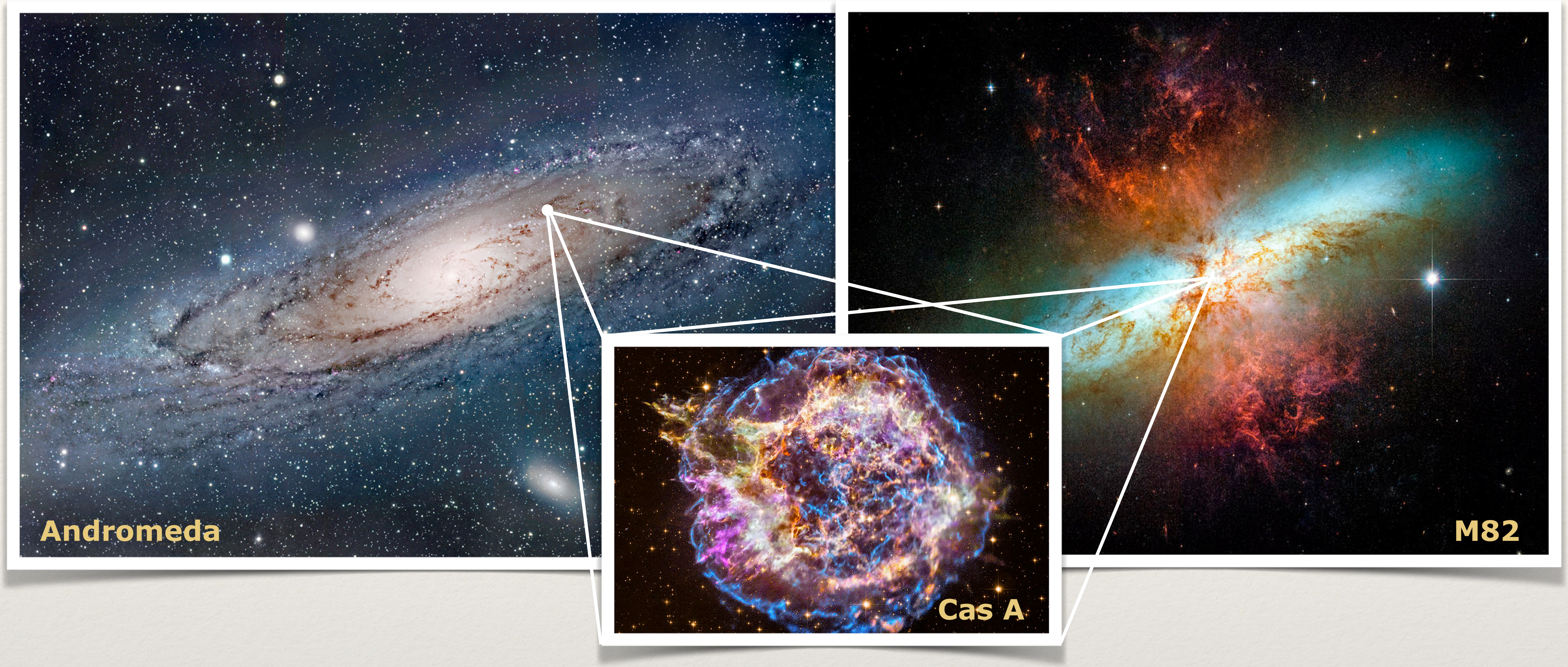

Town Hall KM3NET meeting — 22 September, 2022 — Catania

High energy emission from starburst galaxies and their winds

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Firenze
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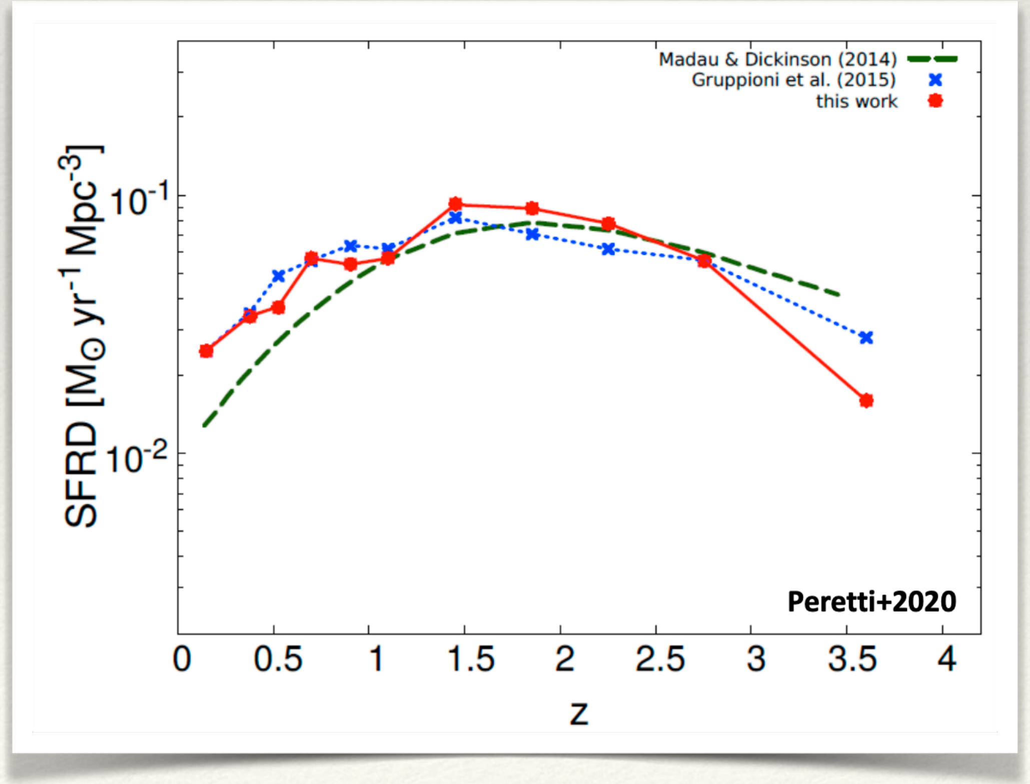
ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

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)

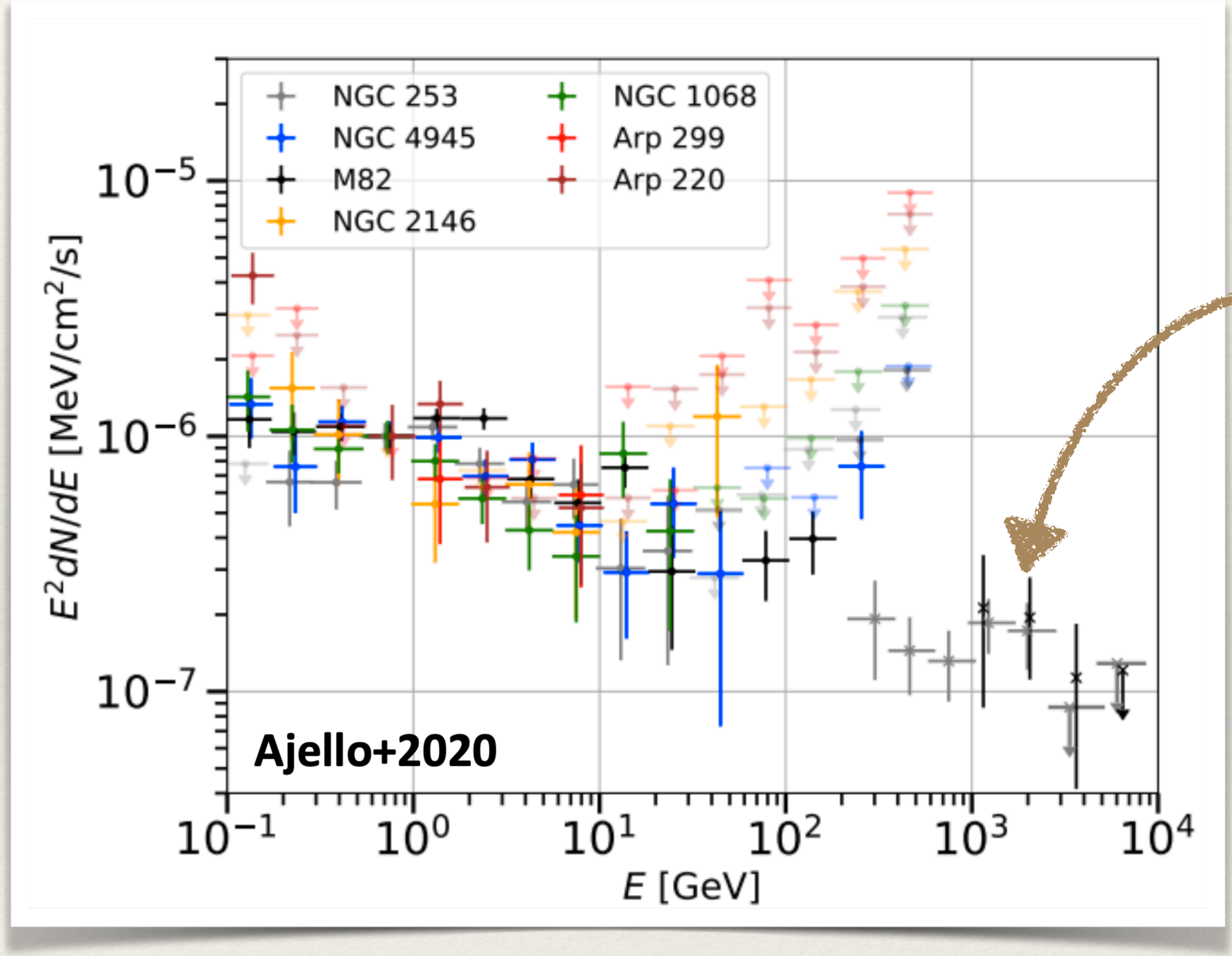
  ⇒ large SN rate ⇒ high CR production
- High level of turbulence ⇒ efficient CR confinement ⇒ Calorimetry?
- High gas density ⇒ efficient γ and ν production
- Abundant at high redshift ⇒ Contribution to diffuse flux?



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 $\simeq 10\ \mathrm{Myr}$

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:

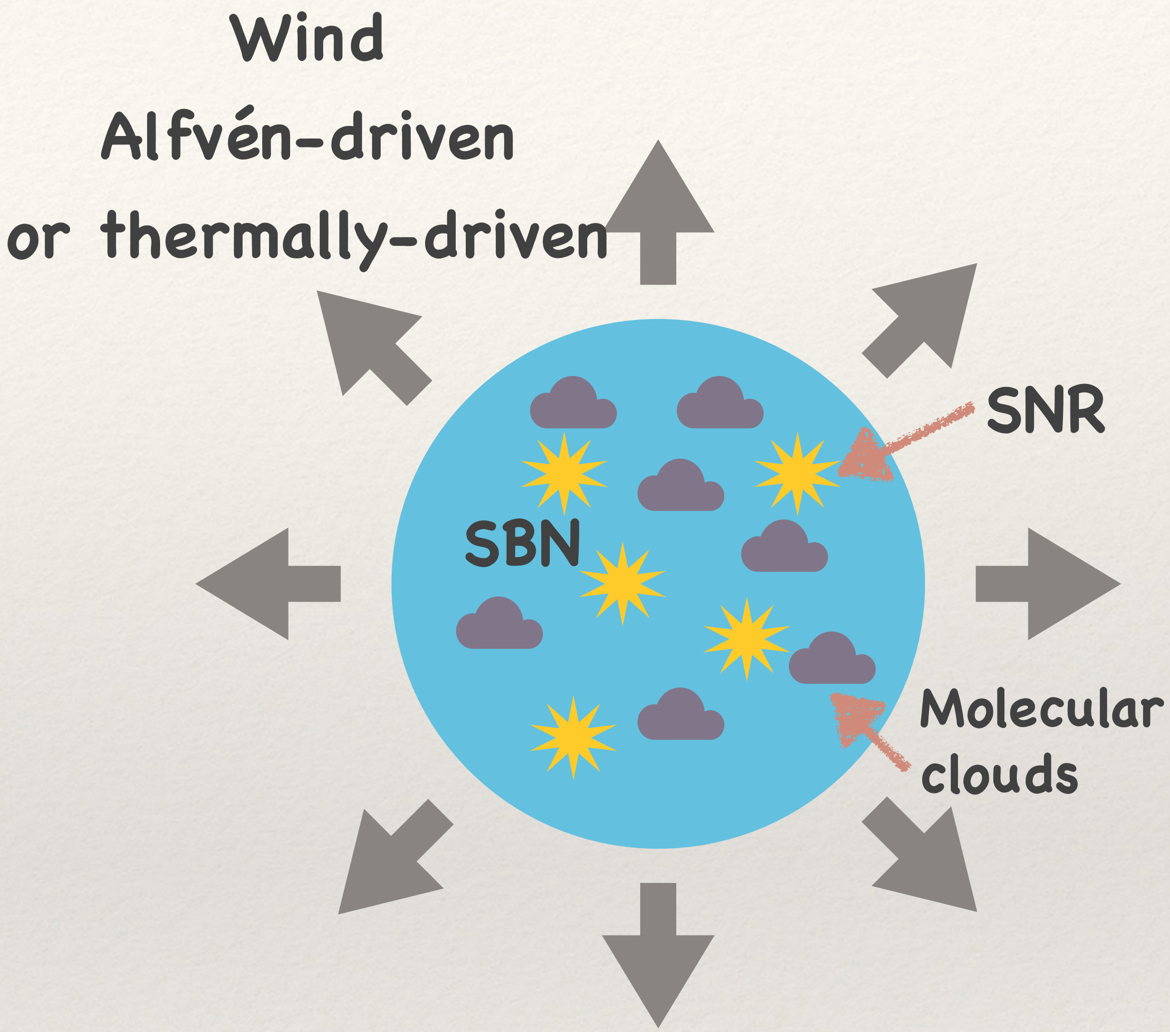
  $\sim E^{-2.2} \div E^{-2.3}$

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 → ionisation, p-p collision, Coulomb
e → 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

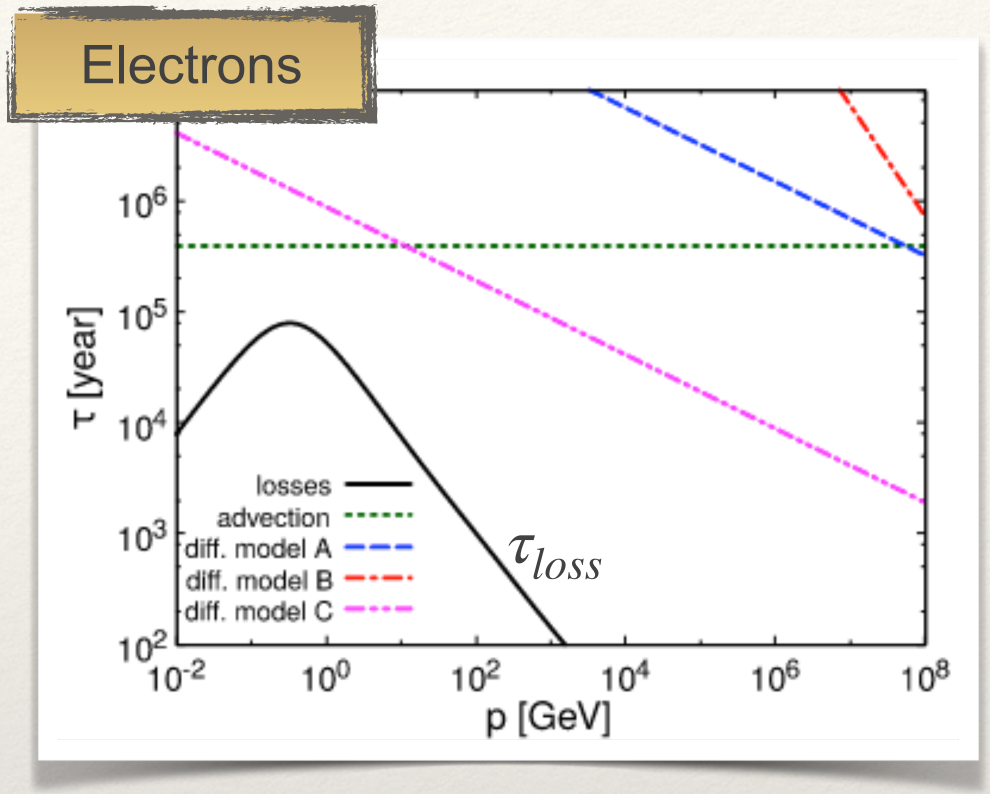
$$W(k) = W_0 \left(k L_0\right)^{-d}$$

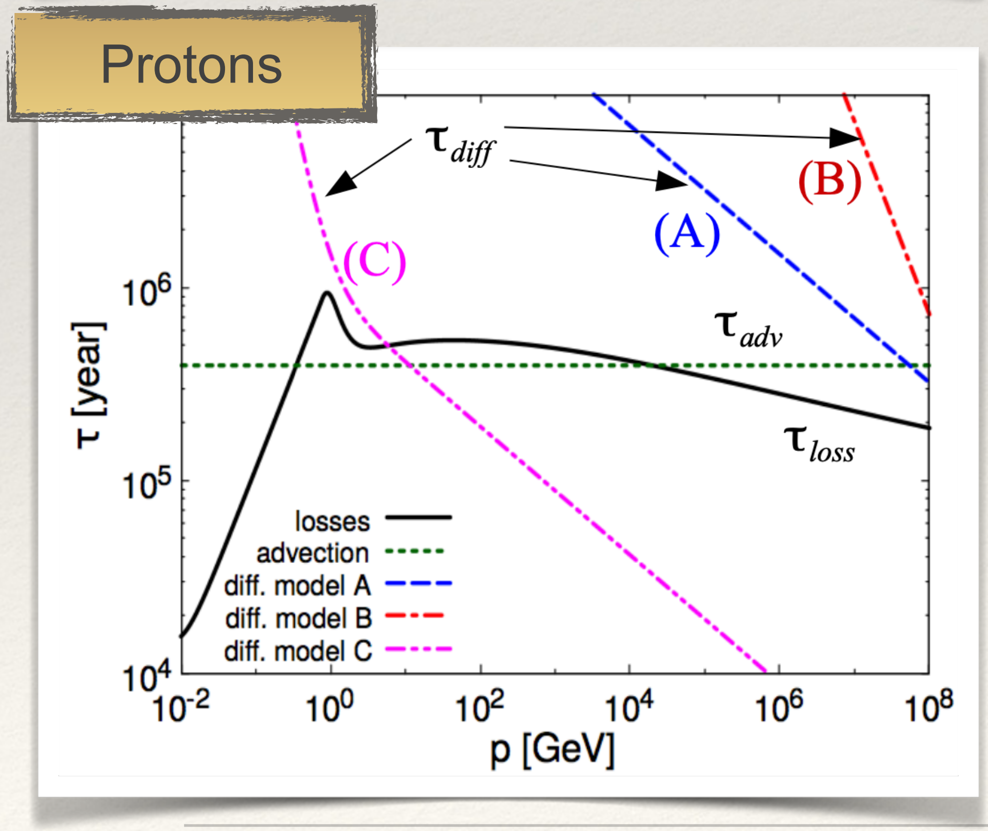
A) Kolmogorov: $d = 5/3$; $L_0 \simeq 1\,\rm pc$

B) Bohm: $d = 0$

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

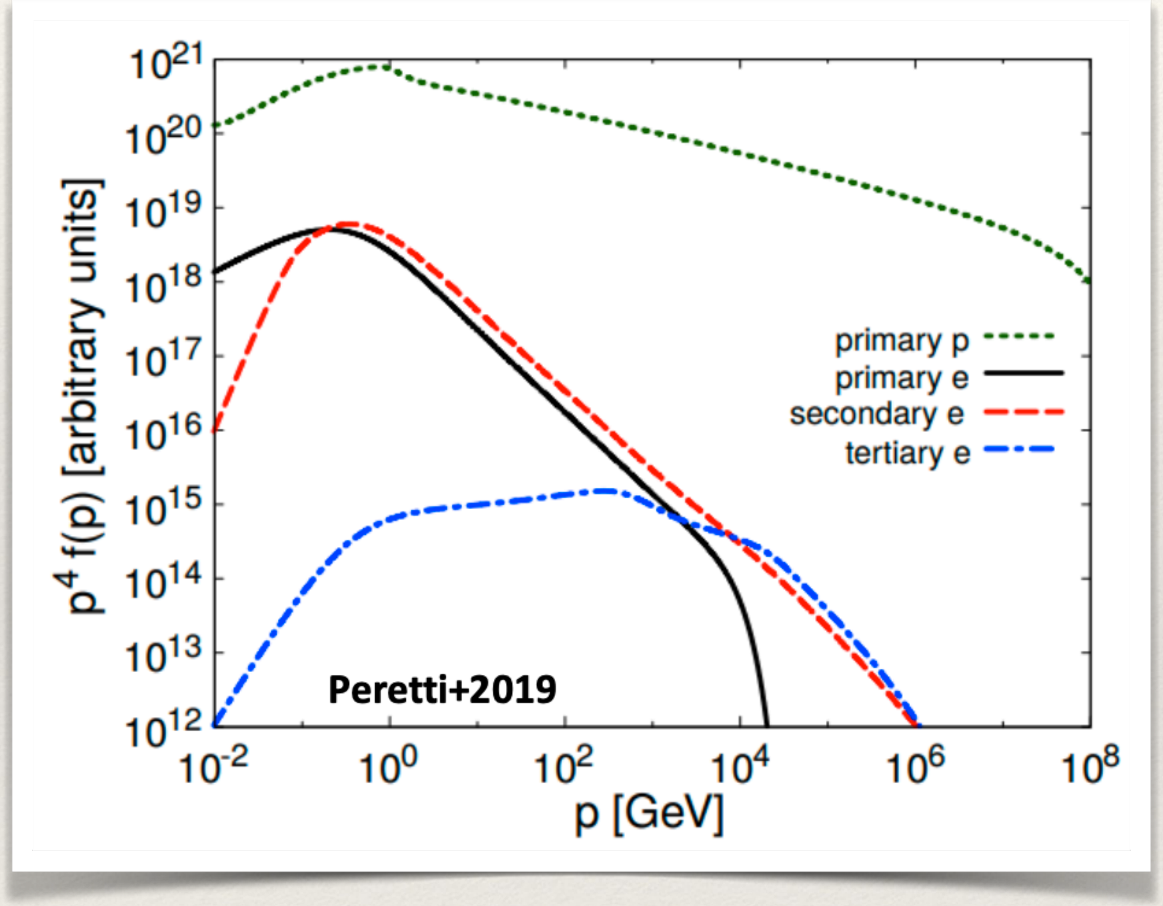
- **Electrons are confined in SBNi**
- **Advection and losses mainly regulate the transport of protons**

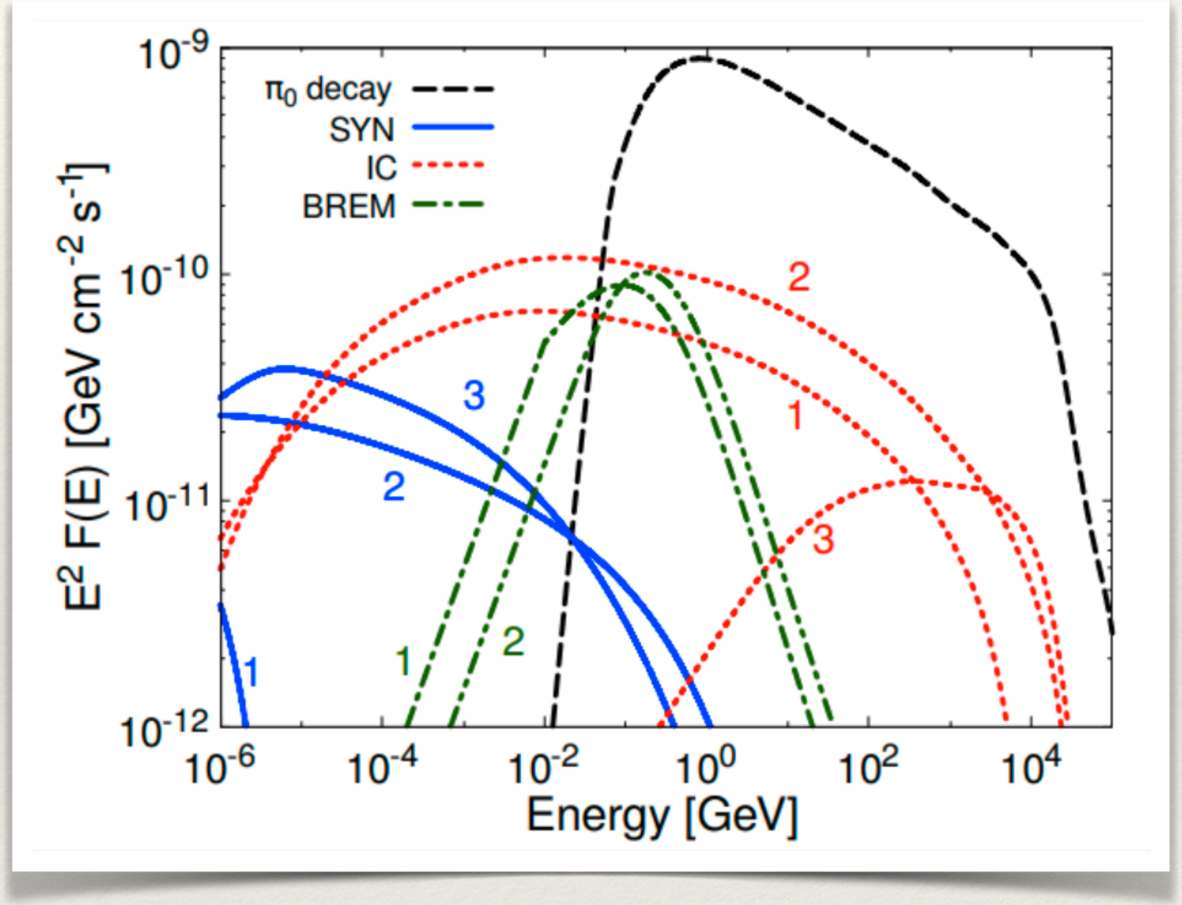




Particle and photon spectra

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





1 → primaries

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

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

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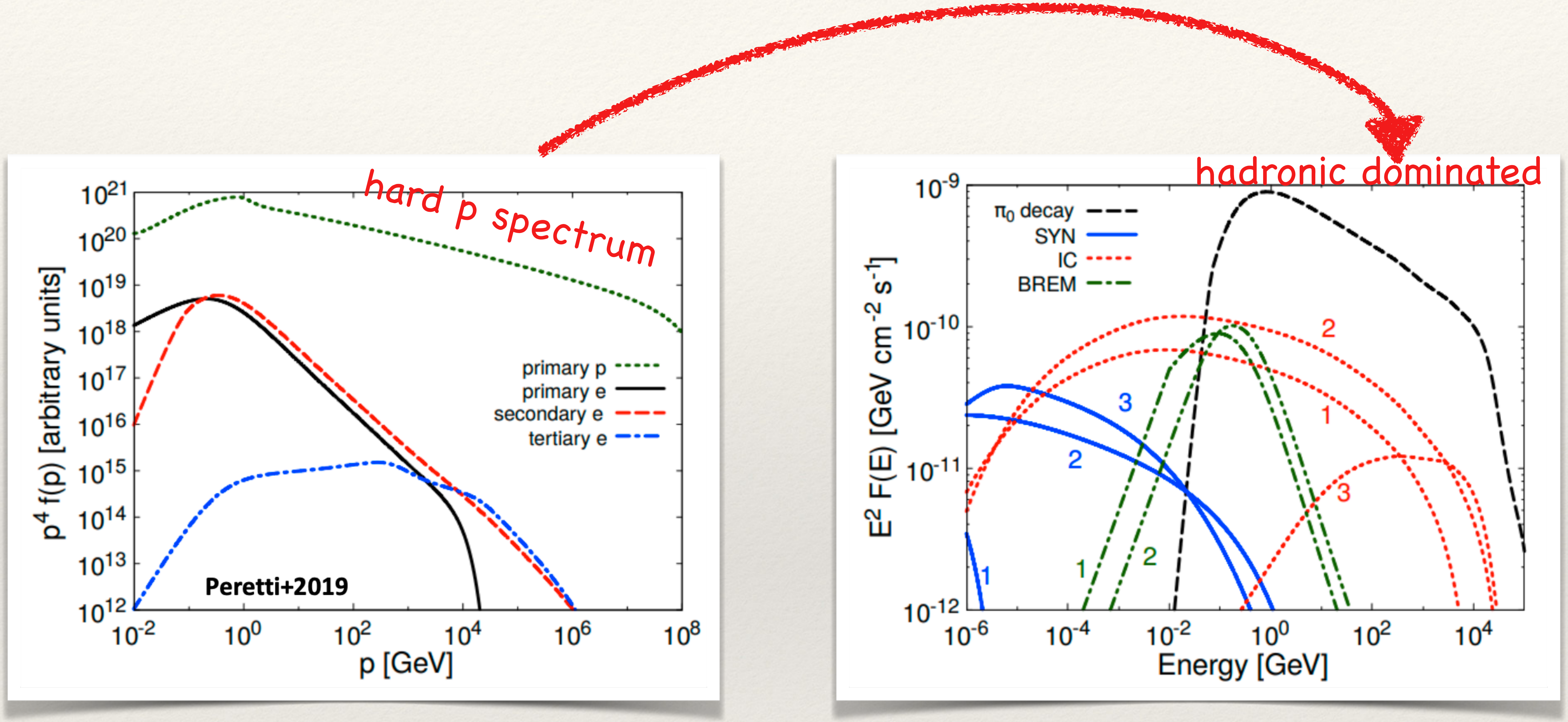

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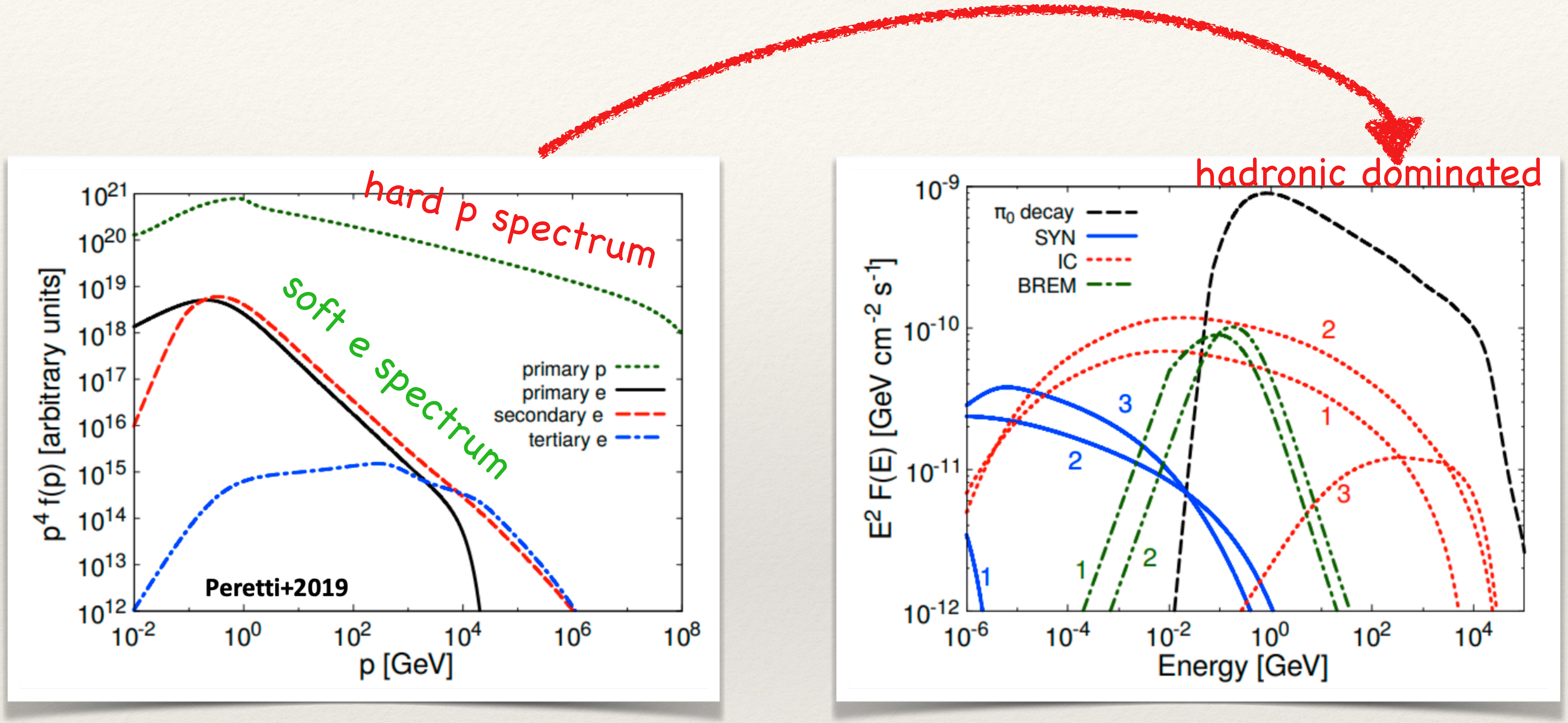

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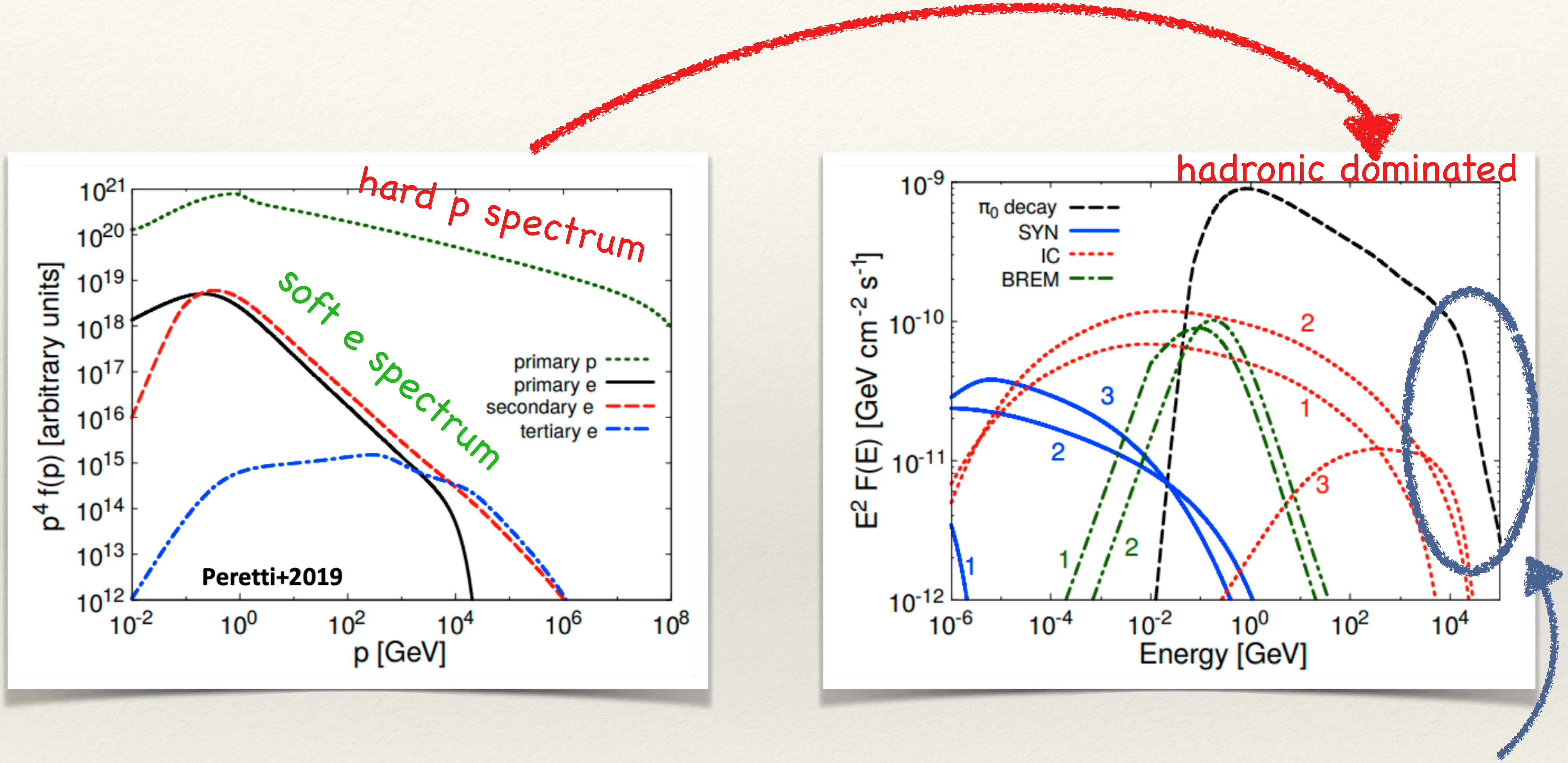


hard p spectrum

soft e spectrum

hadronic dominated

$\gamma\gamma-$absorbed
inside the nucleus

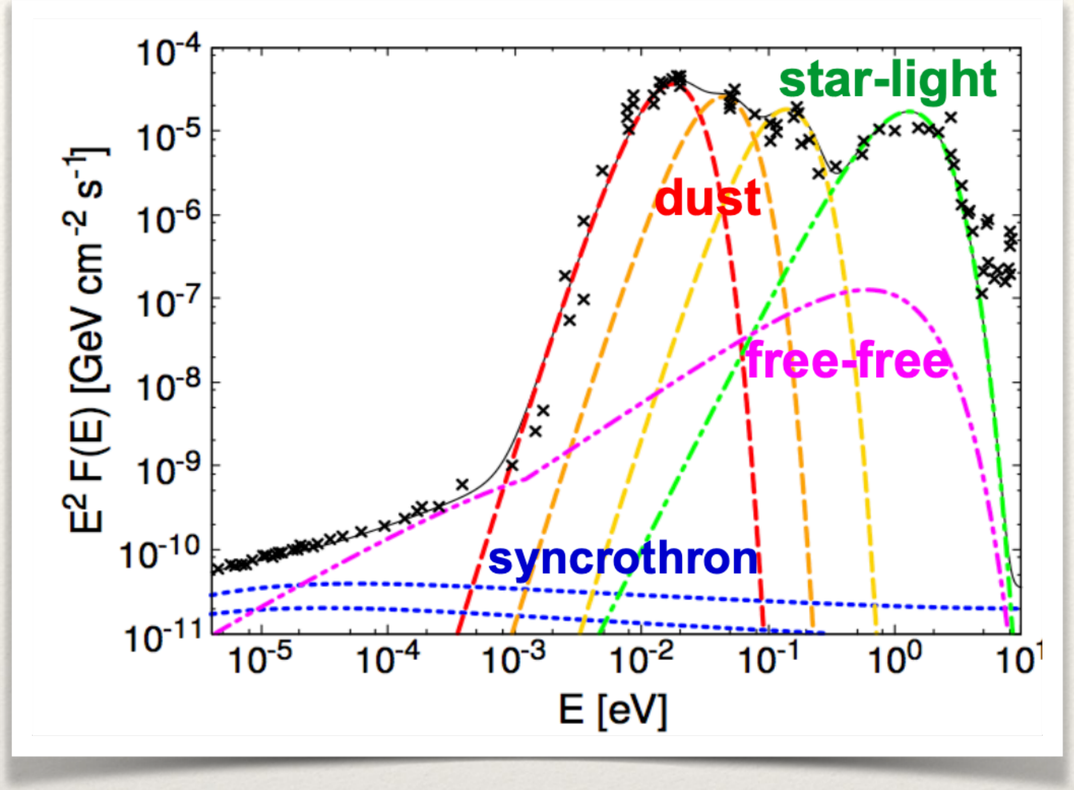
1 → primaries

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

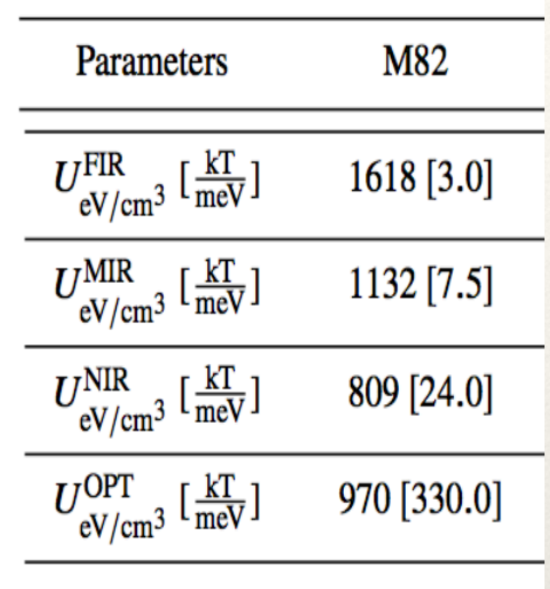
3 → tertiaries: $\gamma\gamma \rightarrow e^{+}e^{-}$

Application to individual SB galaxies: M82

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



Photon background fitted from available data



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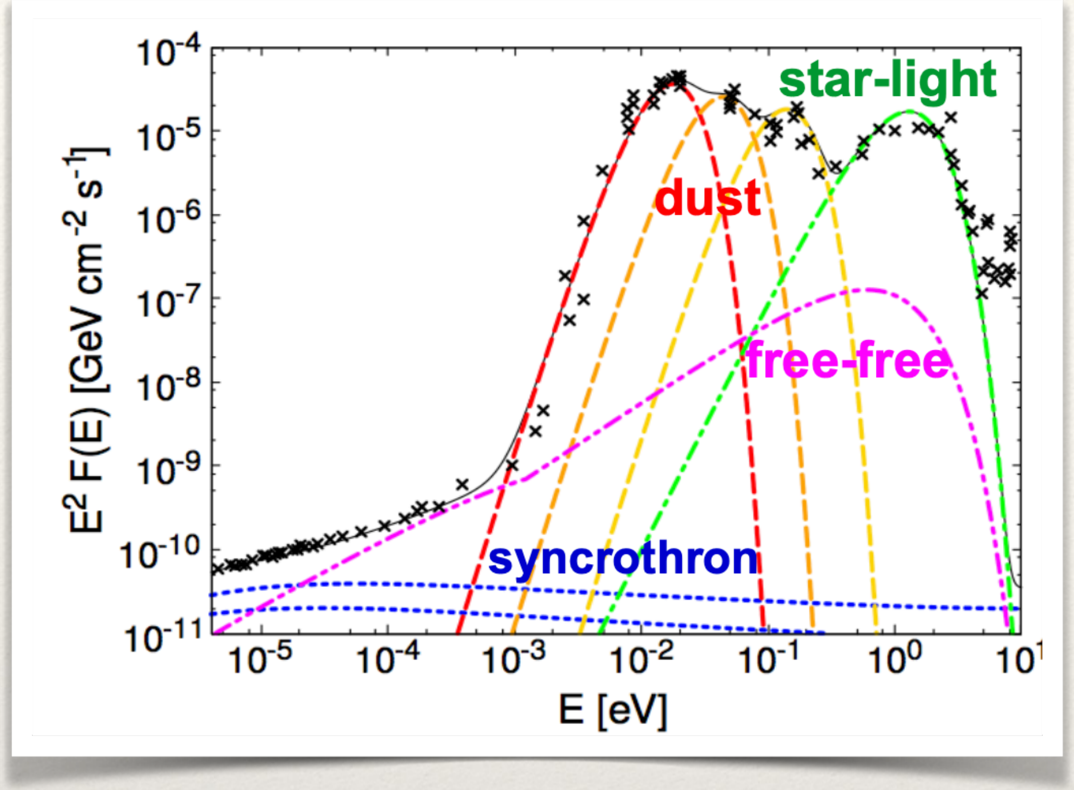

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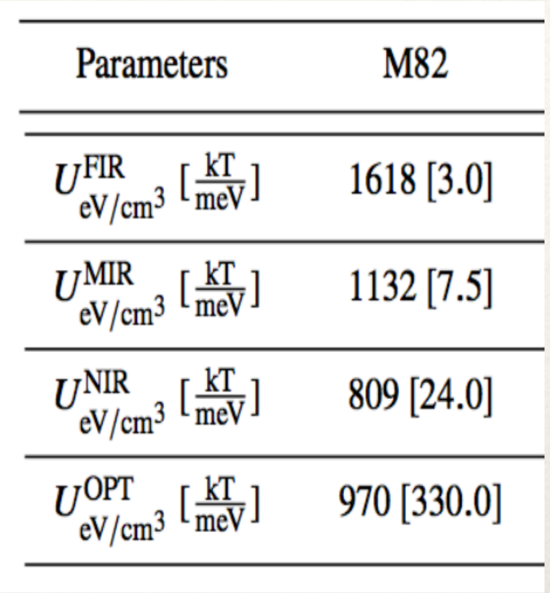

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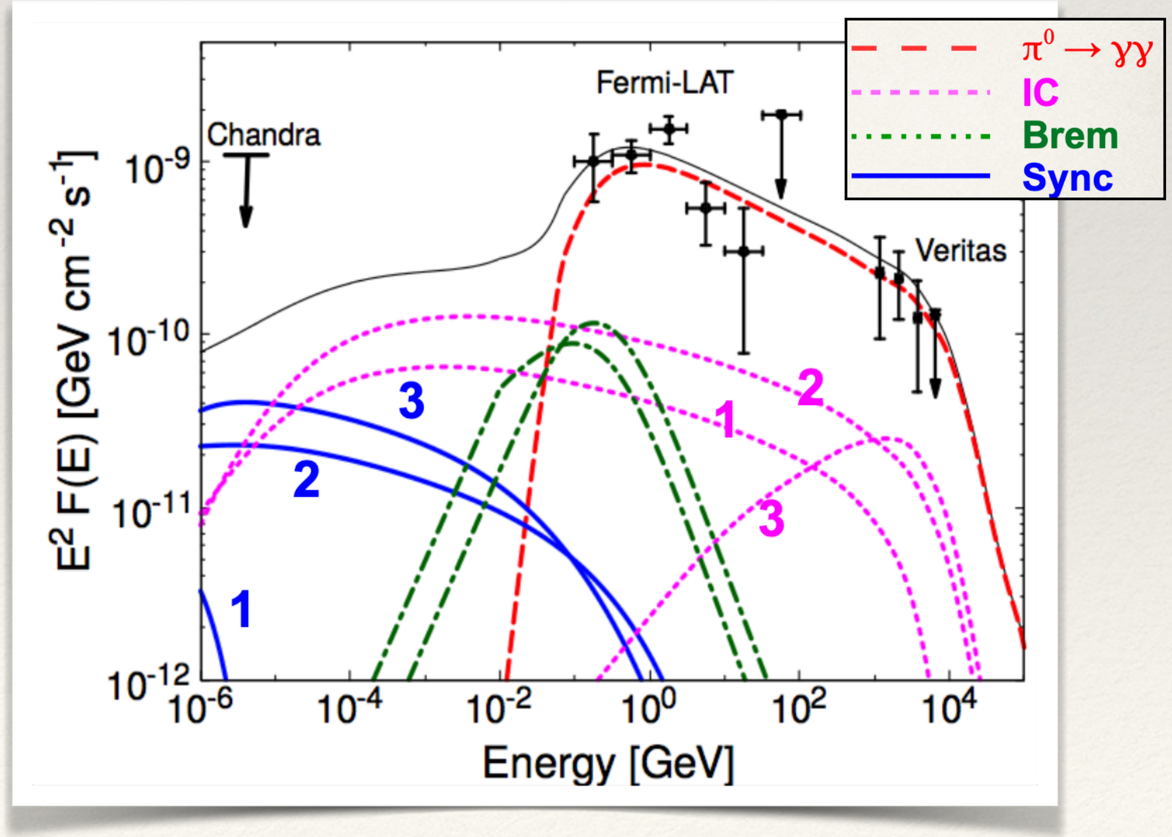
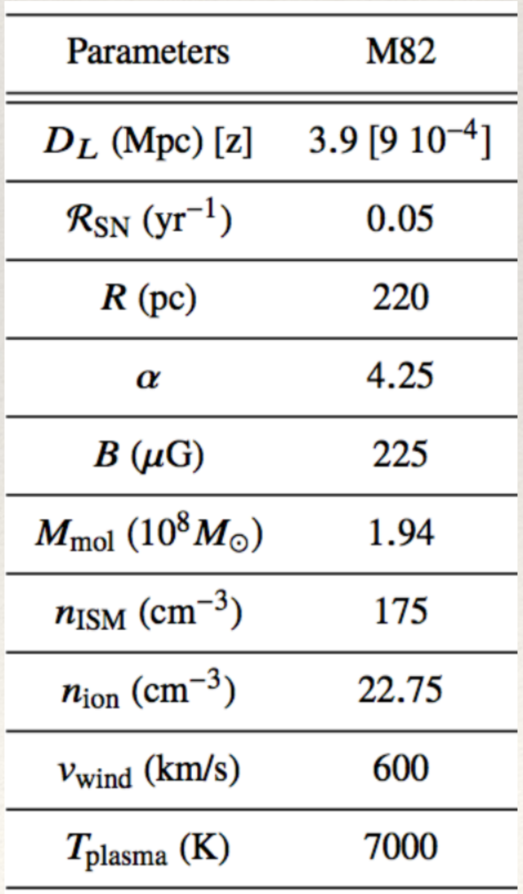


Gamma-ray spectrum



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

Diffuse emission from starburst nuclei

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

Diffuse emission from starburst nuclei

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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

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

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

Using the Kennicutt (1998) relation:

$$\frac{\Sigma^*_{\rm SFR}}{M_\odot {\rm yr}^{-1} {\rm kpc}^{-2}} = (2.5 \pm 0.7) \times 10^{-4} \left[\frac{\Sigma^*_{\rm gas}}{1\ M_\odot {\rm pc}^{-2}}\right]^{1.4 \pm 0.15}$$

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

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

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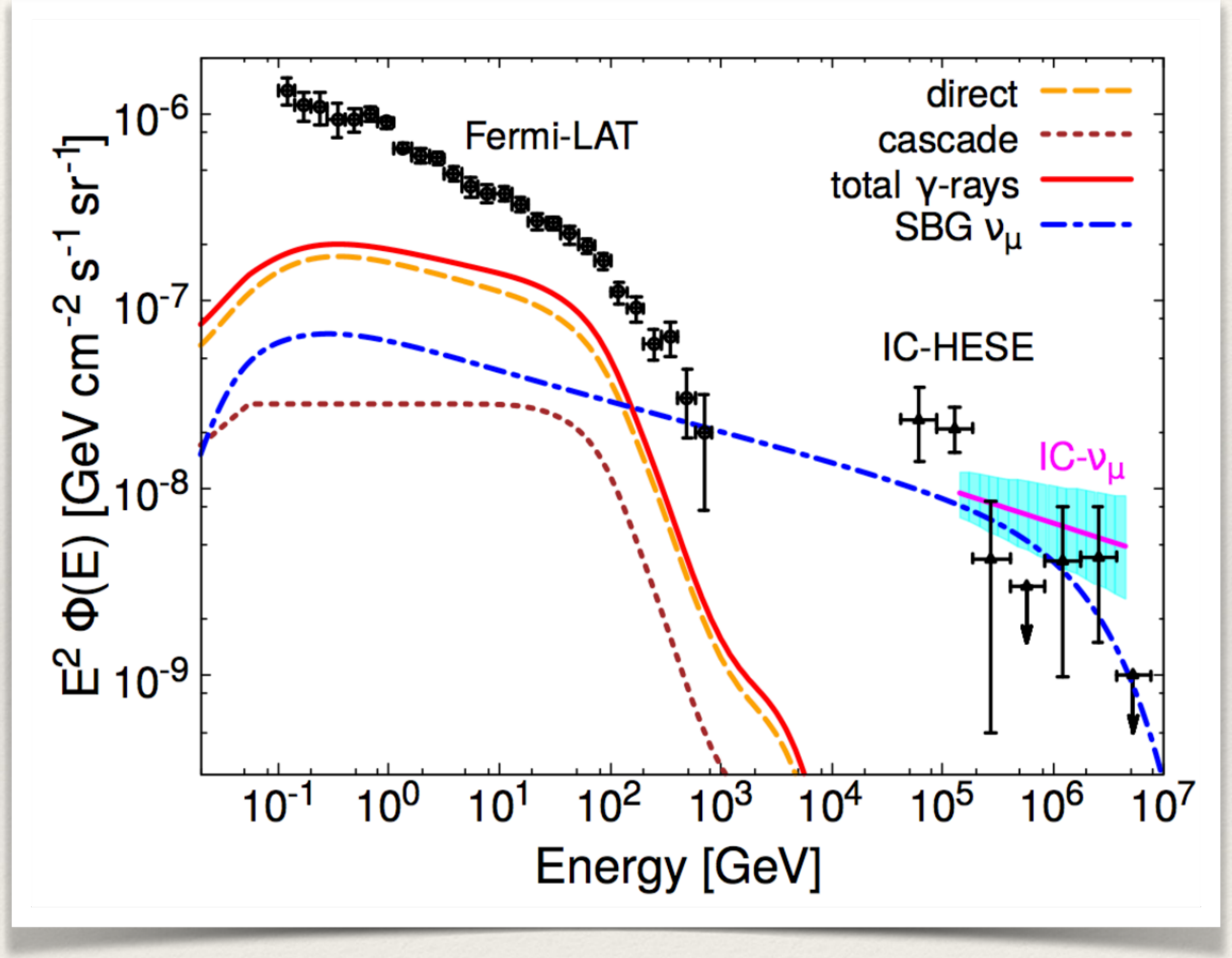

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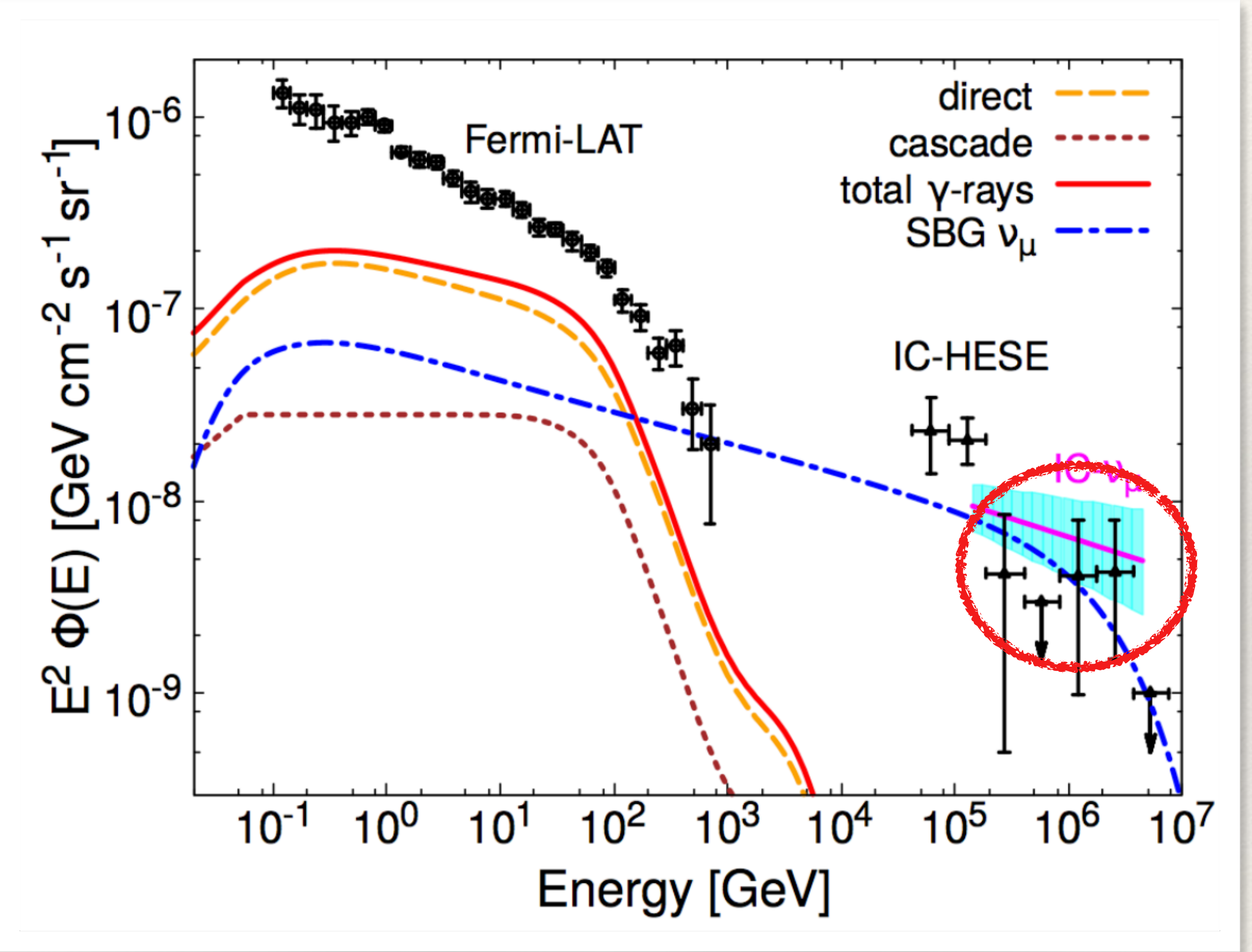

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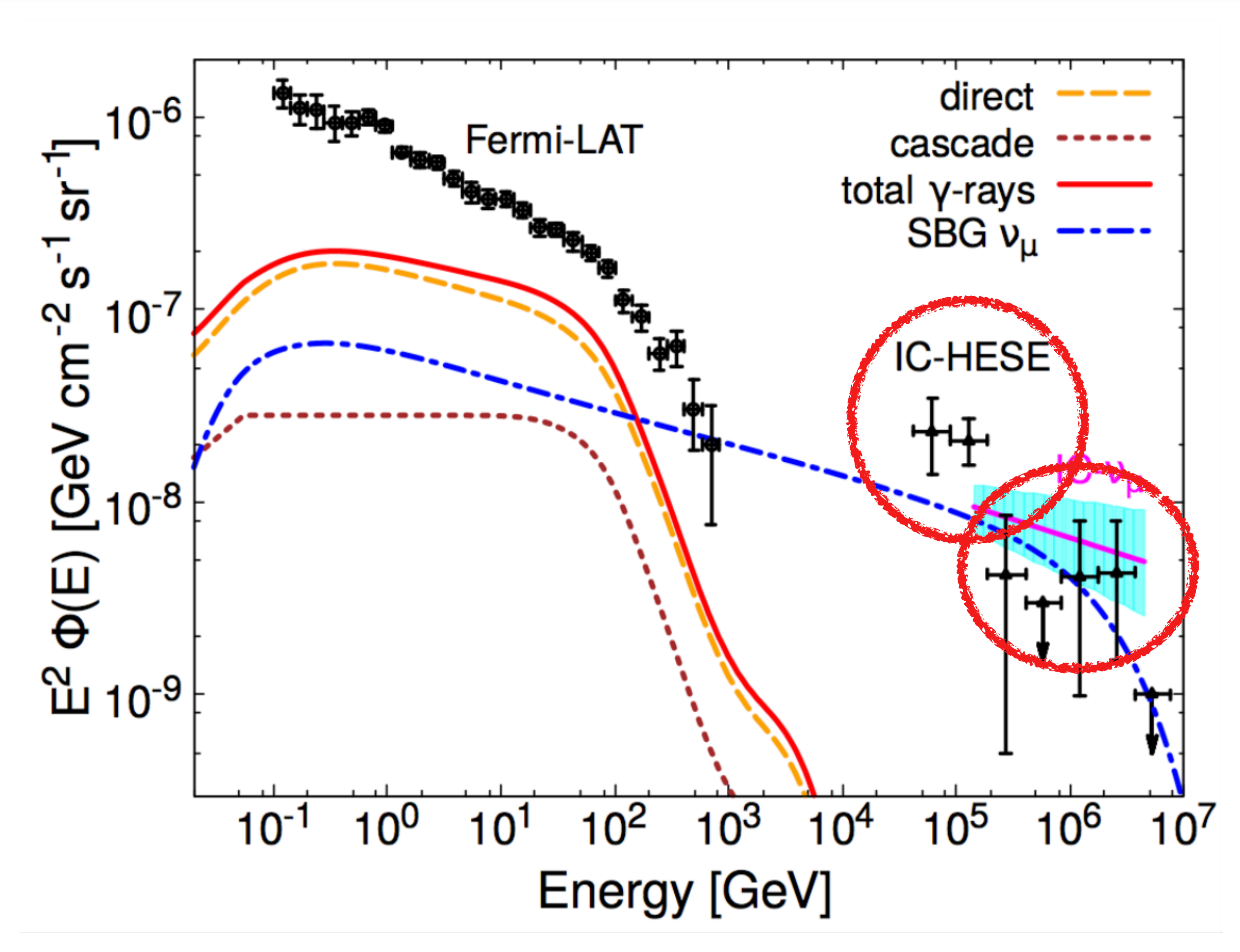

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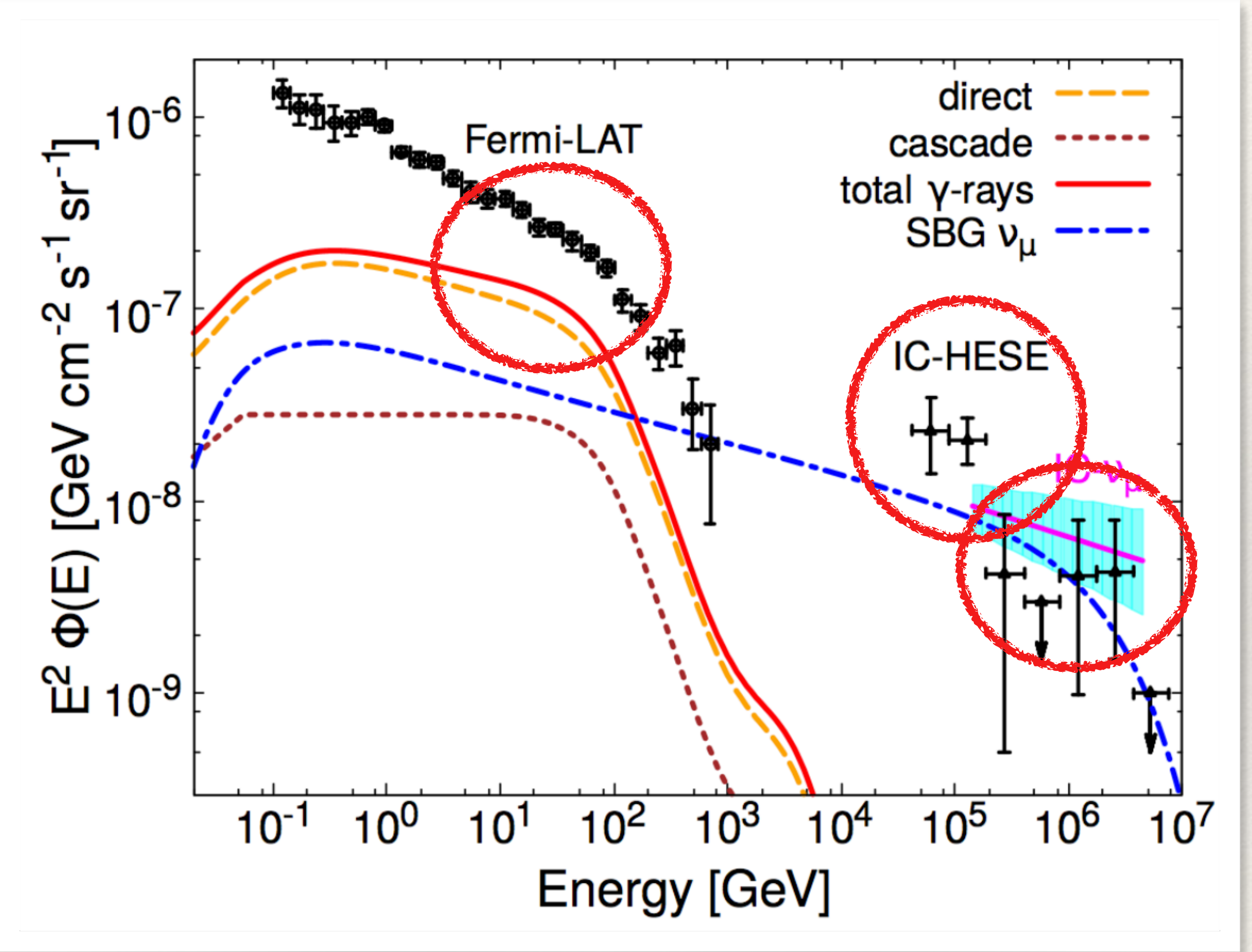

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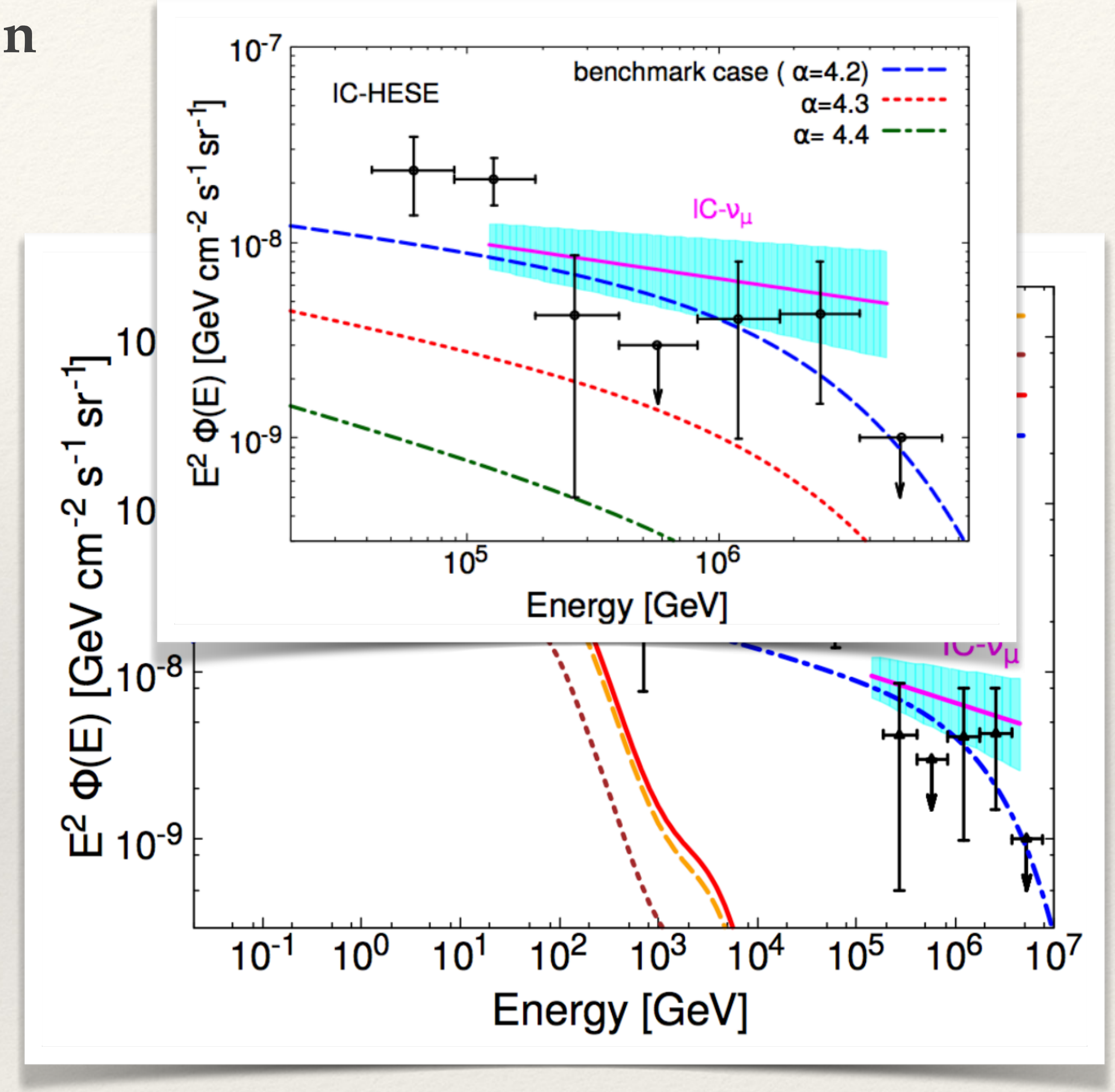

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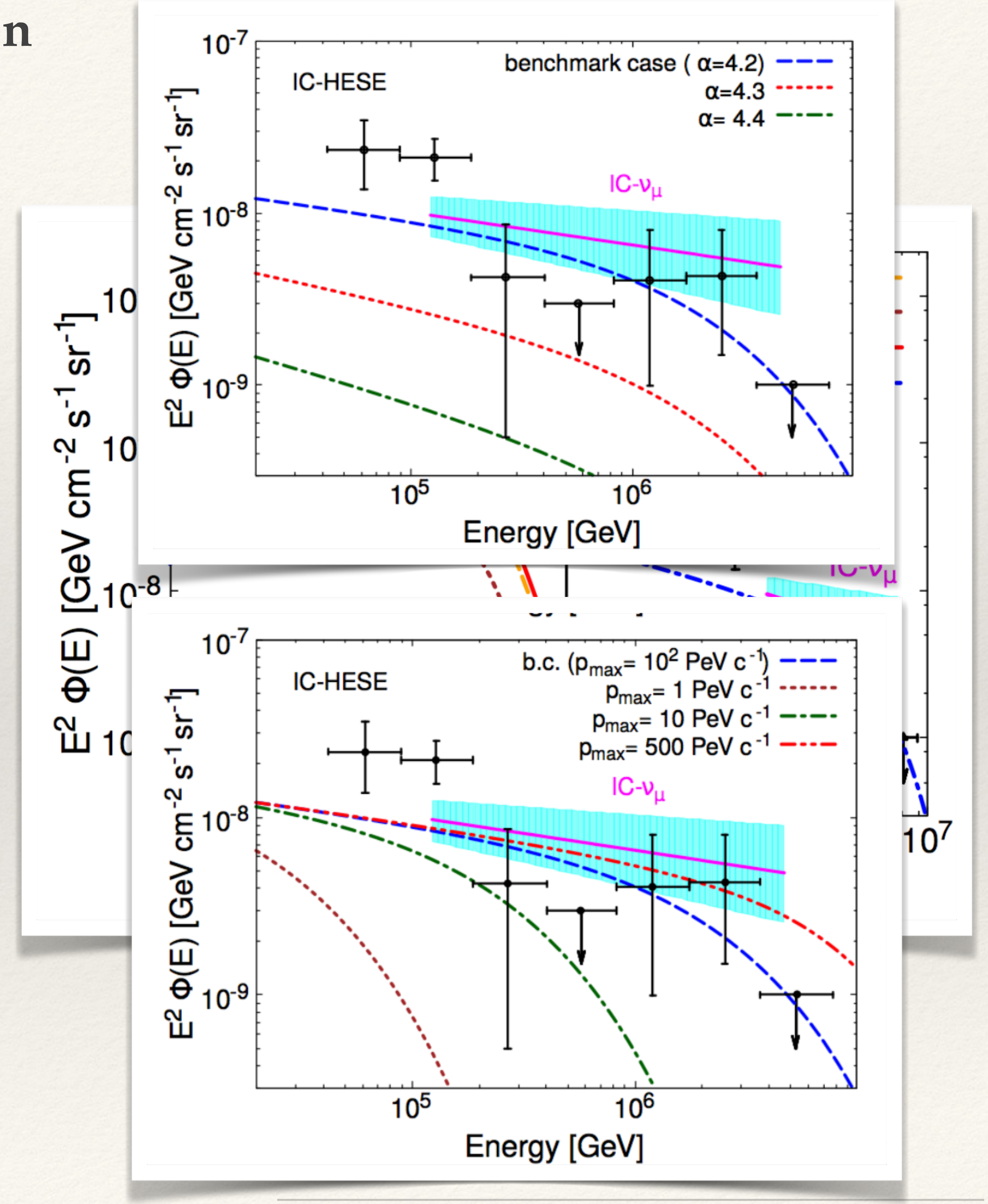

Requirements:

- Hard acceleration slope: $\propto E^{-2.2}$ (Compatible with Milky Way SNRs)
- **Maximum energy ~ 100 PeV is required: How can be produced?**

The problem of maximum energy

- Particle acceleration in SBNi is powered by SNRs
- The dynamic of single SNRs should be similar to the ones in the Milky Way

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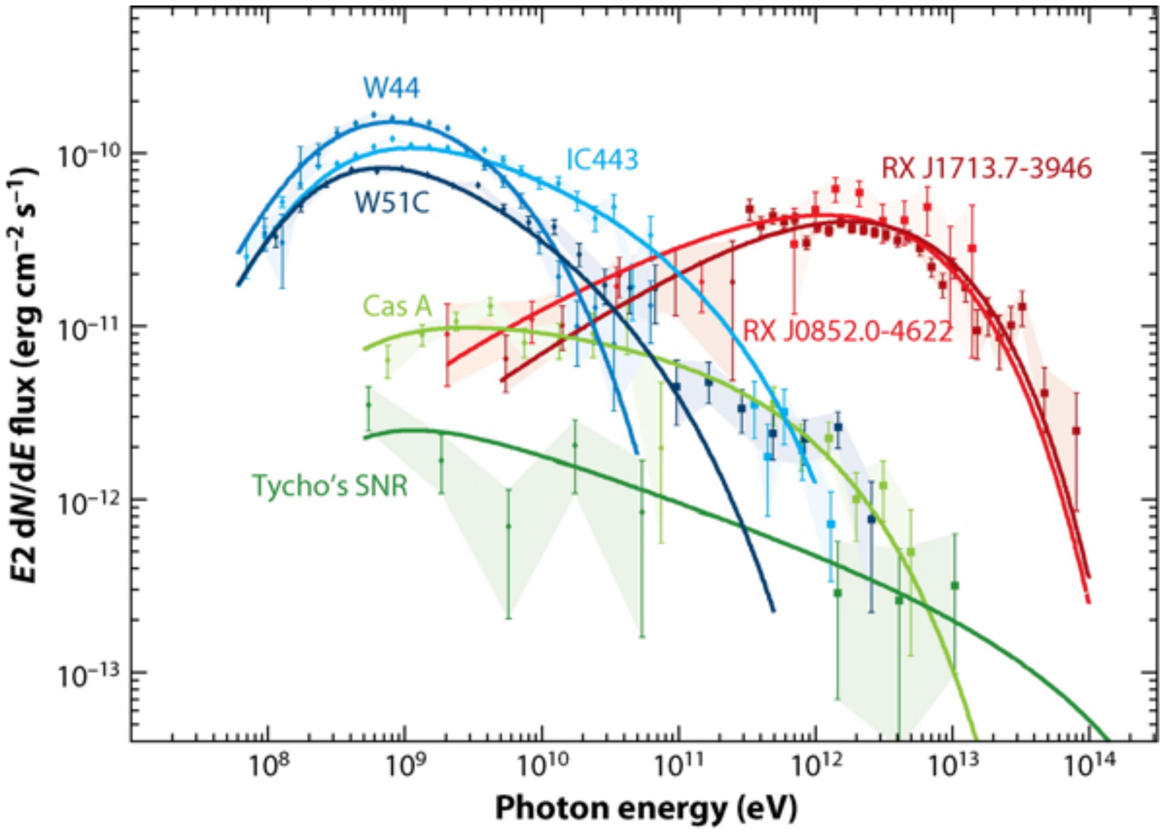

Funk S. 2015.
Annu. Rev. Nucl. Part. Sci. 65:245–77

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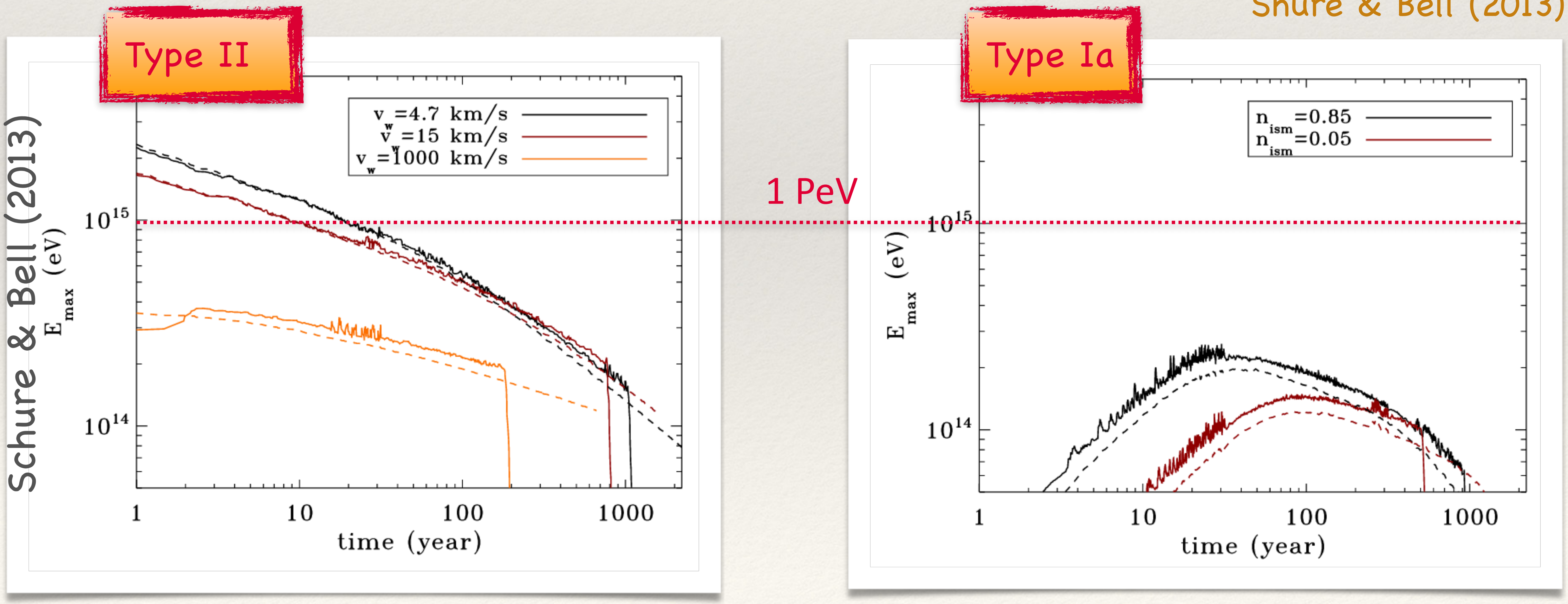
- Even theoretically $E_{\rm max} \lesssim 1$ PeV

Maximum energy predicted using the non-resonant streaming instability [Bell, 2004]

Shure & Bell (2013)



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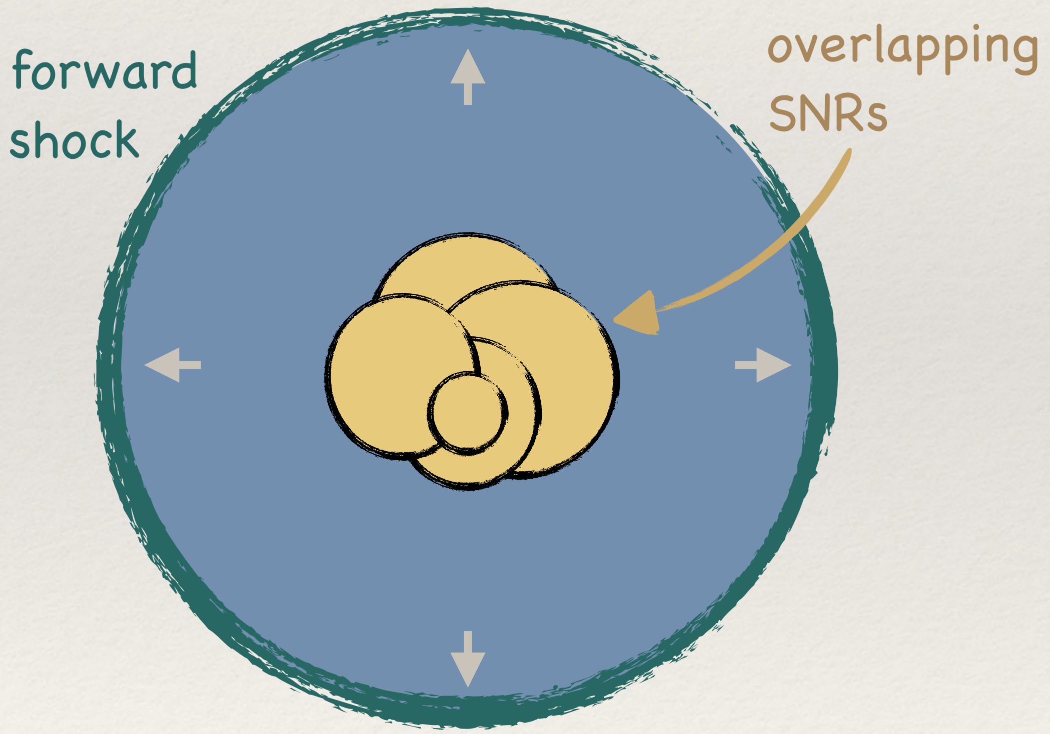
- Larger energies could be obtained as a result of SNRs overlap



Multiple SNR can enhance the level of turbulence

↓

Larger confinement time

↓

Larger $E_{\max}$ due to multiple shock crossing

However difficult to reach 100 PeV

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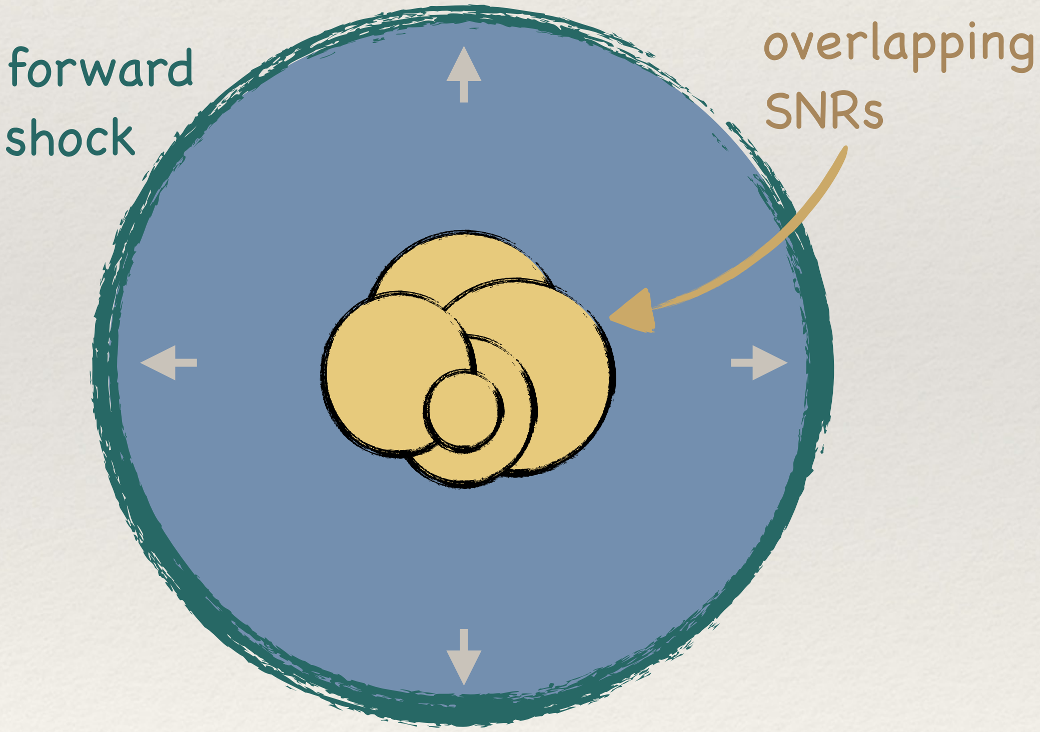

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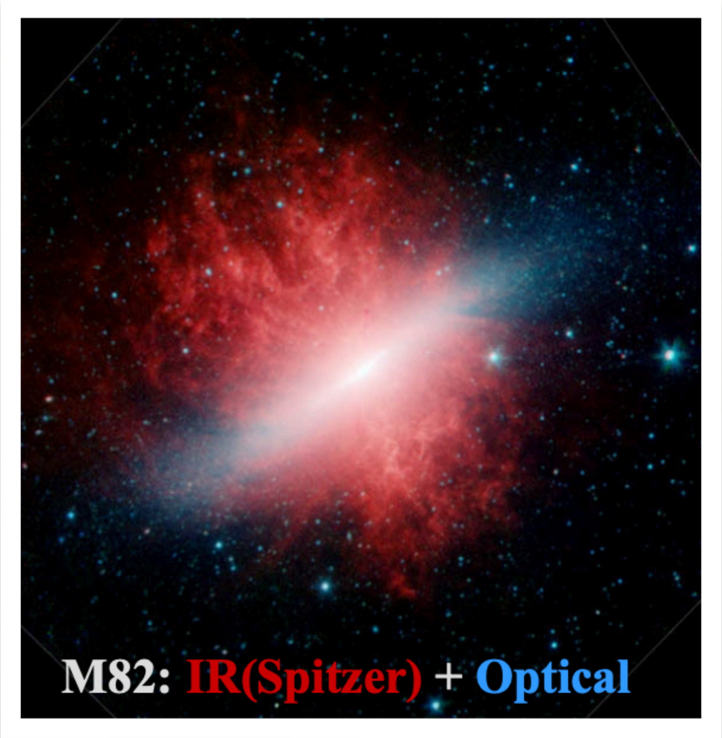
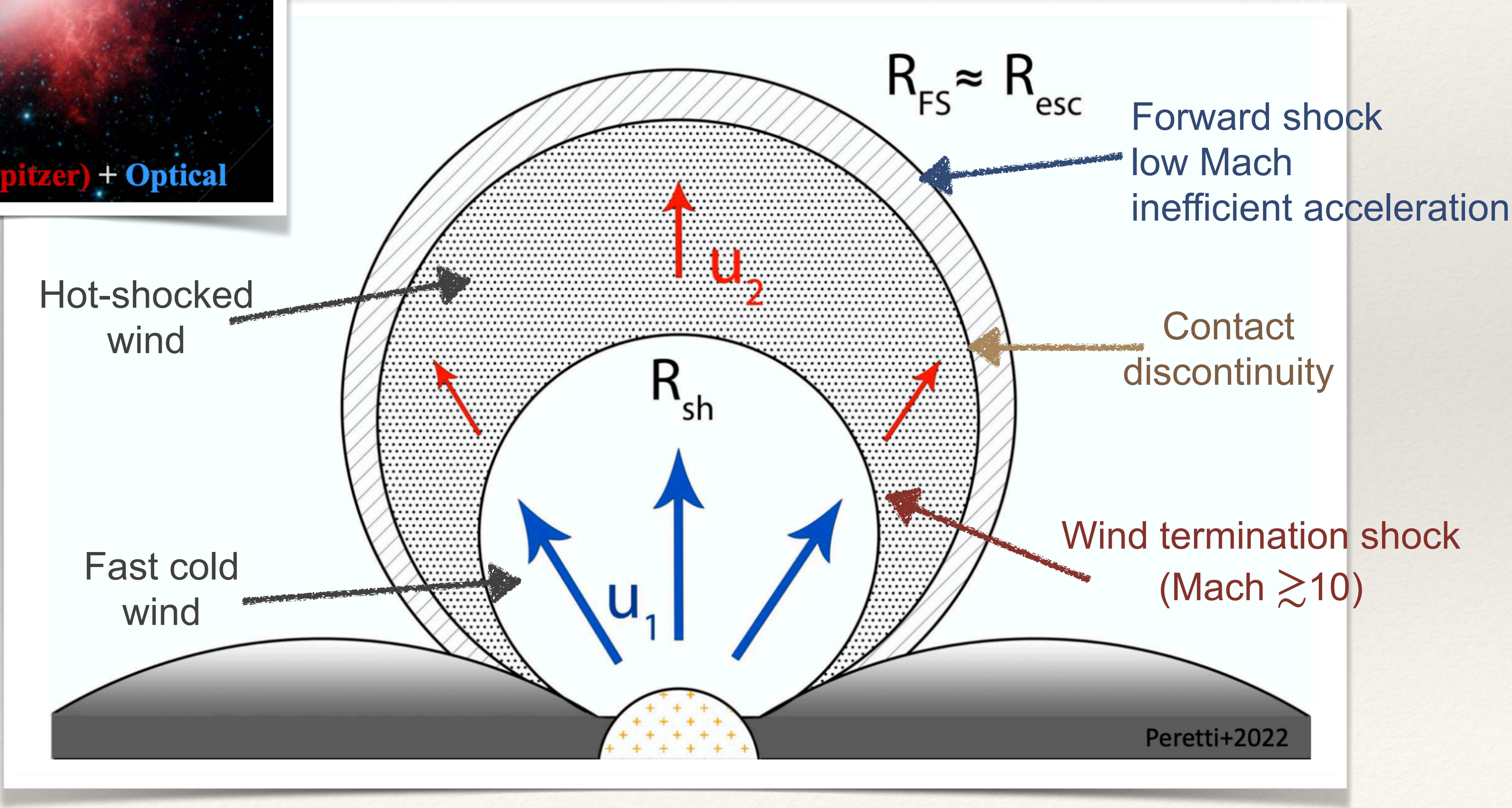
Are there alternatives?

Acceleration at the SB-driven wind

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



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

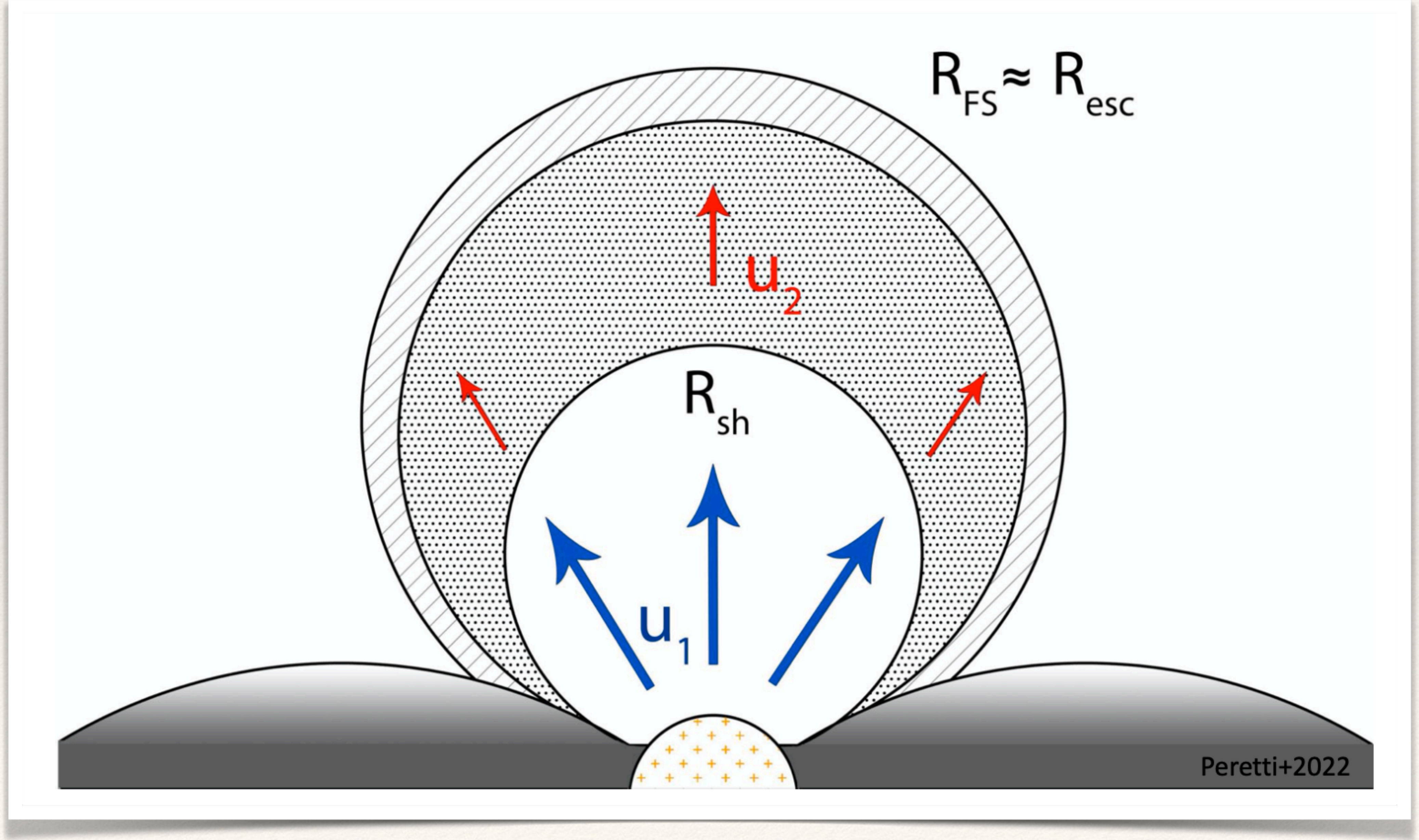


Acceleration at the SB-driven wind

[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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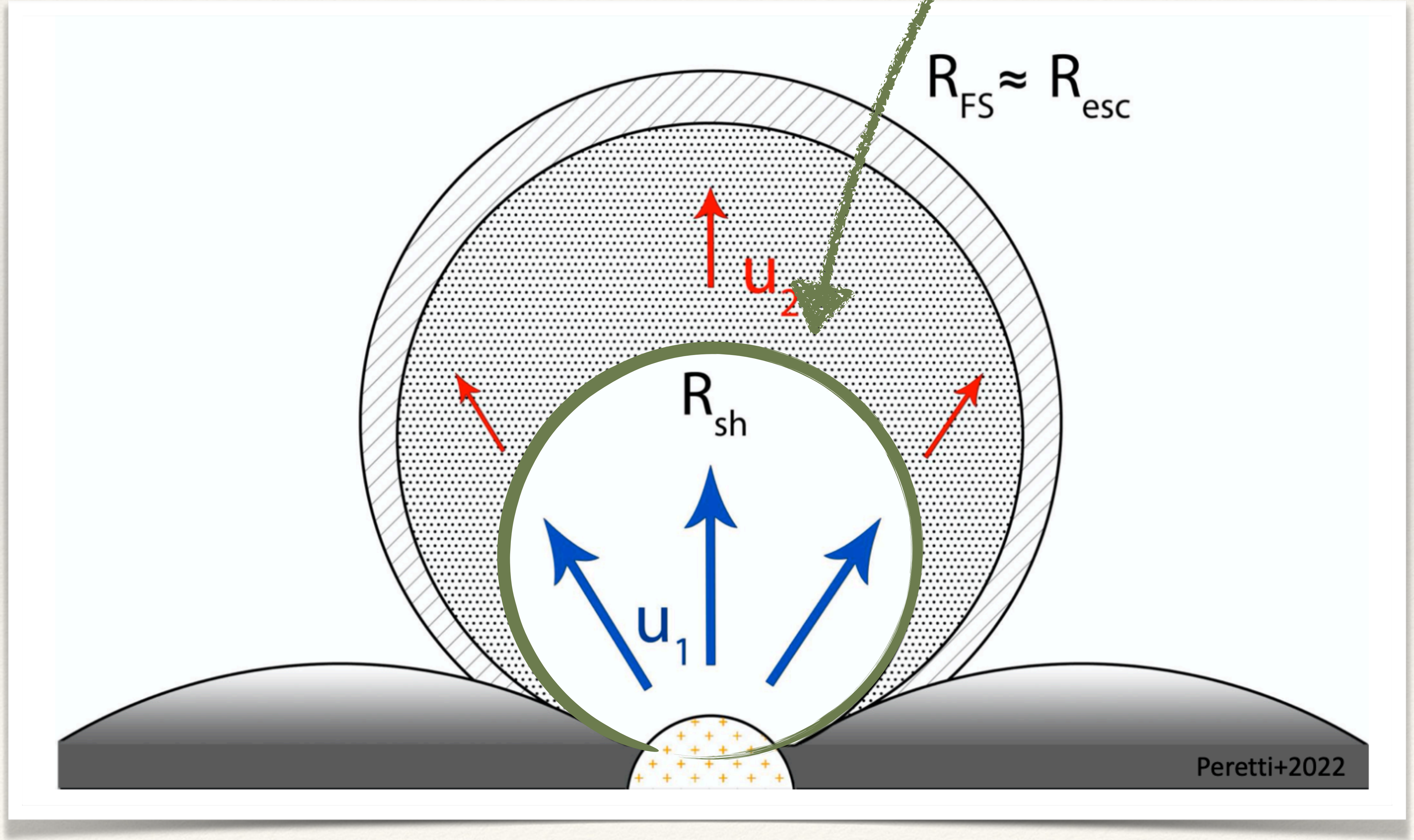

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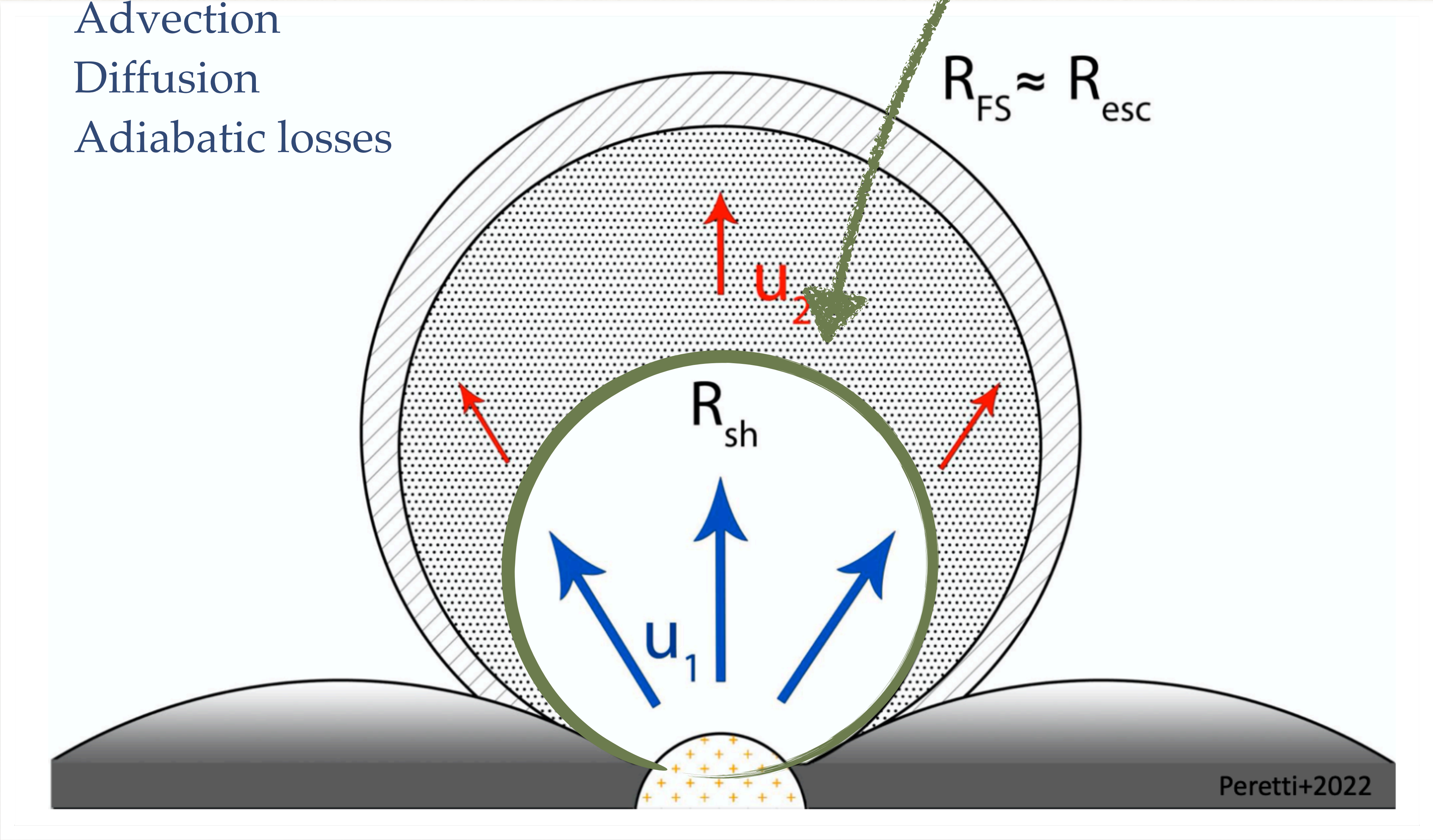

Advection

Diffusion

Adiabatic losses

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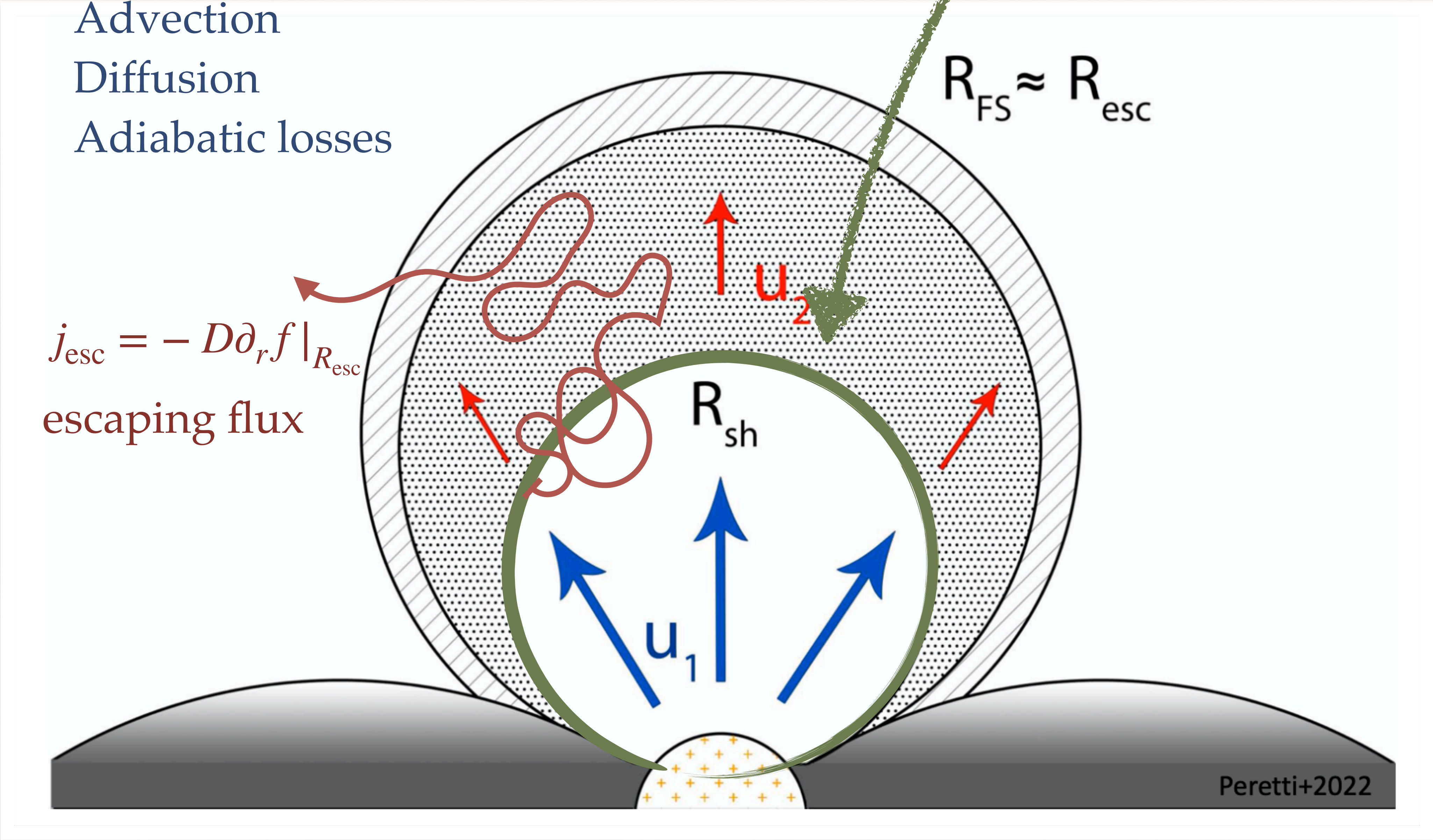

Advection
Diffusion
Adiabatic losses

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

escaping flux

Acceleration at the SB-driven wind

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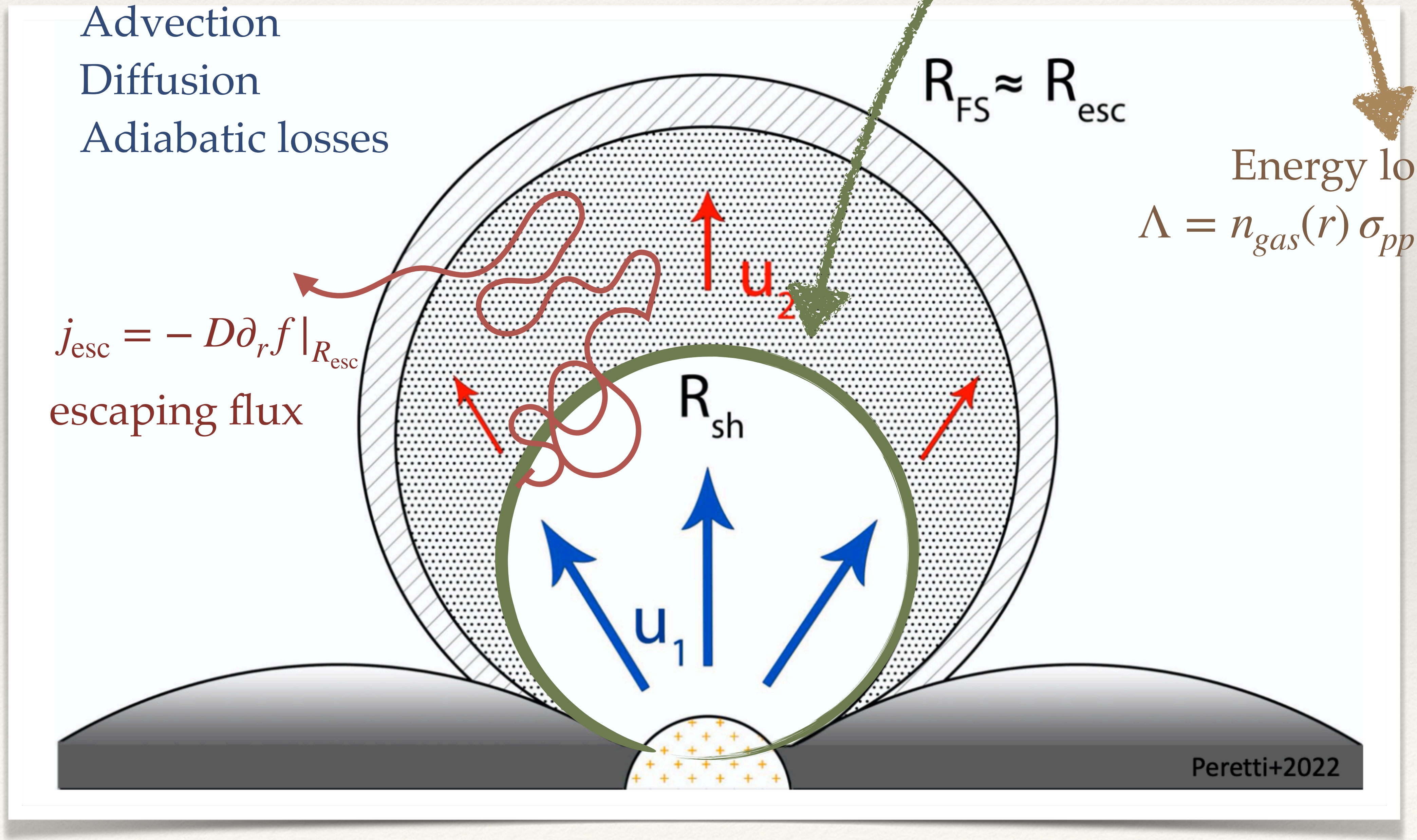
Transport equation in spherical coordinates (approximation)

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



Advection
Diffusion
Adiabatic losses

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

escaping flux

Energy losses

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

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

Maximum energy: a more detailed analysis

GM, Blasi, Peretti & Cristofari (2019)

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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

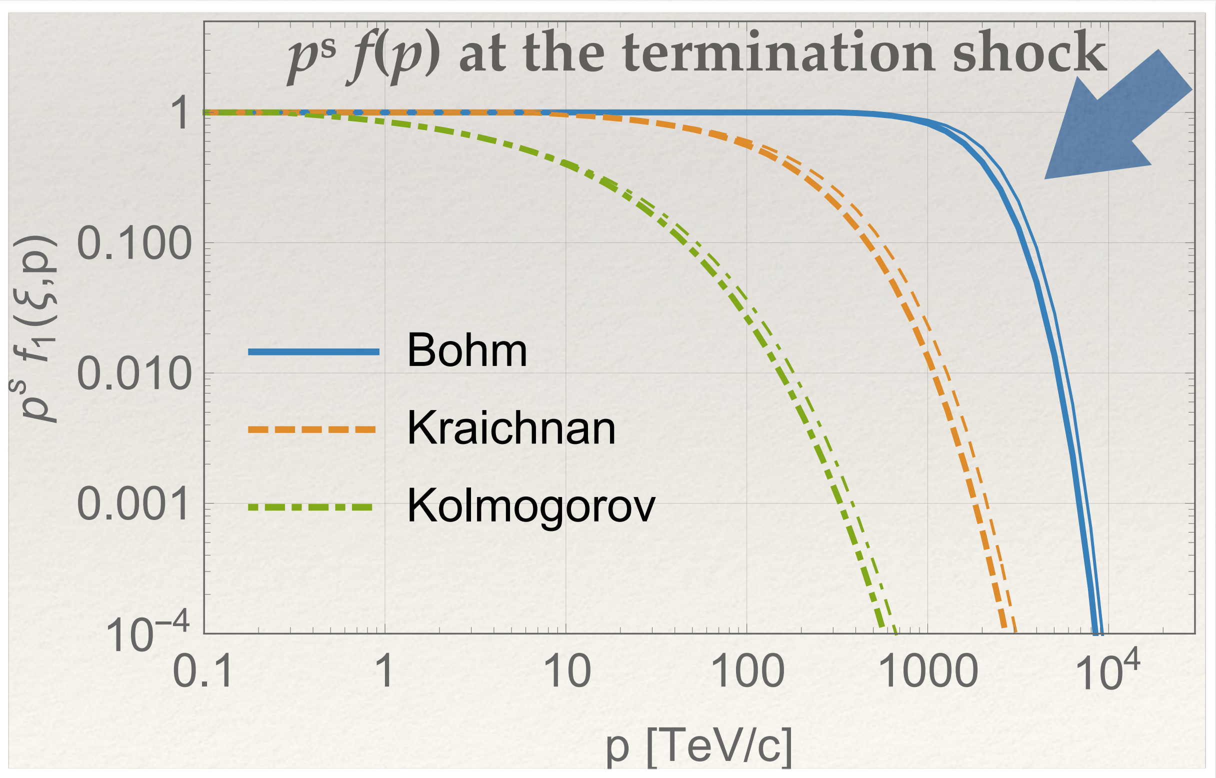
The diffusion coefficient has a strong impact on the cutoff shape and effective maximum energy

Typical values for massive stellar clusters

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

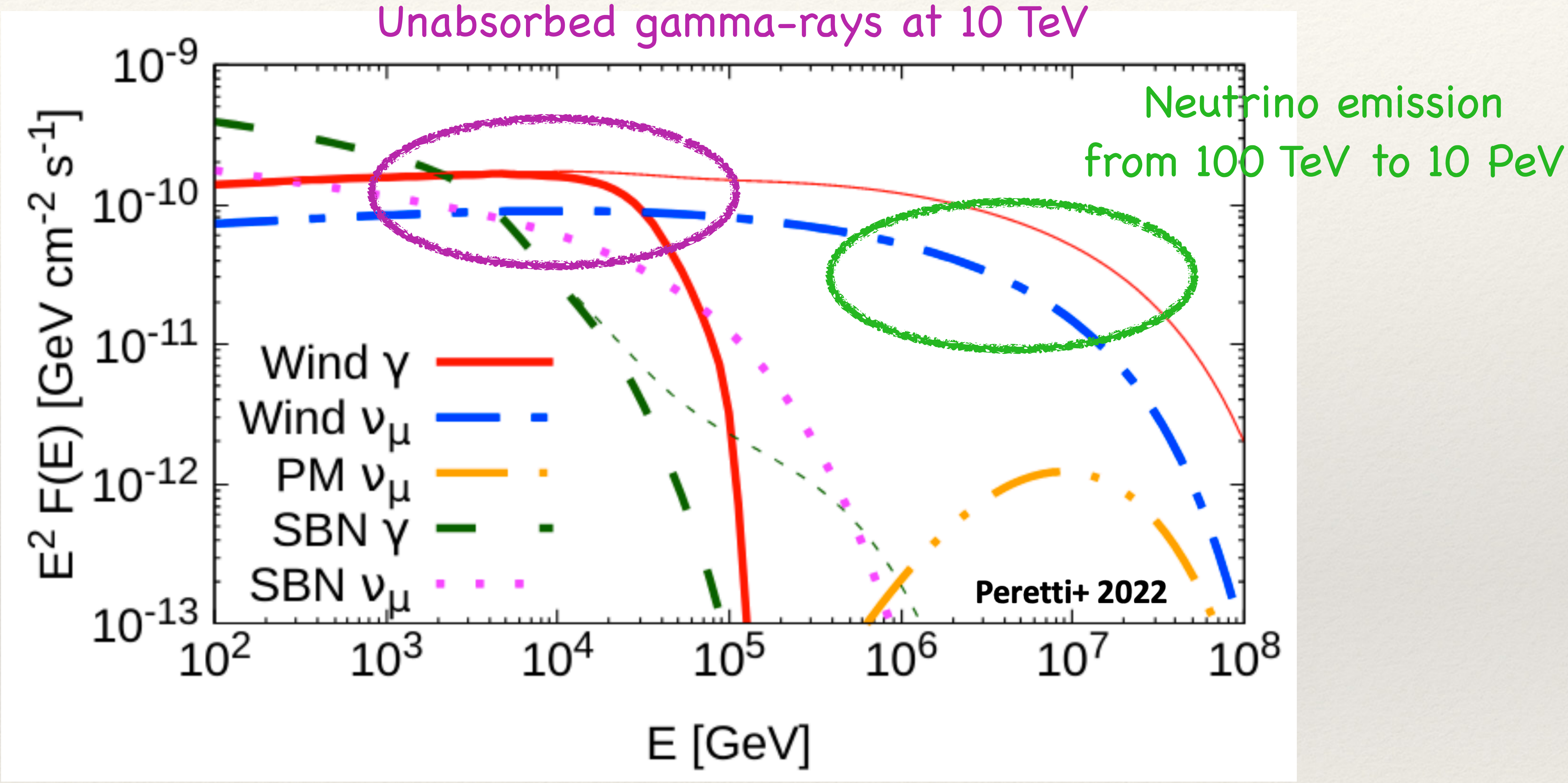
For SBNi

$$\dot{M} \simeq (1-10)\, M_{\odot}{\rm yr}^{-1} \Rightarrow E_{\rm max} \approx 100\ {\rm PeV}$$



High energy SED and neutrinos

Total gamma and neutrino emission from SBN and Wind



Typical parameters

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

→

$$E_{\max} \simeq 100\ \mathrm{PeV}$$

Diffuse emission from SBGs

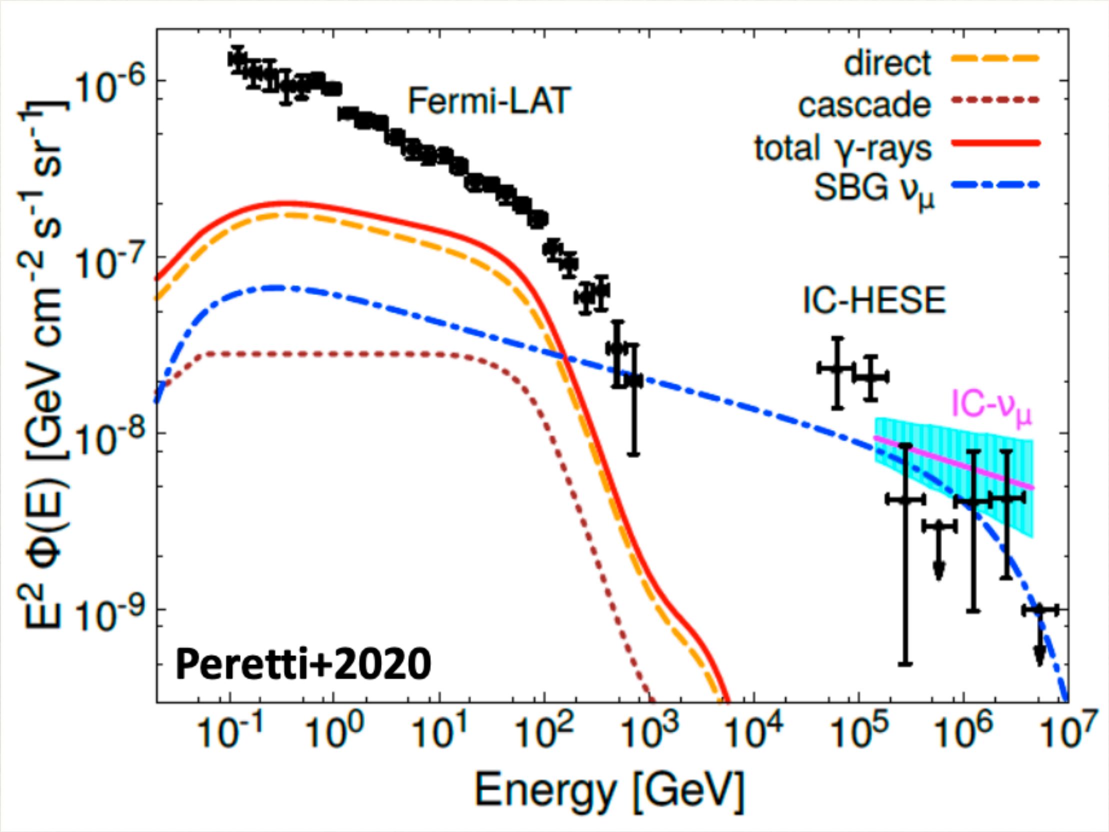
Integrating over the population of SBGs

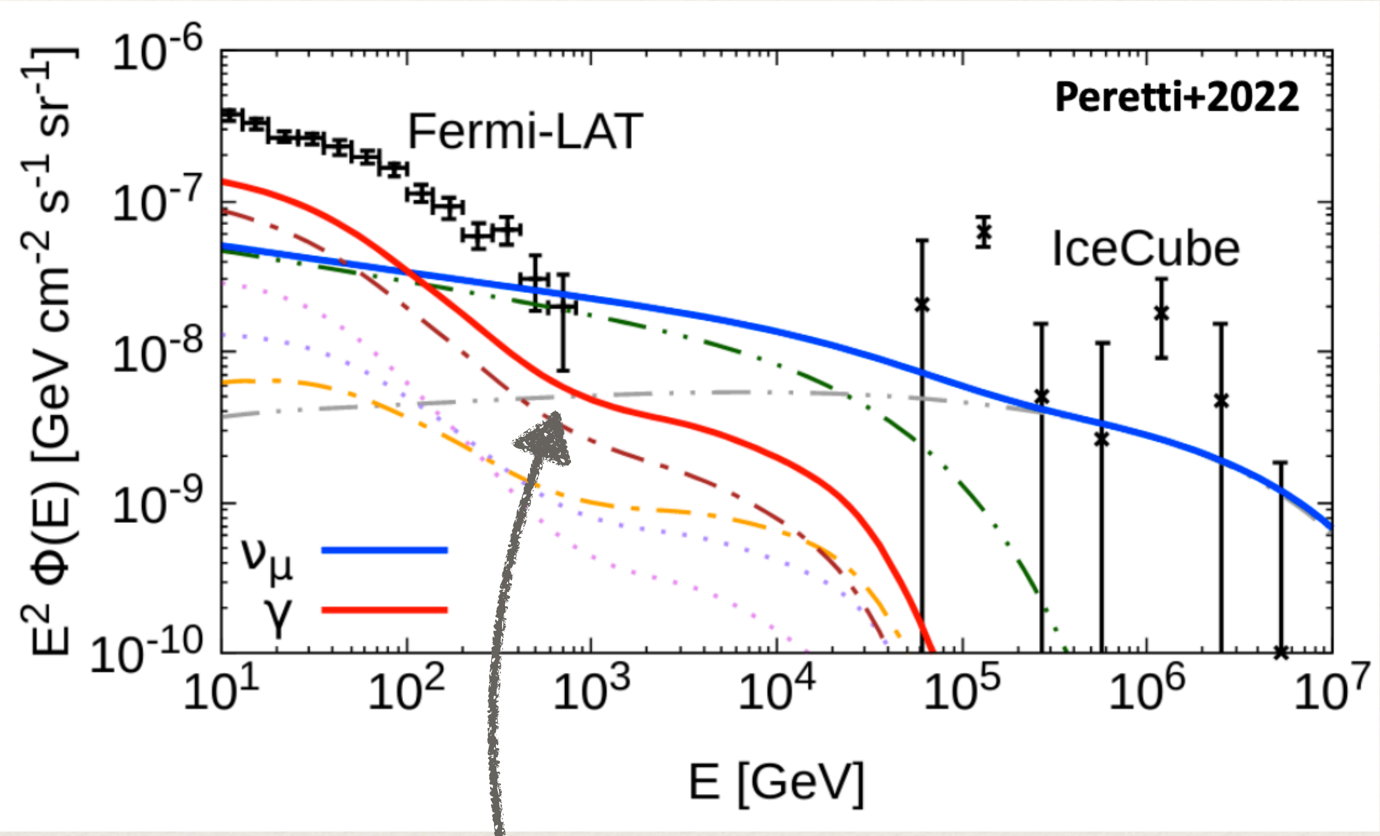
Best fit only SB nuclei

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

SB nuclei + winds

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

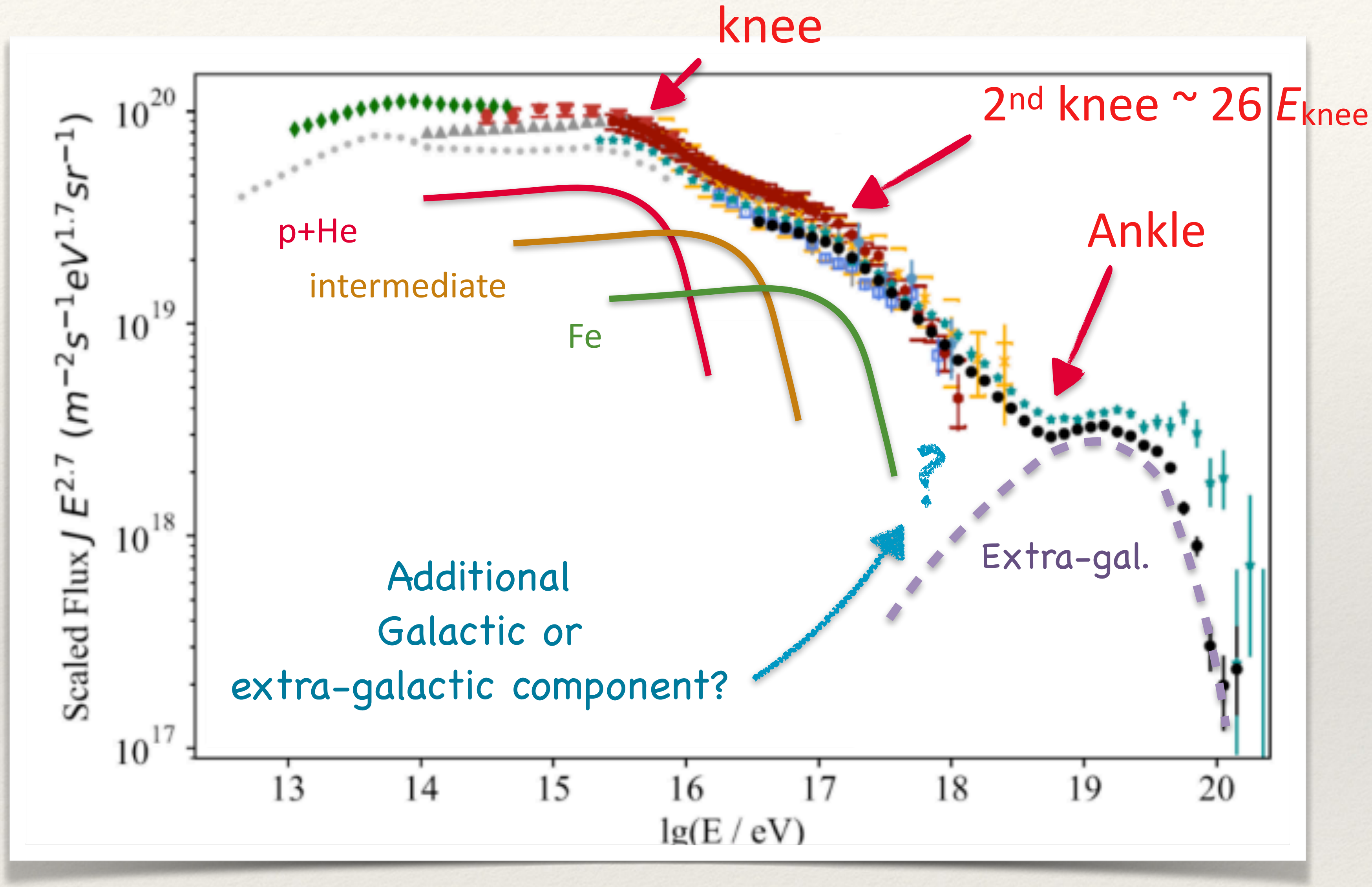




Acceleration at the wind TS need to be harder $\propto E^{-2}$

The transition between Gal. and Extragal. CRs

If galactic sources produce protons with $E_{\max,p} \approx 1$ PeV $\Rightarrow \mathrm{E}_{\max,\mathrm{Fe}} \approx 26$ PeV



What about
$3 \cdot 10^{16}\mathrm{eV} \lesssim E \lesssim 3 \cdot 10^{18}$ eV ?

- Galactic ⇒ "*Super-PeVatrons*"
- Extra-galactic?

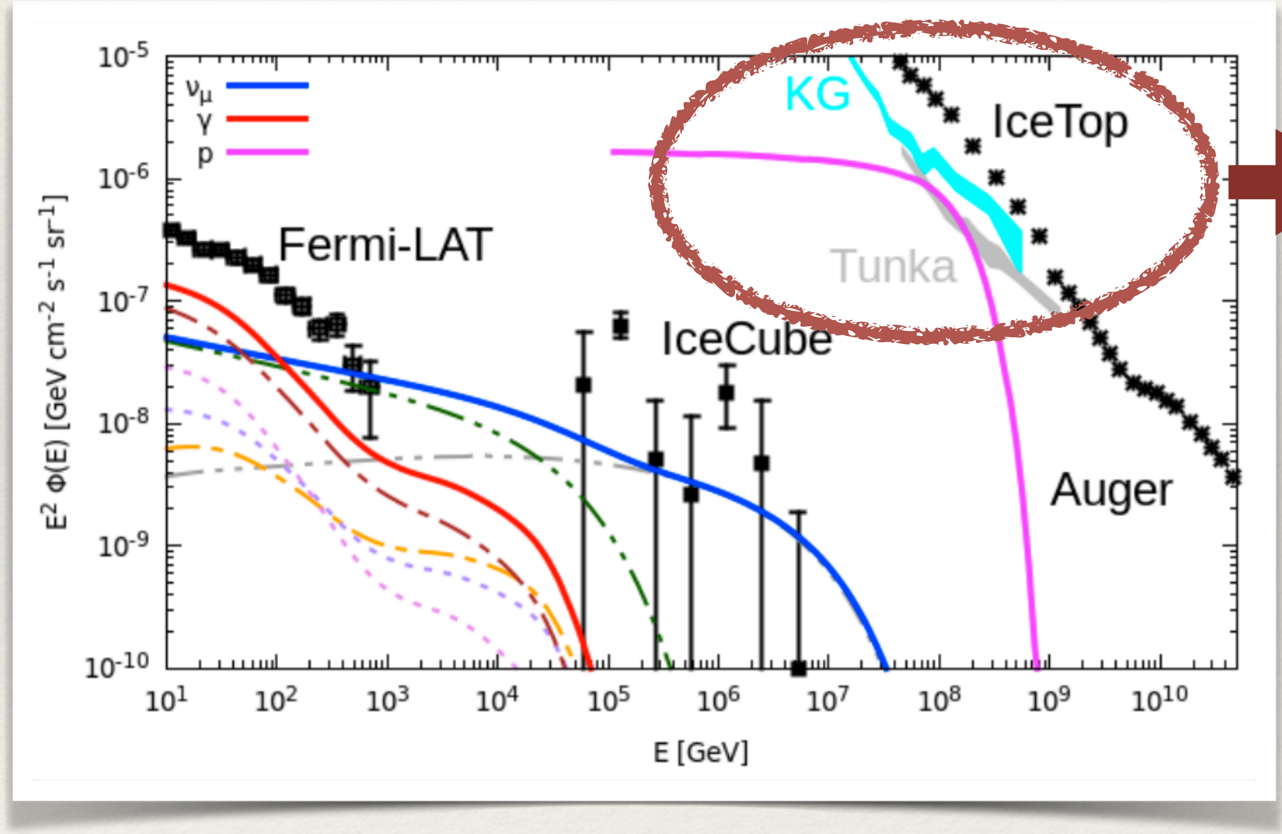
Multi-messenger emission from SBGs

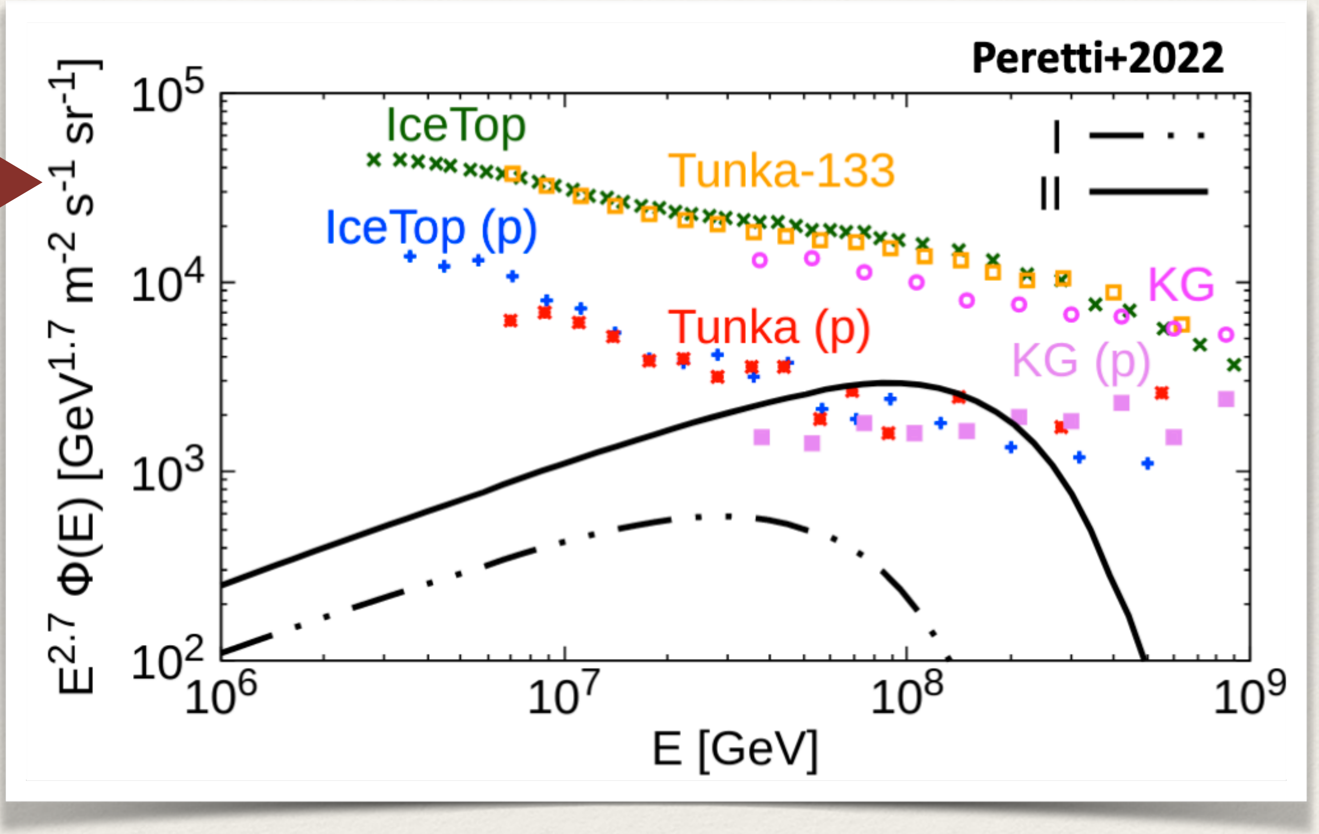
SB nucleus is a calorimeter but the wind bubble is not

↓

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

- **Starburst galaxies can produce a significant fraction of IceCube neutrinos and EBL:**
    - neutrinos compatible with IceCube flux for $E \gtrsim 100$ TeV
    - γ-rays probable responsible of $\lesssim 40\,\%$ of the EBL at ~50 GeV
- **Two possible acceleration sites:**
    - **Starburst nuclei**
        - calorimeters for electrons and protons →efficient production of gamma-rays and neutrinos
        - BUT unclear if maximum emerges of ~100 PeV can be reached
    - **Starburst wind**
        - $E_{\rm max} \approx 100$ PeV can be reached
        - no calorimeter → protons can escape
        - Wind-bubbles can produce a sizeable contribution to the CR spectrum in the range 10^{17} eV $\lesssim E \lesssim 10^{18}$ eV