Using Interstellar Clouds to Search for Galactic PeVatrons

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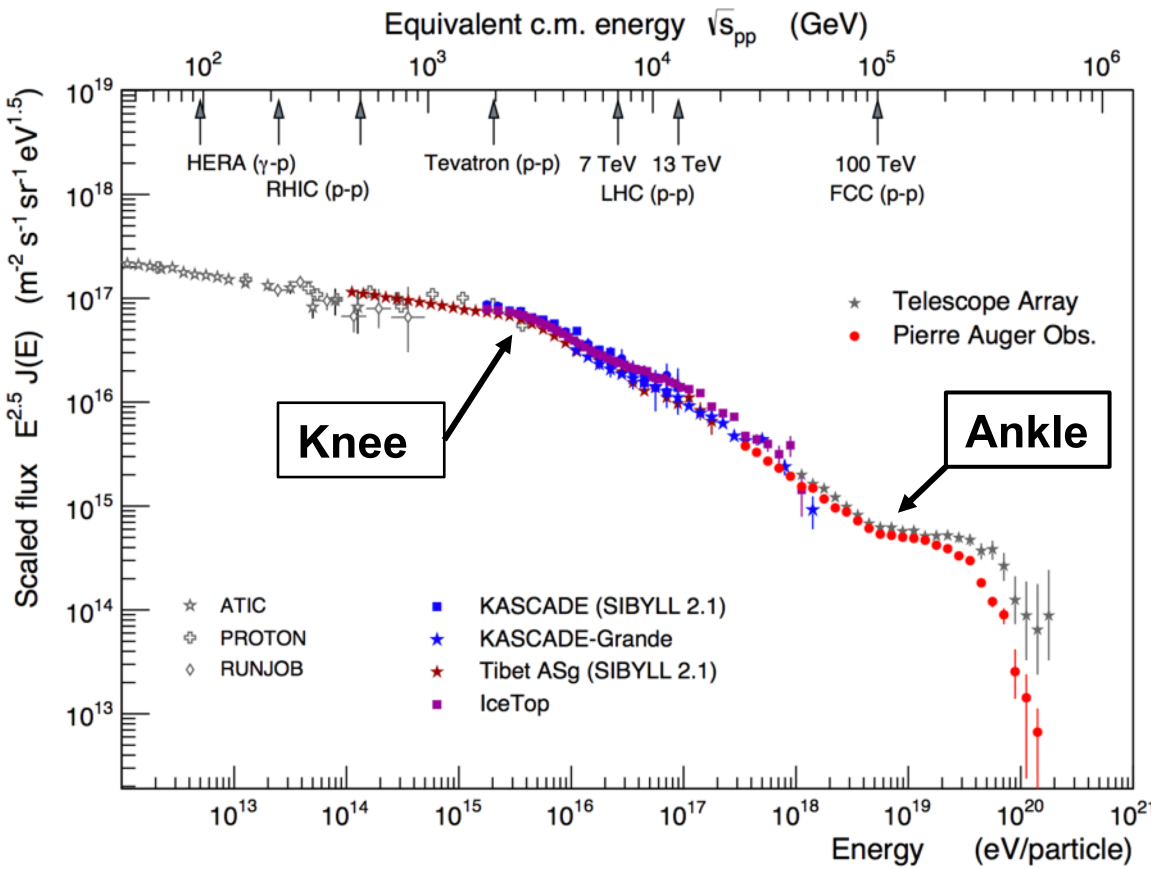
Cosmic Ray Spectrum and the hunt for PeVatrons

PeVatrons: cosmic accelerators of PeV particles

Knee: galactic accelerators turn-off from 10^{15} eV

Ankle: extragalactic accelerators dominant beyond 10^{18} eV

CRs produce γ-rays at source;
γ-rays > 10^{14} eV are a signature of CRs > 10^{15} eV



Supernova Remnants as PeVatron Candidates

Hillas criterion:

$$E_{\max} = Ze\beta cBL$$

Minimum size and B field strength

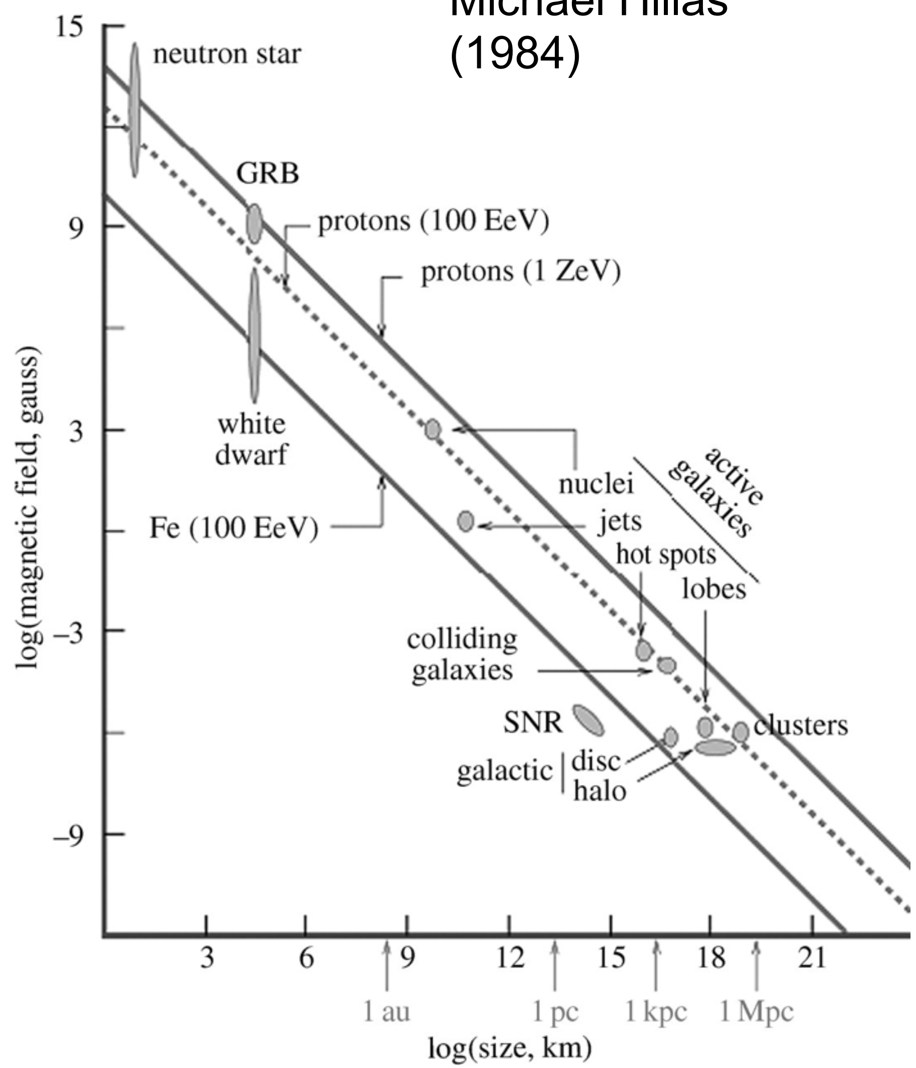
SNR energetics approx. right:

10% CR acceleration efficiency can sustain CR energy density ~ 1eV cm^{-3}

Look for signature gamma-ray emission from SNRs > 100 TeV to confirm CR acceleration to 1 PeV.

→ search so far unsuccessful

Michael Hillas (1984)



SNR spectra

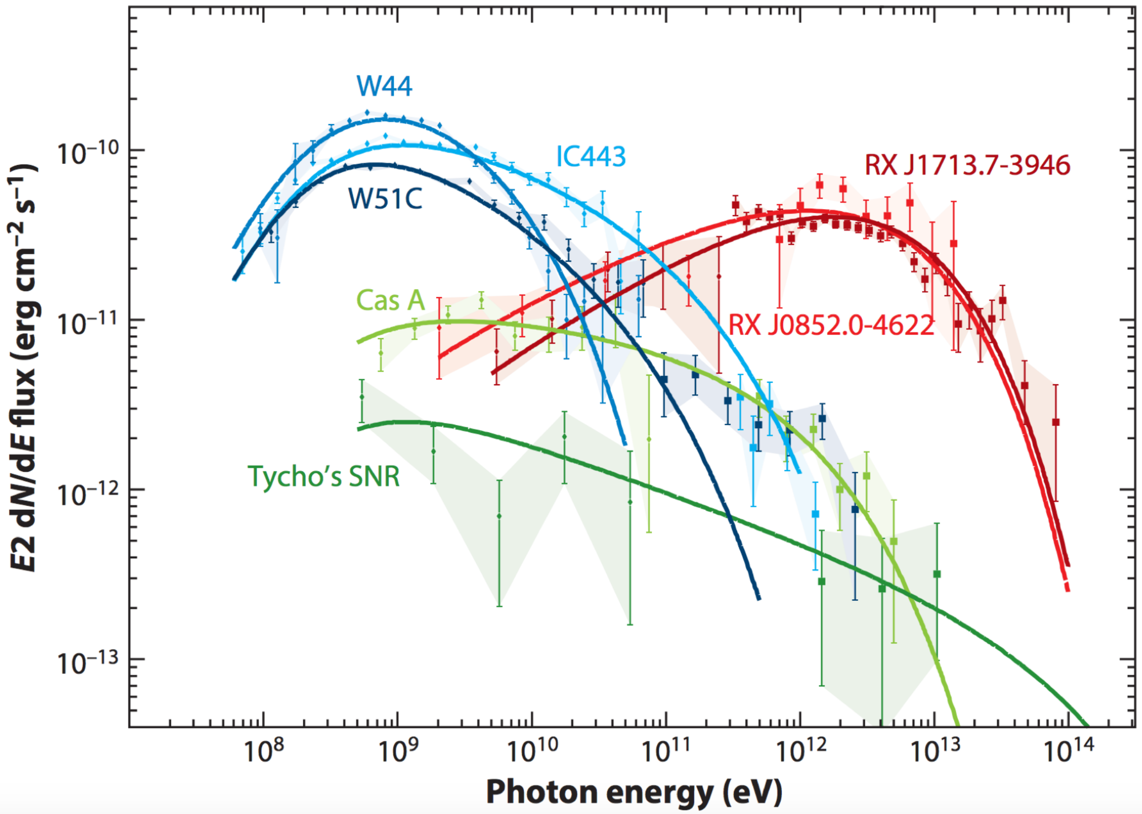
No clear SNR candidate (yet) with evidence of particle acceleration to PeV energies

Spectra typically cut-off at ~few tens of TeV.

End of the SNR paradigm?

Not yet → upper limits are still consistent with SNRs as a dominant CR source.

CRs reaching the maximum energy will **escape** early on.



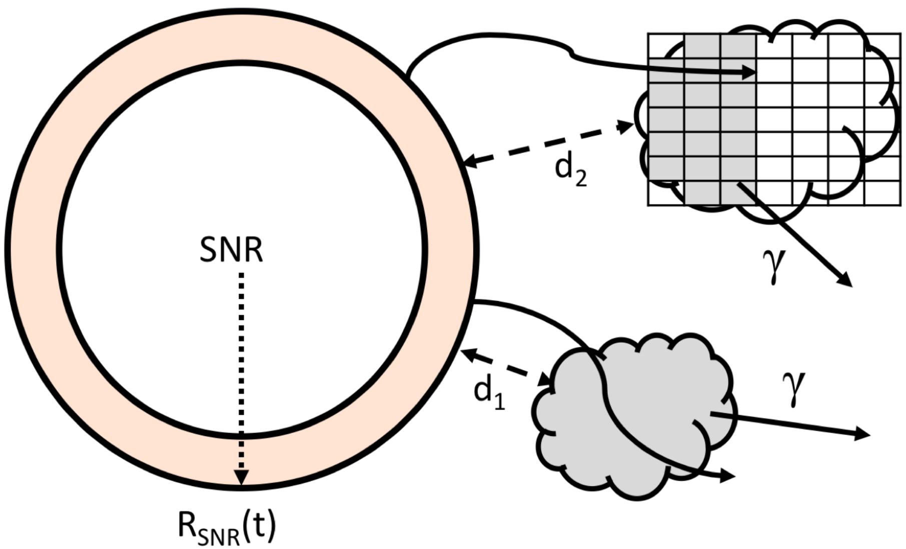
Particle Escape and Cloud Interactions

Escaping CRs – can illuminate nearby clouds

Look instead for evidence of energetic particles interacting with clouds.

<u>This project</u>:

Predict the most promising target clouds for gamma-ray observations with CTA, assuming that CRs were accelerated to PeV energies in the SNR.



Note: CRs may only partly traverse a cloud, in which case we use a cell-based integration approach.

In this presentation we assume the particles always fully traverse the cloud.

Model: particle and gamma-ray flux

Assume: particle flux from an impulsive accelerator, $\alpha = 2$ (Aharonian & Atoyan '96)

$$f(E,r,t) \approx f_0 \frac{N_0 E^{-\alpha}}{\pi^{3/2} R_d^3} \exp\left(-\frac{(\alpha-1)t}{\tau_{pp}} - \frac{R^2}{R_d^2}\right) \text{ph cm}^{-3}\text{GeV}^{-1}$$

Gamma-ray flux Φ_γ produced by interactions with a target cloud (Kelner et al 2006)

$$\Phi_\gamma(E_\gamma) = c n_H \int_{E_\gamma}^{\infty} \sigma_{\text{inel}}(E_p) f(E_p,r,t) F_\gamma\left(\frac{E_\gamma}{E_p}, E_p\right) \frac{dE_p}{E_p}$$

n = density

Assuming particles fully traverse cloud, observable flux *F*:

$$F(E_\gamma) = \Phi_\gamma(E_\gamma) V_c / (D^2 c) \text{ ph cm}^{-2}\text{TeV}^{-1}$$

D = distance, V_c = cloud volume

Model: SNR evolution and particle escape

Particles of different energies are released at different times during the evolution of the SNR.

$$t_{\rm esc} = t_{\rm sed} \left(\frac{p}{p_M} \right)^{-1/\beta} \ {\rm yr}$$

Assume all SNR considered to be in the Sedov-Taylor phase (~ 100yr – 50kyr), Sedov time = 1.6kyr, β = 2.5

Meanwhile, the SNR radius also expands.

$$R_{\rm SNR}(t) = 0.31 \left(\frac{E}{10^{51}{\rm erg}} \right)^{1/5} \left(\frac{t}{1{\rm yr}} \right)^{2/5} \ {\rm pc}$$

Then:

– diffuse through ISM to reach cloud

-- particle interactions with cloud

Model: Diffusion Properties

- Diffusion radius R_d , simplifies to:
$$R_d = 2\sqrt{D(E)t}$$

In the ISM.

$$R_d(E,t) = 2\sqrt{D(E)t\frac{\exp(t\delta/\tau_{pp}) - 1}{t\delta/\tau_{pp}}}\ \mathrm{cm}.$$

- Proton lifetime against particle interactions, τ_{pp} with σ_{pp} given by Kafexhiu et al (2014)

$$\tau_{pp} = (nc\kappa\sigma_{pp}(E))^{-1}\ \mathrm{s}$$

- Diffusion Coefficient D_0 tested with *fast* and ***slow*** values:

(fast case)	D_0 (1 GeV)	$3 \times 10^{27}\ \mathrm{cm^2 s^{-1}}$
(slow case)	D_0 (1 GeV)	$3 \times 10^{25}\ \mathrm{cm^2 s^{-1}}$

$$D(E) = \chi D_0 \left(\frac{E_p(\mathrm{GeV})}{B(n)/3\mu\mathrm{G}}\right)^{\delta}\ \mathrm{cm^2/s},$$

With $\delta = 0.5$ and $\chi = 0.05$ (cloud) or 1 (ISM)

- Magnetic field depends on cloud density:
(Crutcher et al 2010)

$$B(n) = \begin{cases} 10\,\mu\mathrm{G} & (n < 300\mathrm{cm}^{-3}) \\ 10\left(\frac{n}{300}\right)^{0.65}\ \mu\mathrm{G} & (n \geq 300\mathrm{cm}^{-3}) \end{cases}$$

Cloud – SNR properties: example spectra

Primary variables (aside from model assumptions) are:

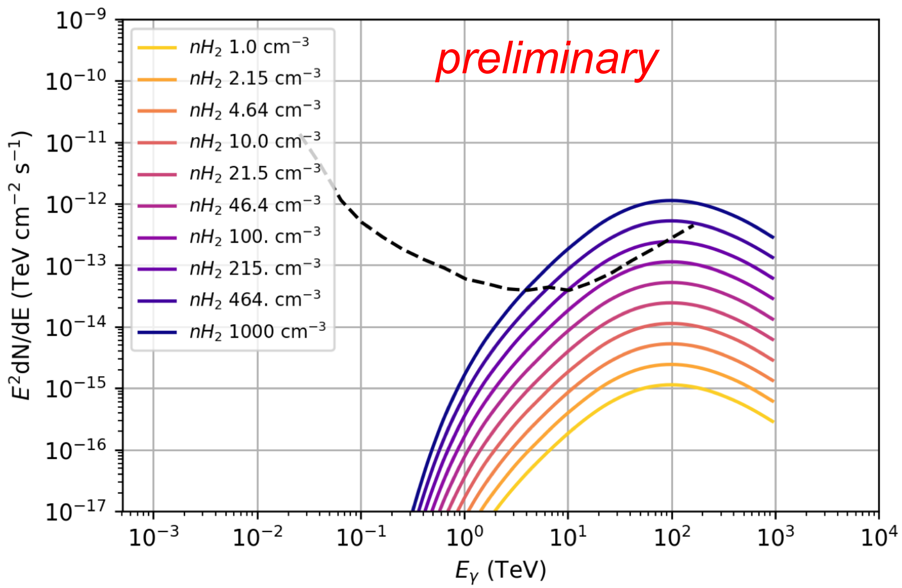
- SNR age (t)
- Cloud density (n)
- SNR-cloud separation distance (d)

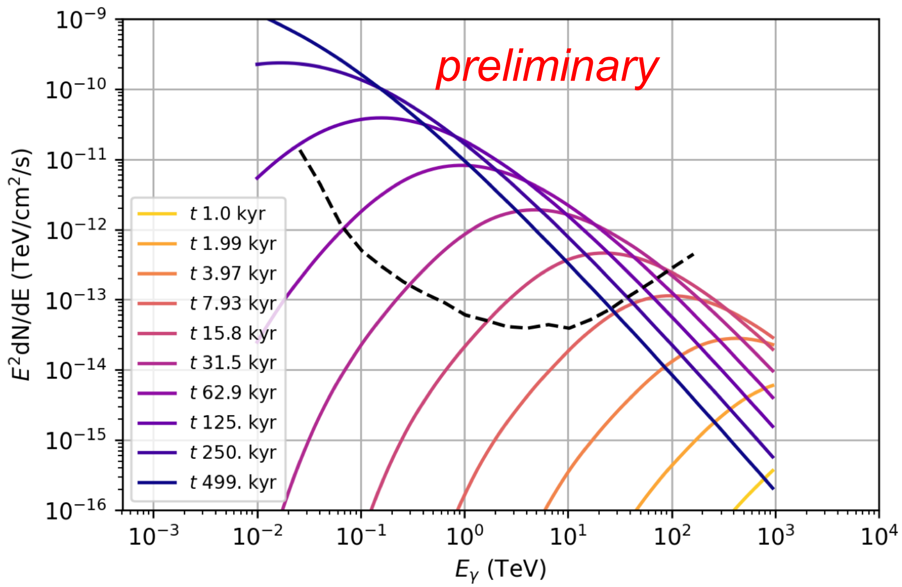
Explore how each of these affects the predicted flux.

Higher density = more flux

With age – peak shifts to lower energies
→ older systems more likely to leave a detectable flux?

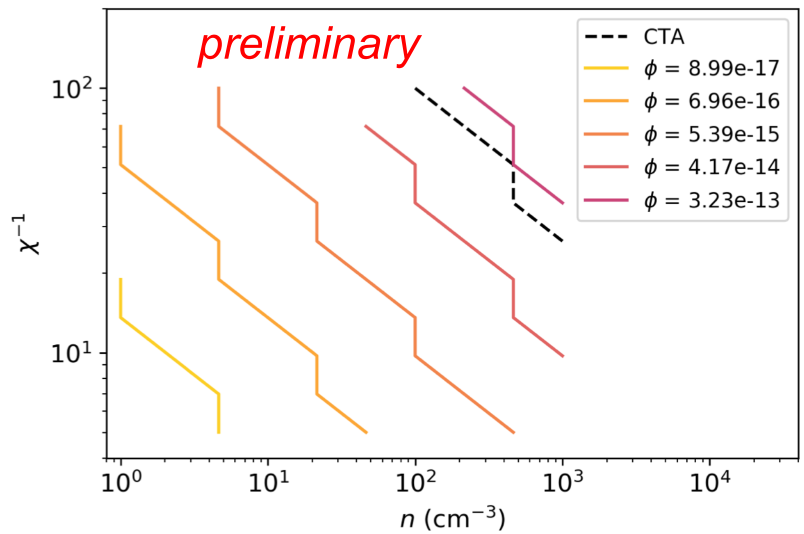
(focus on high energy results)

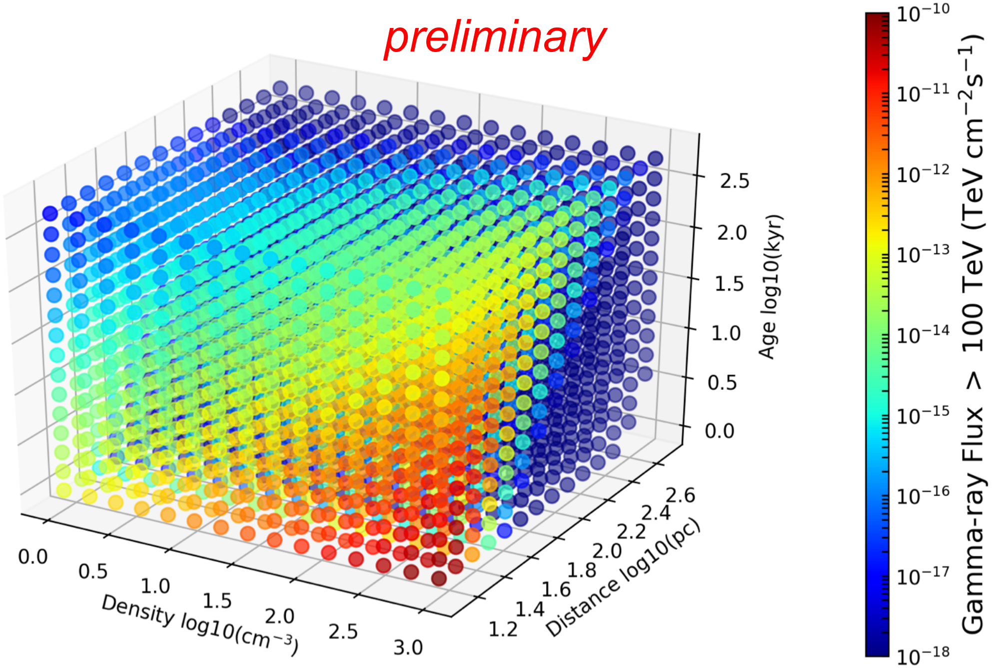




Cloud – SNR properties: phase space for PeVatron signatures

Lines of constant flux & CTA-South 50 h sensitivity at 100 TeV





Integral flux above 100 TeV with n, d, t

SNR and Cloud catalogues

What about real SNRs and clouds?

→Use Green's catalogue for SNR (2019)

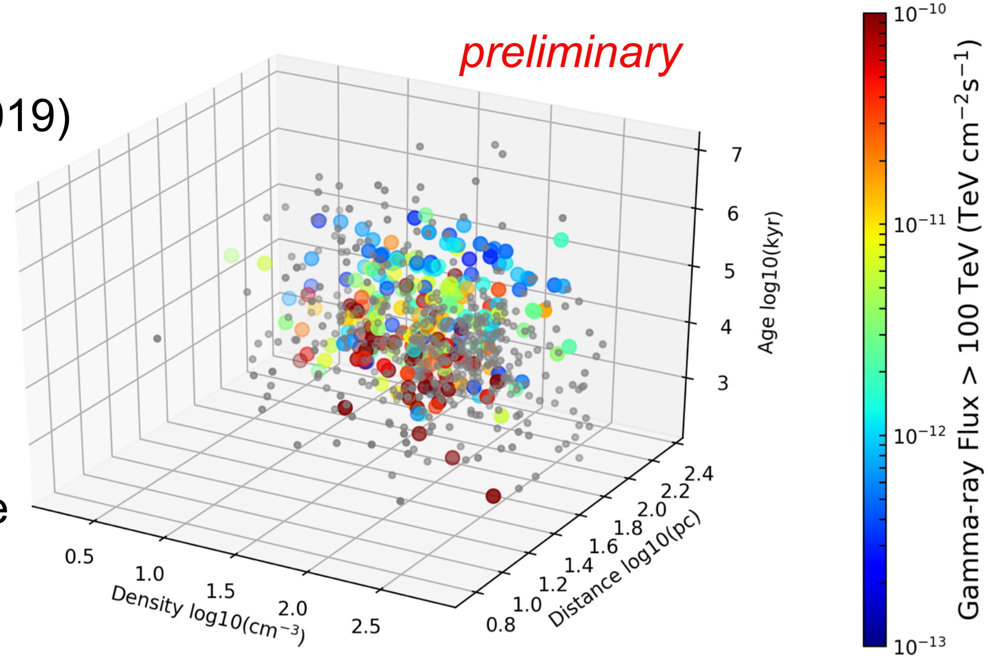
→Use Rice et al 2016 for clouds (CO from Dame et al survey)

Caveat: very few SNRs have a distance estimate → if not available, SNR assumed to be at same distance as cloud.

→ Look for SNR & cloud within 100 pc.

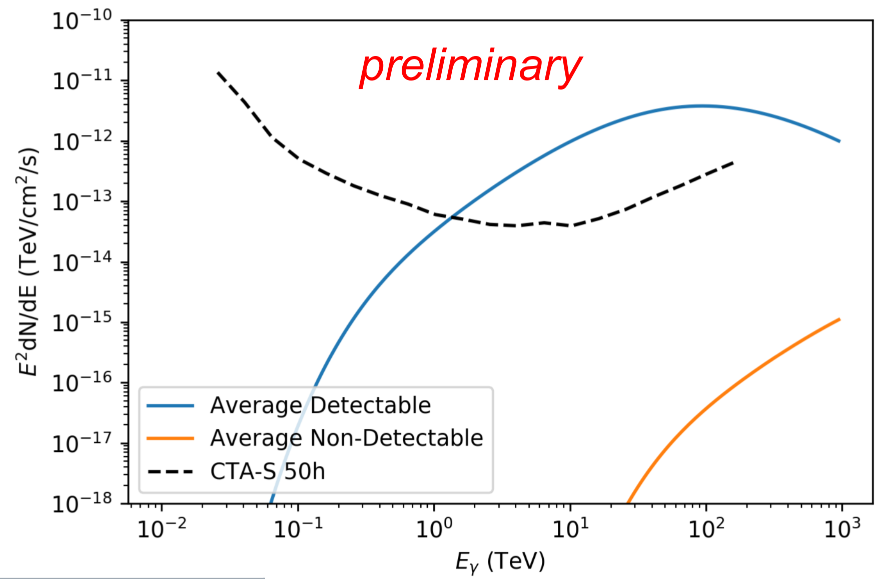
690 SNR-cloud pairs found; about half **(~340)** result in a VHE gamma-ray flux.

About half of these predicted to be detectable by CTA (~180 slow D, ~140 fast D)



Properties of detectable systems

What renders an SNR-cloud system detectable?



Consider median properties: (slow D)

Property	Detectable	Non-detectable
Distance	4.38 kpc	4.42 kpc
SNR age	32 kyr	9 kyr
SNR-cloud separation	56 pc	72 pc
Cloud density	65 cm^{-3}	74 cm^{-3}
Cloud mass	9.2 x10^4 M_{sun}	7.0 x10^4 M_{sun}
Cloud radius	25 pc	21 pc

<u>On average:</u>

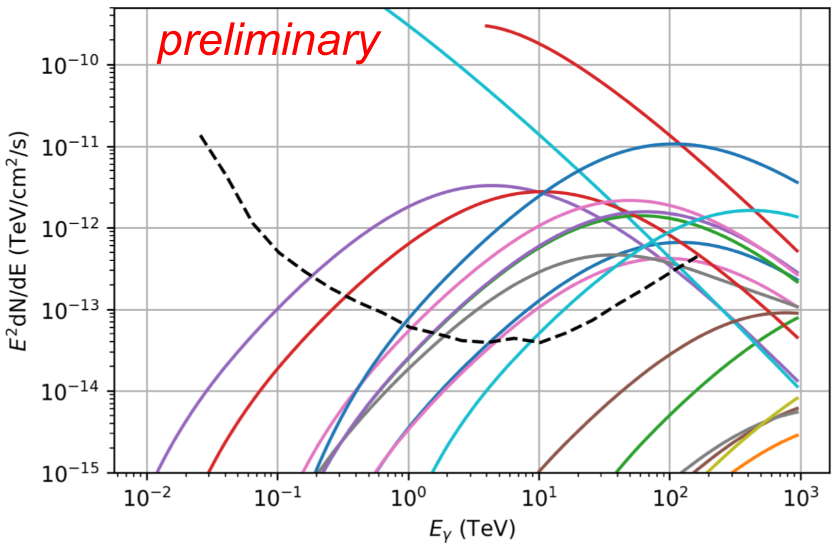
← Older

← Closer

← More target material

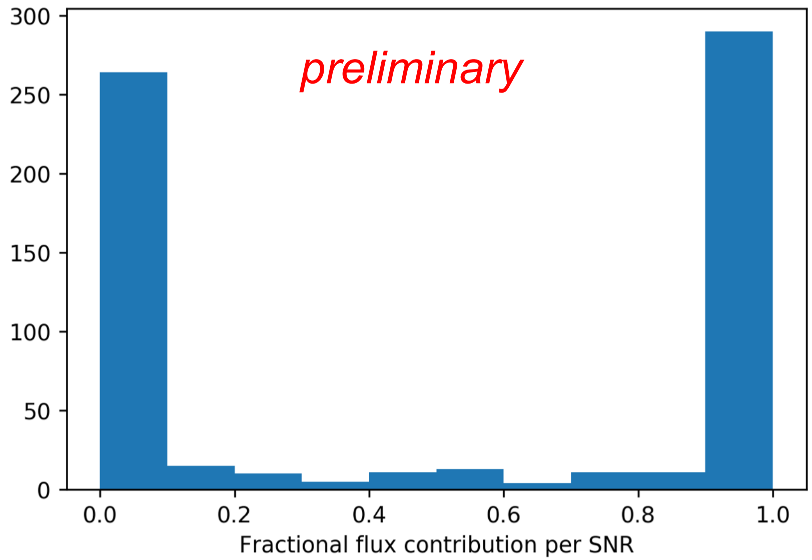
Gamma-ray spectra from clouds: multiple SNR?

Example gamma-ray spectra shown for an arbitrary sub-sample of clouds.



All contributions from different SNRs are summed to provide the total gamma-ray spectrum.

However, in most cases the flux is dominated by the contribution from a single SNR.

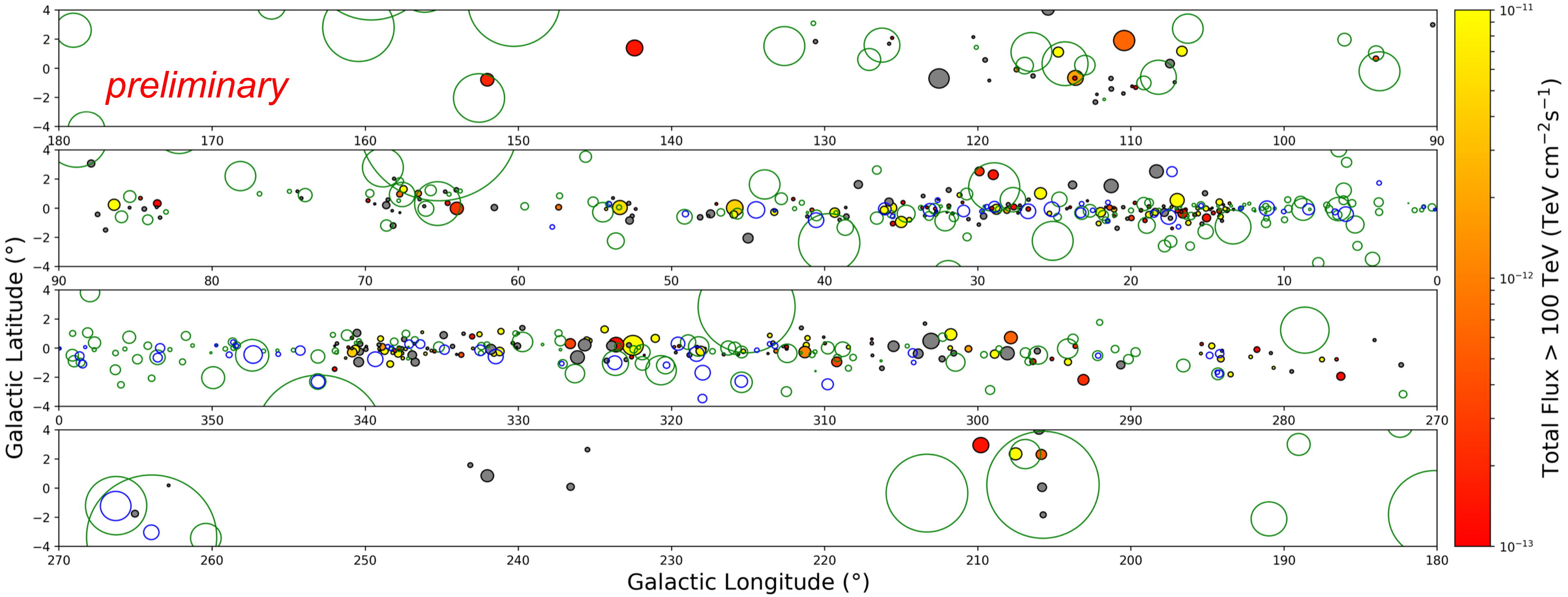


Clouds in the Galactic Plane: γ-rays above 100 TeV

SNR are shown in green, HGPS sources in blue.

Detectable clouds with colour-scale integral flux.

Non-detectable clouds shown in grey.



Other aspects & work in progress

Hypothetical SNRs:

- Far fewer SNR seen than expected: use pulsars to trace hypothetical SNRs
- use characteristic age and original location of pulsar (proper motion) for SNR
- Include additionally these contributions

Upper limits:

- In region covered by HESS Galactic Plane Survey; can extract upper limits, scale to cloud angular size and compare to predicted flux
- If upper limit is violated, one or more of the assumptions are wrong:
  → Constrain SNR distance?
  → Constrain diffusion properties & B-field?

Systematic uncertainties:

- due to (e.g.) particle spectrum index. Using 1.8 or 2.2 instead of $\alpha = 2$ changes flux by a factor ~ 20.

Conclusions

- Interstellar clouds are promising targets to search for evidence of PeVatron activity
- Favourable properties include larger clouds and older SNRs
- A ranked shortlist of promising clouds for CTA will be produced
- Upper limits can be used to constrain SNR distance and/or diffusion properties*
  (*albeit loosely, depending on model assumptions)
- A similar approach can be followed for other classes of accelerators

Thank you for your attention

Any questions?