Investigating the CREDIT history of supernova remnants as cosmic-ray sources

Philipp Mertsch
with Anton Stall and Chun Khai Loo

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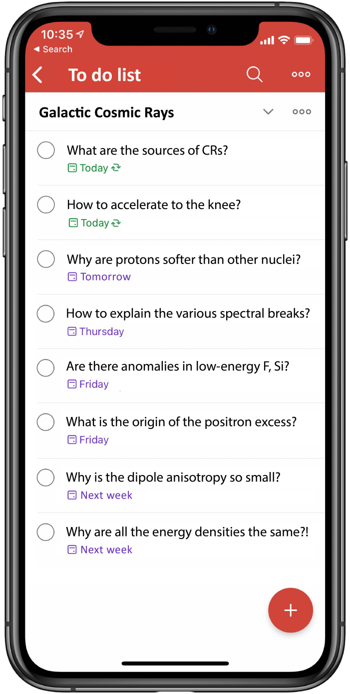
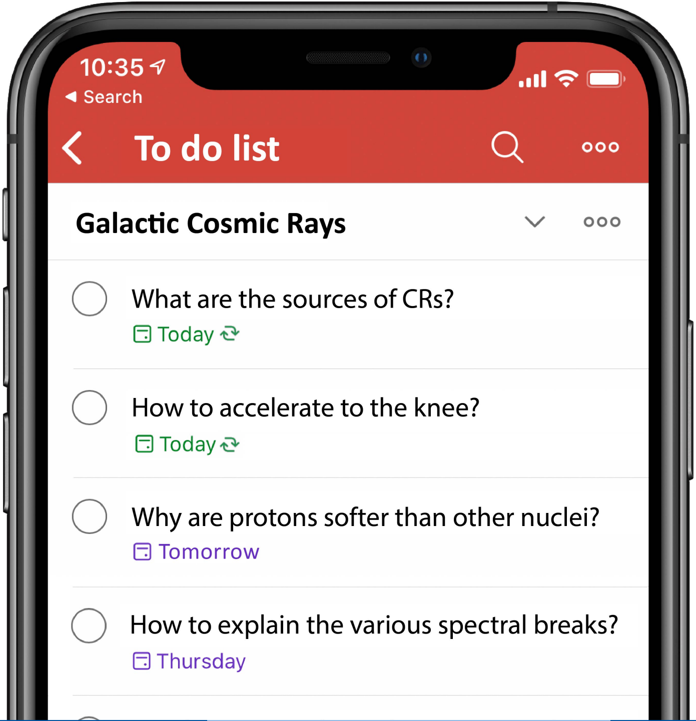
Institute for Theoretical Particle Physics and Cosmology
RWTH AACHEN UNIVERSITY


10:35
Search
To do list
Galactic Cosmic Rays
What are the sources of CRs?
Today
How to accelerate to the knee?
Today
Why are protons softer than other nuclei?
Tomorrow
How to explain the various spectral breaks?
Thursday
Are there anomalies in low-energy F, Si?
Friday
What is the origin of the positron excess?
Friday
Why is the dipole anisotropy so small?
Next week
Why are all the energy densities the same?!
Next week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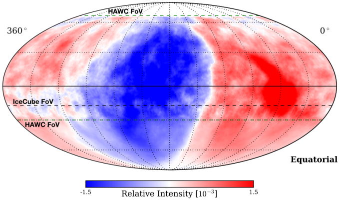
Supernova remnants have long been considered the sources of cosmic rays

1. Observations
2. Energetics
3. Shock acceleartion

Lopez and Fesene (2018)

We do not know individual sources of *local* cosmic rays

Anisotropies:



Problem: cosmic rays diffuse

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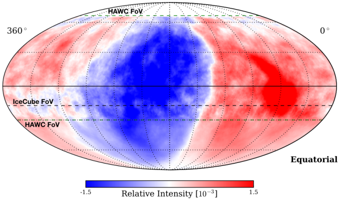
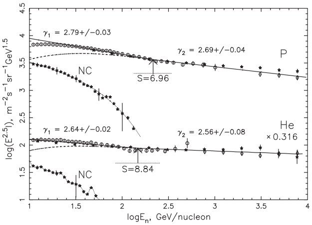


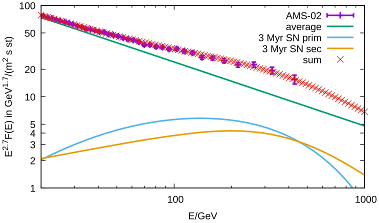
Problem: cosmic rays diffuse

Spectrum:

Erlykin and Wolfendale (2012)



Kachelrieß *et al.* (2018)



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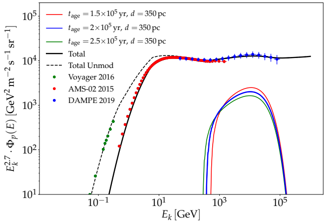

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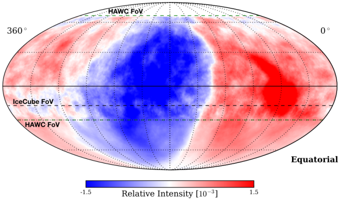

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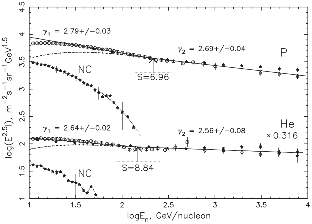

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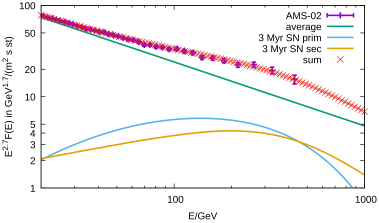

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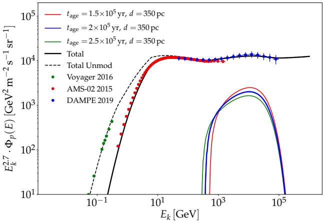
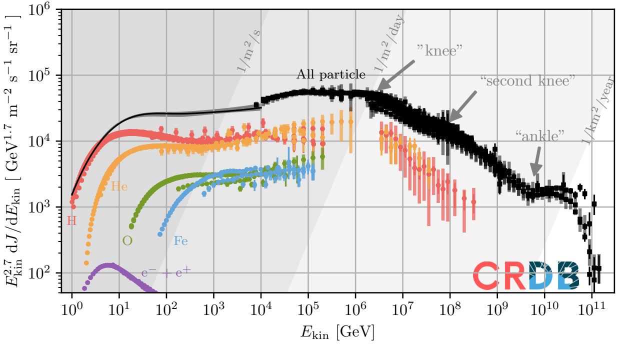


Supernova remnant paradigm

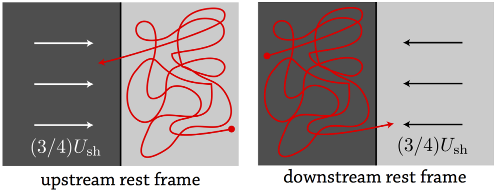
1 000 - 100 000 "active" supernova remnants in the Galaxy

Genolini *et al.* (2017)

Galactic sources should accelerate to E_{knee}, probably via shock acceleration



Axford, Leer, Skadron (1977); Krymskii (1977); Bell (1978); Blandford, Ostriker (1978)



- $E_{\mathrm{knee}} \simeq 3\,\mathrm{PeV}$:
  either maximum energy of source or change in transport regime

$\rightarrow$ $E_{\mathrm{max}} \gtrsim 3\,\mathrm{PeV}$ for protons

Small energy gain ΔE, little particle loss ΔN per cycle

$$\left.\begin{aligned} \frac{\Delta E}{E} &\propto \frac{U_{\mathrm{sh}}}{c} \\ \frac{\Delta N}{N} &\propto \frac{U_{\mathrm{sh}}}{c} \end{aligned}\right\} \Rightarrow \frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-2}$$

We do not understand how supernova remnants accelerate to E_{knee}

What is $E_{\max}$?

- Equate age with acceleration time: $t_{\mathrm{age}} = t_{\mathrm{acc}} = 8 \frac{\kappa}{U_{\mathrm{sh}}^2}$ ← Diffusion coefficient
- Assume Bohm diffusion: $\kappa = \frac{c \ell_{\mathrm{mfp}}}{3} = \frac{c r_{\mathrm{g}}}{3} = \frac{c}{3} \frac{E_{\max}}{qB}$ (Gyro radius → r_{g})
- Hillas-like relation: $\Rightarrow E_{\max} \simeq \frac{U_{\mathrm{sh}}^2}{c} qB t_{\mathrm{age}}$ or $\frac{U_{\mathrm{sh}}}{c} qBR$

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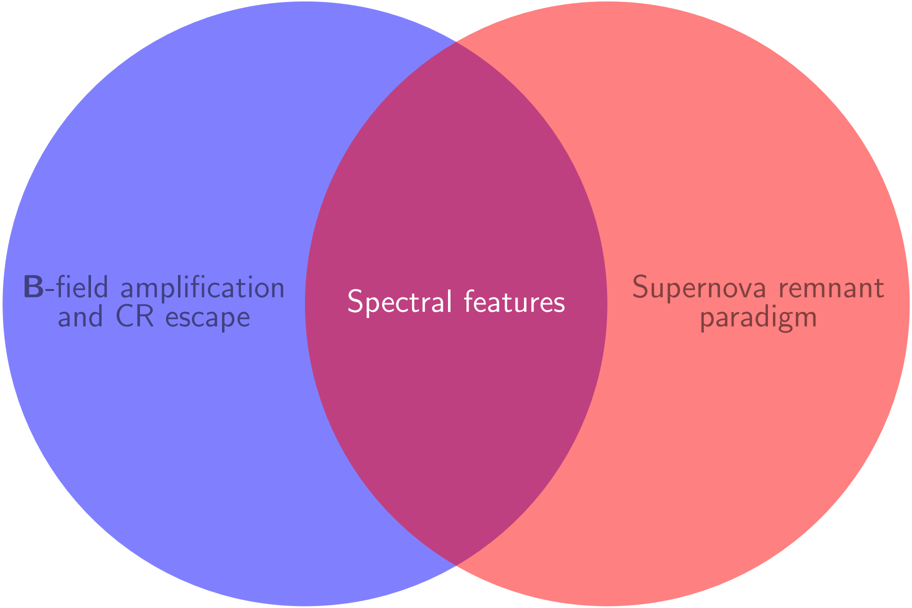
- With typical values: $U_{\text{sh}} = 10^4\,\text{km}\,\text{s}^{-1}\,, \quad B = 1\,\mu\text{G}\,, \quad t_{\text{age}} = 10^3\,\text{yr}$

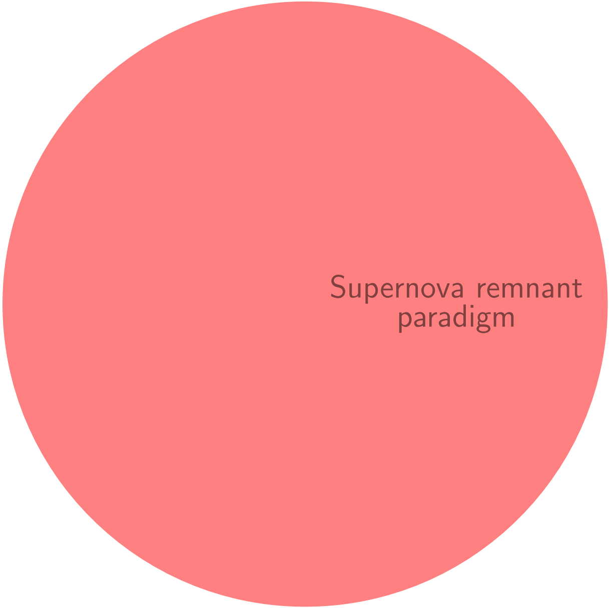
$$\Rightarrow E_{\text{max,b}} \simeq 100\,\text{TeV} \ll E_{\text{knee}}$$

Lagage and Cesarsky (1983)

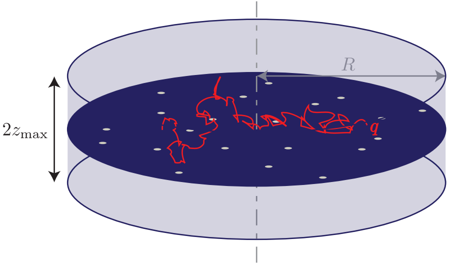
1. Choosing larger t_{age} does not help: $U_{\text{sh}} \propto t_{\text{age}}^{-3/5}$, so E_{max} decreases with time
2. Need to amplify **B**-field to $B \simeq 100\,\mu\text{G}$

Combining standard ingredients, we predict novel spectral features




Supernova remnant
paradigm

The number of sources contributing to CR flux decreases with energy



- Residence time: $t_{\text{esc}} = \frac{z_{\text{max}}^2}{2\kappa}$
- Diffusion distance: $R = \sqrt{2\kappa t_{\text{esc}}} = z_{\text{max}}$
- Source density: $\sigma = \frac{\nu t_{\text{esc}}}{\pi R_{\text{disk}}^2}$
- Source number: $N_{\text{src}} = \sigma \pi R^2 = \nu t_{\text{esc}} \frac{z_{\text{max}}^2}{R_{\text{disk}}^2}$

With typical parameters (for details $\rightarrow$ Appendix):

$$\mathcal{R} = 10\,\text{GV}\,, \quad 10\,\text{TV}\,, \quad 10\,\text{PV}$$
$$N_{\text{src}} \simeq 2 \times 10^4\,,\ 200\,, \quad 4$$

Source density is oftentimes considered smooth, while it really is discrete

Transport equation

$$\frac{\partial \psi}{\partial t} - \boldsymbol{\nabla} \cdot \kappa \cdot \boldsymbol{\nabla} \psi + \ldots = q$$

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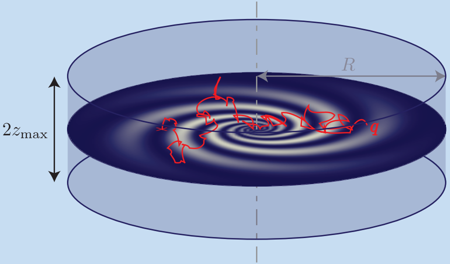
Smoth source density



$$q = q(\mathbf{r}, t, E) = \nu \, \rho(\mathbf{r}) \, Q(E)$$

SN rate

smooth function

spectrum

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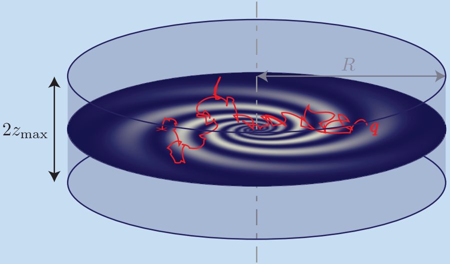

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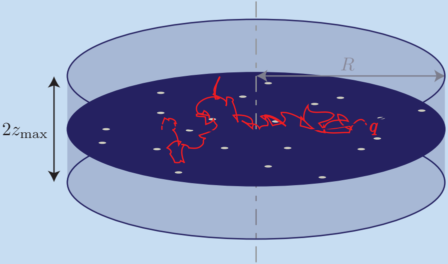
Discrete sources



$$q = q(\mathbf{r}, t, E) = \sum_i \delta^{(3)}(\mathbf{r} - \mathbf{r}_i)\delta(t - t_i)Q(E)$$

$\mathbf{r}_i$ drawn from $\rho(\mathbf{r})$ and t_i from uniform distribution

Source density is oftentimes considered smooth, while it really is discrete

Transport equation

$$\frac{\partial G}{\partial t} - \nabla \cdot \kappa \cdot \nabla G + \ldots = \delta^{(3)}(\mathbf{r} - \mathbf{r}_i)\delta(t - t_i)Q(E)$$

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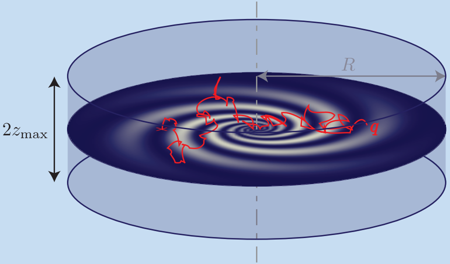

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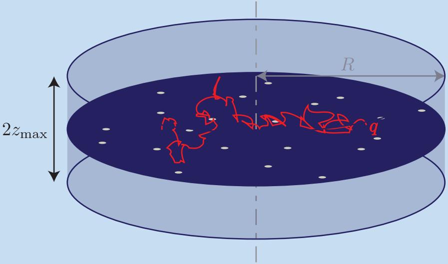

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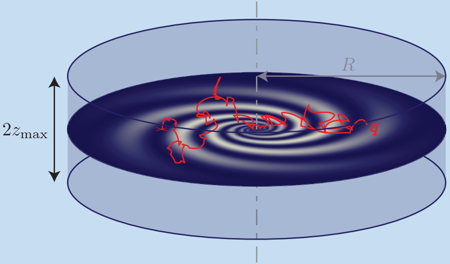

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$$\psi(\mathbf{r}, t, E) = \int \mathrm{d}^3\mathbf{r}'\mathrm{d}t'\, \nu\, \rho(\mathbf{r}')\, G(\mathbf{r} - \mathbf{r}', t - t', E)$$

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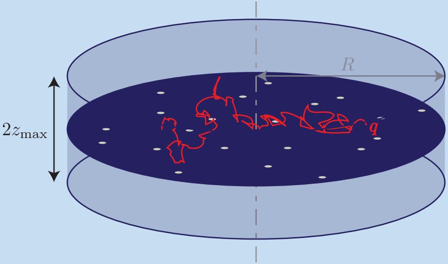

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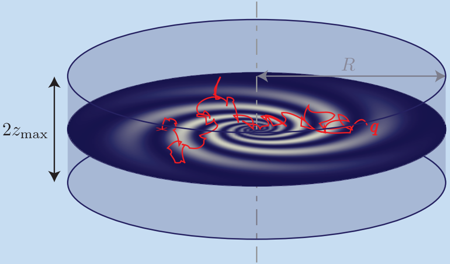

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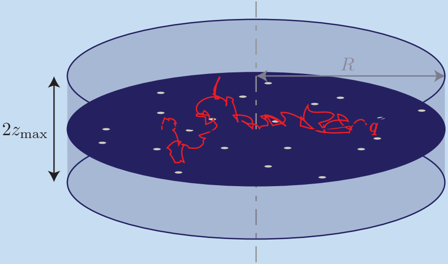

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Stochastic nature of sources implies fluctuations in spectrum

- Solution: $$\psi(\mathbf{r}, t, p) = \sum_i G(\mathbf{r} - \mathbf{r}_i, t - t_i, E)$$
- $\mathbf{r}_i$, t_i are random variables $\Rightarrow$ $\psi(\mathbf{r}, t, p)$ is random variable
- Mean: $$\langle \psi(\mathbf{x}, t, p) \rangle = \int \mathrm{d}^3\mathbf{r}' \mathrm{d}t' \, \nu \, \rho(\mathbf{r}') \, G(\mathbf{r} - \mathbf{r}', t - t', E)$$

Can we use $\psi - \langle \psi \rangle$ to find sources?

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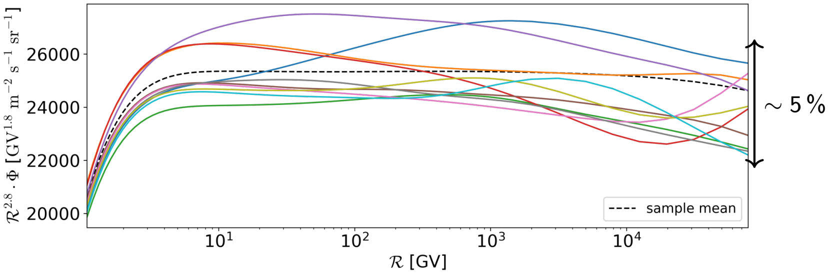

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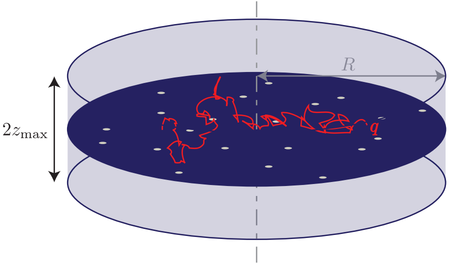

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$$N_{\text{src}} \simeq 2 \times 10^4\,, \; 1\,, \quad 10^{-4}$$

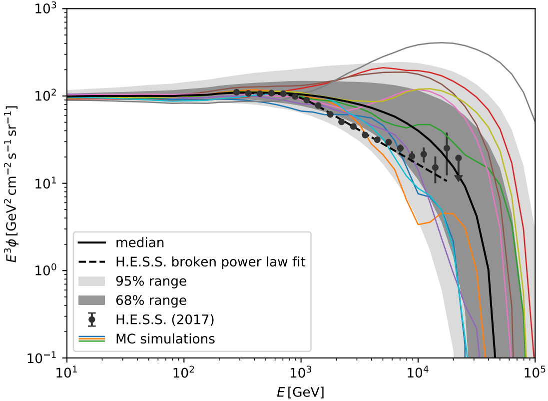
Electrons and positrons at high energies

- Sensitivity to source distances and ages

→ Need to consider when comparing to data

→ Great potential for identifying sources

Mertsch (2018)



Monte Carlo study

1. Draw random distances $\{d_i\}$ and ages $\{t_i\}$
2. Add contributions from $i = 1, \ldots N_{\mathrm{src}}$ sources in *one realisation* of the Galaxy
3. Repeat for *different realisations* of the Galaxy

Density estimation task

N. Frediani, M. Krämer, K. Nippel, P. Mertsch

- Have discrete samples of flux vector $\{\phi_1, \phi_2, \dots \phi_N\}$
- Want multivariate distribution $p(\phi_1, \phi_2, \dots \phi_N)$

$\rightarrow$ Density estimation task

Conditional probabilities

$$p(\phi_1, \phi_2, \dots \phi_N) = p(\phi_1) p(\phi_2|\phi_1) \dots p(\phi_N|\phi_1, \dots \phi_{N-1})$$

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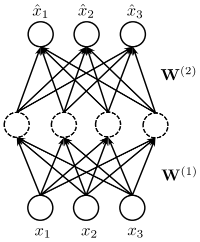

Dense NN

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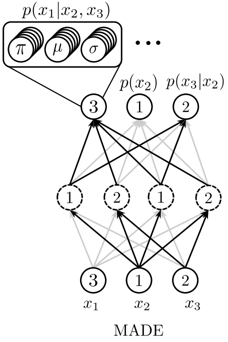

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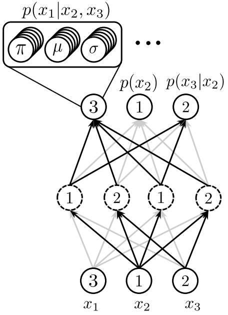

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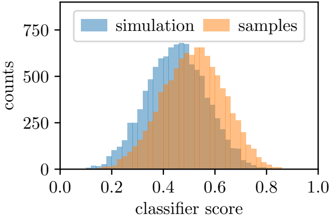
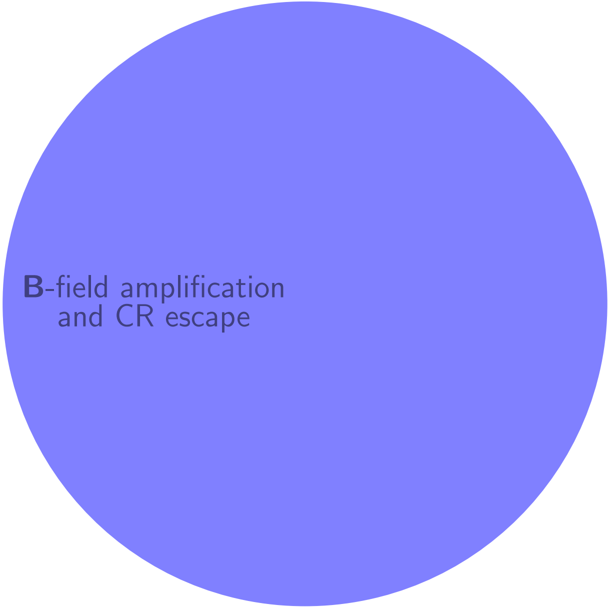
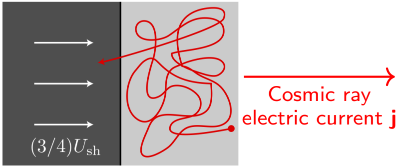



B-field amplification
and CR escape

The Bell instability can amplify B-fields

Bell (2004)



upstream rest frame

- If B-field too weak, particles escape

$\rightarrow$ Electric current **j**

- Waves modes unstable in the presence of current **j**

The Bell instability can amplify B-fields

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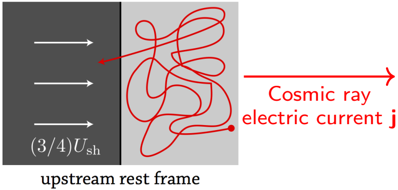

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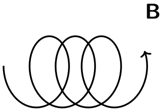

- CRs with gyroradius $r_{\rm g}$ tied to field lines

→ Instability saturates once $\lambda \sim r_{\rm g}$

- **B**-field density satisfies $\varepsilon_B \sim \frac{U_{\rm sh}}{c} \varepsilon_{\rm CR}$

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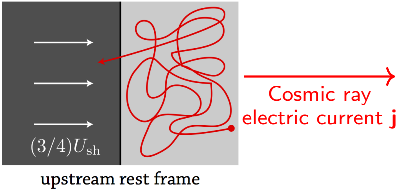

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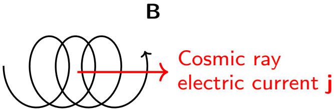

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The Bell instability can amplify B-fields

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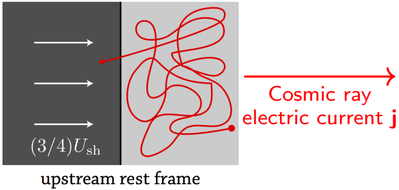
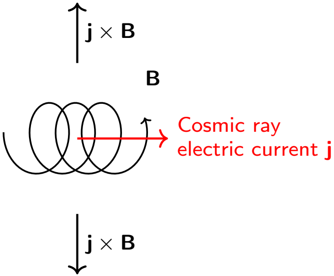


- If B-field too weak, particles escape

→ Electric current **j**

- Waves modes unstable in the presence of current **j**



- CRs with gyroradius r_g tied to field lines

→ Instability saturates once $\lambda \sim r_g$

- **B**-field density satisfies $\varepsilon_B \sim \frac{U_{sh}}{c} \varepsilon_{CR}$

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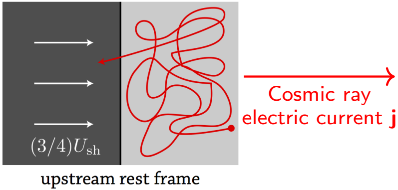

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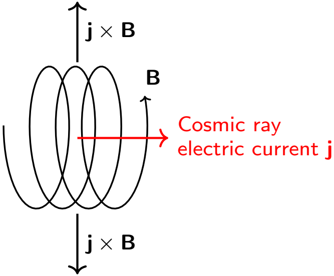

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Bell instability makes optimal use of $\mathbf{j} \times \mathbf{B}$ force

Slide concept: T. Bell

Wave number

- Growth rate: $\gamma \sim \sqrt{\frac{jBk}{\rho}}$ or $\frac{\gamma^2}{k} \sim \frac{jB}{\rho}$
- Compare to acceleration of fluid element of size $z \sim 1/k$ in time $t \sim 1/\gamma$:

$$\frac{z}{t^2} \sim \frac{1}{\rho} |\mathbf{j} \times \mathbf{B}| \lesssim \frac{jB}{\rho} \qquad \rightarrow \qquad \frac{\gamma^2}{k} \lesssim \frac{jB}{\rho}$$

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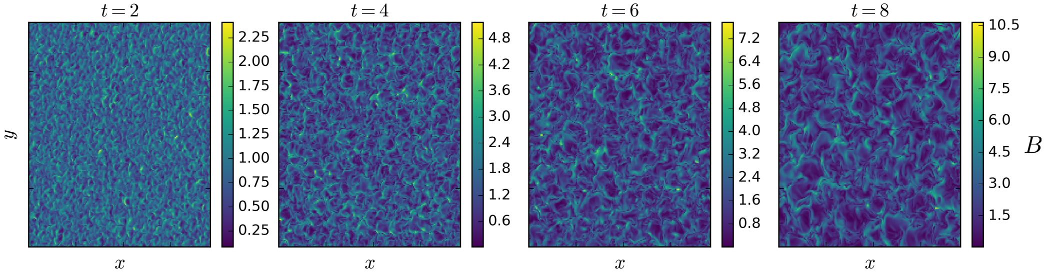
Matthews *et al.* (2017)



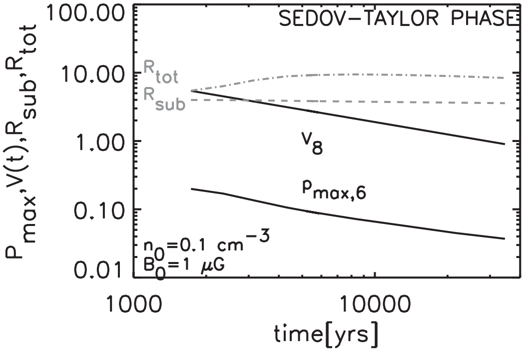
Grows rapidly on small scales

The highest CR energies can be achieved at start of Sedov-Taylor phase

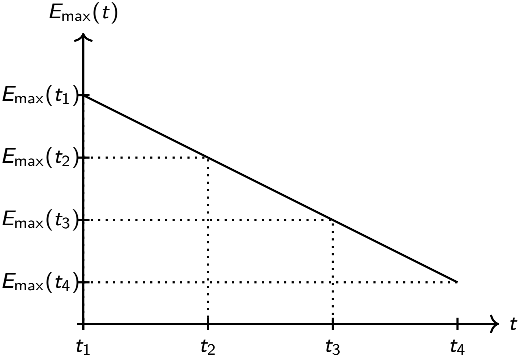
- Shock speed U_{sh} enters into growth rate γ through escape current j
- Saturation field $B \propto U_{\mathrm{sh}}^{3/2}$
- $U_{\mathrm{sh}} \propto t_{\mathrm{age}}^{-3/5}$

$\rightarrow$ $E_{\mathrm{max}} \propto U_{\mathrm{sh}}^2 B t_{\mathrm{age}} \propto t_{\mathrm{age}}^{-11/10}$

Caprioli, Blasi, Amato (2009)



Time-dependence of B-field amplification determines CR escape



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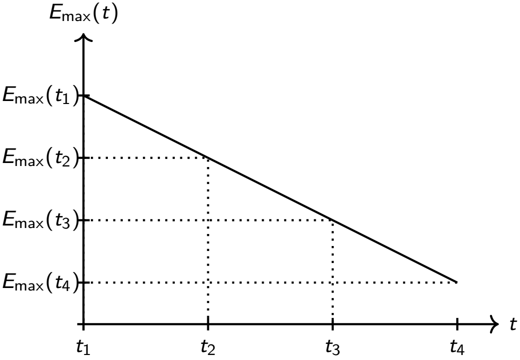

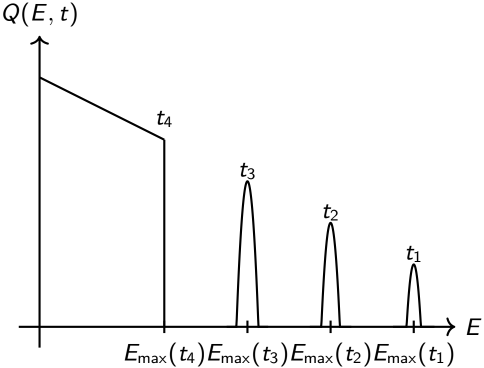

also Gabici, Aharonian, Casanova (2009); Caprioli, Blasi, Amato (2010); Blasi and Amato (2012); Thoudam and Hörandel (2012)

- E_{max} decreases with time
- At any one time t, particles of energy $E_{max}(t)$ escape
- Ultimately, all particles with $E < E_{max,b}$ escape

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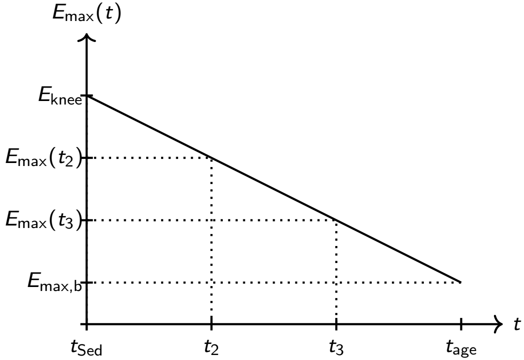

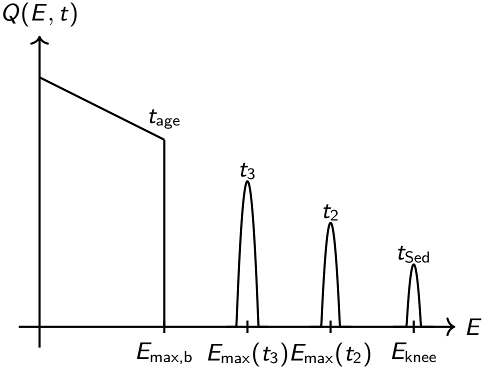

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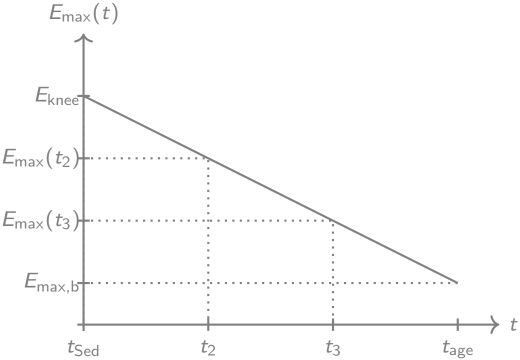

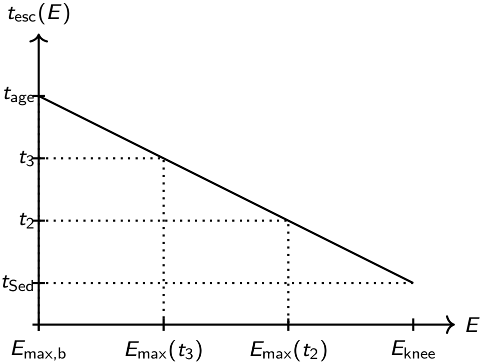

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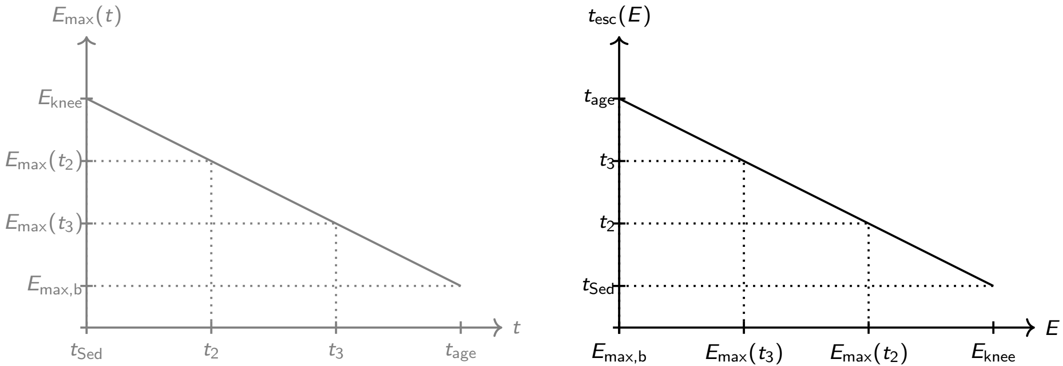
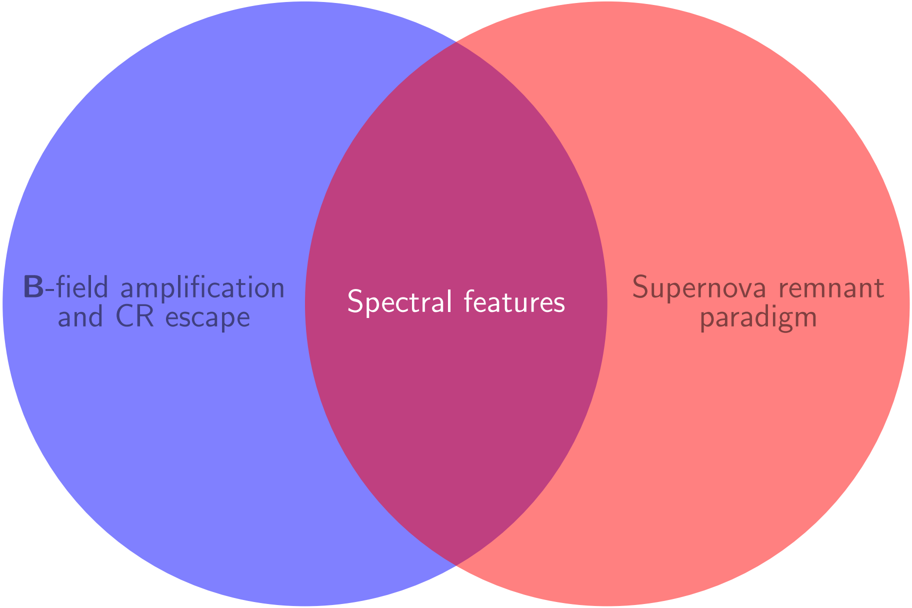
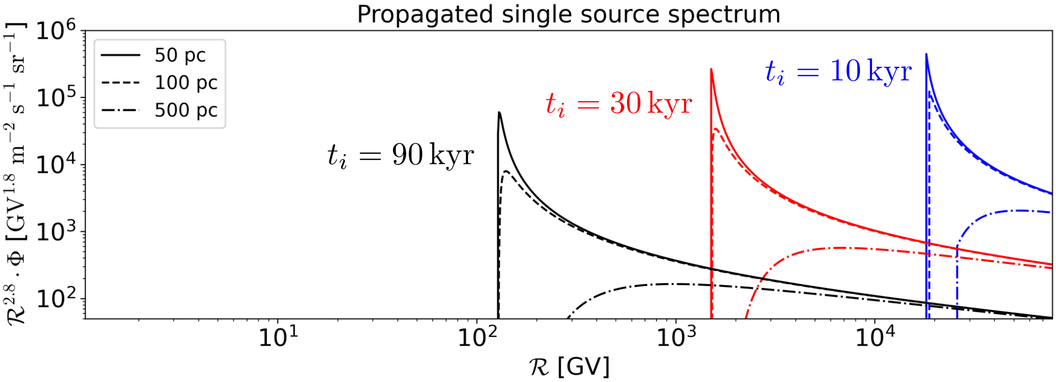


Cosmic-**R**ay **E**nergy-**D**ependent **I**njection **T**ime
(CREDIT) scenario


B-field amplification and CR escape
Spectral features
Supernova remnant paradigm

The Green's function has narrow spectral features

$$\frac{\partial G}{\partial t} - \nabla \cdot \kappa \cdot \nabla G = \delta^{(3)}(\mathbf{r} - \mathbf{r}_i)\delta(t - t_i - t_{\text{esc}}(E))Q(E)$$



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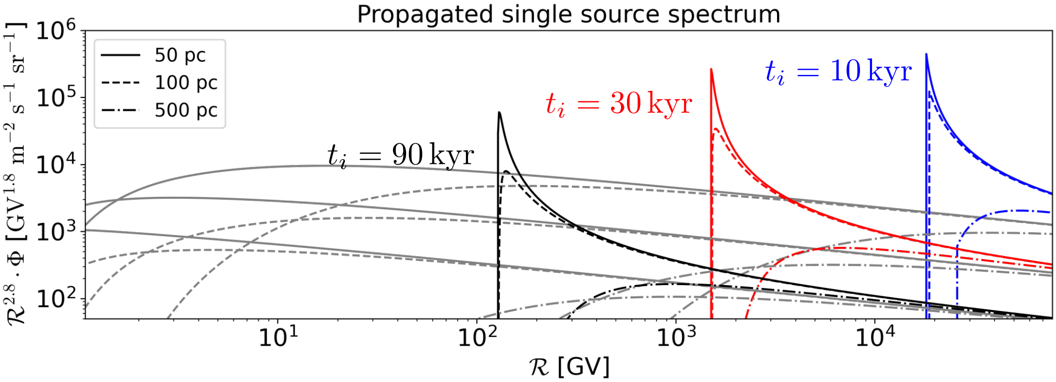

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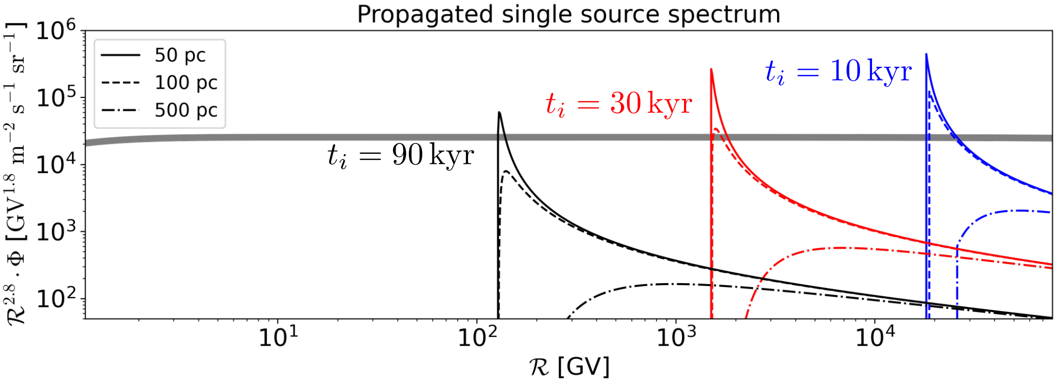
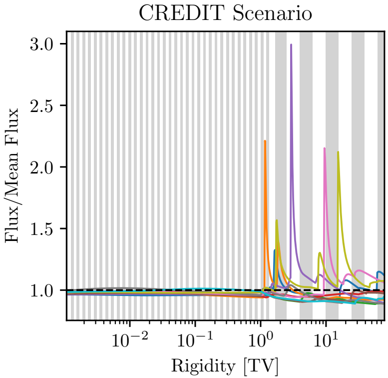


CREDIT scenario predicts dramatic spectral features

Stall, Loo, Mertsch, arXiv:2409.11012



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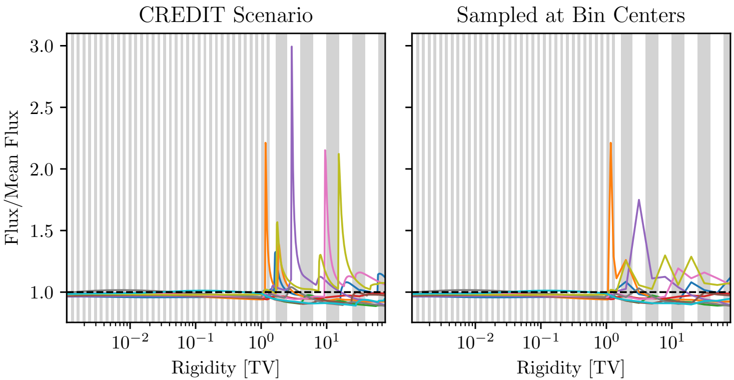
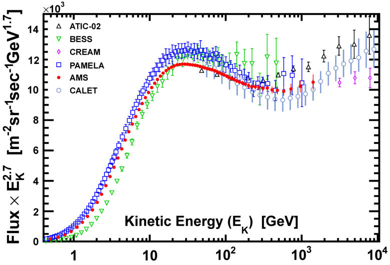
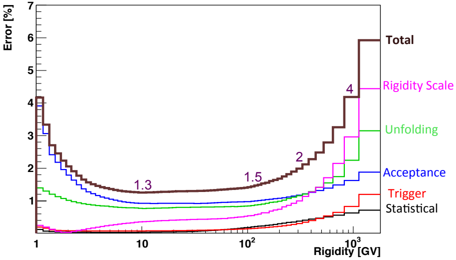


Modern proton data offer unprecedented accuracy

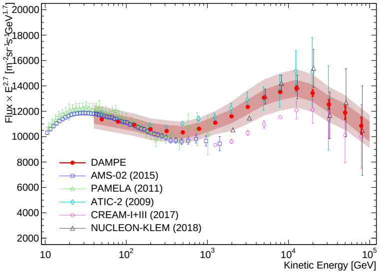
V. Choutko (2015), An *et al.* (2019), Aguilar *et al.* (2020),

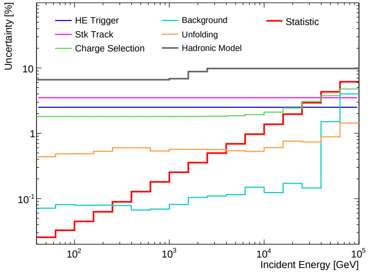
AMS-02





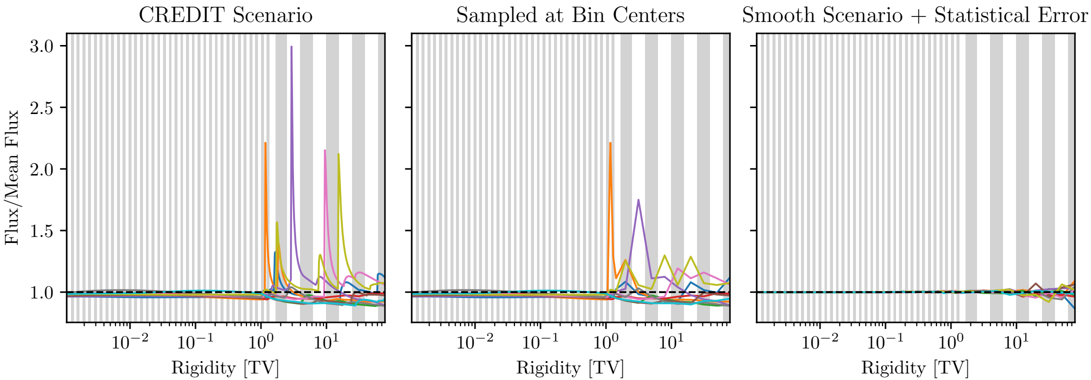
DAMPE





Statistical errors are much smaller than CREDIT features

Stall, Loo, Mertsch, arXiv:2409.11012

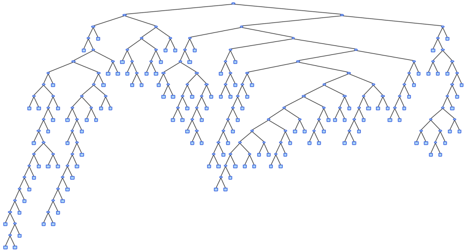


We can confidently discriminate between the different scenarios

Stall, Loo, Mertsch, arXiv:2409.11012

Can discriminate features
from statistical fluctuations?

$\rightarrow$ Classical machine learning task



Decision tree

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Stall, Loo, Mertsch, arXiv:2409.11012

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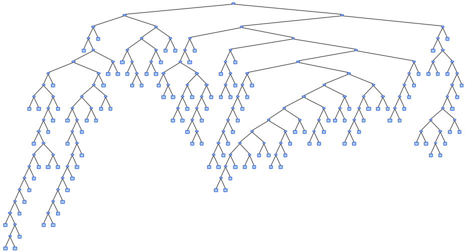

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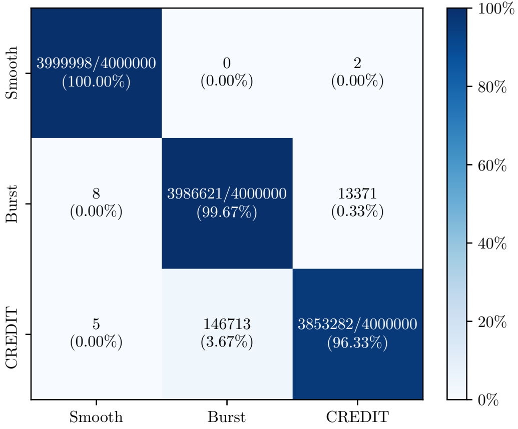
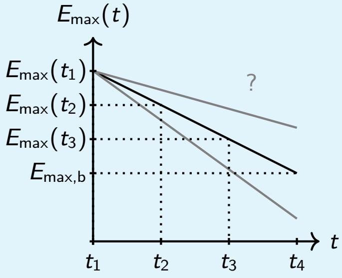


The classification is very robust

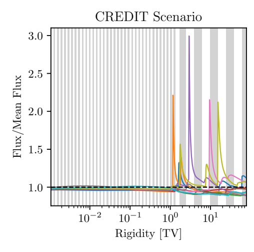
Stall, Loo, Mertsch, arXiv:2409.11012

$E_{\mathrm{max,b}}$ unknown



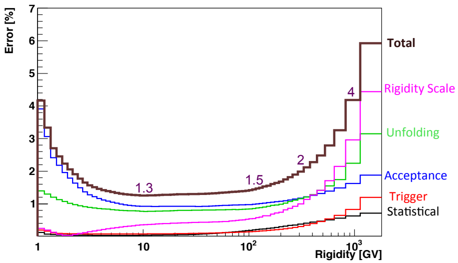
→ $E_{\mathrm{max,b}}$ varied in training

Finite bin widths



→ Integrate over bins

Systematic errors



→ 1 % uncorrelated systematic errors included Aguilar *et al.* (2015); Cavasonza *et al.* (2018)

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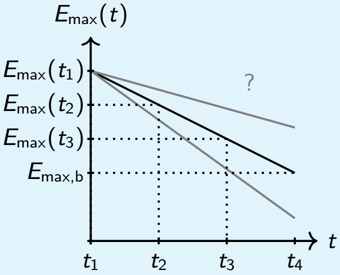

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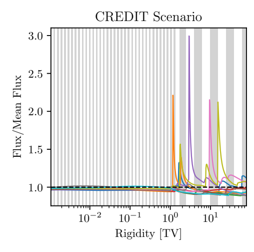

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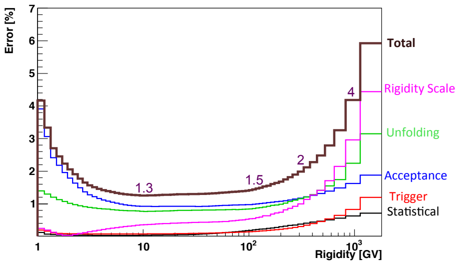

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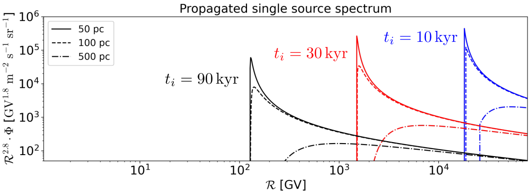
Accuracy virtually unchanged

The results are going to be interesting either way

Classifier finds . . .

1. CREDIT scenario

→ Investigate sources



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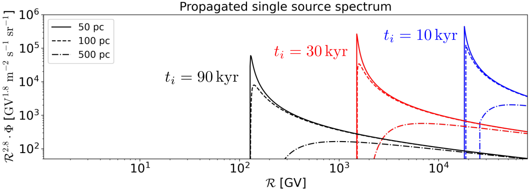
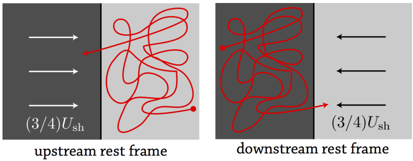


2. Burst-like scenario ($E_{\mathrm{max,b}} \rightarrow \infty$)

$\rightarrow$ Constraints on acceleration models



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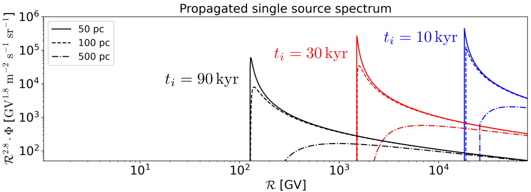

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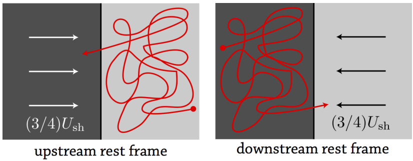
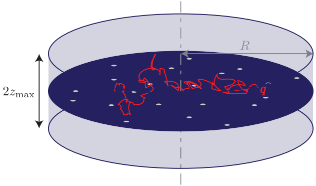
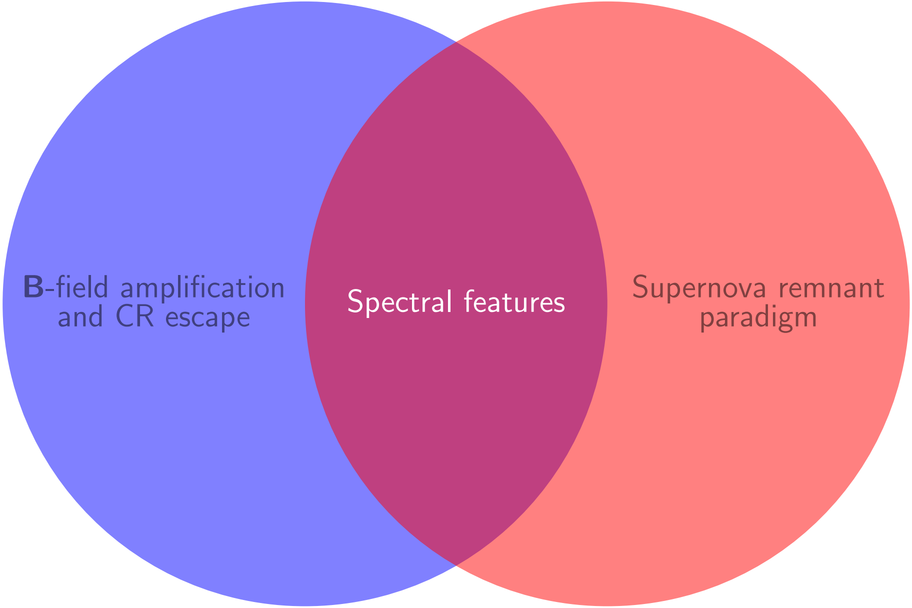


3. Smooth scenario

$\rightarrow$ Trouble for supernova remnant paradigm



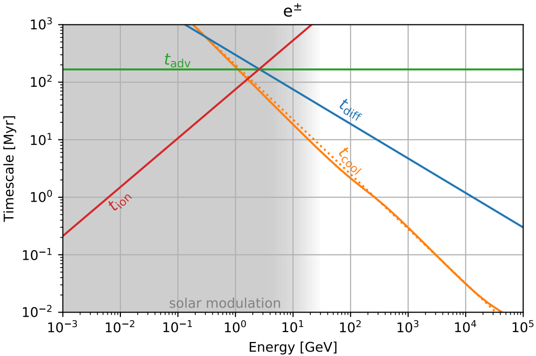
Summary & Conclusion



Backup

Time scales

Time scales:



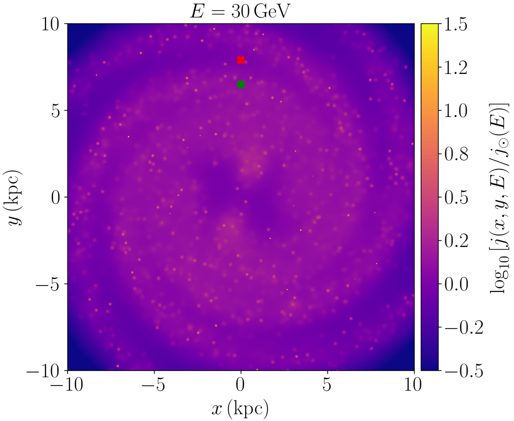
- $t_{diff} = \frac{z_{max}^2}{2\kappa}$ with $z_{max} = 5\,$kpc, $\kappa(10\,\text{GV}) = 5 \times 10^{28}\text{cm}^2\,\text{s}^{-1}$
- t_{cool}: KN cross-section with $\rho = \{0.26, 0.6, 0.6, 0.1\}\,\text{eV}\,\text{cm}^{-3}$ for CMB, IR, opt, UV; $3\,\mu$G B-field
- t_{ion}: $n_H = 0.5\,\text{cm}^{-3}$ (WIM) and $n_H = 0.5\,\text{cm}^{-3}$ (WNM) and 100 pc wide gas disk

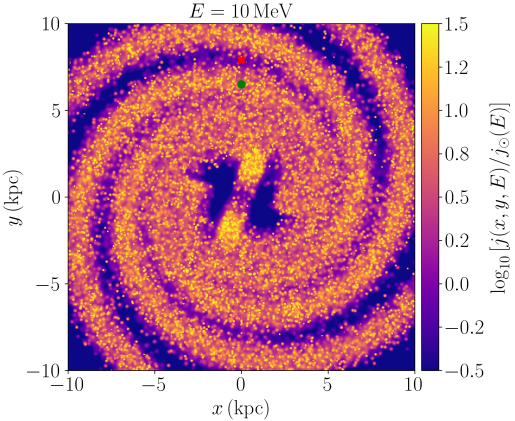
In a diffusion model with $E^{-\Gamma}$ sources in disk:

- $\phi(E) \propto E^{-\Gamma-\delta}$ if diffusion dominated
- $\phi(E) \propto E^{-\Gamma-(\delta+1)/2}$ if cooling dominated

GeV vs MeV

Phan, Schulze, Mertsch, Recchia, Gabici (2023)





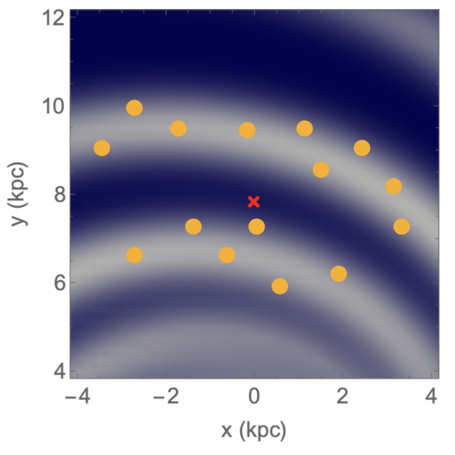
(diffusion-loss length) $\gg$ (average source separation)

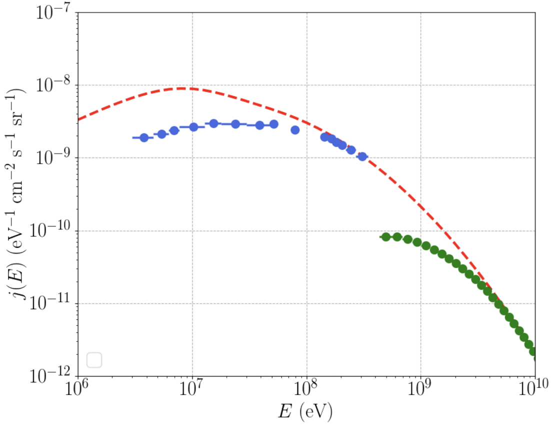
$\Rightarrow$ little fluctuation
$\Rightarrow$ smooth approximation is good

(diffusion-loss length) $\ll$ (average source separation)

$\Rightarrow$ sizeable fluctuations
$\Rightarrow$ smooth approximation is bad

Importance of nearby sources





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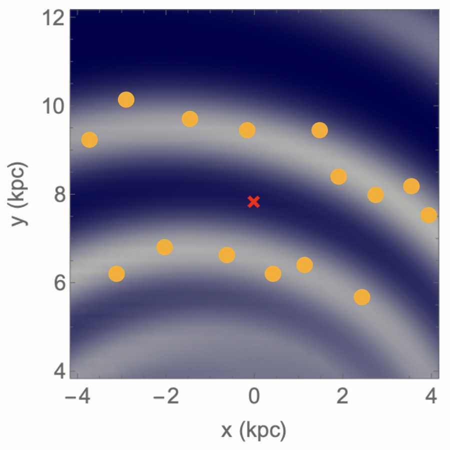

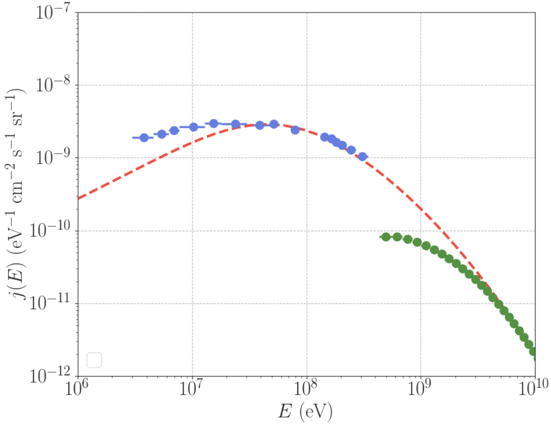

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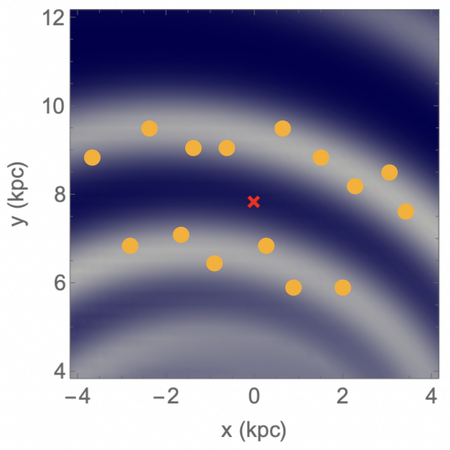

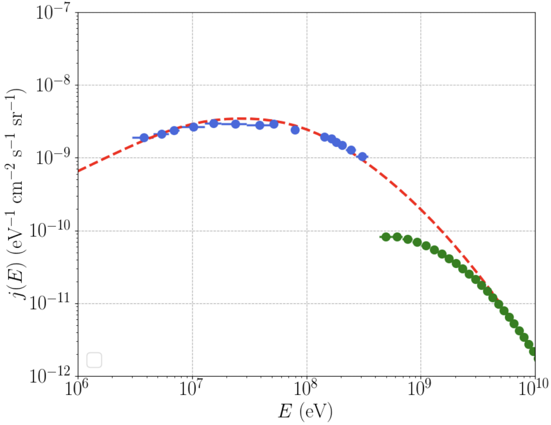

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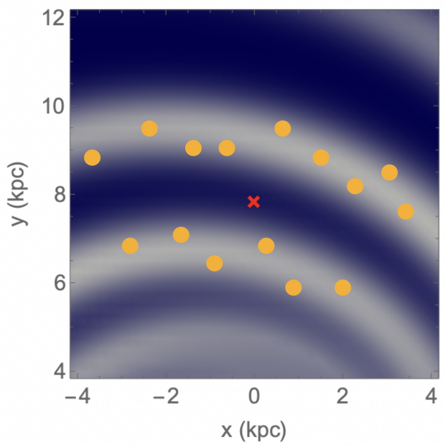
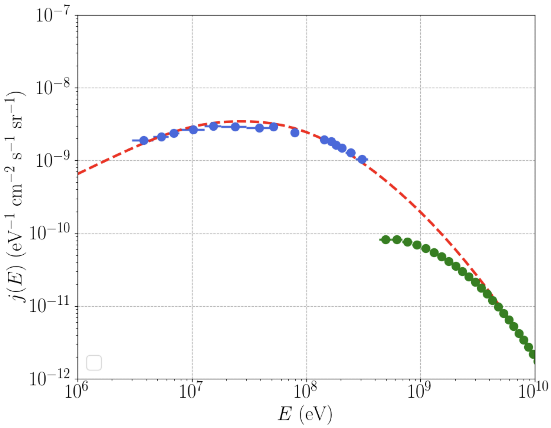
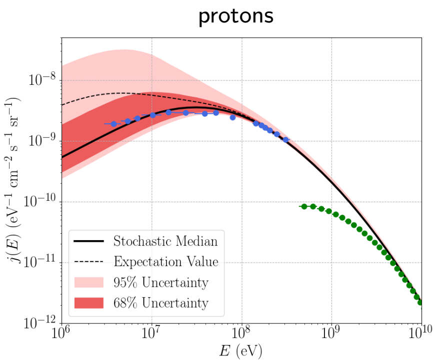


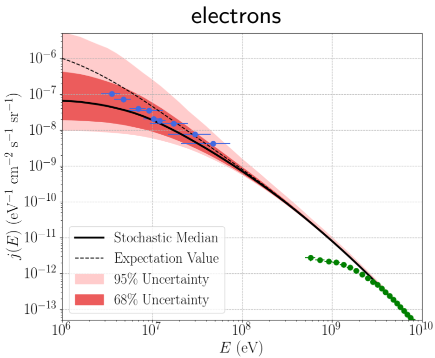


Cosmic ray flux is a stochastic quantity

Results: protons & electrons

Phan, Schulze, Mertsch, Recchia, Gabici (2021)





- Voyager 1 data inside uncertainty band

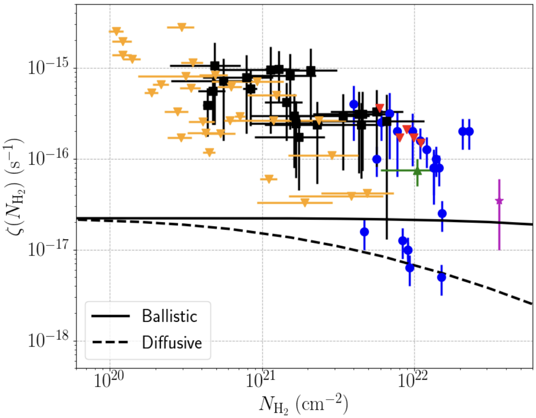
→ Source discreteness effects important

Result # 1

→ No need for unmotivated break in source spectrum!

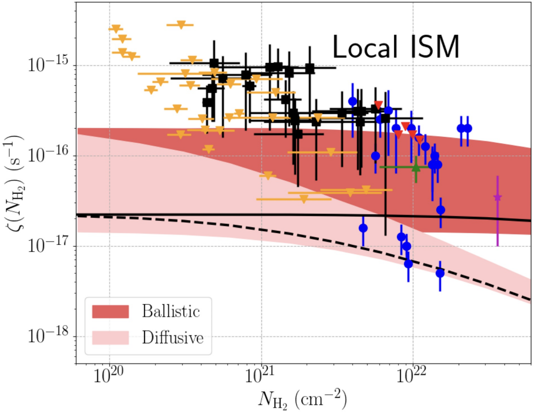
The ionisation puzzle

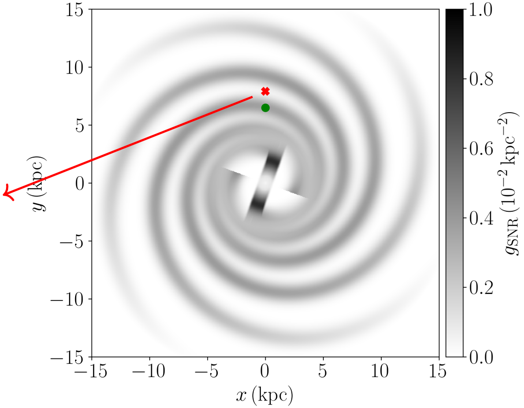
Phan, Schulze, Mertsch, Recchia, Gabici (2023)



The ionisation puzzle

Phan, Schulze, Mertsch, Recchia, Gabici (2023)





Result # 2

- Local ISM: improvement, but still too low

The ionisation puzzle

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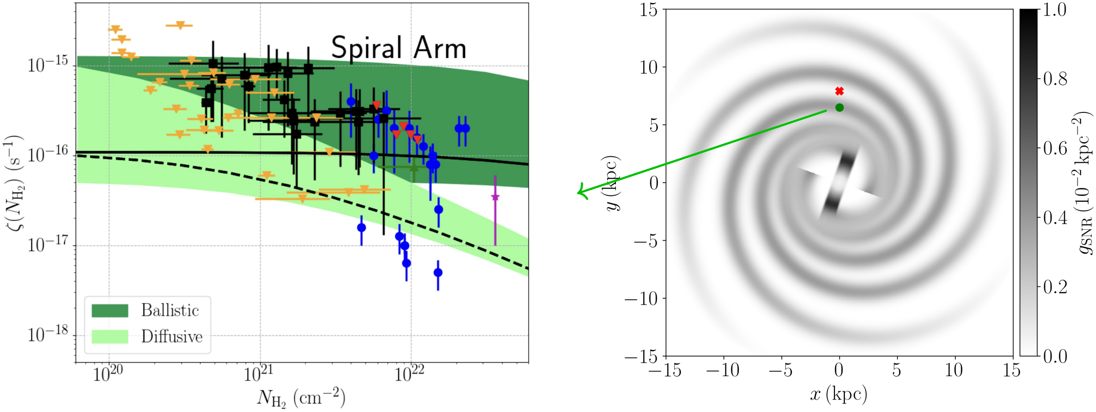

Result # 2

- Local ISM: improvement, but still too low
- Spiral Arm: systematic shift up