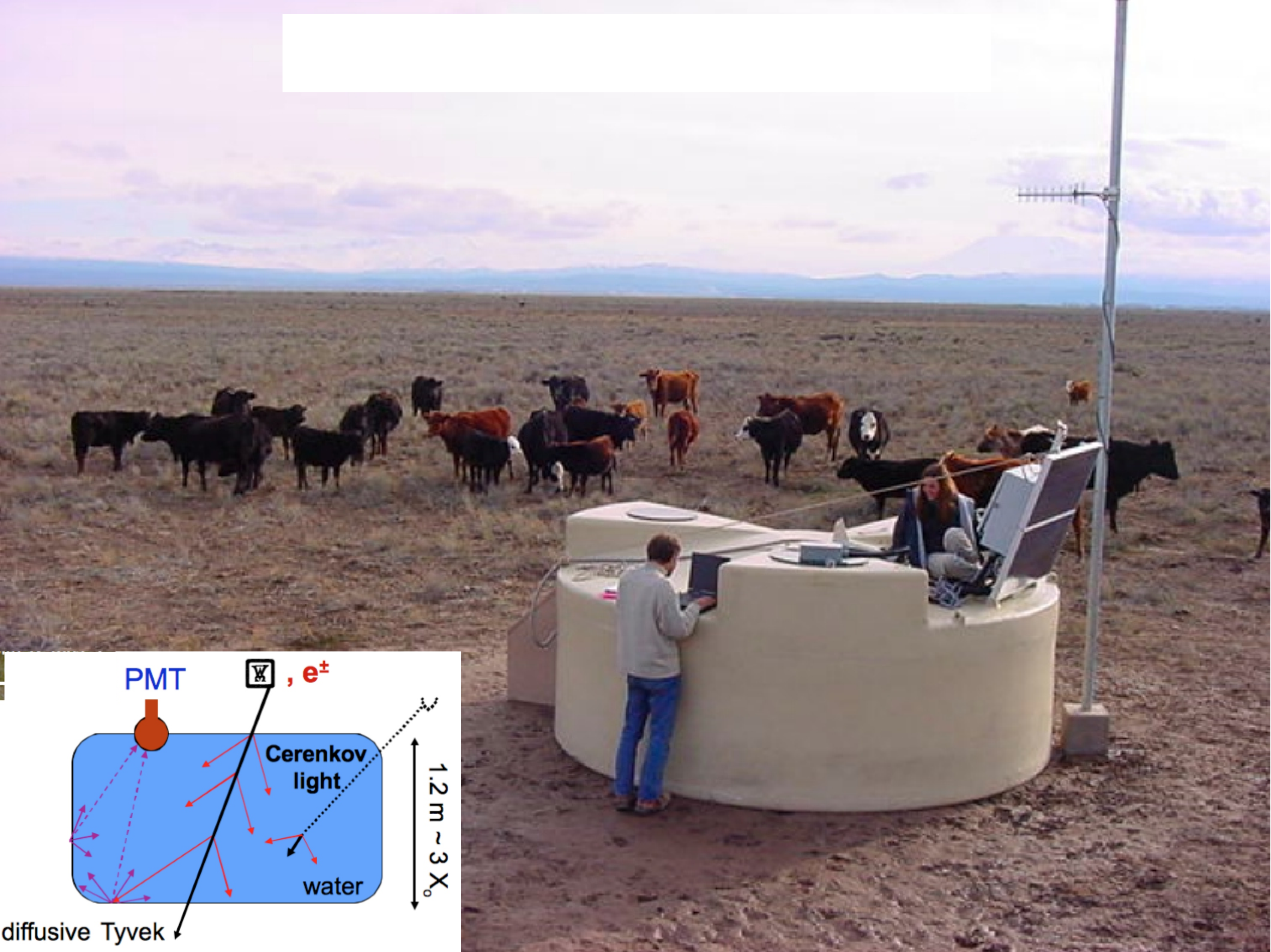
it follows on any reasonable shower model that the energy of the primary particle was about 10^{19} ev. Taking the usual estimate 3×10^{-6} gauss for the galactic magnetic field, one finds the radius of curvature of the path of a proton of such energy to be about 10^4 light years. Since, according to current estimates, the radius of the galactic halo is only about five times this value, while the thickness of the galactic disk is about five or ten times smaller, it seems certain that the primary particle acquired its energy outside our galaxy.

An important question is whether the primary particle was a proton or a heavier nucleus.

Hadronic interaction Modeling

Mass A

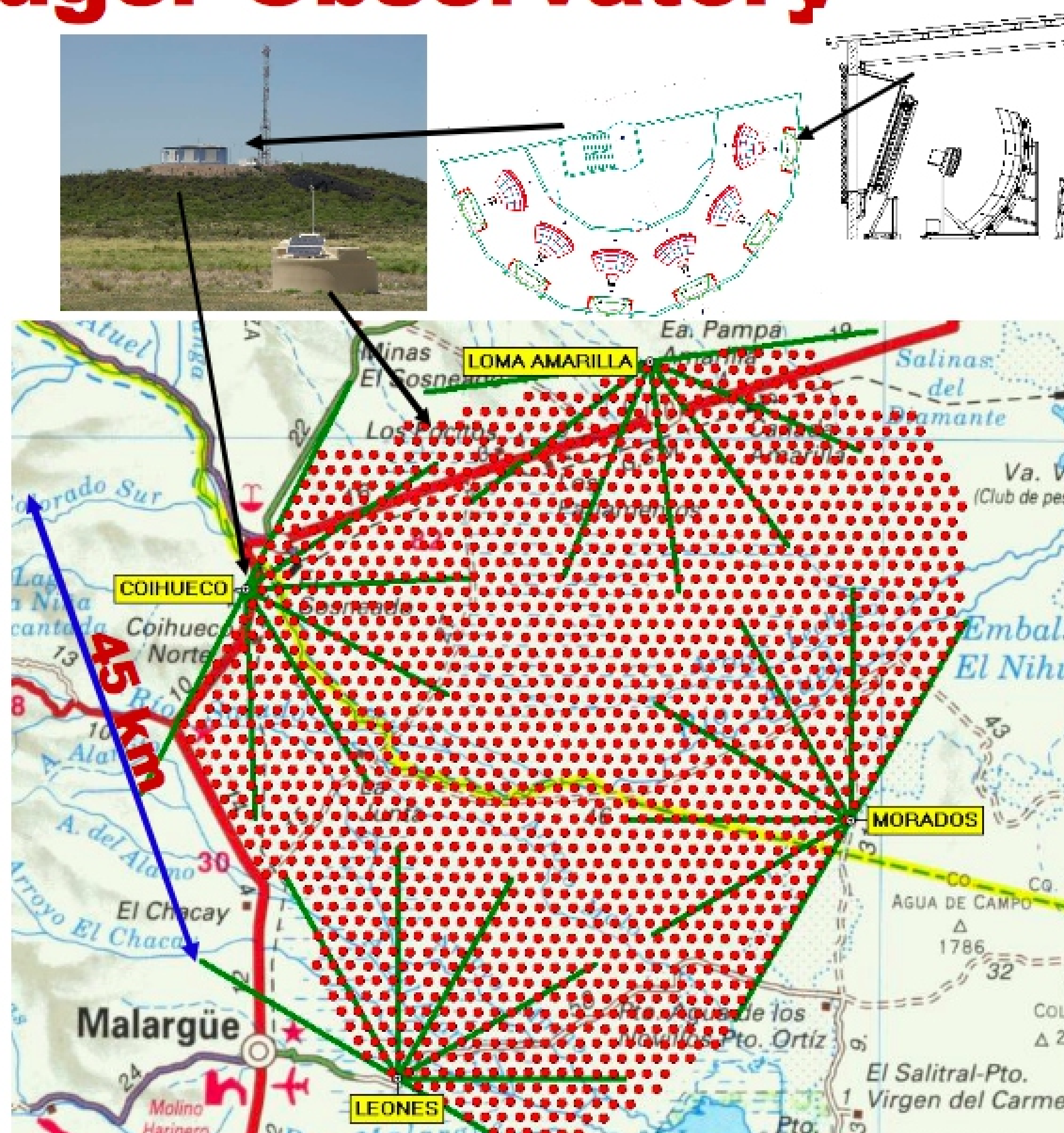

AUGER detector in ARGENTINA
1.5 Km


PMT
, e±
Cerenkov light
water
1.2 m ~ 3 X$_o$
diffusive Tyvek

The Pierre Auger Observatory

Argentina, Mendoza, Malargue
1.4 km altitude, 870 g/cm²

Argentina	Mexico
Australia	Netherlands
Bolivia*	Poland
Brazil	Slovenia
Czech Republic	Spain
France	United Kingdom
Germany	USA
Italy	Vietnam*

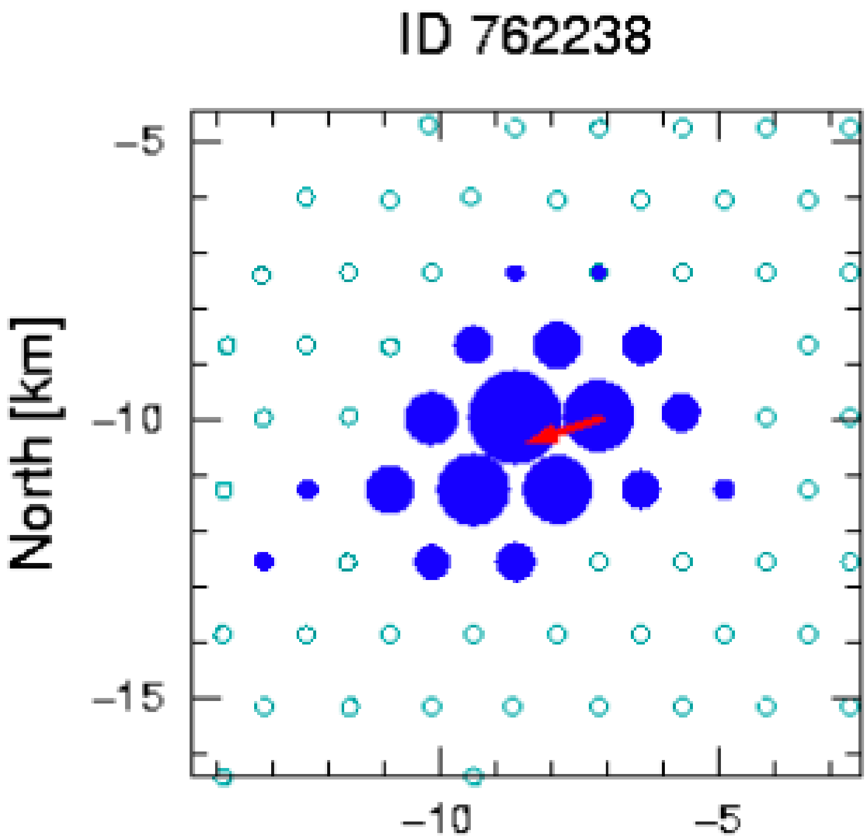


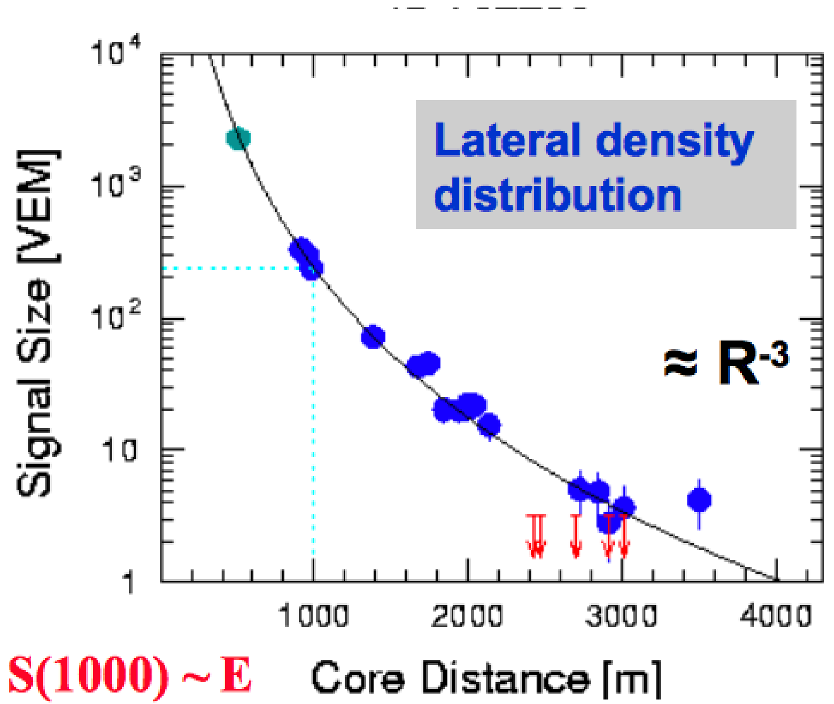
1600 water Cherenkov detectors,

1.5 km spacing, 3000 km²,

4 x 6 fluorescence telescopes

Auger – Surface-Detector



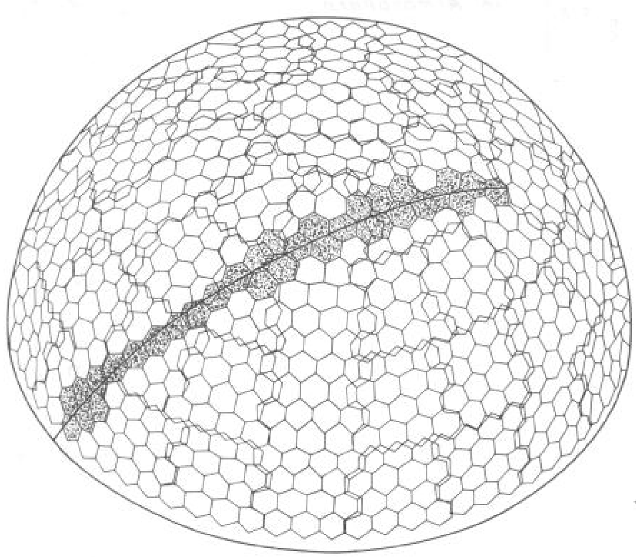


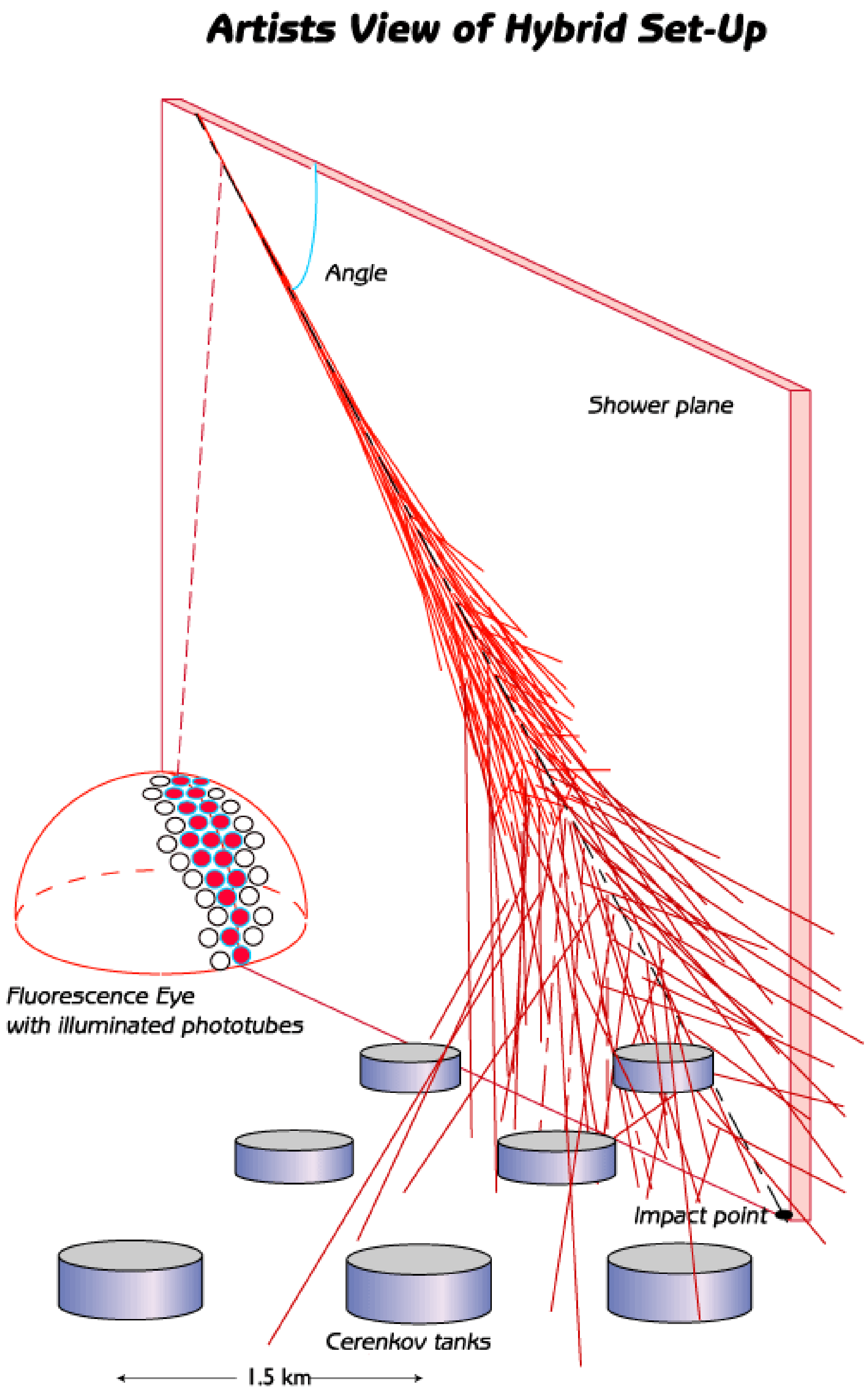
Timing of tank-signals give shower direction

VEM = Vertical-Equivalent-Muon

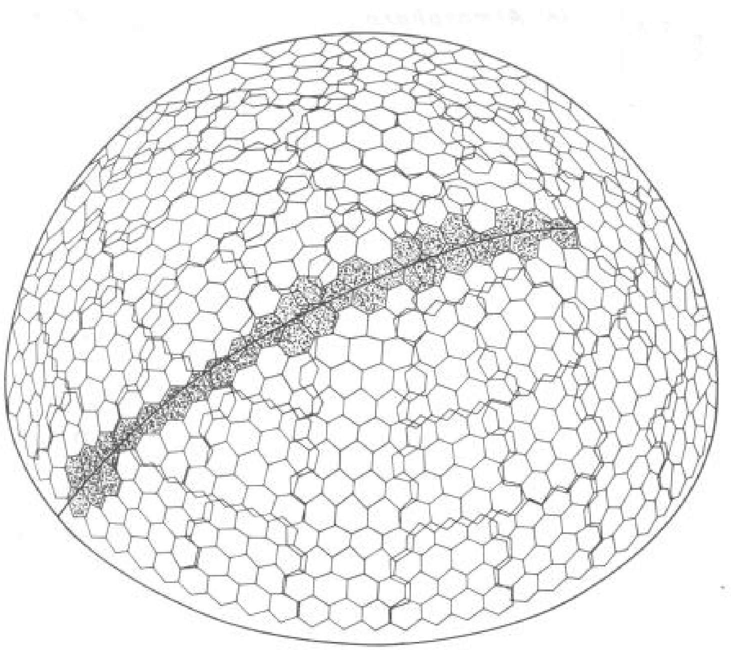
How can one estimate the energy ?

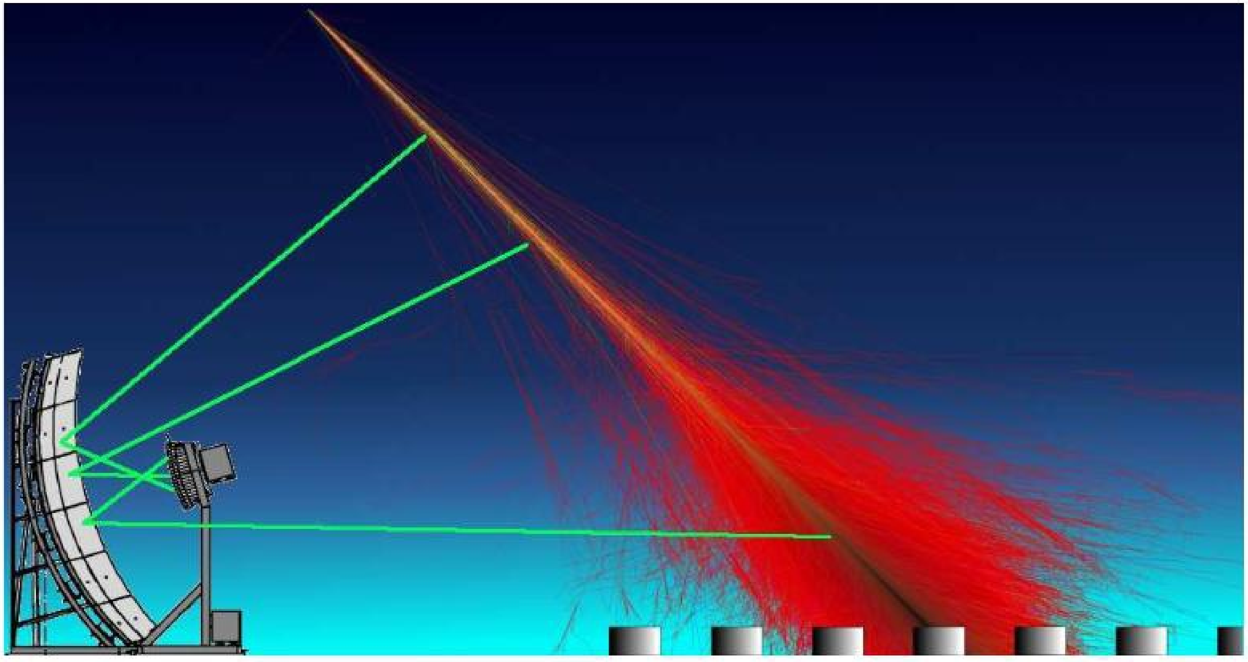
The **Fly's Eye** Detection concept





The **Fly's Eye** Detection concept

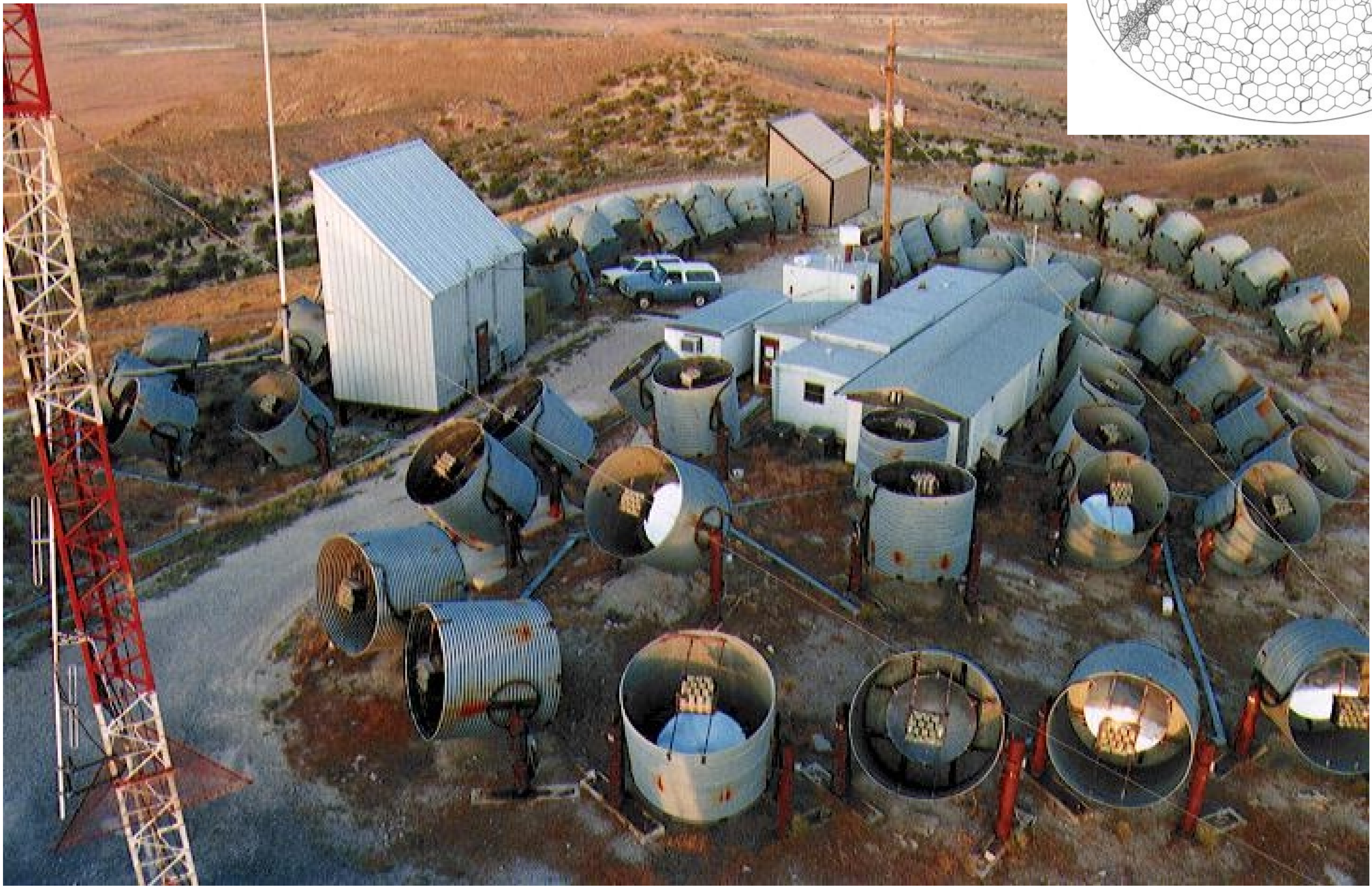


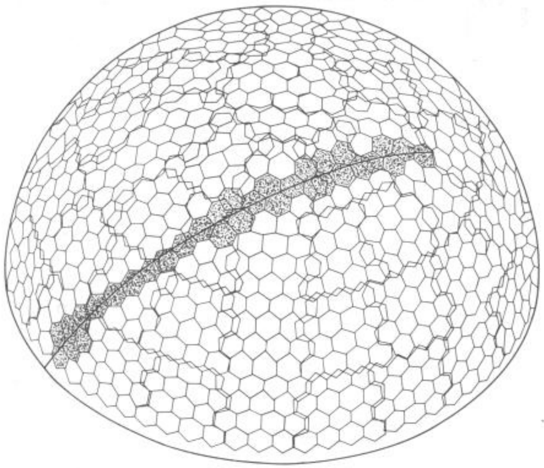


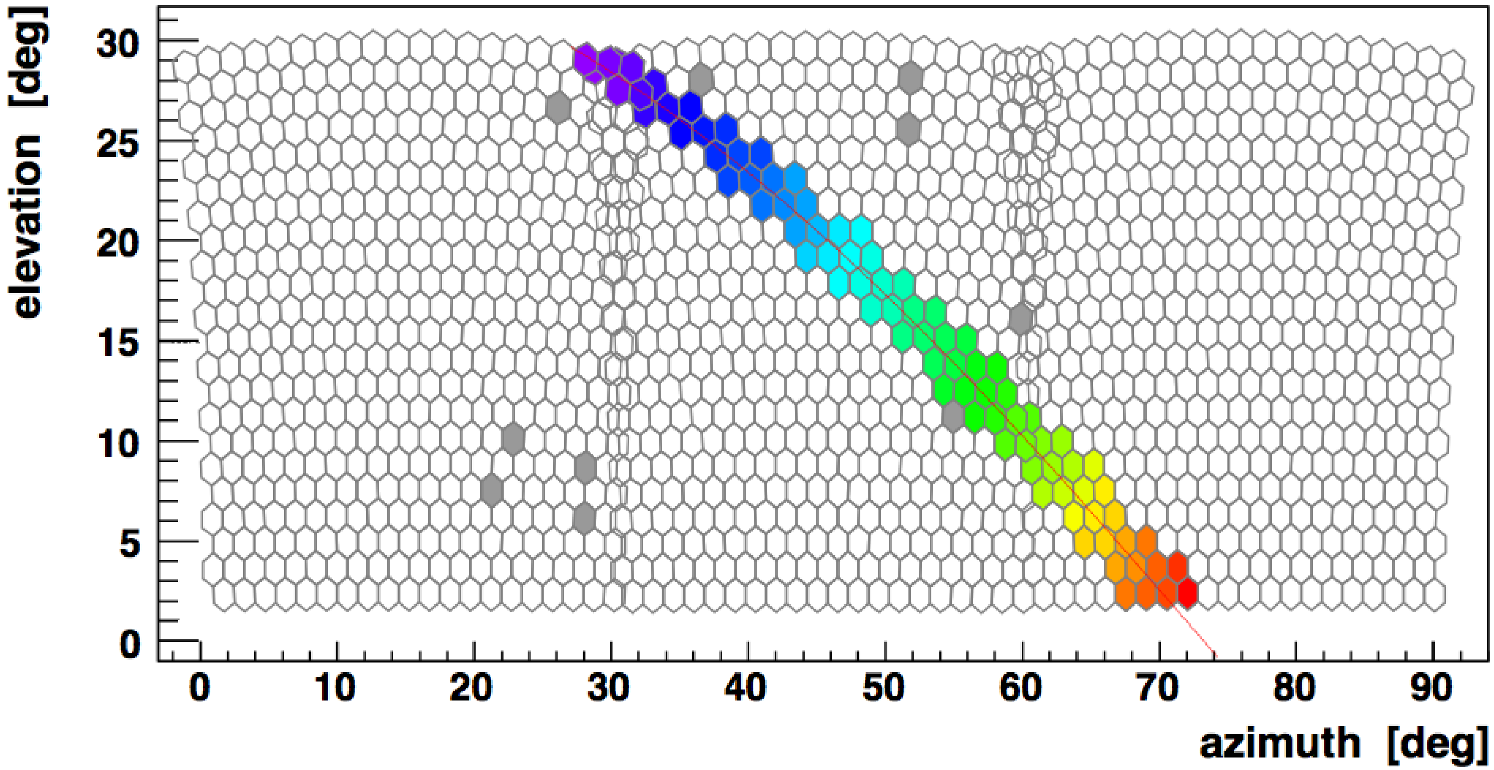
Fluorescence light emitted isotropically by excited Nitrogen molecules

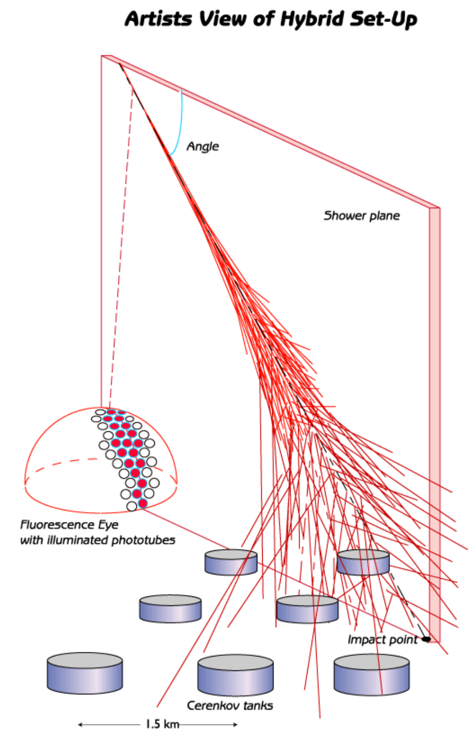
Yield ~ 4 photons/meter
300-400 nm

Original Fly's Eye detector
(1981 - 1993)







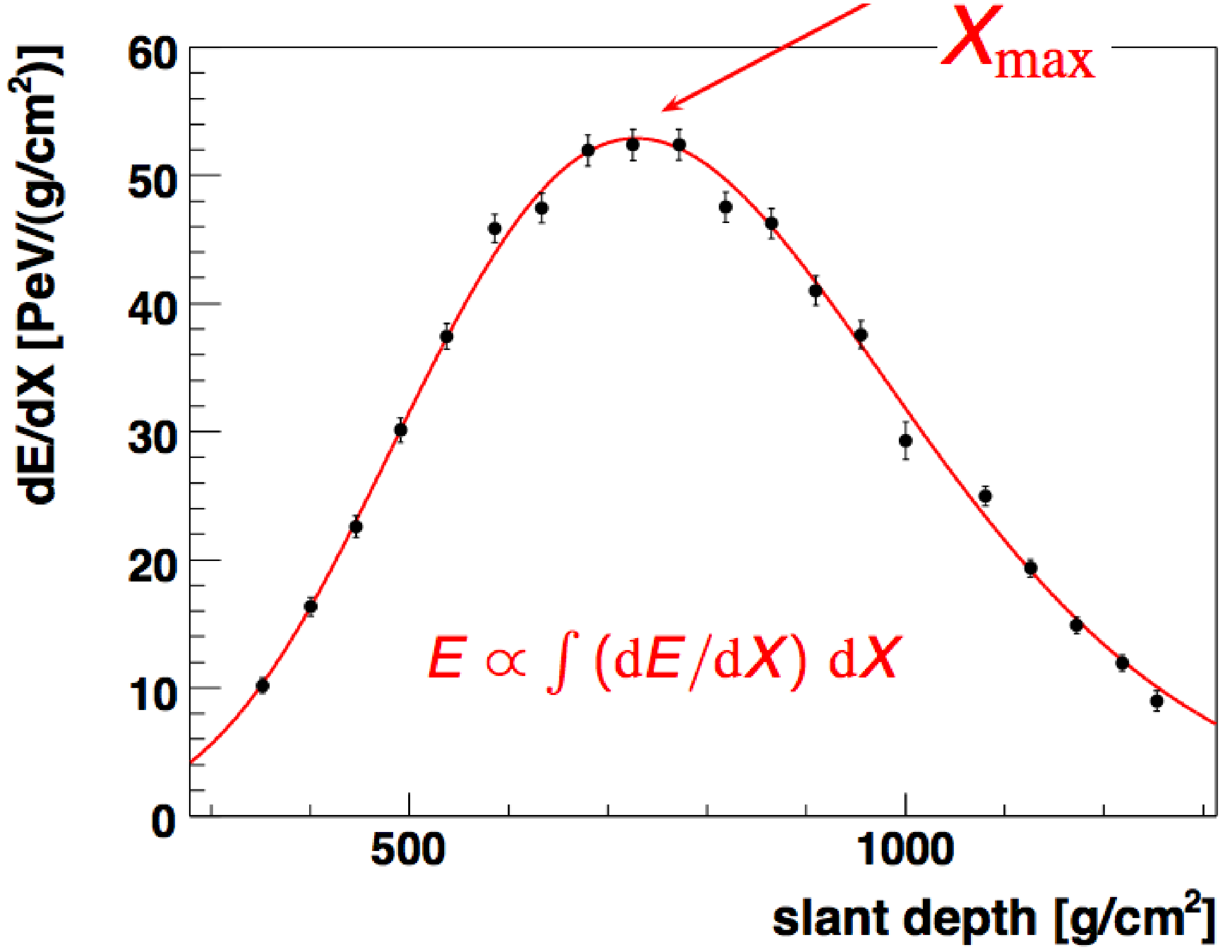


$$L(\Omega) \rightarrow F_{\gamma}(X) \rightarrow N_{e^{\pm}}(X)$$

Observed Light → Emitted Photons → Shower Size

Geometry, atmospheric absorption

Fluorescence yield



Energy Reconstruction:

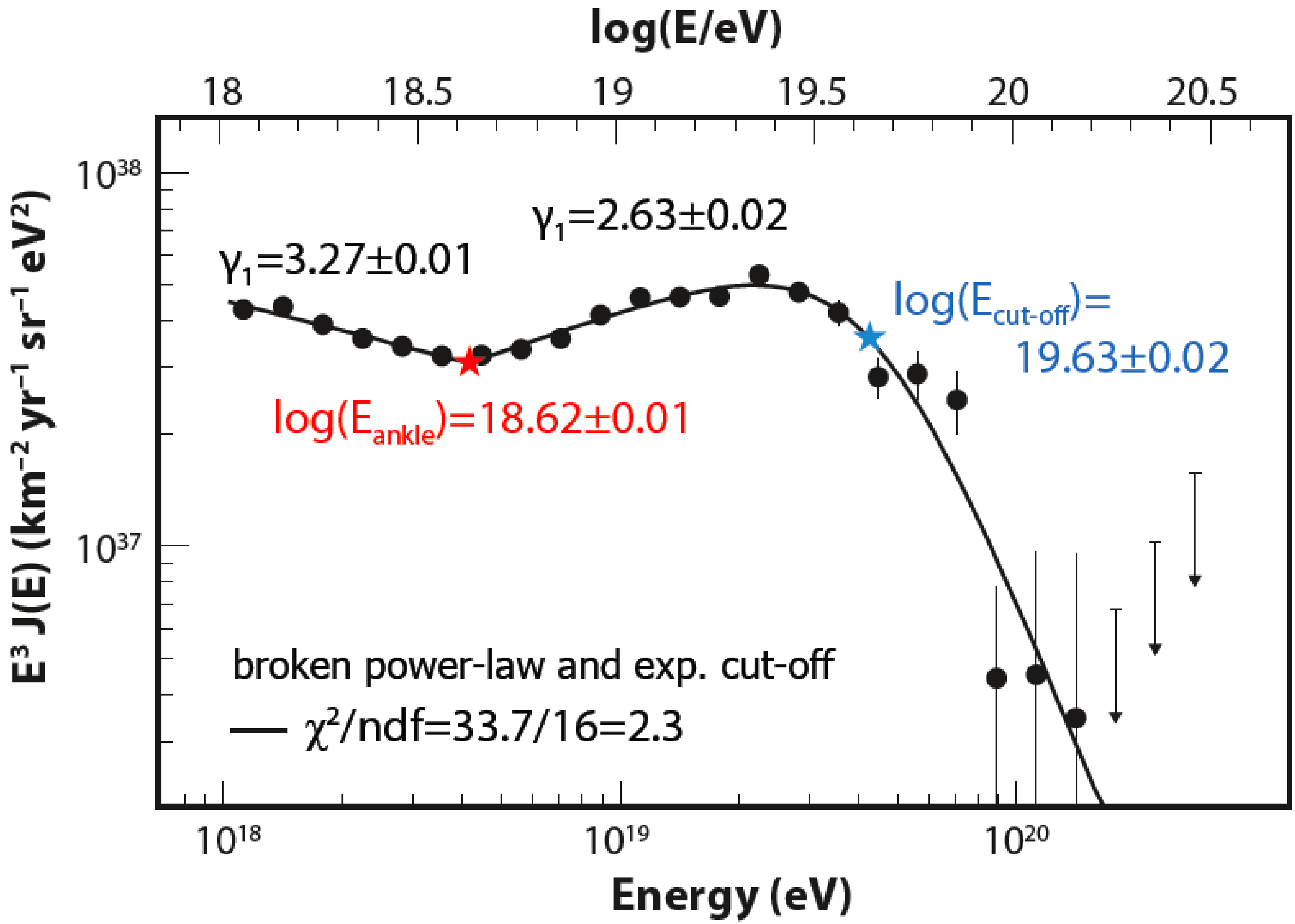
Area $\propto$ Energy

Small Model dependence

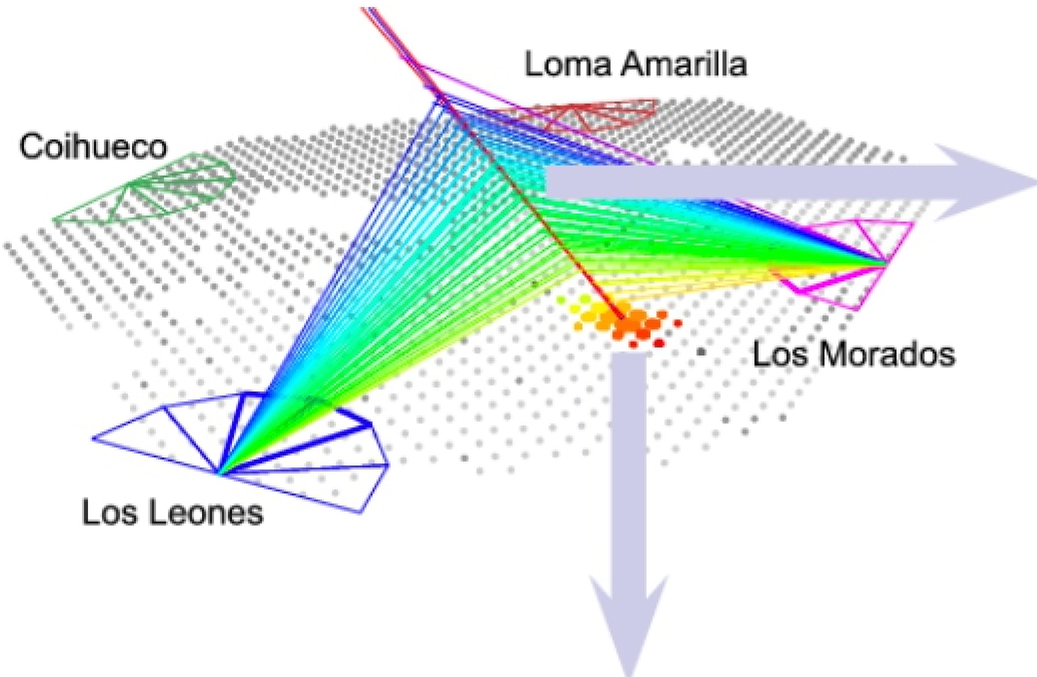
$$E_{\text{ionization}} = \int dX\ N_e(X) \left\langle -\frac{dE}{dX} \right\rangle$$

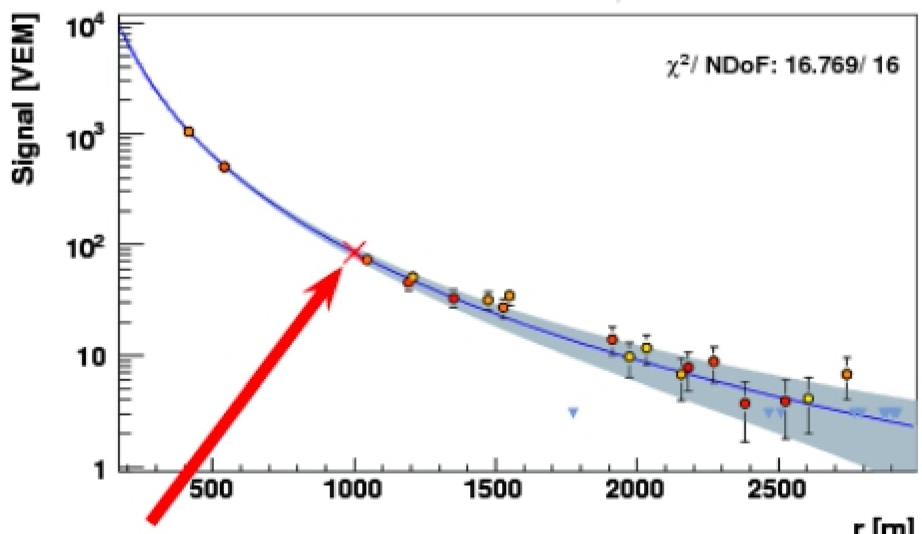
$$E_{\text{tot}} = E_{\text{ionization}} + E_\nu + E_\mu + E_{\text{ground}}$$

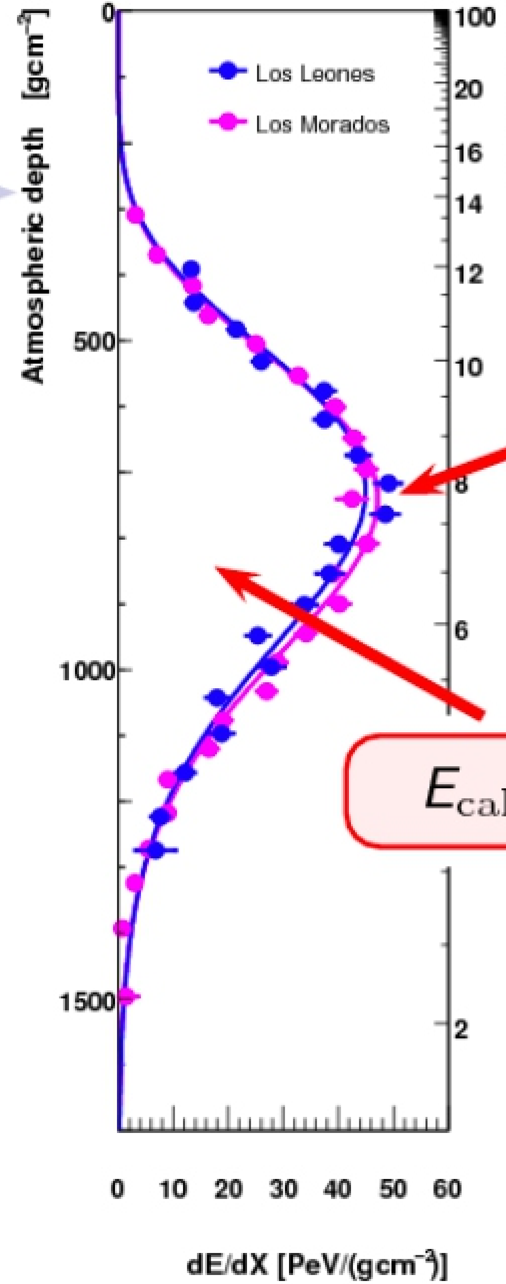
AUGER Energy Spectrum



The Auger ‘hybrid’ detector







$\sigma_{X_{\max}} < 20\,\mathrm{g/cm^2}$

$\Delta_{\mathrm{sys}} \approx 15\,\mathrm{g/cm^2}$

$X_{\max}$

$E_{\mathrm{cal}} = \int \mathrm{d}X\ \frac{\mathrm{d}E}{\mathrm{d}X}$

$\sigma_E/E \sim 8\,\%$

$\Delta_{\mathrm{sys}} \approx 22\,\%$

Fluorescence yield ~14%

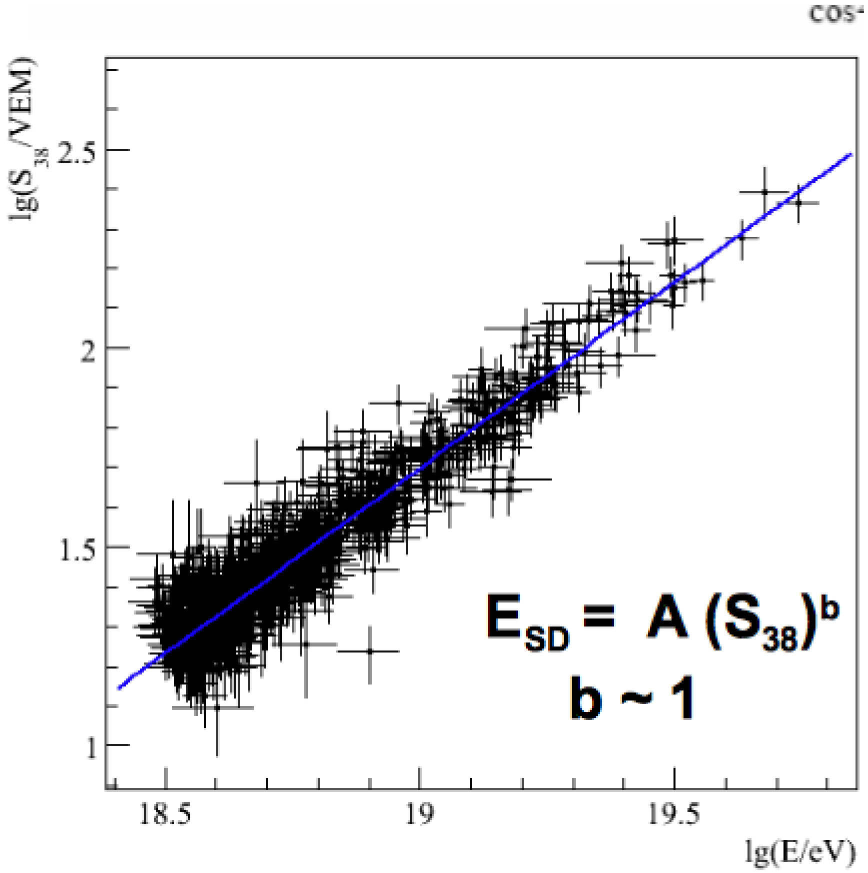
S_{1000}

$E_{\mathrm{surface}} = f(S_{1000},\ \theta)$

Calibration of the energy measurement
of the Surface detector

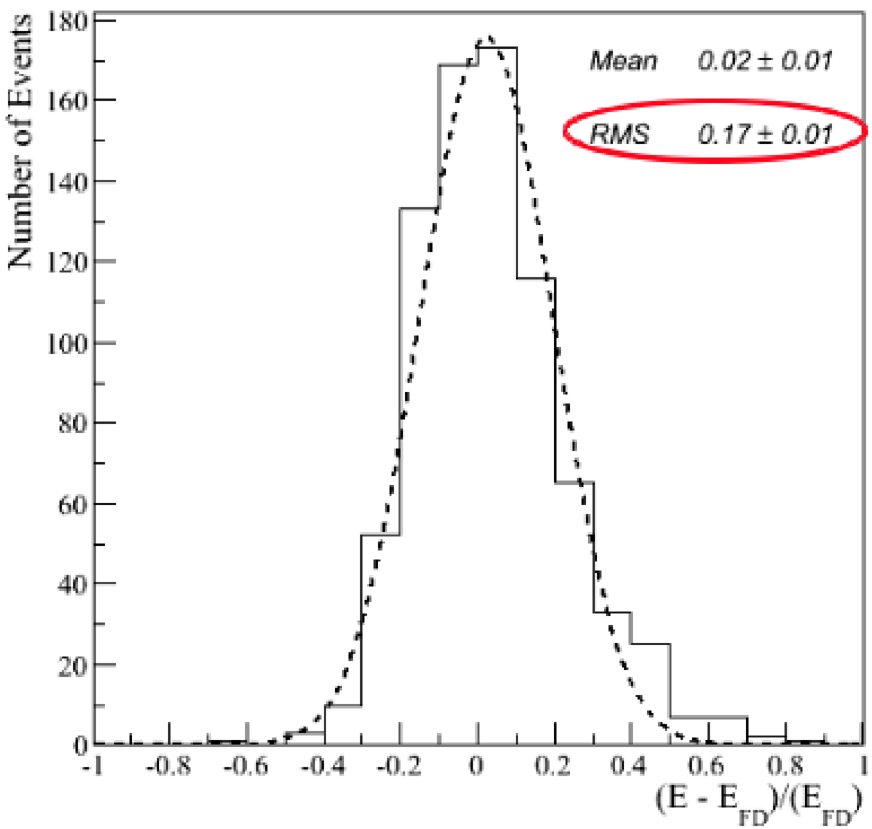
with fluorescence light observations

SD



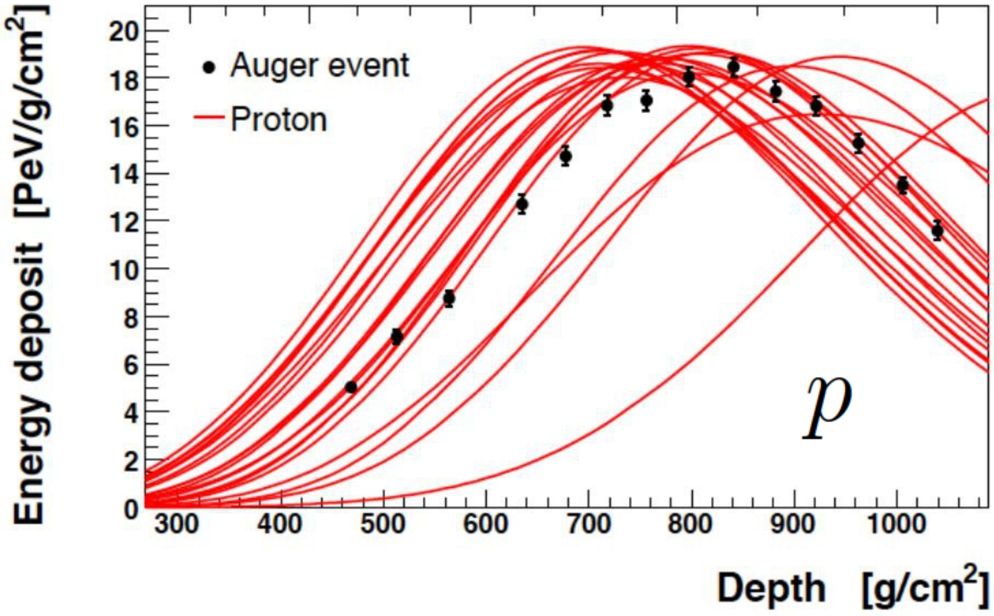
FD

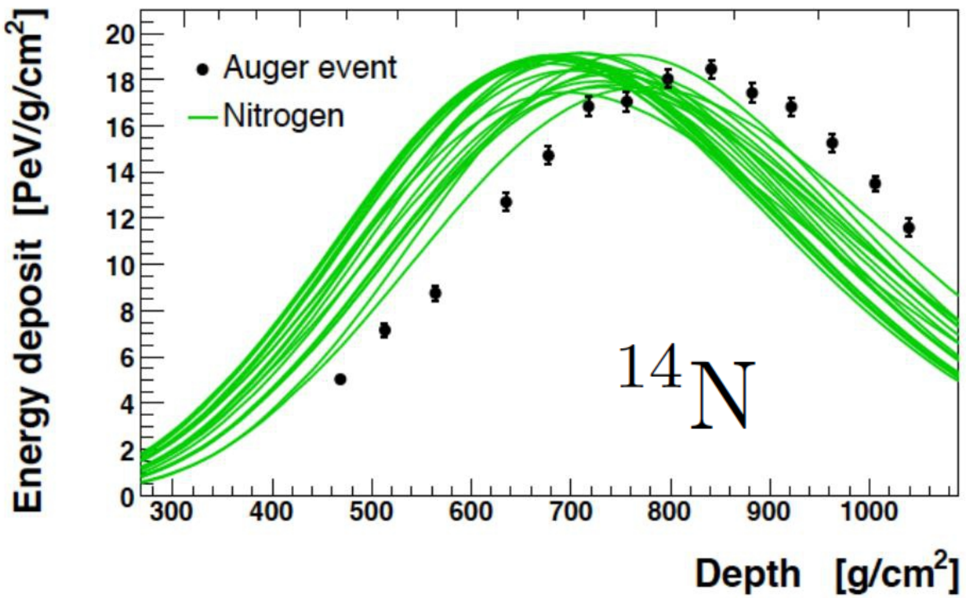
SD Energy resolution
better than 20%

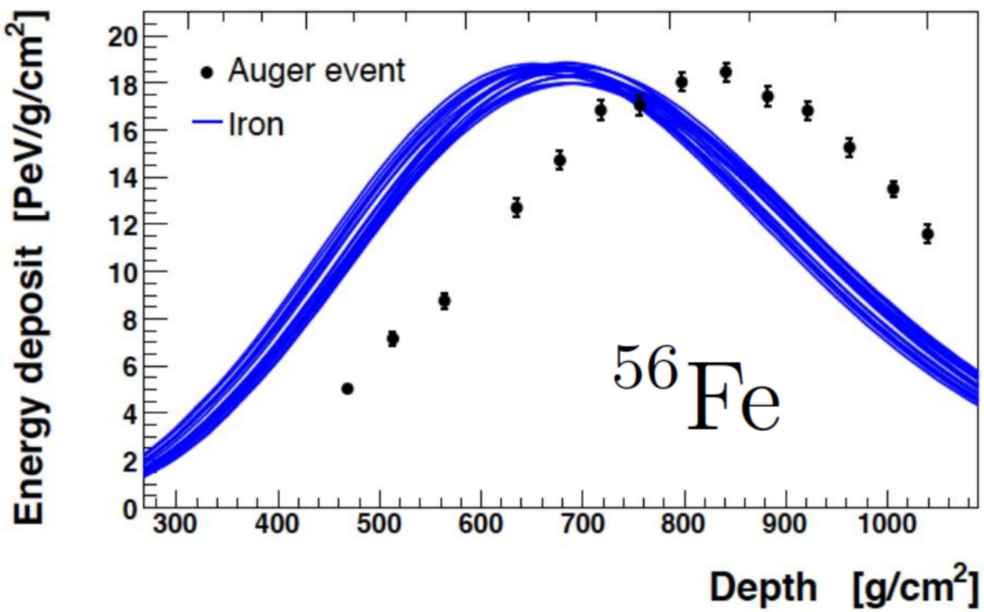


Shape of the
Longitudinal development
depends on the particle mass

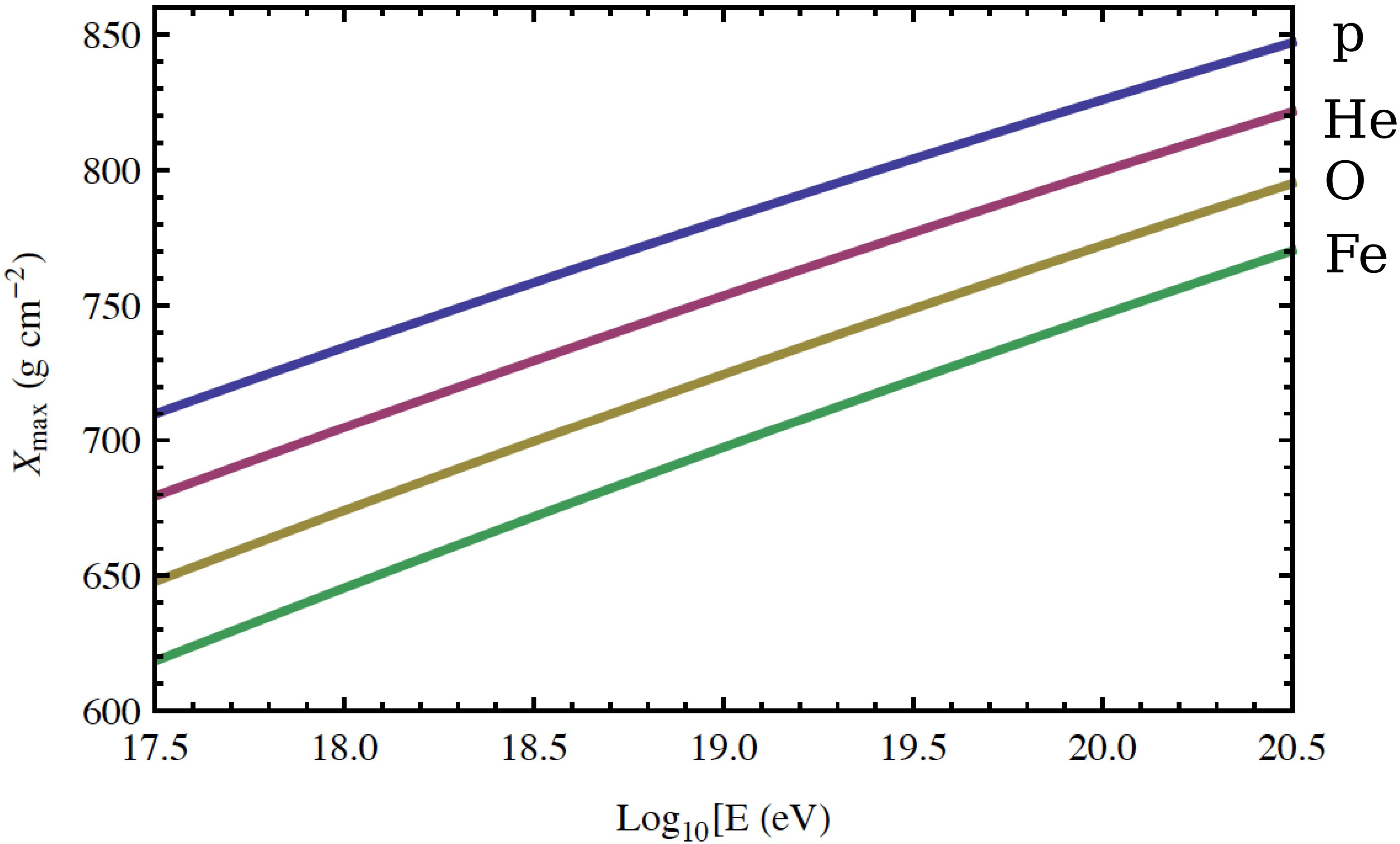
[and on the modeling
of the shower development
i.e. the description of
Hadronic Interactions]







One Montecarlo Model: [Sibyll 2.1]

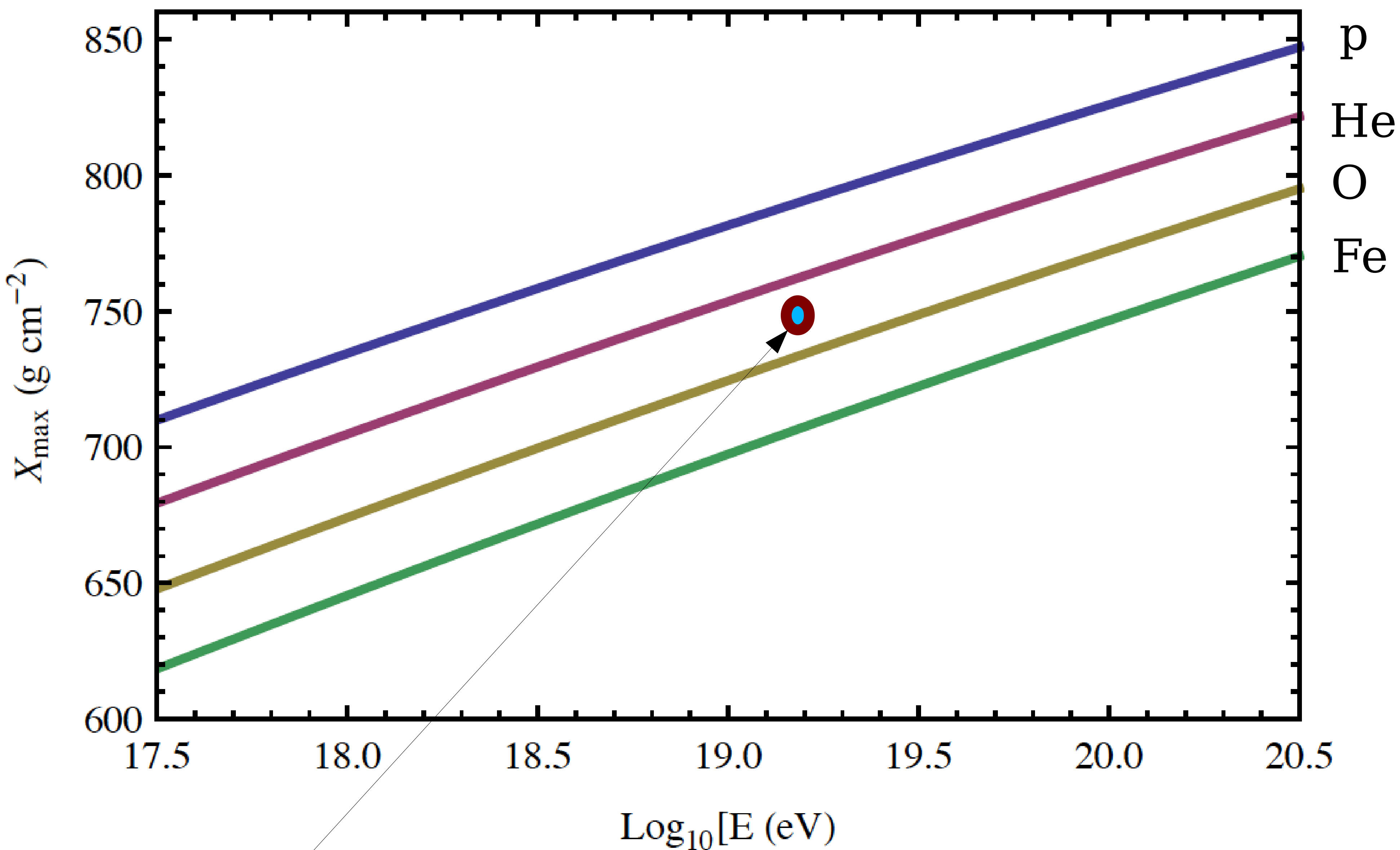


$$\boxed{\langle X_A \rangle \simeq \langle X_p \rangle - D_p \; \log_{10} A}$$

$$\langle X_{\mathrm{He}} \rangle \simeq \langle X_p \rangle - 30 \text{ g cm}^{-2}$$

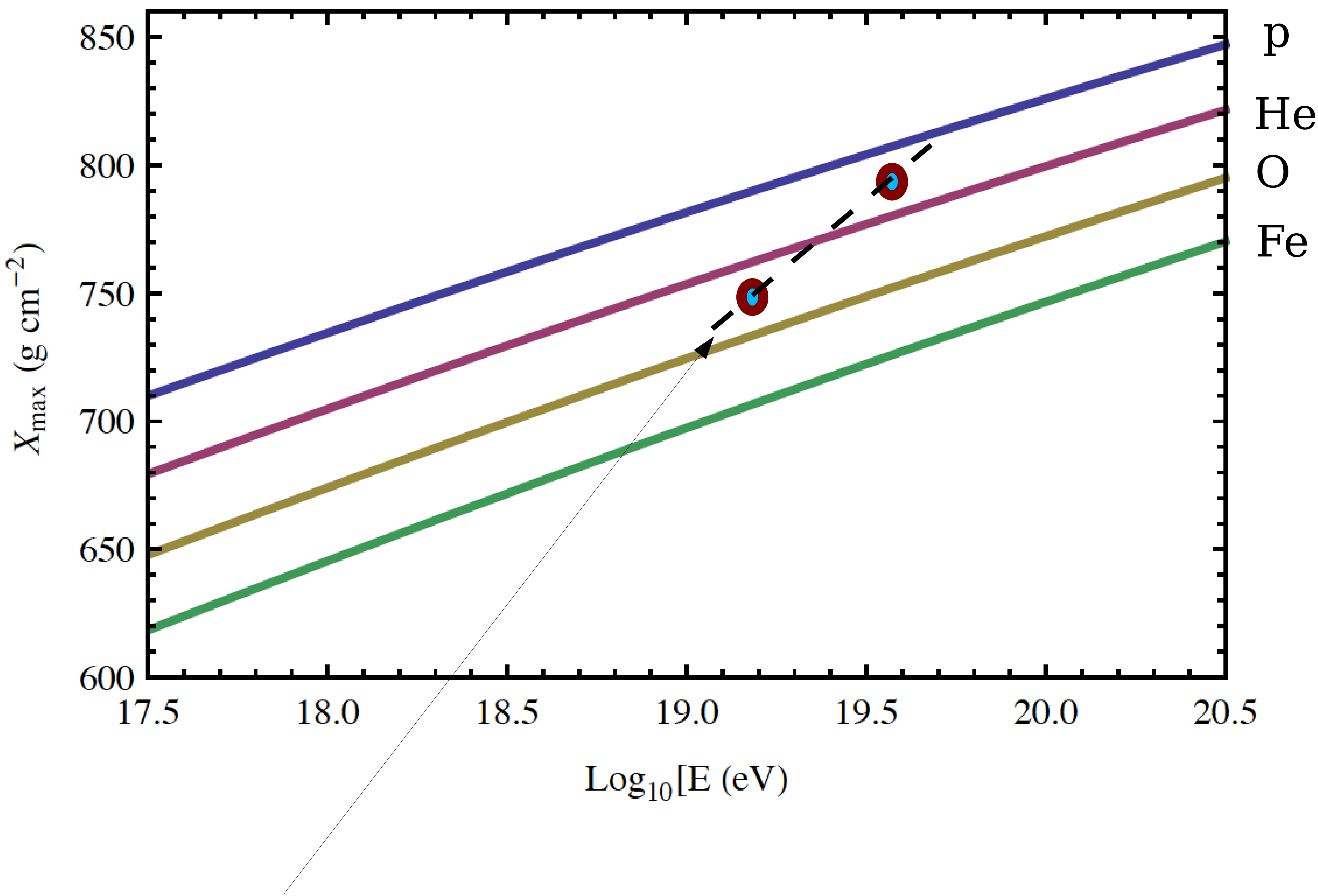
$$\langle X_{\mathrm{O}} \rangle \simeq \langle X_p \rangle - 60 \text{ g cm}^{-2}$$

$$\langle X_{\mathrm{Fe}} \rangle \simeq \langle X_p \rangle - 90 \text{ g cm}^{-2}$$

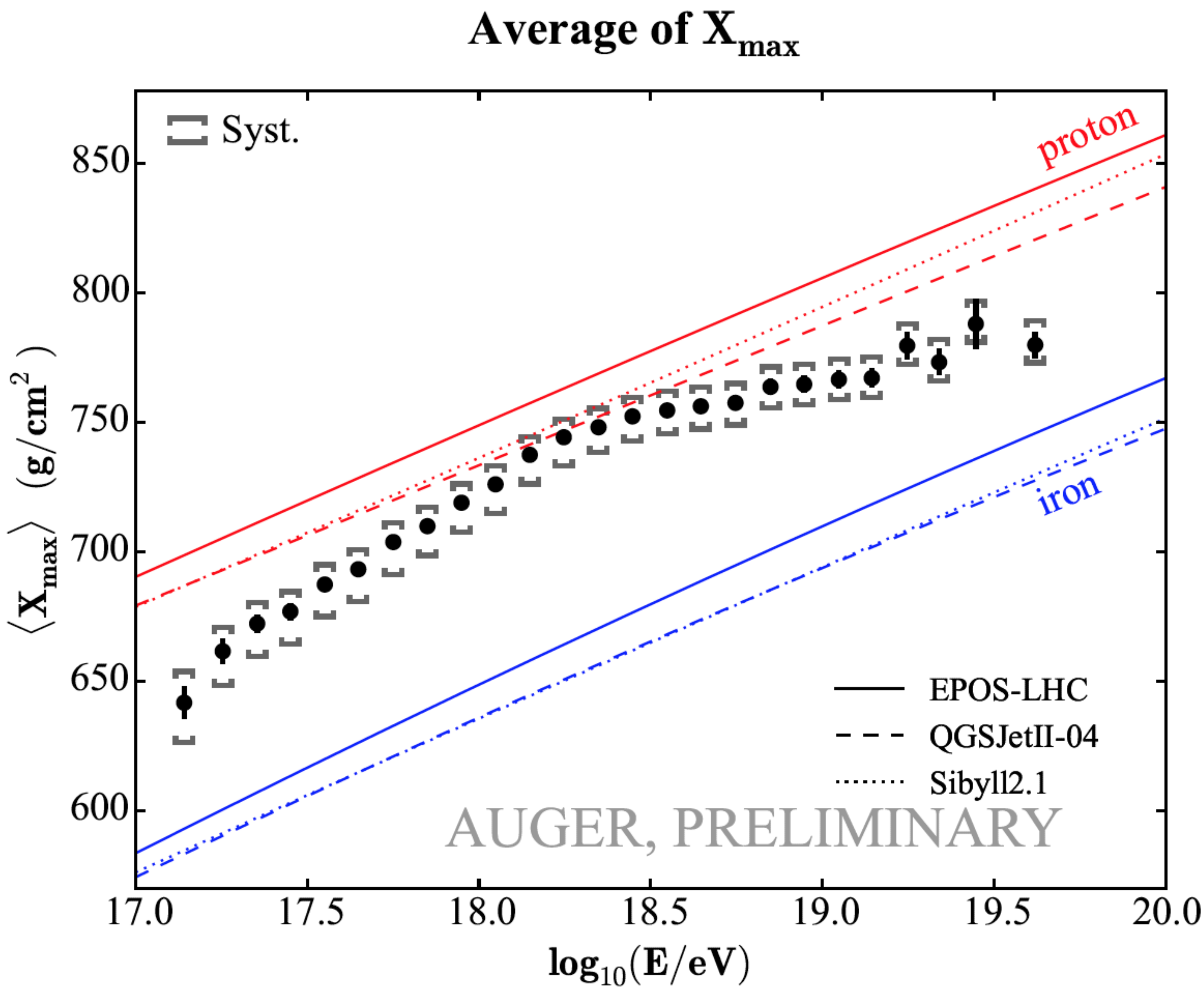


Measurements of

$$\langle \log A \rangle$$



Measurements of Composition evolution.

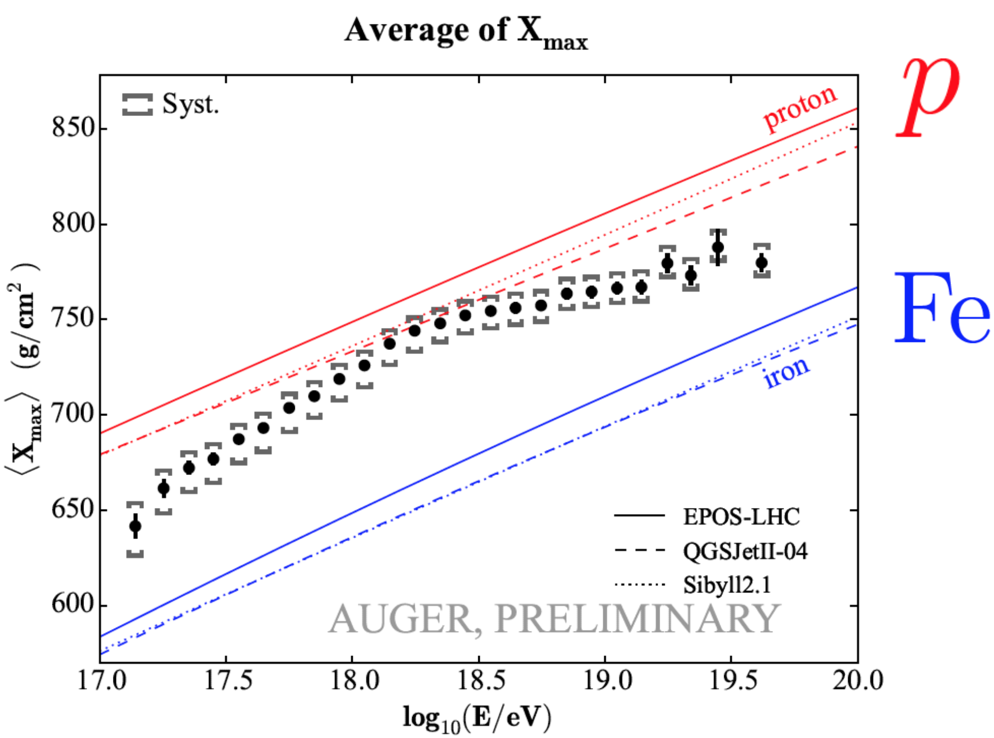


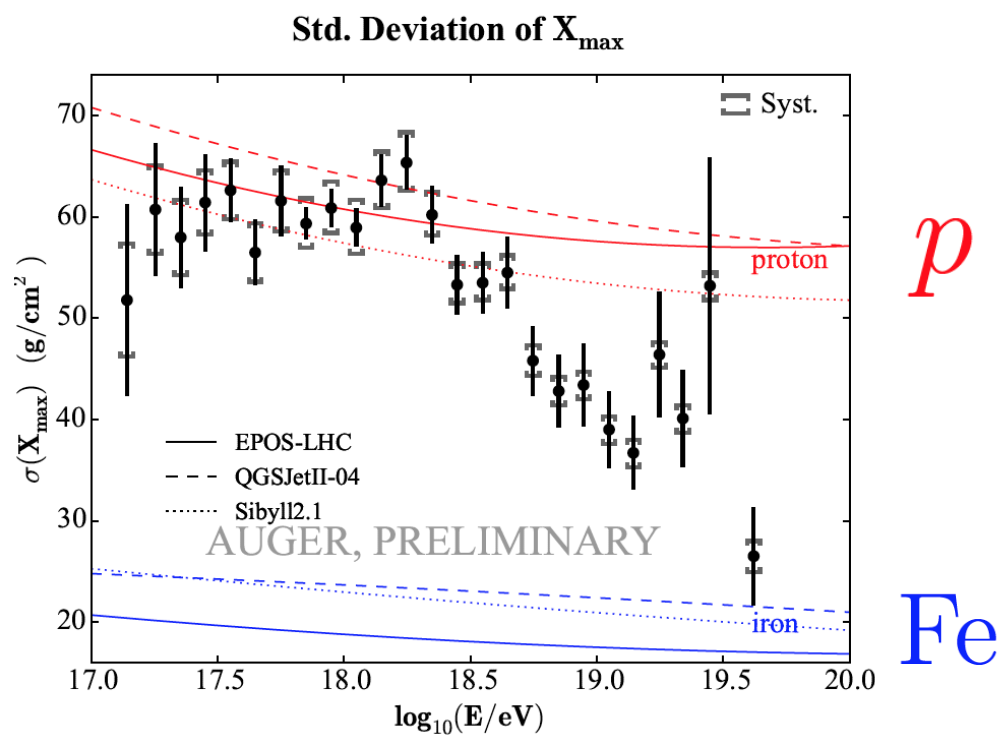
Average of X_{max}
Syst.
proton
iron
EPOS-LHC
QGSJetII-04
Sibyll2.1
AUGER, PRELIMINARY
850
800
750
700
650
600
17.0
17.5
18.0
18.5
19.0
19.5
20.0
$\langle X_{max} \rangle$ (g/cm^2)
$\log_{10}(E/eV)$

Auger composition study :

Average position of shower Maximum

Dispersion of shower Maximum





ICRC 2015

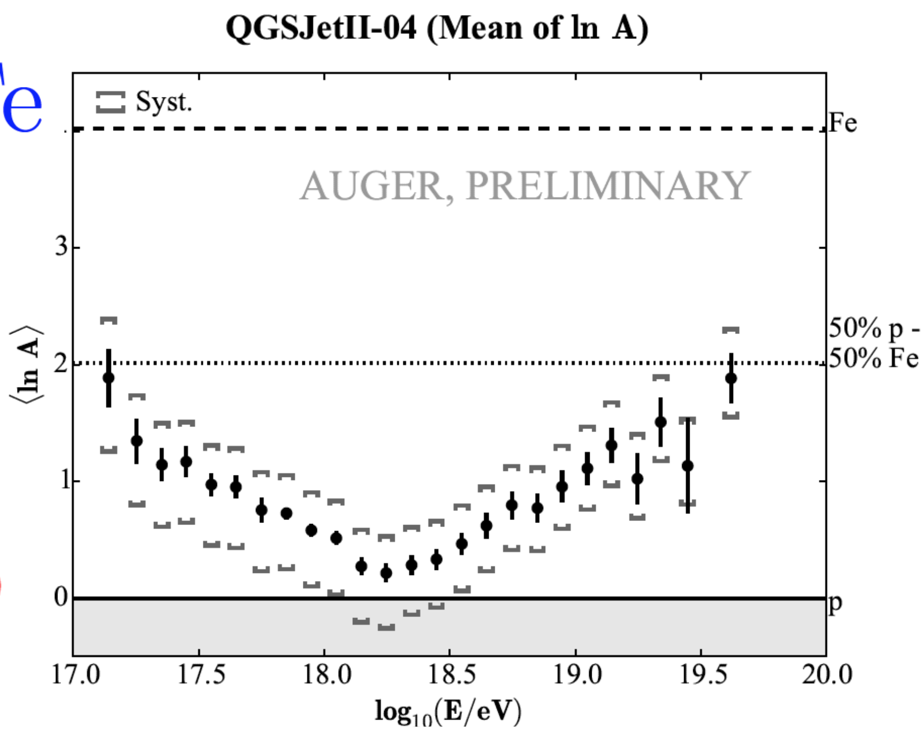
Model dependence QGSJetII-04
[description of Shower development]

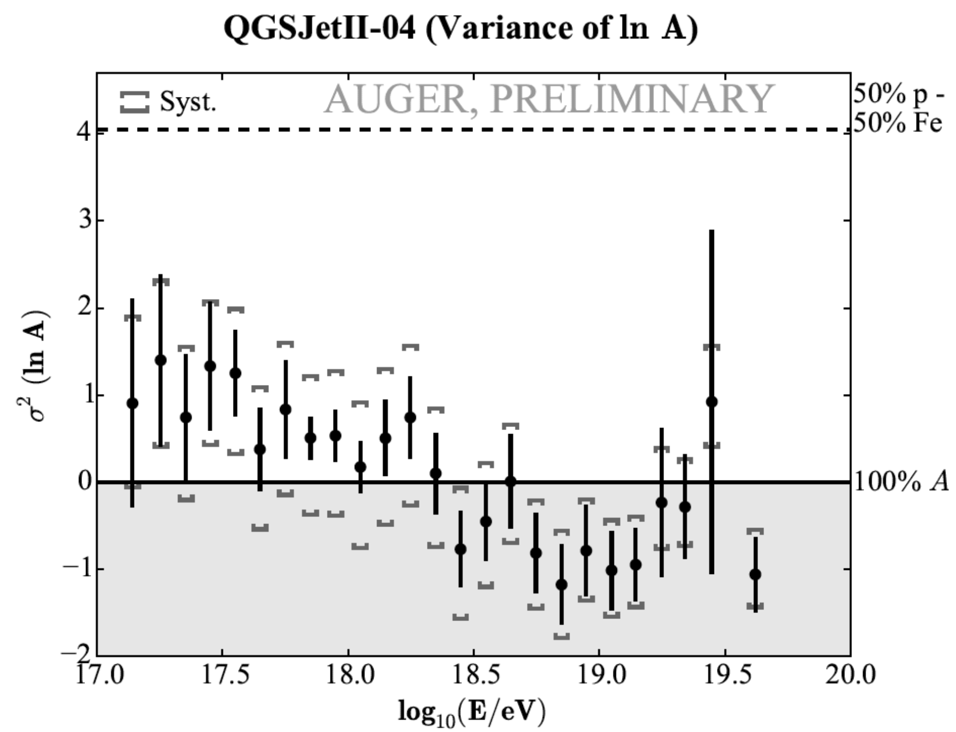
$\langle \ln A \rangle$

$\sigma^2 [\ln A]$

Fe

p



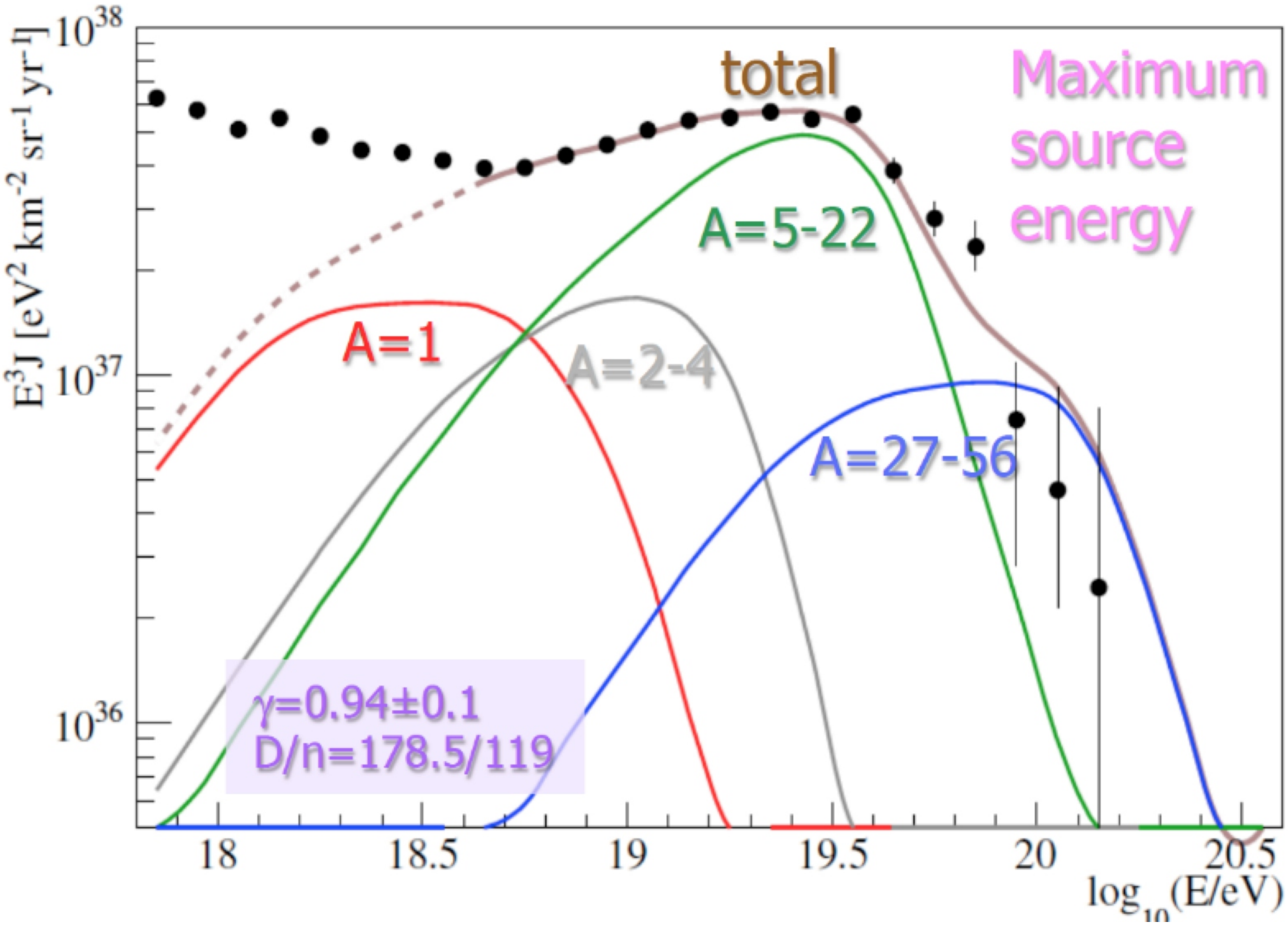


Very light CR population for $E \simeq 10^{18}$ eV

and becoming heavier !

Small dispersion: small range of A contributing to the CR population

Possible Interpretation (Auger at ICRC-2015)



1. Very hard spectra

2. Cutoff is the maximum energy of acceleration in the sources

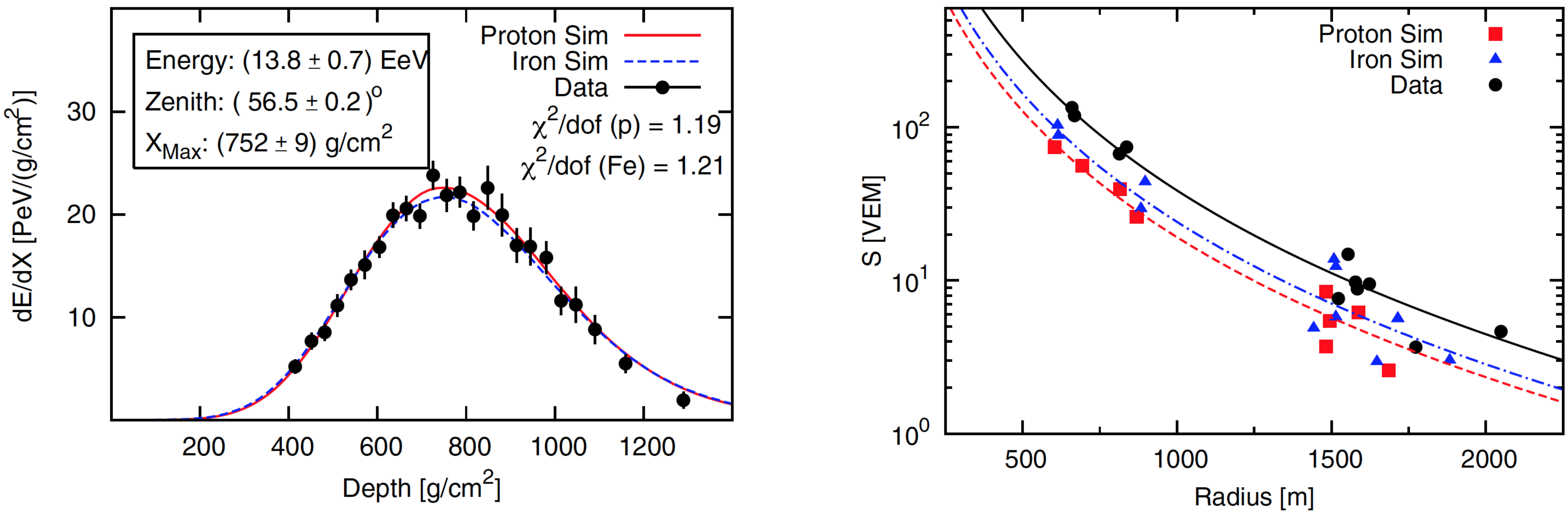
$$E_{\max}(Z) = Z\ E_p$$

Auger Collaboration

PRL **117,** 192001 (2016)

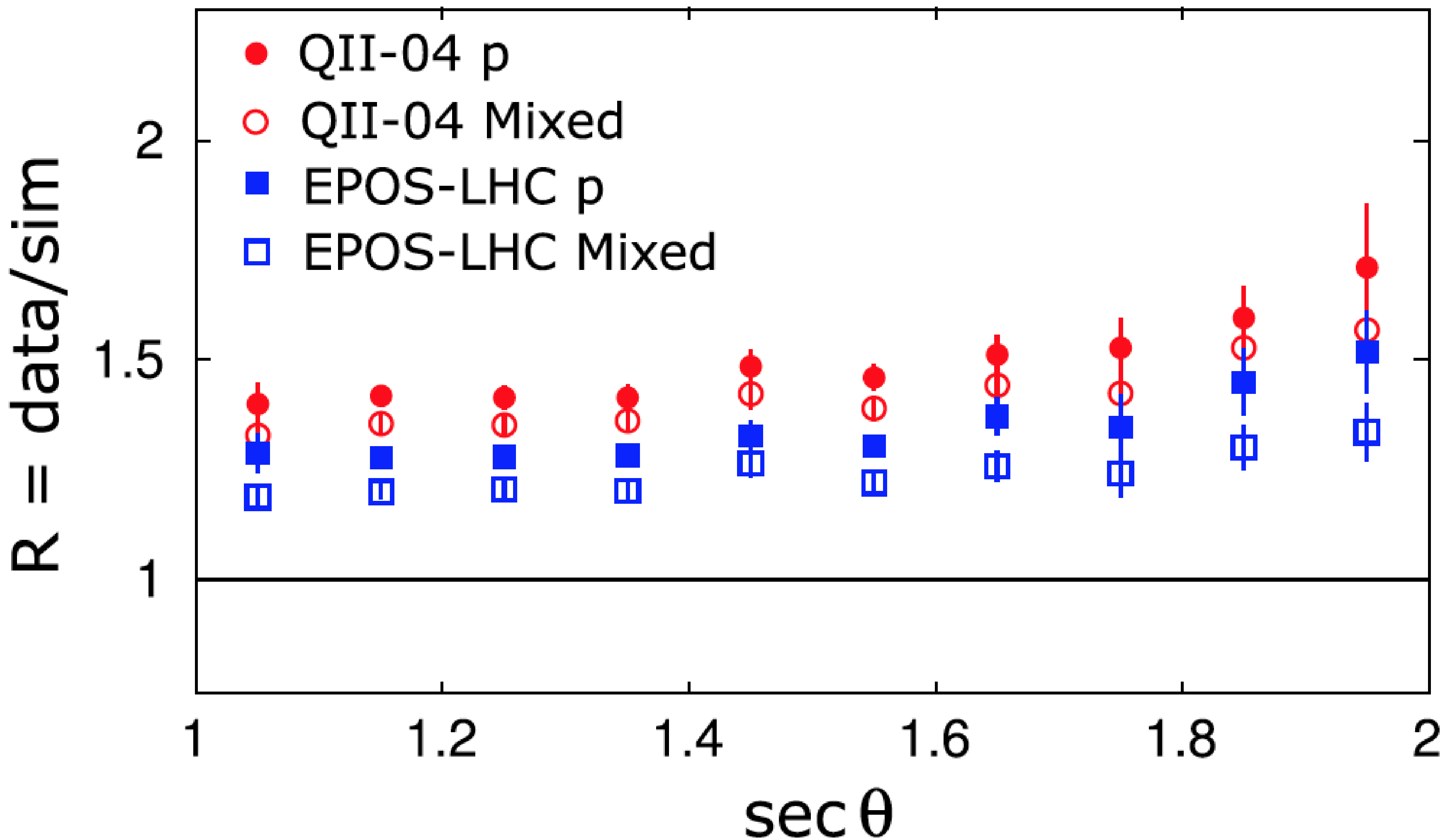
week ending
4 NOVEMBER 2016

Testing Hadronic Interactions at Ultrahigh Energies with Air Showers Measured by the Pierre Auger Observatory

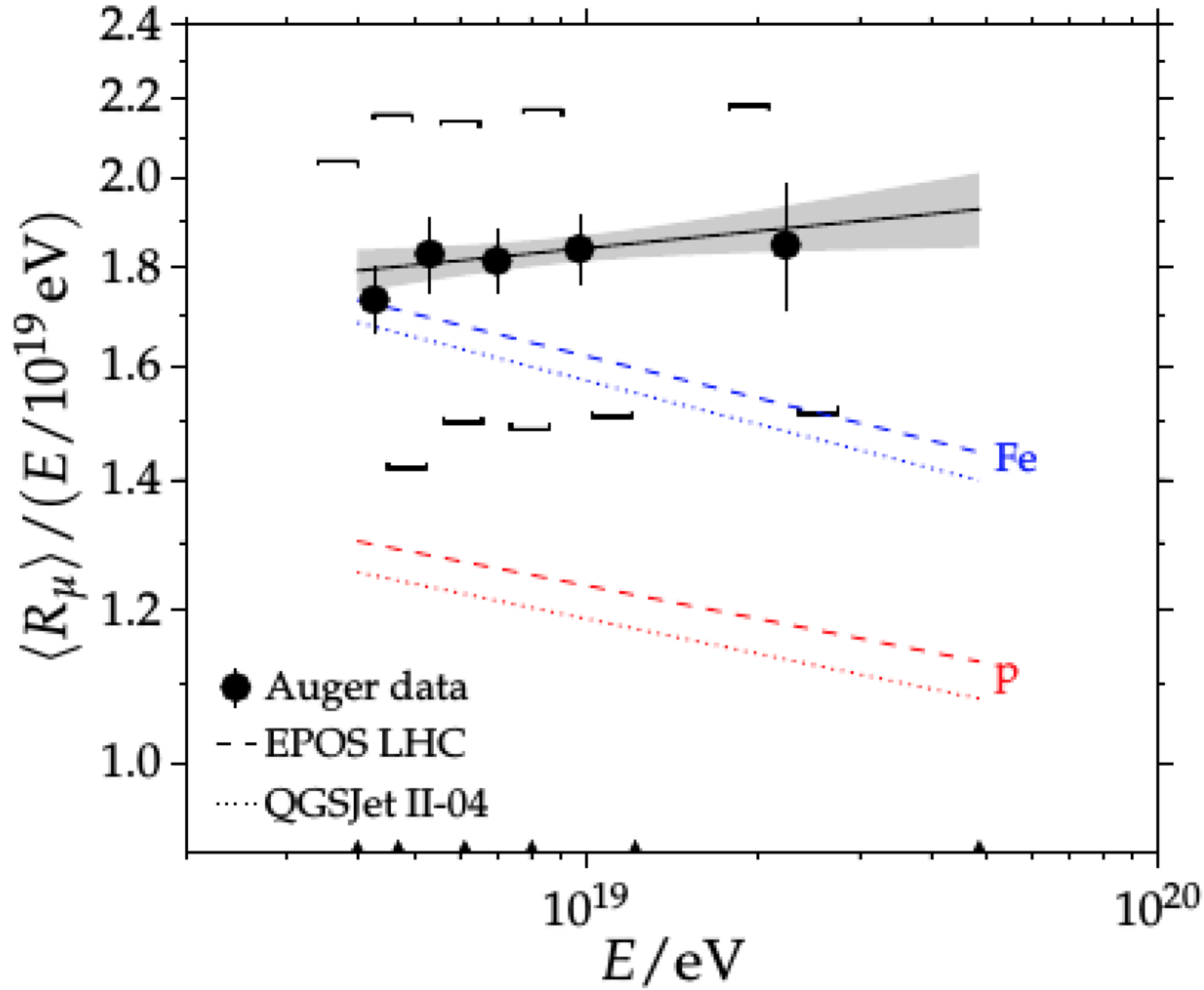


Predict the Surface detector response from the measurement of the longitudinal development of the shower

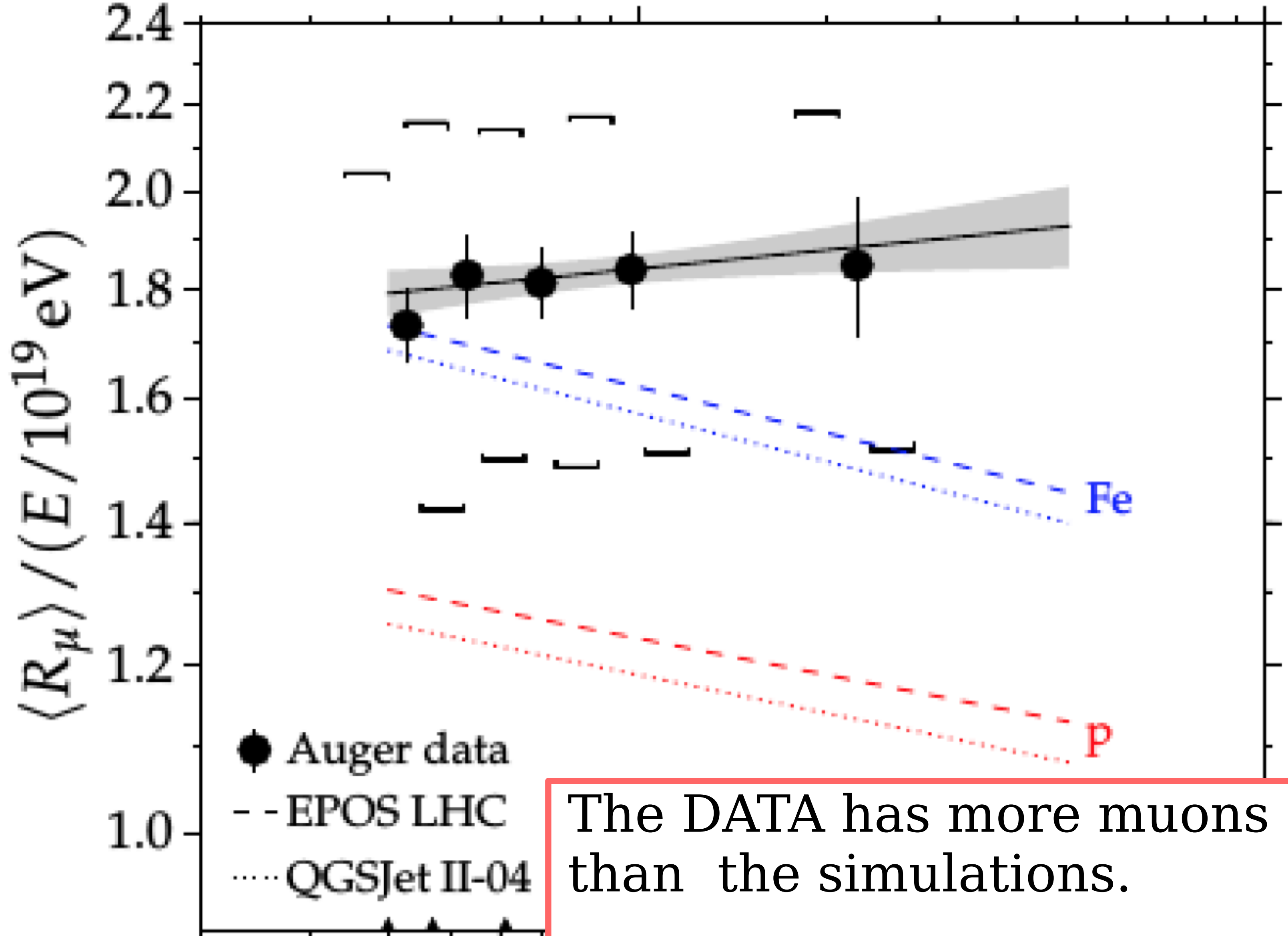
Data systematically higher than the Montecarlo prediction.
[MC showers contain too few muons]



Study of Composition with muons (inclined showers)



Study of Composition with muons (inclined showers)



The DATA has more muons than the simulations.

Why ? What are the implications ?

Planned upgrade of Auger

Scintillator
Detector

Combine:
Tank
Scintillator

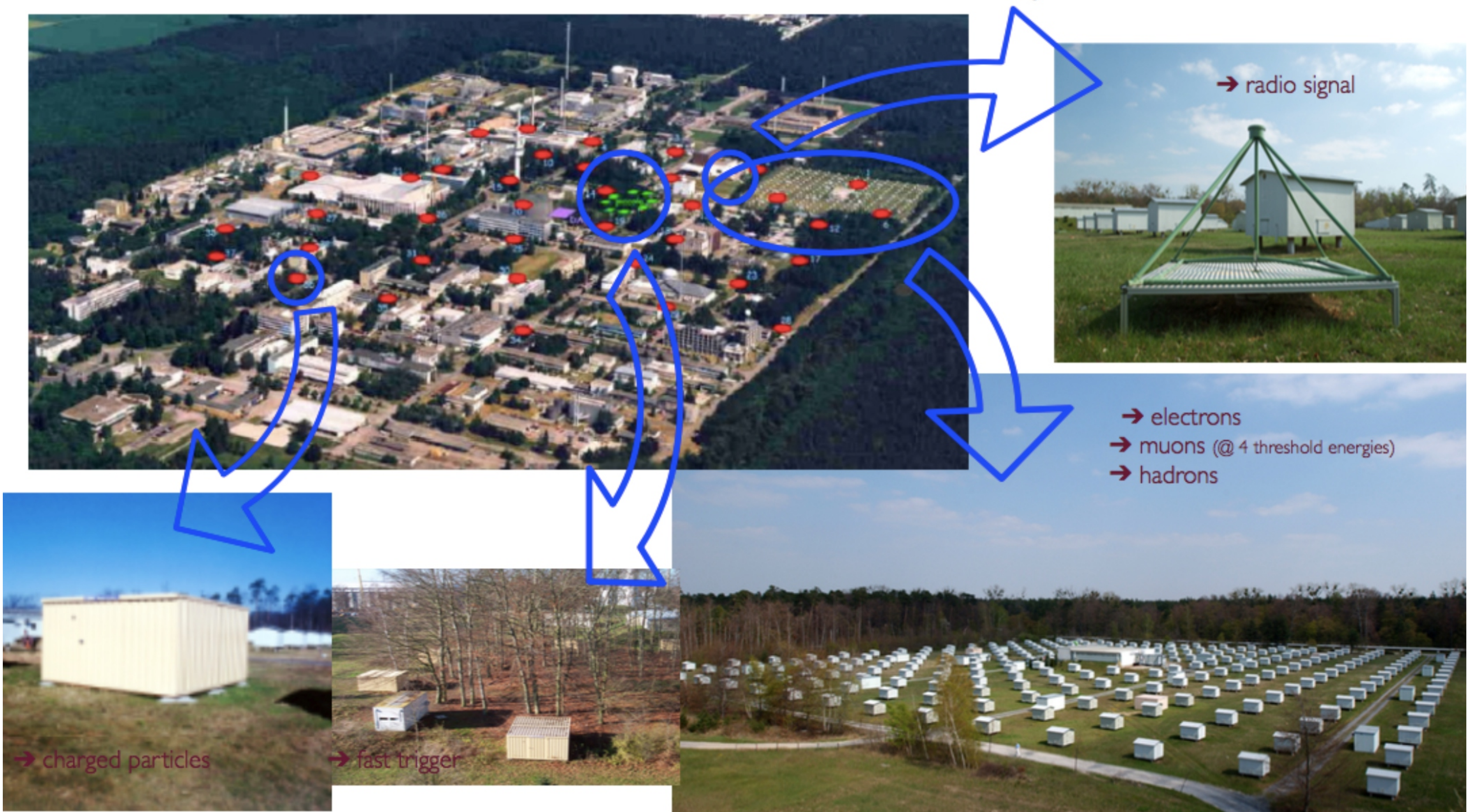
to separate
muon / e.m.
components

Above the knee : KASCADE-Grande

2005 m a.s.l. [820 g cm^{-2}]

A ~ 10^5 m^2

10^{16} - 10^{18} eV



Shower Components at Ground Level:

Electromagnetic
Component

$e^{\mp}, \ \gamma$

Muon Component

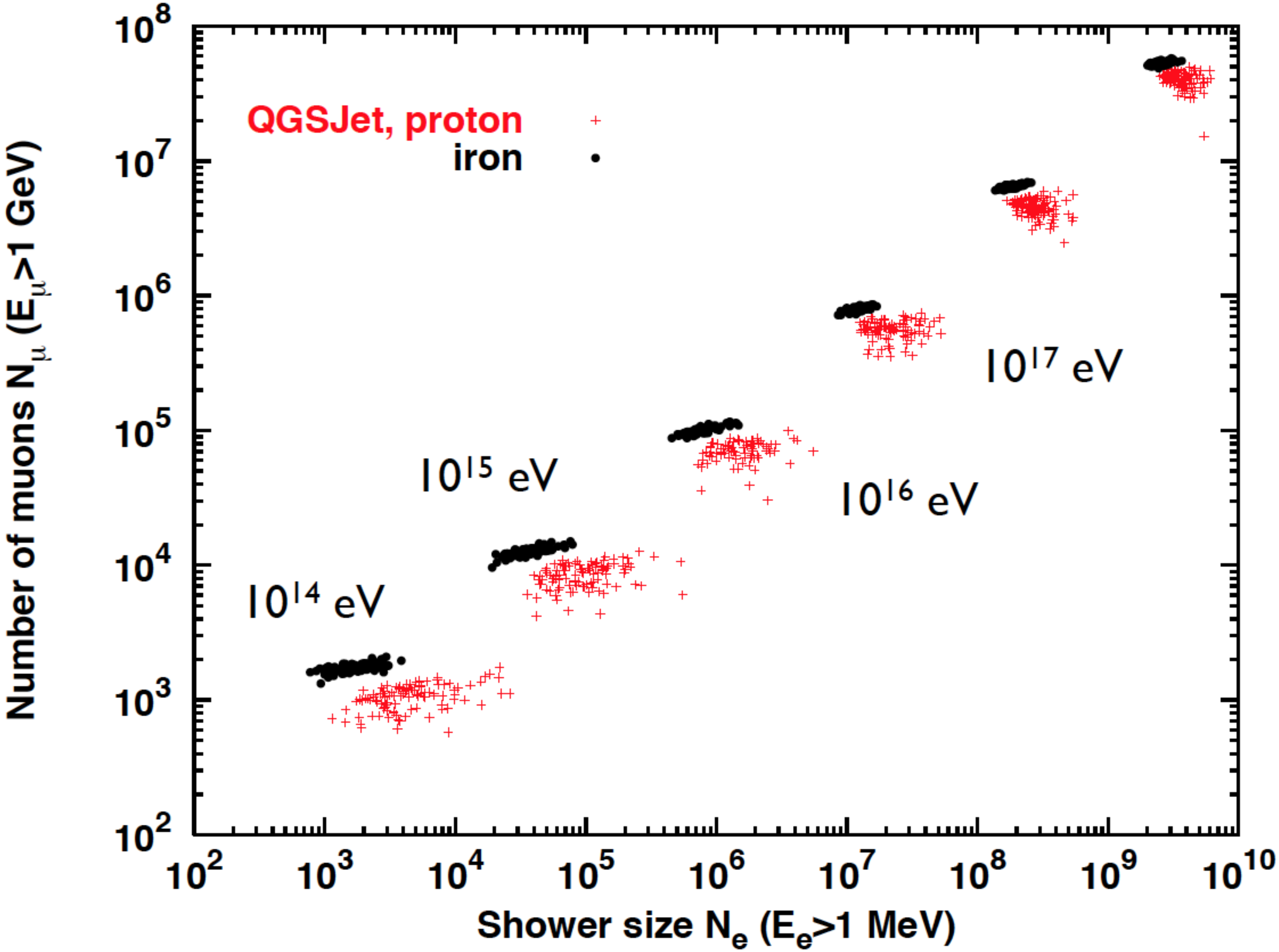
$\mu^{\mp}$

(Invisible) Neutrino component

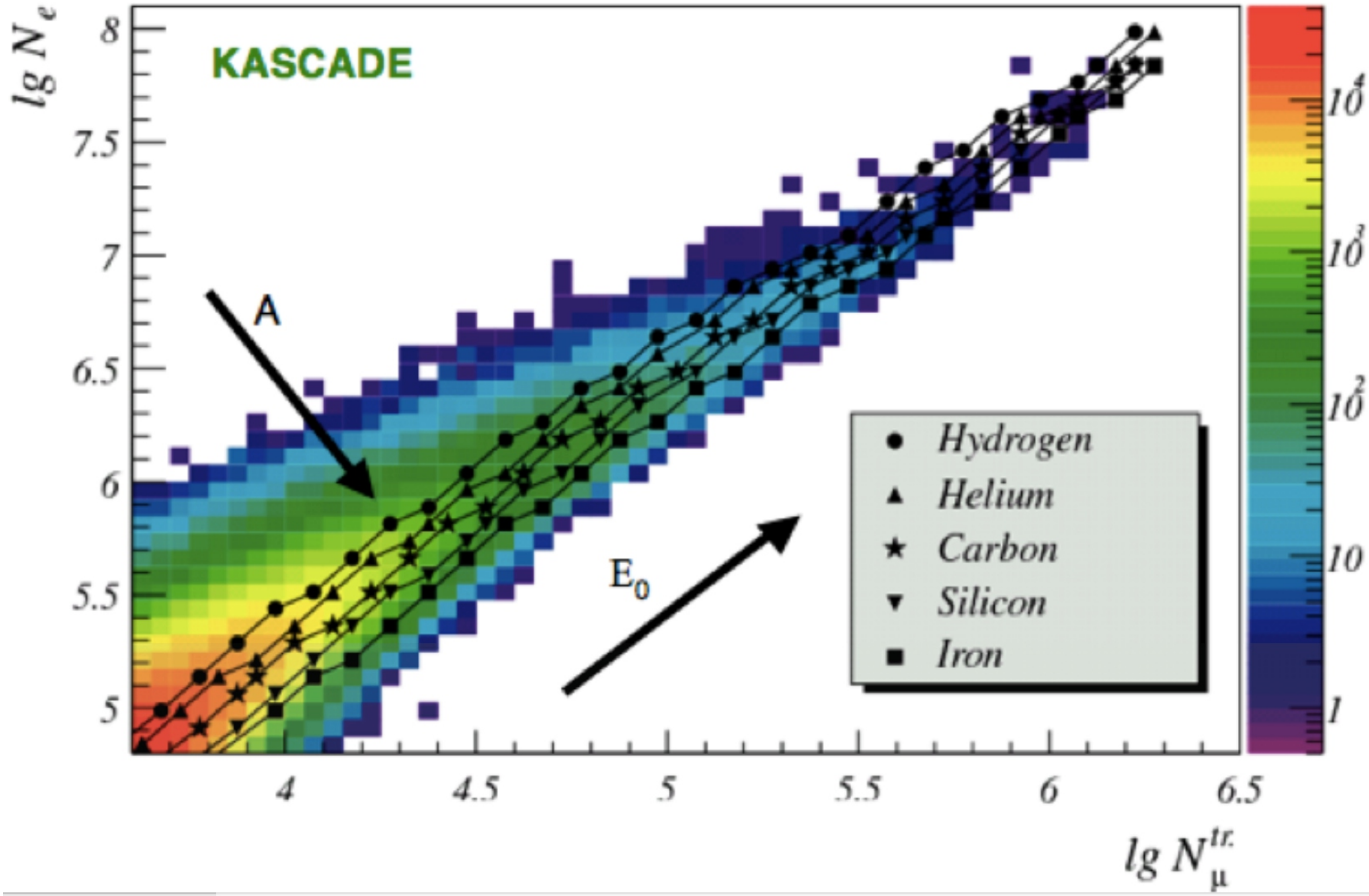
Hadronic component
[small and close to the shower axis]

Iron Shower: Muon rich

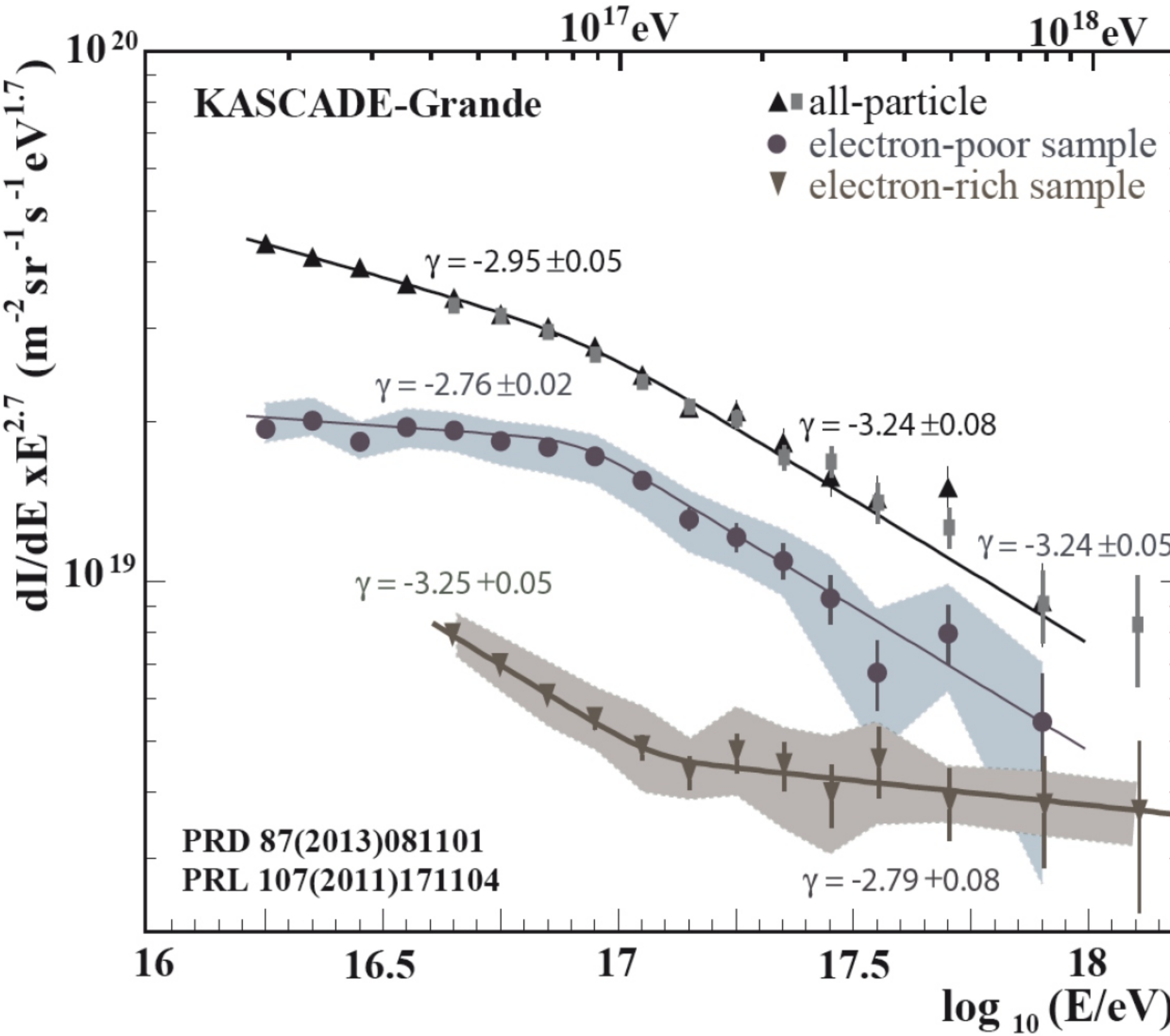
N_μ versus N_e



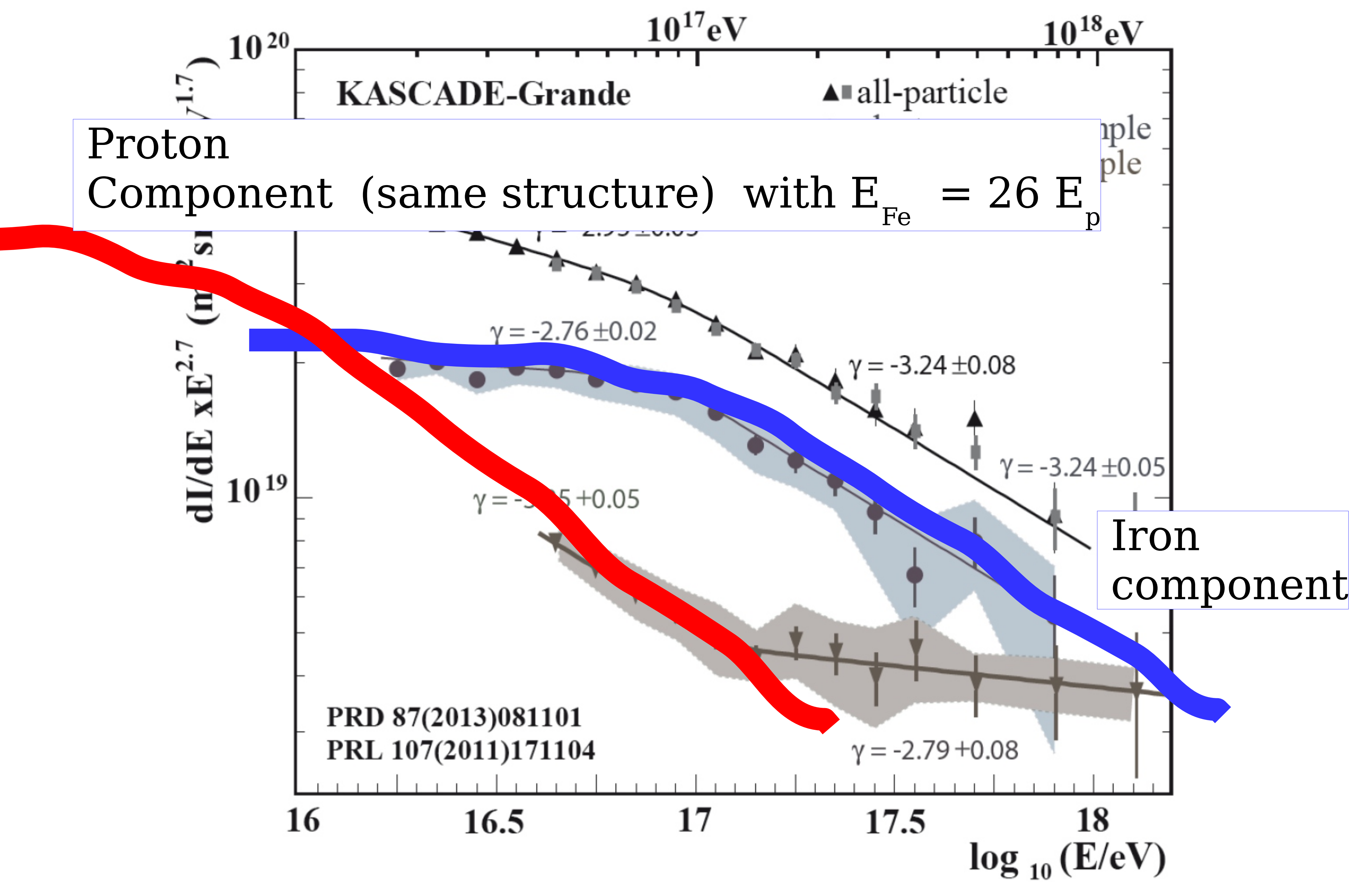
Data Interpretation



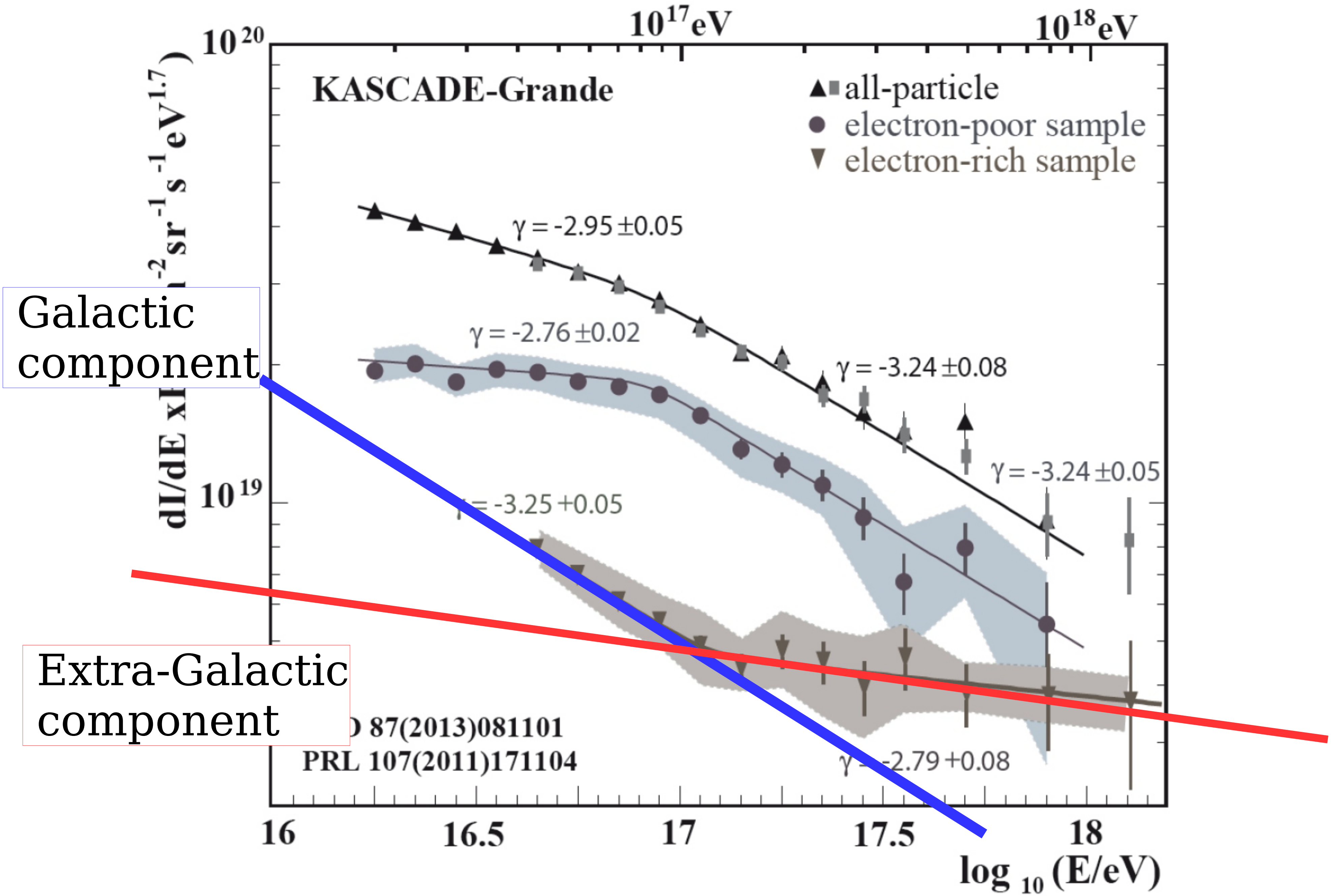
Kascade Grande "ankle" in the light component.



Kascade Grande "ankle" in the light component.

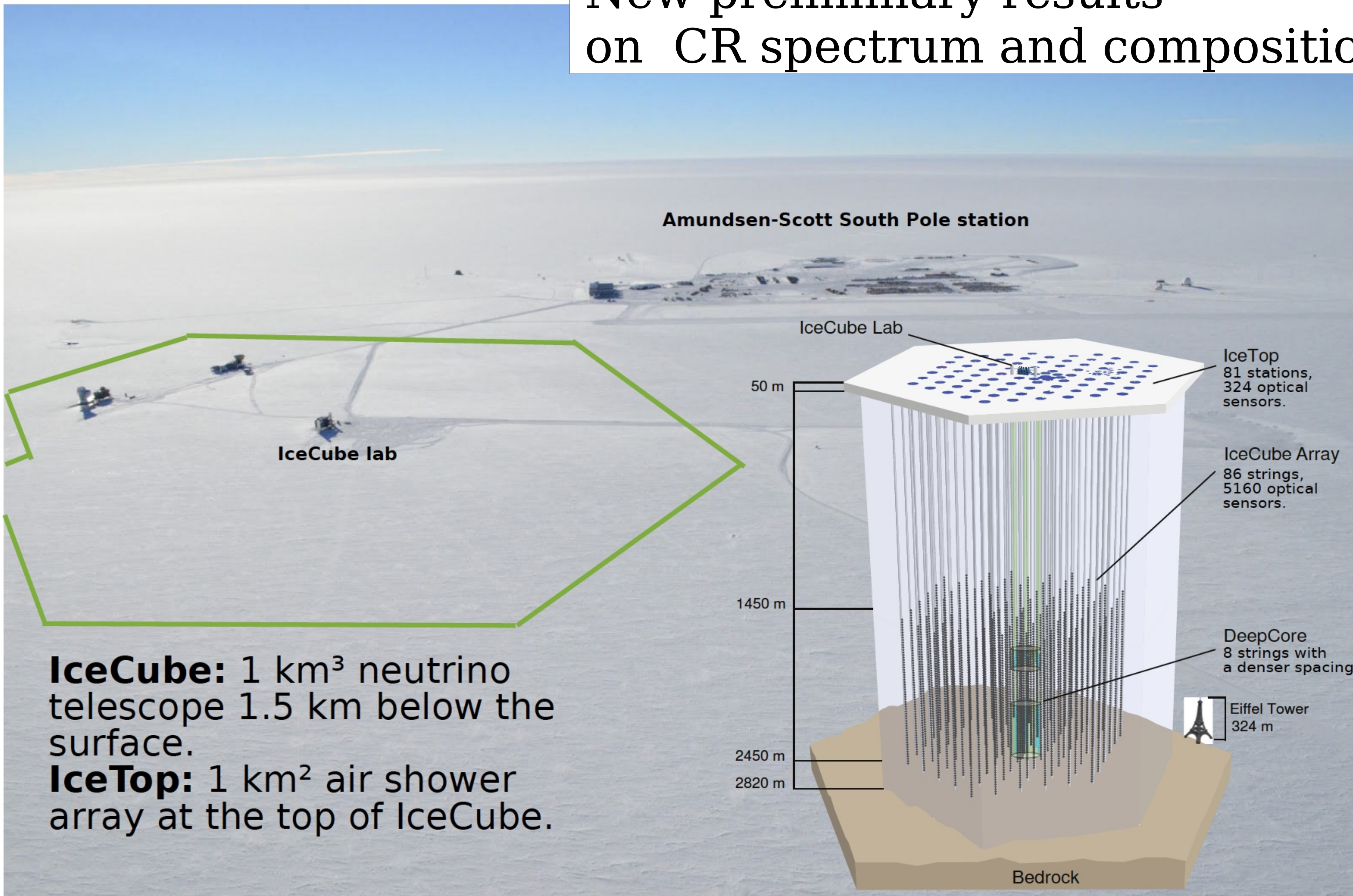


Kascade Grande "ankle" in the light component.



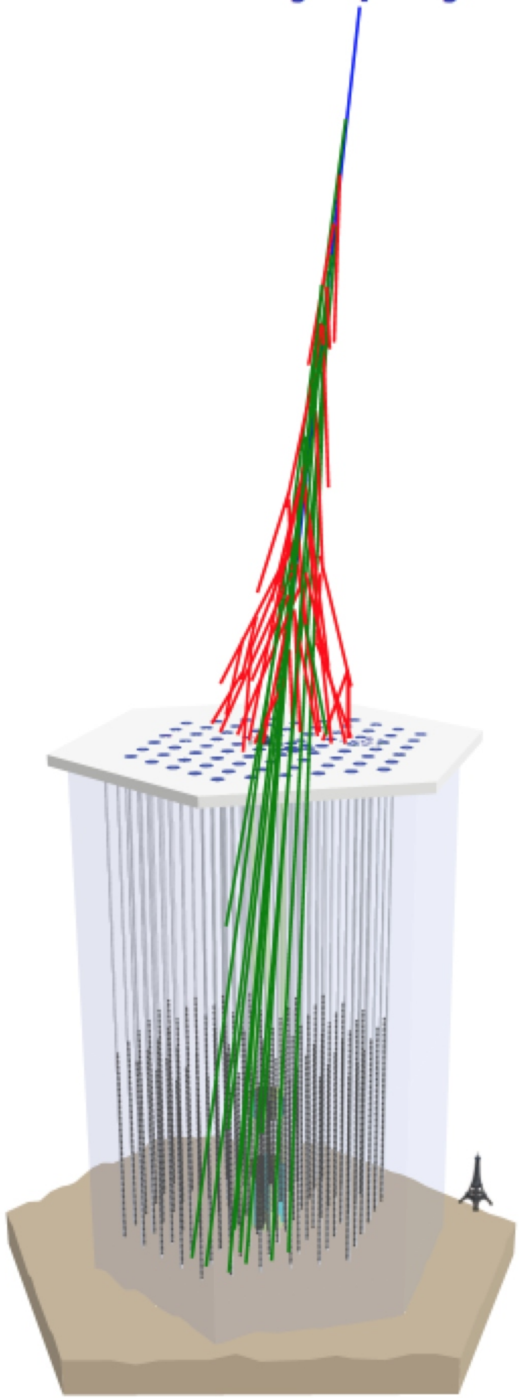
The IceCube Neutrino Observatory

New preliminary results
on CR spectrum and composition



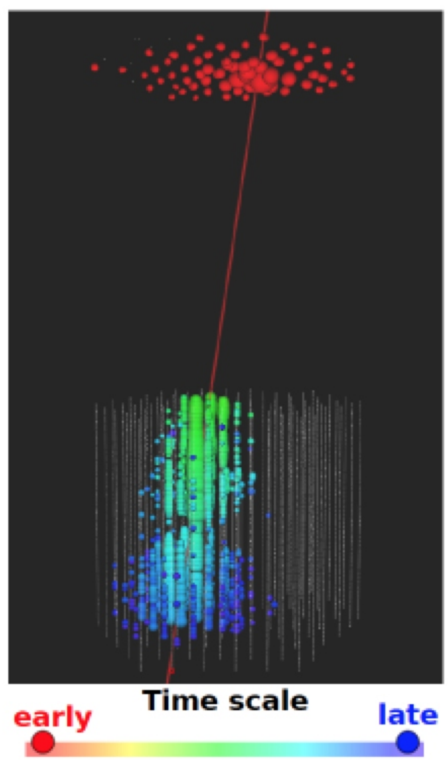
IceCube: 1 km^3 neutrino telescope 1.5 km below the surface.
IceTop: 1 km^2 air shower array at the top of IceCube.

Cosmic ray physics with the IceCube Neutrino Observatory



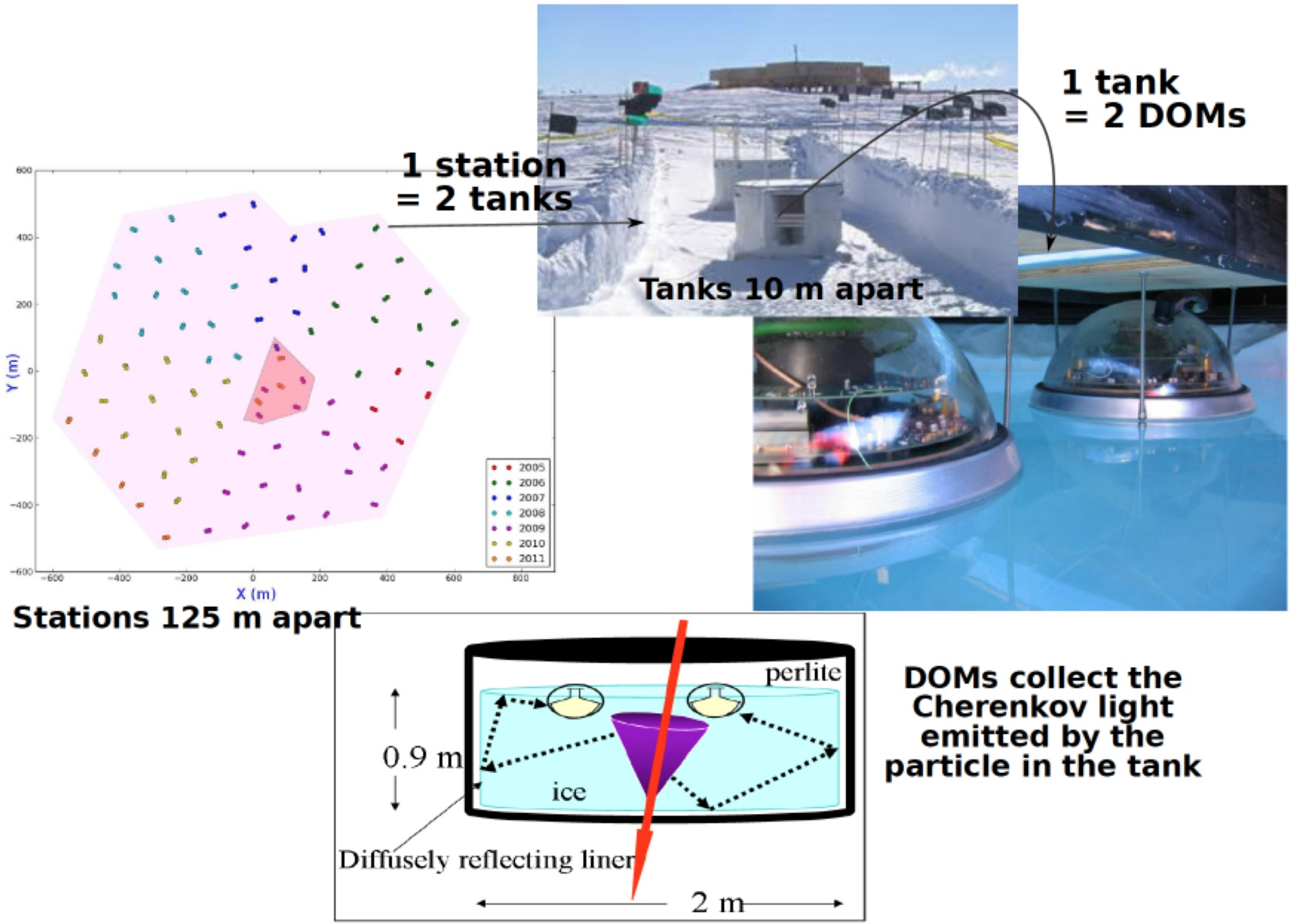
Coincident analysis:

- IceTop stations detect the **electromagnetic** component (and low-energy muons): sensitive to the energy of the shower.
- High-energy **muon bundles** travel down to the IceCube detector:



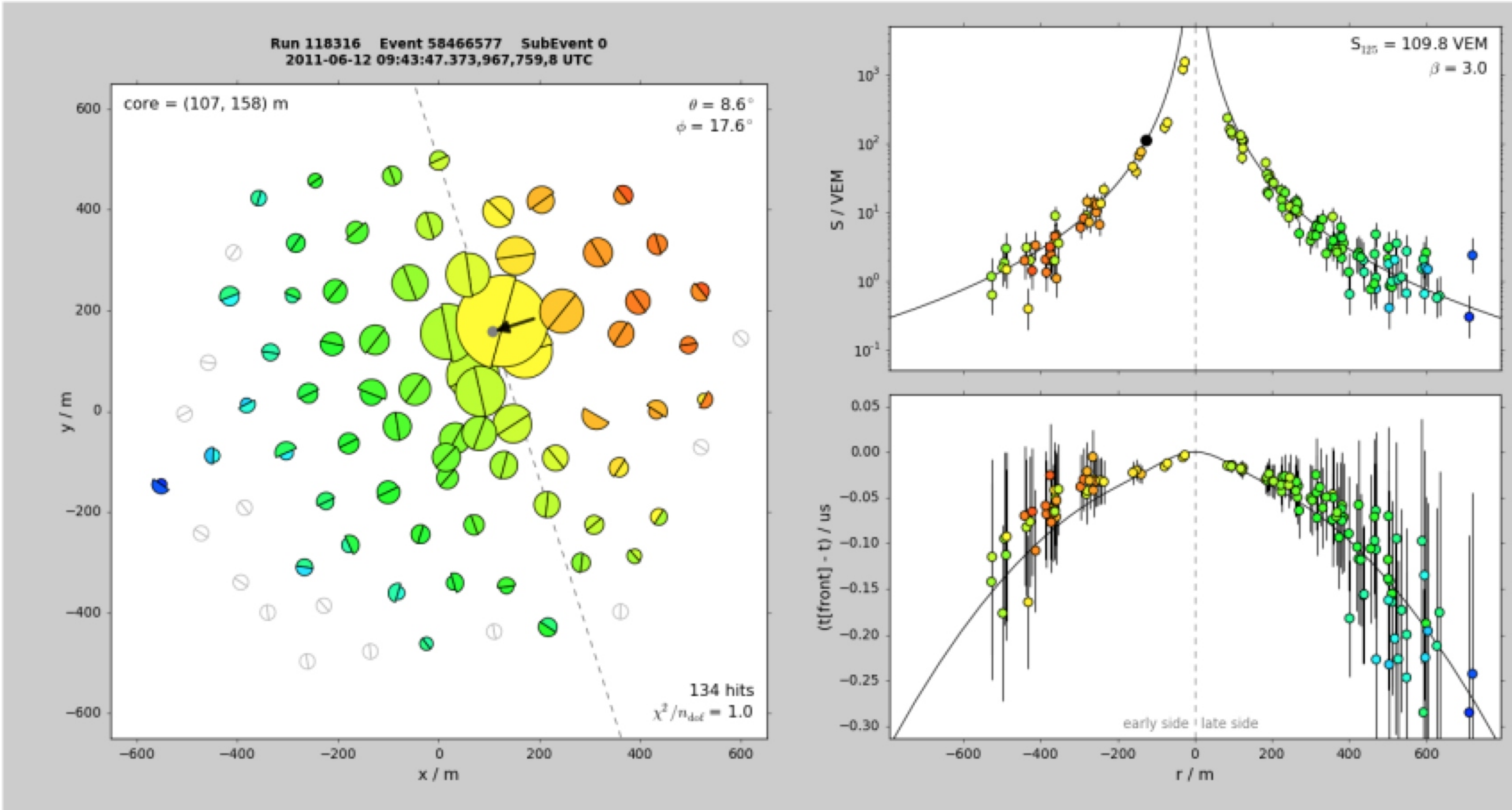
- Minimal muon energy: ~ 275 GeV.
- Multiplicity: 1 - 1000s.
- Created high in the atmosphere.
- Typical radius: $\sim 20 - 50$ m
- Ionization + radiative, stochastic energy loss.

IceTop



IceTop is at an altitude of $\sim$2835 m $\approx$ 692 g/cm^2

Air shower reconstruction with IceTop



Lateral distribution function (LDF):

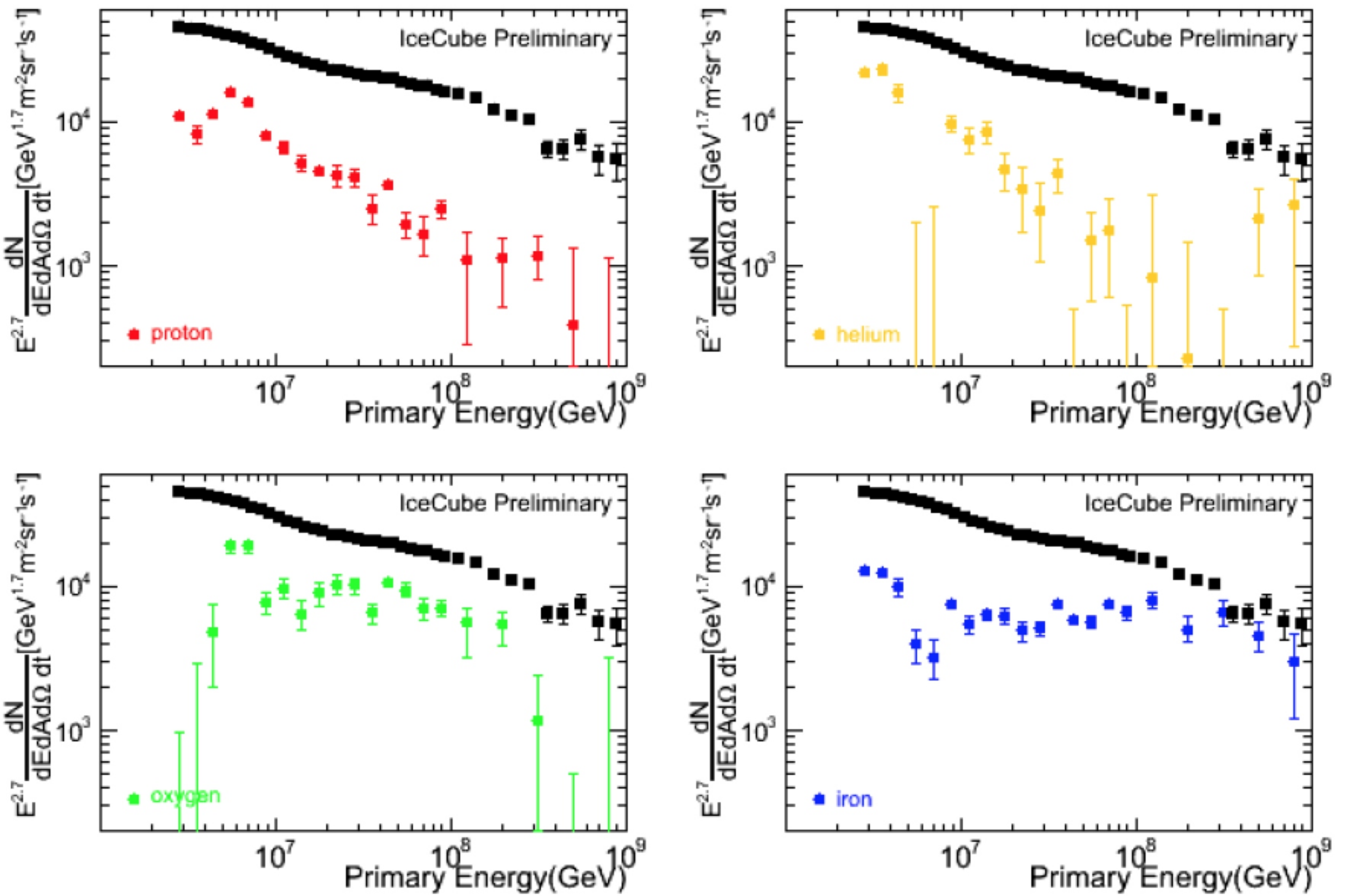
$$S(r) = S_{125} \cdot \left(\frac{r}{125\ \mathrm{m}}\right)^{-\beta-\kappa\log\left(\frac{r}{125\ \mathrm{m}}\right)}$$

Time residuals:

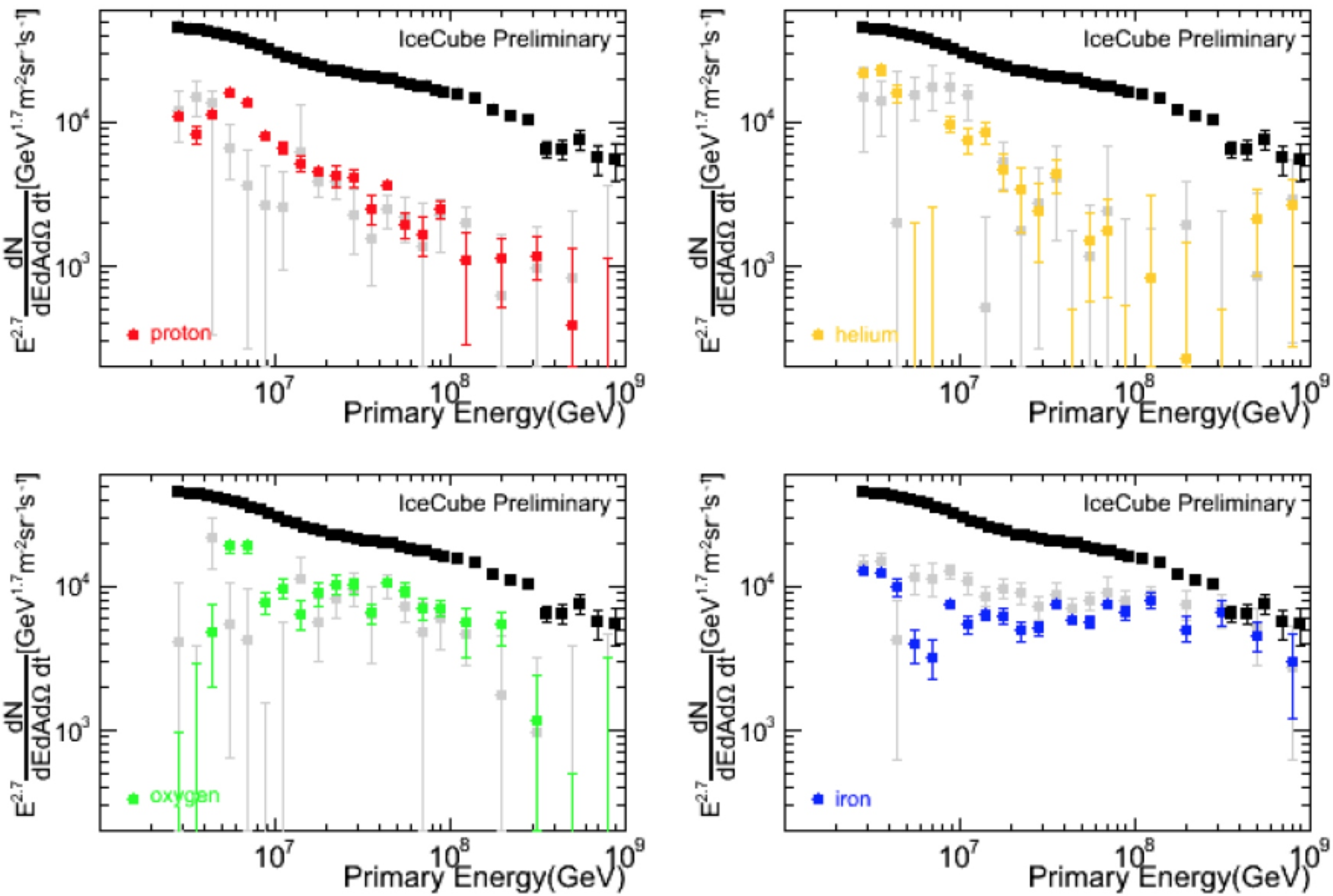
$$\Delta t(r) = ar^2 + b\left(\exp\left(-\frac{r^2}{2\sigma^2}\right) - 1\right)$$

$\rightarrow$ **x, y, z, θ, ϕ, β, $\mathbf{S}_{125}$ (signal at 125 m from core)**

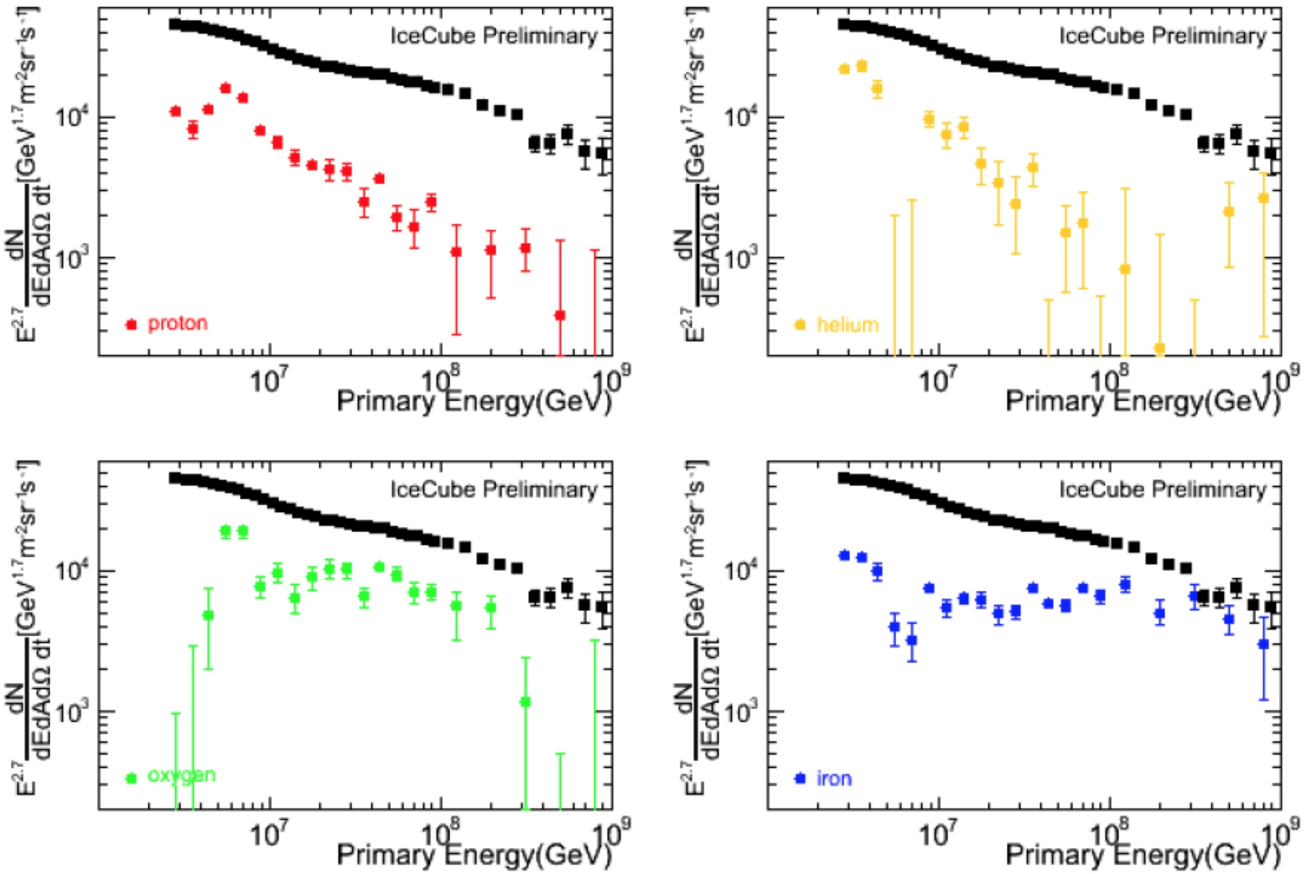
Results: Individual energy spectra



Systematics: Individual energy spectra, QGSJET



Results: Individual energy spectra



Results is in sharp contrast
with the studies of fluorescence detectors.

Experimental problem ? Model incorrect ?

5. Outlook

- Experimental Studies

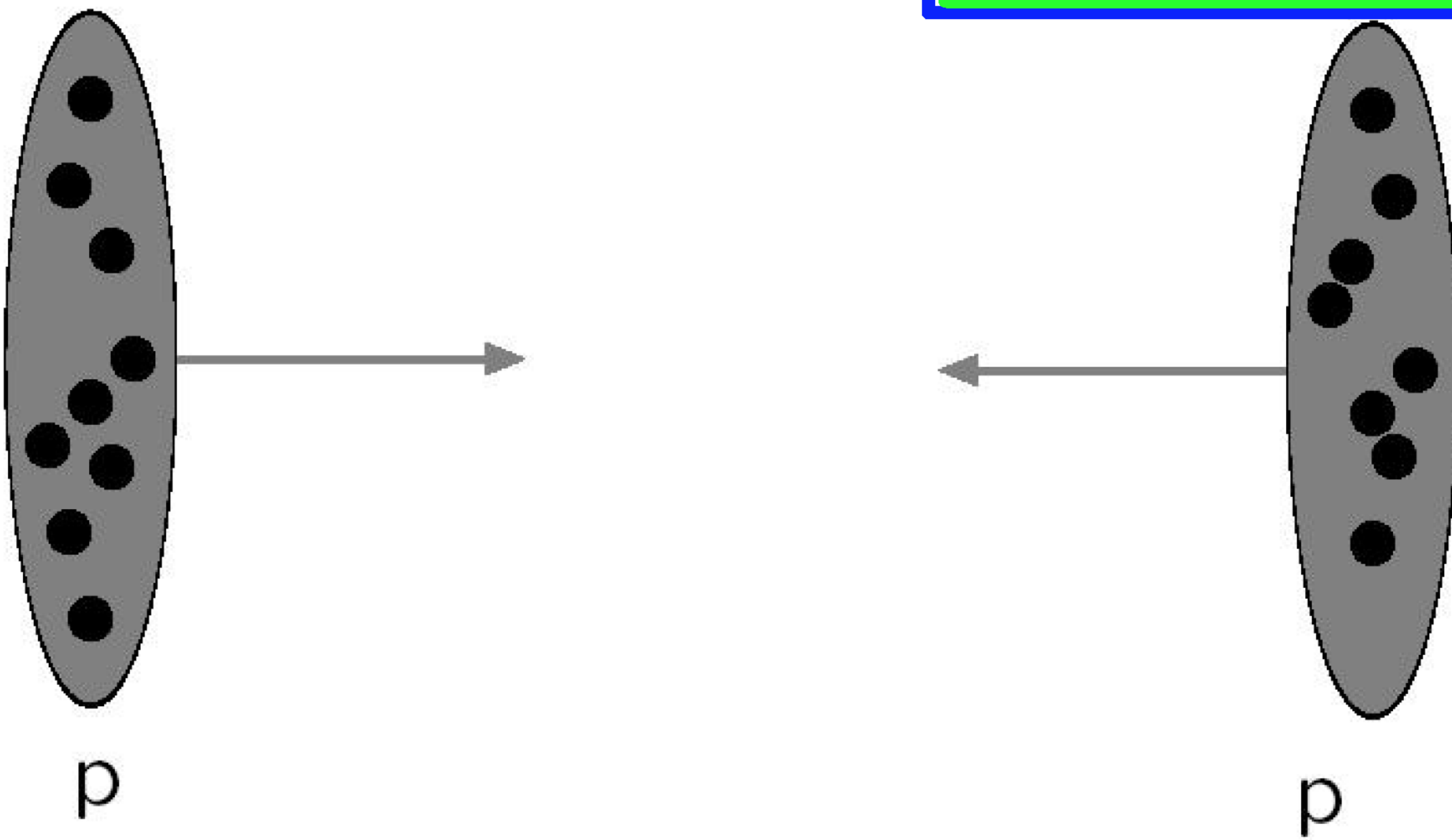
  LHC and lower energy
- Theory

Quantum
Chromo
Dynamics

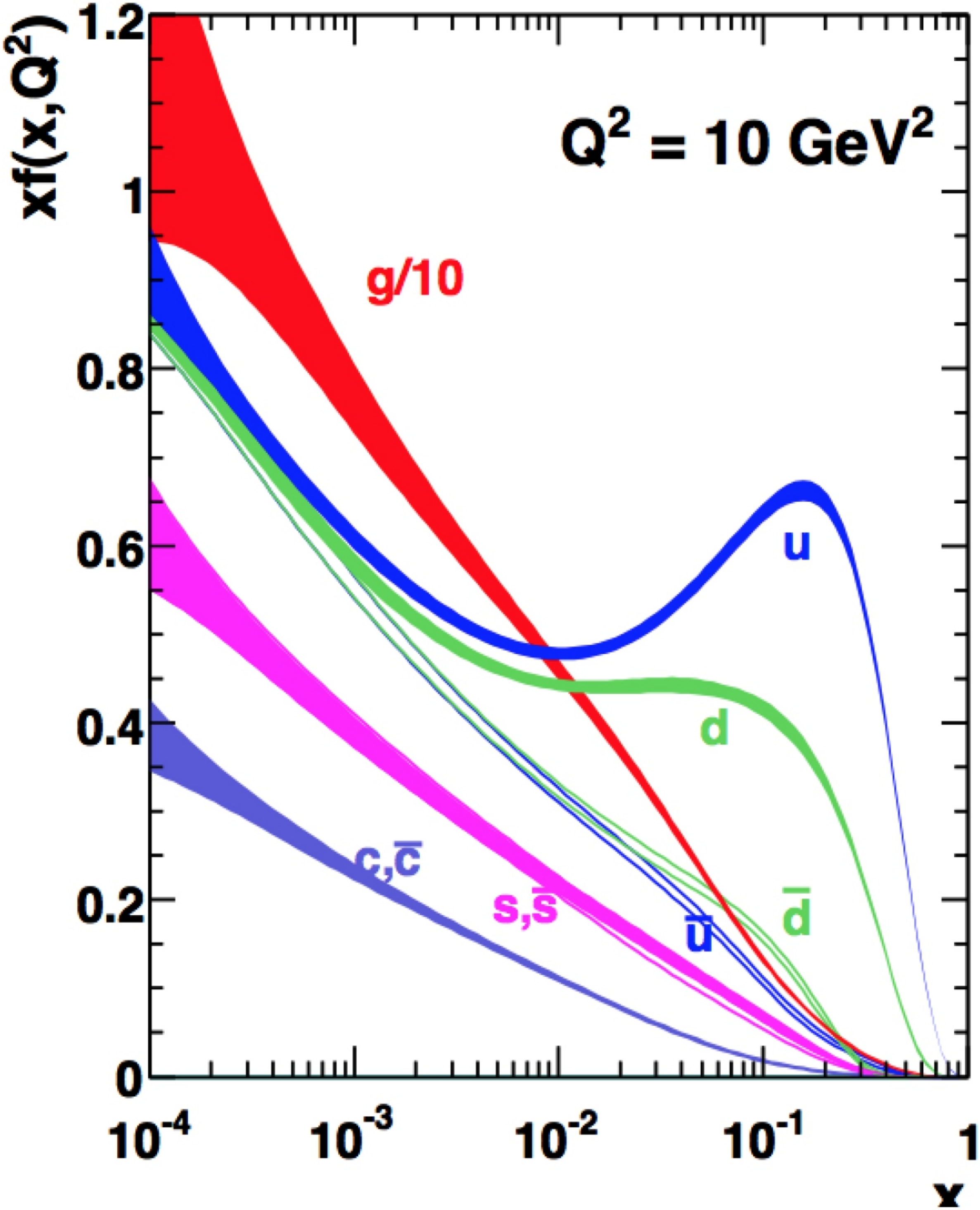
Hadronic Interactions

Composite (complex) Objects
Multiple interaction structure

QCD



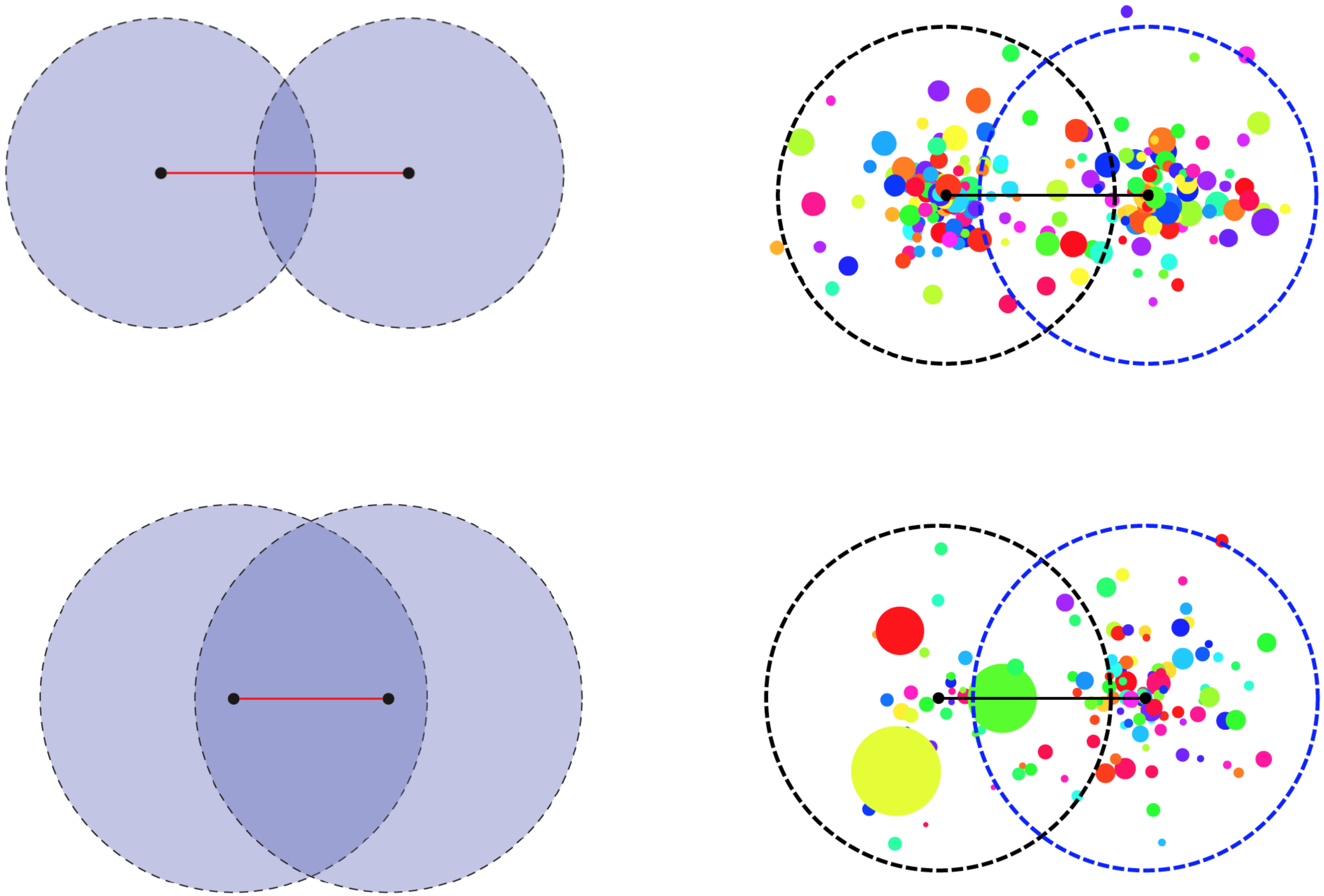
Multiple Parton Interactions
(in the same collision)
is the essential element in the modeling



Parton Distribution Functions

$$f_j(x) \propto \frac{1}{x^{1+\delta}}$$

Rapid growth for $x \to 0$



$$\hat{s} = s\, x_1\, x_2$$

$$Q^2 \leq \frac{\hat{s}}{2}$$

(c.m. energy)^2
of parton-parton system

Interacting Partons

$$x_1 \;\; x_2 \gtrsim \frac{(\Lambda_{\mathrm{QCD}})^2}{s}$$ all

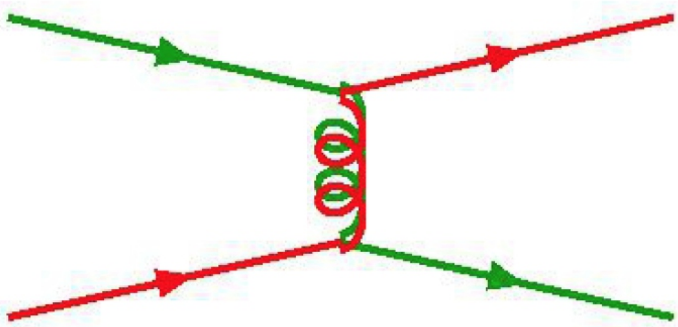
$$x_1 \;\; x_2 \gtrsim \frac{Q^2_{\mathrm{min}}}{s}$$ hard

Increasing the
c.m. Energy:

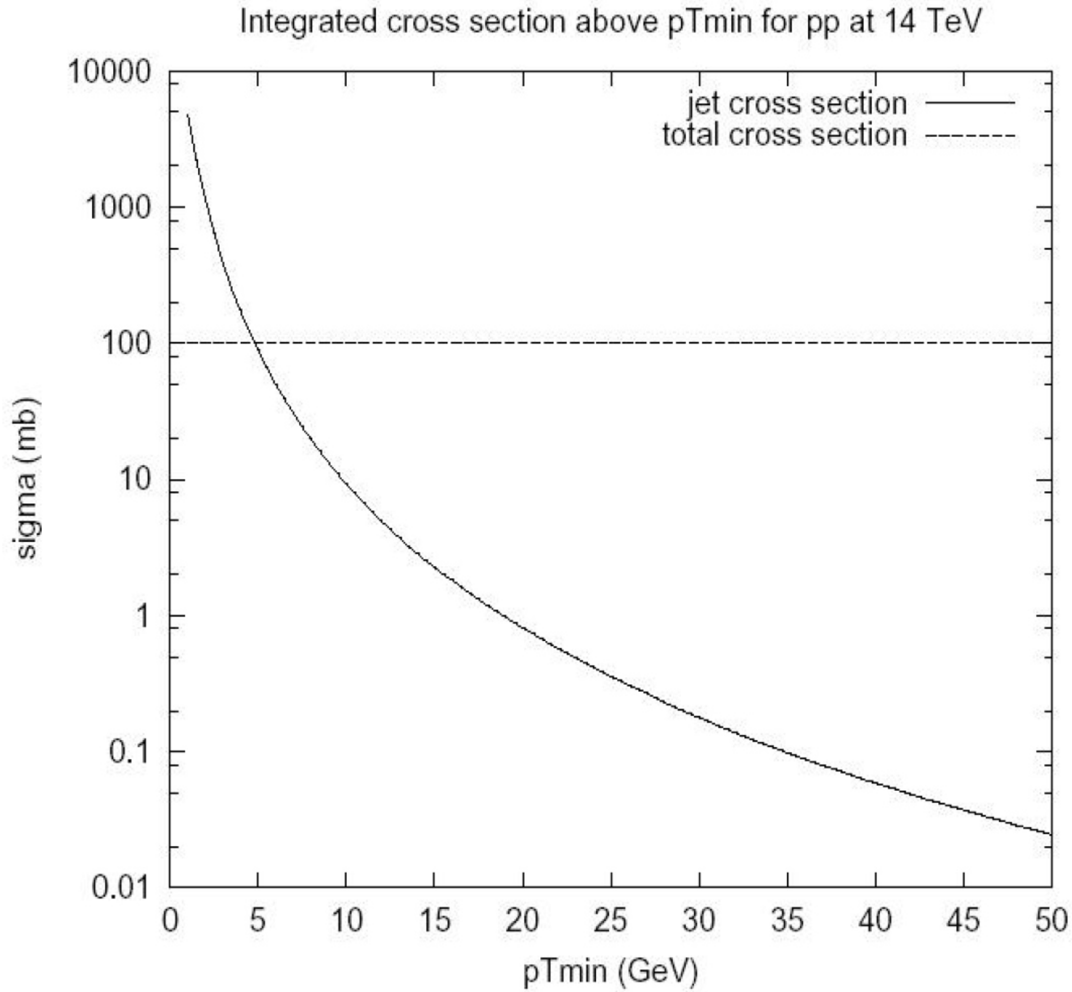
More parton-parton
Interactions

pp cross section grows
Higher multiplicity.
More complex event.
Softer energy spectra.

QCD $2 \to 2$



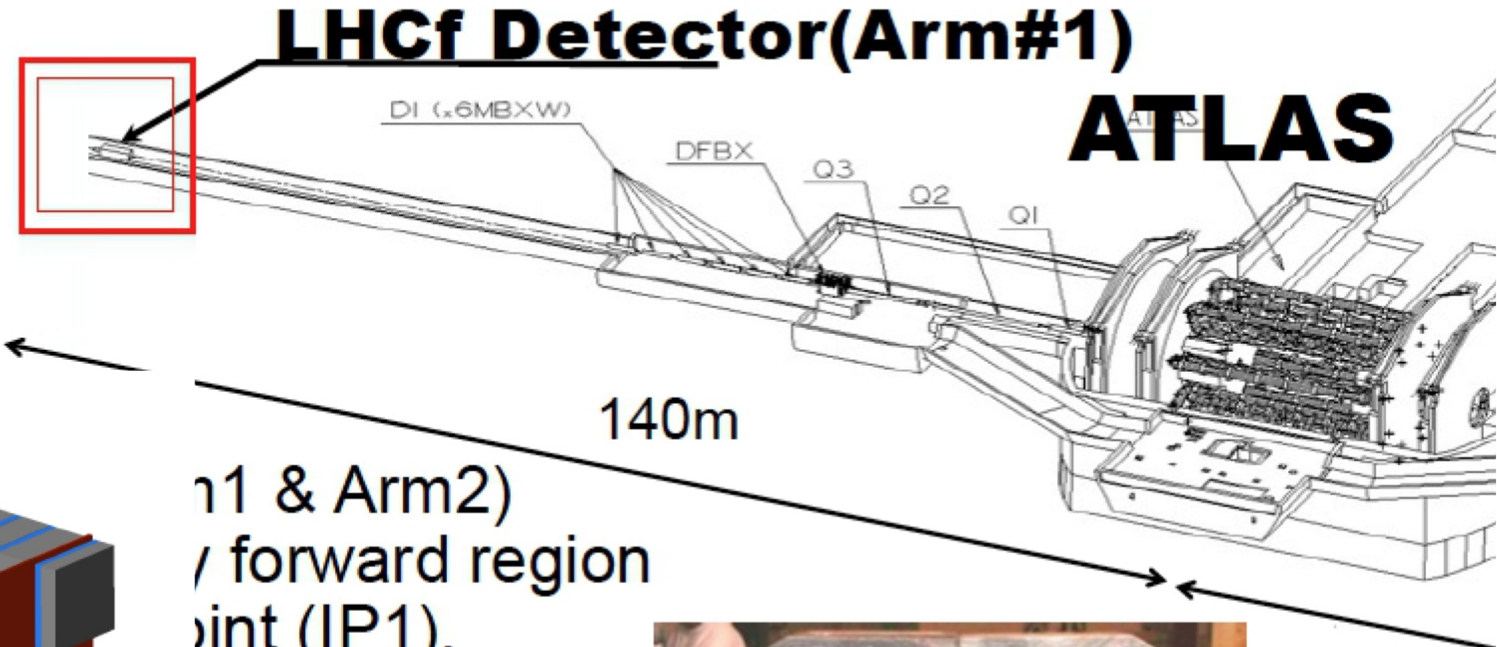
$$qq' \to qq'$$
$$q\overline{q} \to q'\overline{q}'$$
$$q\overline{q} \to gg$$
$$qg \to qg$$
$$gg \to gg$$
$$gg \to q\overline{q}$$

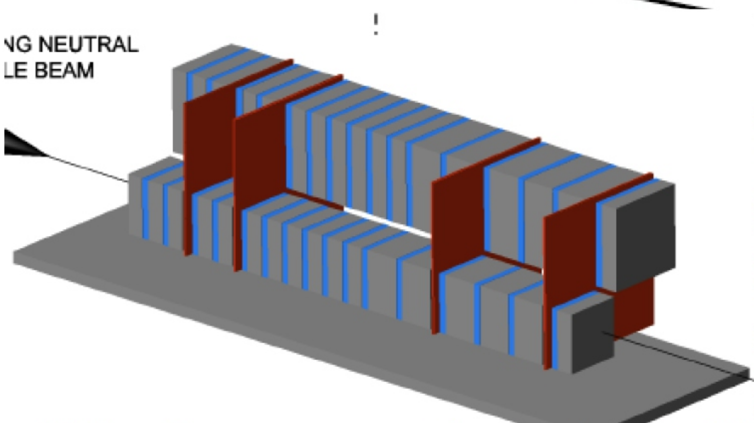


$$\mathrm{d}\sigma/\mathrm{d}p_\perp^2 \approx 1/p_\perp^4 \text{ for } p_\perp \to 0.$$

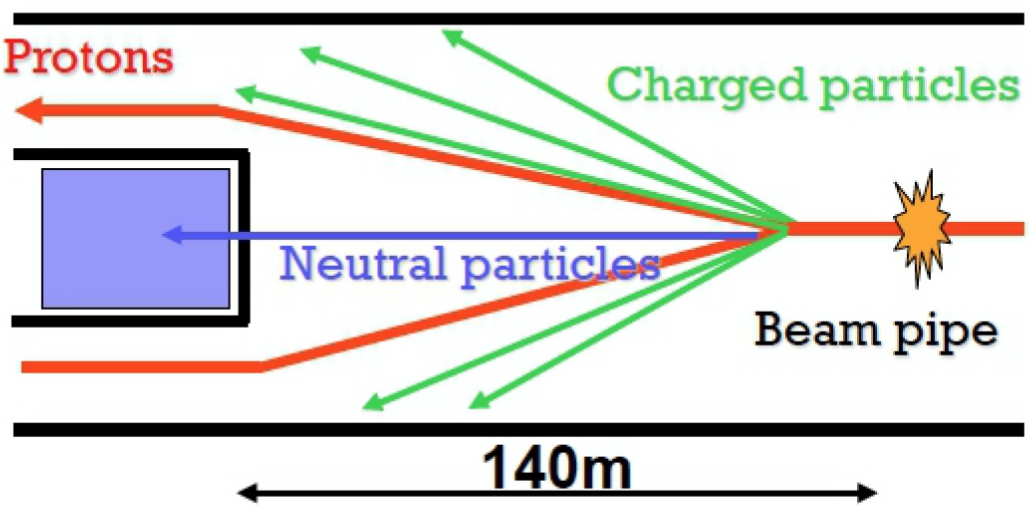
LHCf Experiment

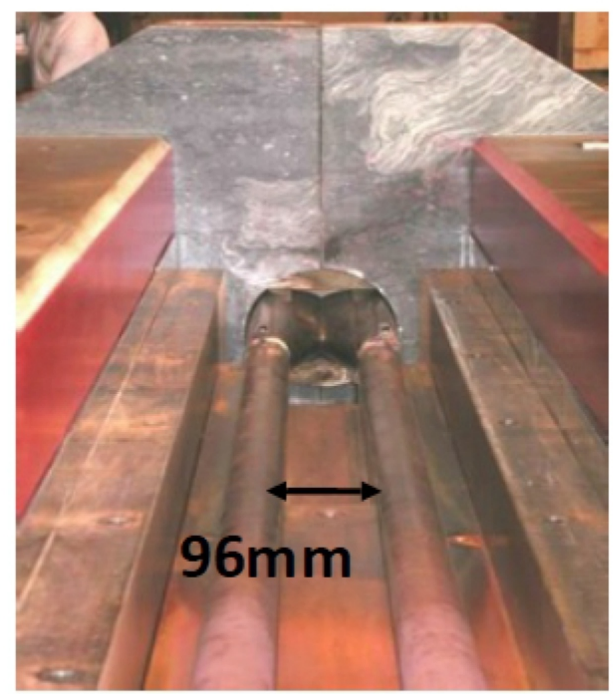
Yoshitaka ITOW
Hiroaki MENJO





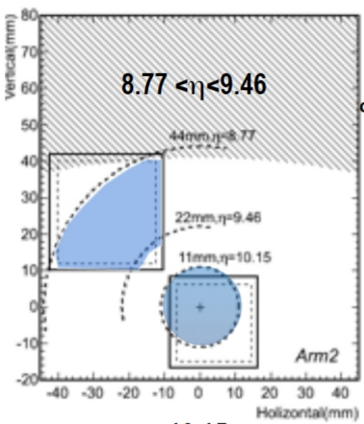
ı1 & Arm2)
/ forward region
›int (IP1).
al particles
e **η > 8.4.**



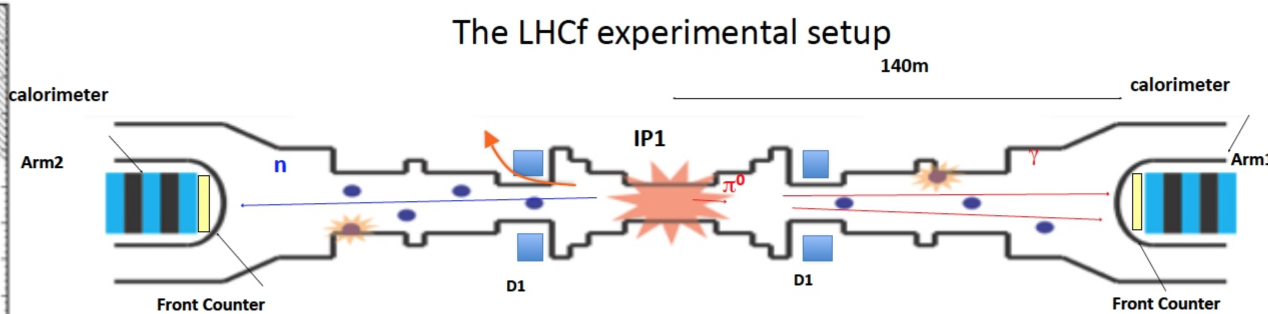


LHCf: very forward photon production

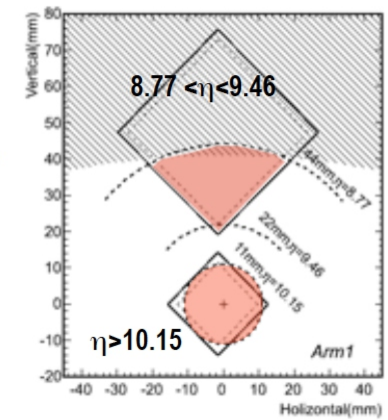
Arm 2



η>10.15

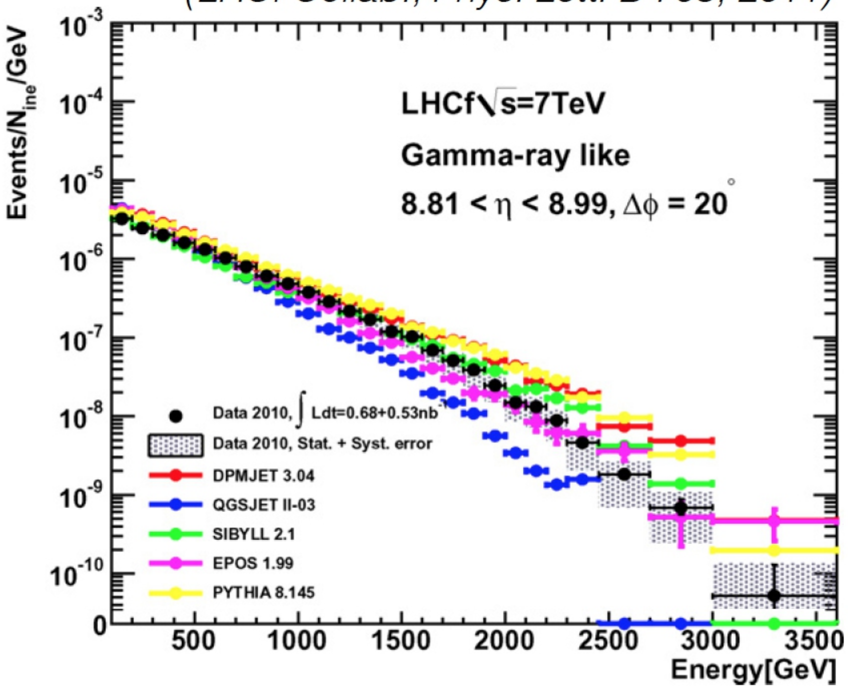


Arm 1

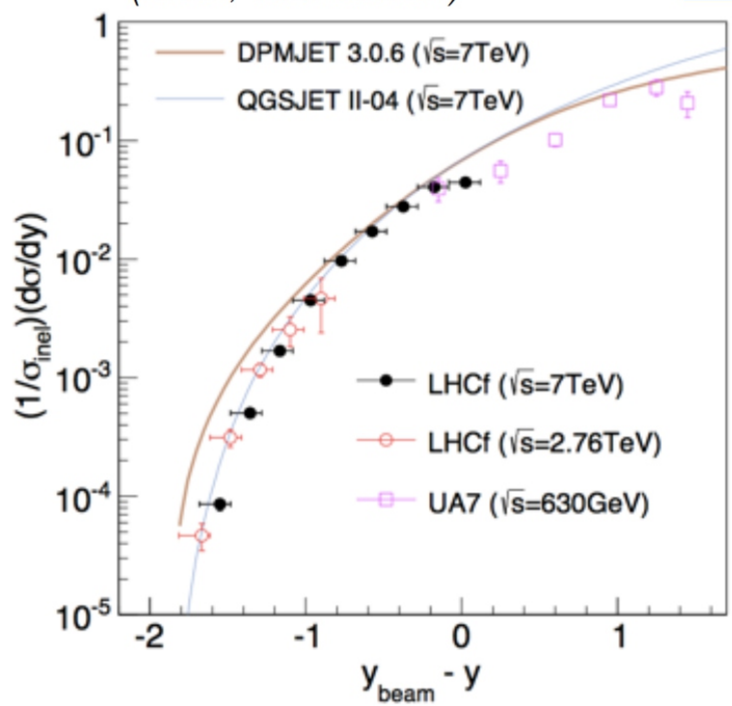


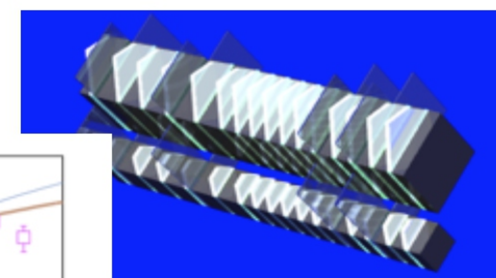
$$pp \to \gamma X$$

(LHCf Collab., Phys. Lett. B 703, 2011)



(LHCf, 1507.08764)



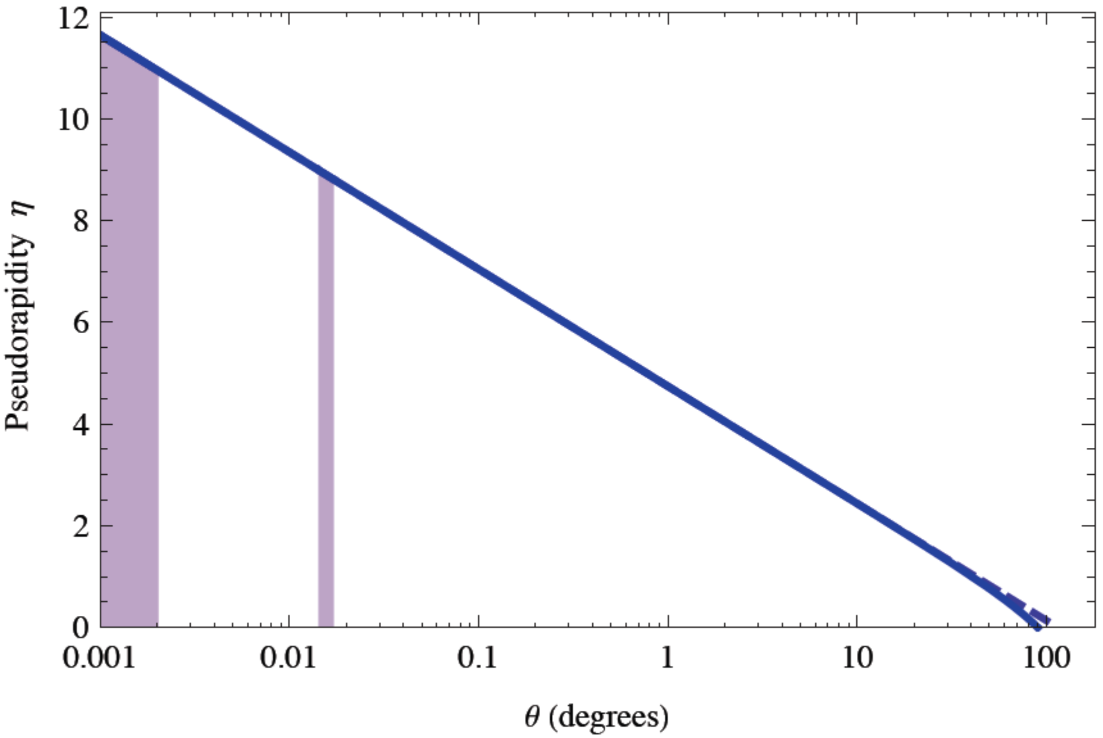


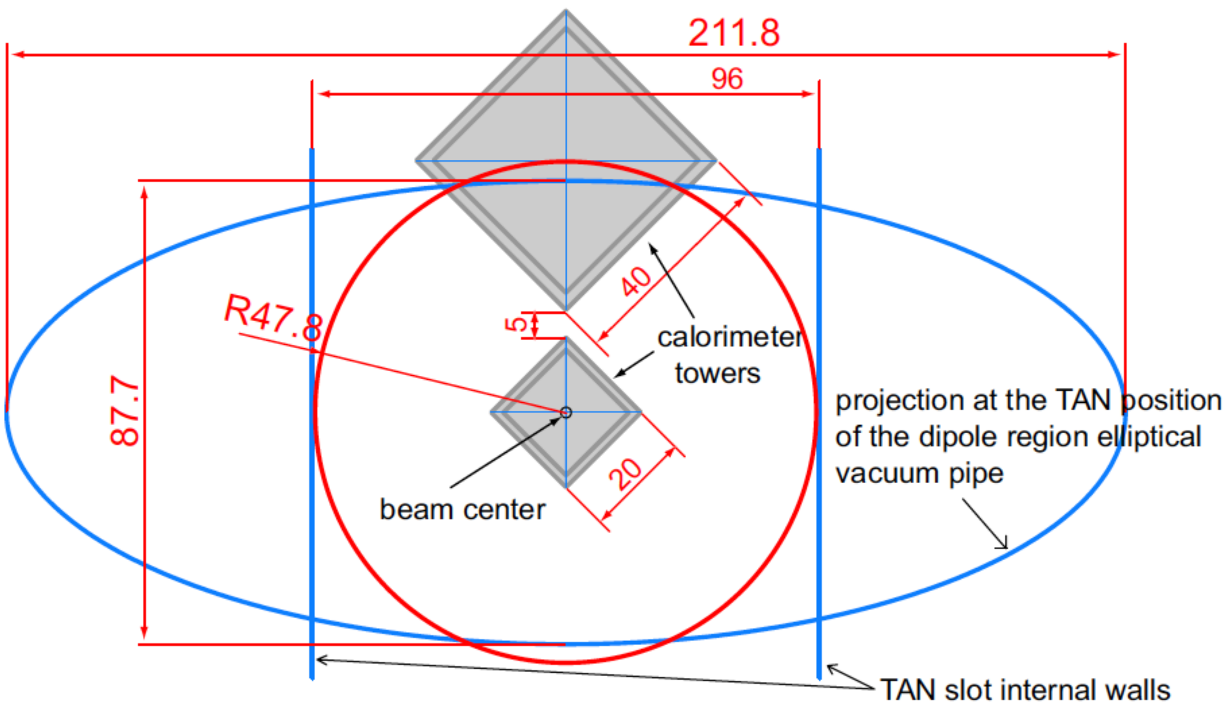
(Itow, ICRC 2015)

LHCF data

Pseudo-Rapidity versus angle:

Very small angle production:





LHCf $\sqrt{s}$=7TeV

Gamma-ray like

$8.81 < \eta < 8.99$, $\Delta\phi = 20^\circ$

LHCf $\sqrt{s}$=7TeV

Gamma-ray like

$\eta > 10.94$, $\Delta\phi = 360^\circ$

$$\left[\frac{dN_\gamma}{dE_\gamma}(E_\gamma)\right]_{8.81\leq\eta\leq8.99} = \frac{dN_\gamma}{dE_\gamma}(E_\gamma) \times \frac{dN_\gamma[8.81 \leq \eta \leq 8.99]}{dN_\gamma[\text{all }\eta]}$$

$$\left[\frac{dN_\gamma}{dE_\gamma}(E_\gamma)\right]_{\eta>10.94} = \frac{dN_\gamma}{dE_\gamma}(E_\gamma) \times \frac{dN_\gamma[\eta > 10.94]}{dN_\gamma[\text{all }\eta]}$$

$$\left[\frac{dN_\gamma}{dE_\gamma}(E_\gamma)\right]_{8.81\leq\eta\leq 8.99} = \frac{dN_\gamma}{dE_\gamma}(E_\gamma) \times \frac{dN_\gamma[8.81 \leq \eta \leq 8.99]}{dN_\gamma[\text{all } \eta]}$$

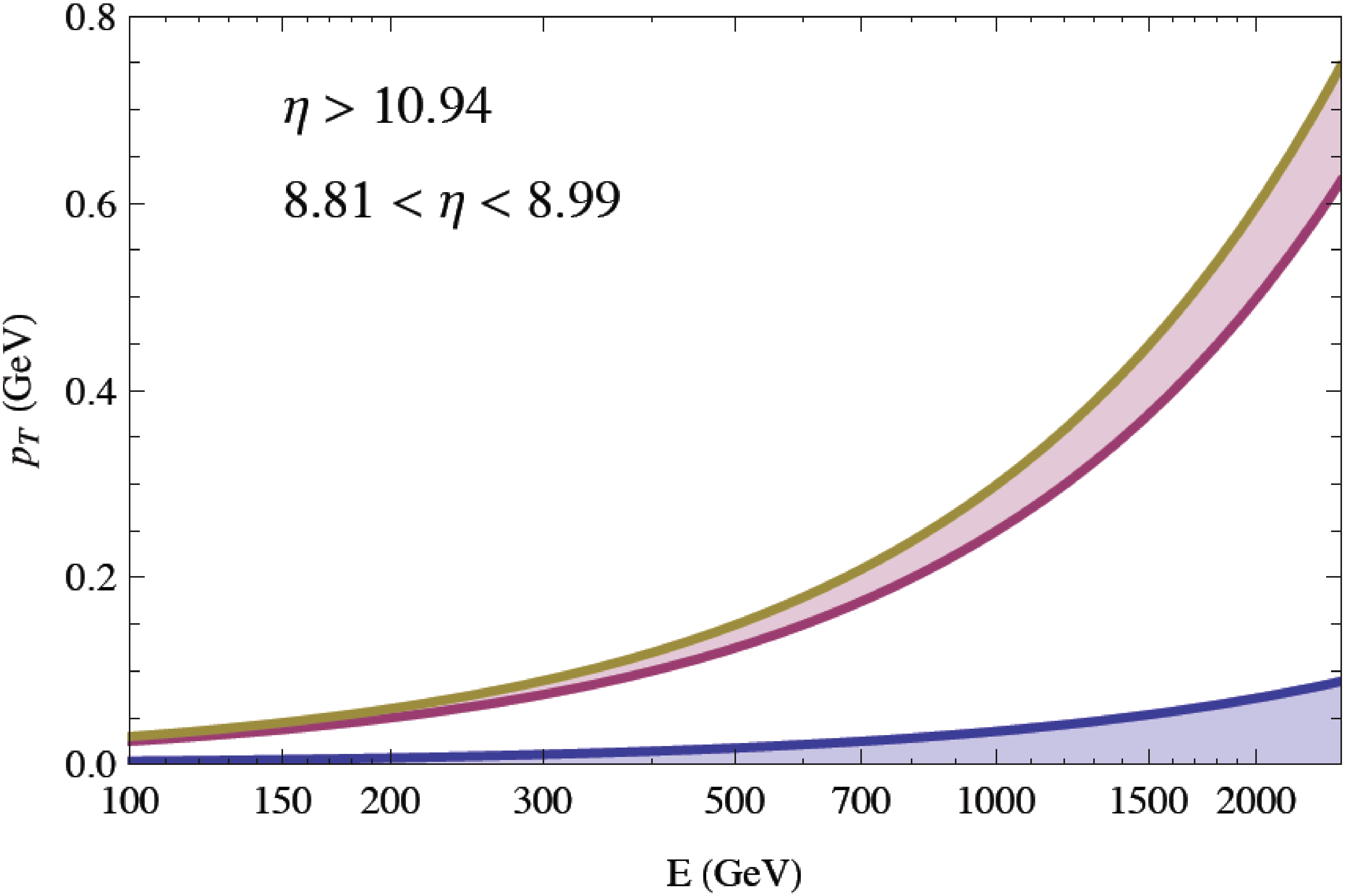
$$\left[\frac{dN_\gamma}{dE_\gamma}(E_\gamma)\right]_{\eta>10.94} = \frac{dN_\gamma}{dE_\gamma}(E_\gamma) \times \frac{dN_\gamma[\eta > 10.94]}{dN_\gamma[\text{all } \eta]}$$

Directly relevant for UHECR shower development

pT distribution dependence

$$p_\perp = \sqrt{E^2 - m^2}\ \sin\left[2\ \tan^{-1}\left(e^{-\eta}\right)\right]$$

$$p_\perp \simeq p\ 2\ e^{-\eta}$$



What are the most significant measurements (for cosmic ray studies) to be performed at LHC ?

0. c.m. Energy extension (...obvious)

1. *Observed **Phase Space** extension*
   (very difficult .. but in my view also very important)

2. Better **diffraction cross section** determination.

3. Program of **proton/light-nucleus** observations

3a. Program of nucleus/light-nucleus

Is a p-light nucleus of interest
for the ALICE/Heavy Ions community at CERN ?

…. well of course the most fascinating science
is in Lead-Lead collisions. This is where
New behaviours (Quark-Gluon-Plasma…)

But (it seems to me) that it is possible to
construct a robust argument that to develop
a full understanding of "normal behavior"
In nucleus-nucleus collisions,
a more full span of Phase Space is very important

The interest of the Cosmic Ray community in the continuation (and development !) of The "forward Physics", (Full Phase Space) Programs at LHC is VERY STRONG !

A full understanding of the Multi-Parton-Interaction structure of inelastic collisions *requires* a coverage of the entire phase space including the Very-forward – very/backward Fragmentation region.

So significant "intrinsic" (Particle Physics) interest in these programs

More in general:

Uncertainties on soft hadronic interactions remain a significant source of systematic uncertainties for many different studies on a broad energy range

[From very low energy: pp $\rightarrow$ p p + few pions]
Study of acceleration in SN remnants
Production of neutral pions (that decay into gammas)

[Up to sqrt[s] = 430 TeV

Bridging the Gap

between

Soft and Hard

Hadronic Interactions

Problem of CONFINEMENT

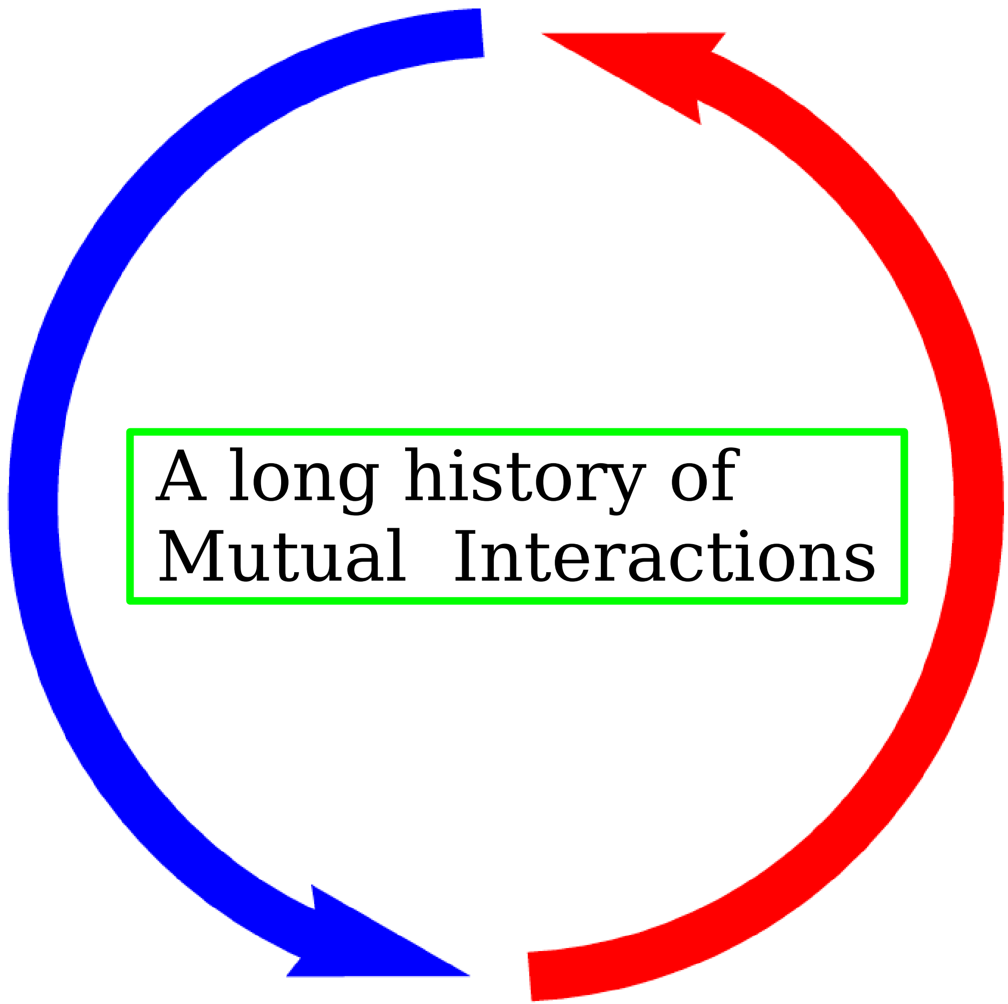
SOFT QCD studies

Have NOT only a simple “engineering” interest
as a instrument to reconstruct the primary particle
mass and energy in a shower.

They confront a very significant scientific
open problem for the Standard Model

(In my view) they deserve a strong, broad
Experimental *and theoretical* program.

PARTICLE PHYSICS



COSMIC RAYS ASTROPHYSICS

With UHECR one studies at the same time

“Gigantic Astrophysical Beasts”
Millions of light years away
Length scale 10^{+24} cm

Microscopic
Partonic constituents of matter
Length scale 10^{-15} cm

Exciting

Difficult

My final message:

The interconnection between

Particle Physics

and

Cosmic Ray science

[High Energy, multi-messenger-Astrophysics]

has a very long past-history

... and a very promising future.