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Search for galactic cosmic ray sources: a multi-wavelength approach

Julia Tjus (born: Becker)

FAKULTÄT FÜR PHYSIK & ASTRONOMIE
Theoretische Physik IV

The origin of cosmic rays

- Charged CRs: GeV – 1e11 GeV
- CR electrons < 1e3 GeV
- γ-rays: GeV – 100 TeV (CR energy equiv.; mostly ambiguous still – IC/brems)
- Neutrinos: 100 TeV – 20 PeV (CR energy equiv.; no directional information yet)

Energies and rates of the cosmic-ray particles

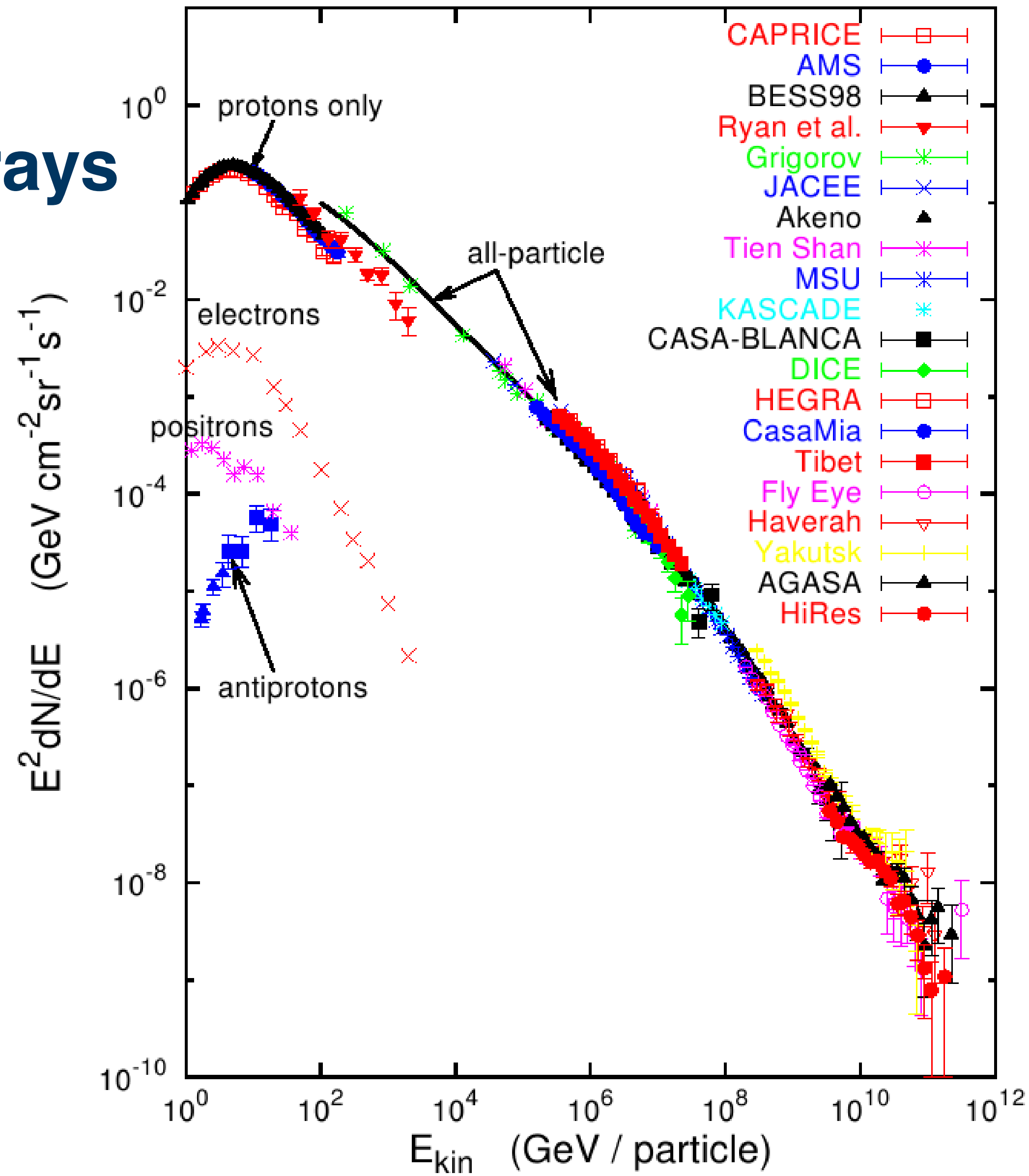

Figure: M. Hillas, astro-ph/0607109

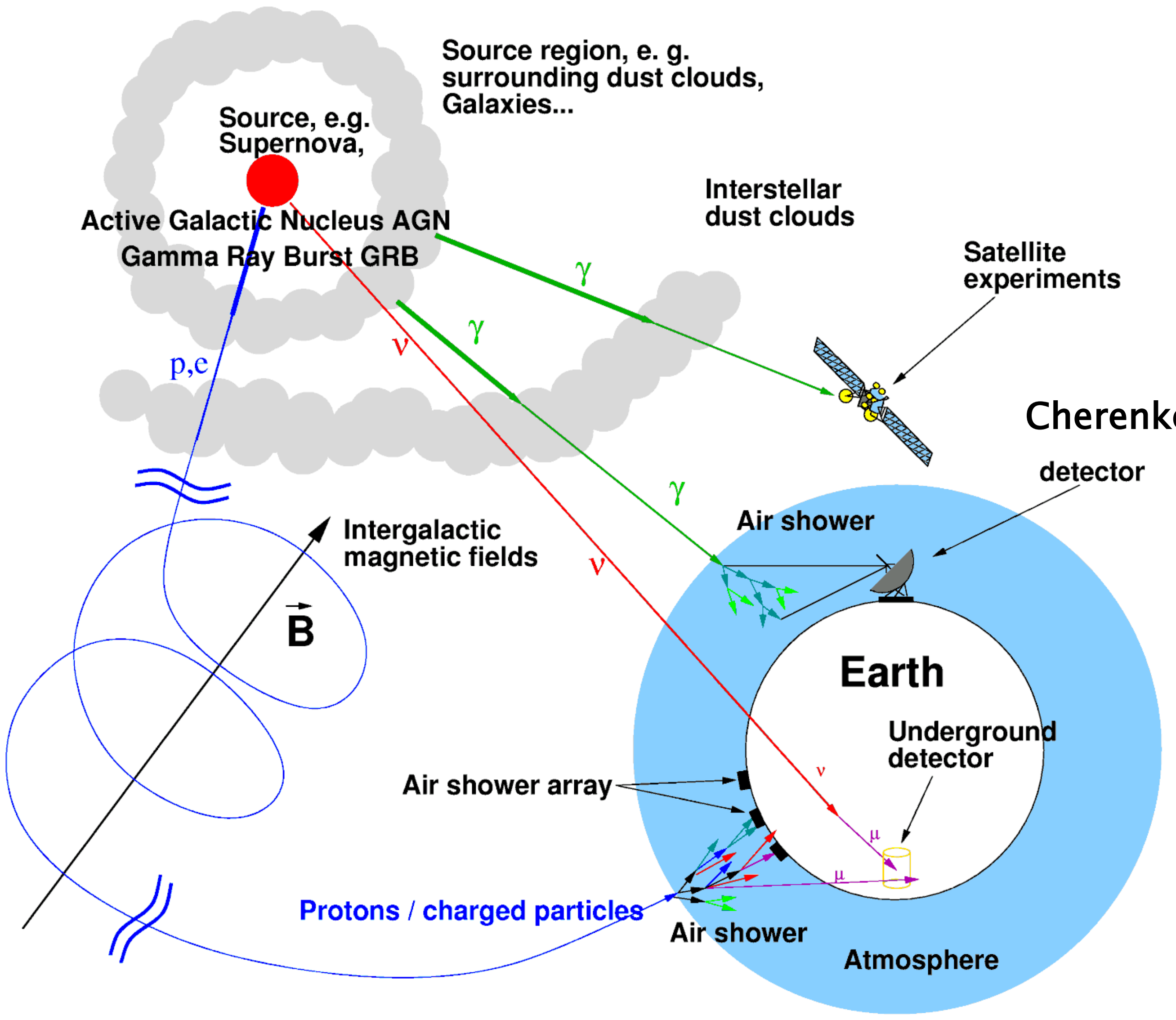

Fig: W. Wagner, PhD thesis, TU Dortmund, Germany (2004)

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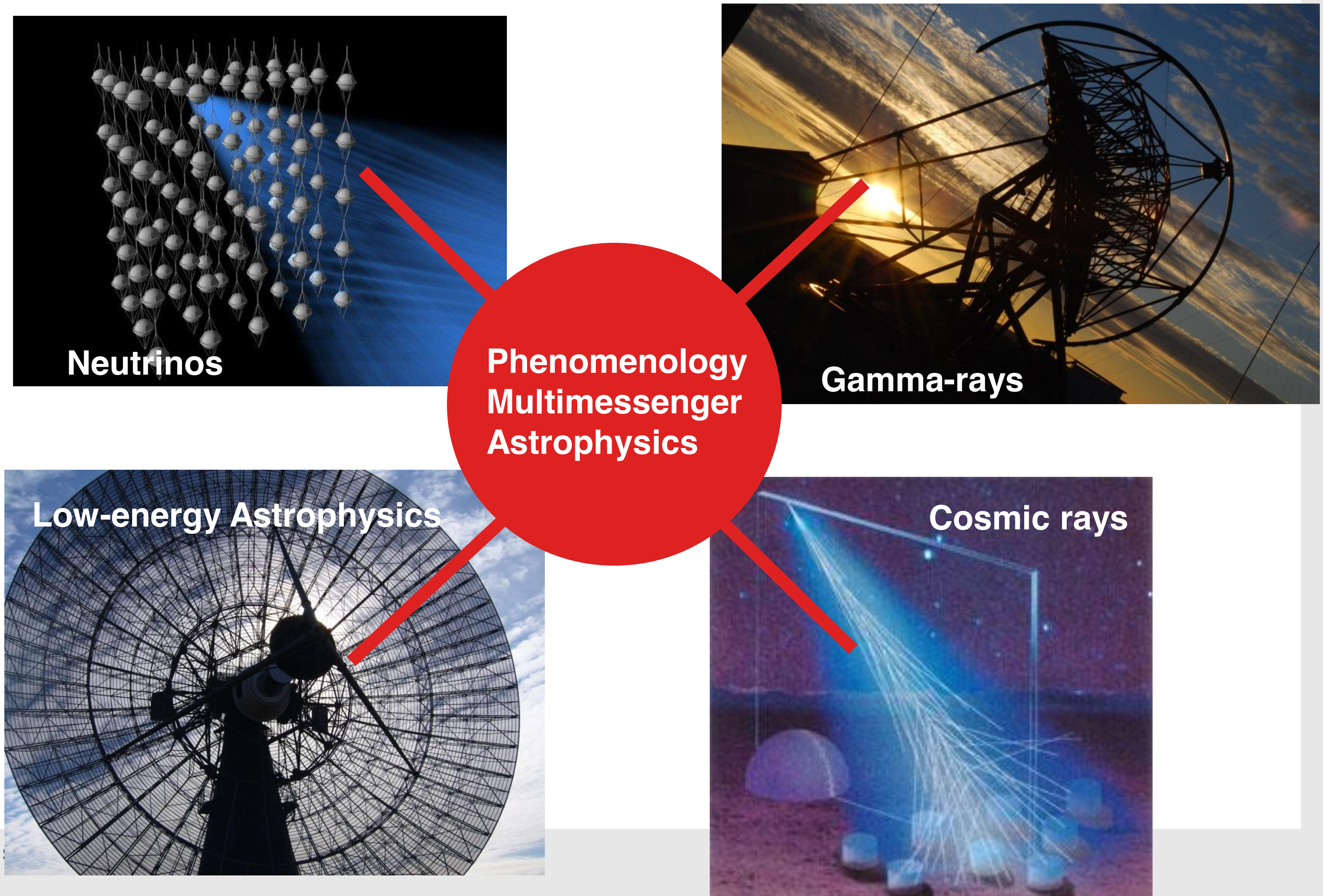
Multimessenger Astroparticle Physics



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Contents

- Basic arguments from cosmic ray measurements
  - Information from ***observations & (transport + source)-modeling***
- SNRs as central candidates:
  - ***direct*** information from **photons and neutrinos**
- **Outlook:** expectations for the future
- **Summary**

Basic conditions from CR observations
(1) Luminosity criterion

- **Cosmic ray luminosity**
  - v_{cr} ~ c → CR velocity
  - $\tau \sim 10^7$ yrs → CR lifetime in Galaxy
  - V ~ 10^{67} cm^3 → Galactic volume

$$L_{\rm CR} = \int\int v_{\rm CR}/(4\pi)\cdot\tau\cdot dN/dE\cdot E\,dE\,dV$$

- **Comparison Supernova Remnants:**

$$L_{\rm CR} \approx 2\cdot 10^{41}\,{\rm erg/s}\cdot\left(\frac{\eta}{0.1}\right)\cdot\left(\frac{\dot{n}}{0.02\,{\rm yr}^{-1}}\right)\cdot\left(\frac{E_{\rm SN}}{10^{51}\,{\rm erg}}\right)$$

(e.g. Drury (2014); Gaisser (1991))

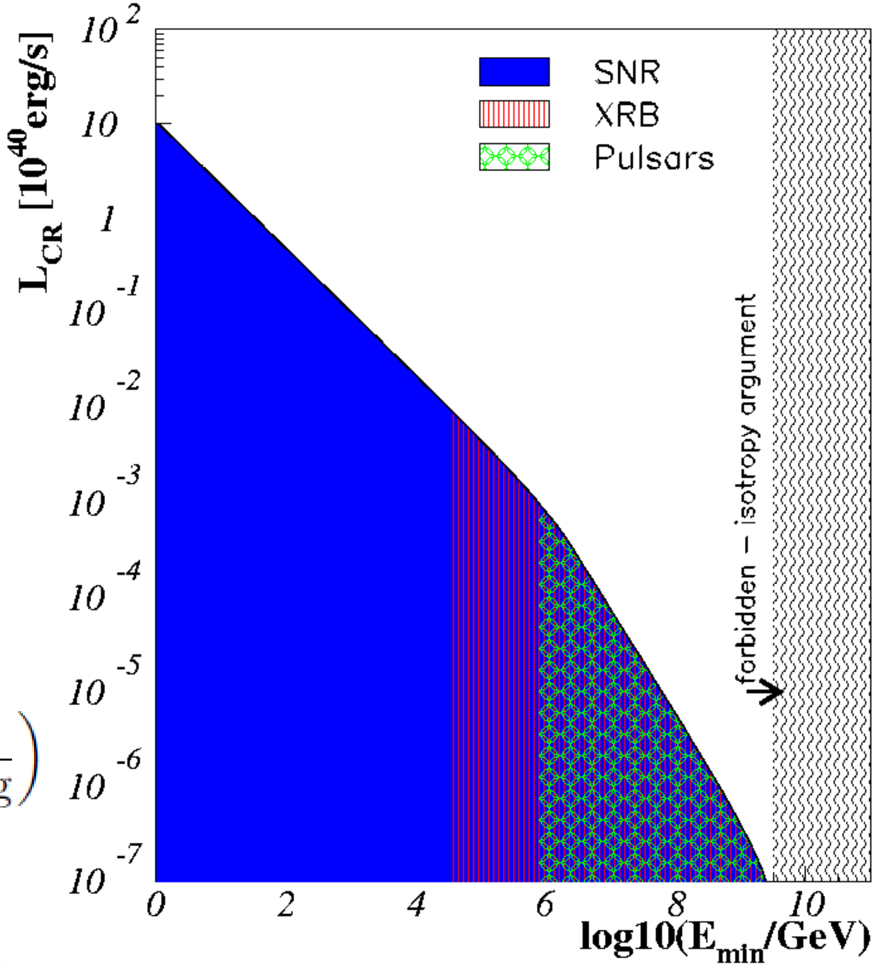

Fig: Becker, Phys. Rep. (2008)

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Basic conditions from CR observations (2) Hillas criterion and maximum energy

- Breaks from different source classes? → E_{max} ~ 10^{15}eV/3*10^{18}eV/ >3*10^{18}eV
- Hillas criterion: **E < Z*e*B*R**

(Hillas 1984)

- **Necessary condition!**
- **Time scale comparison for SNR shows:**

$$E < 3 \cdot TeV \cdot \left(\frac{\tau_{fr-ex}}{300 \ yrs}\right) \cdot \left(\frac{v_{shock}}{10^8 \ cm/s}\right)^2 \cdot \left(\frac{B}{\mu G}\right)$$

See e.g. Blasi, A&A review (2013)

- **→ magnetic field needs to be enhanced over ISM-field (B ~ 100 – 1000 μG)**

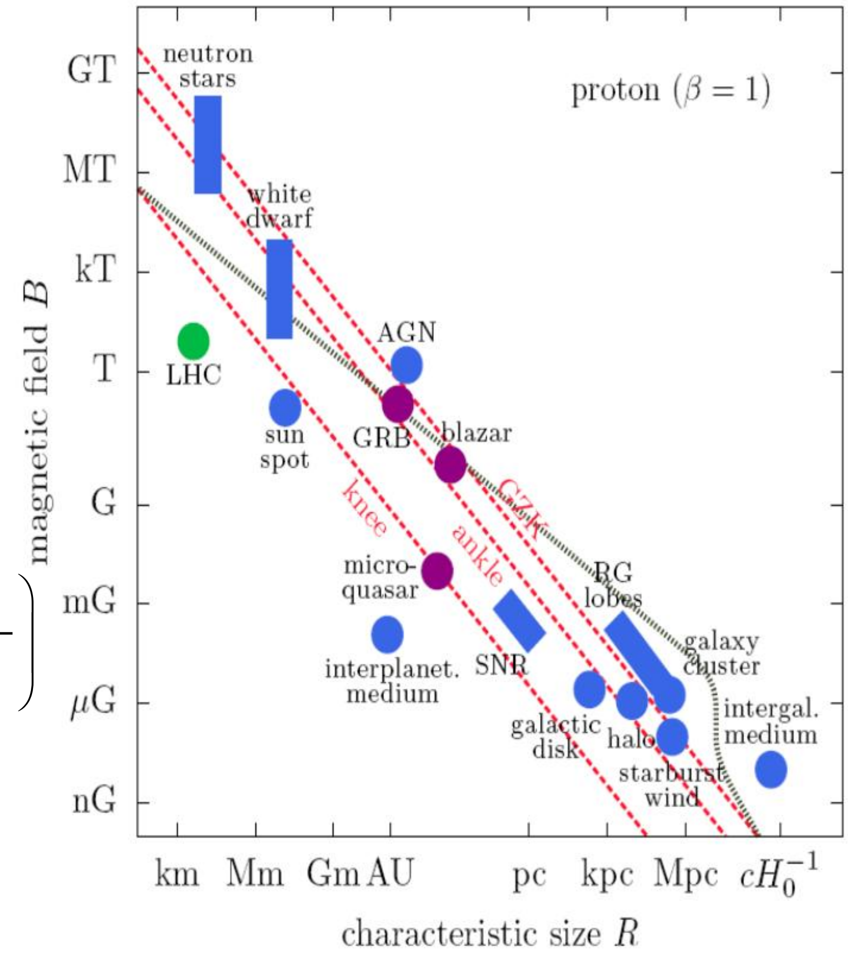

Fig: Ahlers et al, in prep

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Magnetic field amplification

- **Non-linear DSA**, plasma instabilities

(see e.g. Bell 1978, 2004, 2014; Blasi & Amato 2009)

- Supported by **observations of X-ray filaments**

(e.g. Vink et al 2006, 2012;
Ballet 2006 → rim width;

e.g.Patnaude and Fesen 2007,
Uchiyama et al. 2007 → X-ray variability)

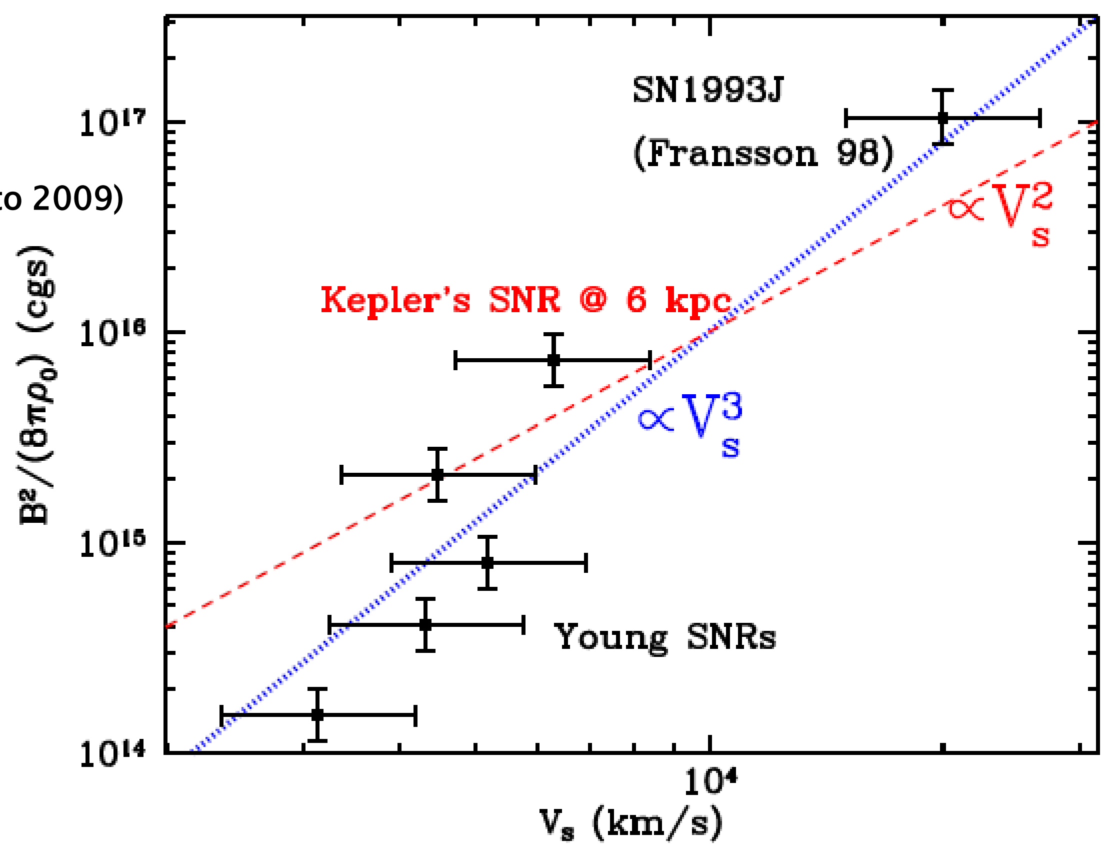
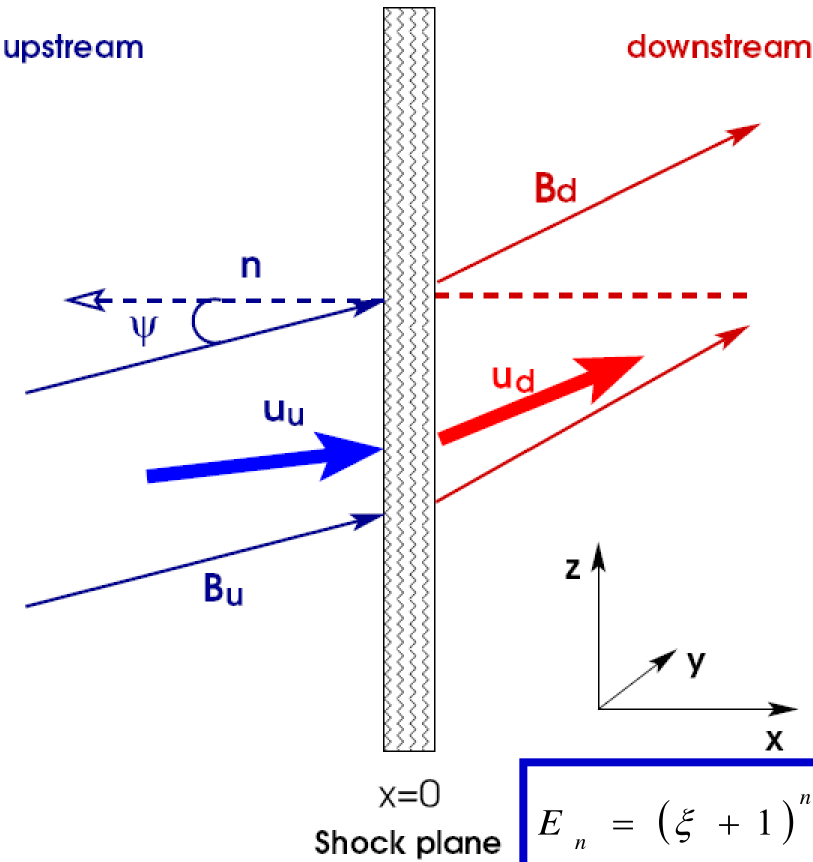


Fig: Vink, A&A review (2012)

Basic conditions from CR observations
(3) Spectral behavior

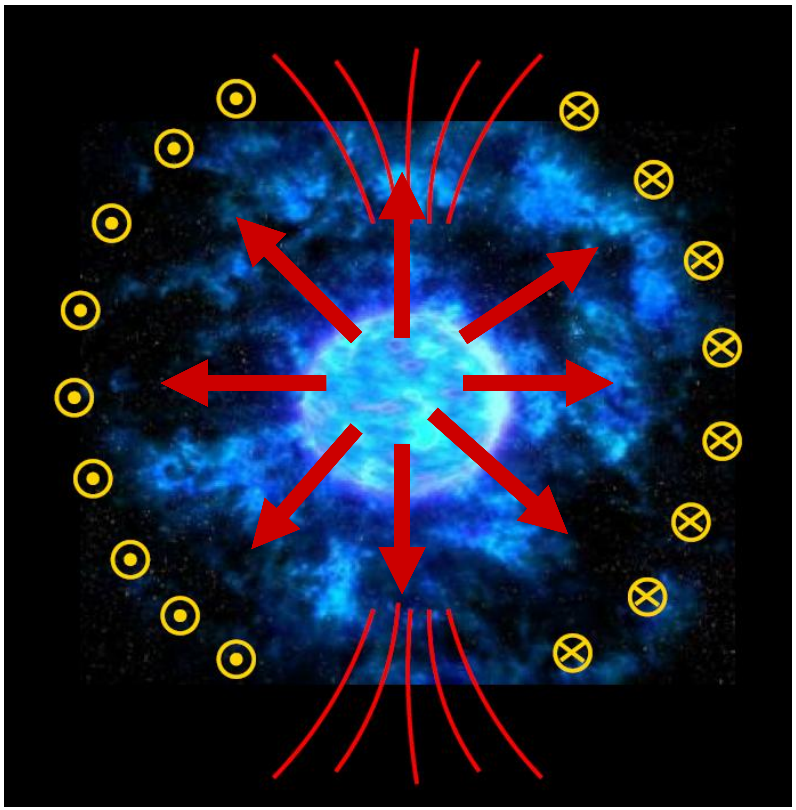
- Observed below knee:
- **Leaky box model** (simplest version):
- $dN/dE \sim dQ/dE * \tau_{esc}$
- $dQ/dE \sim E^{-\alpha}$
- $\tau_{esc} \sim D^{-1} \sim E^{-\delta}$
- ➔ $dN/dE \sim E^{-\alpha-\delta} \sim E^{-2.7}$



$$E_n = (\xi + 1)^n \cdot E_0$$

$$N(>E) = \sum_{i=n}^{\infty} (1 - P_{esc})^{n(E)} = \ldots \propto E^{-\gamma}$$

Source spectra – massive star projenitor SNR



Diffusion coefficient

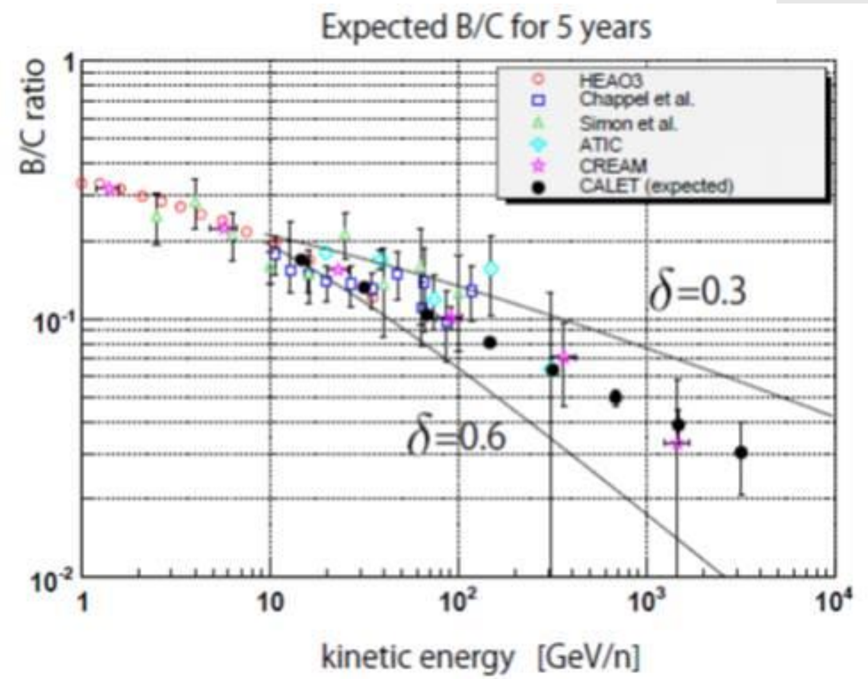


Fig: CALET experiment

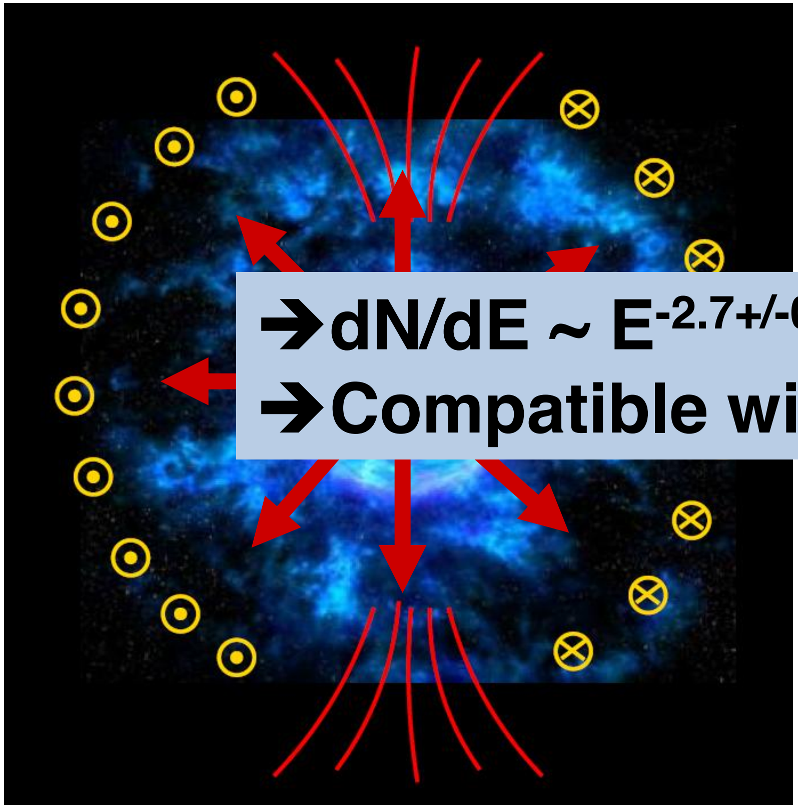
$\tau_{esc} \sim E^{-0.3} - E^{-0.6}$

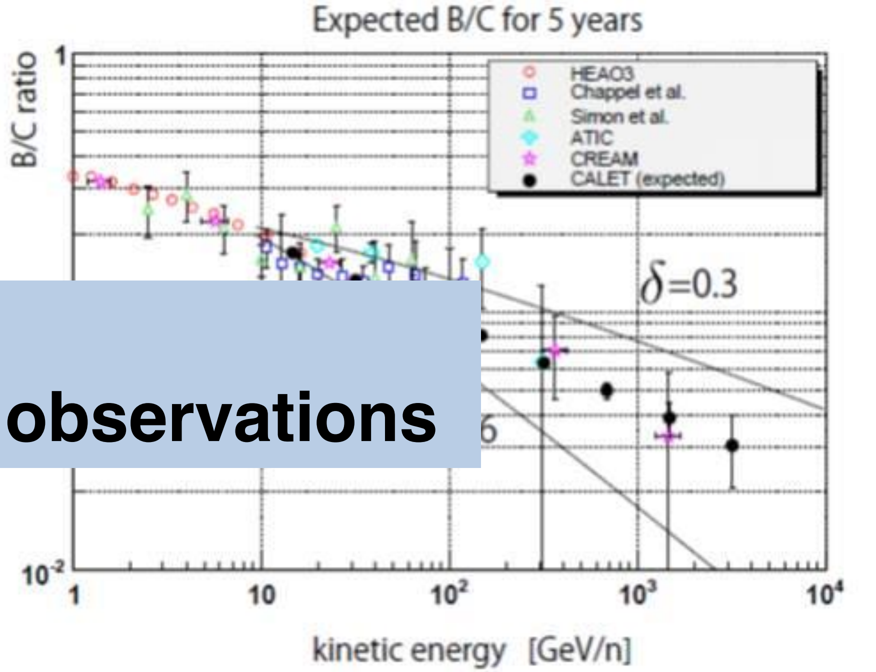
Massive star progenitor (→ explosion into dense wind)
Perpendicular shock, acceleration E^{-2},
locally steepened by turbulence, $dQ/dE \sim E^{-2.2} - E^{-2.3}$

Biermann, Becker et al, PRL 103:061101 (2009)

Source spectra – massive star projenitor SNR

Diffusion coefficient





→dN/dE ~ $E^{-2.7+/-0.2}$
→Compatible with observations

Fig: CALET experiment

$\tau_{esc} \sim E^{-0.3} - E^{-0.6}$

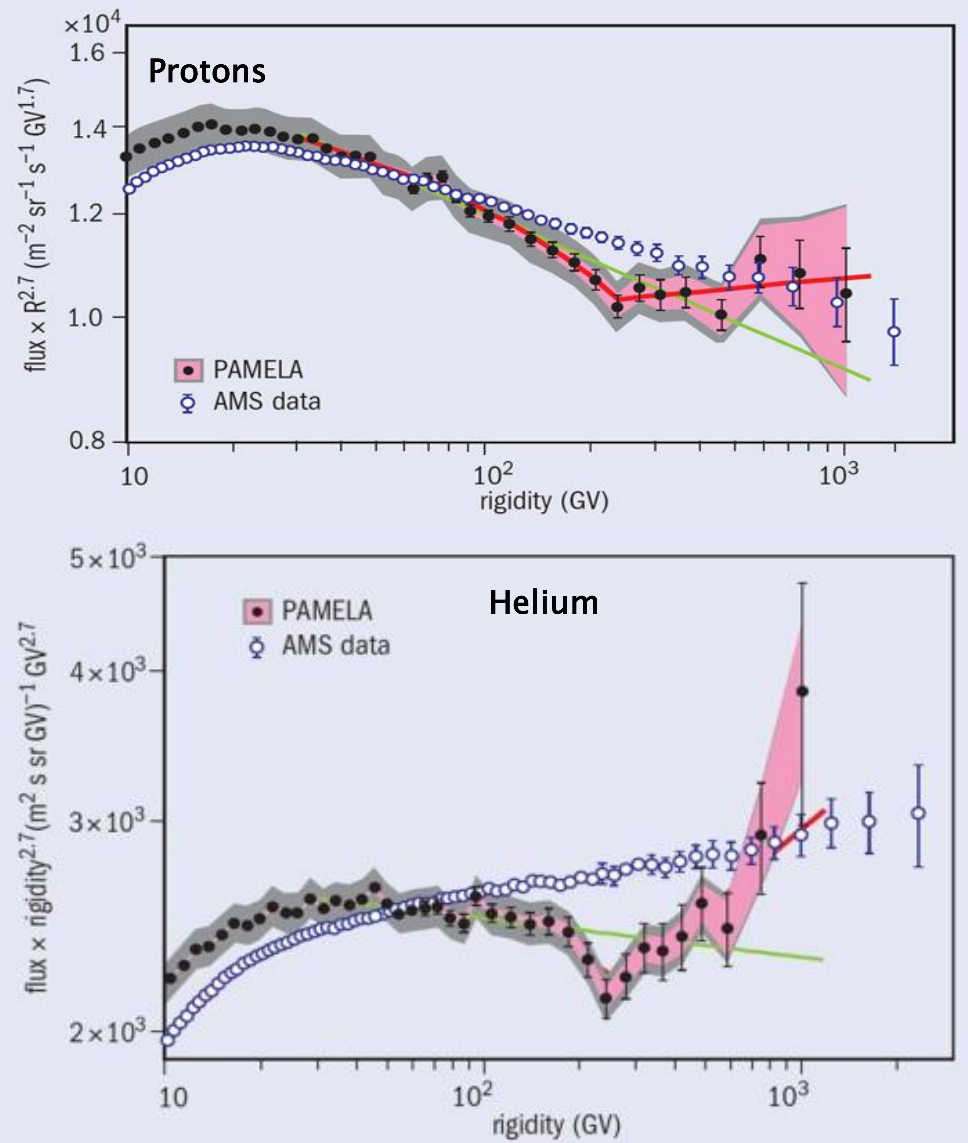
Massive star progenitor (→ explosion into dense wind)
Perpendicular shock, acceleration E^{-2},
locally steepened by turbulence, $dQ/dE \sim E^{-2.2} - E^{-2.3}$

Biermann, Becker et al, PRL 103:061101 (2009)

Basic conditions from CR observations
(4) Composition

- Flattening of the spectrum around **100-1000 GeV/N**
- Not clear yet how pronounced break is for **H & He**

(talk Pasquale Blasi)

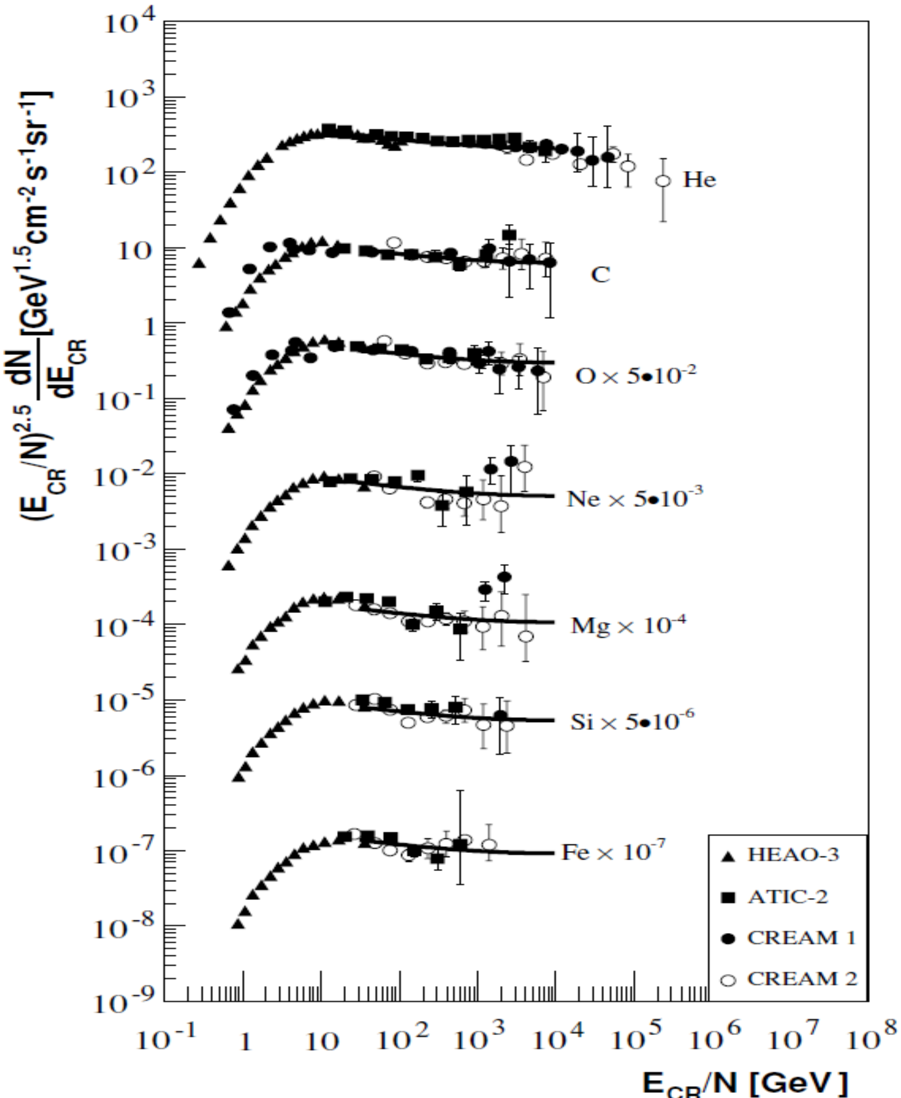


AMS, ICRC 2013

Basic conditions from CR observations (4) Composition

- **Break** clearly visible for **heavier nuclei** (CREAM data)

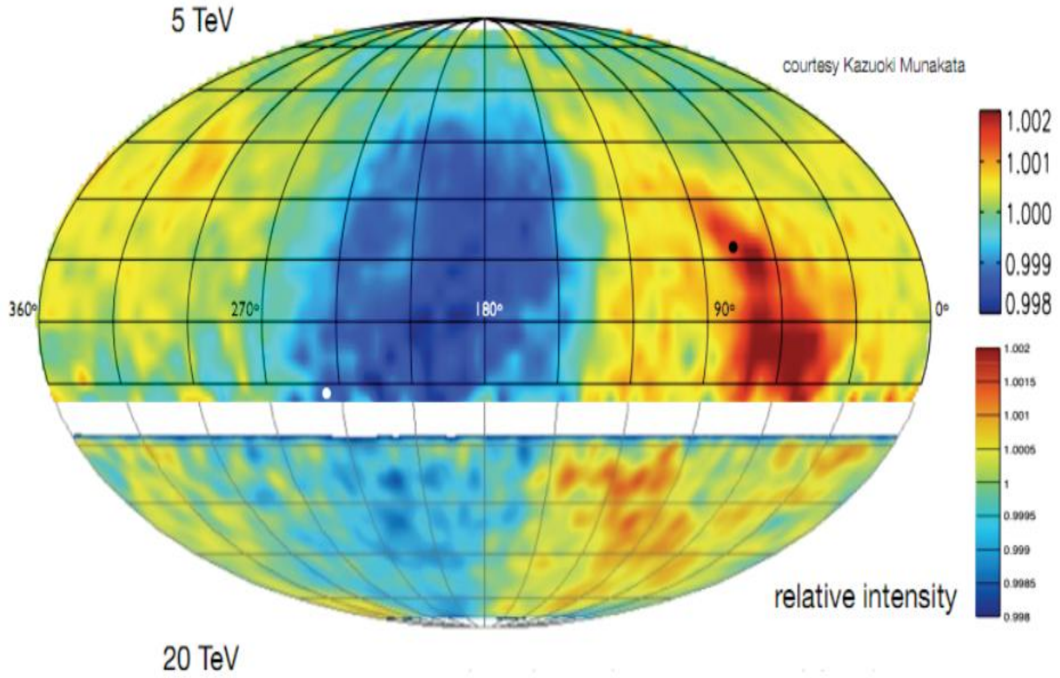
- Explanations?
  - **Galactic Transport** → difficult to explain difference between steep proton spectra and flat nuclei spectra
  - **Intrinsic source properties** (e.g. local effects → Biermann et al 2010; Tomassetti (2012); Blasi et al (2012);…)



(talk Pasquale Blasi)

Basic conditions from CR observations (5) Anisotropy

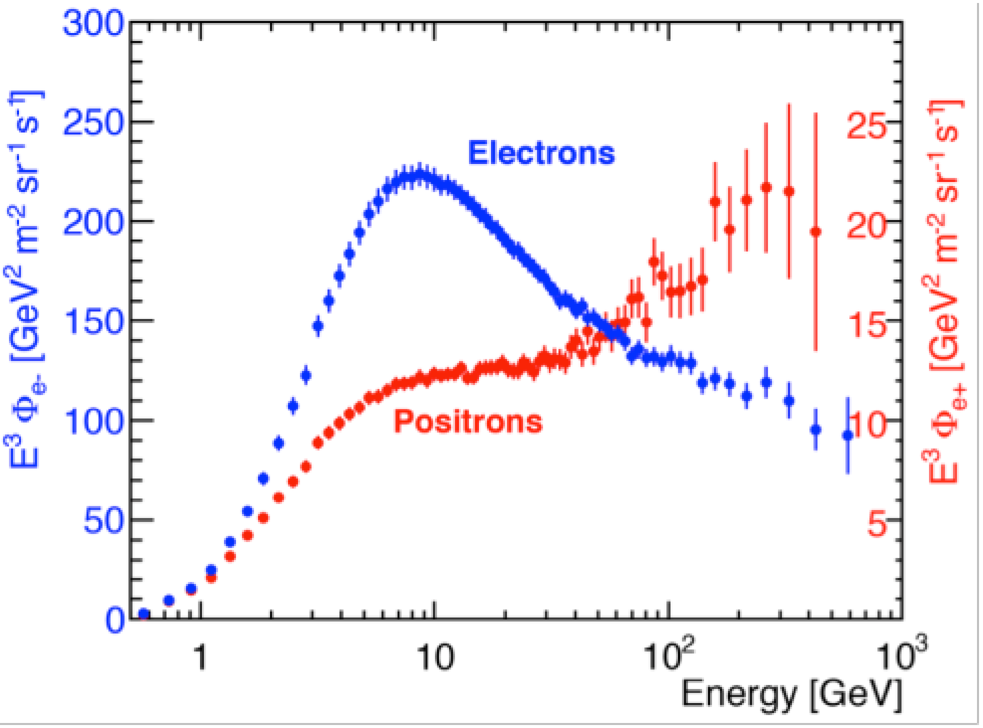
- **Northern hemisphere:** MILAGRO and TIBET
- **Southern hemisphere:** IceCube
- **Level ~ 10^{-3} – 10^{-4}**

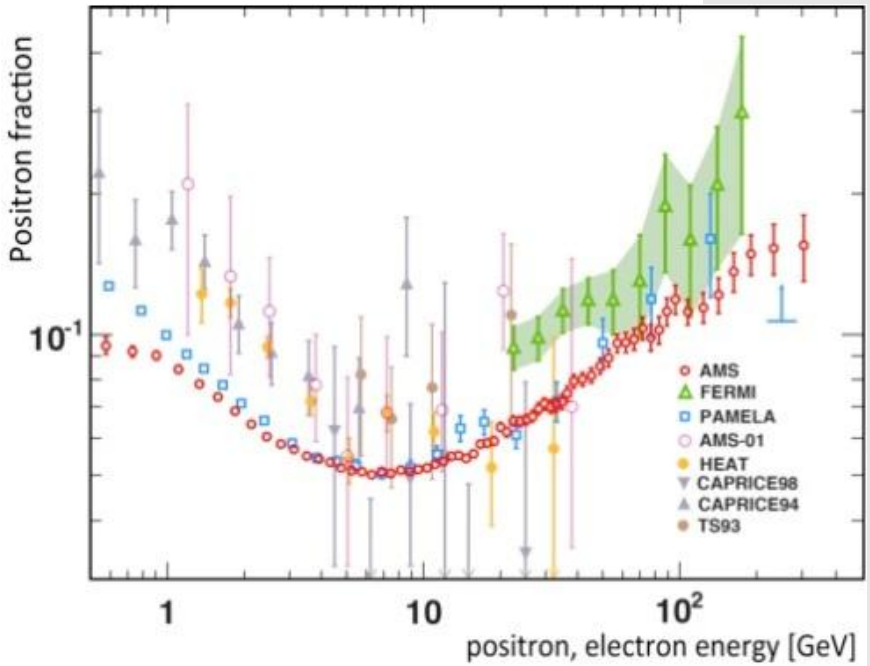


(talks Paolo Desiati, Segev BenZvi)

If you don‘t know yet what to do next week and want to know more about cosmic ray anisotropies:

Basic conditions from CR observations (6) Electrons and positrons

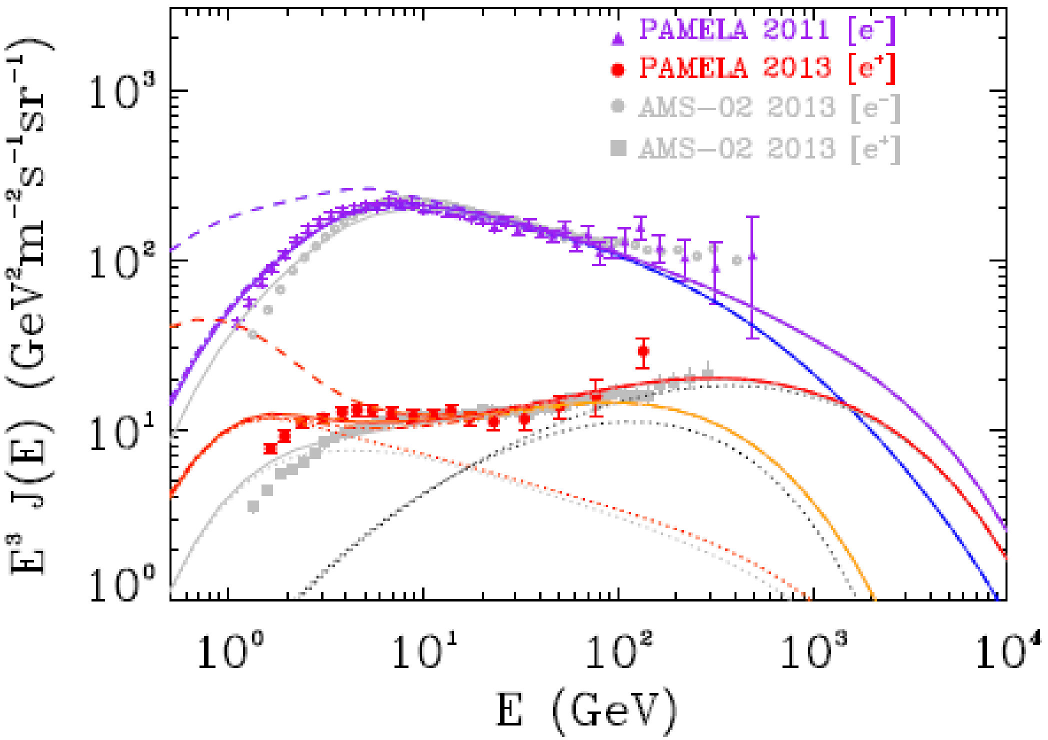




Figs: AMS 2014

Astrophysical explanations

- manifold →
- SNRs in **dense CSM** (e.g. Biermann et al, PRL 2009; Mertsch & Sarkar, PRL 2014)
- **Pulsars** (e.g. Yüksel, Stanev & Kistler, PRL 2008)
- **improved transport modeling** (e.g. Gaggero et al, PRD 2013)
- No real need for DM, but who knows…



Gaggero et al, PRD (2013)

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SNRs as THE cosmic ray sources – a basic check

1. **Luminosity** criterion → ok
2. **Maximum energy** criterion → possible (but still with open questions)
3. **Spectral behavior** → ok
4. **Composition** → ok
5. **Anisotropy** → ok
6. **Electrons and Positrons** → different possible explanations

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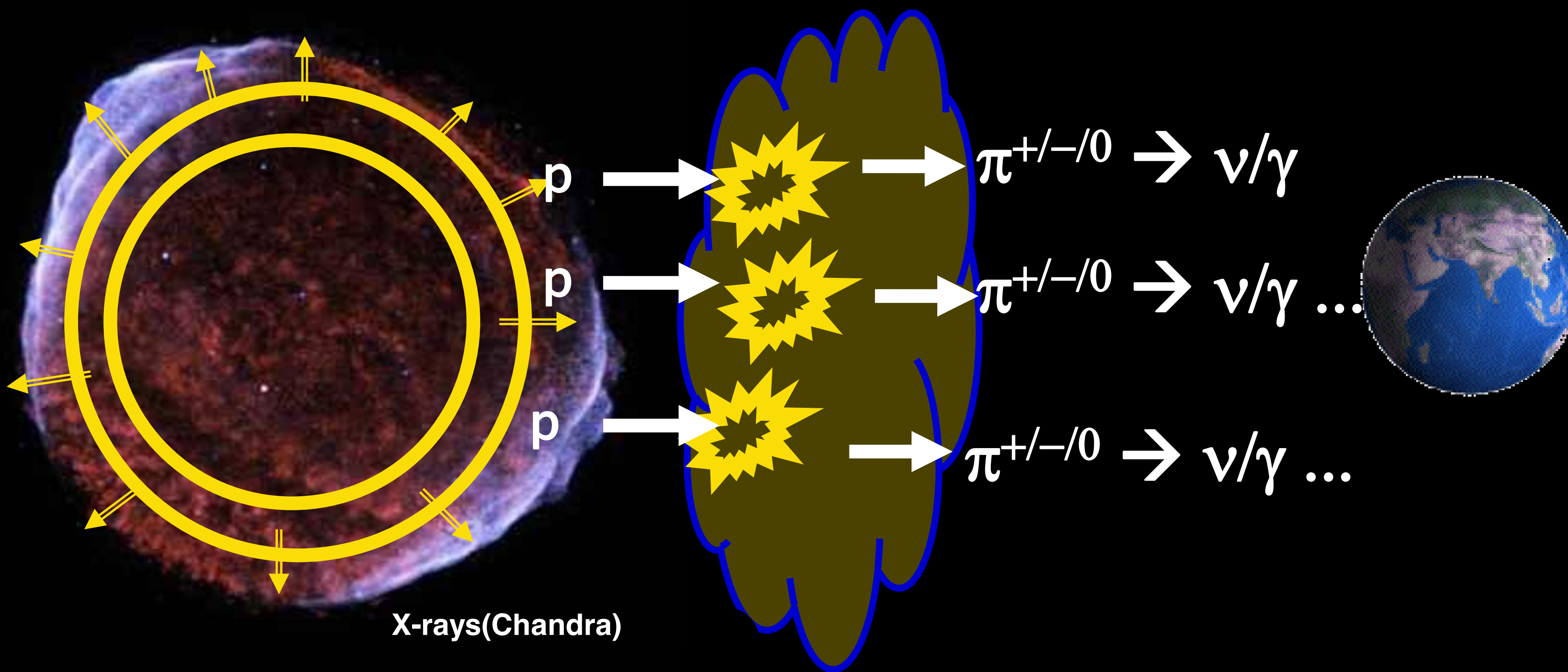
1.) CR acceleration 2.) CR interaction 3.) Detection



$dN_{CR}/dE_{CR} \sim E_{CR}^{-p}$ $dN_{\nu/\gamma}/dE_{\nu/\gamma} \sim E_{\nu/\gamma}^{-p}$

$E_{max} \sim 10^{15-17}$eV $E_{max} \sim 10^{14-16}$eV

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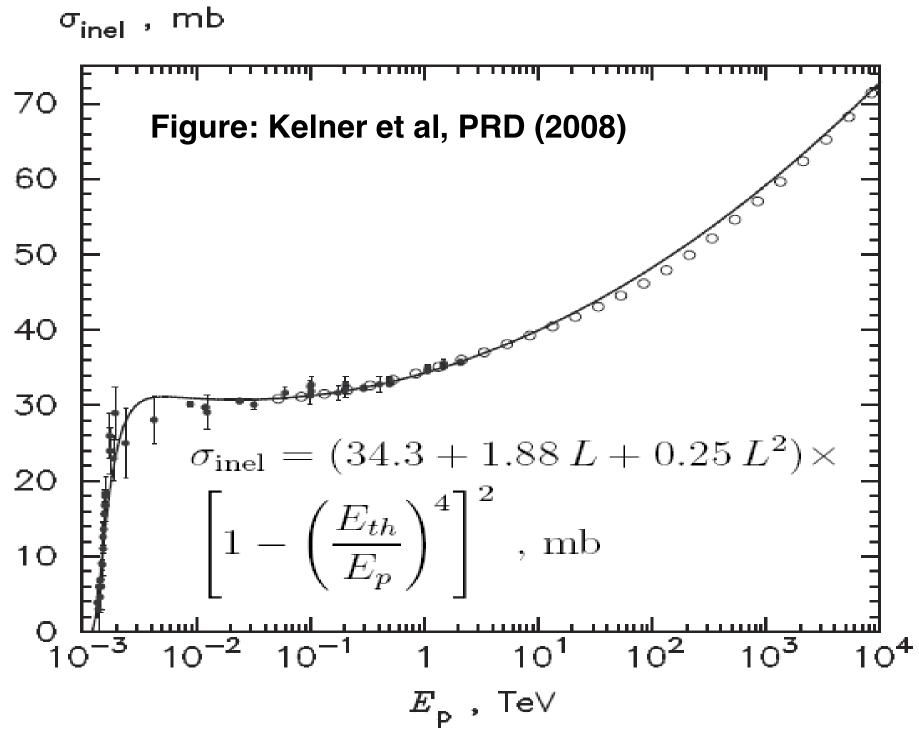
Dominant interaction process

$p\,p \rightarrow \#(\pi^{+/-/0})/(K)$

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

$\pi^0 \rightarrow \gamma\gamma$ (E~TeV)



Sources:
available information from observations

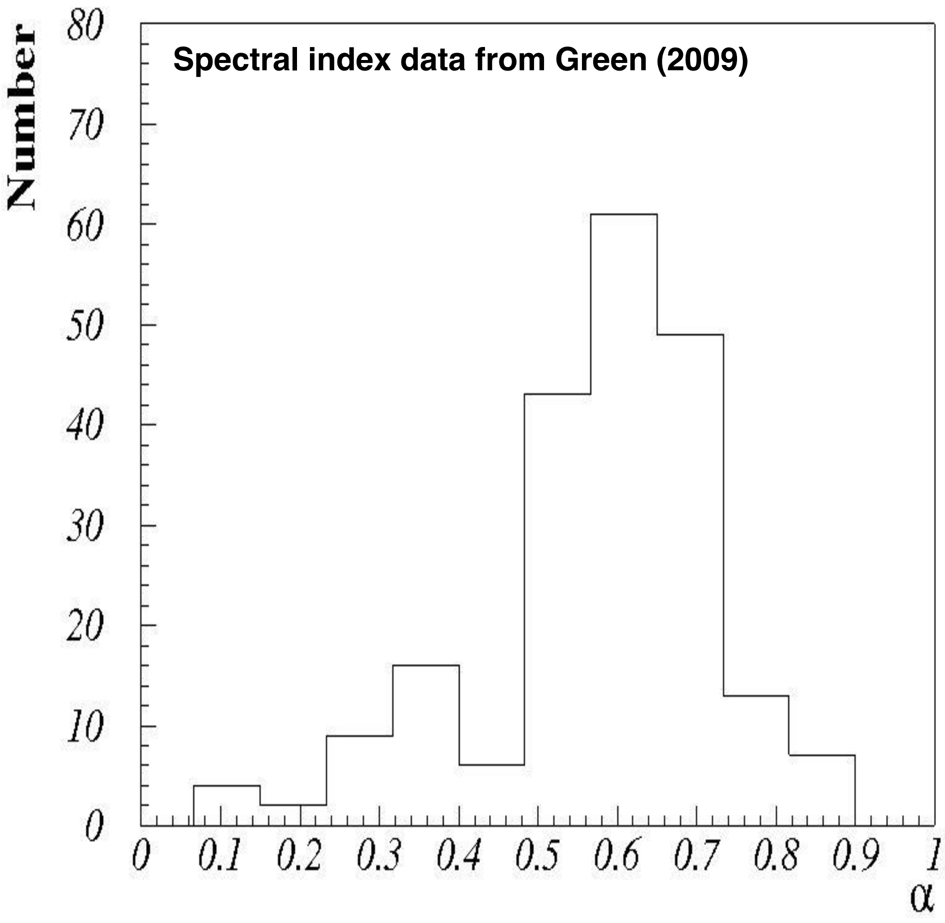
- **Radio observations → sources of non-thermal electrons**
  - *Difficulty:* losses through synchrotron radiation change spectral behavior, dependent on B-field at the sources.
  - Signal can be influenced by other processes

- **Gamma-ray radiation → hadronic sources**
  - GeV – TeV radiation
  - *Difficulty:* Other radiation processes (IC/bremsstrahlung)

- **Molecular ions: lines**
  - Cosmic ray ionization
  - *Difficulty:* CR spectrum at low energies not known

Radio: Synchrotron spectrum as electron spectrum tracer

- Details of spectral behavior complex
- Distribution of SNR radio spectral indices, $S_\nu \sim \nu^{-\alpha}$
- **$p = 2^*\alpha+1$, $dN/dE \sim E^{-p}$**
- Green's catalog:
- **$<\alpha> \sim 0.6$ ➔ $<p_e> \sim 2.2$**
- Same true for protons?



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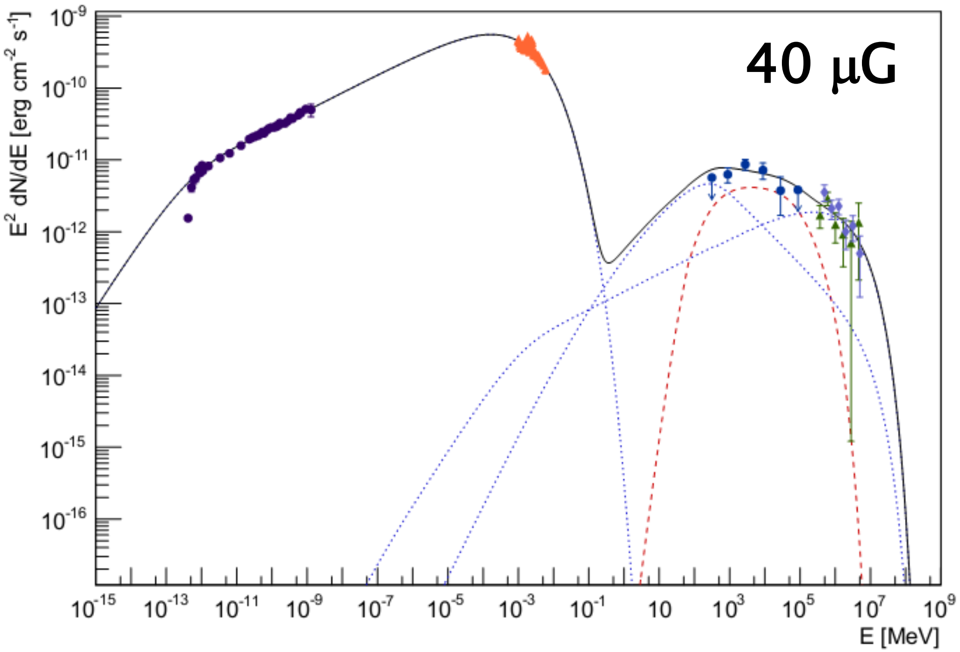
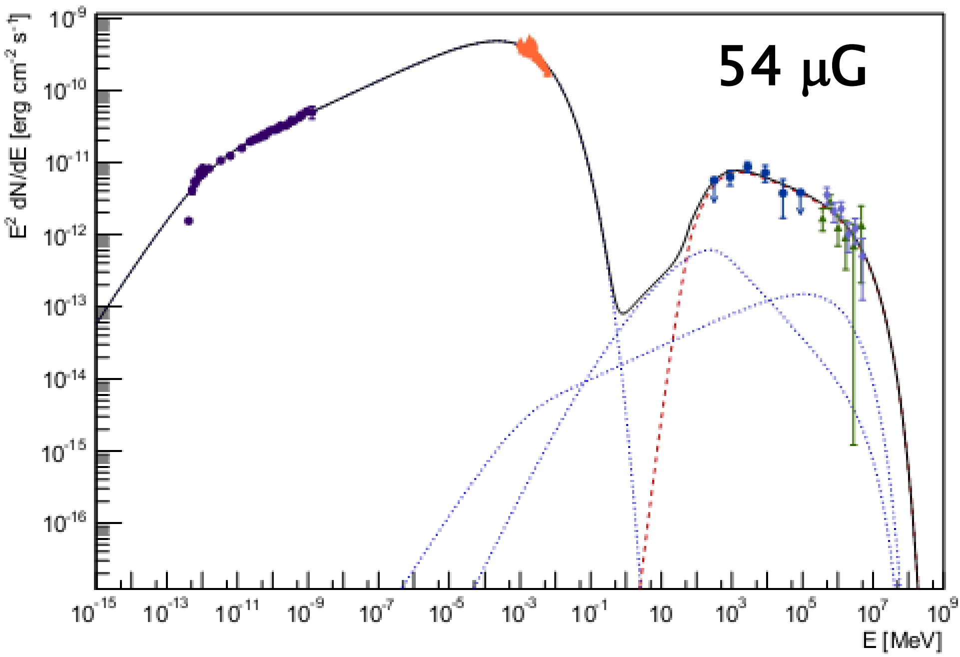
Example: CasA
IC + brems + π0

- **Brems + IC** works with current data
- **π0** works as well
- → discrimination of models:
    - high-energy cutoff (hadronic models > IC)
    - Low-energy cutoff (hadronic models > brems)
- → extension of detected energy range will help to distinguish models (→CTA/HAWC)

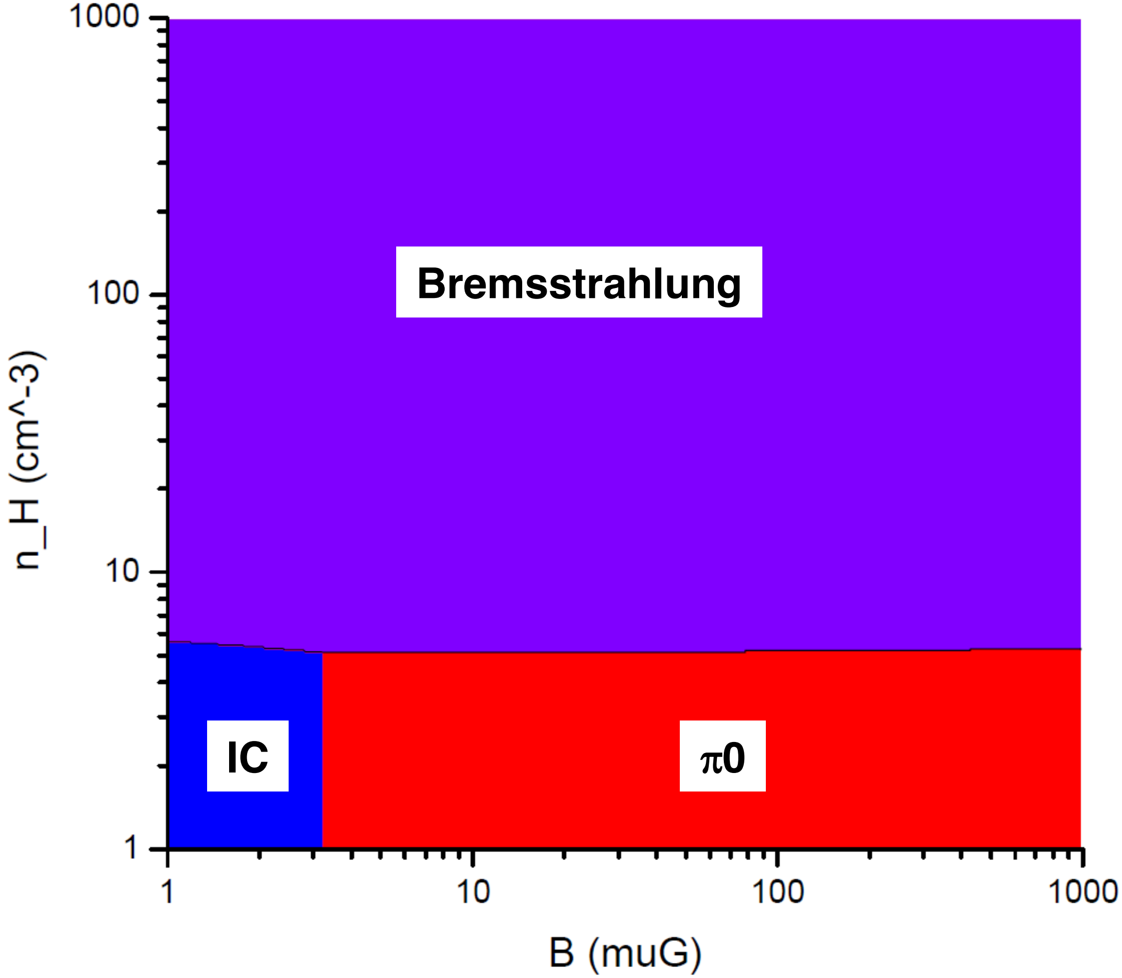




Figs from Mandelartz & Becker Tjus, Astrop.Phys. (2015)

Brems – IC – π^0

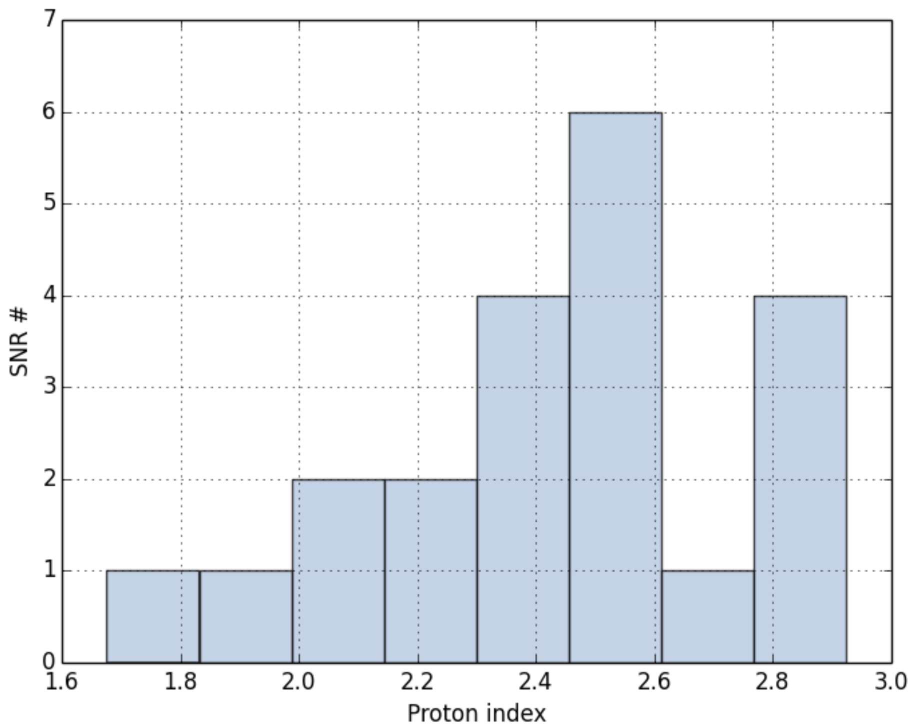
- Simplified example,
- Assumptions:
  - same number of particles accelerated
  - same injection spectrum (E^{-2})
  - fixed synchrotron spectrum

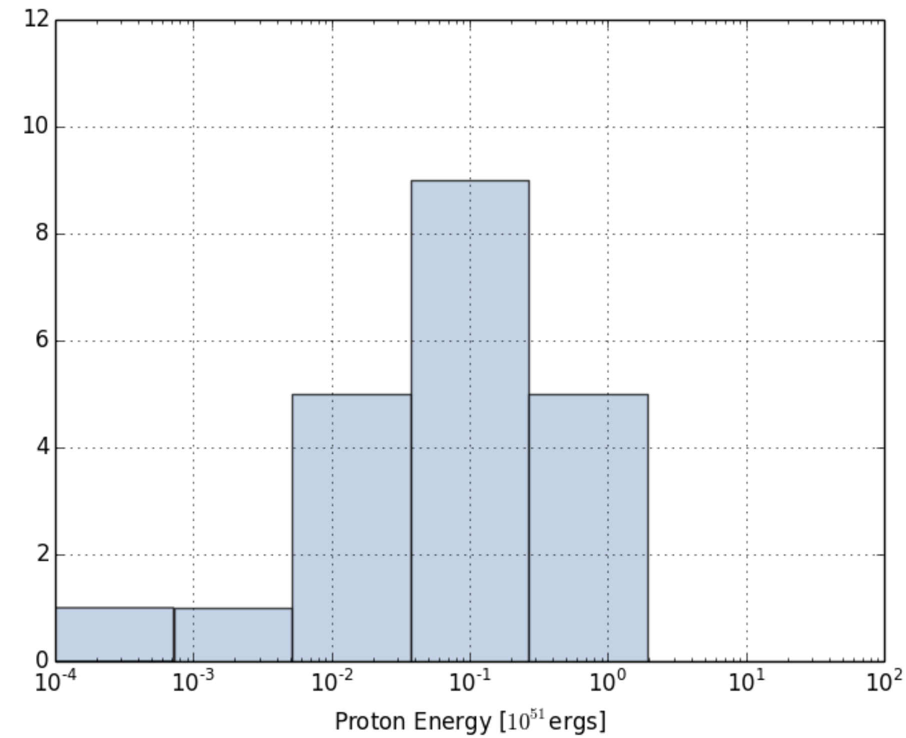


Mandelartz & Becker Tjus, Astrop. Phys. (2015)

24 γ-ray spectra – derivation of maximum contribution from protons

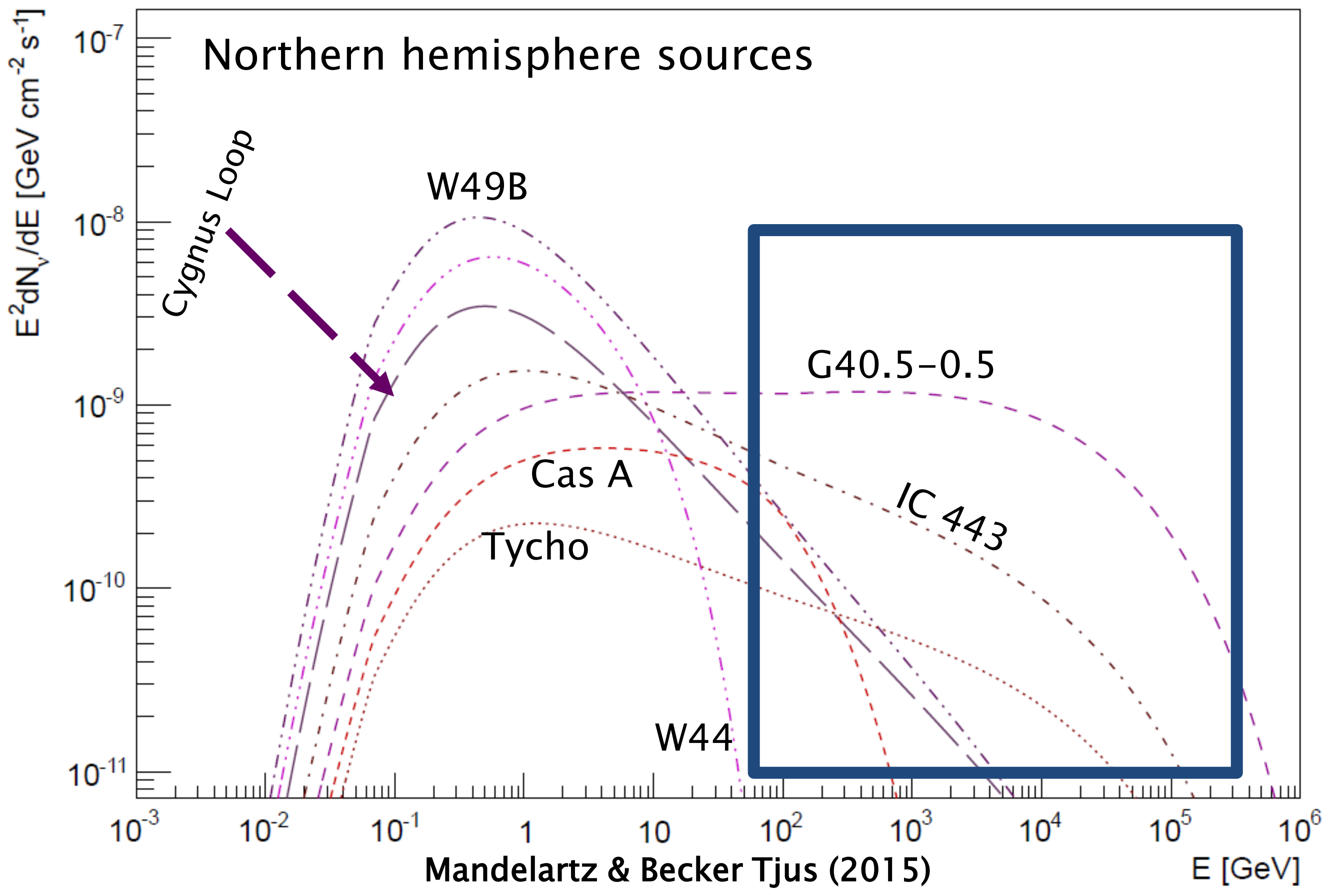
- 21 out of 24 possible to fit hadronically





Figs from Mandelartz & Becker Tjus, Astrop. Phys. (2015)

SNRs:Neutrino emission



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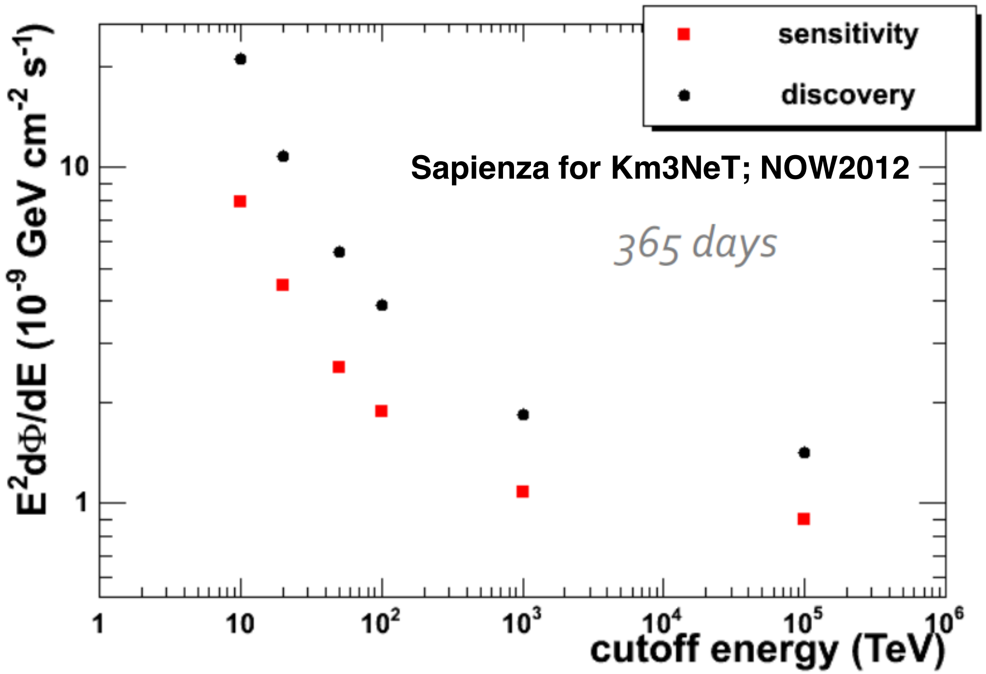
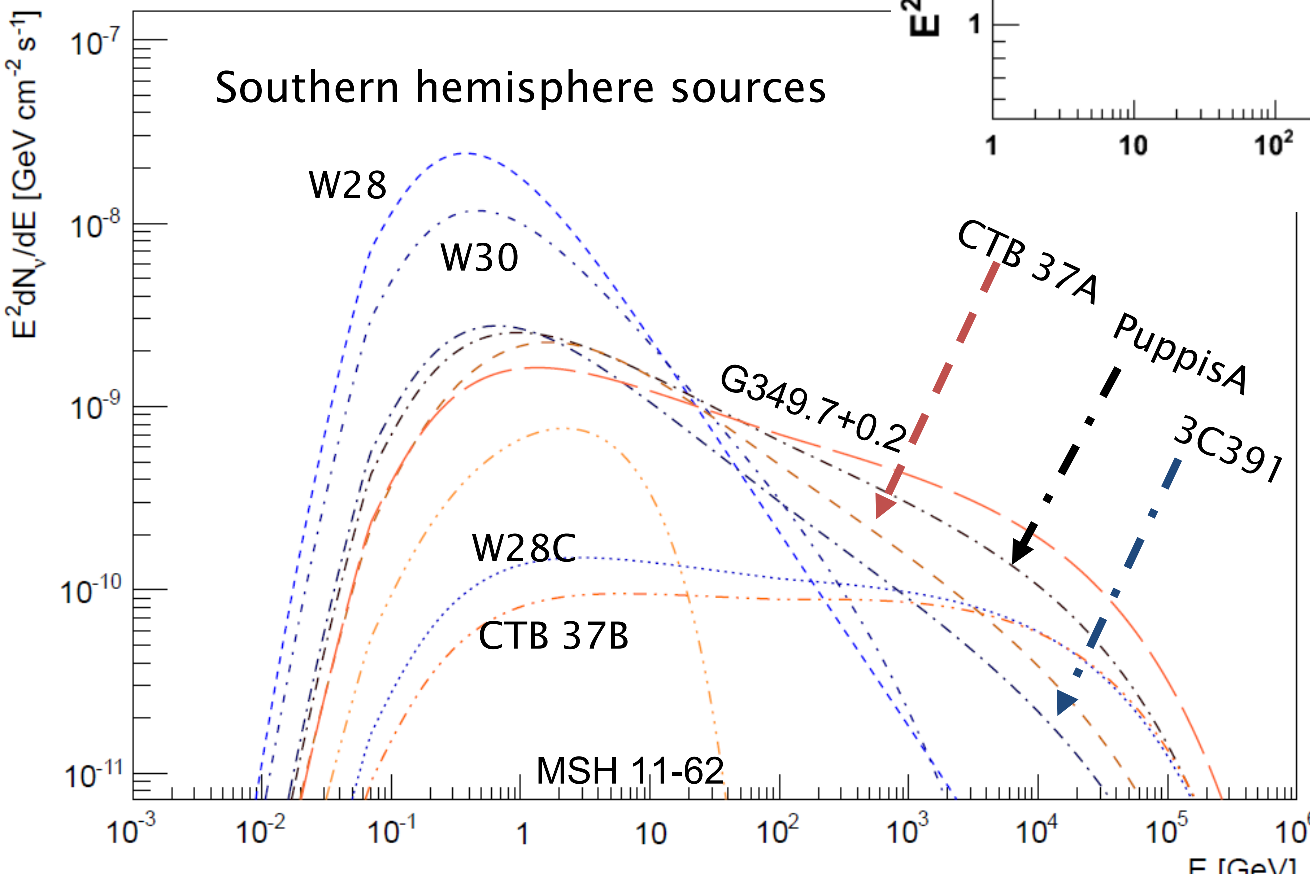
Neutrino emission from SNRs





Mandelartz & Becker Tjus, Astrop. Phys. (2015)

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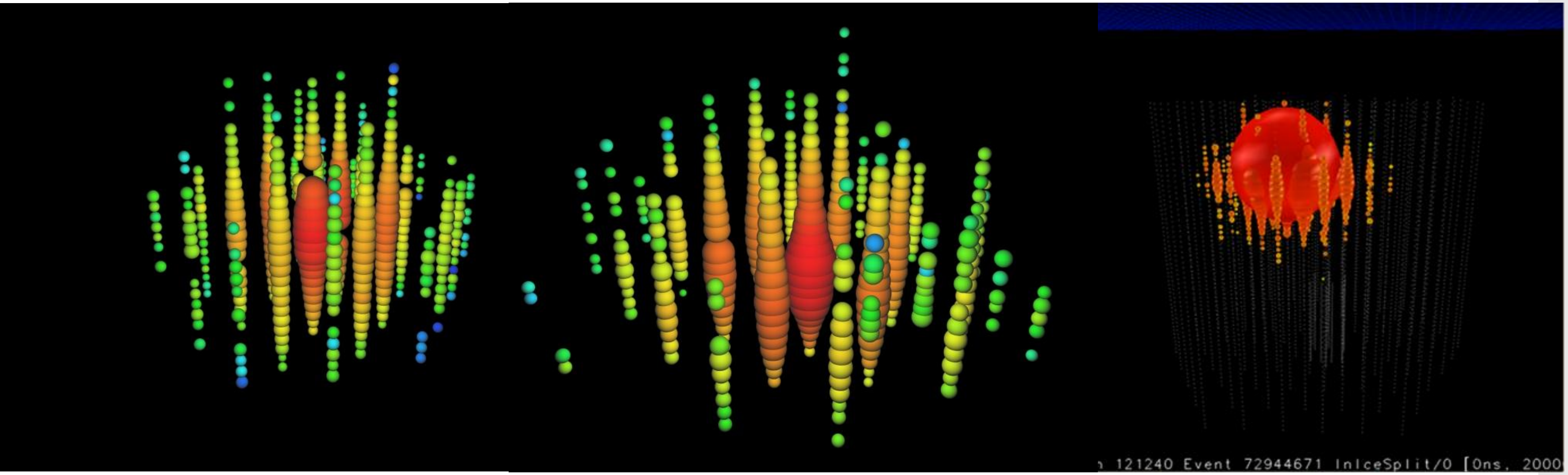
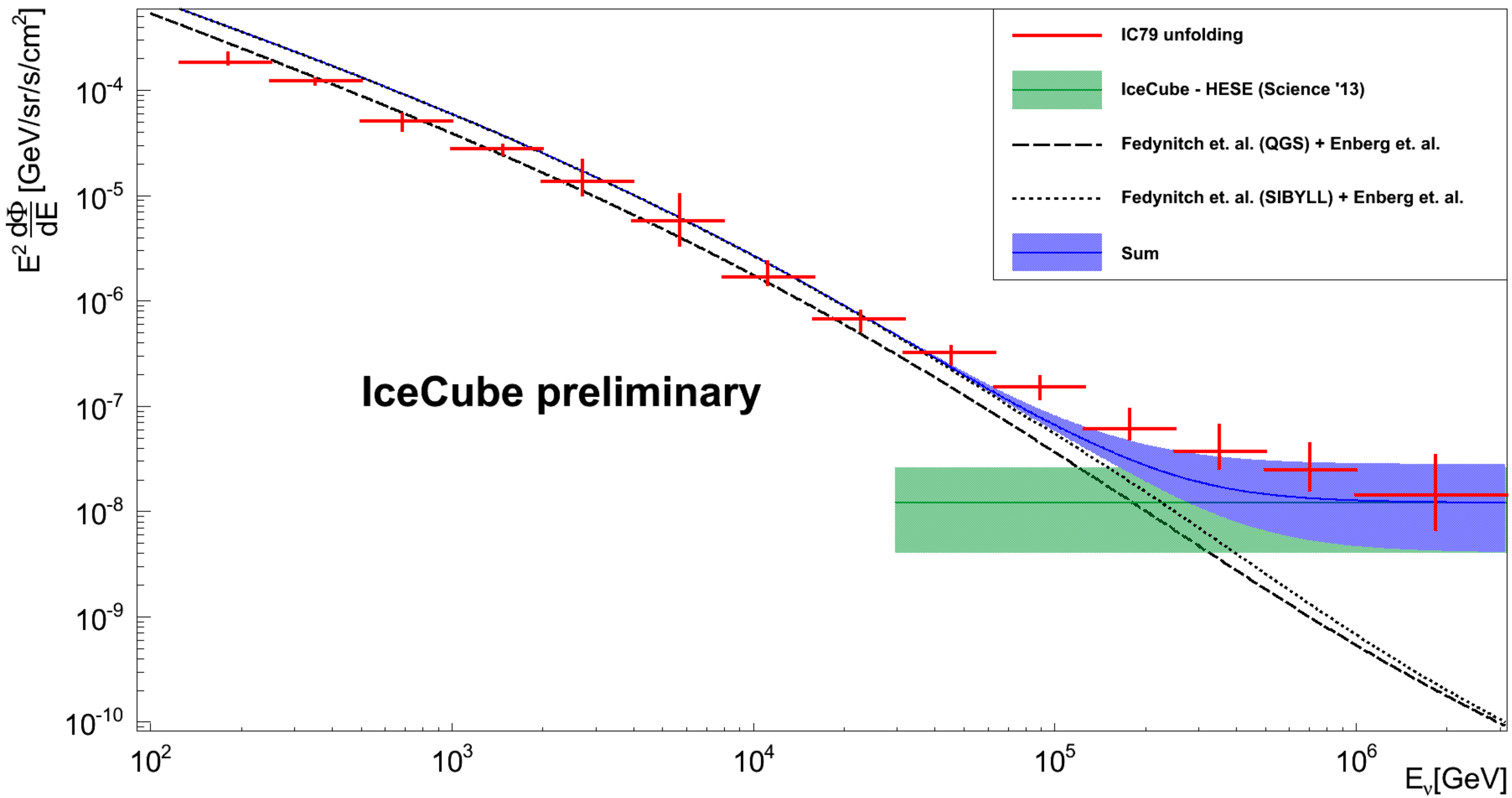
IceCube: first detection of astrophysical high-energy neutrinos

- Neutrino energy range ~ 10 TeV to > 2 PeV
- ➔ cosmic ray energy range covered: ~ 200 TeV to > 40 PeV
- ➔ transition region knee to ankle: mix of Galactic and extragalactic sources expected



Aartsen et al (IceCube Coll), Science, Nov 2013
Aartsen et al (IceCube Coll), PRL 2014

Energy spectrum up to PeV energies



Florian Scheriau, Wolfgang Rhode et al, for the IceCube Collaboration, ECRS 2014

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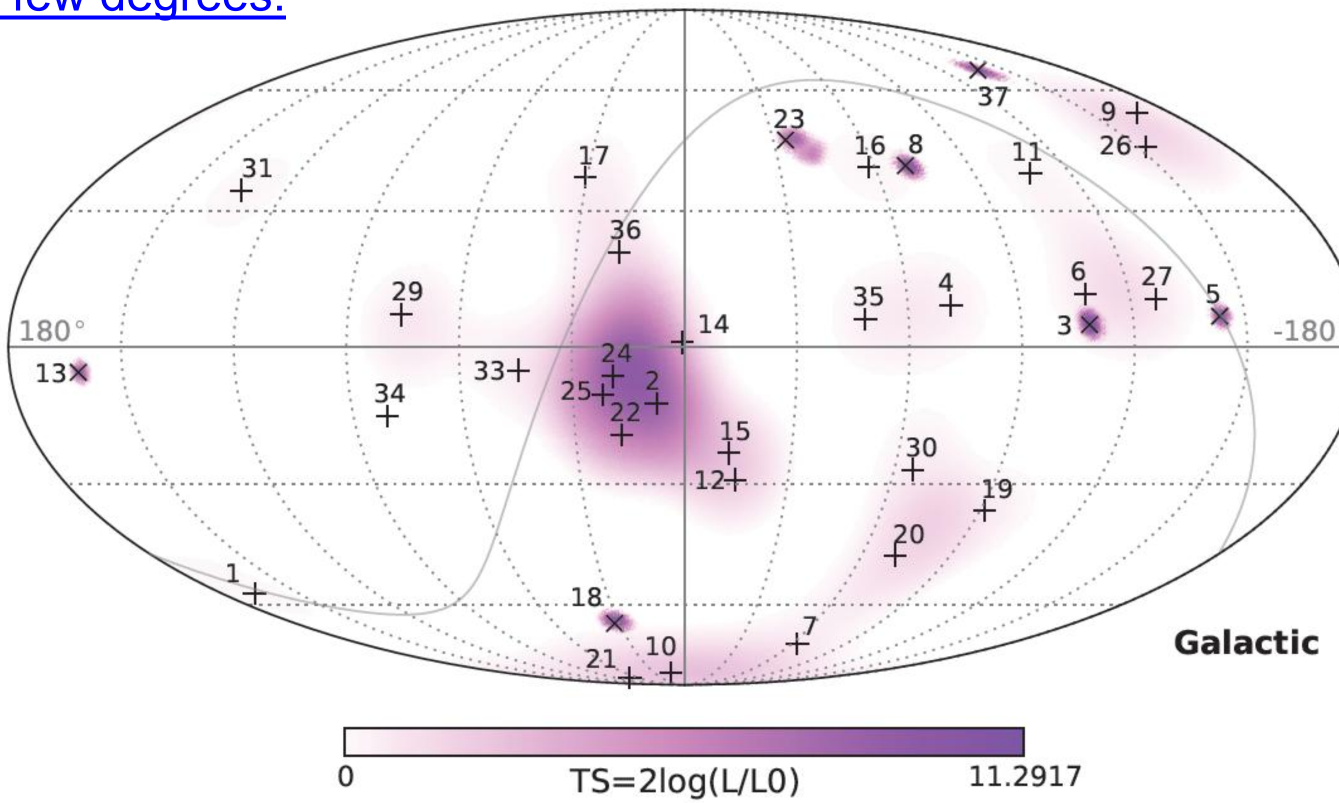
No significant clustering in the Galactic Plane

- Temporal evolution of a cascade can be used to get to resolutions of a few degrees:



Aartsen et al (IceCube Coll), Science, Nov 2013
Aartsen et al (IceCube Coll), PRL 2014

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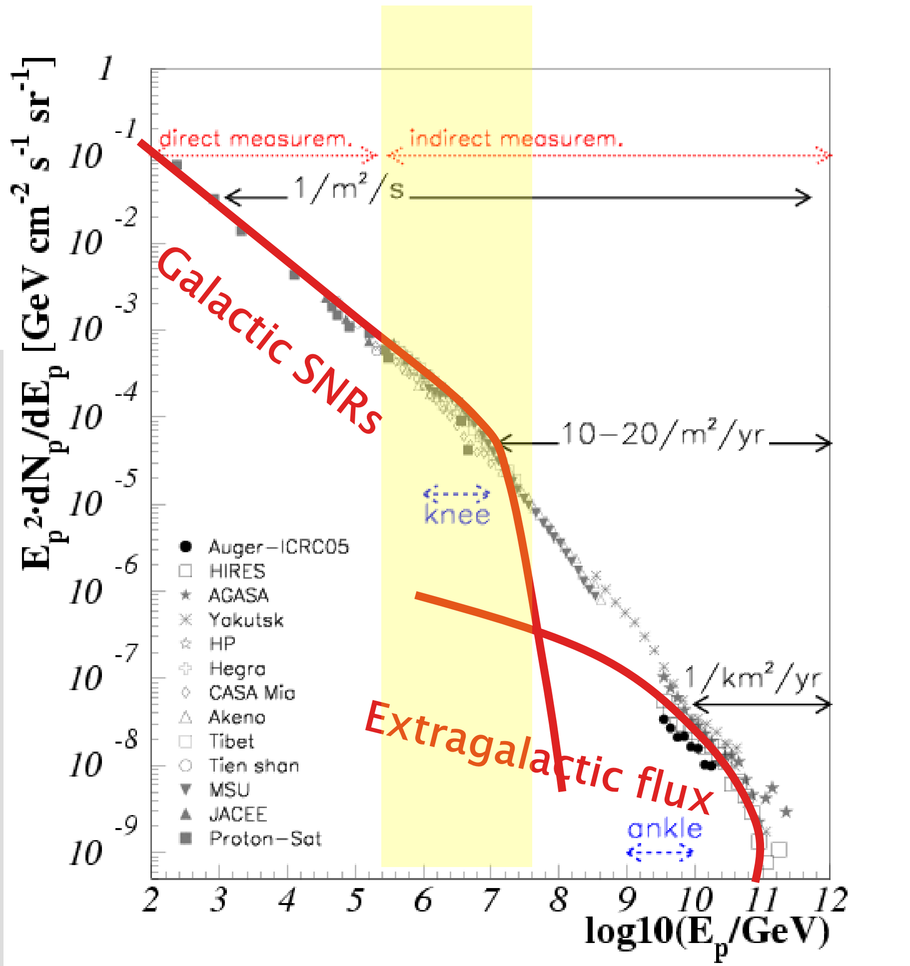
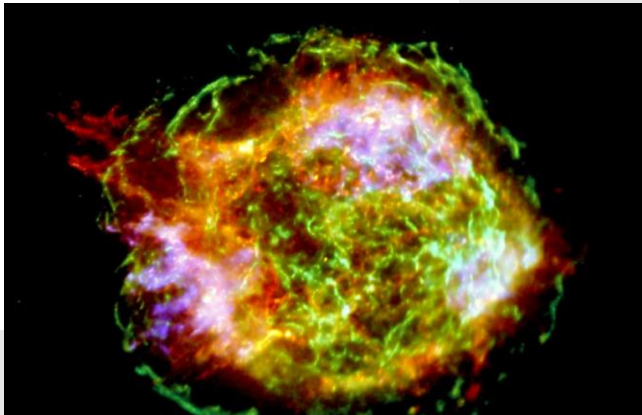
Galactic origin ν signal?
Supernova remnants

- **Astrophysical signal of strength:** $E^2*dN_\nu/dE_\nu \sim 10^{-8}$ GeV s^{-1} cm^{-2} sr^{-1}
  - **Too strong**
- **Spectral behavior ~ E^-2.3:**
  - **ok**
  - **Cutoff needed!**
- **Spatial Clustering?: isotropic**
  - **would expect clustering in the Galactic plane**
- **Temporal Clustering?:** no
  - **not expected**





Prediction: Neutrinos from Galactic sources

Conclusions from basically all papers: MAX 1-2 events per year contributing to „HESE" results (→ max 10%-20%)

- **Unidentified γ-ray sources: max 2 events**
  - **Fox, Kashiyama, Meszaros ApJ (2013)**
  - **Neronov, PRD (2013)**
  - **Razzaque, PRD (2013)**
- **CR interactions: <<1event**
  - **Joshi, Winter & Gupta, MNRAS (2014)**
- **Well-identified γ-ray SNRs: <<1event**
  - **Becker Tjus & Mandelartz Astrop. Phys. (2014)**

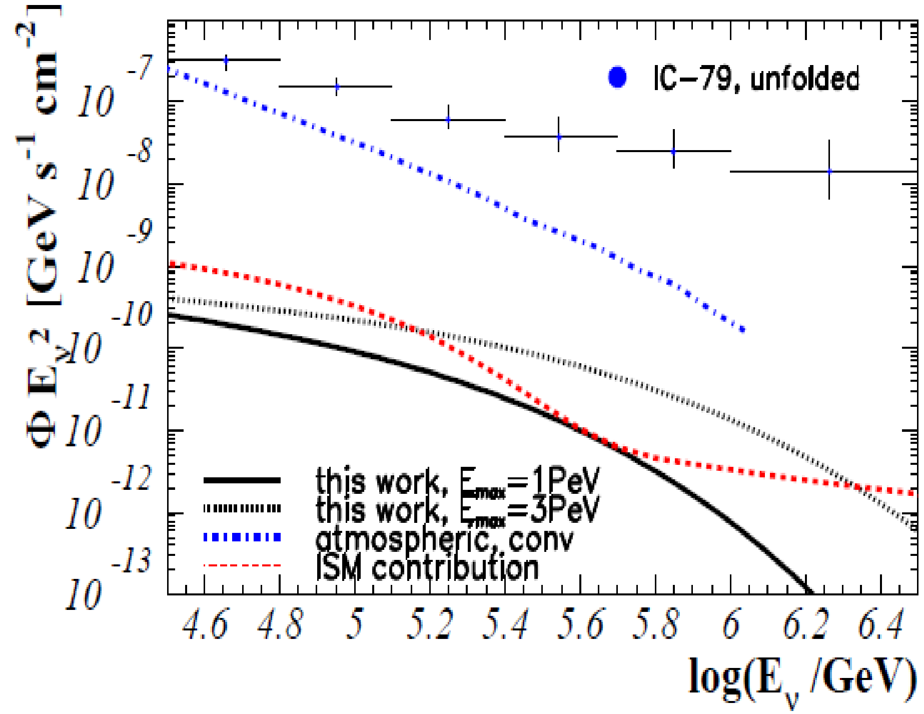


Fig: Mandelartz & Becker Tjus, Astrop.Phys (2015)
ISM-νs: Joshi, Winter & Gupta, MNRAS (2014)

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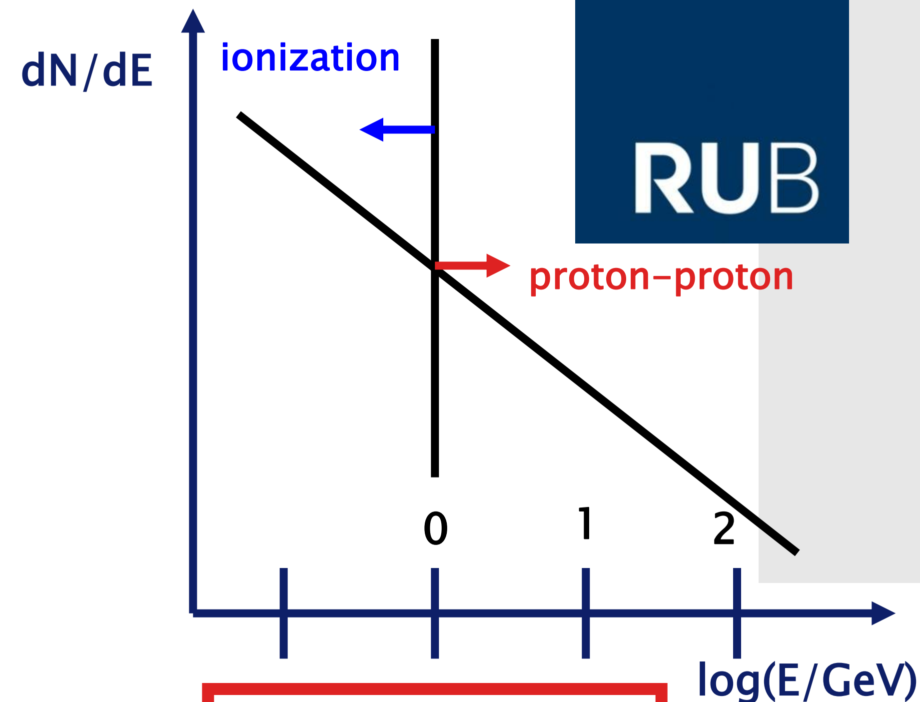
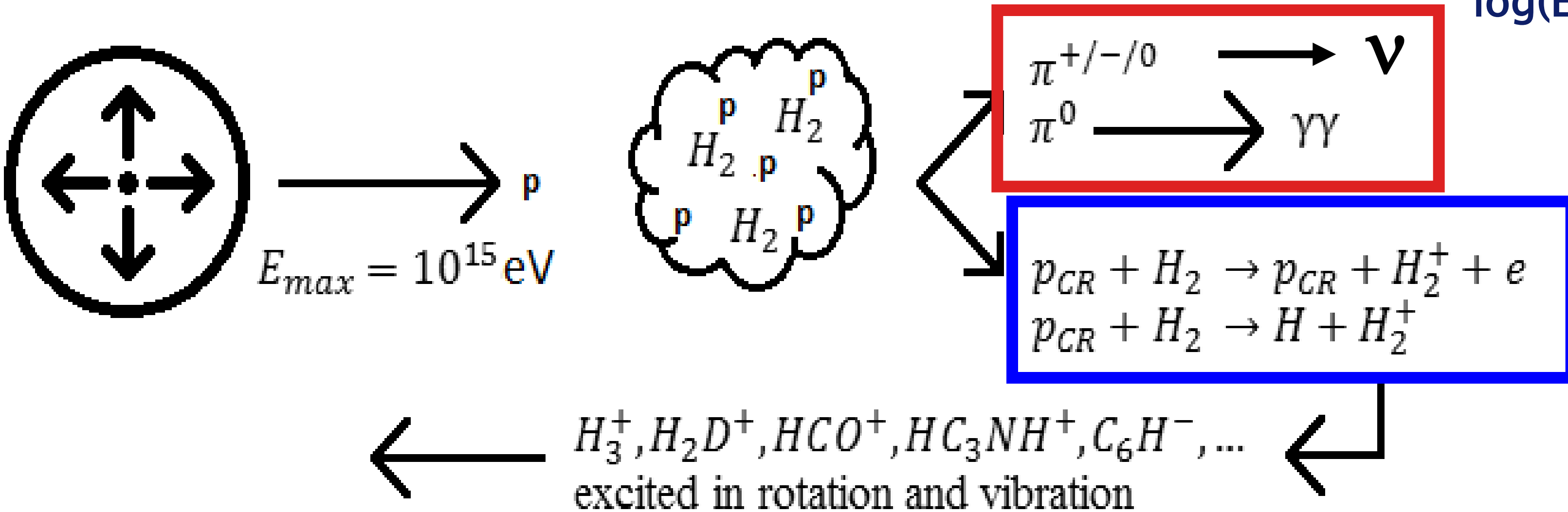
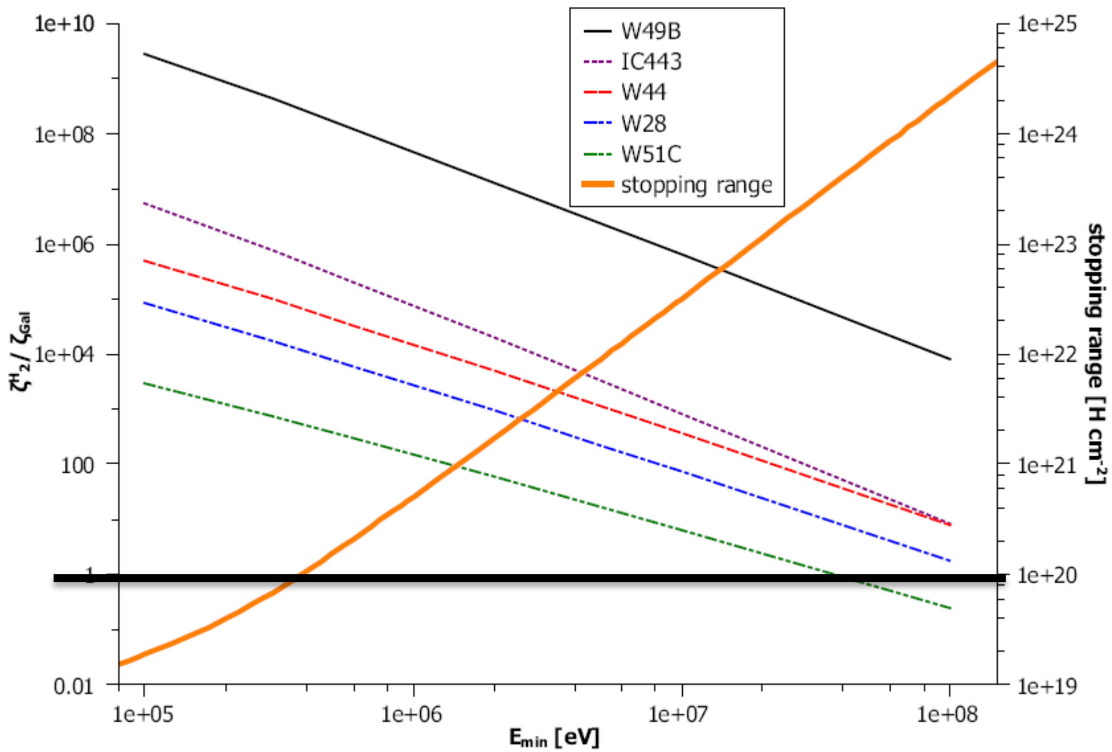
Low-energy signatures from cosmic ray interactions

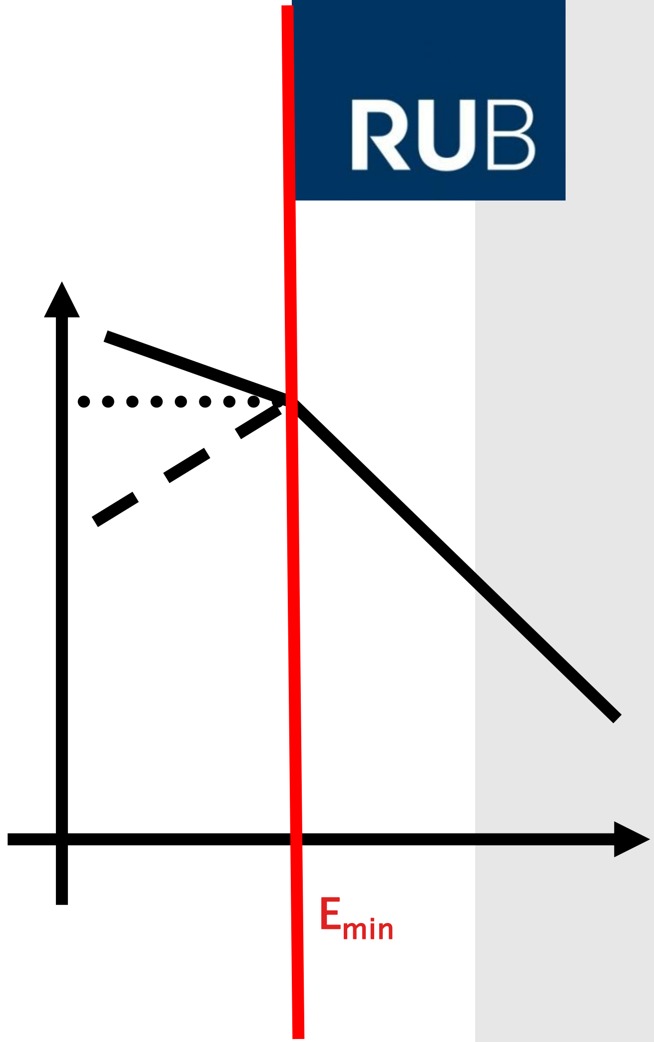




Signatures: gamma-rays; neutrinos; ionization-induced molecules

Ionization rates for five SNRs





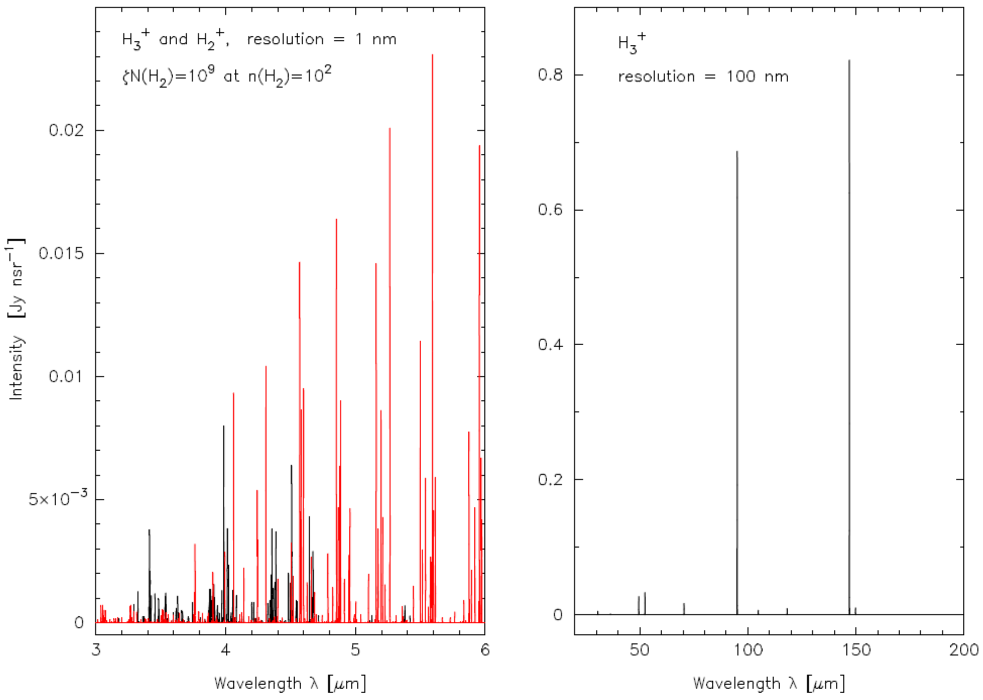
(Careful: dependence on extrapolation towards low energies increases with decreasing Emin)

Still → Expectations even for large Emin can be far above Galactic average

Becker, Black, Safarzadeh & Schuppan, ApJL (2011)
Schuppan, Becker, Black, Casanova, ApJ (2012)

Molecule spectra at SNR: H_2^+ and H_3^+

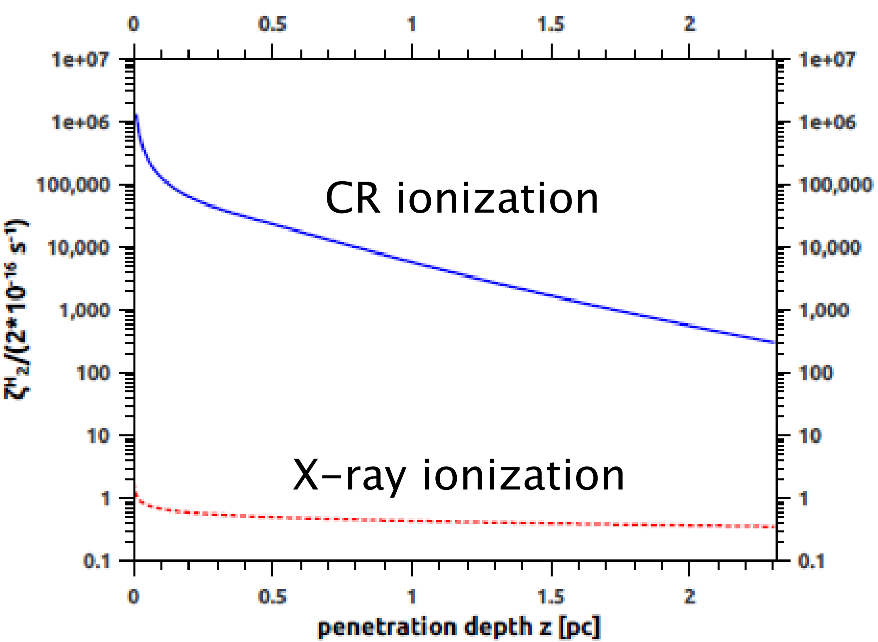
- First prediction of an observable **H_2^+ spectrum**
- **H_3^+** simplest **tracer of ionization** rate (Herschel etc, see papers by Indriolo et al)
- Coincident observations with significant spatial resolution → **submm arrays + IACTs**



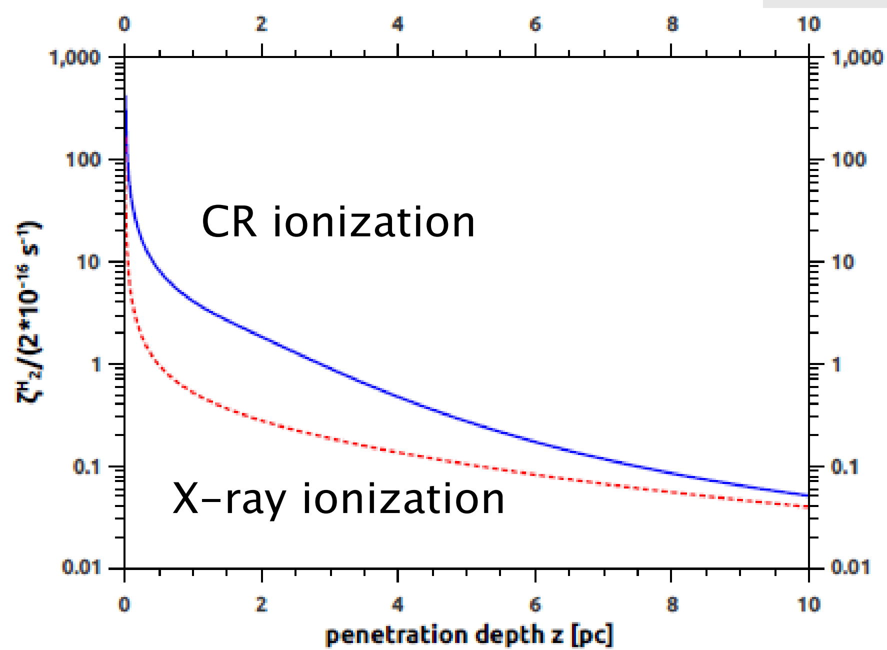
Becker, Black, Safarzadeh & Schuppan, ApJL (2011)
Schuppan, Becker, Black, Casanova, ApJ (2012)

Radial profiles

- Examples W49 and W44



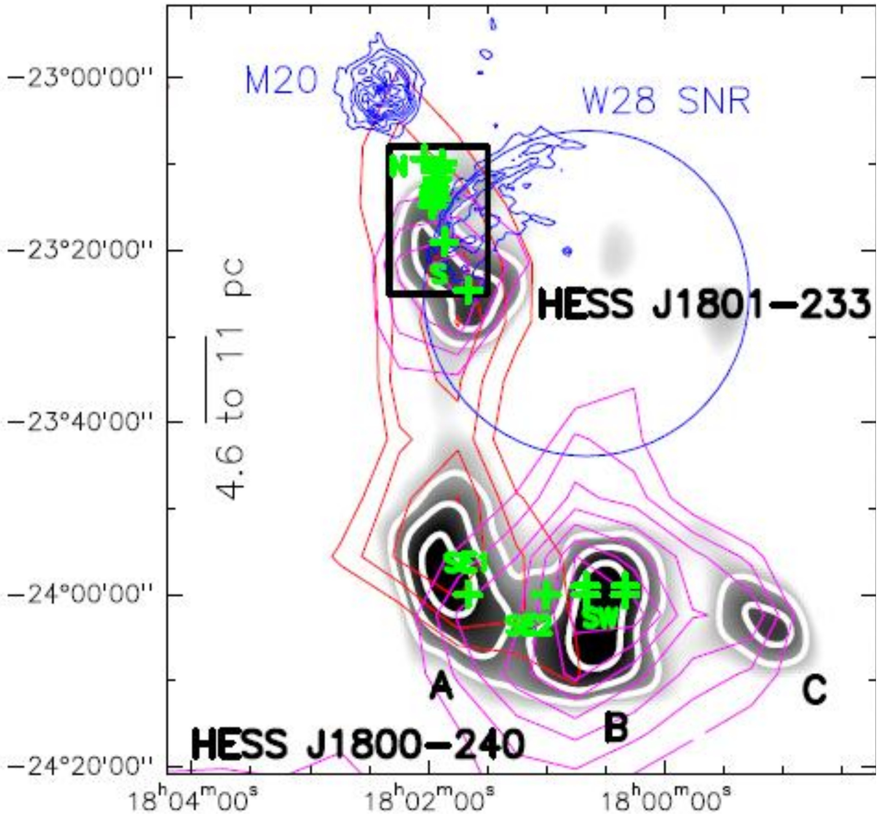
(a)



(b)

Schuppan, Röken, Becker Tjus, A&A (2014)

γ-rays & molecular ions: W28



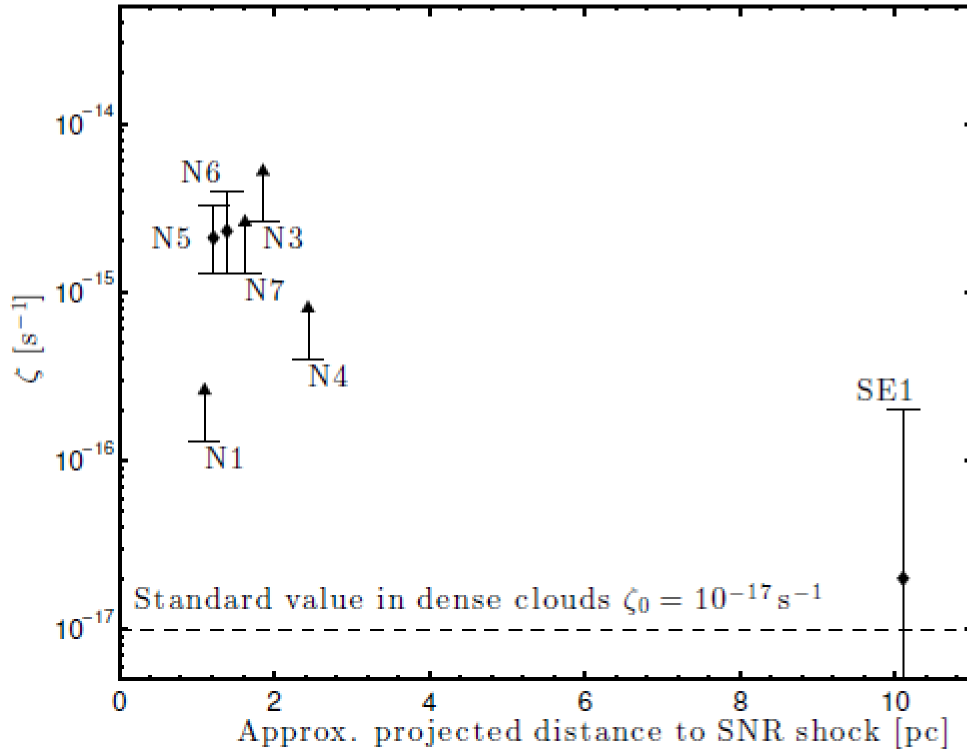
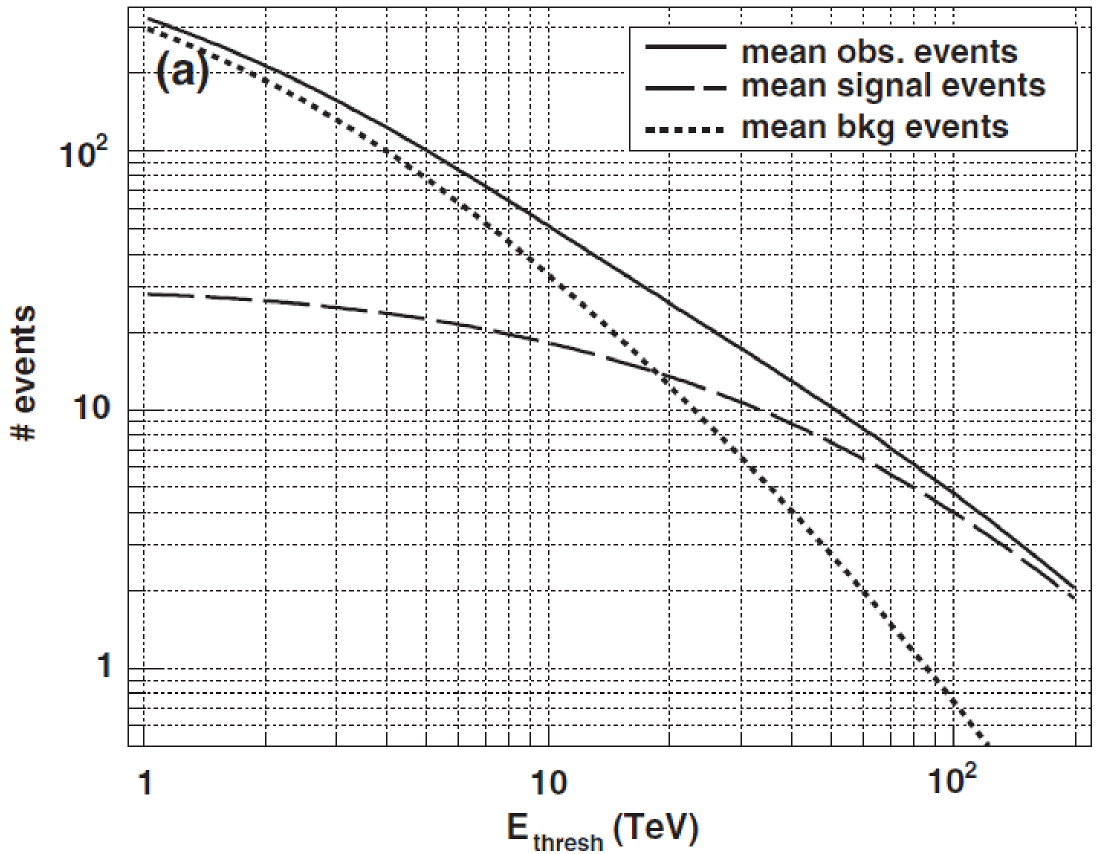


Fig. 7. CR ionisation rate ζ as a function of the approximat projected distance from the SNR radio boundary (blue circle i Fig. 1), assuming a W28 distance of 2 pkc. We note that the error bars are dominated by the uncertainties on the H_2 densitie (see text).

(Careful → Derived from CO/HCO+/DCO+: more parameter dependent than H_3^+)

Vaupré et al, A&A (2014)

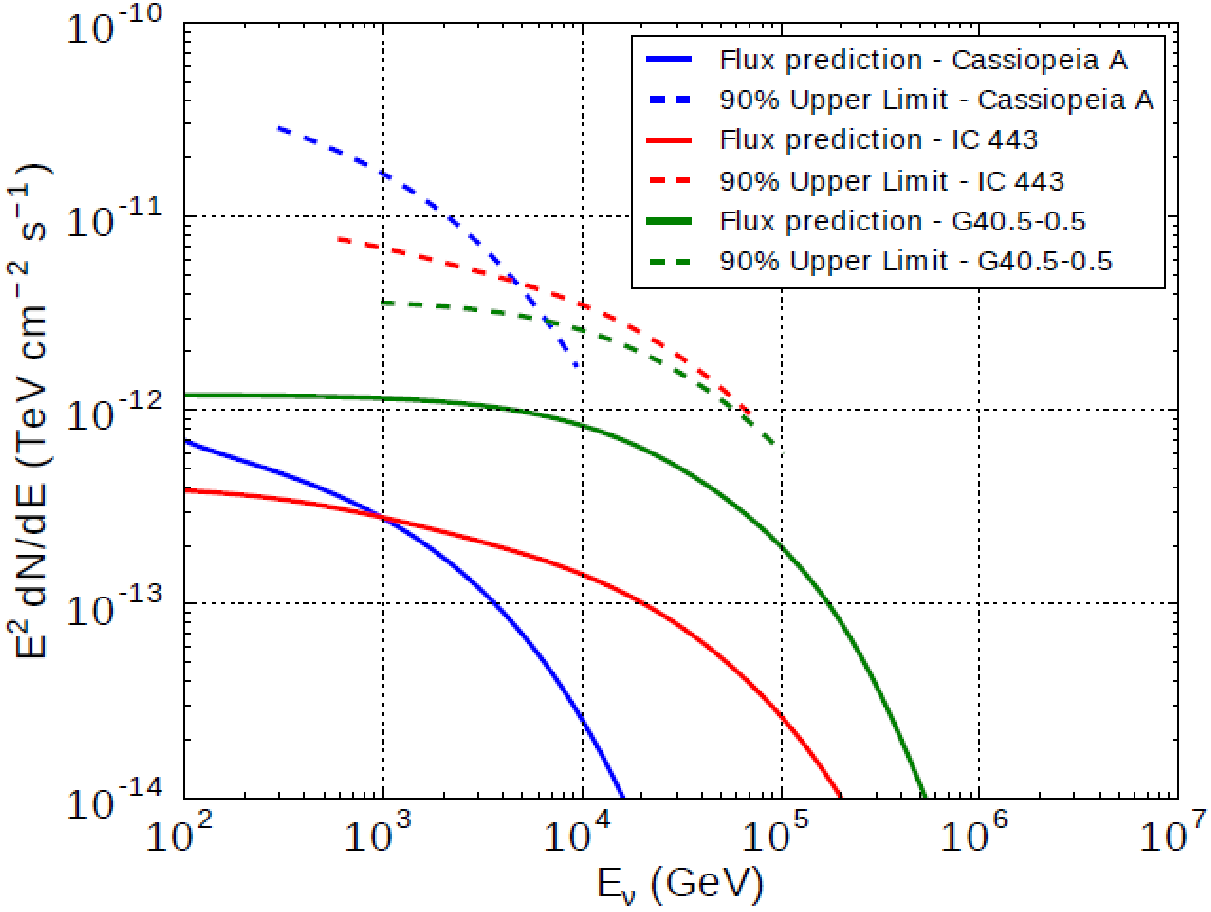
SNRs: Expected number of ν_μ-induced events



PeVatrons should be visible within IceCube lifetime for E^{-2} spectrum, BUT:

Halzen, Kappes, Ó Murchadha, PRD (2008)

Best-case SNRs in IceCube: 4 years of data



IceCube, ApJ (2014)

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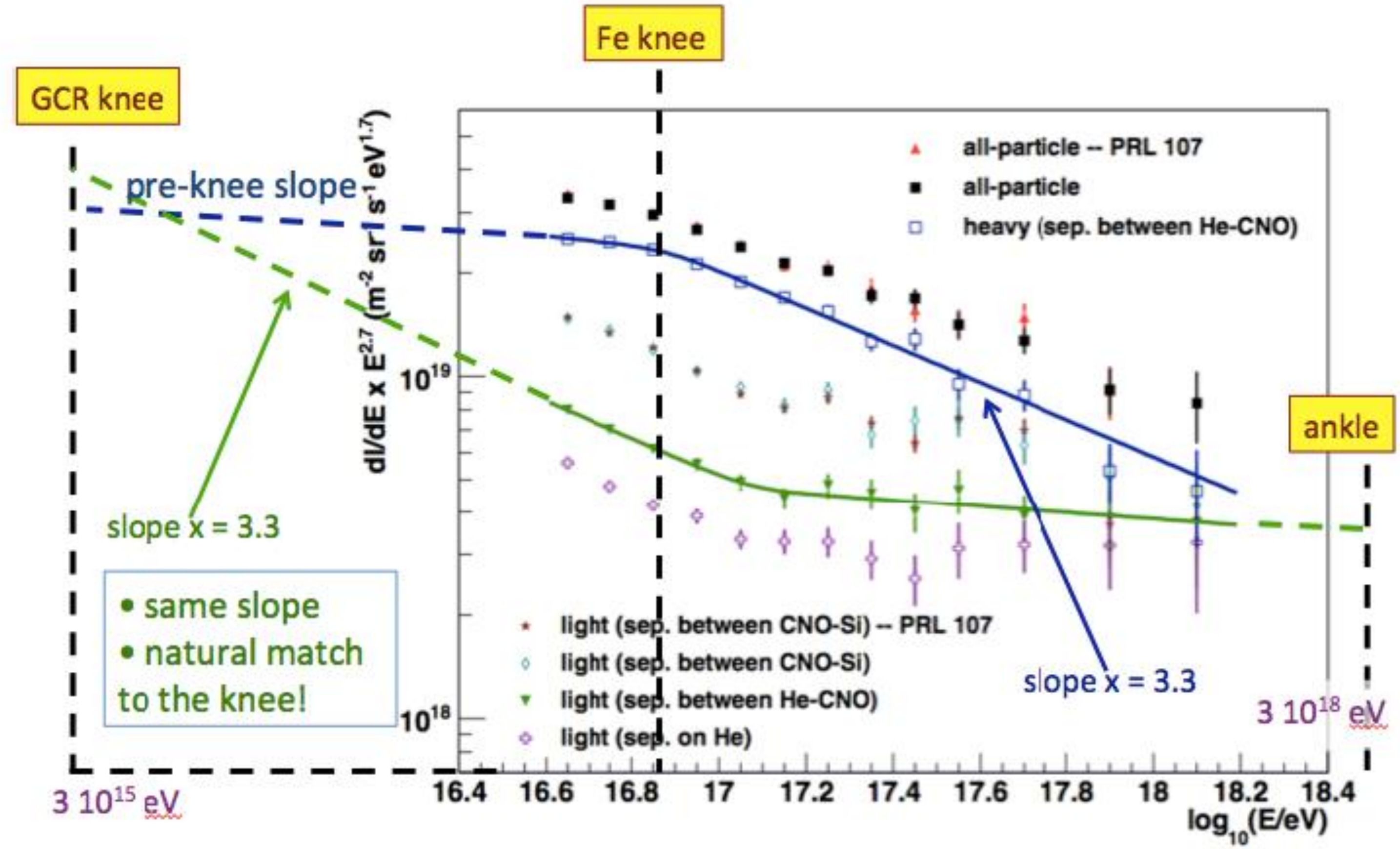
- **Summary**

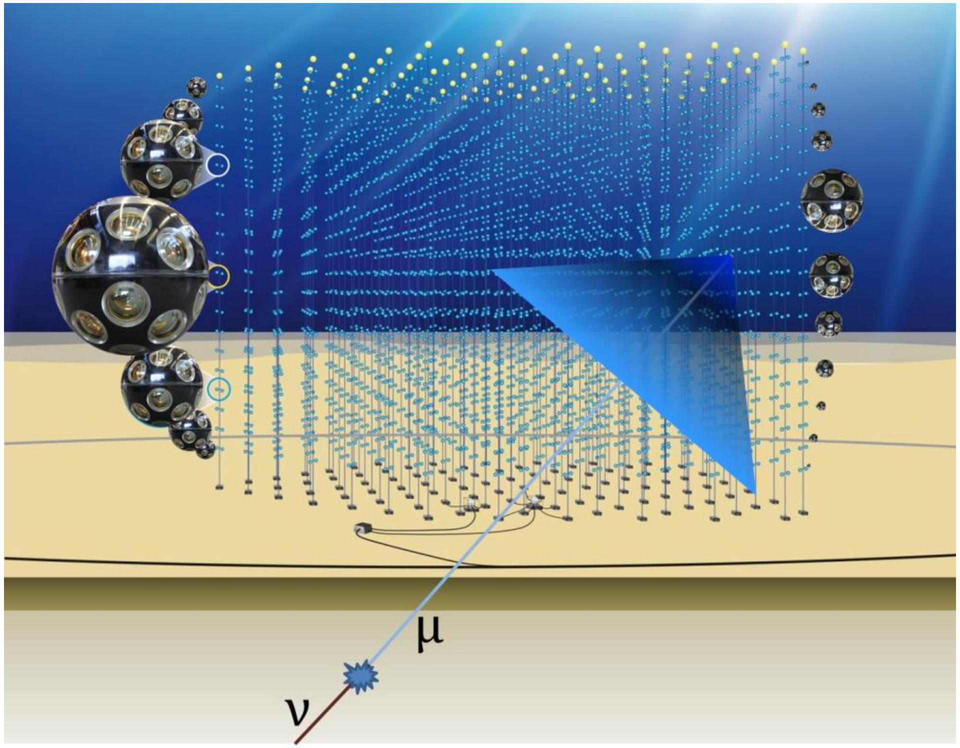
Composition in knee-to-ankle region

(see talks Pasquale Blasi; Gwaenel Giacinti)

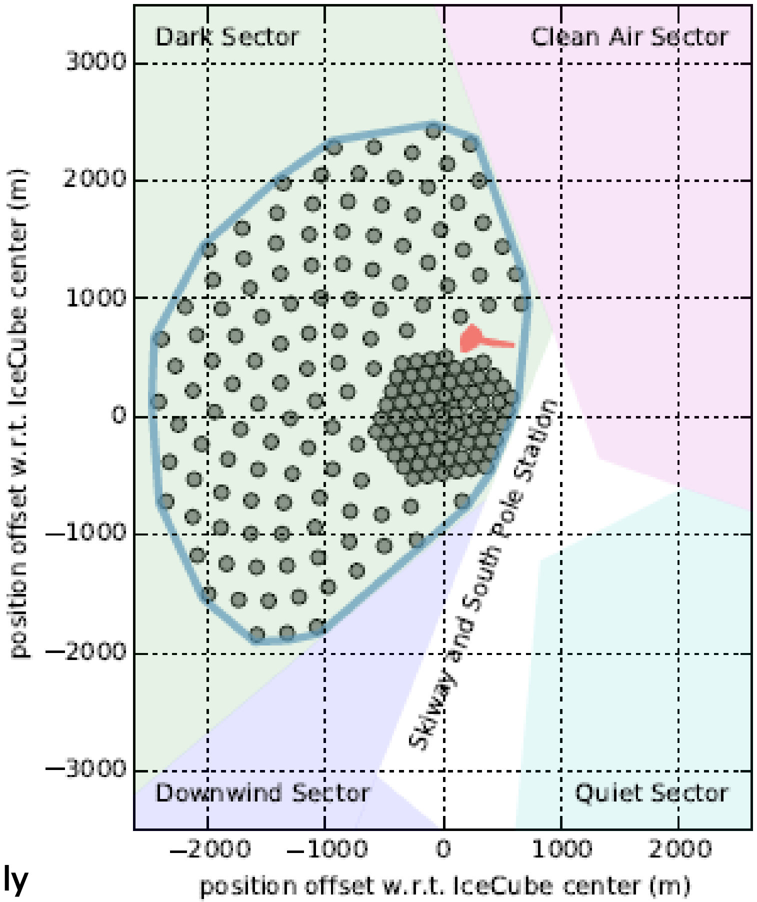


Data: KASCADE-Grande, Astrop.Phys. 2013 & 2014
Fig: E. Parizot, Nucl.Phys.B (2014)

Future: neutrino point sources?! → KM3NeT & IceCube-Gen2



KM3NeT:First test arrays installed off-shore of Toulon and Sicily



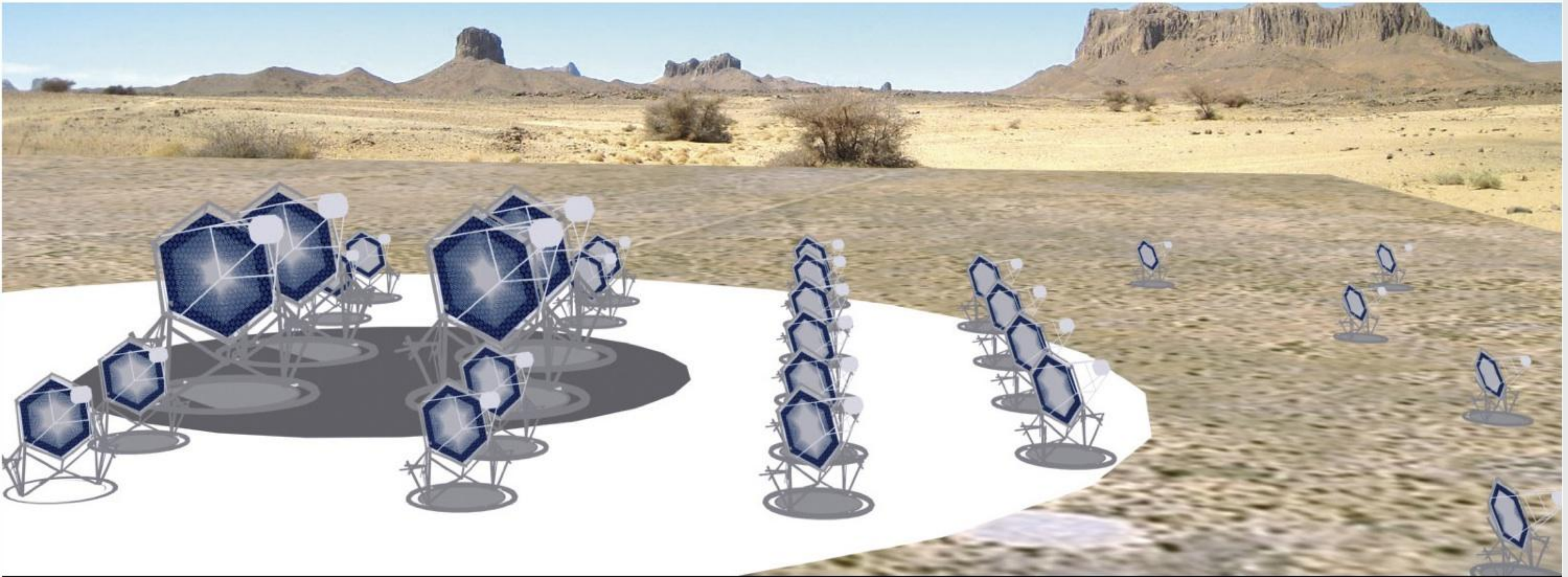
IceCube-Gen2 whitepaper, arXiv:1412.5106

RUB

Cherenkov Telescope Array (CTA)

- Energy range of
  10 GeV < E < 300 TeV →
  Low- and high-energy behavior to distinguish leptonic from hadronic scenarios

- Resolution up to $\theta \sim 0.03°$
  → Exact origin of radiation & improved correlation studies



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The future of multimessenger astroparticle physics

- Charged CRs: GeV – 1e11 GeV including composition
- γ-rays: GeV to >PeV (CR energy equiv.)
- Neutrinos: 100 TeV – 100 (?) PeV (CR energy equiv.)
- **Theory/Phenomenology have to (!) provide tools to connect pieces of information!**

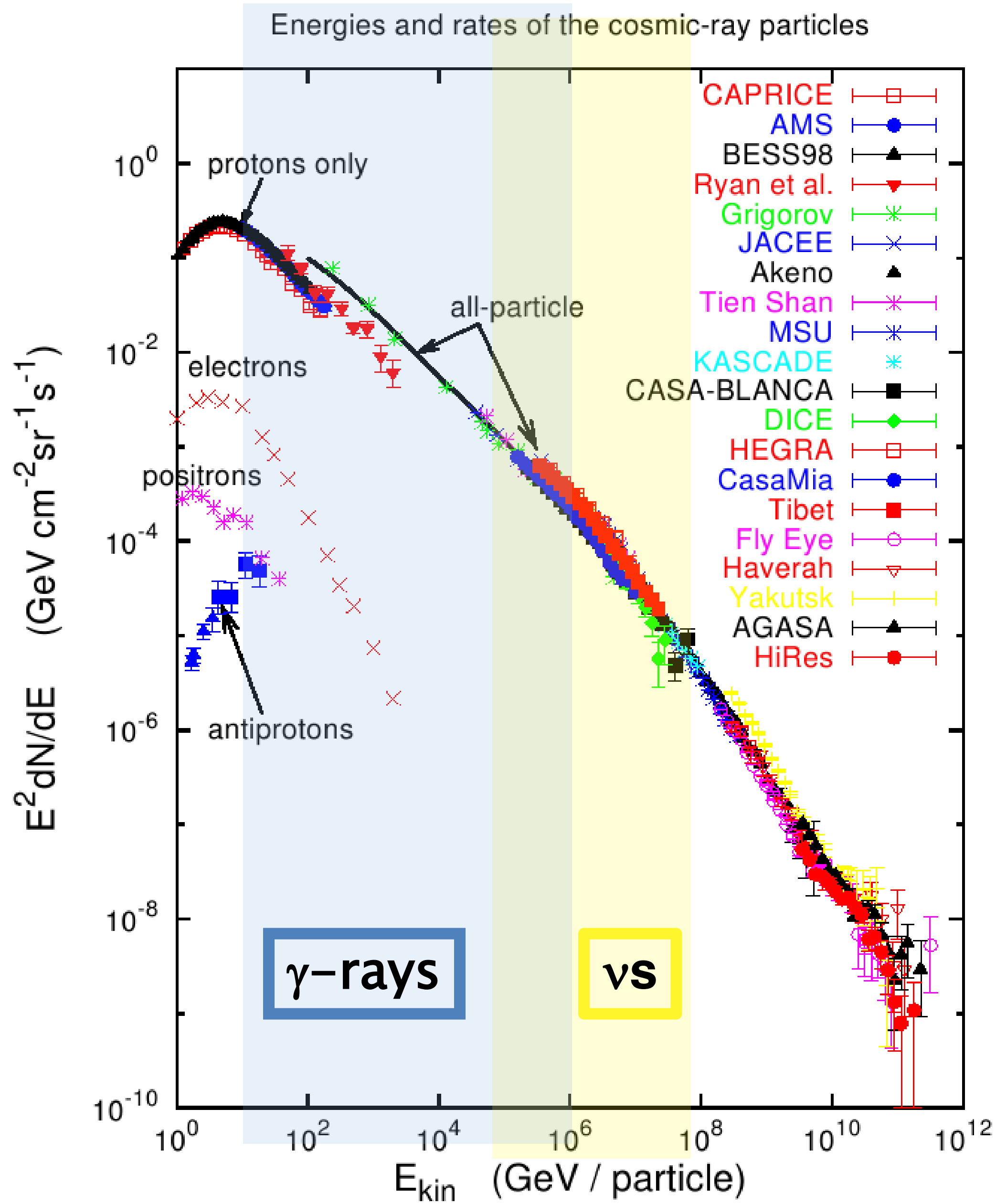
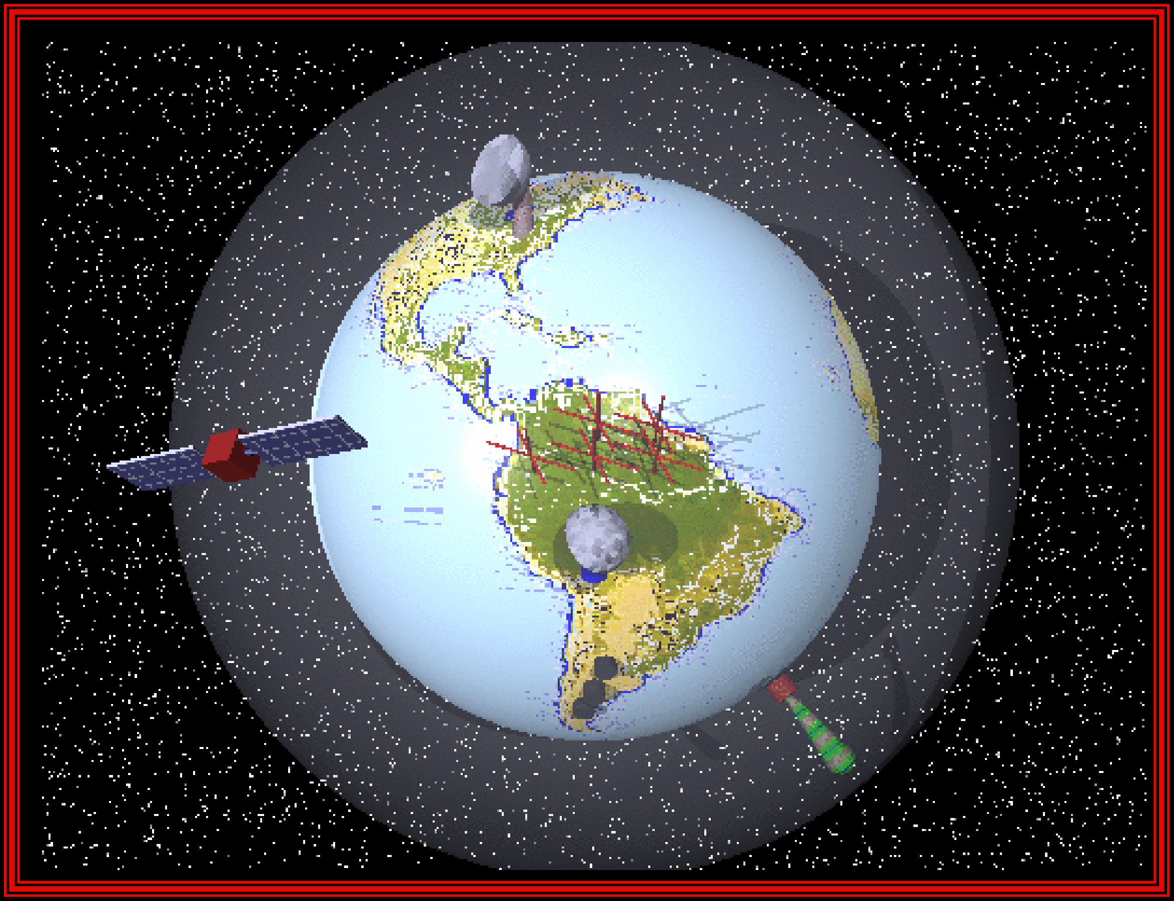


Figure: M. Hillas, astro-ph/0607109



Animation generated with povray