Neutrino Astronomy / Astro-physics

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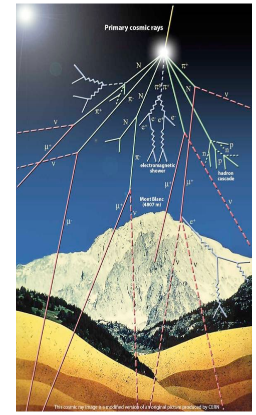
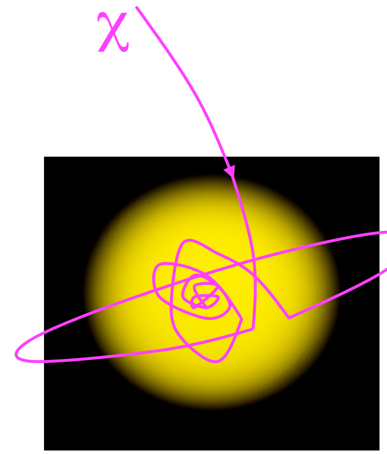


3 Lectures of one hours + Afternoon Group Work
-Focus on **Cosmic Neutrinos**
- Particle Physics at neutrino telescopes covered by S. Sarkar (lecture on Atmospheric neutrinos) and Rameez (lecture on Dark Matter at Neutrino Telescopes)

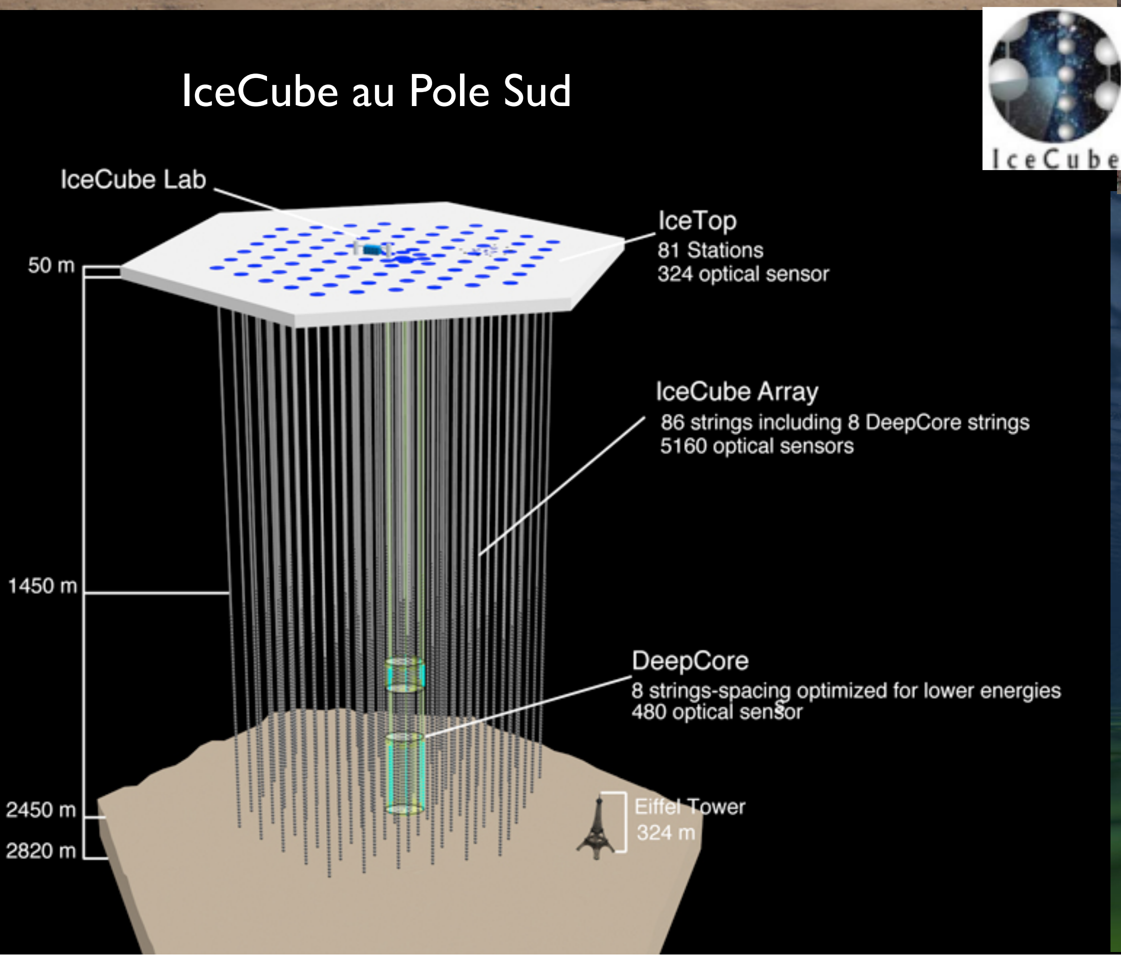


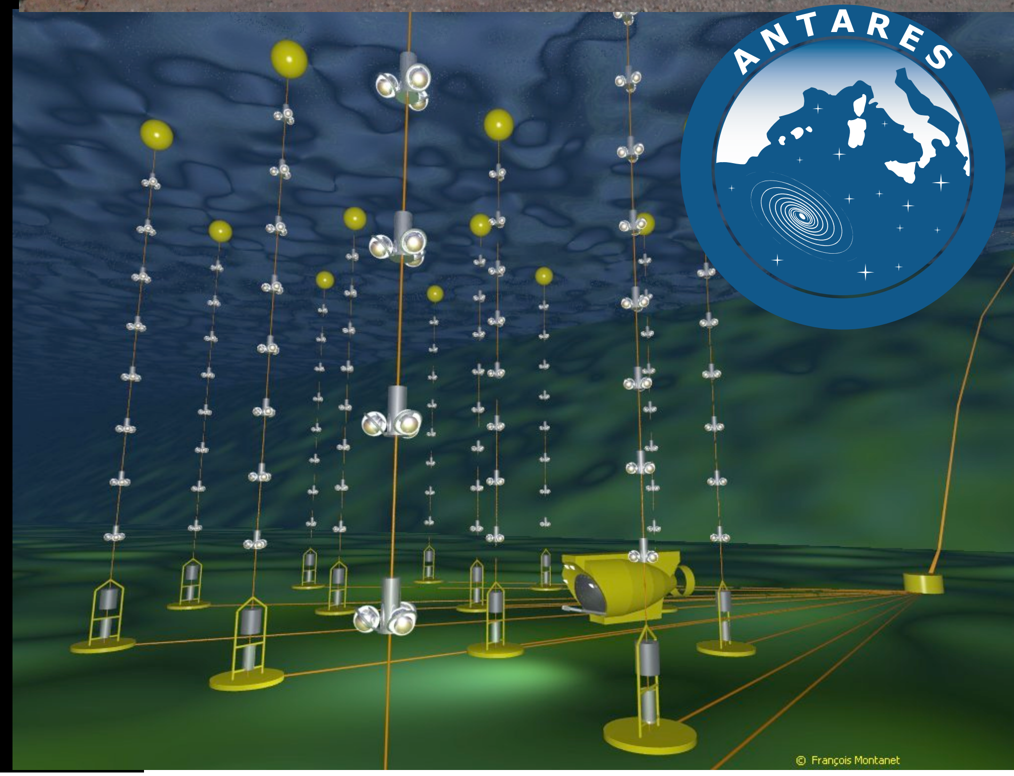
Our Subjects:

- The Neutrino Horizon at High Energy
- the cosmic ray - gamma - neutrino connection
- Detection Technique and experiments
- The Future with KM3NeT and Gen-2.

Niels Bohr Institute PhD School, 1 Aug. 2015

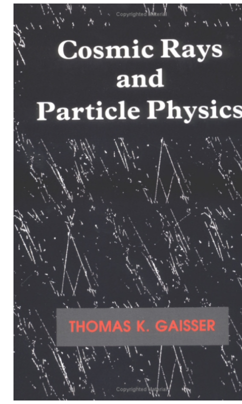
One word on my research

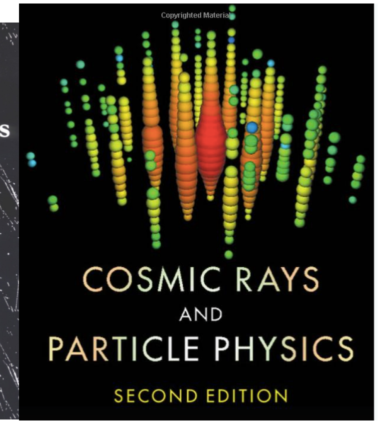


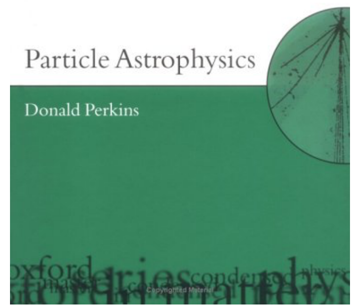


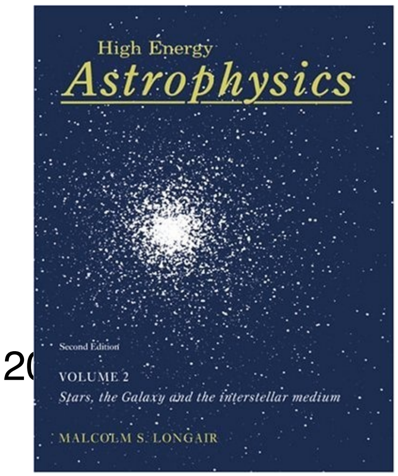
My favorite textbooks in Astroparticle

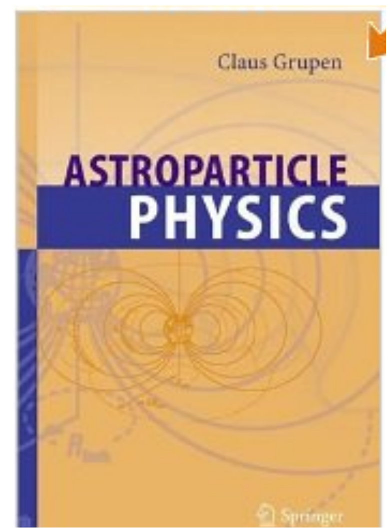
- T.K. Gaisser Cosmic Rays and Particle Physics (new edition 2016 available!)
- T. Stanev, High Energy Cosmic Rays, Springer, 2004
- M. S. Longair, High Energy Astrophysics, Cambridge U. Press, 2010
- D. Perkins, Particle Astrophysics (2nd ed. 2009)
- S. Rosswog & M.Bruggen High-Energy Astrophysics
- C. Grupen, Astroparticle Physics, Springer, 2005
- M. Spurio Particles and Astrophysics, Springer
- L. Bergstrom and A. Goobar, Cosmology and Particle Astrophysics, Springer (2nd edition,2
- M. Fukugita and Y. Yanagida, Physics of Neutrinos, Springer, 2003

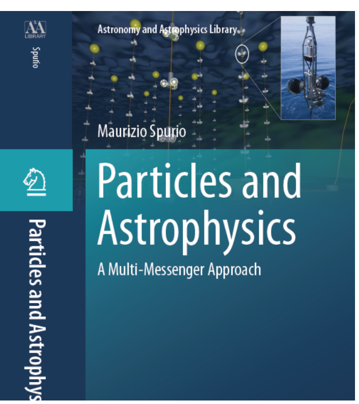










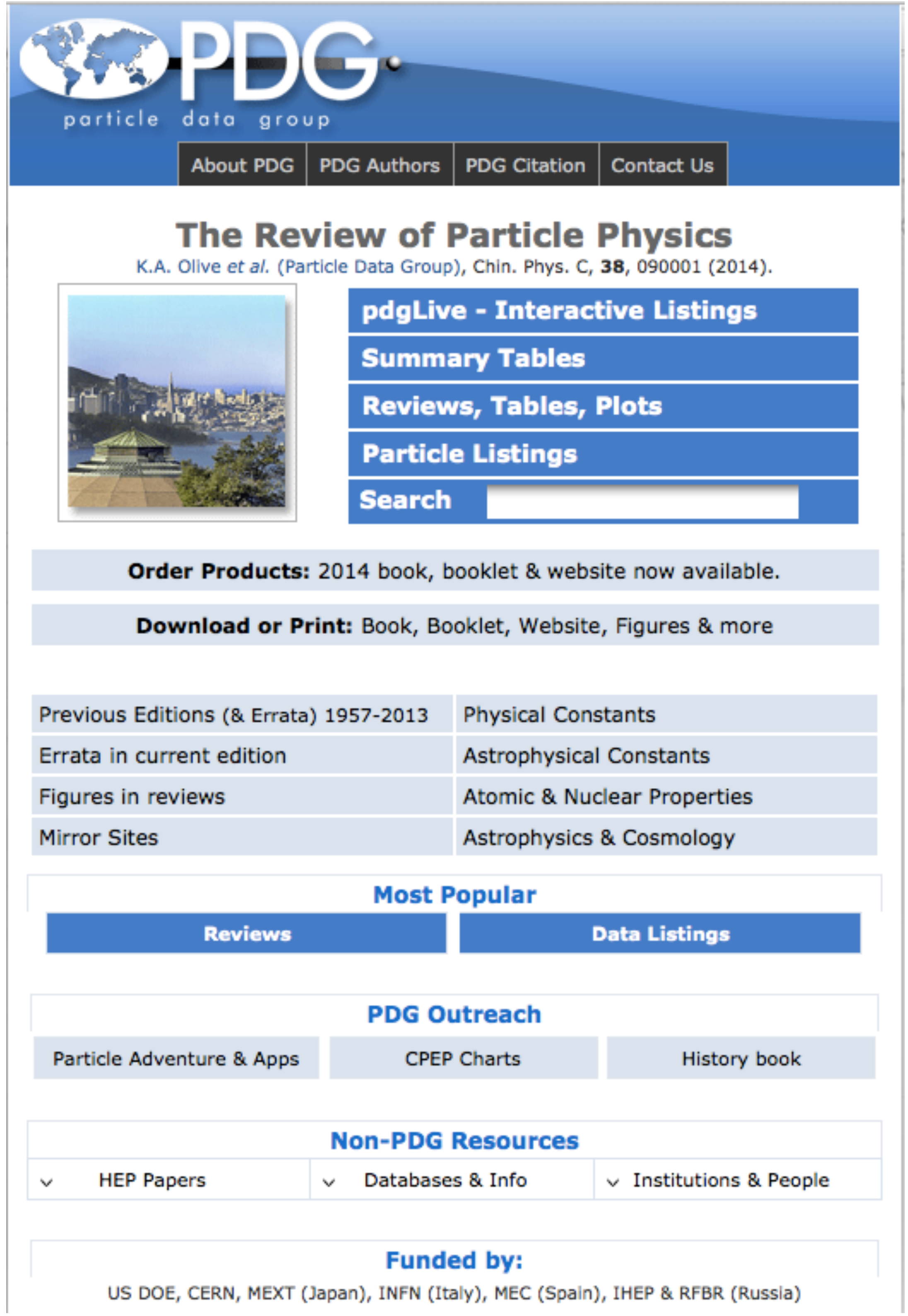


Data Particle Book

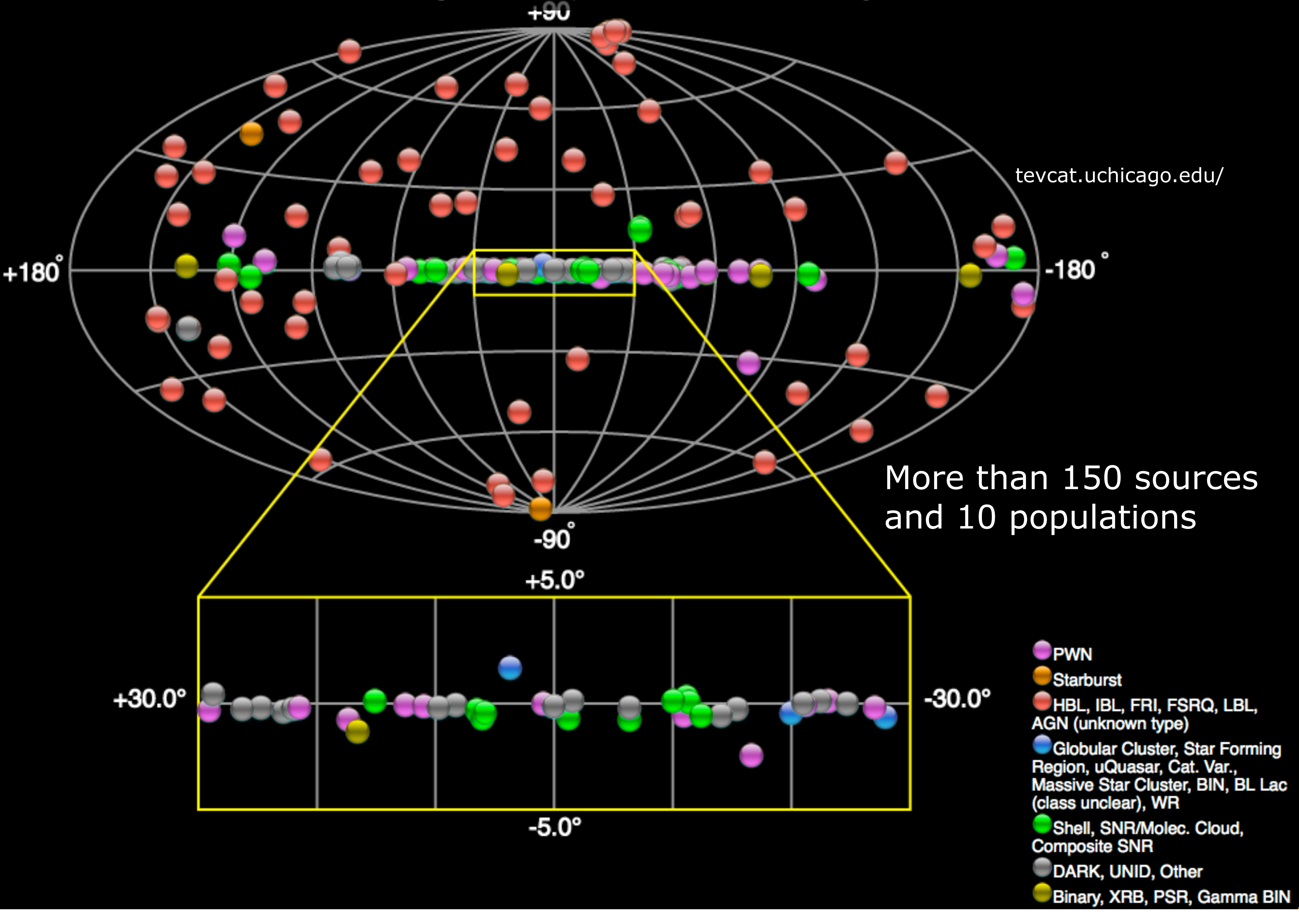
http://pdg.lbl.gov/

The physicist's book of truth

> 200 particles listed in PDB
But only 27 have $c\tau > 1\mu m$
and only 13 have $c\tau > 500\mu m$



Database of TeV gamma-sources for your exercises



tevcat.uchicago.edu/

More than 150 sources and 10 populations

Neutrinos winners!

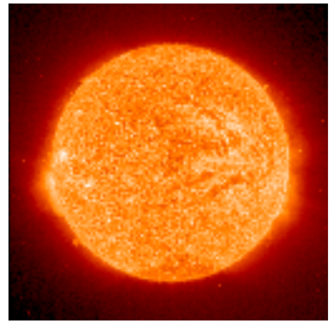
Nobel prize 2002

Oscillations with neutrinos from thermonuclear reactions in the Sun

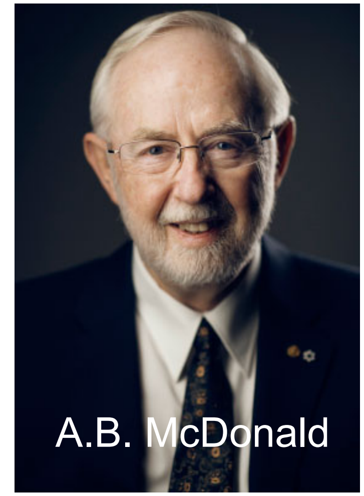
$$4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e$$

$\sim 6 \times 10^{10}\ \nu\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

$E_\nu \sim 0.1 - 20$ MeV



Nobel prize 2015

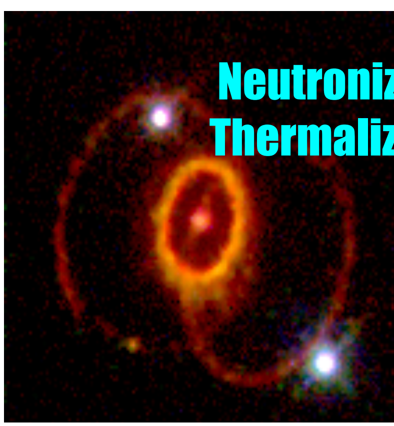


~ 100,000 billion solar neutrinos pass through your body/s

~1 neutrino stops in a lifetime!

M. Koshiba

~ 10 s bursts of 10 MeV vs from stellar collapse (I. Tamborra's lectures)



Neutronization $e^- + p \rightarrow n + \nu_e$

Thermalization: $e^- + e^+ \rightarrow \bar{\nu} + \nu$

Nobel prize 2016
Oscillations with atmospheric neutrinos

Localized extra-terrestrial neutrinos

D = 55 kpc

Let's pick up 2 of these events (similar emission time)

$T_1 = 0$ $E_1 = 20$ MeV

$T_2 = 12.5$ s $E_2 = 10$ MeV

$\Delta t_e = 0$ and $\Delta t_d = |t_2 - t_1| = 12.5s$ and we find solving for the mass:

$$mc^2 = \sqrt{\frac{2cE_1E_2|\Delta t_d|}{d\times|E_2^2 - E_1^2|}} = 24 \text{ eV}$$

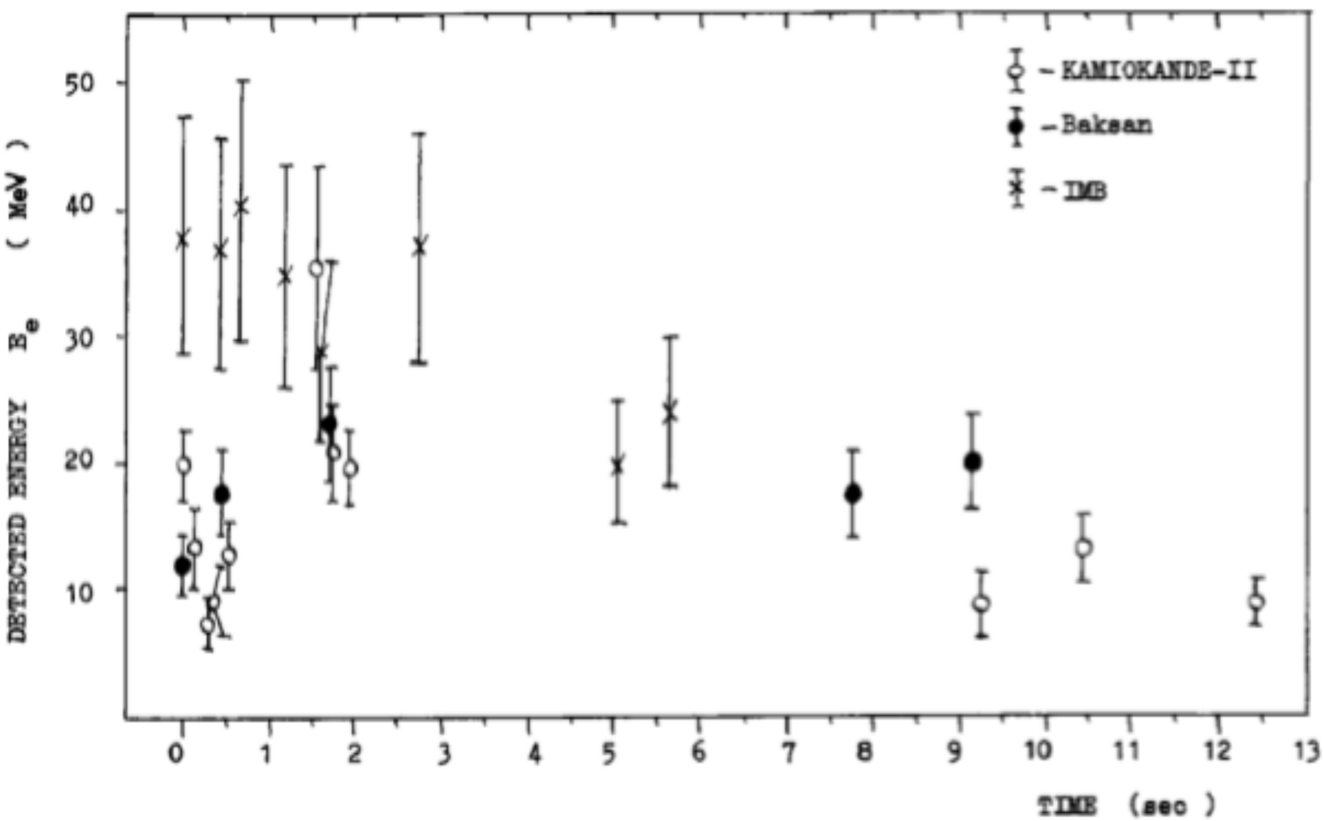
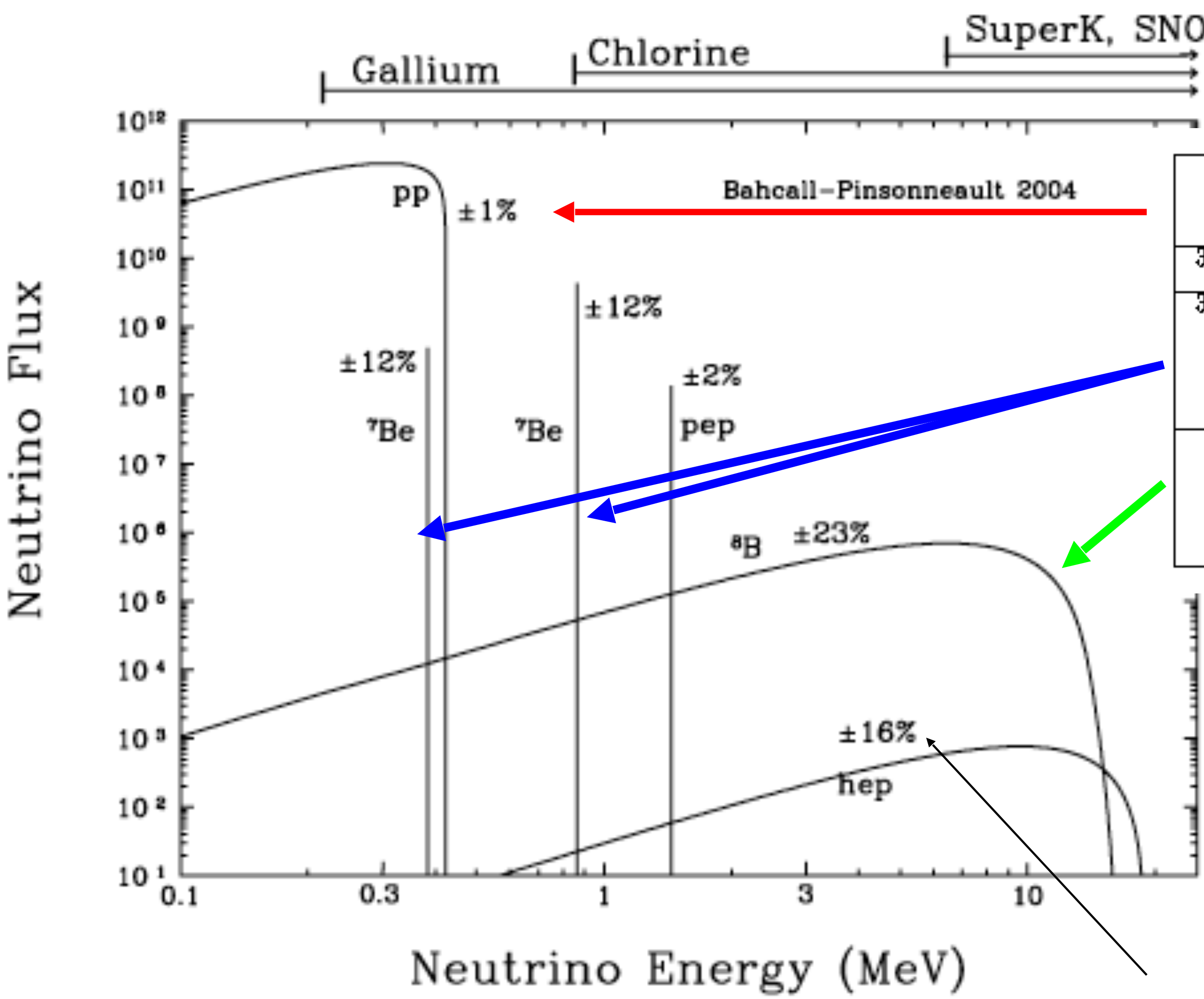


Fig. 3. Energies of all events detected at 7:35 UT on February 23, 1987 versus time. t=0.0 is set as to be the time of the first event of each signal observed.

Solar Neutrinos



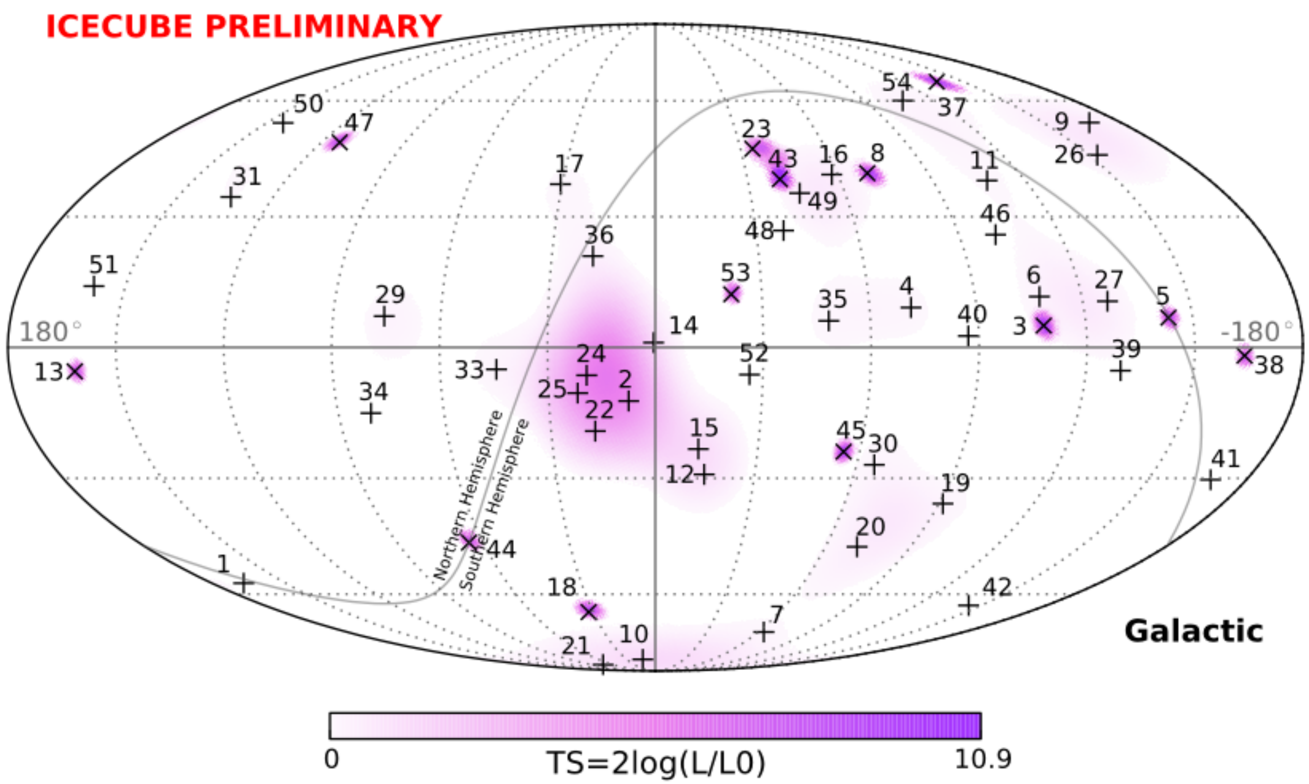
pp	$\rightarrow$	$^2H + e^+ + \nu_e$	ppI
$^2H + p$	$\rightarrow$	$^3He + \gamma$	
$^3He + {}^3He$	$\rightarrow$	$^4He + 2p$	
$^3He + {}^4He$	$\rightarrow$	$^7Be + \gamma$	ppII
$e^- + {}^7Be$	$\rightarrow$	$^7Li + \nu_e$	
$^7Li + p$	$\rightarrow$	$2\,{}^4He$	
$p + {}^7Be$	$\rightarrow$	$^8B + \gamma$	ppIII
^8B	$\rightarrow$	$^8Be^* + e^+ + \nu_e$	
$^8Be^*$	$\rightarrow$	$2\,{}^4He$	

Sun

Theoretical uncertainties

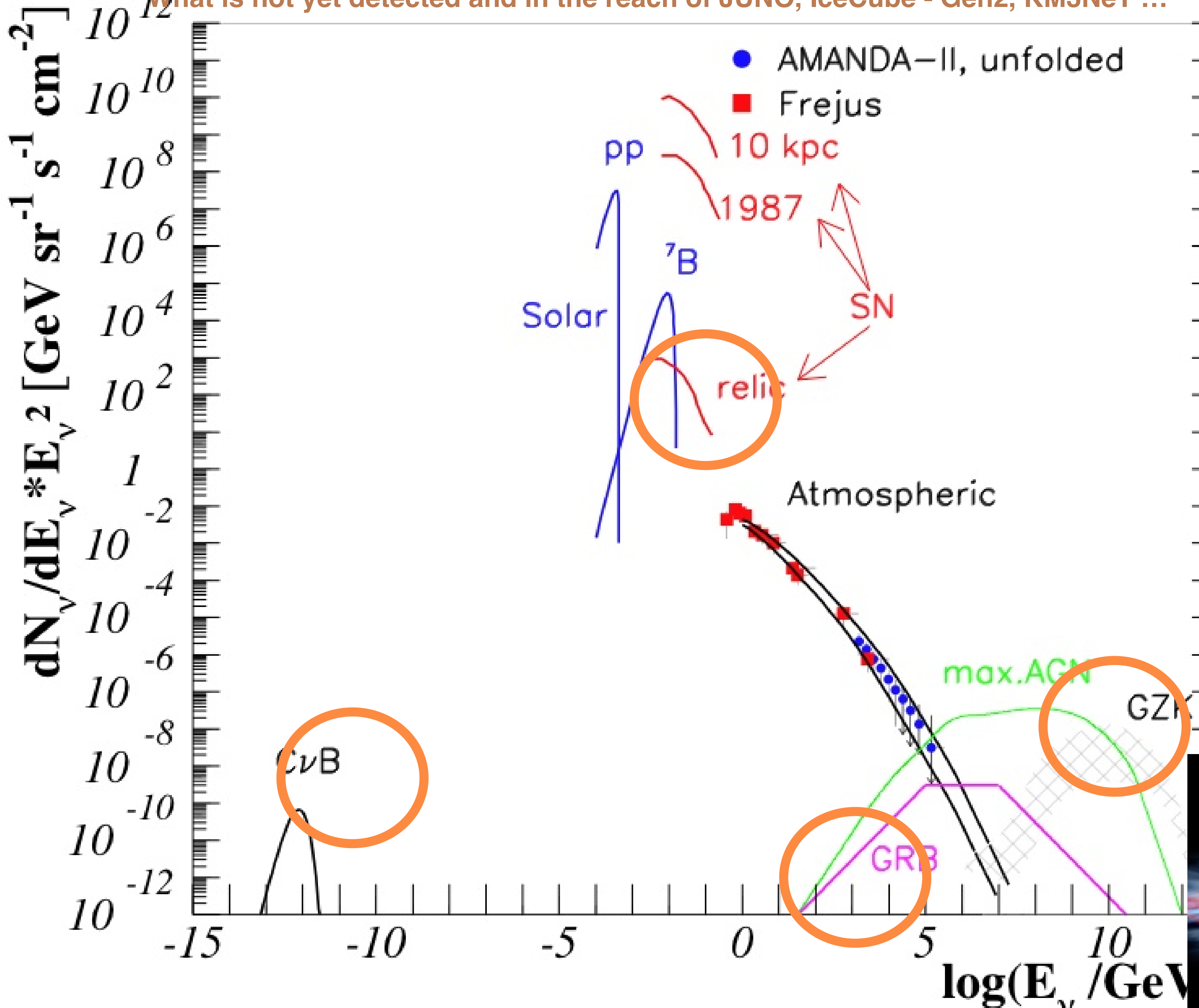
Cosmic neutrinos yet of unknown origin

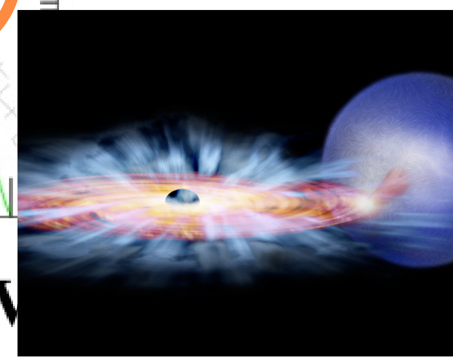
IceCube PeV energy astrophysical component



Cosmic fluxes

What is not yet detected and in the reach of JUNO, IceCube - Gen2, KM3NeT …





https://inspirehep.net/record/763437

High Energy Astrophysics Quests:

- **Origin and propagation of cosmic rays and their role in the universe:**
  - ➡*Where and how are particles accele[illegible] our Galaxy and beyond?*
  - ➡*Which are the galactic PeVatrons [illegible]e cosmic rays to the knee?* What role do accelerated particles play in feedback on [illegible]rmation and galaxy evolution? when are shocks efficient accelerators?
  - ➡*The nature and variety of black holes: [illegible]kes them efficient particle accelerators? how do their jets form?*
- **Transient phenomena in the Galaxy and [illegible]nd:**
  - ➡*what causes Active galactic nuclei f[illegible] what is the origin of Gamma-ray bursts: do their PL extend to TeV energies?*
- **Extreme magnetic fields in pulsars, unidentified sources, leptonic/hadronic phenomena in sources**
- **Probing cosmogenic neutrino fluxes and galaxy evolution**

New Physics: nature of matter and forces beyond the Standard Model

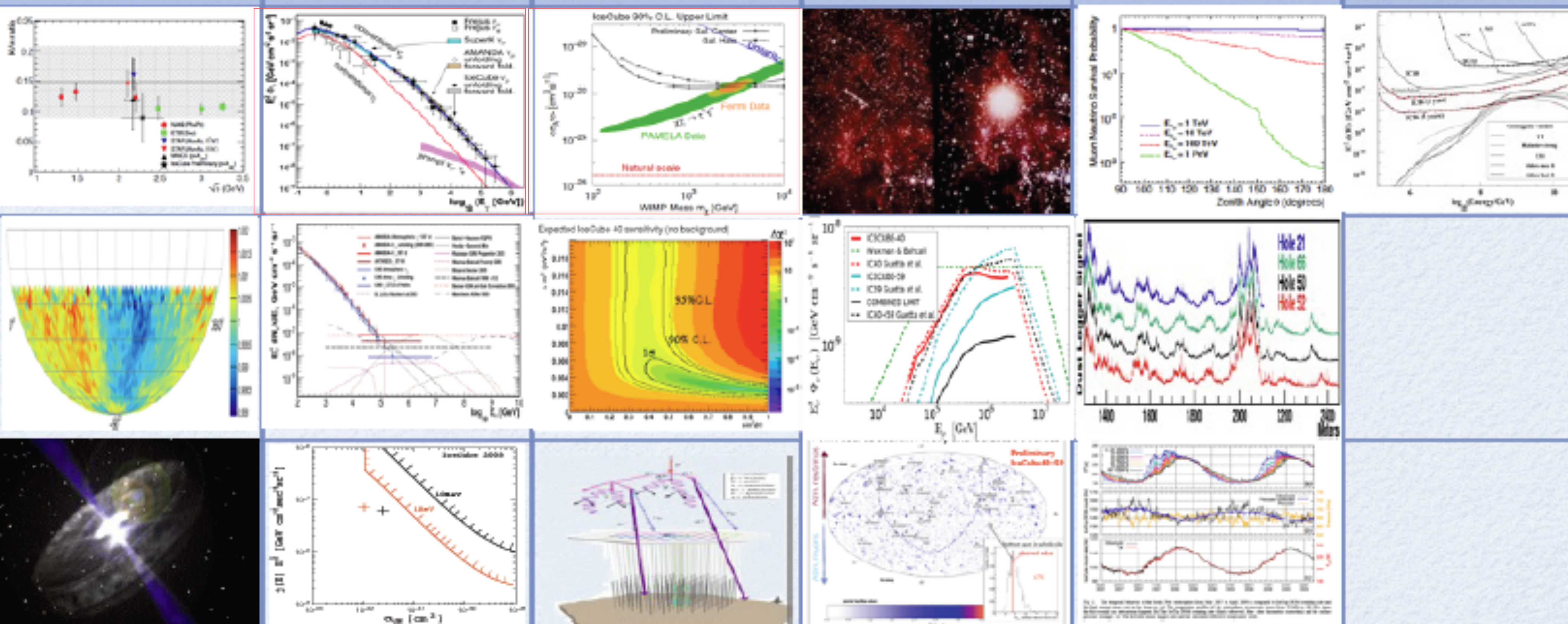
- ➡ ***What is the nature of dark matter? How is it distributed in the universe? Are axions part of CDM and do they convert into photons in the presence of B-fields?***
- ➡ ***Is there violation of Lorentz Invariance? Is the speed of light constant for high energy photons?***

Scientific program

E. Lisi's Neutrino properties
S. Sarkar's Atmospheric Neutrinos
Rameez Indirect search for Dark Matter
I. Tamborra SN neutrinos

This has to do with :
- **particle acceleration in extreme B-fields**
- **matter content of the universe**
- **neutrino properties**

Cosmic Rays	Atmospheric neutrinos	Particle Physics	Astronomy	Applied science	Cosmology

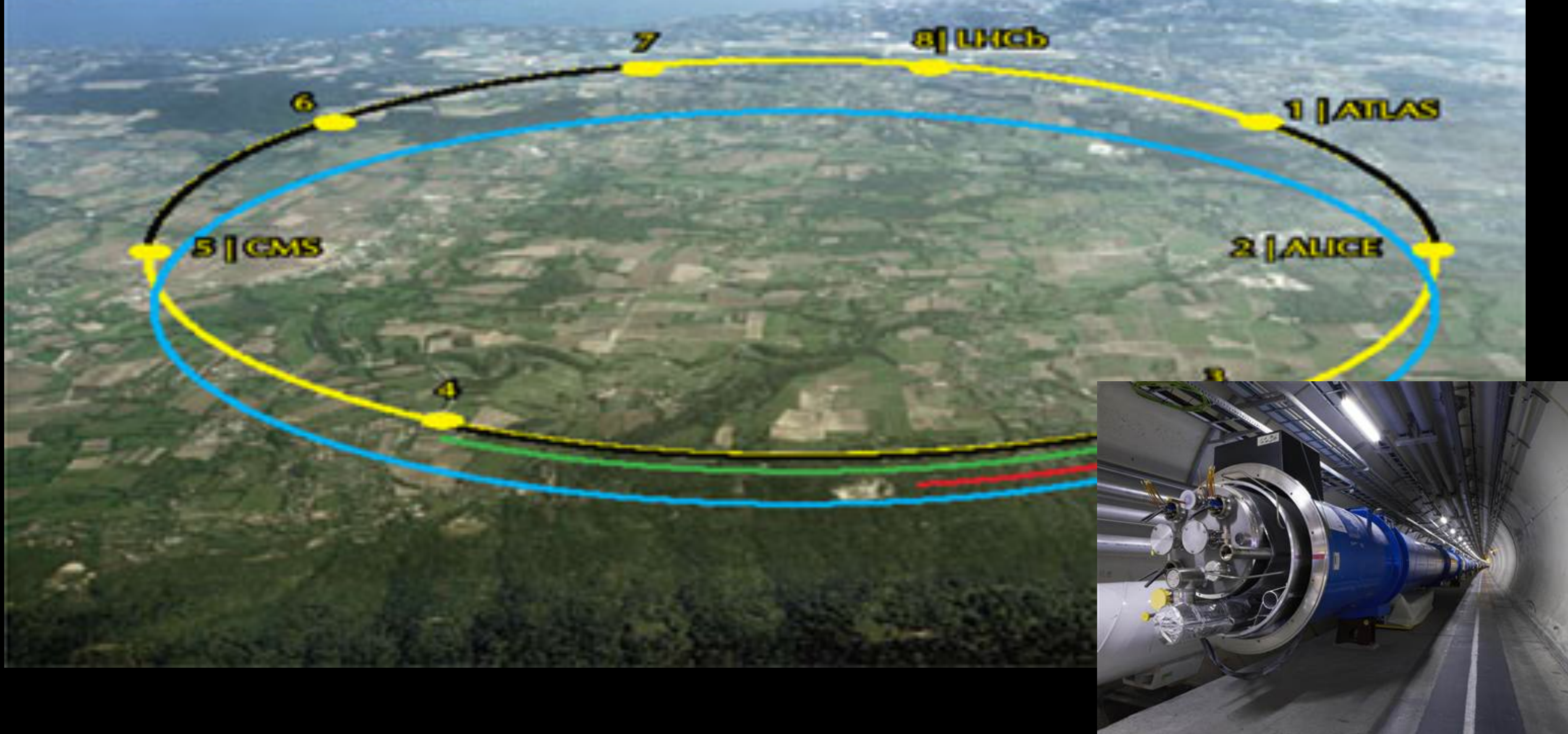


Large Hadron Collider:

$E_{max} = c \cdot e \cdot B \cdot R = 7 \times 10^{12}$ eV

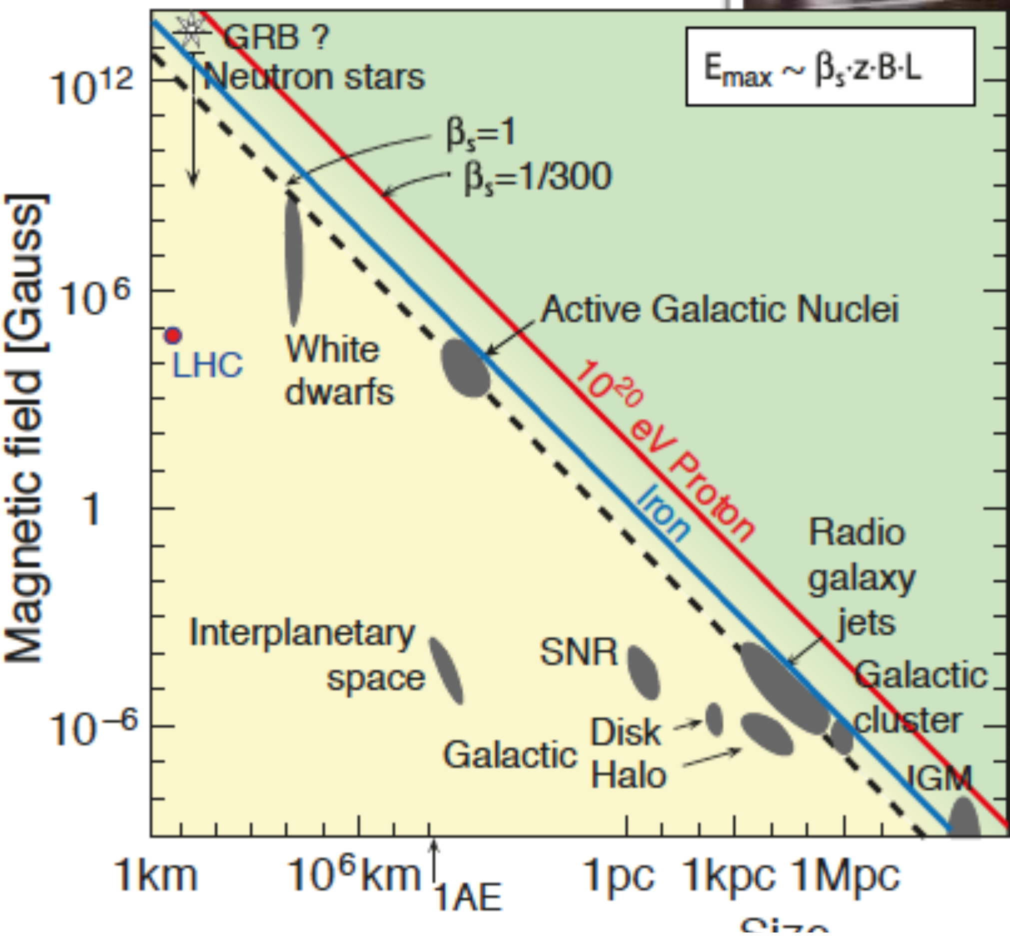
Man made accelerators:

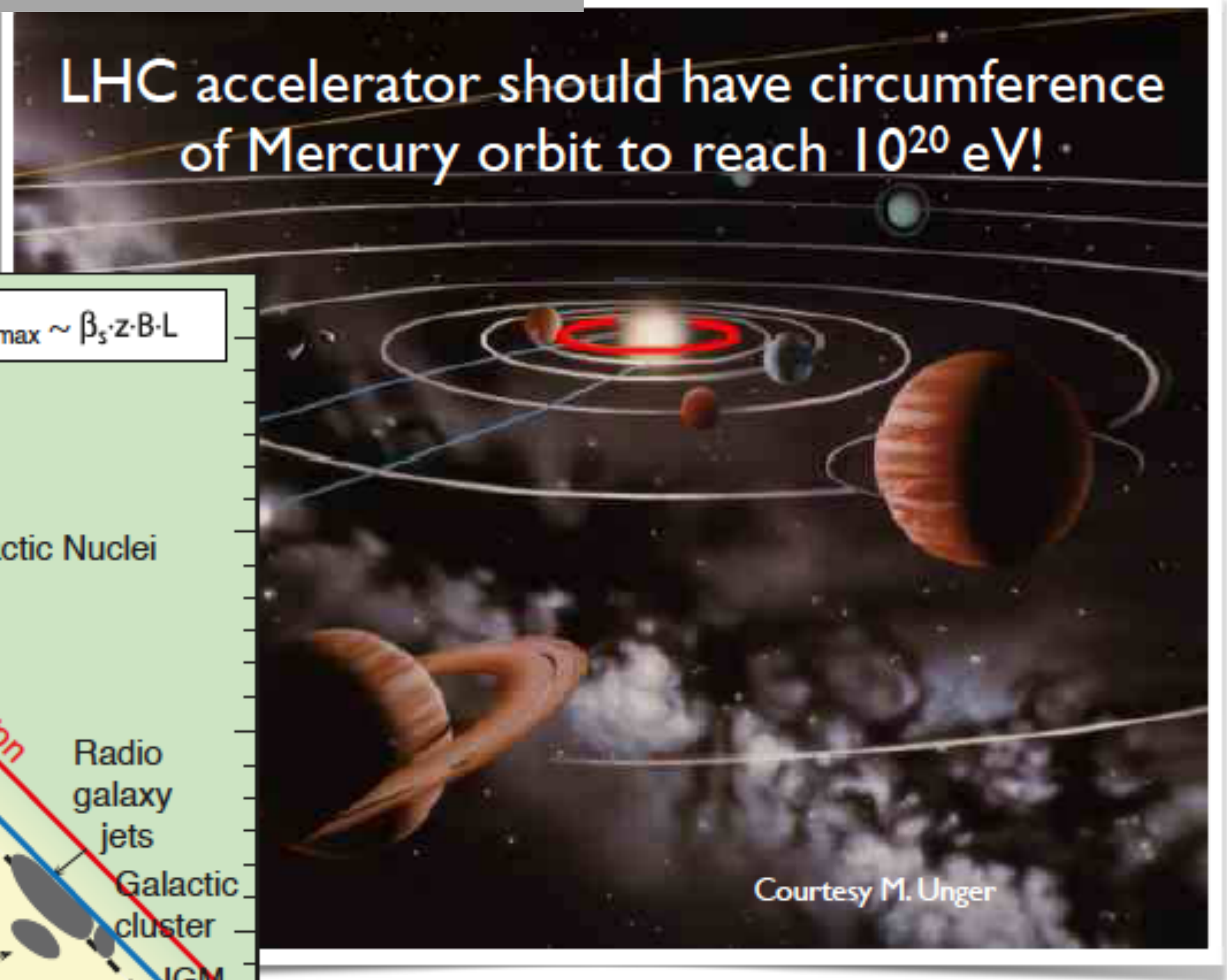
- dynamical (collisions between particles)
- Electromagnetic: f.e.m are produced according to $\nabla \times \mathbf{E} = -\delta \mathbf{B}/\delta t$



Magnetic field B vs accelerator's size R

Hillas plot (1984)





Acceleration charged particles in shocks: stochastic/turbulent acceleration of CRs due to repeated collisions of particles with a shock wave for instance due to a SN explosion or galaxy merging, winds of pulsars, or in jets of black holes or GRBs. Other processes: annihilation of DM, decay of heavy particles, leptons in B-fields (bremsstrahlung, synchrotron, inverse Compton)

Reminders of relativistic kinematics

Momentum: $\vec{p} = \gamma m \vec{v} = \gamma m \vec{\beta} c$ $\qquad (E/c)^2 - \mathbf{p}^2 = m^2c^2$

Total energy: $E = \sqrt{m^2c^4 + m^2\gamma^2\beta^2c^4} = mc^2\sqrt{1+\gamma^2\beta^2}$

$$\beta = \frac{cp}{E} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}} \rightarrow \beta^2 = 1 - \frac{1}{\gamma^2}$$

$$E = mc^2\sqrt{1+\gamma^2-1} = mc^2\gamma$$

Kinetic energy:

$$E_k = E - mc^2 = mc^2(\gamma - 1)$$

Lorentz transf. from la frame moving with velocity β_f with respect to another:

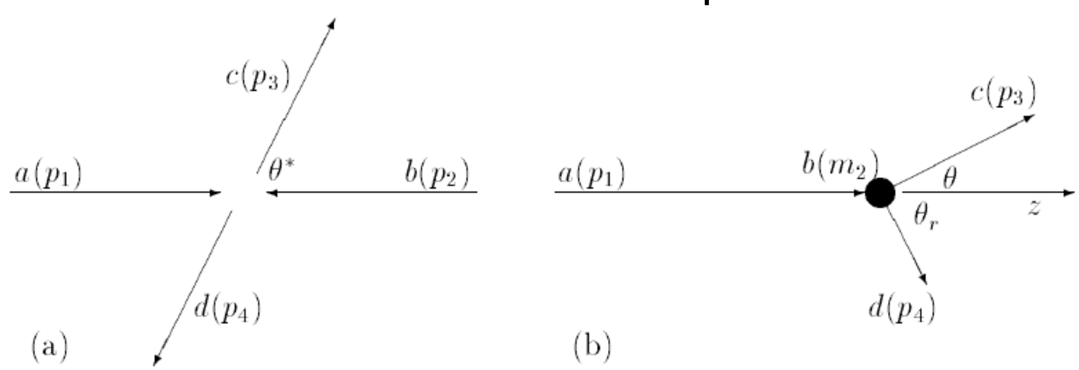
$$\begin{pmatrix} E^* \\ p^*_{\parallel} \end{pmatrix} = \begin{pmatrix} \gamma_f & -\gamma_f\beta_f \\ -\gamma_f\beta_f & \gamma_f \end{pmatrix} \begin{pmatrix} E \\ p_{\parallel} \end{pmatrix}, \qquad p^*_T = p_T$$

$p_{\parallel}$ parallel to β_f

$p_{\perp}$ orthogonal to β_f

CM frame: $\mathbf{p}^* = 0$ and $s = E^{*2}$

Lab: Where the target particle is at rest



Invariants:

c = 1

4-momenta of 2 particles $P_1 = (E_1, \mathbf{p}_1)$ $P_2 = (E_2, \mathbf{p}_2)$

3 invariants: $P_1^2 = m_1^2$ $P_2^2 = m_2^2$ $[P_1 P_2 \text{ or } (P_1 \pm P_2)^2]$

We call s the total energy squared of the colliding particles 1 and 2 in the CM

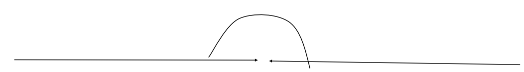
Fixed target

$s = (P_1+P_2)^2 = m_1^2+m_2^2+2(E_1E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2)^2 \Rightarrow ECM = \sqrt{s} = [m_1^2+m_2^2+2E_1E_2(1-\beta_1\beta_2\cos\theta)]^{1/2}$

$m_2 = M >> m_1$ and $\beta_2 = 0$, $\varepsilon_2 = M \Rightarrow E_{CM} = \sqrt{s} \sim \sqrt{(2EM)}$ for $E >> M$

Colliding beams

$\theta = 180°$



$s = (P_1 + P_2)^2 = (E_1+E_2)^2 - 0 = 2E \Rightarrow E_{CM} \sim 2E$

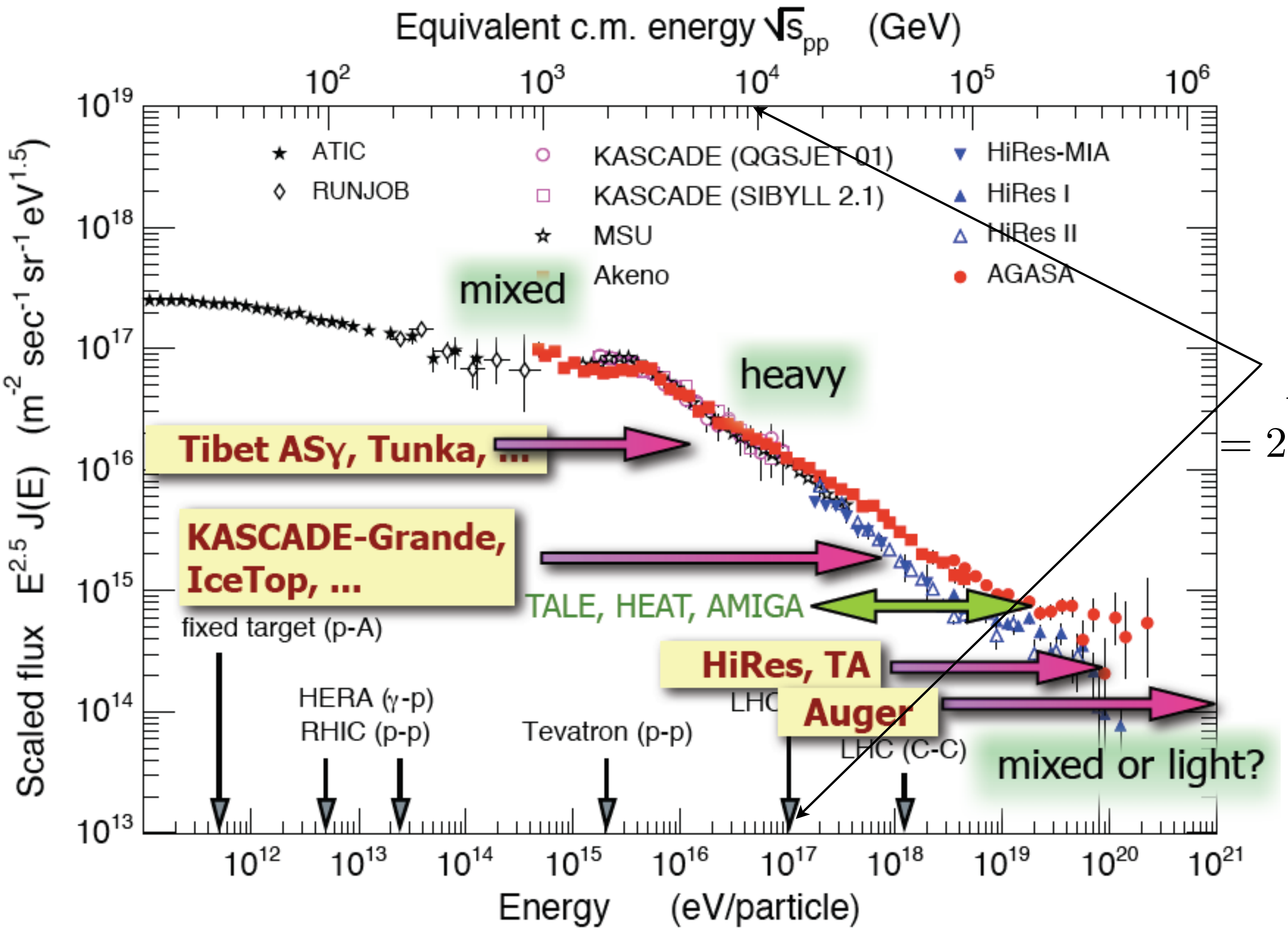
since in an collider $E = E_1 = E_2$, $m_1 = m_2 = m << E$, $\beta_1 = \beta_2 \approx 1$ $\theta = 180°$

Cosmic rays

$$E_{\rm cm} = \left[(E_1+E_2)^2 - (\boldsymbol{p}_1+\boldsymbol{p}_2)^2\right]^{1/2} ,$$
$$= \left[m_1^2 + m_2^2 + 2E_1E_2(1-\beta_1\beta_2\cos\theta)\right]^{1/2}$$

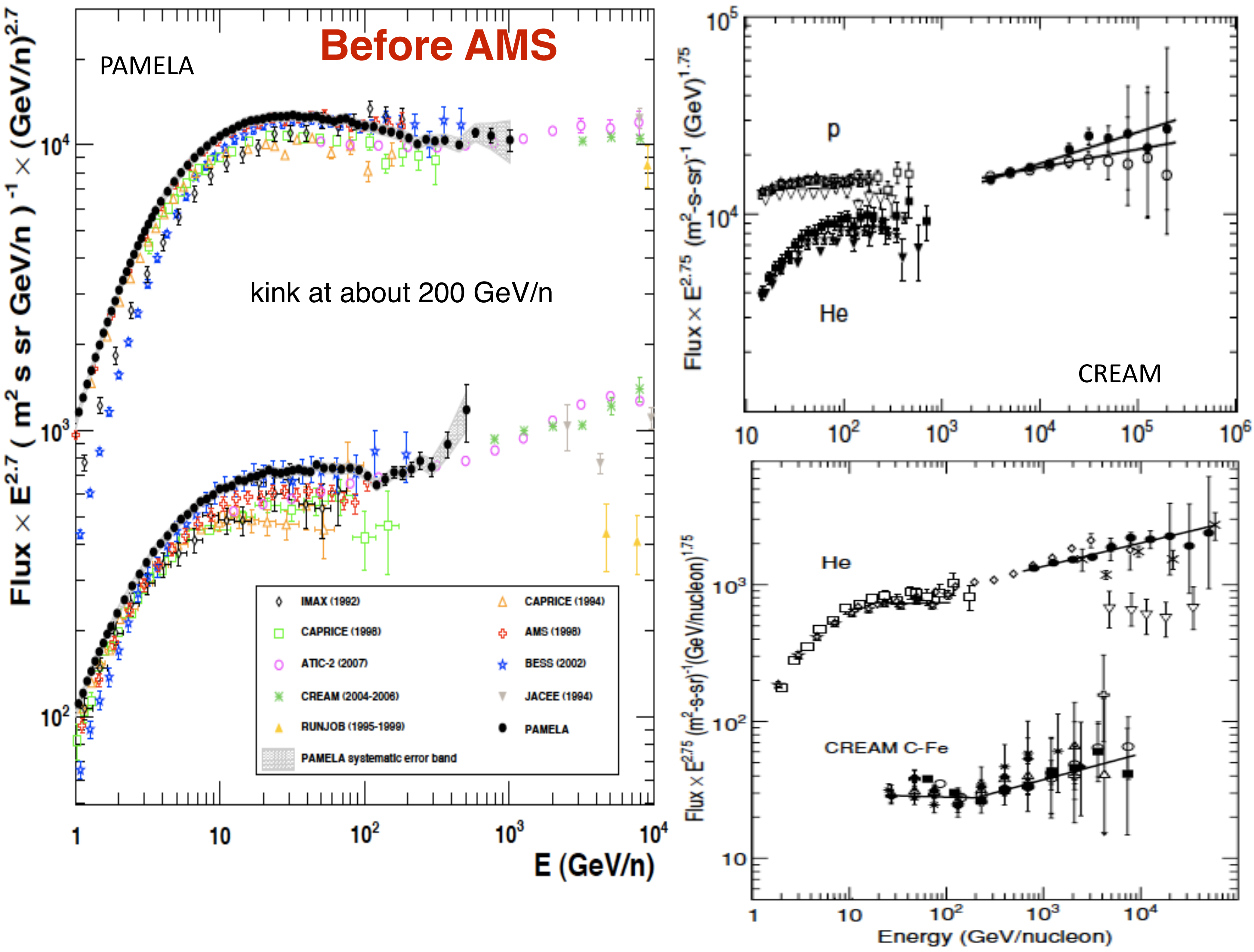
fixed target

$E_{cm} \approx \mathrm{sqrt}(2mE_{projectile})$



LHCpp
7TeV+7TeV

$$E_{proj} = \frac{14\times10^{12}}{2\times10^{9}}$$
$$= 2\times10^{17}\ \mathrm{eV}$$



Before AMS
PAMELA
kink at about 200 GeV/n
Flux × E^2.7 (m^2 s sr GeV/n)^-1 × (GeV/n)^2.7
E (GeV/n)
IMAX (1992)
CAPRICE (1994)
CAPRICE (1998)
AMS (1998)
ATIC-2 (2007)
BESS (2002)
CREAM (2004-2006)
JACEE (1994)
RUNJOB (1995-1999)
PAMELA
PAMELA systematic error band
p
He
CREAM
Flux × E^2.75 (m^2-s-sr)^-1 (GeV)^1.75
He
CREAM C-Fe
Flux × E^2.75 (m^2-s-sr)^-1(GeV/nucleon)^1.75
Energy (GeV/nucleon)

p/He ratio

$$qvB = \frac{mv^2}{r_L} \Rightarrow r_L = \frac{p}{ZeB}$$

Gyroradius

$$r_L = 33.36\,\text{km} \left(\frac{p}{\text{GeV}/c}\right)\left(\frac{1}{Z}\right)\left(\frac{G}{B}\right)$$

Rigidity

$$R \equiv r_L B c = \frac{pc}{Ze}$$

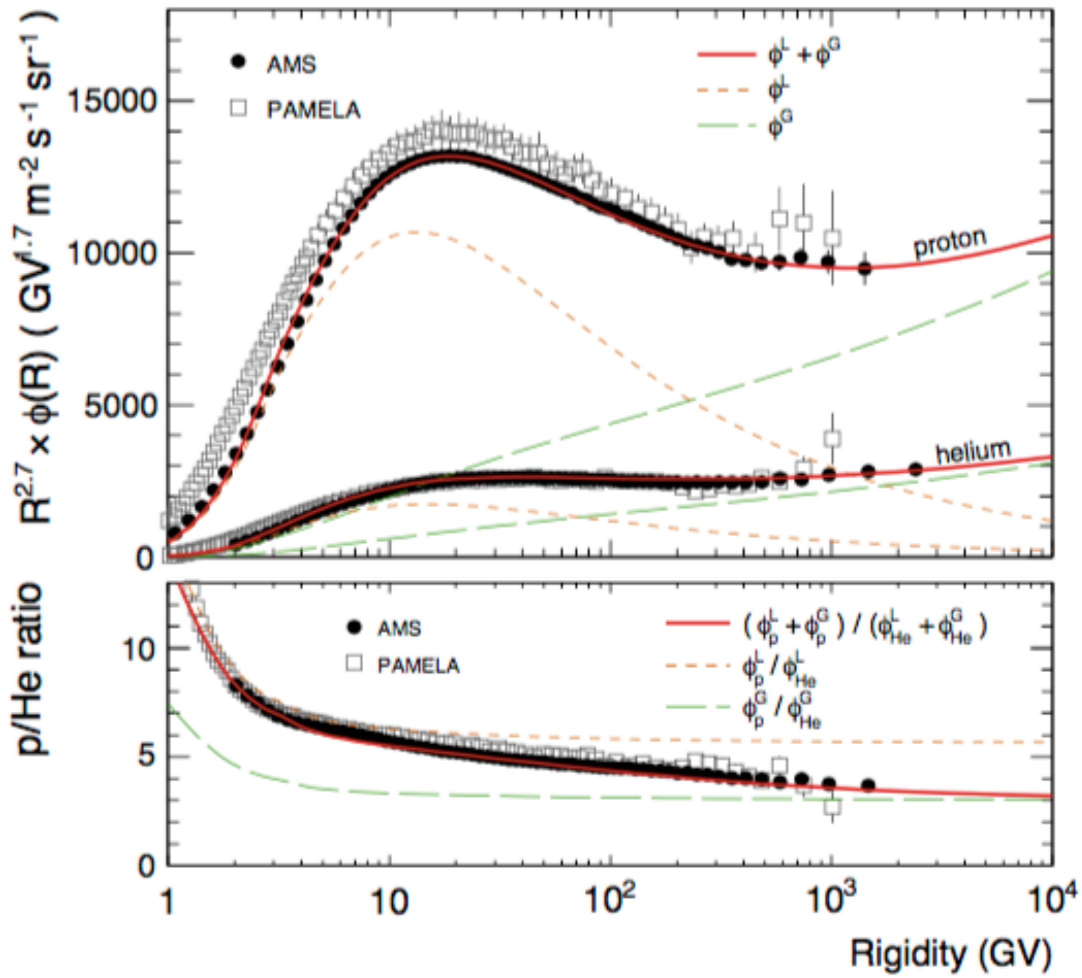


FIG. 2.— Top: rigidity spectra proton and helium multiplied by $\mathcal{R}^{2.7}$. The solid lines indicate the model calculations. The flux contribution arising from the two components ϕ^L and ϕ^G are shown as dashed lines. The data are from and AMS (Aguilar et al. 2015a,b) and PAMELA (Adriani et al. 2011).

http://arxiv.org/pdf/1511.04460v3.pdf

Preamble: Flux and particle number density

Flux: $\Phi = \frac{dN}{dAdt}$ Rate at which a flux of parallel particles cross the plane of surface dA perpendicular to the beam

The number density of particles corresponding to the beam of particles (the flux) is :

$$n(\vec{x}) = \frac{dN}{d^3x} = \frac{dN}{dldA} = \frac{1}{\beta c}\frac{dN}{dtdA} = \frac{1}{\beta c}\Phi$$

$$d^3x = dV = dldA \qquad\qquad dl = \beta c dt$$

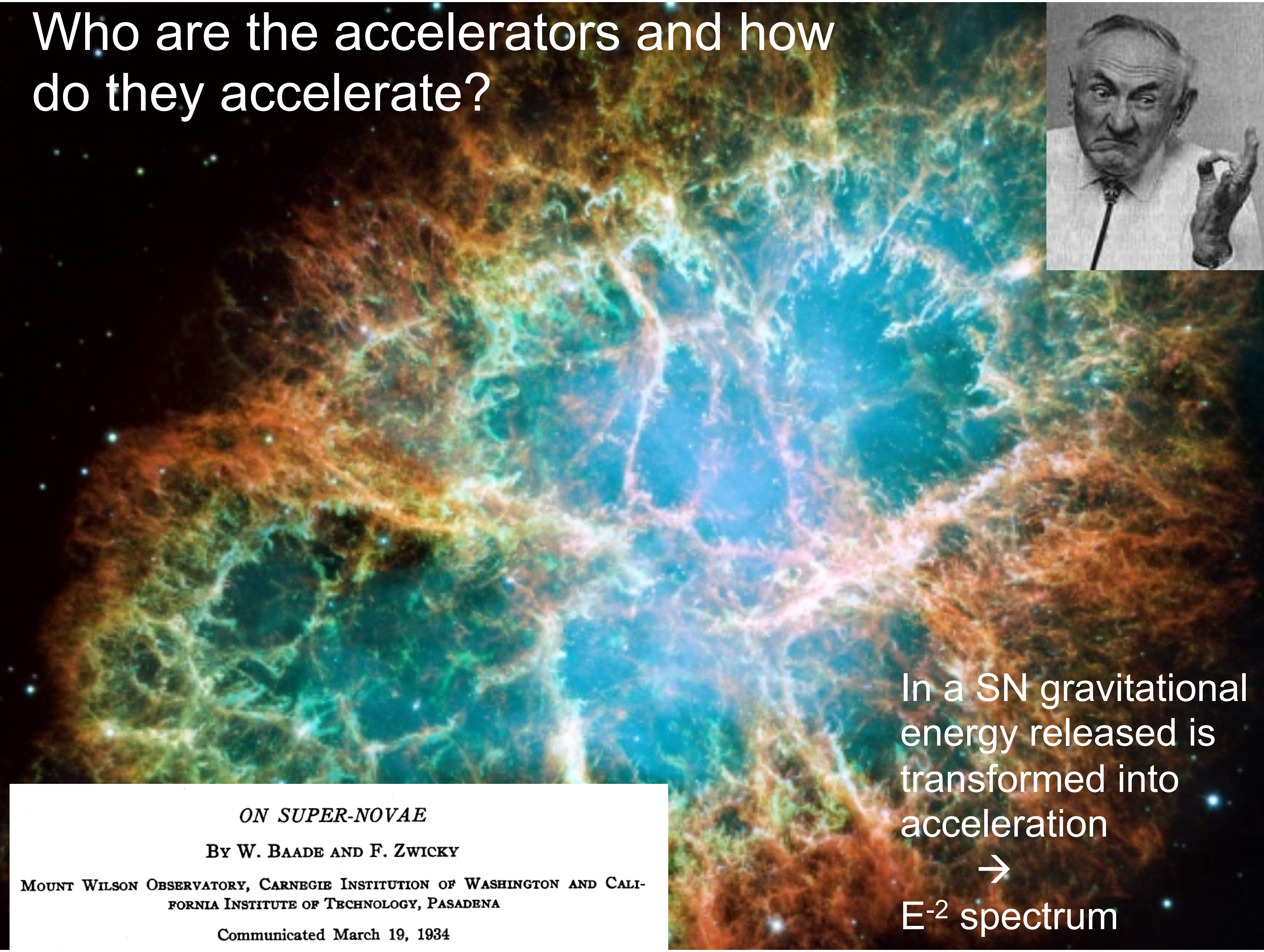
For astrophysical applications one considers the flux in an energy interval E, E+dE coming from an angle dΩ:

$$\Phi(E) = \frac{dN}{dEdAdtd\Omega}$$

For an isotropic flux over the solid angle 4 π :

$$n(E, \vec{x}) = \frac{dN}{dEd^3x} = \frac{4\pi}{\beta c}\Phi(E)$$

Who are the accelerators and how do they accelerate?



In a SN gravitational energy released is transformed into acceleration

→

E^{-2} spectrum

ON SUPER-NOVAE

BY W. BAADE AND F. ZWICKY

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON AND CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA

Communicated March 19, 1934

Galactic cosmic ray energy density-spectrum relation

$$Flux\left(\frac{particles}{cm^2 ssr}\right) = \frac{\rho_{CR}\beta c}{4\pi}$$

Hence the energy density (provided by CR sources) is:

$$\rho_E = 4\pi \int \frac{E}{\beta c}\frac{dN}{dE}dE$$

Below the knee (1 GeV-100 TeV): $\phi = \frac{dN}{dE}$ $= I_N(E)\, E^{-2.7}$

$$I_N(E) \approx 1.8 \times 10^4\ (E/1\,\mathrm{GeV})^{-\alpha}\ \frac{\mathrm{nucleons}}{\mathrm{m^2\ \ s\ \ sr\ \ GeV}}$$

$\alpha = 2.7$

$$\rho_E = \frac{4\pi}{c}\int_{1GeV}^{1\times 10^6 GeV} 1.8\times 10^4 E^{-1.7} dE = \frac{4\pi}{c}\left[\frac{-E^{-0.7}}{0.7}\right]_{1\ GeV}^{1\times 10^6 GeV} \times 1.8 \times 10^4 =$$

$$1.1\times 10^{-3} GeV/m^3 \sim 10^{-3}\times 10^9/10^6 eV/cm^3 \sim 1eV/cm^3$$

comparable with the galactic magnetic field energy density of $B^2/8\pi$

1 kpc = 3.085×10^{21} cm

$$V_{\mathrm{disk}} \simeq \pi\, R_{\mathrm{disk}}^2\, h_{\mathrm{disk}}$$

$$\sim \pi\,[15\ \mathrm{Kpc}]^2\,[0.3\ \mathrm{Kpc}]$$

$$\sim 6\times 10^{66}\ \mathrm{cm}^3$$

Energy balance

The luminosity in galactic CRs is:

$$L_{CR} = \rho_E \frac{V}{\tau_{esc}} \sim \frac{1\mathrm{eV/cm^3}}{6.24\times10^{11}\mathrm{erg/eV}} \times \frac{6\times10^{66}\mathrm{cm^3}}{3\times10^6 yr\times3.15\times10^7\mathrm{s/yr}} \sim 10^{41}\mathrm{erg/s}$$

1 eV = 6.24 x 10^{11} erg

For a typical SN:

M = 10M_{sun} (=10×2×10^{33} g)

K=10^{51} erg

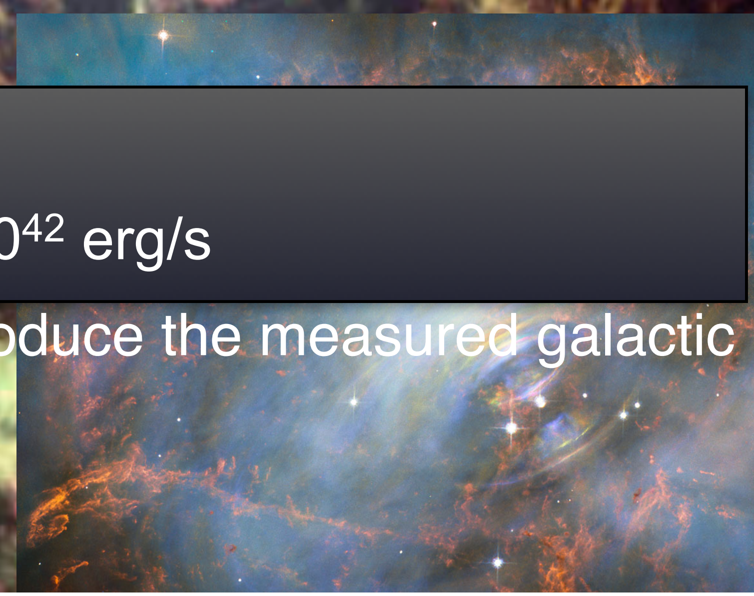
$$V \cong \sqrt{\frac{2K}{M}} = \sqrt{\frac{2\cdot10^{51} erg}{10\cdot(2\cdot10^{33} g)}} \cong 3\cdot10^8 cm/s$$

$$\frac{V}{c} \cong 10^{-2}$$

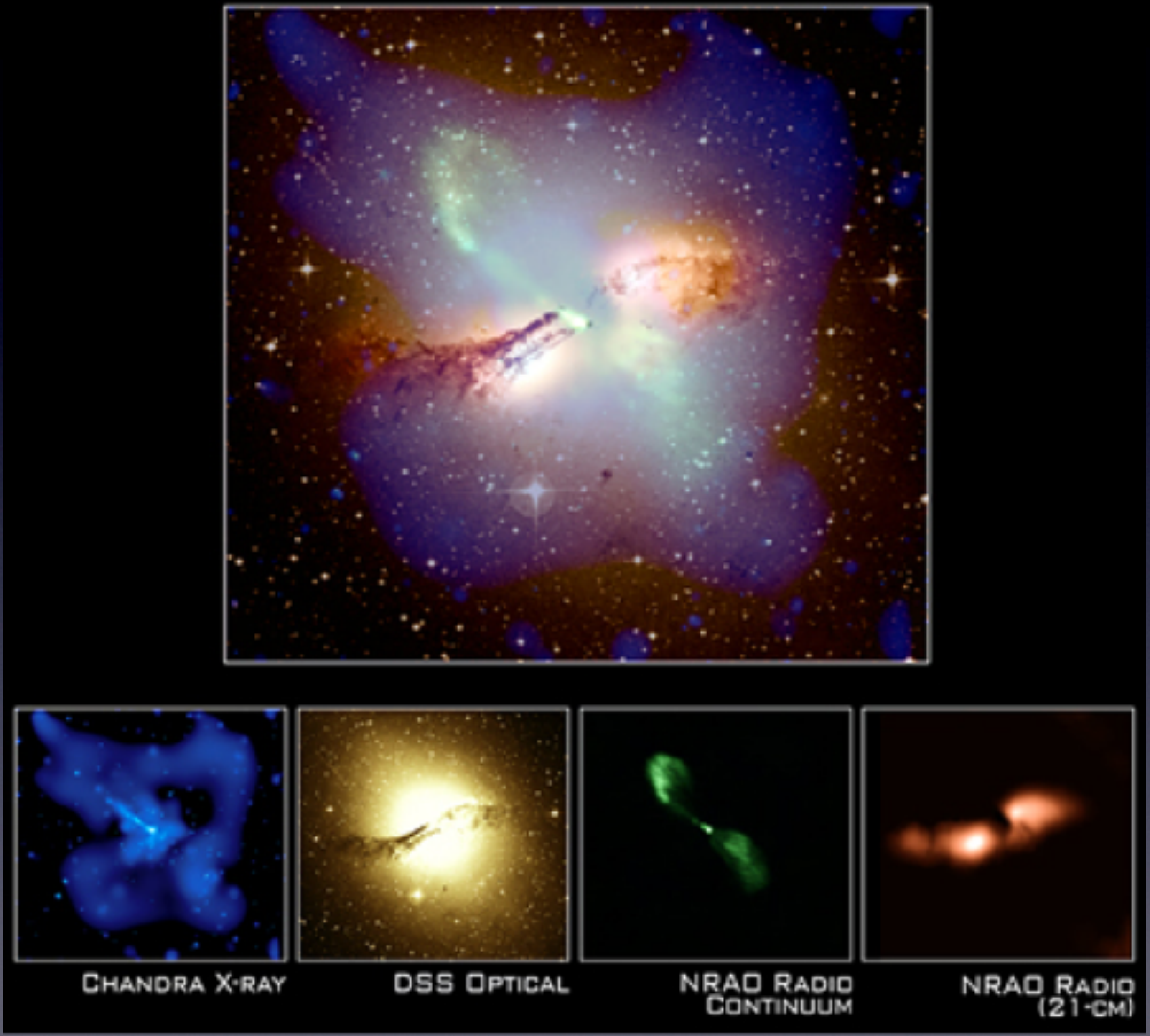
Rate of SN ~ 3 / century

Power = K x rate =10^{51} erg x 9.5 x 10-10 ~ 10^{42} erg/s

10% of the energy in the ejecta suffices to produce the measured galactic CR flux

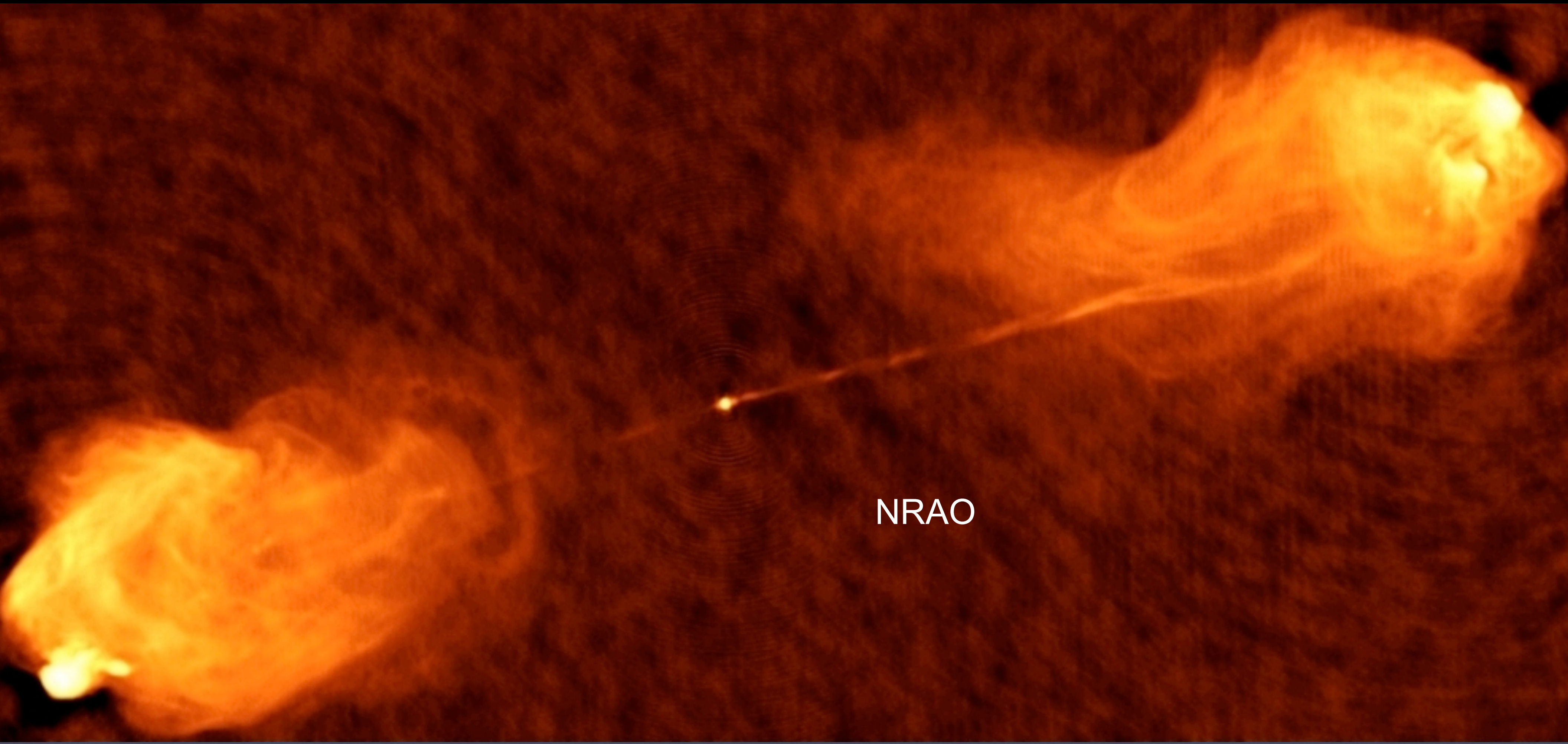


The most powerful sky accelerators: AGN jets, GRB fireballs



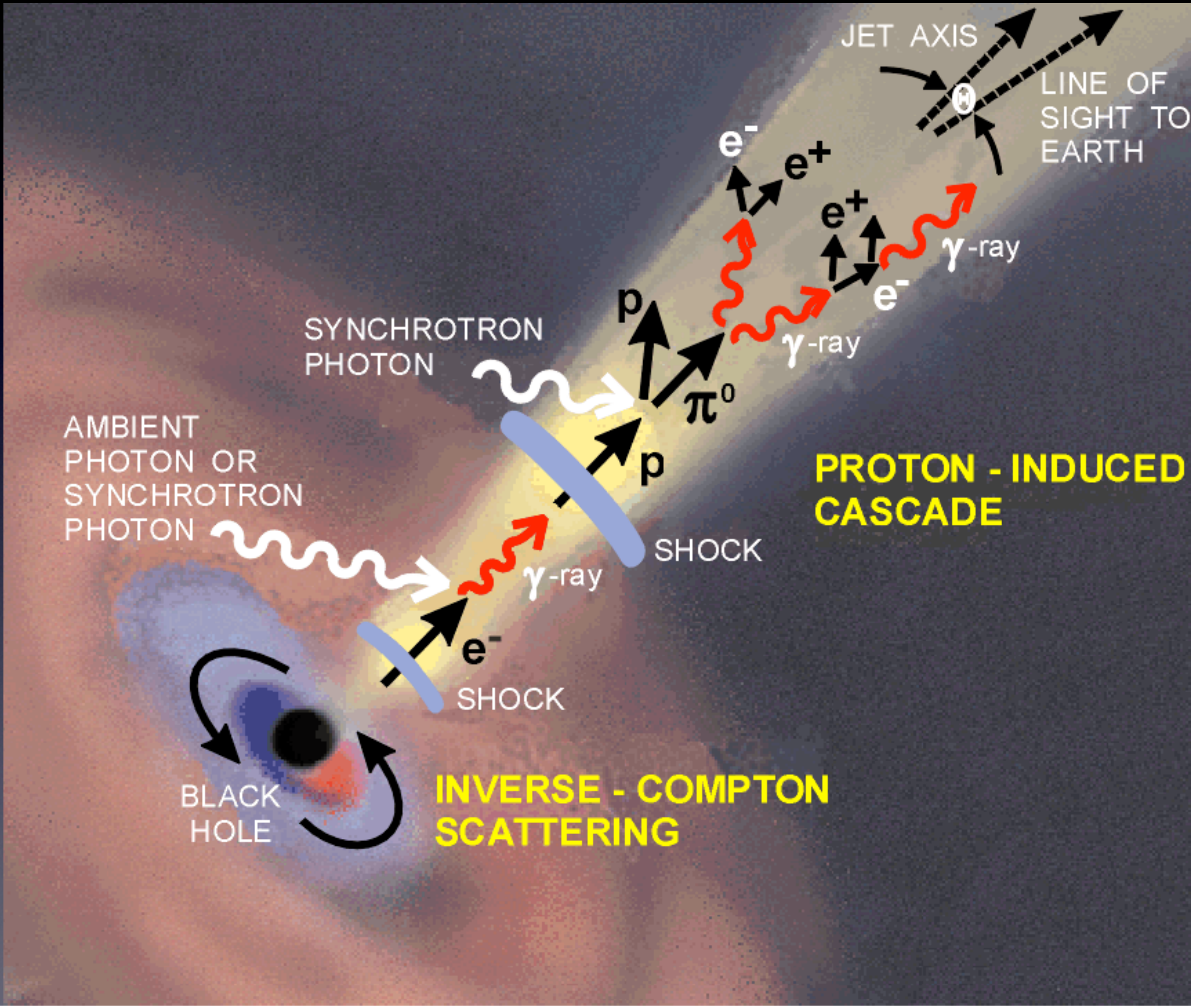
Centaurus A

The most powerful sky accelerators: AGN jets, GRB fireballs



io source Cygnus A is produced in a galaxy some 600 million light-years away. The radio waves are
from electrons propelled at nearly the speed of light from the bright center of the galaxy -- the location
ck hole. Electrons are trapped by the magnetic field around the galaxy.

The most powerful sky accelerators: AGN jets, GRB fireballs



POWER OF EXTRAGALACTIC CR SOURCES

1) $p+\gamma \rightarrow \Delta^+ \rightarrow p\pi^0$

2) $p+\gamma \rightarrow \Delta^+ \rightarrow n\pi^+$

Waxman & Bahcall, PRD59, 1999 and PRD64, 2001)

$$E\left(E\frac{dE_{CR}}{dE}\right) = \frac{3\times10^{10}\mathrm{GeV}}{(10^{10}\mathrm{cm}^2)(3\times10^7\mathrm{s})\mathrm{sr}} = 10^{-7}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

Energy density in extra-galactic CRs: $\rho_E = \frac{4\pi}{c}\int_{E_{min}}^{E_{max}} \frac{10^{-7}}{E} dE \frac{GeV}{cm^3} \sim 3\times10^{-19}\frac{erg}{cm^3}$

$E_{max}/E_{min} \sim 10^3$

Power needed by a population of sources of protons with E^{-2} to generate ρ_E over the Hubble time $= 10^{10}$ yrs $\approx 10^{44}$ erg Mpc^{-3} yr^{-1}

3×19^{39} erg/s per galaxy
3×10^{42} erg/s per cluster of galaxies
2×10^{44} erg/s per AGN
2×10^{51} erg per cosmological GRB.

From BATSE: *300 GRB / Gigaparsec³ yr* $\quad 1Gpc^3 = 2.9\times10^{82}cm^3 \quad Hubble\ time = 10^{10}\ years$

$$2\times10^{51}erg\times\frac{300}{Gpc^3\ yr}\times10^{10}yr = 3\times10^{-19}\frac{erg}{cm^3}$$

observed energy density of extragalactic CRs: $\sim 10^{-19}$ erg / cm^3

The Fermi mechanism

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On the Origin of the Cosmic Radiation

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A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

I. INTRODUCTION

IN recent discussions on the origin of the cosmic radiation E. Teller[1] has advocated the view that cosmic rays are of solar origin and are kept relatively near the sun by the action of magnetic fields. These views are amplified by Alfvén, Richtmyer, and Teller.[2] The argument against the conventional view that cosmic radiation may extend at least to all the galactic space is the very large amount of energy that should be present in form of cosmic radiation if it were to extend to such a huge space. Indeed, if this were the case, the mechanism of acceleration of the cosmic radiation should be extremely efficient.

I propose in the present note to discuss a hypothesis on the origin of cosmic rays which attempts to meet in part this objection, and according to which cosmic rays originate and are accelerated primarily in the interstellar space, although they are assumed to be prevented by magnetic fields from leaving the boundaries of the galaxy. The main process of acceleration is due to the interaction of cosmic particles with wandering magnetic fields which, according to Alfvén, occupy the interstellar spaces.

Such fields have a remarkably great stability because of their large dimensions (of the order of magnitude of light years), and of the relatively high electrical conductivity of the interstellar space. Indeed, the conductivity is so high that one might describe the magnetic lines of force as attached to the matter and partaking in its streaming motions. On the other hand, the magnetic field itself reacts on the hydrodynamics[3] of the interstellar matter giving it properties which, according to Alfvén, can pictorially be described by saying that to each line of force one should attach a material density due to the mass of the matter to which the line of force is linked. Developing this point of view, Alfvén is able to calculate a simple formula for the velocity V of propagation of magneto-elastic waves:

$$V = H/(4\pi\rho)^{\frac{1}{2}}, \qquad (1)$$

where H is the intensity of the magnetic field and ρ is the density of the interstellar matter.

One finds according to the present theory that a particle that is projected into the interstellar medium with energy above a certain injection threshold gains energy by collisions against the moving irregularities of the interstellar magnetic field. The rate of gain is very slow but appears capable of building up the energy to the maximum values observed. Indeed one finds quite naturally an inverse power law for the energy spectrum of the protons. The experimentally observed exponent of this law appears to be well within the range of the possibilities.

The present theory is incomplete because no satisfactory injection mechanism is proposed except for protons which apparently can be regenerated at least in part in the collision processes of the cosmic radiation itself with the diffuse interstellar matter. The most serious difficulty is in the injection process for the heavy nuclear component of the radiation. For these particles the injection energy is very high and the injection mechanism must be correspondingly efficient.

II. THE MOTIONS OF THE INTERSTELLAR MEDIUM

It is currently assumed that the interstellar space of the galaxy is occupied by matter at extremely low density, corresponding to about one atom of hydrogen per cc, or to a density of about 10^{-24} g/cc. The evidence indicates, however, that this matter is not uniformly spread, b
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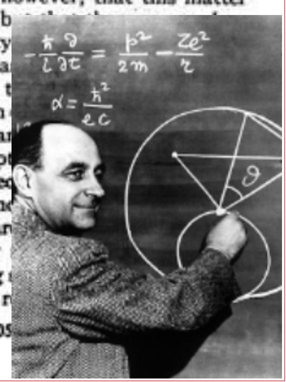
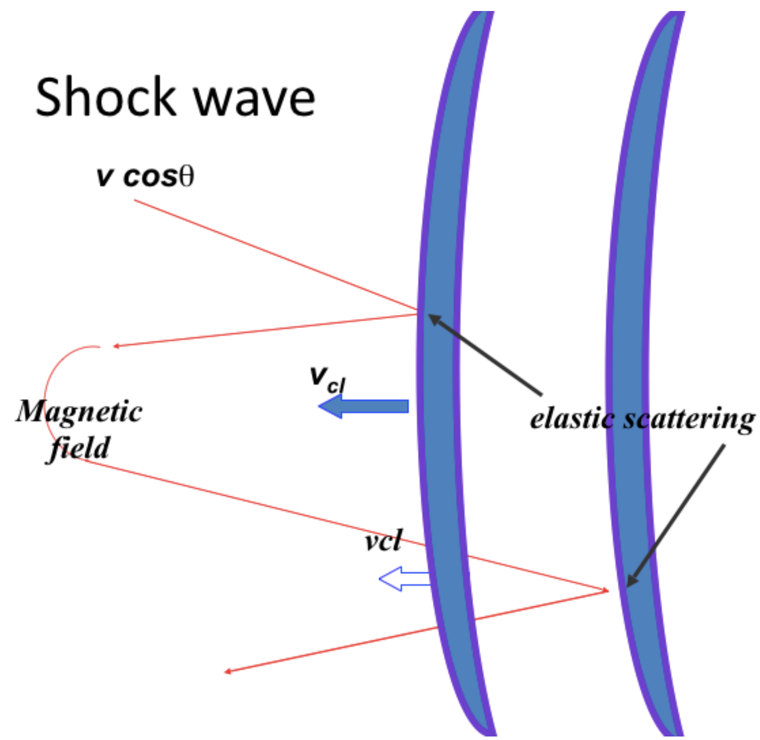
or a hundred times as la
average dimensions of t
(1 parsec. $= 3.1\times 10^{18}$ cm
the measurements of Adar
of the interstellar absorpt
radial velocity with respec
of such clouds located at n
us. The root mean squar
corrected for the proper
respect to the neighboring
We may assume that the r

[1] Nuclear Physics Conference, Birmingham, 1948.
[2] Alfvén, Richtmyer, and Teller, Phys. Rev., to be published.
[3] H. Alfvén, Arkiv Mat. f. Astr., o. Fys. 29B, 2 (1943).
[4] W. S. Adams, A.p.J. 97, 105



A "collision" with a magnetic cloud or the crossing across high magnetic fields close to a shock can cause an increase in energy of a particle. The energy increase is ***ΔE/E=ξ***



Cosmic Ray acceleration

- CR acceleration is a stochastic process. At each accelerating event particle gains:

$$\Delta E = \xi E$$

- Probability that the particle is not followed up: P_{esc}
- Probability that the particle is iterated in acceleration: $1 - P_{esc}$
- For a particle with injection energy E_0, after k iterations:

$$E_k = E_0(1+\xi)^k \quad \Rightarrow \quad k = \frac{ln(E_k/E_0)}{ln(1+\xi)}$$

- The probability of having received k accelerations and then escape is:

$$P_k = (1 - P_{esc})^k P_{esc}$$

- The number of particles after k encounters that remain (if N_0 where there initially) is

$$N_k = N_0 P_k = N_0(1 - P_{esc})^k P_{esc}$$

Spectrum

$$N_k = N_0 P_{esc}(1-P_{esc})^{\frac{ln(E_k/E_0)}{ln(1+\xi)}} = N_0 P_{esc} exp\left[ln(1-P_{esc})^{\frac{ln(E_k/E_0}{ln(1+\xi)}}\right] =$$

$$N_0 P_{esc} exp\left[\frac{ln(E_k/E_0) ln(1-P_{esc})}{ln(1+\xi)}\right] \Rightarrow N_k = N_0 P_{esc}\left(\frac{E_k}{E_0}\right)^{\frac{ln(1-P_{esc})}{ln(1+\xi)}}$$

Differentiating we get: $$\frac{dN}{dE} \propto E^{\frac{ln(1-P_{esc})}{ln(1+\xi)}-1} = E^{-\gamma-1}$$

$ln(1+x) \sim x + \frac{x^2}{2} - \frac{x^3}{3} + ... \sim x$ for $x << 1$
$ln(1-P_{esc}) \sim -P_{esc} + ...$
$ln(1+\xi) \sim \xi + ...$

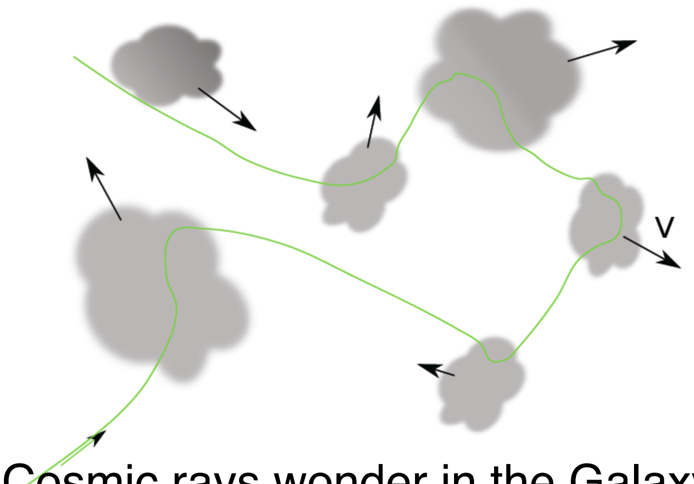
Integral spectrum slope

$$\gamma = -\frac{ln(1-P_{esc})}{ln(1+\xi)} \sim \frac{P_{esc}}{\xi}$$

for $P_{esc} << 1$ and $\xi << 1$

2nd Fermi acceleration

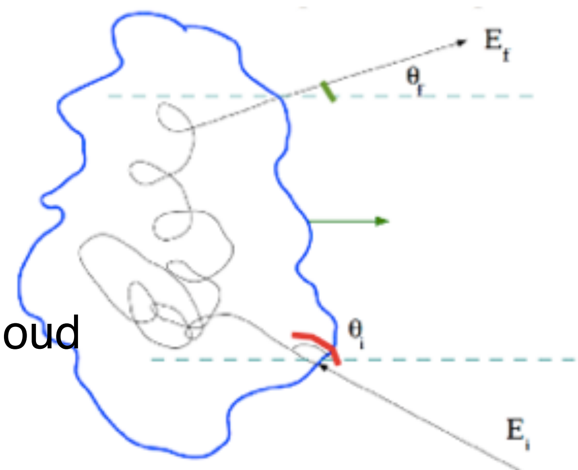
2nd order Fermi acceleration: elastic scattering on irregularities of the B-field into magnetized clouds



$$\xi = \frac{\Delta E}{E_i} \sim \frac{4}{3}\beta^2$$

in the ref frame moving with the cloud

$-1 \leq \cos\theta'_f \leq 1 \Rightarrow \langle\cos\theta'_f\rangle = 0$



Cosmic rays wonder in the Galaxy few millions of years. From the ratio of secondary to primary nuclei (eg B / C or O) it can be inferred that GeV CRs travers a grammage of 5-10 g and it decreases with increasing energy

$$\tau_{esc} \sim 10^6 yrs$$

prob to exit the Galaxy between one encounter and the next with the clouds

$$\gamma = \frac{P_{esc}}{\xi} \sim \frac{(\Delta t)_{encounters}/\tau_{esc}}{\frac{4}{3}\beta^2} \sim \frac{n_{clouds}(\pi r^2_{cloud})c}{\frac{4}{3} \times (10^{-2})^2} \sim 1\text{-}10$$

positive energy gain but inefficient!

1^{st} order Fermi acceleration

1^{st} order Fermi acceleration on a shock wave:

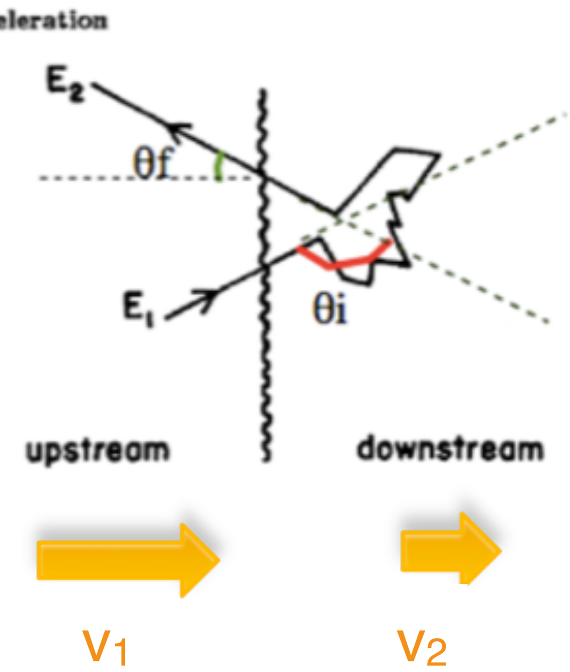
$$\xi = \frac{\Delta E}{E_i} \sim \frac{4}{3}\beta$$

Diffusion of charged particles back and forth through the shock leads to an increase of speed at each crossing of 3/4V_s. There are only head-on collisions.

$$\xi = \frac{4}{3}\beta = \frac{4}{3}\frac{3}{4}\frac{V_s}{c} = \frac{V_s}{c}$$

In the ref frame of the cloud : $0 \leq \cos\theta_f' \leq 1$ ⇨ $\langle\cos\theta_f'\rangle = 2/3$

In the lab frame: $-1 \leq \cos\theta_i \leq 0$ ⇨ $\langle\cos\theta_i\rangle = -2/3$



shock velocity $V_s = v_1 - v_2$

Shock = discontinuity surface in thermodynamic properties (density, temperature, velocity and pressure)

For a strong shock (Mach number is very large) and for a monoatomic gas:

$$\mathcal{M}_1 >> 1 \rightarrow \frac{v_2}{v_1} = \frac{1}{4} \Rightarrow \frac{\rho_2}{\rho_1} = 4$$

Escape probability

The average number of ultra-relativistic particles crossing the shock is:

$$\int_0^1 dcos\theta \int_0^{2\pi} d\phi \frac{c\rho_{CR}}{4\pi} \cos\theta = \frac{c\rho_{CR}}{4}$$

ρ_{CR}= number density of relativistic particles

The rate of convection downstream away from the shock is: $\rho_{CR} \times v_2$

$$P_{esc} = \frac{\rho_{CR} v_2}{c\rho_{CR}/4} = \frac{4v_2}{c}$$

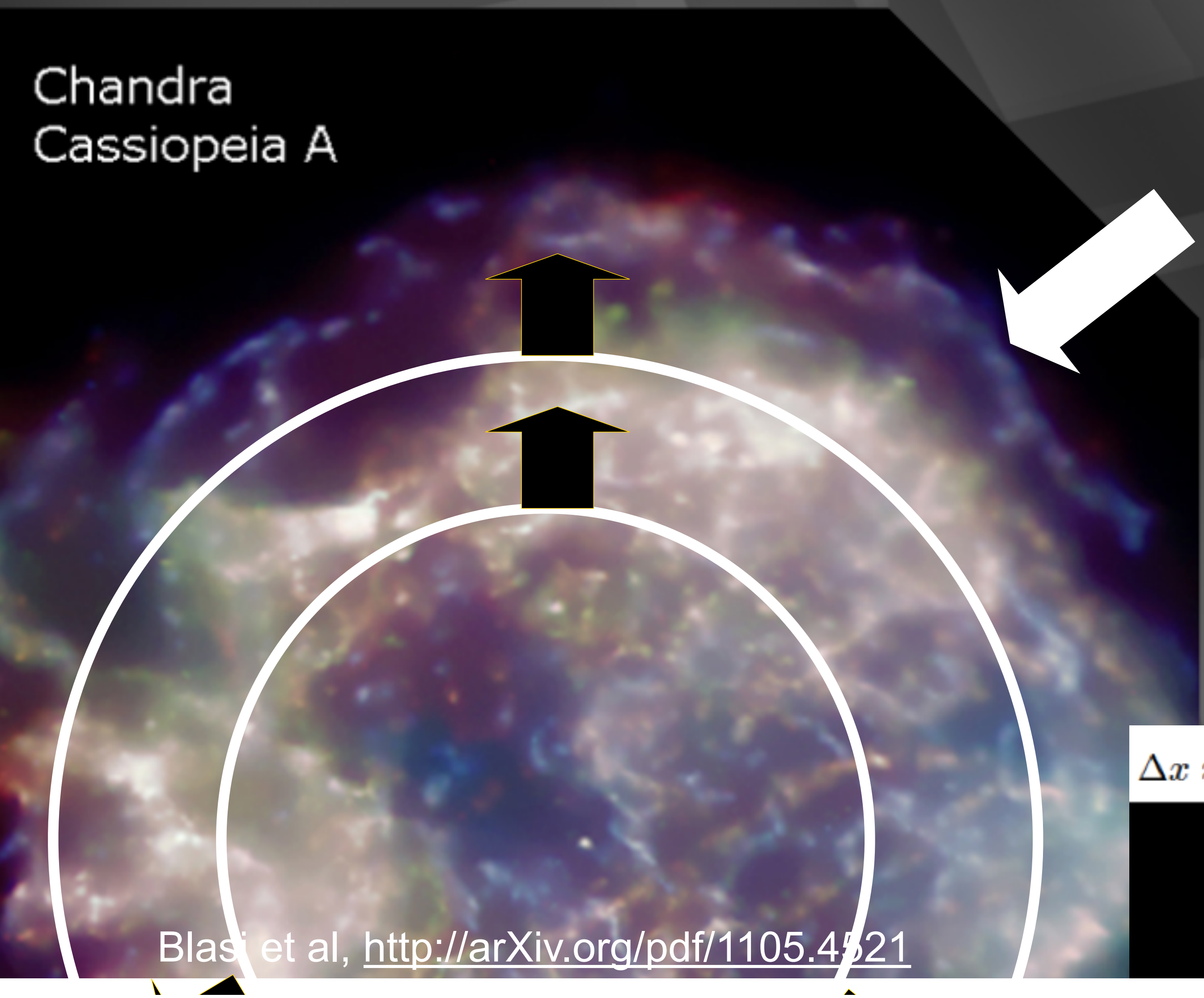
$$\gamma = \frac{P_{esc}}{\xi} = \frac{4v_2}{\frac{4}{3}V_s} = \frac{3}{v_1/v_2 - 1} = 1$$

= 4

$$\frac{dN}{dE} \propto E^{-(\gamma+1)} = E^{-2}$$

Are SN able to accelerate CRs to the knee?

Not in Diffusive Shock Acceleration: $E_{max} \sim 100$ TeV x Z
Need non-linear processes of magnetic field amplification consistent with observed filaments of dimension 10^{-2} pc that imply synch. emission in large magnetic fields



$$\Delta x \approx \sqrt{D(E_{max})\tau_{loss}(E_{max})} \approx 0.04\ B_{100}^{-3/2}\ \mathrm{pc}$$

$$B \approx 100\ \mu\mathrm{Gauss}$$

Blasi et al, http://arXiv.org/pdf/1105.4521