Super-PeV Cosmic-rays in Interacting Supernovae: spectrum and composition

Nick Ekanger, Shigeo S Kimura, Kazumi Kashiyama

Outline

I. CR observations
- Flux
- Composition

II. Interacting SNe CRs
- Max energies
- Nuclei injection

III. Data comparison
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IV. Summary and outlook
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- Multimessenger tests?

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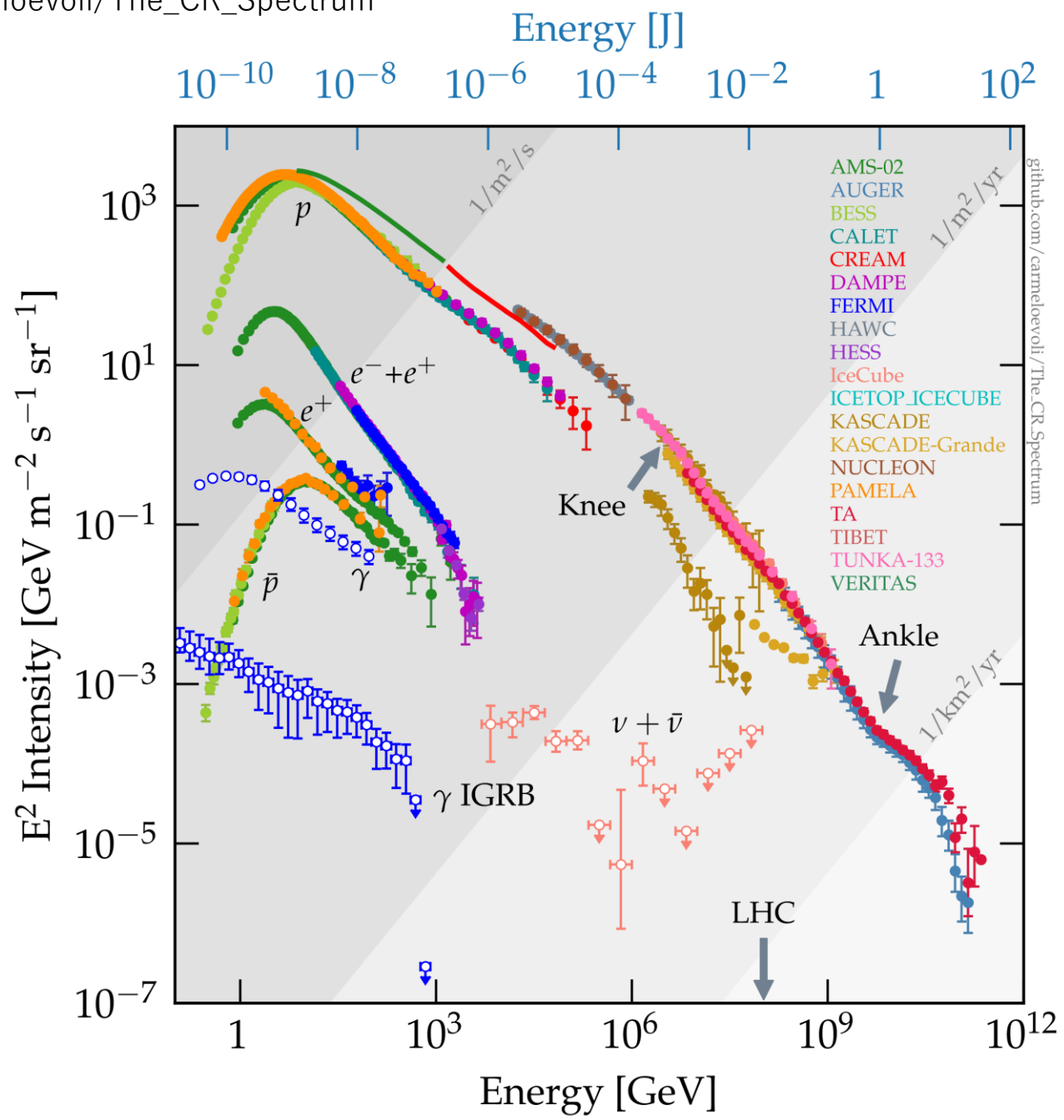

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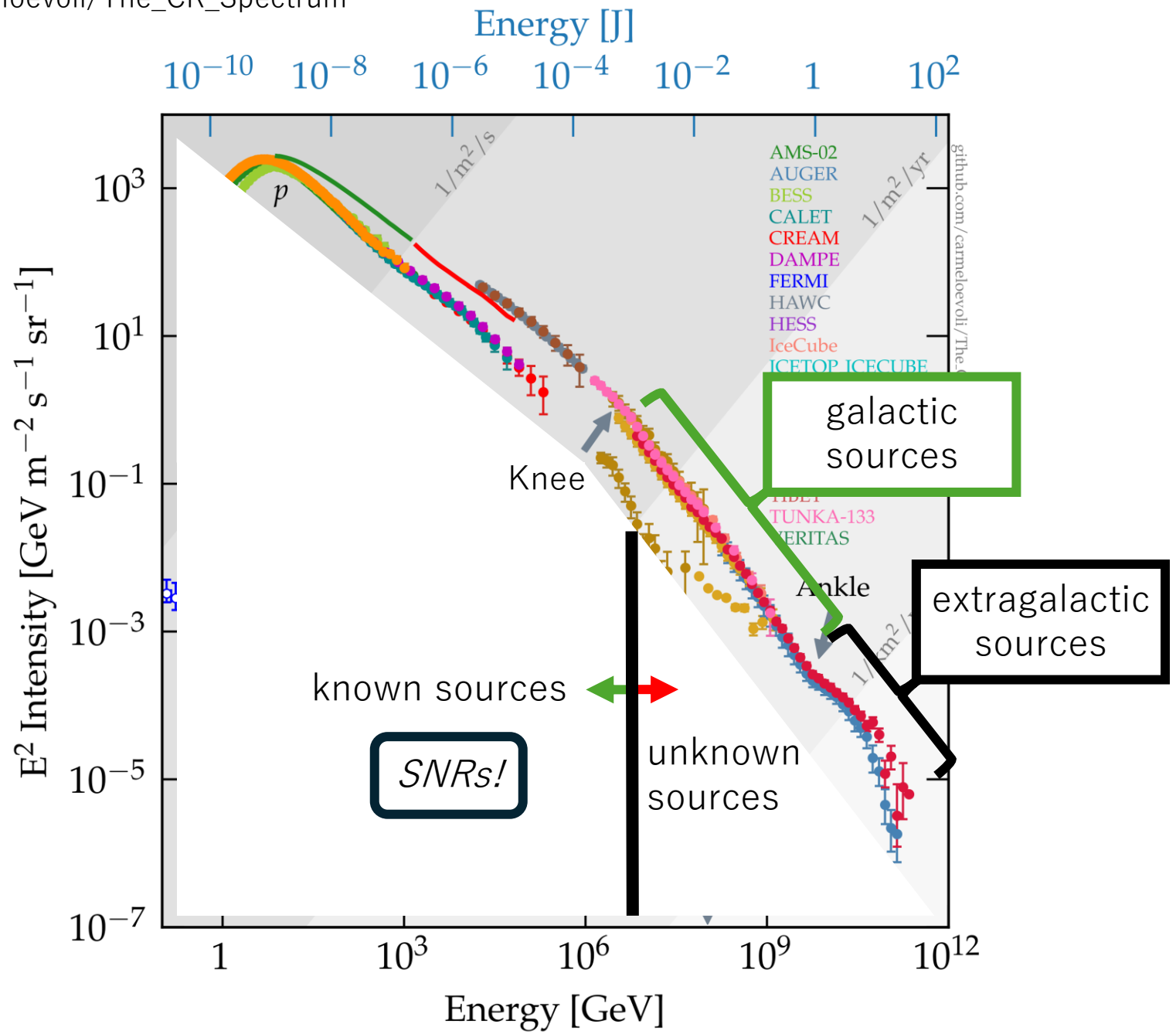

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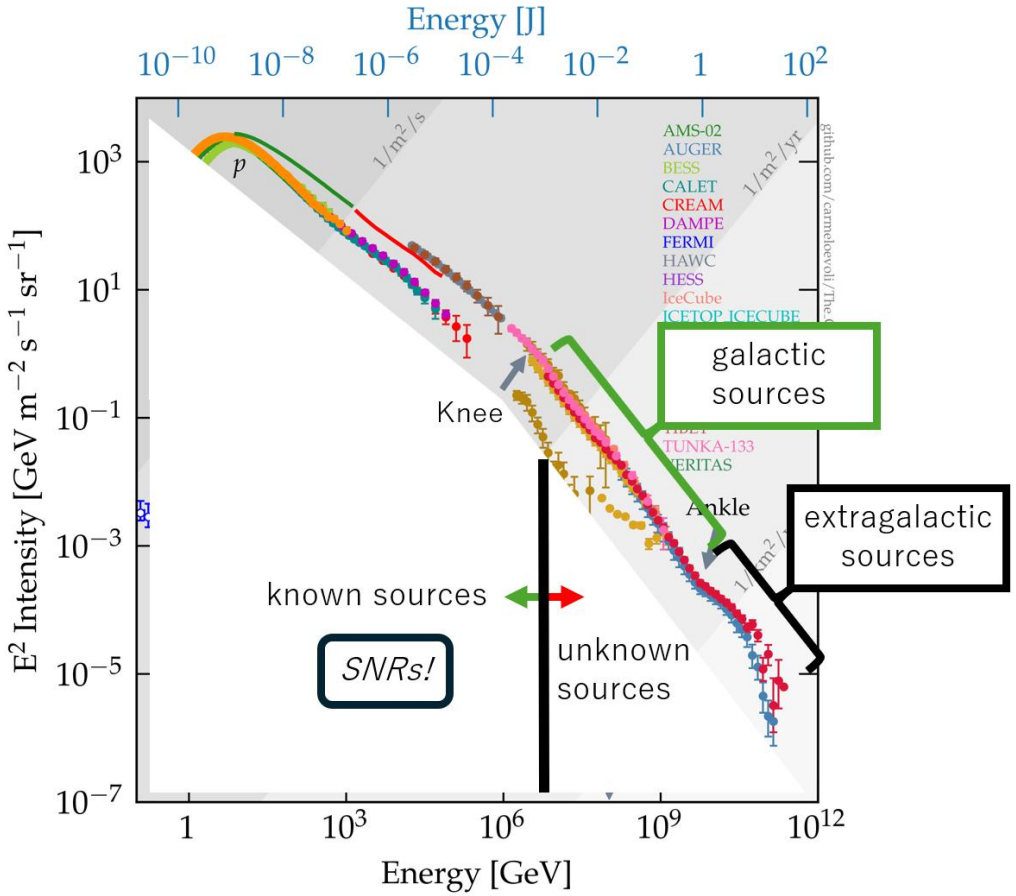

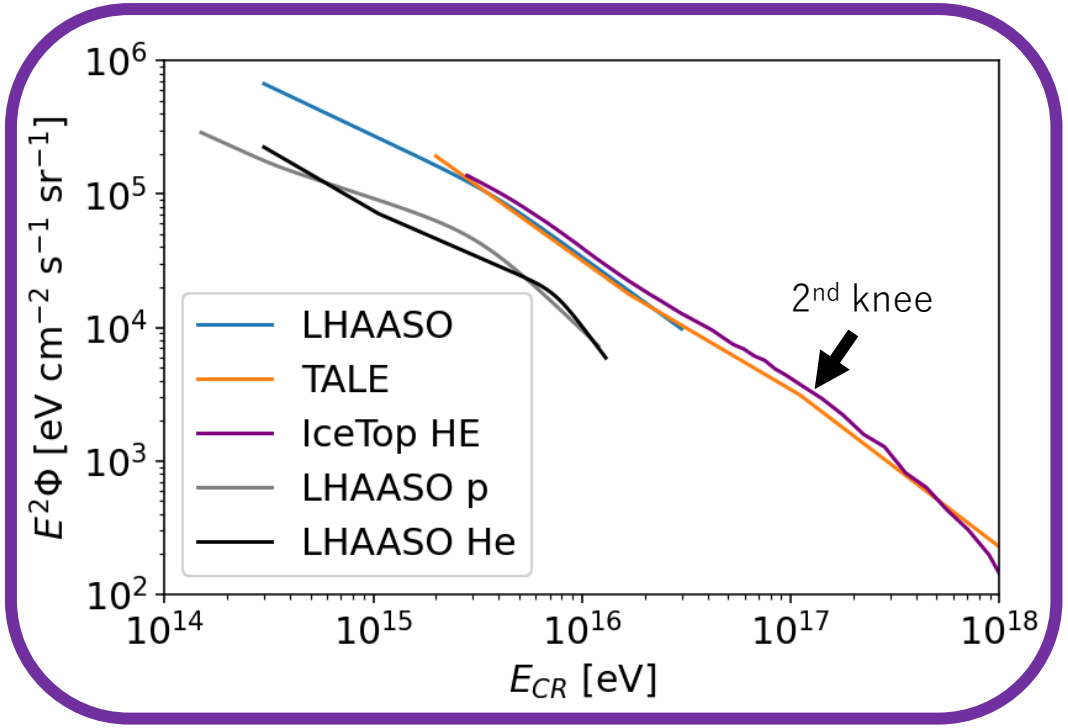

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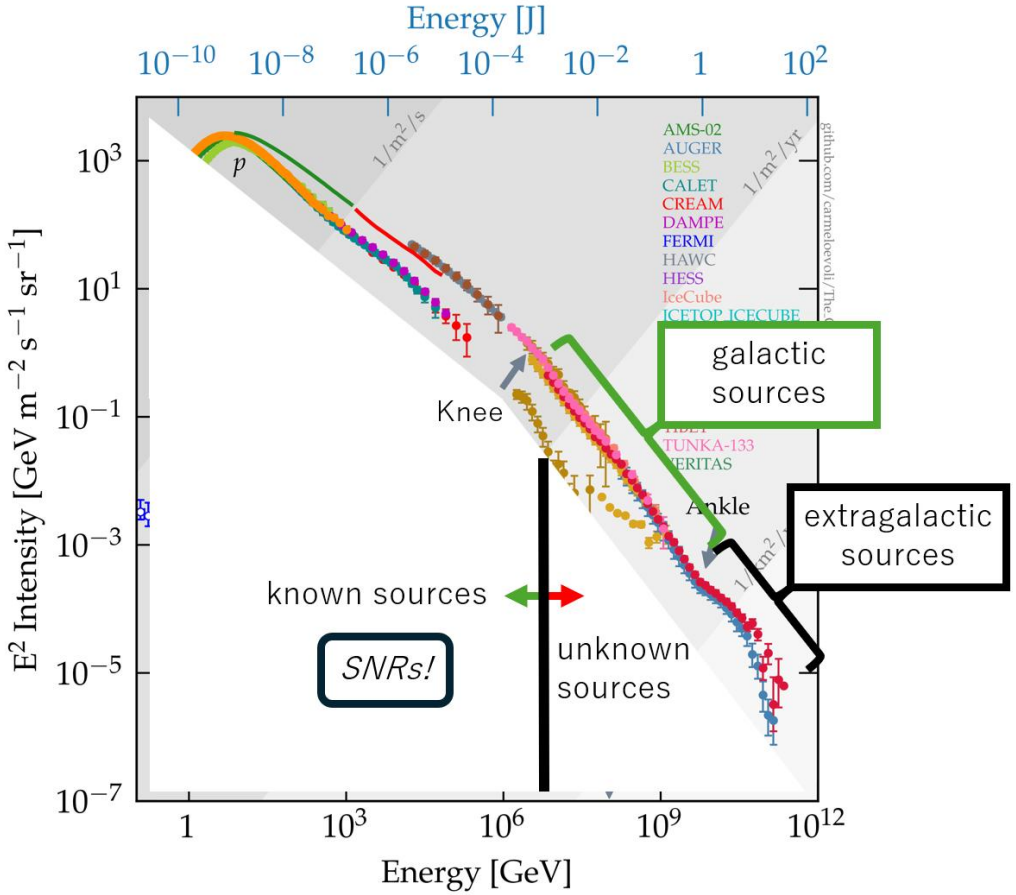

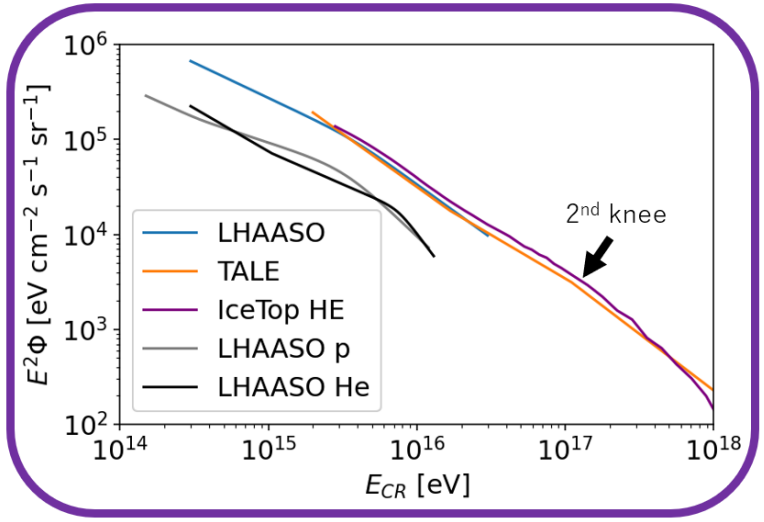

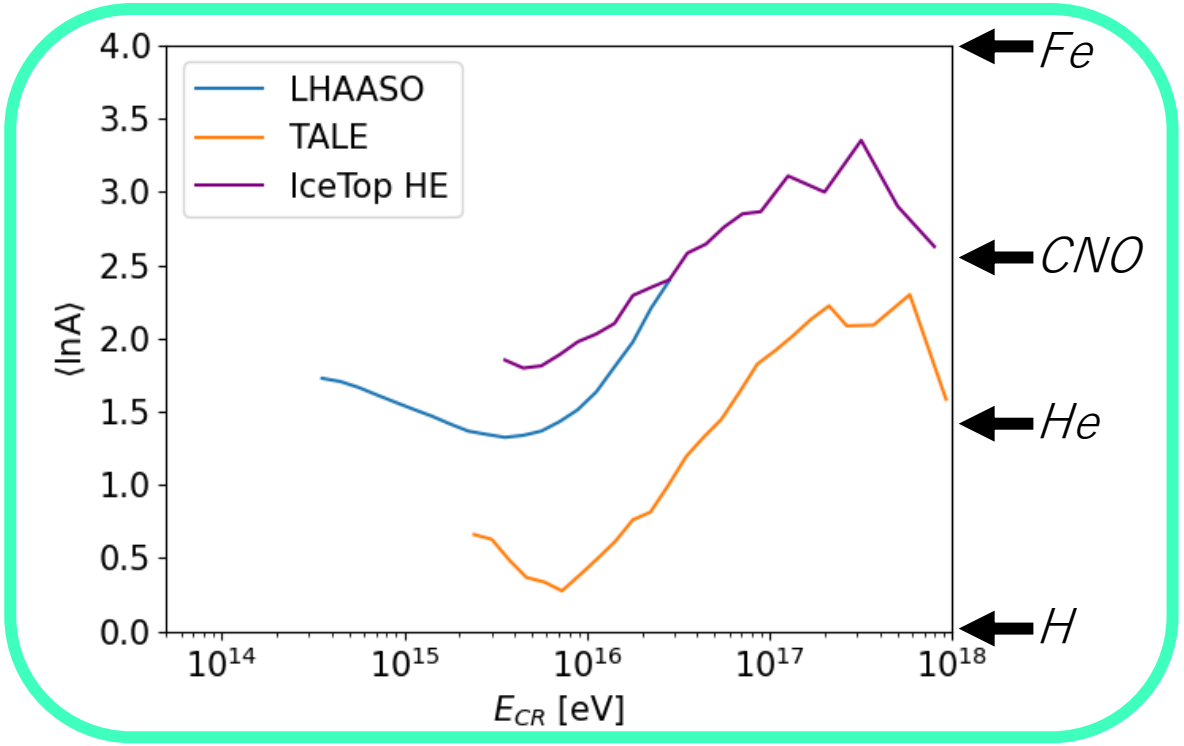

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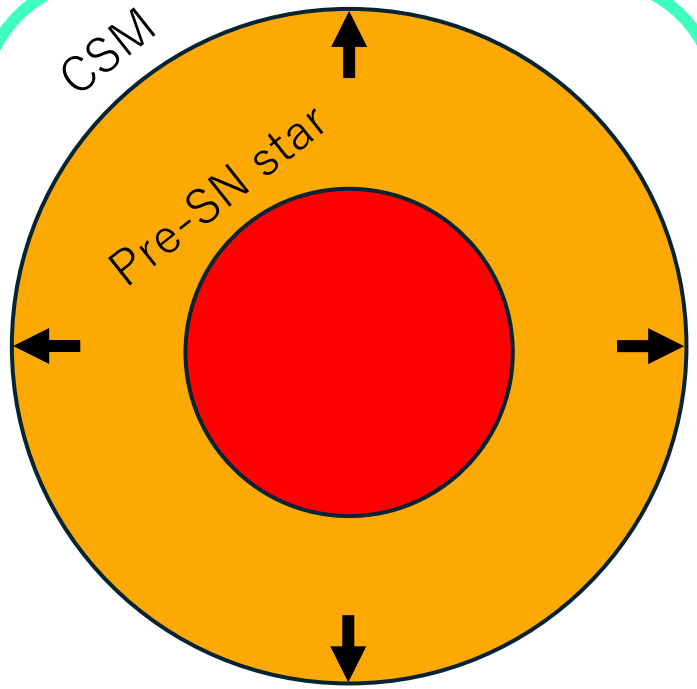
= super-PeV CRs

Interacting supernovae



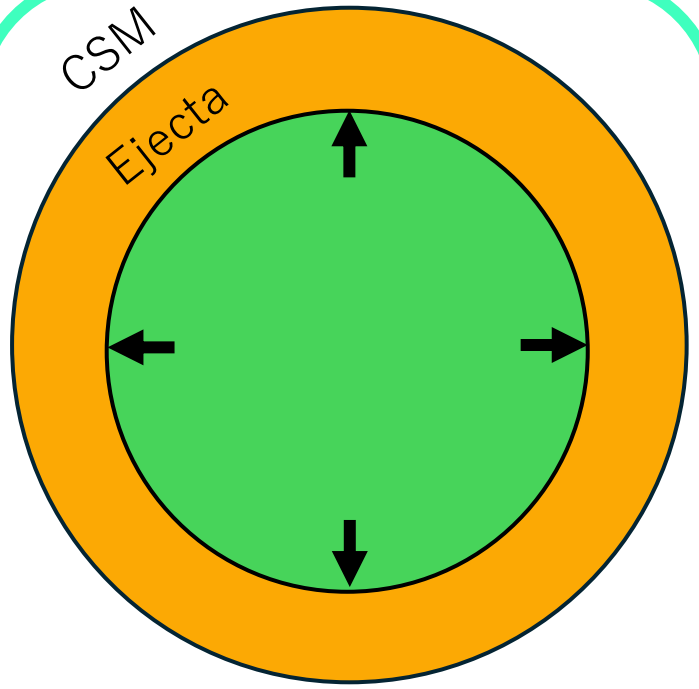
Pre-SN mass loss ➡ CSM

* ***IIn:***

$\dot{M} \sim 5 \times 10^{-2} M_{\odot}\ yr^{-1}$

$v_w \sim 100\ km\ s^{-1}$

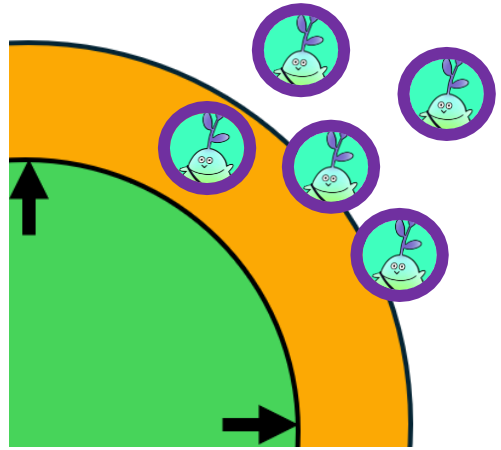
$\sim 5\%\ R_{SN}$



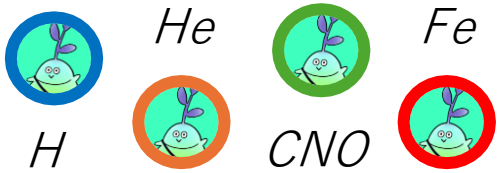
Compared to SNRs,
CSM higher:

$\rho \propto B^2$

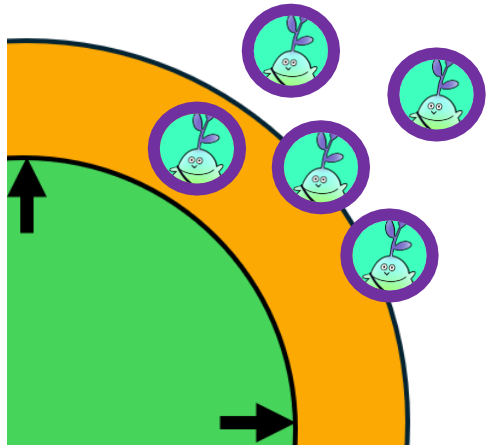
$B \rightarrow E_{max}$



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



Preferred injection of
heavier nuclei



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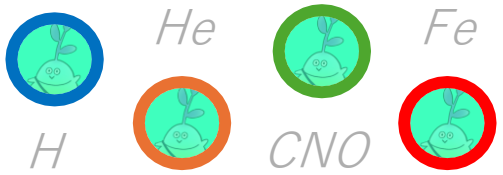
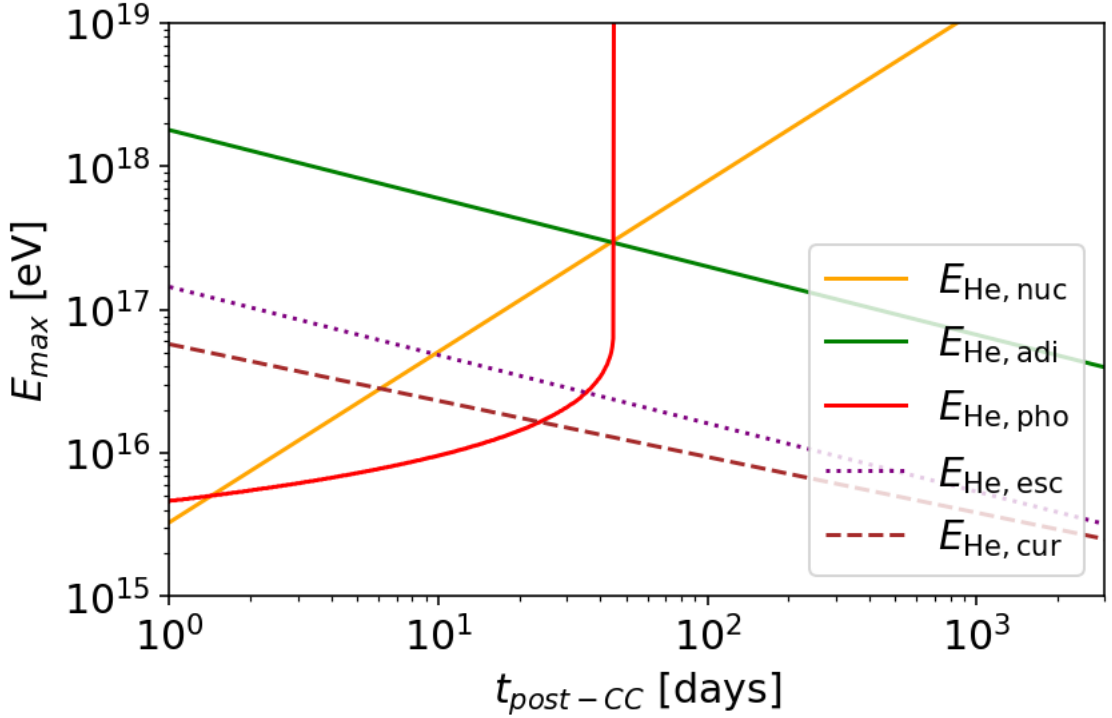
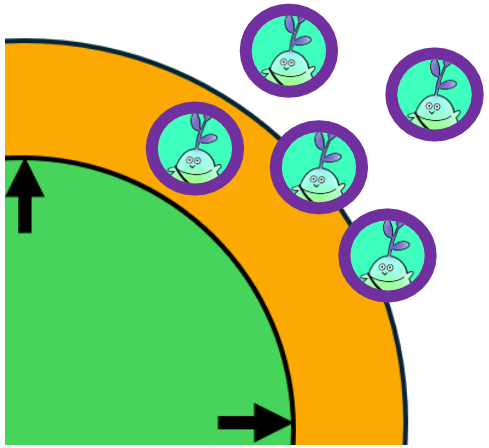


Preferred injection of heavier nuclei

- ***B field amplification:***
  - CRs escape, produce current
  - Excite modes $< r_L$ (Non-resonant streaming or Bell instability)
  - $\times 2 - 4$ w/ IIn parameters
- Compare acceleration timescale for E_{max}





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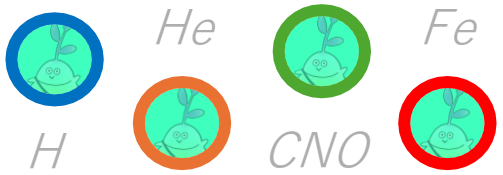
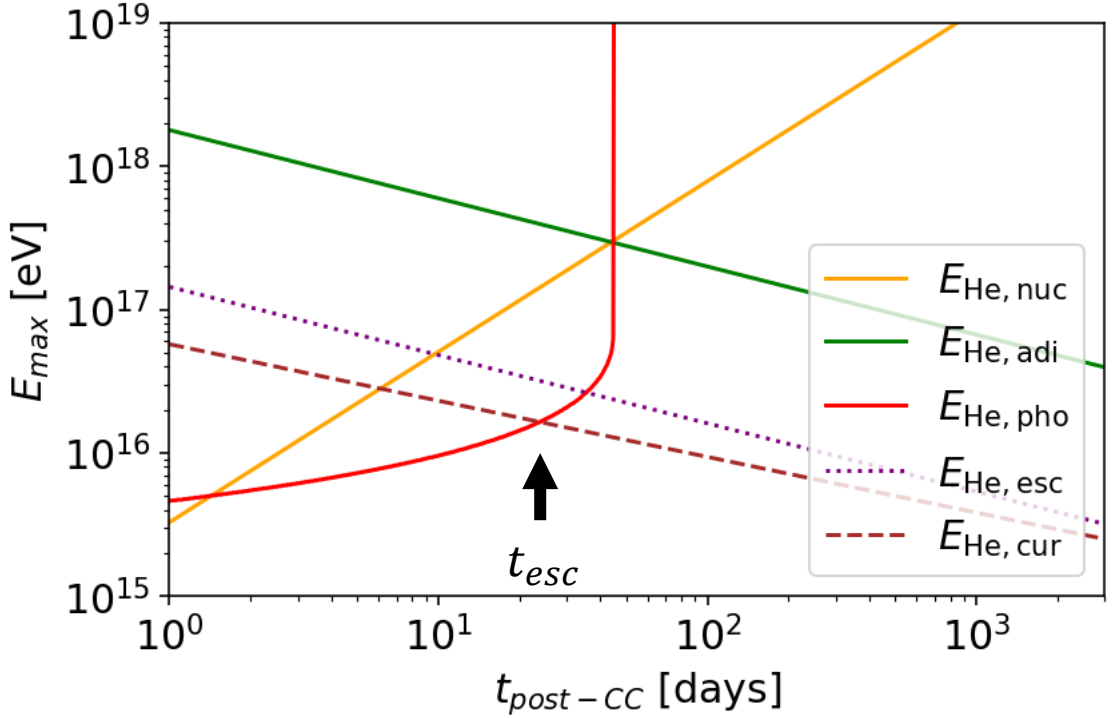
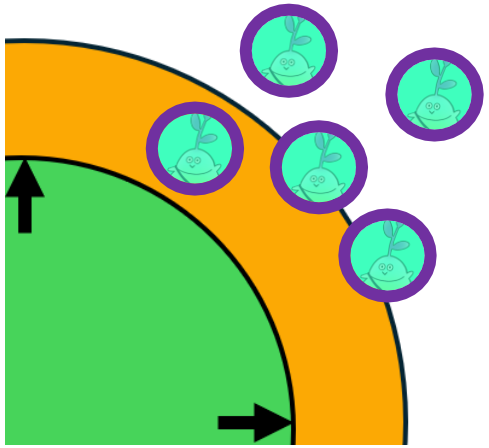


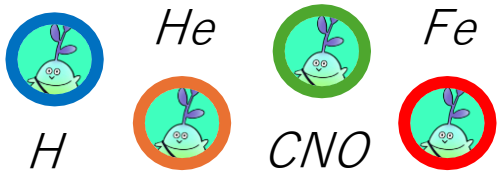
Preferred injection of heavier nuclei

- Escape-limited model (~20-30 d)
  - $l_{diff} \sim R_{sh}$ or
  - $E_{He,cur}$ most limiting
- Few $\times 10^{16}$ eV max energies



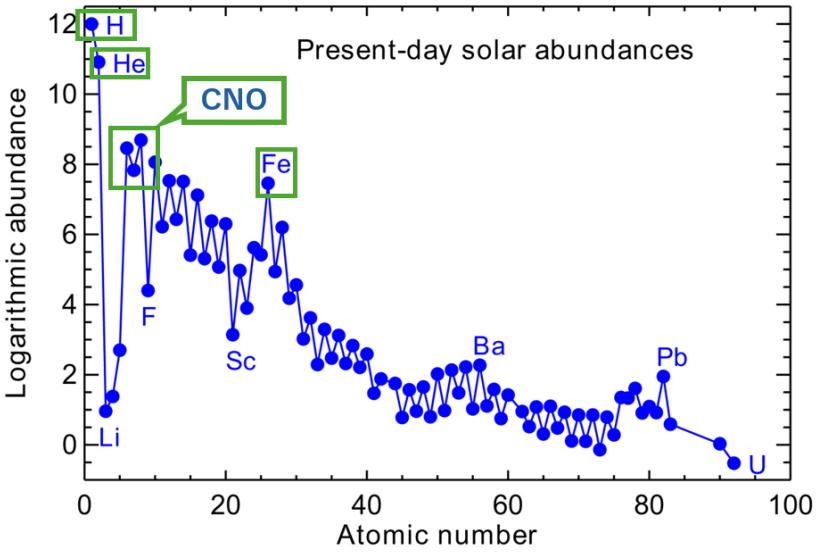


Diffusive shock acceleration w/ ***amplified B field***



Preferred injection of heavier nuclei

Asplund+ 2021



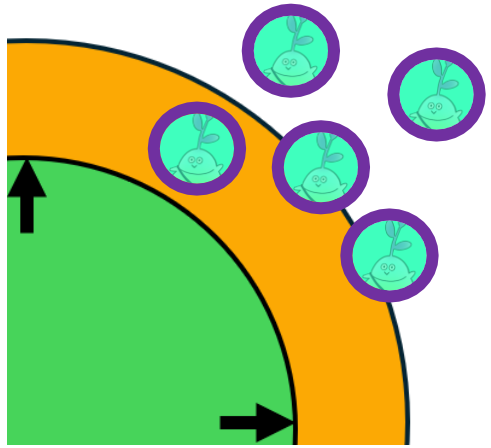
$H \sim 90\%$

$He \sim 9\%$

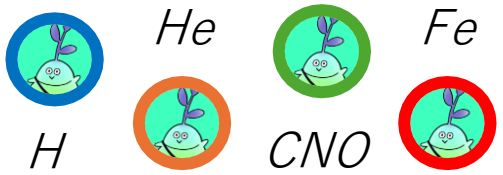
$CNO \sim 0.1\%$

$Fe \sim 0.002\%$

- Simulations show $f_{inj} \sim (A/Z_{ion})^{5/2}$
  - Heavy, singly-ionized nuclei are ***more efficiently injected***
- Z_{ion} from *CLOUDY* photoionization code
  - ~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* ~ 100% (0%)
  - *He* ~ 50% (0%)
  - *CNO* ~ 100% (0%)
  - *Fe* ~ 0% (100%)

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

H	~ 90%	→ *28%*
He	~ 9%	→ *45%*
CNO	~ 0.1%	→ *24%*
Fe	~ 0.002%	→ *3%*

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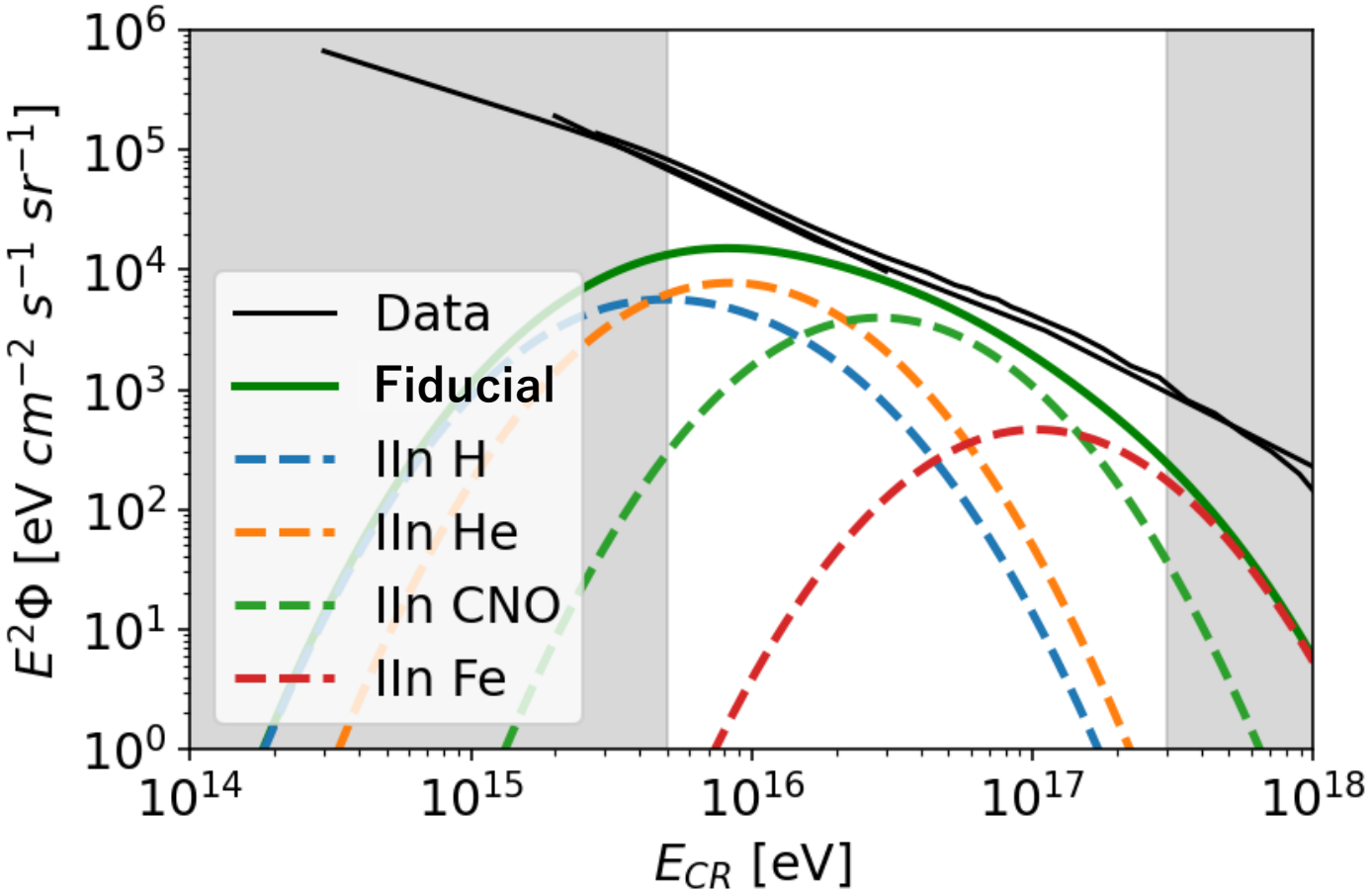
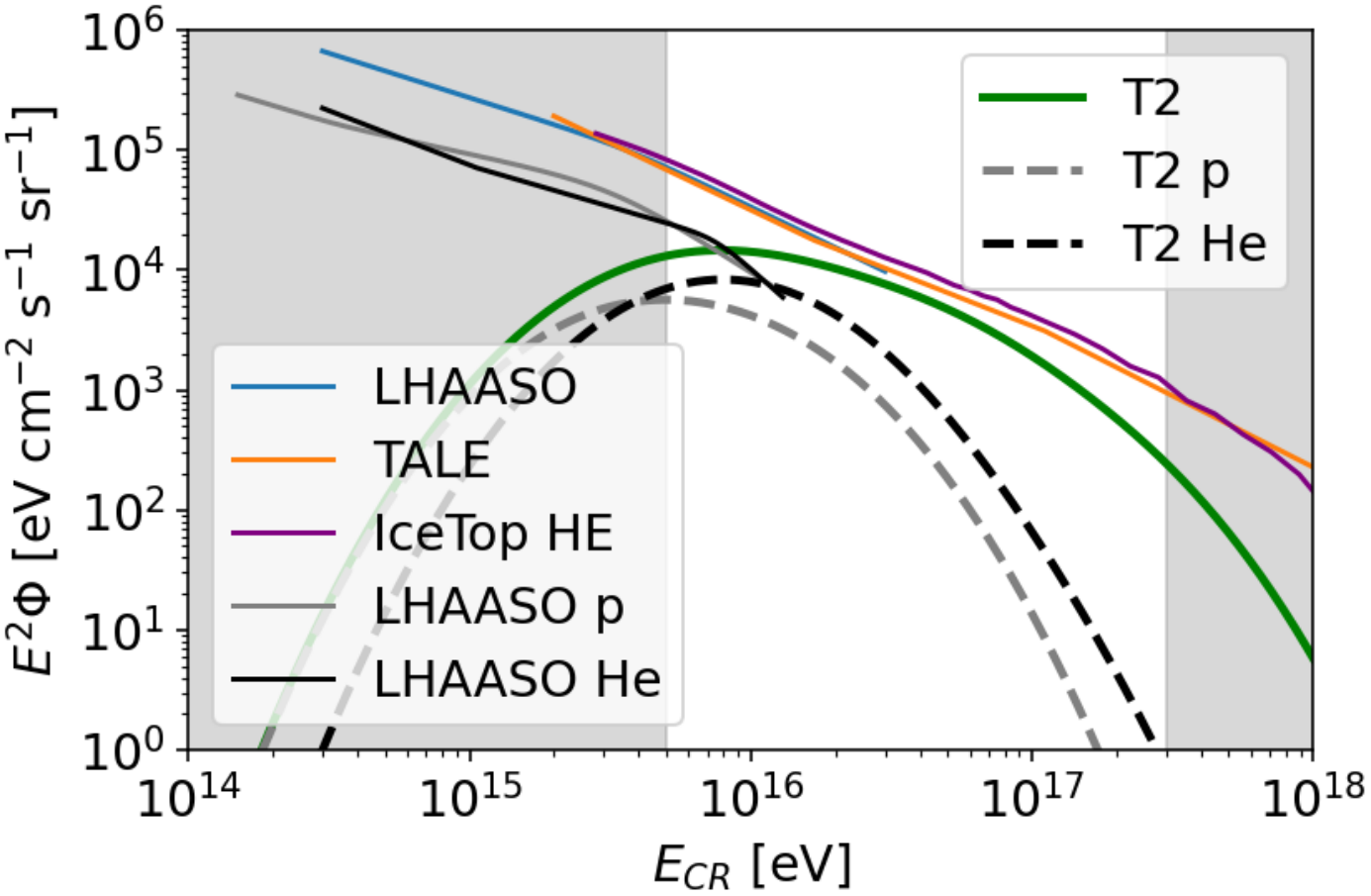
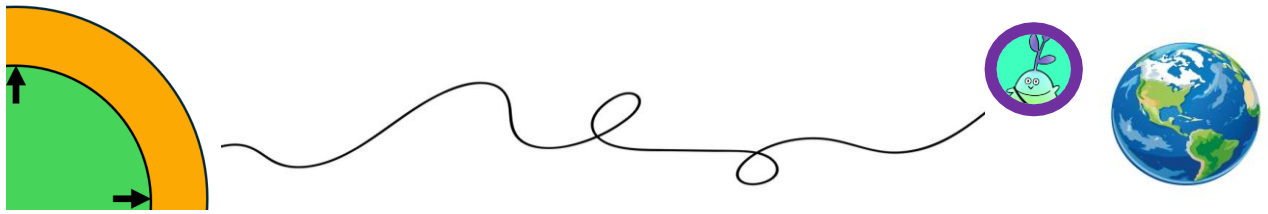
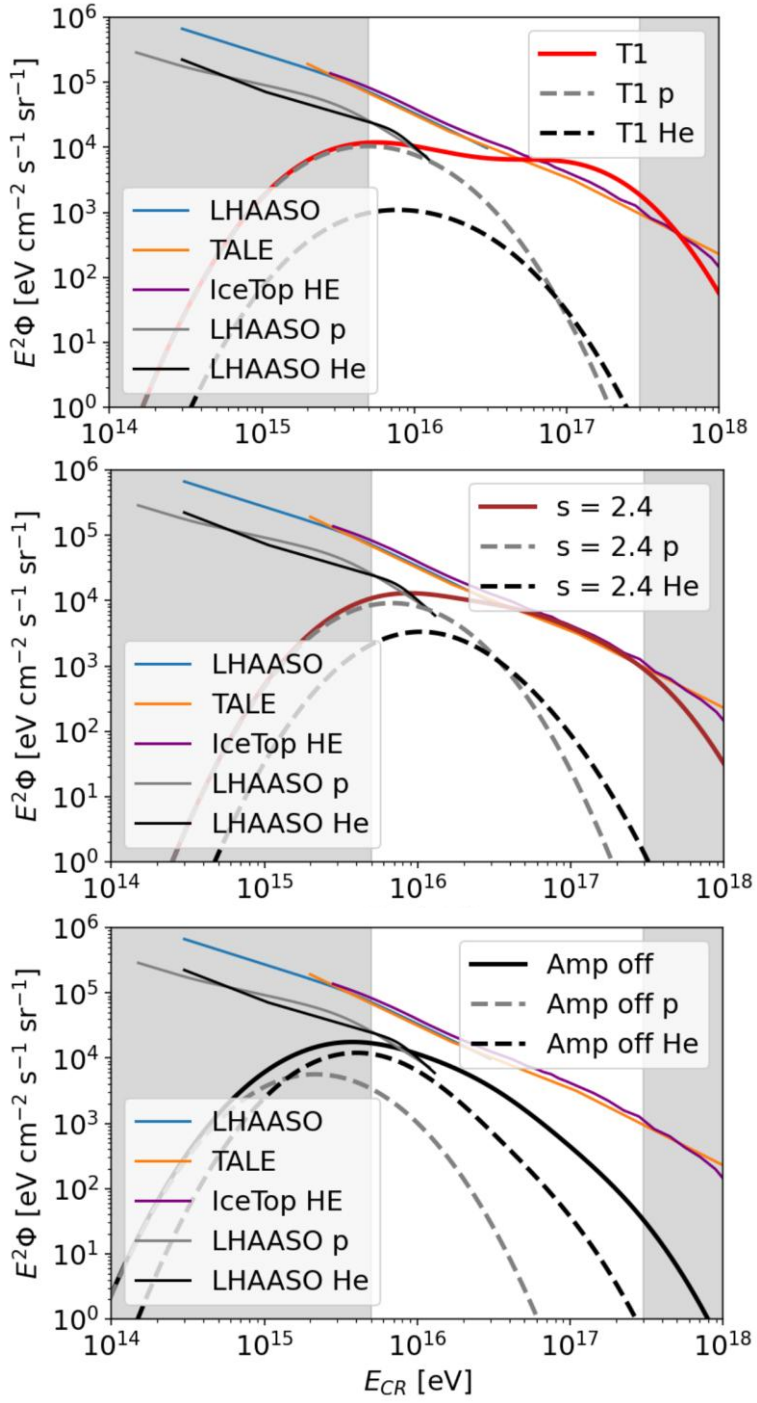


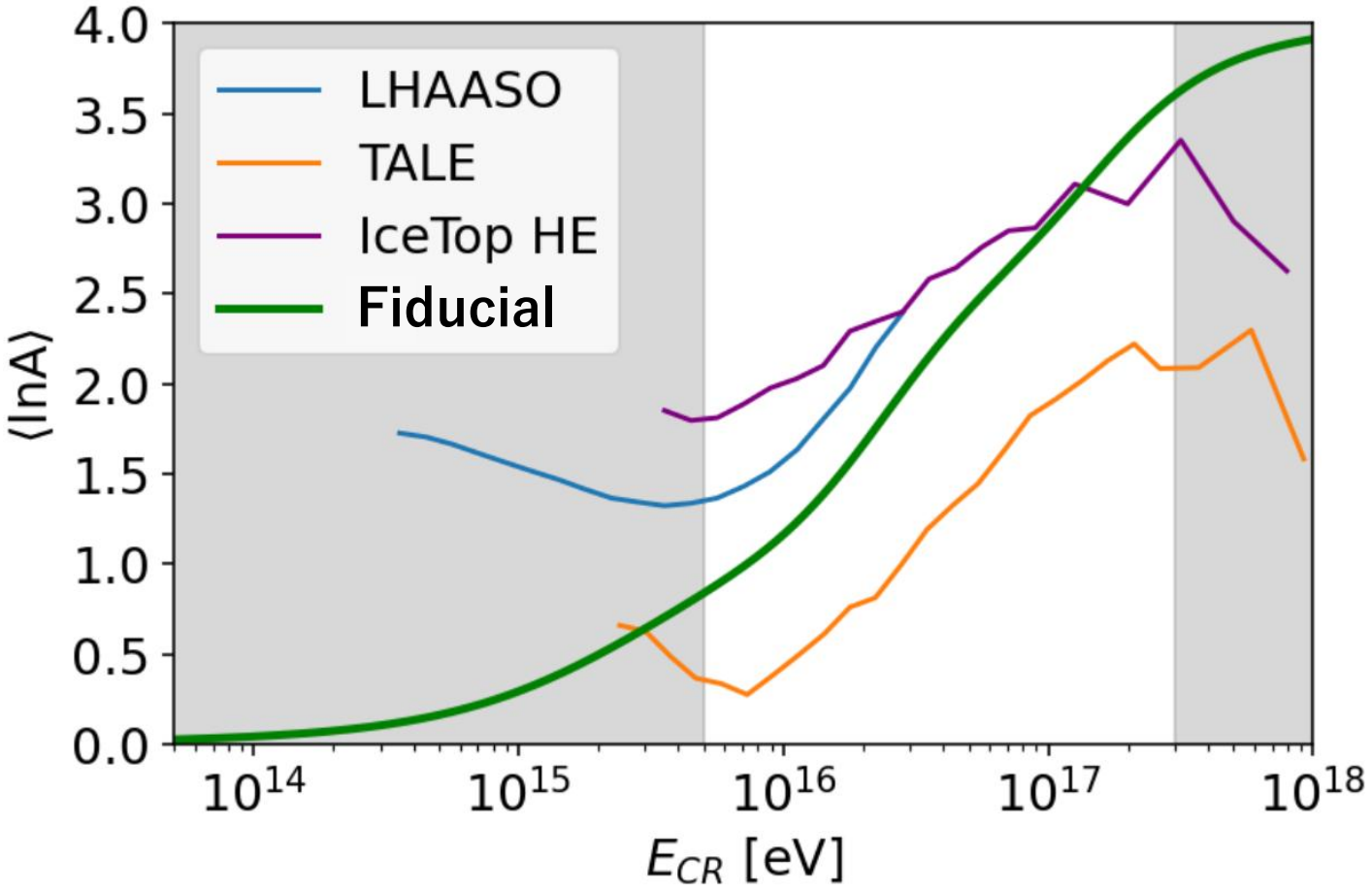
- CRs diffused in galactic B fields
- Can supply $\sim 10^{16} eV$ – $\sim 10^{17} eV$ flux
- Increasingly heavy composition



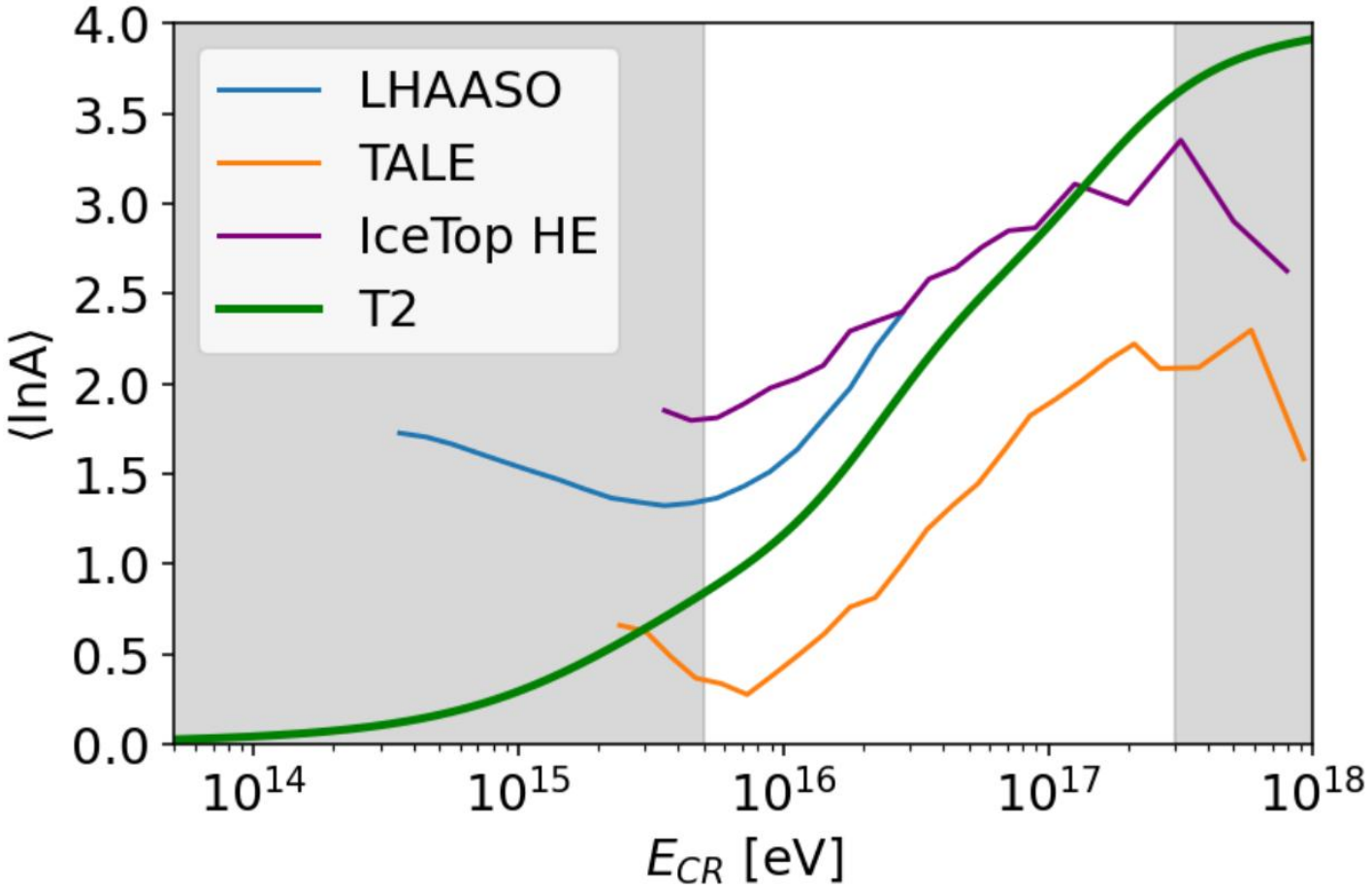


Additional models





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



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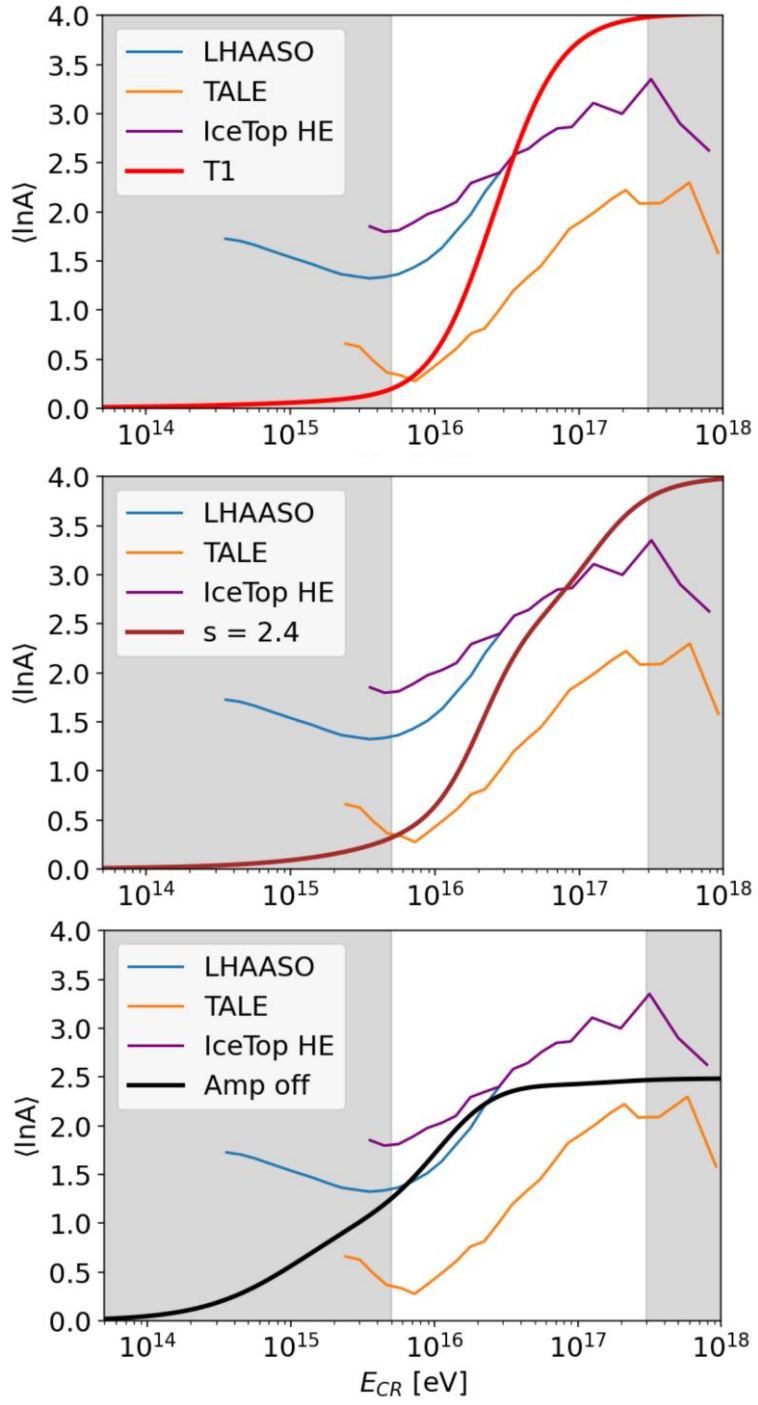

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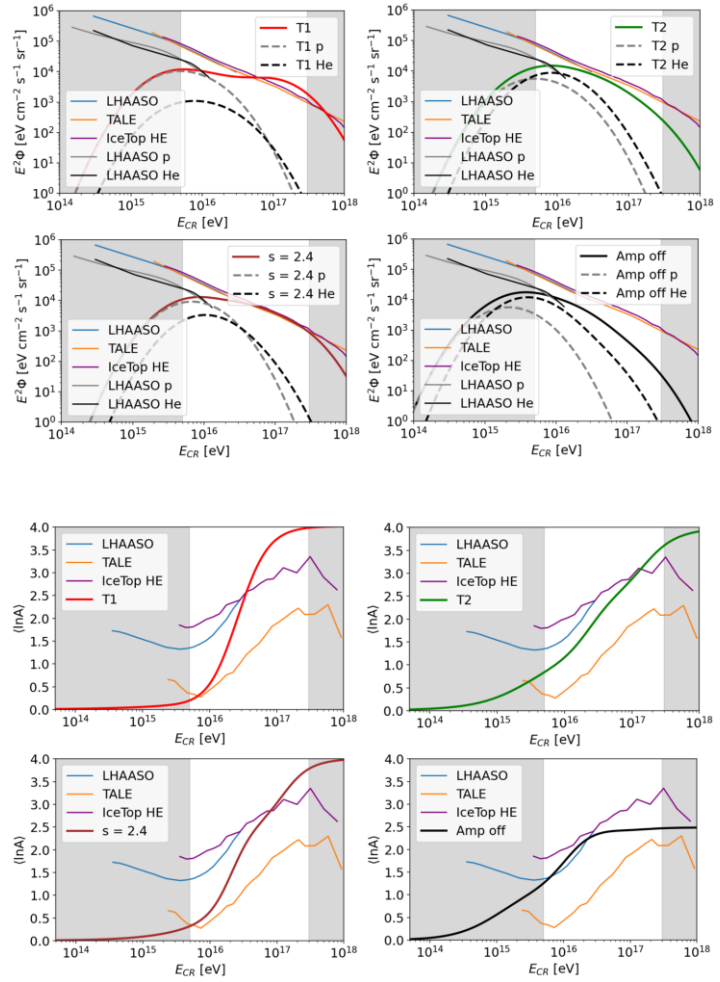
Summary and outlook

- Interacting SNe (especially IIn)
  - Acceleration above PeV
    - ***Amplified magnetic field***
  - Increasingly heavy composition until 2nd knee
    - ***Preferred injection of heavy ions***

- Paper coming soon!

- Multimessenger tests
  - γ and ν possibly detectable
  - Possible coincidences found: 2 IIn + ν, 1 Ibn + ν

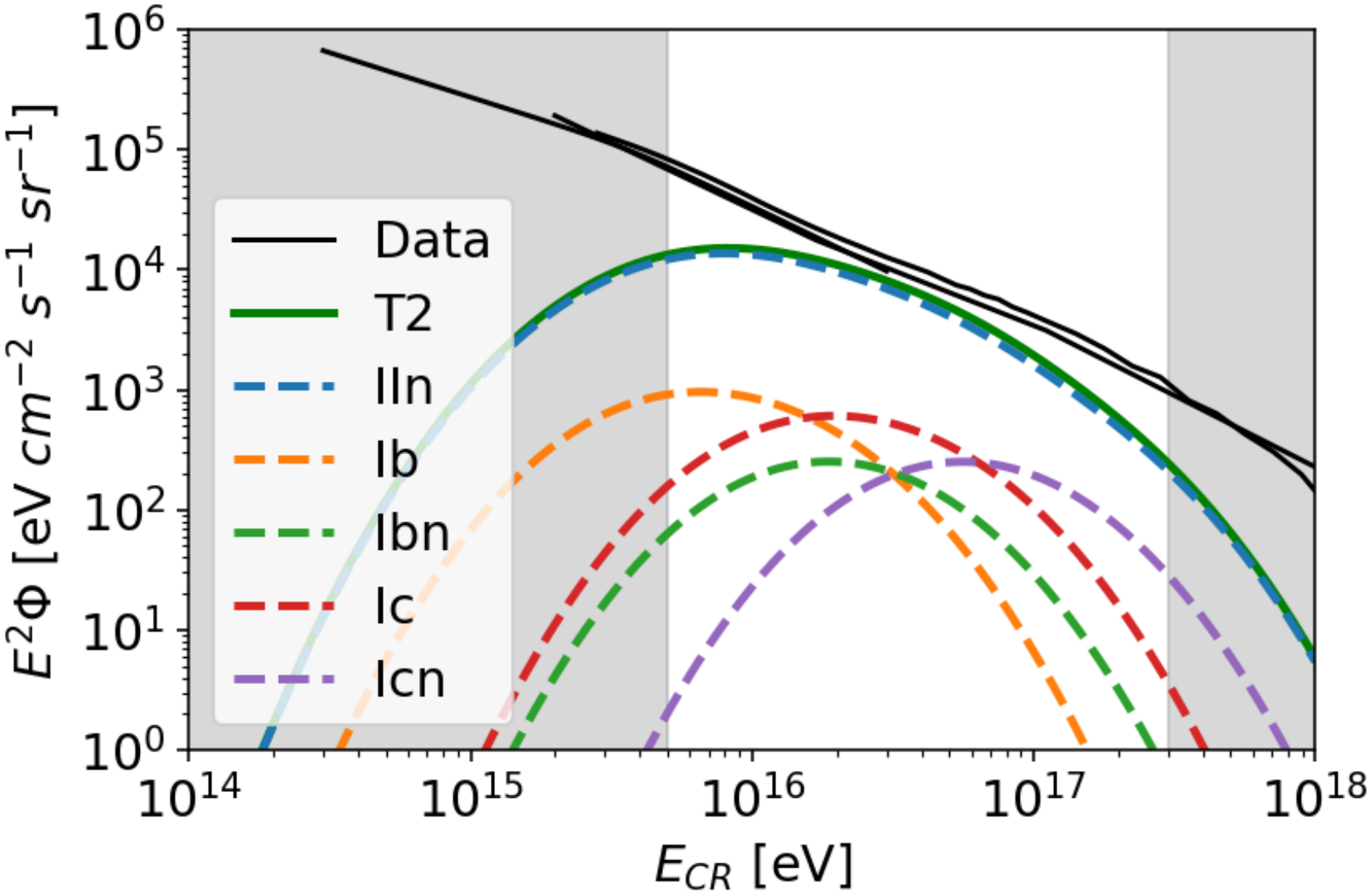


&

$$p + p/\gamma \rightarrow \pi^0/\pi^{\pm}$$

γ ν

Backup


10^6
10^5
10^4
10^3
10^2
10^1
10^0
$E^2\Phi$ [eV cm^{-2} s^{-1} sr^{-1}]
Data
T2
IIn
Ib
Ibn
Ic
Icn
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
E_{CR} [eV]

lln + neutrino events?

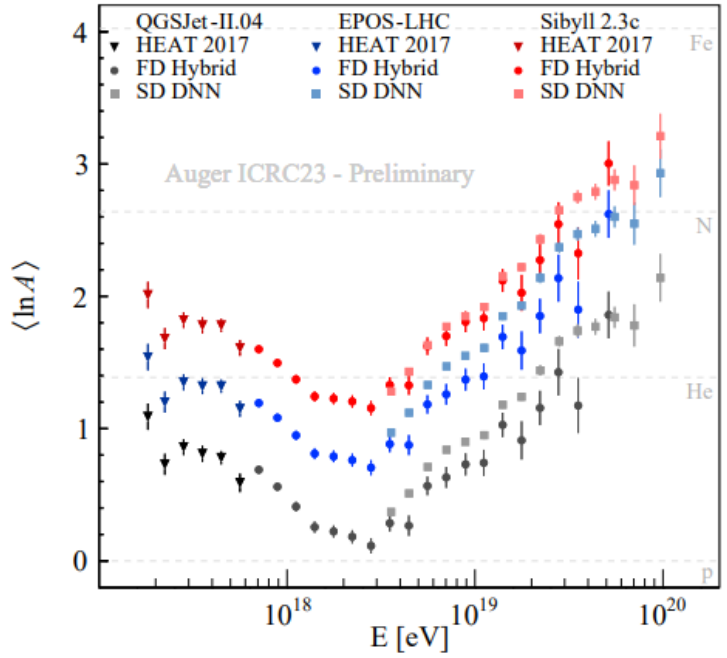
- Not statistically significant, but…

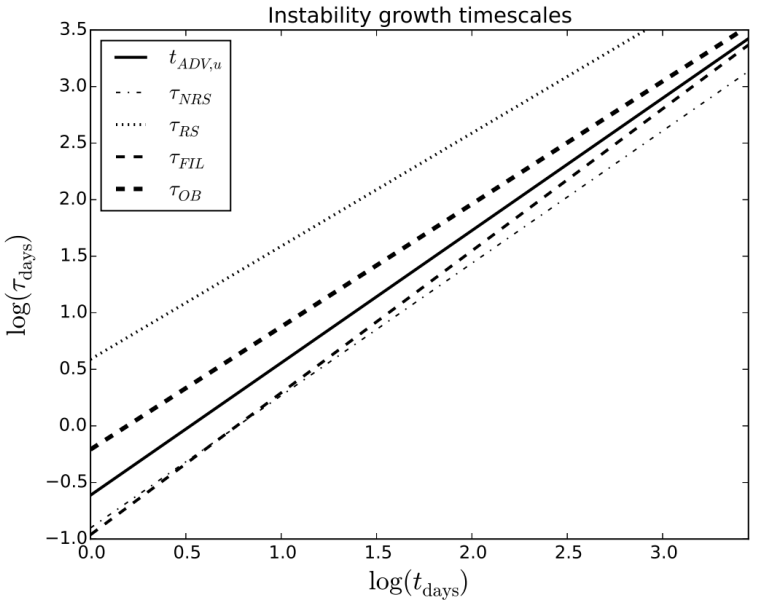
	$t_{\rm rise,obs}$ [days]	Time delay [days]	$M_{\rm abs}$	Redshift	RA [deg]	DEC [deg]	Association	E_ν [TeV]
SN2023syz	10	38	−17.58	0.037	268.85	45.22	IC231027A	191.5
SN2025cnj	50	61	−19.15	0.0675	239.92	27.11	IC250421A	151.4

- Also a potential lbn association

Neutrino Event	Full Area [sq. deg.]	ZTF Coverage [sq. deg.]	Signalness	Best-Fit Energy [TeV]	Ref
IC191001A	25.64	20.73	0.59	217	[172, 173]
⋮					
IC250727A	2.00	2.40	0.29	115	[236, 237]
IC231004A	**4.29**	**3.59**	**0.84**	**442**	[71, 72, 74]
IC231103A	15.27	15.09	0.59	180	[238, 239]

- Consistent with PAO lnA?
  - We overestimate around ~few 1e17, 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 ~ Larmor, doesn't grow as fast
  - NRSI fastest





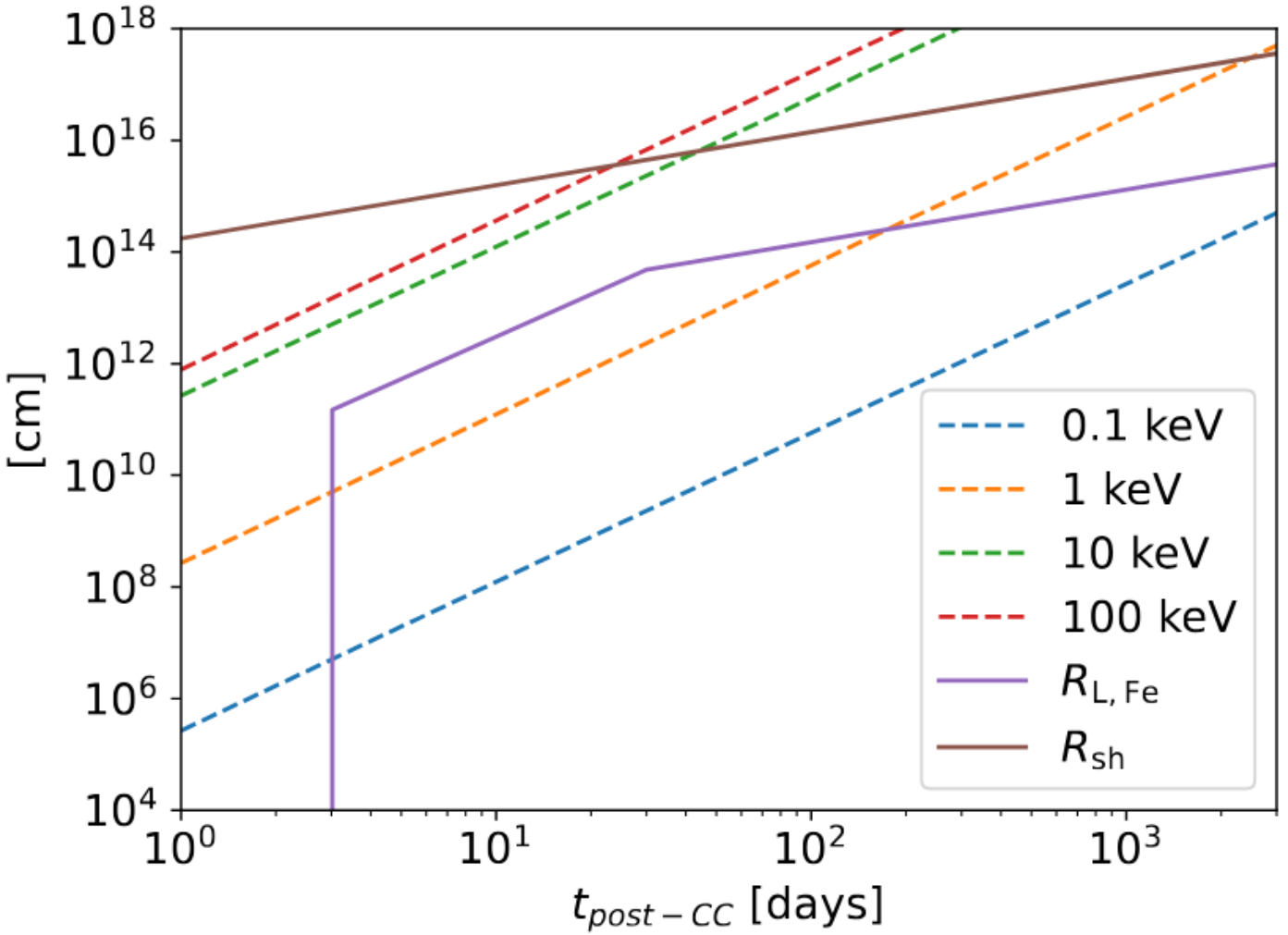
- X-ray reprocessing

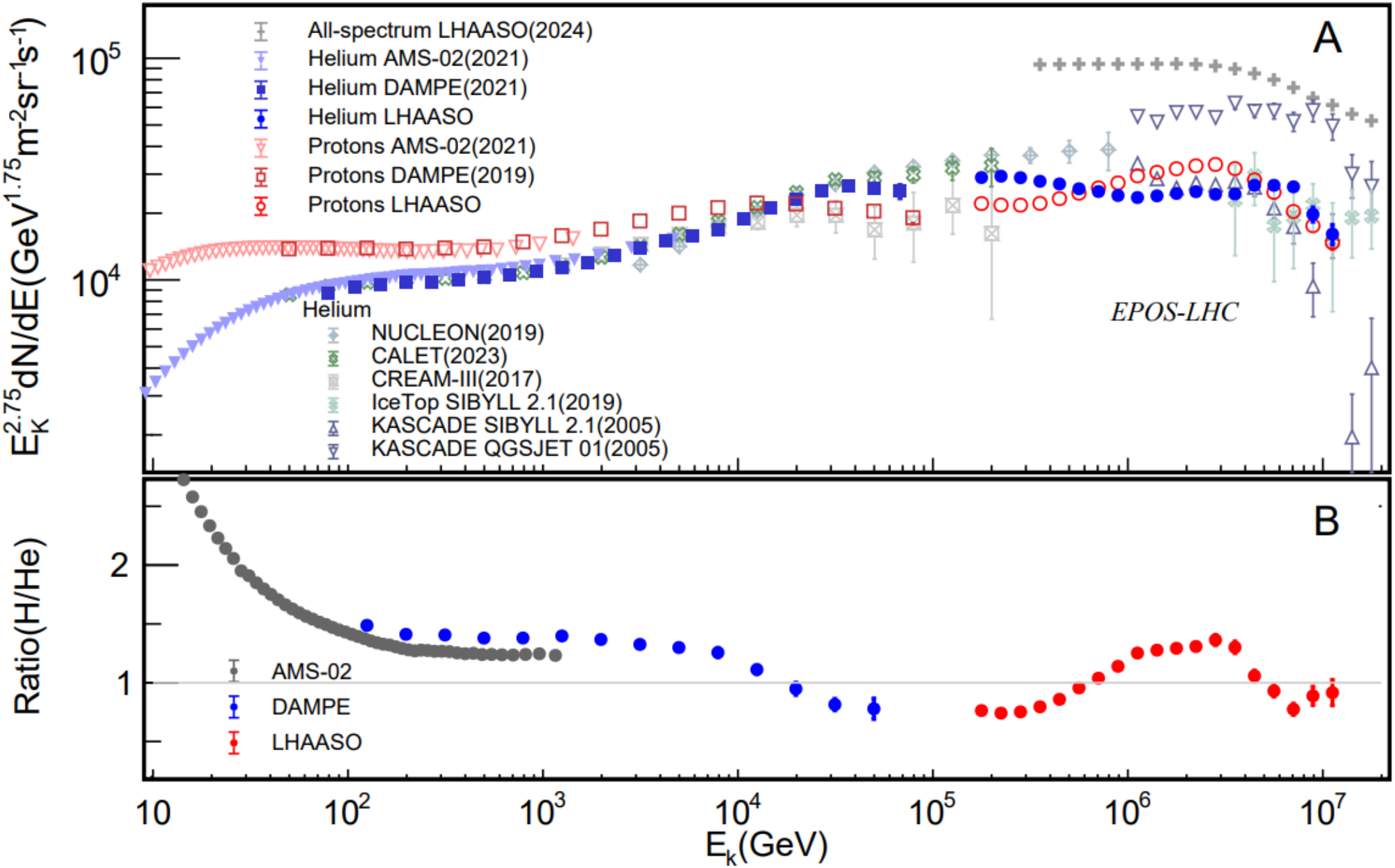
$$\lambda_{mfp} = 1/(\kappa_X \rho_{CSM})$$

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

$$\kappa_s \sim 0.34$$

- Hard X-rays may not contribute




A
All-spectrum LHAASO(2024)
Helium AMS-02(2021)
Helium DAMPE(2021)
Helium LHAASO
Protons AMS-02(2021)
Protons DAMPE(2019)
Protons LHAASO
Helium
NUCLEON(2019)
CALET(2023)
CREAM-III(2017)
IceTop SIBYLL 2.1(2019)
KASCADE SIBYLL 2.1(2005)
KASCADE QGSJET 01(2005)
EPOS-LHC
$E_K^{2.75}dN/dE(GeV^{1.75}m^{-2}sr^{-1}s^{-1})$
10^5
10^4
B
Ratio(H/He)
2
1
AMS-02
DAMPE
LHAASO
10
10^2
10^3
10^4
10^5
10^6
10^7
E_k(GeV)