Galactic cosmic ray sources:
a multimessenger view

Julia Tjus,
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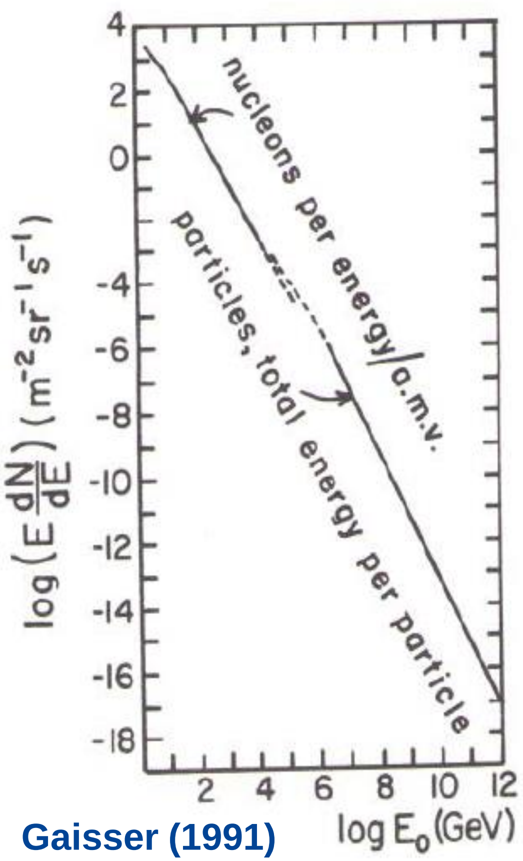
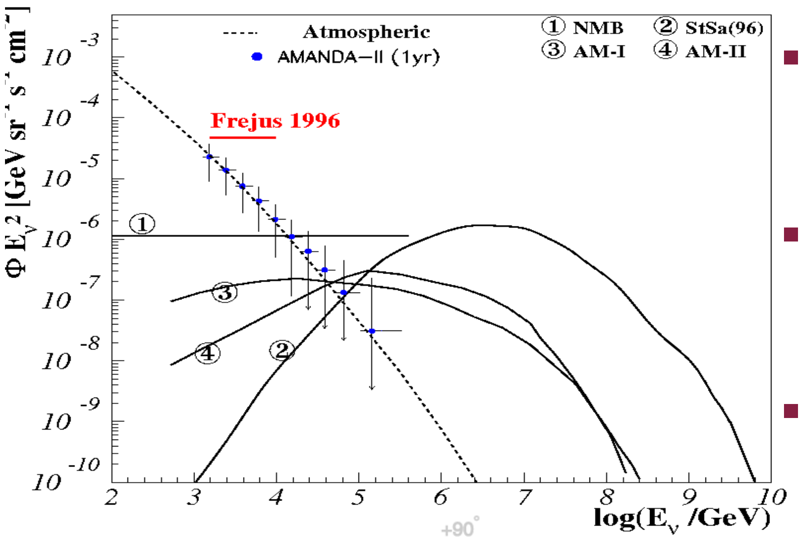
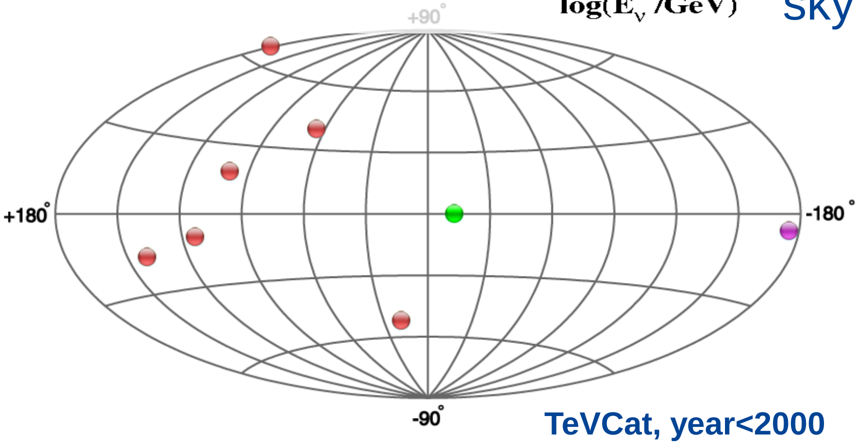
Bochum, Germany

Astroparticle physics in the 1990s



Gaisser (1991)





TeVCat, year<2000

- **CRs:** All-particle spectrum and B/C @ GeV
- **Neutrinos:** limits @ TeV energies (~few times 1e-5 GeV/(s sr cm2)
- **Gammas:** 8 TeV sources confirmed in the sky

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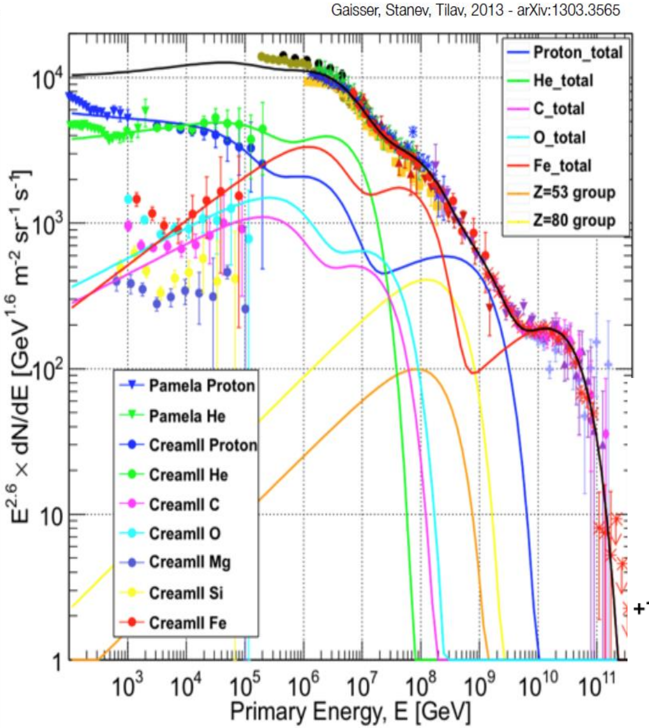
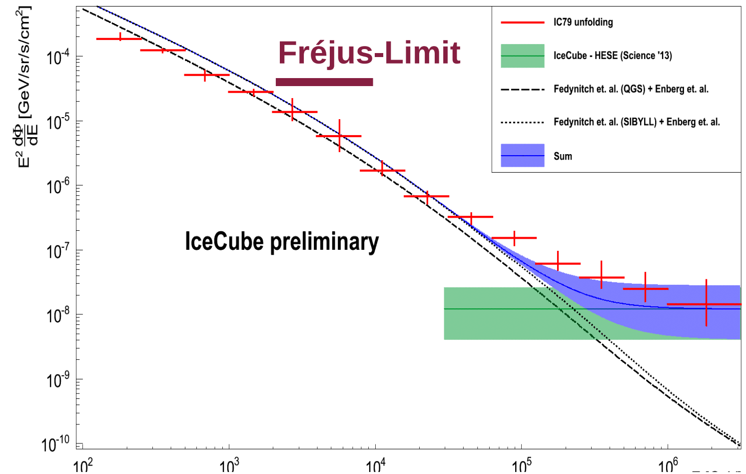
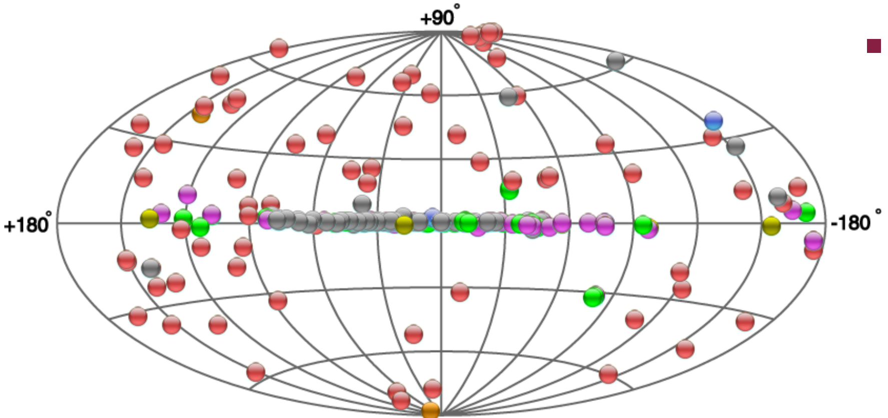
Astroparticle physics today – keeps us all busy!



Gaisser, Stanev, Tilav (2013)





- **CRs:** + composition + anisotropy + spectral breaks +++
- **Neutrinos:** detection~ 1e-8 GeV/(s sr cm2)
- **Gammas:** >150 TeV sources

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Galactic origin of cosmic rays? – basic arguments from the 1990s

- Intensity

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

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

  - Central candidates SNRs (following Baade & Zwicky 1934)
  - Extragalactic sources can only reproduce part above ankle
  - ➔ Part below knee must be of Galactic origin, best candidate: SNRs
- Isotropy

(e.g. Sigl 2017)

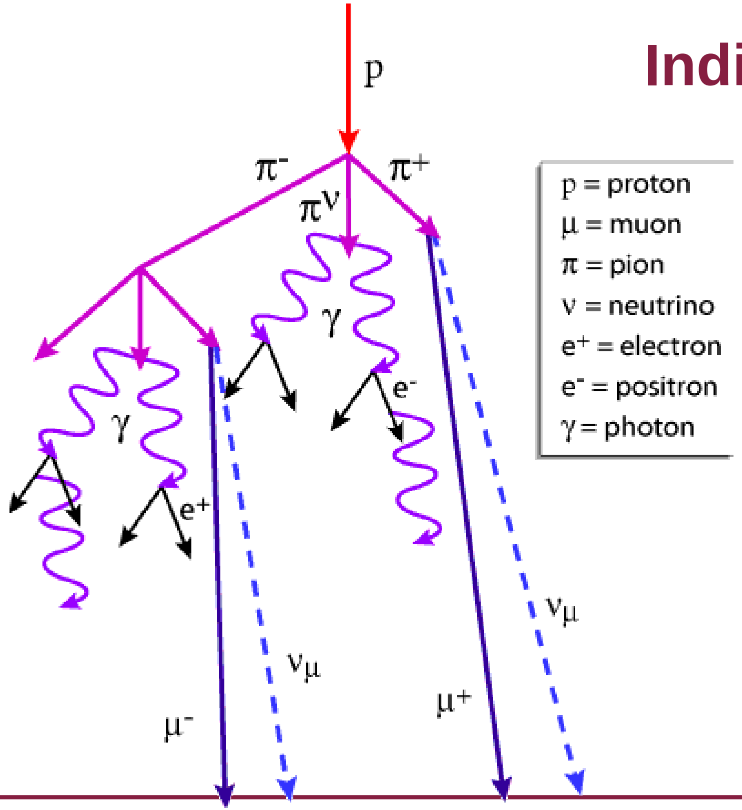
$$\theta(E,d) \sim 1^\circ \cdot Z \cdot \left(\frac{E}{10^{19.5}\,eV}\right)^{-1} \cdot \left(\frac{l_c}{10\,pc}\right)^{1/2} \cdot \left(\frac{d}{8\,kpc}\right)^{1/2} \cdot \left(\frac{B_{rms}}{3\mu G}\right)$$

  - ➔ 10^{20} eV particles would lead to a highly anisotropic signature if they originate in the Milky Way: part above ankle should be extragalactic

Information available today to investigate origin

Direct: cosmic rays

- Hadrons: Spectral behavior (all-particle and chemical composition)
  MeV – ZeV
- Electrons: primary spectrum (local)
  MeV – 20 TeV
- Anisotropy level
  TeV – 10 PeV, EeV

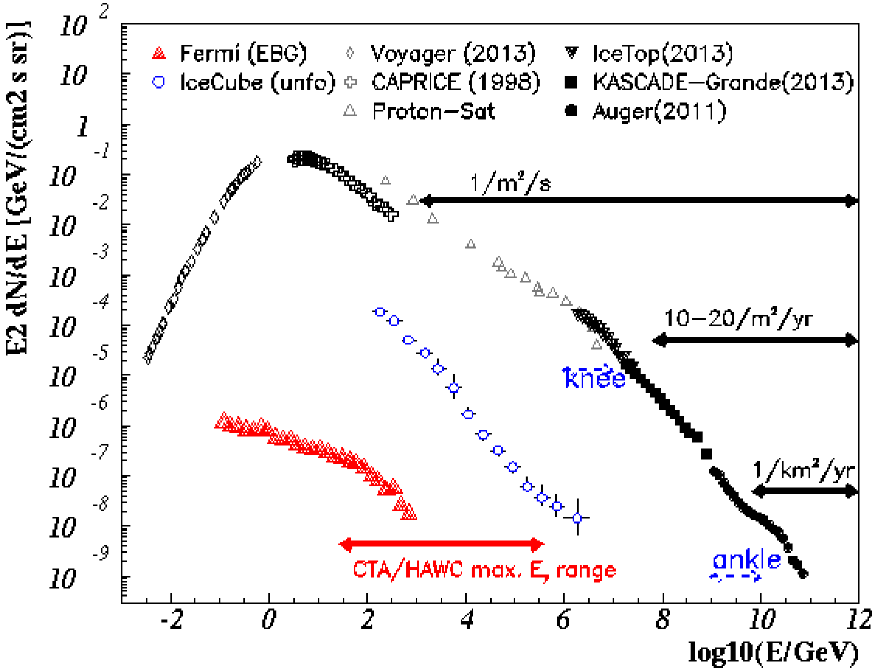


Indirect: e, ν, γ, ...

- Positronspectrum/ -fraction **MeV - TeV**
- Gammas: Sources, diffuse emission
  MeV – 10(0) TeV
- Neutrinos: first detection
  TeV – PeV

Talk today: Galactic multimessenger approaches from MeV to EeV

1) MeV – GeV: Voyager, Ionization and Gamma-rays
2) GeV – PeV: Composition, Anisotropy, Gamma-rays and Neutrinos
3) PeV – EeV: Composition



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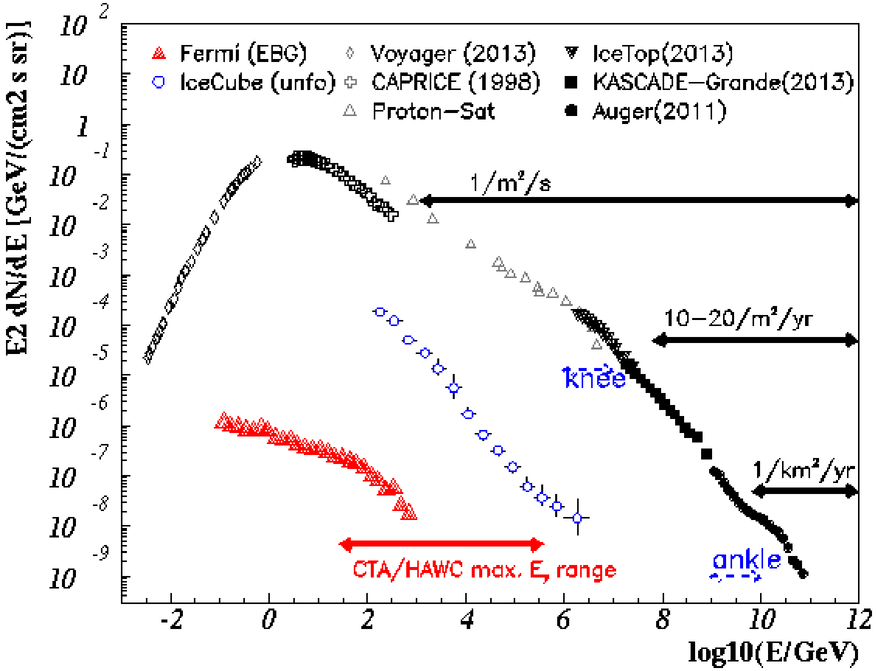
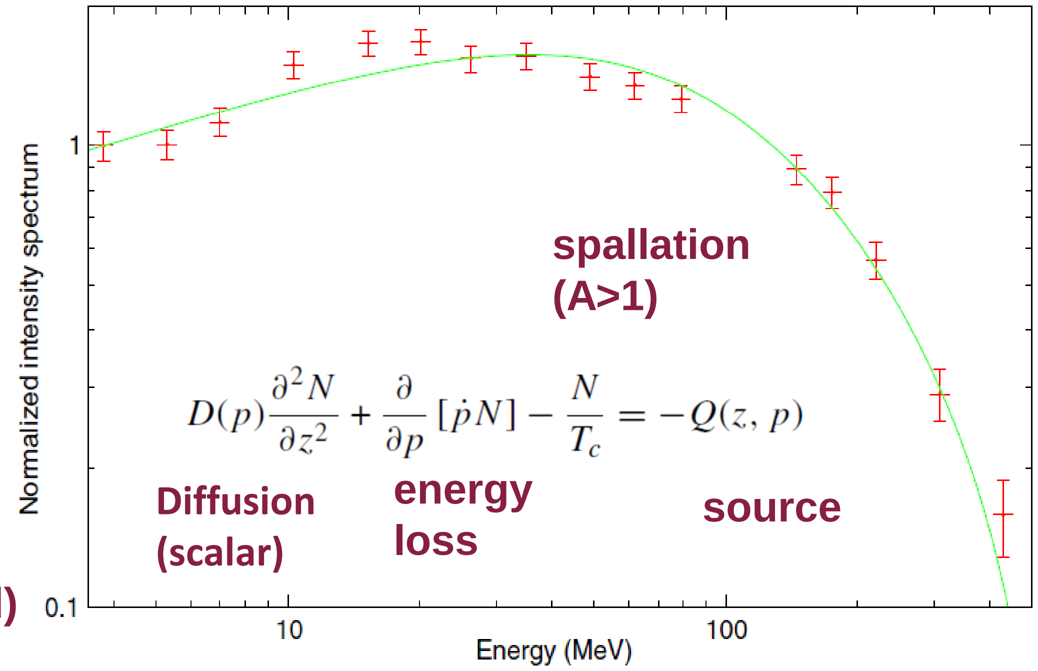


Voyager-I: direct view, uninfluenced MeV spectrum

- Transition ionization/pion dominated at ~ 100 MeV
- Total momentum loss:

$$\dot{p} \simeq n_{\rm gas}[b_I Z^2 p^{-2} + b_\pi (1+a) p]$$

Ionization — π production — adiabatic cooling (wind)



Schlickeiser, Webber, Kempf (2014)

Ionization by cosmic rays: influence on the ISM

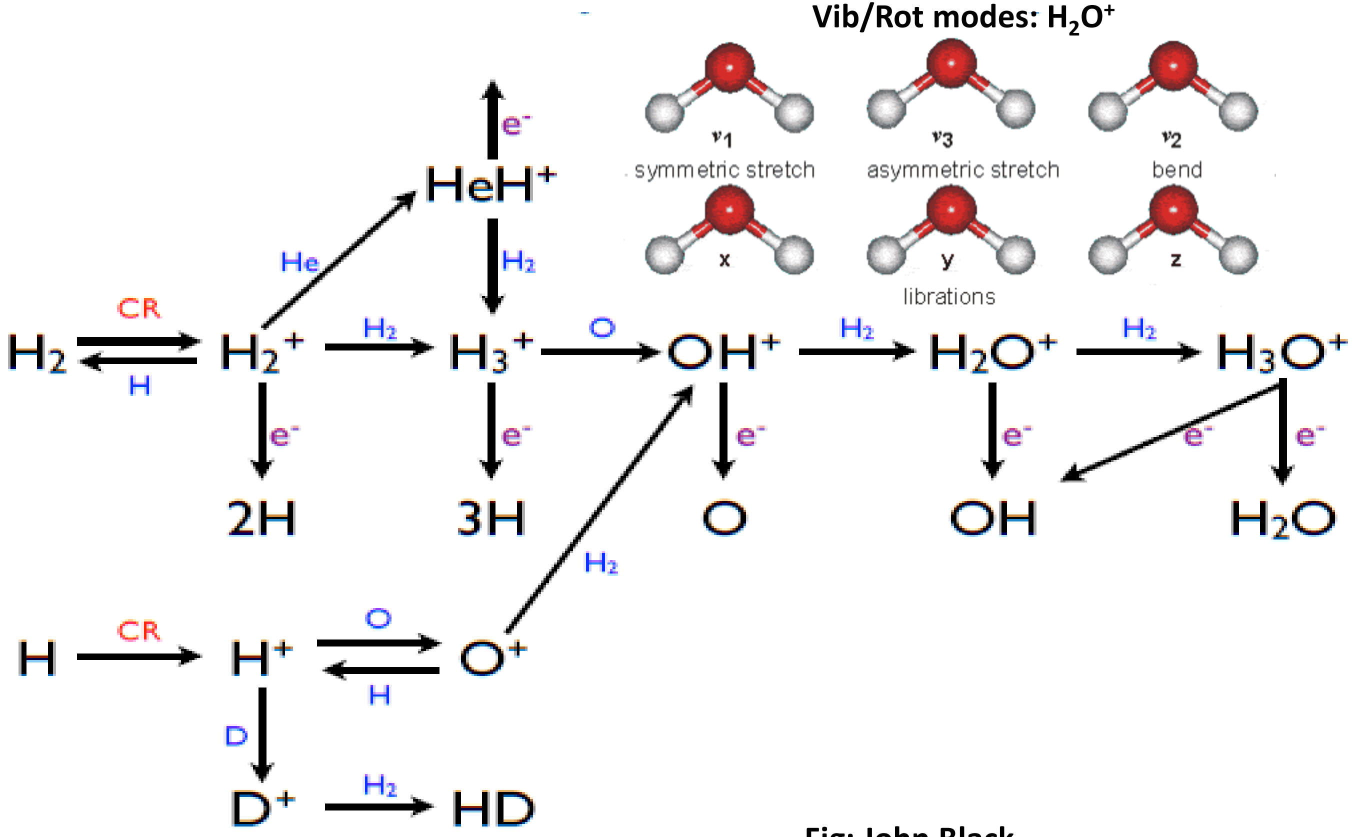
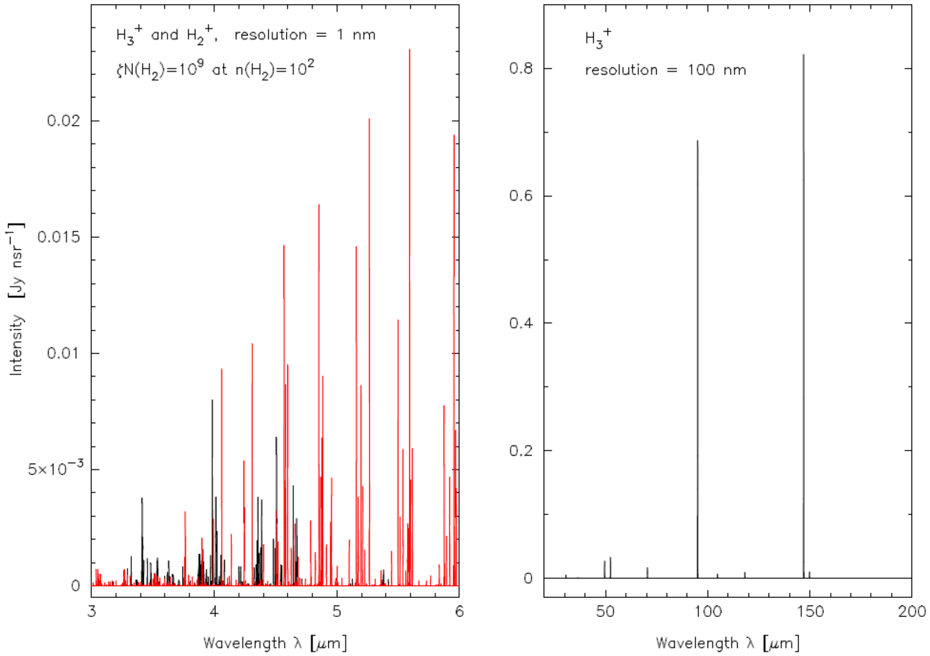


Fig: John Black

- Molecules in rotationally/ vibrationally excited states
- Cosmic ray tracers?

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)
- H_2^+ would be best tracer, but with half-life of ~6 months
- Prediction for possible detection in extreme ionization environments (Crab?; SNRs?)



Becker, Black, Safarzadeh & Schuppan, ApJL (2011)

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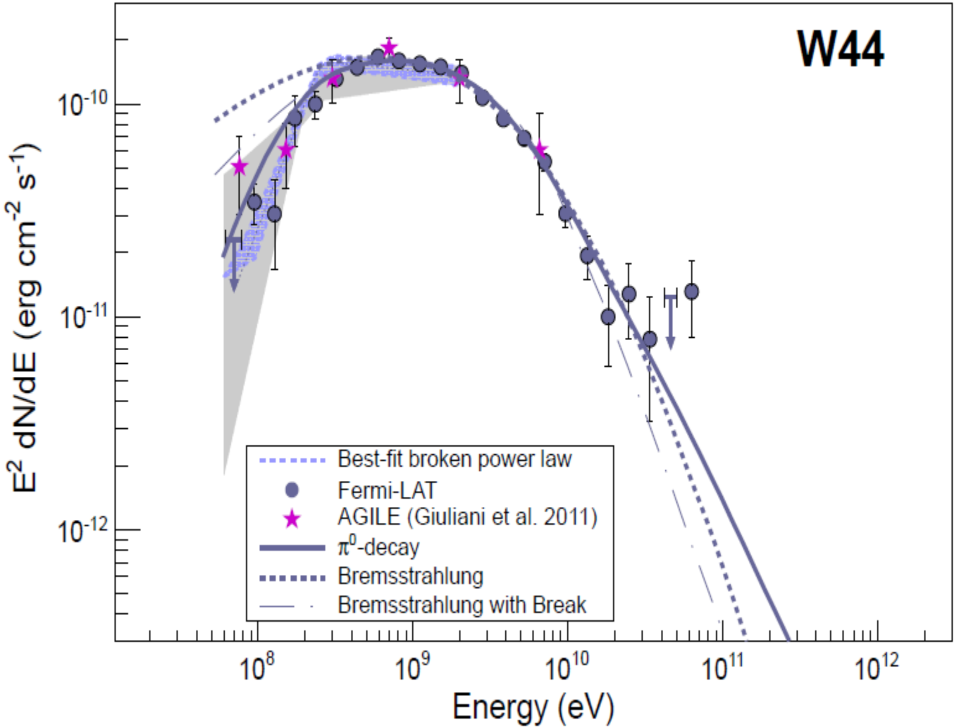
Fermi detection of pion bump (W44, IC44 & W51C)



Ackermann et al , Science (2013)

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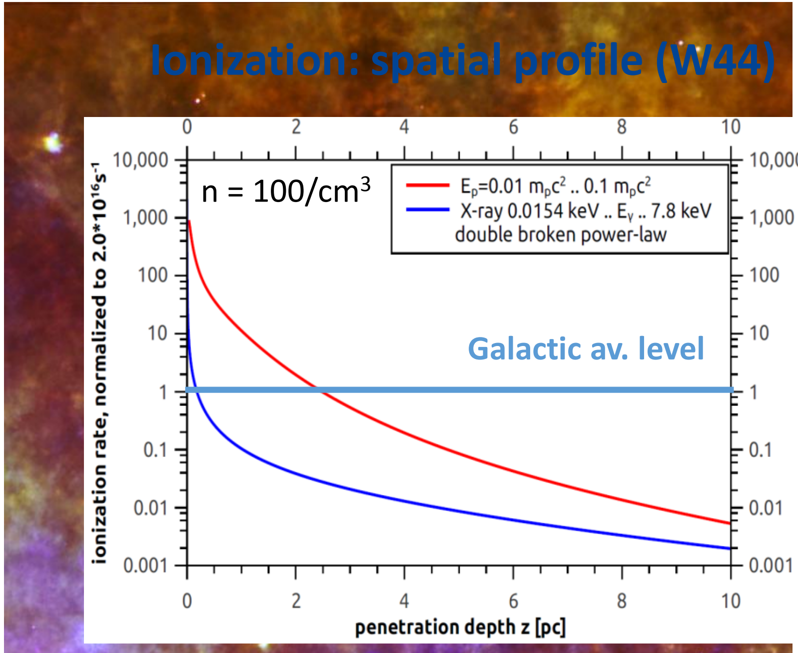
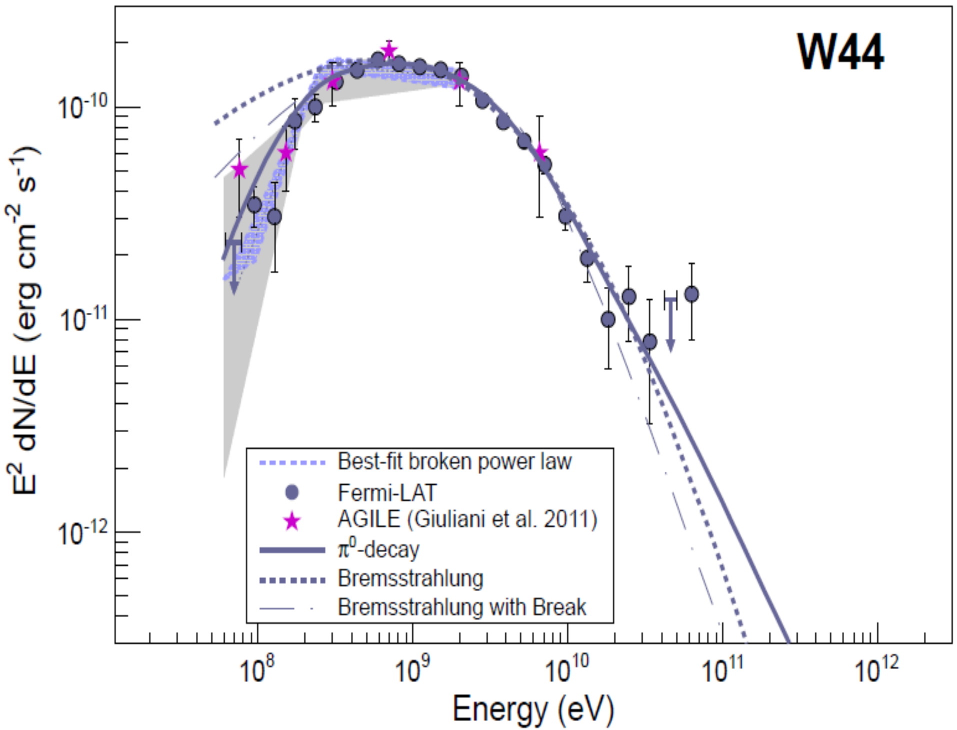


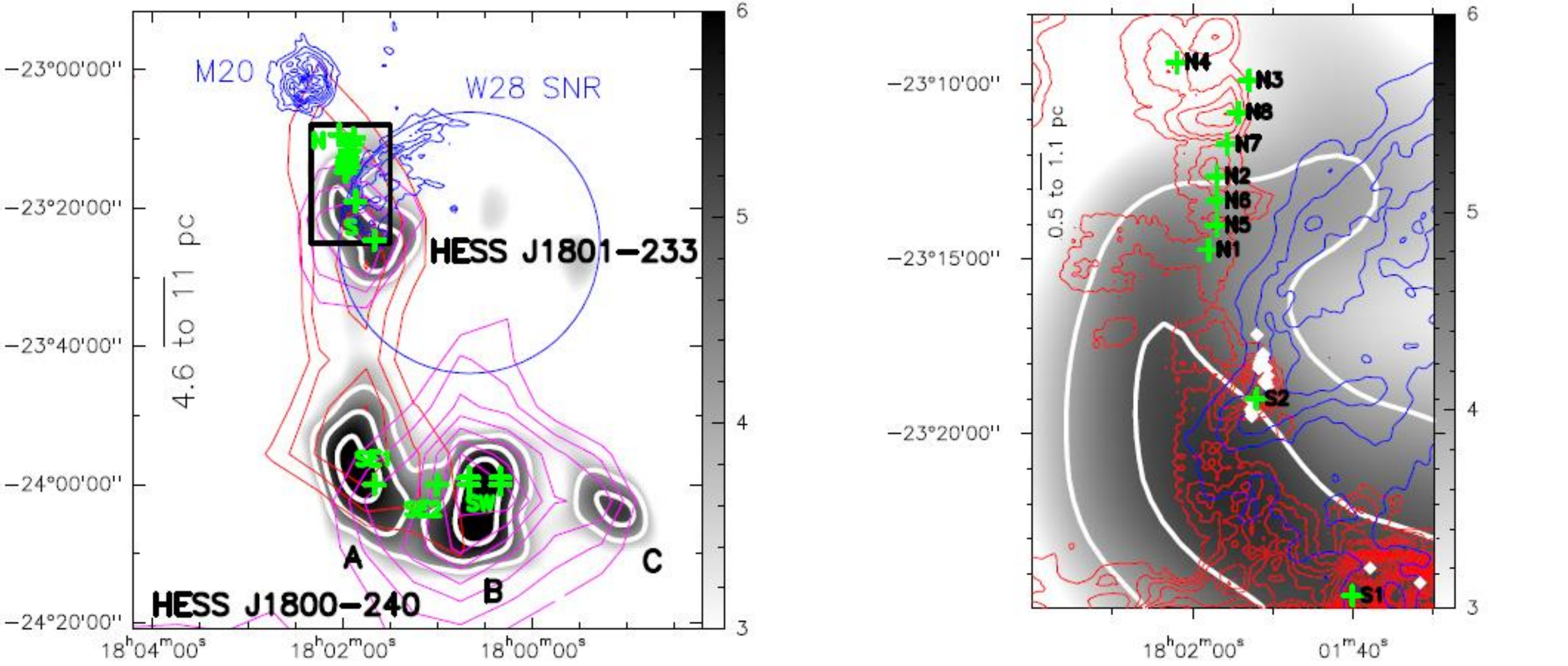
Schuppan, Röken, Becker Tjus, A&A (2014)



Ackermann et al , Science (2013)

Enhanced ionization rates @ TeV sources

Vaupré et al, A&A (2014)



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

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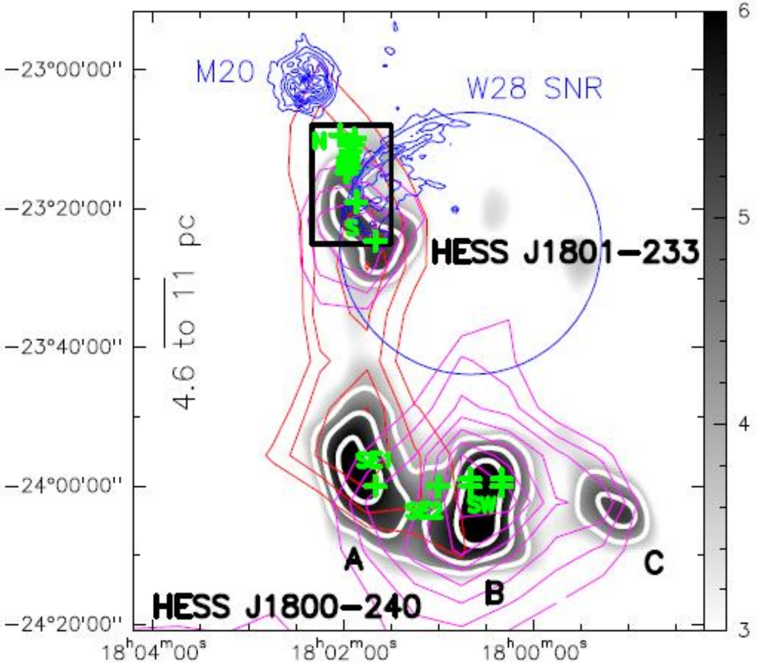

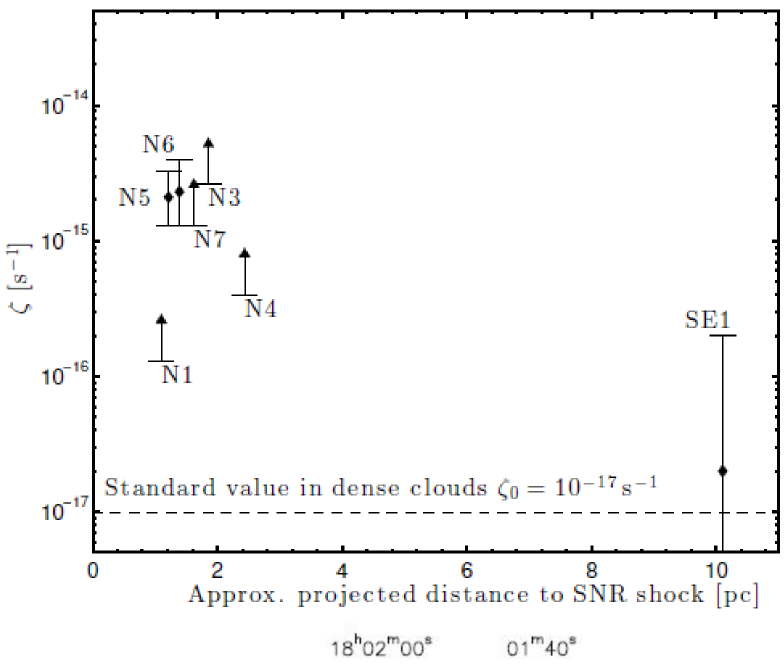

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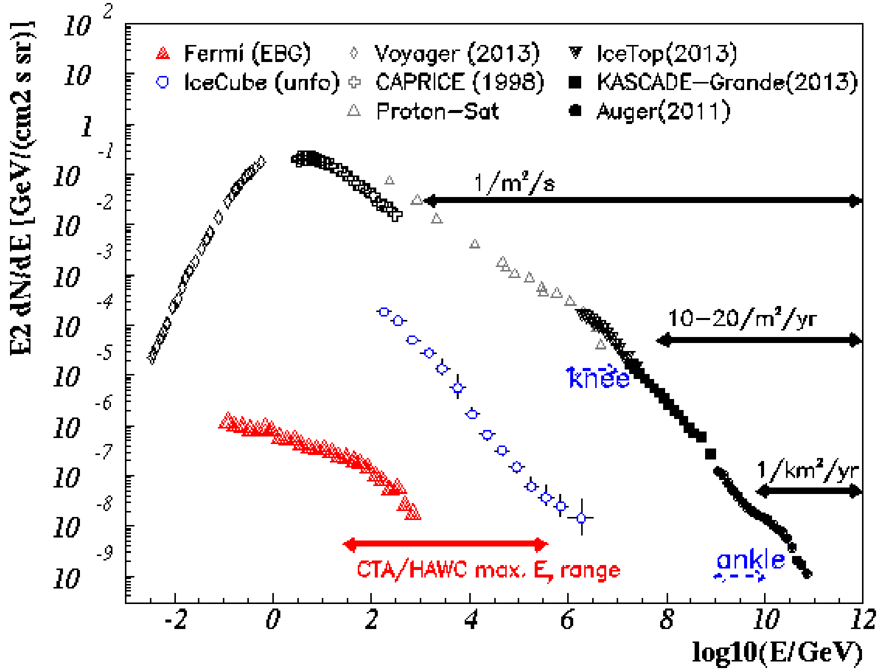
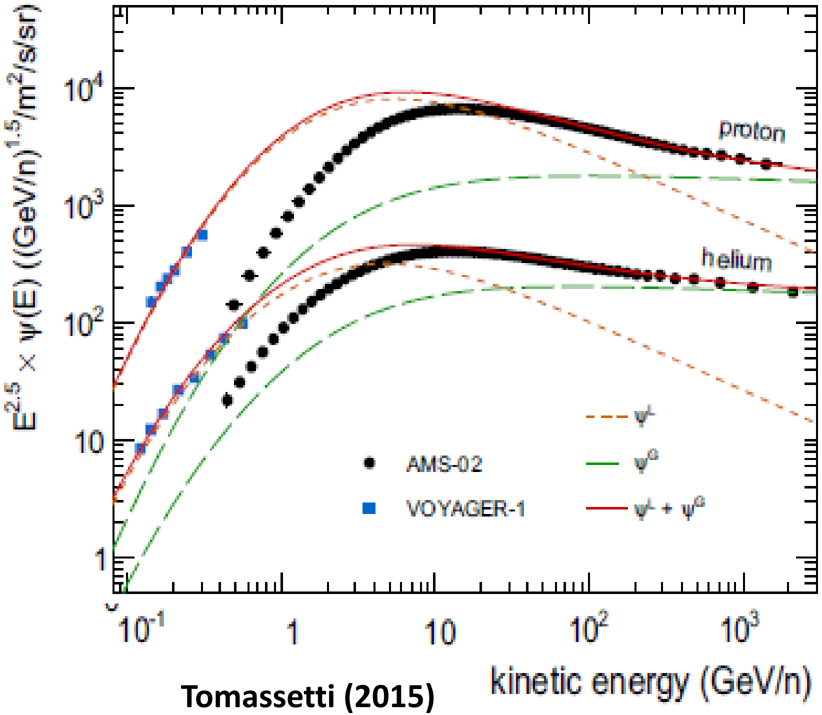


Voyager & AMS: p/He explanation?

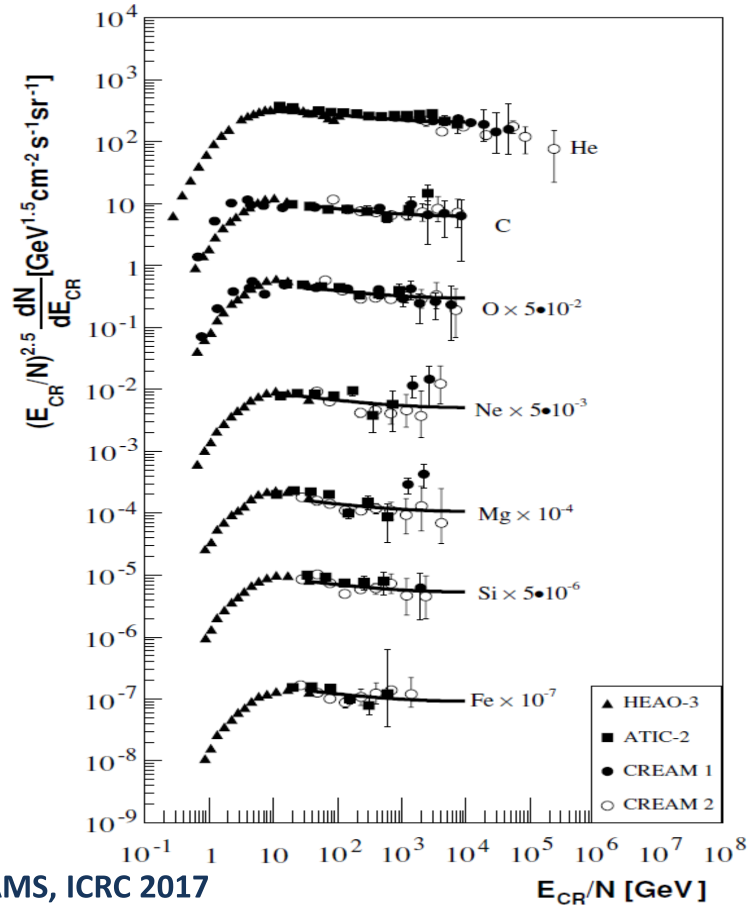
- Rigidity-dependent ratio
- Possible explanation:
  - lower-mass SNRs with high H/He ratio (red-dotted)
  - Wind-SNRs (lower p/He ratio, harder spectrum)
  - But: fine-tuning of break position
  - ➔ heavier nulei?



Tomassetti (2015)

Chemical Composition (AMS, CREAM, PAMELA)

- Break at same rigidity ~ 300 GV
  - diffusion-related (but why at 100 – 1000 GV?)
  - source-related
    - NLDSA-curvature (e.g. Ptuskin et al 2013)
    - 2-component spectrum (Wind-SNRs, polar cap, e.g. Biermann, JBT et al 2010)
  - B/C could help to distinguish transport (-> break in B/C: transport; no break source-scenario)



AMS, ICRC 2017

see also talks by Daniele Gaggero (Wednesday), Veronica Bind (Thursday) and Stephan Zimmer (Friday)

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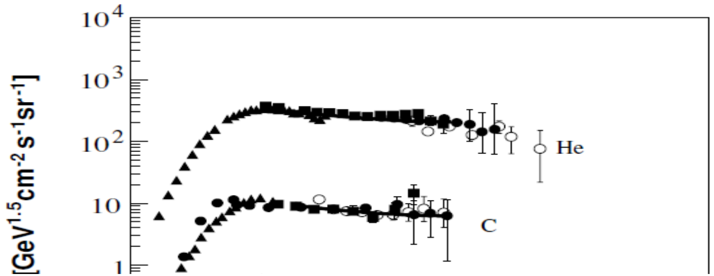

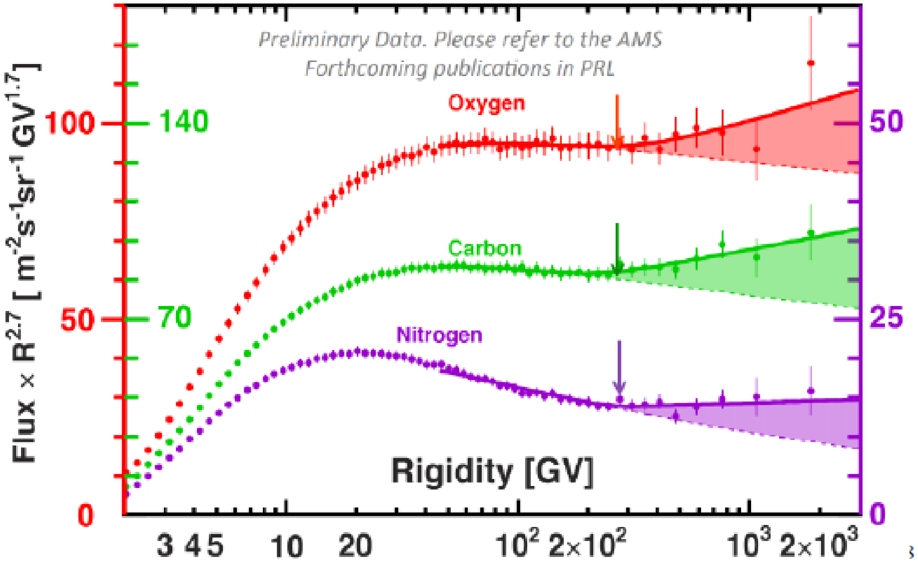

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Cosmic ray dipole anisotropy

- Dipole vector:

$$\vec{\delta} = 3\,\hat{K}\nabla(\ln n') + (\alpha+2)\cdot\frac{\vec{v}_{ism}}{c} \sim A e_B + B\, e_v$$

- ➔Options below flip:
  - Local source anistropy **(e.g. Erlykin & Wolfendale 2006, Pohl & Eichler 2013),** projected onto local B-field **(Ahlers 2017)**
  - ISM velocity **(Biermann, JBT et al 2013)**
- ➔Above flip:
  - change in B-field OR velocity field?
  - Galactic Center?

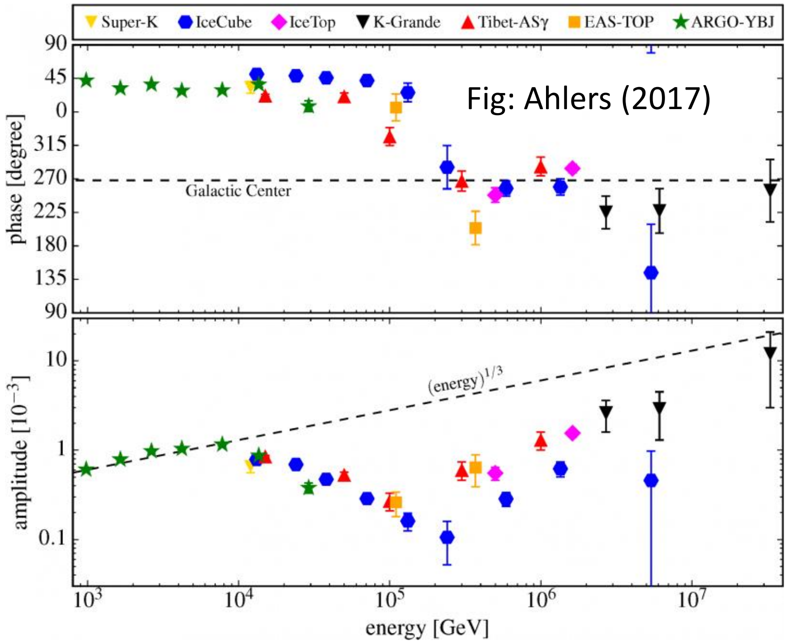
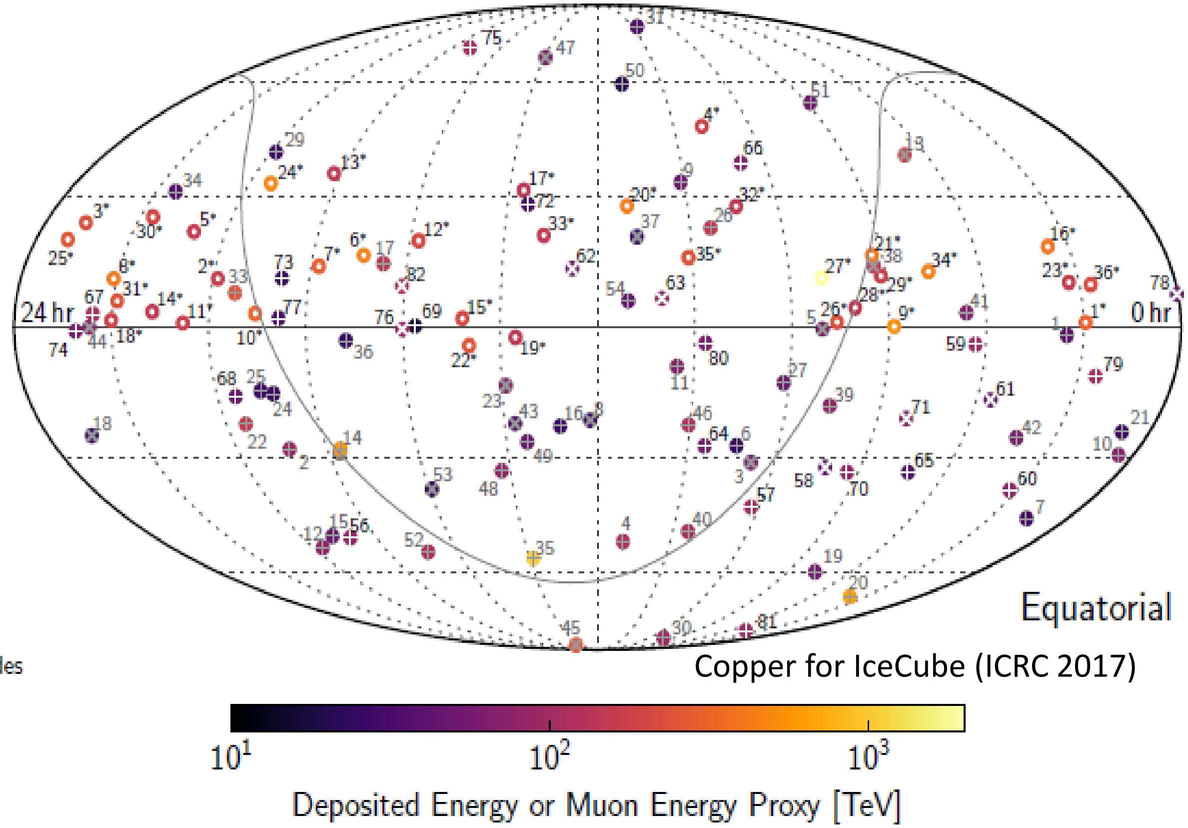


Fig: Ahlers (2017)

High-energy neutrinos from the Cosmos

- No significant clustering along the Galactic Plane

Only fraction of detected neutrinos of Galactic origin (or halo-scenario)



N* Throughgoing Tracks

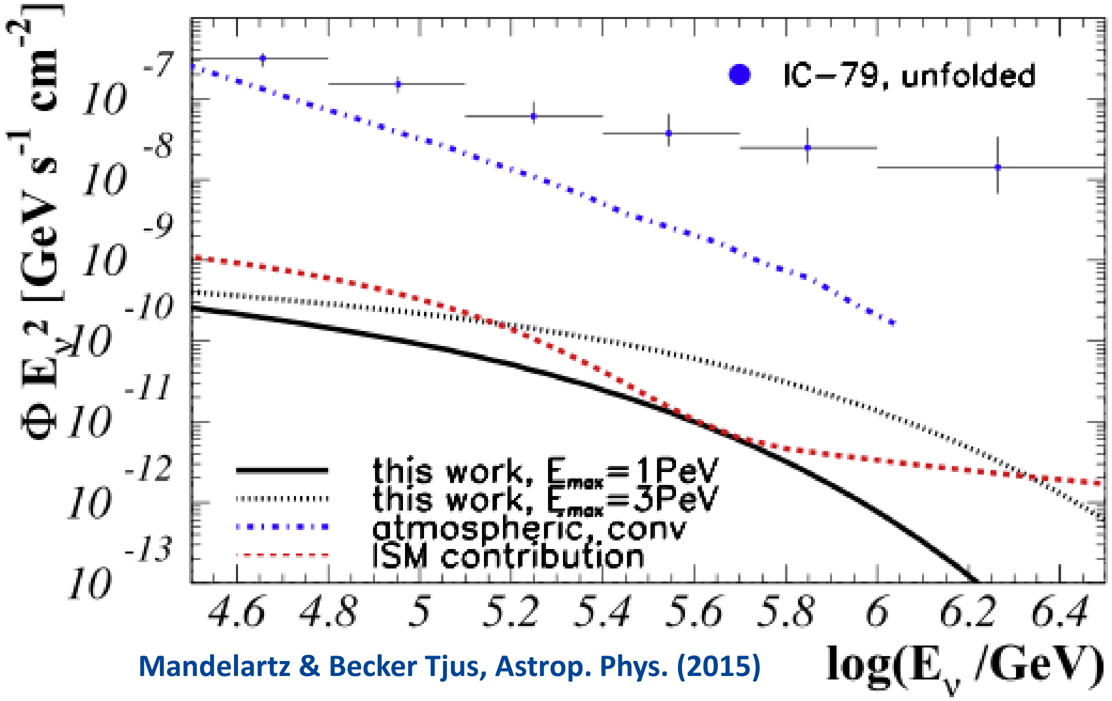
N New Starting Tracks
N New Starting Cascades
N Earlier Starting Tracks
N Earlier Starting Cascades

Copper for IceCube (ICRC 2017)

See also talks by Francis Halzen and Marek Kowalski (both Tuesday)

Galactic neutrinos – diffuse intensity?

- γ-ray emission too low to produce the full signal (e.g. Mandelartz & JBT, Winter et al, Neronov et al, Ahlers et al)
- all models << 10%
- Maximum energy should be lower than the observed few PeV:
- $E_{max\nu} \sim E_{max,CR}/20 \sim 100$ TeV



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

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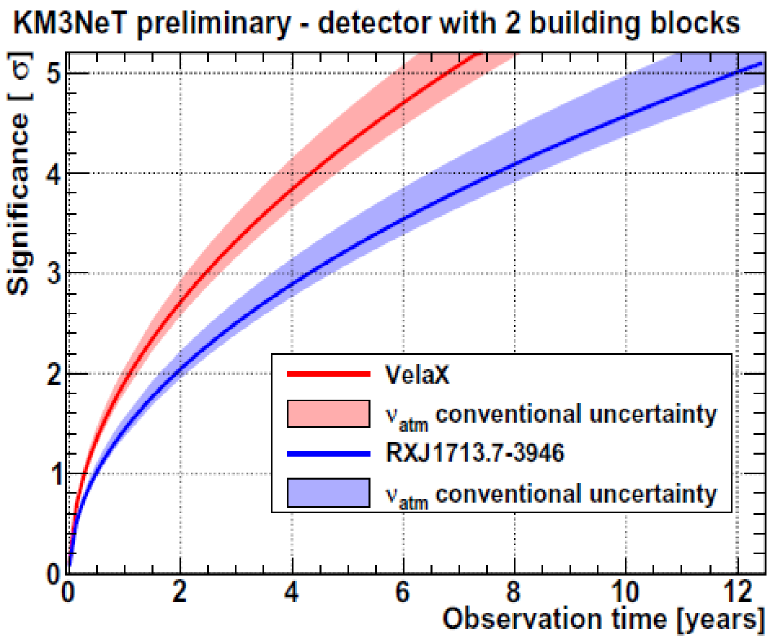
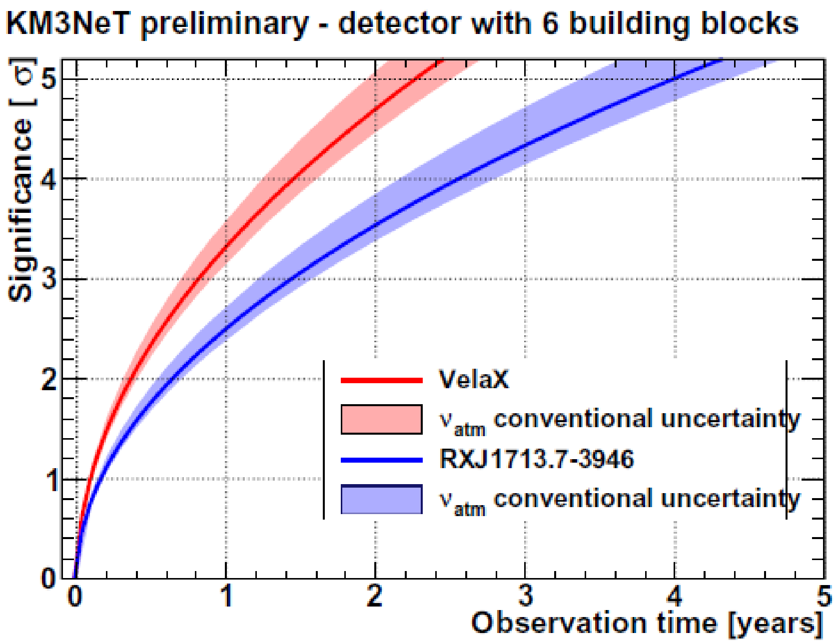
Galactic Neutrinos:
localized regions – point sources

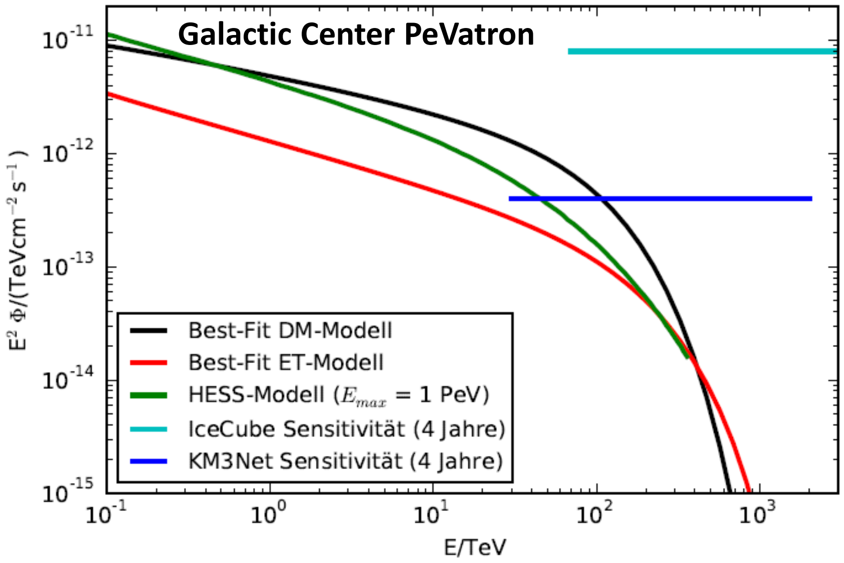


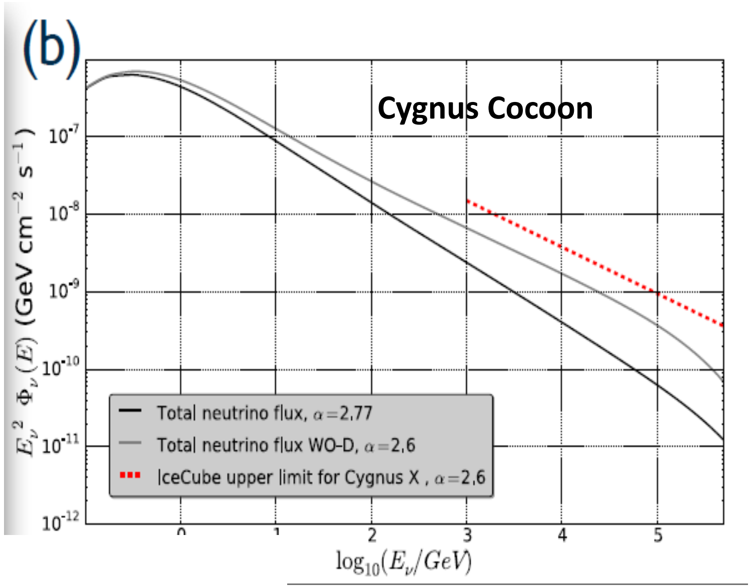


Trovato for KM3NeT, RICAP 2014

Galactic Neutrinos: localized extended regions

Gündüz, Eichmann, JBT, Halzen, arXiv:1705.08337





see also Gaggero PRL 2017

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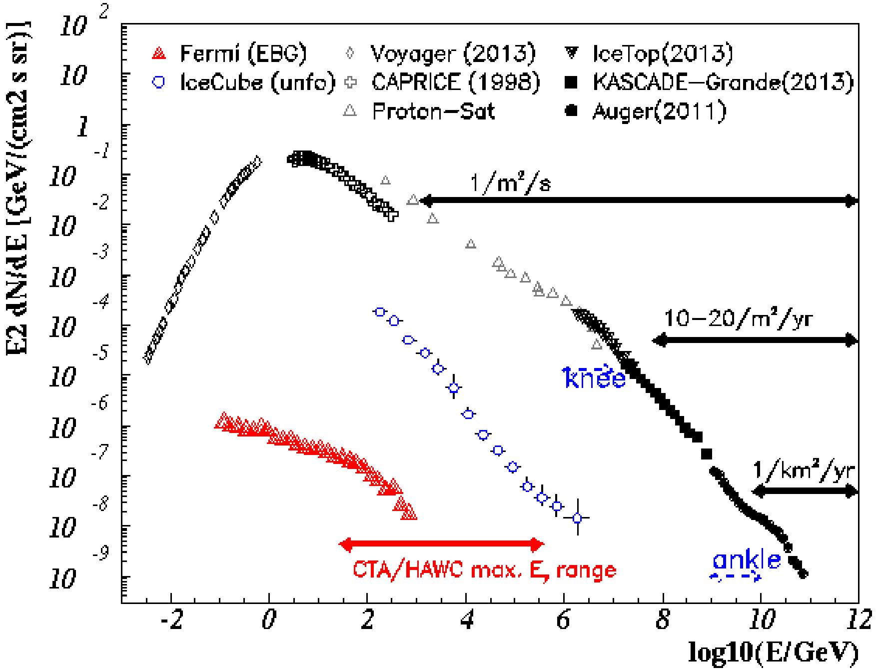
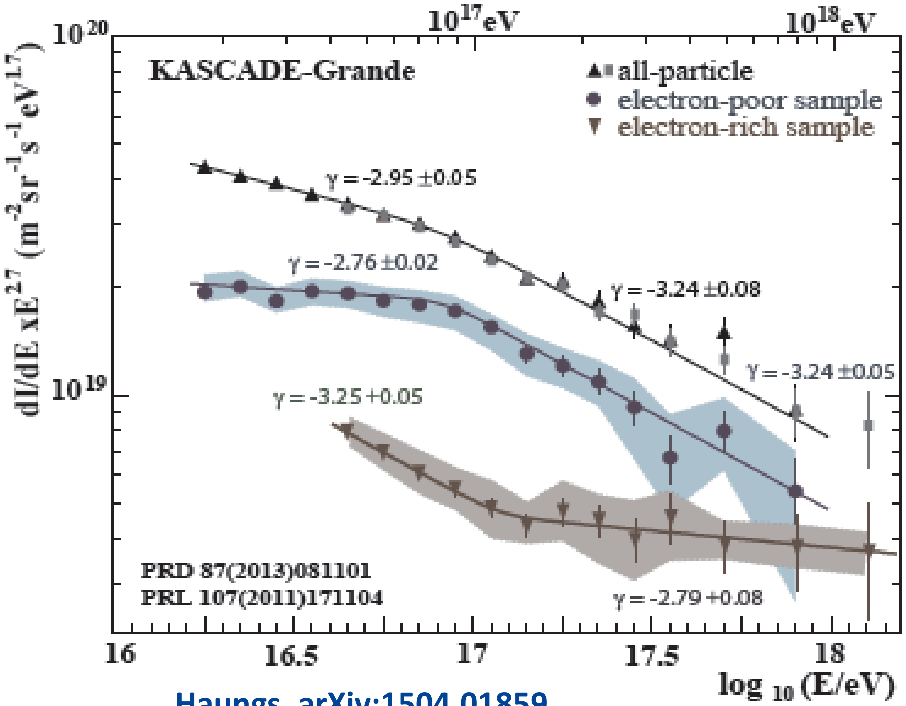


Spectrum & Composition above the knee

- Flattening of the all-particle spectrum at ~ 10^{16} eV, re-hardening at ~ 1017 eV (KASCADE-Grande, TUNKA, IceTop)
- Composition becomes heavier toward ankle (KASCADE-Grande)

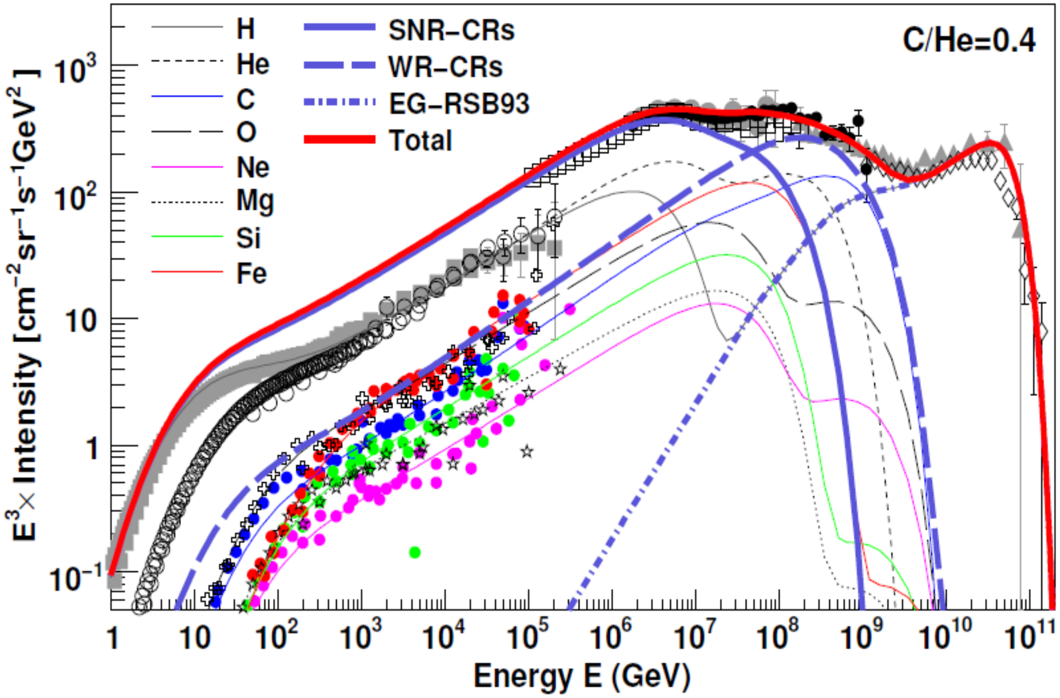


Haungs, arXiv:1504.01859

Acceleration at Wind-SNR

Thoudam et al (2016)

- Acceleration at WR-SNRs (Stanev, Biermann, Gaisser 1991)
- Extreme maximum energies possible due to possibly large
- Good fit of the overall-spectrum (but: details of rigidity breaks?



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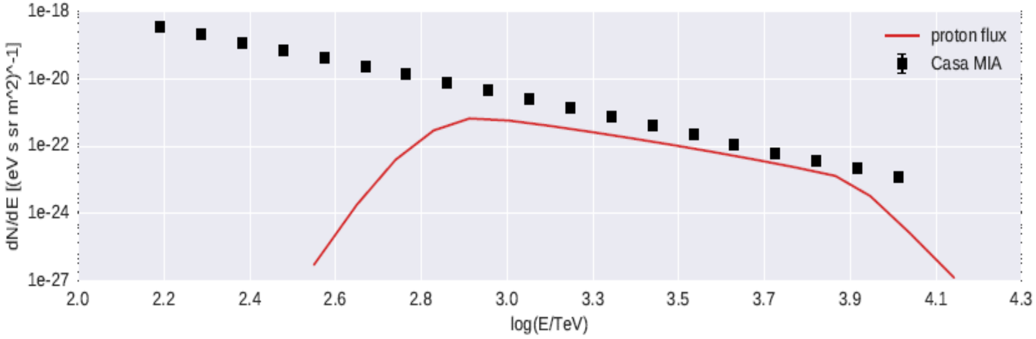
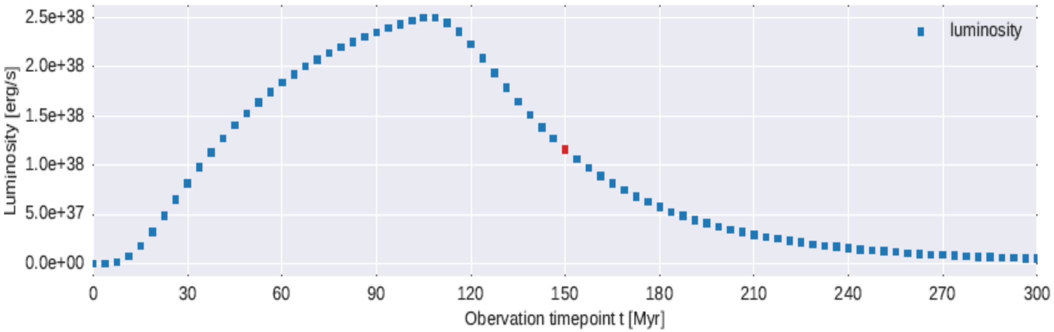
Contribution from Galactic Wind Termination Shock?

- v_{wind} = 600 km/s (MHD modeling, Bustard et al 2017)
- L = 10^{41}erg/s (10% of E_{kin})
- O(5%-20%) of particles travel back to Galaxy: could contribute to CR spectrum above the knee
- (details in prep)





Lukas Merten, talk in „Cosmic Rays“ @ 2pm

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Summary & Outlook

- Data have revealed many detailed features of the CR spectrum in the past 10 – 15 years that challenge astroparticle theory
- SNR-scenario still works quite well (including wind-SNRs), but questions on details have become more
- Future developments in theory:
  - Full anisotropic diffusion models on the way
  - Careful analysis of plasma parameters necessary to determine diffusion tensor

PICARD [Kissmann, Astrop.Phys. 2014],
DRAGON-2 [Evoli et al 2017],
CRPropa 3.1 [Merten,JBT, Fichtner, Eichmann, Sigl, JCAP 2017]

- Experiments:
  - ISS-CREAM, Auger Prime, KM3NeT, IceCube-Gen2, CTA, LIGO ++ on the way
- We have the privilege to work in exciting times!