

Interacting SNe: super-PeV CR candidates that explain the nuclear composition trends

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Outline

I. CR observations

- Flux
- Composition

II. Interacting SNe CRs

- Max energies
- Nuclei injection

III. Data comparison

- Flux
- Composition

IV. Summary and outlook

- Interacting SNe provide flux and composition at super-PeV
- Multimessenger tests?

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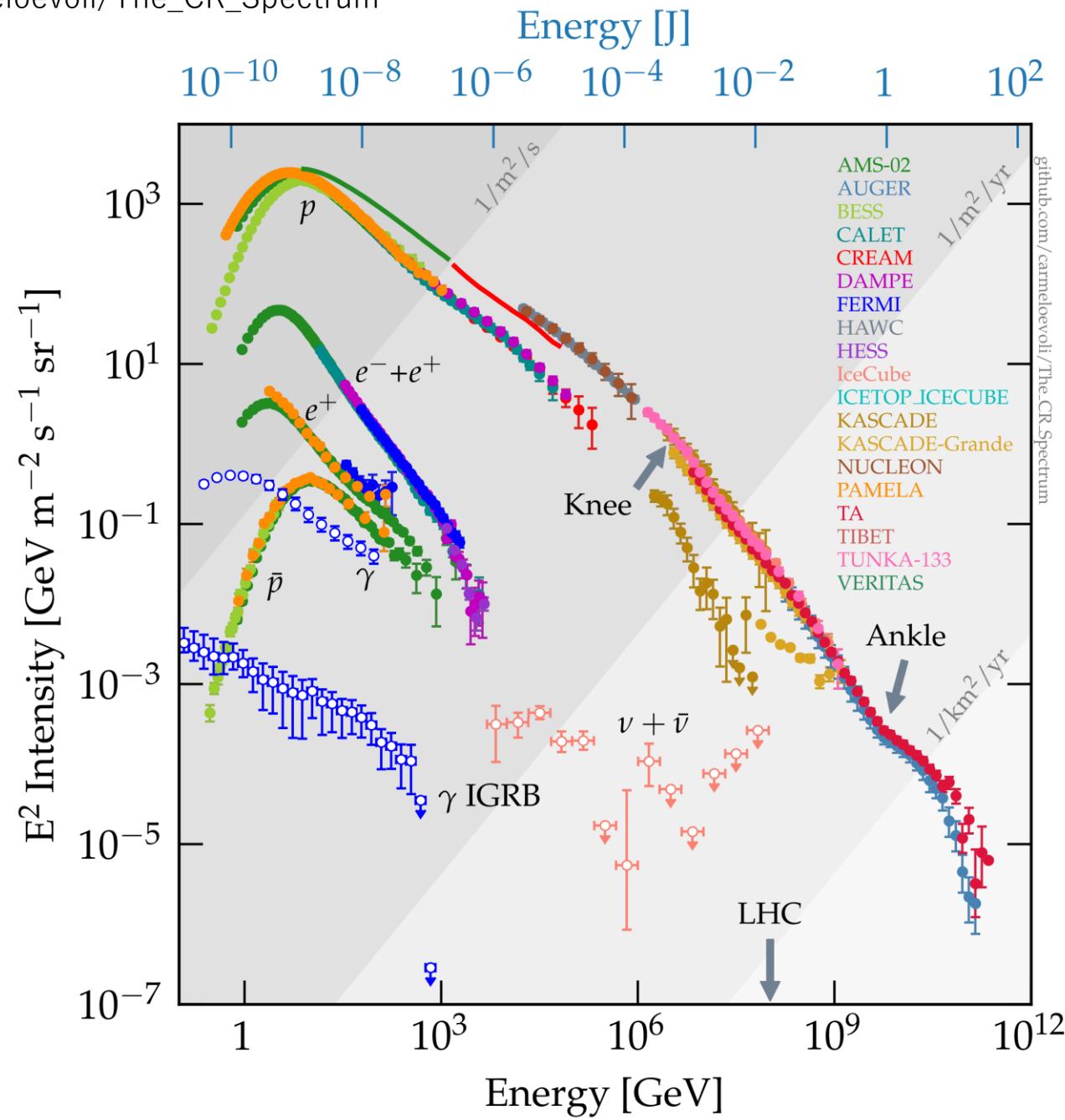
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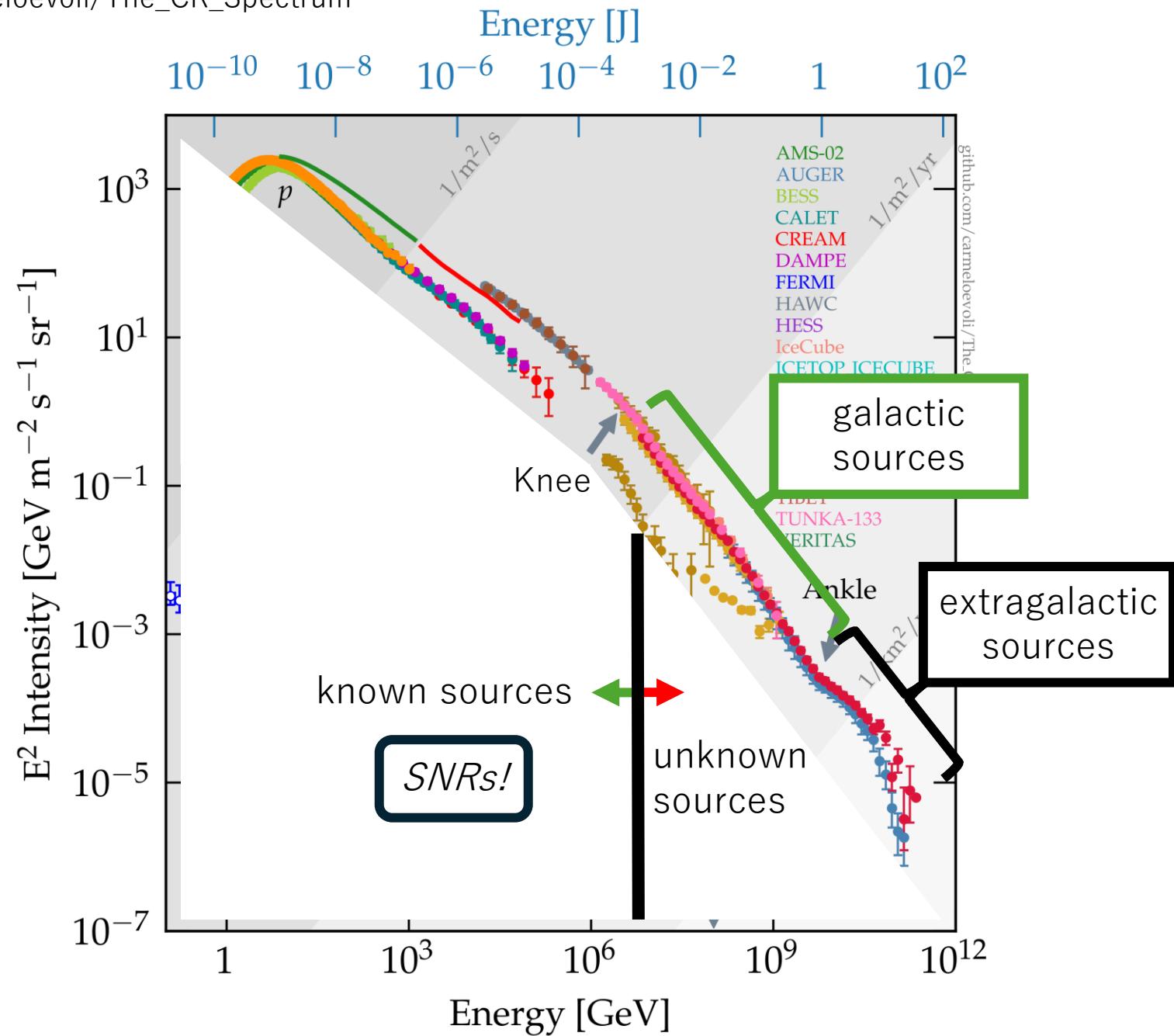
III. Data comparison

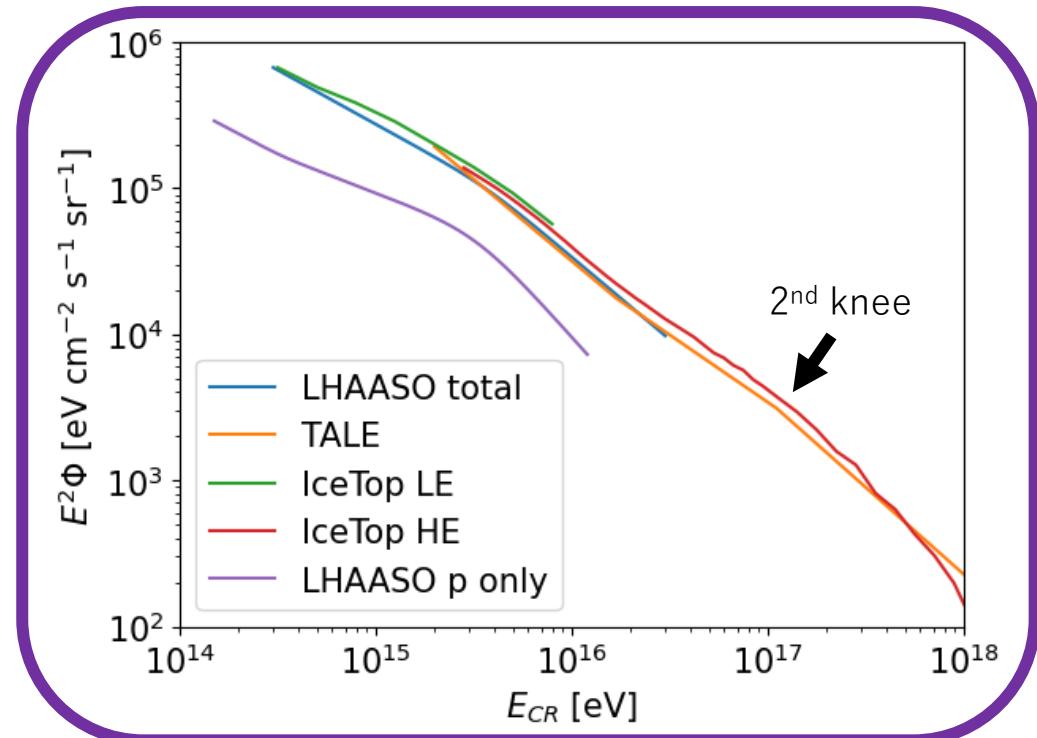
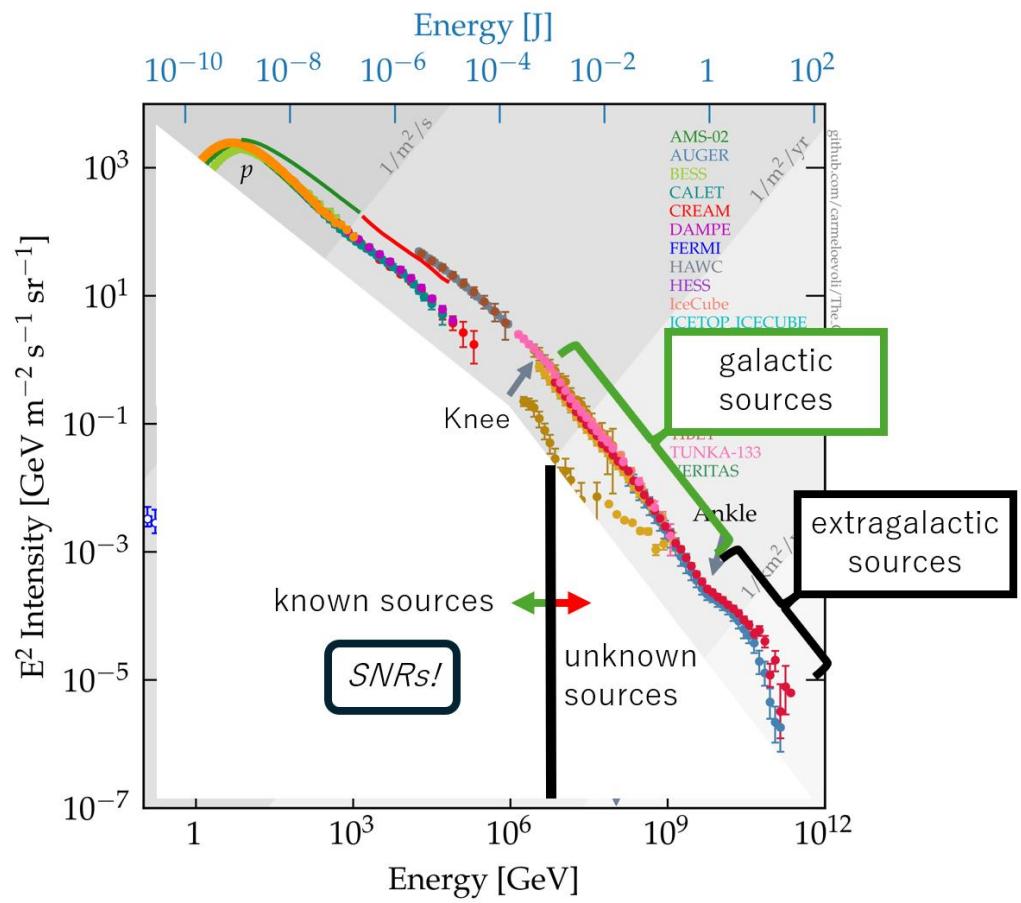
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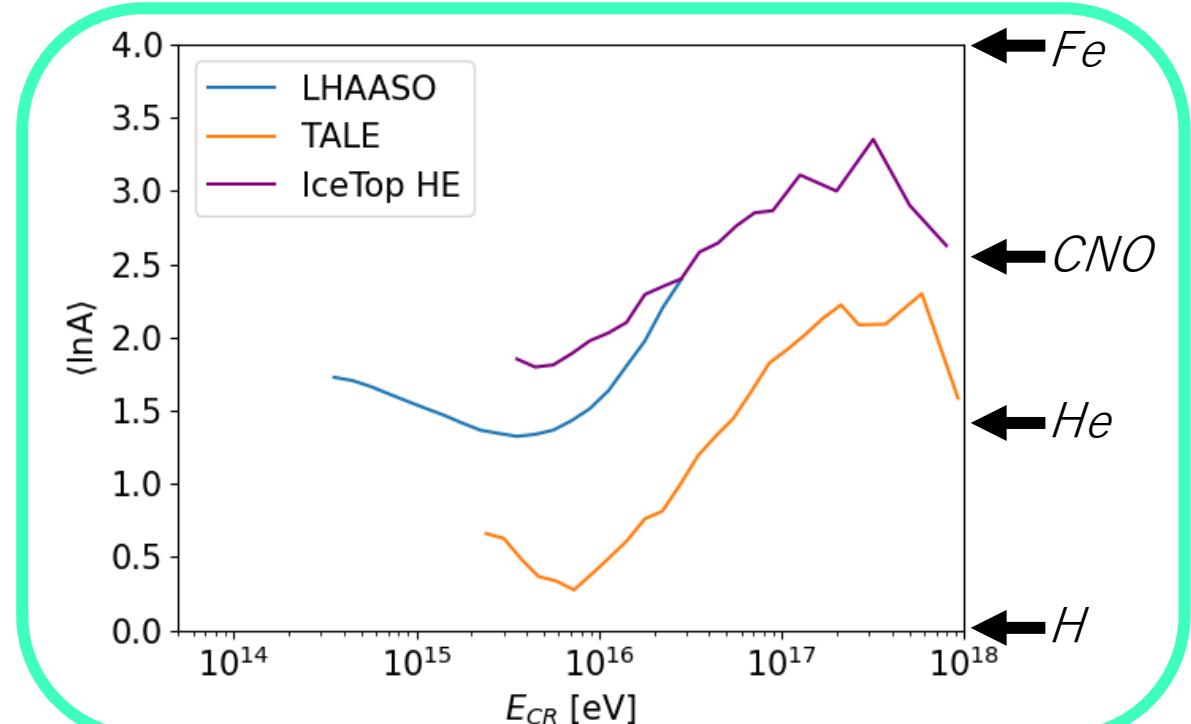
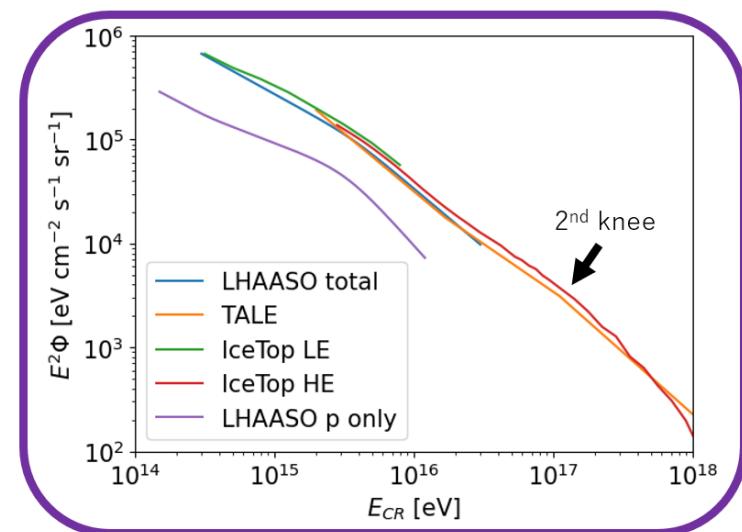
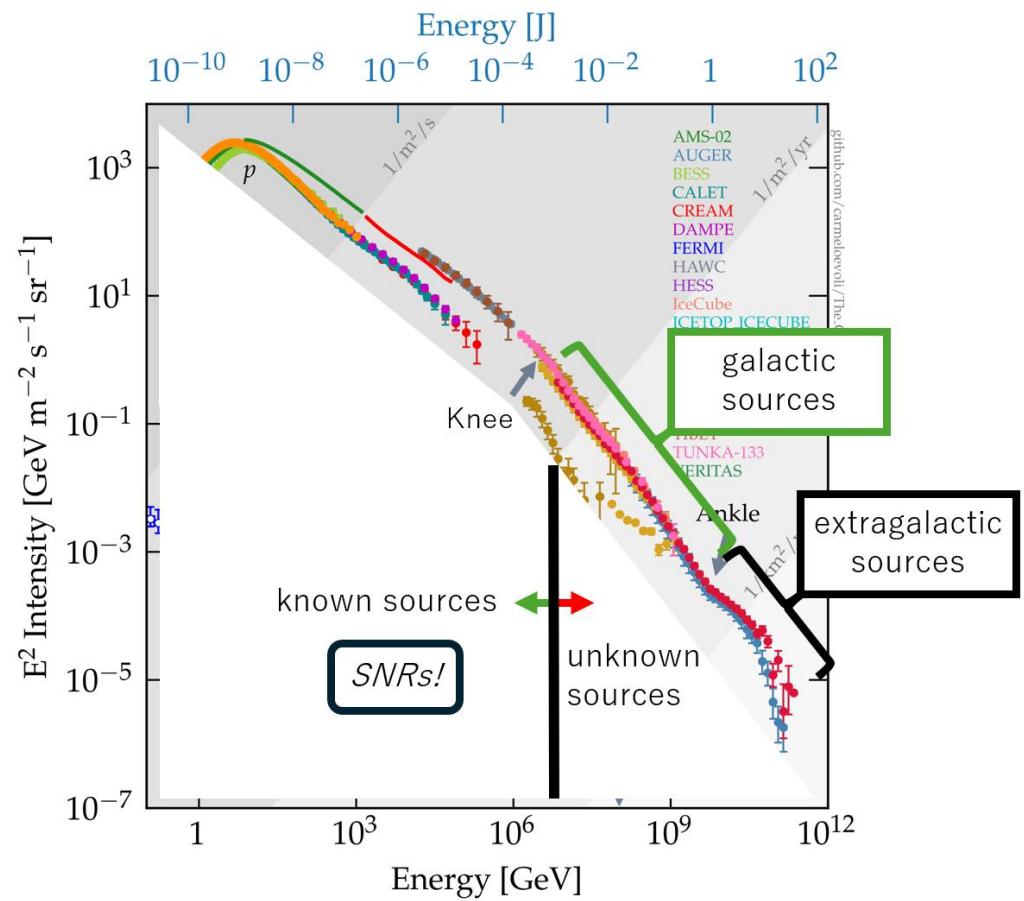
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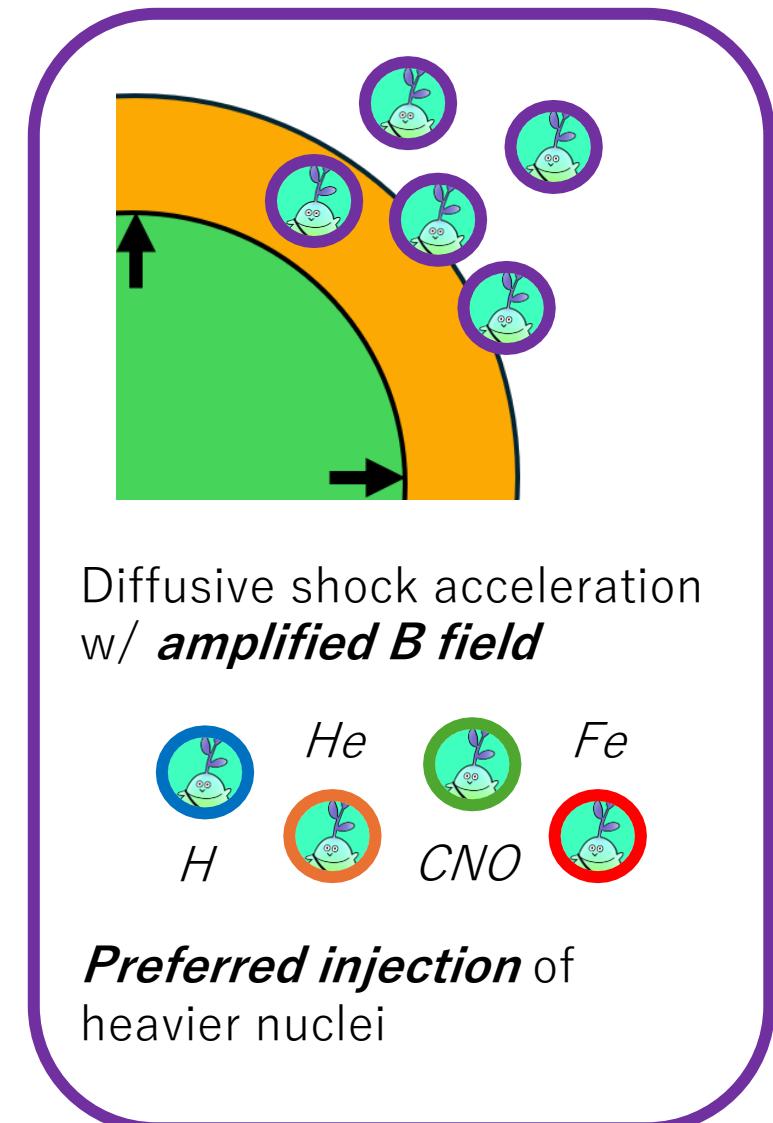
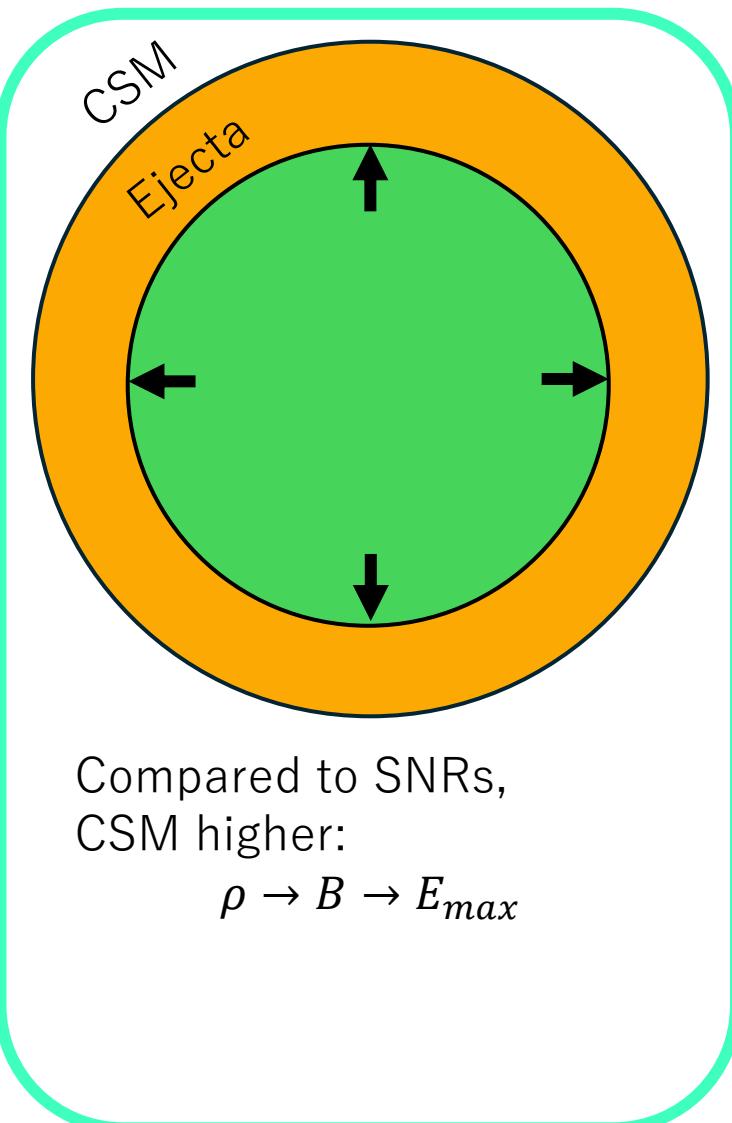
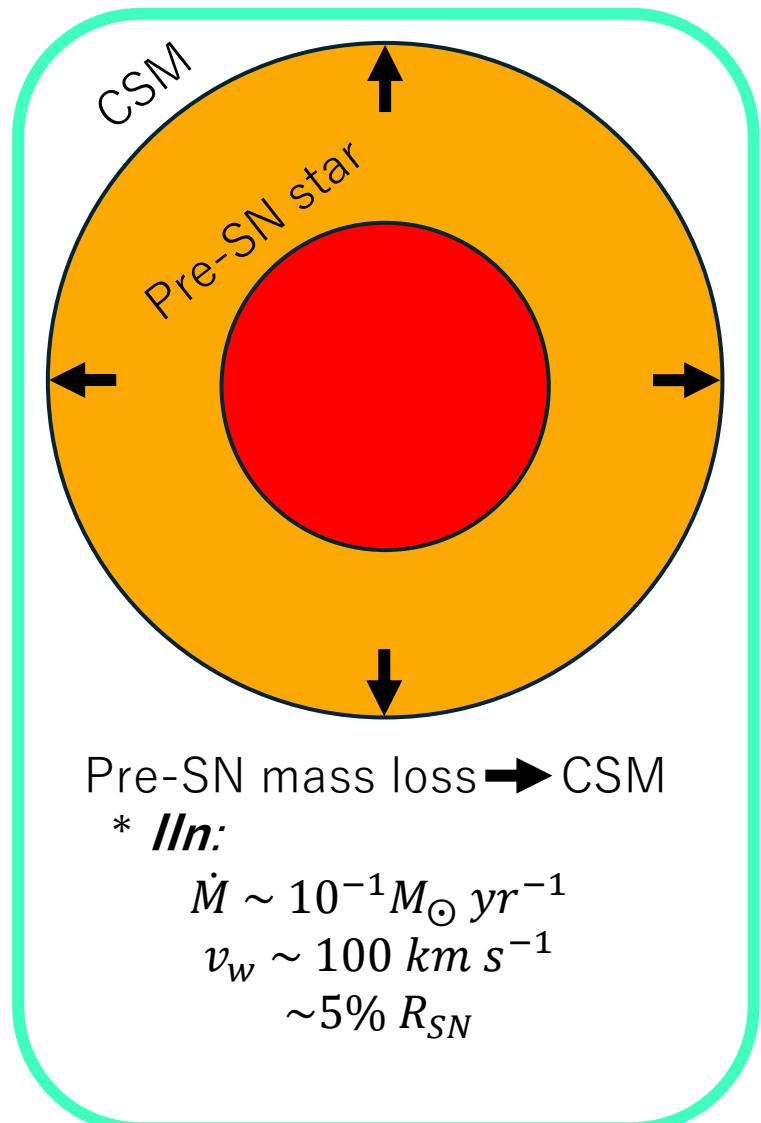
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Interacting supernovae

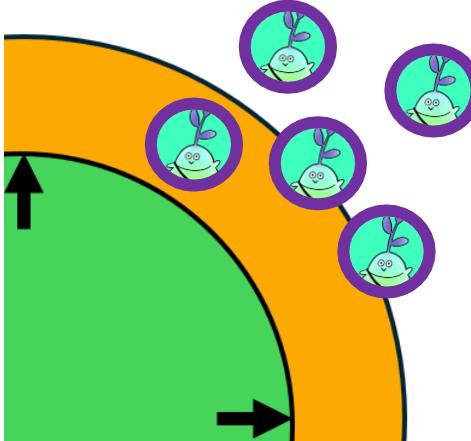


= super-PeV CRs

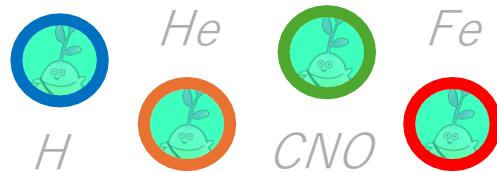


- ***B field amplification:***

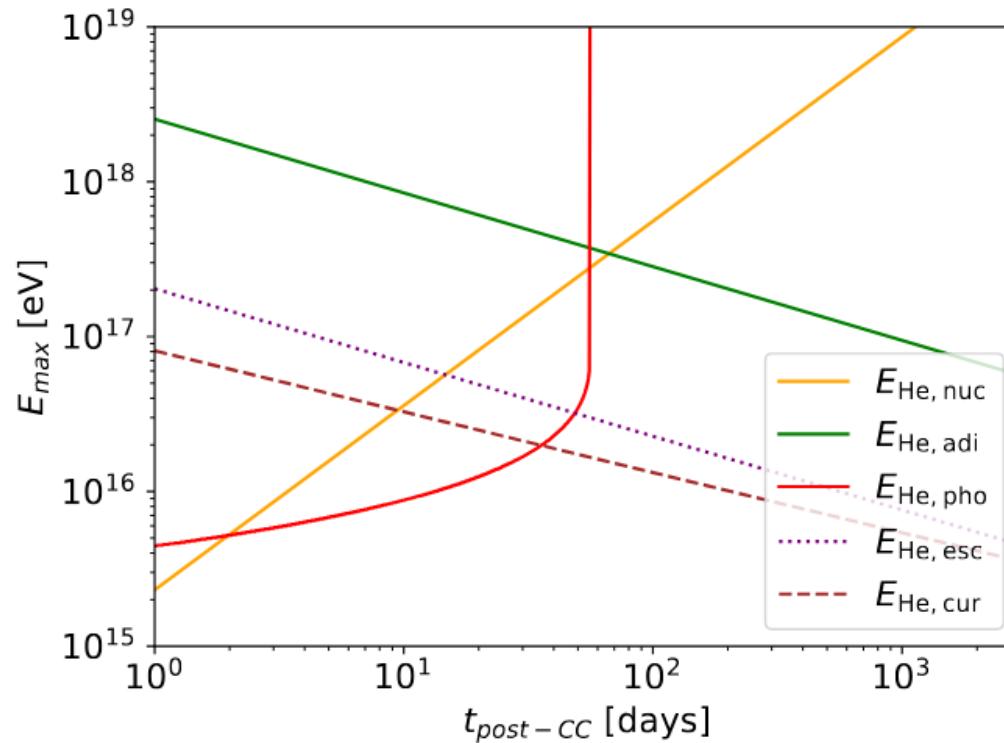
- CRs escape, produce current
- Excite modes $< r_L$ (Non-resonant streaming or Bell instability)
- x3-5 w/ IIn parameters
- Compare acceleration timescale for E_{max}



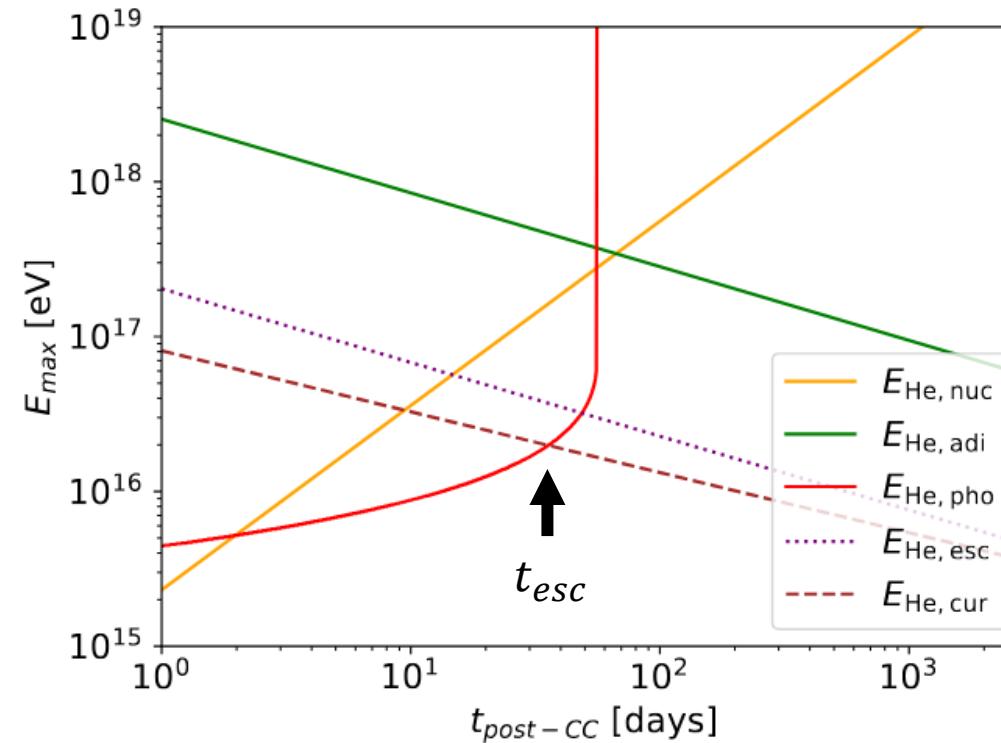
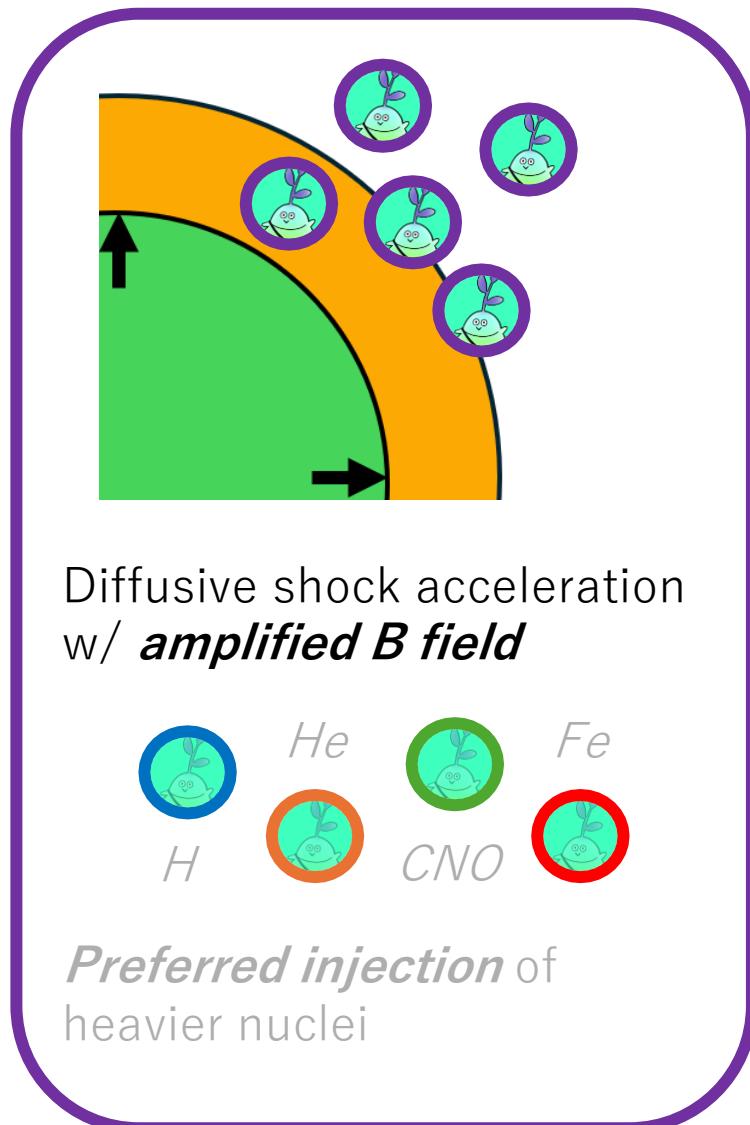
Diffusive shock acceleration
w/ ***amplified B field***



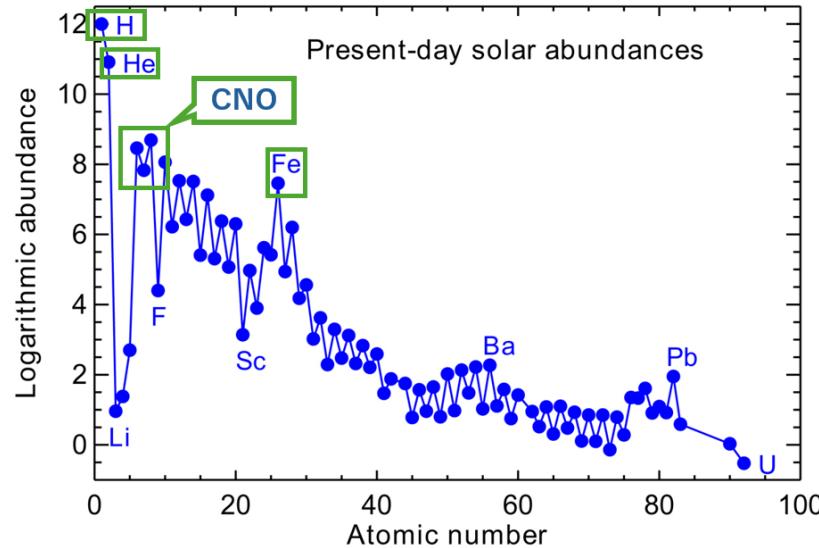
Preferred injection of
heavier nuclei



- Escape-limited model ($\sim 30\text{-}40$ d)
 - $l_{diff} \sim R_{sh}$ or
 - $E_{He,cur}$ most limiting
- Few $\times 10^{16}$ eV max energies

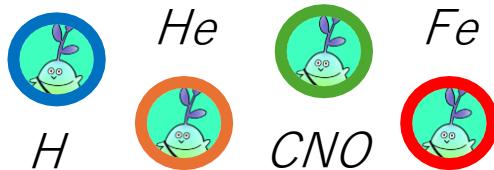


Asplund+ 2021



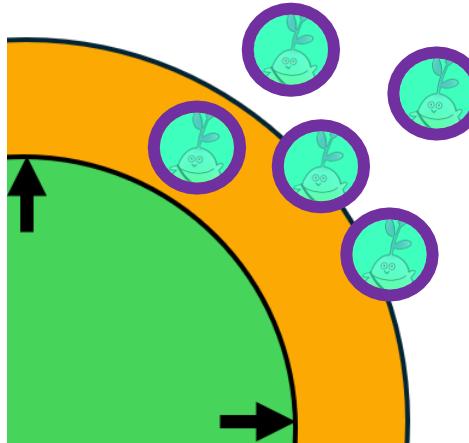
$H \sim 90\%$
 $He \sim 9\%$
 $CNO \sim 0.1\%$
 $Fe \sim 0.002\%$

Diffusive shock acceleration
w/ *amplified B field*

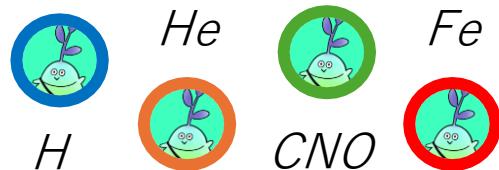


Preferred injection of
heavier nuclei

- Simulations show $f_{inj} \sim (A/Z_{ion})^{5/2}$
 - Heavy, singly-ionized nuclei are **more efficiently injected**
- Z_{ion} from *CLOUDY* photoionization code
 - ~ 15000 K at t_{esc}



Diffusive shock acceleration
w/ *amplified B field*



Preferred injection of
heavier nuclei

- *CLOUDY* fraction of singly (doubly) ionized nuclei
 - $H \sim 100\% (0\%)$
 - $He \sim 50\% (0\%)$
 - $CNO \sim 100\% (0\%)$
 - $Fe \sim 0\% (100\%)$

$$f_{inj} \sim (A/Z_{ion})^{5/2}$$

H	$\sim 90\%$	$\rightarrow 28\%$
He	$\sim 9\%$	$\rightarrow 45\%$
CNO	$\sim 0.1\%$	$\rightarrow 24\%$
Fe	$\sim 0.002\%$	$\rightarrow 3\%$

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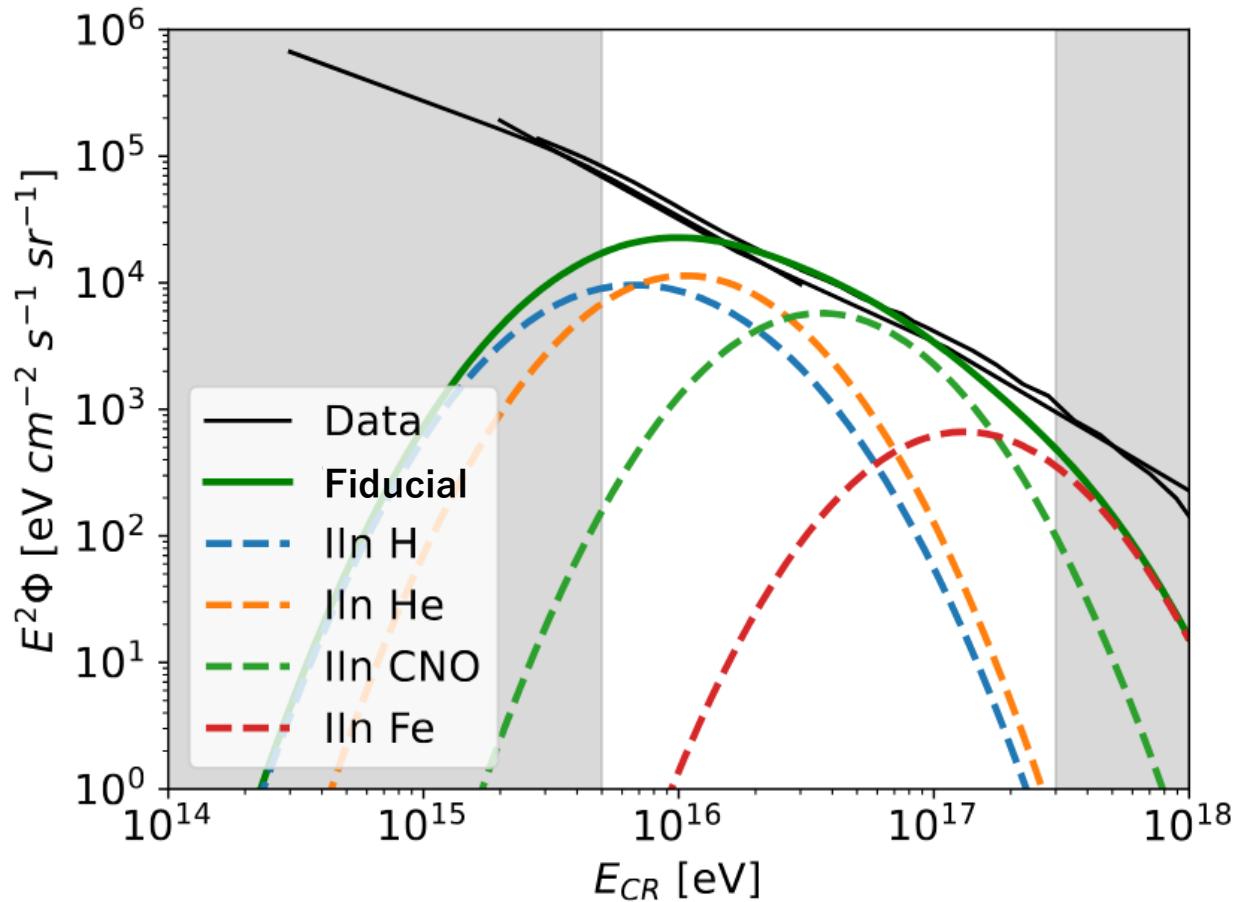
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- Nuclei injection

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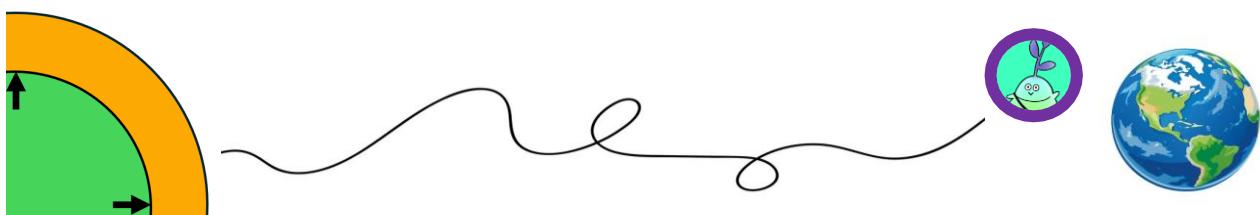
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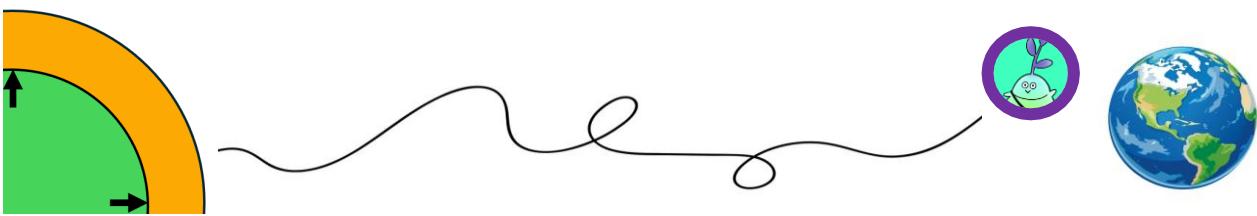
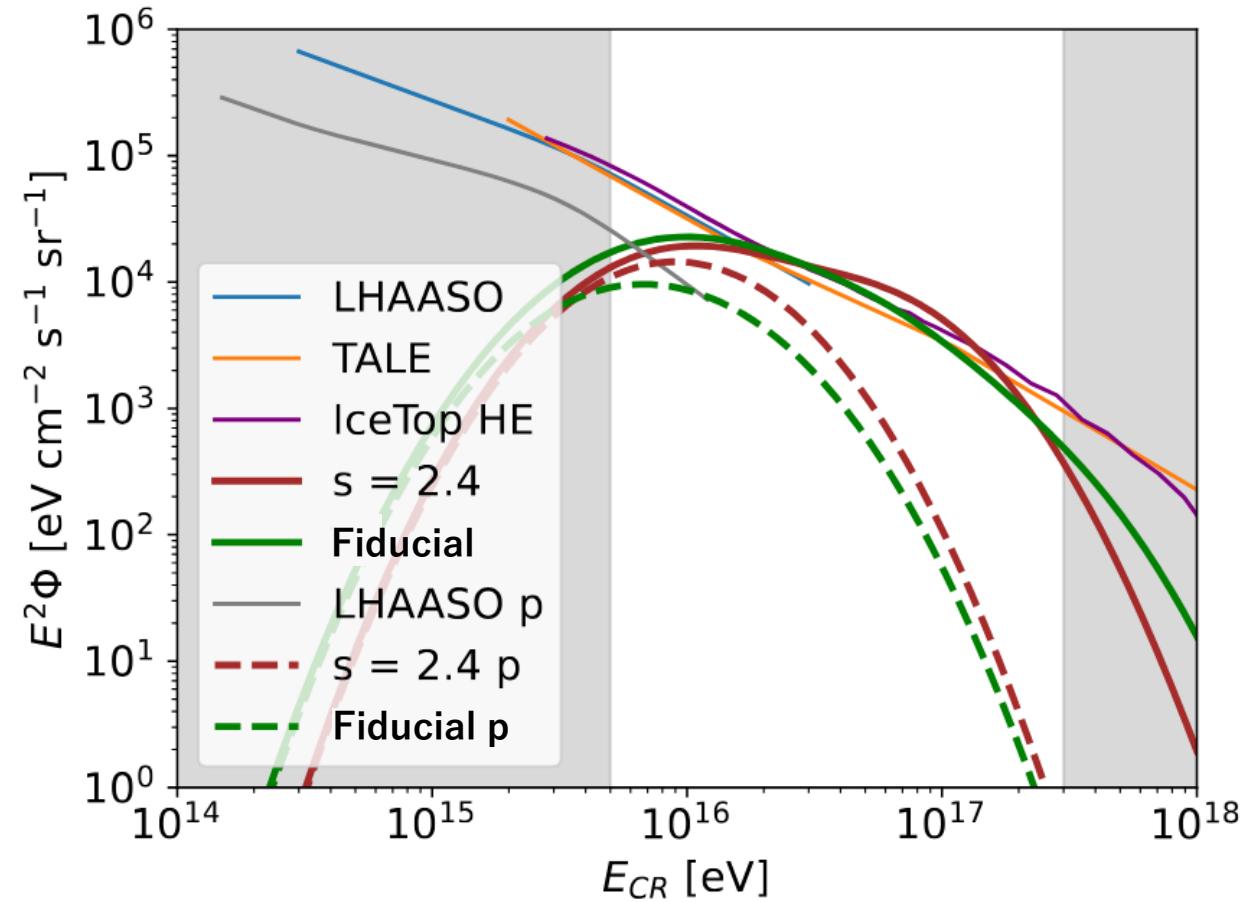
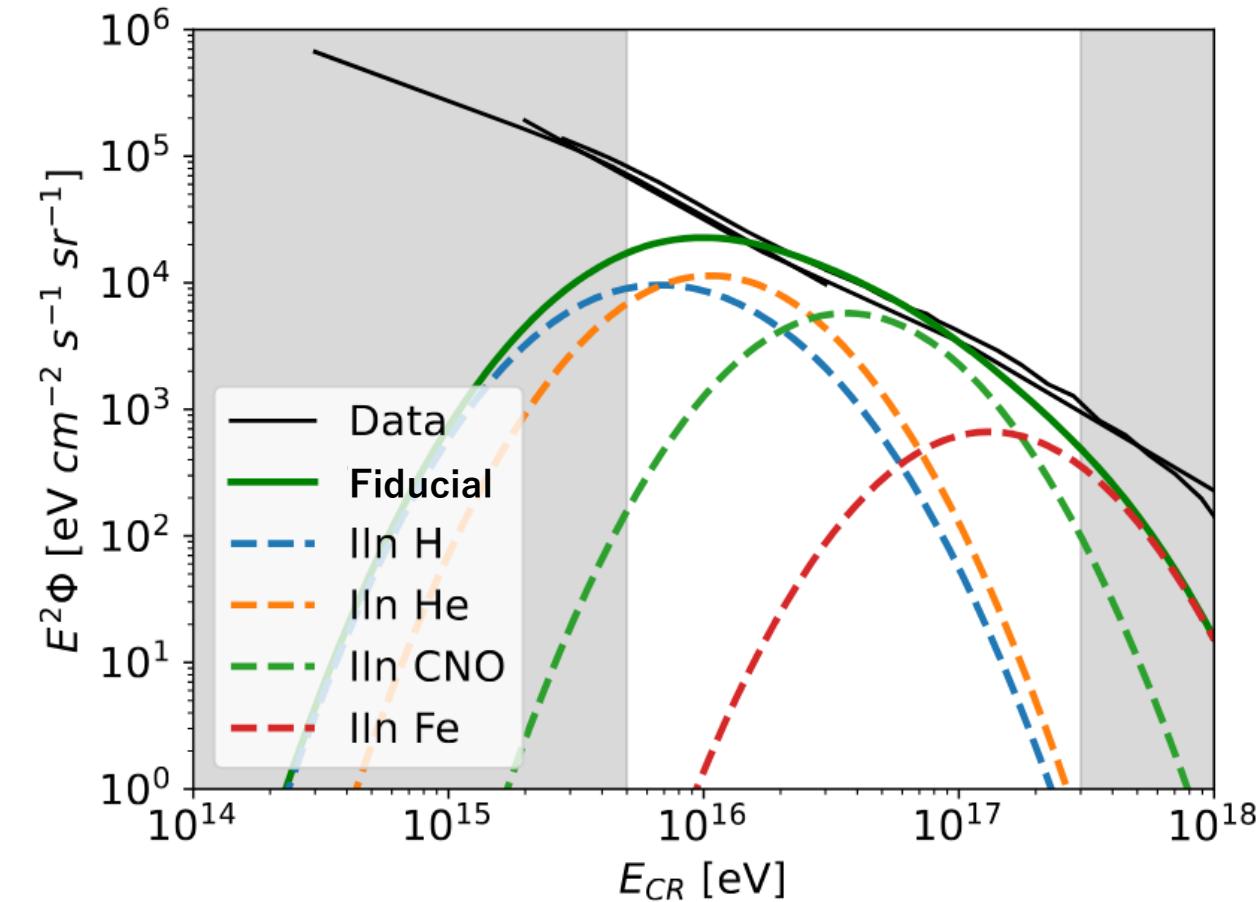
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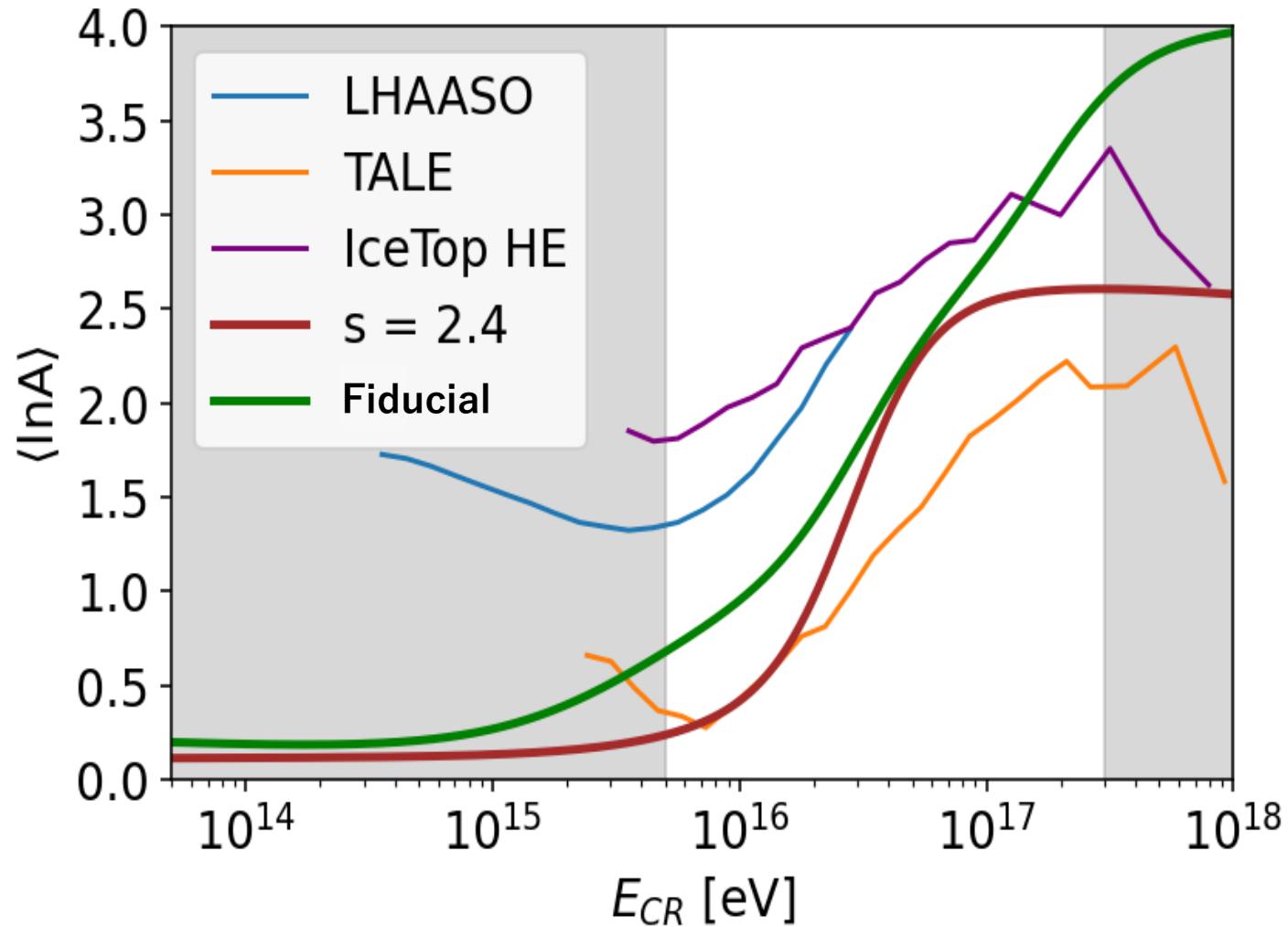


- CRs diffused in galactic B fields
- Can supply $10^{16} eV$ – few $\times 10^{17} eV$ flux
- Increasingly heavy composition





Some parameters disfavored



- Roughly consistent with average mass numbers
 - Increasingly heavy approaching 2nd knee
- Discrepancy between experiments?

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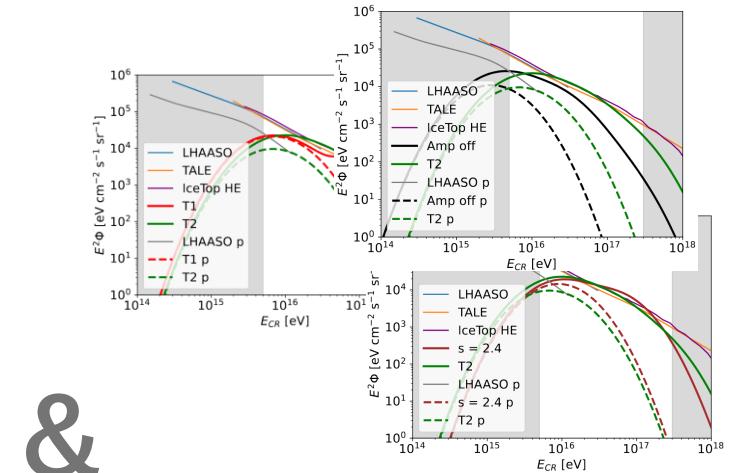
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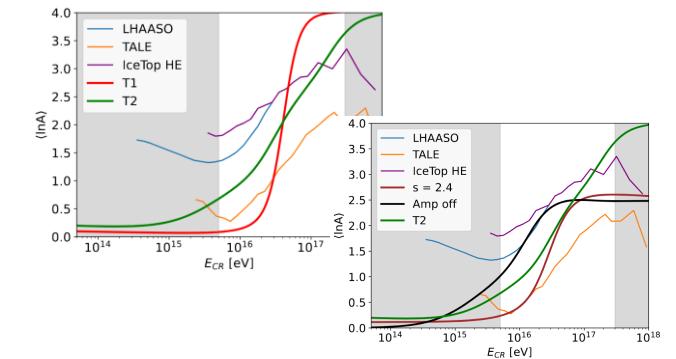
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Summary and outlook

- Interacting SNe (especially IIIn)
 - Acceleration above PeV
 - *Amplified magnetic field*
 - Increasingly heavy composition until 2nd knee
 - *Preferred injection of heavy ions*
- Paper coming soon!
- Multimessenger tests
 - γ and ν possibly detectable
 - Possible coincidences found: 2 IIIn + ν , 1 IIn + ν



&



$$p + p/\gamma \rightarrow \pi^0/\pi^+$$

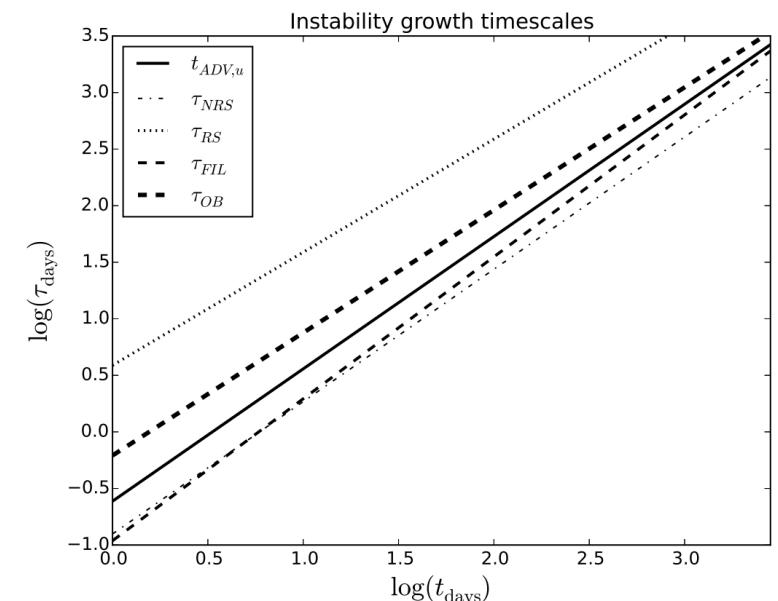
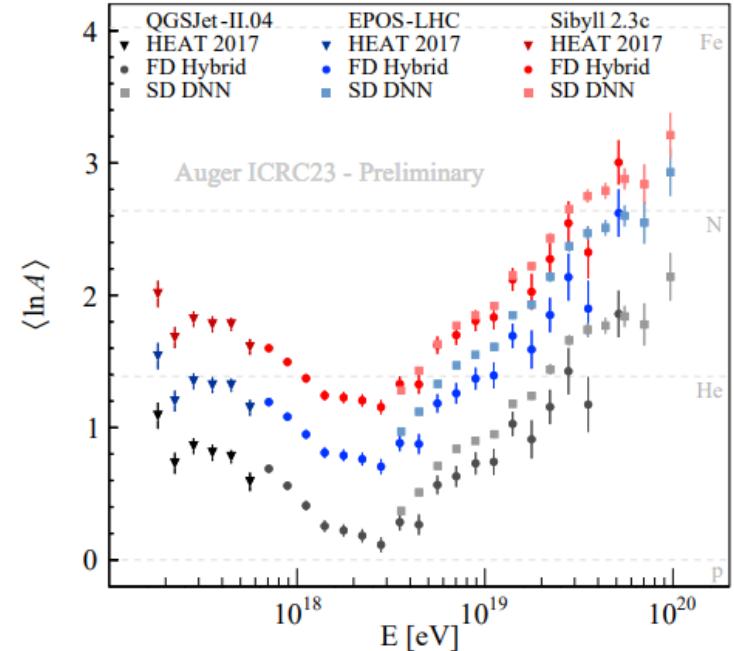
\downarrow \downarrow

γ ν

Backup

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- Consistent with PAO InA?
 - We overestimate around \sim few 10^{17} , different source becomes dominant
 - Large variation in hadronic interaction models
- What hadronic interaction models do we use?
 - EPOS
- Resonant streaming and other instabilities?
 - RSI scales \sim Larmor, doesn't grow as fast
 - NRSI fastest



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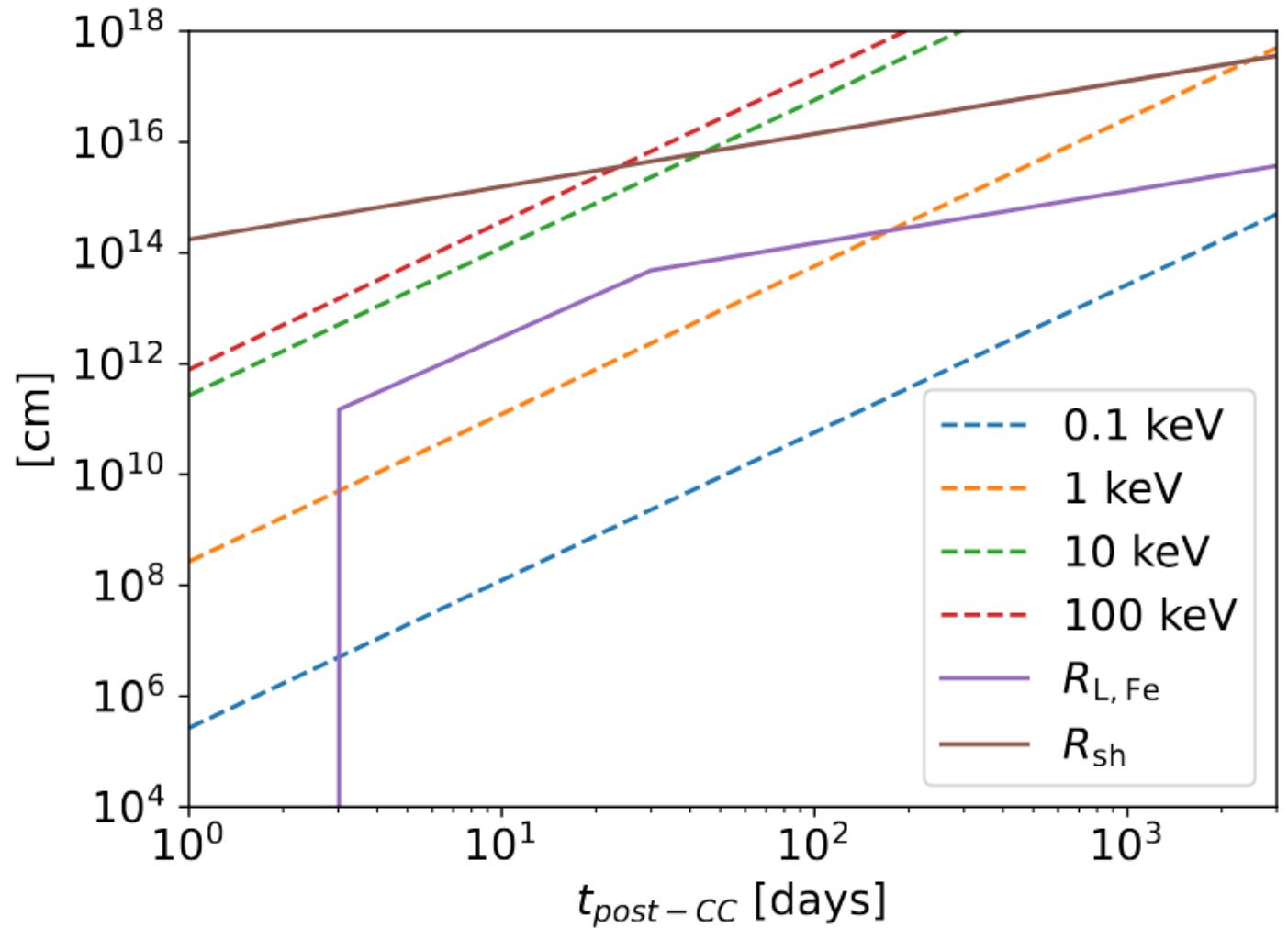
- X-ray reprocessing

$$\lambda_{mfp} = 1/(\kappa_X \rho_{CSM})$$

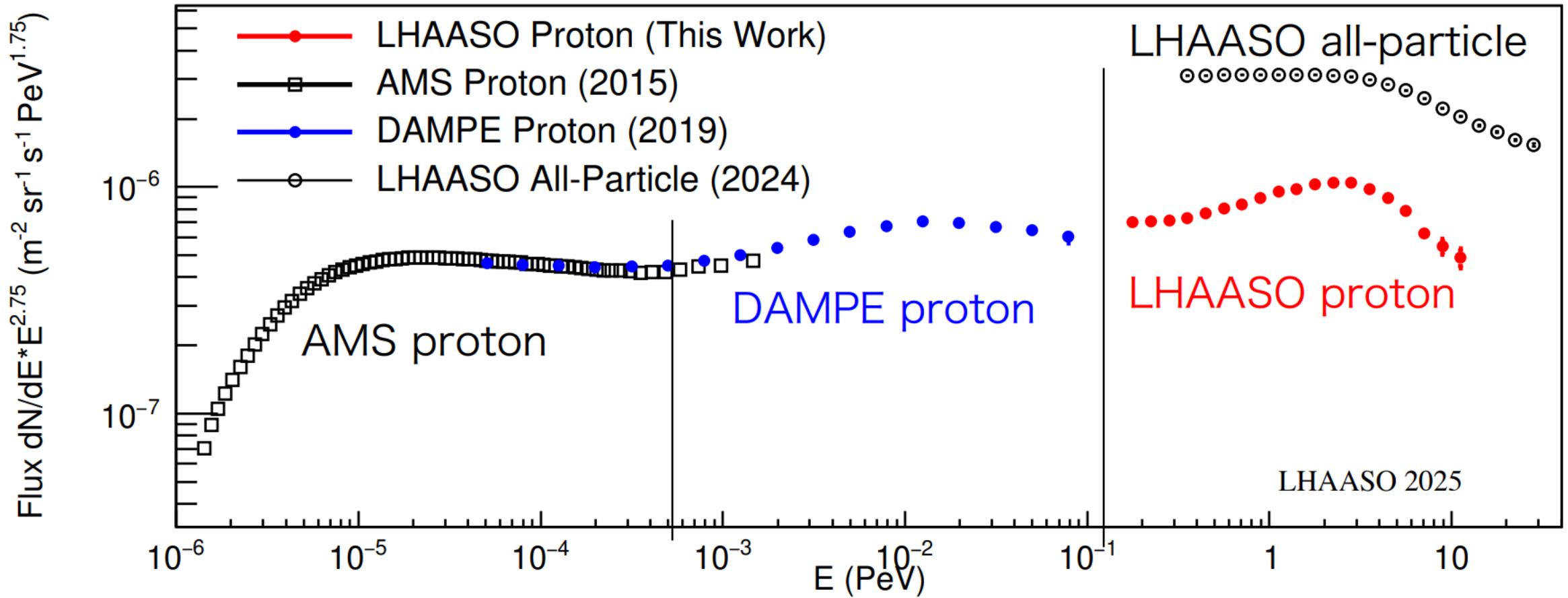
$$\kappa_X = \text{Max}(10^3 E_X^{-3}, \kappa_s) \text{ cm}^2 \text{ g}^{-1}$$

$$\kappa_s \sim 0.34$$

- Hard X-rays may not contribute



Below PeV



IIIn + neutrino events?

- Not statistically significant, but...

	$t_{\text{rise,obs}}$ [days]	Time delay [days]	M_{abs}	Redshift	RA [deg]	DEC [deg]	Association	E_{ν} [TeV]
SN2023syz	10	38	−17.58	0.037	268.85	45.22	IC231027A	191.5
SN2025cnj	50	61	−19.15	0.0675	239.92	27.11	IC250421A	151.4

- Also a potential Ibn association

More figures

