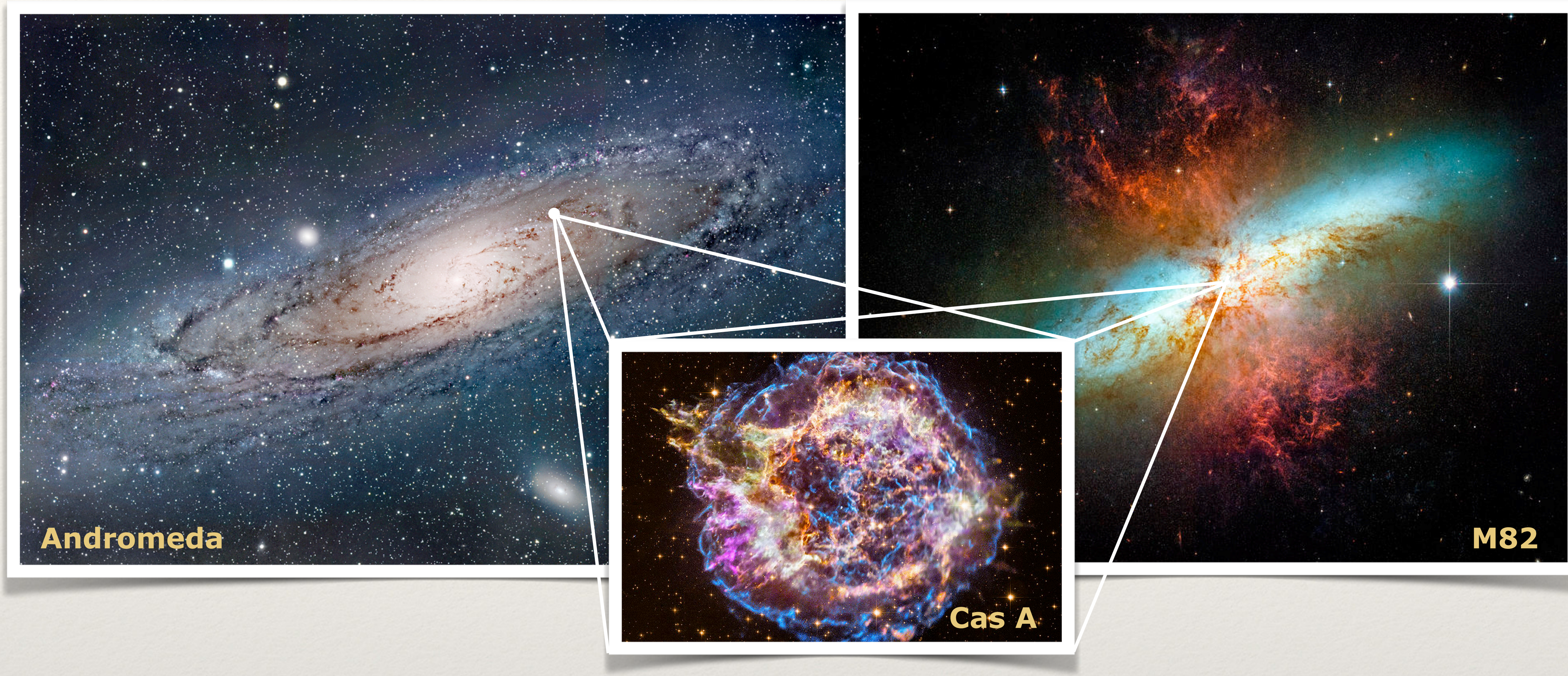


CDY seminar — 21 September, 2022

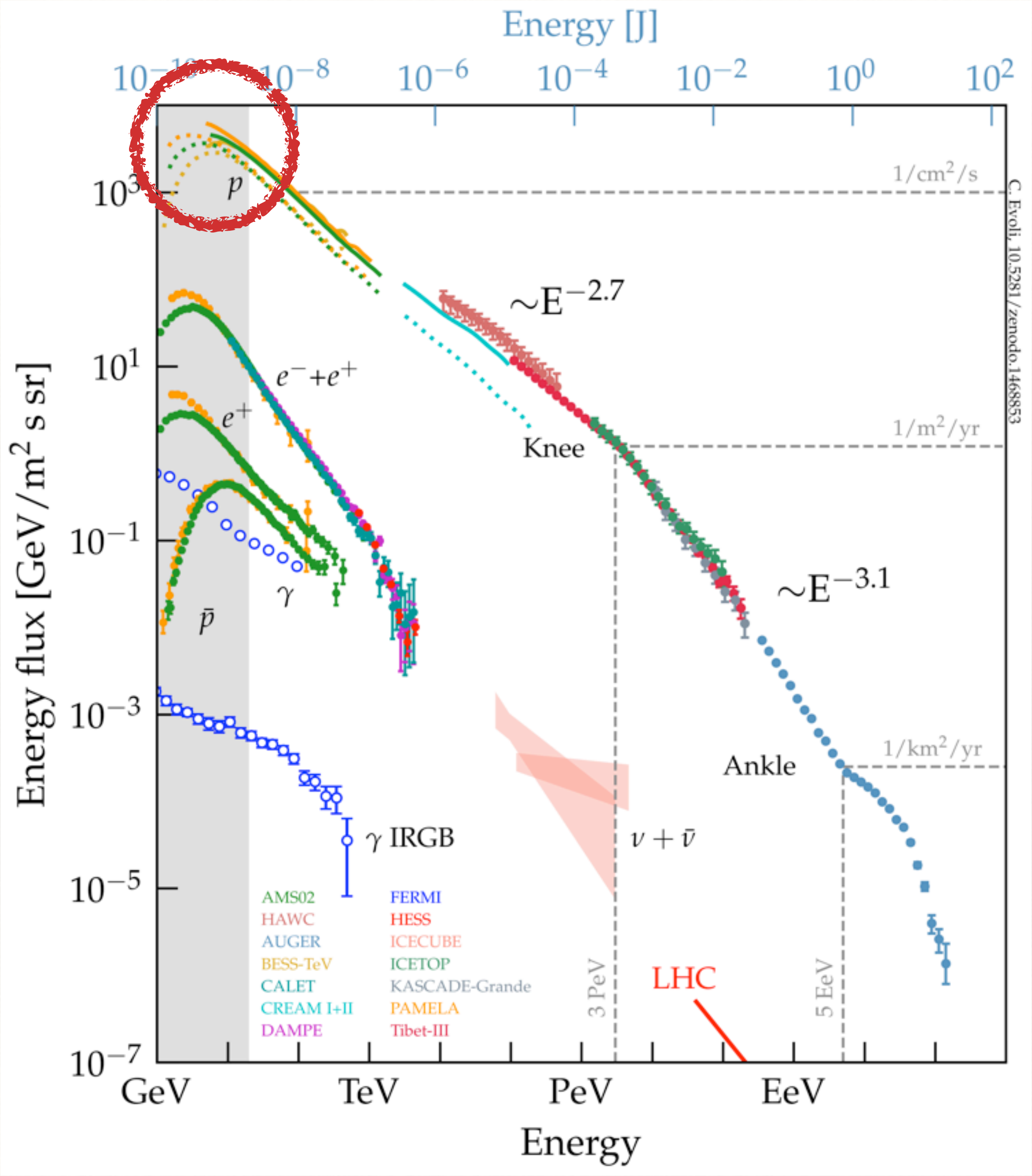
Supernova remnants as Cosmic Rays Accelerators: from the Milky Way to starburst galaxies

Giovanni Morlino
INAF/Oss. Astrofisico di Arcetri
Firenze
ITALY

Outline

- SNRs in the context of particle acceleration
- The Galactic context
  - Isolated SNR
  - Star clusters: $\left\{ \begin{array}{l} \text{- Stellar winds} \\ \text{- Interacting SNRs} \end{array} \right.$
- The extra-galactic context
  - SNRs and starburst nuclei
  - Winds from starburst nuclei
  - The multi-messenger prospective

How to explain the origin of Galactic CRs



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

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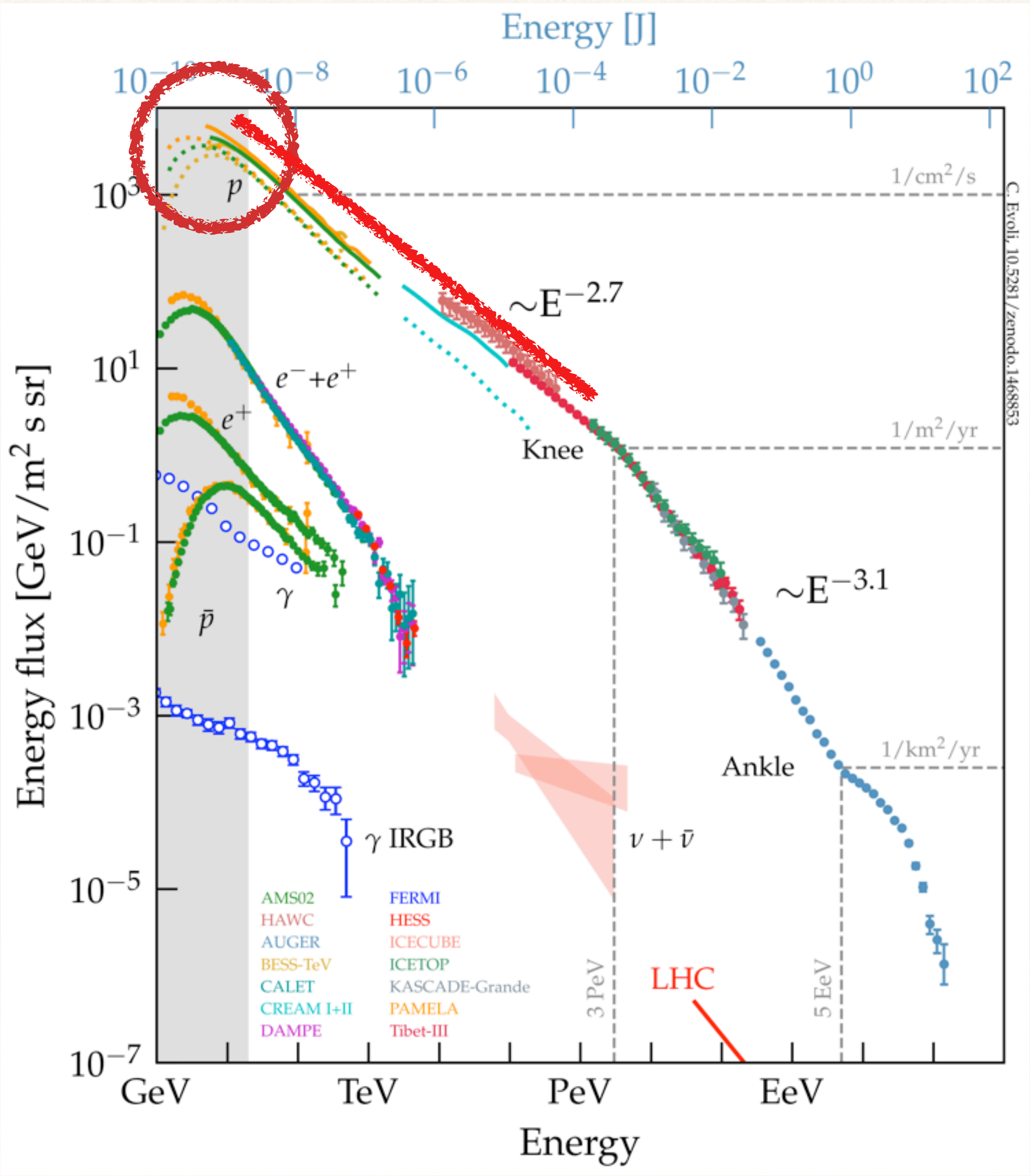

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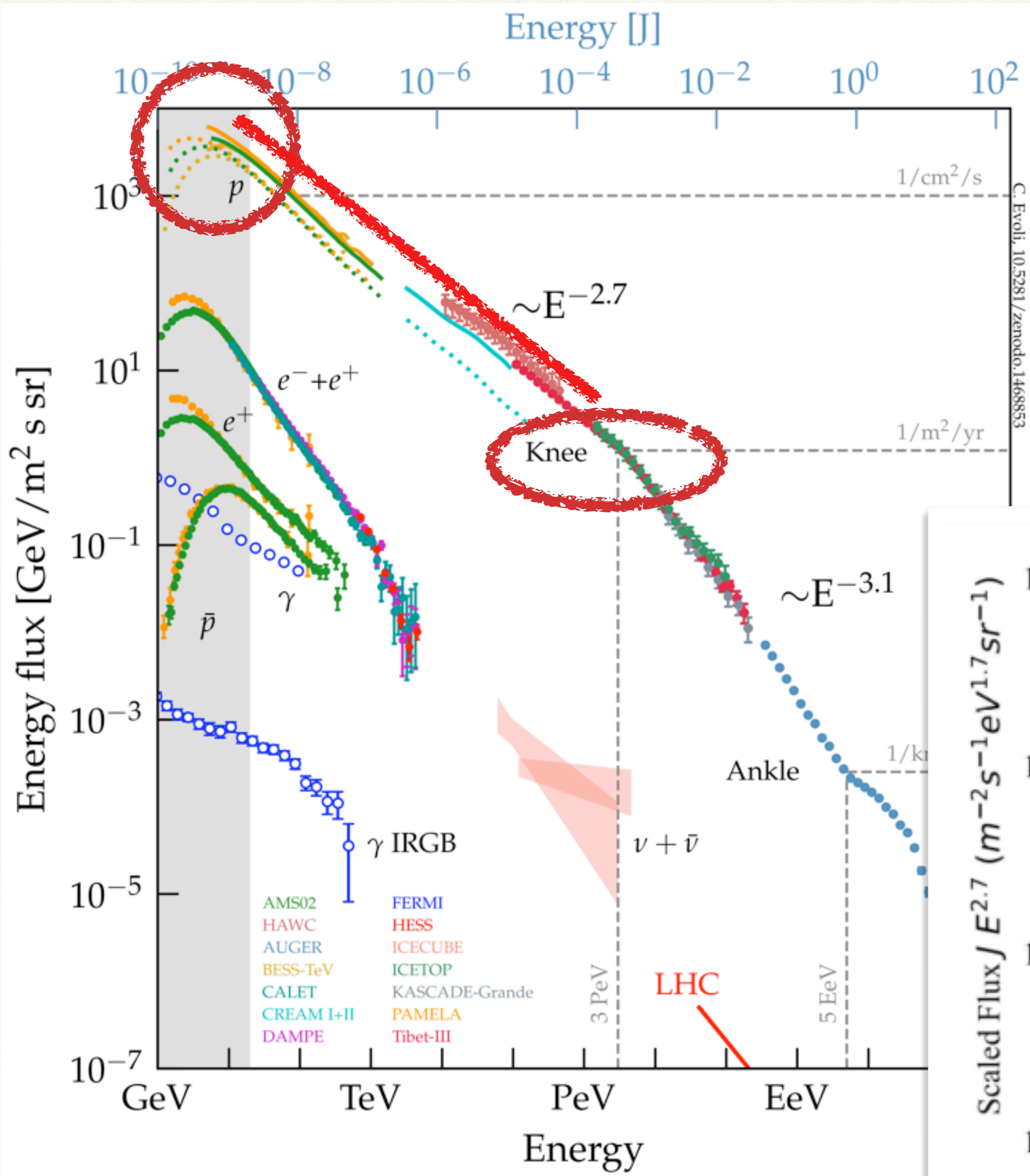

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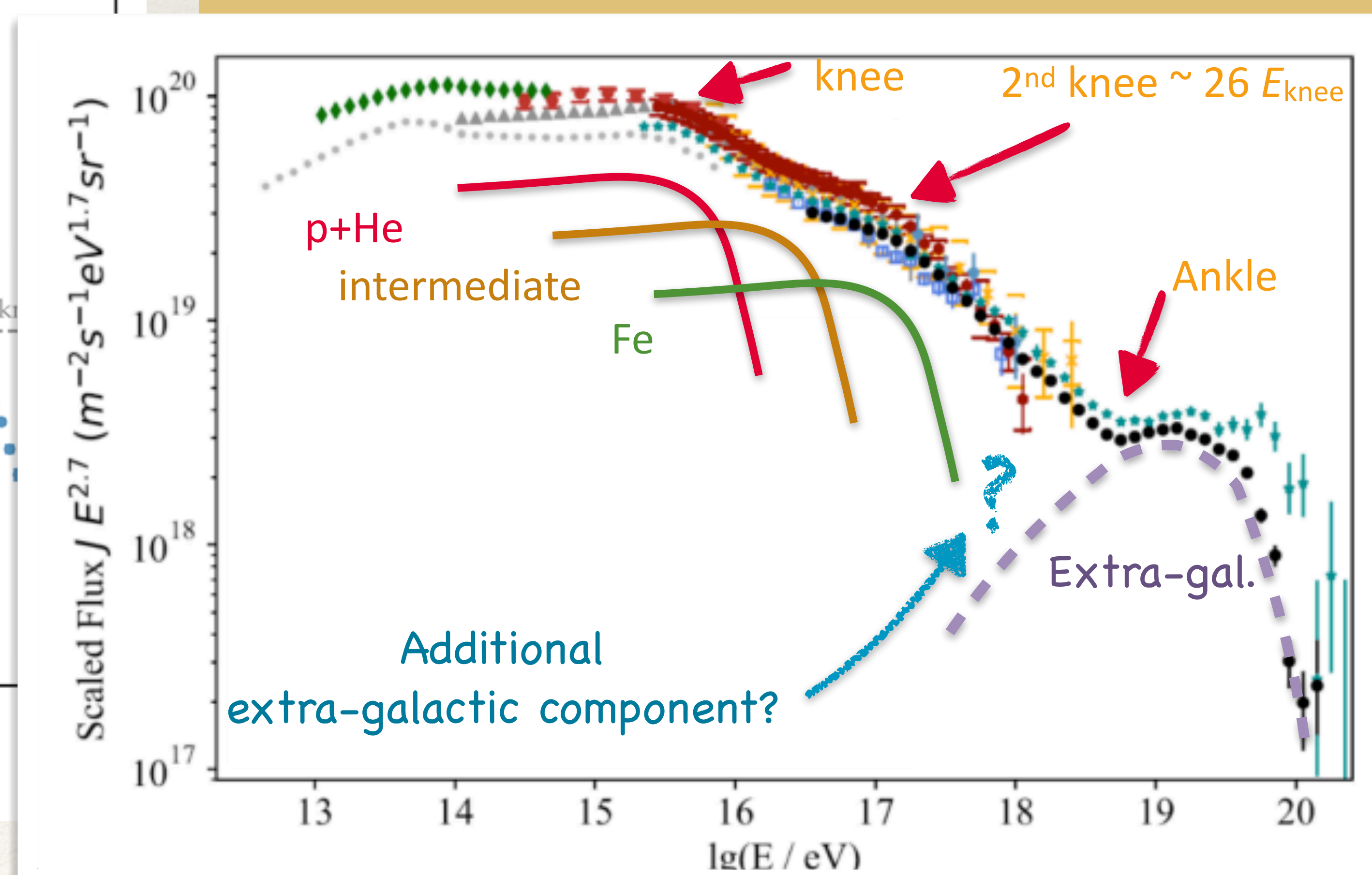

G. Morlino, CDY talk, 21 Sept. 2022

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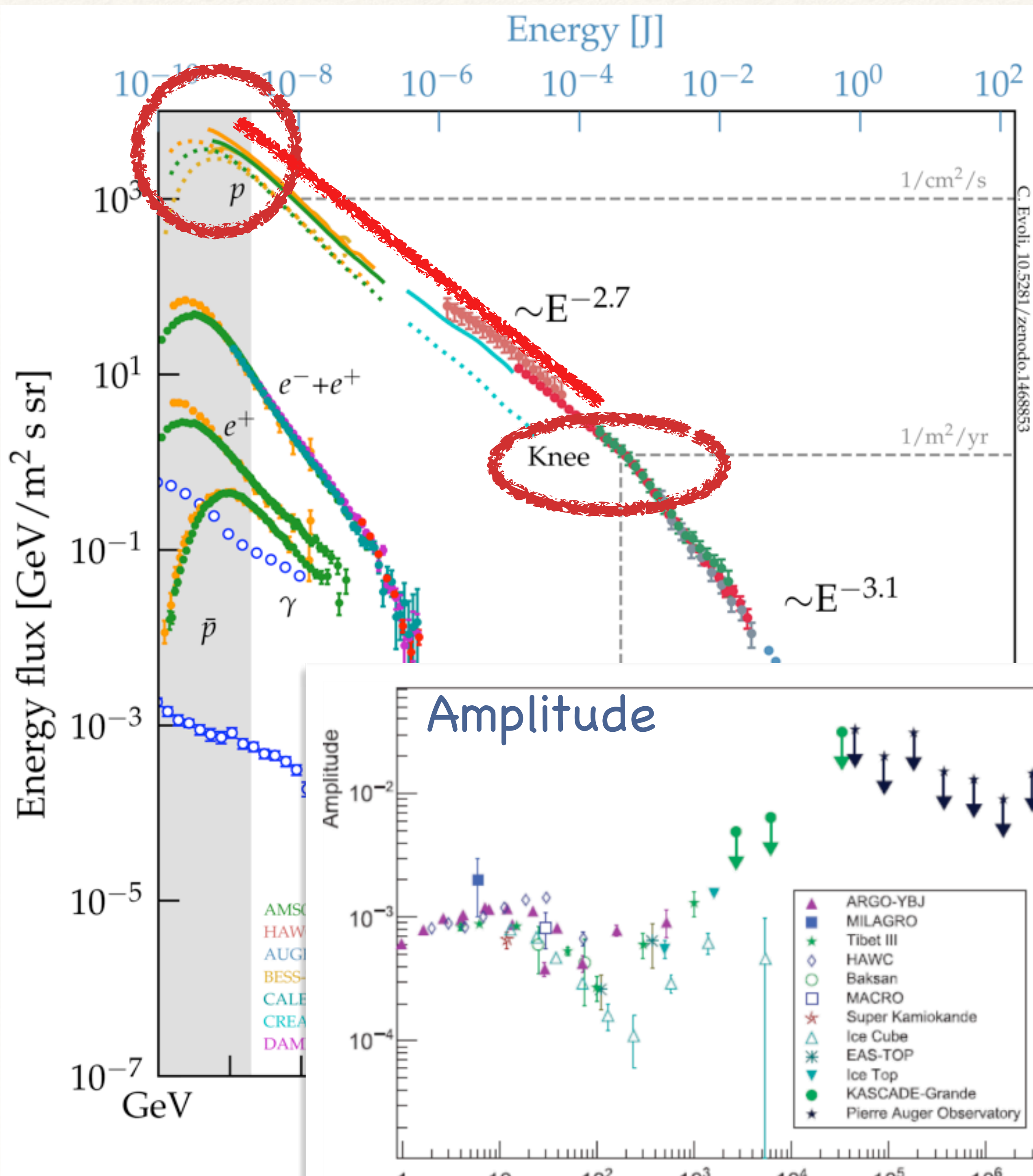

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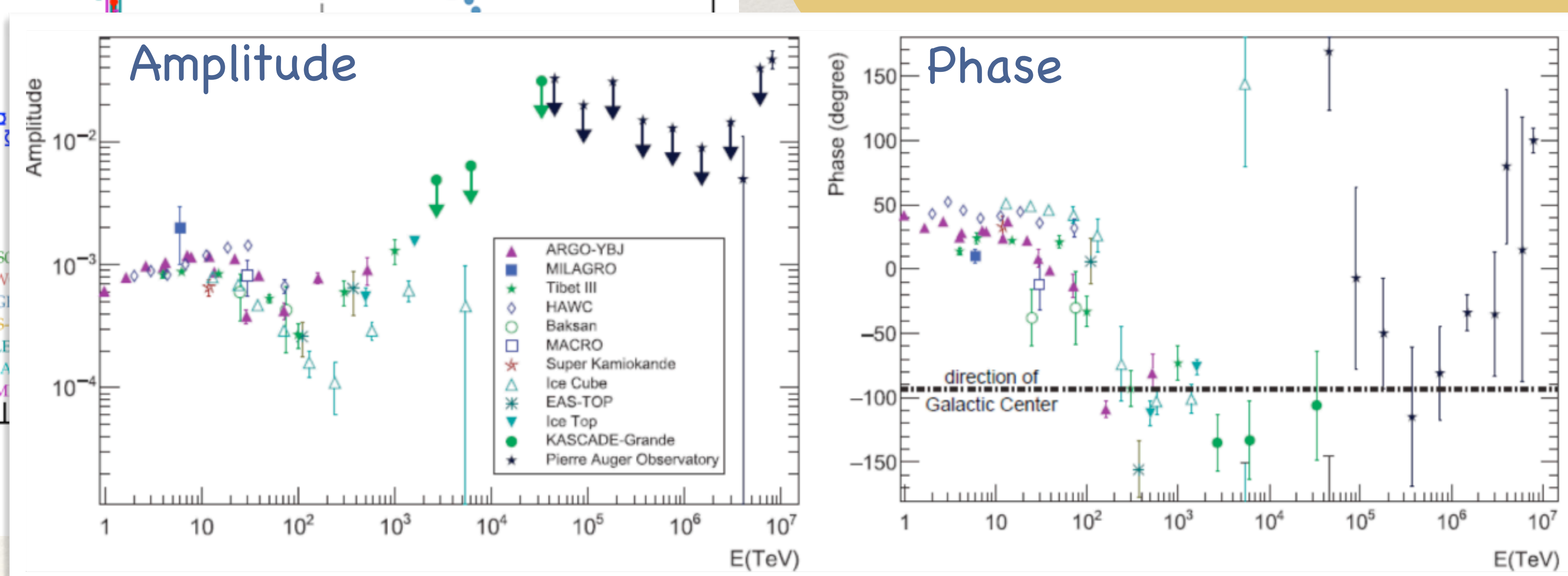

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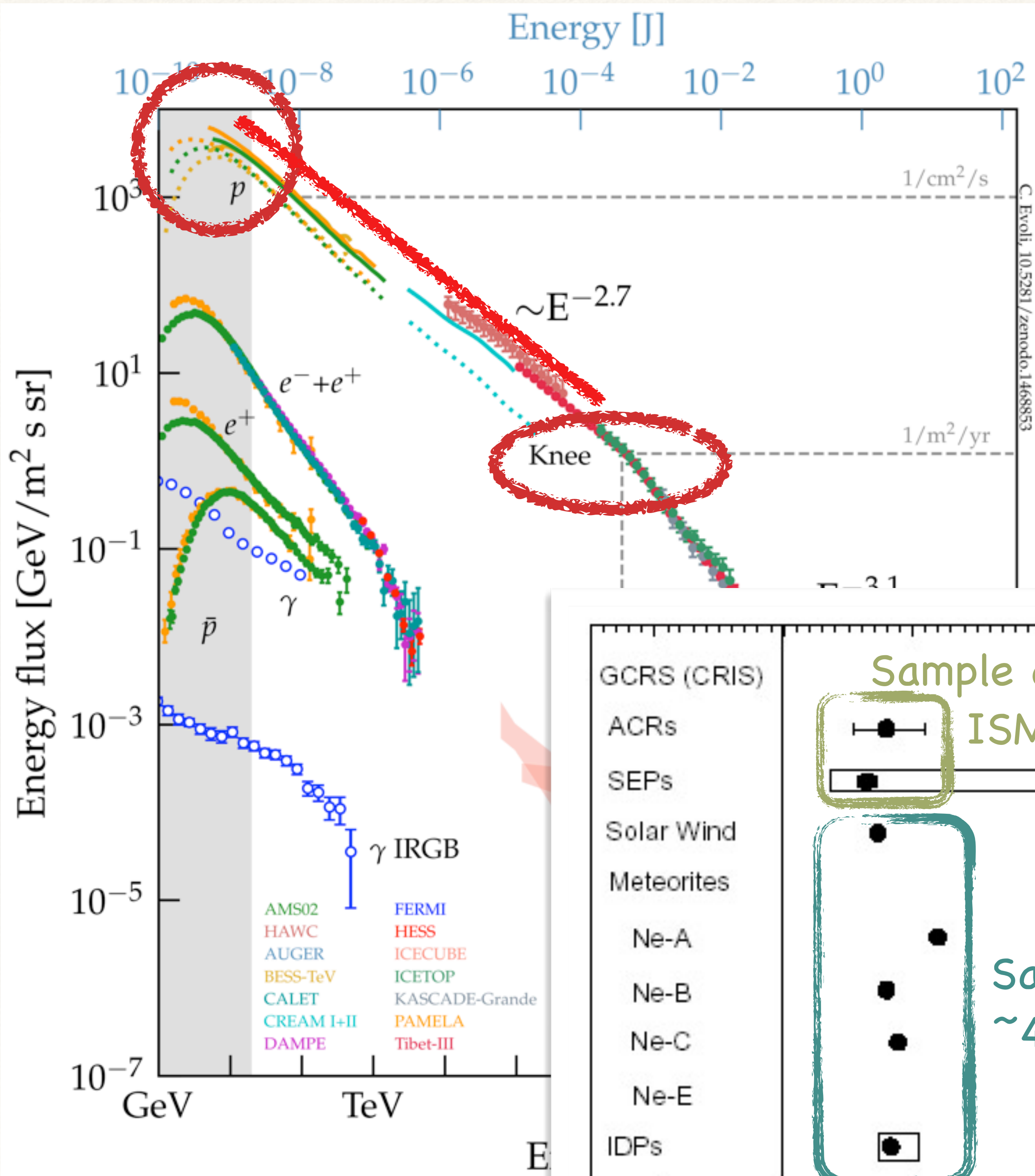

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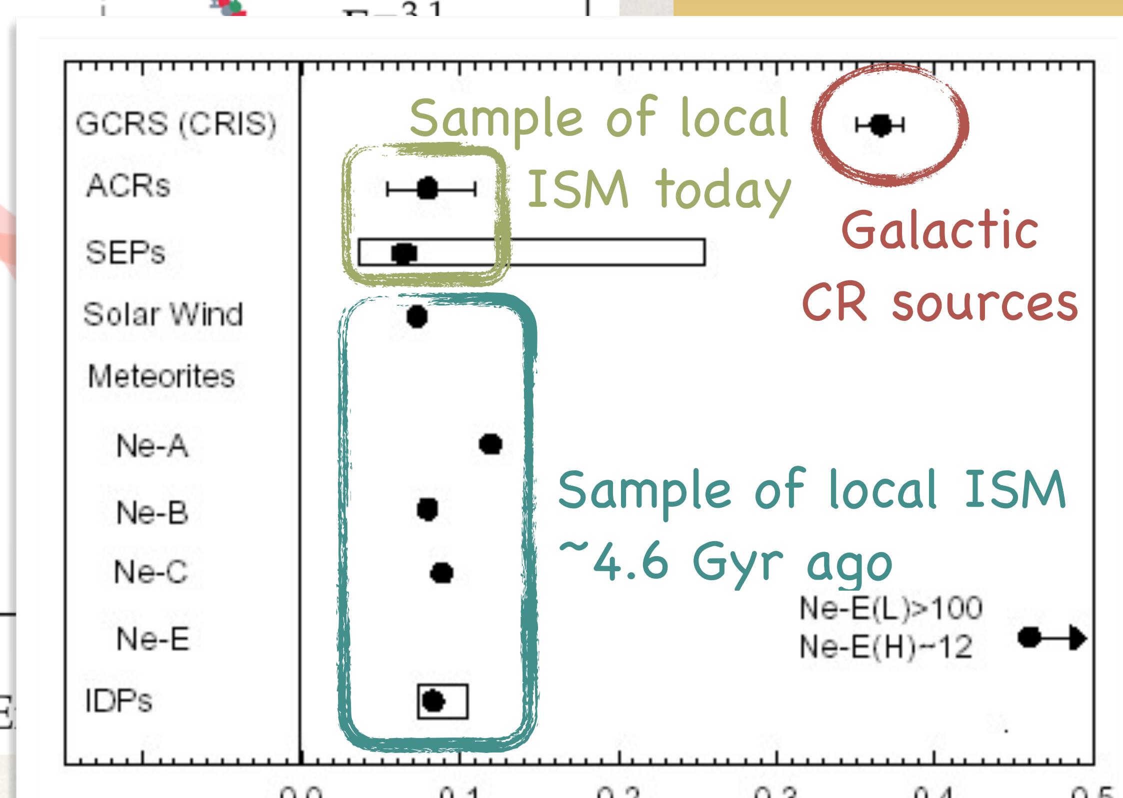

W. R. Binns (2003)

G. Morlino, CDY talk, 21 Sept. 2022

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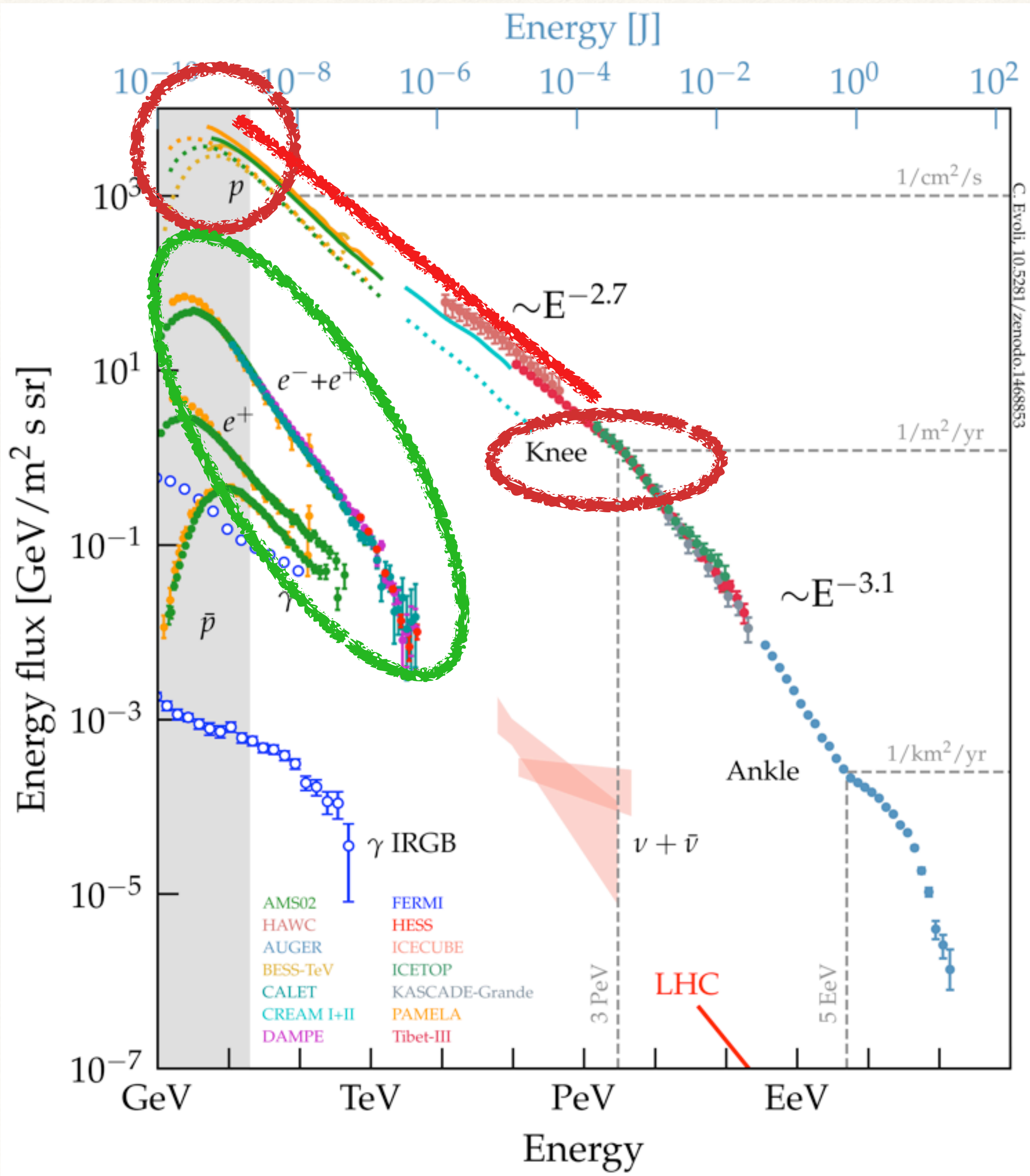

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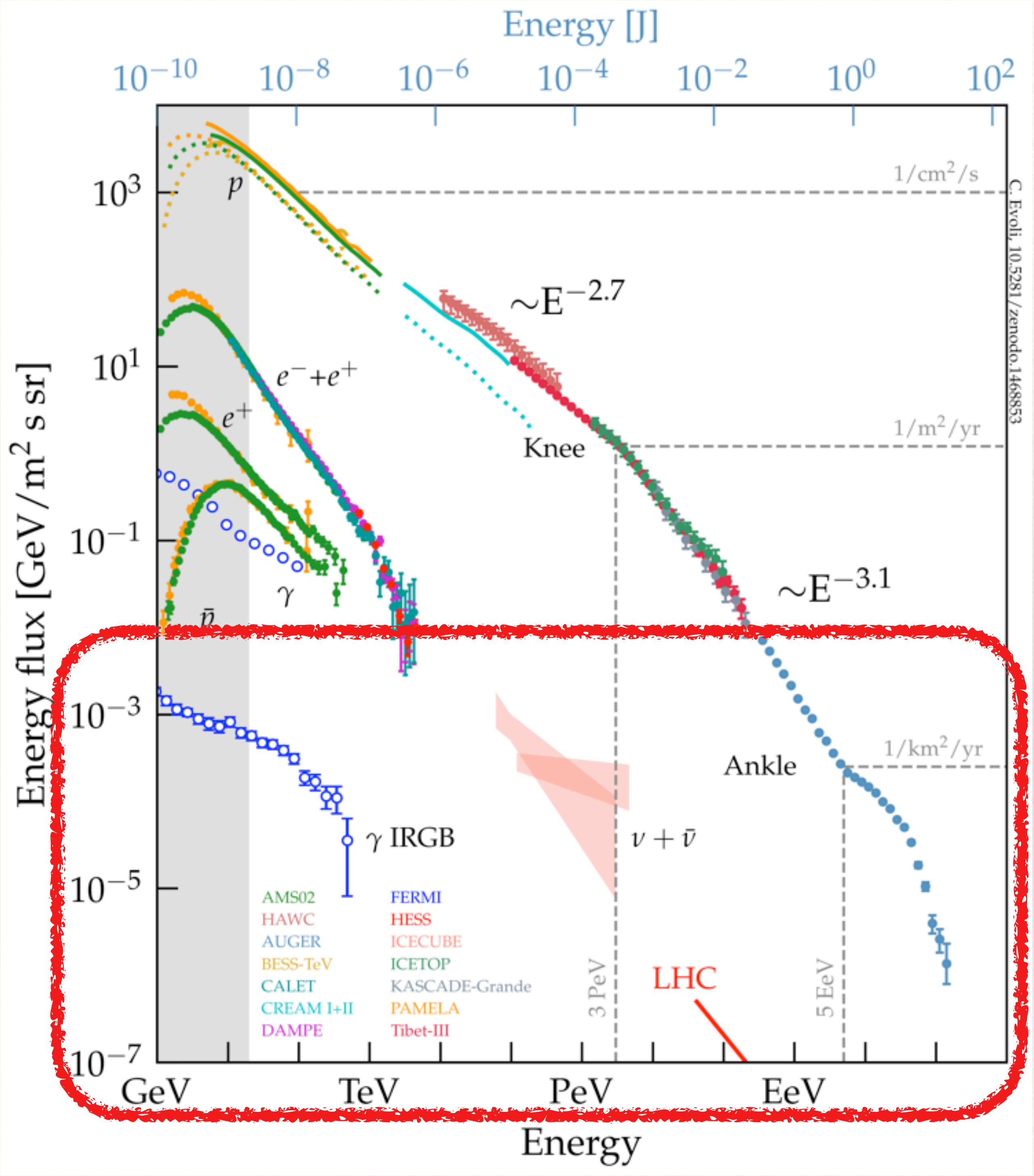
- Electrons: energetically subdominant but spectrum significantly steeper than p

Extra-galactic component



What contribute to the extra-galactic flux?

- UHECR
- Neutrinos
- gamma-rays

I will claim that SNRs may be responsible for a non-negligible fraction of the extra-gal. component

The Galactic context

The most popular scenario: DSA@SNR shocks

- **Why supernova remnant are so popular?**
  1. Enough power to sustain the CR flux (enough ~10% of the explosion energy)
  2. Spatial distribution of SNR compatible with CR distribution (inferred from diffuse gamma-ray emission)
  3. Enough sources to explain the small anisotropy:

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

  5. Presence of non thermal emission from SNRs
  6. A well developed theory for particle acceleration: Diffusive Shock Acceleration

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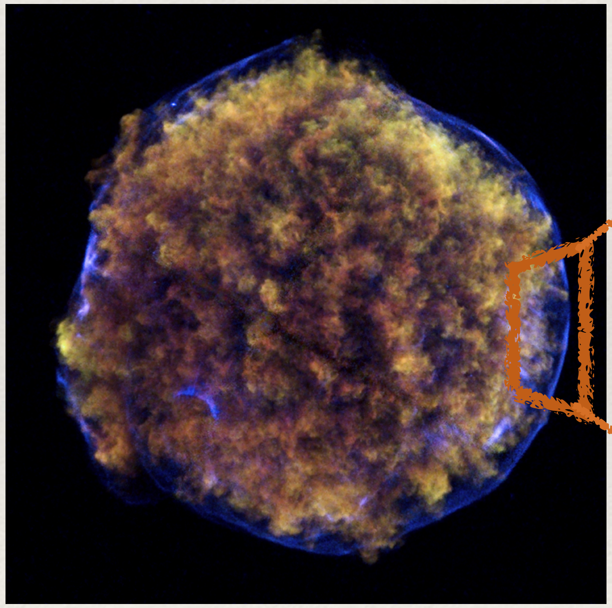
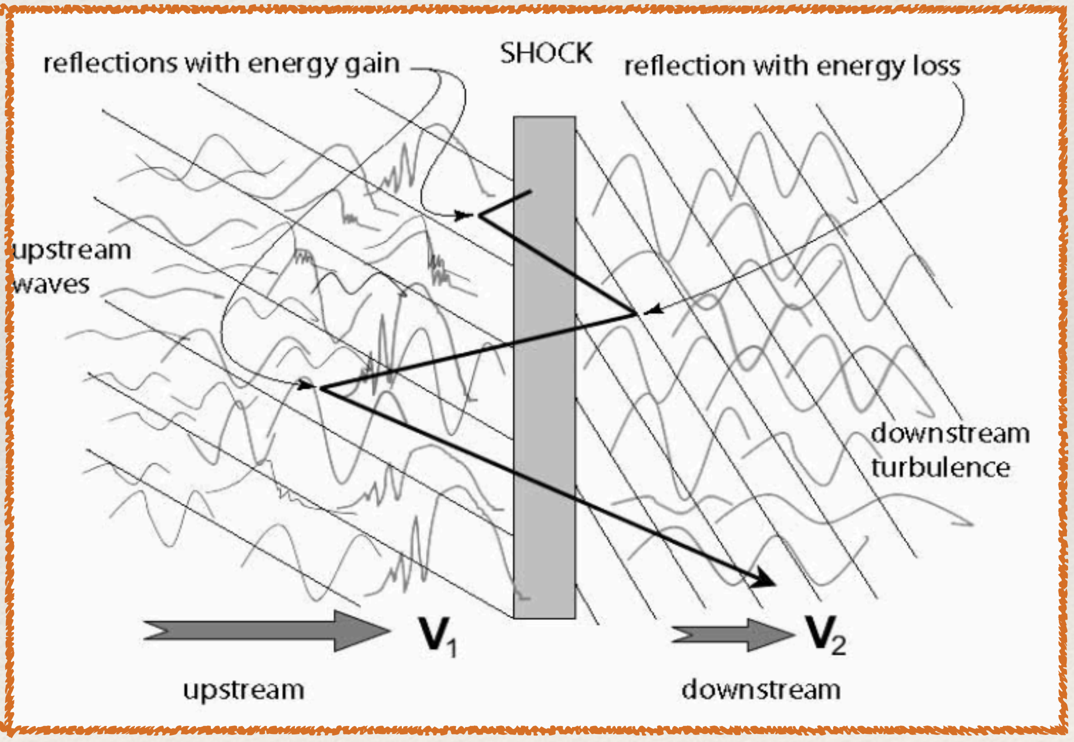
  6. A well developed theory for particle acceleration: Diffusive Shock Acceleration

- **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)
  - Unclear explanation for the electron spectrum

Where does the acceleration occurs?

- Repeated multiple scatterings with magnetic turbulence produce small energy gain at each shock crossing (*I order Fermi acceleration*)
- Balance between energy gain and escape probability results into a featureless power-law spectrum





The non-linear fashion of DSA

What makes DSA a non-trivial theory is the non-linearity due to CR feedback onto the shock dynamics

Magnetic turbulence confines particles around the shock

Shock transfer momentum to particles

Accelerated particles amplify magnetic turbulence

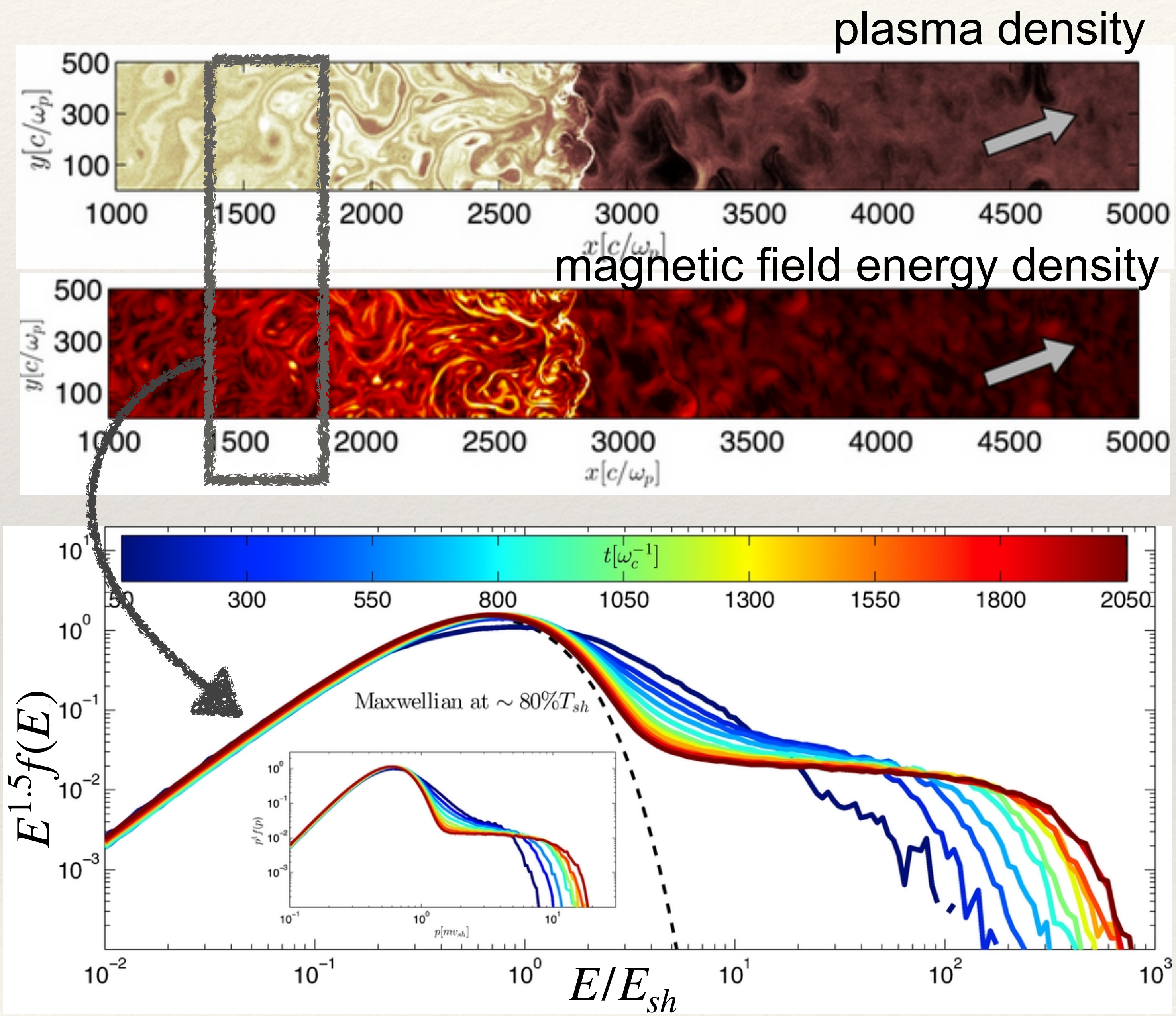
This chain of processes determines simultaneously:

- Acceleration efficiency
- Spectral slope
- Maximum energy
- Particle escape

The key aspect of the whole process is the magnetic field amplification

PIC simulation of DSA

[Caprioli & Spitkovsky, ApJ 2014]



Particle spectrum downstream
at different times

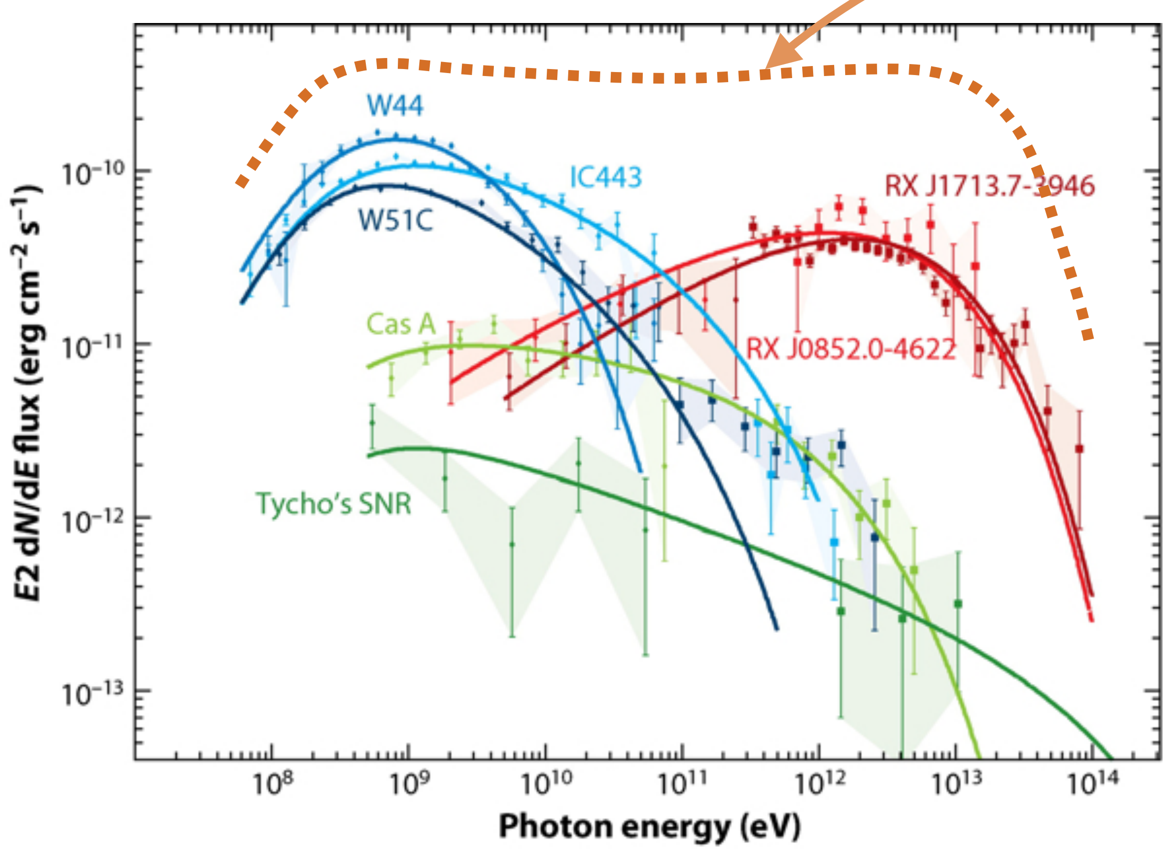
- A nice confirmation of DSA predictions comes from *particle in cell* (PIC) simulations
  - ✓ Large efficiency ~ 10-20%
  - ✓ Spectrum ~ p^{-4} (~ $E^{-1.5}$ at non-relativistic energies)
  - ✓ CRs generate their own magnetic turbulence

- However, PICs can only simulate the beginning of the acceleration process (small dynamical range: $E_{\max} \ll 1$ GeV)

Gamma-ray emission from SNRs: what's wrong with DSA?

Collection of Gamma-ray emission from shell-type SNRs

Prediction from test particle theory, i.e. $n(E) \propto E^{-2}$



Funk S. 2015.
Annu. Rev. Nucl. Part. Sci. 65:245–77

How to get slope different from 2?

- Modification to test-particle DSA (e.g. scattering centres with non-negligible speed)
- Environmental conditions (clumpy media)
- Particle escape (for middle-age SNRs)
- etc…

	Very young (~300 yr)	Young (~2000 yr)	Middle-age (~10^4 yr)
Emission type	hadronic	unclear (had./lept.)	hadronic
spectrum	soft (~$E^{-2.3}$)	hard (~$E^{-1.5}$ - $E^{-1.8}$)	soft (~E^{-3})
E_{max} (protons)	10-100 TeV	10-100 TeV	<~10 TeV

Not enough to explain the knee at ~PeV

Maximum energy at SNR shocks

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

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

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

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

But for standard ISM $\mathcal{F}\left(1/r_L(1\mathrm{PeV})\right) \sim 10^{-3}$ → $E_{max} \sim few\ \mathrm{GeV}$

→ **Need of magnetic field amplification**

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→ Need of magnetic field amplification

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

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

Only very young CC SNR can accelerate to PeV

Shure & Bell (2013)

Magnetic field at saturation for Bell instability $\frac{B_{\rm sat}^2}{B_0^2} \sim \frac{U_{\rm CR}}{U_{B_0}} \frac{v_d}{c} \propto n_0 v_{sh}$ → Efficient amplification requires:

- large densities
- large shock speed

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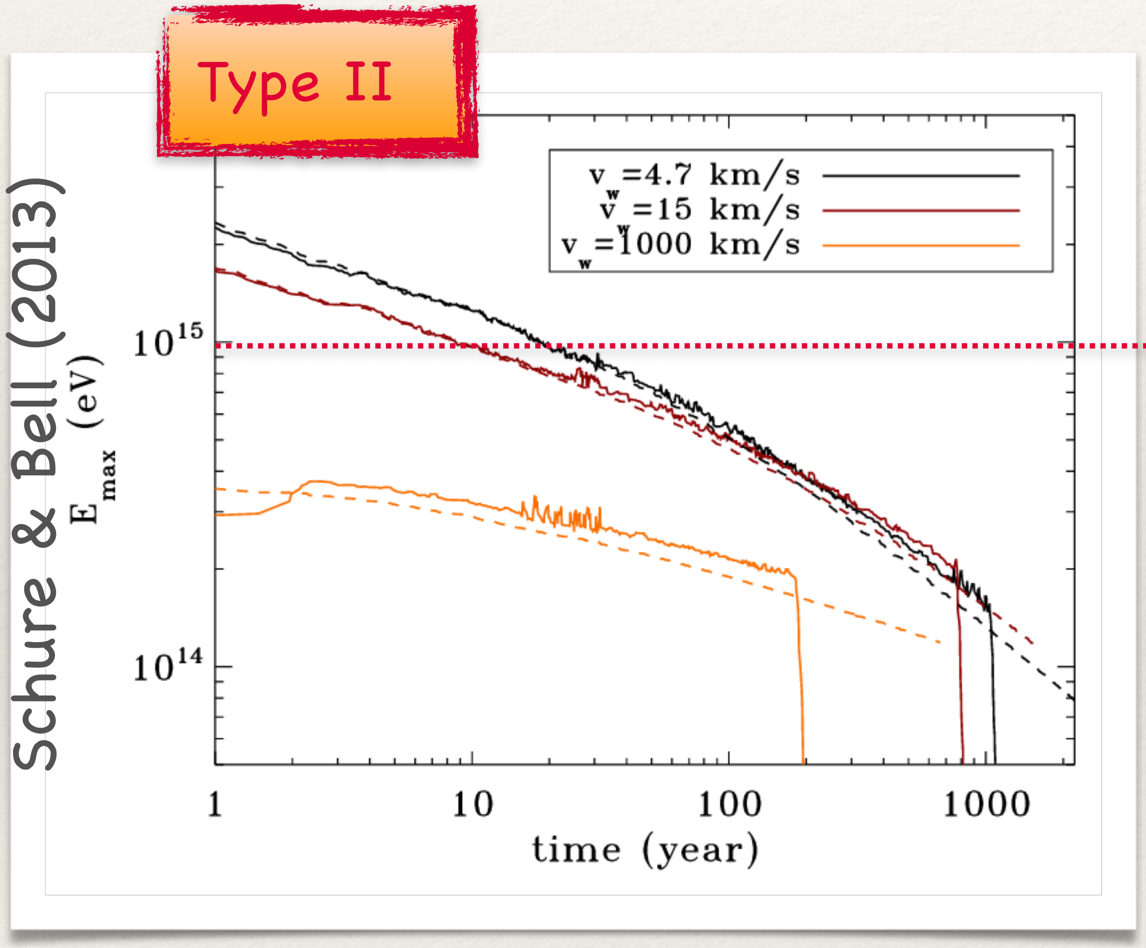
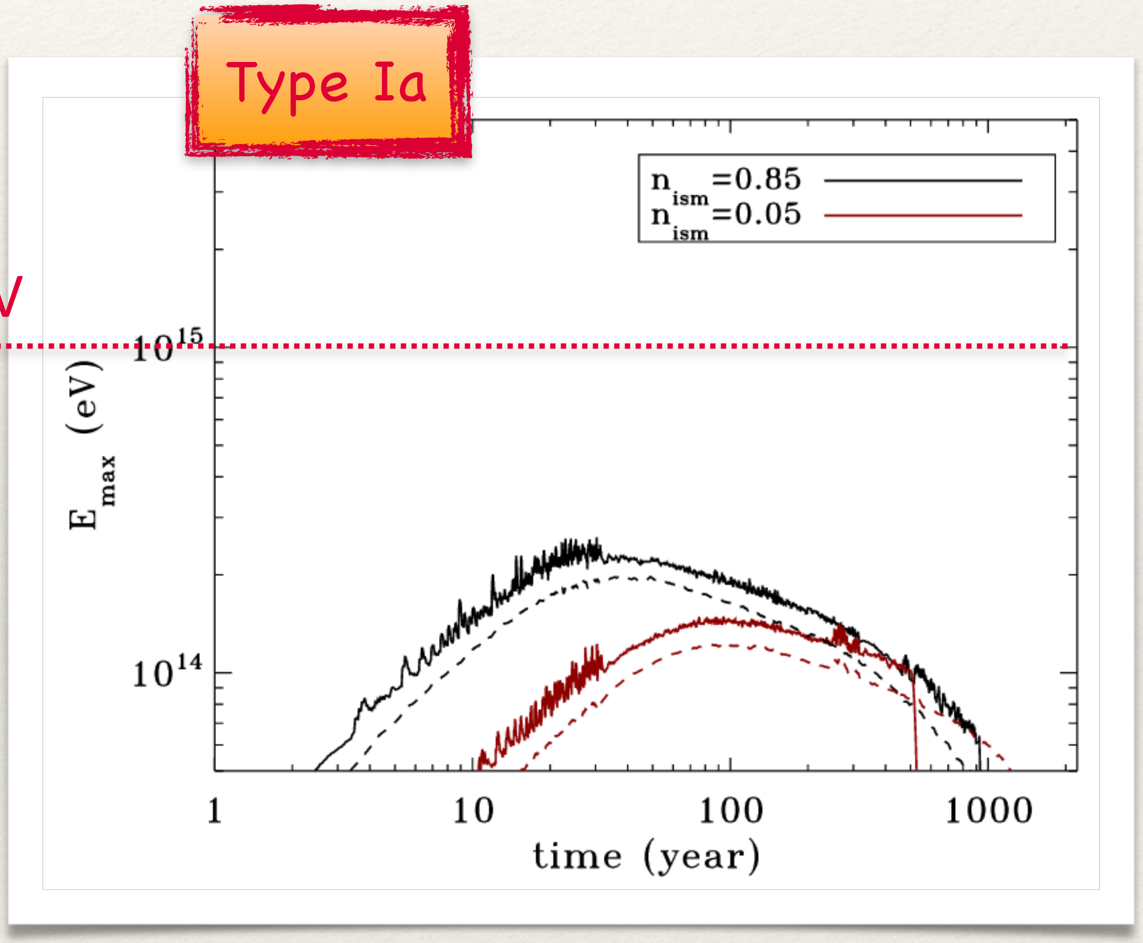


1 PeV



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_{ej} [M_{Sol}]	1.4	5	1
E_{SN} [10^{51} erg]	1	1	10
M_{wind} [10^{-5} M_{Sol}/yr]	—	1	10
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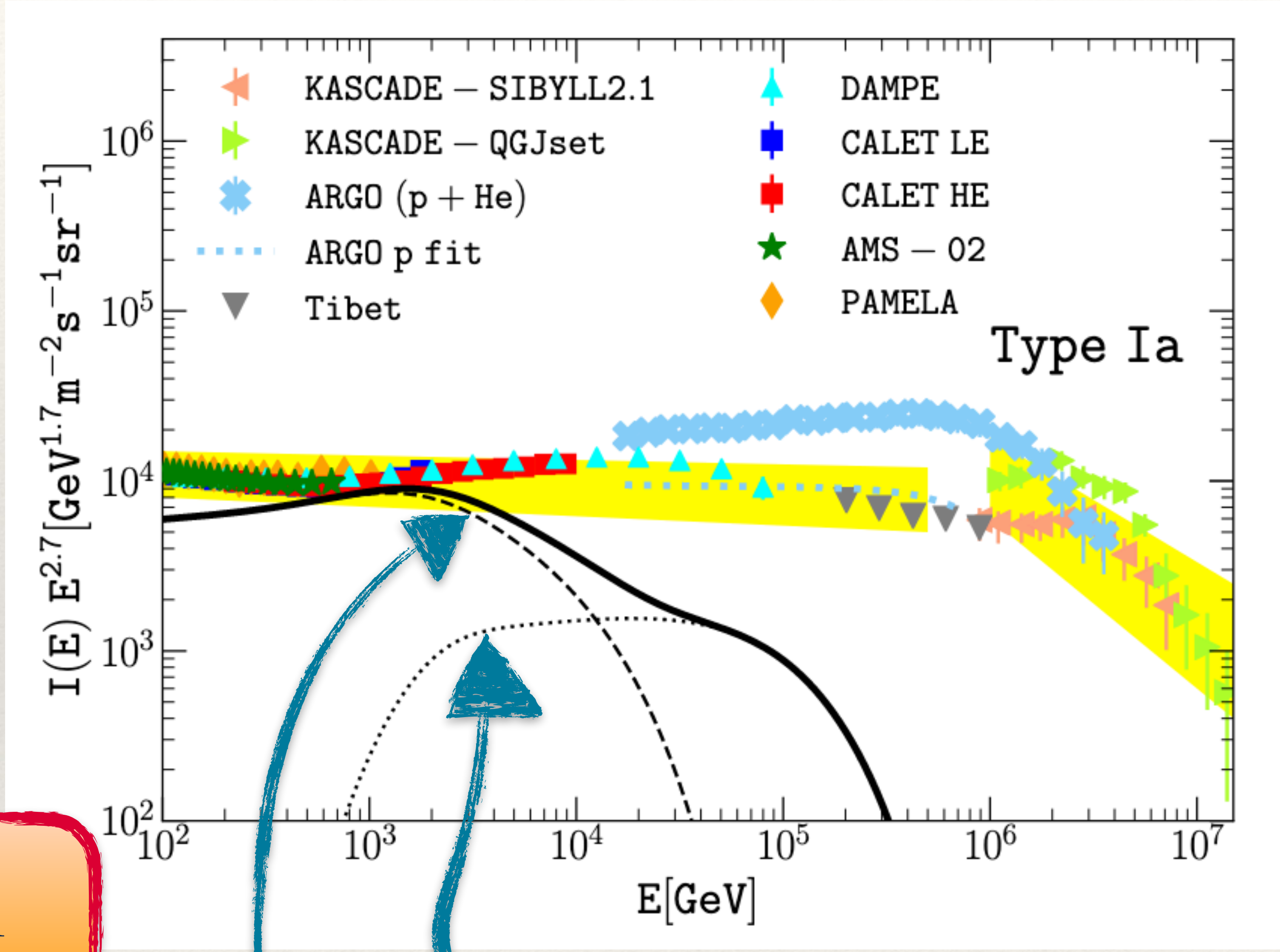
COMPARISON WITH THE CR SPECTRUM DETECTED AT THE EARTH



Confined particles

Particles escaping during the acceleration

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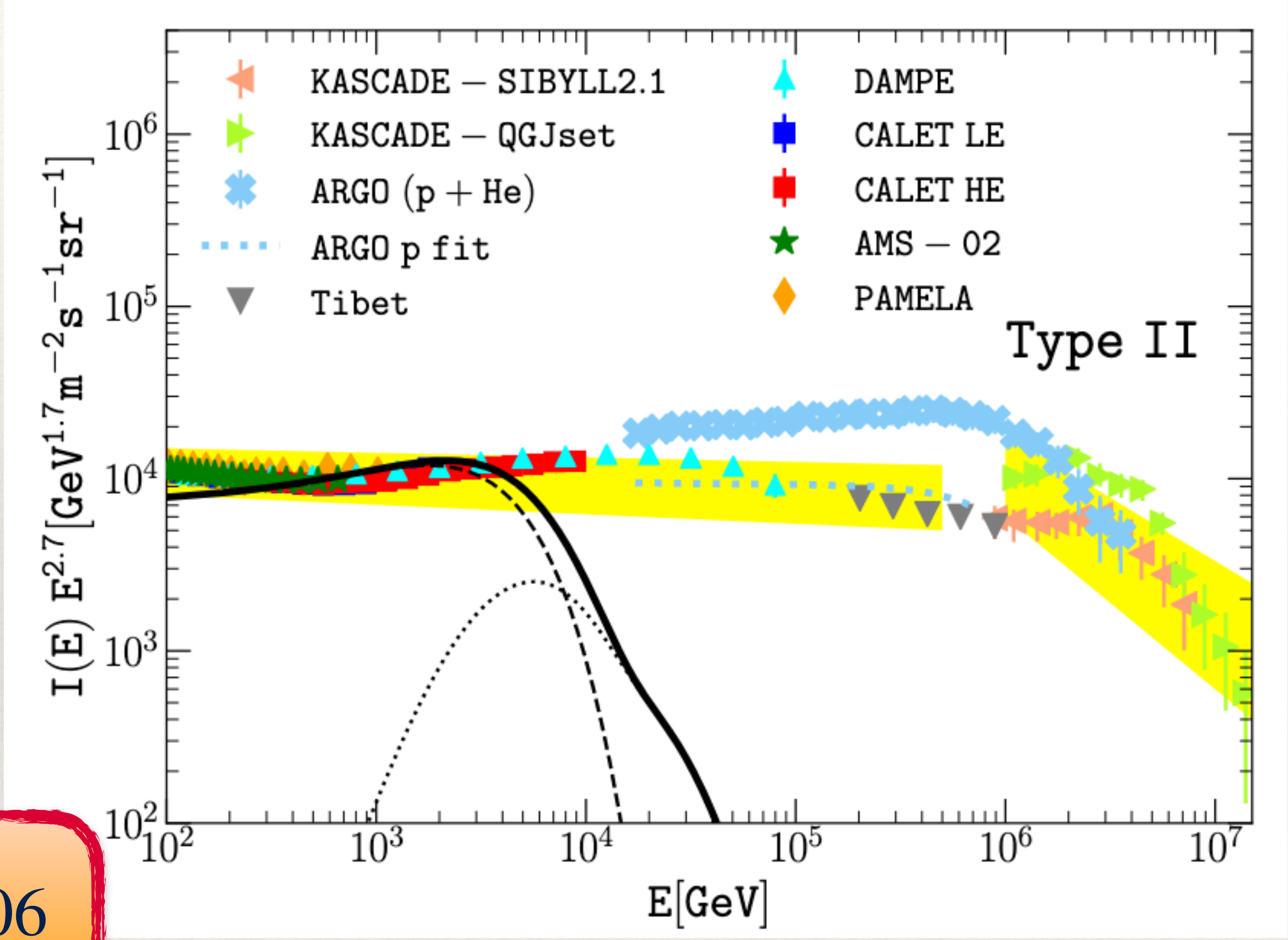

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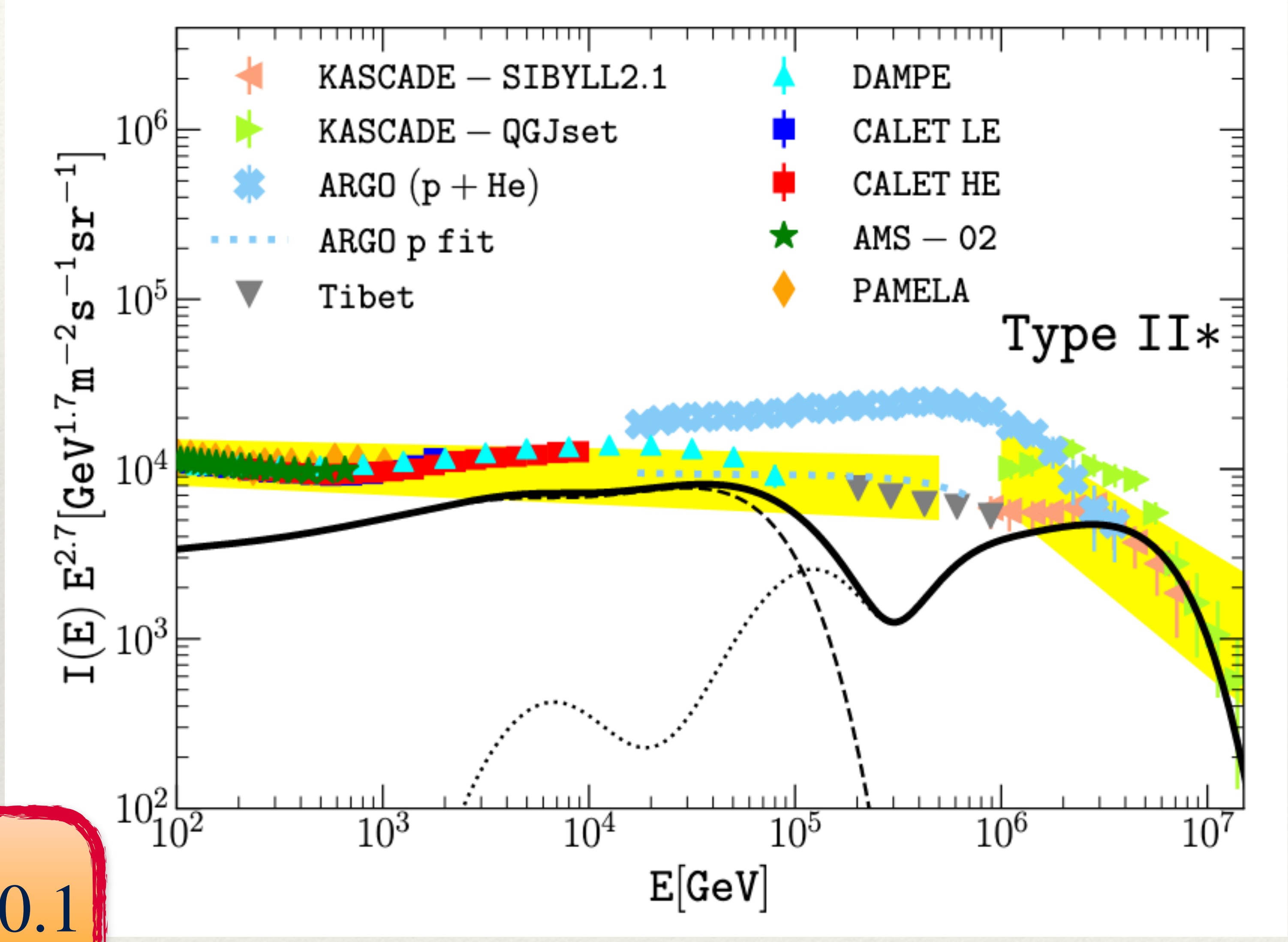
$$\mathrm{Rate} = \frac{3}{10000\ \mathrm{yr}}\ ;\ \xi_{CR} = 0.1$$

COMPARISON WITH THE CR SPECTRUM DETECTED AT THE EARTH



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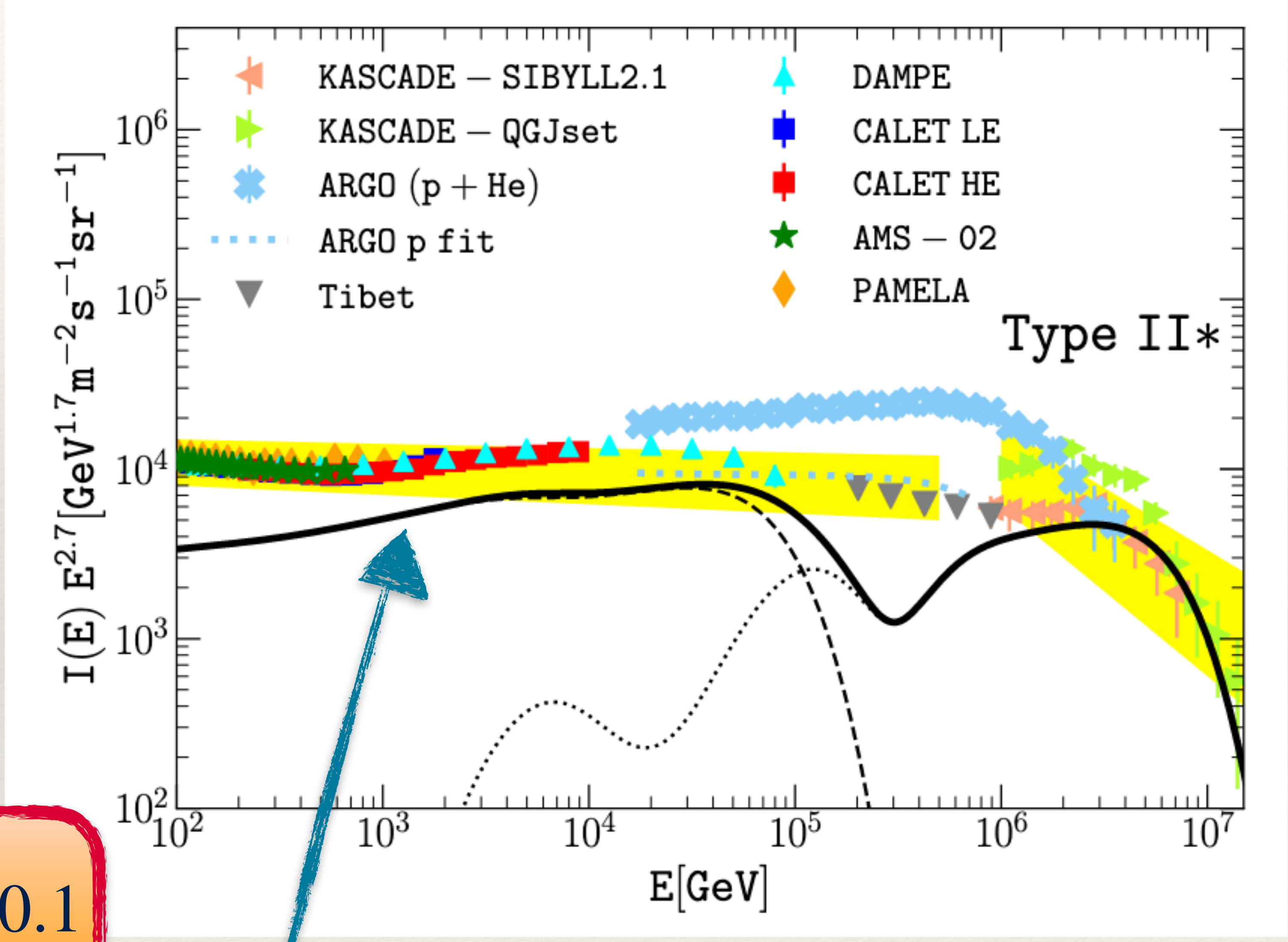

No room for other SNRs

Accounting for SNR evolution and CR propagation

Cristofari, Blasi & Amato (2020)

COM

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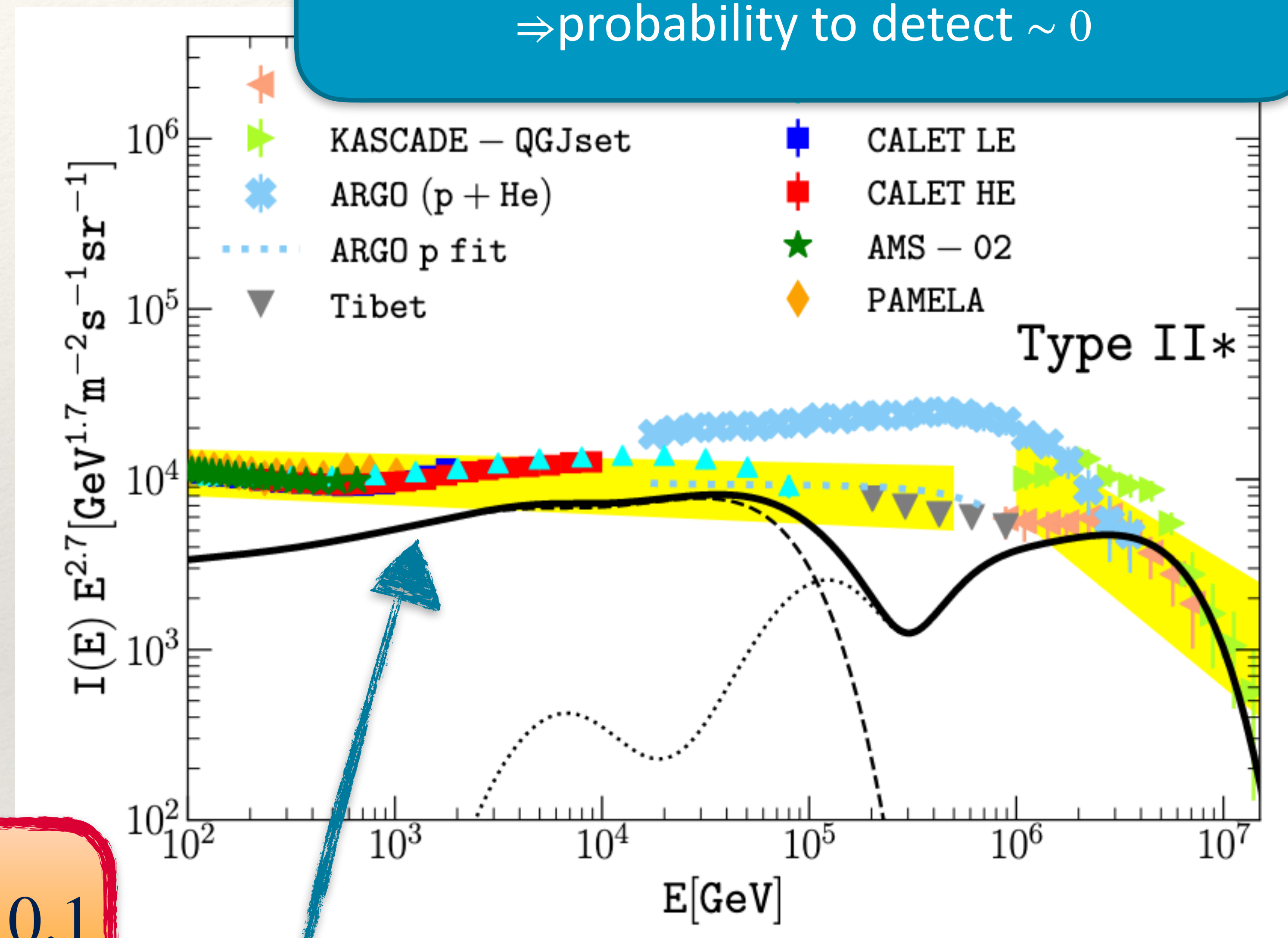
If only Tipe II* are PeVatrons
⇒probability to detect ~ 0



No room for other SNRs

Role of stellar clusters

What are the other possibilities?
SN explosion occurs mainly in OB associations
→ **we need to consider SNe in the context of star clusters**

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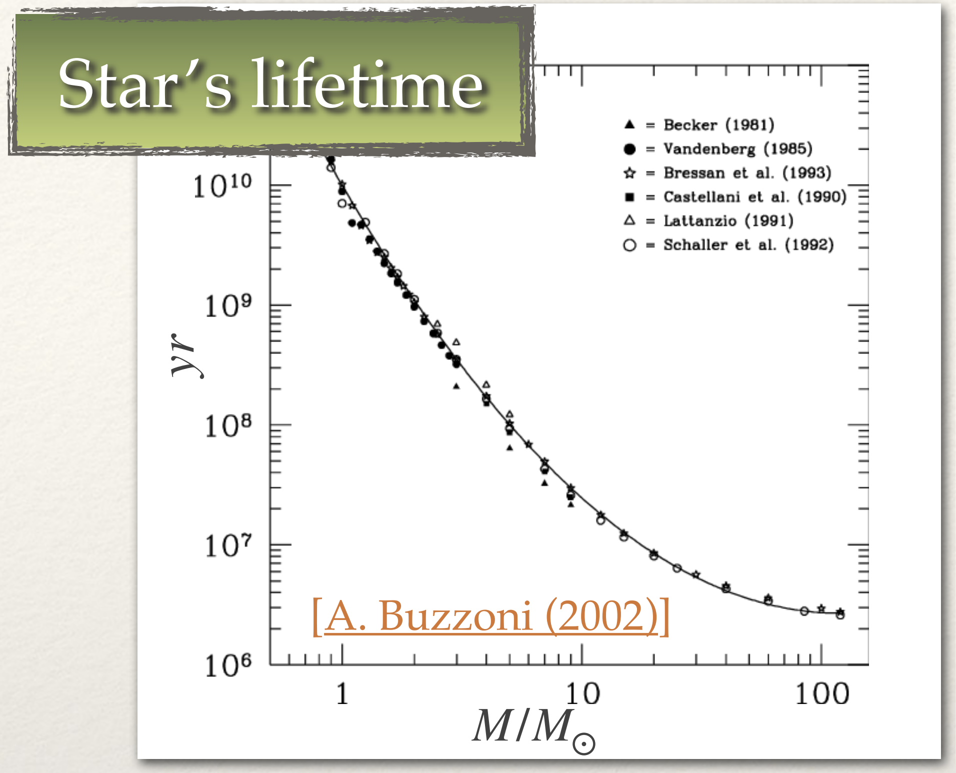
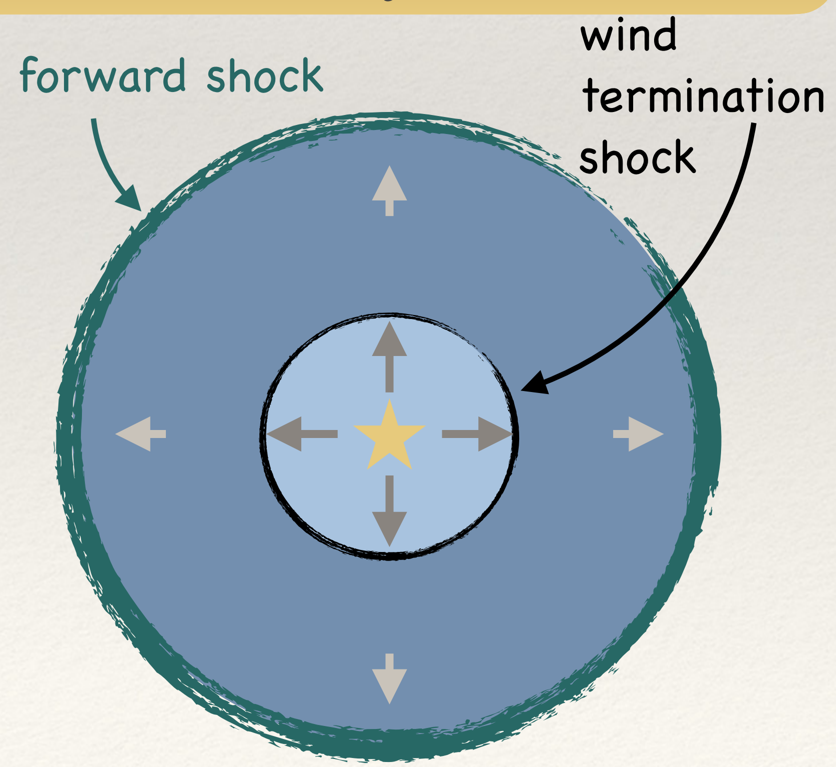
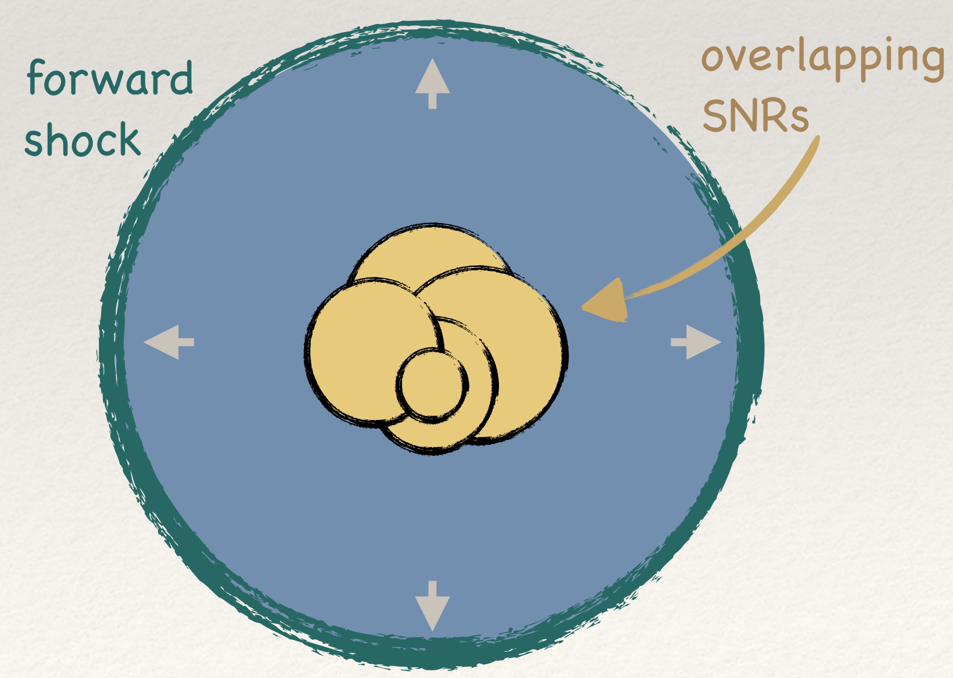


$t \lesssim 3\,\mathrm{Myr}$ only stellar winds



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



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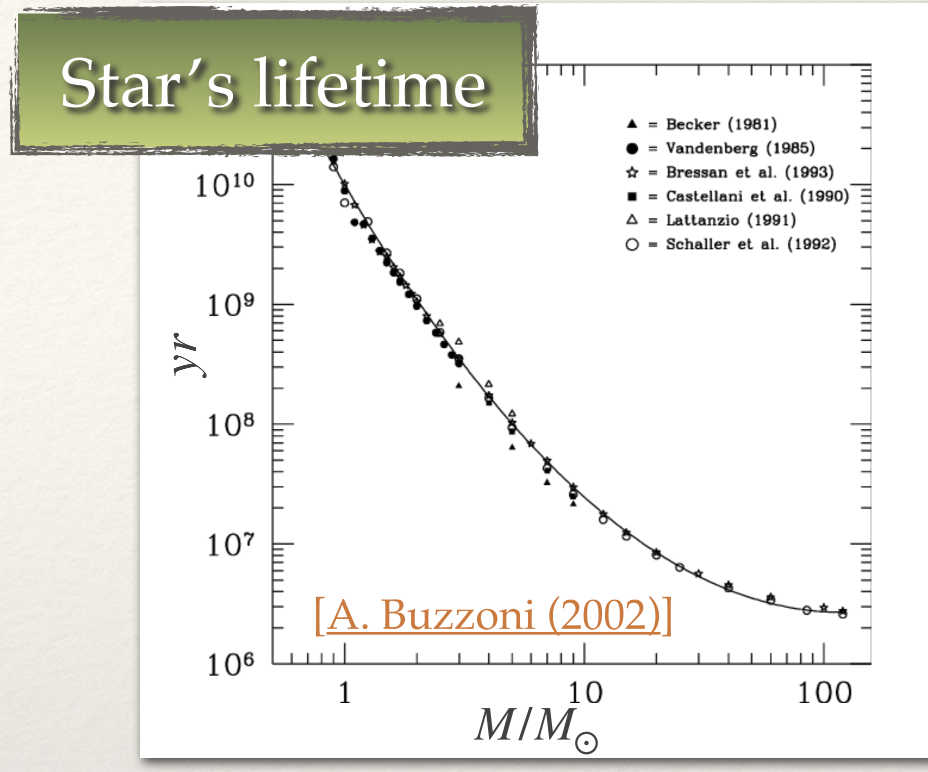

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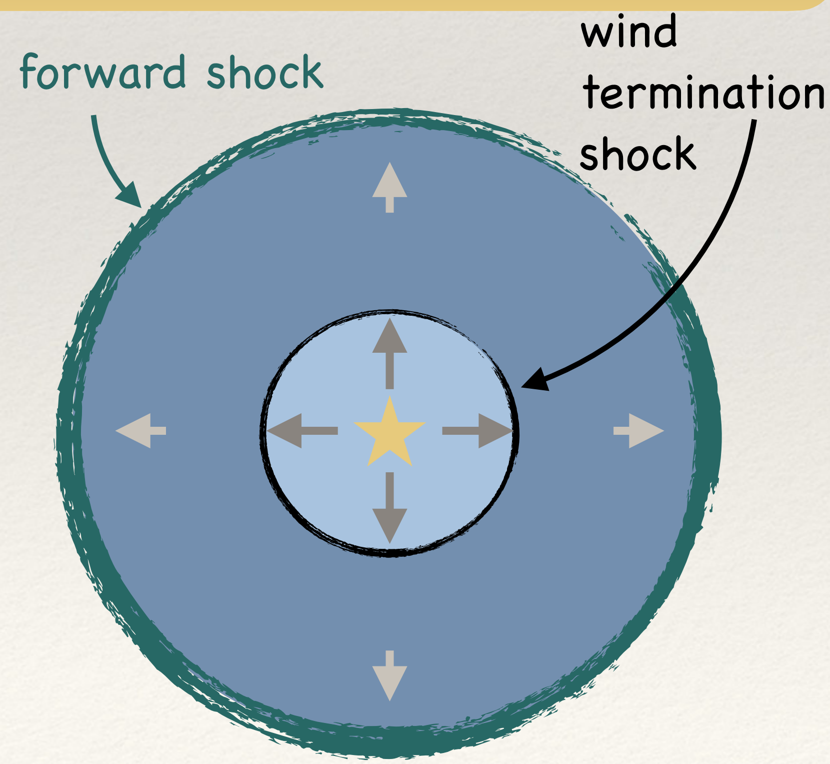

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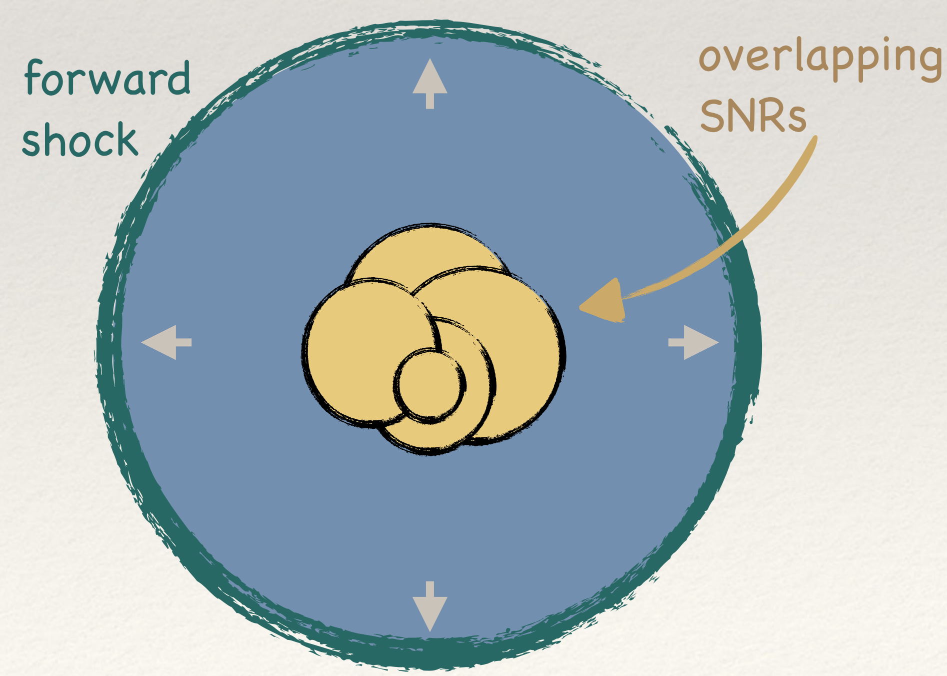


Energetics: stellar winds vs. SNe

Salpeter (1955) initial mass function of stars: $f(M) = \frac{dN_{\rm star}}{dM} \propto M^{-2.35}$

Power injected by SNe $P_{\rm SNe} = \boxed{10^{51}\,{\rm erg}} \int_{8M_\odot}^{M_1} f(M)\,dM$

Power injected by winds $P_{\rm wind} = \int_{M_{\rm min}}^{M_{\rm max}} \boxed{\frac{1}{2}\dot{M}_w(M)\,v_w(M)^2\,\tau_{\rm life}(M)}\, f(M)\,dM$

$v_w = 2.5\sqrt{2G_N M/R}$ for line-driven winds;

$\dot{M}$ from analytical (approximated) models [Nieuwenhuijzen & de Jager(1990)]

$$\frac{P_{\rm wind}}{P_{\rm SNe}} \simeq 0.1 \div 0.5$$

main uncertainty due to mass loss rate

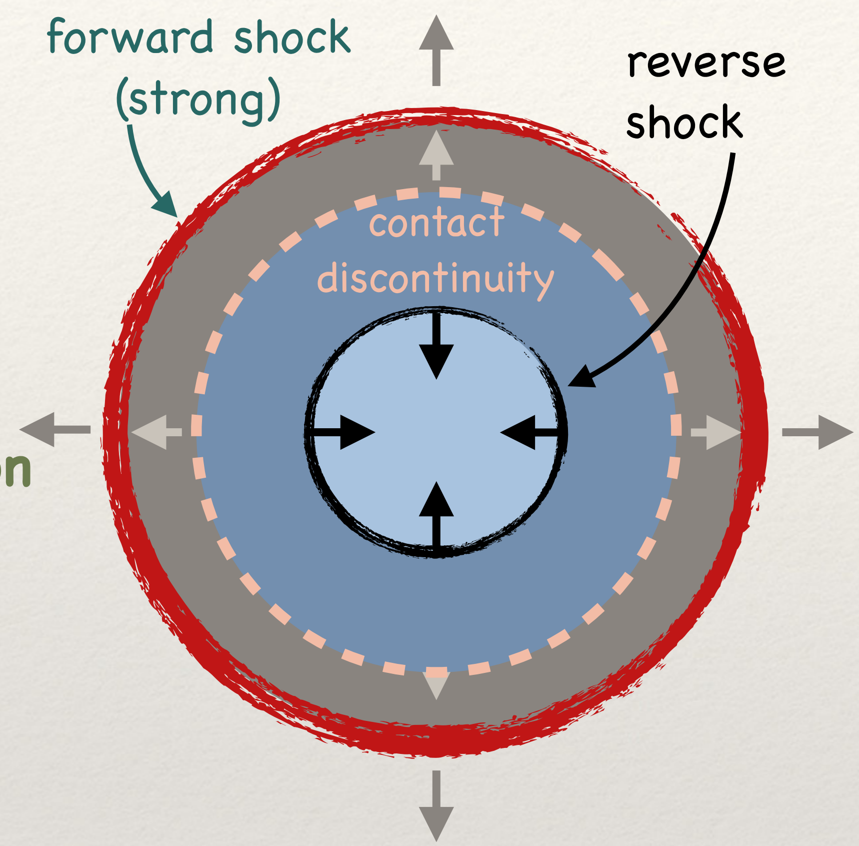
- Not accounting for WR stars

- Not accounting for failed supernovae ~10% of the total [Adams et al. (2017, MNRAS 469)]

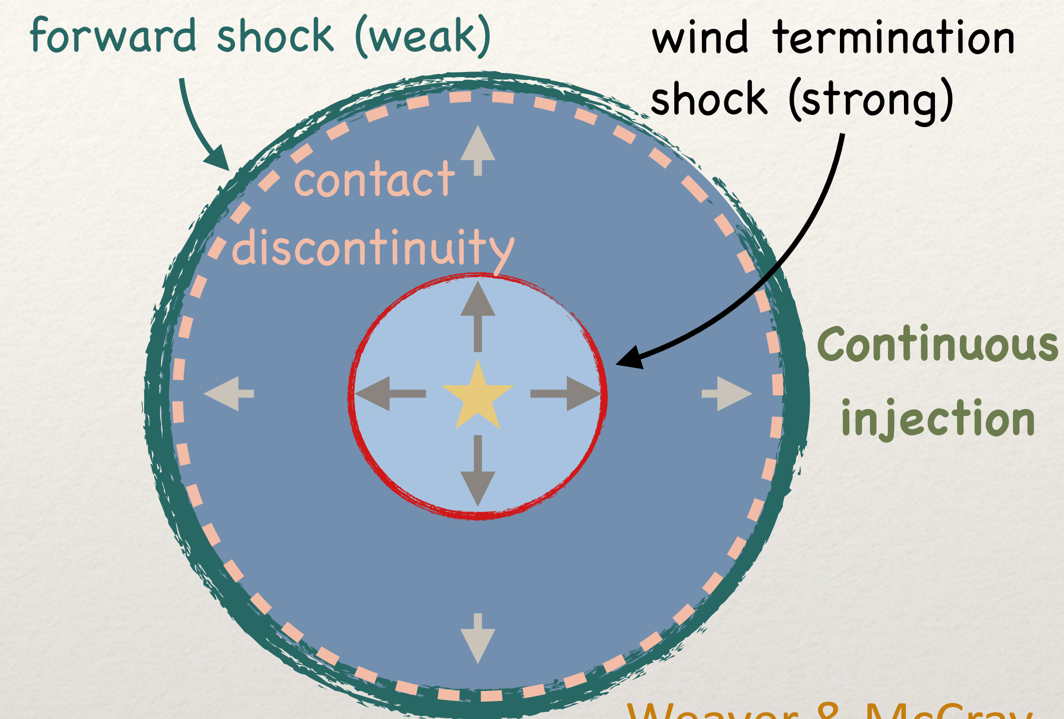
Stellar winds vs. SNRs

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

SNR



Wind-blown bubble



Weaver & McCray, ApJ 218 (1977)

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

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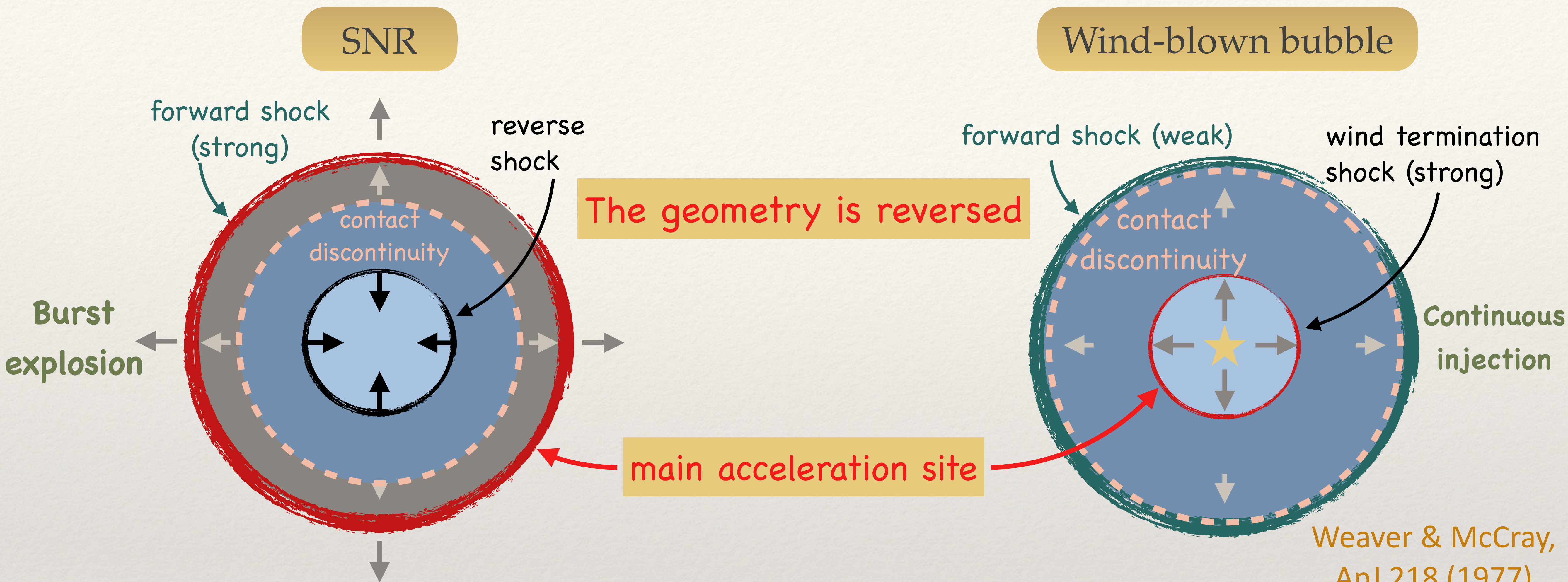

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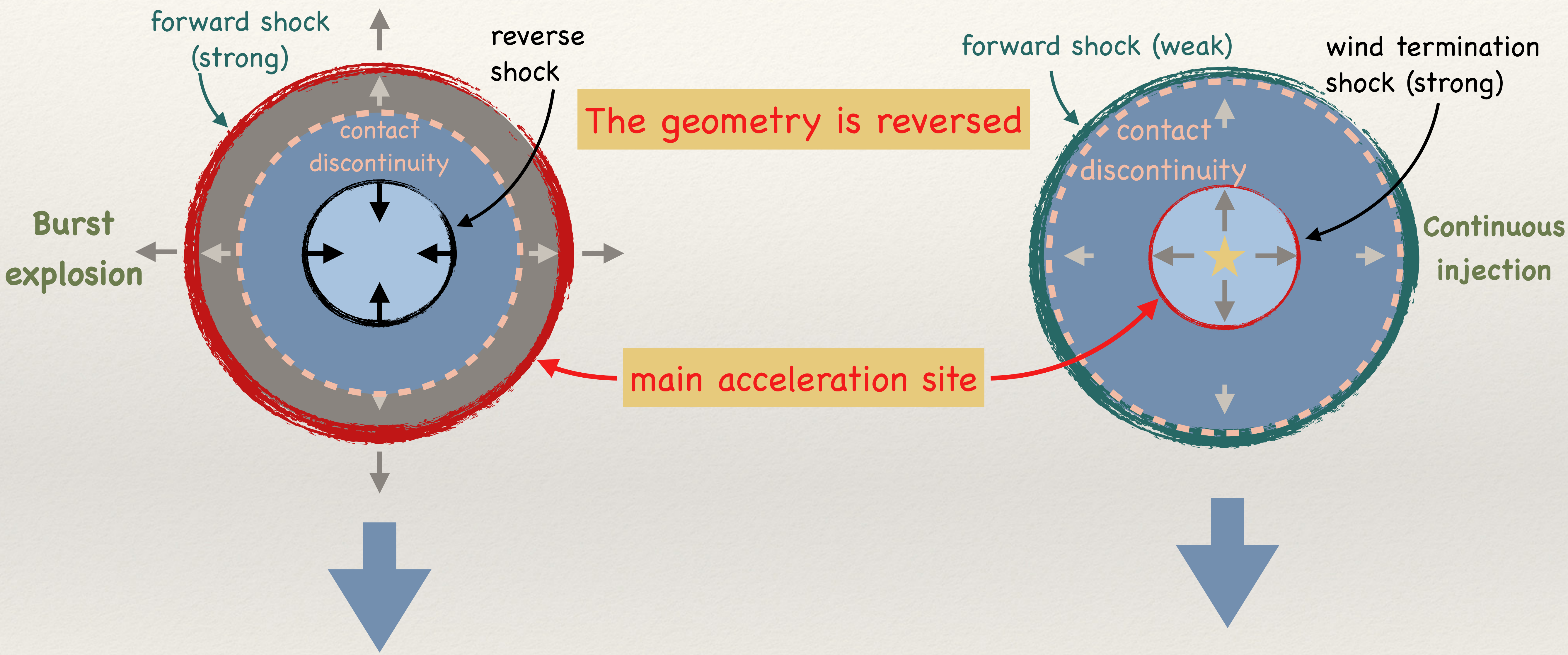


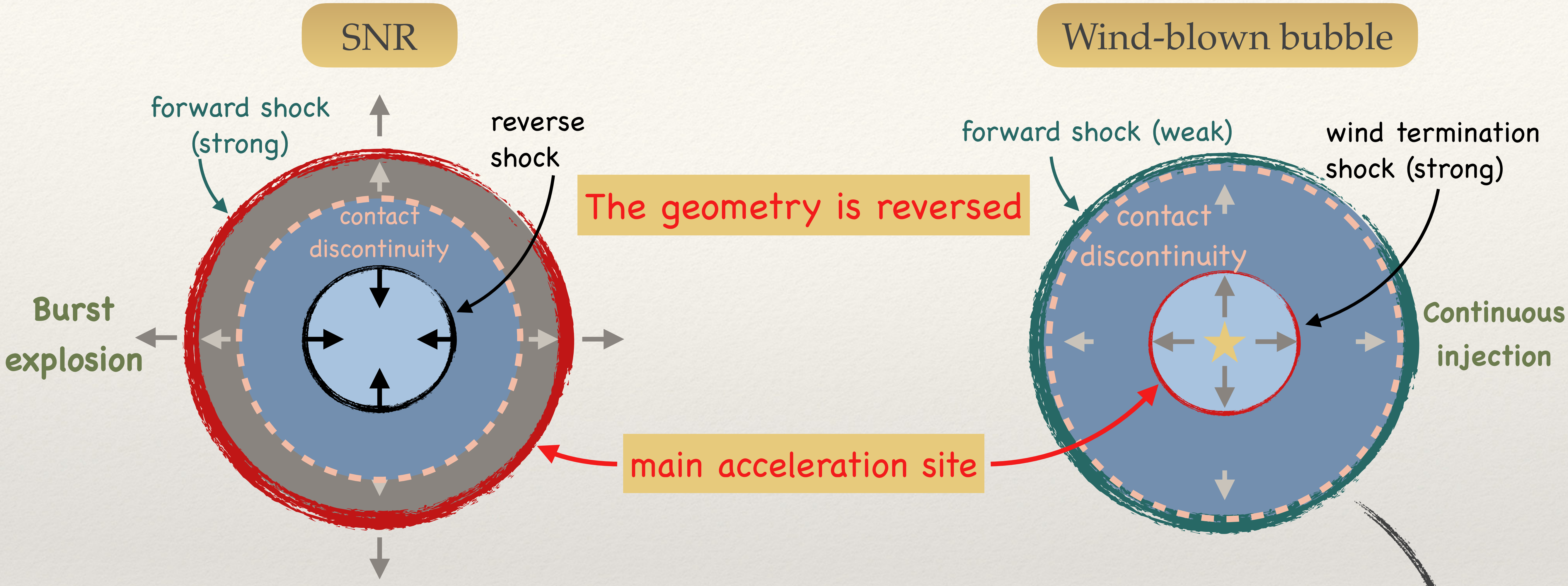
Self-generated by accelerated particles

MAGNETIC FIELD

Amplified by MHD turbulence in the wind

Stellar winds vs. SNRs

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



We need to solve the transport equation in spherical coordinates

$$r^2 u(r)\frac{\partial f}{\partial r} = \frac{\partial}{\partial r}\left[r^2 D \frac{\partial f}{\partial r}\right] + \frac{1}{3}\frac{\partial}{\partial r}\left[r^2 u\right] p \frac{\partial f}{\partial p} + r^2 Q(r,p)$$

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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Standard power-law for plane shocks

$$s = \frac{3u_1}{u_1 - u_2}$$

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$$s = \frac{3u_1}{u_1 - u_2}$$

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

Maximum energy: a more detailed analysis

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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

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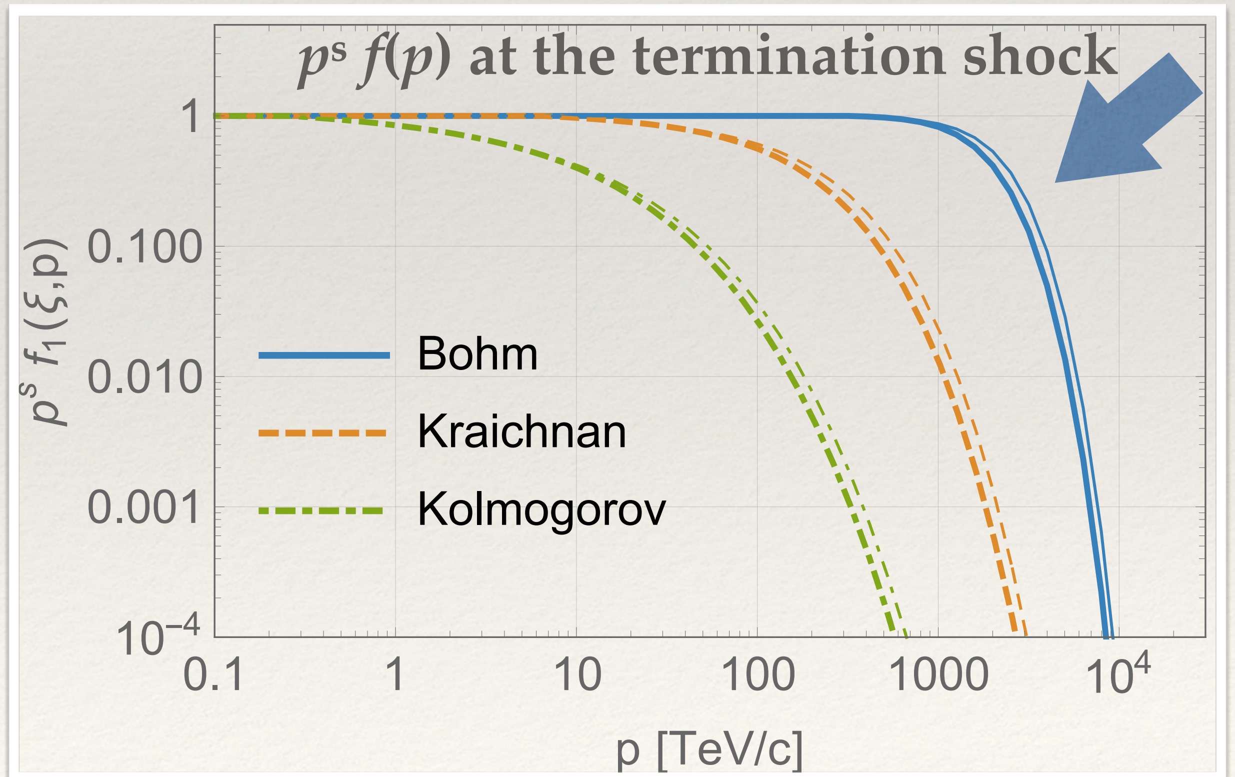
Maximum energy due to escaping from the downstream

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

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



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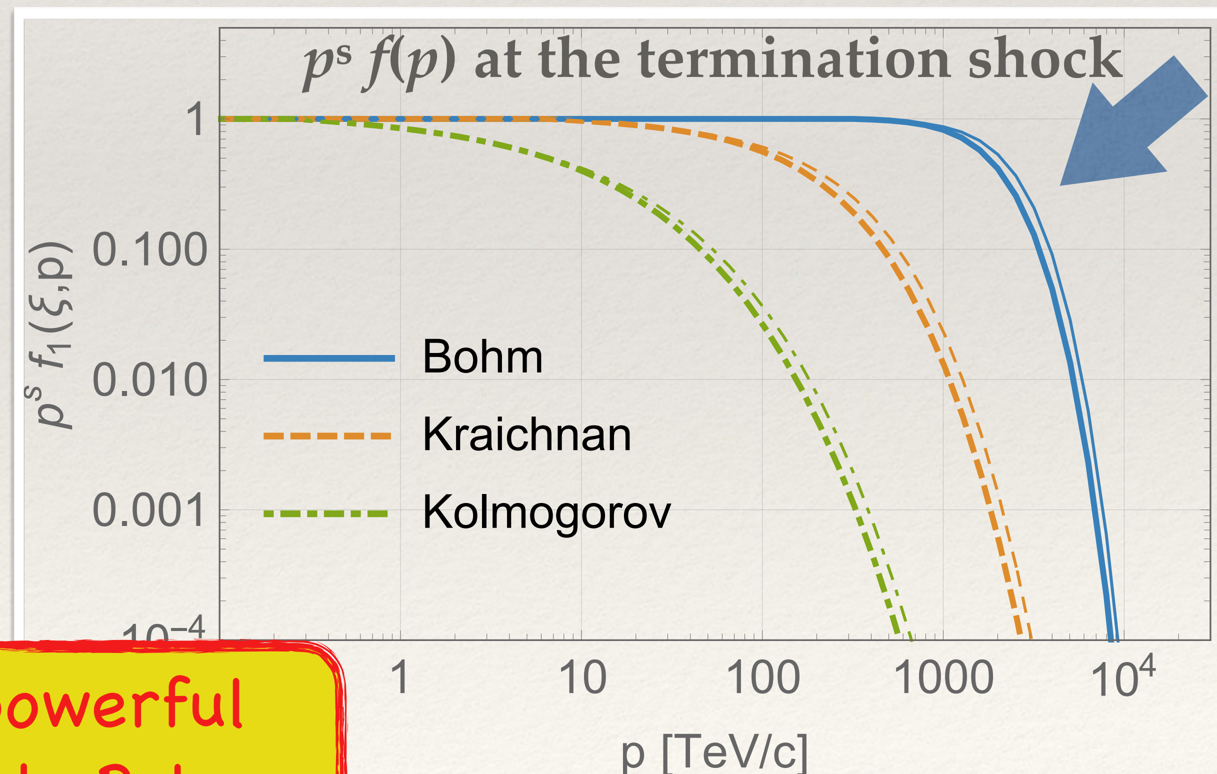
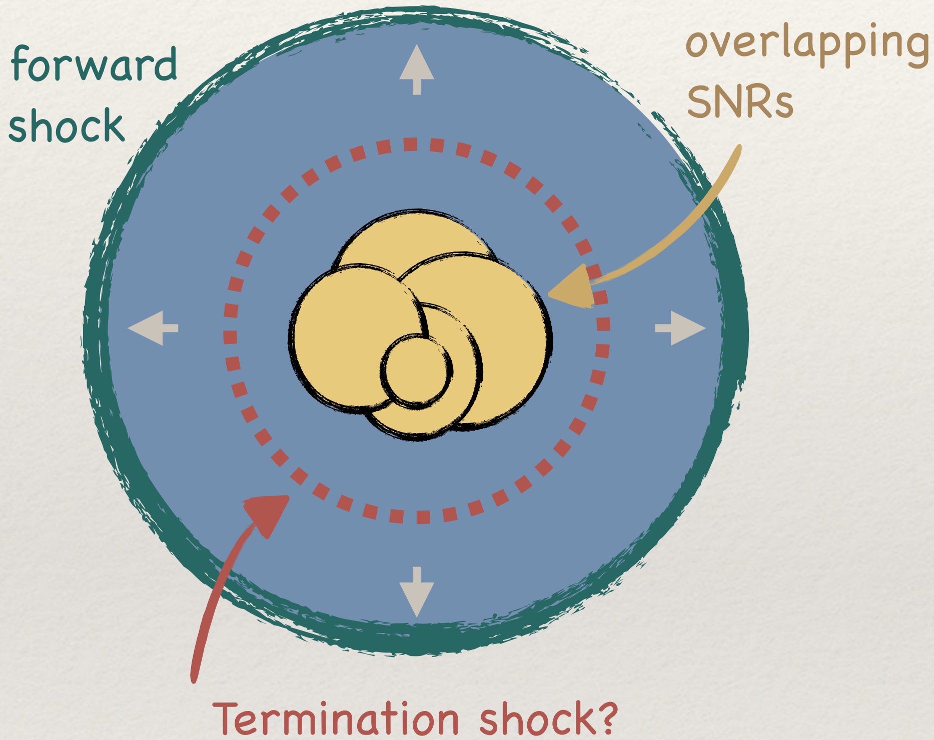


PeV energies can be reached in very powerful stellar clusters if the diffusion is close to Bohm

Old clusters → super-bubbles

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



- Does the TS still exist?
- The turbulence in the bubble remains high due to wind and SN explosions
  ➡ Efficient particles confinement in the bubble
- Maximum energy probably similar to the WTS case

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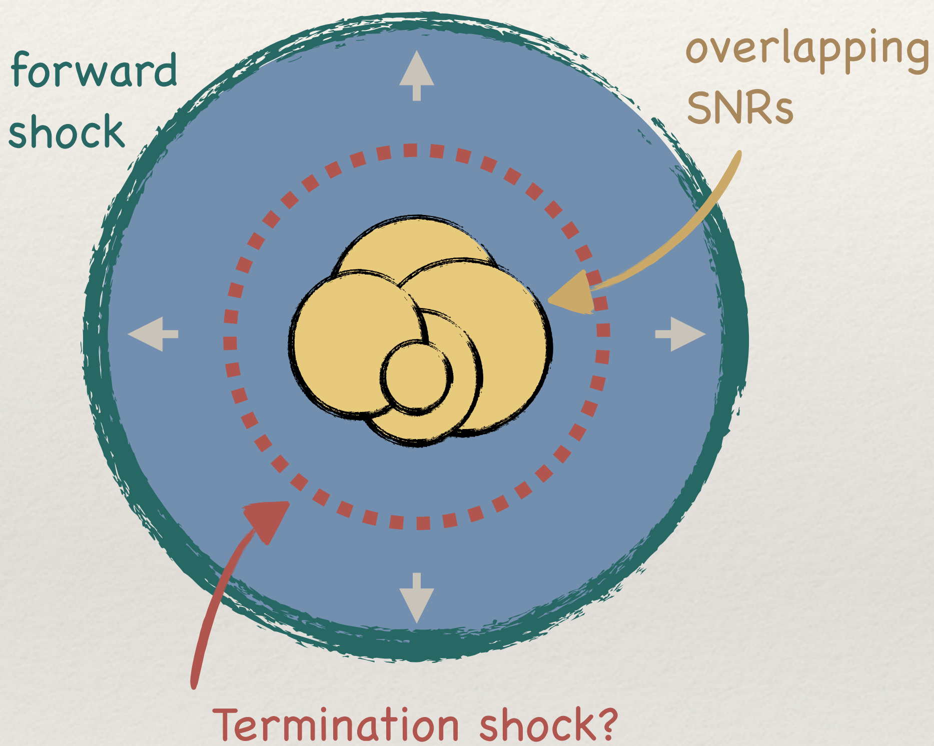
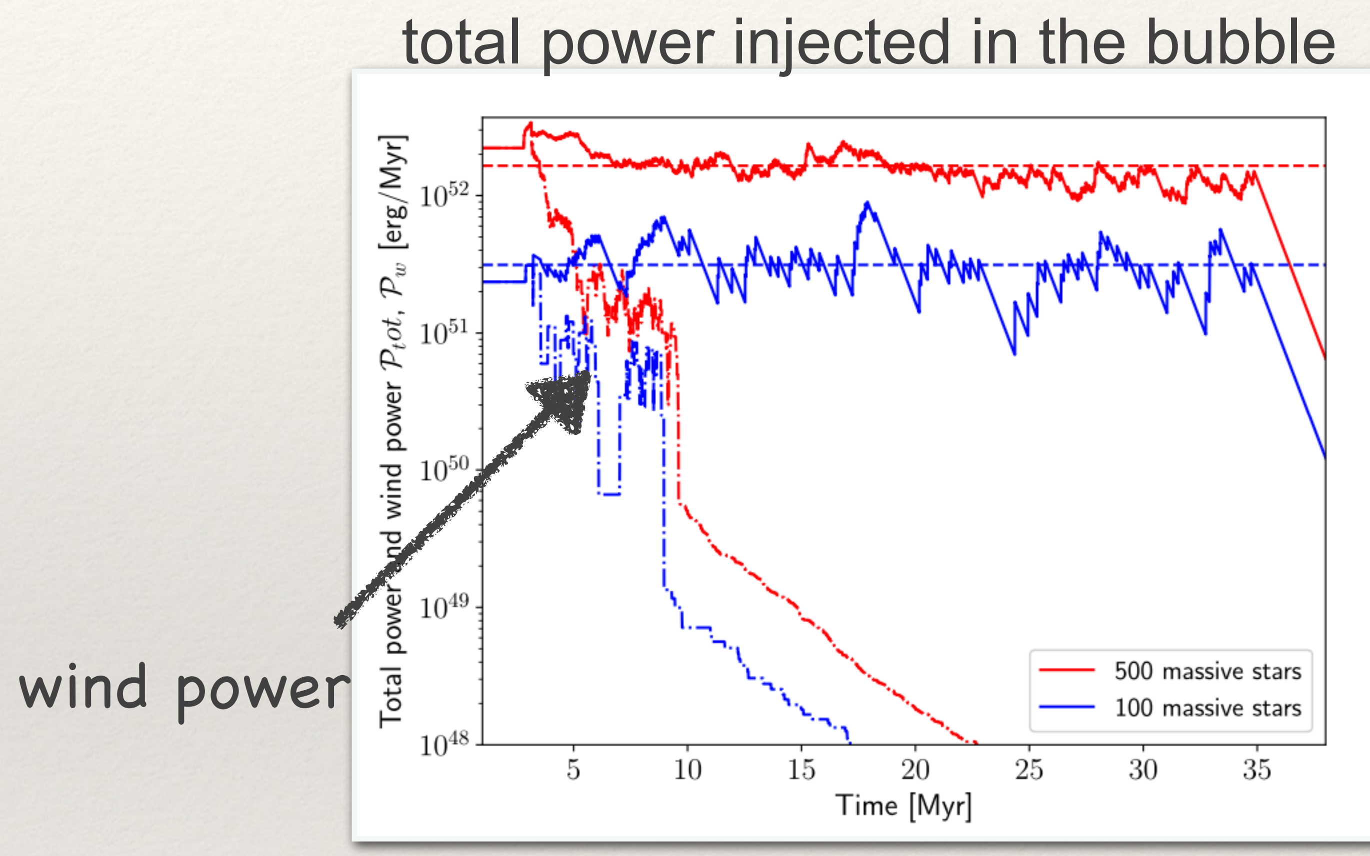


Vieu et al. (2022)



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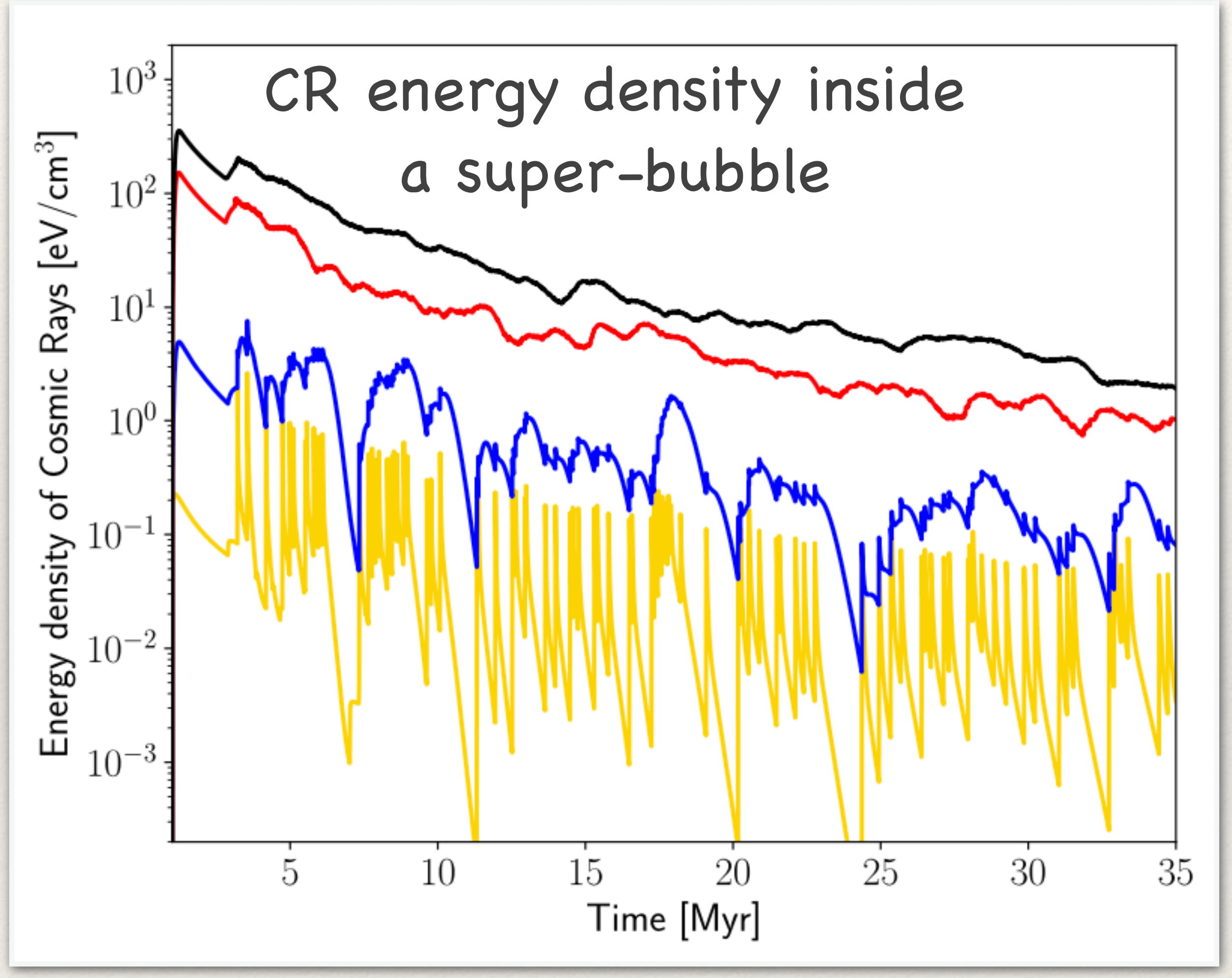
Particle acceleration in super-bubbles: intermittency

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

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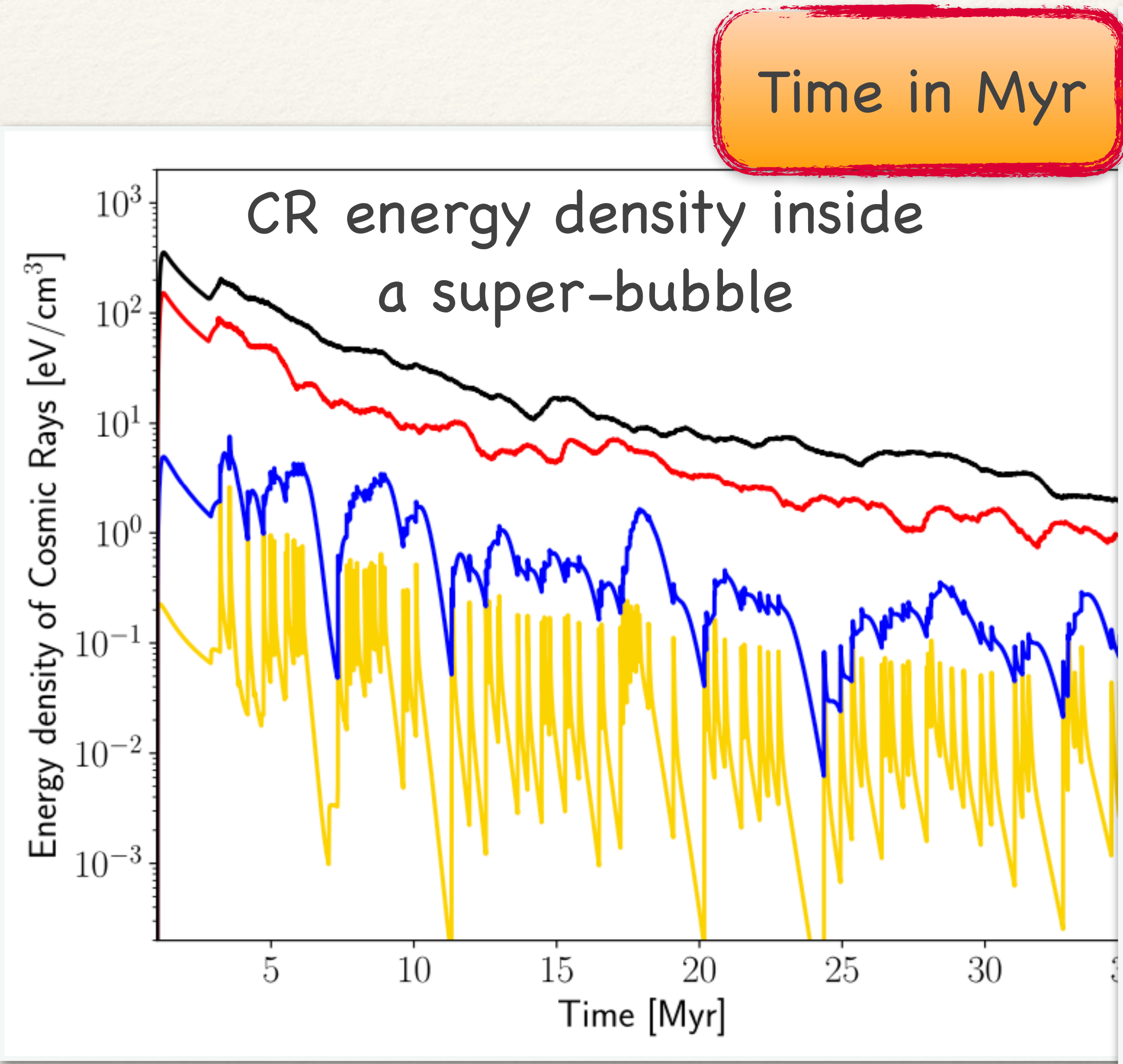
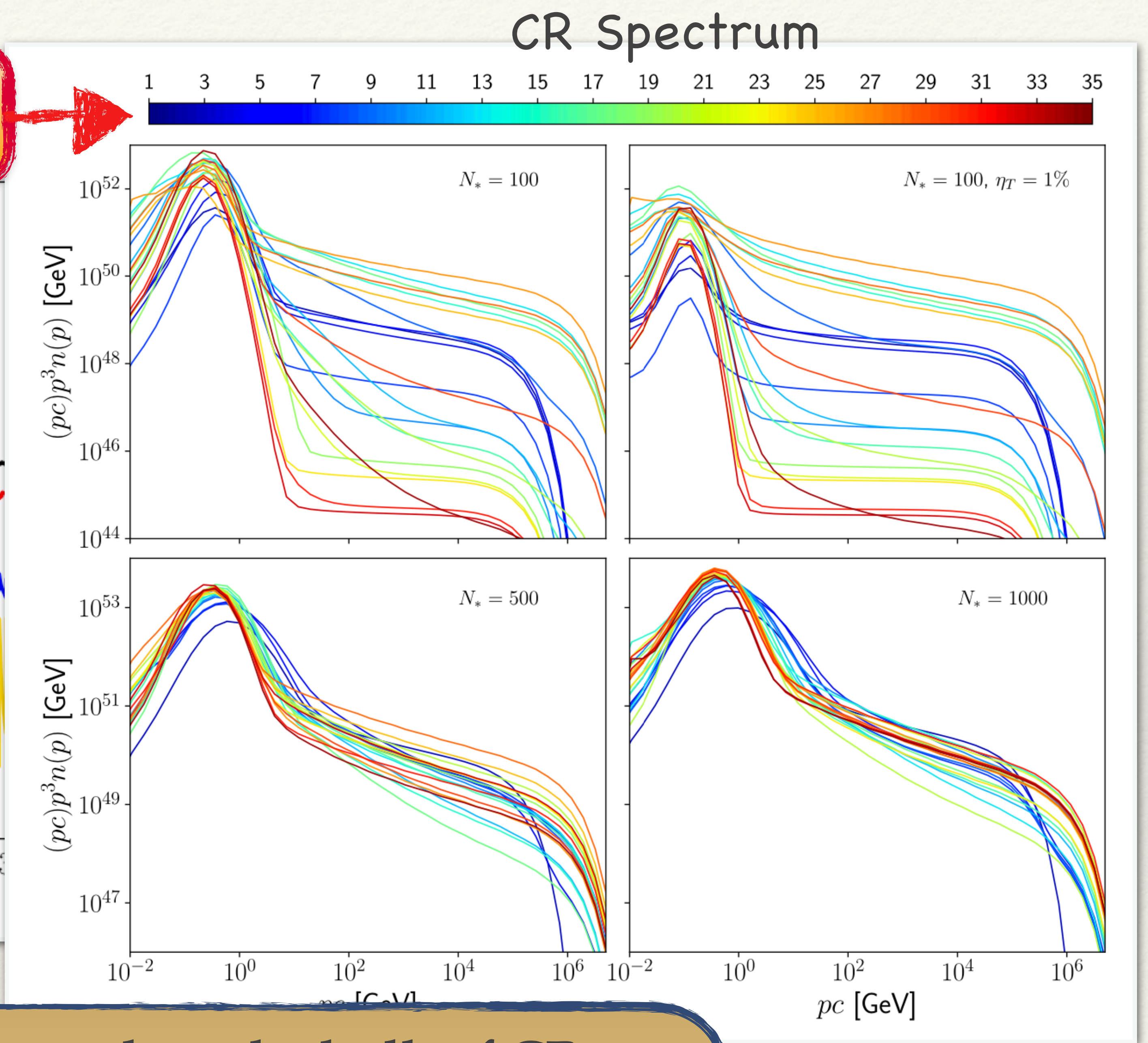




- **Energetically Super-bubbles may produce the bulk of CRs**
- **Maximum energy can reach ~PeV**
- **The spectrum is not universal -> strong intermittency**

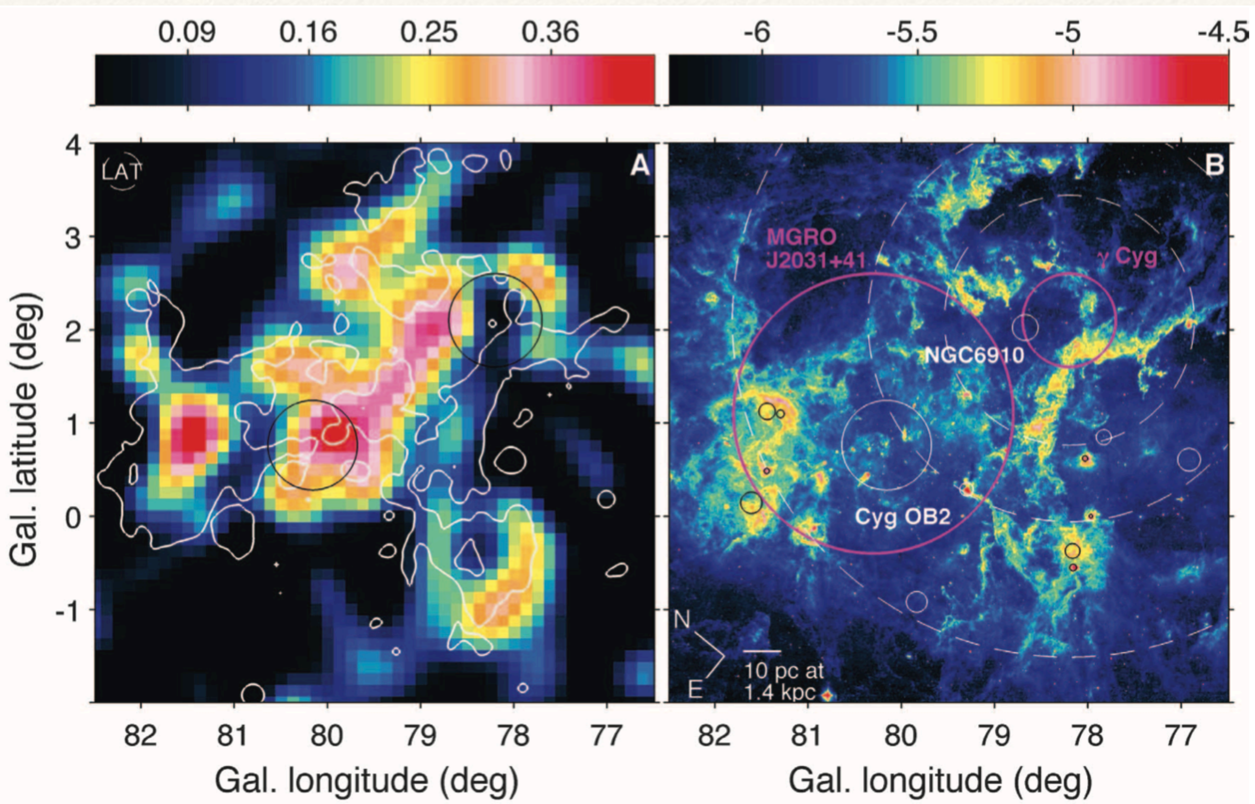
YSCs detected in gamma-rays

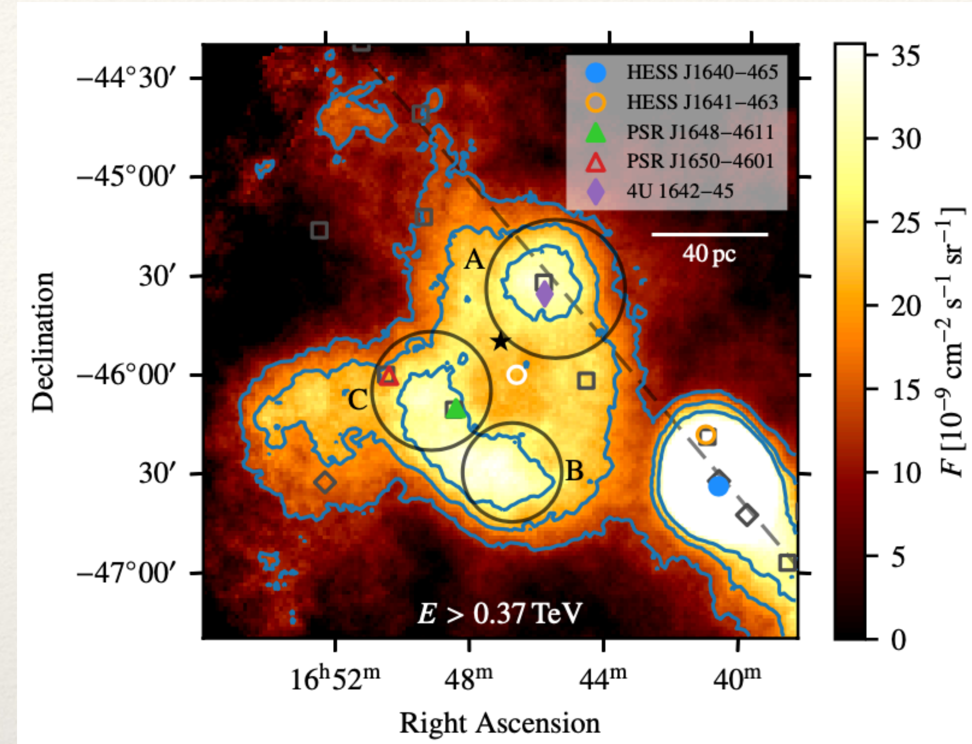
Recently several massive star clusters have been associated with gamma-ray sources

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

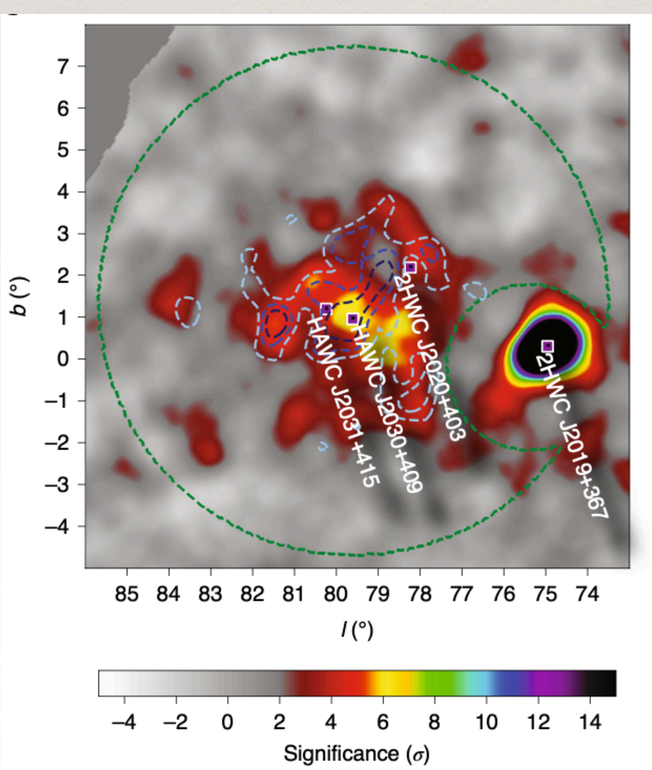
YSCs detected in gamma-rays

Cygnus Cocoon FermiLAT - Ackermann et al. (2011)



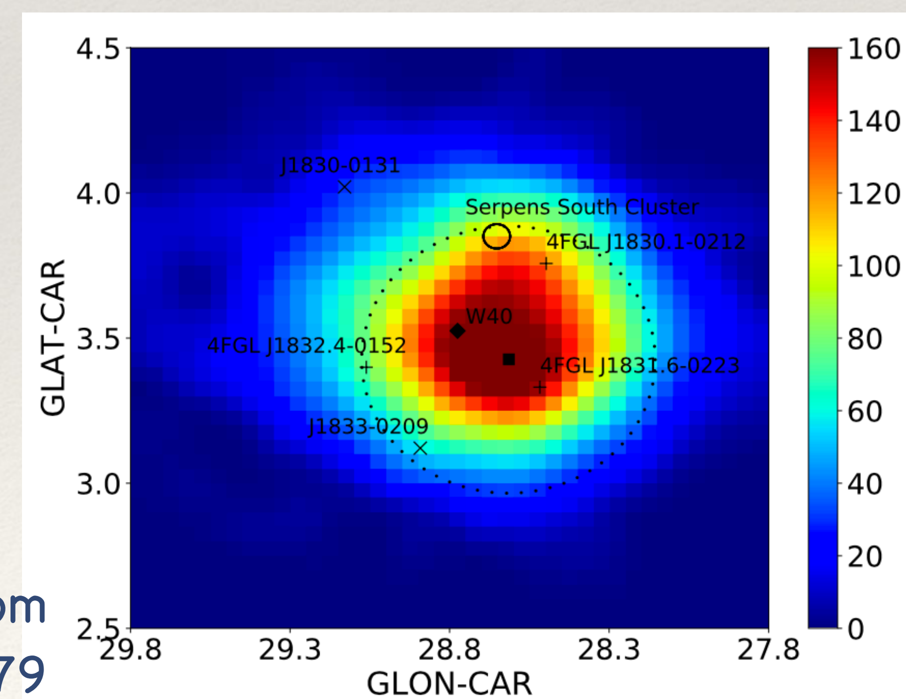


Westerlund 1
HESS coll. A&A (2022)



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

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

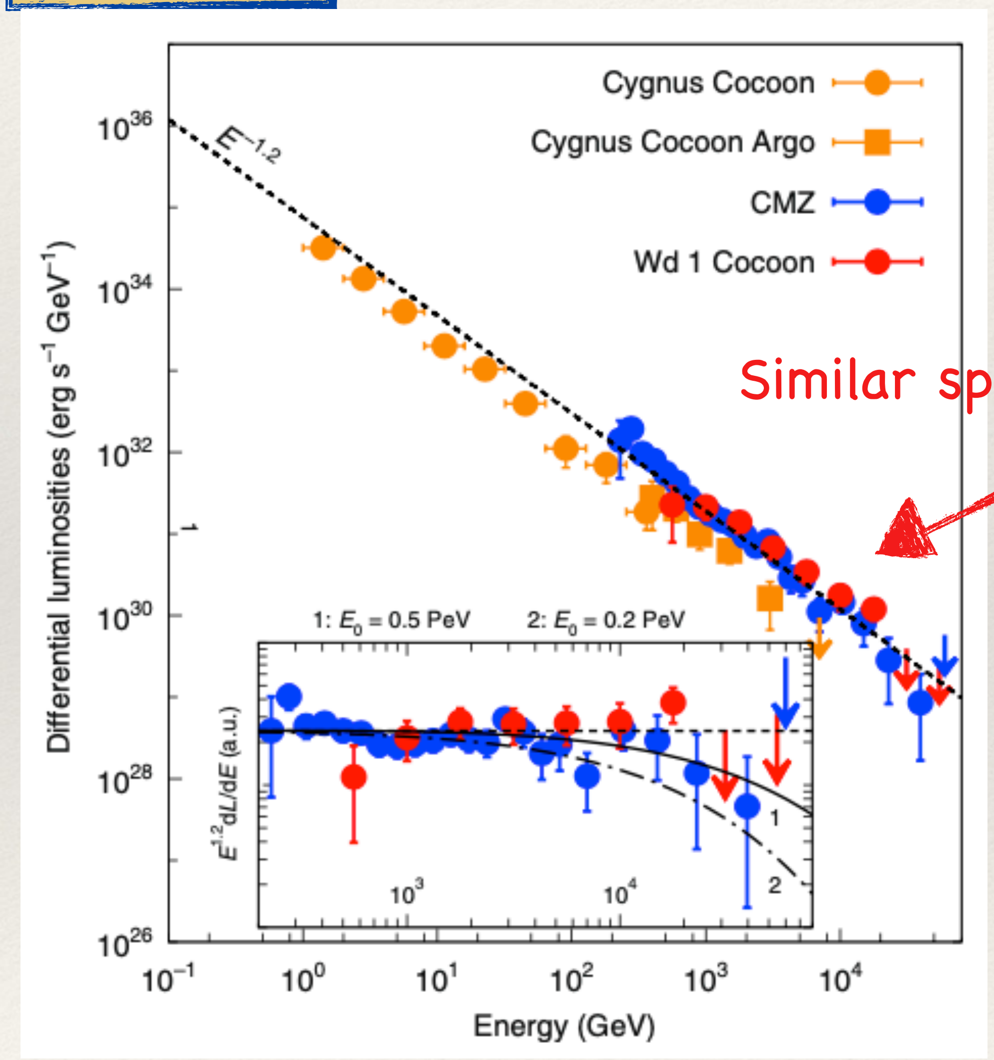


YSCs detected in gamma-rays

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

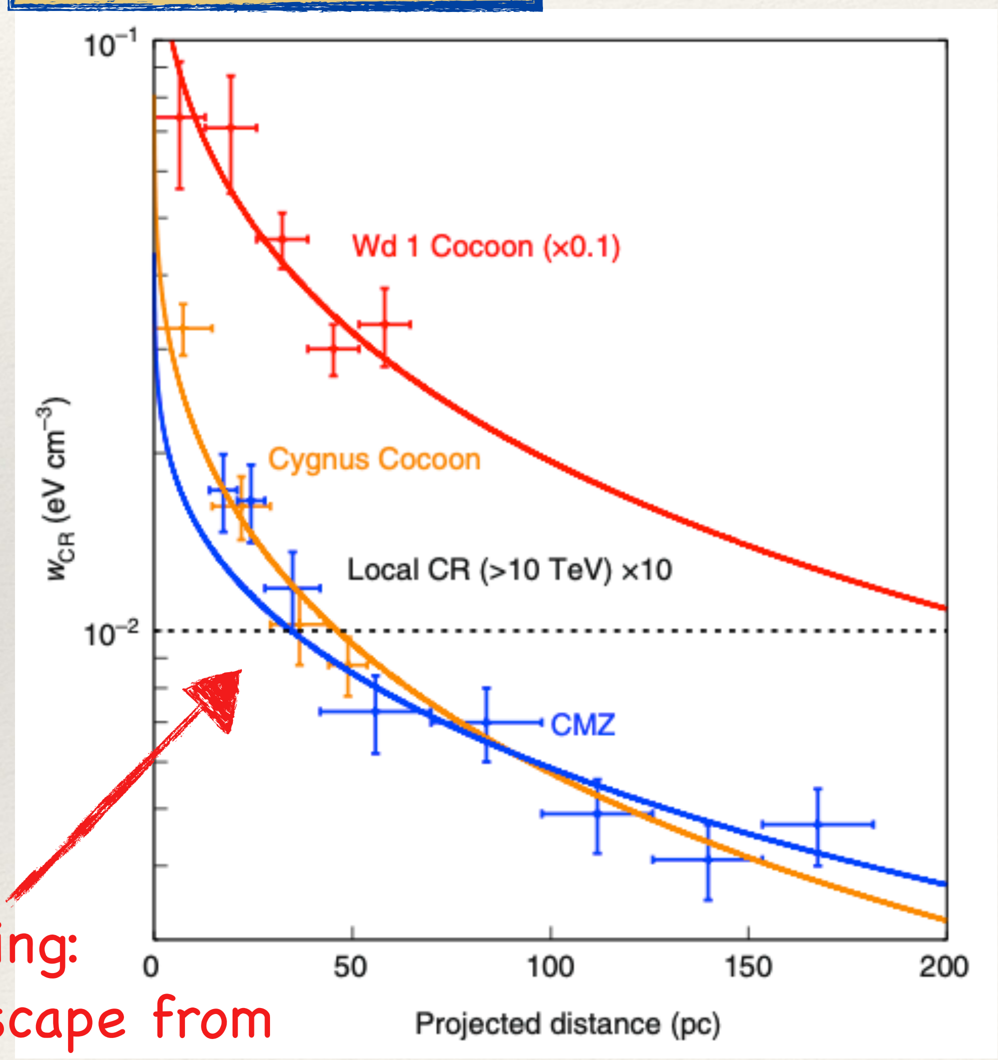
Some clusters show similar spectra and radial profile

Spectrum



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

Radial CR profile



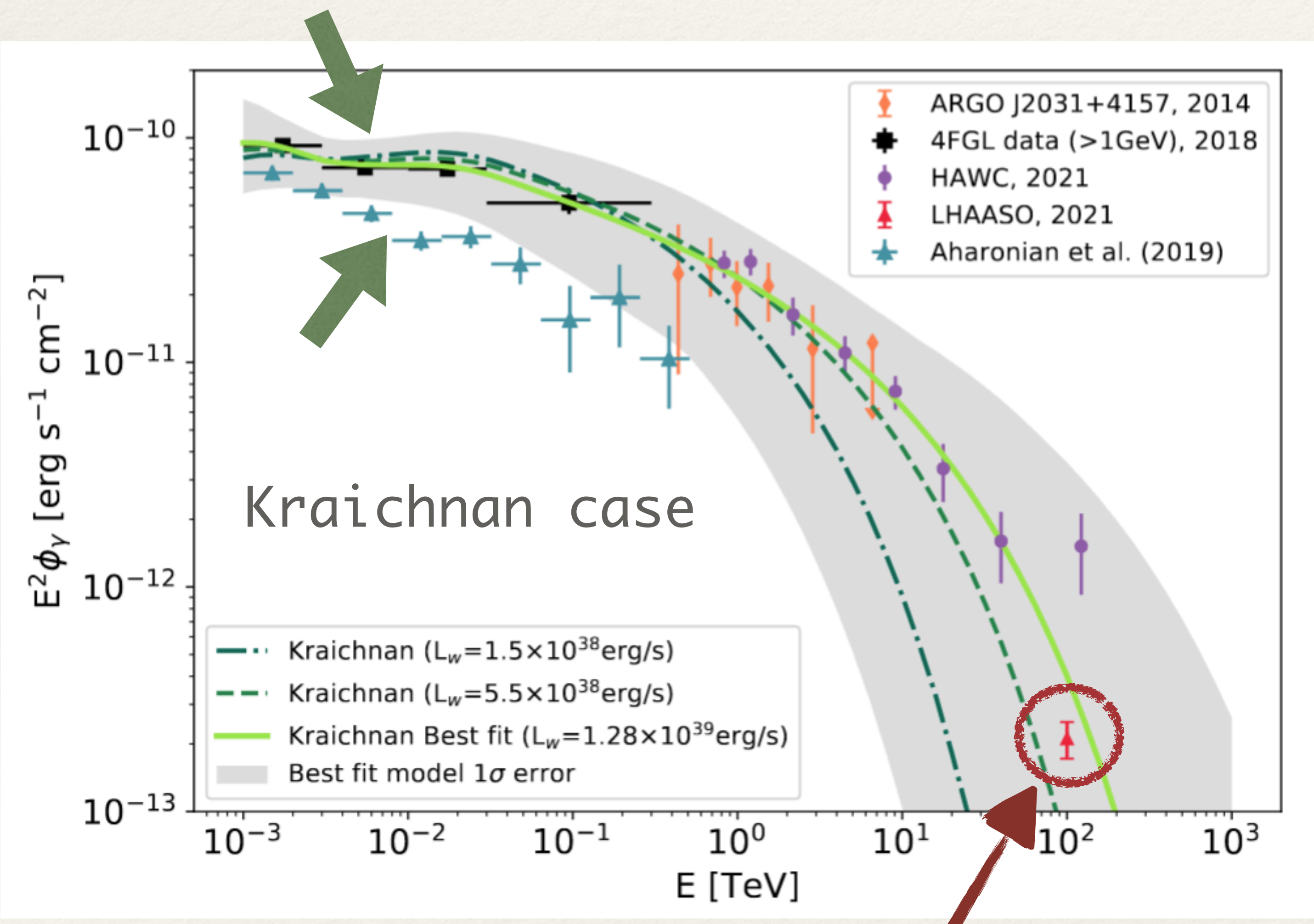
1/r scaling:
CR diffusive escape from
continuous point source?

The case of Cygnus Cocoon

[S. Menchiari et al. in preparation]

LHAASO has detected photos up to 1.4 PeV!

However, looking at the present data we infer $E_{max} \sim 100$ TeV



LHAASO spectrum not published yet

Some caveats:

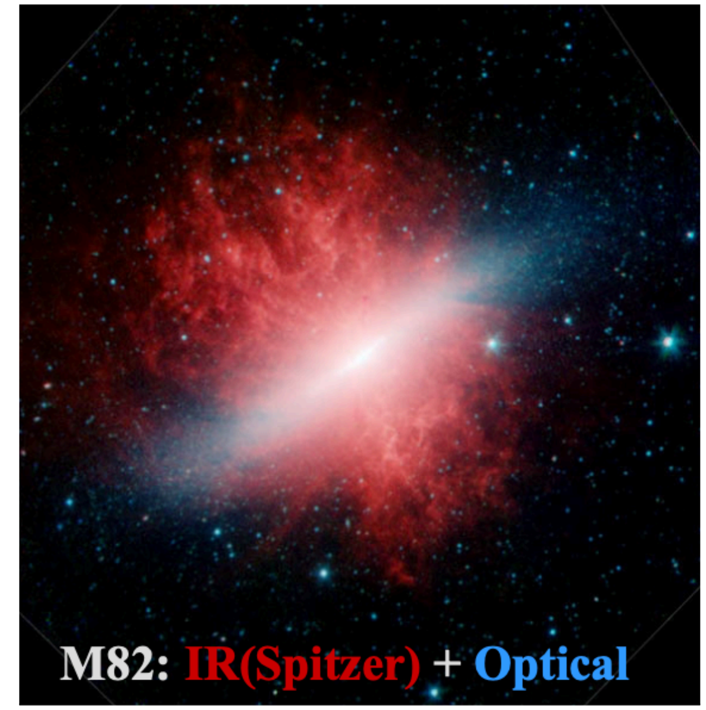
- The analysis is difficult de to the **extended nature of the source**: different analysis of Fermi-LAT data gives different results
- In comparing different experiments we need to correctly account for the **different extraction area**: LHAASO data-point is not used for the fit because the extraction area is not specified

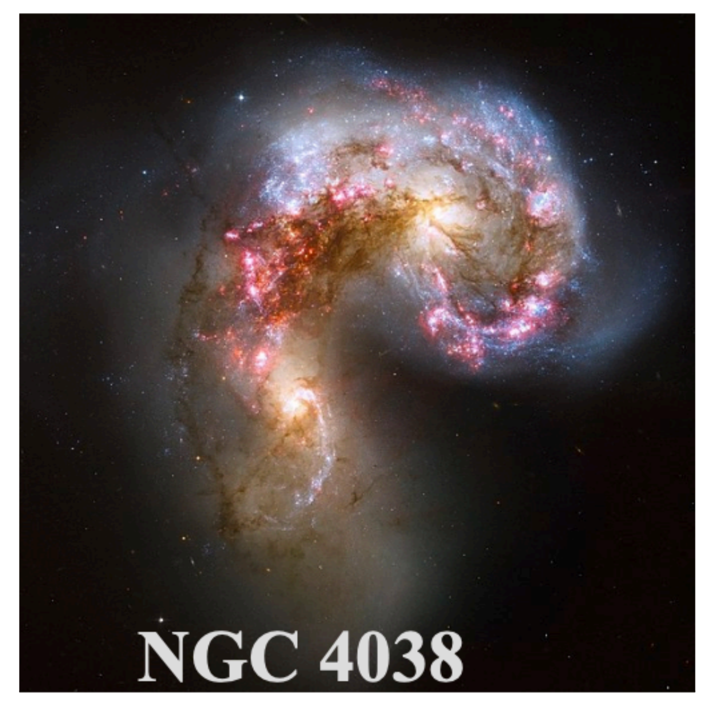
Extra-galactic context: SNR and starburst galaxies

Starburst Galaxies

OUTLINE

- Why Starburst Galaxies are interesting?
- Observation of Starburst Galaxies
- Possible acceleration regions:
    - Starburst nuclei
    - Starburst-driven winds
- Diffuse emission from Starburst Galaxies





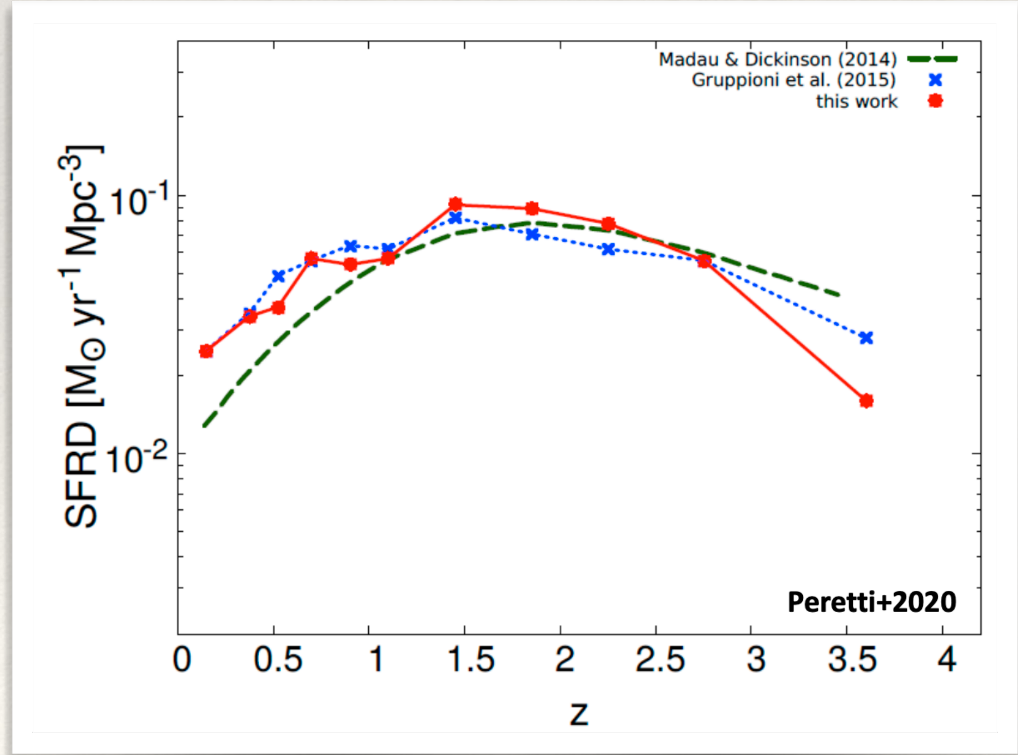
Starburst Galaxies

SB galaxies are usually associated to events of galaxy mergers

- High star formation rate (10-100 times the Milky Way) in a small region (~200 pc)

  $\Rightarrow$ large SN rate $\Rightarrow$ high CR production

- High level of turbulence $\Rightarrow$ efficient CR confinement $\Rightarrow$ Calorimetry?
- High gas density $\Rightarrow$ efficient γ and ν production
- Abundant at high redshift $\Rightarrow$ Contribution to diffuse flux?



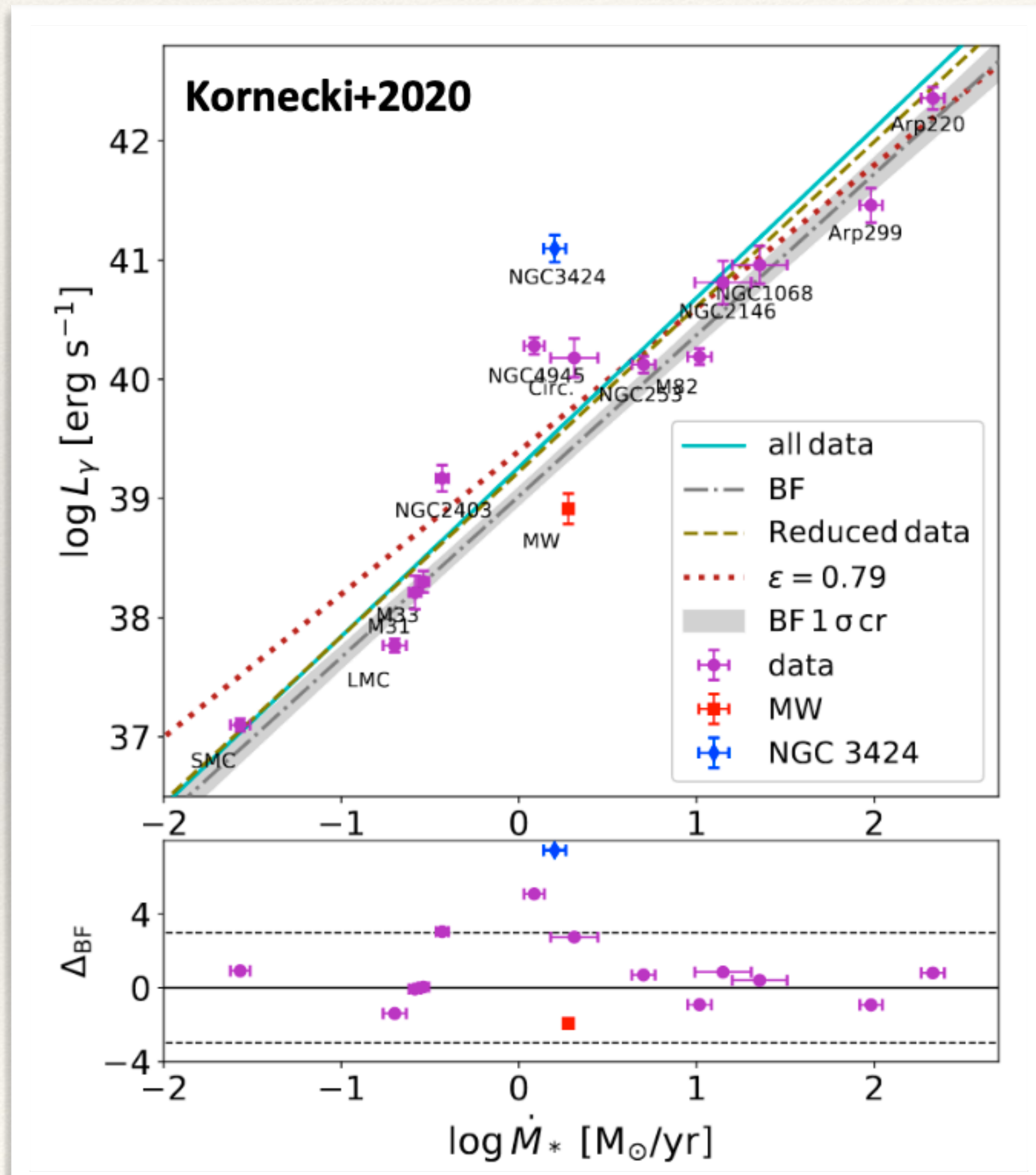
Typical starburst environment

- SFR $\simeq 10 - 100\ M_{\odot}\mathrm{yr}^{-1}$
- Average ISM density $n \simeq 10^2 - 10^3\ \mathrm{cm}^{-3}$
- Magnetic field $B \simeq 50 - 250\ \mu\mathrm{G}$
- Radiation field density $U_{\mathrm{rad}} 10^3\ \mathrm{eV\ cm}^{-3}$
- Wind velocity $v_{\mathrm{wind}} \simeq 500\ \mathrm{km/s}$
- Supernova rate $\mathscr{R}_{\mathrm{SN}} \simeq 0.03 - 0.3\ \mathrm{yr}^{-1}$
- Starburst lifetime $\simeq 10$ Myr

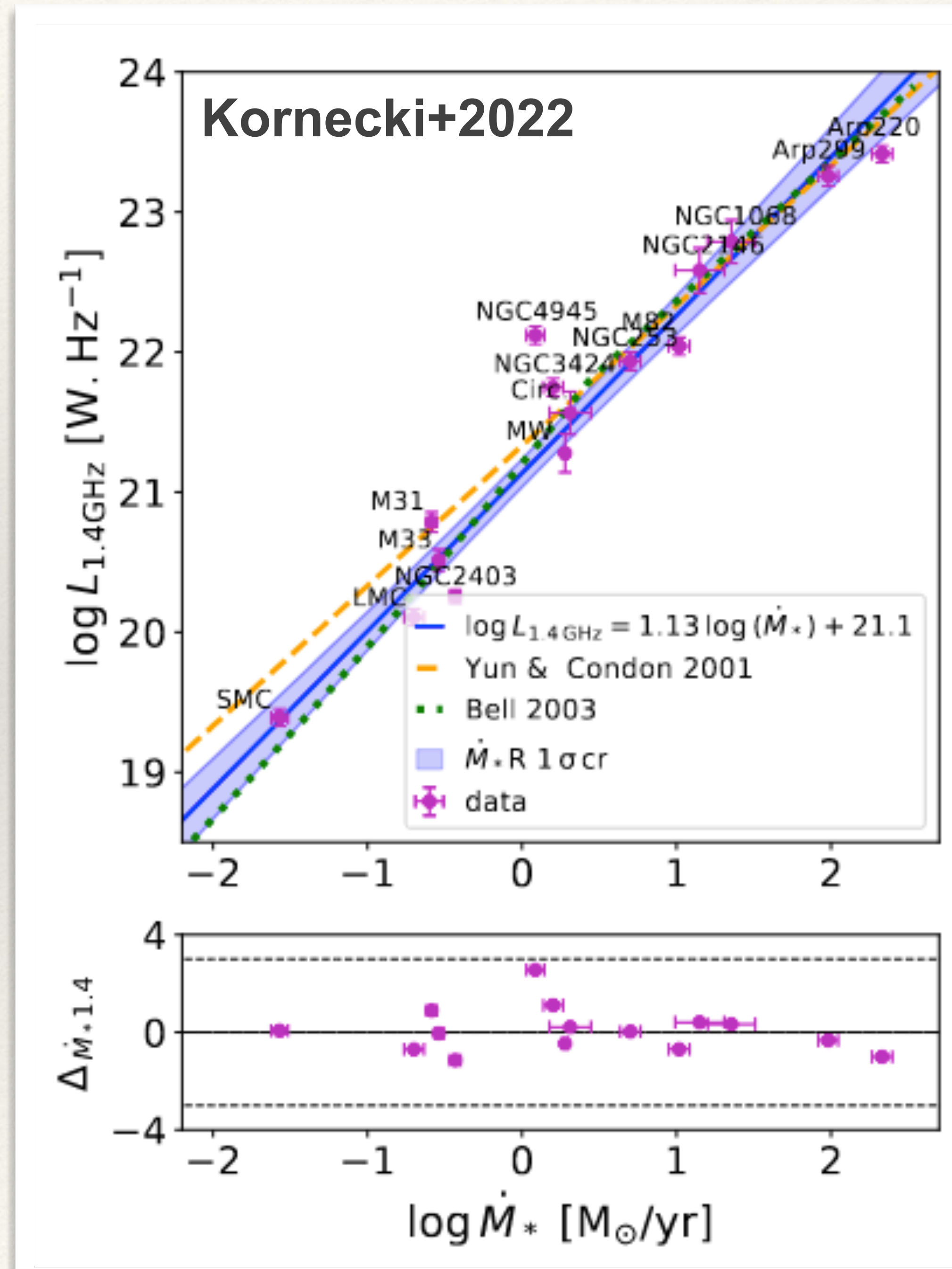
Observation of Starburst Galaxies - gamma

Star formation rate correlate with non-thermal emission

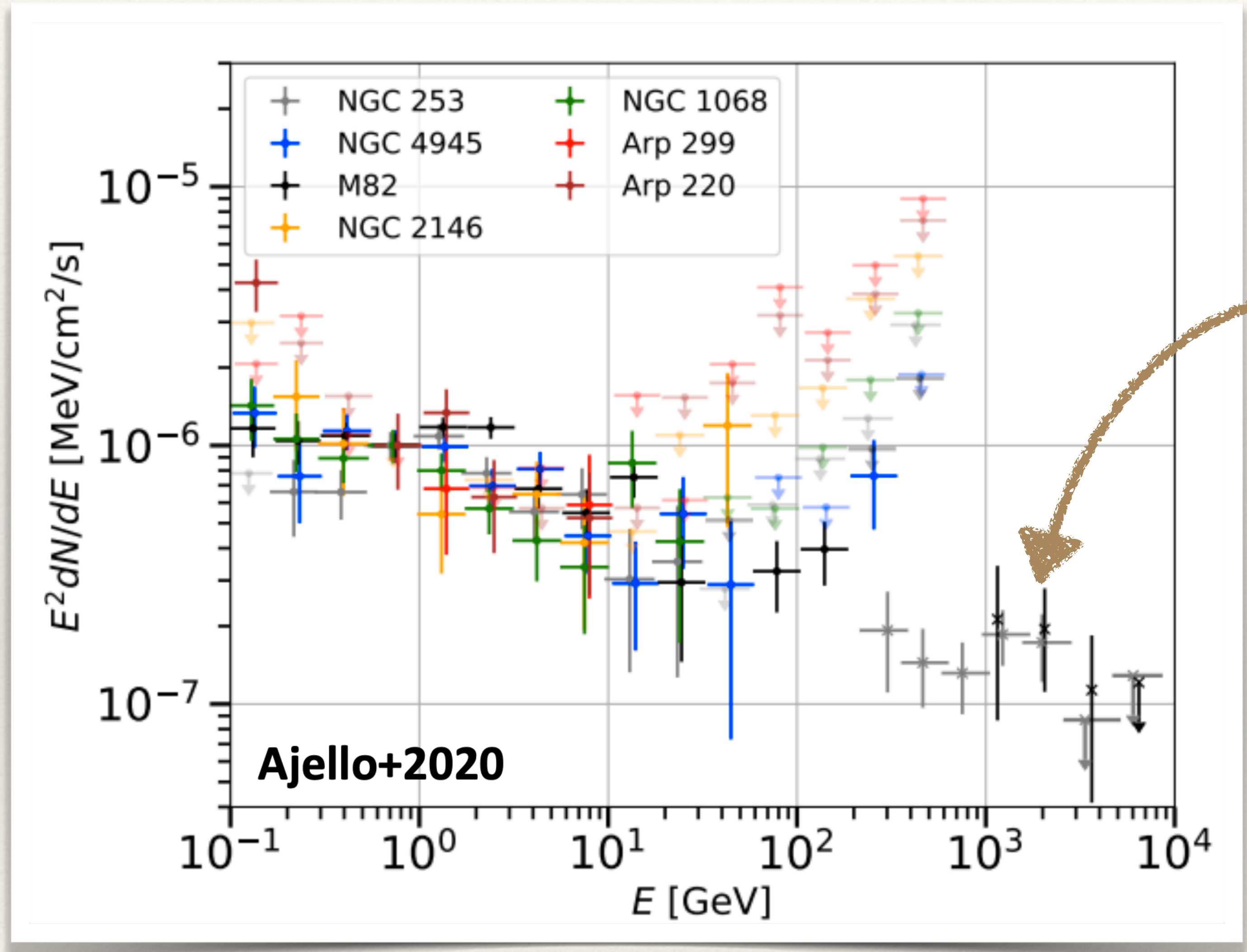
Gamma-ray



Radio



Observation of Starburst Galaxies - gamma



- Many SB observed at GeV
- Most nearby also detected at TeV

  M82, NGC 253 (<4 Mpc)
- Most distant source: Arp 220 (77 Mpc)
- Observed spectrum usually hard:

  $\sim E^{-2.2} \div E^{-2.3}$

CR propagation and confinement in SB nuclei

[Peretti, Blasi, Aharonian, GM (2019)]

We adopt a leaky-box model

$$\frac{f(p)}{\tau_{\rm loss}} + \frac{f(p)}{\tau_{\rm adv}} + \frac{f(p)}{\tau_{\rm diff}} = Q_{\rm inj}(p)$$

Injection

$$Q_{\rm inj}(p) = N(p)\,\mathscr{R}_{\rm SN}\,V^{-1}$$

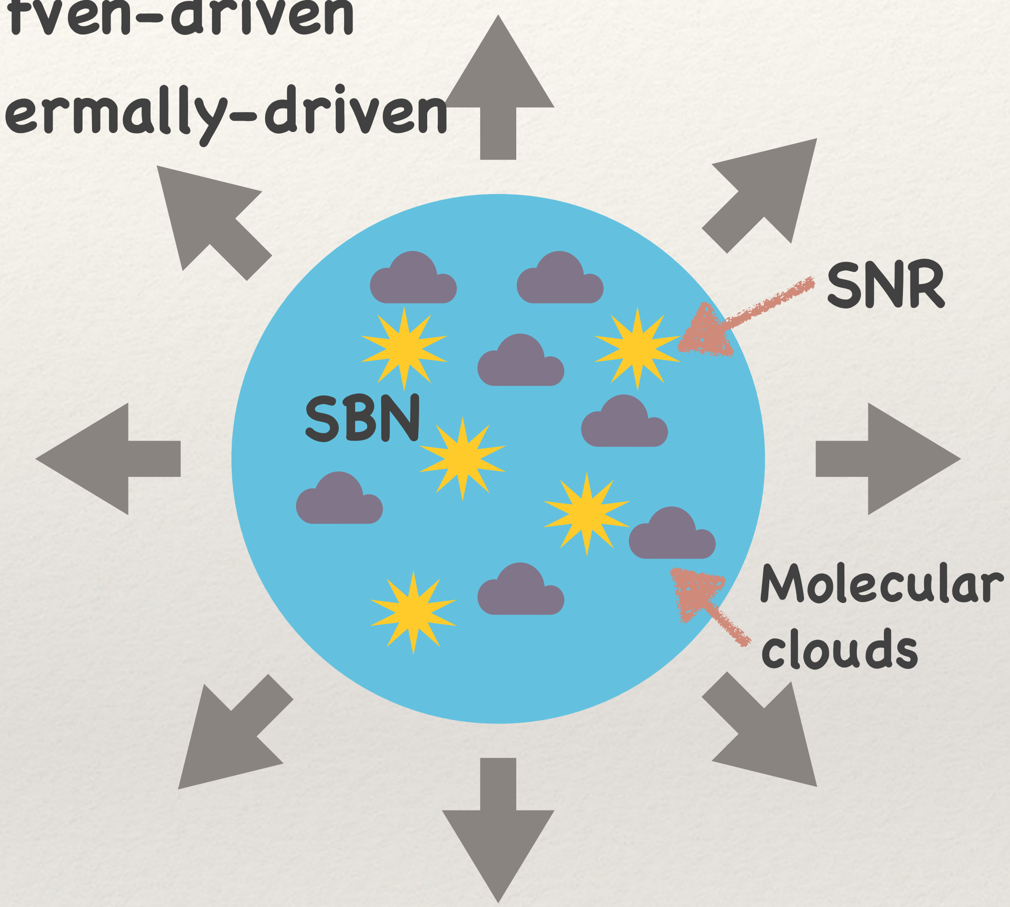
$$N_p(p) \propto p^{-\alpha}\,e^{-p/p_{\rm max}}$$

$$N_e(p) \propto k_{\rm ep}\,p^{-\alpha}\,e^{-(p/p_{\rm max})^2}$$

Losses

$$\frac{1}{\tau_{\rm loss}} = \Sigma_i \left(-\frac{1}{E}\frac{dE}{dt}\right)_i$$

$p \to$ ionisation, p-p collision, Coulomb
$e \to$ ionisation, sync. IC, brem.



CR propagation and confinement in SB nuclei

[Peretti, Blasi, Aharonian, GM (2019)]

Diffusion

$$D(p) = \frac{r_L(p)v}{3}\frac{1}{k_{\rm res}W(k_{\rm res})}$$

Magnetic turbulence

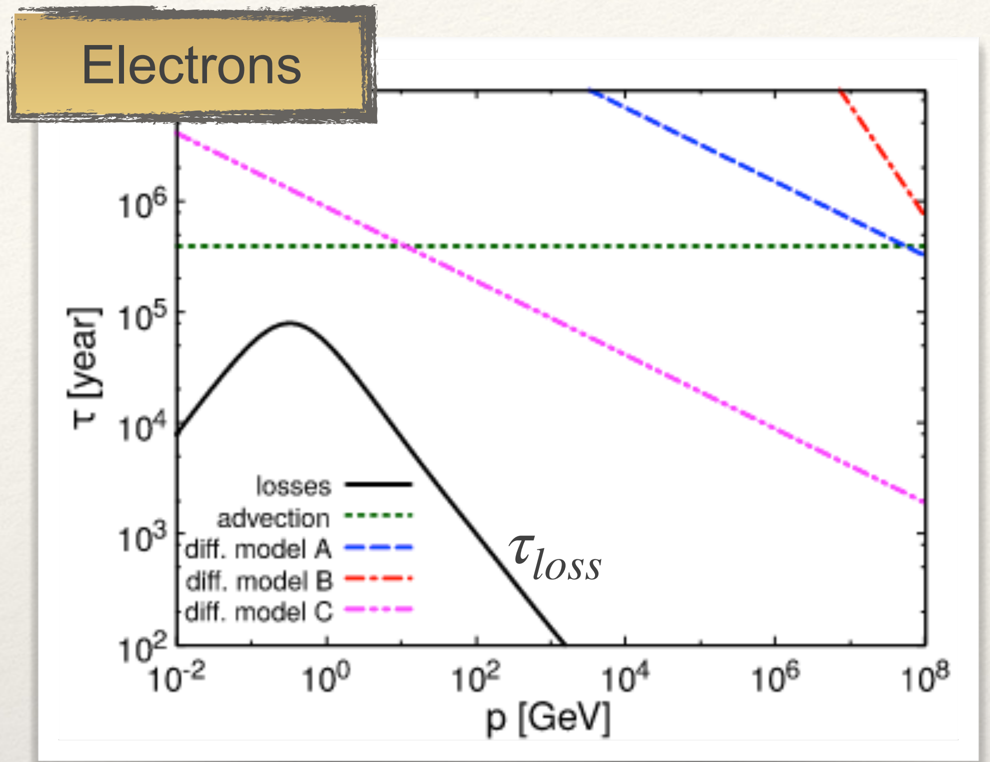
$$W(k) = W_0\left(kL_0\right)^{-d}$$

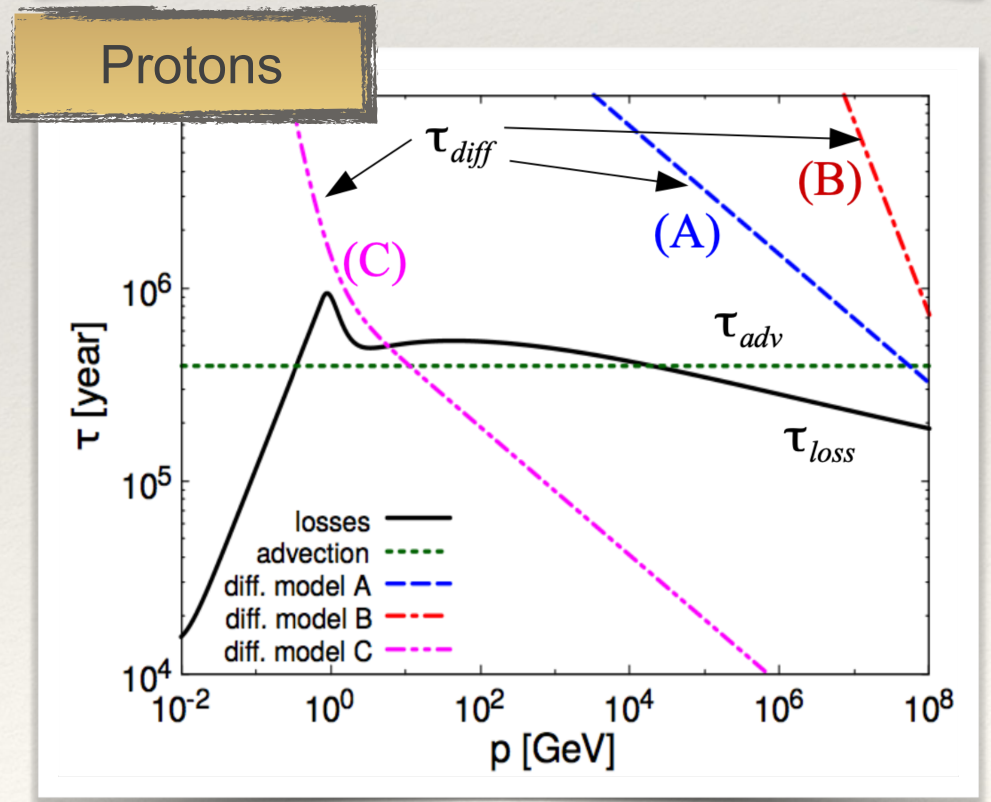
A) Kolmogorov: $d = 5/3$; $L_0 \simeq 1\,\mathrm{pc}$

B) Bohm: $d = 0$

C) Milky Way-like: $d = 5/3$; $L_0 = 100\,\mathrm{pc}$

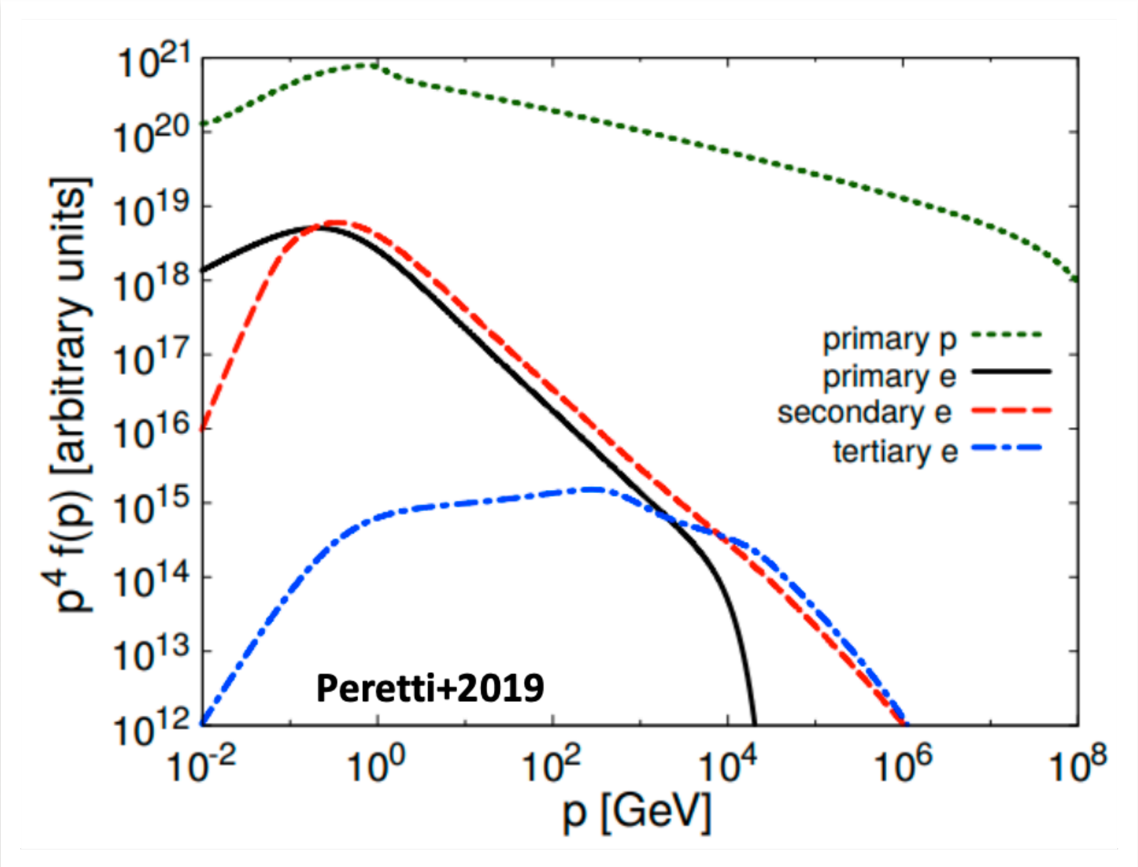
- Electrons are confined in SBNi
- Advection and losses mainly regulate the transport of protons

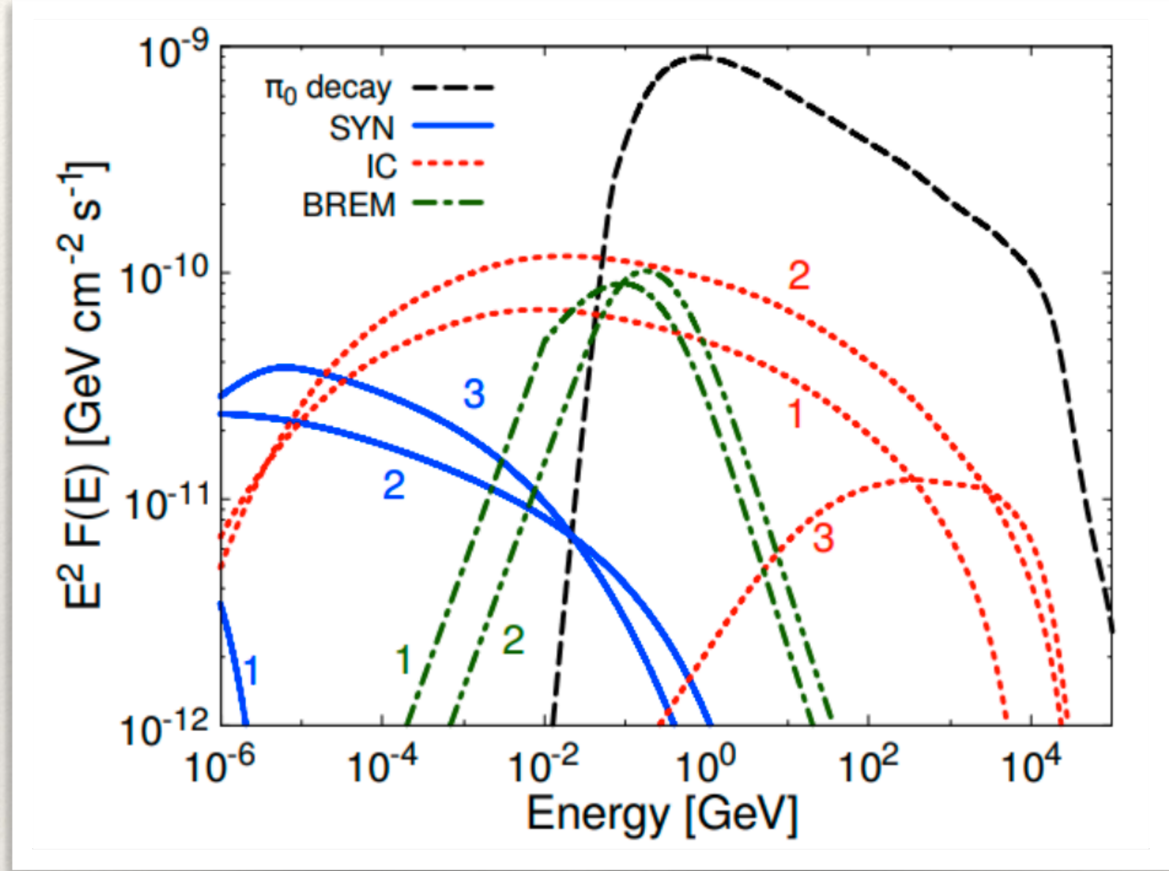




Particle and photon spectra

[Peretti, Blasi, Aharonian, GM (2019)]





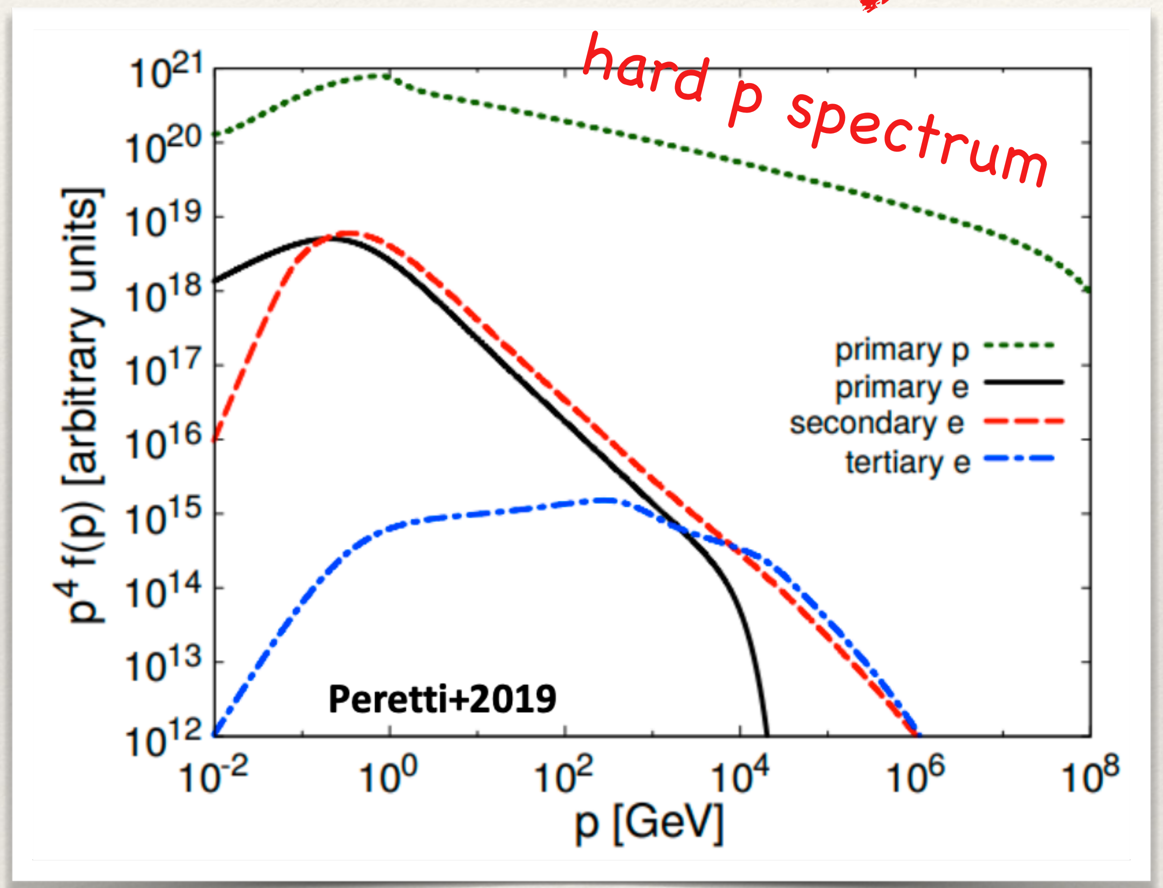
1 → primaries

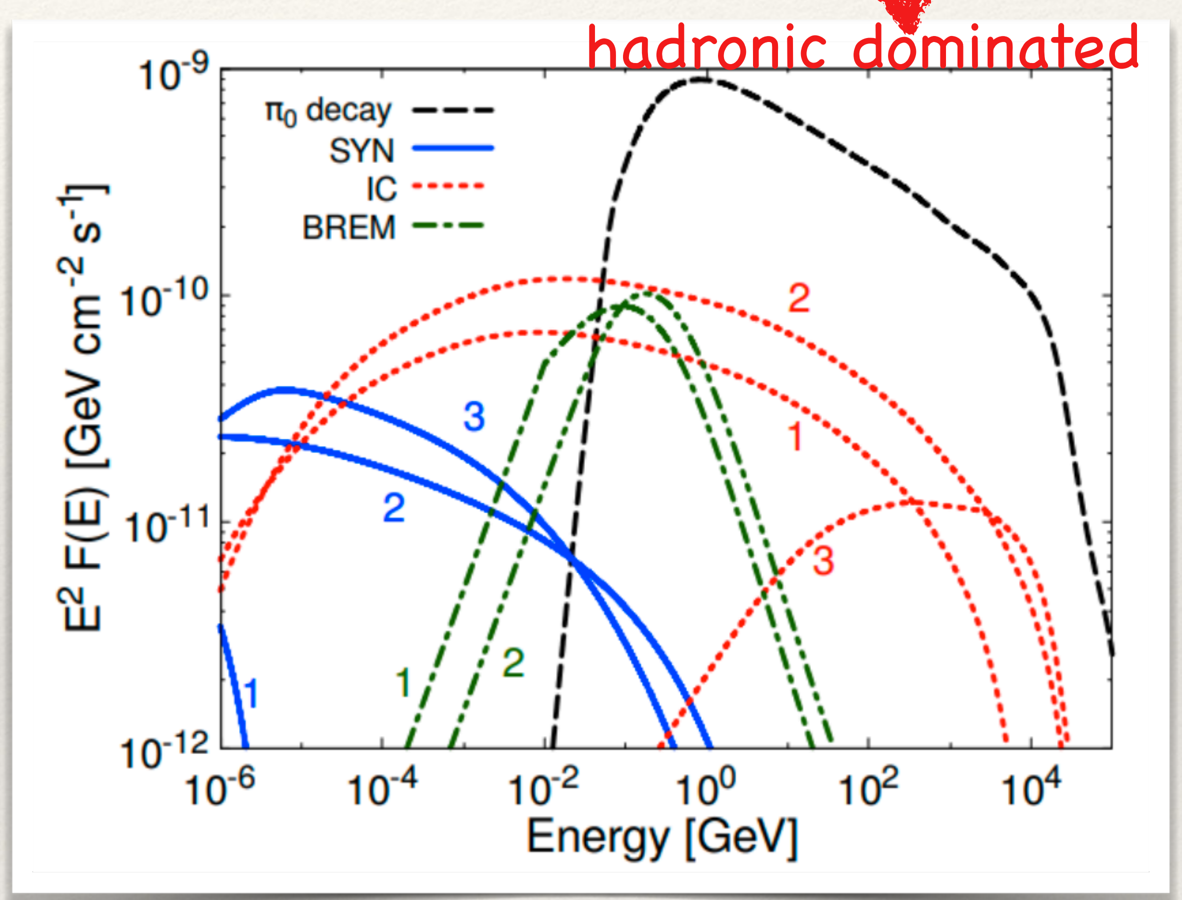
2 → secondaries: $\pi^\pm \to \mu^\pm \to e^\pm$

3 → tertiaries: $\gamma\gamma \to e^+ e^-$

Particle and photon spectra

[Peretti, Blasi, Aharonian, GM (2019)]





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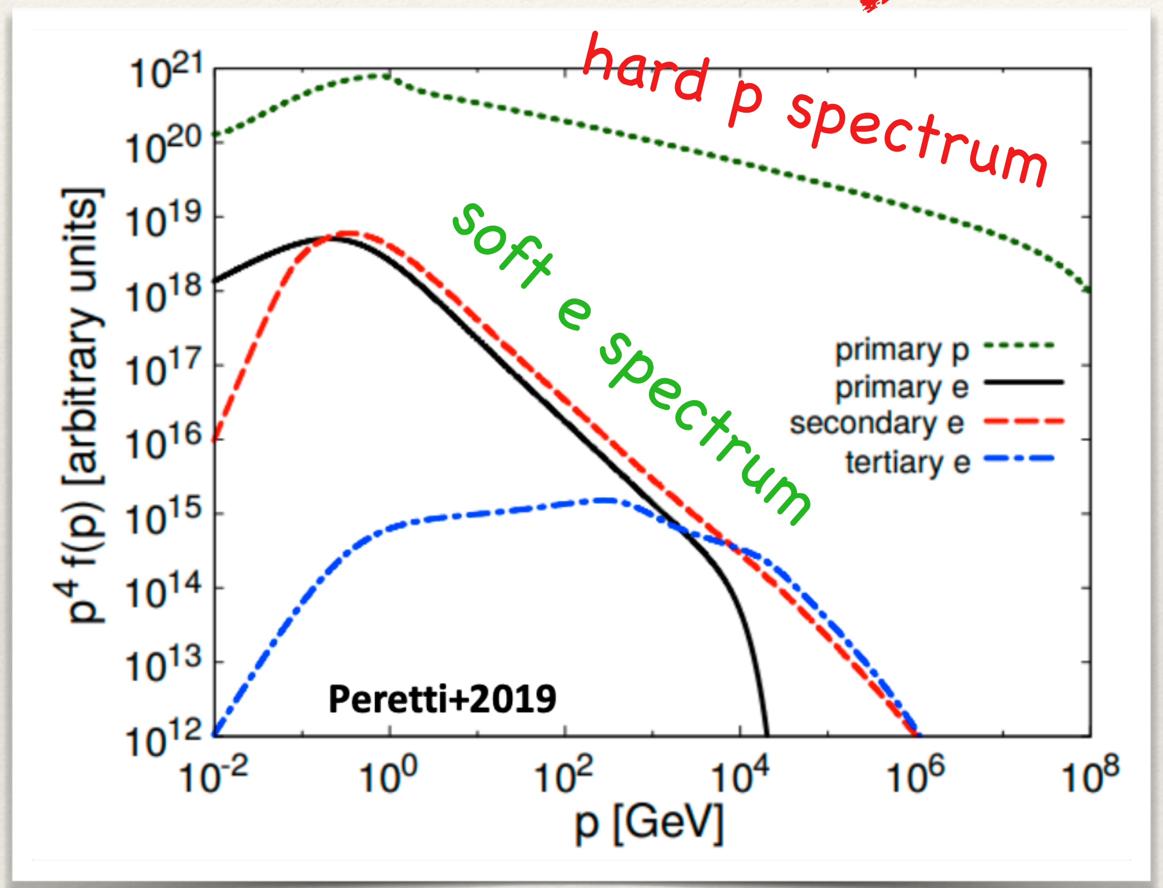

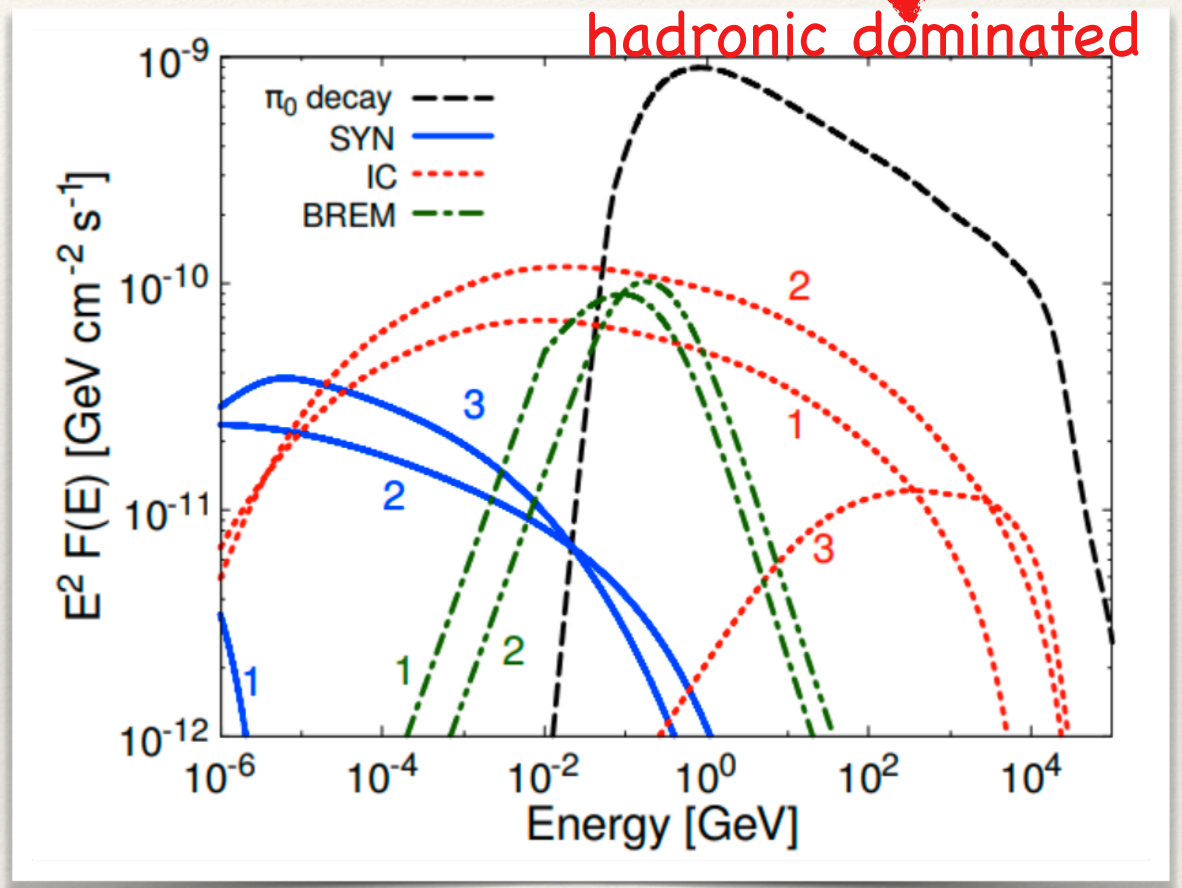

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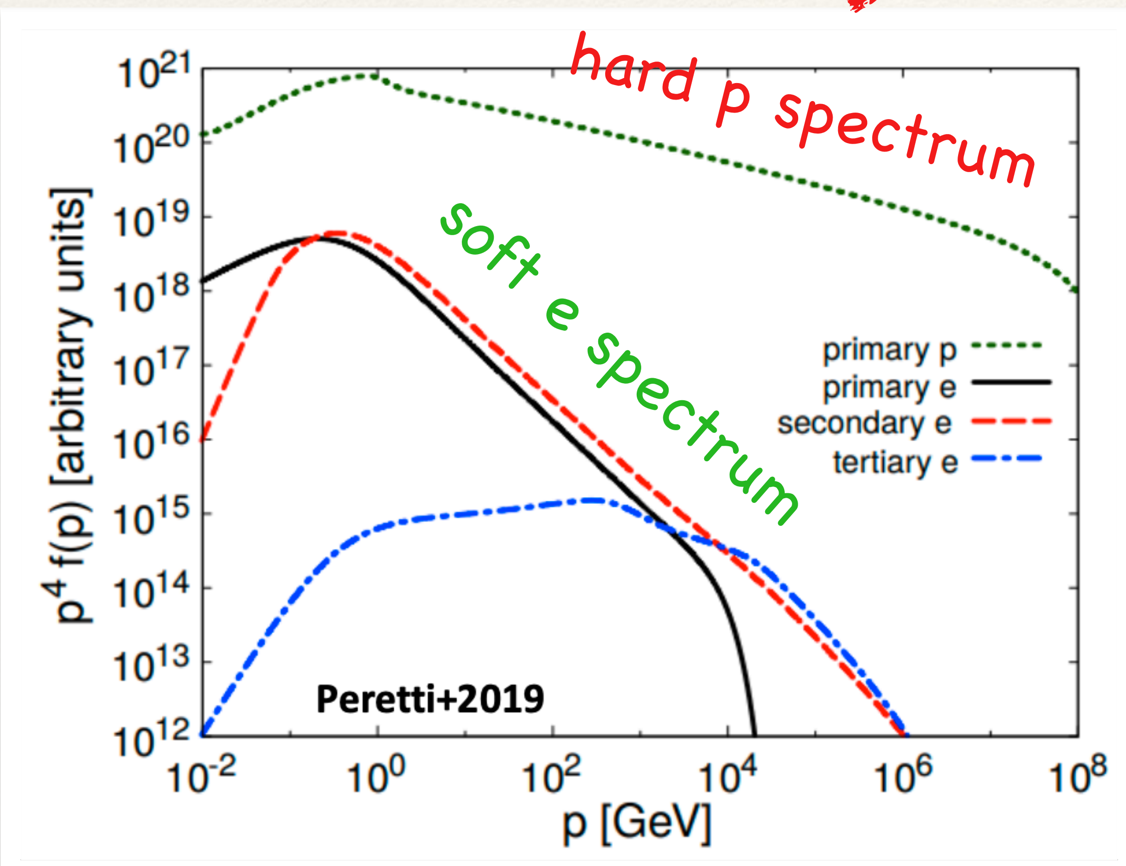
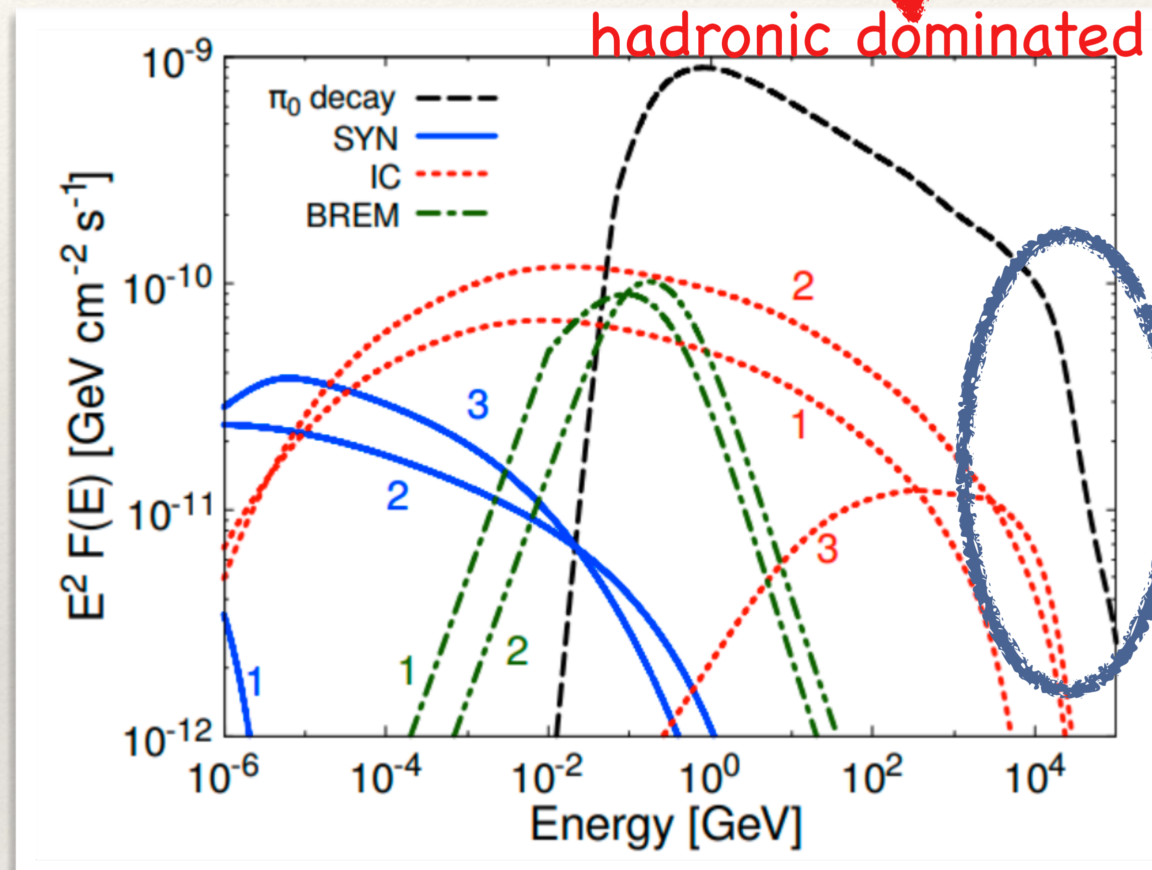




1 → primaries

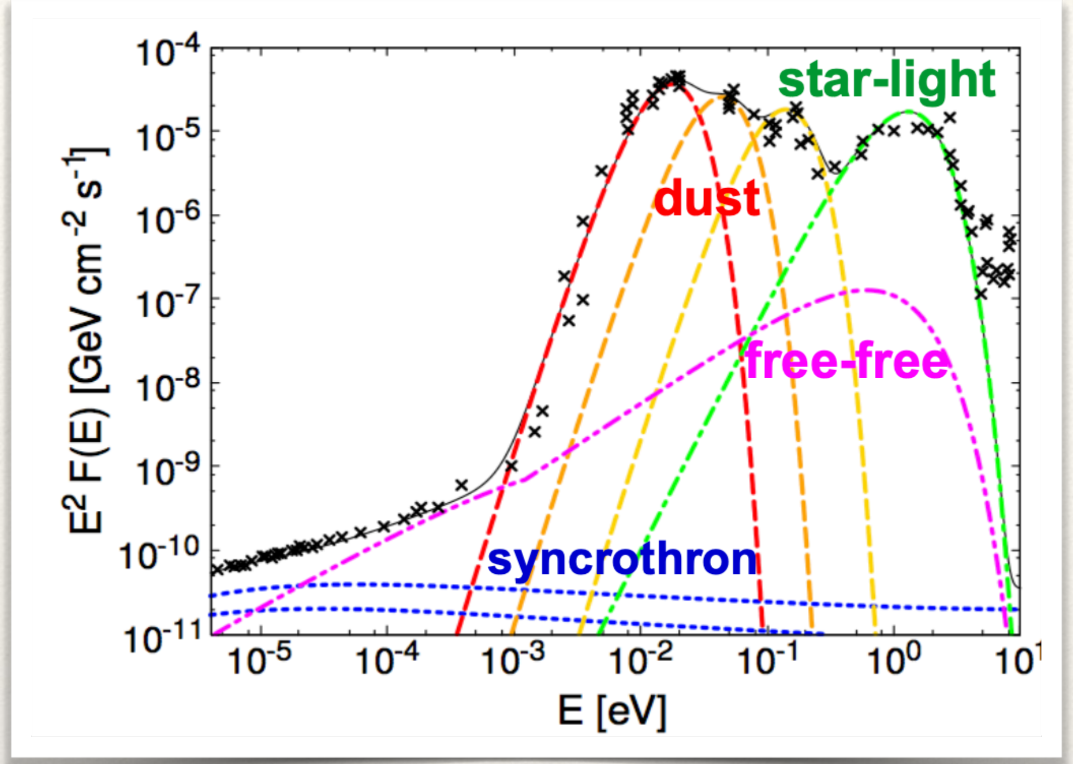
2 → secondaries: $\pi^{\pm} \to \mu^{\pm} \to e^{\pm}$

3 → tertiaries: $\gamma\gamma \to e^{+}e^{-}$

$\gamma\gamma -$absorbed
inside the nucleus

Application to individual SB galaxies: M82

[Peretti, Blasi, Aharonian, GM (2019)]



Photon background fitted from available data

Parameters	M82
U^{FIR}_{eV/cm^3} $[\frac{kT}{meV}]$	1618 [3.0]
U^{MIR}_{eV/cm^3} $[\frac{kT}{meV}]$	1132 [7.5]
U^{NIR}_{eV/cm^3} $[\frac{kT}{meV}]$	809 [24.0]
U^{OPT}_{eV/cm^3} $[\frac{kT}{meV}]$	970 [330.0]

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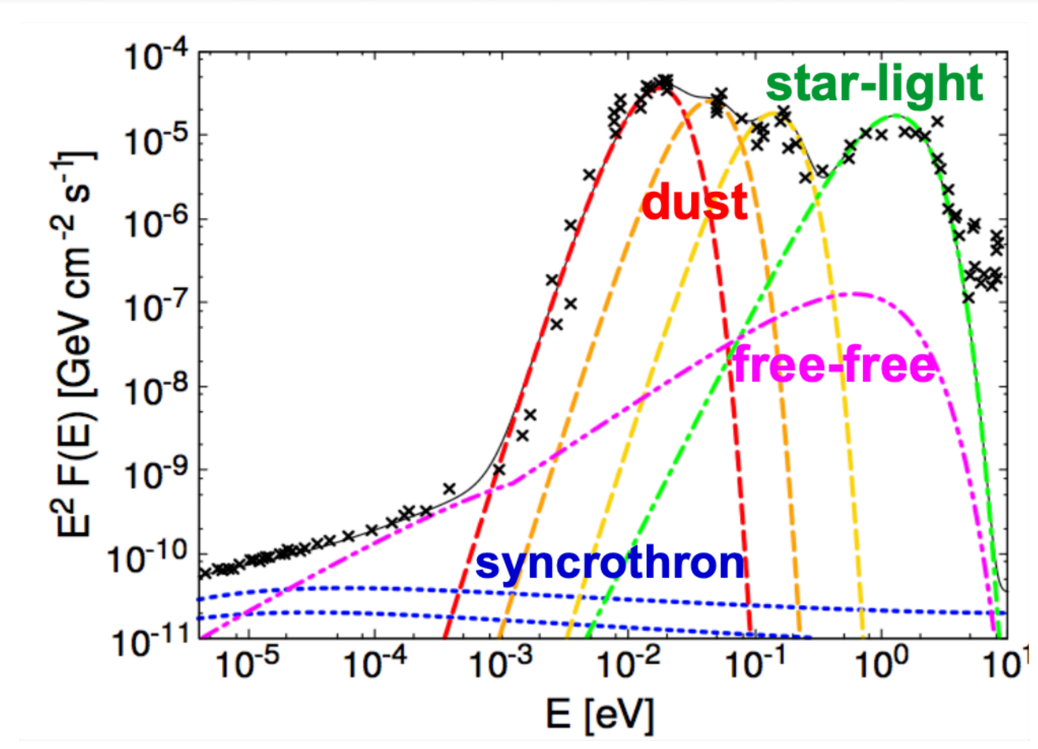

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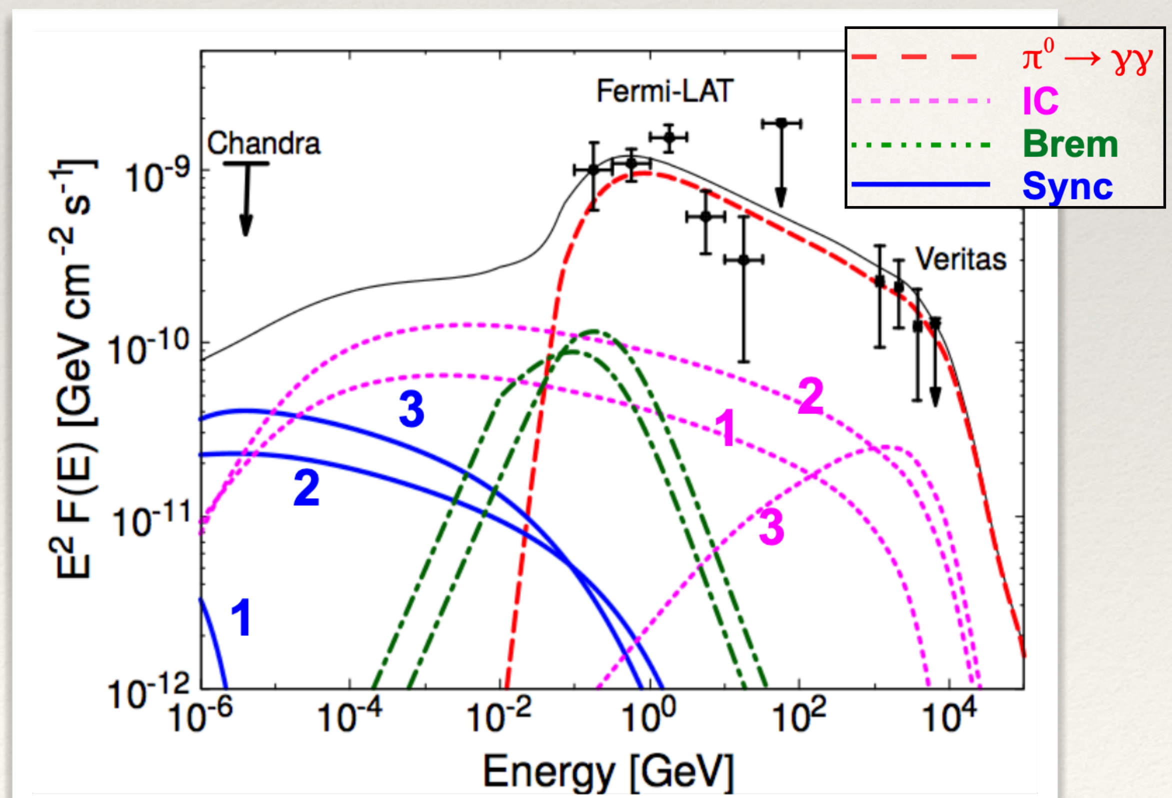


Gamma-ray spectrum

Parameters	M82
D_L (Mpc) [z]	3.9 [9 10^{-4}]
$\mathcal{R}_{\mathrm{SN}}$ (yr^{-1})	0.05
R (pc)	220
α	4.25
B (μG)	225
M_{mol} ($10^8 M_\odot$)	1.94
n_{ISM} (cm^{-3})	175
n_{ion} (cm^{-3})	22.75
v_{wind} (km/s)	600
T_{plasma} (K)	7000

Diffuse emission from starburst nuclei

[Peretti, Blasi, Aharonian, GM, Cristofari (2020)]

Diffuse emission from starburst nuclei

[Peretti, Blasi, Aharonian, GM, Cristofari (2020)]

1) Determining the calorimetric condition

To be efficient neutrinos factories, SB nuclei should confine CRs efficiently

$$\boxed{\tau_{\rm loss} < \tau_{\rm esc} \approx \tau_{\rm adv}}$$

$$\begin{cases} \tau_{\rm loss} = \dfrac{1}{n_{\rm gas} c \sigma_{pp} \eta} \\ \tau_{\rm adv} = R/v_{\rm wind} \end{cases}$$

Surface gas density

$$\Sigma_{\rm gas} = n_{\rm gas} m_p R$$

$$\Sigma_{\rm gas} \geq \Sigma^*_{\rm gas} \approx 1068 \left[\frac{v_{\rm wind}}{10^3 \text{ km/s}}\right] \frac{M_\odot}{pc^2},$$

Using the Kennicutt (1998) relation:

$$\frac{\Sigma^*_{\rm SFR}}{M_\odot \text{yr}^{-1}\text{kpc}^{-2}} = (2.5 \pm 0.7) \times 10^{-4} \left[\frac{\Sigma^*_{\rm gas}}{1 \ M_\odot \text{pc}^{-2}}\right]^{1.4\pm0.15}$$

$$\psi^* = \Sigma^*_{\rm SFR} \pi R^2 \approx 0.9^{+2.2}_{-0.7} \left[\frac{R}{0.25 \text{ kpc}}\right]^2 \text{M}_\odot \text{yr}^{-1}.$$

Efficient calorimeter if $\psi > \psi^*$

Diffuse emission from starburst nuclei

[Peretti, Blasi, Aharonian, GM, Cristofari (2020)]

1) **Determining the calorimetric condition**
2) **Counting the SBNi**

- Gamma and neutrino spectra

$$q_{\gamma,\nu}(E) \propto \begin{cases} q(p) & \tau_{\rm loss} \ll \tau_{\rm adv} \\ [n_{\rm ISM}\sigma_{pp}c]q_p(p)R/v_{\rm wind} & \tau_{\rm loss} \gg \tau_{\rm adv} \end{cases}$$

Calorimetric limit

- Gamma and neutrino flux from a single SNB

$$f^{\rm SBN}_{\gamma,\nu}(E,\psi) = \left(\frac{\psi}{\psi_{\rm M82}}\right) f^{M82}_{\gamma,\nu}(E),$$

for $\psi > \psi^*$

- Determining the SFRF from a fit to the IR+UV data [Gruppioni et al. (2015)]

$$\Phi(\psi)\, d\log\psi = \tilde{\Phi}\left(\frac{\psi}{\tilde{\psi}}\right)^{1-\tilde{\alpha}} \exp\left[-\frac{1}{2\tilde{\sigma}^2}\log^2\left(1+\frac{\psi}{\tilde{\psi}}\right)\right] d\log\psi,$$

- Gamma-ray and neutrino flux integrated over the cosmological history

$$\Phi_{\gamma,\nu}(E) = \frac{1}{4\pi}\int d\Omega \int_0^{4.2} dz\, \frac{dV_C(z)}{dz\, d\Omega} \times \int_{\psi^*} d\log\psi\, \Phi_{\rm SFR}(\psi,z)\, [1+z]^2 f_{\gamma,\nu}(E[1+z],\psi).$$

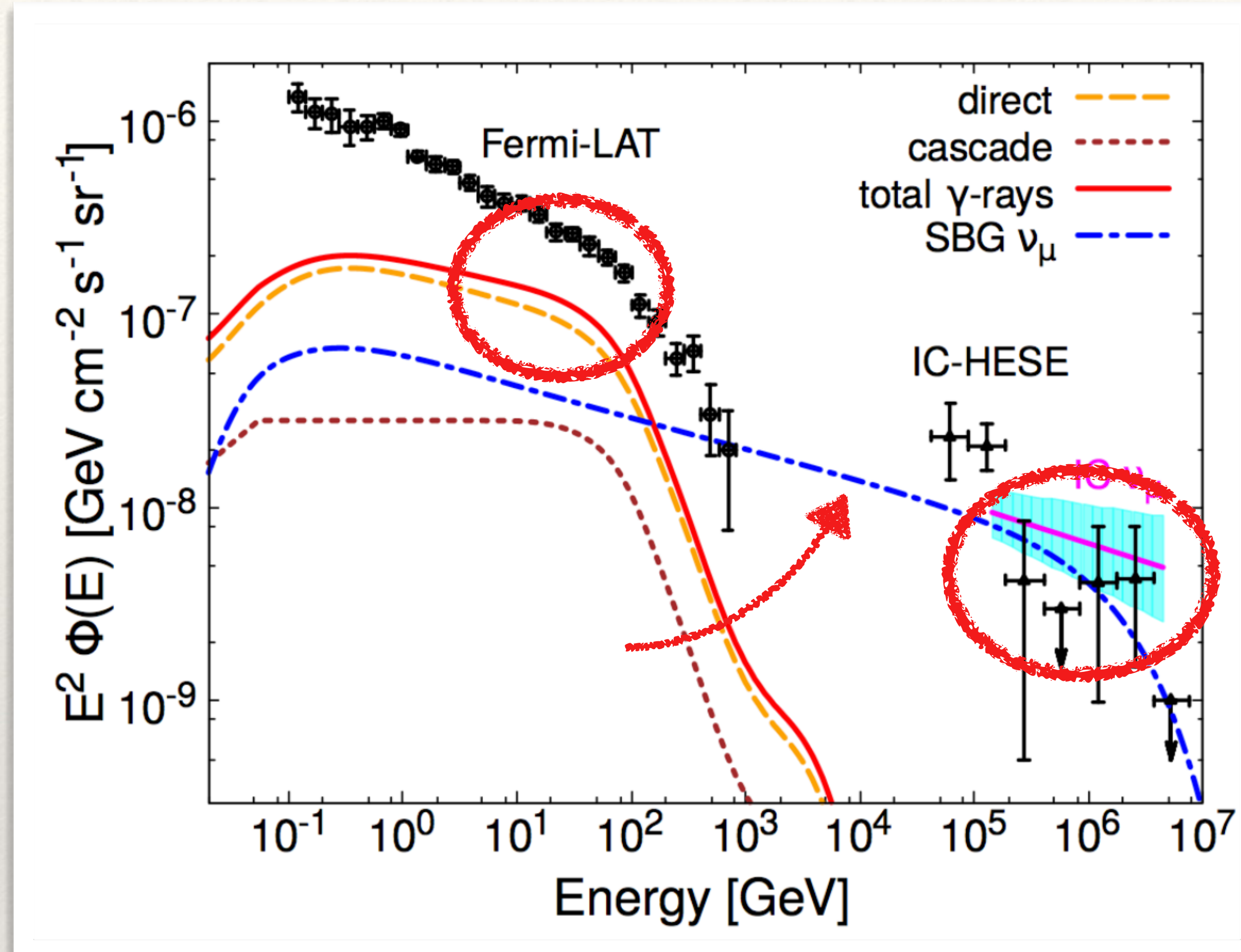
Diffuse emission from starburst nuclei

[Peretti, Blasi, Aharonian, GM, Cristofari (2020)]

1) **Determining the calorimetric condition**
2) **Counting the SBNi**
3) **Results**

Values tuned to M82

parameter	value
$p_{p,\max}$	10^2 PeV
α	4.2
R	0.25 kpc
D_L	3.9 Mpc
$\xi_{\rm CR}$	0.1
$\mathcal{R}_{\rm SN}$	0.06 yr^{-1}
B	200 μG
$n_{\rm ISM}$	100 cm^{-3}
$v_{\rm wind}$	700 km/s
$U_{\rm rad}$	2500 eV/cm^3



- IceCube ν can be explained by SBNi at $E > 100$ TeV
- Diffuse gamma-ray flux still compatible with FermiLAT: $\lesssim 40\,\%$ (Blazar contribution is between 60% and 85%)
- Hard acceleration slope: $\propto E^{-2.2}$

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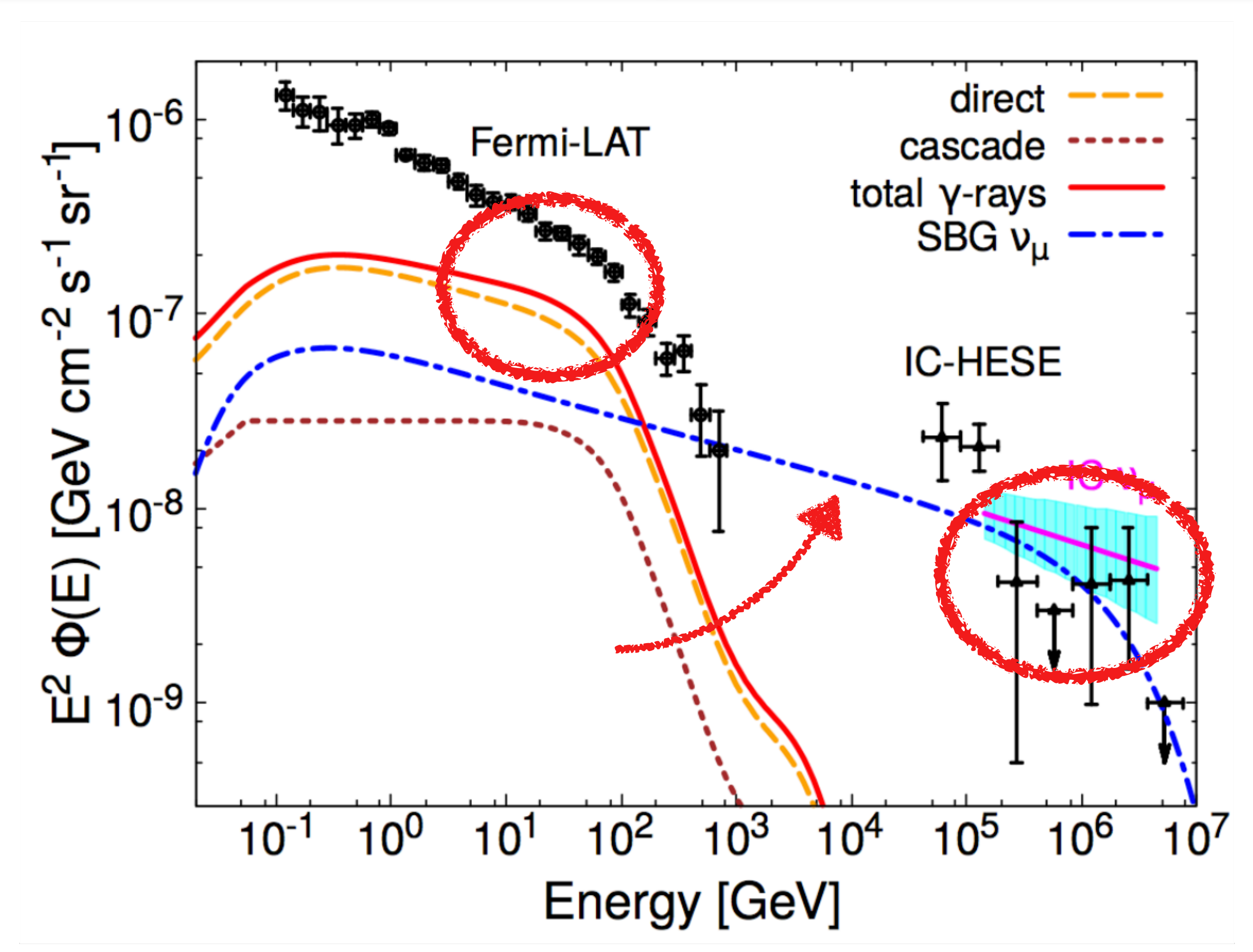

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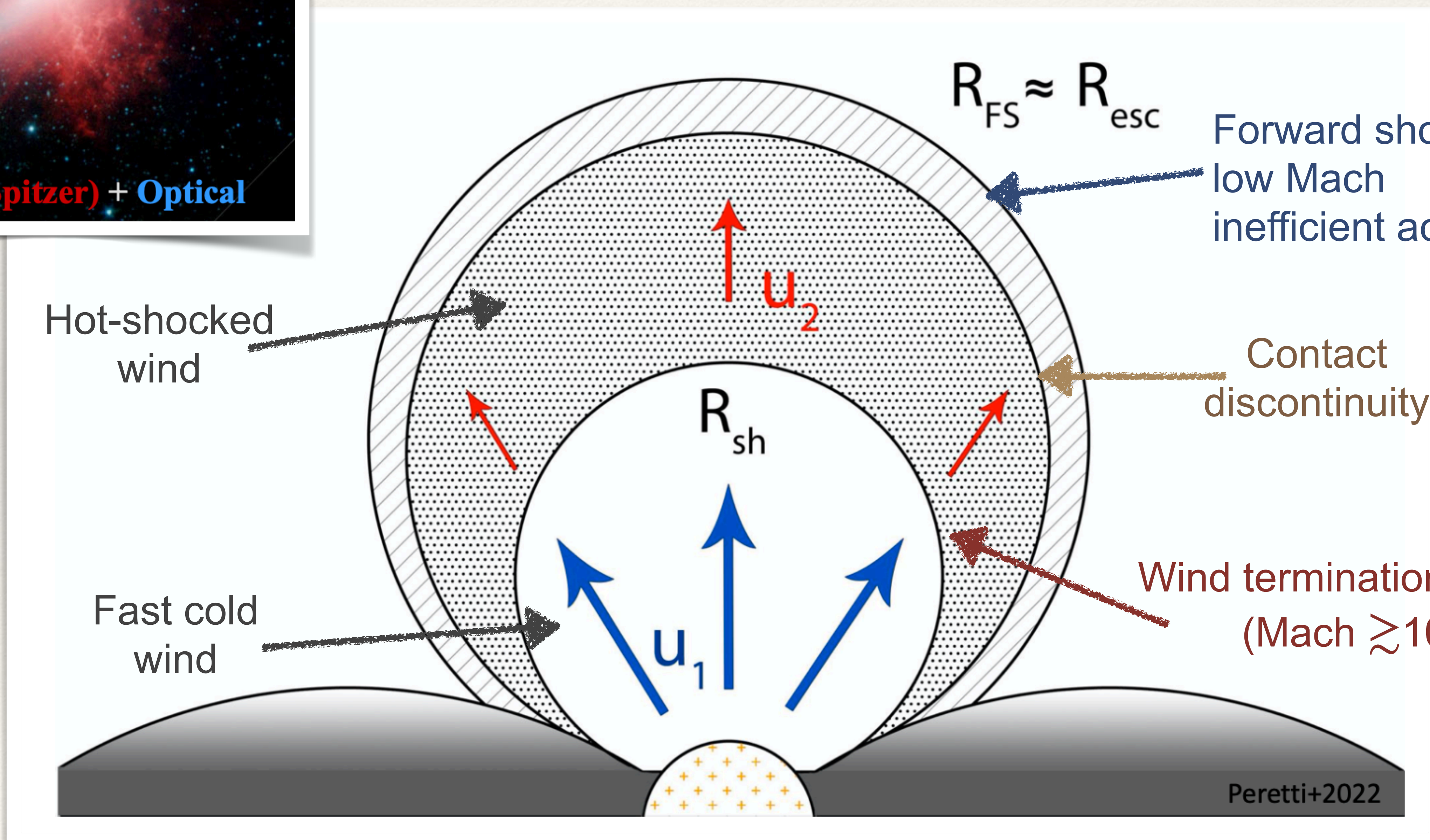
- Diffuse gamma-ray flux still compatible with FermiLAT: $\lesssim 40\,\%$ (Blazar contribution is between 60% and 85%)
- Hard acceleration slope: $\propto E^{-2.2}$
- Maximum energy > 50 PeV is required: how can be produced? (If sources are SNRs, the physics should be similar to Milky Way SNRs)
- Possible role of turbulence like super-bubbles?

Acceleration at the SB-driven wind

[Peretti, GM, Blasi, Cristofari, (2022)]

Thermal pressure and CR pressure in the nucleus may drive a galactic wind

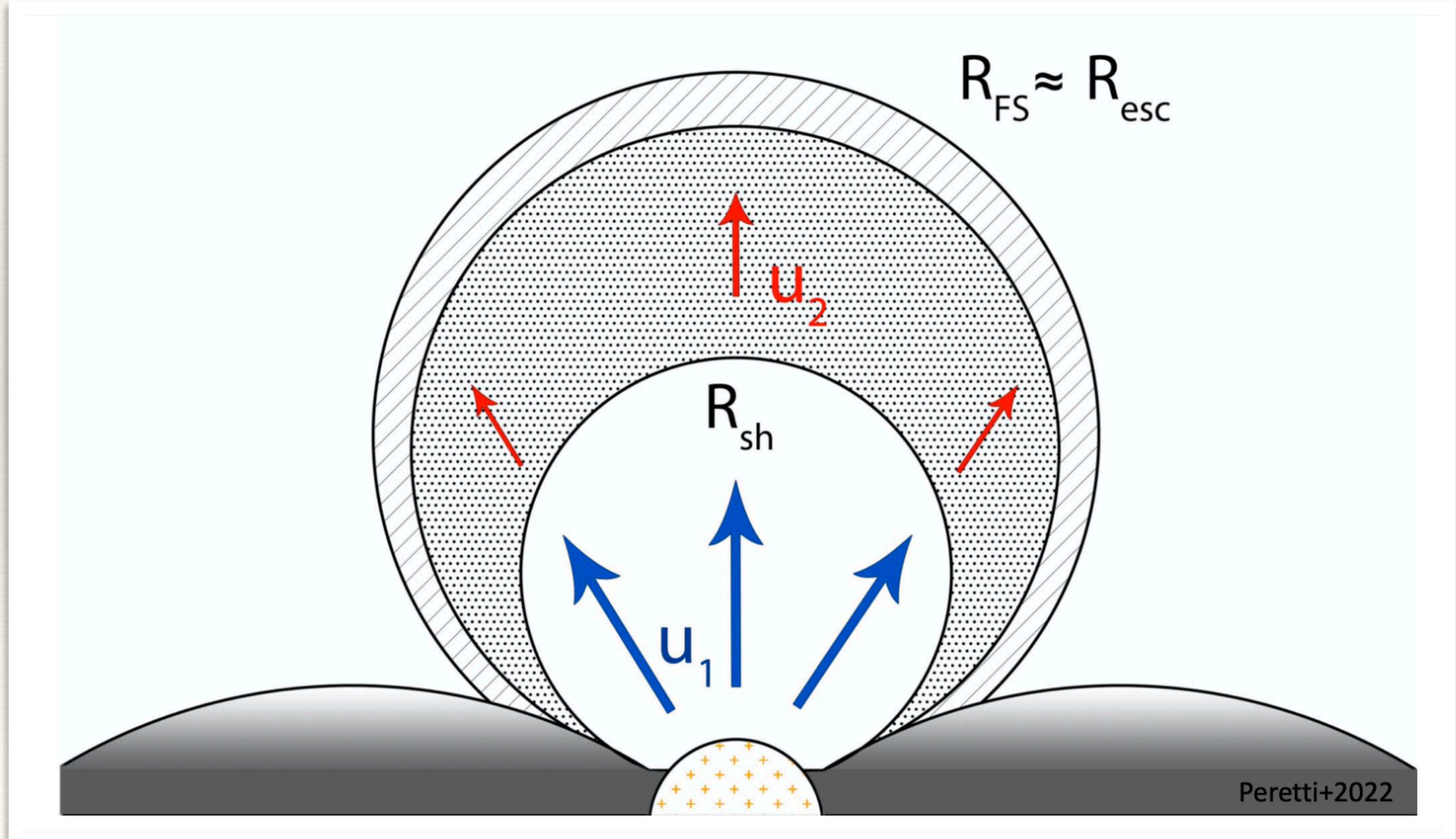


Acceleration at the SB-driven wind

[Peretti, GM, Blasi, Cristofari, (2022)]

Transport equation in spherical coordinates (approximation)

$$r^2 u(r)\frac{\partial f}{\partial r} = \frac{\partial}{\partial r}\left[r^2 D \frac{\partial f}{\partial r}\right] + \frac{1}{3}\frac{\partial}{\partial r}\left[r^2 u\right]\, p\frac{\partial f}{\partial p} + r^2 Q(r,p) - r^2 \Lambda(r,p)$$



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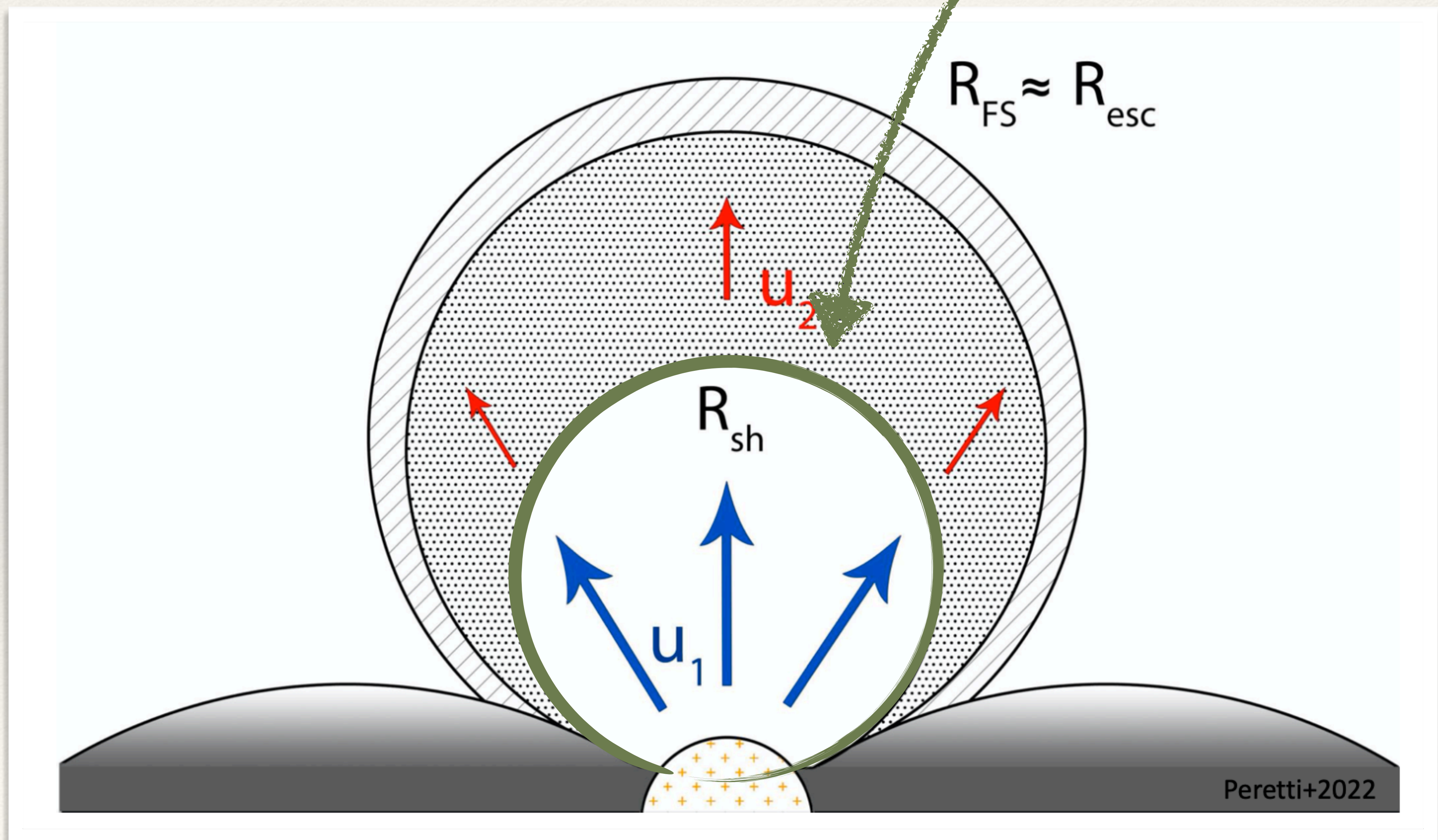

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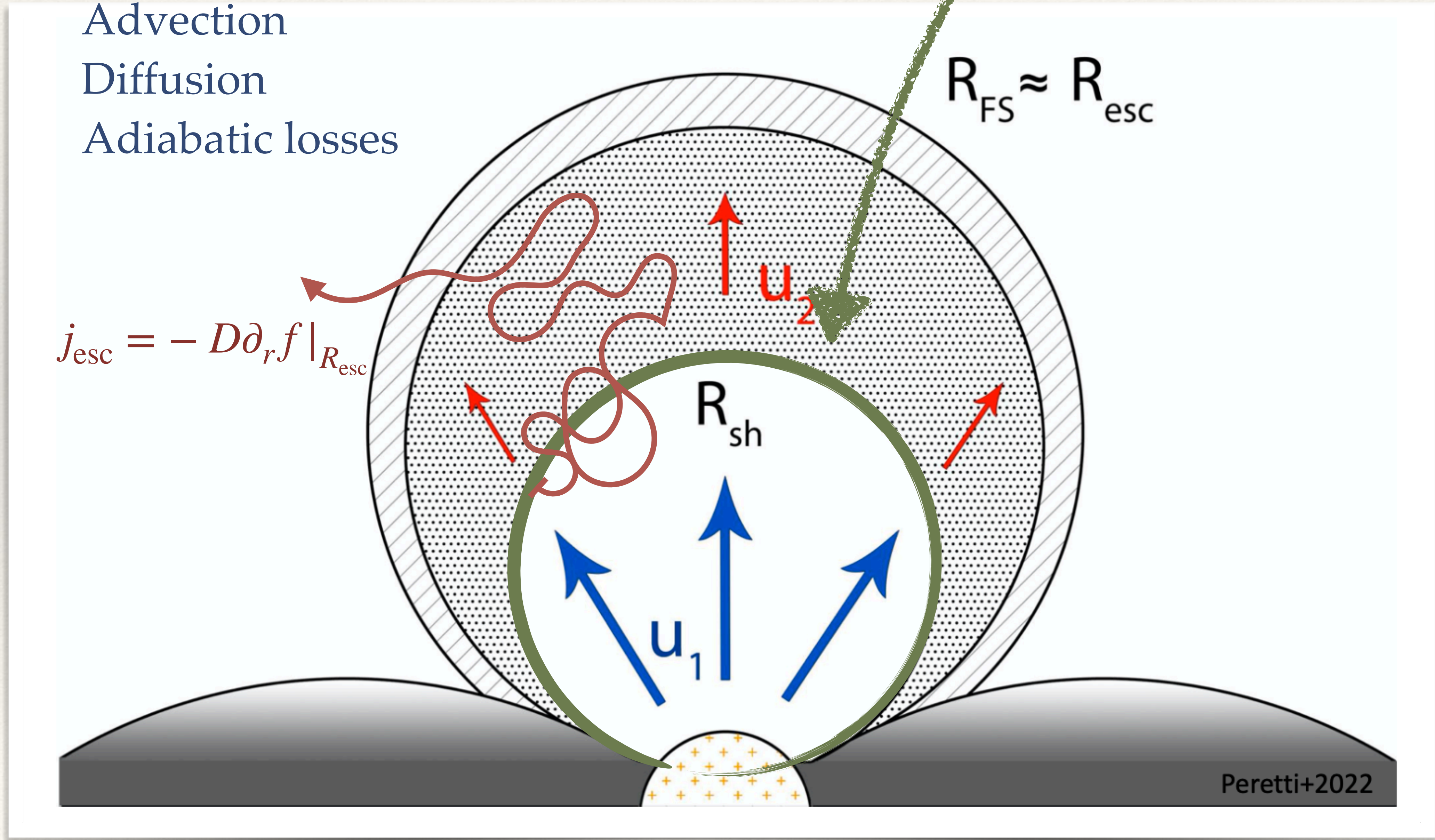
Advection
Diffusion
Adiabatic losses



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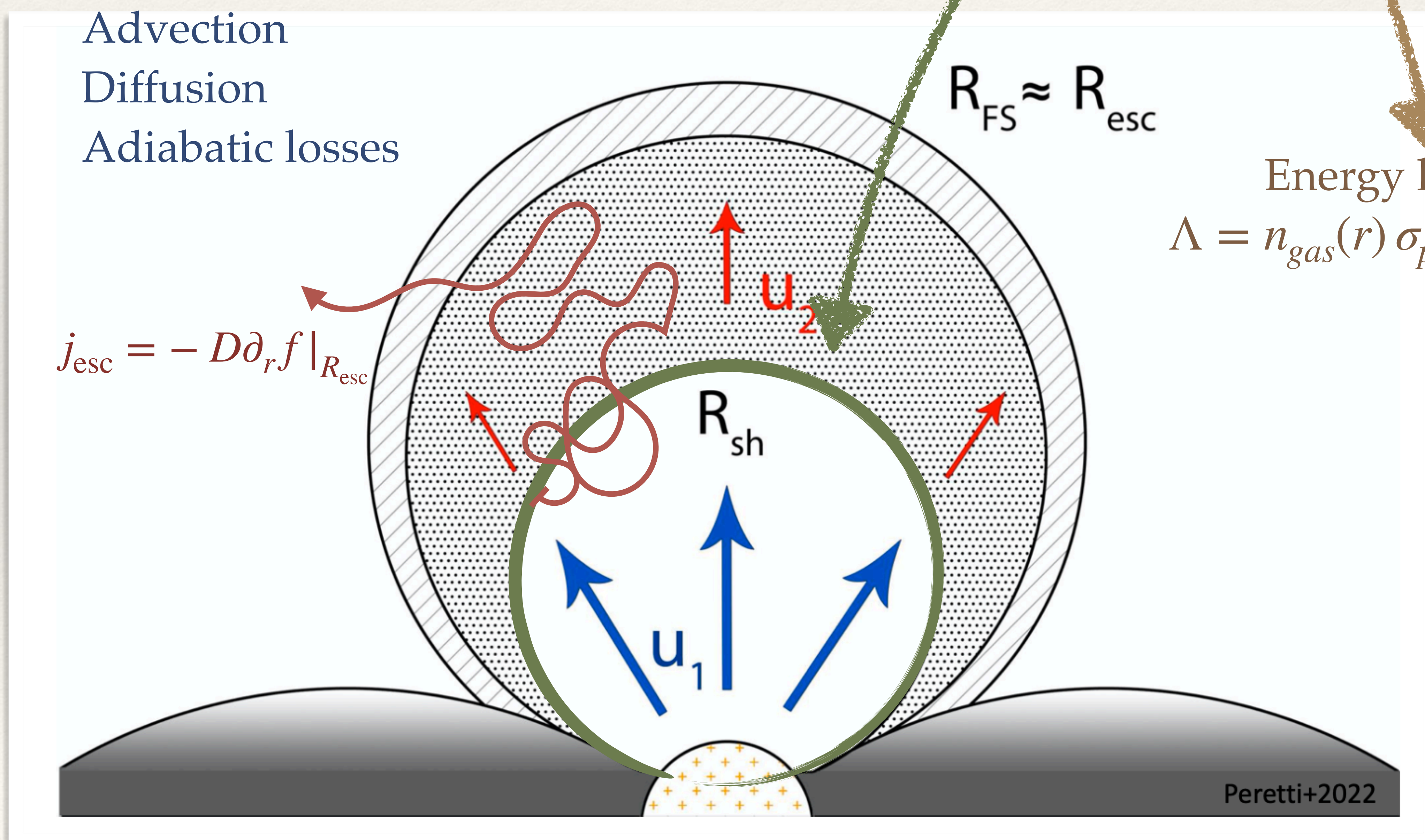
Advection

Diffusion

Adiabatic losses



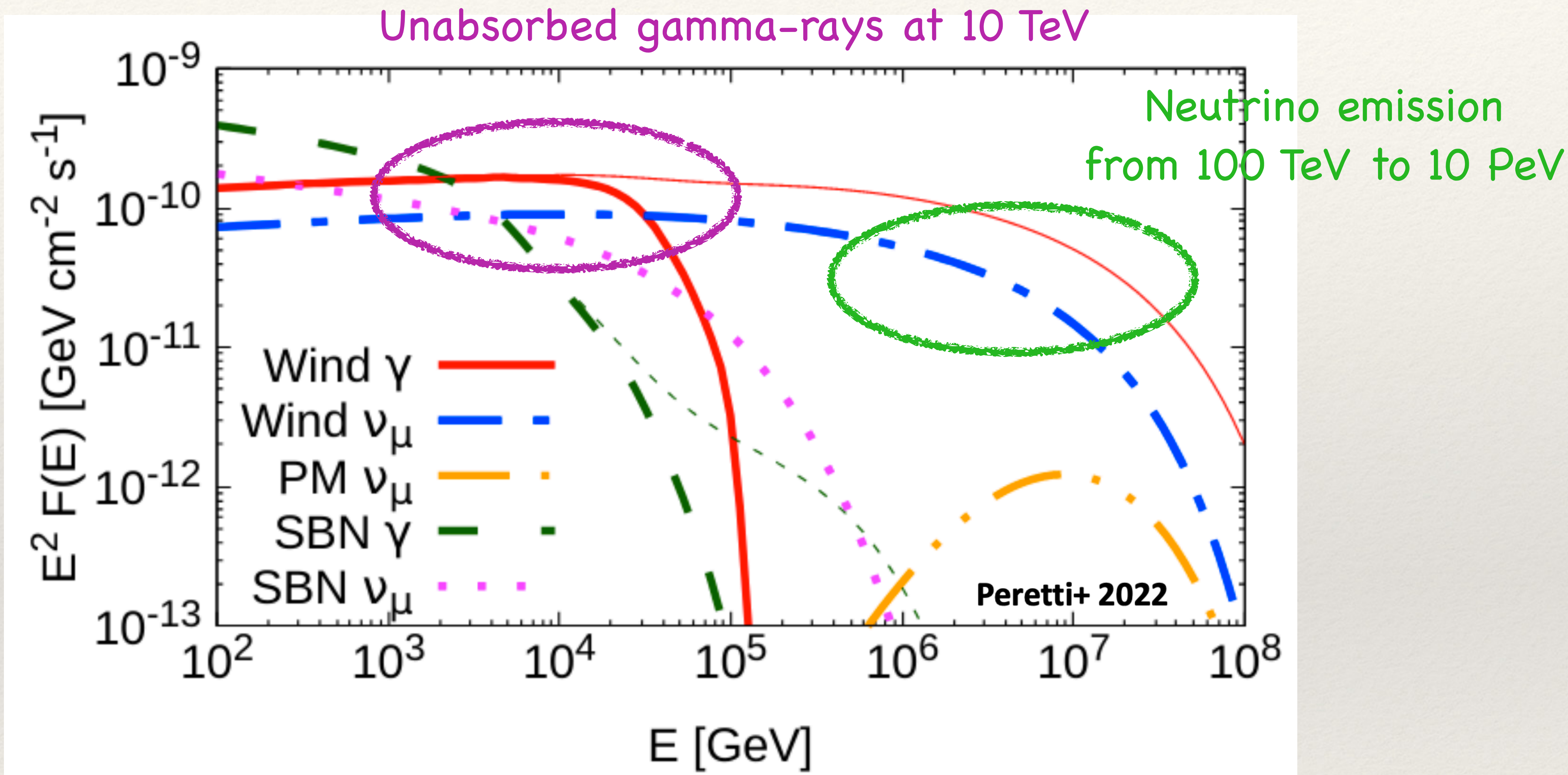
$j_{\rm esc} = -D\partial_r f\,|_{R_{\rm esc}}$

Energy losses

$\Lambda = n_{gas}(r)\,\sigma_{pp}(p)\,v(p)\,f$

High energy SED and neutrinos

Total gamma and neutrino emission from SBN and Wind



Typical parameters

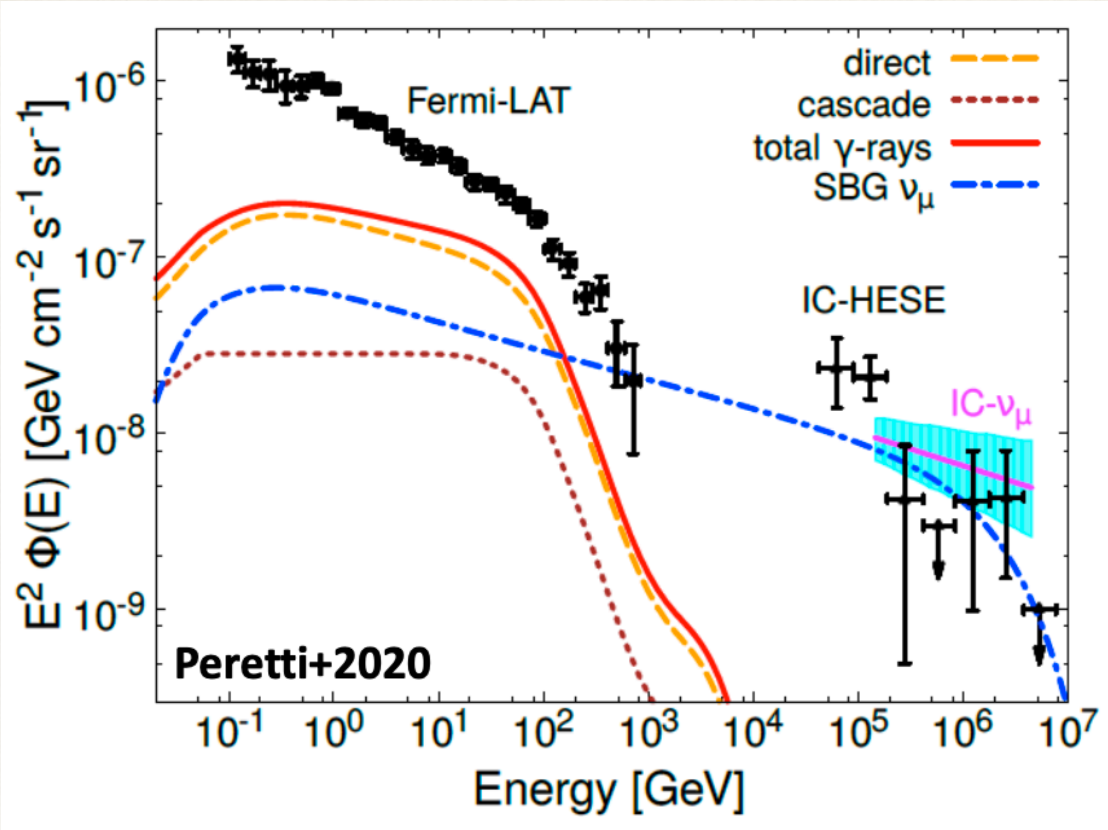
$$\begin{cases} \dot{M} = 10\, M_\odot\, \mathrm{yr}^{-1} \\ v_w = 3000\ \mathrm{km/s} \\ R_{TS} = 12\ \mathrm{kpc} \\ R_{FS} = 55\ \mathrm{kpc} \end{cases} \Rightarrow \boxed{E_{\max} \simeq 100\ \mathrm{PeV}}$$

Diffuse emission from SBGs

Integrating over the population of SBGs

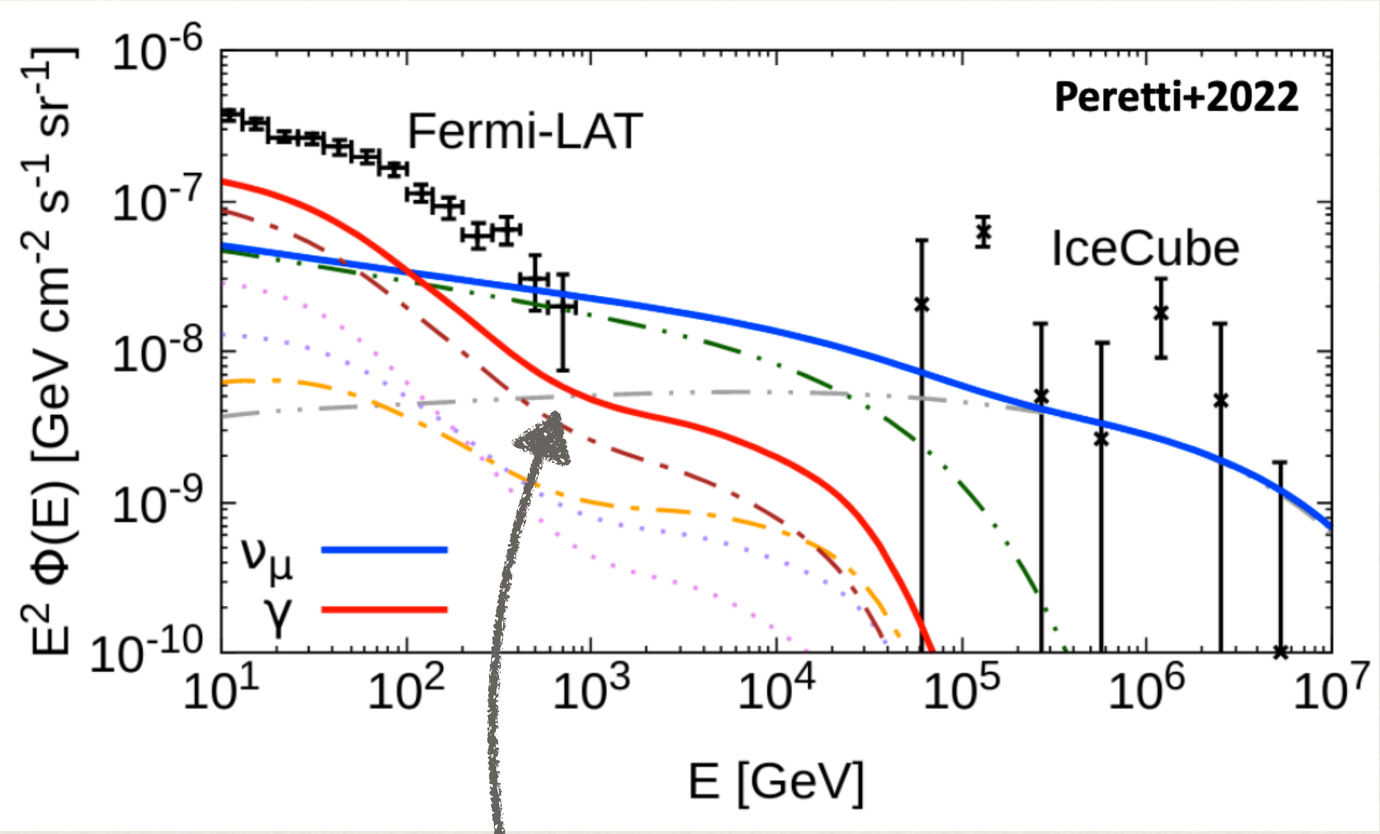
Best fit only SB nuclei

Requires $E_{max}^{nucleus} \simeq 100\,\mathrm{PeV}$



SB nuclei + winds

Requires $E_{max}^{nucleus} \simeq 1\,\mathrm{PeV}$



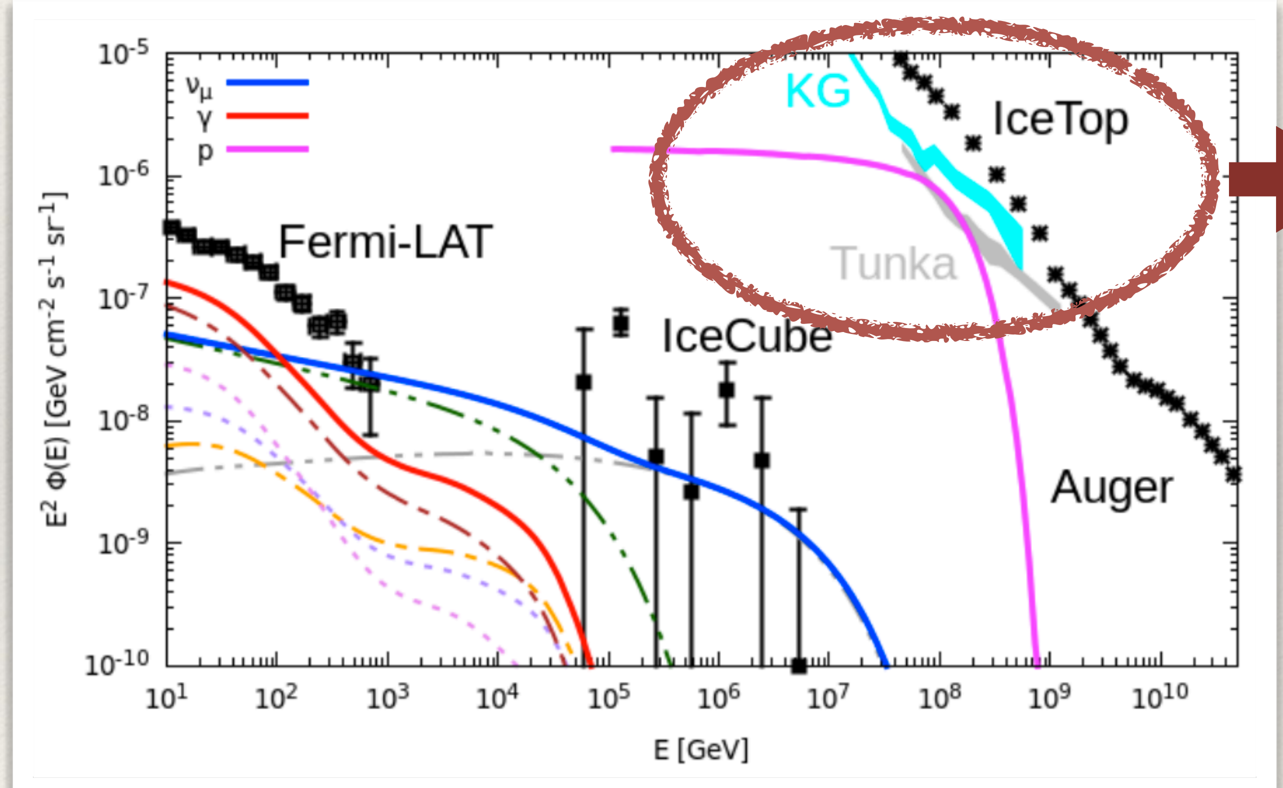
Acceleration at the wind TS need to be harder $\propto E^{-2}$

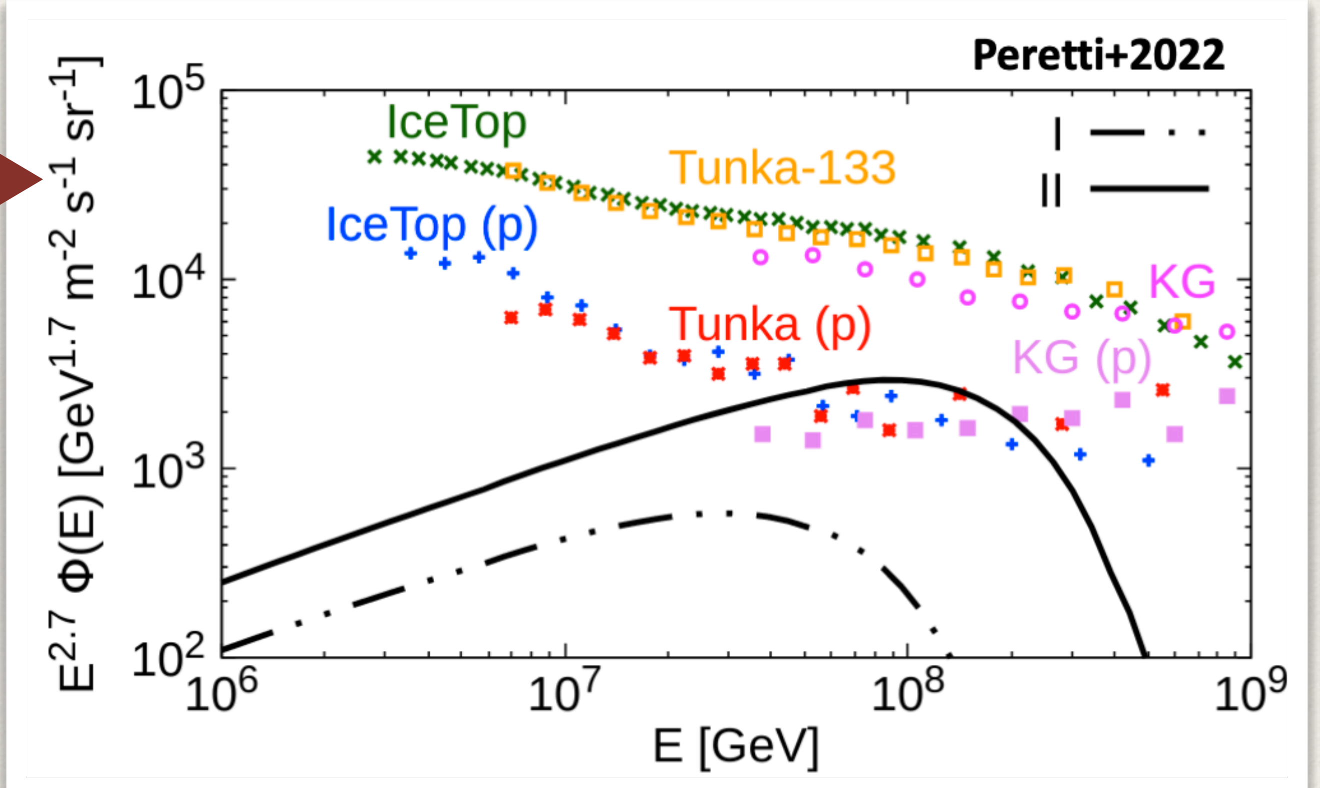
Multi-messenger emission from SBGs

SB nucleus is a calorimeter but the wind bubble is not

CRs can escape from the wind-bubble

Proton contribution from SB winds to the all-particle CR spectrum





A possible non negligible contribution at ~100 PeV

Heavy CR nuclei up to $\gtrsim 1000$ PeV

Conclusions

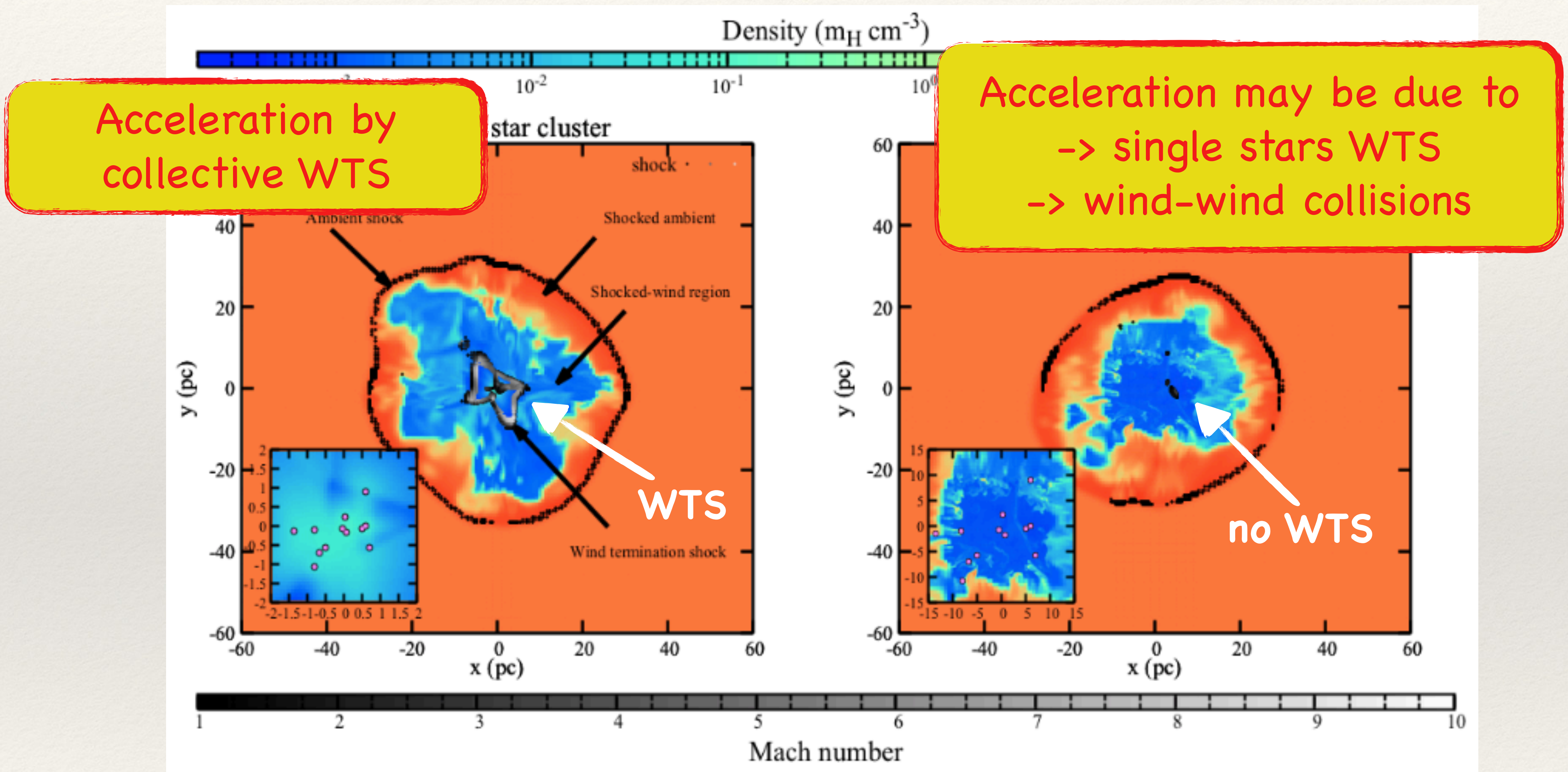
- **SNRs in the Milky Way remains the principal candidates for the acceleration of Galactic CRs**
  - Isolated (regular) SNRs unable to accelerate beyond ~100 TeV
  - Stellar winds and super-bubbles could reach $E_{\rm max} \gtrsim 1$ PeV
    - However no clear indication yet from observations
- **SNRs power the nuclei of starburst galaxies and the large scale winds**
  - SBNi can approach the calorimetric conditions; wind-bubbles do not
  - We expect gamma-rays and neutrinos both from SBNi and winds
    - neutrinos compatible with IceCube flux for $E \gtrsim 100$ TeV
    - γ-rays probable responsible of $\lesssim 40\,\%$ of the EBL at ~1 TeV
  - SB wind-bubbles can produce a sizeable contribution to the CR spectrum in the range 10^{17} eV $\lesssim E \lesssim 10^{18}$ eV

Backup slides

Cluster compactness

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

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



Compact cluster

Loose cluster