COSMIC-RAY INTERACTIONS IN ASTROPHYSICAL SOURCES

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Star-Begotten by H.G. Wells (1937)

I. The Mind of Mr. … Is Greatly Troubled

II. Mr… Learns about Cosmic Rays

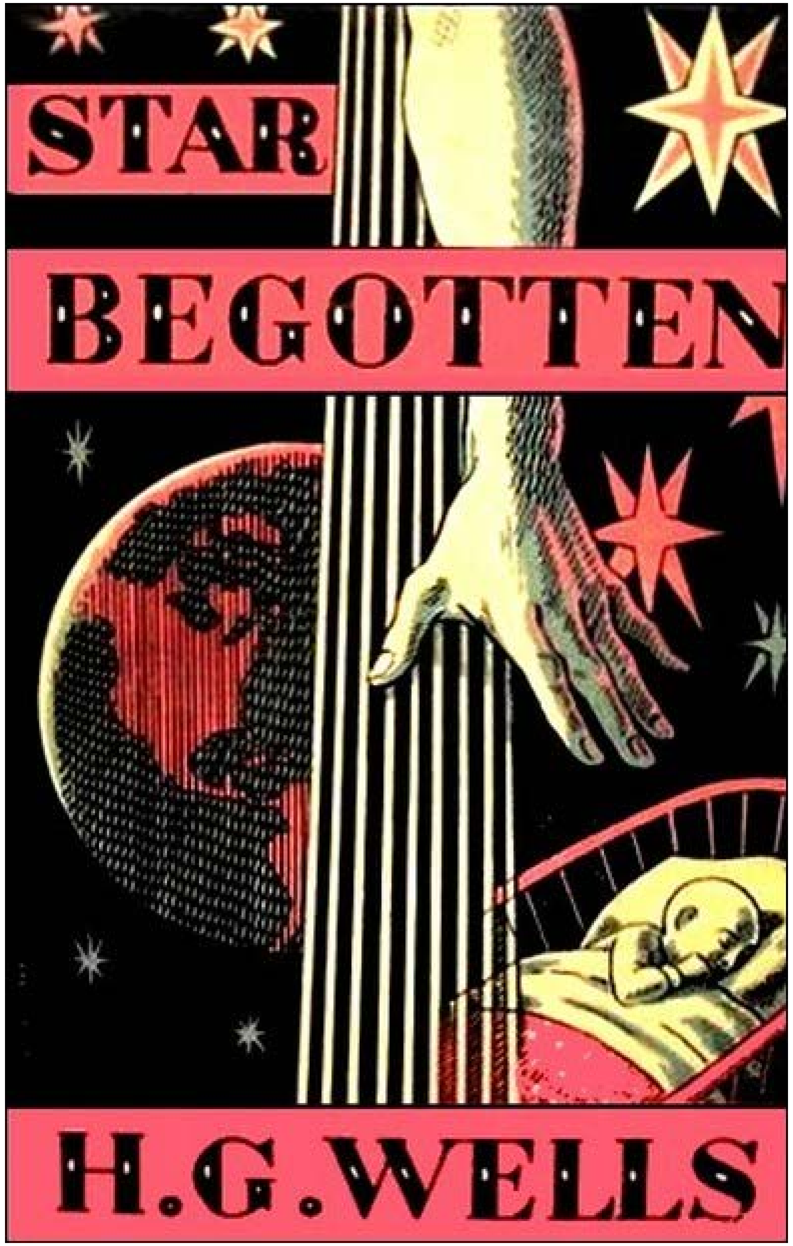
III. Mr. … Wrestles with an Incredible Idea

IV. Dr. … Is Infected with the Idea

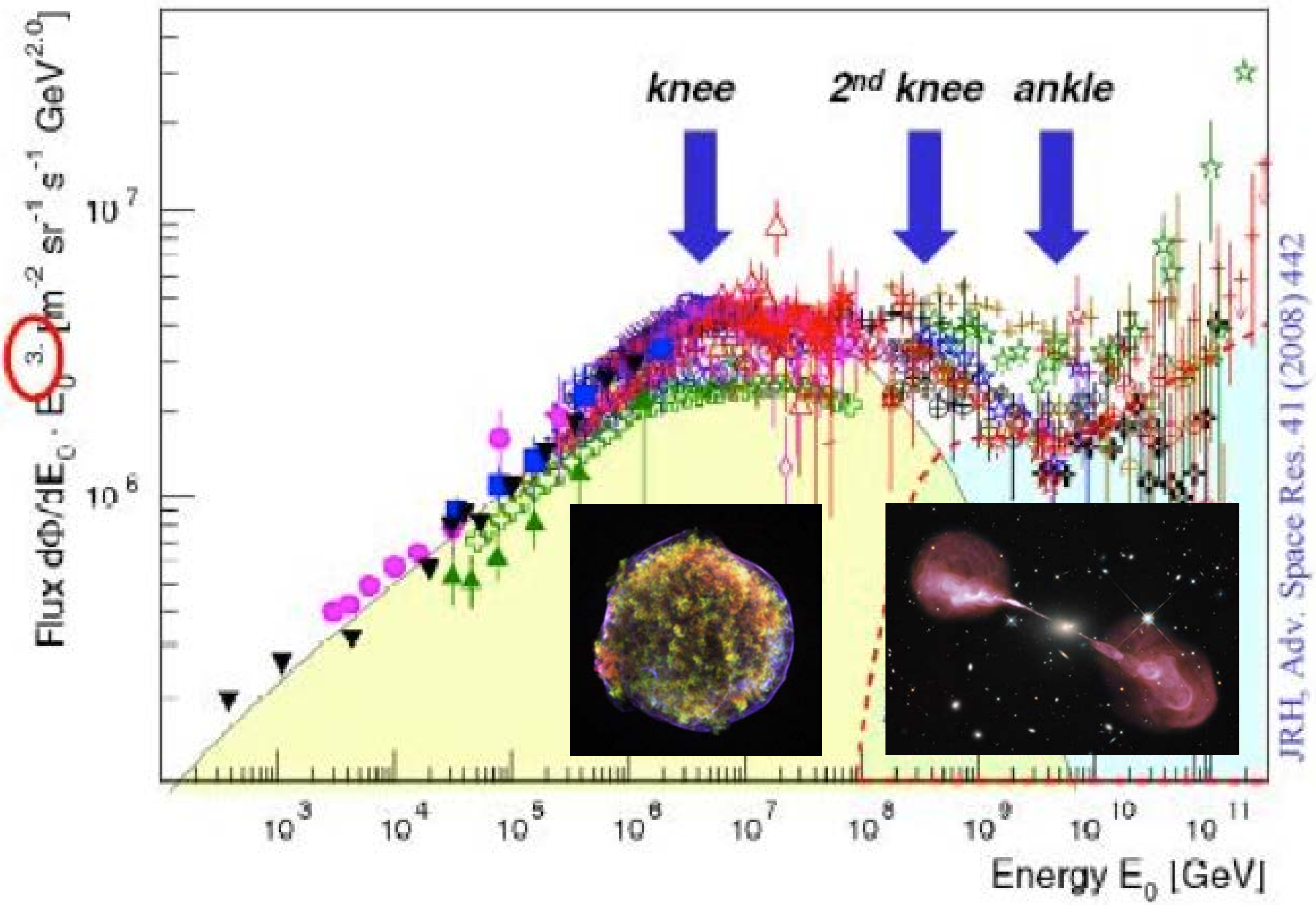
V. Prof. … Takes Up the Idea in His Own Peculiar Fashion

'…you lay the burden of change and mutation—and in fact all the responsibility for evolution—on those little cosmic rays! Countless myriads fly by and miss. Then one hits—Ping! Ping!—and we get a double-headed calf or a superman.'

'What an *unsettled* universe it is!'



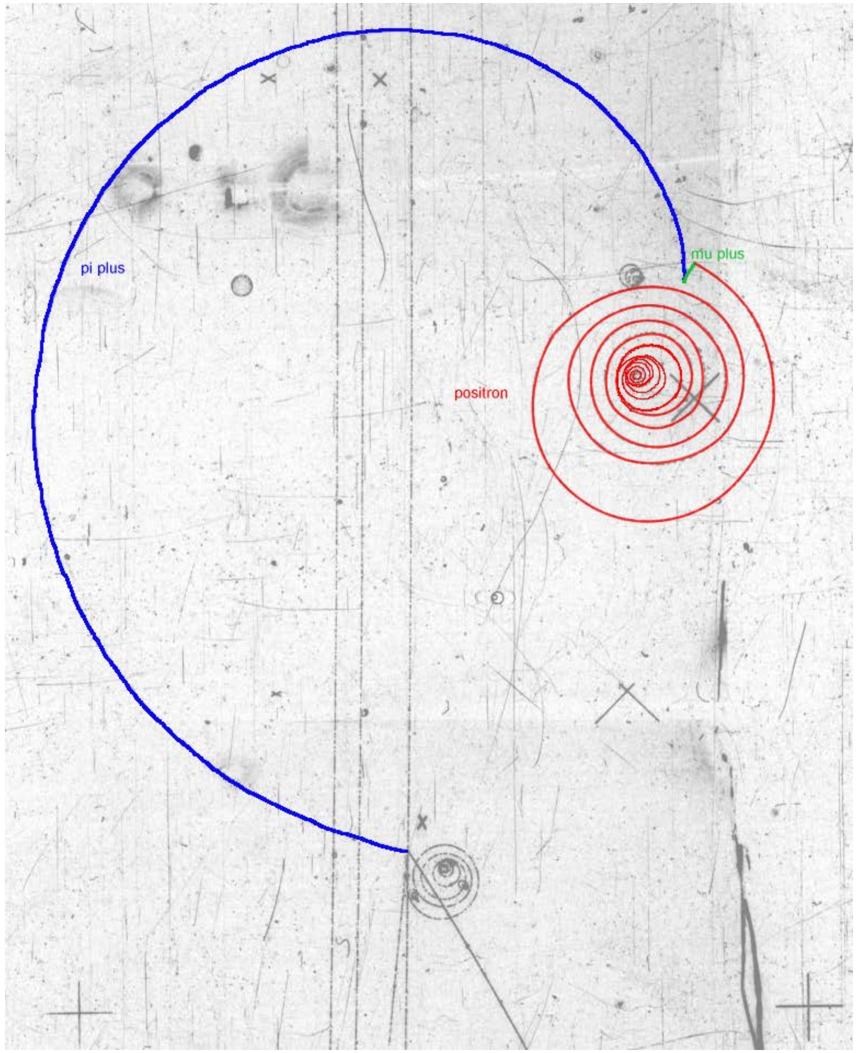
Cosmic-Ray Energy Spectrum



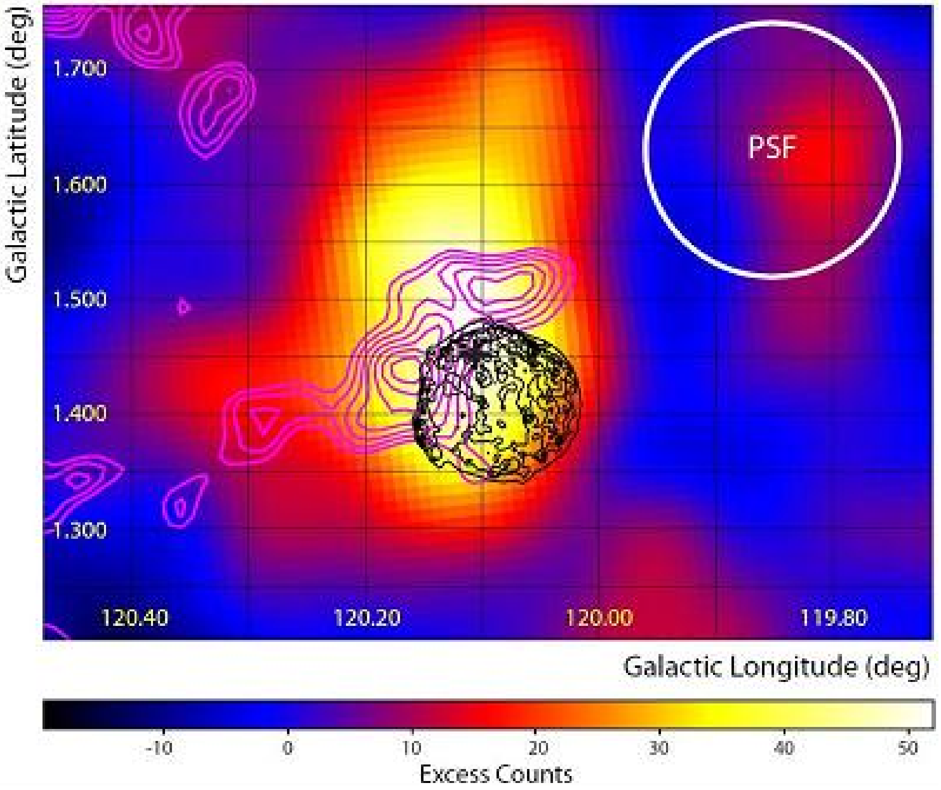
Diagnosis of cosmic rays

Interactions of cosmic rays with

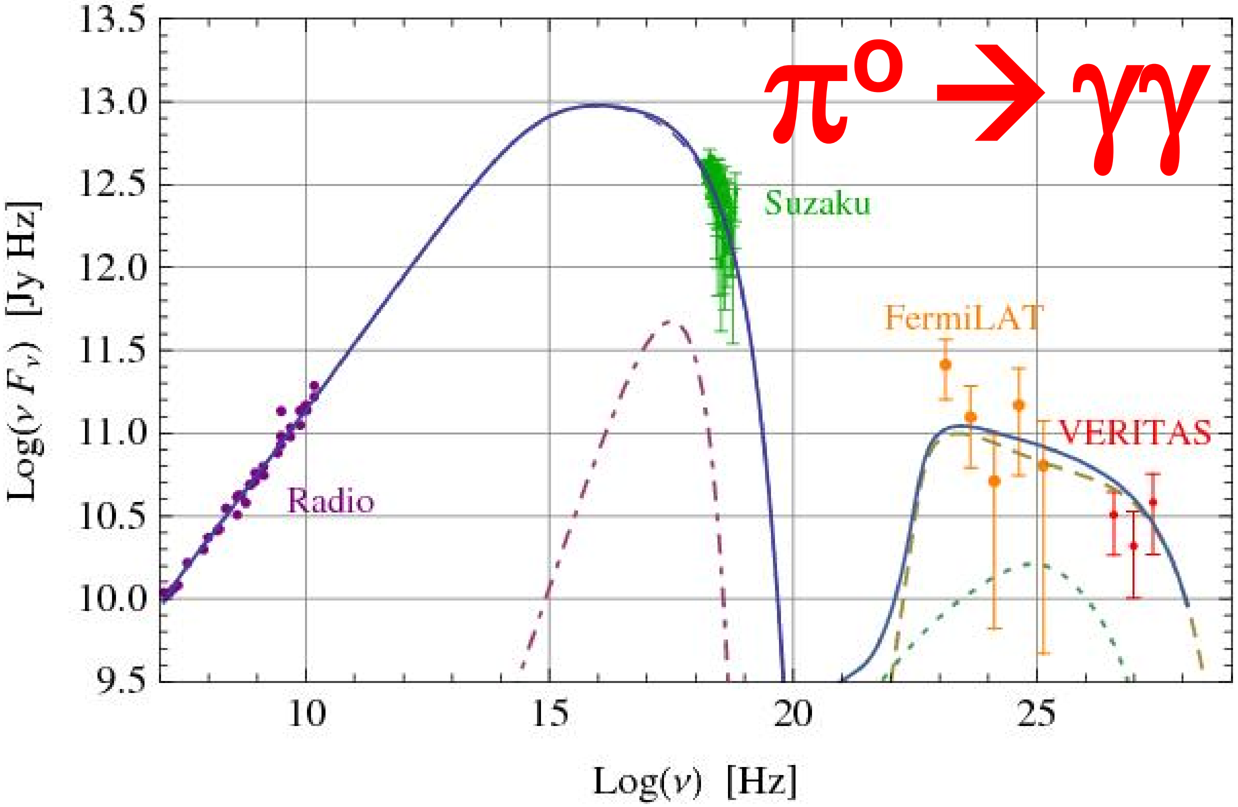
- Matter
  - Ionization and bremsstrahlung
  - Pair and pion production
  - Nuclear excitations
- Photons and magnetic fields
  - Inverse Compton scattering
  - Synchrotron and curvature radiation
- Collective plasma modes
  - Resonant waves and turbulent cascade
  - Thermal dissipation



Cosmic ray interactions with matter in Tycho's Supernova Remnant: Gamma rays

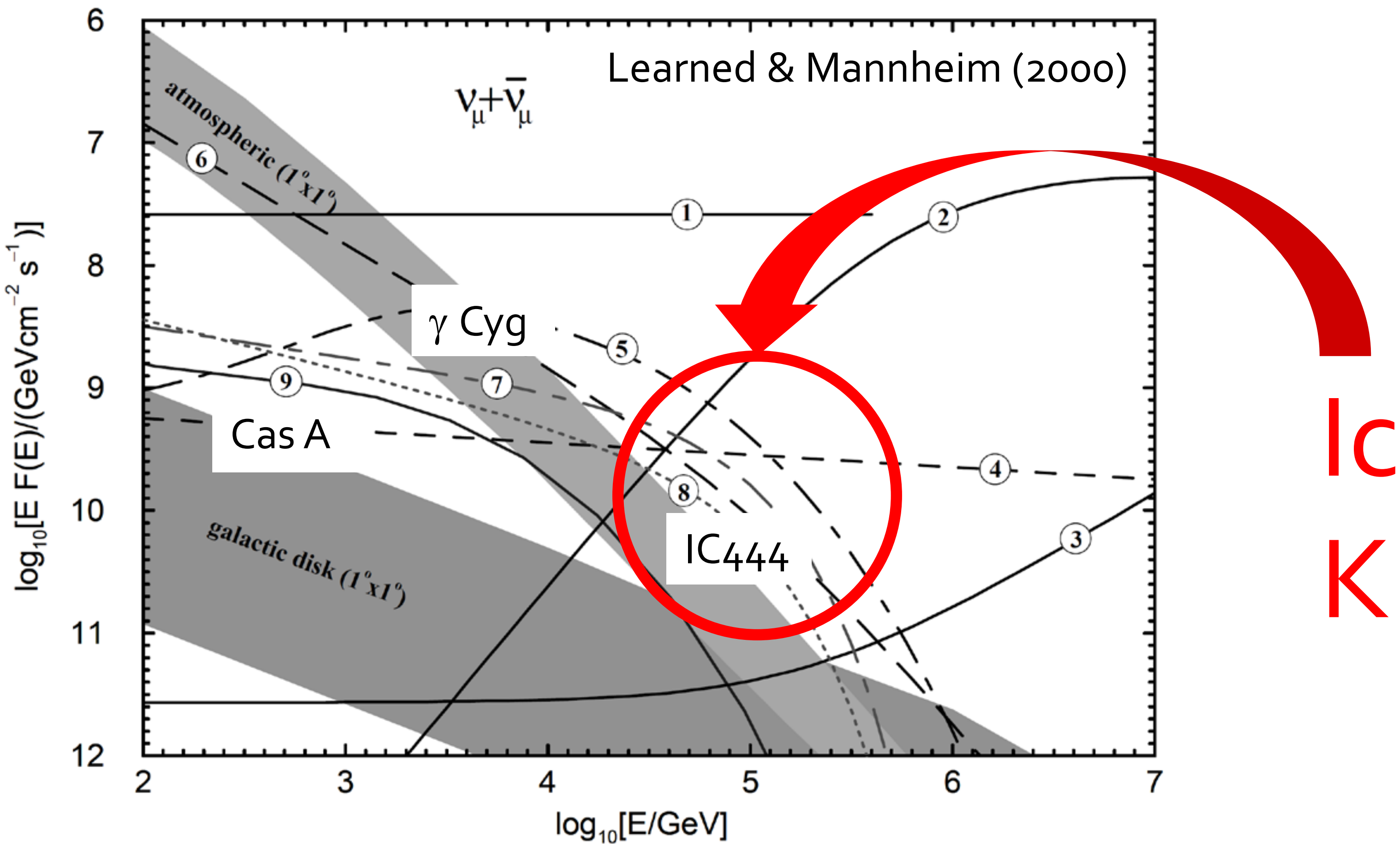


Acciari et al. (2011)



Morlino (2012)

Cosmic ray interactions with matter: Neutrinos from Supernova Remnants

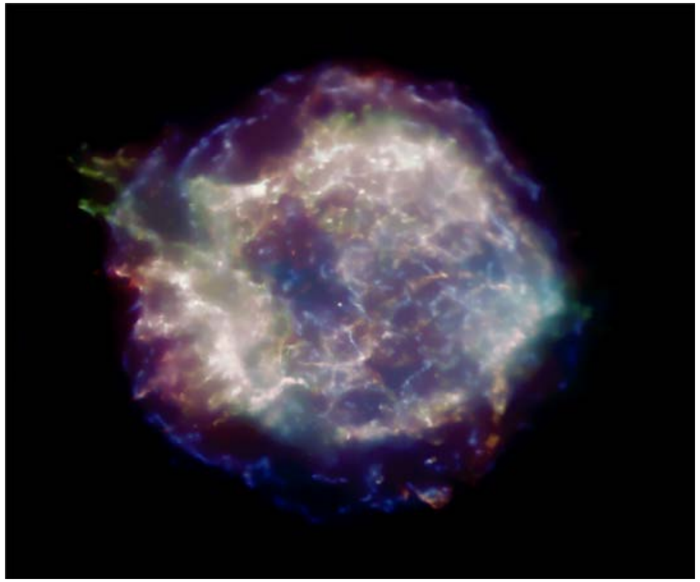


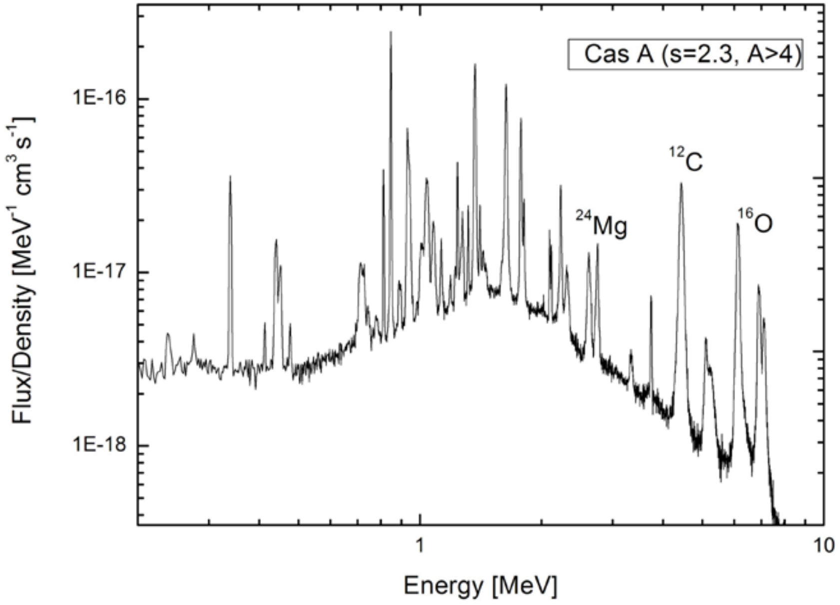
IceCube

KM3Net

Feedback of cosmic rays: nuclear abundances

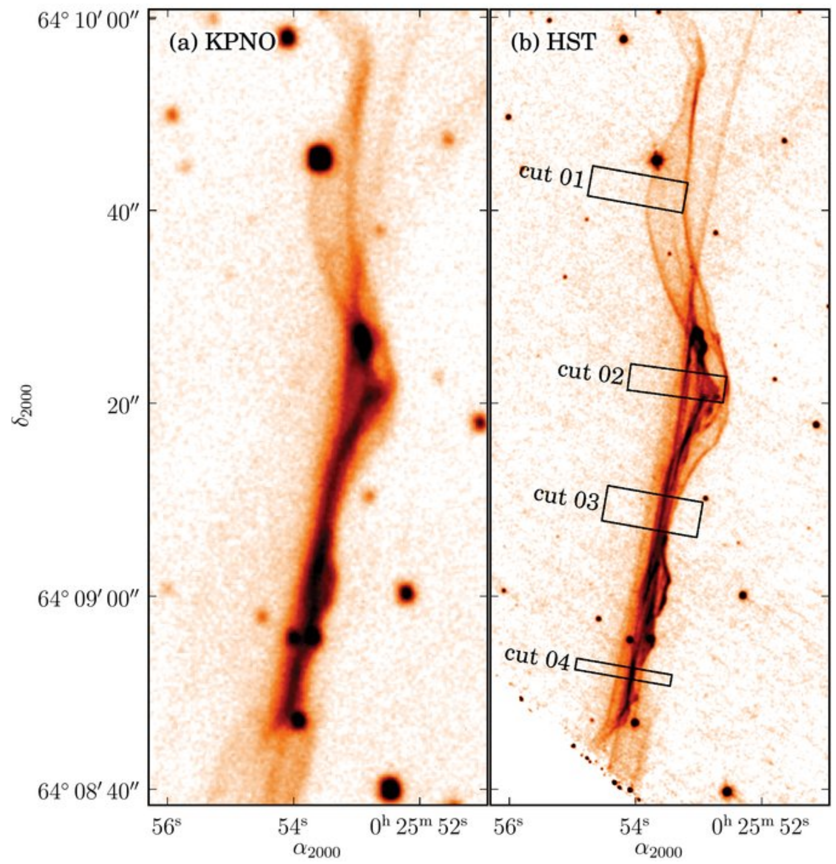
- Nuclear collisions enrich the ISM with spallation products
- Cosmic rays 10 MeV – 100 MeV determine spallation yields
- Increase primordial abundances of light elements (Lithium and Boron)
- Nuclear de-excitation lines at MeV energies
- Observable with next-generation MeV space telescope (eASTROGAM)

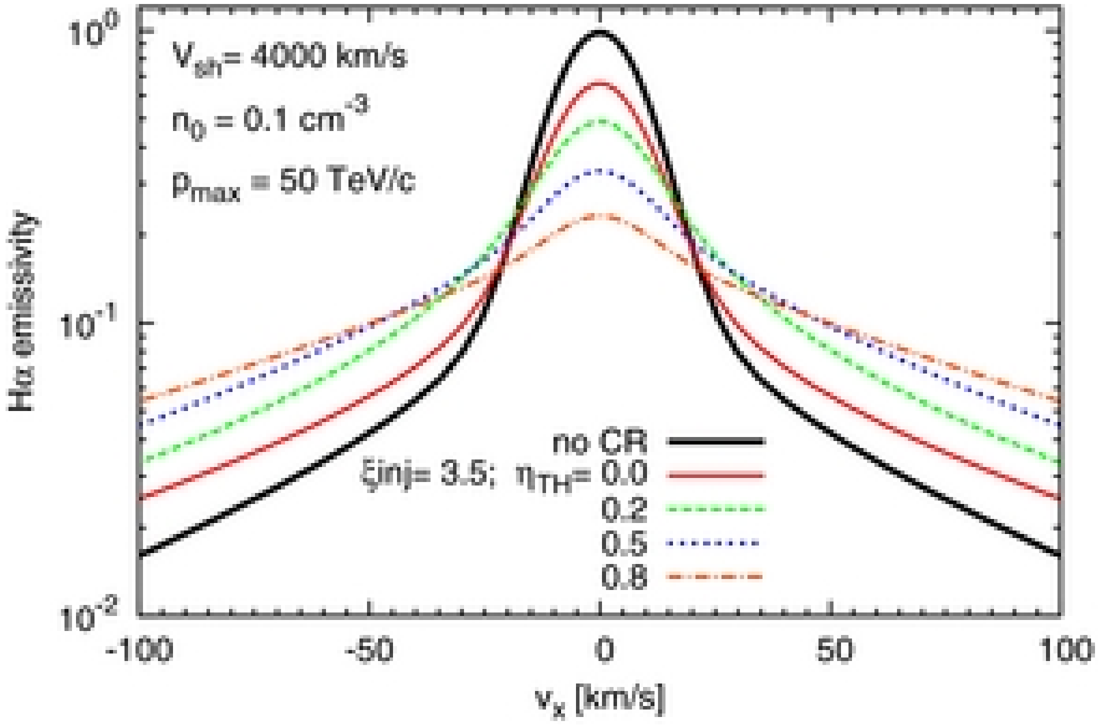




Cosmic ray interactions with neutral gas: Injection efficiency from Balmer lines

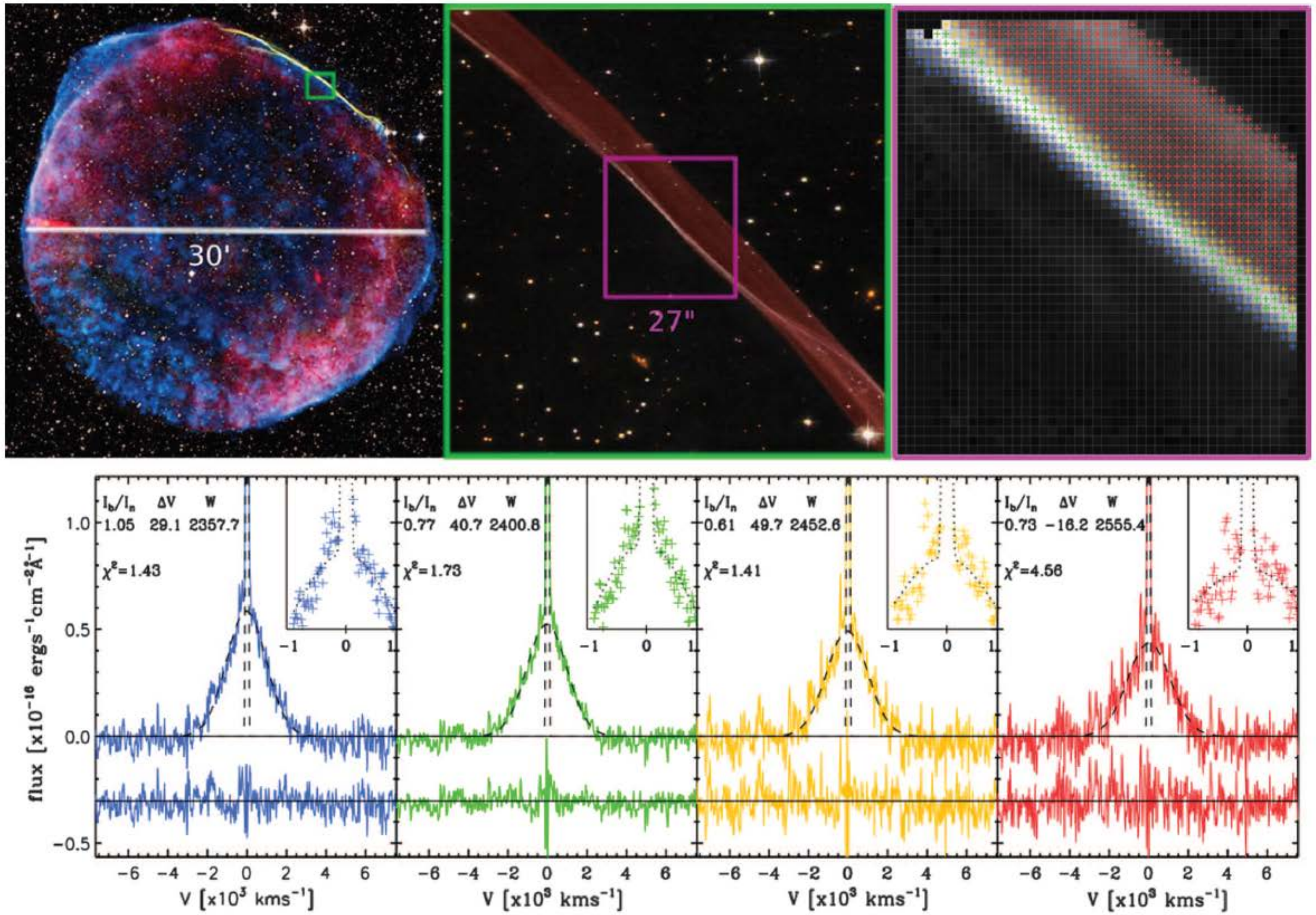
Lee et al. (2010)





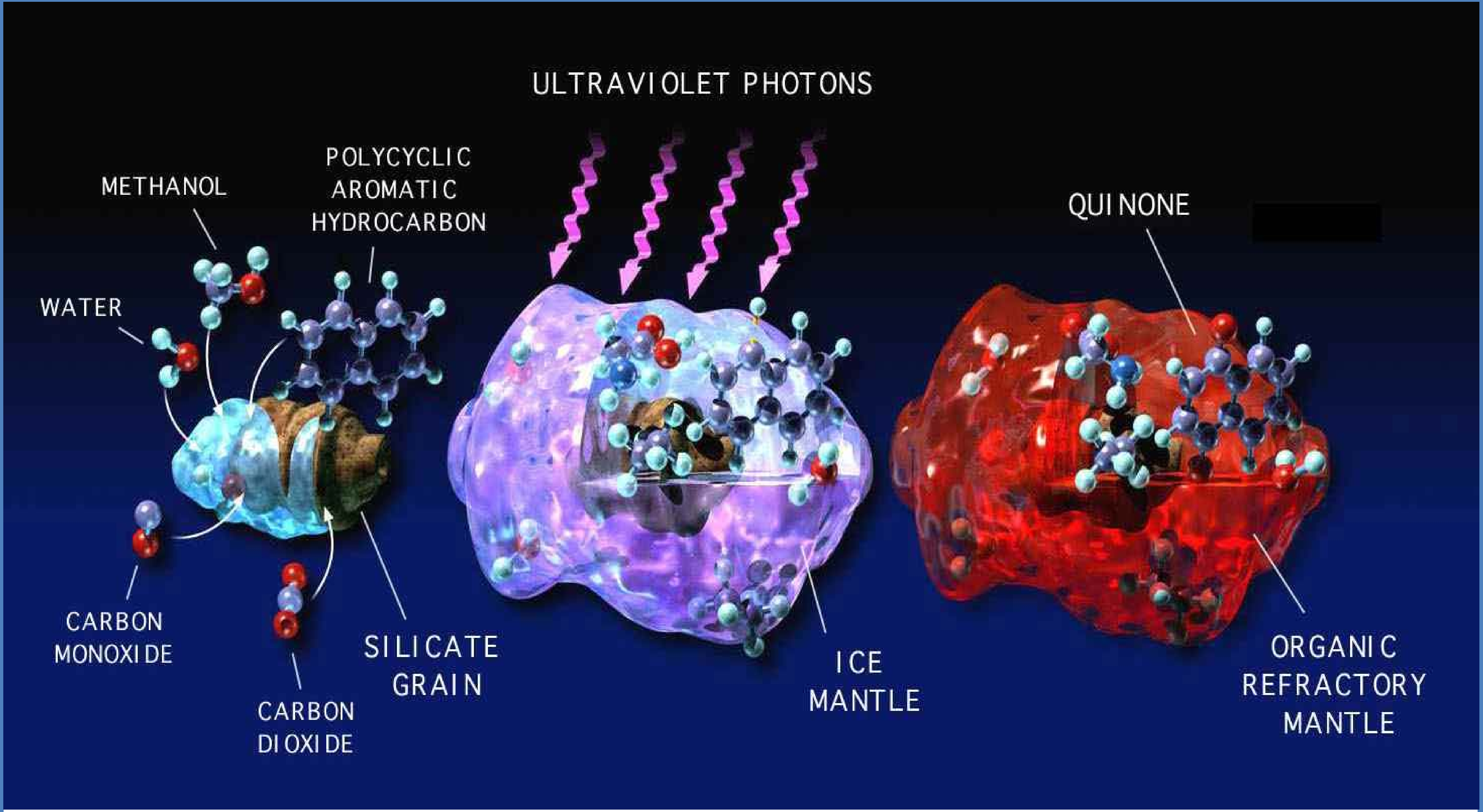
Morlino (2012)

Integral field spectroscopy: SN 1006

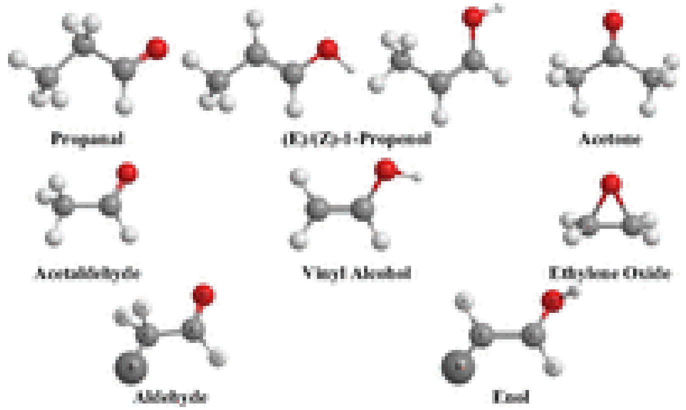


„Variations in the broad line widths and the broad-to-narrow line intensity ratios across tens of atomic mean free paths suggest the presence of suprathermal protons, the potential seed particles forgenerating high-energy cosmic rays.“

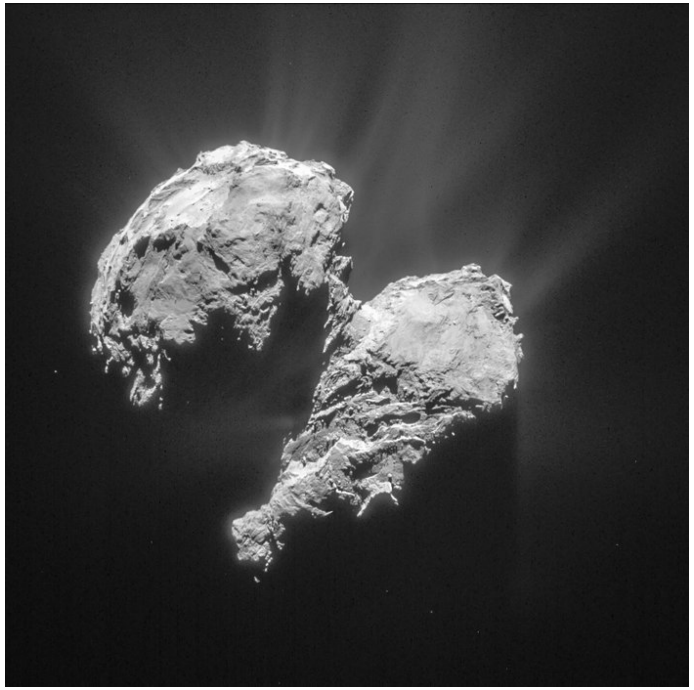
Nicolic et al. (2013)


ULTRAVIOLET PHOTONS
METHANOL
POLYCYCLIC AROMATIC HYDROCARBON
WATER
QUINONE
[redacted]
CARBON MONOXIDE
CARBON DIOXIDE
SILICATE GRAIN
ICE MANTLE
ORGANIC REFRACTORY MANTLE

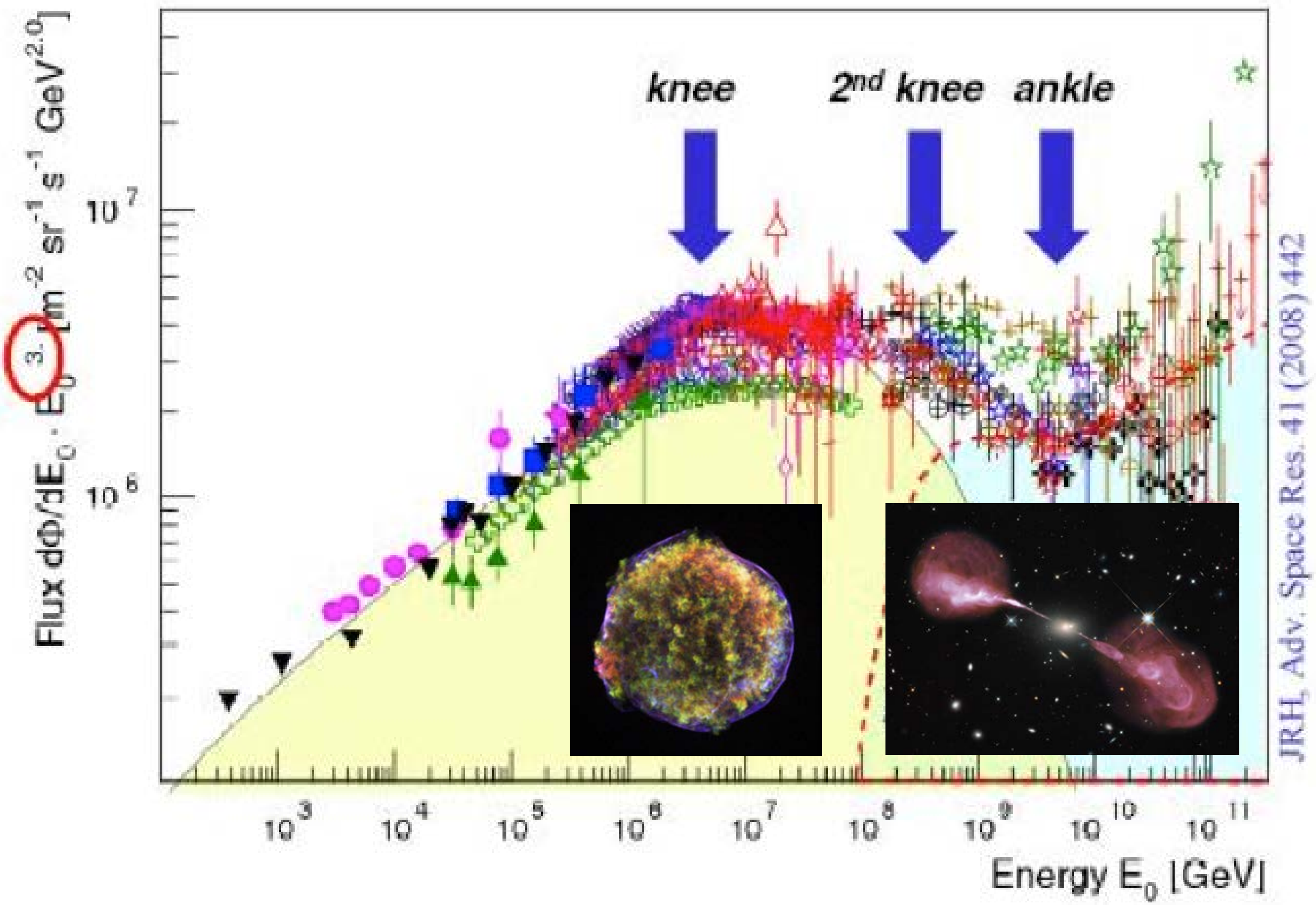
Feedback of cosmic rays: The cold (non-equilibrium) chemistry in ice



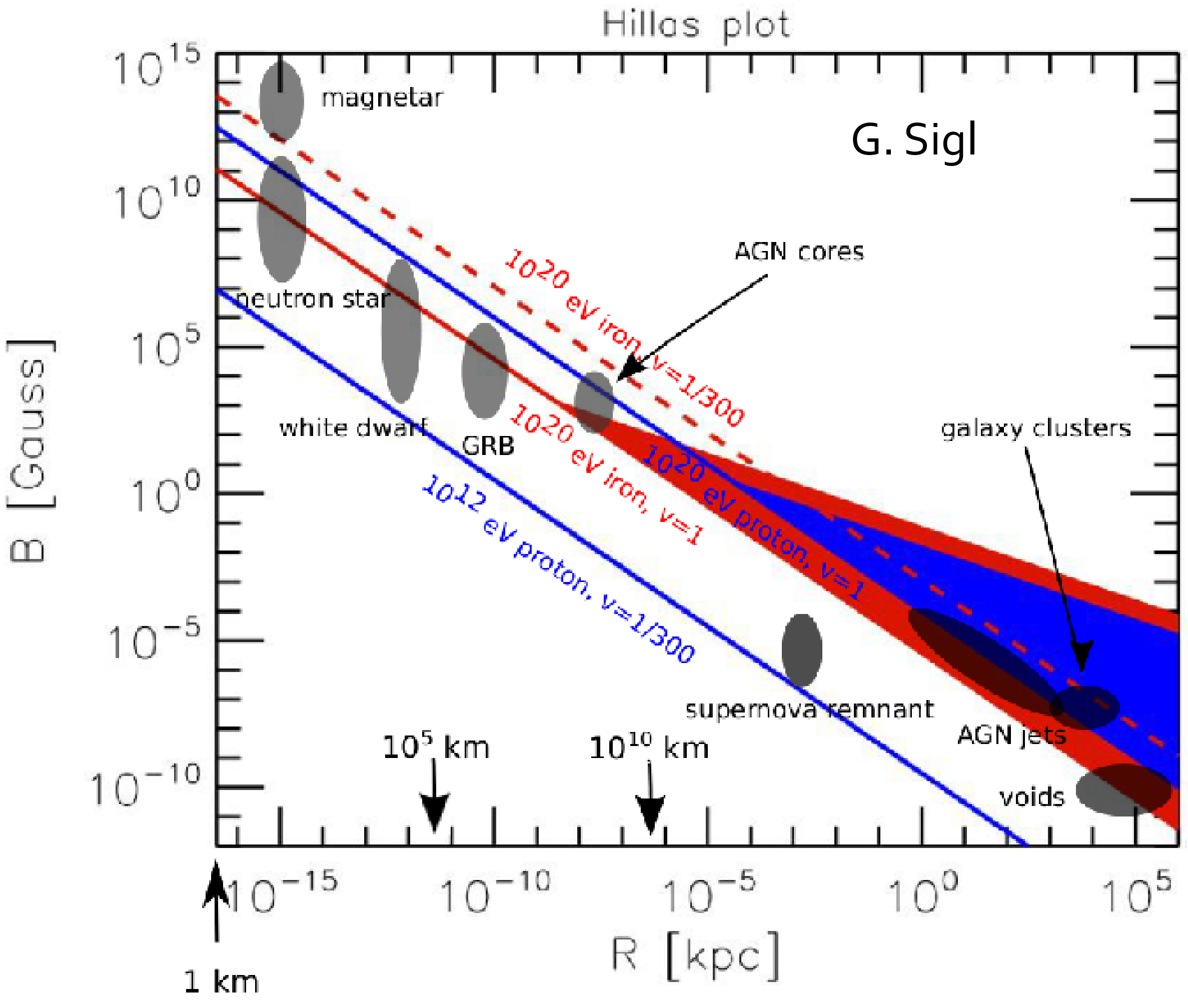
- Interstellar space and in partiular molecular clouds are filled with icy grains formed by water sticking on silicate or ferrite cores
- Cosmic rays induce complex molecular reaction networks in these ice grains
- Confirmed in laboratory experimtents and simulations (M.J. Abplanalp, PNAS, 2016)
- Rosetta probe contained organic molecules from icy material formed in the Kuiper belt

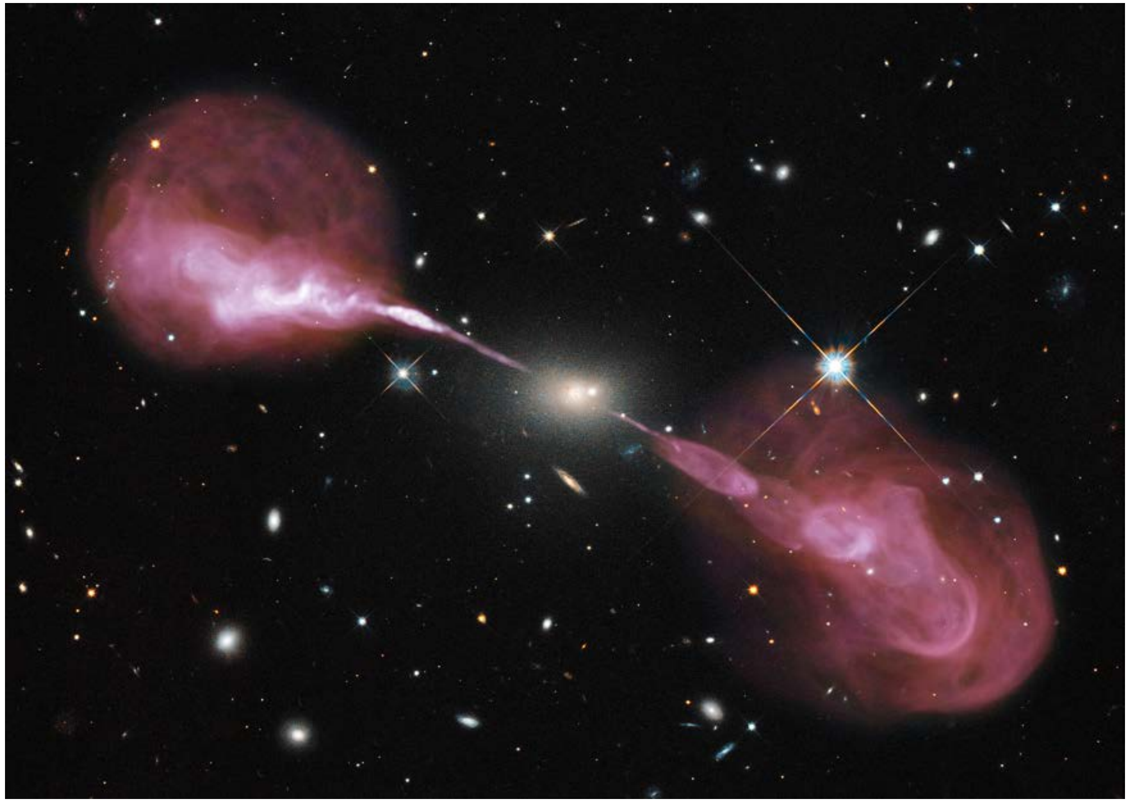


Cosmic-Ray Energy Spectrum

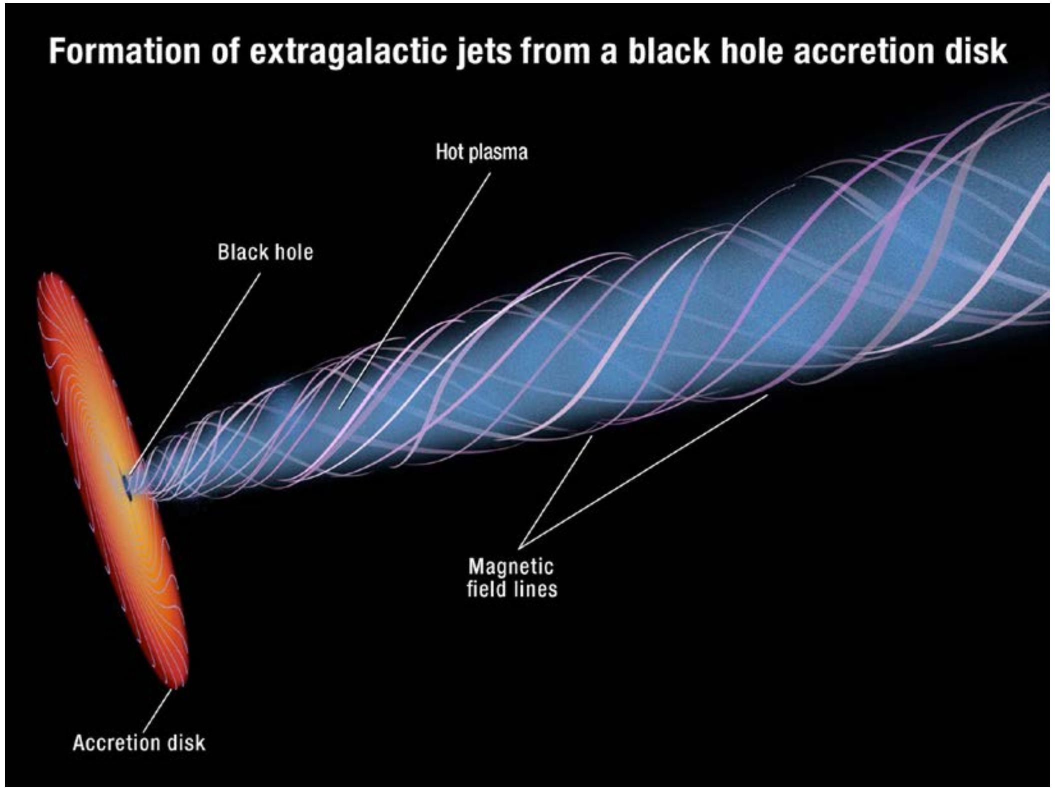


Extragalactic jets

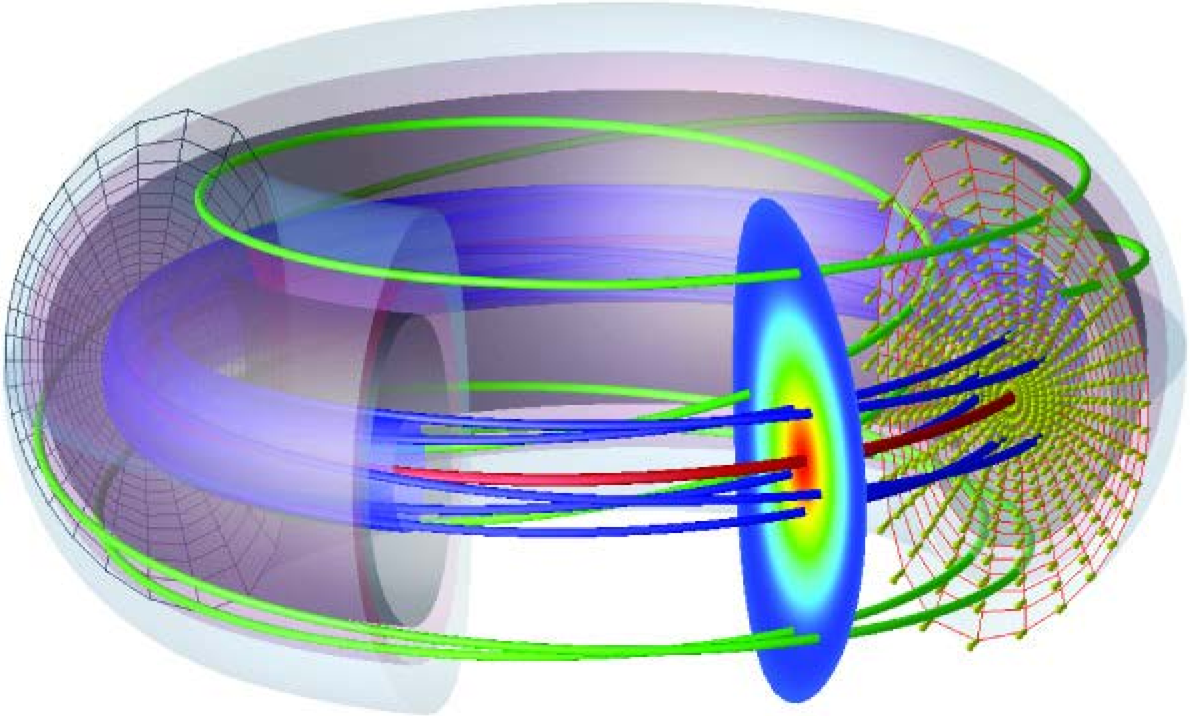




Grad-Shafranov Equation

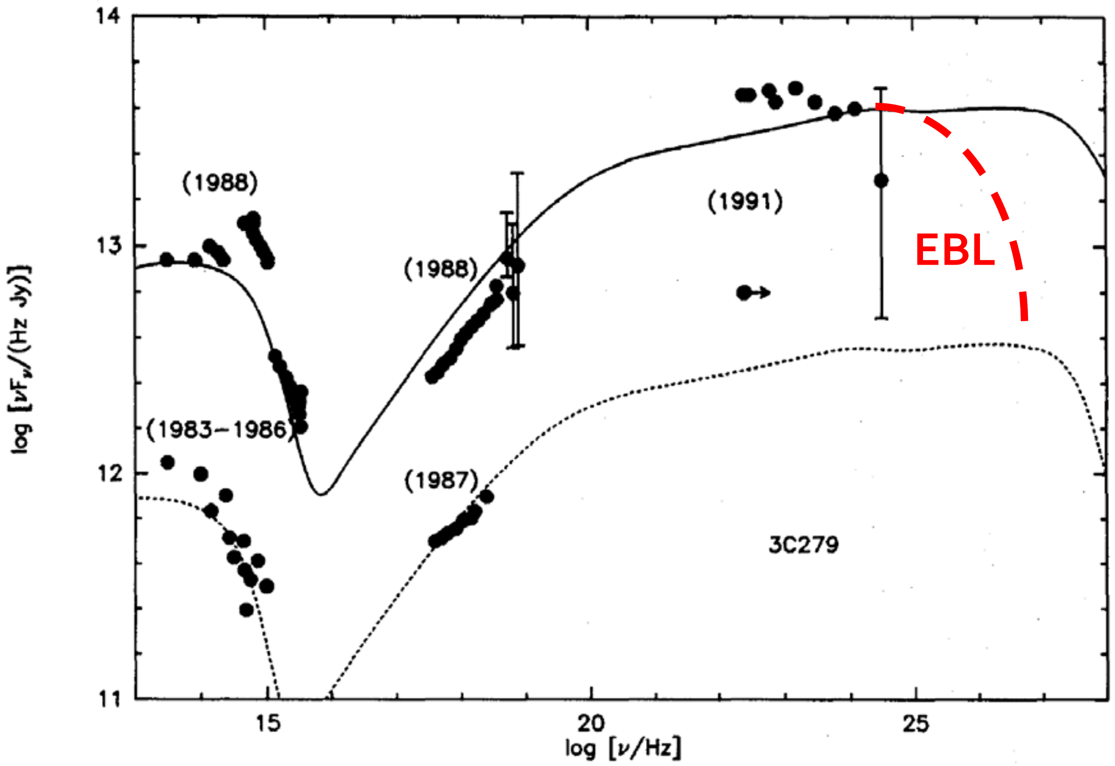


Black Hole Jet

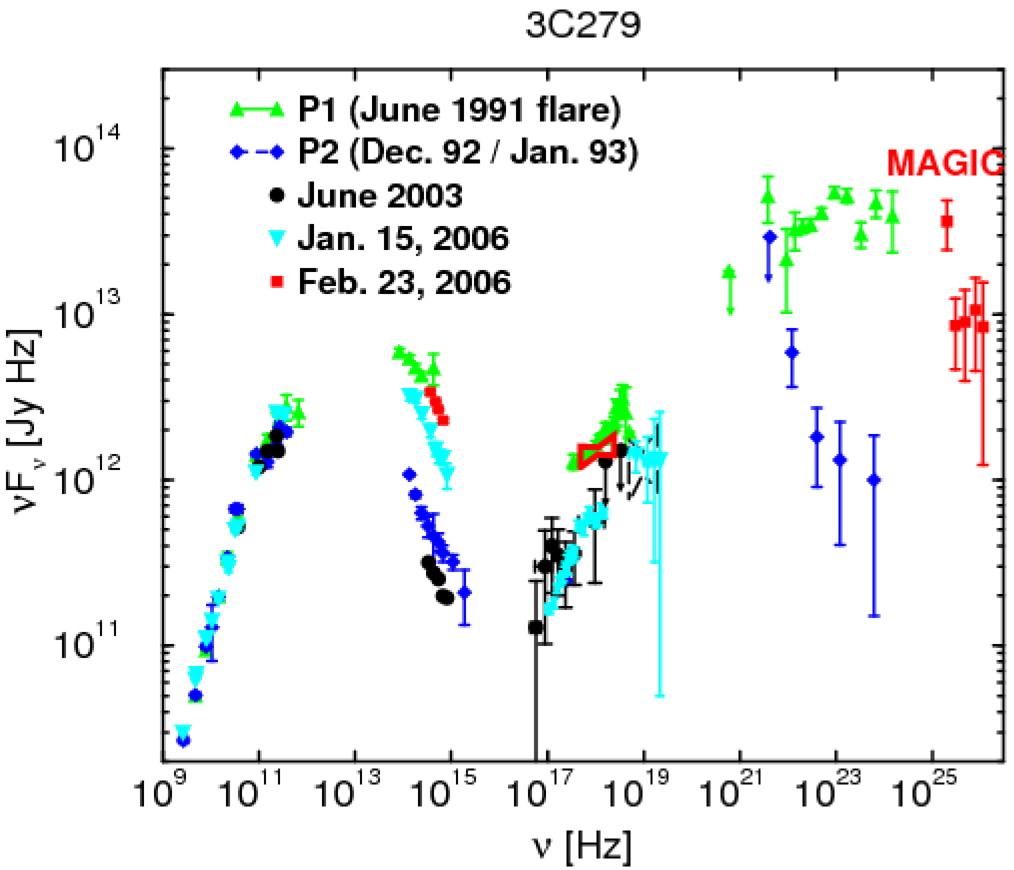


Tokamak

UHE Cosmic rays in extragalactic jets: Gamma-ray emission



Mannheim (1993)

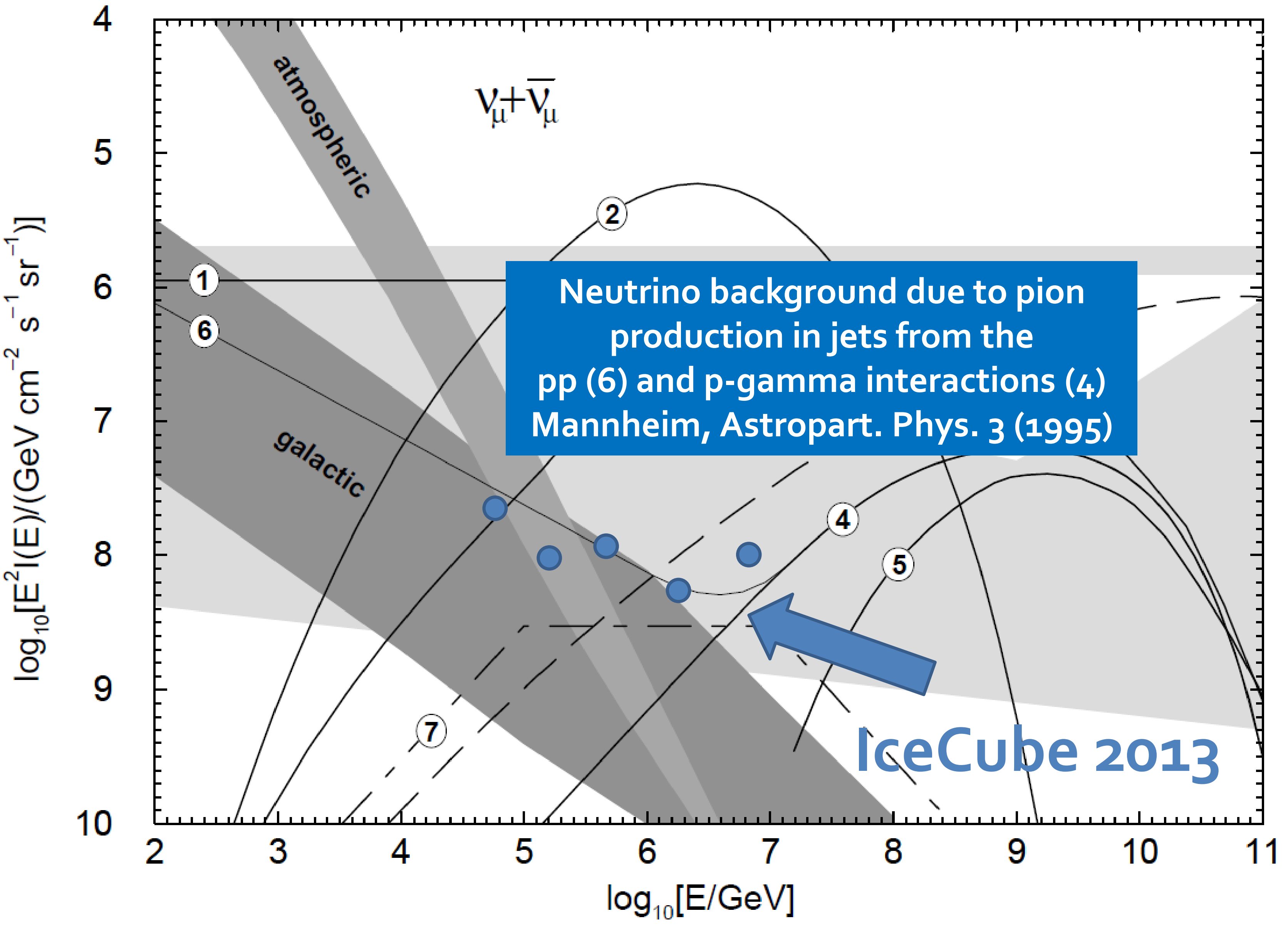


Boettcher (2009)

1995 Conjecture

KM, Astroparticle Physics 3, 295-302 (1995):

„… A striking similarity exists between the energy fluxes of diffuse γ-rays above 100 MeV and cosmic ray protons above the ankle … The corresponding prediction of a neutrino flux therefore rests on a firm basis. "

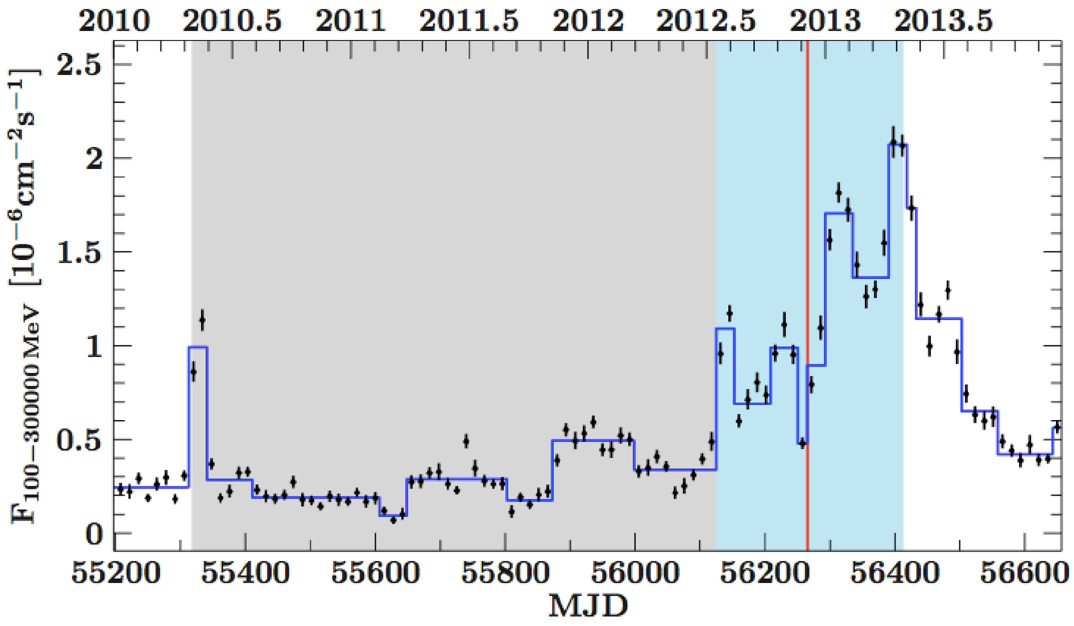


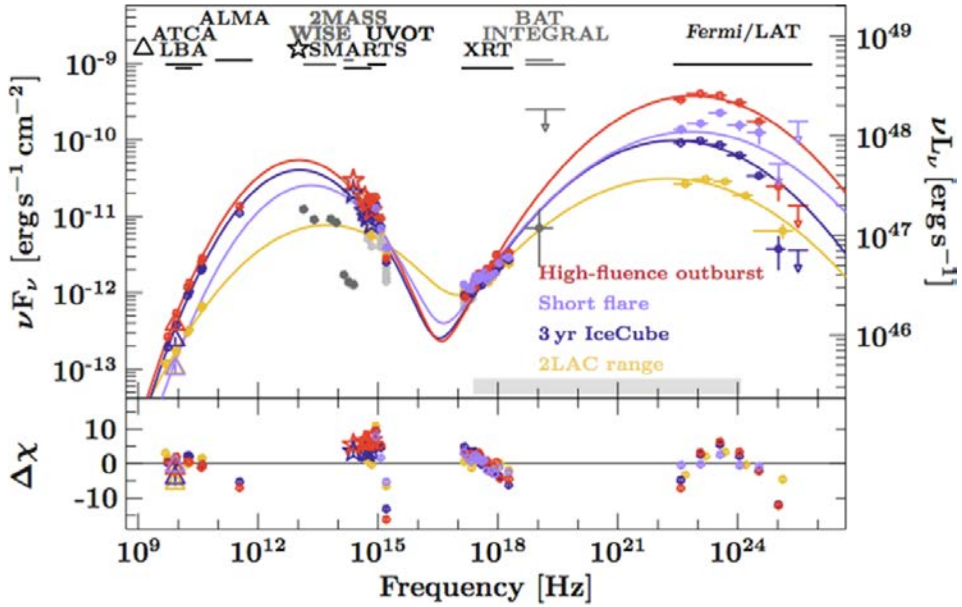
Neutrino background due to pion production in jets from the
pp (6) and p-gamma interactions (4)
Mannheim, Astropart. Phys. 3 (1995)
IceCube 2013
atmospheric
galactic
$\nu_\mu+\bar{\nu}_\mu$
1
2
4
5
6
7
$\log_{10}[E^2 I(E)/(\text{GeV cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1})]$
$\log_{10}[E/\text{GeV}]$

PKS B1424-418 Gamma Outburst: Fluence corresponding to 2.2 PeV neutrino events during IceCube measurements

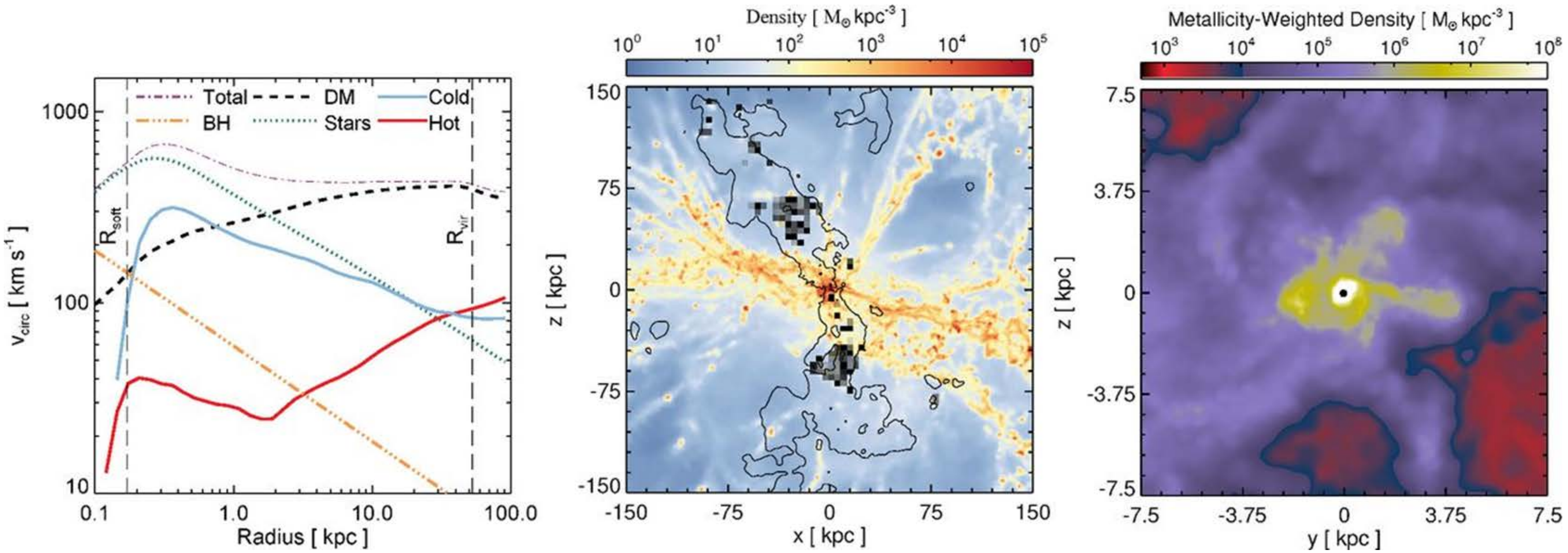
Kadler et al., Nature Phys. (2016)

5% chance probability for the brightest blazar outburst at the position of the most energetic neutrino event during the first HESE exposure (IceCube, Science 2013)





Feedback of cosmic rays: Cosmic ray driven outflows



Costa et al., MNRAS (2014)

"Obwohl **das menschliche Genie** in verschiedenen Erfindungen mit verschiedenen Mitteln zu einem und demselben Ziel antwortet, **wird** es **nie eine Erfindung** weder schöner, noch leichter, noch kürzer **als die der Natur finden, weil in ihren Erfindungen nichts fehlt und nichts überflüssig ist**.,,

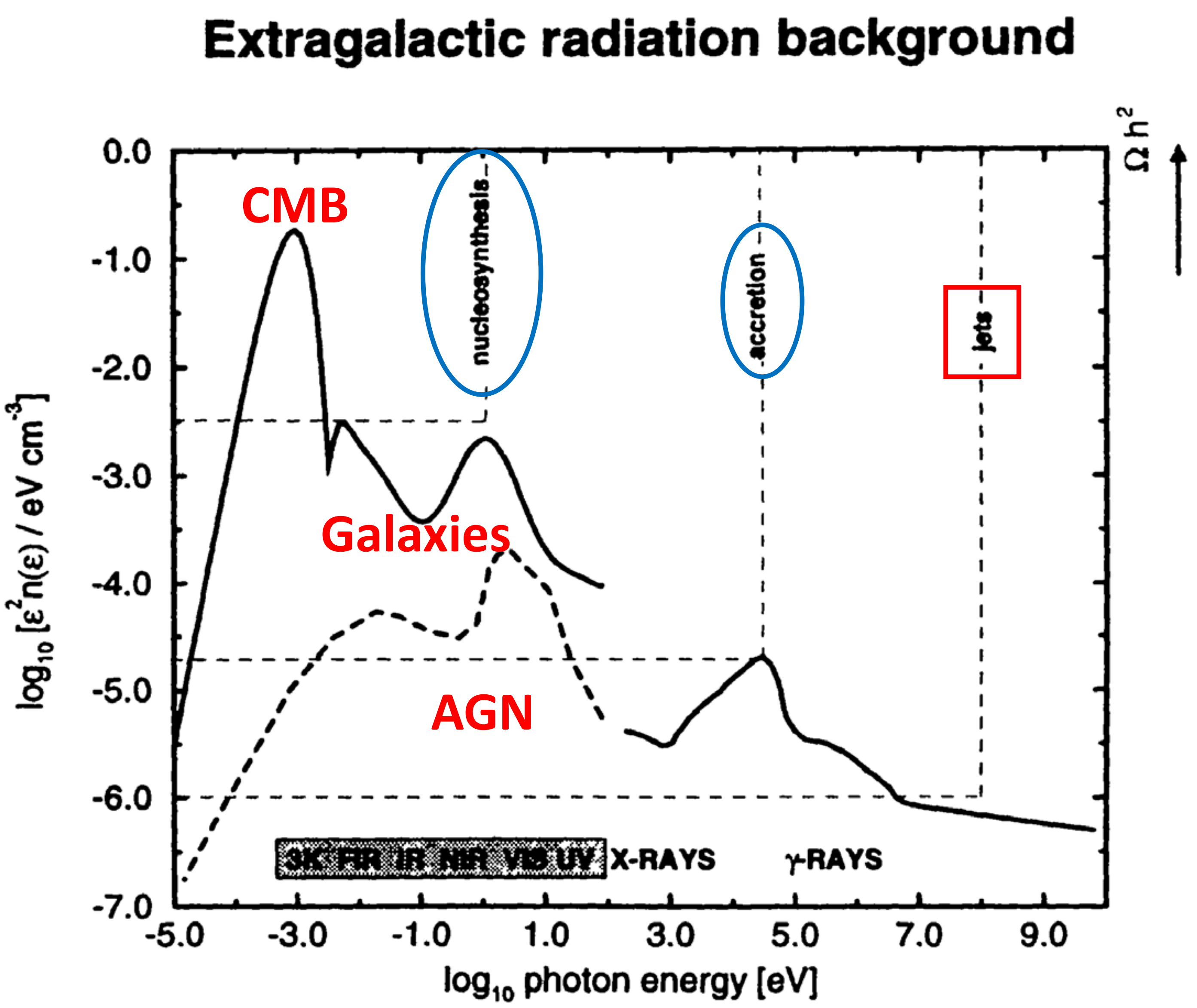
Leonardo da Vinci

Cosmic ray interactions: summary

- Diagnosis of particle acceleration in astrophysical objects

- Affect the physical state of the astrophysical plasma in a major way
  - Light element abundances
  - ISM heating and star formation
  - Turbulence and magnetic fields
  - Winds

- Trigger the chemical reaction networks that lead to the complex organic molecules in ice grains



$$u_{\rm ns} \sim \frac{\rho_* Z \epsilon c^2}{1+z_{\rm f}}$$ Peebles!

$$u_{\rm ns} \sim 6\times 10^{-3}\left(\frac{\Omega_* h^2}{0.01}\right)\left(\frac{1+z_{\rm f}}{3}\right)^{-1} \ {\rm eV\ cm^{-3}}$$

$$u_{\rm accr} \sim \frac{\epsilon_{\rm accr} M_{\rm bh}}{Z\epsilon M_*}\frac{t_{\rm agn}}{t_*}u_{\rm ns} \sim 1.4\times 10^{-4}\ {\rm eV\ cm^{-3}}$$

AGN average SED (Elvis et al.): $u_X \sim 0.2\, u_{acc}$

$$u_{\rm x} \sim 2.8\times 10^{-5}\ {\rm eV\ cm^{-3}}$$

$$\xi_{\rm rl} \sim 20\,\%$$

$$u_{\rm j} = \left(\frac{\xi_{\rm rl}}{0.2}\right) u_{\rm accr} \sim \left(\frac{\xi_{\rm rl}}{0.2}\right) 2.8\times 10^{-5}\ {\rm eV\ cm^{-3}}$$

$$\xi_{\rm acc} = \frac{u_{\rm acc}}{u_{\rm j}} = \frac{u_\gamma}{\xi_{\rm rad} u_{\rm j}}$$

$$\xi_{\rm acc} \geq 0.18\,\xi_{\rm rad}^{-1}\left(\frac{\xi_{\rm rl}}{0.2}\right)^{-1}$$