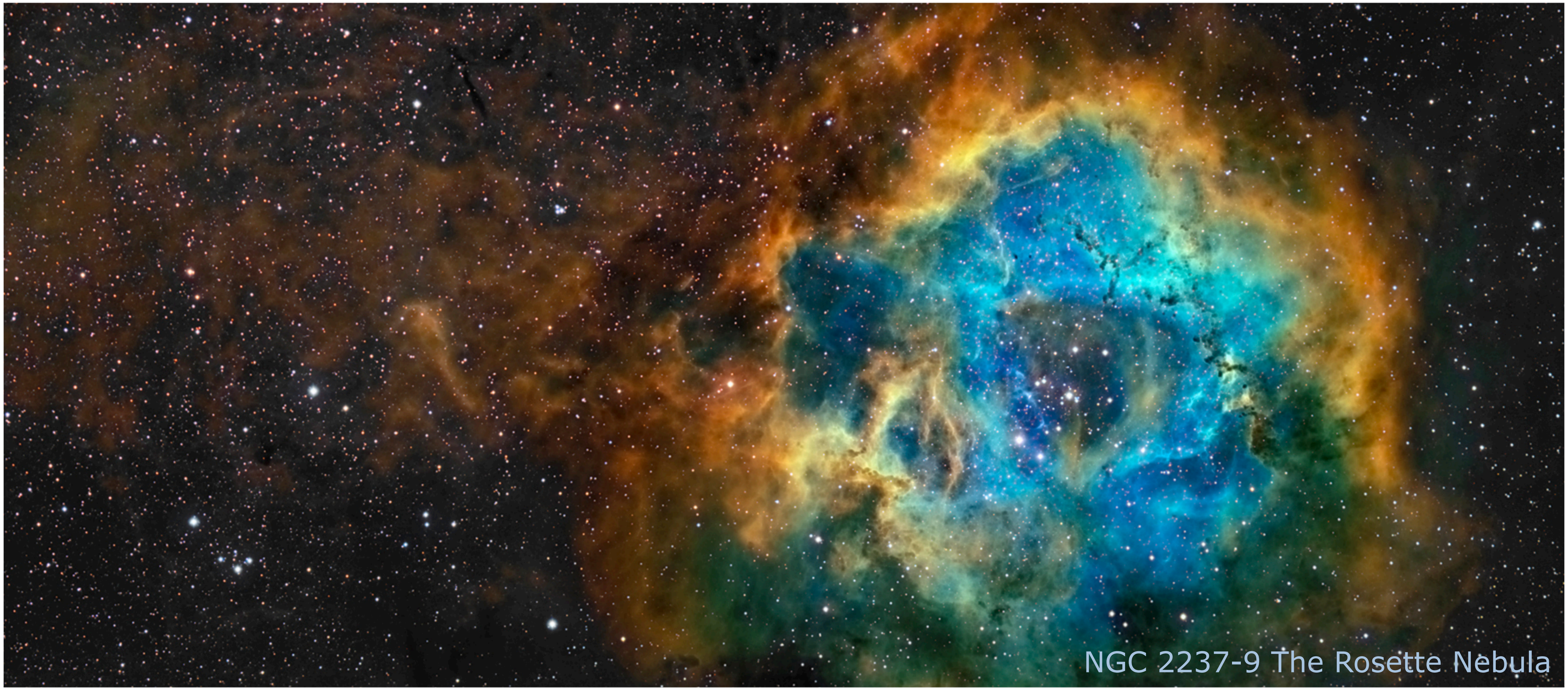
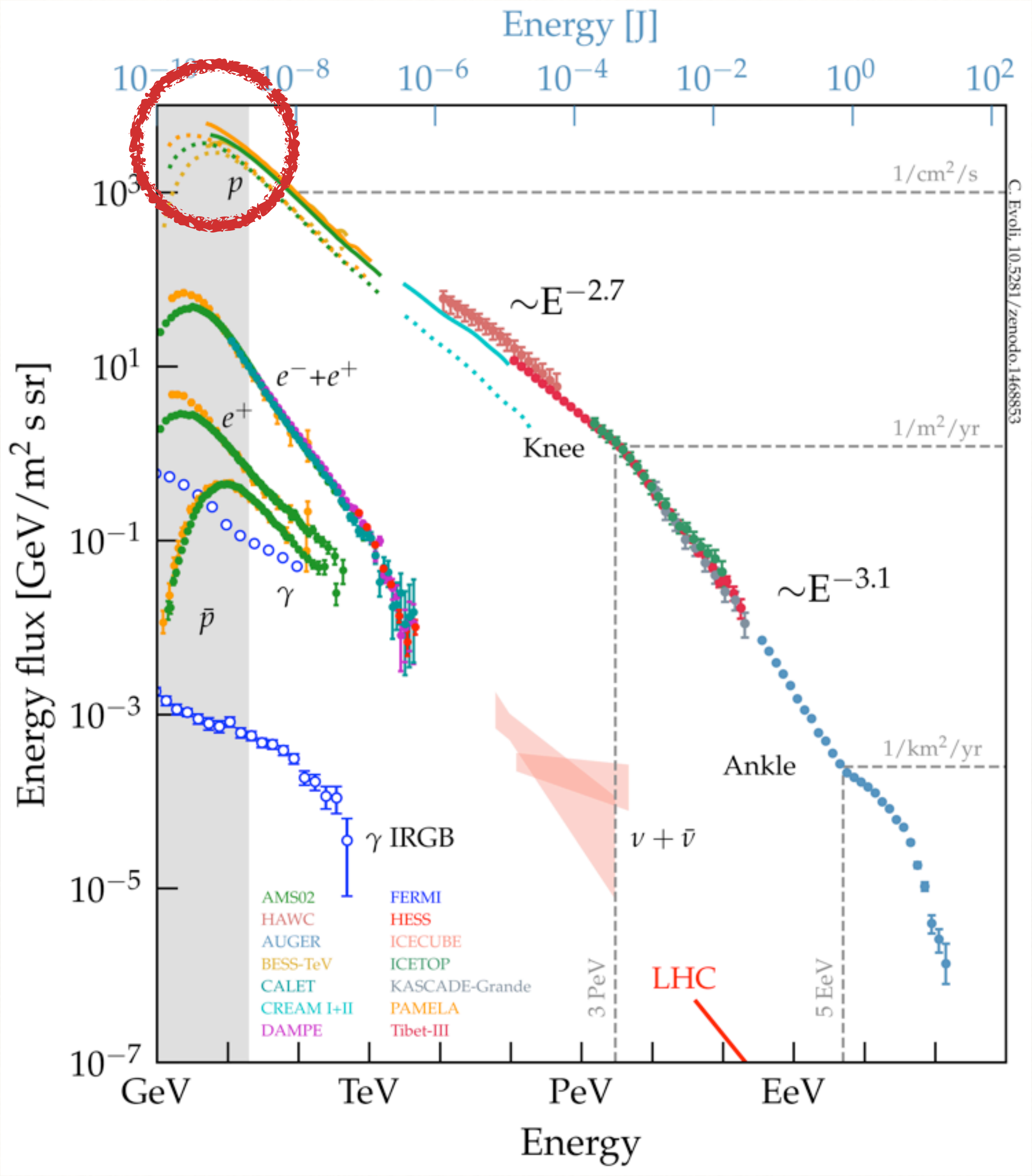


TeVPA 2022 — August 9, 2022 — Kingston (ON) CANADA

Young stellar clusters: new players in the field of Cosmic Ray origin

Giovanni Morlino
INAF/Oss. Astrofisico di Arcetri
Firenze
ITALY

How to explain the origin of Galactic CRs



Requirements

- Energetics: $\sim 10^{40}$ erg/s

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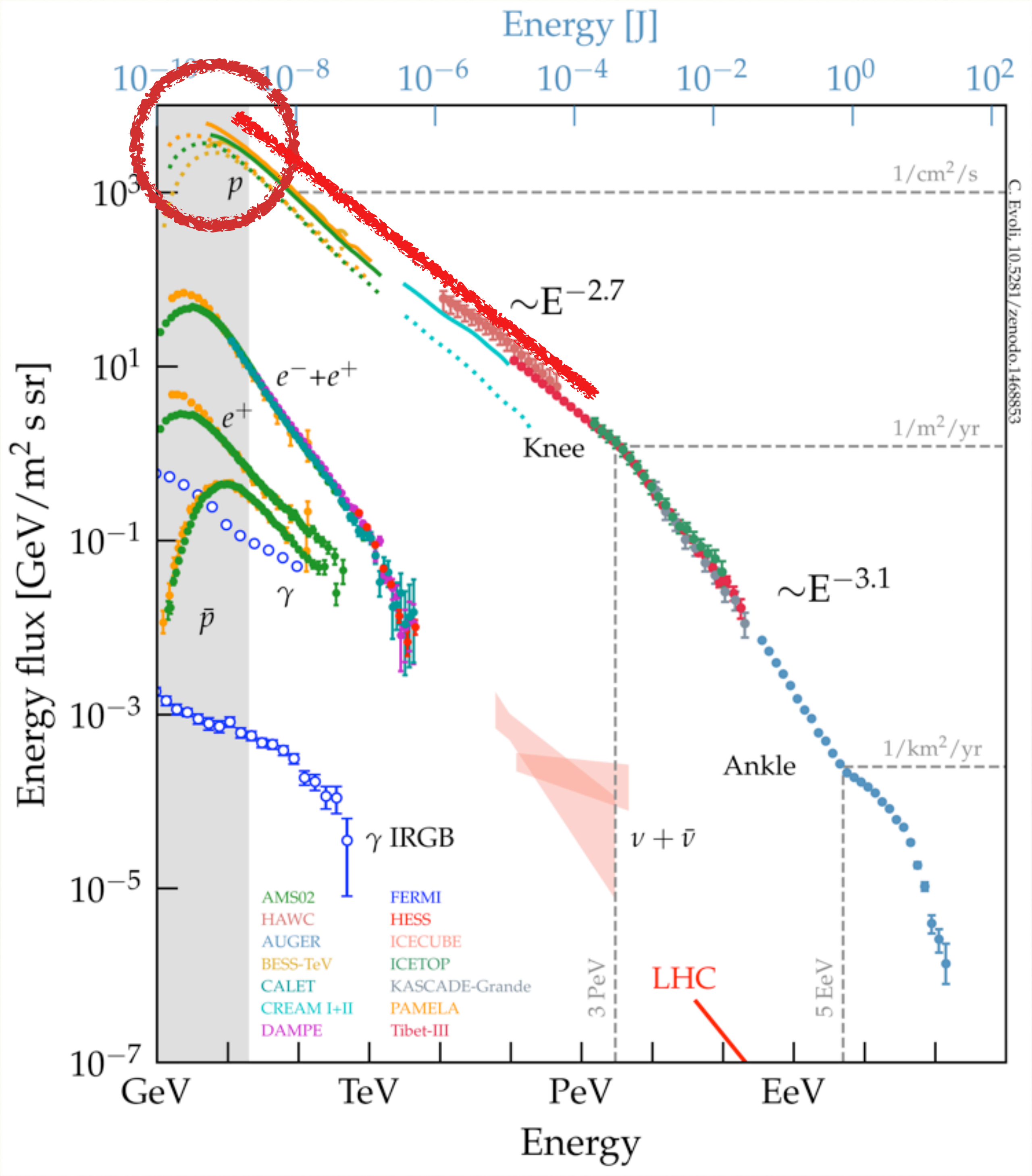

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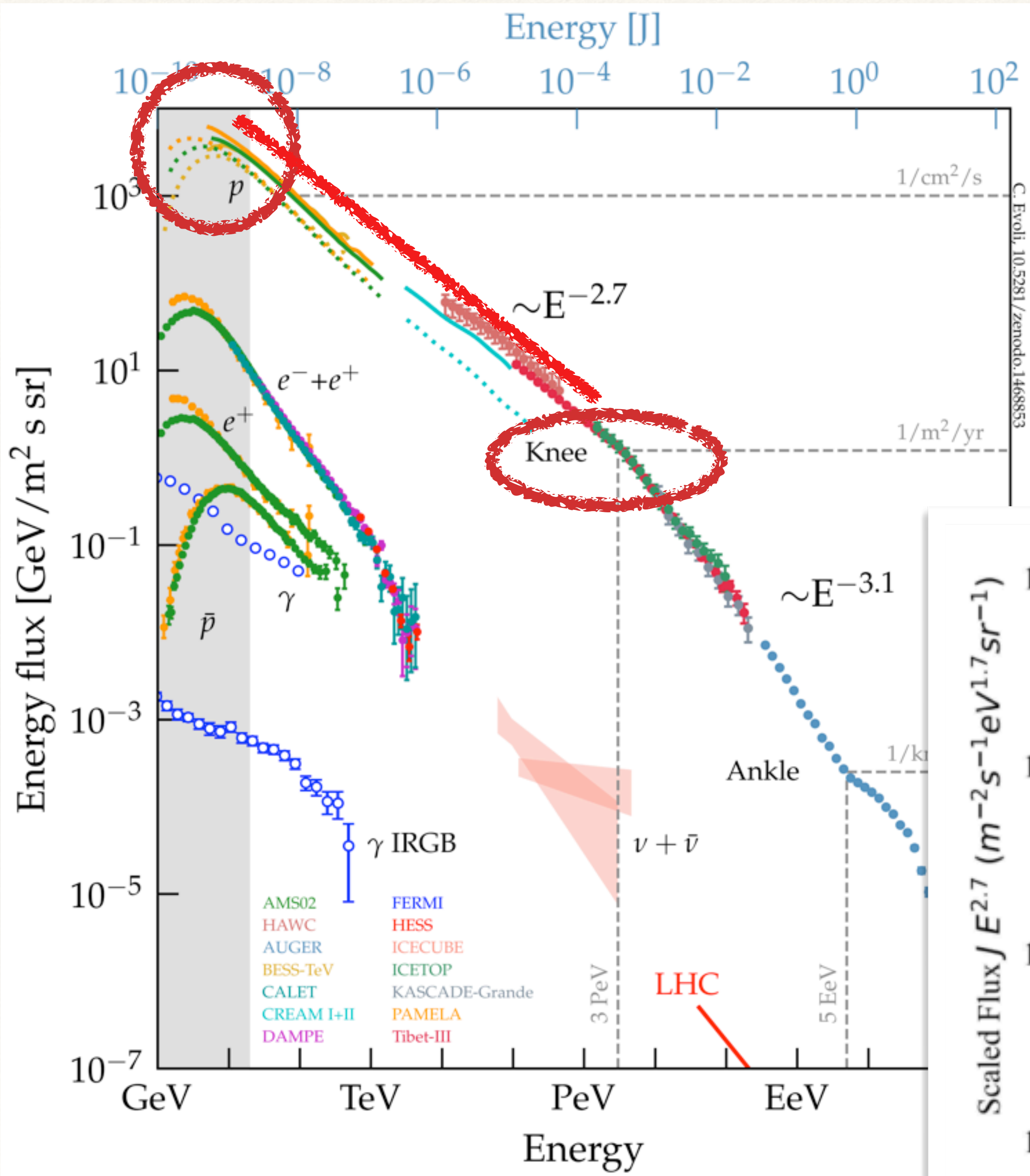

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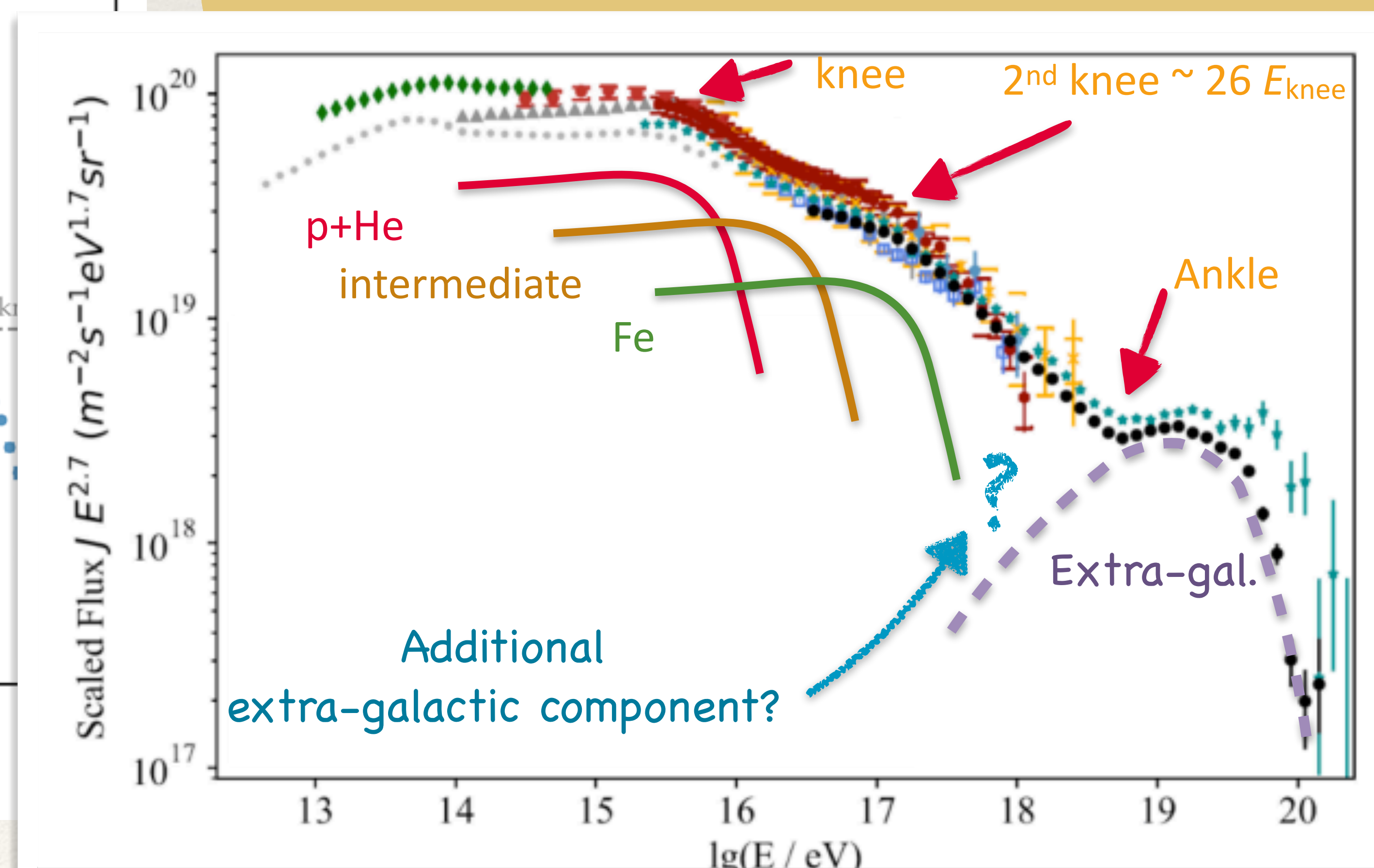

G. Morlino, TeVPA 2022

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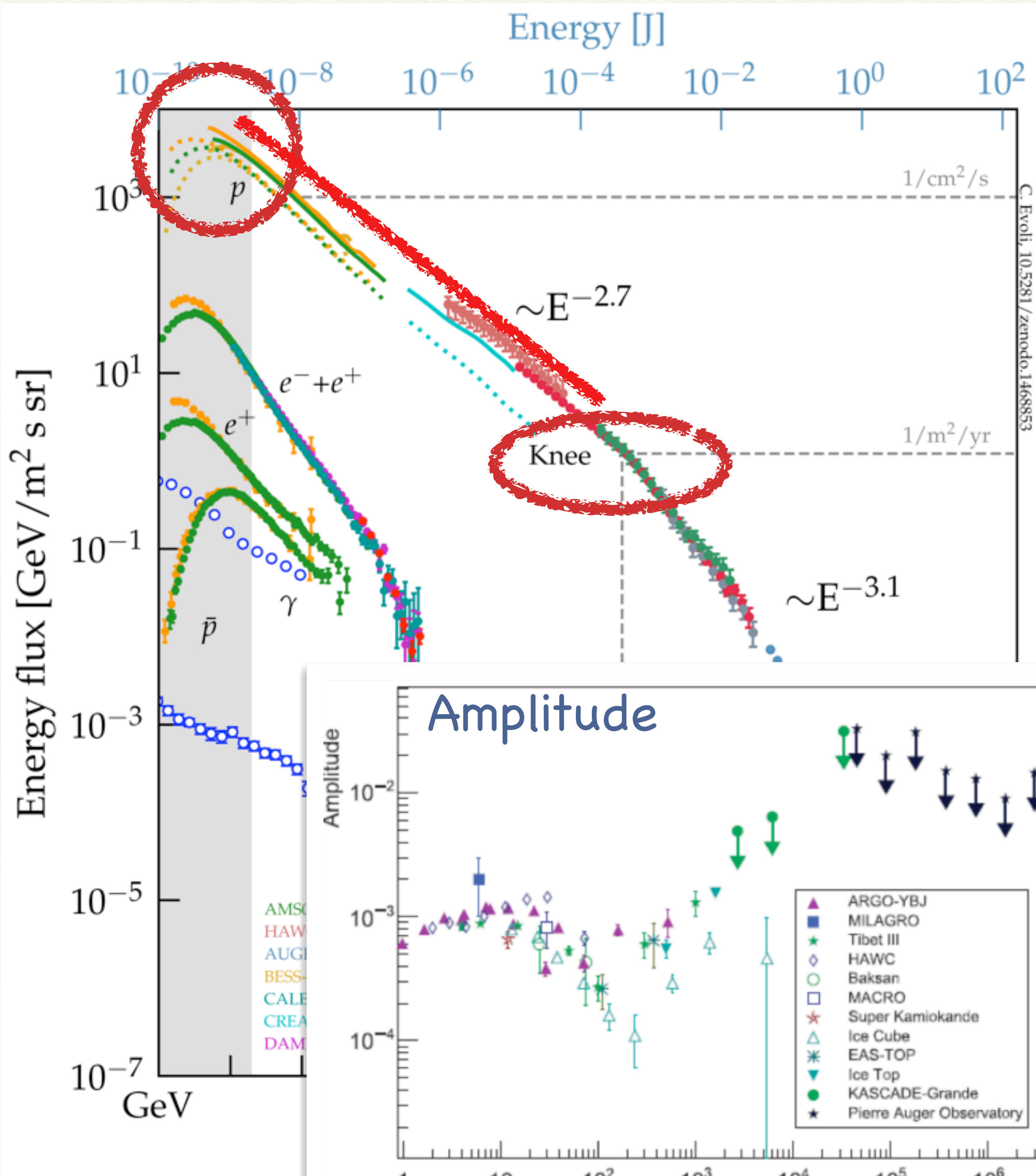

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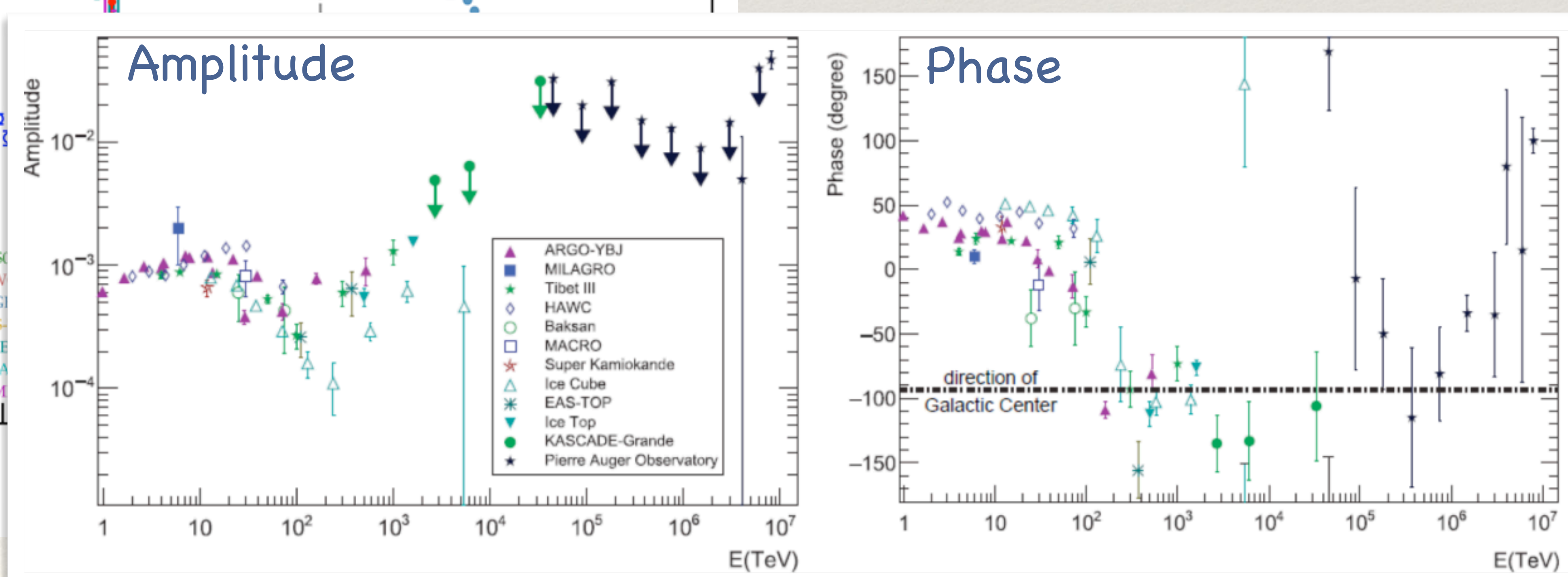

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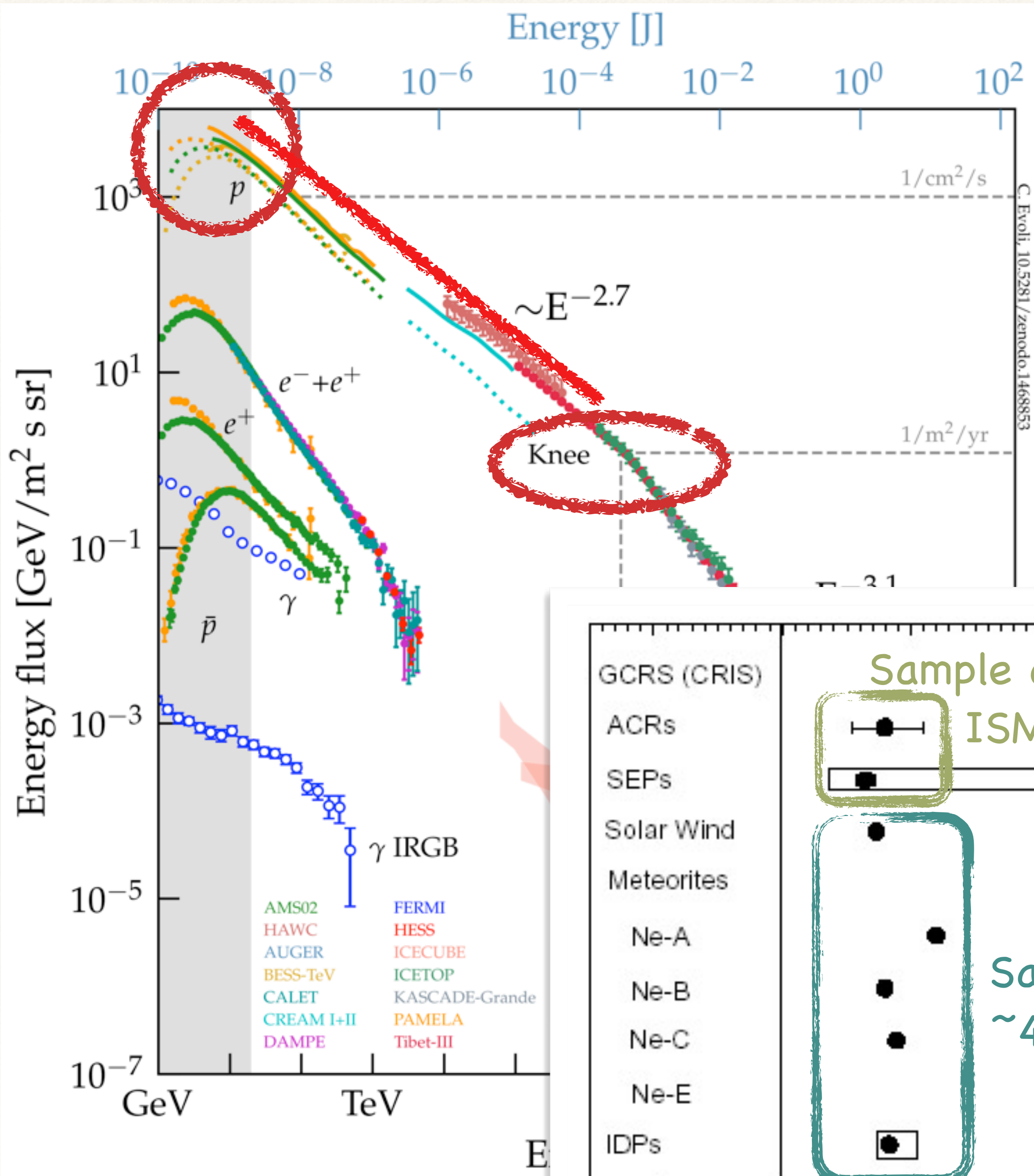

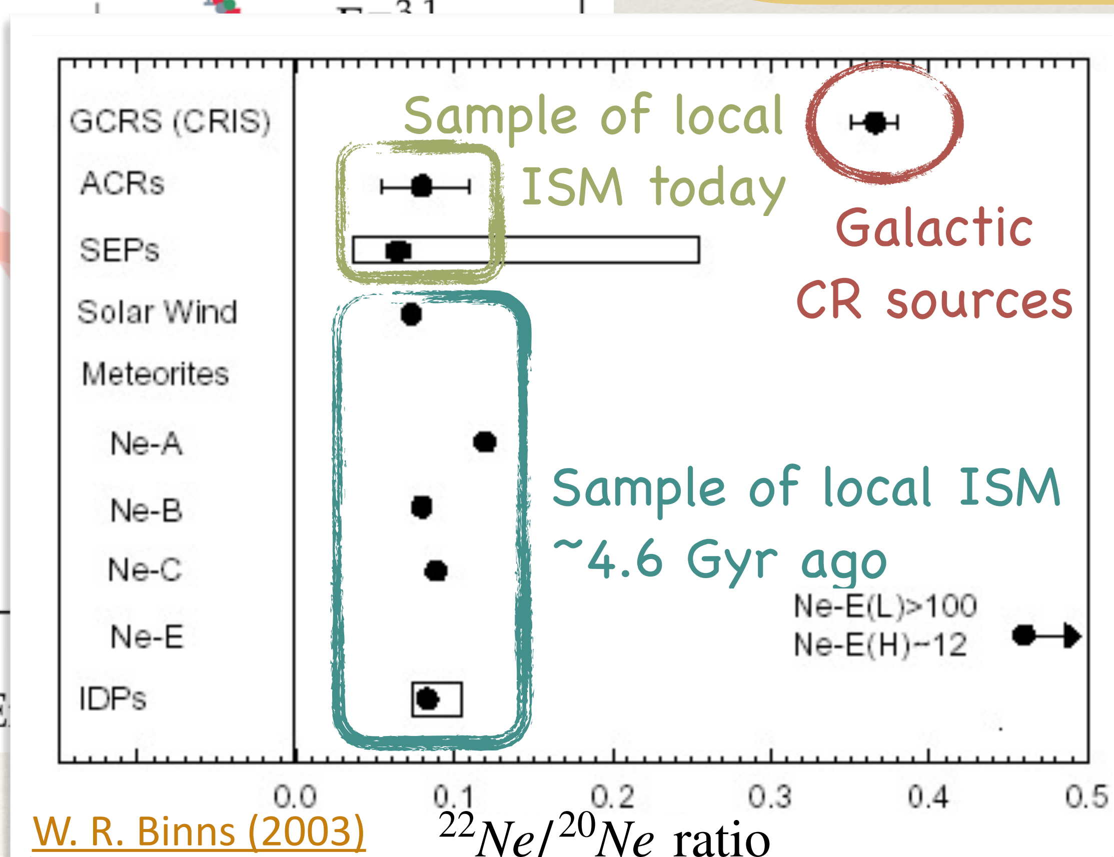

W. R. Binns (2003)

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- Composition: few anomalies w.r.t. Solar

The most popular scenario: DSA@SNR shocks

- **Why supernova remnant are so popular?**
  1. Enough power to sustain the CR flux:

$$P_{\rm CR} \sim \frac{U_{\rm CR} V_{\rm CR}}{\tau_{\rm esc}(1\,{\rm GeV})} \sim 10^{40}\,{\rm erg}$$

$$P_{\rm SN} \sim R_{\rm SN} E_{\rm SN} \sim 3 \times 10^{41} \frac{R_{\rm SN}}{(100\,{\rm yr})^{-1}} \frac{E_{SN}}{10^{51}{\rm erg}}\ {\rm erg/s}$$

$$\Rightarrow \quad \boxed{P_{\rm CR} \simeq 1 - 10\,\%\, P_{\rm SN}}$$

  2. Enough sources to explain anisotropy:

$$N(<d, E) \sim {\rm R}_{\rm SN}\,\left(d/R_d\right)^2 \tau_{\rm esc}(E) = \frac{1}{100yr}\left(\frac{5{\rm kpc}}{15{\rm kpc}}\right)^2 2\,{\rm Myr} \simeq 7000$$

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  5. Observations show the presence of non thermal particles

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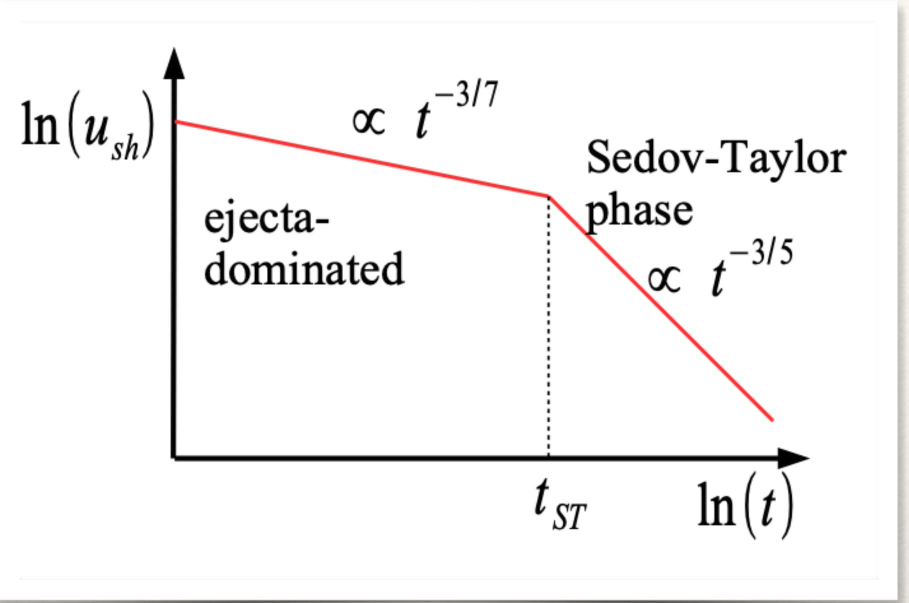
  4. A well developed theory for particle acceleration: DSA
  5. Observations show the presence of non thermal particles

- **However**
  - No evidence of acceleration beyond ~ 100 TeV even in very young SNRs
  - From theory only very powerful and rare SNRs can reach PeV
  - Anomalous CR composition cannot be easily explained
  - Spectral anomalies (p, He, CNO have different slopes)

Maximum energy at SNR shocks

Maximum energy can only increase during the ejecta dominated phase



$$E_{\max} \sim \left(\frac{q}{c}\right) B_{\rm sh} u_{\rm sh} R_{\rm sh}$$ Hillas criterium

Shock radius
$$\begin{cases} R_{\rm sh} \propto t^{4/7} & \text{ejecta-dominated} \\ R_{\rm sh} \propto t^{2/5} & \text{Sedov-Taylor phase} \end{cases}$$

But particle diffuse ahead of the shock: $d \propto \sqrt{D\,t}$

During the ST phase the highest energy particles cannot be reached by the shock and escape towards upstream

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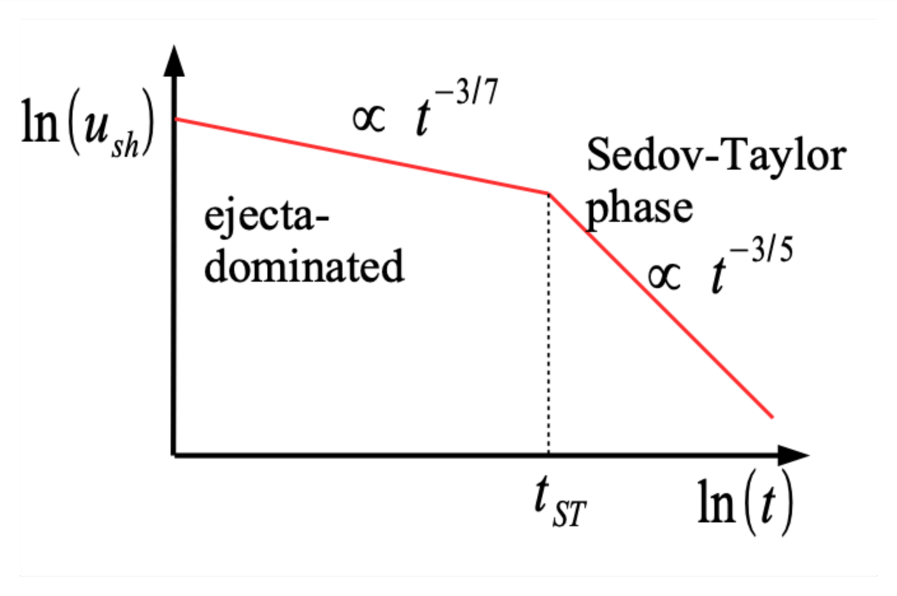

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Maximum energy obtained from the condition $t_{\rm acc} = t_{\rm ST}$

$$E_{\rm max} \simeq 5 \times 10^{13} \mathcal{F}(k_{\rm max}) \left(\frac{B_0}{\mu G}\right) \left(\frac{M_{\rm ej}}{M_\odot}\right)^{-1/6} \left(\frac{E_{\rm SN}}{10^{51}\,{\rm erg}}\right)^{1/2} \left(\frac{n_{\rm ism}}{{\rm cm}^{-3}}\right)^{-1/3} {\rm eV}$$

$E_{\rm max}$ is weakly dependent on all parameters but the magnetic field

PeV energies requires $\mathcal{F} = \left(\frac{\delta B_k}{B}\right)^2 \gg 1$

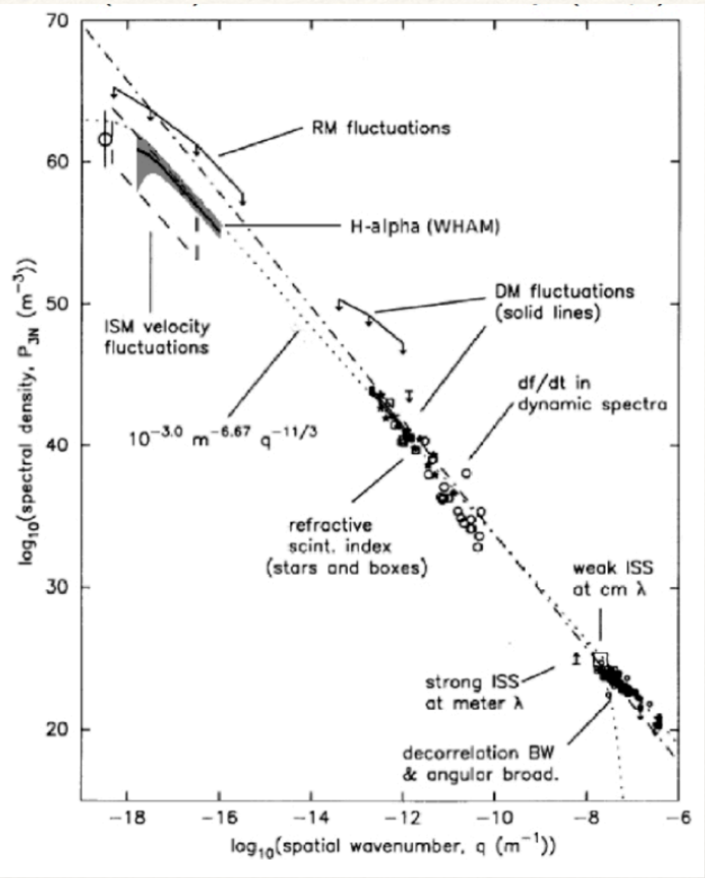
Need of magnetic field amplification

How to amplify the magnetic field

For reviews see: Drury (1994); Blasi (2013, 2019); Gabici et al (2019)

- In the regular ISM turbulence is injected by SNR and stellar winds:
  - Kolmogorov power spectrum $\mathscr{F}(k) = k \frac{\langle \delta B(k) \rangle^2}{B_0^2} = \frac{2}{3} \eta_B \left(L_{\rm tur} k\right)^{-2/3}$
  - Injection scale $L_{\rm tur} \sim 10 - 100$ pc
  - Total power in turbulence $\eta_B \sim 0.01 - 0.1$

$\Rightarrow$ $\mathscr{F}\left(1/r_L(1 \mathrm{PeV})\right) \sim 10^{-3}$ $\boxed{E_{\max} \sim \mathit{few}\ \mathrm{GeV}}$



Electron density fluctuation in the ISM
[Armstrong et al.(1995) ApJ 443, 209]

- **Proposed magnetic field amplification mechanisms:**
  - Resonant streaming instability [Skilling (1975)] $\Rightarrow$ $\mathscr{F} \lesssim 1$
  - MHD instability due to density perturbation [Giacalone & Jokipii (2007)]
  - Acoustic instability [Drury & Falle (1983)]

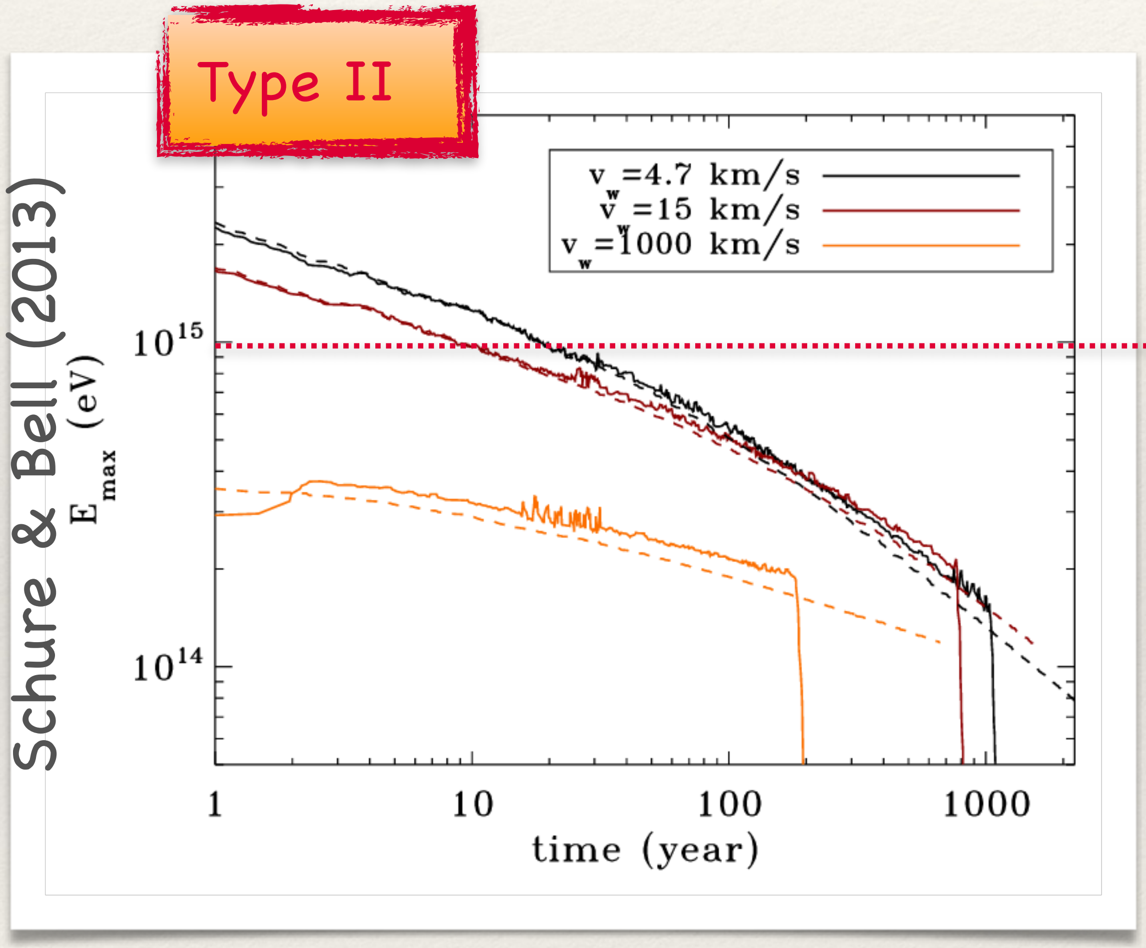
  $\Rightarrow$ $\mathscr{F} \sim 1$ in realistic conditions
  - Non-resonant streaming instability [Bell (2004)] $\Rightarrow$ $\mathscr{F} \gtrsim 1$

Only very young CC SNR can accelerate to PeV

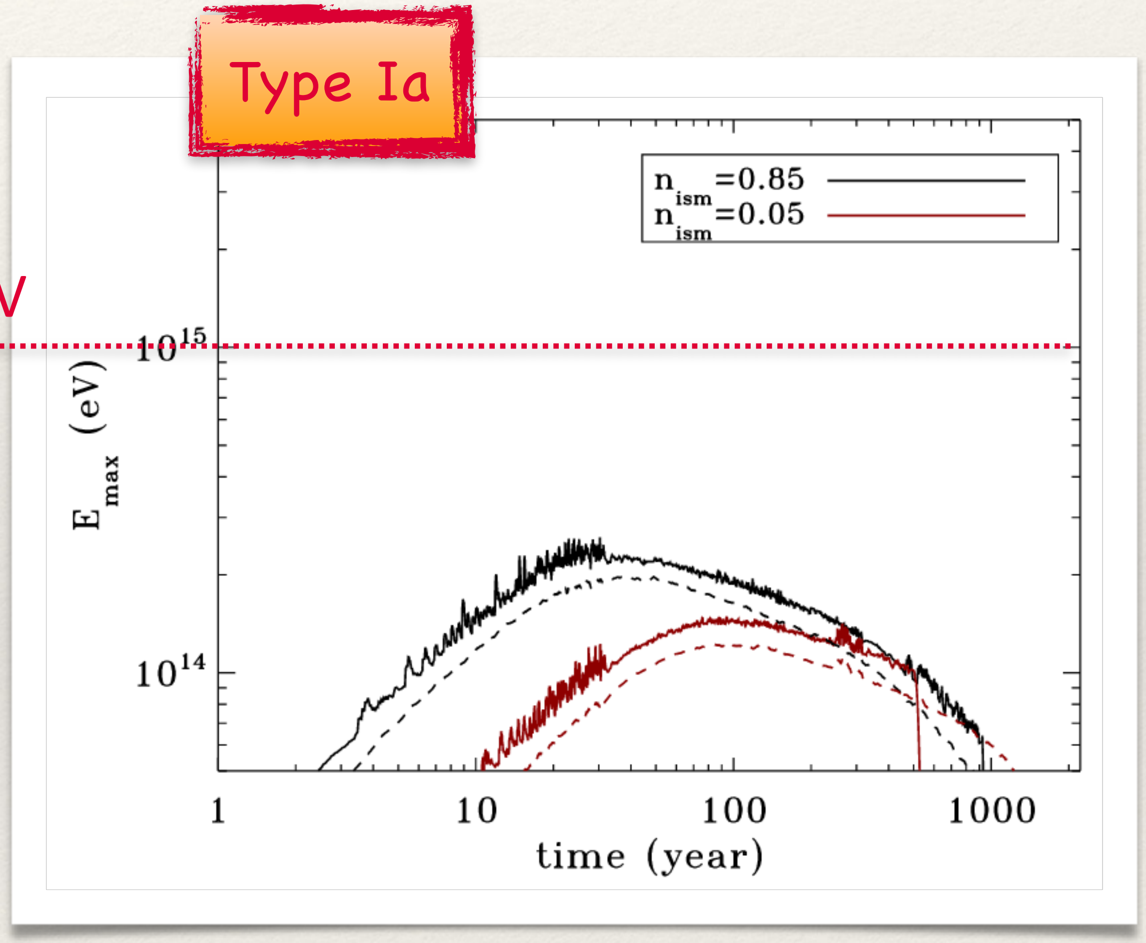
Shure & Bell (2013)

Magnetic field at saturation $$\frac{B_{\rm sat}^2}{B_0^2} \sim \frac{U_{\rm CR}}{U_{B_0}} \frac{v_d}{c} \propto n_0 v_{sh}$$

Efficient amplification requires:
- large densities
- large shock speed



1 PeV



PeV energies can be reached:

- Only by core-collapse SN expanding into dense environment (slow and dense progenitor's wind)
- During the very early phase (age $\lesssim 50$ years)

Accounting for SNR evolution and CR propagation

Cristofari, Blasi & Amato (2020)

Parameters for different type of SNRs

Type	Ia	II	II*
$M_{\rm ej}$ [$M_{\rm Sol}$]	1.4	5	1
$E_{\rm SN}$ [10^{51} erg]	1	1	10
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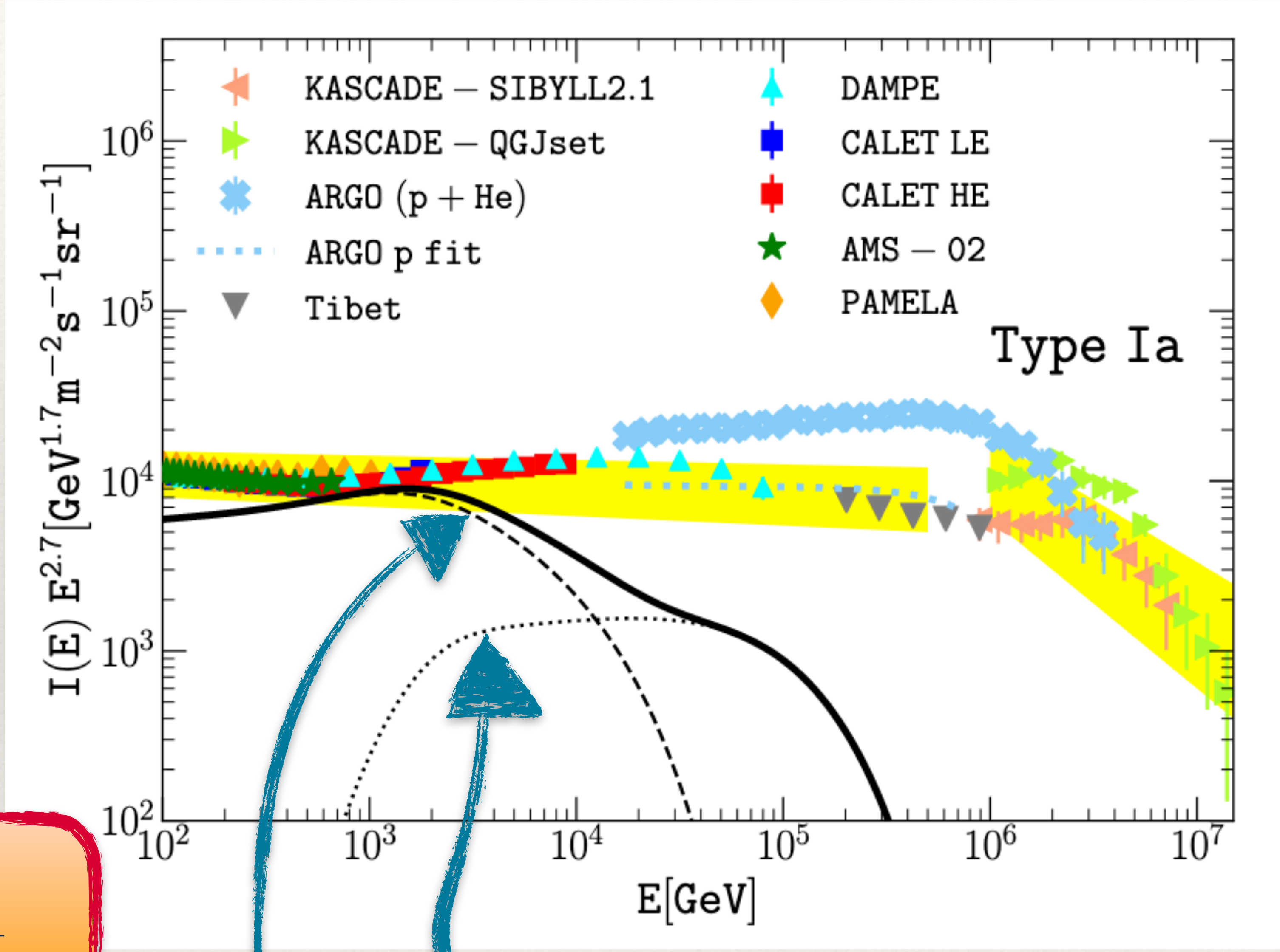
$$\text{Rate} = \frac{1}{100\ \text{yr}}\ ;\ \xi_{CR} = 0.1$$

COMPARISON WITH THE CR SPECTRUM DETECTED AT THE EARTH



Confined particles

Particles escaping during the acceleration

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$$\text{Rate} = \frac{2}{100\ \text{yr}}\ ;\ \xi_{CR} = 0.06$$

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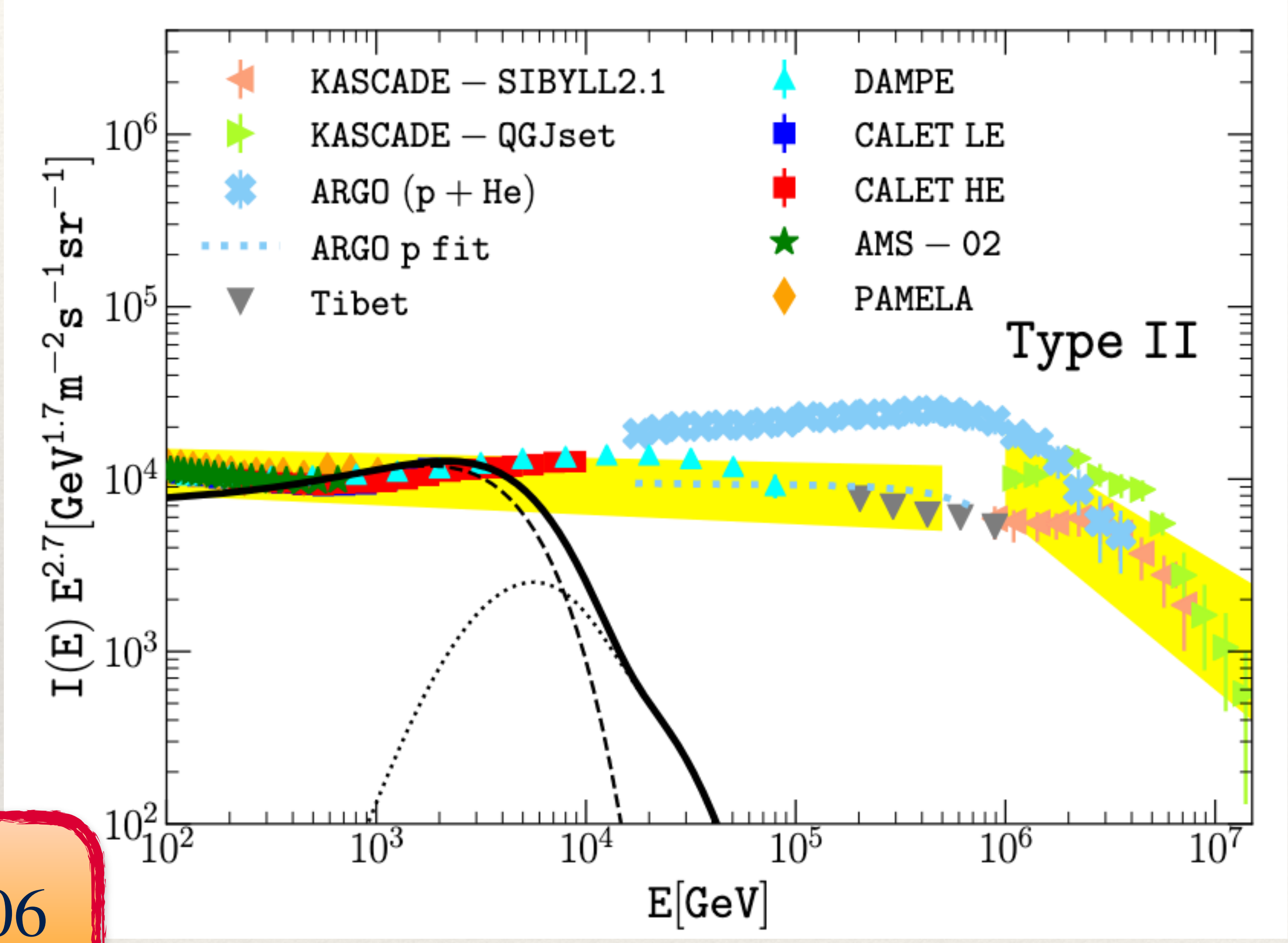

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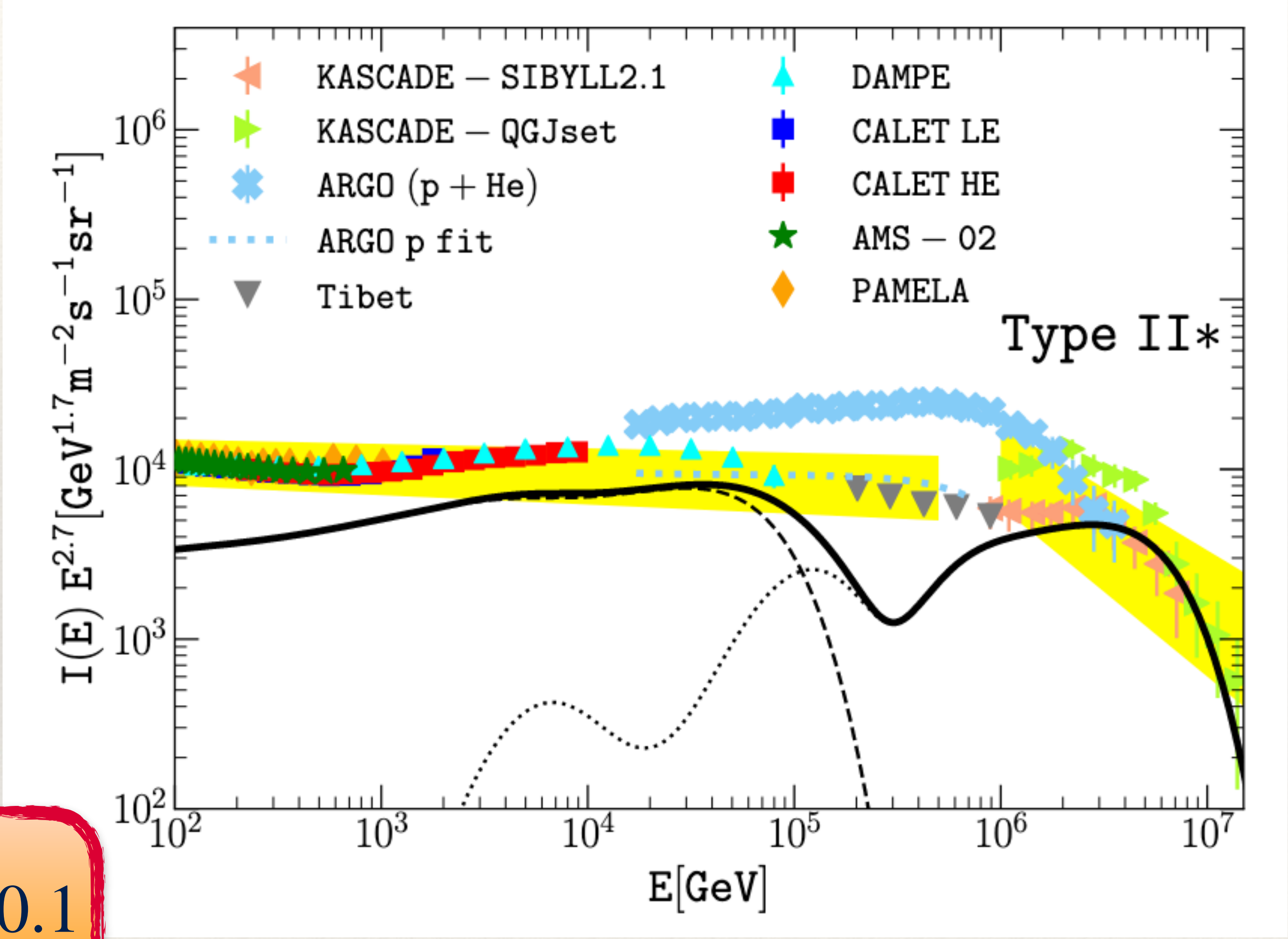

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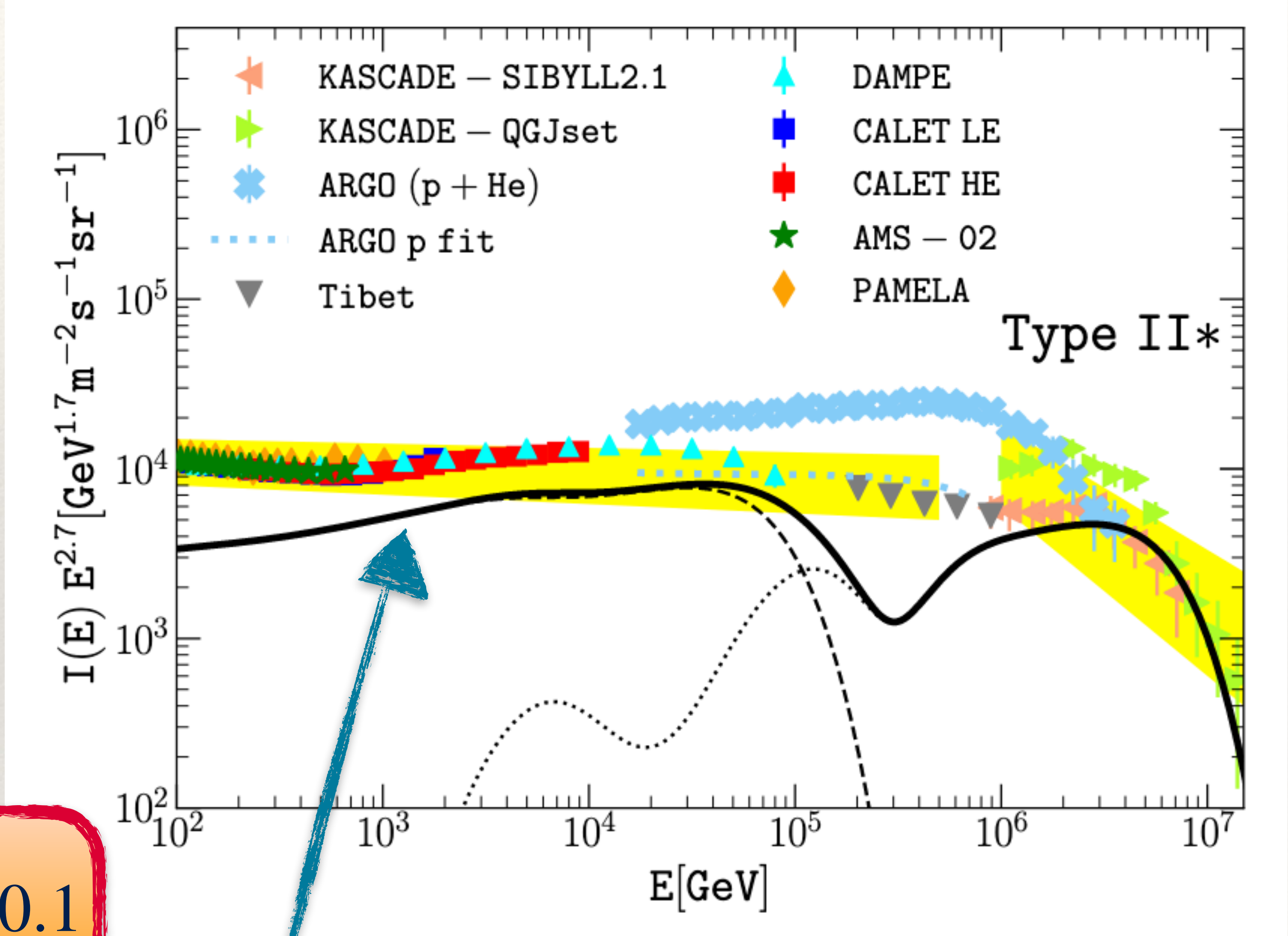

No room for other SNRs

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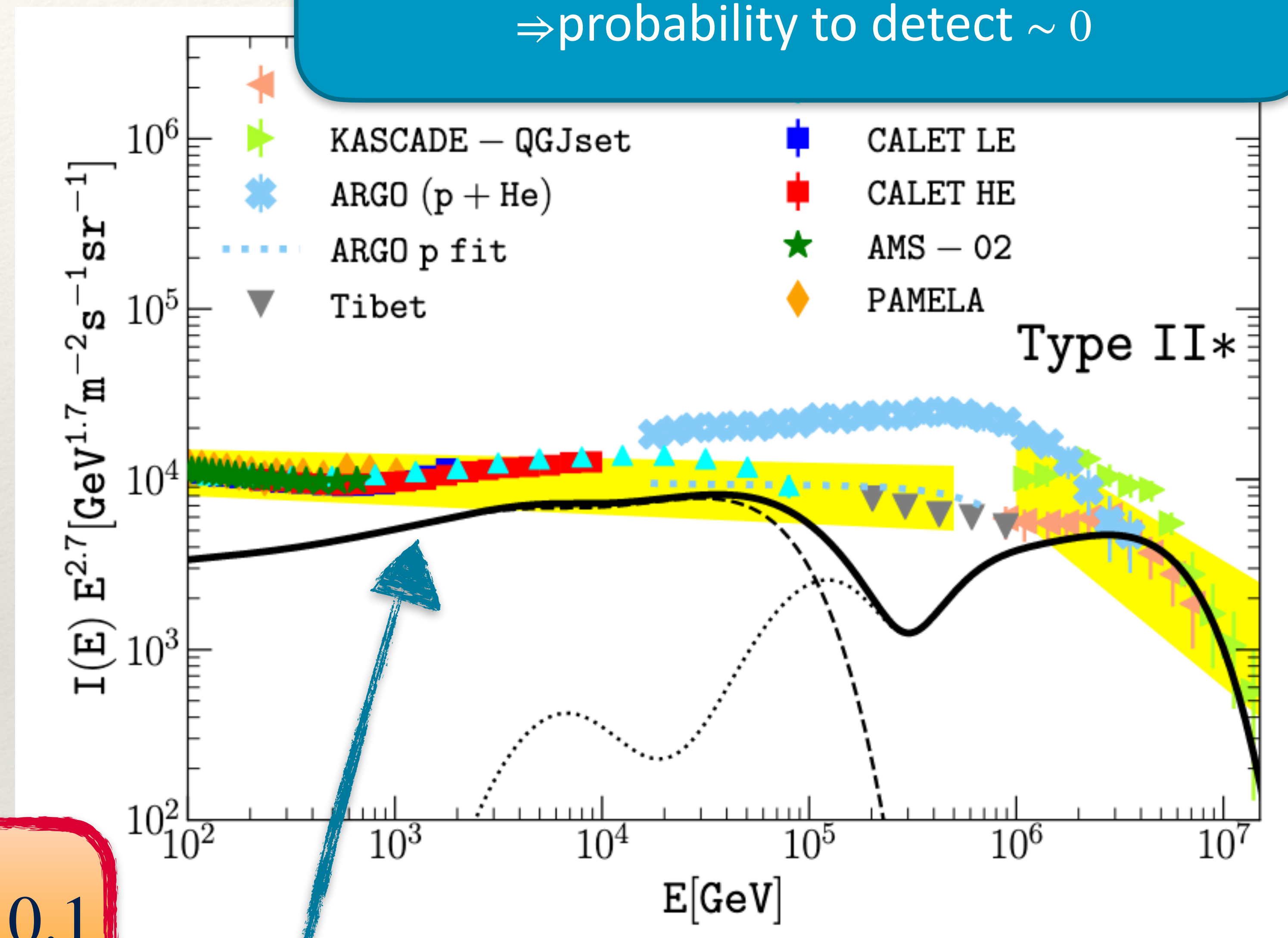
COM

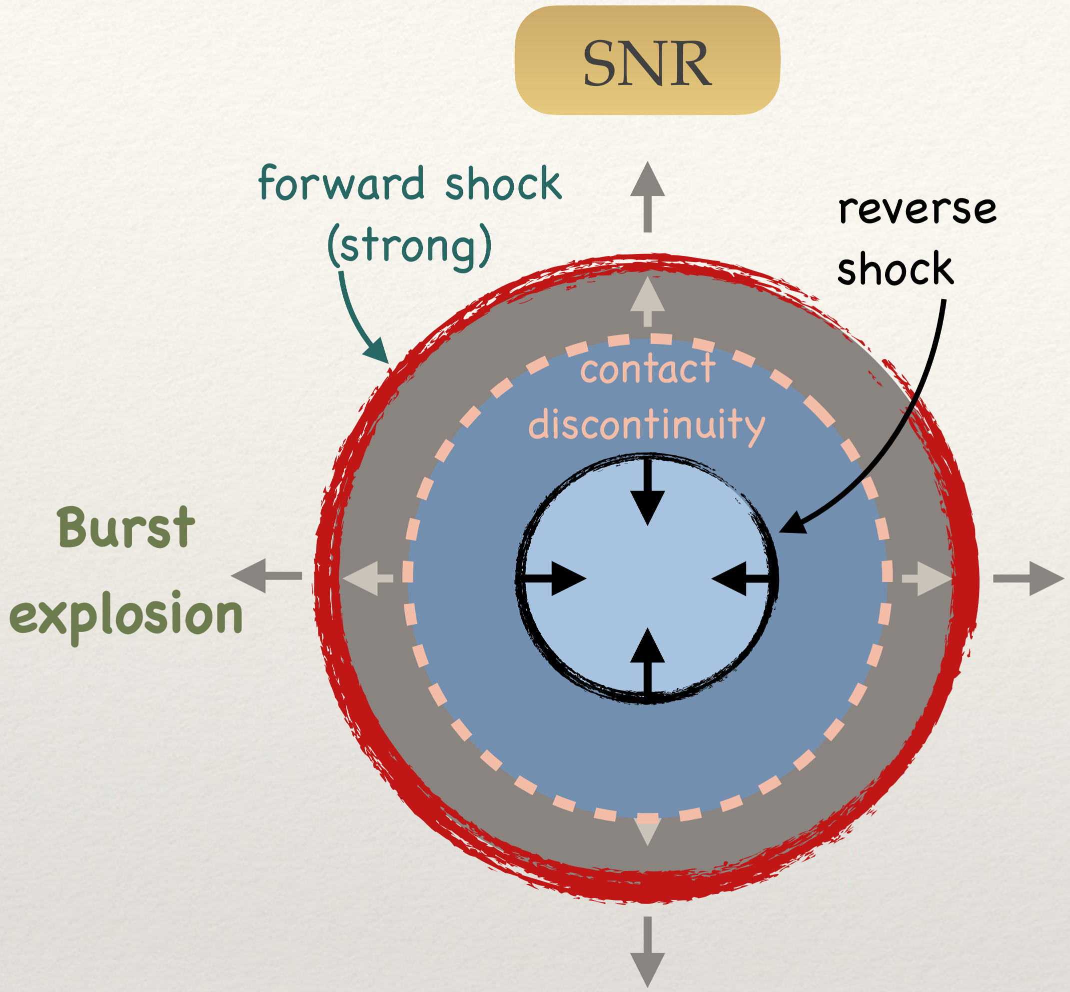
If only Tipe II* are PeVatrons
⇒probability to detect ~ 0



No room for other SNRs

Stellar winds vs. SNRs

Cassé & Paul (1980, 1982) — Cesarsky & Montmerle (1983)



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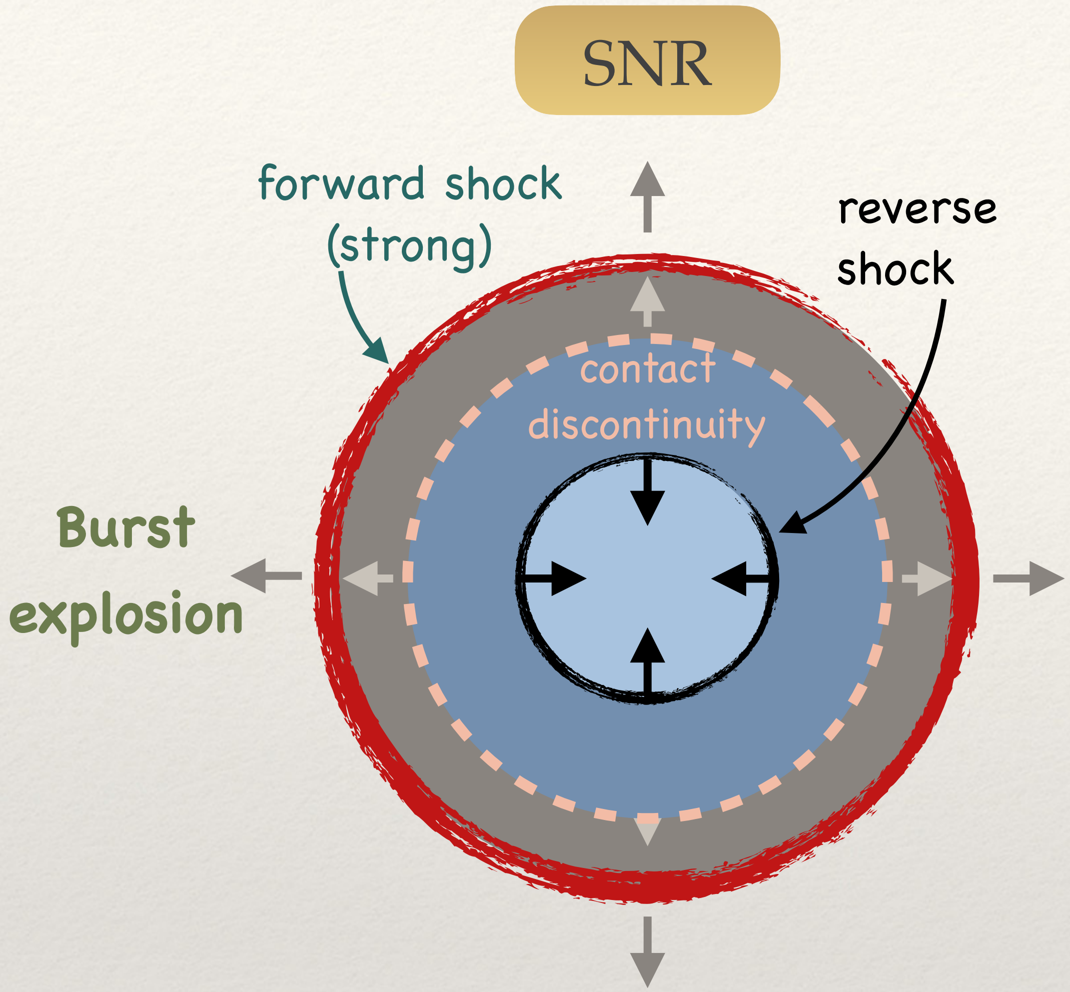

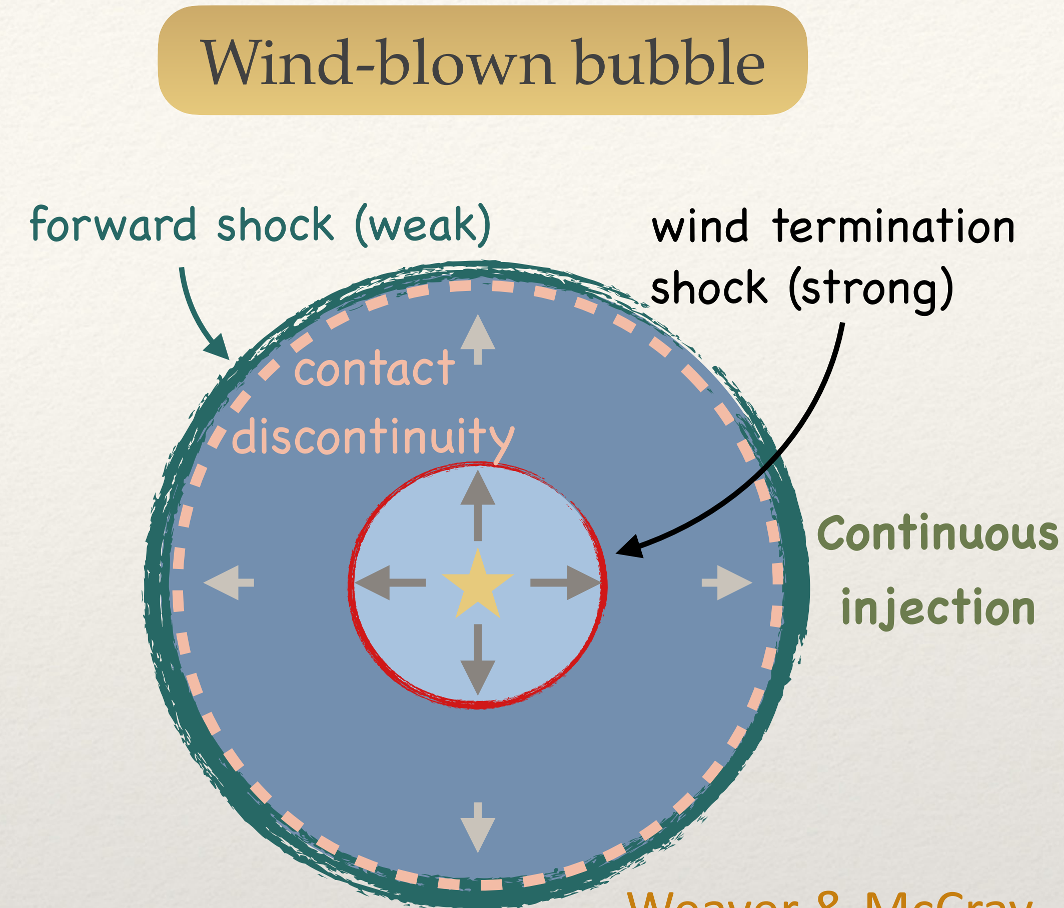

Weaver & McCray,
ApJ 218 (1977)

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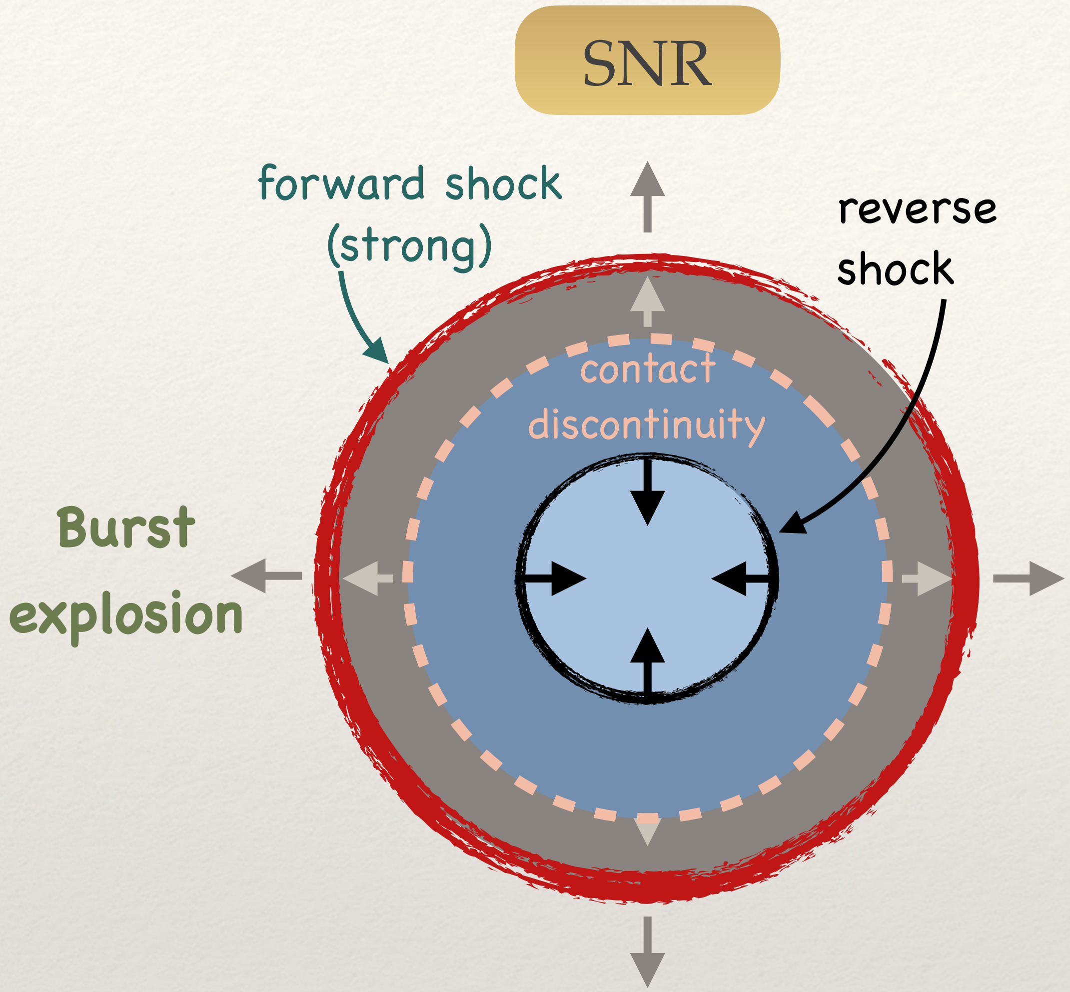

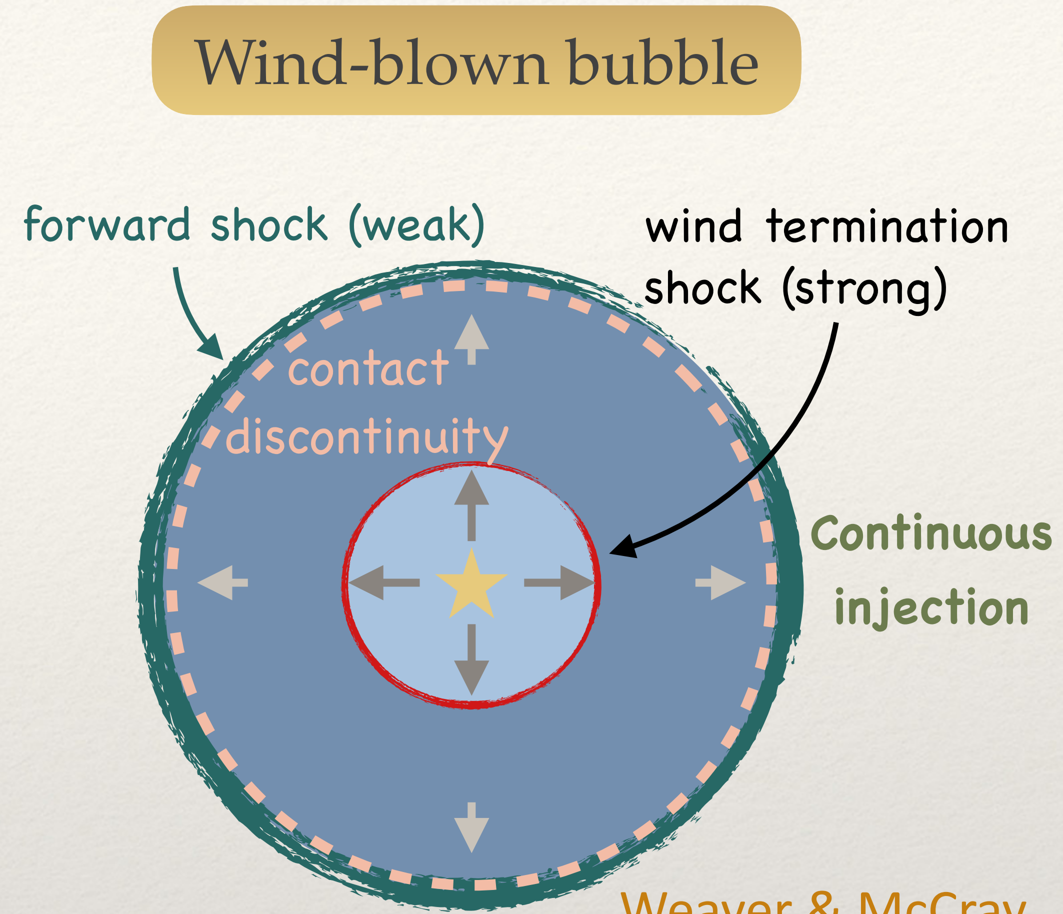

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	age	Forward shock V_{FS} [km/s]	Forward shock R_{FS} [pc]	Reverse shock V_{RS} [km/s]	Reverse shock R_{RS} [pc]
SNR	kyr	> 5000	< 1	< 3000	< 1
Wind bubble	Myr	10 - 20	50-100	< 3000	1-10

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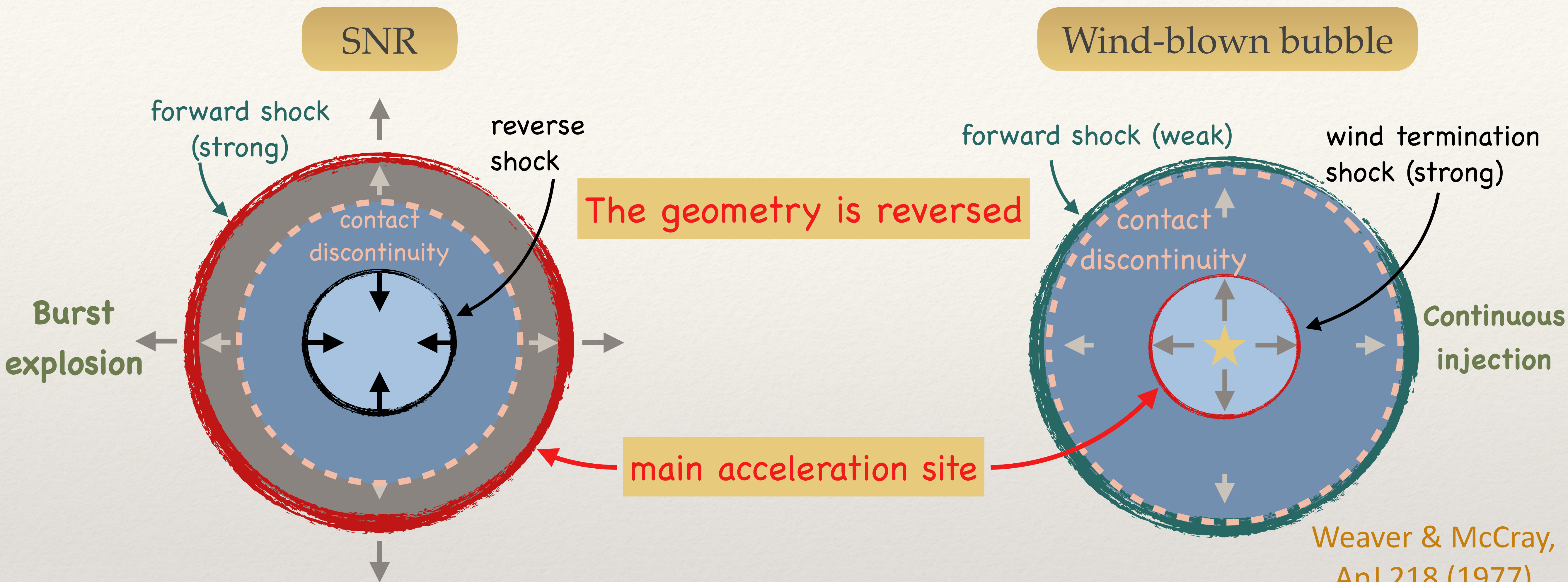

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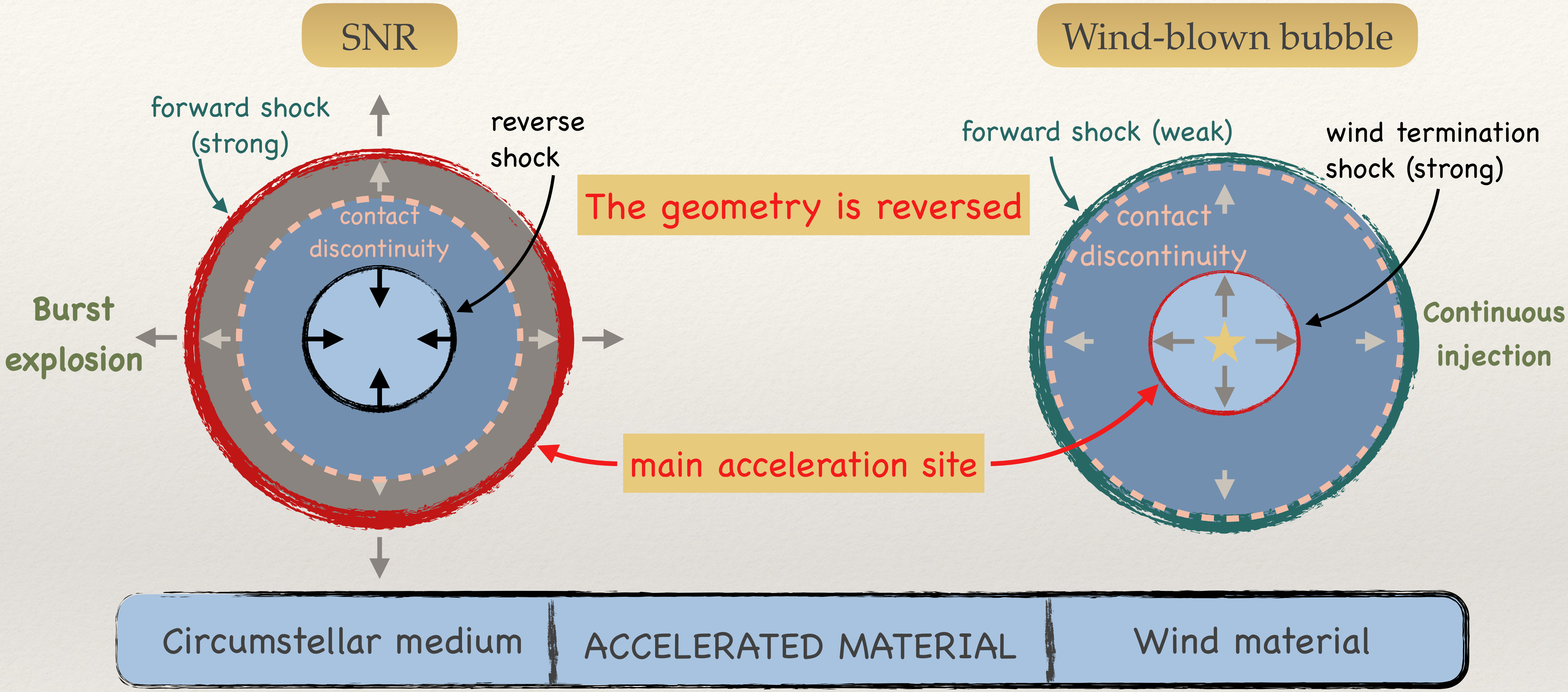

Bonus: massive star winds are enriched in ^{22}Ne

-> possibility to solve the ^{22}Ne/^{20}Ne anomaly

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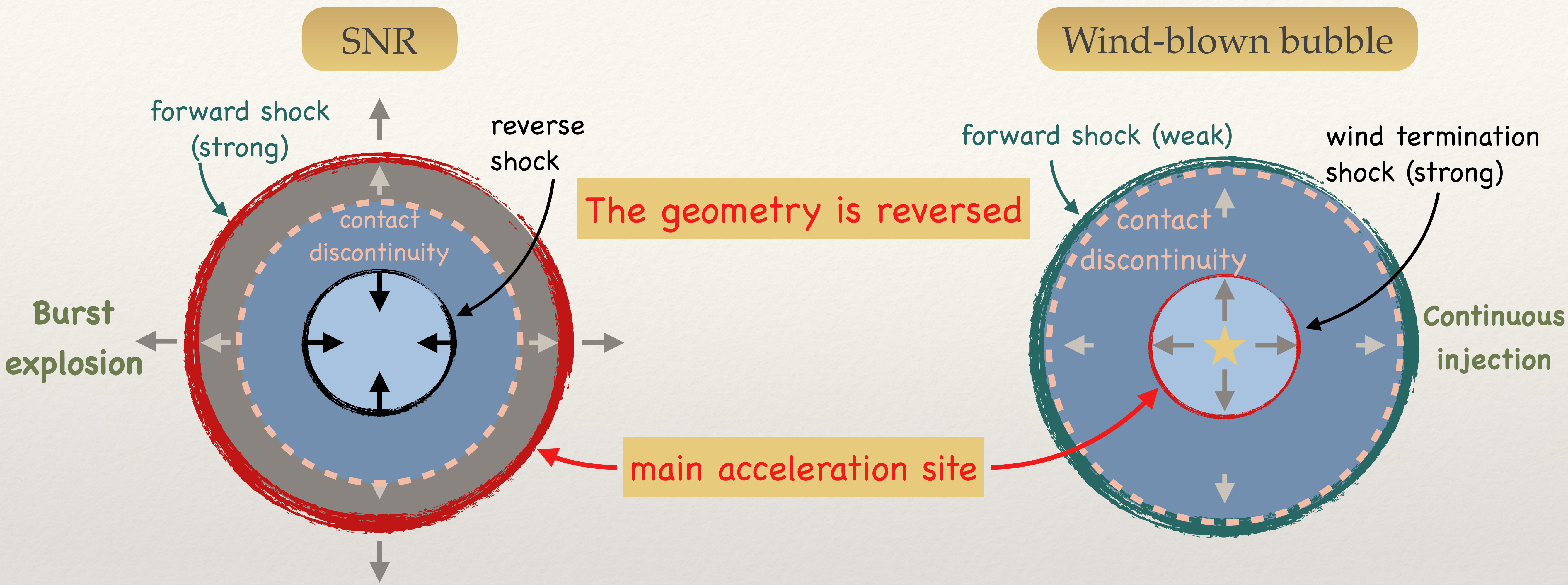

Circumstellar medium	ACCELERATED MATERIAL	Wind material

Bonus: massive star winds are enriched in ^{22}Ne

-> possibility to solve the ^{22}Ne/^{20}Ne anomaly

Self-generated by accelerated particles	MAGNETIC FIELD	Amplified by MHD turbulence in the wind

Maximum energy: first order estimate

Hillas criterium

$$E_{\max} \sim \left(\frac{q}{c}\right) B_{\rm sh} u_{\rm sh} R_{\rm sh}$$

	dM/dt M_{sol}/yr	u_{sh} km/s	R_{sh} pc	B μG	*age* yr	lim E_{max}	E_{max} TeV
SNR	—	> 5000	< 1	~100 self-amplification	~10^3	time limited	~10-100
WTS (single star)	10^{-6}	< 3000	~ 1	~ 1 MHD turbulence	~10^6	space limited	~ 10
WTS (massive cluster)	10^{-4}	< 3000	> 10	> 10 MHD turbulence	~10^6	space limited	~> 1000

For massive star cluster ($\gtrsim 10^4 M_\odot$) PeV energies can be reached

Maximum energy: a more detailed analysis

GM, Blasi, Peretti & Cristofari (2019)

Solution of diffusive shock acceleration in spherical geometry

$$f_s(p) = s\frac{\eta_{\rm inj}\, n_1}{4\pi\, p_{\rm inj}^3}\left(\frac{p}{p_{\rm inj}}\right)^{-s} e^{-\Gamma_1(p)}\; e^{-\Gamma_2(p)}$$

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Maximum energy due to confinement in the upstream:
the effective plasma speed decreased reducing the energy gain

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Maximum energy due to escaping from the downstream

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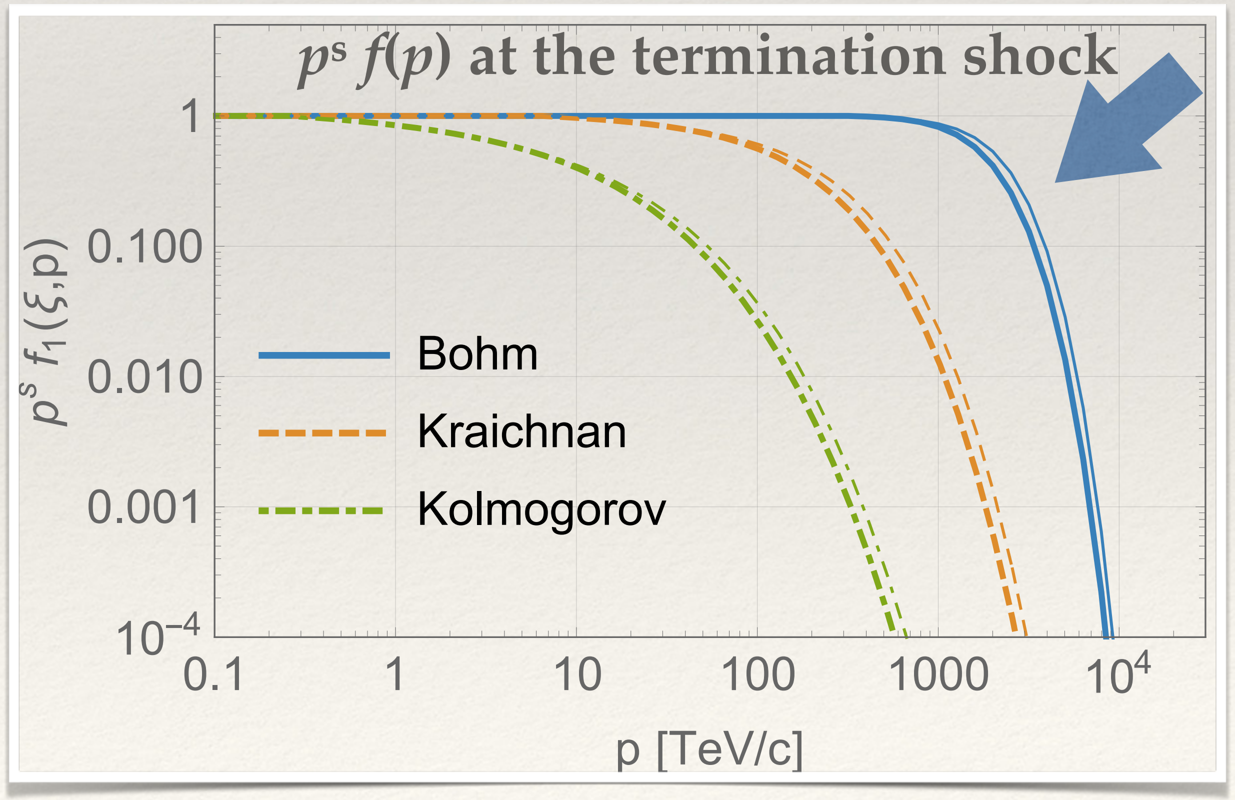
Maximum energy due to escaping from the downstream

Maximum energy due to confinement in the upstream: the effective plasma speed decreased reducing the energy gain

The diffusion coefficient has a strong impact on the cutoff shape and effective maximum energy

Typical values for massive stellar clusters

$$\begin{cases} \dot{M} = 10^{-4}\, M_\odot\, {\rm yr}^{-1} \\ v_w = 3000 \text{ km/s} \\ L_{\rm CR} = 0.1\, L_w \\ \eta_B = 0.01 \end{cases}$$



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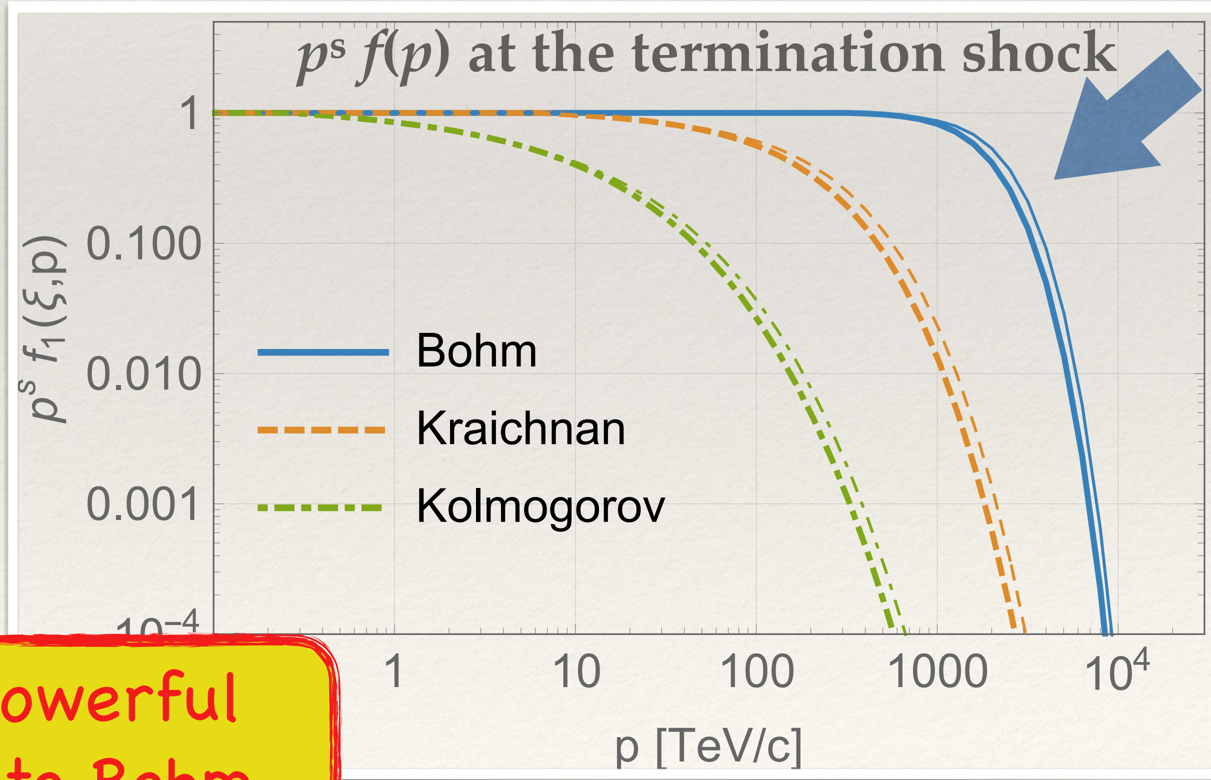
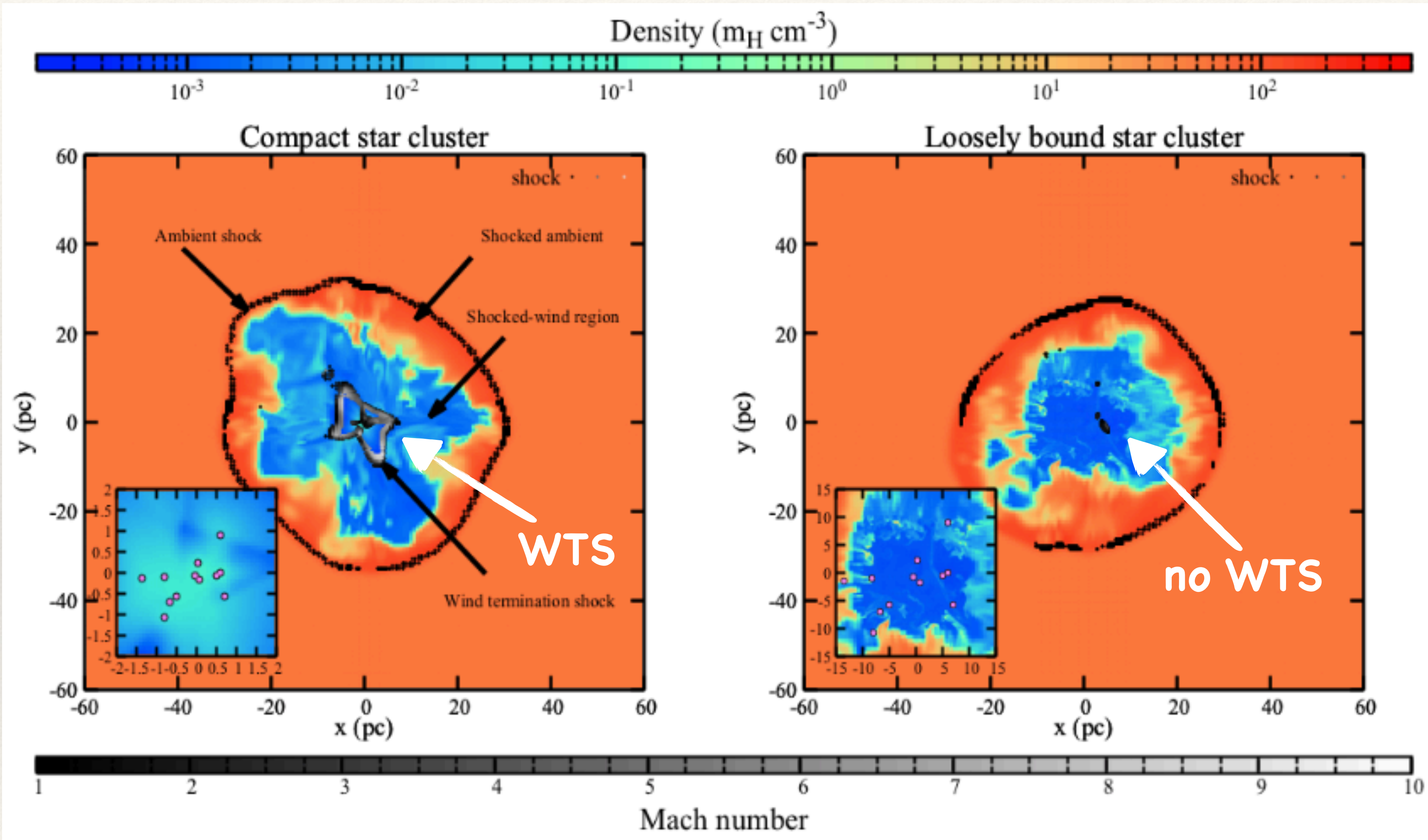


PeV energies can be reached in very powerful stellar clusters if the diffusion is close to Bohm

Cluster compactness

[Gupta, Nath, Sharma & Eichler, MNRAS 2020]

A WTS is generated if the cluster is compact enough, such that $R_{\rm cluster} \ll R_{\rm ts}$



Compact cluster

Loose cluster

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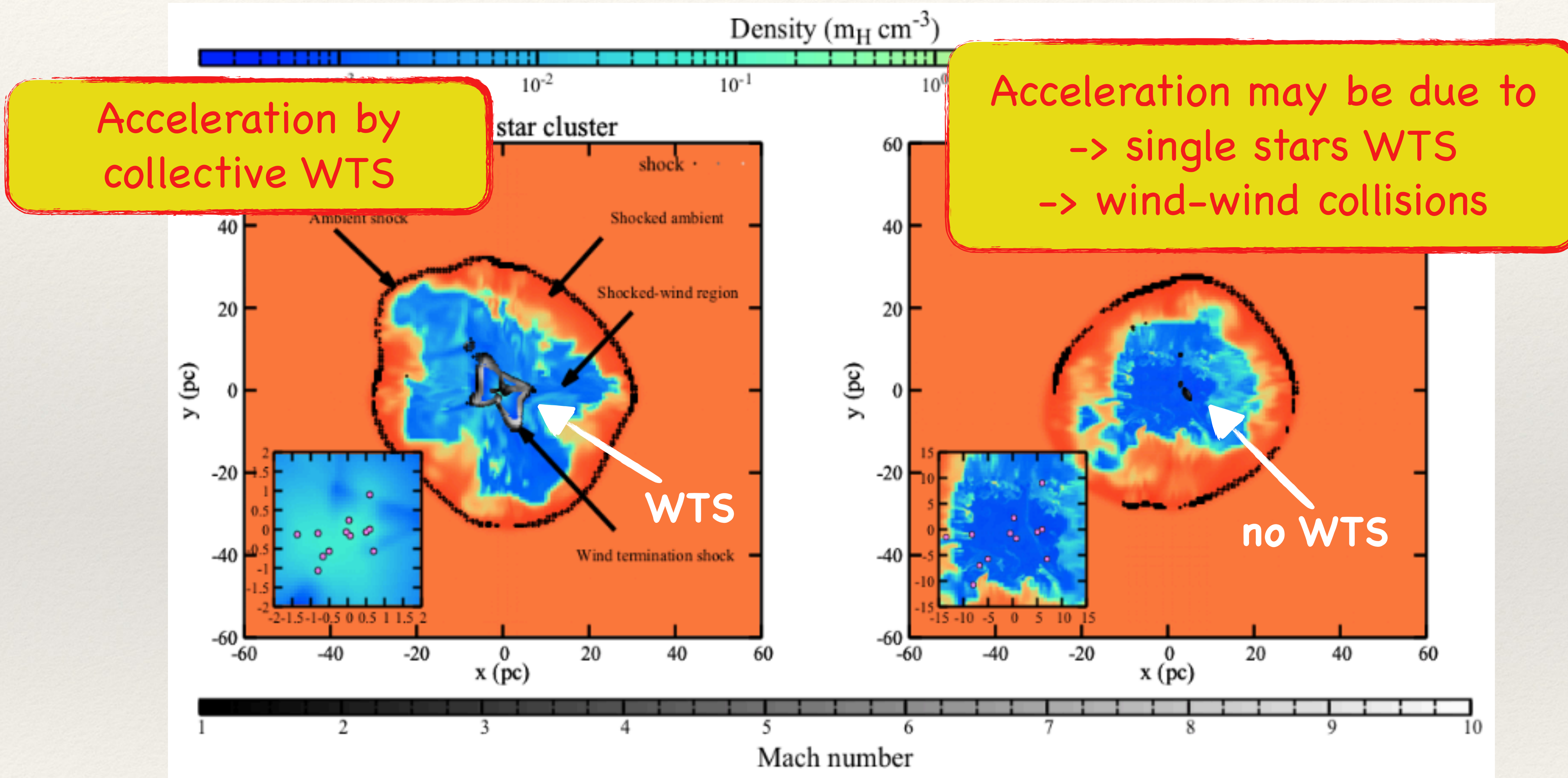

Compact cluster

Loose cluster

The energy problem

Cassé & Paul (1980, 1982) — Cesarsky & Montmerle (1983)

Stellar wind are radiation drive

$$\dot{M}_{\rm wind} u_{\rm wind} \approx \eta \frac{L_\star}{c} \propto M_\star^3$$

Momentum carried by the wind

Momentum carried by starlight

Total wind power dominated by most massive stars

$$u_{\rm wind} \propto M_\star^{1/2}$$

$$P_{\rm wind} = \frac{1}{2} \dot{M}_{\rm wind} u_{\rm wind}^2 \propto M_\star^4$$

For the most massive stars:

$$\int P_{\rm wind}\, dt \simeq 10^{51}\, {\rm erg} \sim E_{\rm SN}$$

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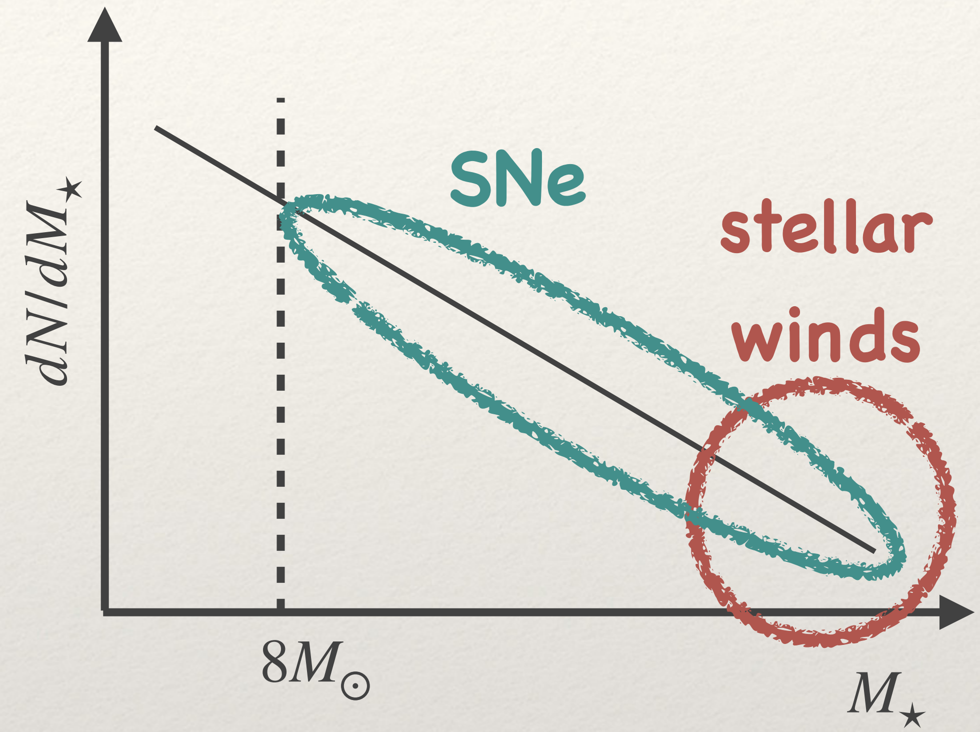
Very steep mass-luminosity scaling



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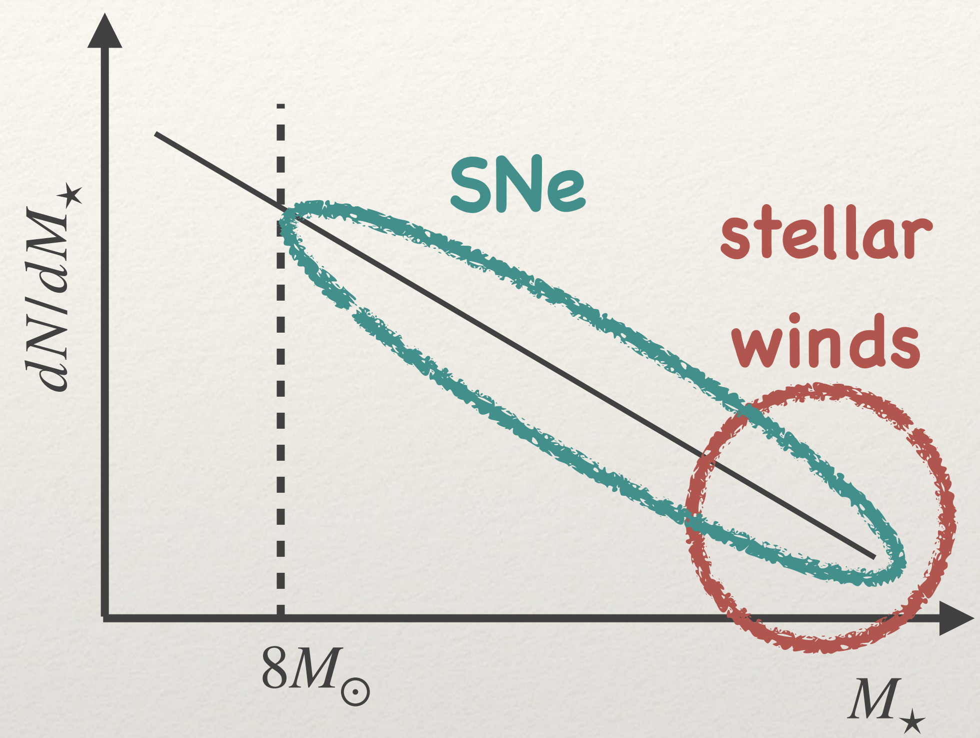

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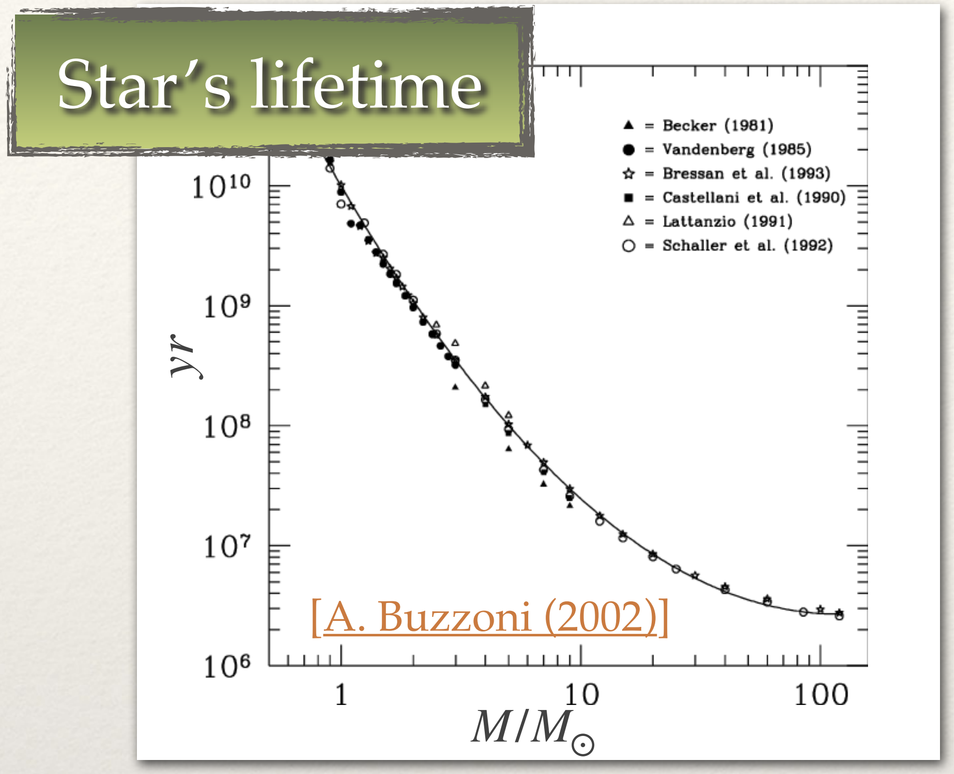
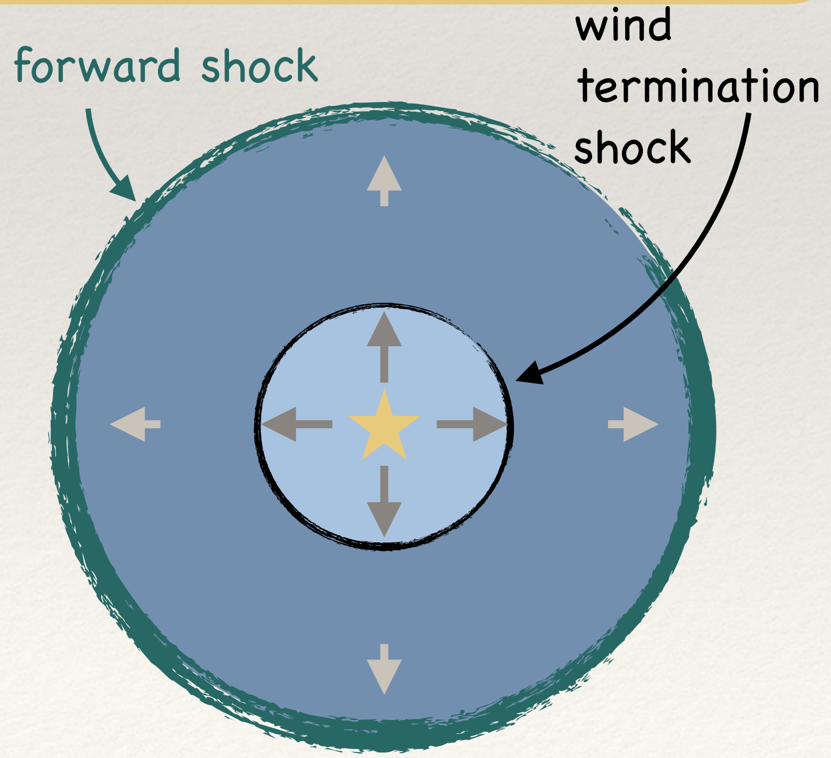
- Supernovae win by a factor ~ 10 [Caveat: failed supernovae]
- Stellar winds may be subdominant but dominate the maximum energies

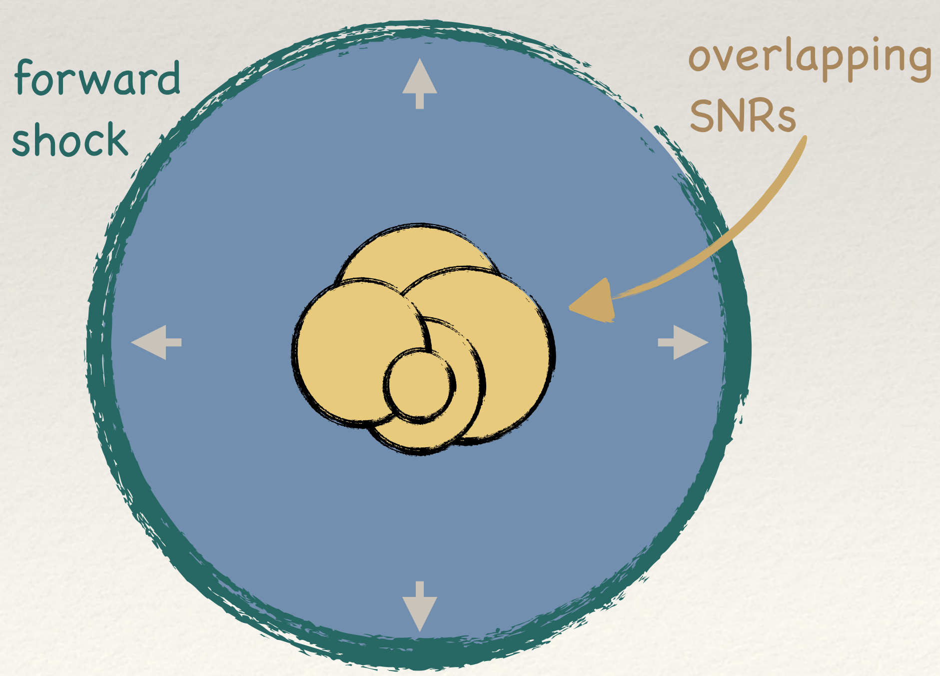
Young vs. old clusters



$t \lesssim 3\,\mathrm{Myr}$ only stellar wind

$t \gtrsim 3\,\mathrm{Myr}$ stellar wind + SNe





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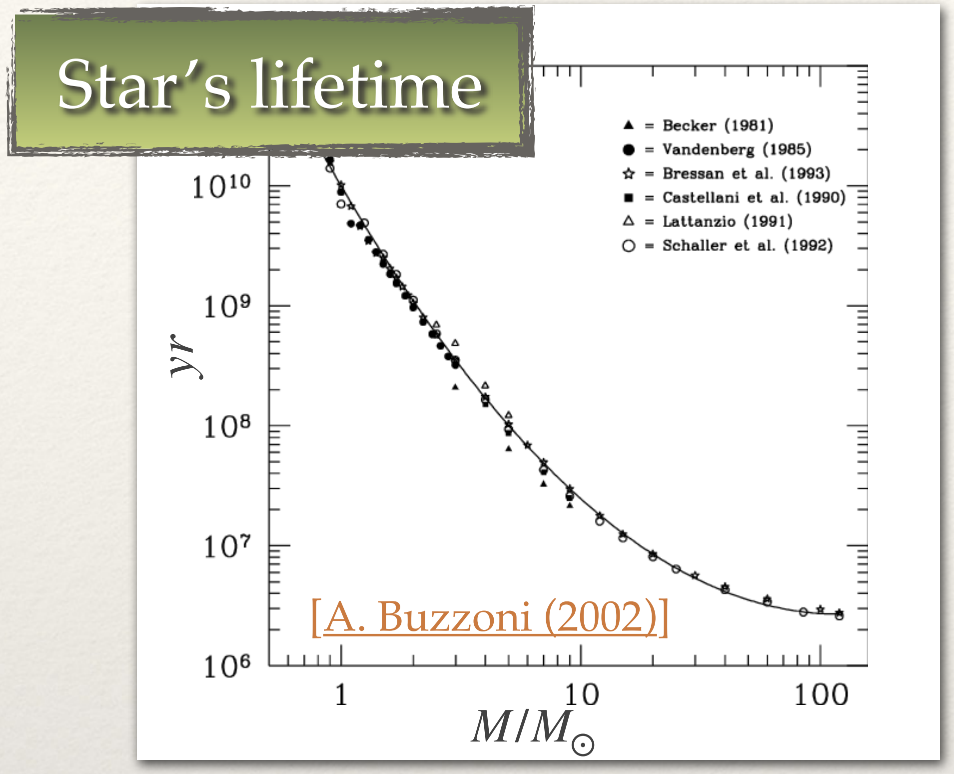

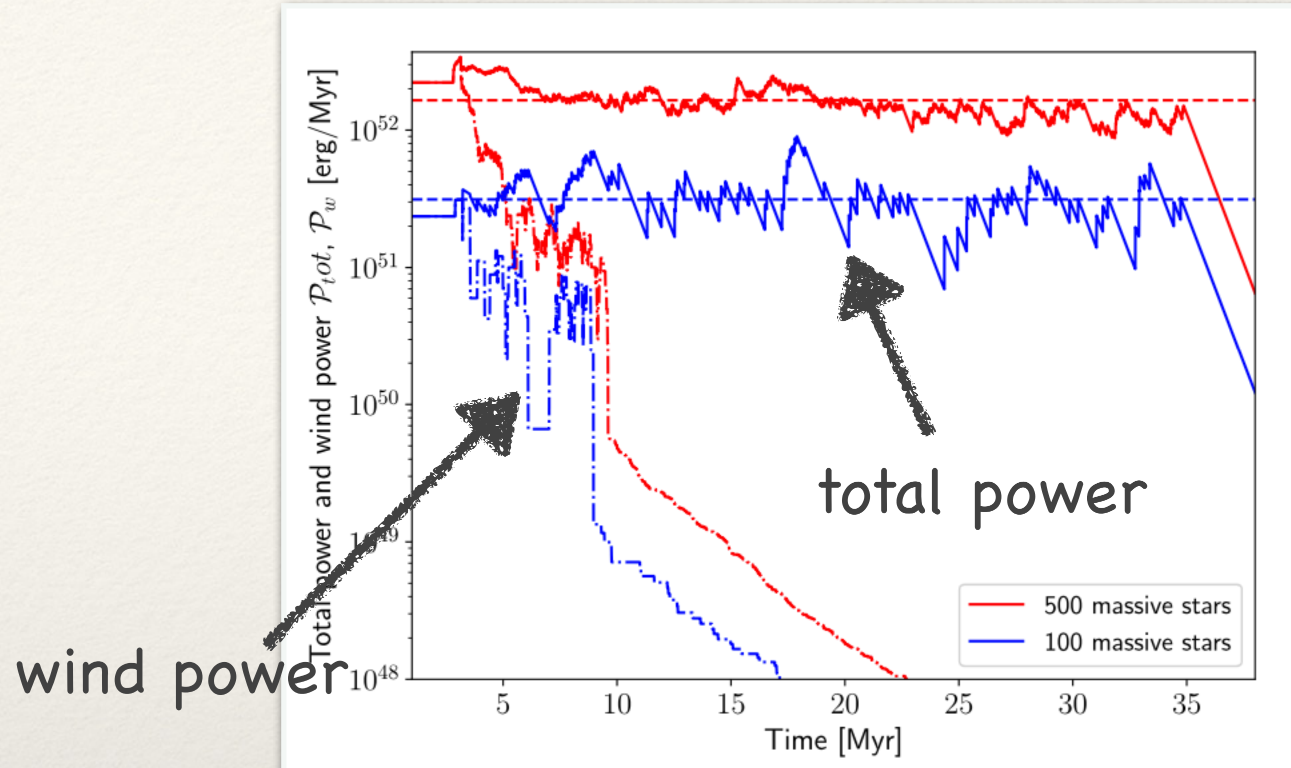

Vieu et al. (2022)

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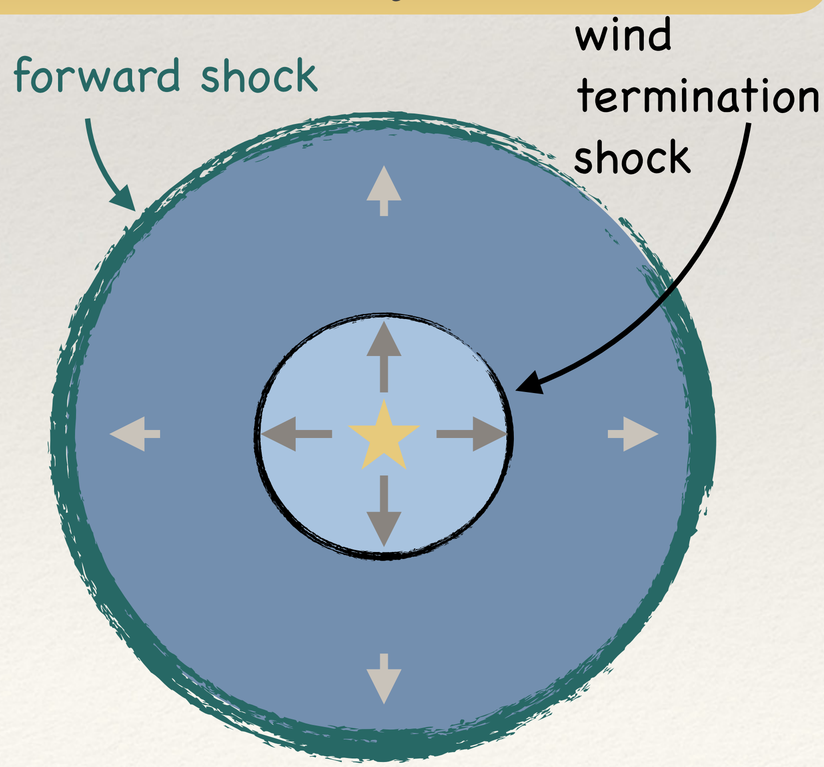
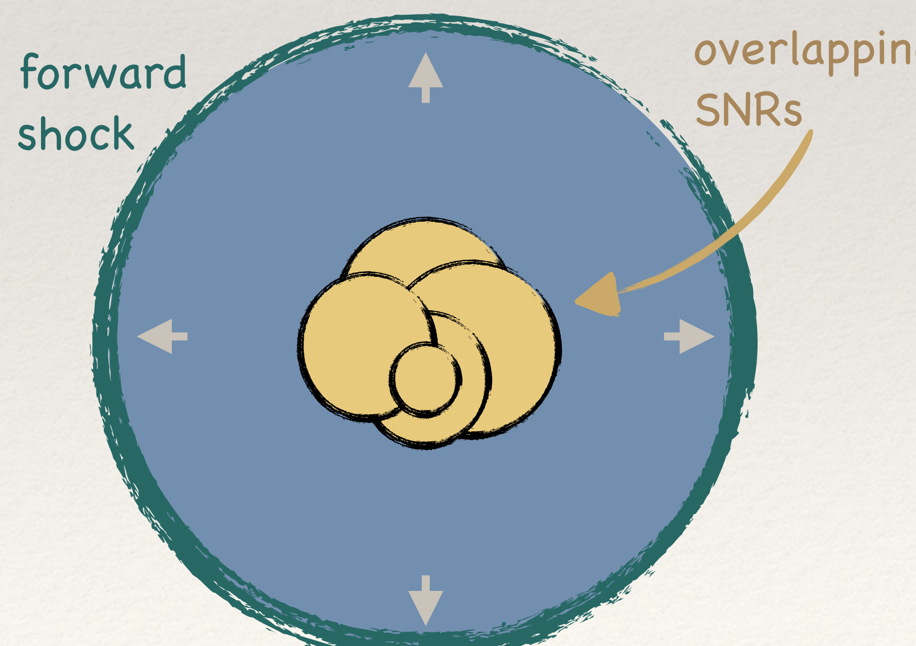
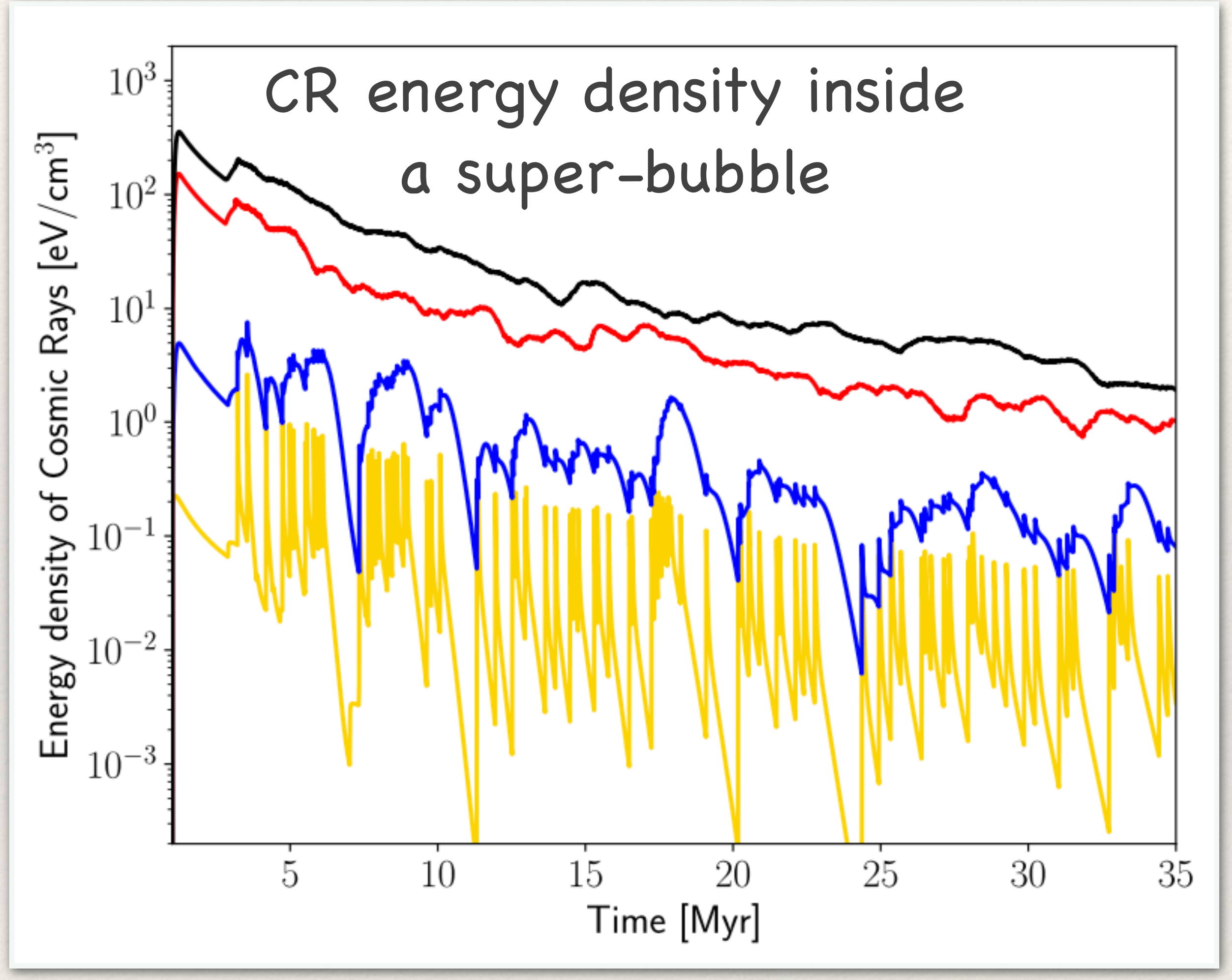




Particle acceleration in super-bubbles: intermittency

Vieu et al. (2022): consider acceleration at WTS + SNR forward shock + turbulent acceleration



$N_\star = 1000$

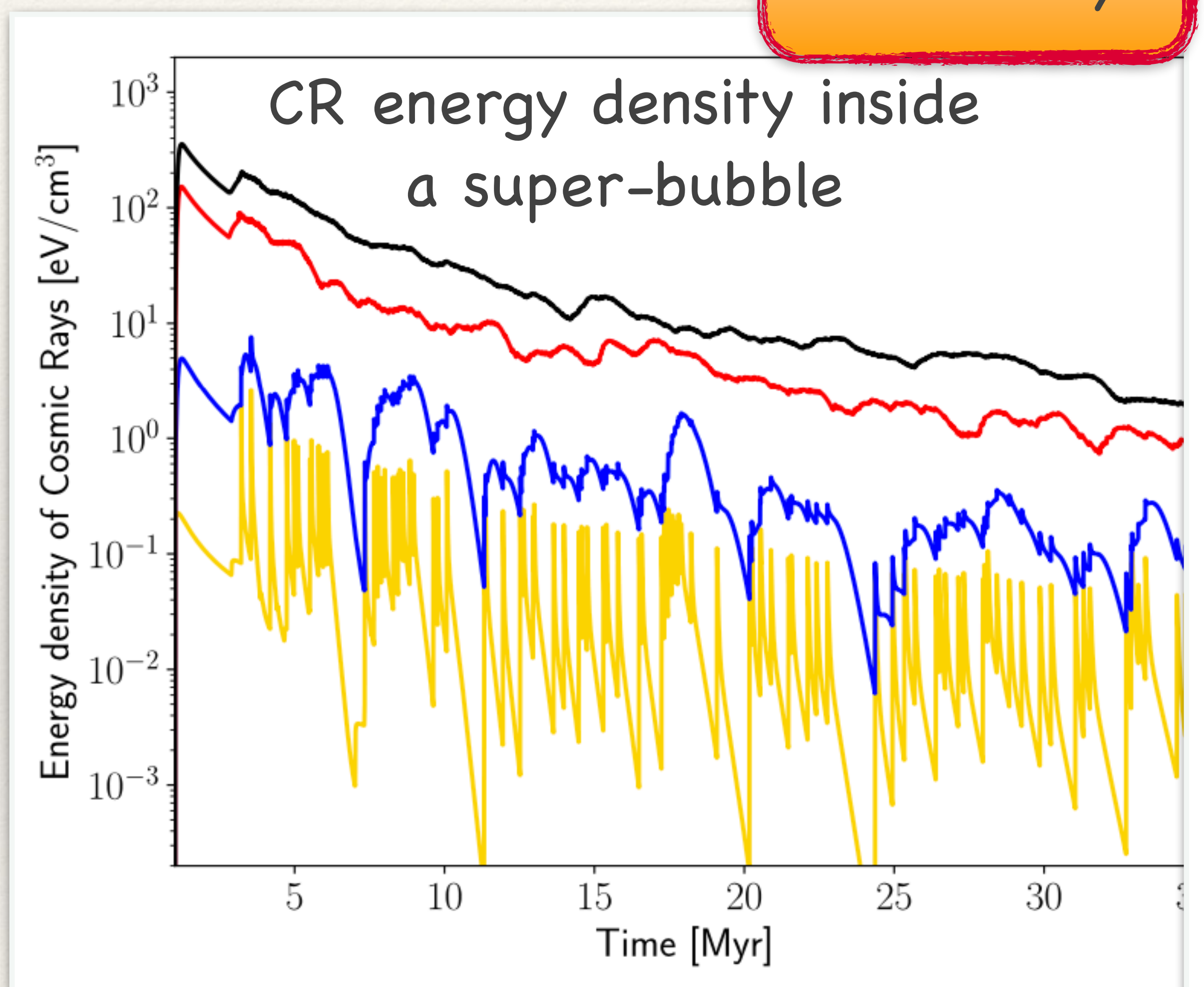
$N_\star = 500$

$N_\star = 100$

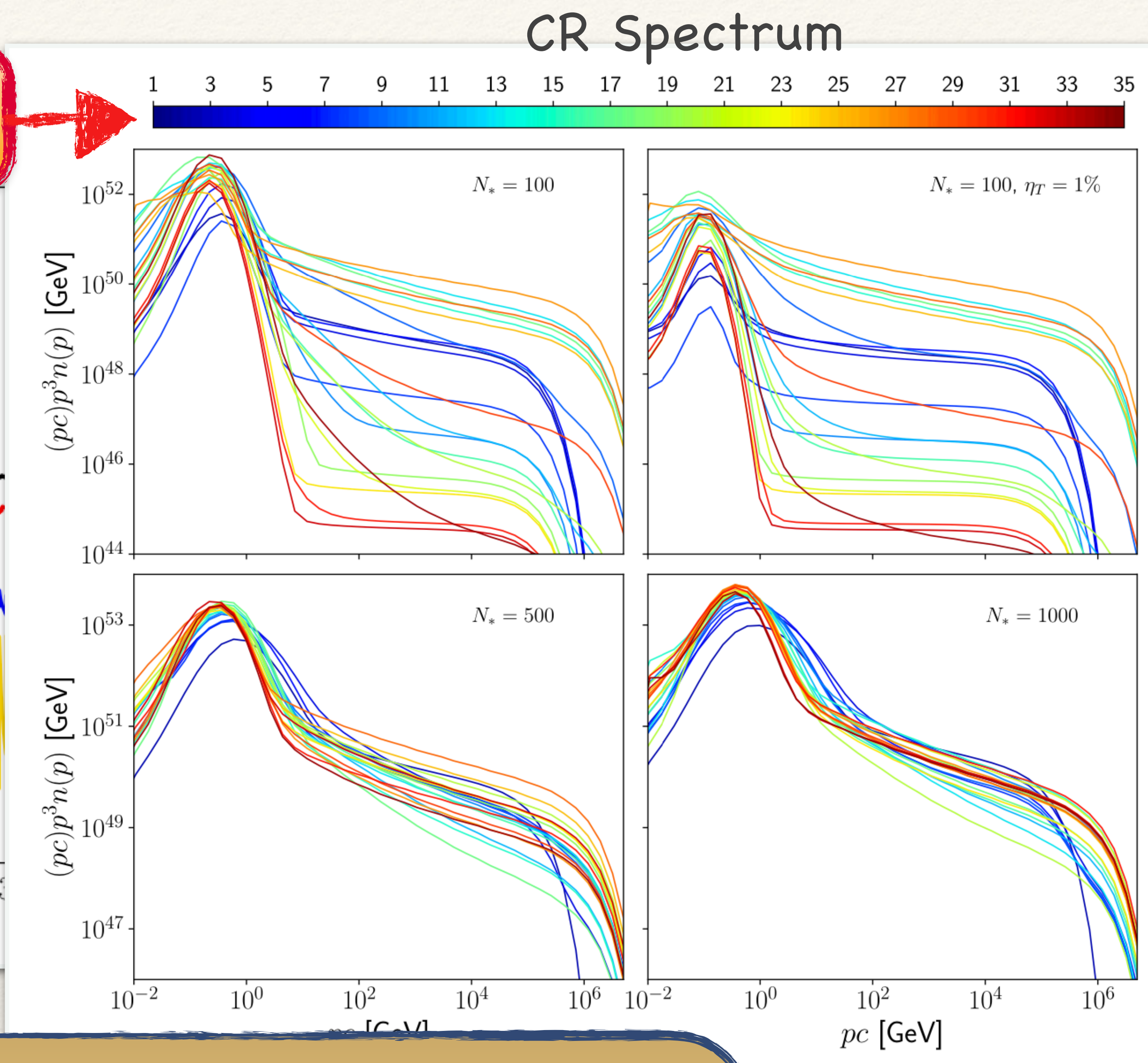
$N_\star = 100 \quad \eta_T = 1\,\%$

Particle acceleration in super-bubbles: intermittency

Vieu et al. (2022): consider acceleration at WTS + SNR forward shock + turbulent acceleration



Time in Myr



- Energetically Superbubble may produce the bulk of CRs
- The spectrum is not universal -> strong intermittency

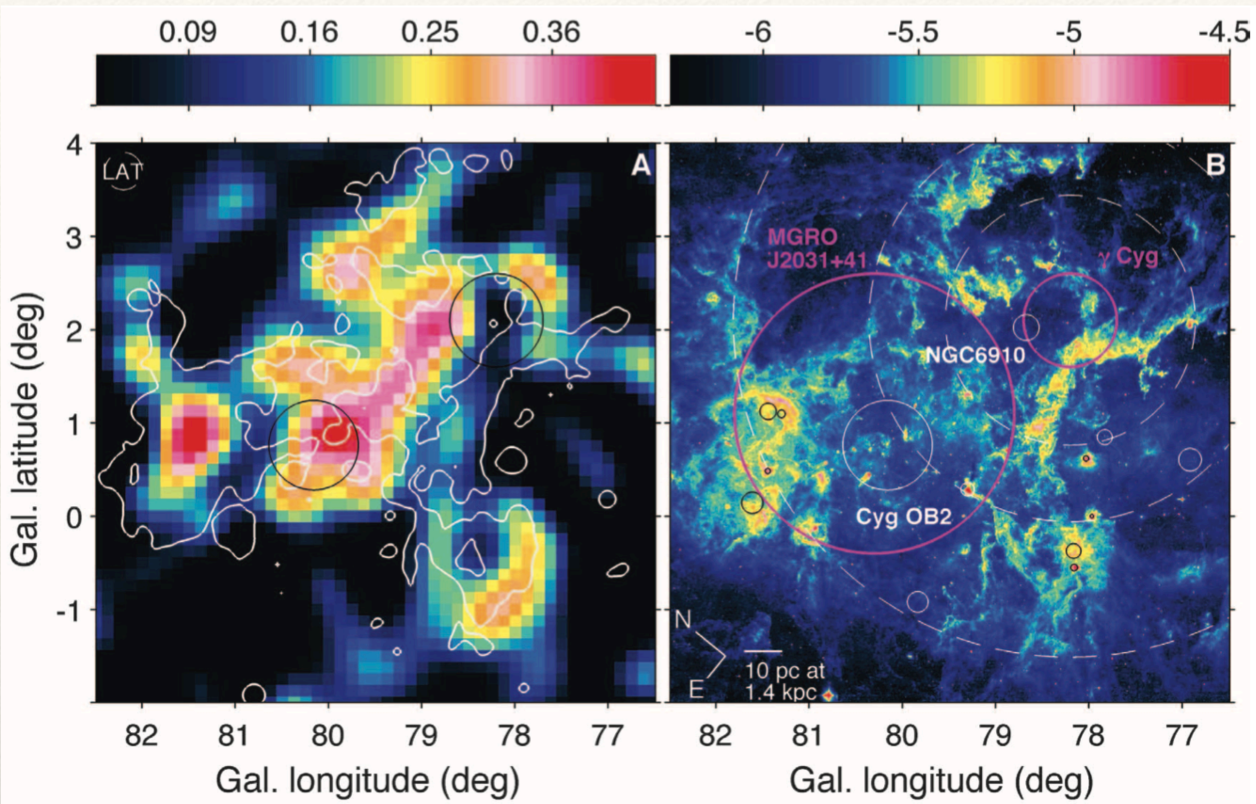
YSCs detected in gamma-rays

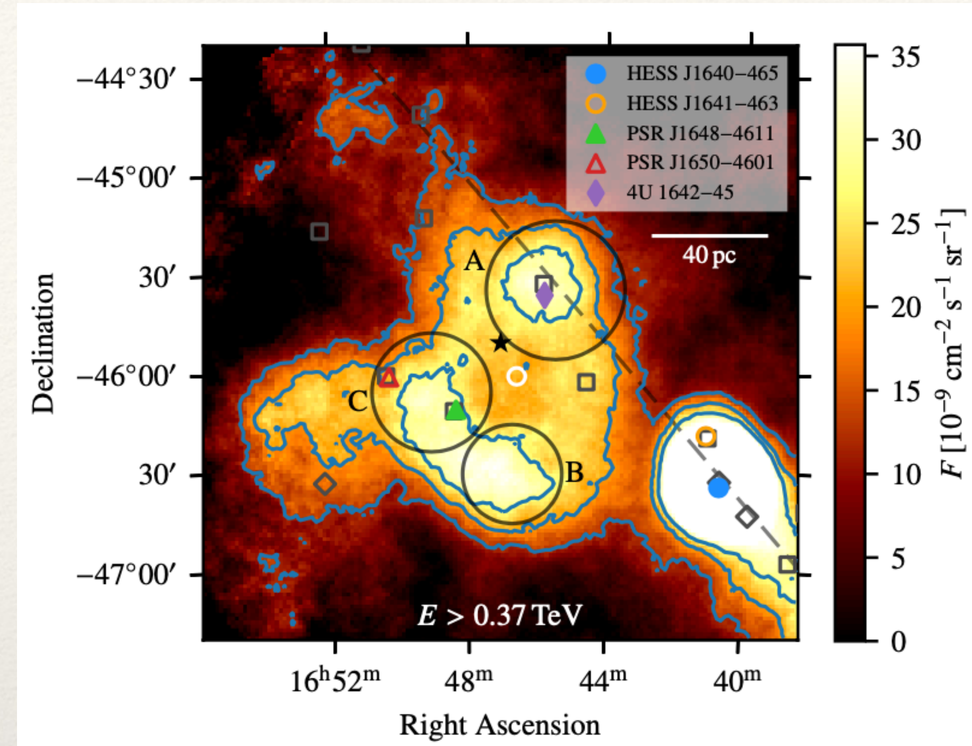
Recently several massive star clusters have been associated with gamma-ray sources

Name	log M/M_{sun}	r_c/pc	D/kpc	age/Myr	L_w/ 10^{38} erg s^{-1}	Reference
Westerlund 1	4.6 ± 0.045	1.5	4	4-6	10	Abramowski A., et al., 2012, A&A, 537, A114
Westerlund 2	4.56 ±0.035	1.1	2.8 ± 0.4	1.5-2.5	2	Yang, de Oña Wilhelmi, Aharonian, 2018, A&A,
Cyg. OB2	4.7±0.3	5.2	1.4	3-6	2	Ackermann M., et al. 2011, Science, 334, 1103
NGC 3603	4.1 ± 0.10	1.1	6.9	2-3	?	Saha, L. et al 2020, ApJ, 897, 131
BDS 2003	4.39	0.2	4	1	?	Albert A., et al., 2020, arXiv:2012.15275
W40	2.5	0.44	0.44	1.5	?	Sun, X.-N. et al. 2020, A&A, 639, A80
30 Dor (LMC) NGC 2070/RCM 136	4.8-5.7 4.34-5	multiple sub-clusters	50	1 5	?	H. E. S. S. Collaboration et al., 2015, Science, 347, 406

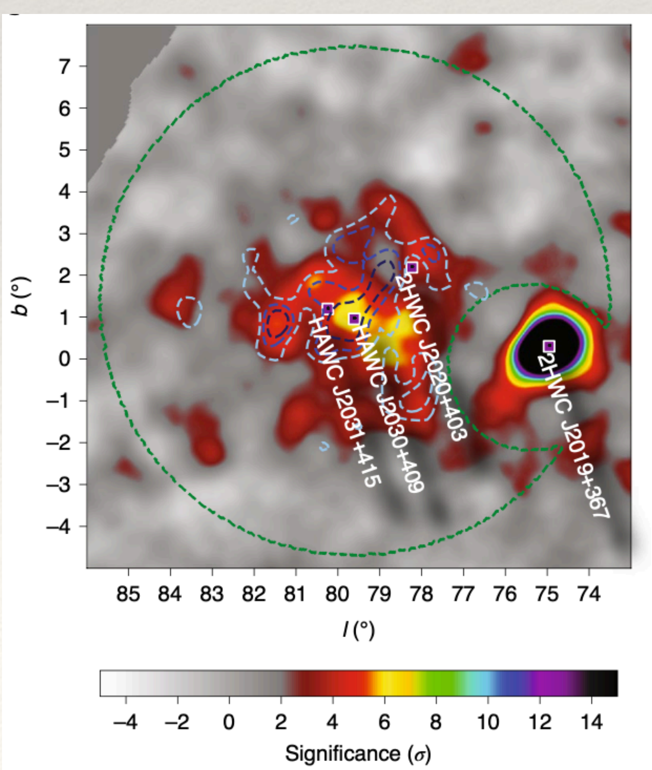
YSCs detected in gamma-rays

Cygnus Cocoon FermiLAT - Ackermann et al. (2011)



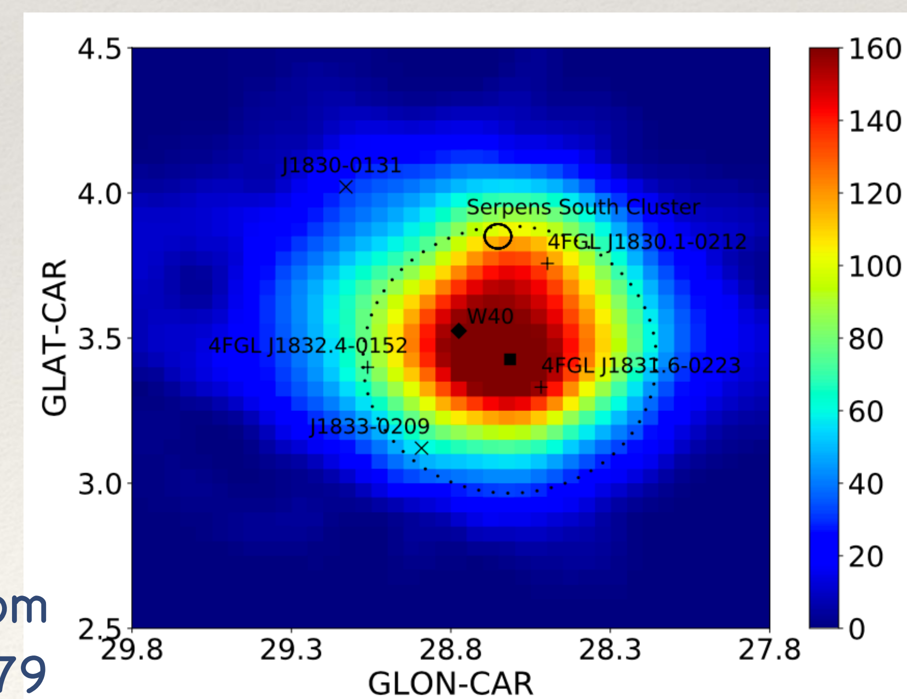


Westerlund 1
HESS coll. A&A (2022)



Cygnus Cocoon
HAWC coll. Nat. Astr.(2020)

W40 - FermiLAT data from
Sun et al. (2020) arxiv:2006.00879

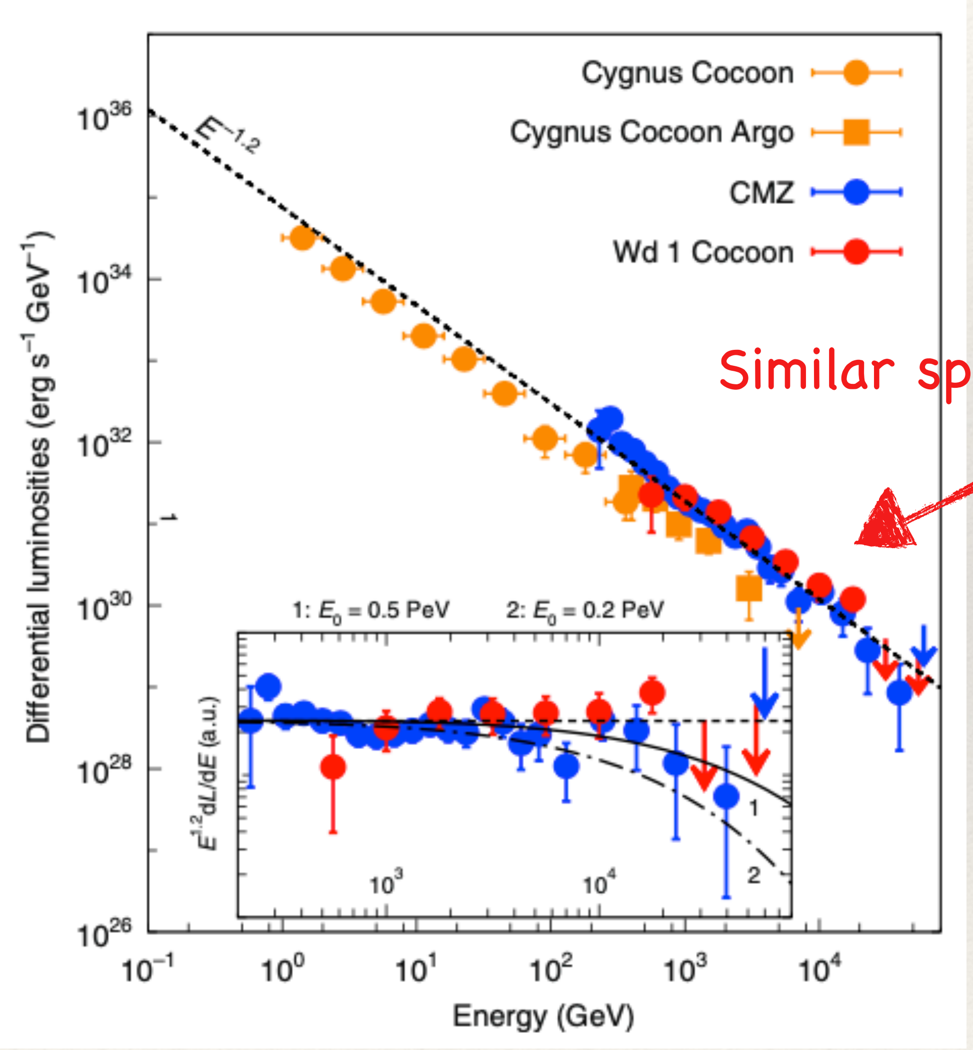


YSCs detected in gamma-rays

[Aharonian, Yang & Wilhelmi, Nat. Astr. (2019)]

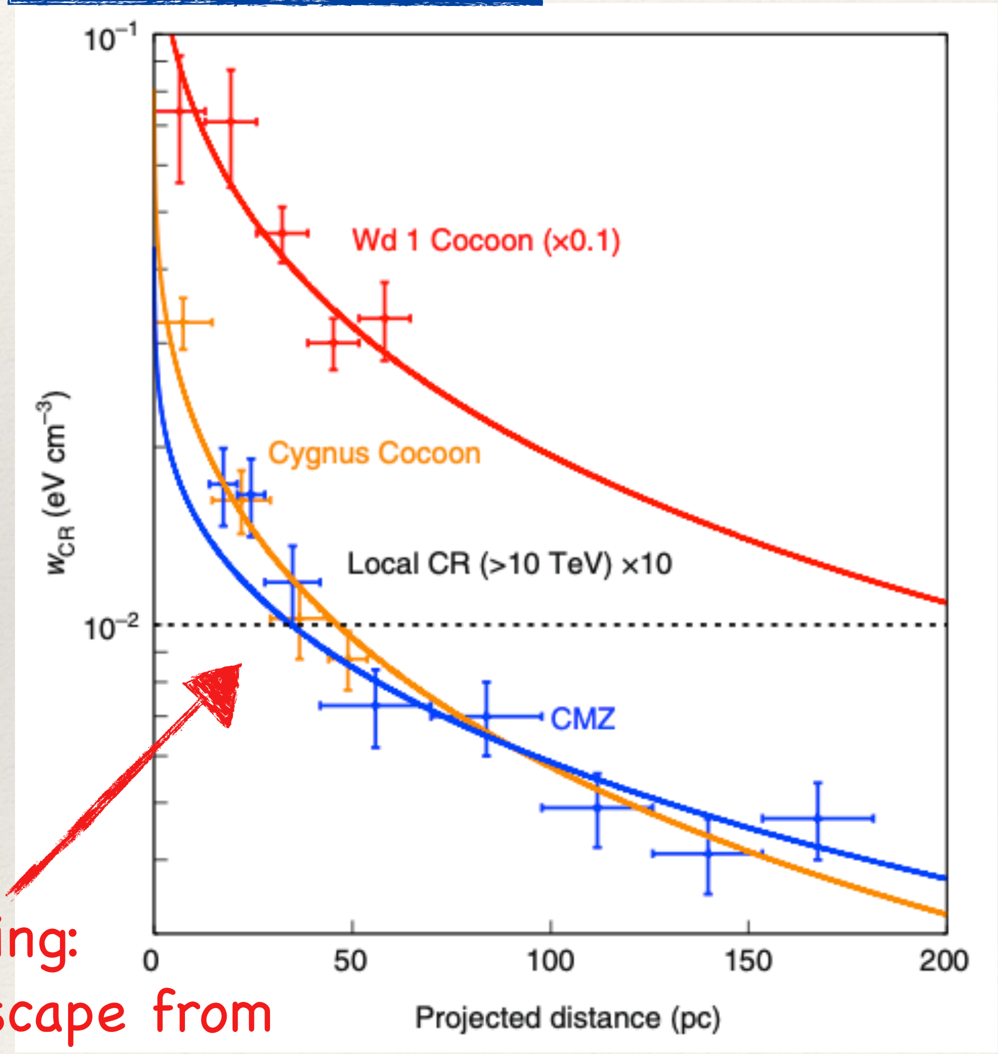
Some clusters show similar spectra and radial profile

Spectrum



Similar spectra $\sim E^{-2.2}$

Radial CR profile



1/r scaling:
CR diffusive escape from continuous point source?

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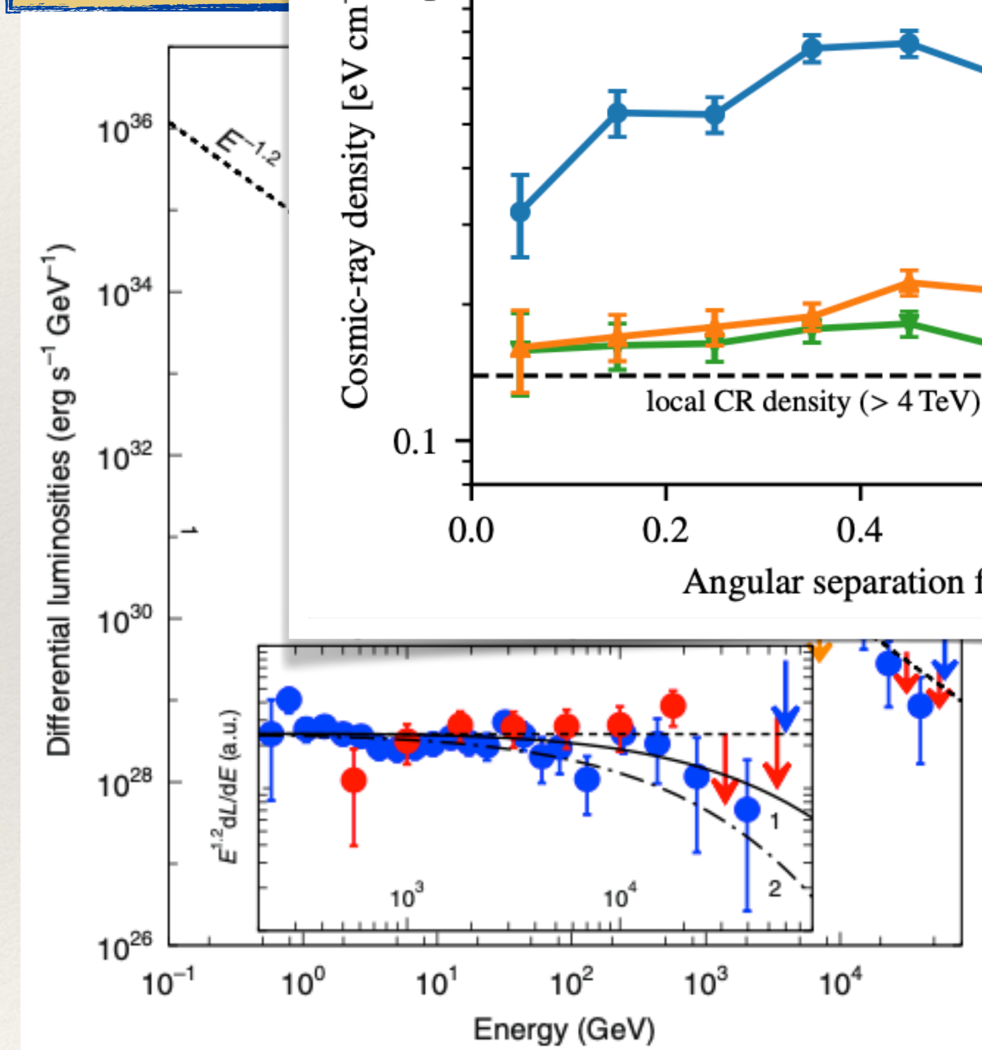

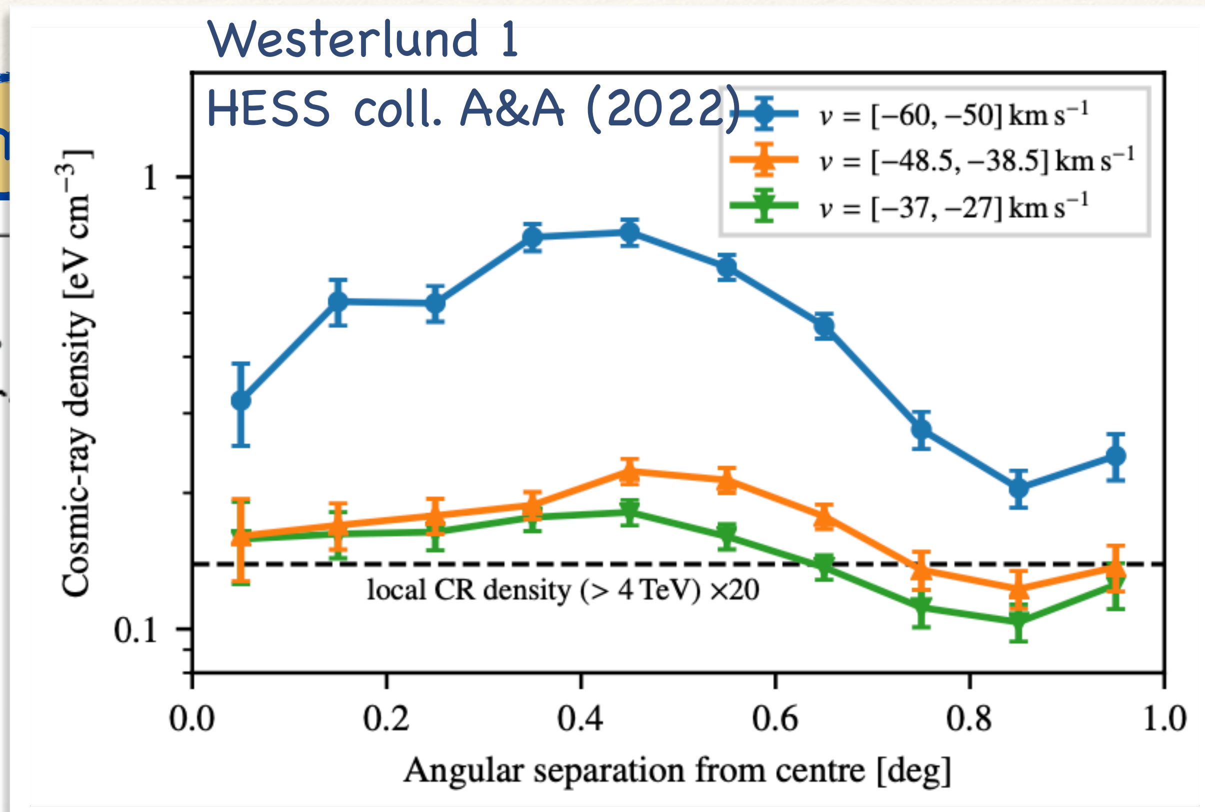

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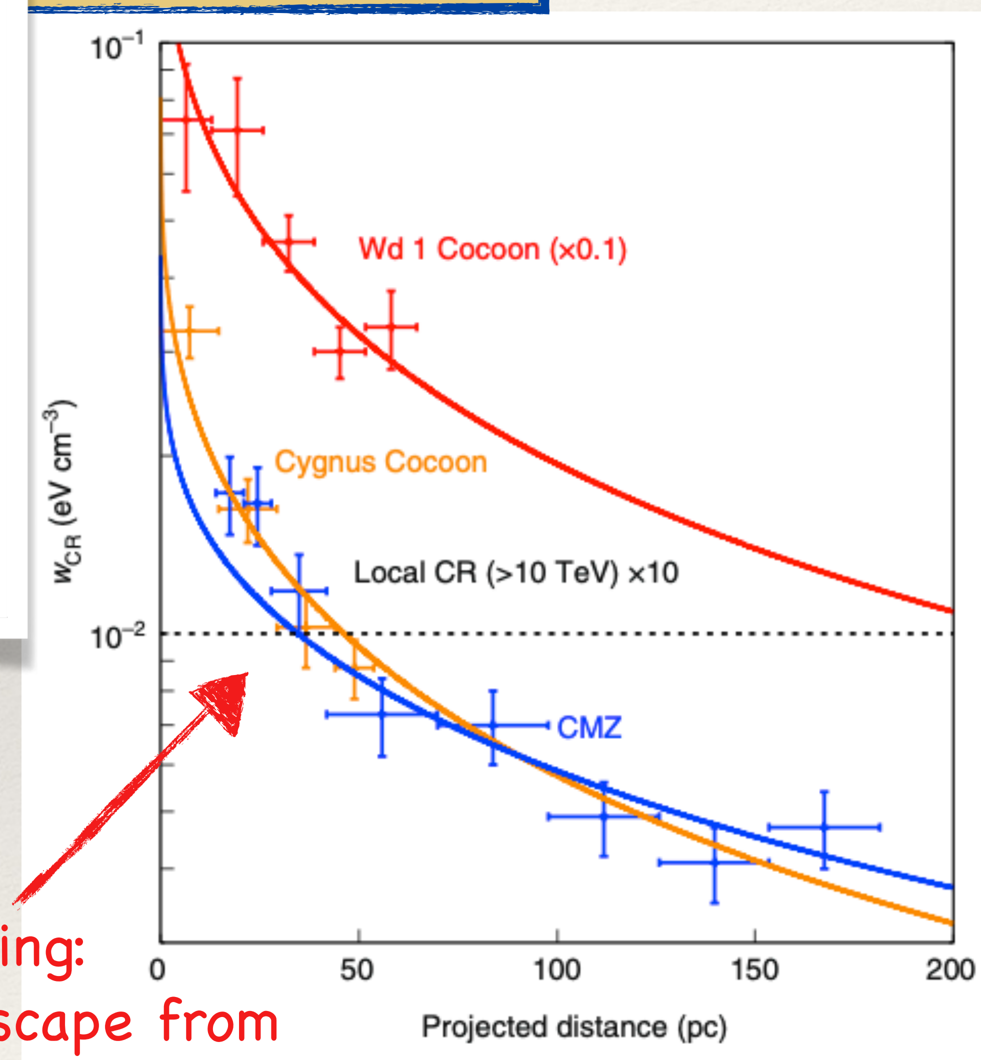

1/r scaling:
CR diffusive escape from
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Possible role of YSC in the Galactic Center

[H.E.S.S. coll., Abramowski et al. Nat. 531 (2016)]

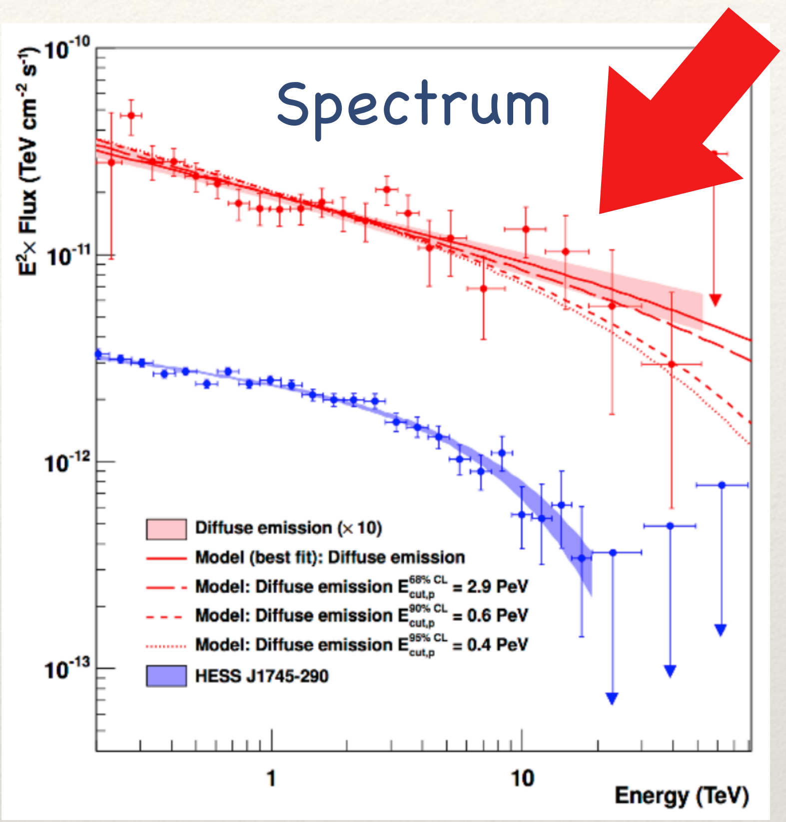
The Galactic Centre has been recognised as a PeVatron

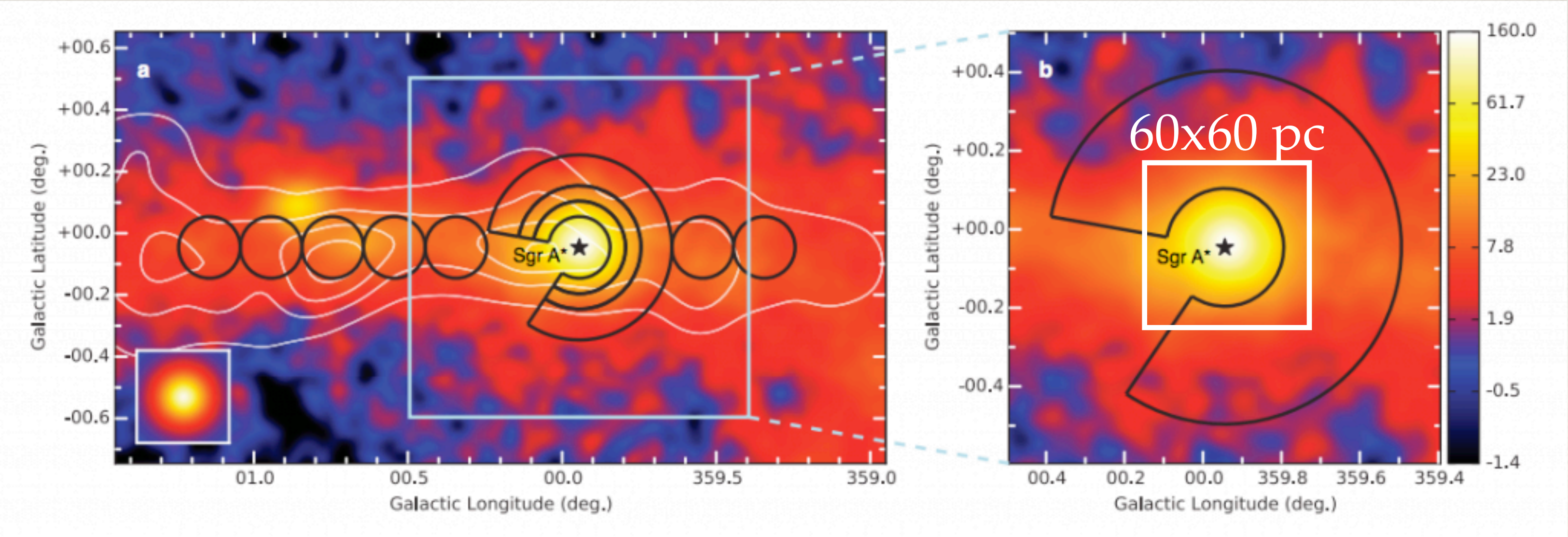
- Minimum proton energy > 0.4 PeV
- Spatial profile compatible with continuous emission

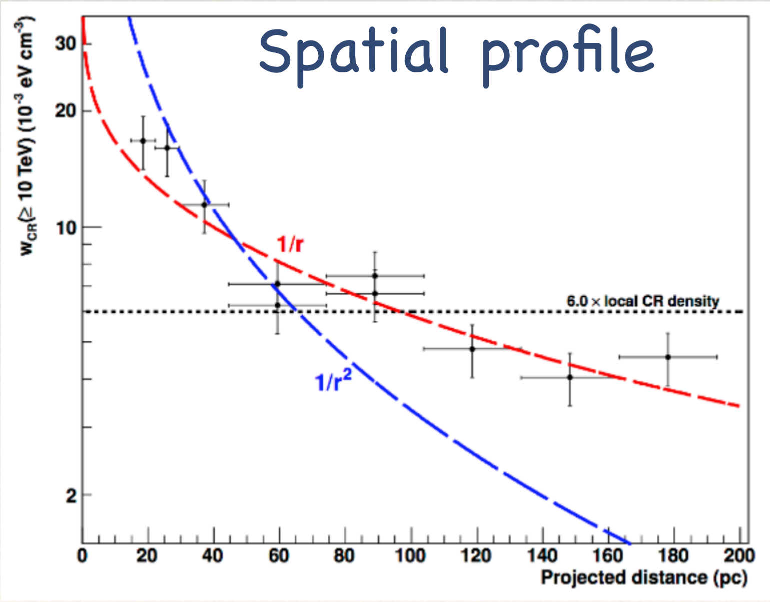
  ➡ SNR disfavoured

- CR luminosity: $L_{\rm CR}(>10\,{\rm TeV}) = 4\times10^{37}\left({\rm D}/10^{30}\,{\rm cm}^2{\rm s}^{-1}\right)$ erg/s
(could be supplied by a powerful cluster wind if diffusion is suppressed)

- Stellar clusters in the GC region:
  - Arches (~30 pc from Sgr A*, Mass~$10^4 M_\odot$, age ~ 2.5 Myr)
  - Quintuplet (~30 pc from Sgr A*, Mass~$10^4 M_\odot$, age ~ 4 Myr)
  - Central cluster (~200 young stars at $r \lesssim 1$ pc from Sgr A* including ~30 WR stars) [e.g. von Fellenberg et al. (2022) and Poumard T. (2008)]

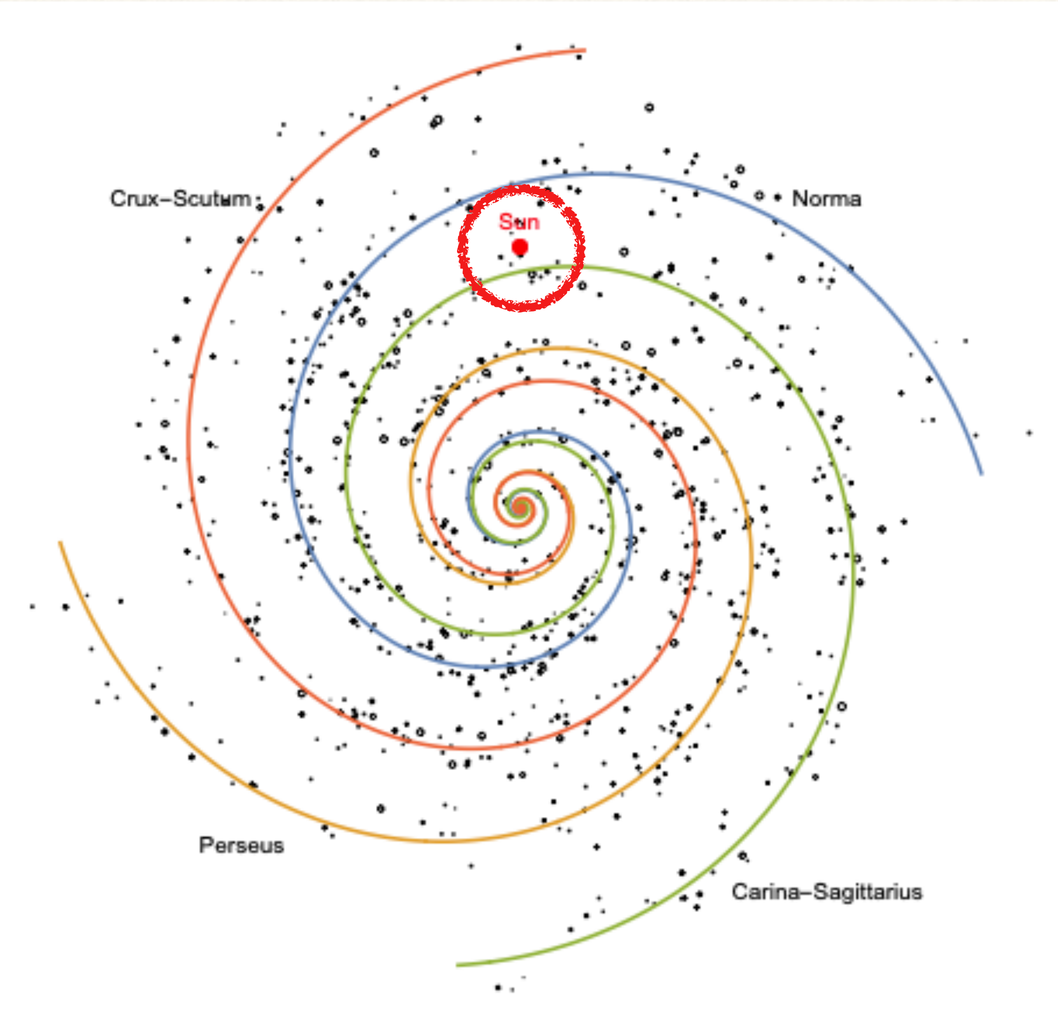






How many Star Clusters?

Synthetic realisation of Stellar cluster population



- *Age < 10 Myr*
- $100\ M_\odot < \mathrm{Mass} < 6 \times 10^4\ M_\odot$

- total number of SC in the Galaxy ≈ 1000
- SCs within 2 kpc from the Sun $\simeq 70$

Present number of clusters detected in gamma-rays ~ 10

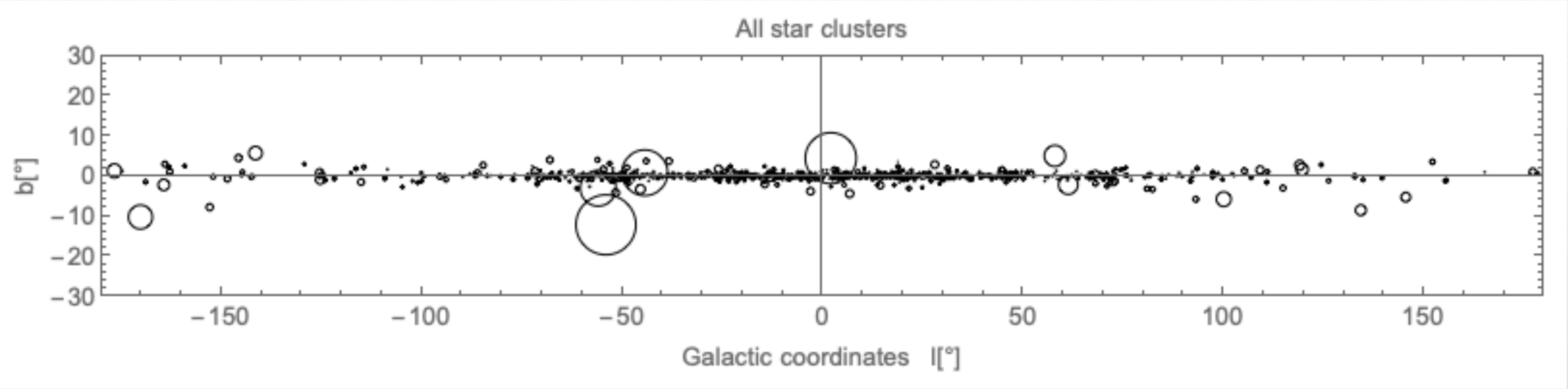
Bubble size ~ degree ⇒ diffuse sources with low surface brightness ⇒ difficult to detect

$$R_{bubble} \simeq 2.9^\circ \left(\frac{L_w}{2\times 10^{38}\,\mathrm{erg/s}}\right)^{1/5} \left(\frac{n_0}{10\,\mathrm{cm}^{-3}}\right)^{-1/5} \left(\frac{t_{age}}{1\,\mathrm{Myr}}\right)^{3/5} \left(\frac{d}{2\,\mathrm{kpc}}\right)$$

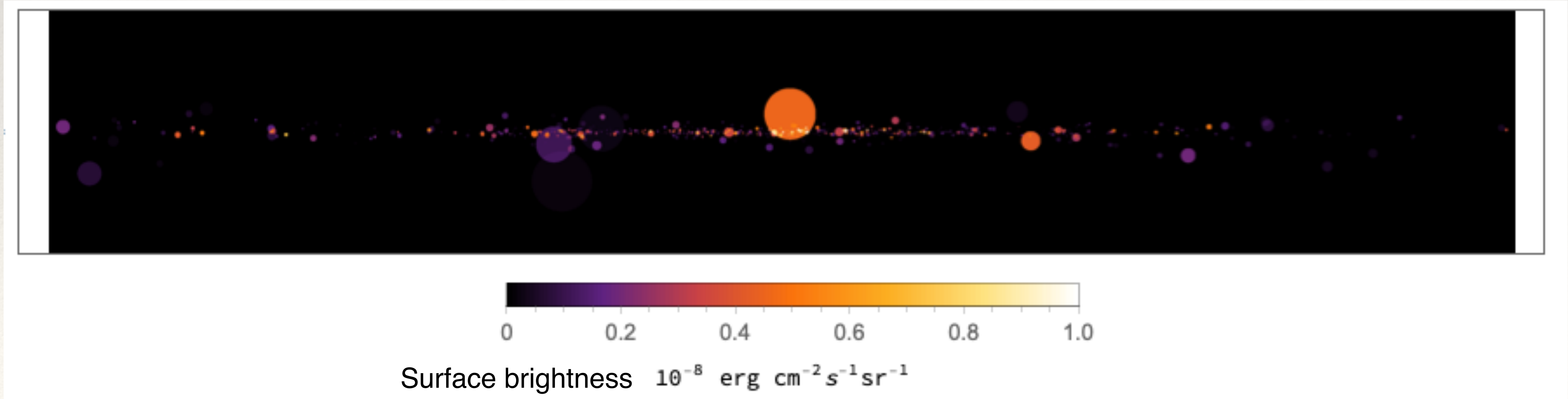
Weaver & McCray, ApJ 218 (1977)

How many Star Clusters?

Bubble size in the sky from the entire population of SC in galactic coordinates:



Some bubbles disappear when plotted against their surface brightness



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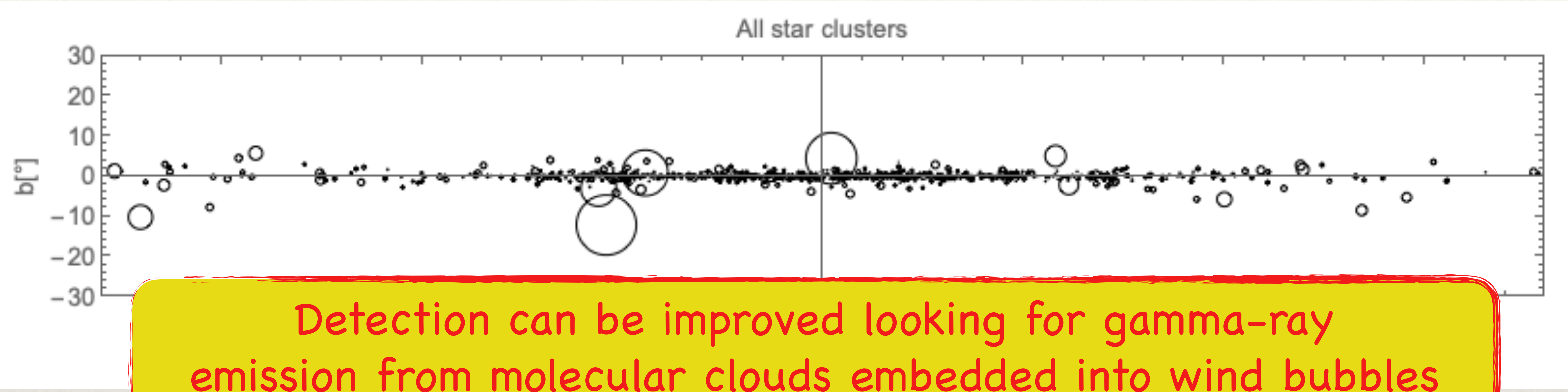
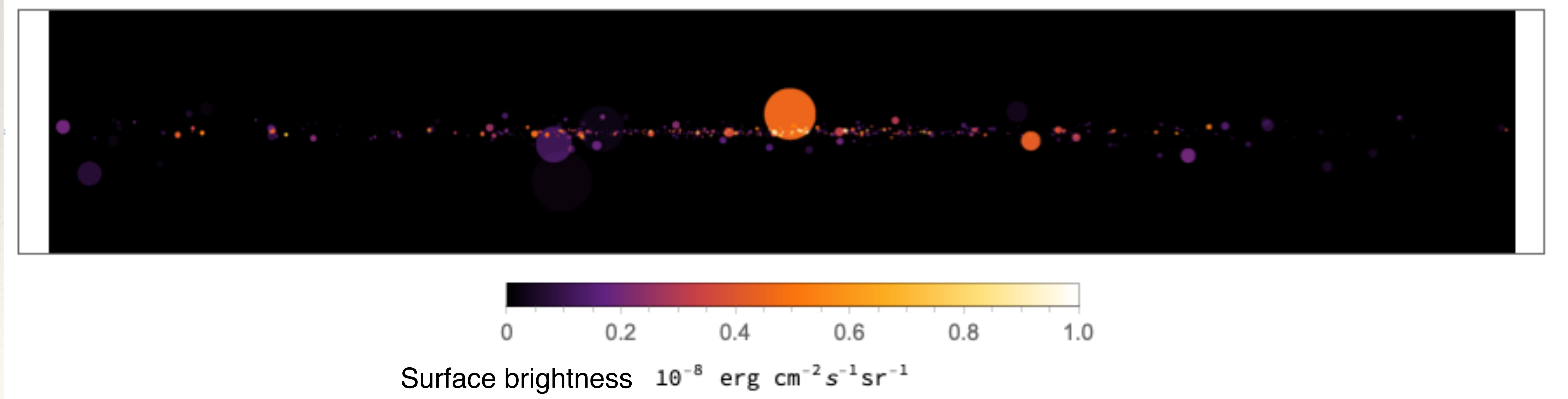


Detection can be improved looking for gamma-ray emission from molecular clouds embedded into wind bubbles

Some bubbles disappear when plotted against their surface brightness



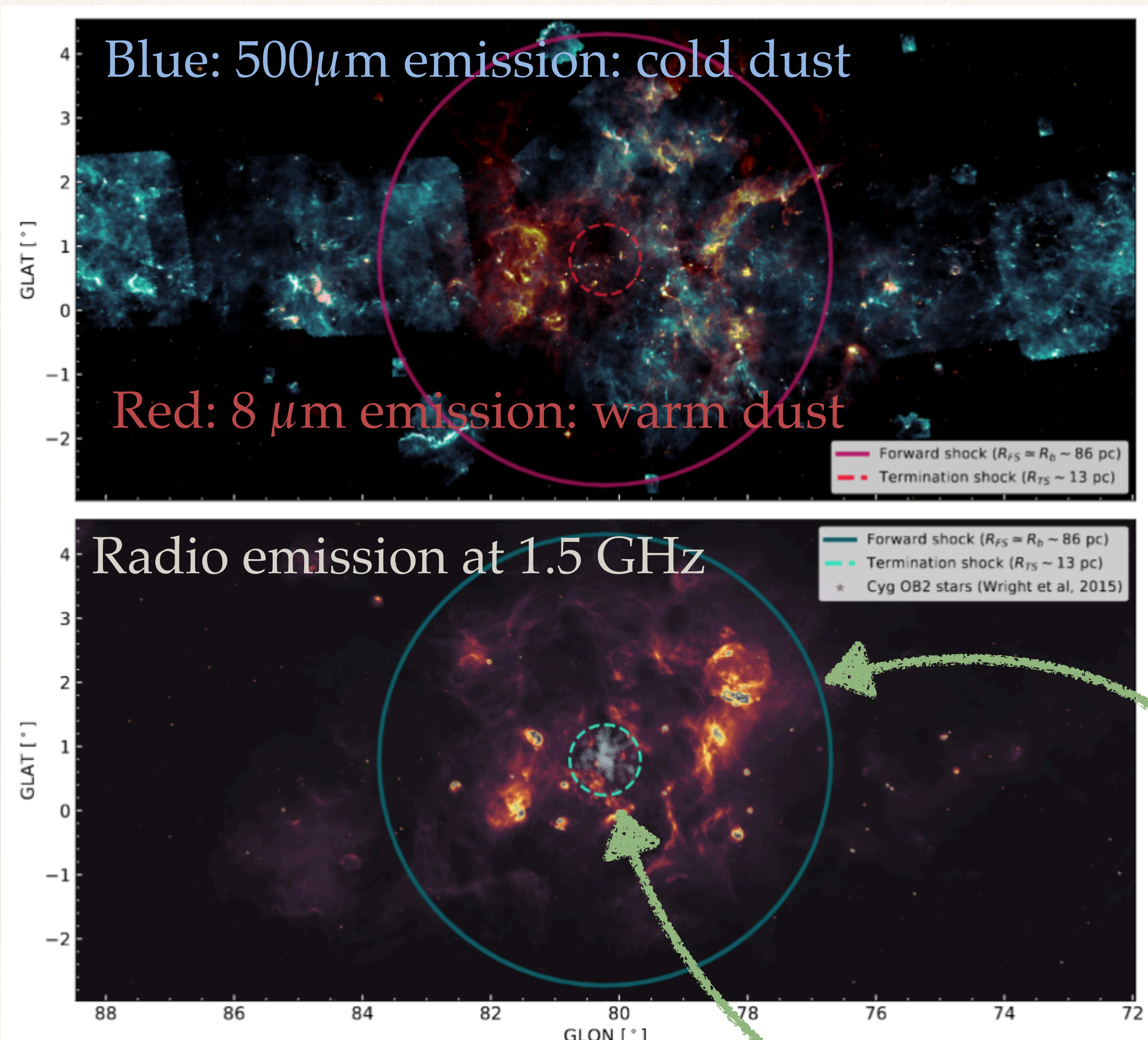
Conclusions

- Young stellar clusters are promising gamma ray sources
- YSC can significantly contribute to Galactic CRs
- Maximum energies can reach ~PeV (but strong dependence on diffusion)
- Super-bubbles (= older SCs with stellar winds+ SNRs) may be the major contributors of Galactic CRs (but theoretical models still incomplete)
- Next generation IACT will probably detect many new stellar clusters (~several tens) (but extended sources with low surface brightness)
- Observational strategy: look for gamma-ray emission from molecular clouds close to stellar clusters

Backup slides

The case of Cygnus Cocoon

[S. Menchiari et al. in preparation]



Assumed properties

- Wind luminosity $\simeq 2 \times 10^{38}\, \mathrm{erg\, s^{-1}}$
- Ejecta mass $\dot{M} \simeq 10^{-4} M_{\odot}\, \mathrm{yr}^{-1}$;
- wind speed $v_w \simeq 2300\, \mathrm{km s}^{-1}$
- Cluster age $\simeq 3$ Myr
- Average ISM density $\simeq 10\, \mathrm{cm}^{-3}$

Estimated size of the bubble $\simeq$ 90 pc

Termination shock radius $\simeq$ 13 pc

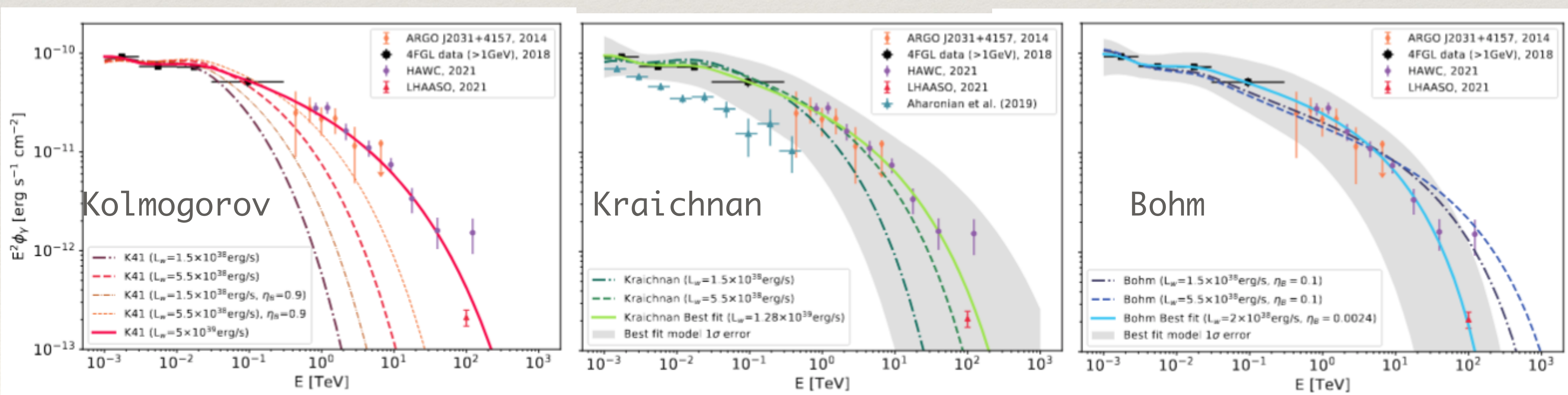
The case of Cygnus Cocoon

[S. Menchiari et al. in preparation]

Model	Kolmogorov	Kraichnan	Bohm
Wind luminosity	5×10^{39} erg s^{-1}	1.3×10^{39} erg s^{-1}	2×10^{37} erg s^{-1}
Acc. efficiency	0.4%	0.7%	13%
Slope	4.17	4.23	4.27
E_{max}	23 PeV	4 PeV	0.5 PeV

Unrealistically high

The most realistic scenario is something in between Bohm and Kraichnan



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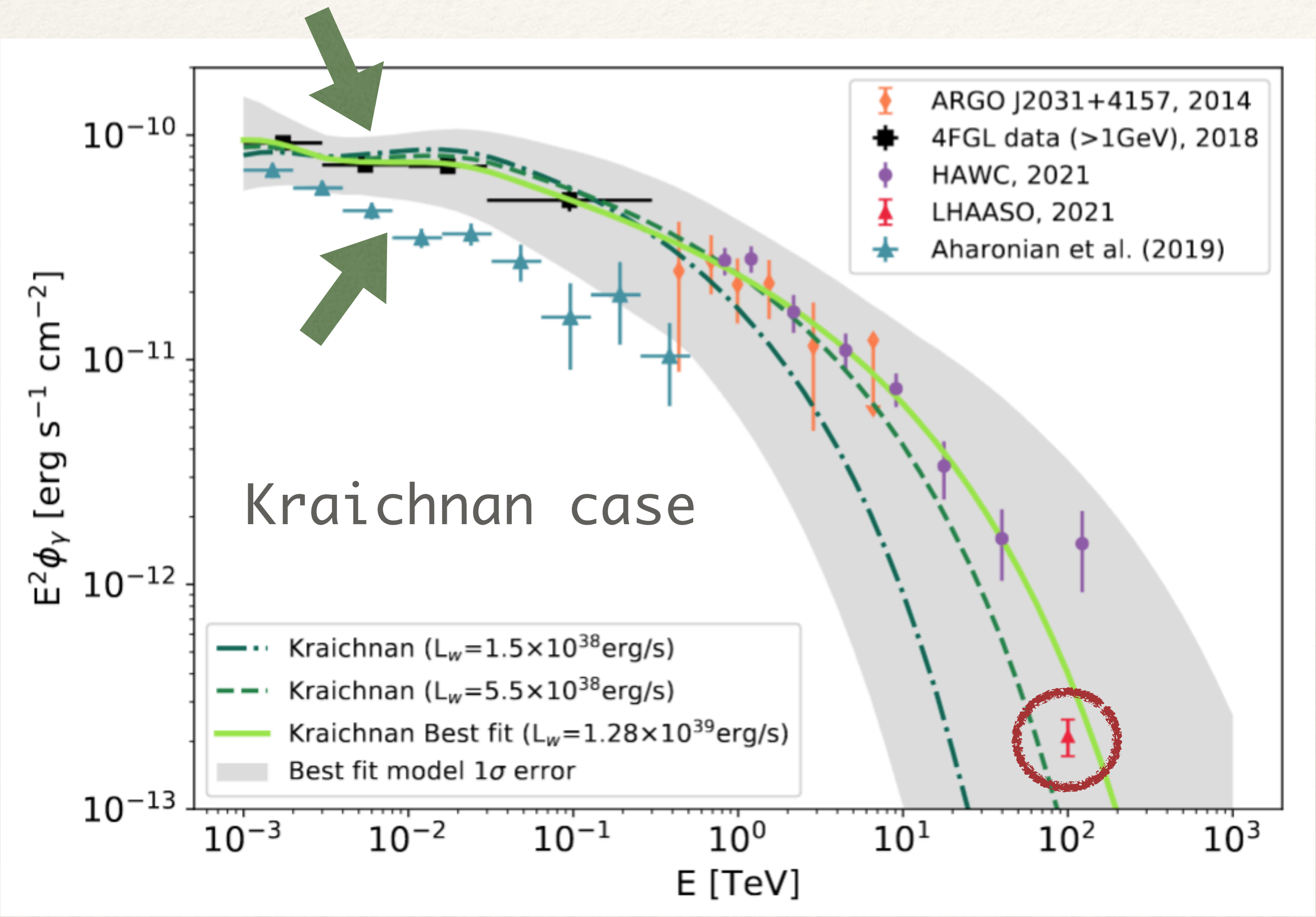


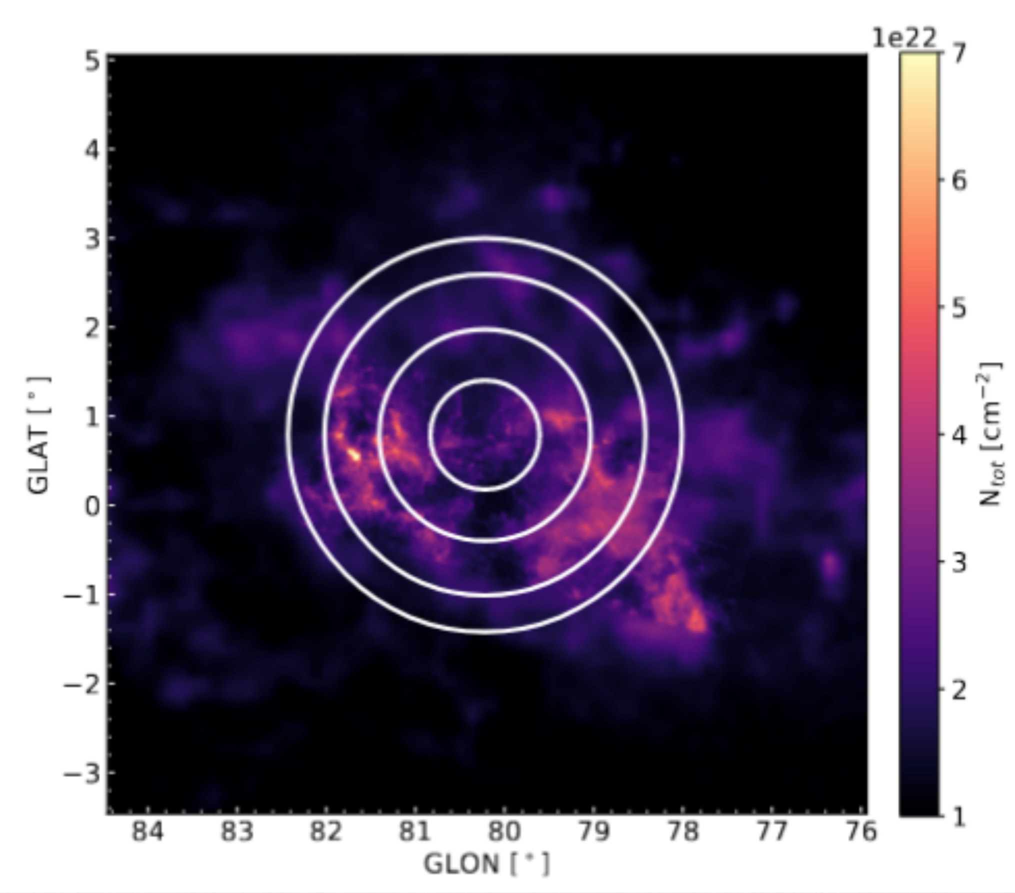
Some caveats:

- Different analysis of Fermi-LAT data gives different results
- In comparing different experiments we need to correctly account for the different extraction area
- LHAASO data-point is not used for the fit because the extraction area is not specified

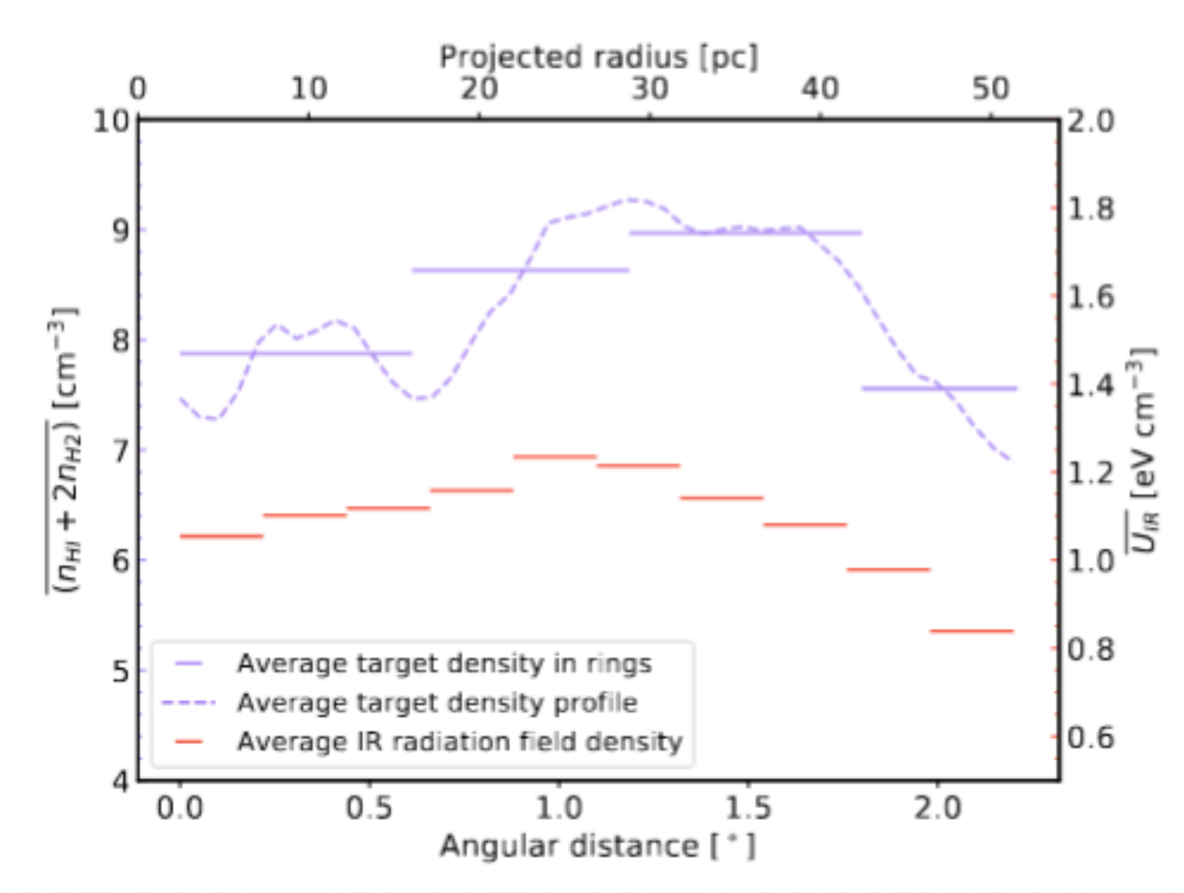
Gas and photons distribution

[S. Menchiari et al. in preparation]

Gas distribution from CO map



Photon background is dominated by IR radiation Star-light form Cyg. OB2 is negligible

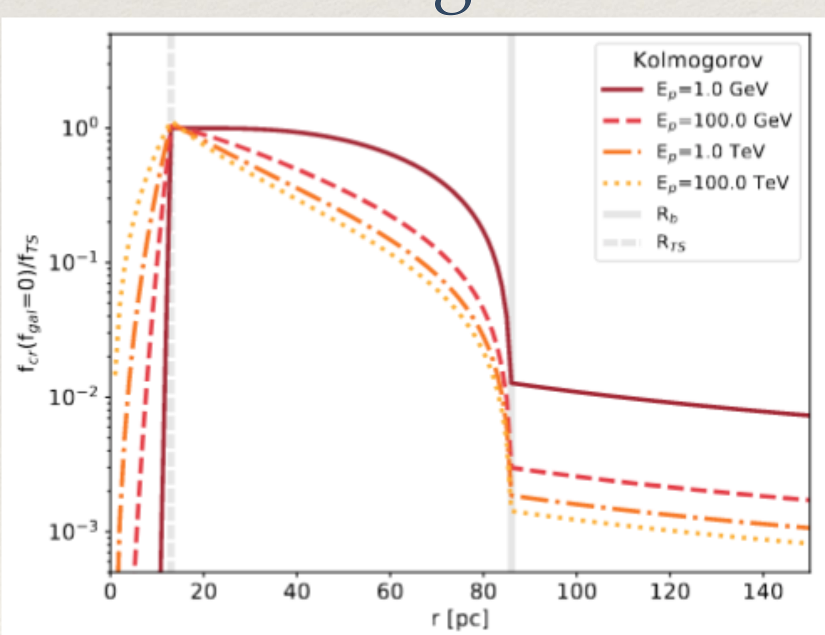


CR radial profile

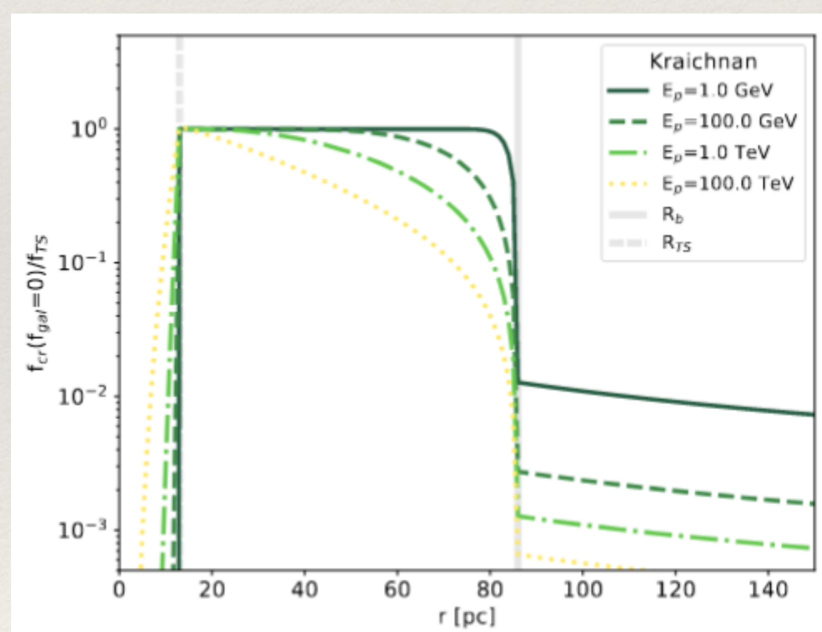
[S. Menchiari et al. in preparation]

The harder is the diffusion coefficient the flatter is the CR distribution

Kolmogorov



Kraichnan



Bohm