Cosmic rays in the GeV-TeV energy range from two types of supernovae

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Outline of this talk

- ✤ Introduction.
- ✤ Two component model for the origin of cosmic rays:
    - ✤ Cosmic rays from regular supernova remnants,
    - ✤ Cosmic rays from Wolf-Rayet supernovae.
- ✤ Cosmic-ray transport in the Galaxy including re-acceleration.
- ✤ Method of calculation.
- ✤ Results: Comparison of model prediction with the observed data.
- ✤ Summary.

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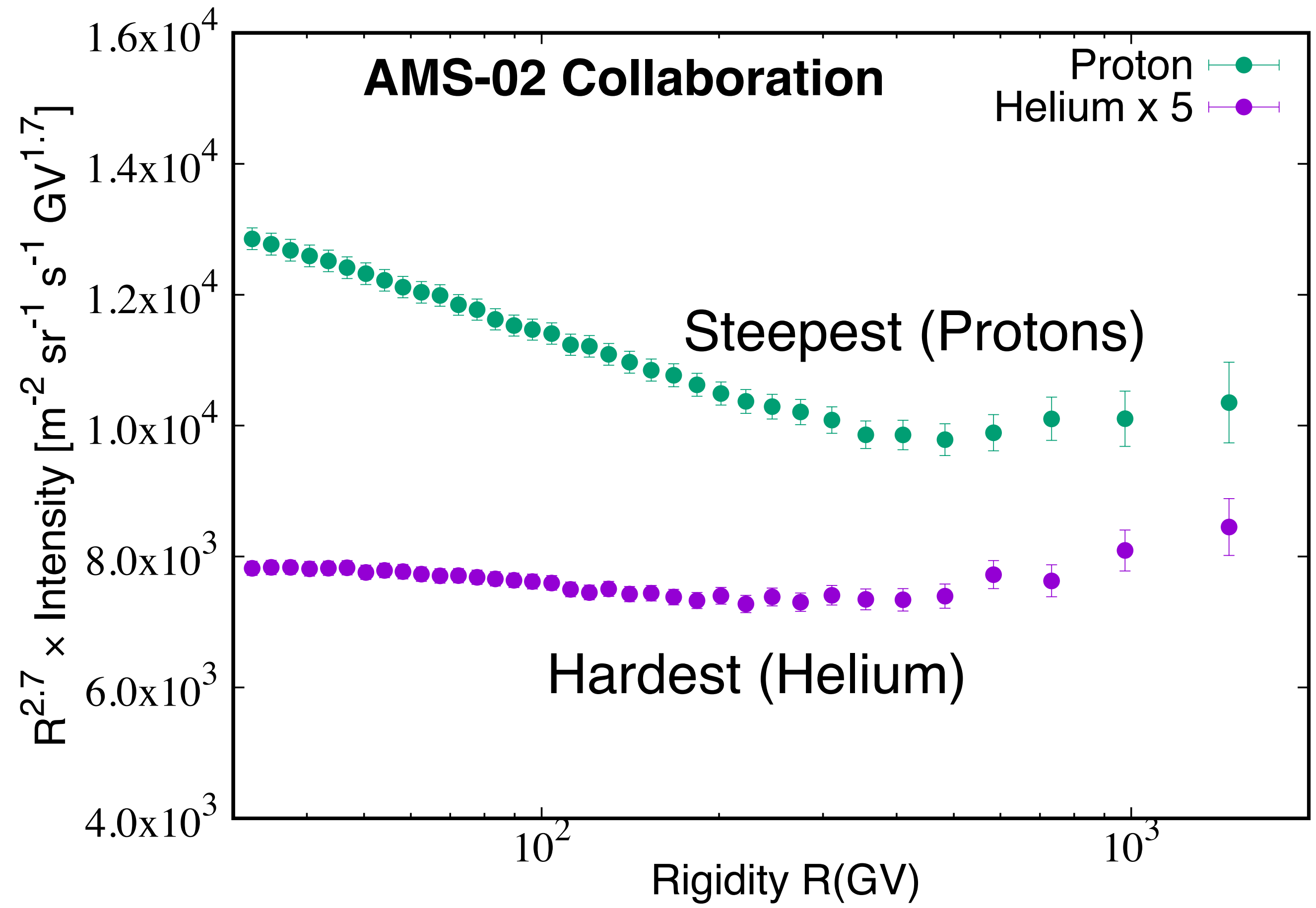
Introduction

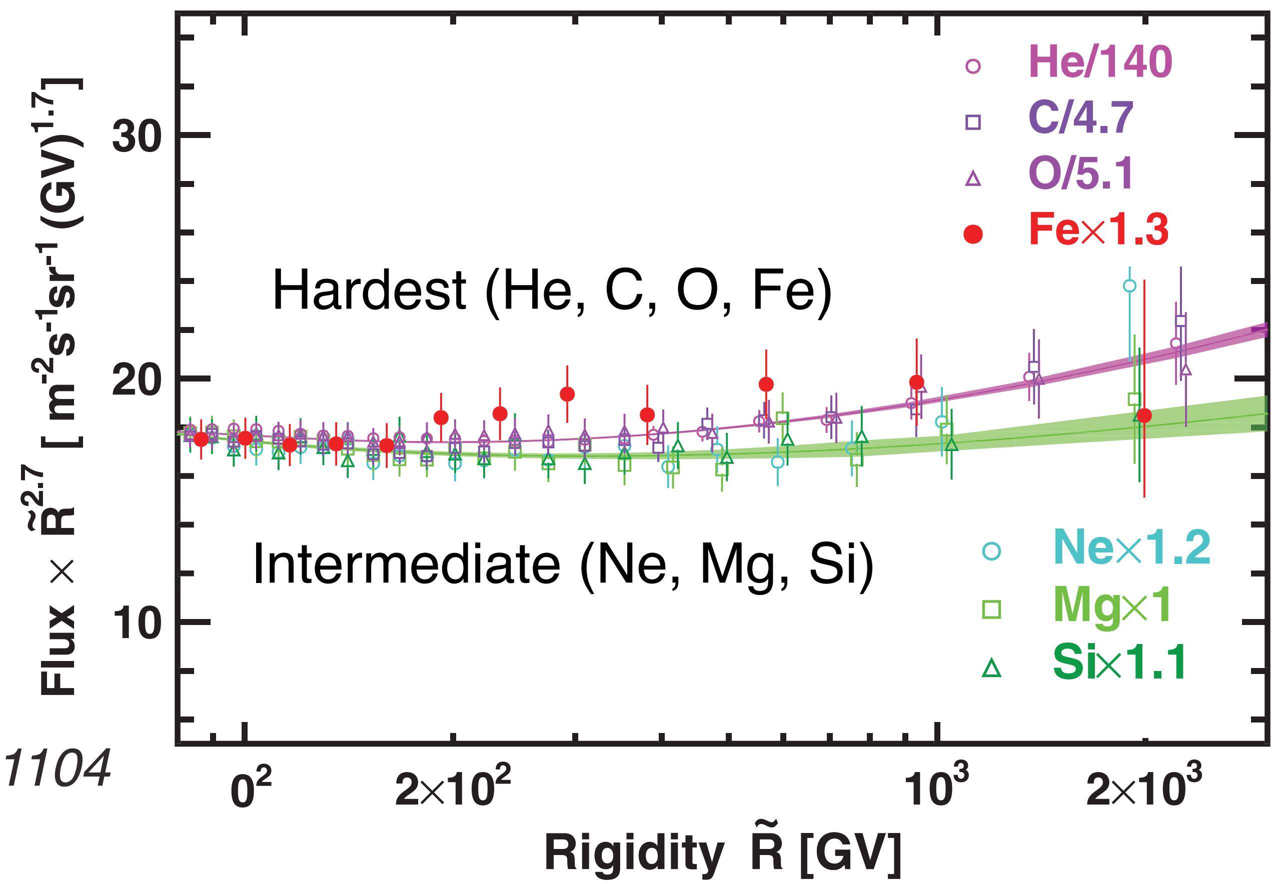
2015, PRL, 114,171103
2015, PRL, 115, 211101

- **AMS-02, CALET, CREAM, DAMPE,…..**
- **Different spectral shapes between primary cosmic-ray species.**
- **Protons: Steepest spectrum.**
- **Then, Ne, Mg, Si**
- **He, C, O, Fe: Hardest.**



Diffusive shock acceleration theory + propagation: Spectral index independent of the type of nuclei.

Krymsky 1977, Bell 1978
Blandford & Eichler 1987
Ginzburg & Ptuskin 1976



2021, PRL, 126, 041104

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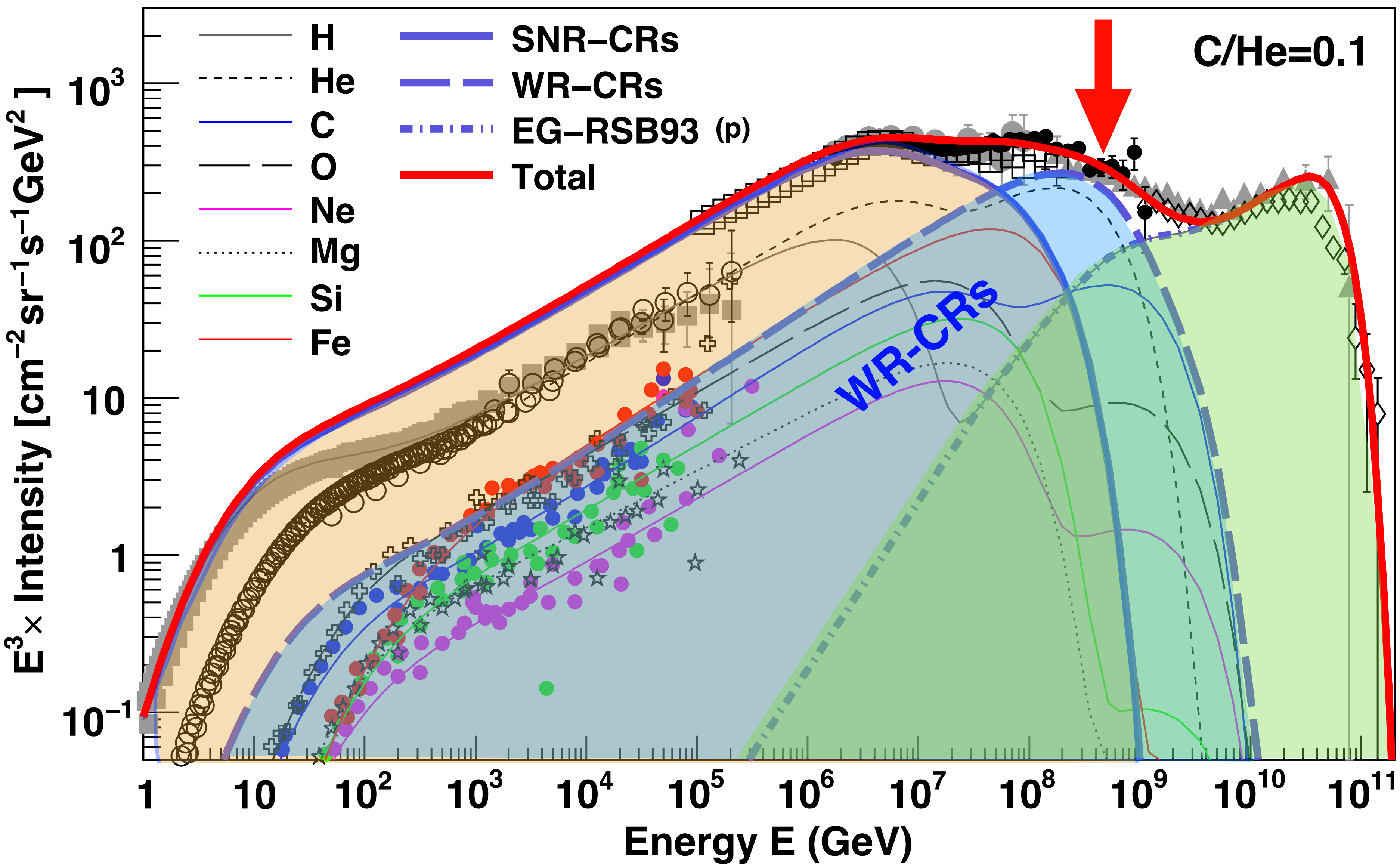
Possible explanations

- **Re-acceleration of pre-existing CRs by nearby shocks** *(Malkov & Moskalenko 2021).*

- **We discuss here a two-component model for the origin of cosmic rays:**

Thoudam+ 2016, A&A, 595, A33



***Initially proposed to explain the "unexpected" light composition around the second knee.**

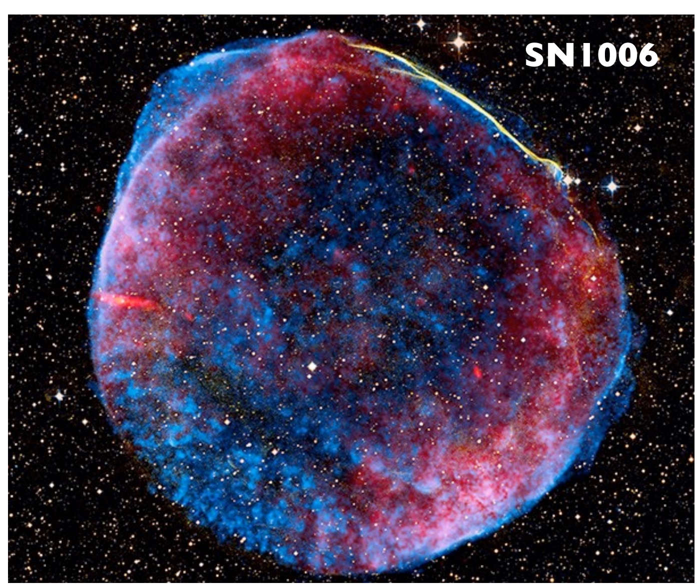
Two-component model for the origin of cosmic rays

(1) CRs from regular supernovae (SNR-CRs)

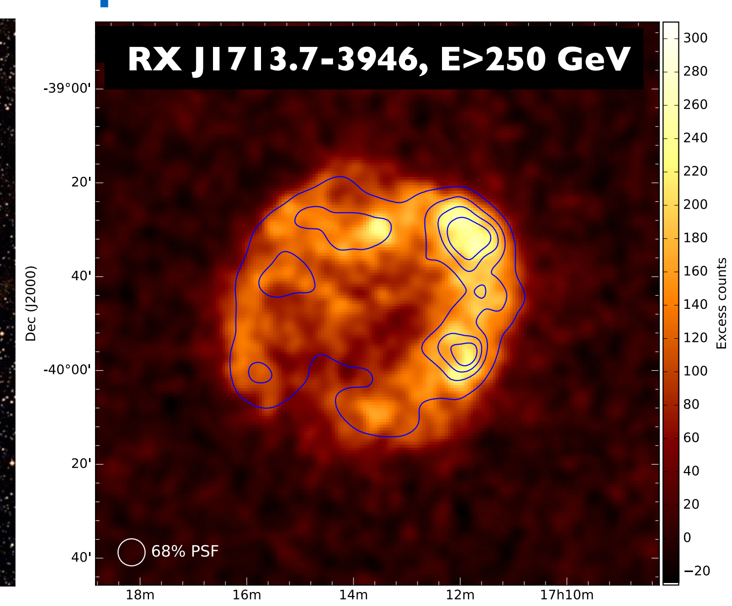
- **Supernova shock waves in uniform interstellar medium.**
- **Particle acceleration by diffusive shock acceleration process** *(Krymsky 1977, Bell 1978, Blandford & Eichler 1987).*

- **CR composition <=> elemental solar abundance.**
- **Typical frequency ~ 1/30 yr.**
- **Dominant contributor of cosmic rays in the Galaxy at low energies.**
- **Accelerate particles up to about 10^{15} eV.**

Indication of non-thermal particle acceleration



Credit: Chandra observatory



Credit: H.E.S.S

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Two-component model for the origin of cosmic rays

(2) CRs from Wolf-Rayet supernovae (WR-CRs)

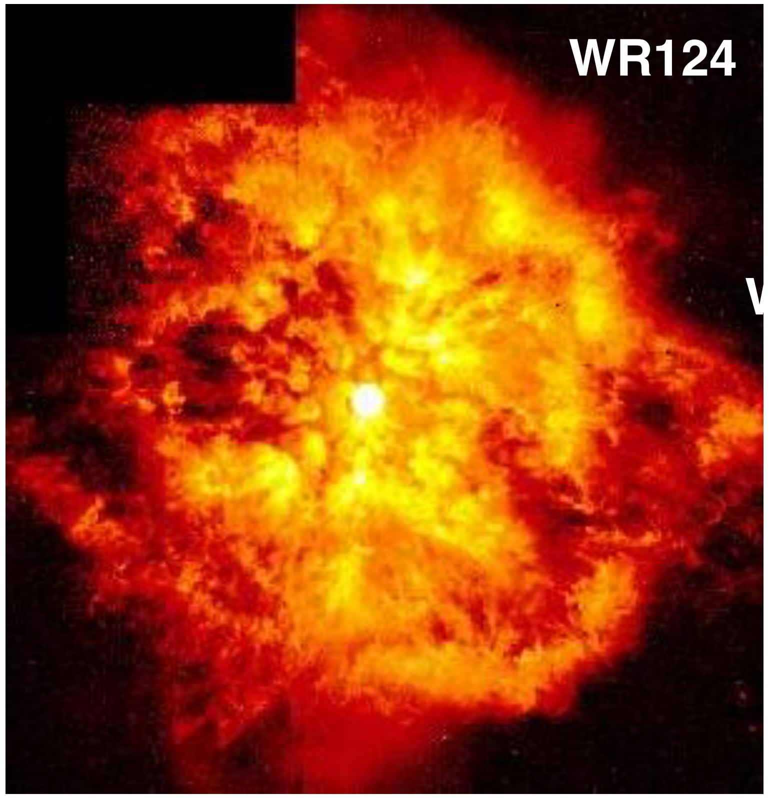
- Similar distribution in the Galactic disk like the regular supernovae.
- Massive stars with fast winds. Likely progenitors of Type Ib/Ic SNe *(Crowther 2007).*
- Supernova shock waves in the wind environment: **Flatter spectrum than SNR-CRs.** *(Eichmann & Rachen, these proceedings).*

- **Low protons in WR-CRs** due to lack of hydrogen in the wind *(Pollock+ 2005).*
- Frequency ~1/210 yr^{-1} = 1/6 of regular SN: **Subdominant CR contribution at low energies**.
- Accelerate particles up to ~ 10^{18} eV *(Biermann & Cassinelli 1993, Stanev+ 1993).*

Wolf-Rayet wind composition

Nuclei	C/He=0.1	C/He=0.4
Proton	low	low
Helium	1.0	1.0
Carbon	0.1	0.4
Oxygen	3.19×10^{-2}	7.18×10^{-2}
Neon	0.42×10^{-2}	1.03×10^{-2}
Magnesium	2.63×10^{-4}	6.54×10^{-4}
Silicon	2.34×10^{-4}	5.85×10^{-4}
Iron	0.68×10^{-4}	1.69×10^{-4}

Pollock+ 2005



Credit: NASA, HST

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Cosmic-ray transport including re-acceleration

Thoudam & Hörandel 2014, A&A, 567, A33

$$\nabla \cdot (D\nabla N) - [\bar{n}v\sigma + \xi]\,\delta(z)N + \left[\xi s p^{-s} \int_{p_0}^{p} du\; N(u)u^{s-1}\right]\delta(z) = -Q\delta(z)$$

Diffusion

$D(p) \propto p^a$

- Particle momentum

Loss:

Re-acceleration ξ
+
Inelastic $\bar{n}v\sigma$

- ISM matter density
- Velocity of CRs
- Interaction crossection

Gain:

Re-acceleration

$\xi \propto V\nu$

- Volume of SNR
- Rate of SN explosion

Source

$Q(p) \propto \nu p^{-\Gamma} \exp\left(-\frac{p}{Zp_{\mathrm{m}}}\right)$

- Charge of nuclei
- Proton cut-off momentum

- **Propagation parameters:** D_0, a } **(Same for both the components)**
- **Reacceleration parameters:** V, s }
- **Source index:** Γ **(Same for all CR species within the source class)**
- **Source normalization** **(Solar abundance/wind composition x Injection efficiency at shocks)**

Calculation flow chart

Tasks

B/C ratio fit using a known C and O spectra

Output parameters

- Diffusion parameters **(D_0, δ).**
- Reacceleration parameters (q_{reacc}, η_{reacc}).
- Solar modulation (ϕ).

Range scanned

D_0: 1.e28 - 1.e29, Δ =0.5e28
δ: 0.29 - 0.33, Δ = 0.01
q_{reacc}: 3.5 - 4.6, Δ = 0.01
η_{reacc}: 0.3 - 0.6, Δ = 0.1
ϕ: 600-710 MeV, Δ = 10

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Calculation flow chart

Tasks

B/C ratio fit using a known C and O spectra

↓

Proton spectrum fit using only SNR-CRs

Output parameters

- Diffusion parameters (D_0, δ).
- Reacceleration parameters (q_{reacc}, η_{reacc}).
- Solar modulation (ϕ).

- Proton source index ($q_{p\text{-}SNR}$)
- Injection energy ($f_{p\text{-}SNR}$).

Range scanned

D_0: 1.e28 - 1.e29, Δ =0.5e28

δ: 0.29 - 0.33, Δ = 0.01

q_{reacc}: 3.5 - 4.6, Δ = 0.01

η_{reacc}: 0.3 - 0.6, Δ = 0.1

ϕ: 600-710 MeV, Δ = 10

$q_{p\text{-}SNR}$: 2.2 - 2.4, Δ = 0.01

$f_{p\text{-}SNR}$: (3 - 10)%, Δ = 0.1%

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Calculation flow chart

Tasks	Output parameters	Range scanned
B/C ratio fit using a known C and O spectra	- Diffusion parameters (D_0, δ). - Reacceleration parameters (q_{reacc}, η_{reacc}). - Solar modulation (ϕ).	D_0: 1.e^{28} - 1.e^{29}, Δ =0.5e^{28} δ: 0.29 - 0.33, Δ = 0.01 q_{reacc}: 3.5 - 4.6, Δ = 0.01 η_{reacc}: 0.3 - 0.6, Δ = 0.1 ϕ: 600-710 MeV, Δ = 10
Proton spectrum fit using only SNR-CRs	- Proton source index (q_{p-SNR}) - Injection energy (f_{p-SNR}).	q_{p-SNR}: 2.2 - 2.4, Δ = 0.01 f_{p-SNR}: (3 - 10)%, Δ = 0.1%
Helium spectrum fit using (WR+SNR) CRs - Same source index as SNR-CR protons - Solar elemental abundance	- WR He source index (q_{He-WR}). - WR He injection energy (f_{He-WR}). - Injection efficiency for SNR-CR helium ($f_{inj-He-SNR}$).	q_{He-WR}: 2.0 - 2.2, Δ = 0.01 f_{He-WR}: (0.2-0.5)%, Δ = 0.01% $f_{inj-He-SNR}$: 0.9 - 1.25, Δ = 0.05

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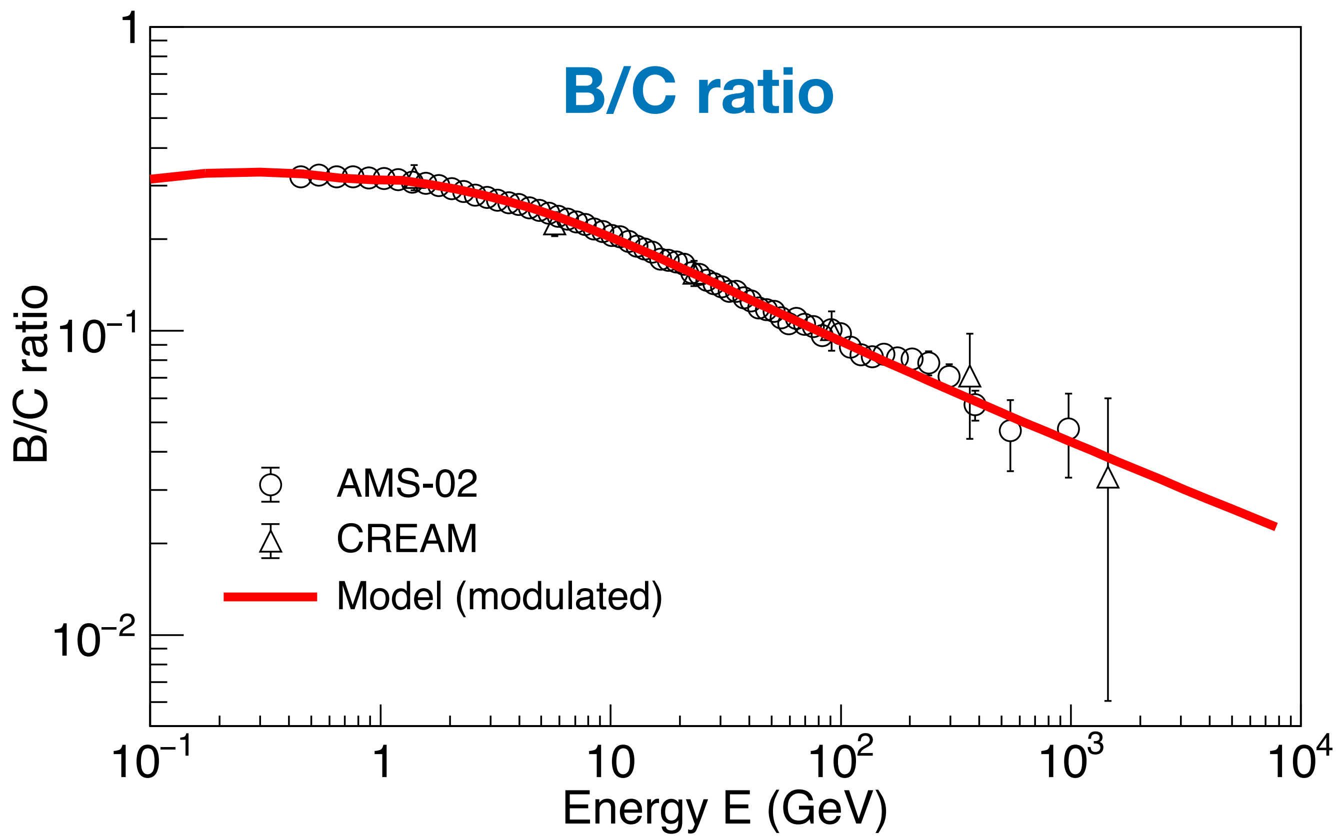
Calculation flow chart

Iterate until all the fits converge

Tasks	Output parameters	Range scanned
B/C ratio fit using a known C and O spectra	- Diffusion parameters (D_0, δ). - Reacceleration parameters (q_{reacc}, η_{reacc}). - Solar modulation (ϕ).	D_0: 1.e^{28} - 1.e^{29}, Δ =0.5e^{28} δ: 0.29 - 0.33, Δ = 0.01 q_{reacc}: 3.5 - 4.6, Δ = 0.01 η_{reacc}: 0.3 - 0.6, Δ = 0.1 ϕ: 600-710 MeV, Δ = 10
Proton spectrum fit using only SNR-CRs	- Proton source index ($q_{p\text{-}SNR}$) - Injection energy ($f_{p\text{-}SNR}$).	$q_{p\text{-}SNR}$: 2.2 - 2.4, Δ = 0.01 $f_{p\text{-}SNR}$: (3 - 10)%, Δ = 0.1%
Helium spectrum fit using (WR+SNR) CRs - Same source index as SNR-CR protons - Solar elemental abundance	- WR He source index ($q_{He\text{-}WR}$). - WR He injection energy ($f_{He\text{-}WR}$). - Injection efficiency for SNR-CR helium ($f_{inj\text{-}He\text{-}SNR}$).	$q_{He\text{-}WR}$: 2.0 - 2.2, Δ = 0.01 $f_{He\text{-}WR}$: (0.2-0.5)%, Δ = 0.01% $f_{inj\text{-}He\text{-}SNR}$: 0.9 - 1.25, Δ = 0.05
Carbon & Oxygen spectra fit: - Use the same source index as SNR-CR protons and WR-CR helium, - Wolf-Rayet wind composition.	- Injection efficiencies for C ($f_{inj\text{-}C\text{-}SNR}$, $f_{inj\text{-}C\text{-}WR}$). - Injection efficiencies for O ($f_{inj\text{-}O\text{-}SNR}$, $f_{inj\text{-}O\text{-}WR}$).	$f_{inj\text{-}C\text{-}WR}$: 0.1 - 1.0, Δ = 0.01 $f_{inj\text{-}C\text{-}SNR}$: 10 - 15, Δ = 0.1 $f_{inj\text{-}O\text{-}WR}$: 1.0 - 2.0, Δ = 0.01 $f_{inj\text{-}O\text{-}SNR}$: 5 - 10, Δ = 0.1

Results



Fit to AMS data only

D_0: 5 x 10^{28} cm^2/s

δ: 0.31

q_{reacc}: 4.45

η_{reacc}: 0.4

ϕ: 690 MV

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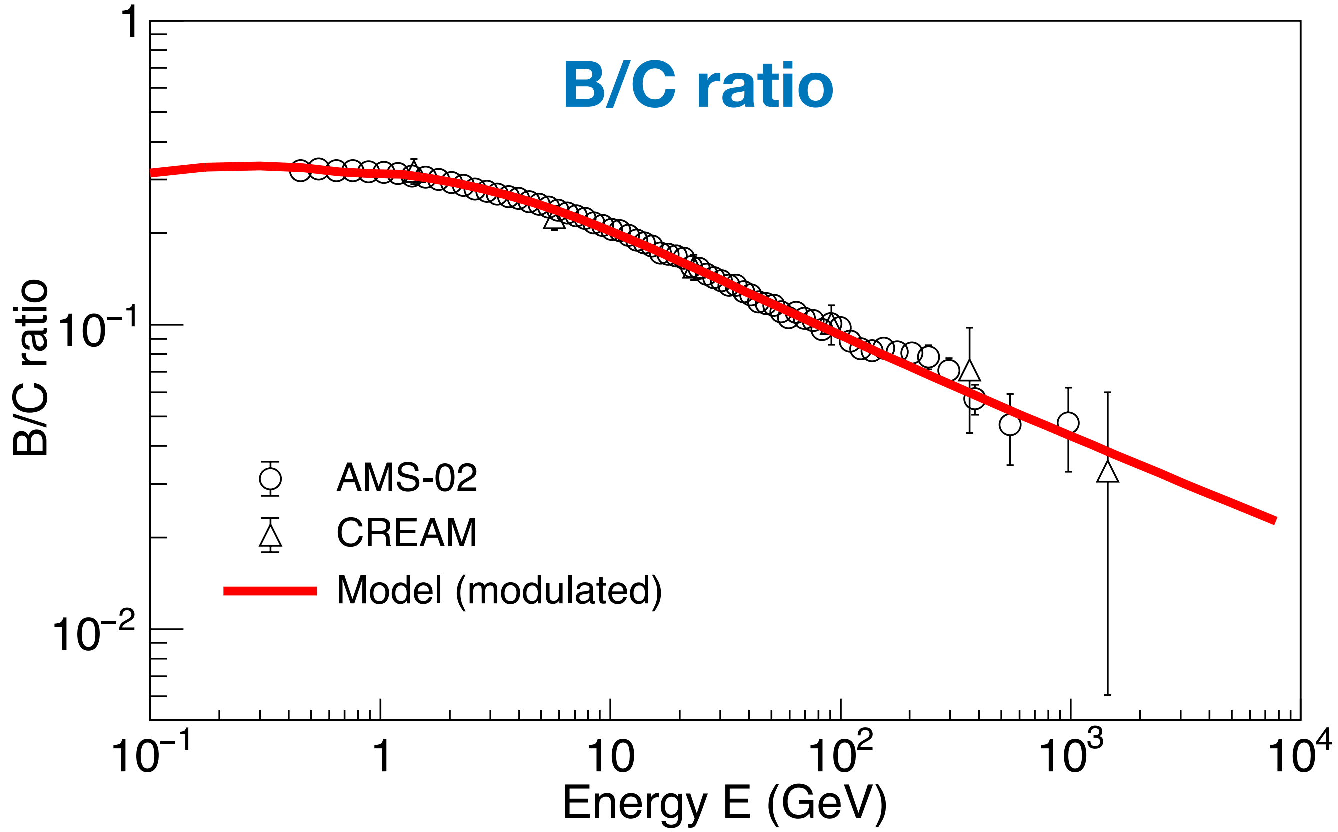
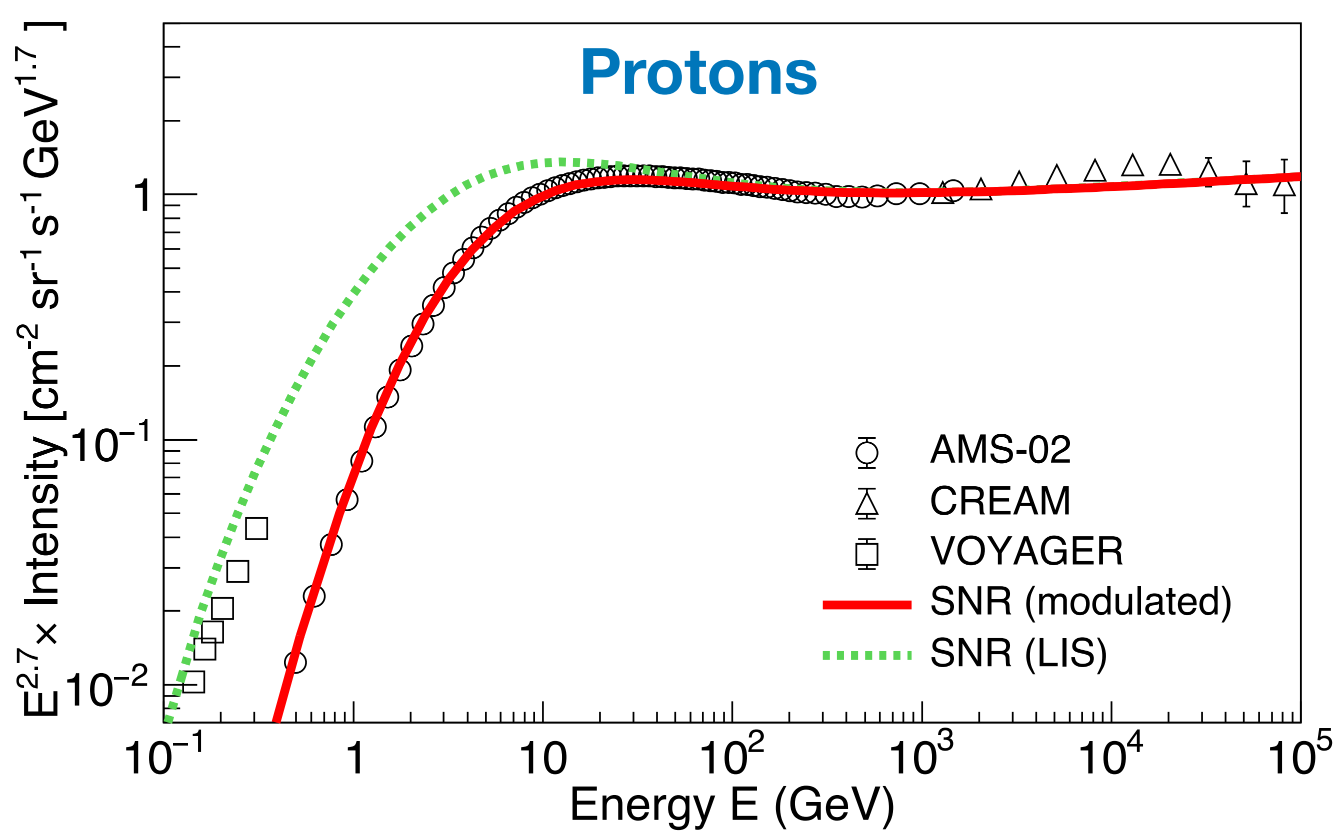
Results



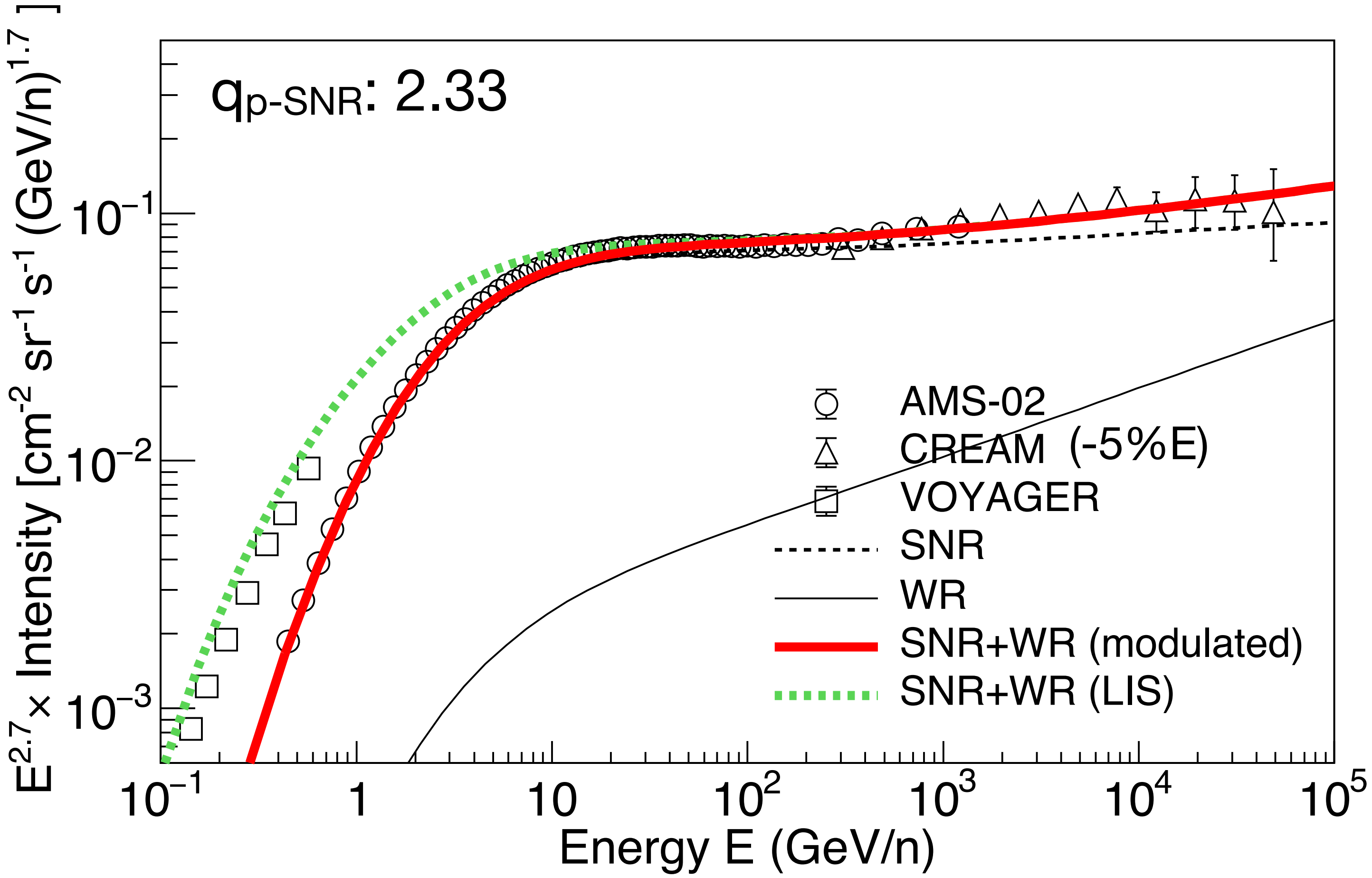
Fit to AMS data only

D_0: 5 x 10^{28} cm^2/s
δ: 0.31
q_{reacc}: 4.45
η_{reacc}: 0.4
ϕ: 690 MV



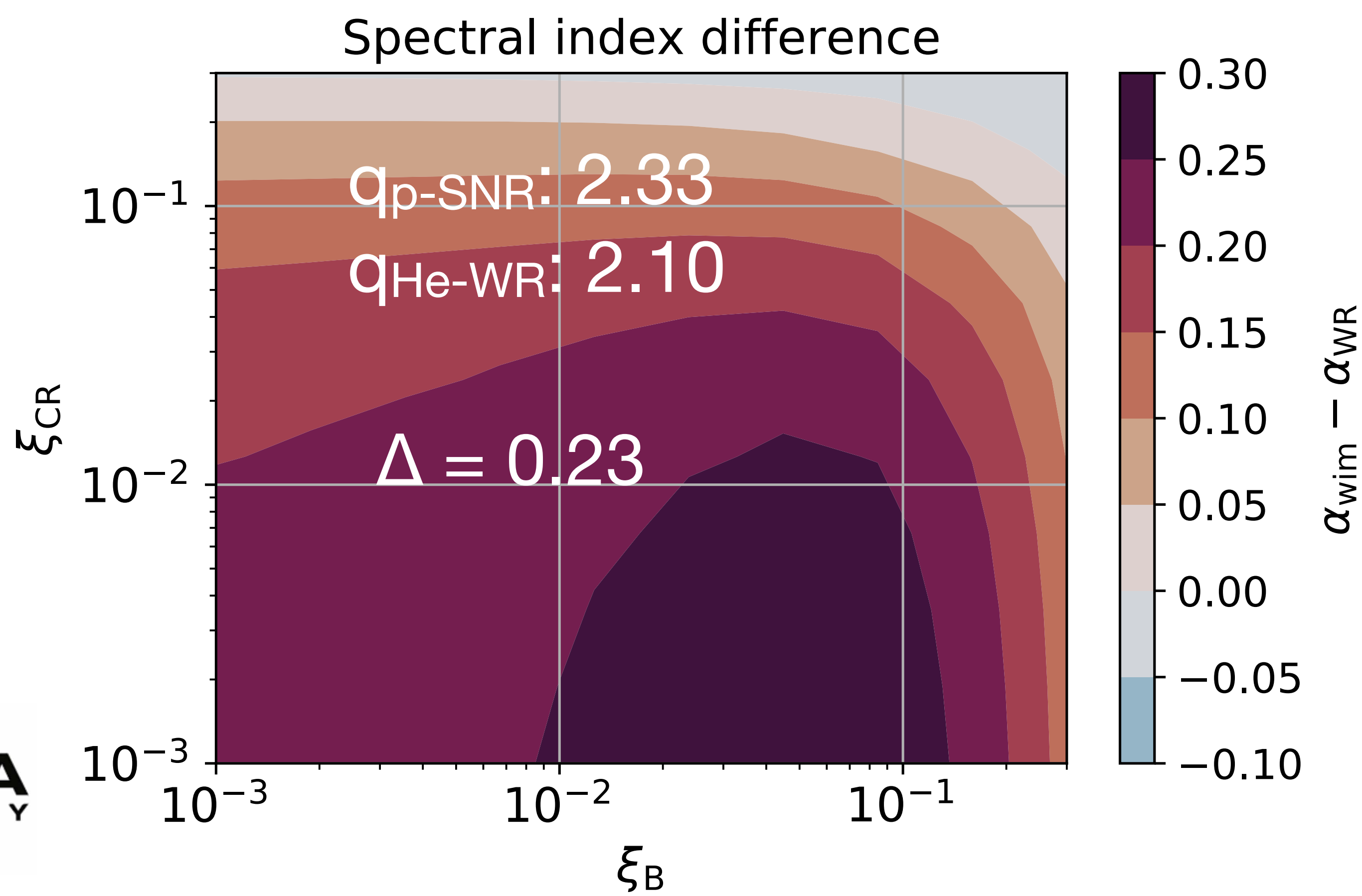
$q_{p\text{-}SNR}$: 2.33
$f_{p\text{-}SNR}$: 4.8% x 10^{51} ergs
ϕ: 690 MV

Results: Helium spectrum



Fit to AMS data only

q_{He-WR}: 2.10
f_{He-WR}: 0.28% x 10^{51} ergs
f_{He-SNR}: 0.47% x 10^{51} ergs
$f_{inj-He-SNR}$: 1.17



Eichmann & Rachen, these proceedings

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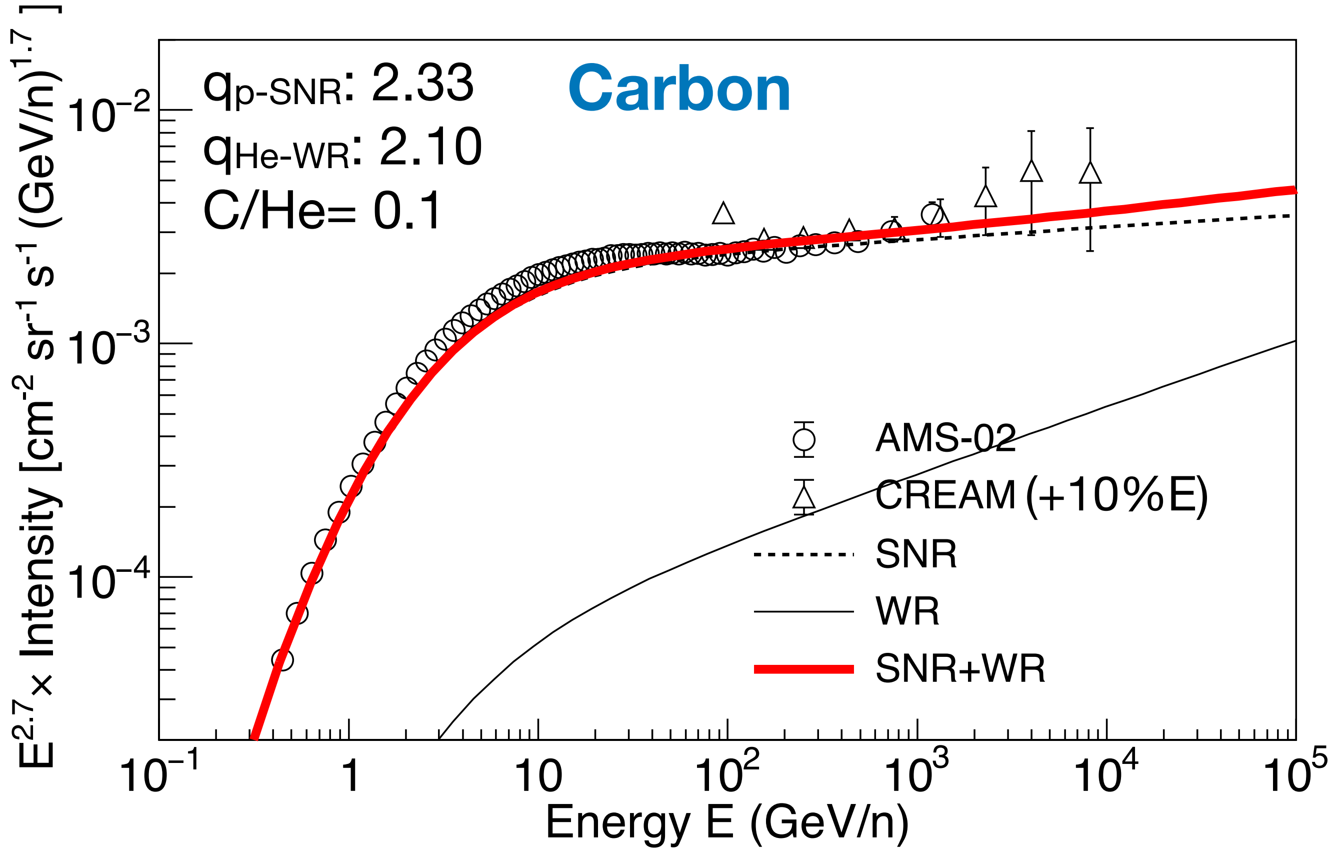
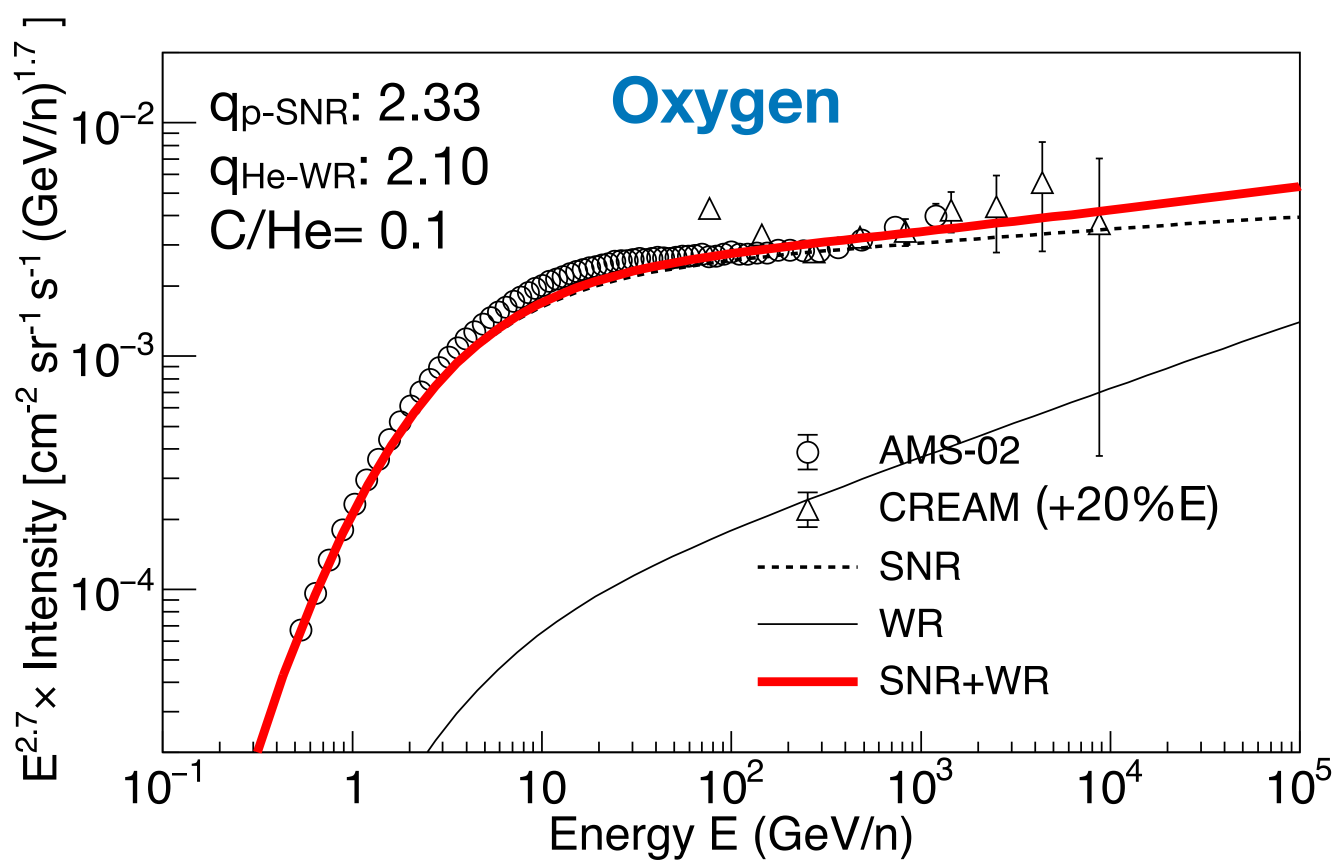
Results: Carbon and Oxygen spectra



Fit to AMS data only

$f_{C\text{-}SNR}$: 0.018% x 10^{51} ergs
$f_{inj\text{-}C\text{-}SNR}$: 13.0
$f_{C\text{-}WR}$: 0.008% x 10^{51} ergs
$f_{inj\text{-}C\text{-}WR}$: 0.28 (w.r.t He)



$f_{O\text{-}SNR}$: 0.02% x 10^{51} ergs
$f_{inj\text{-}O\text{-}SNR}$: 8.0
$f_{O\text{-}WR}$: 0.01% x 10^{51} ergs
$f_{inj\text{-}O\text{-}WR}$: 1.2 (w.r.t He)

Summary

- The observed spectral differences between cosmic-ray species (at least H to O) can be explained using two components of cosmic-rays:
  - One from regular supernova remnants,
  - Other from supernovae in Wolf-Rayet wind environment.
- The model requires cosmic-ray source indices of 2.33 for the regular supernovae and 2.10 for the Wolf-Rayet supernovae.
- These values along with the CR injection factors obtained are within the range predicted by simulation of shock acceleration in different environments which have explained the CR abundances at low energies *(Eichmann & Rachen, JCAP01(2021)049).*

Thank you for your attention!

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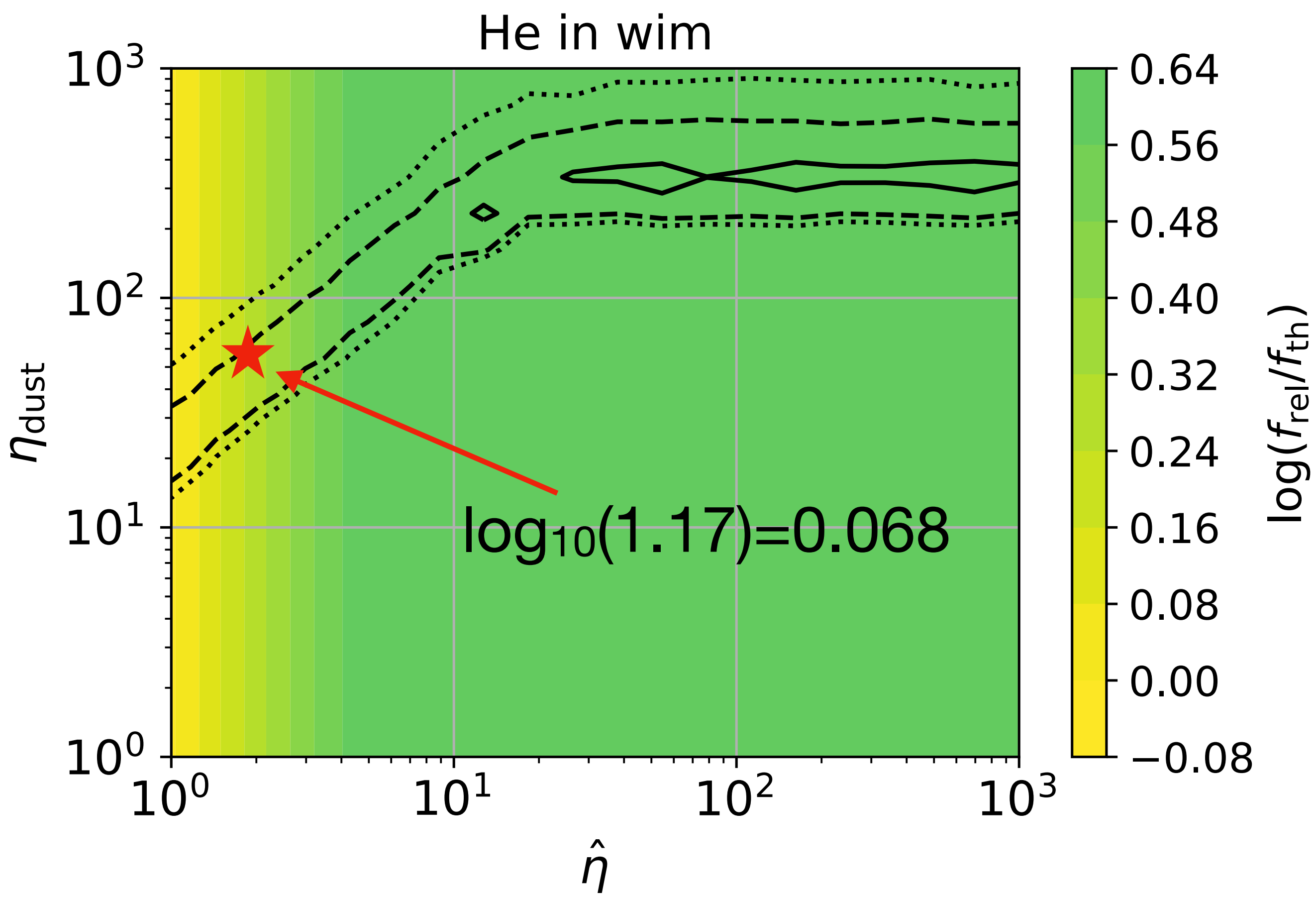
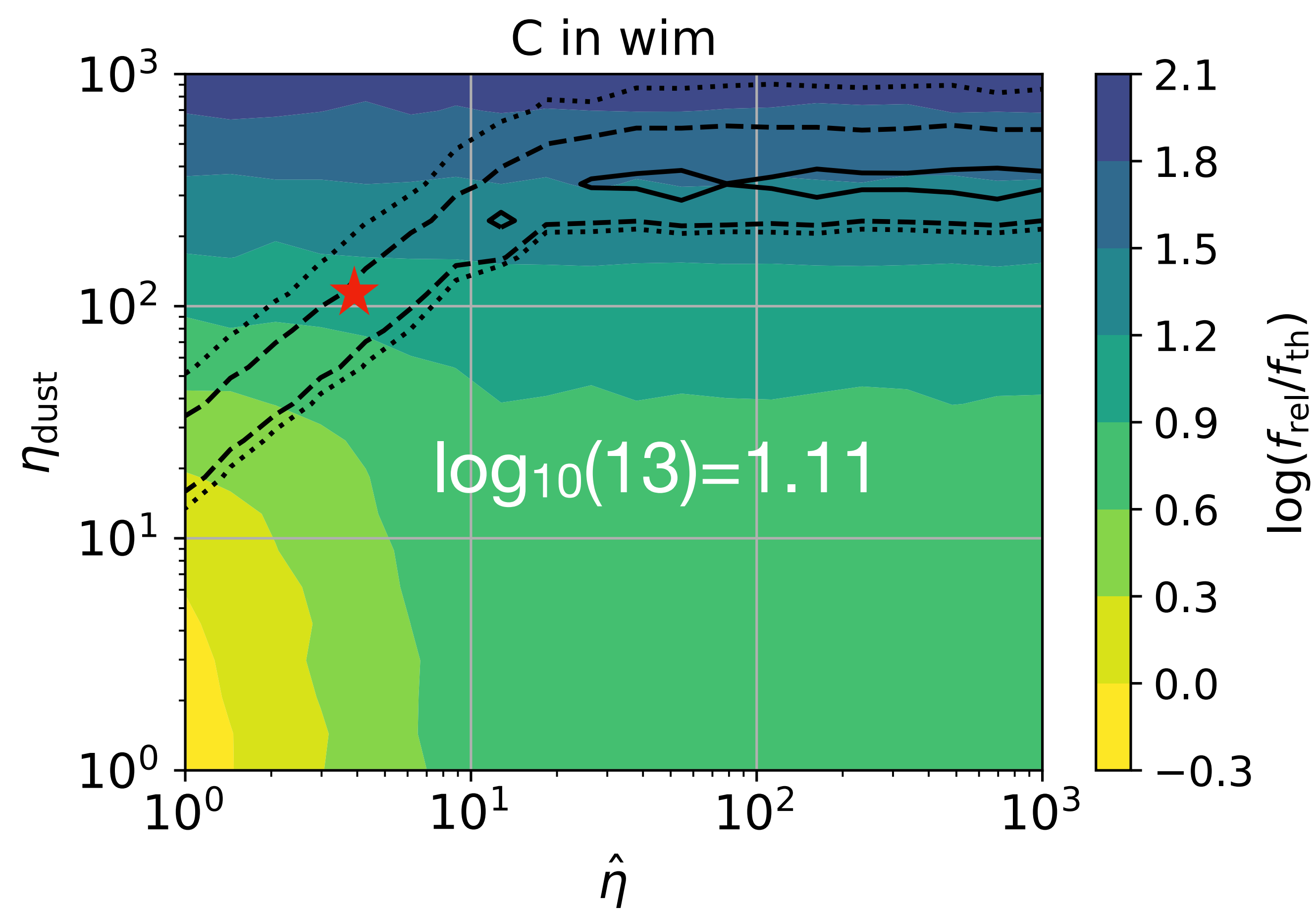
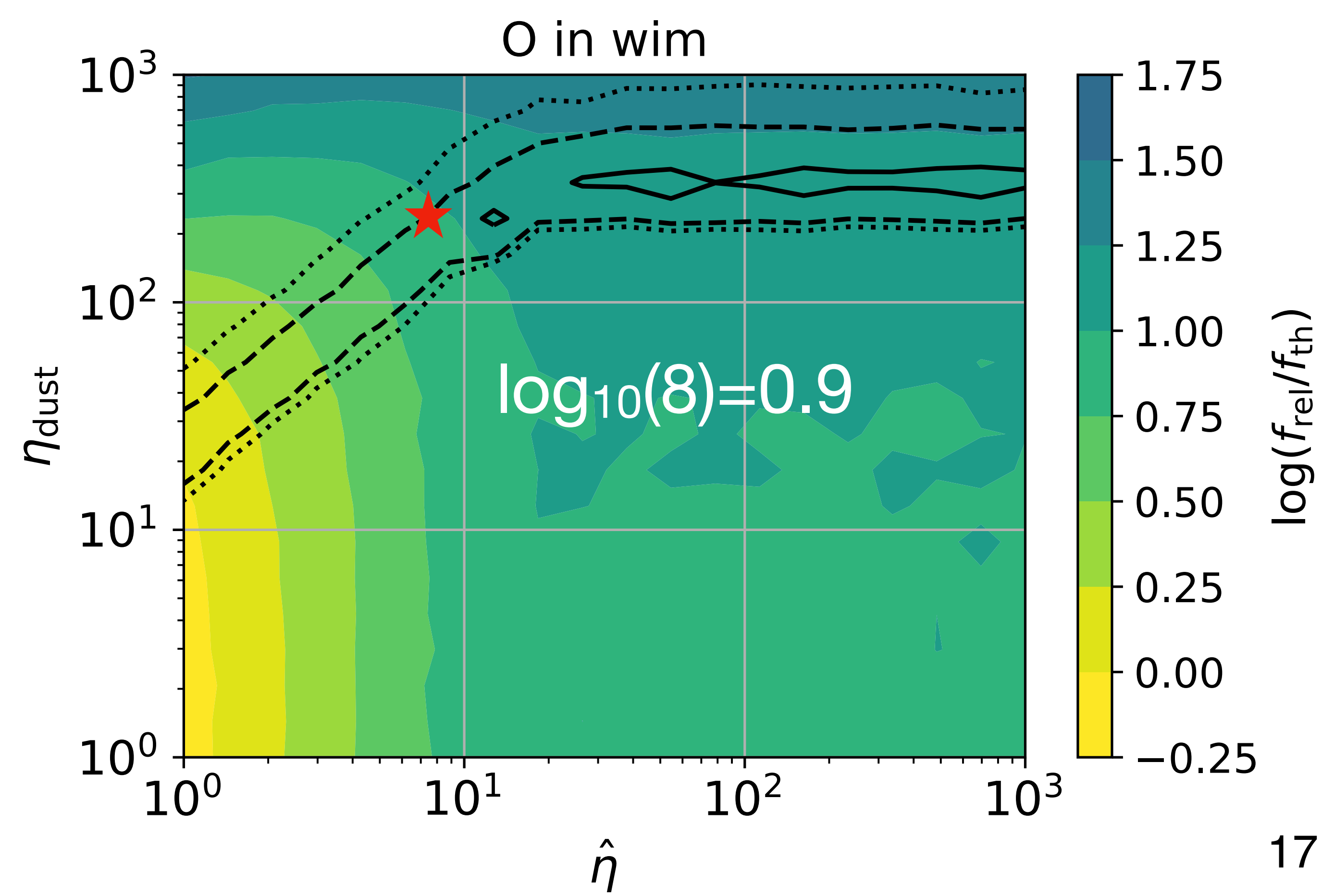
BACKUP slides

CR injection efficiencies in warm ISM from simulation







For details including prediction of CR abundance at low energies: Eichmann & Rachen, JCAP01(2021)049