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Thermal-to-nonthermal element abundances in different Galactic environments

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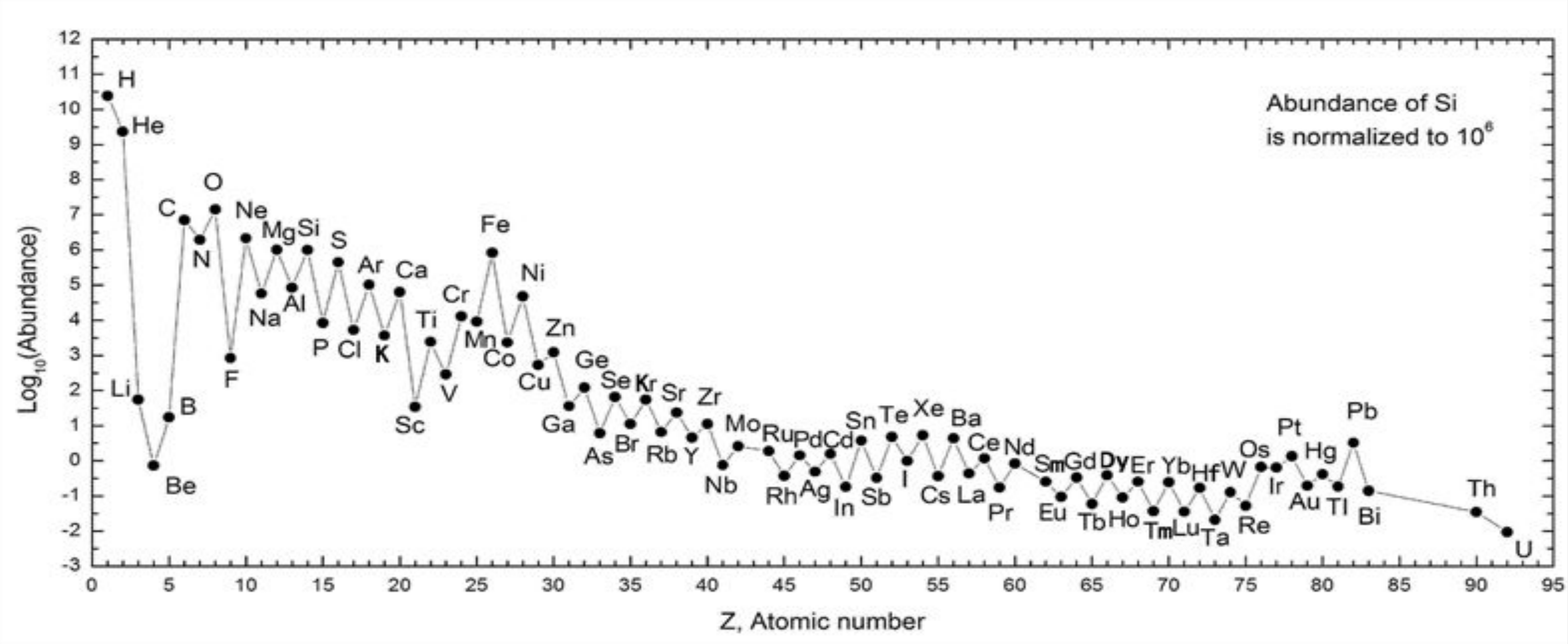
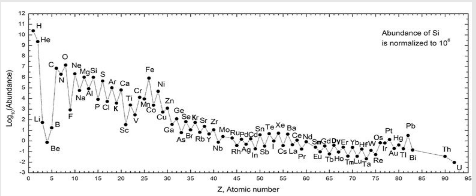
Introduction

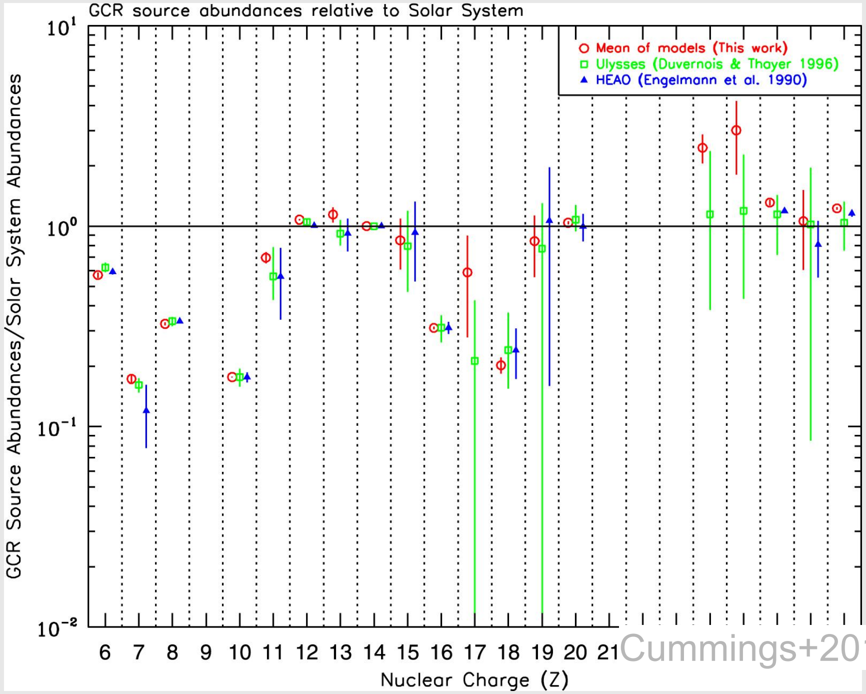
- Thermal-...
  - **Thermal element abund.** (TEA) in the ISM are likely close to the (well-known) solar abund.



Introduction

- ❖ Thermal-to-nonthermal element abundances...
  - ➢ **TEA** in the ISM are likely close to the (well-known) solar abund.
  - ➢ **At an acceleration site** elements (i.e. gas and dust) with a certain $p_{\rm inj}$ enter the acceleration process and **become non-thermal** (CRs).





Cummings+2016

Observations indicate a **significant change of the nonthermal source abund.**

Introduction

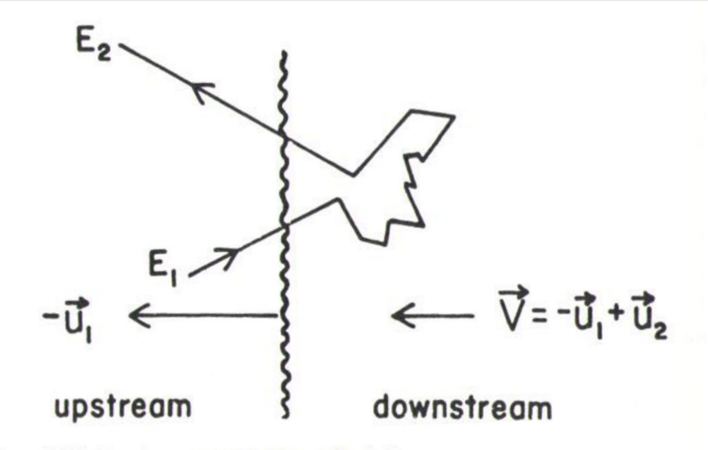
- ...in different Galactic environments
  - **ISM** exhibits three (to five) phases in thermal pressure equilibrium:
    - **C**old **N**eutral **M**edium (1-5%)
    - **W**arm **N**eutral **M**edium (10-20%) & (**D**ense) **W**arm **I**onized **M**edium (20-50%)
    - **H**ot **I**onized **M**edium (30-70%)

	$T_+^{\langle\mathrm{env}\rangle}$ [K]	$\Delta T_+^{\langle\mathrm{env}\rangle}$ [K]	$n^{\langle\mathrm{env}\rangle}$ [cm^{-3}]	$\Delta n^{\langle\mathrm{env}\rangle}$ [cm^{-3}]	$\Phi_{11}^{\langle\mathrm{env}\rangle}$	$\langle\Phi\rangle^{\langle\mathrm{env}\rangle}$	$n_{\mathrm{ion}}^{\langle\mathrm{env}\rangle}$
CNM	125	75	42	38	3.0×10^{-6}	1.5×10^{-4}	0.010
WNM	5 750	2 750	0.35	0.25	0.011	0.011	0.0096
WIM	8 000	2 000	0.20	0.01	0.997	0.994	0.20
DWIM	20 000	2 000	42	38	0.934	0.879	37
HIM	550 000	450 000	0.0055	0.0045	1.0	1.0	0.0055

  - **Wind zones** of progenitor Wolf-Rayet (WR) stars
    - Quite different TEA, e.g. no H but predominantly He and C
    - Can explain the observed HECR flux around the second knee (Thoudam+2016)

Introduction

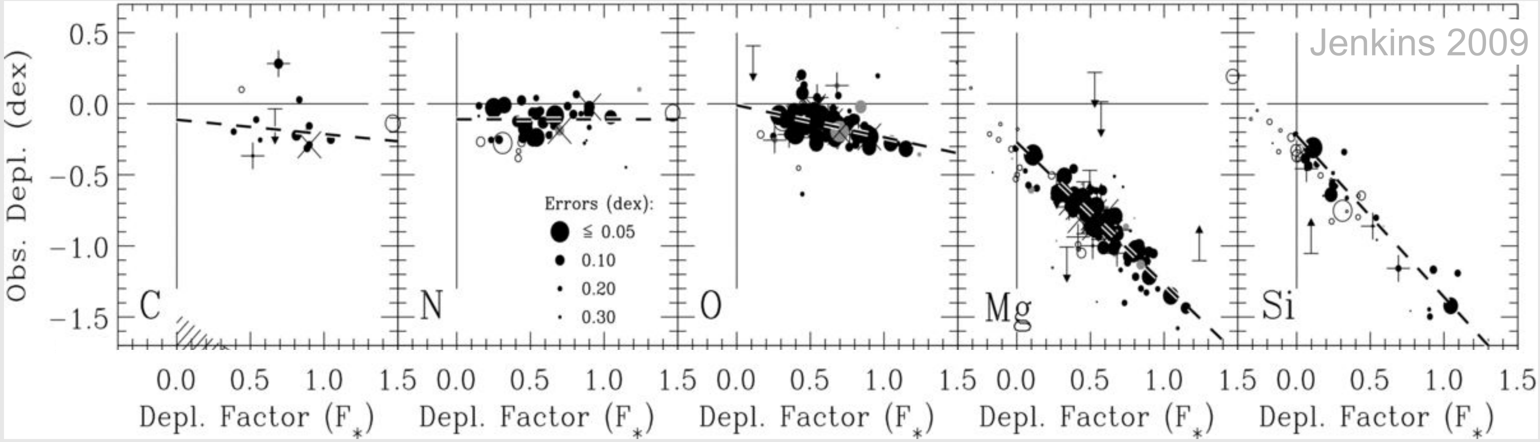
- But who accelerates the LECRs?
  - Diffusive shock acceleration (**DSA**);
  - Differential number density ***dN/dp*** $\boldsymbol{\propto p^{-\alpha}}$, with α~2, for all elements;
  - **Acceleration efficiency *H*** - i.e. prop. factor of *dN/dp* - **depends on *A, Q***.
  - Galactic supernova remnants (**SNRs**) are the most prominant source class - especially at its early non-radiative phases ($t \lesssim 10^5$yr)
  - **SNR evolution**: *H*, α depend on the ambient medium



...the model

Let's build a model

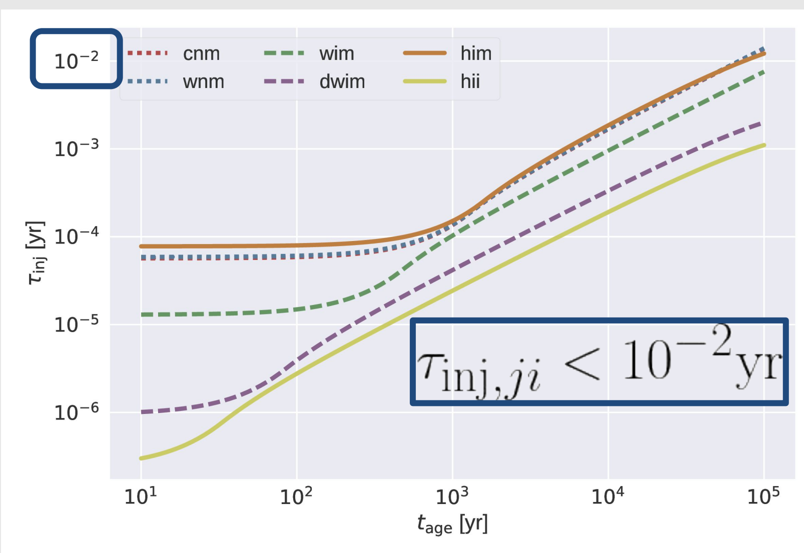
- … to provides the **nonTEA at the source** based on the given TEA dependent on the given shock environment and:
  - ➢ differentiate between **volatile and refractory** elements;
    - **Dust grain behave like ions** of a high mass-to-charge ratio (Epstein 1980, Ellison+1997): **Grain is sputtered during the acceleration process** → element breaks out and receives the same velocity as the parental grain.
    - **Dust fraction** depends on the element and the Galactic environment

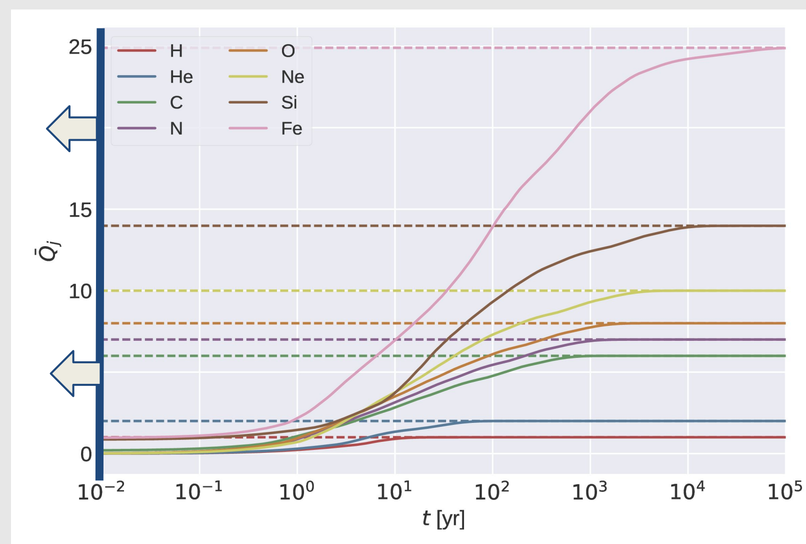


Let's build a model

❖ … to provides the **nonTEA at the source** based on the given TEA dependent on the given shock environment and:

- ➢ differentiate between **volatile and refractory** elements;
- ➢ include the **individual ionization states of the gas elements** in the upstream & downstream region of the shock;

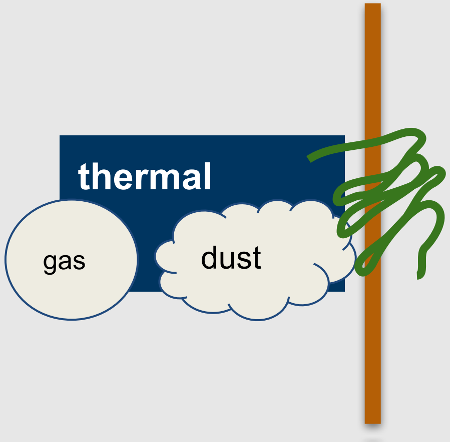




Temporal evolution of the **mean charge number** of the CNM in a downstream plasma of T=10^8K.

Let's build a model

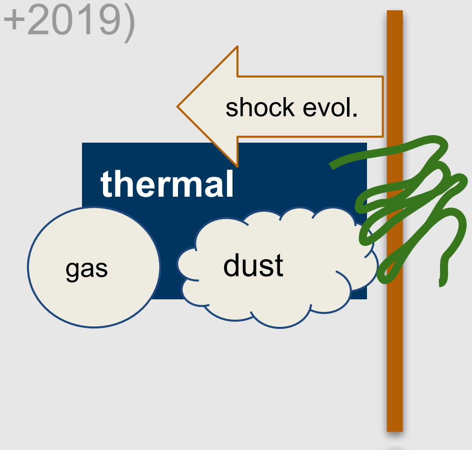
- … to provides the **nonTEA at the source** based on the given TEA dependent on the given shock environment and:
  - differentiate between **volatile and refractory** elements;
  - include the **individual ionization states of the gas elements** in the upstream ~~& downstream~~ ($\tau_{inj} << \tau_{ion}$) region of the shock;



Let’s build a model

❖ … to provides the **nonTEA at the source** based on the given TEA dependent on the given shock environment and:

- ➢ differentiate between **volatile and refractory** elements;
- ➢ include the **individual ionization states of the gas elements** in the upstream ~~& downstream~~ ($\tau_{inj} << \tau_{ion}$) region of the shock;
- ➢ take the recent results from PIC simulations on the **acceleration efficiency** $\boldsymbol{\eta_{ij}}$ of gas phase elements. (Caprioli+2017; Hanusch+2019)
- ➢ include recent findings on the impact of **non-linear DSA** (Haggerty+2020; Caprioli+2020)
- ➢ include the **shock evolution** in its different phases (free expansion→ Sedov-Taylor → snowplow).
- ➢ include **dependence on the Galactic environment**



Let’s build a model

❖ … to provides the **nonTEA at the source** based on the given TEA dependent on the given shock environment and:

Overall differential (LE)CR number at the end (t_f) of the SNR evolution:

$$N(p,t_\mathrm{f}) = \int_0^{t_\mathrm{f}} dt\, \boxed{n(p,t)}\, A_\mathrm{sh}(t)\, \beta_\mathrm{sh}(t) c\, \boxed{\Lambda_\mathrm{ad}(t,t_\mathrm{f})} \quad \text{with} \quad n(p,t) = \frac{(\alpha-1)\,\tilde{n}_j^{\langle\mathrm{env}\rangle}}{p_\mathrm{inj}} \left(\frac{p}{p_\mathrm{inj}}\right)^{-\alpha}$$

CR particle density at an age t

adiabatic losses

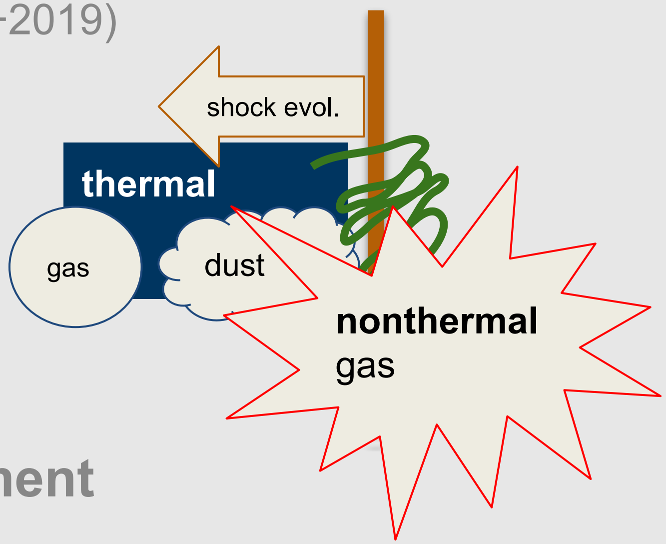
$$\text{and} \quad p_\mathrm{inj} = \zeta_\mathrm{inj}\, A m_\mathrm{p} c\, \beta_\mathrm{sh}(t) c$$

η_{ij} of gas phase elements. (Caprioli+2017; Hanusch+2019)

➢ include recent findings on the impact of **non-linear DSA** (Haggerty+2020; Caprioli+2020)

➢ include the **shock evolution** in its different phases (free expansion→ Sedov-Taylor → snowplow).

➢ include **dependence on the Galactic environment**



...the results (pt.1)

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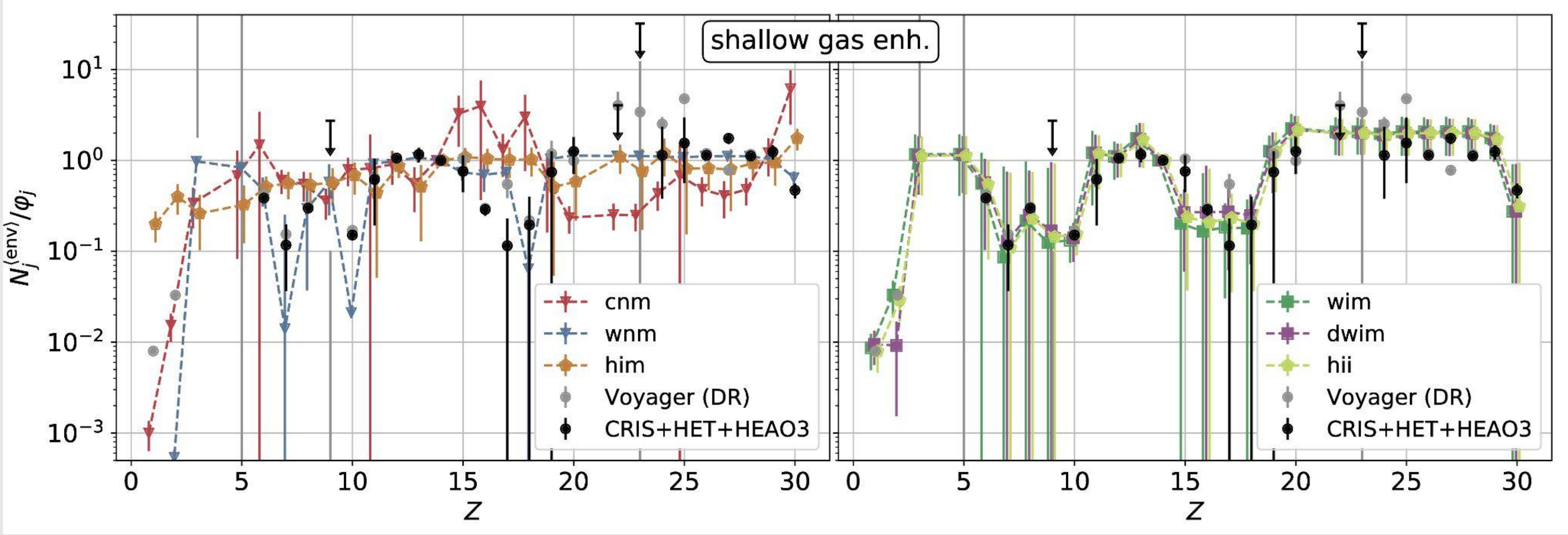
Predicting LECR source abundances
The best fit results

...depends on η_{ij} , *the dust fraction*, the *TEA*, the *ambient particle density*

$p = p_{inj}$

$$N_j(p_{\rm inj}, t_{\rm f}) = (\alpha - 1)c \int_0^{t_{\rm f}} dt \, \frac{\tilde{n}_j^{\langle \rm env \rangle}}{p_{\rm inj}} A_{\rm sh} \, \beta_{\rm sh} \, \Lambda_{\rm ad}$$



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Predicting LECR source abundances
The best fit results

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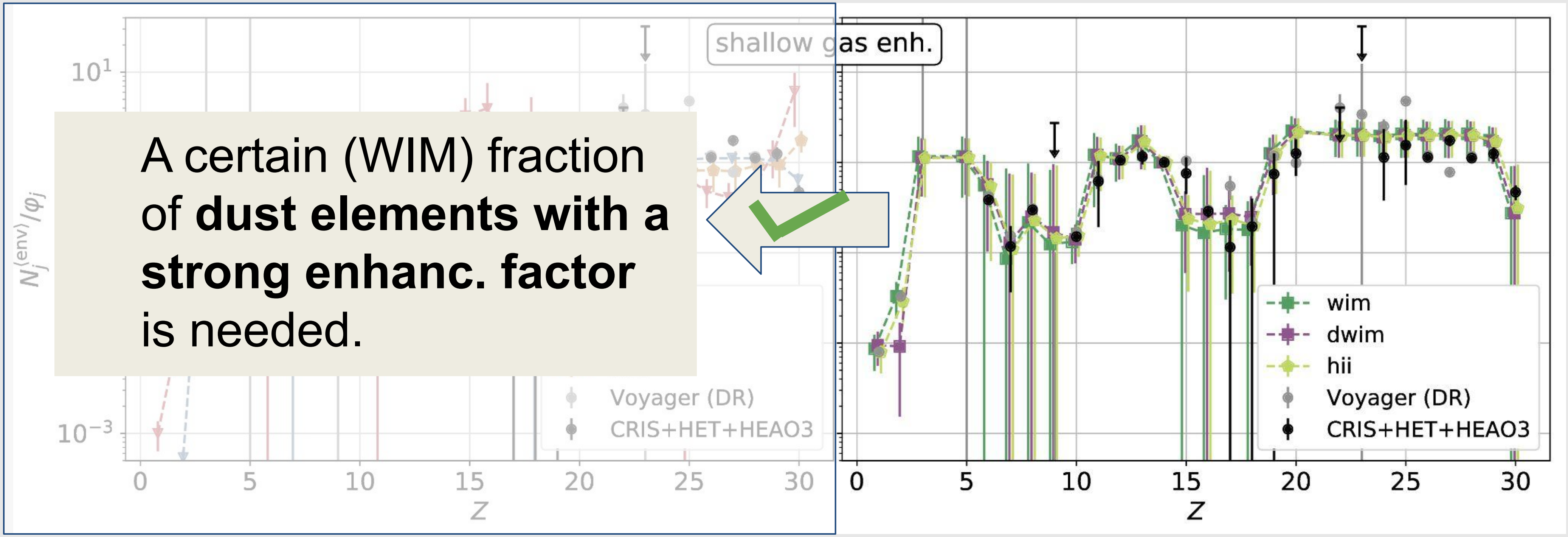

A certain (WIM) fraction of **dust elements with a strong enhanc. factor** is needed.

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...the results (pt.2)

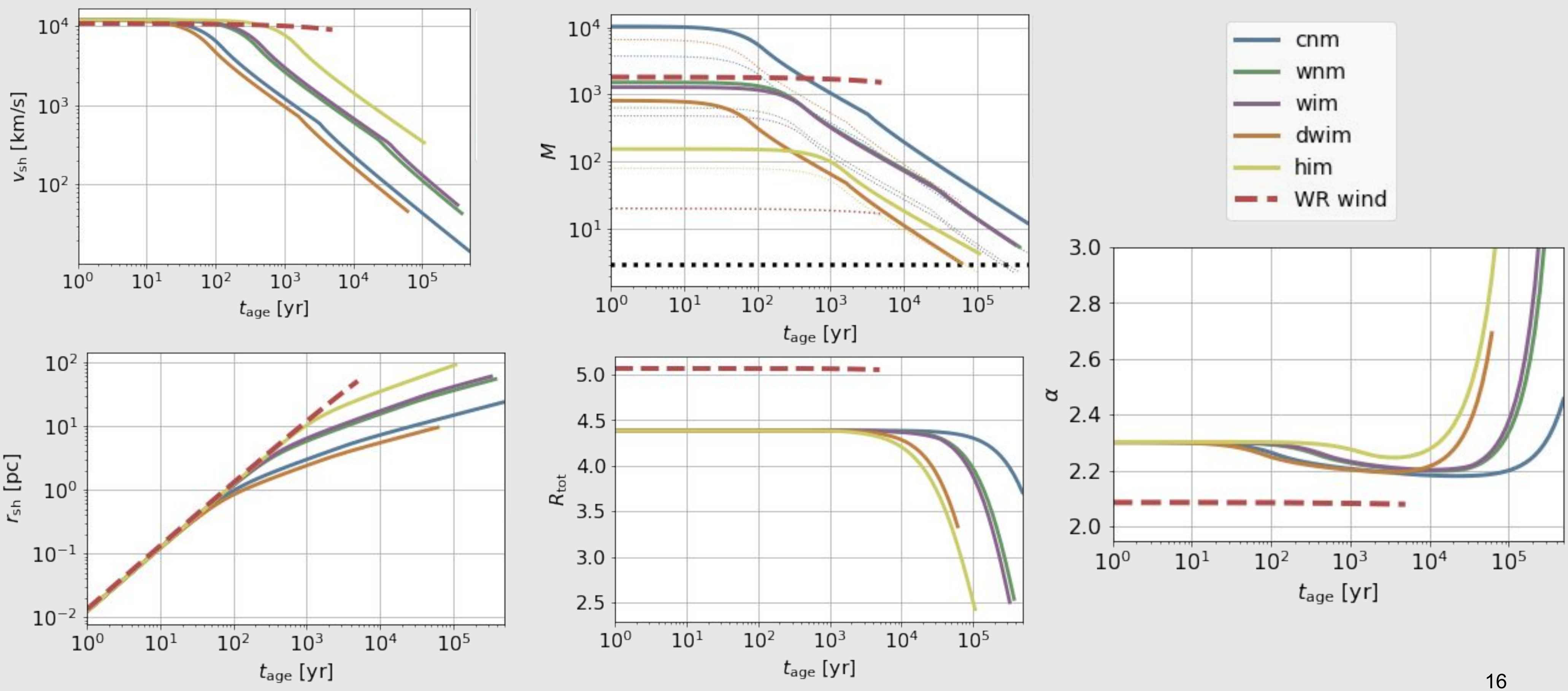
Predicting LECR source abundances

The best fit results

...**evolves with the SNR age** and depends on the ambient medium

SED

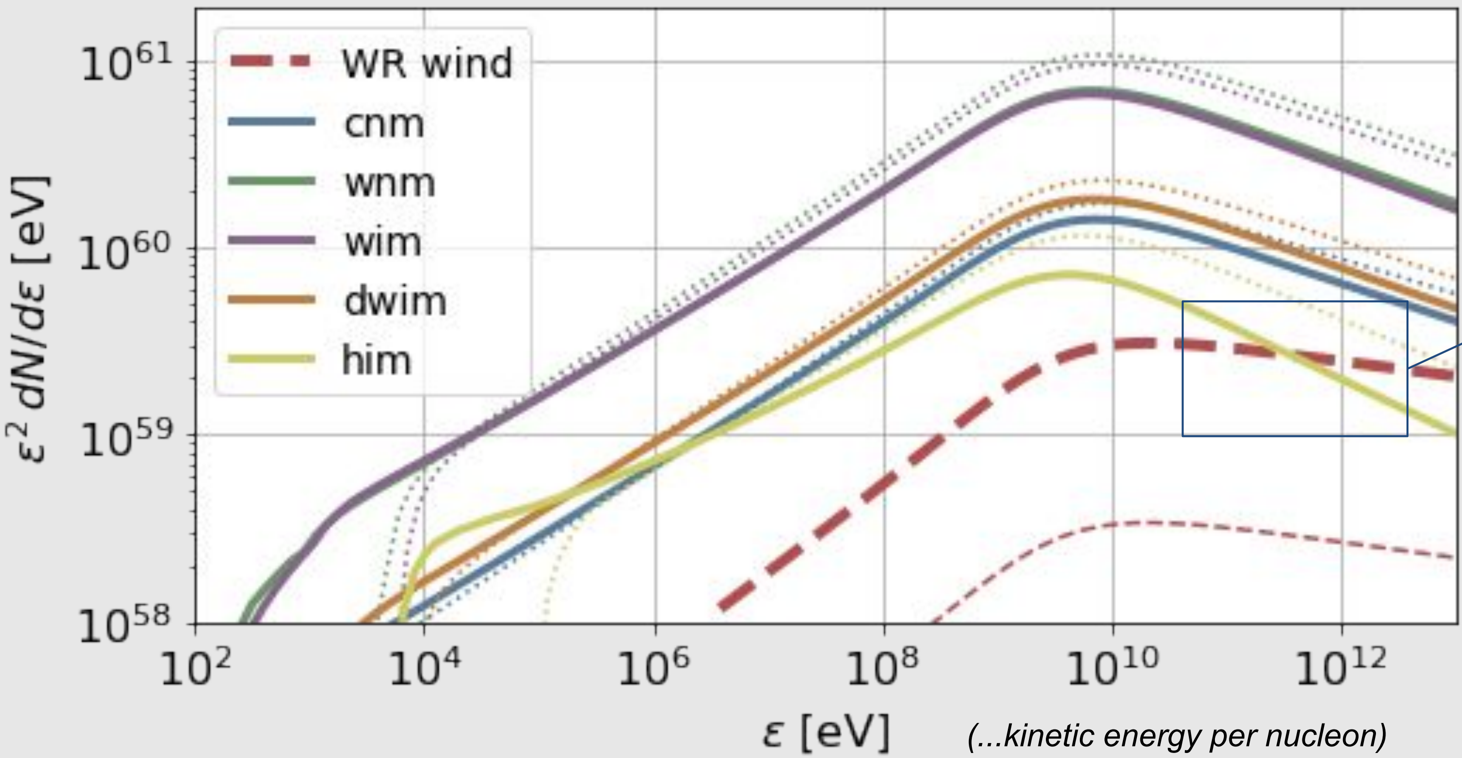
$$N_j(p, t_\mathrm{f}) = (\alpha - 1) c \int_0^{t_\mathrm{f}} dt \, \frac{\tilde{n}_j^{\langle \mathrm{env} \rangle}}{p_\mathrm{inj}} \left(\frac{p}{p_\mathrm{inj}} \right)^{-\alpha} A_\mathrm{sh} \, \beta_\mathrm{sh} \, \Lambda_\mathrm{ad}$$



Predicting LECR source abundances
The best fit results

SED

$$N_j(p,t_\mathrm{f}) = (\alpha-1)c\int_0^{t_\mathrm{f}} dt\, \frac{\tilde{n}_j^{\langle\mathrm{env}\rangle}}{p_\mathrm{inj}} \left(\frac{p}{p_\mathrm{inj}}\right)^{-\alpha} A_\mathrm{sh}\,\beta_\mathrm{sh}\,\Lambda_\mathrm{ad}$$



(...kinetic energy per nucleon)

...**WR supernova** yield a **harder** (overall) spectrum and can exceed SNR contr. from regular ISM environments

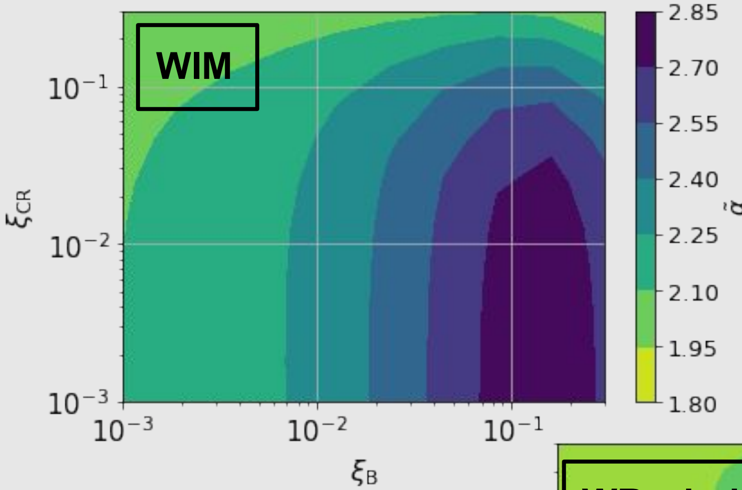
Predicting LECR source abundances

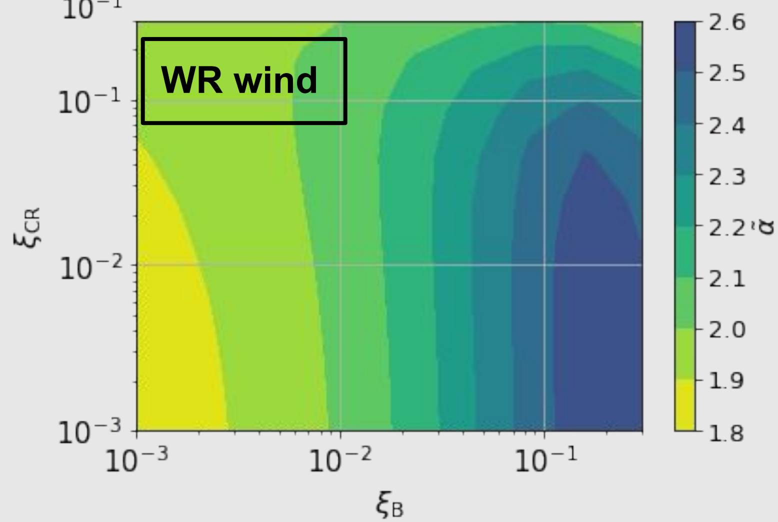
The best fit results

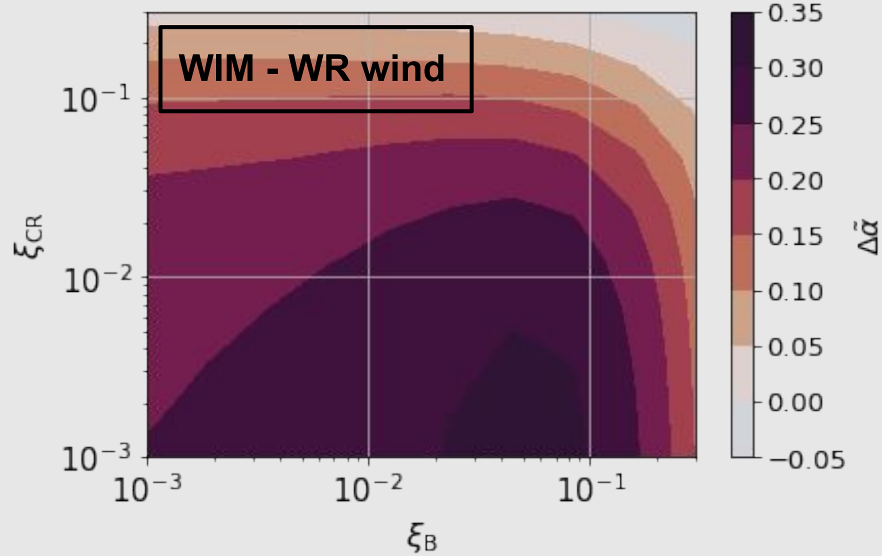
…(overall) spectral behavior **depends on the norm. magnetic and CR pressure**

SED

$$N_j(p, t_\mathrm{f}) = (\alpha - 1)c \int_0^{t_\mathrm{f}} dt \, \frac{\tilde{n}_j^{\langle \mathrm{env} \rangle}}{p_\mathrm{inj}} \left(\frac{p}{p_\mathrm{inj}} \right)^{-\alpha} A_\mathrm{sh} \, \beta_\mathrm{sh} \, \Lambda_\mathrm{ad}$$



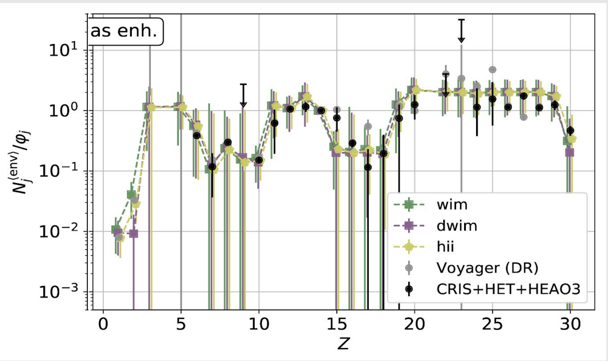




...summing up

Conclusions

- The dominant uniform environment of SNRs in order to explain the LECRs are the **(D)WIM and HII-regions**.
  [as expected from observations of M31 and M33]
- A **strong enhancement of refractory elements** is needed.



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- **WR wind** environments provide a **harder spectrum** than the uniform ISM
  ...possible explanation of the observed LECR anomalies?

See Talk **#934** by S.Thoudam for more details