

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

*Nick Ekanger*, Shigeo S Kimura, Kazumi Kashiyama



# 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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## II. Interacting SNe CRs

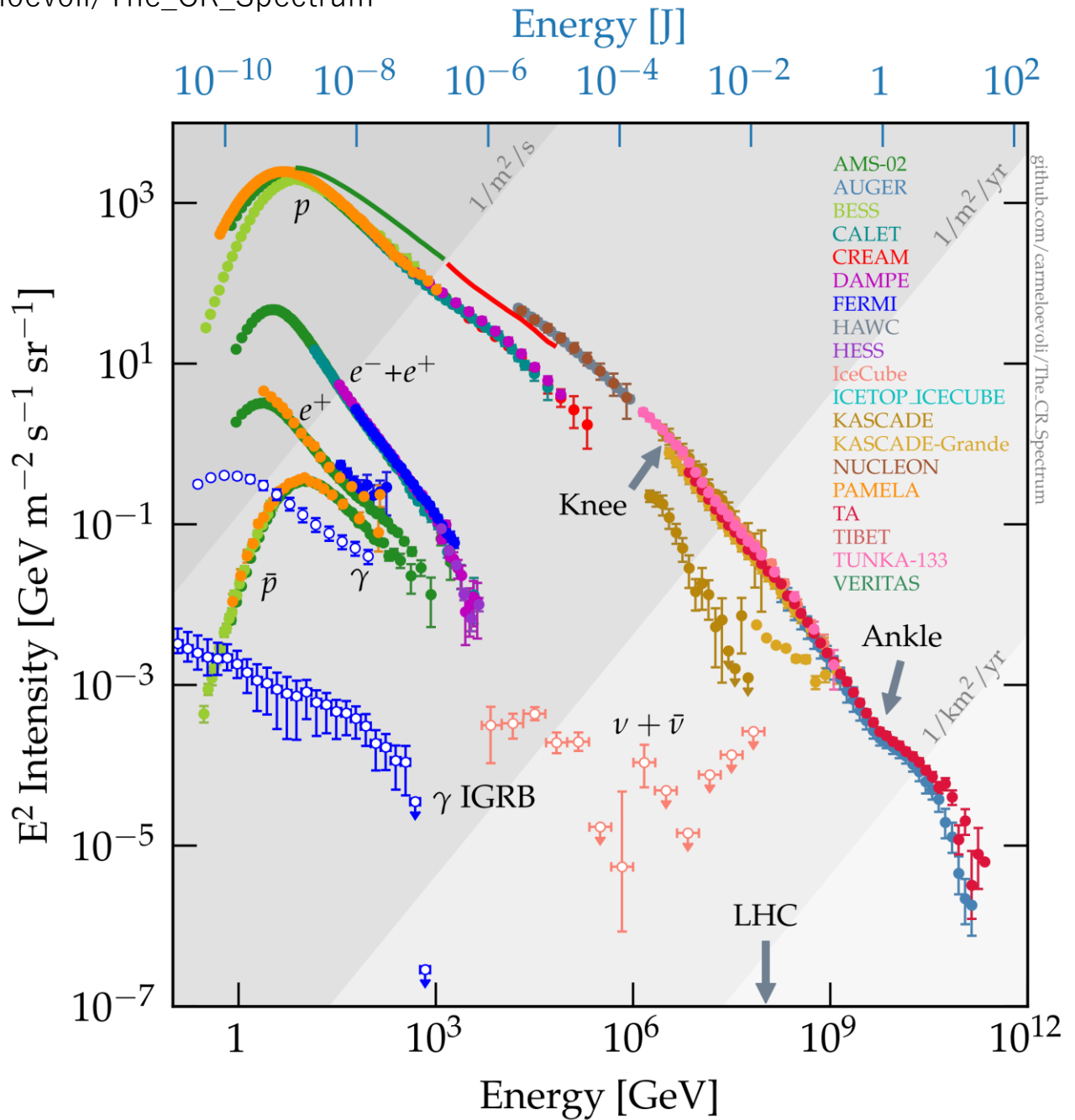
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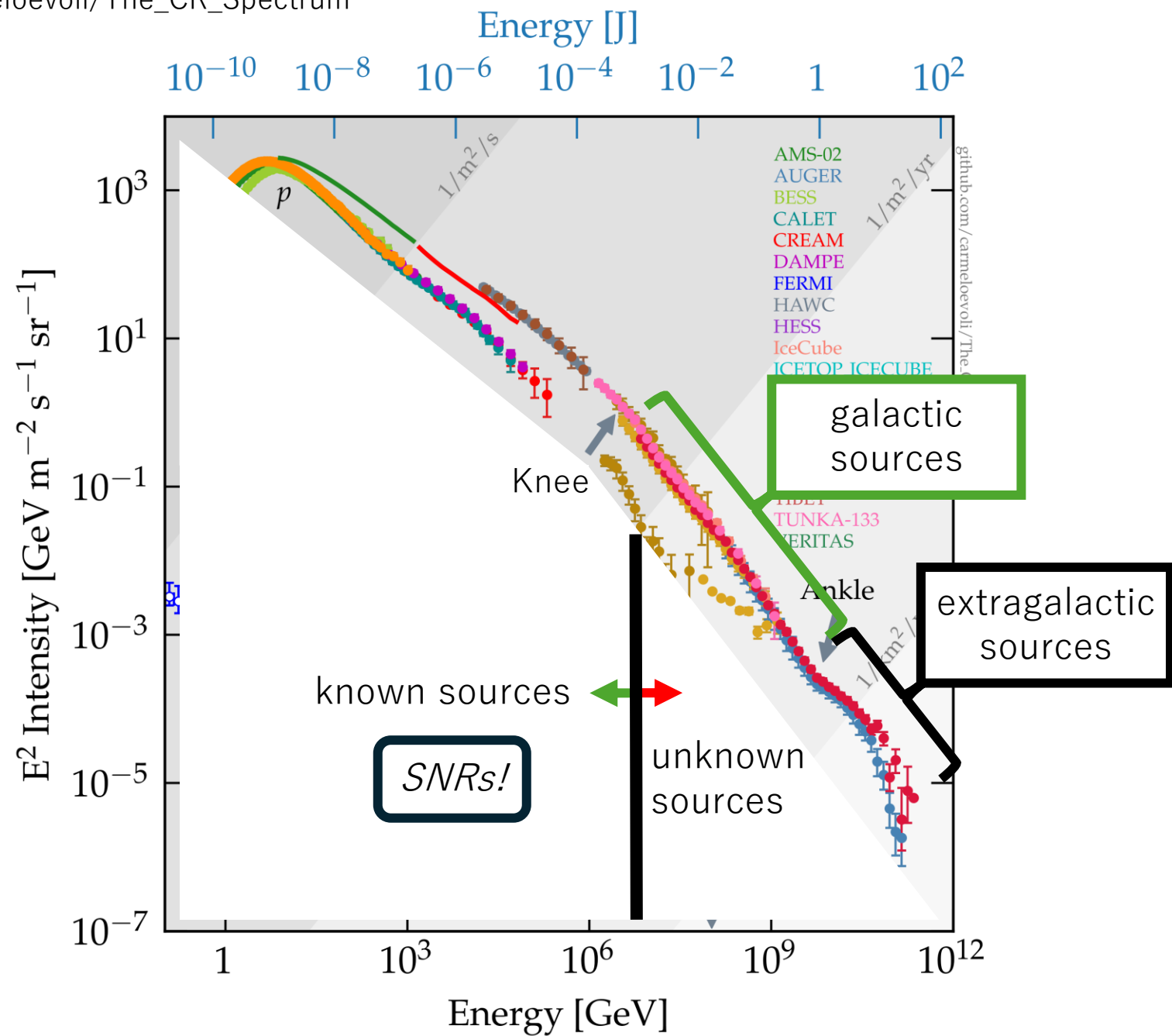
## III. Data comparison

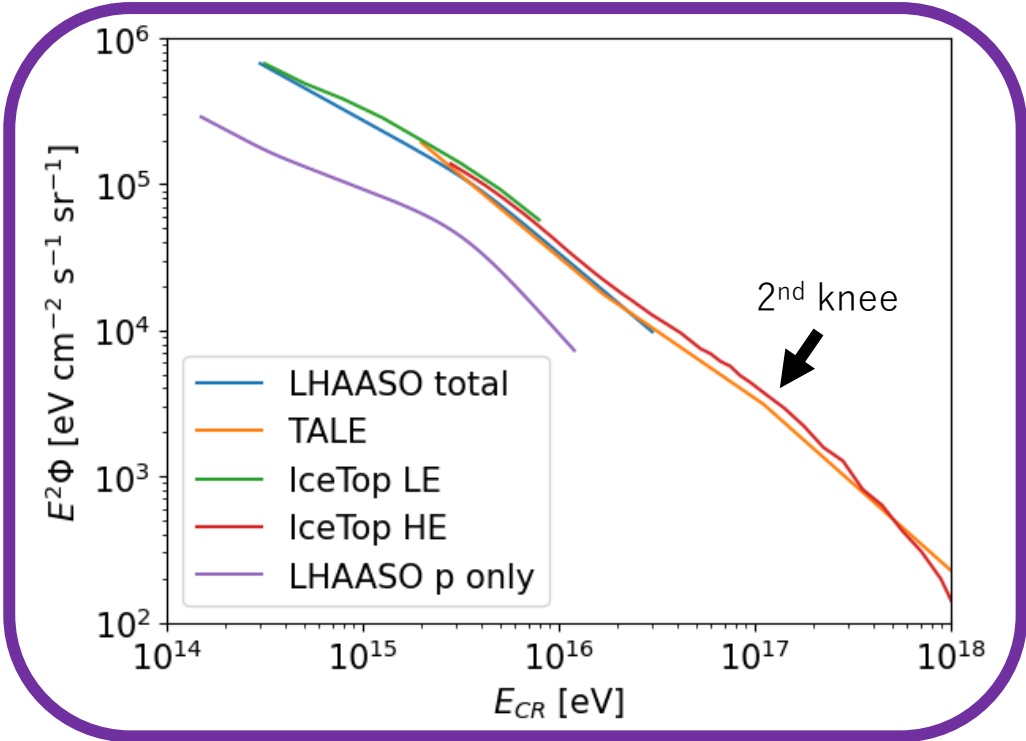
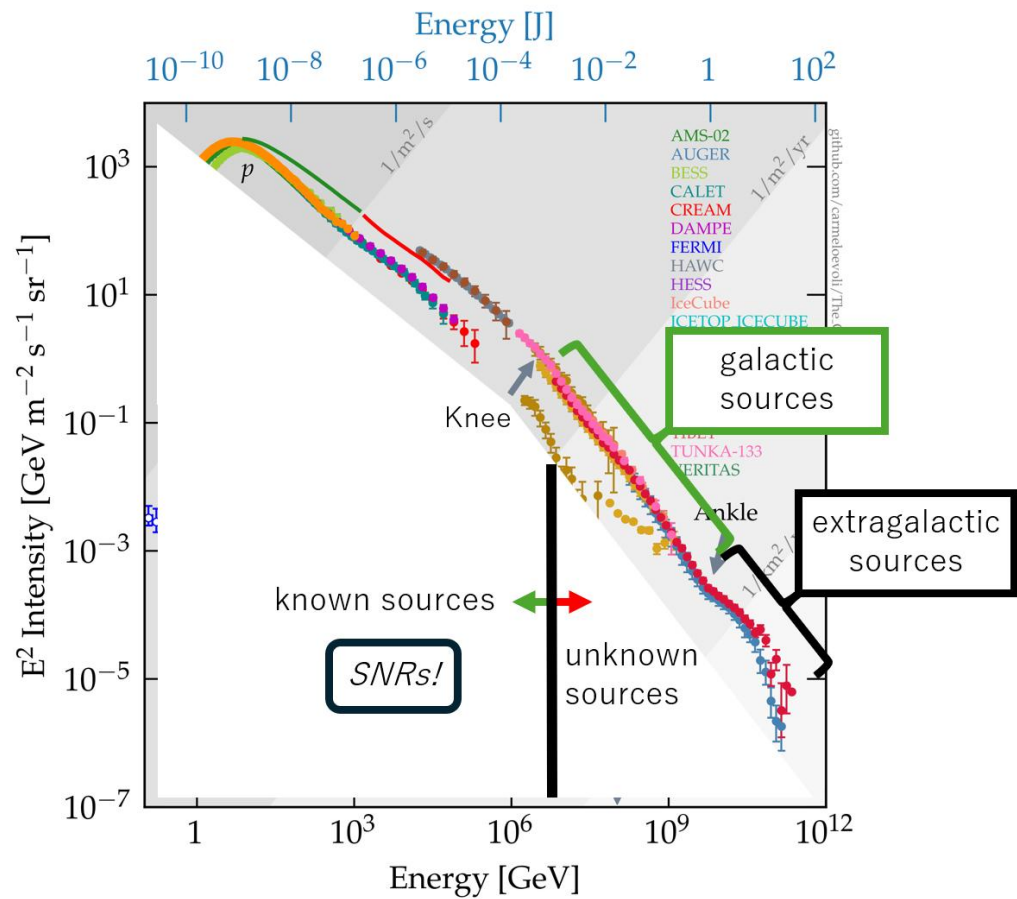
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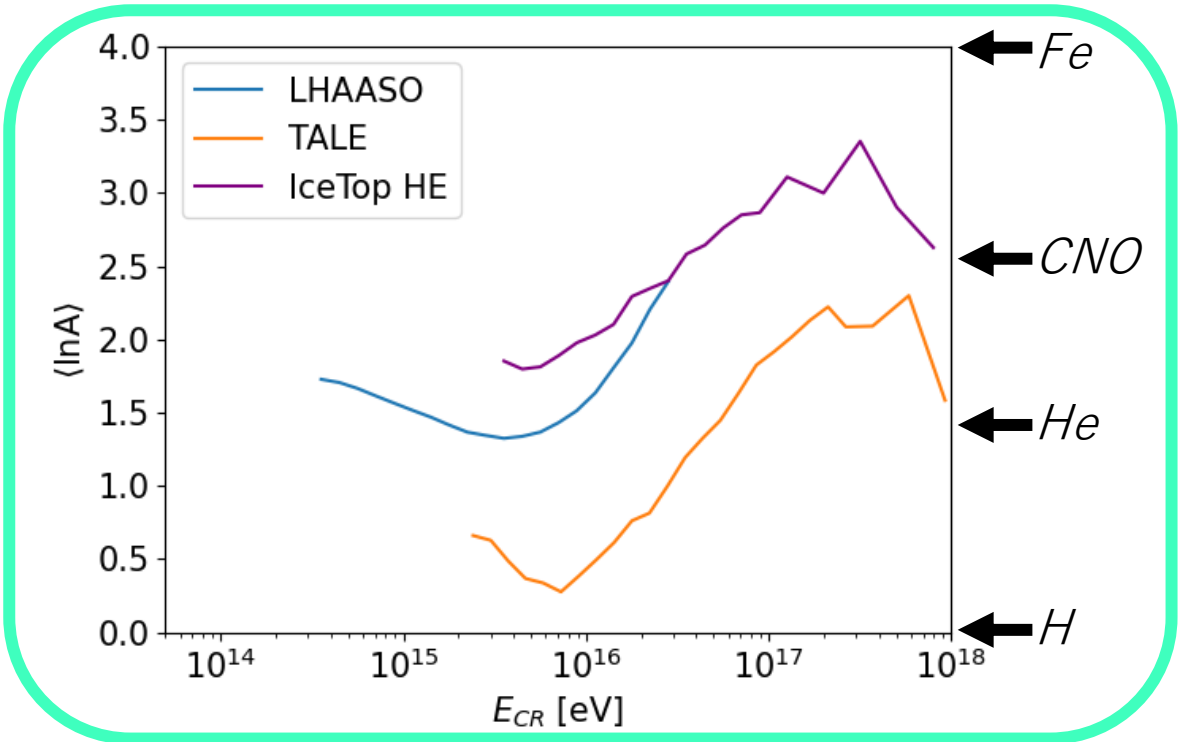
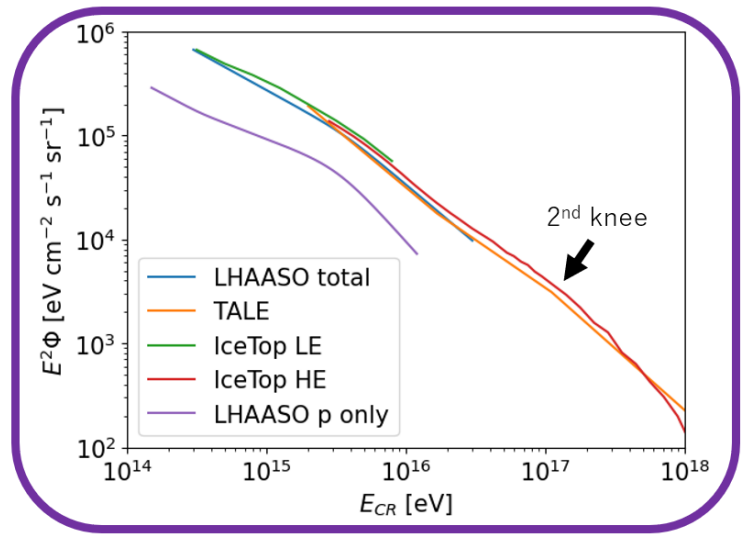
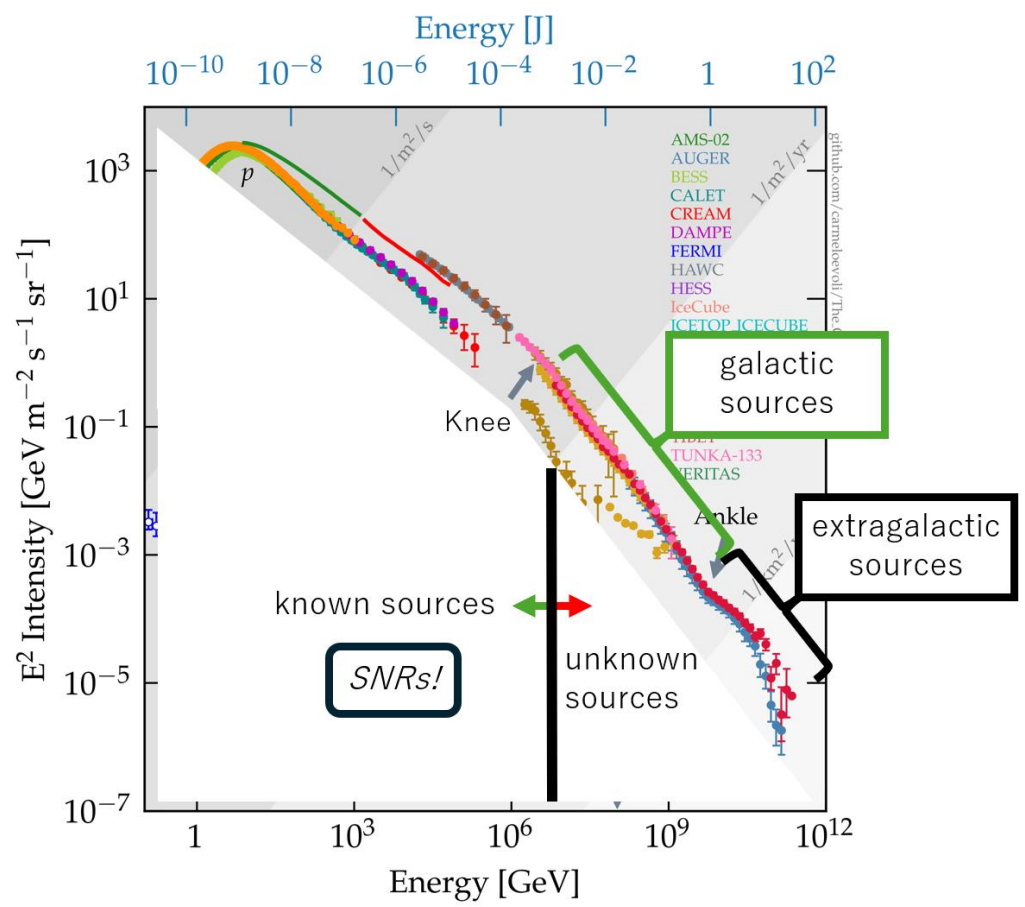
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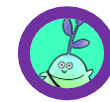
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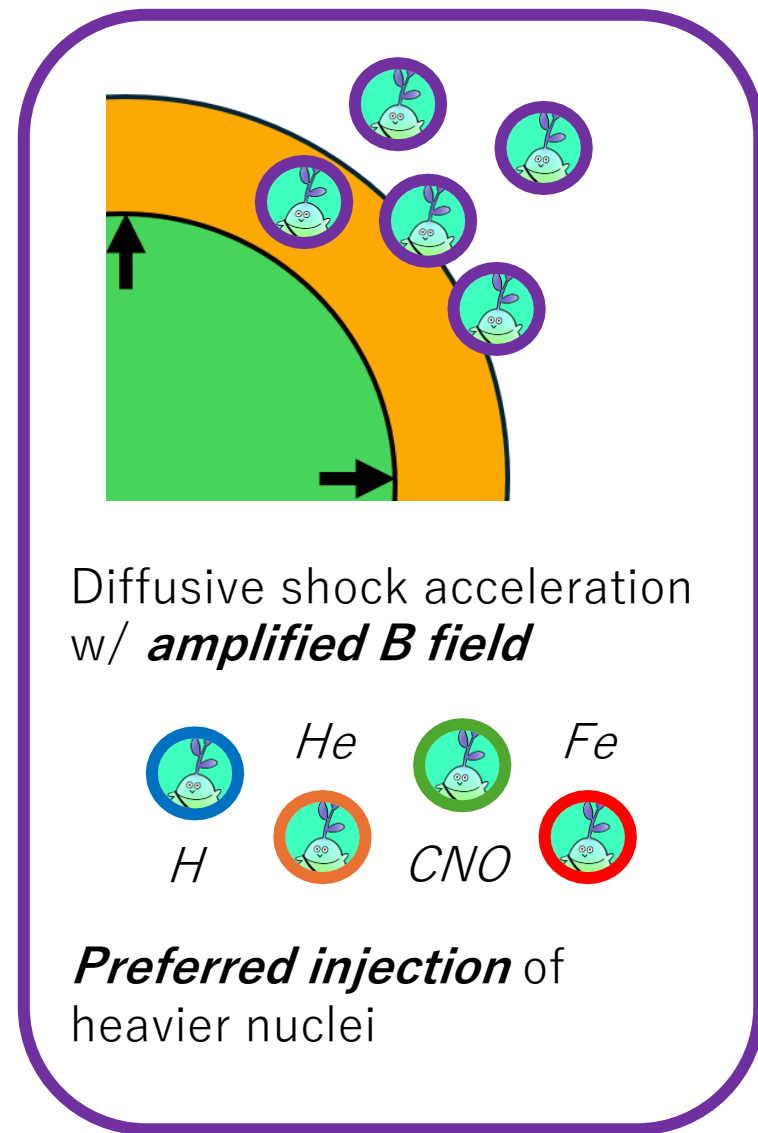
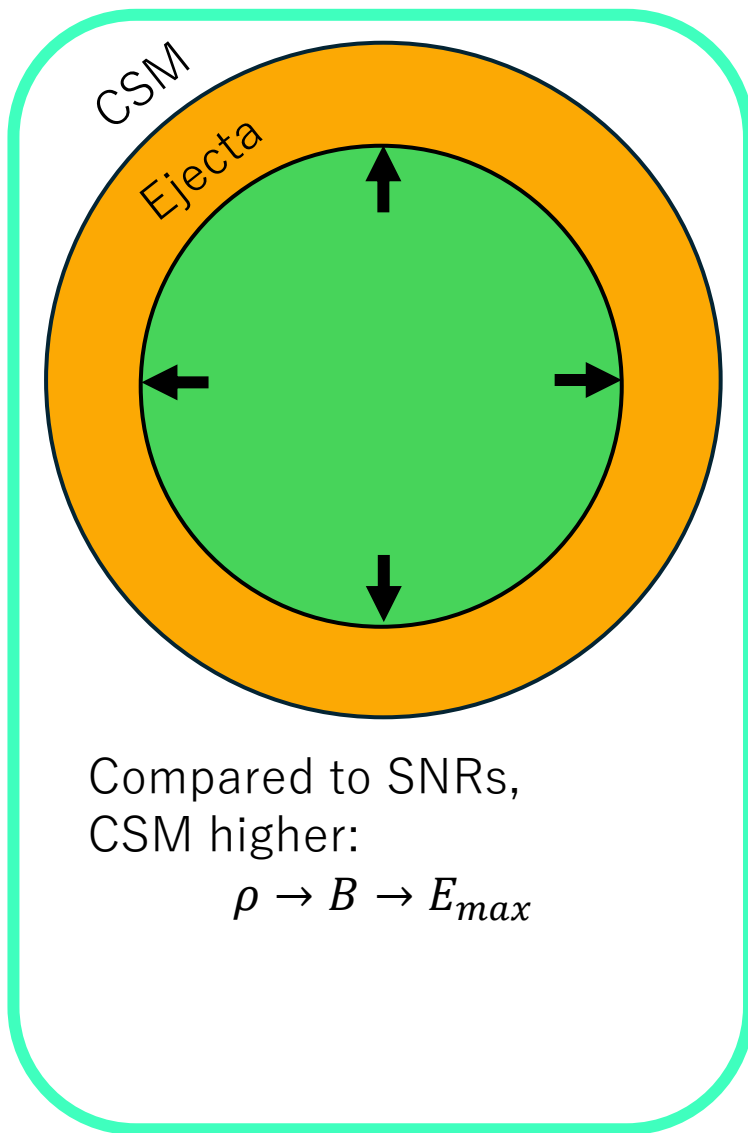
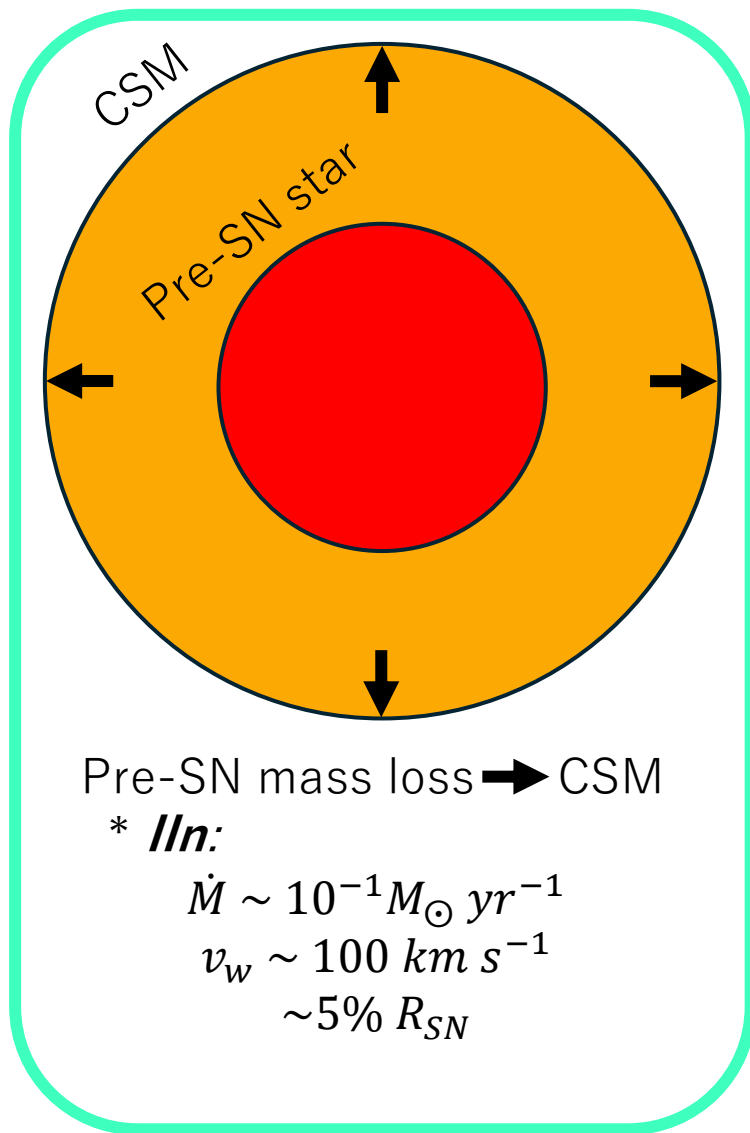
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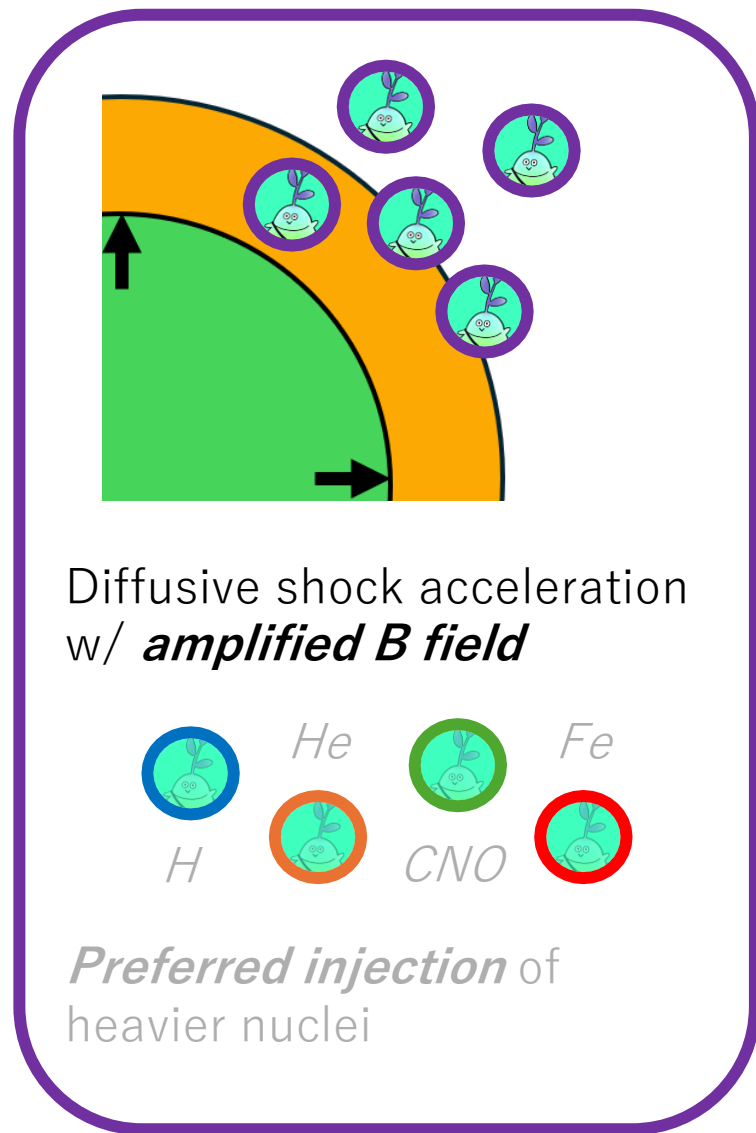


# Interacting supernovae

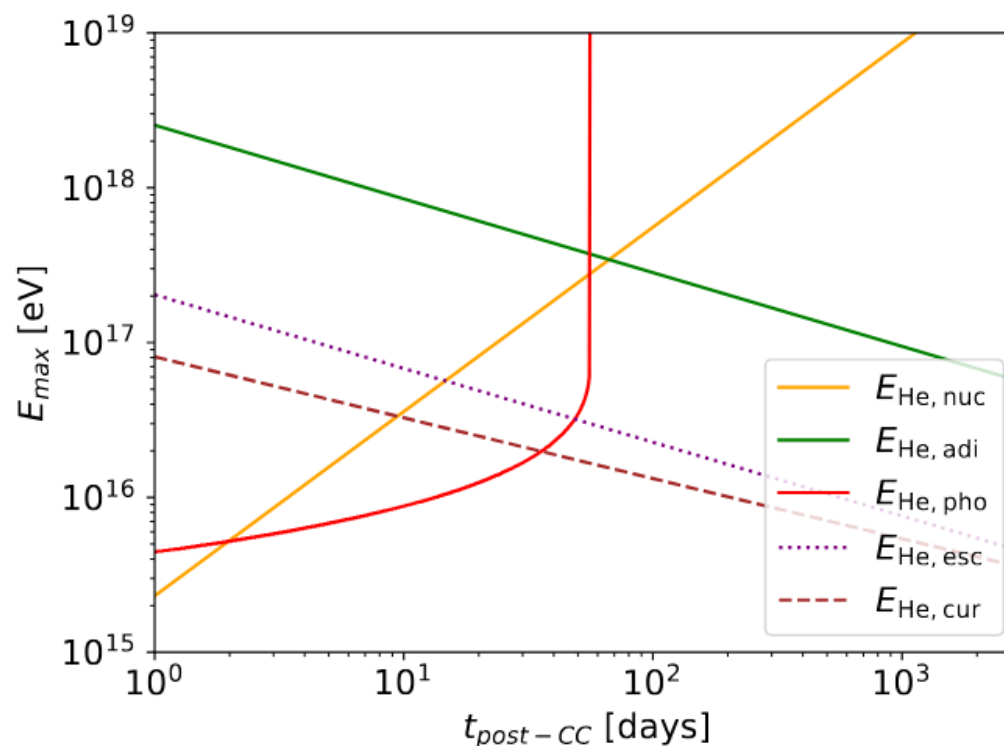


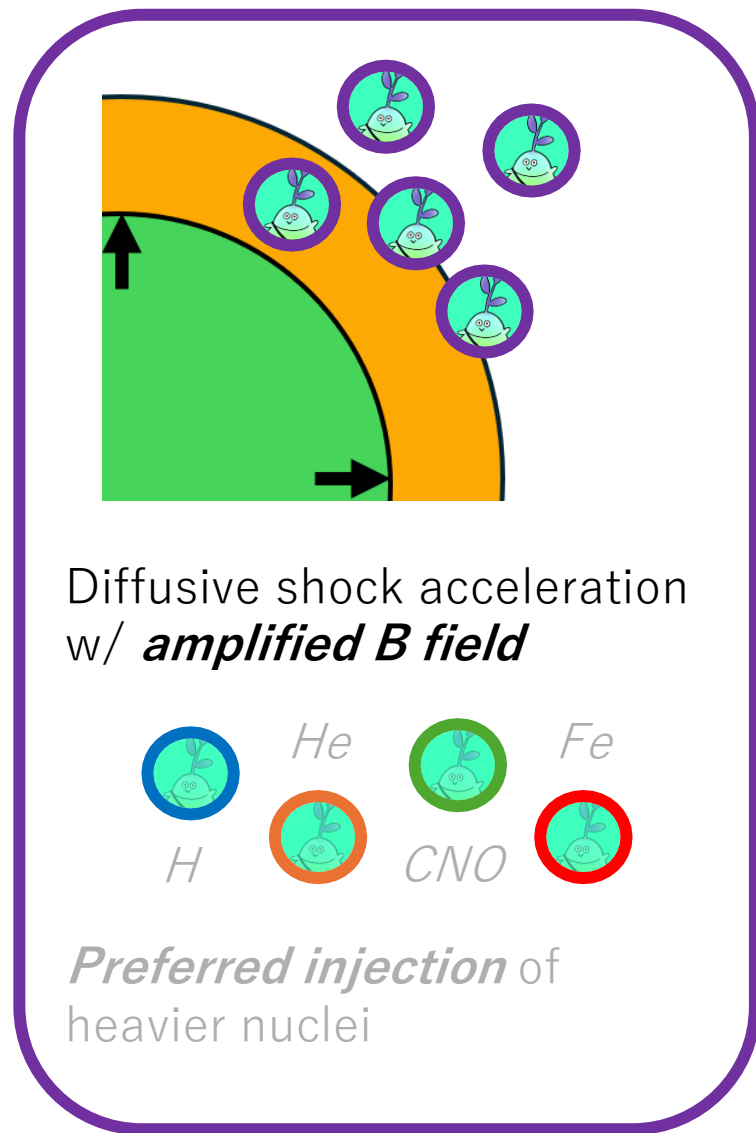
= super-PeV CRs



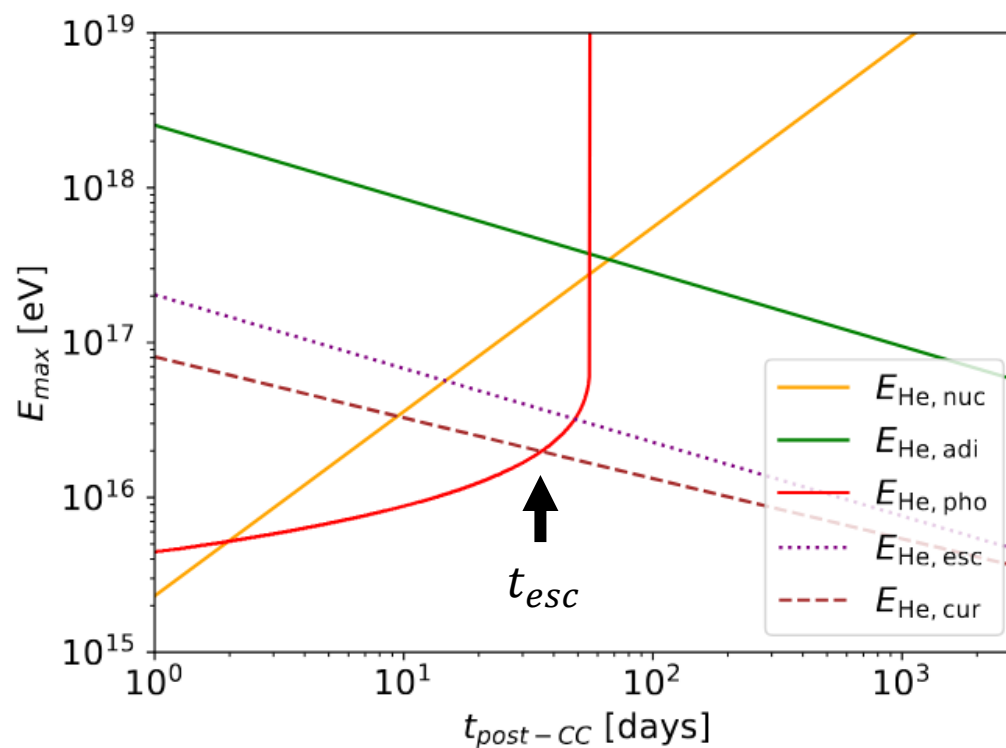


- ***B field amplification:***
  - CRs escape, produce current
  - Excite modes  $< r_L$  (Non-resonant streaming or Bell instability)
  - x3-5 w/ IIn parameters
- Compare acceleration timescale for  $E_{max}$

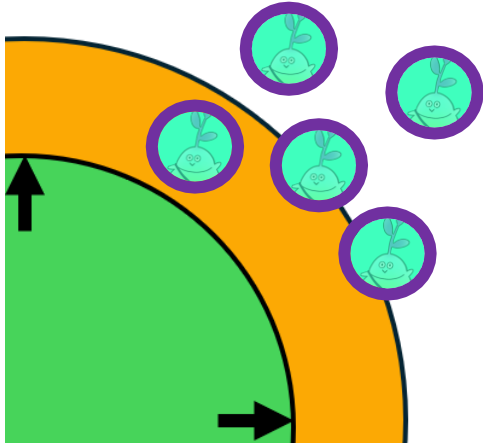




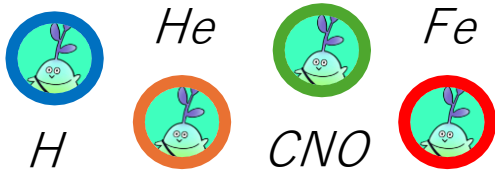
- Escape-limited model ( $\sim 30\text{-}40$  d)
  - $l_{diff} \sim R_{sh}$  or
  - $E_{He,cur}$  most limiting
- Few  $\times 10^{16}$  eV max energies



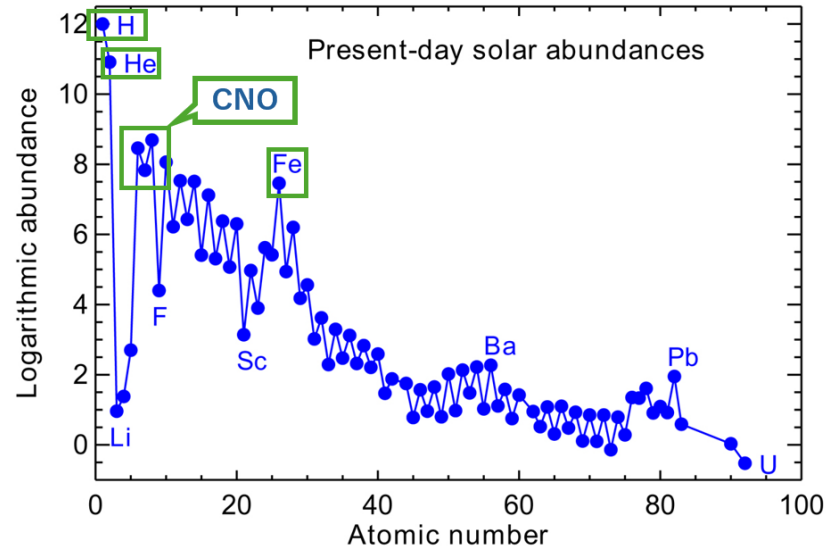
Asplund+ 2021



Diffusive shock acceleration  
w/ *amplified B field*



**Preferred injection** of  
heavier nuclei



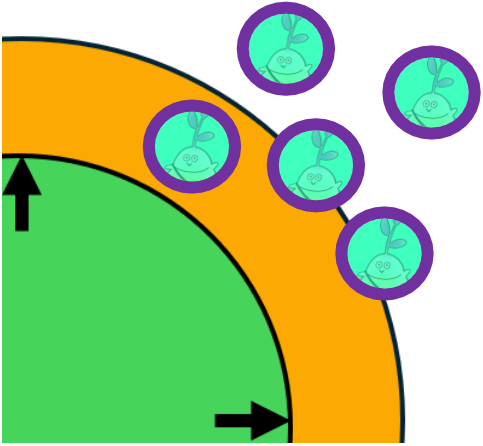
$H \sim 90\%$

$He \sim 9\%$

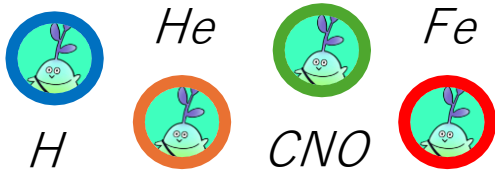
$CNO \sim 0.1\%$

$Fe \sim 0.002\%$

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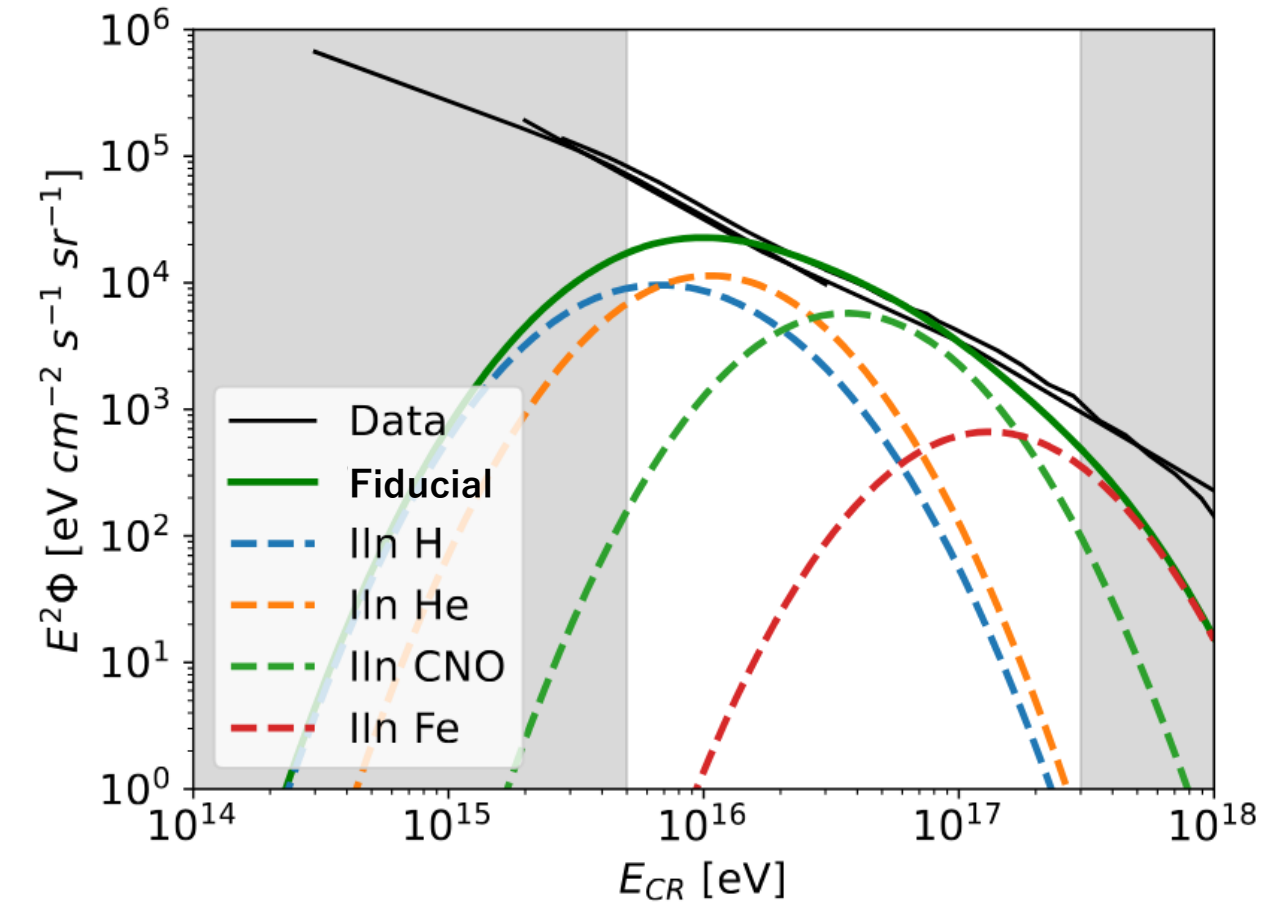
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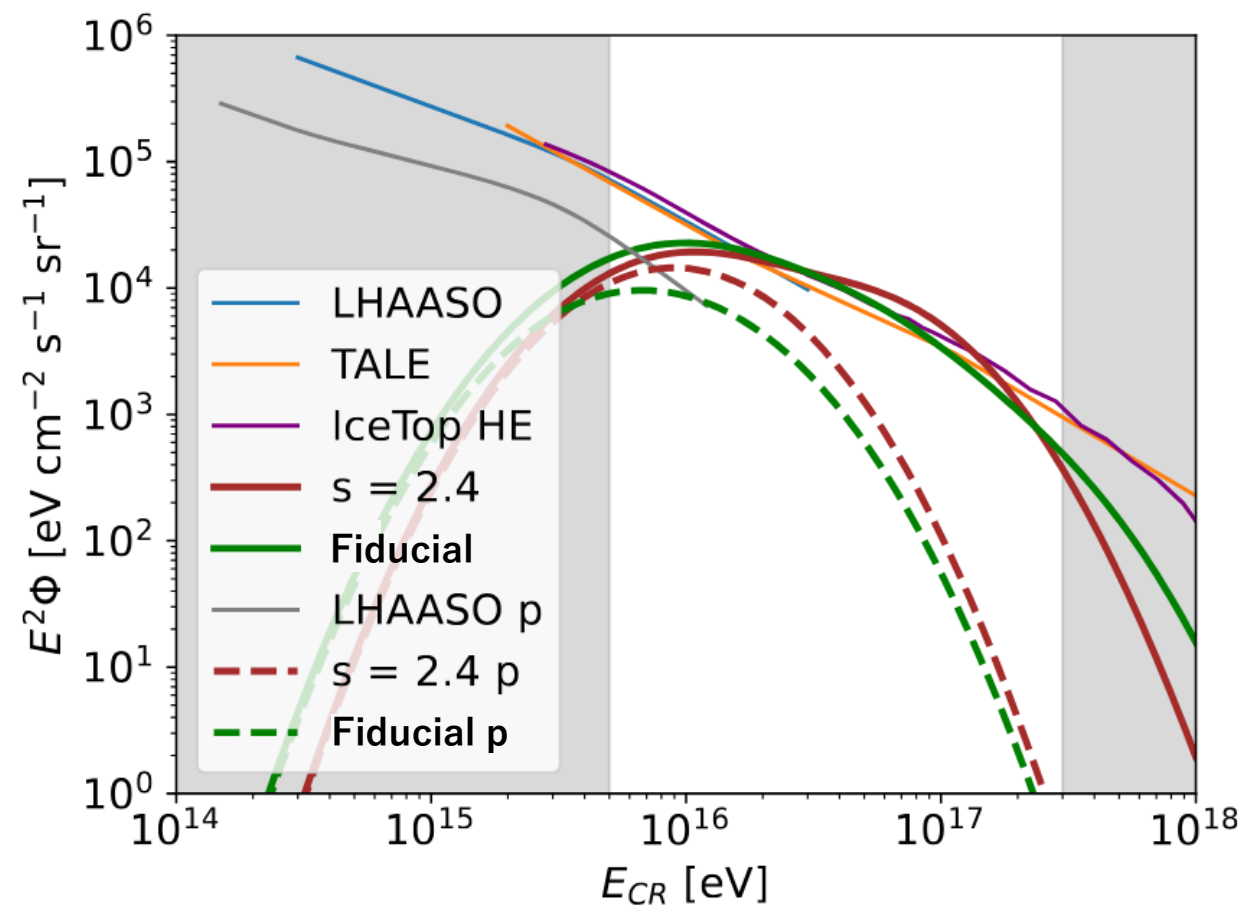
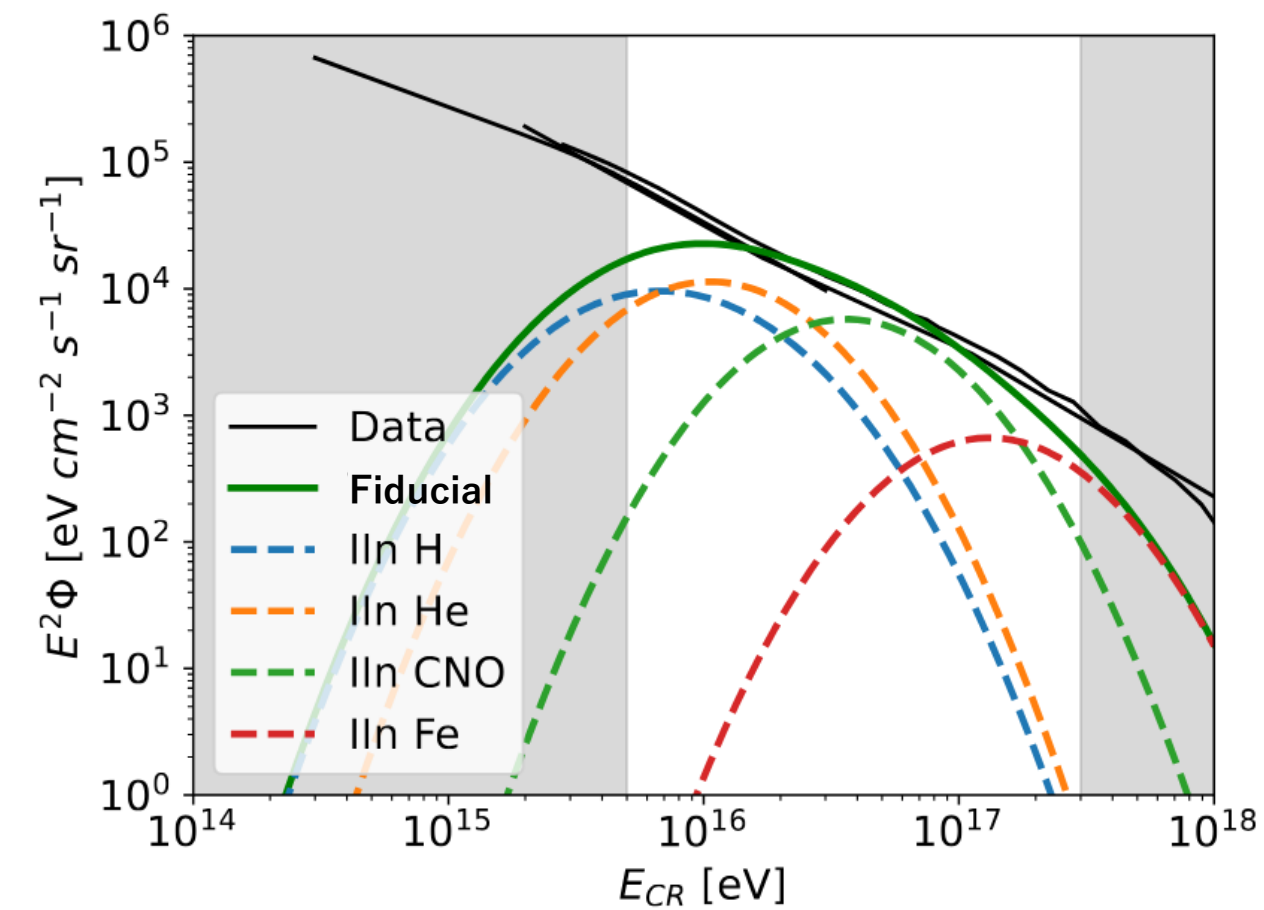
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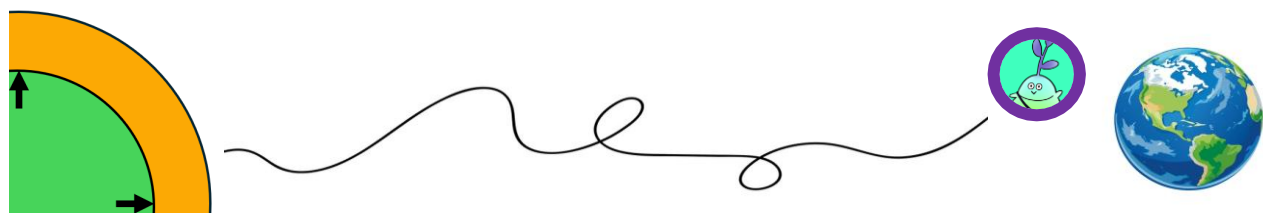


- CRs diffused in galactic B fields
- Can supply  $10^{16} \text{ eV}$  – few  $\times 10^{17} \text{ eV}$  flux
- Increasingly heavy composition

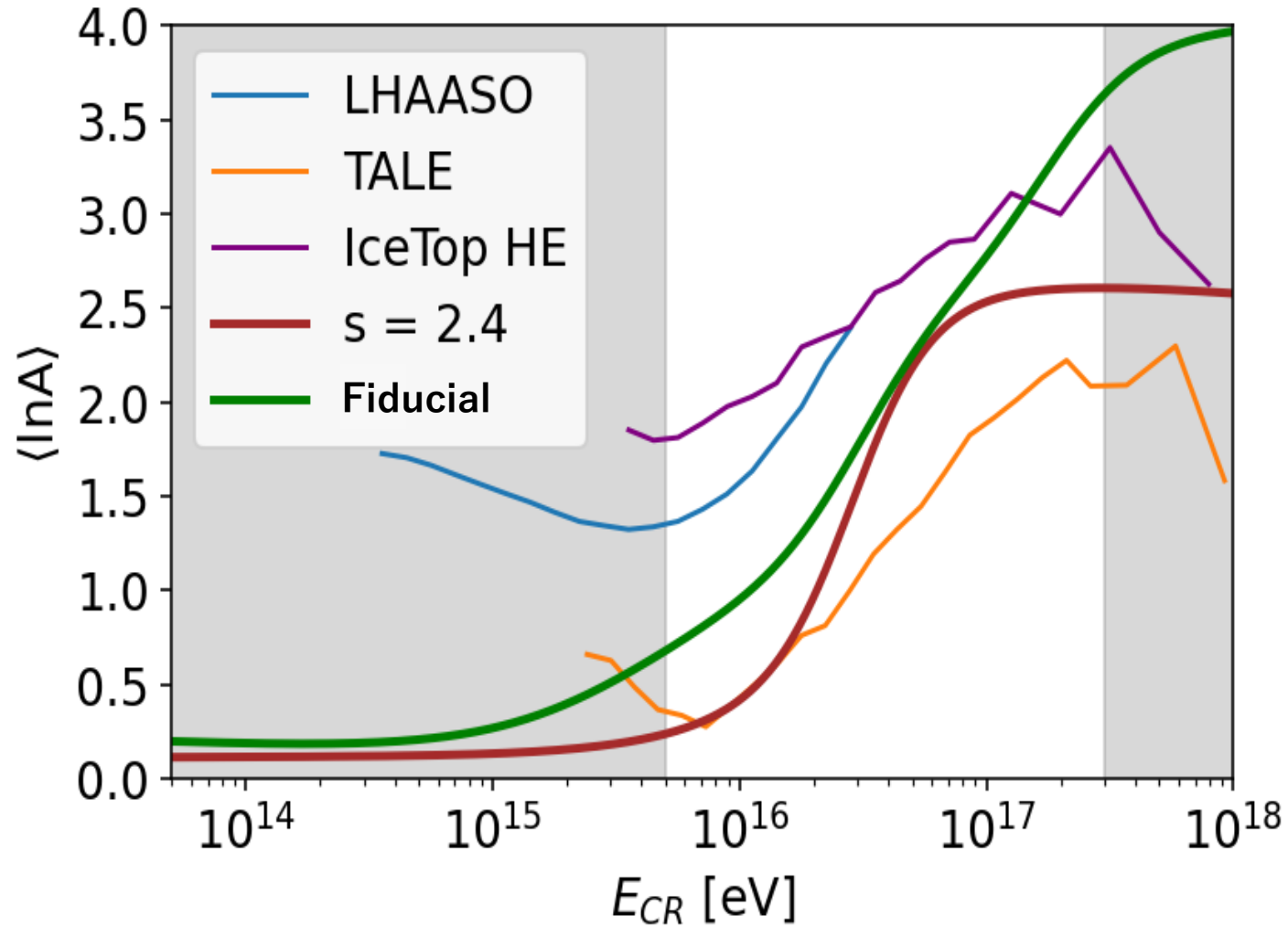




Some parameters disfavored







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

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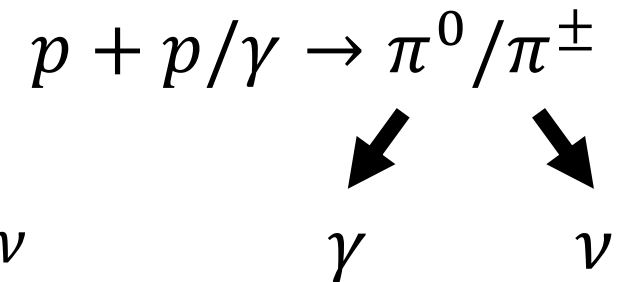
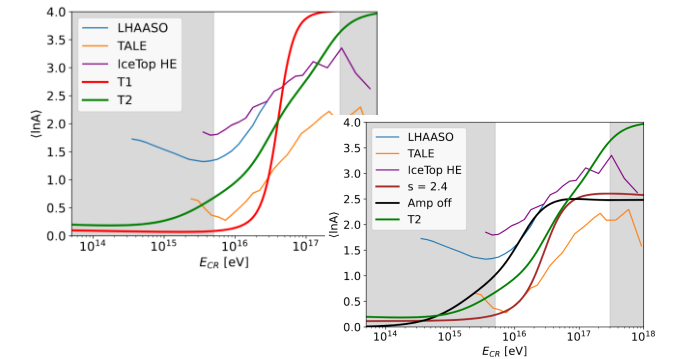
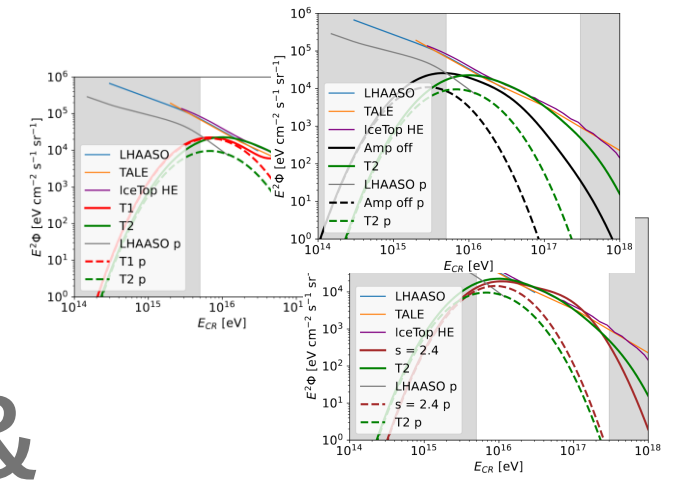
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# Summary and outlook

- Interacting SNe (especially IIn)
  - Acceleration above PeV
    - *Amplified magnetic field*
  - Increasingly heavy composition until 2<sup>nd</sup> knee
    - *Preferred injection of heavy ions*
- Paper coming soon!
- Multimessenger tests
  - $\gamma$  and  $\nu$  possibly detectable
  - Possible coincidences found: 2 IIn +  $\nu$ , 1 Ibn +  $\nu$

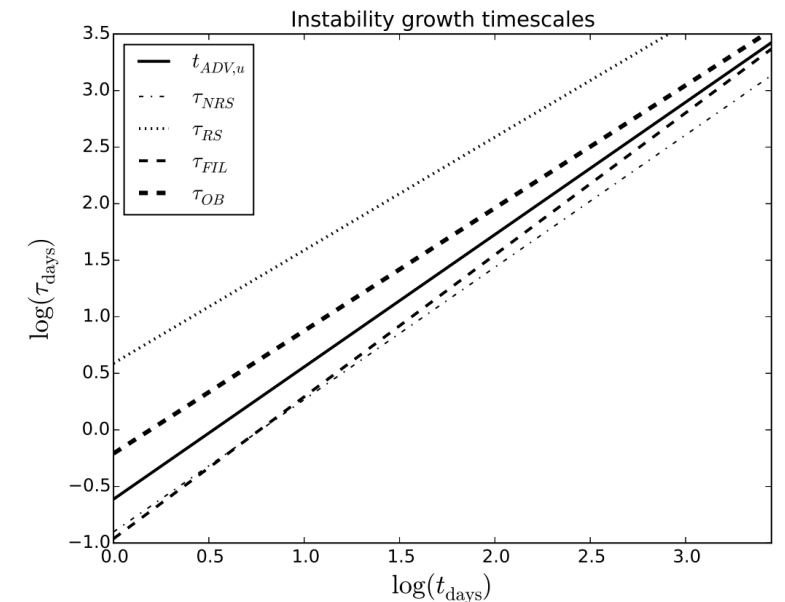
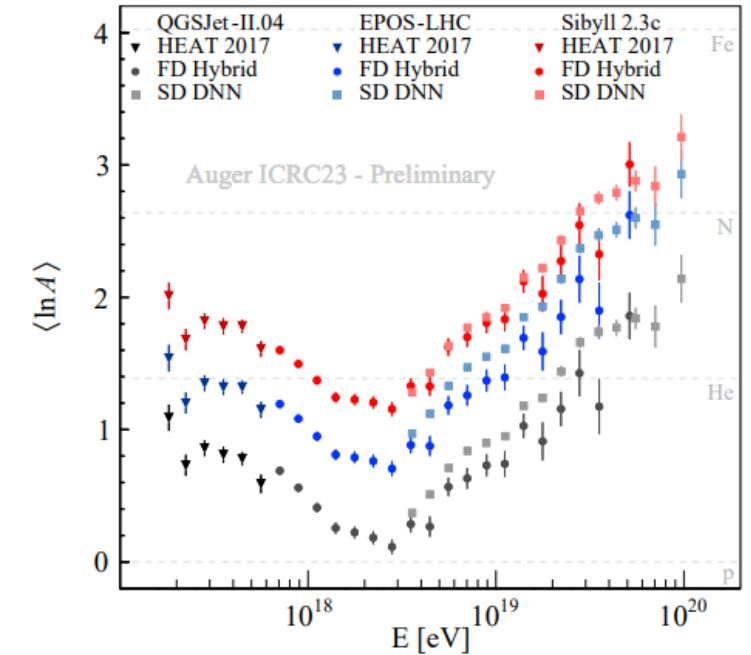
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Backup

# Backup

- 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



# Backup

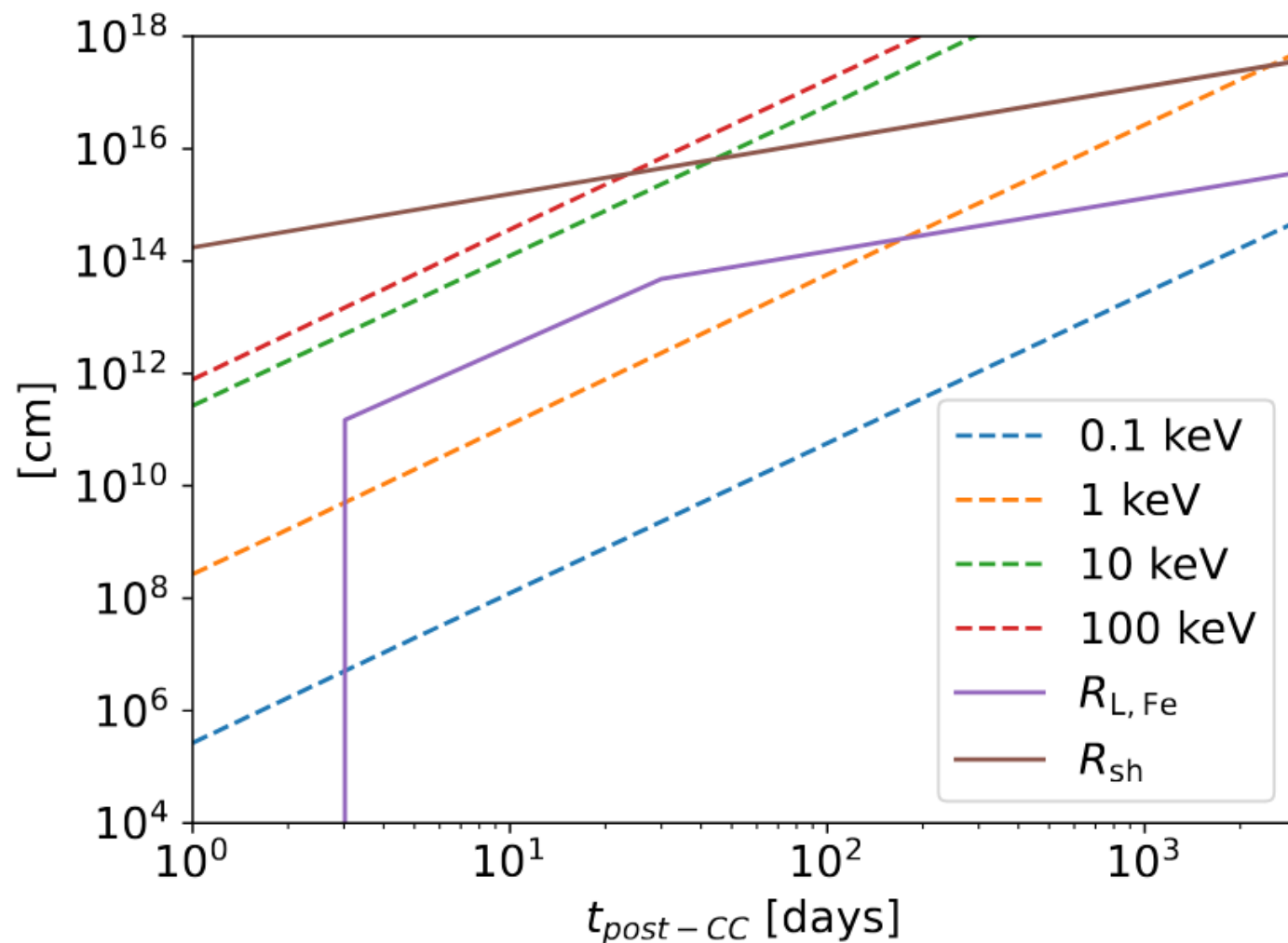
- X-ray reprocessing

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

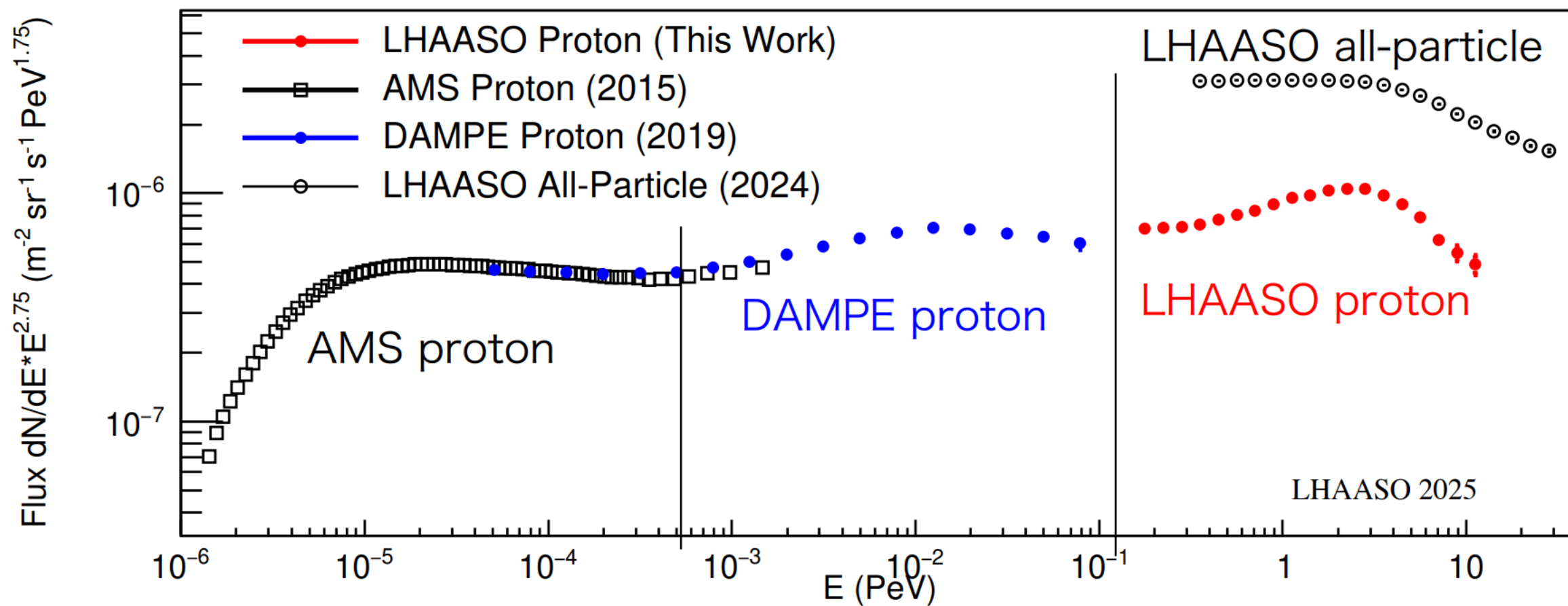
$$\kappa_X = \text{Max}(10^3 E_X^{-3}, \kappa_s) \text{ cm}^2 \text{ g}^{-1}$$

$$\kappa_s \sim 0.34$$

- Hard X-rays may not contribute



# Below PeV



# Iln + neutrino events?

- Not statistically significant, but...

	$t_{\text{rise,obs}}$ [days]	Time delay [days]	$M_{\text{abs}}$	Redshift	RA [deg]	DEC [deg]	Association	$E_{\nu}$ [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 lbn association



# More figures

