

Particle acceleration and high-energy emission from star-forming galaxies

Enrico Peretti

enrico.peretti.science@gmail.com



VILLUM FONDEN


UNIVERSITY OF
COPENHAGEN



Niels Bohr Institutet



The Niels Bohr
International Academy

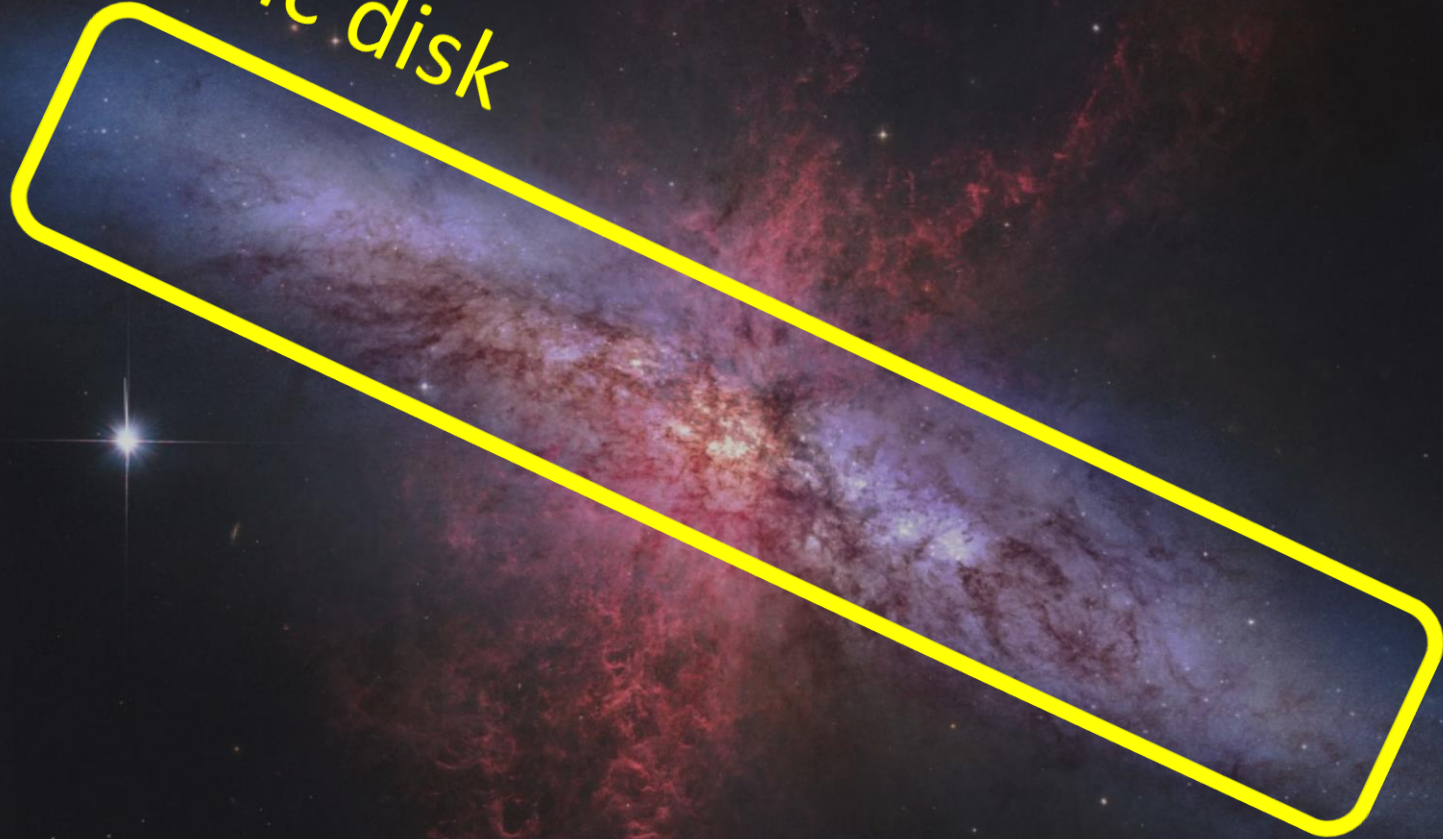


Co-financed by the Connecting Europe
Facility of the European Union



Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

Galactic disk



Galactic disk

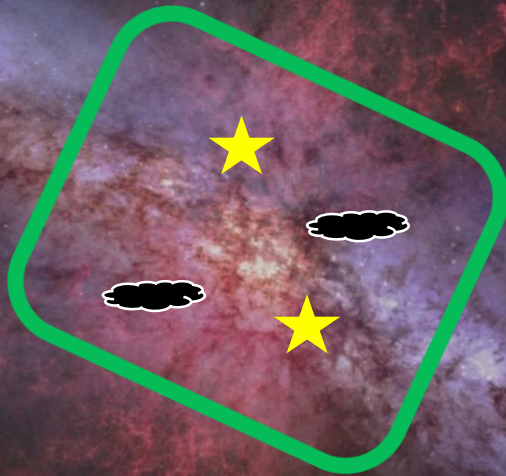
Starburst
nucleus

Galactic disk

Starburst wind

Starburst nucleus

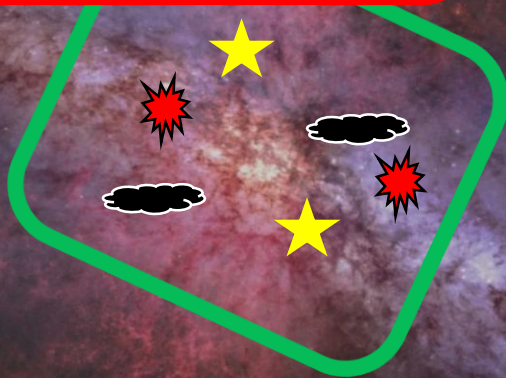
High star
formation rate



Starburst
nucleus

High star
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Young stars and
supernovae



Starburst
nucleus

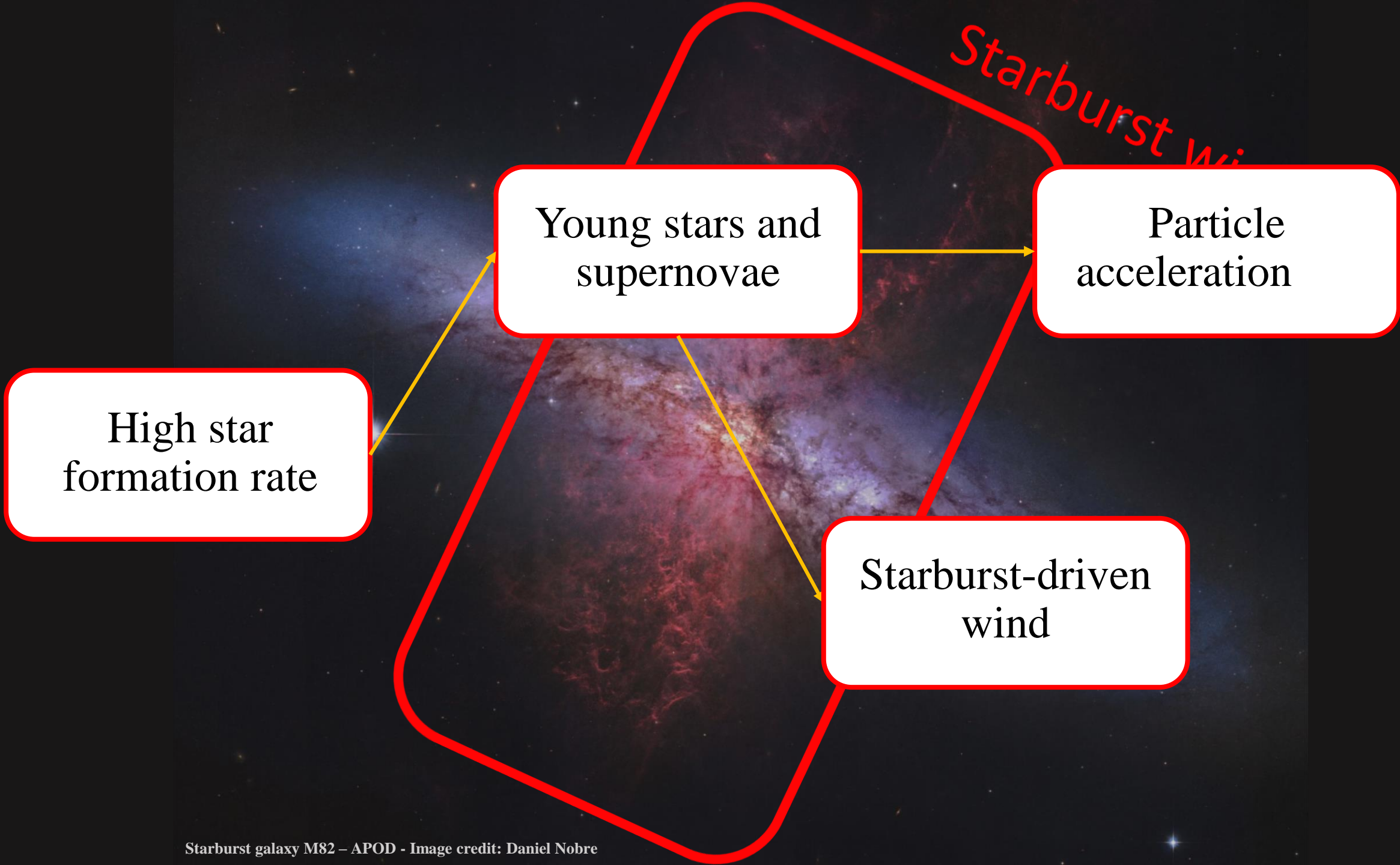
High star formation rate

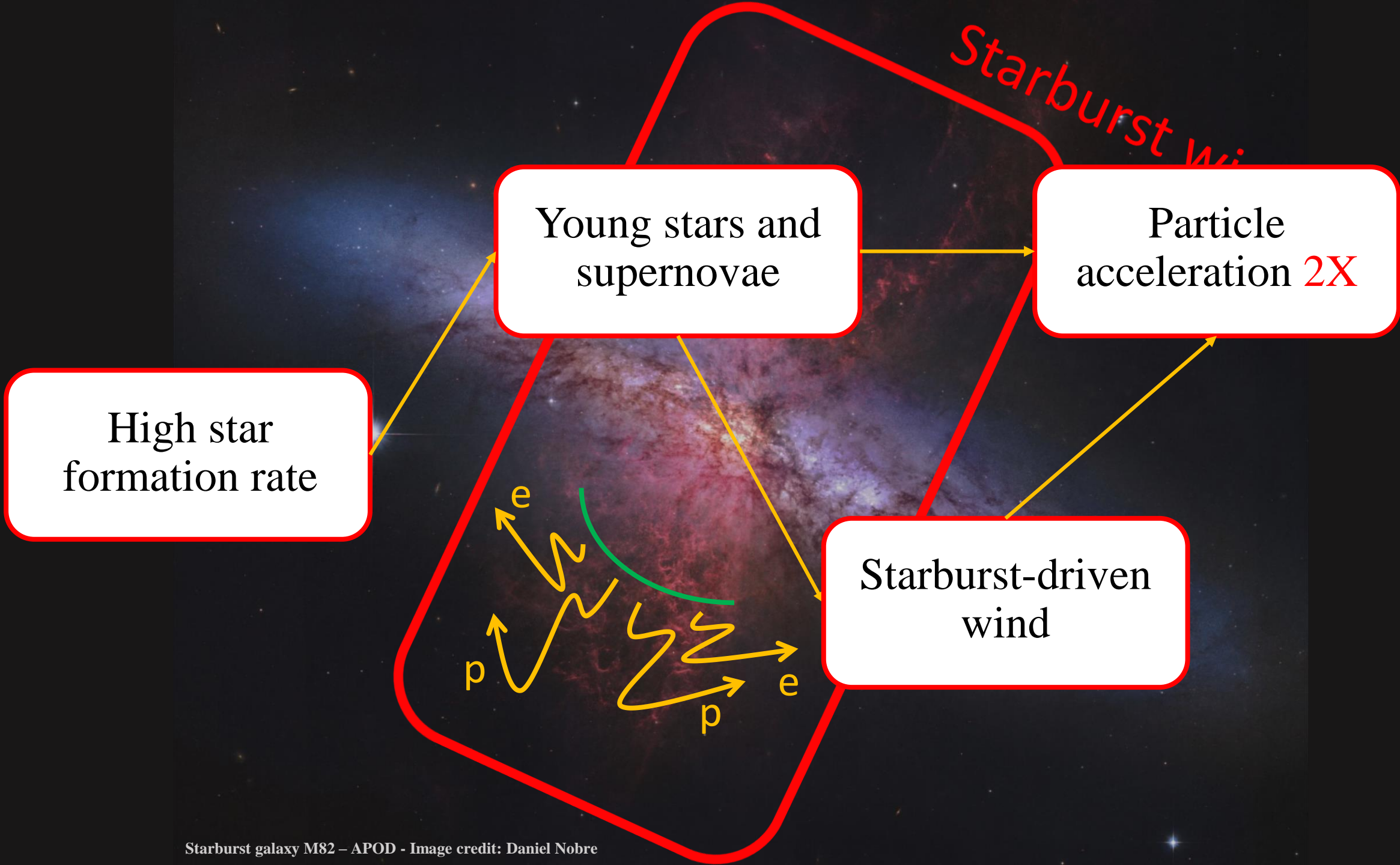
Young stars and supernovae

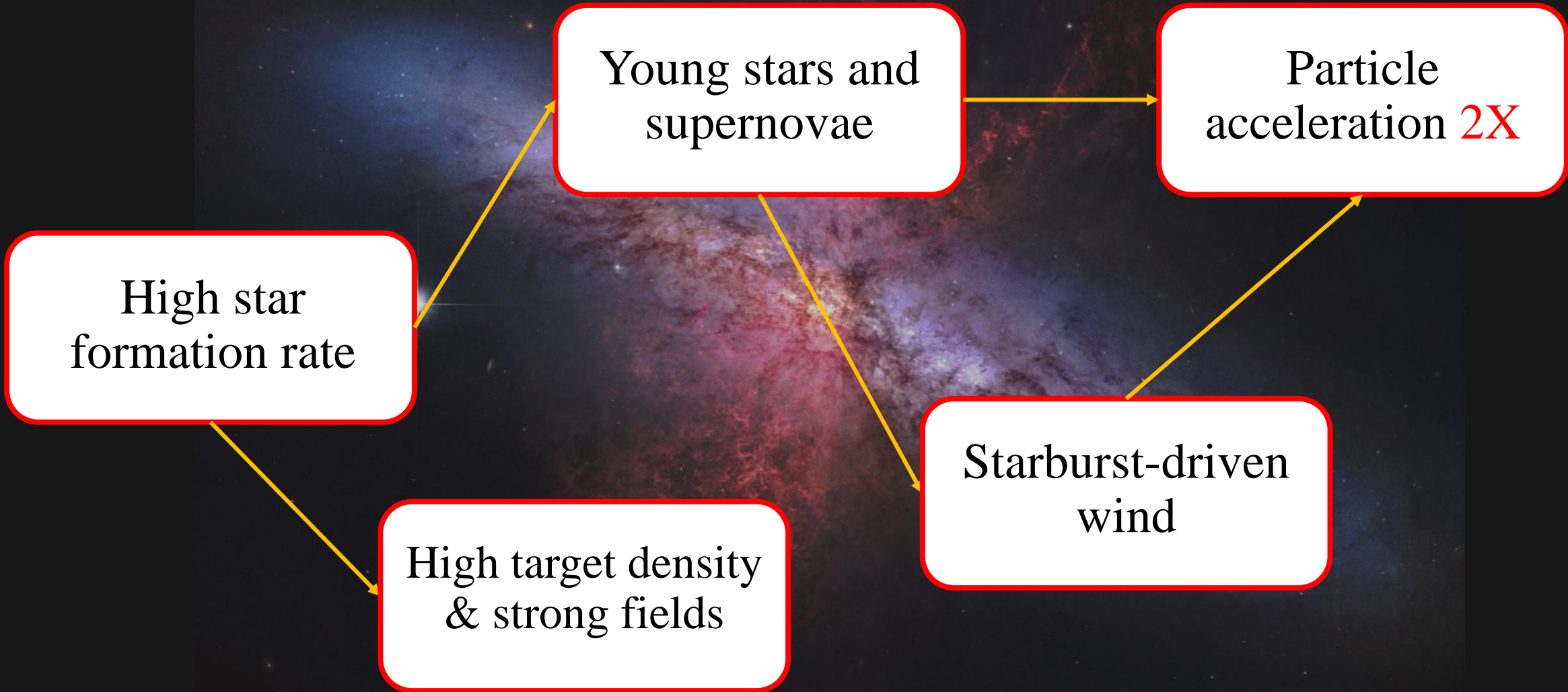
Particle acceleration

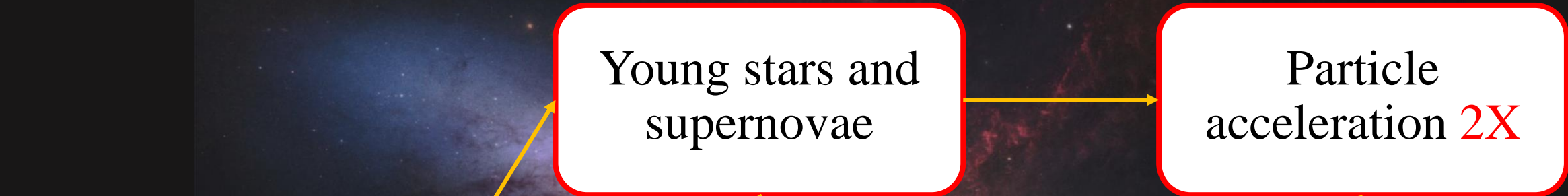


Starburst nucleus







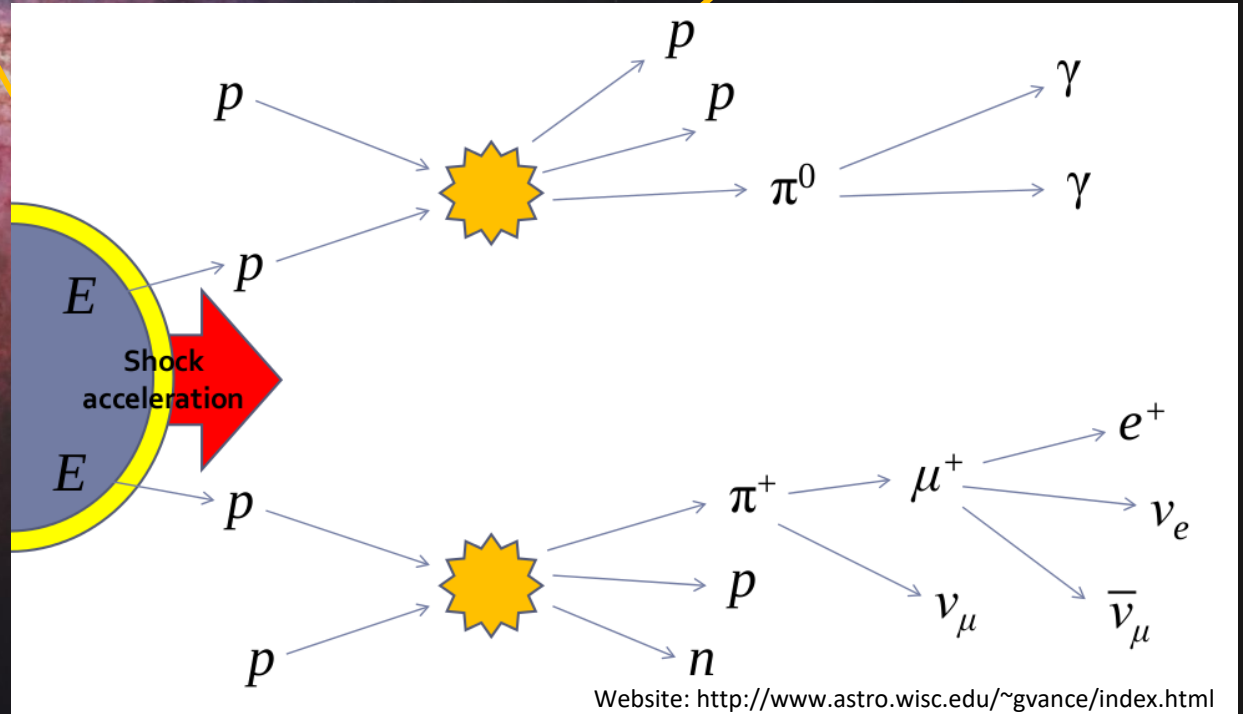


High star formation rate

Young stars and supernovae

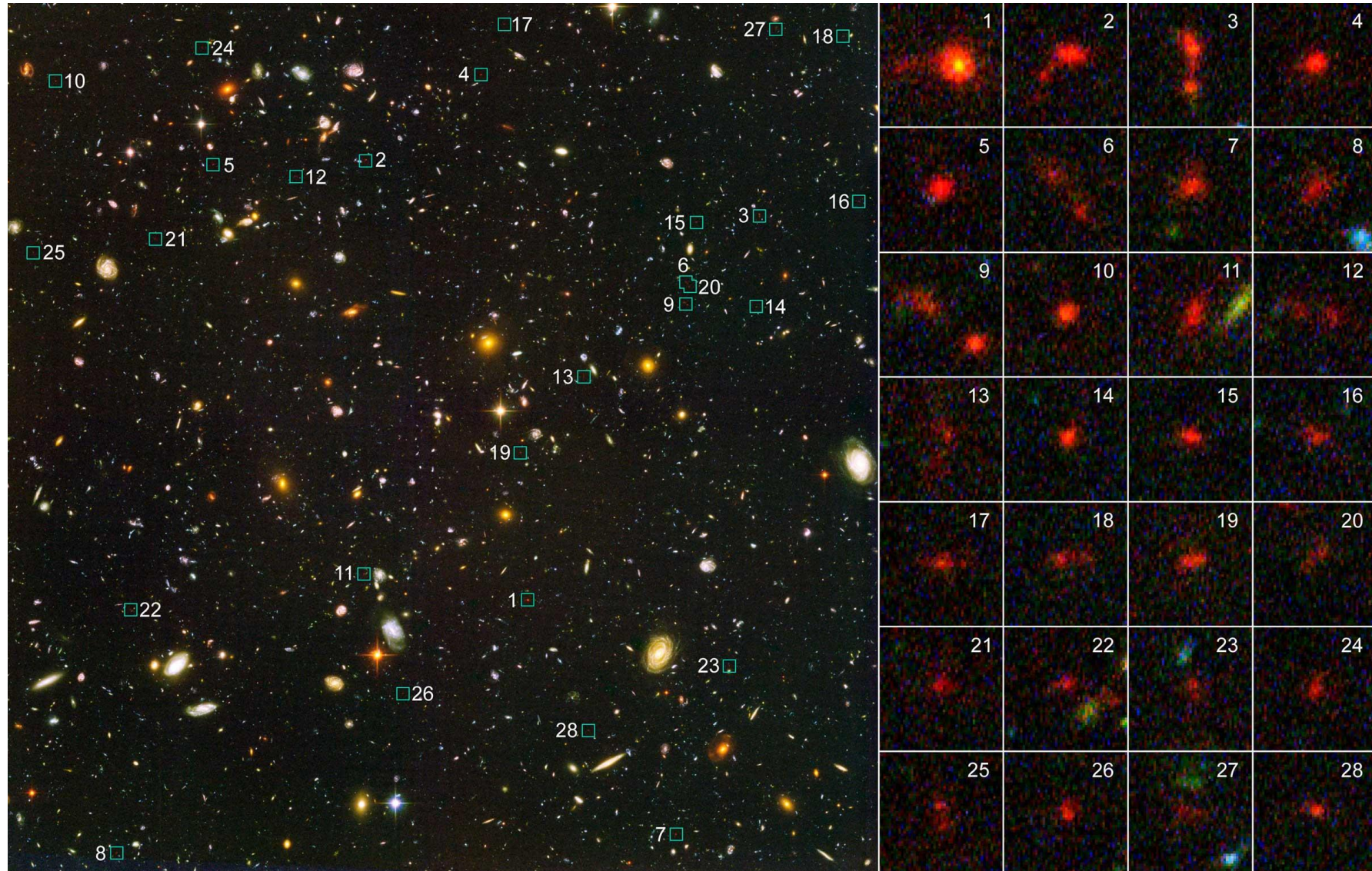
Particle acceleration **2X**

High target density & strong fields

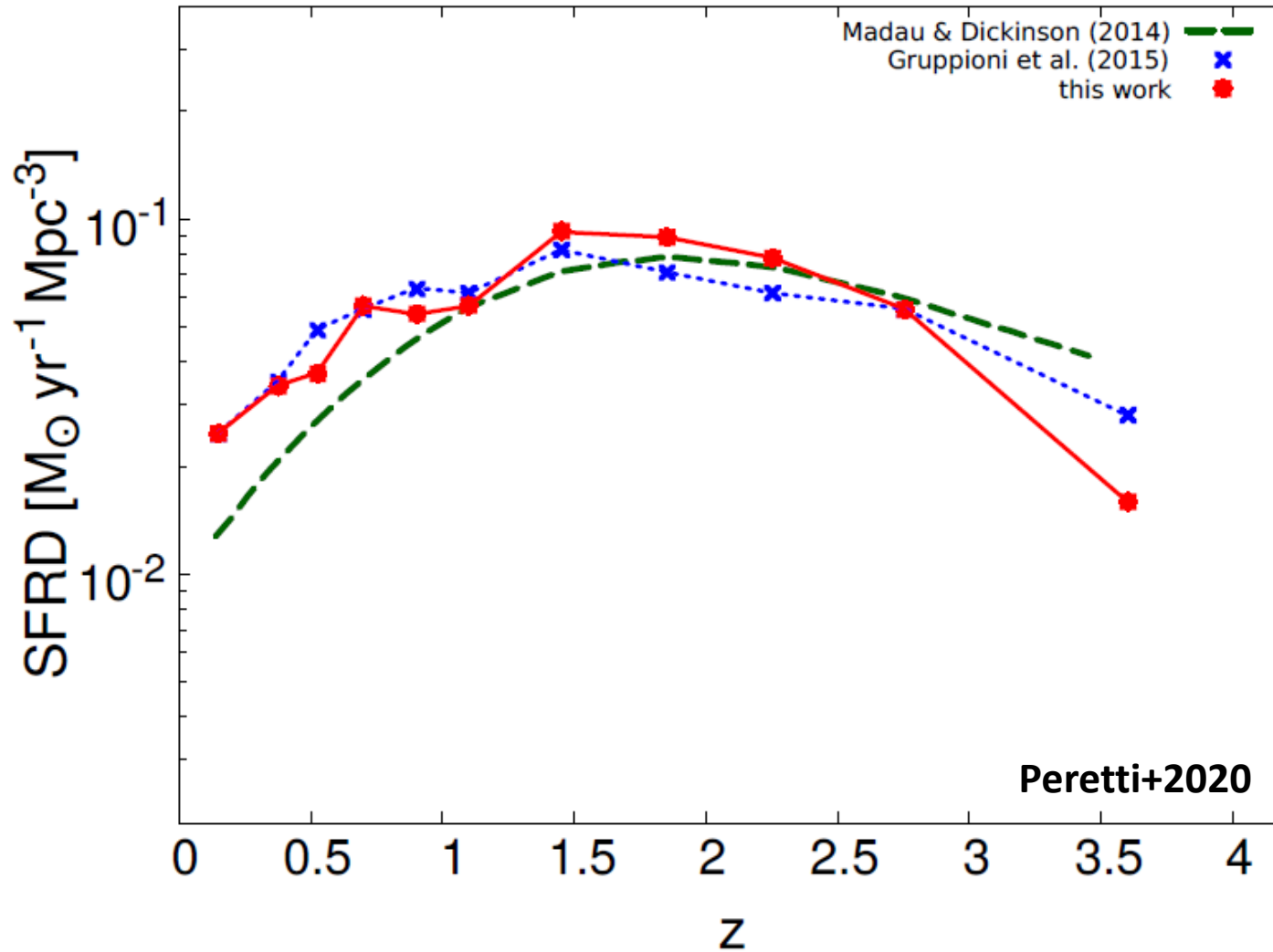


Website: <http://www.astro.wisc.edu/~gvance/index.html>

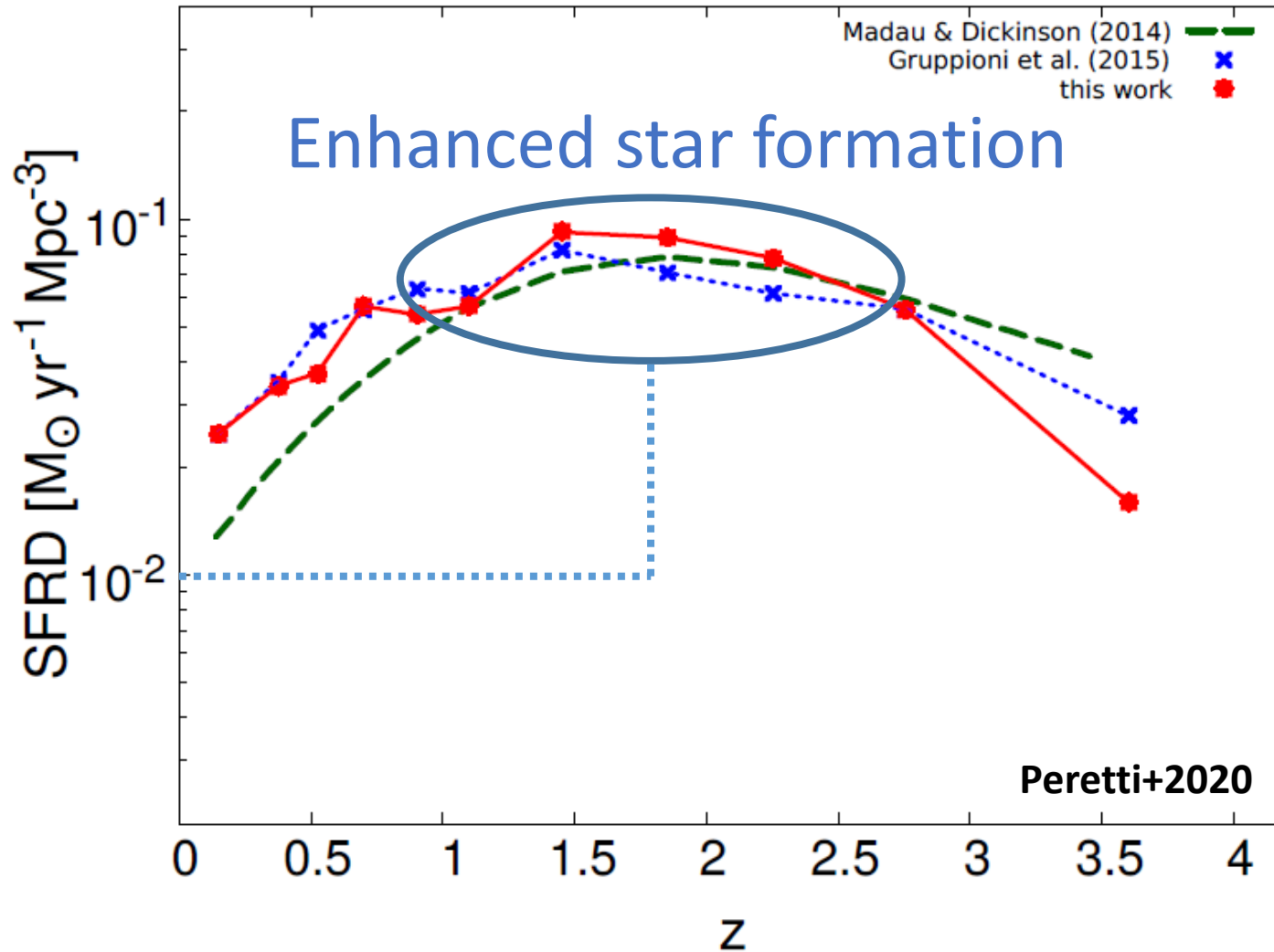
Another reason to study Star-forming galaxies



Another reason to study Star-forming galaxies



Another reason to study Star-forming galaxies



Motivations for studying Star-forming Galaxies

- Several acceleration sites (SBN + wind)
- High rate of interactions → Calorimetry?
- Numerous at high redshift → Diffuse flux?

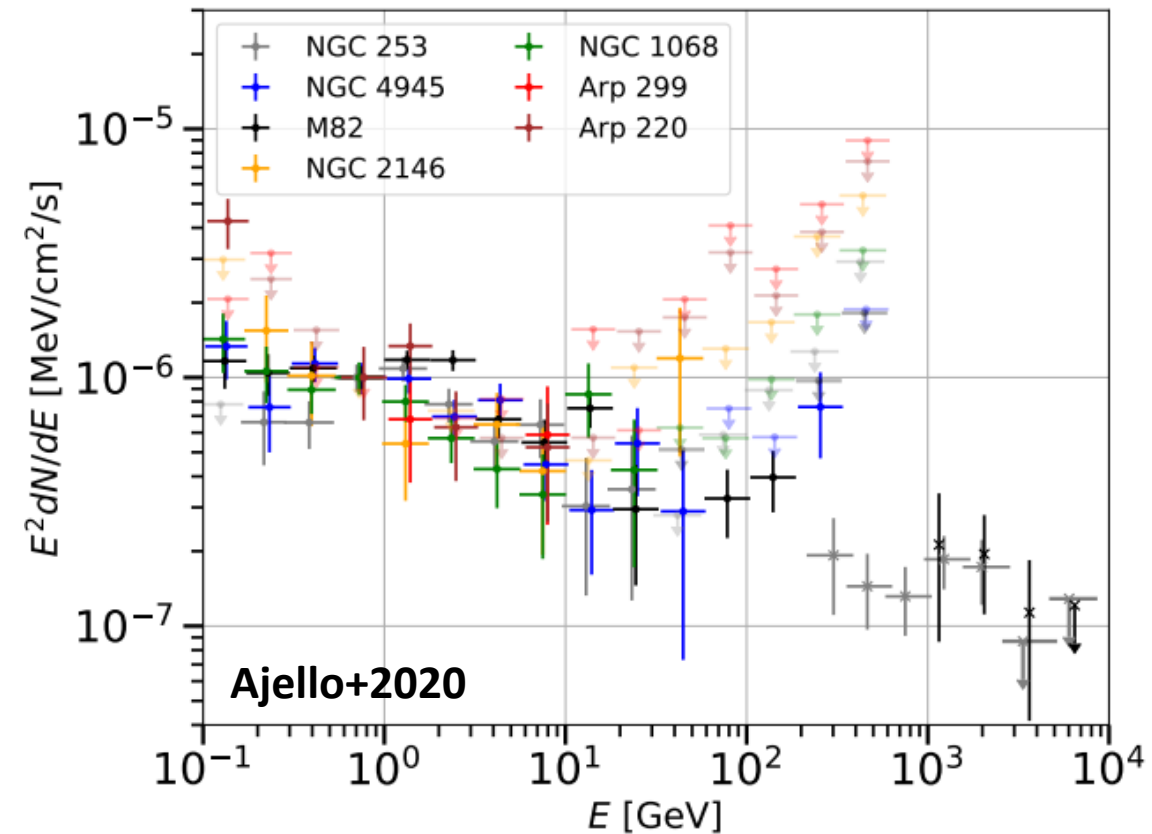
Outline

- Observations of Star-forming galaxies
- Particle Transport in Starburst Nuclei
 - Starburst-driven winds
 - Multi-messenger diffuse flux

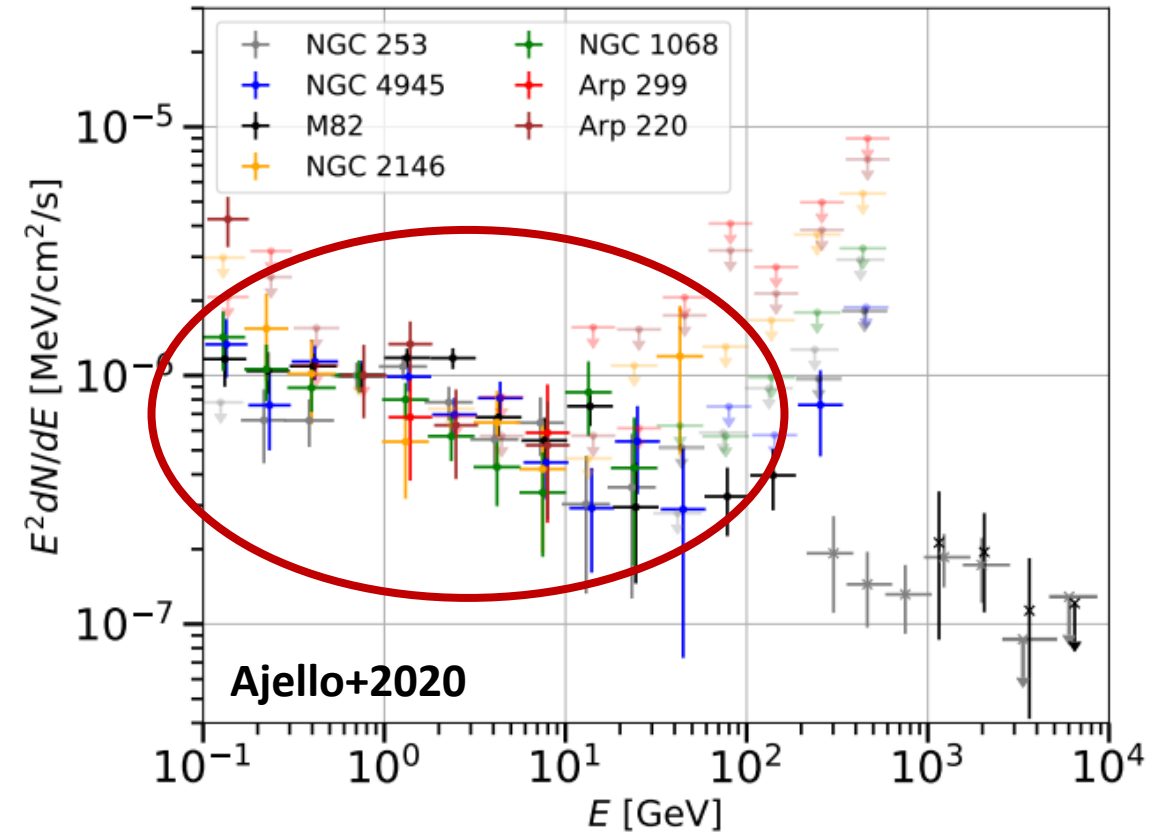
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Observation of Star-forming Galaxies - Gamma

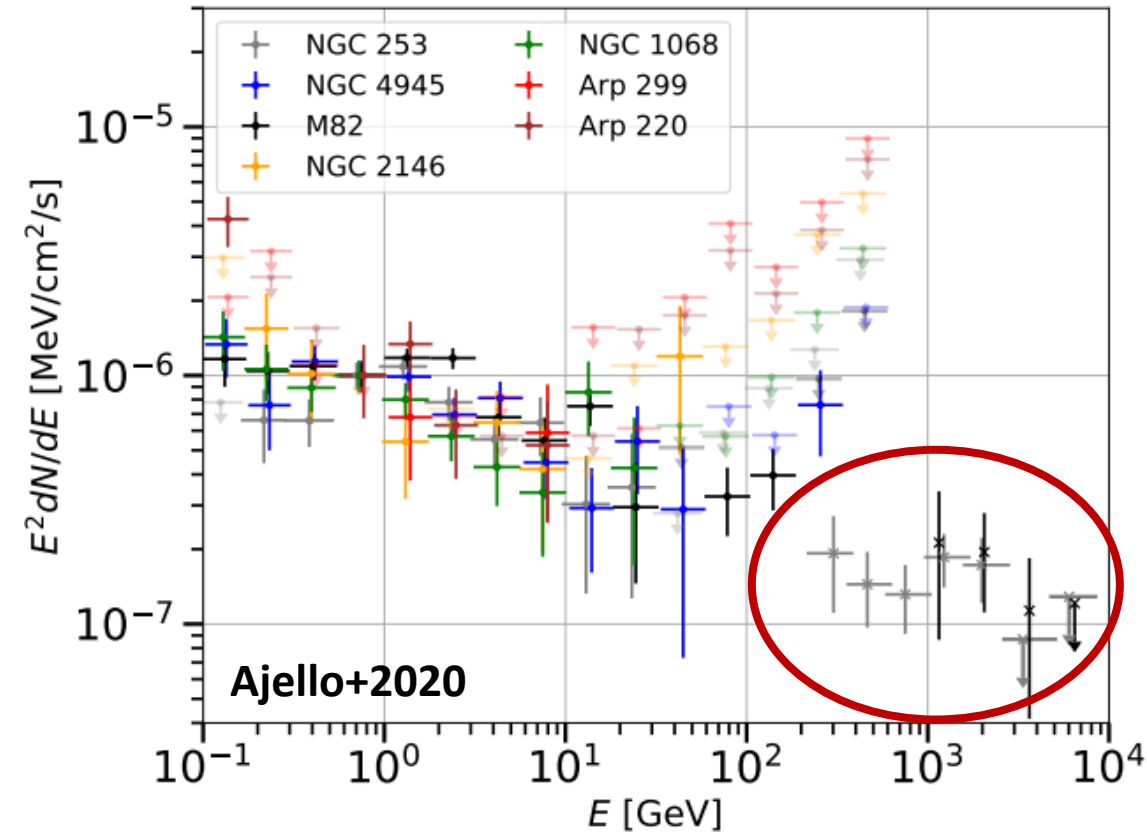


Observation of Star-forming Galaxies - Gamma



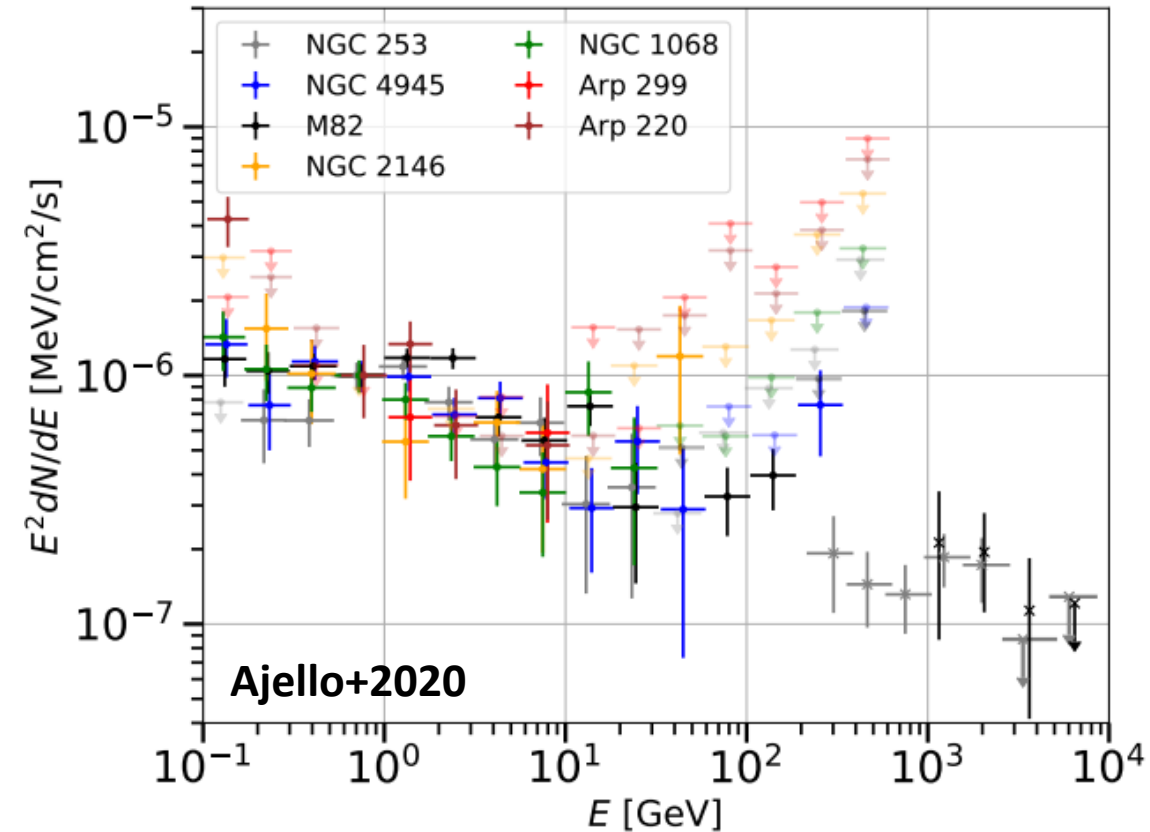
- Star-forming observed at GeV

Observation of Star-forming Galaxies - Gamma



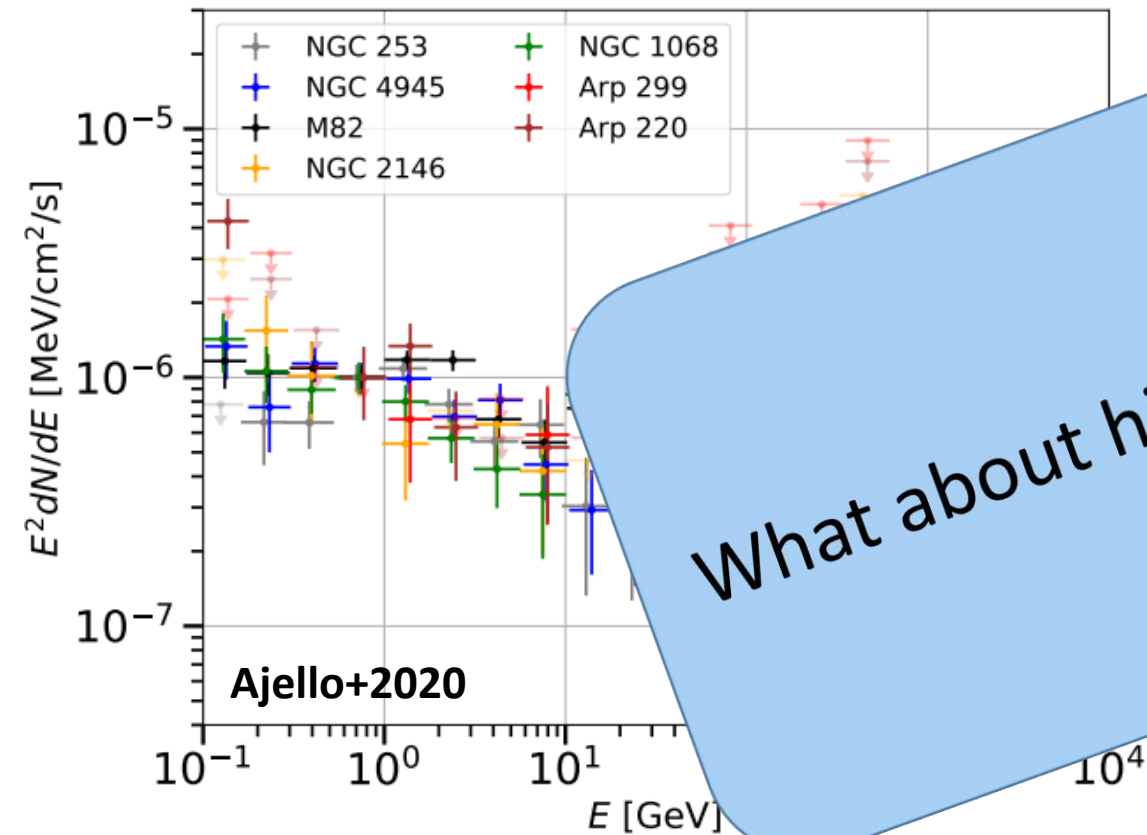
- Star-forming observed at GeV
- Most nearby at TeV (<4 Mpc)

Observation of Star-forming Galaxies - Gamma



- Star-forming observed at GeV
- Most nearby at TeV (<4 Mpc)
- Most distant: Arp 220 (77 Mpc)

Observation of Star-forming Galaxies - Gamma



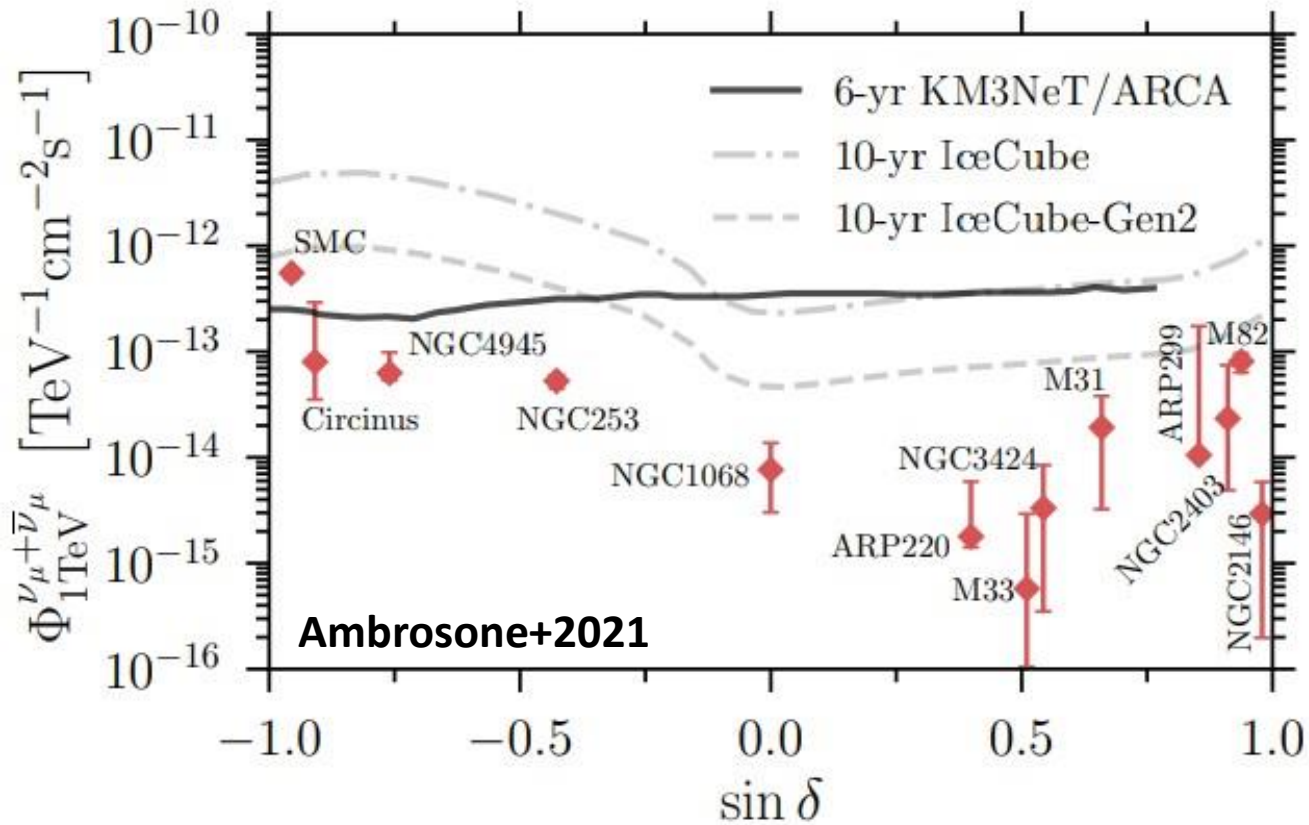
What about high-energy neutrinos?

observed at GeV

TeV (<4 Mpc)

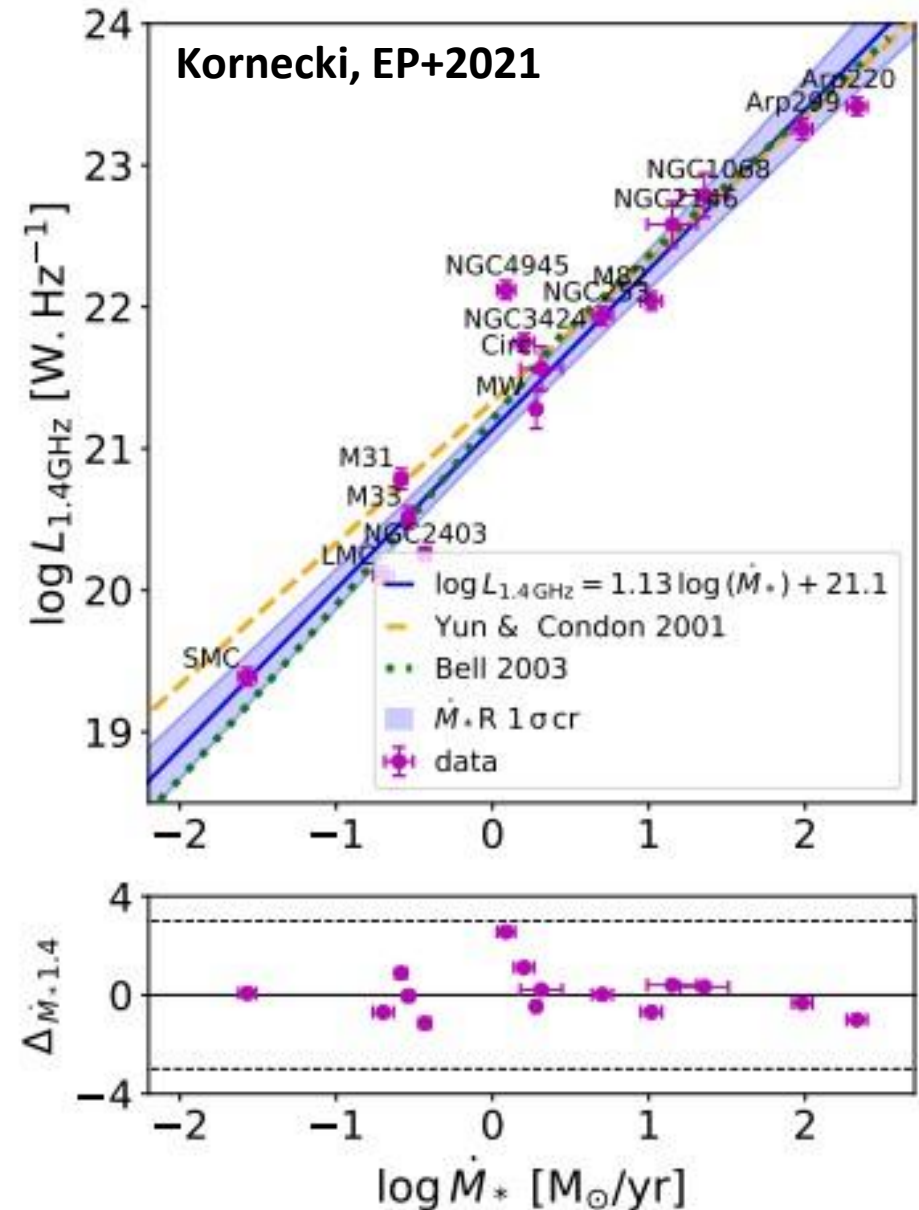
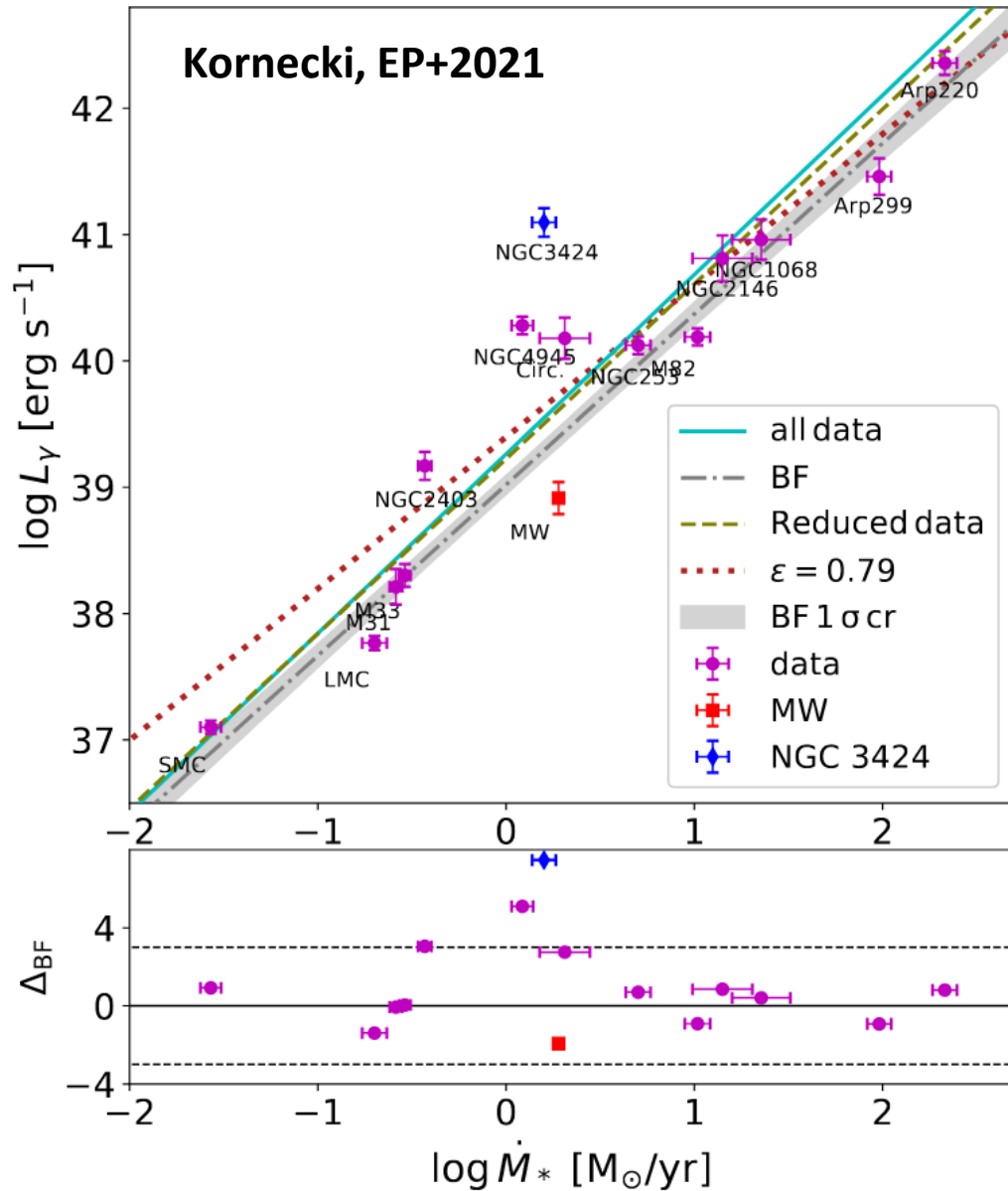
most distant: Arp 220 (77 Mpc)

Observation of Star-forming Galaxies - Neutrinos

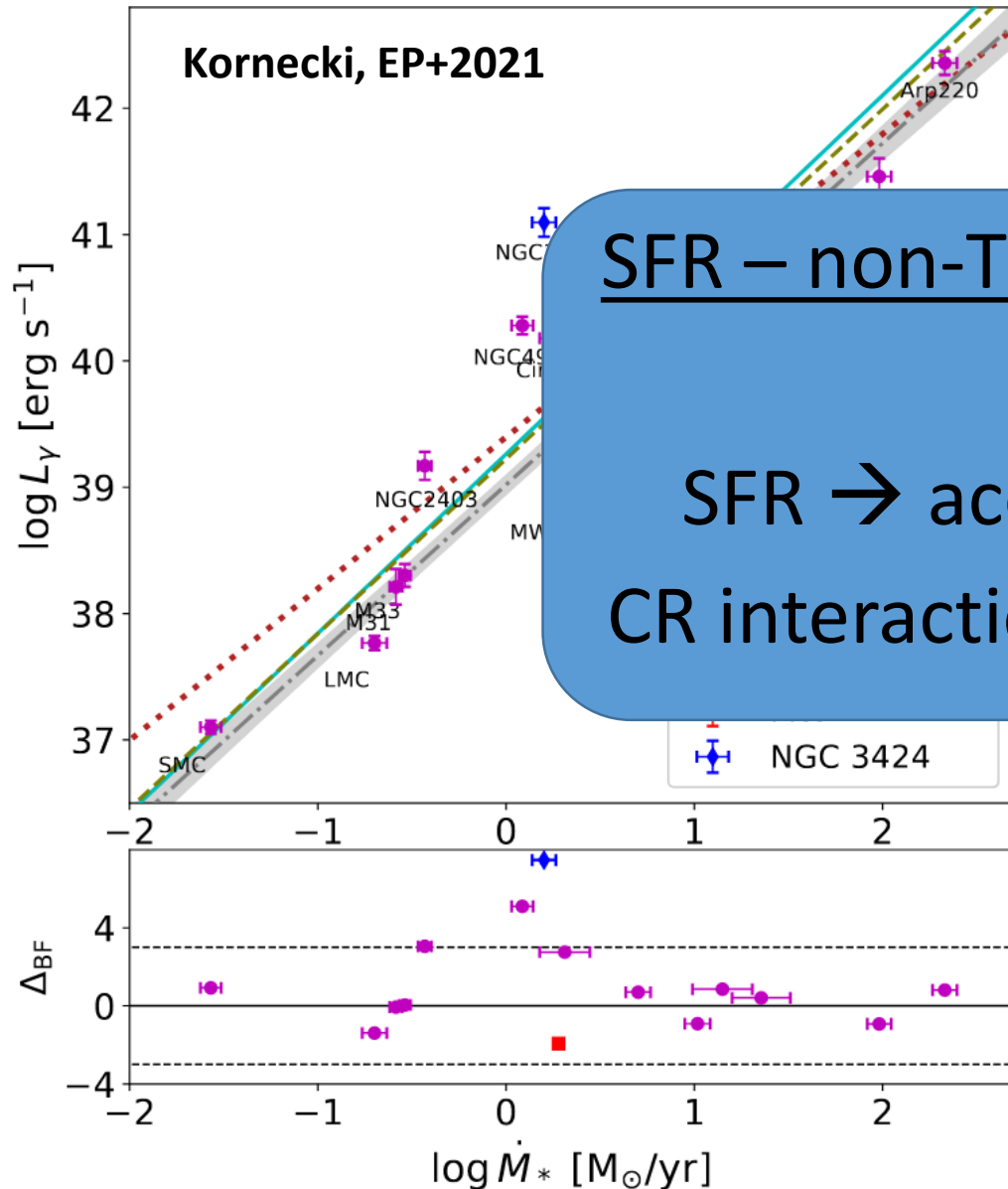


- Star-forming observed at GeV
- Most nearby at TeV (<4 Mpc)
- Most distant: Arp 220 (77 Mpc)
- SBGs are currently undetected neutrino sources (*)

Observation of Star-forming Galaxies - Correlations

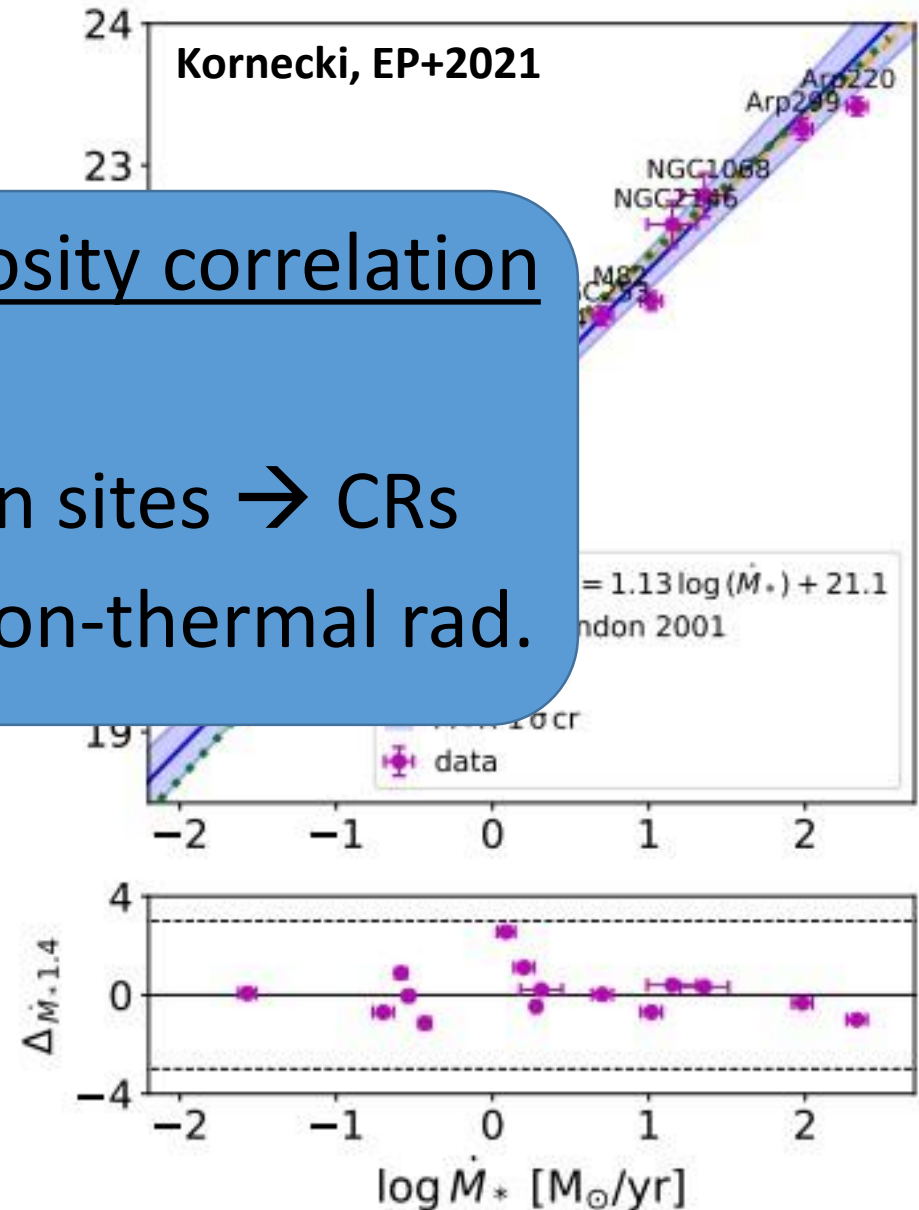


Observation of Star-forming Galaxies - Correlations



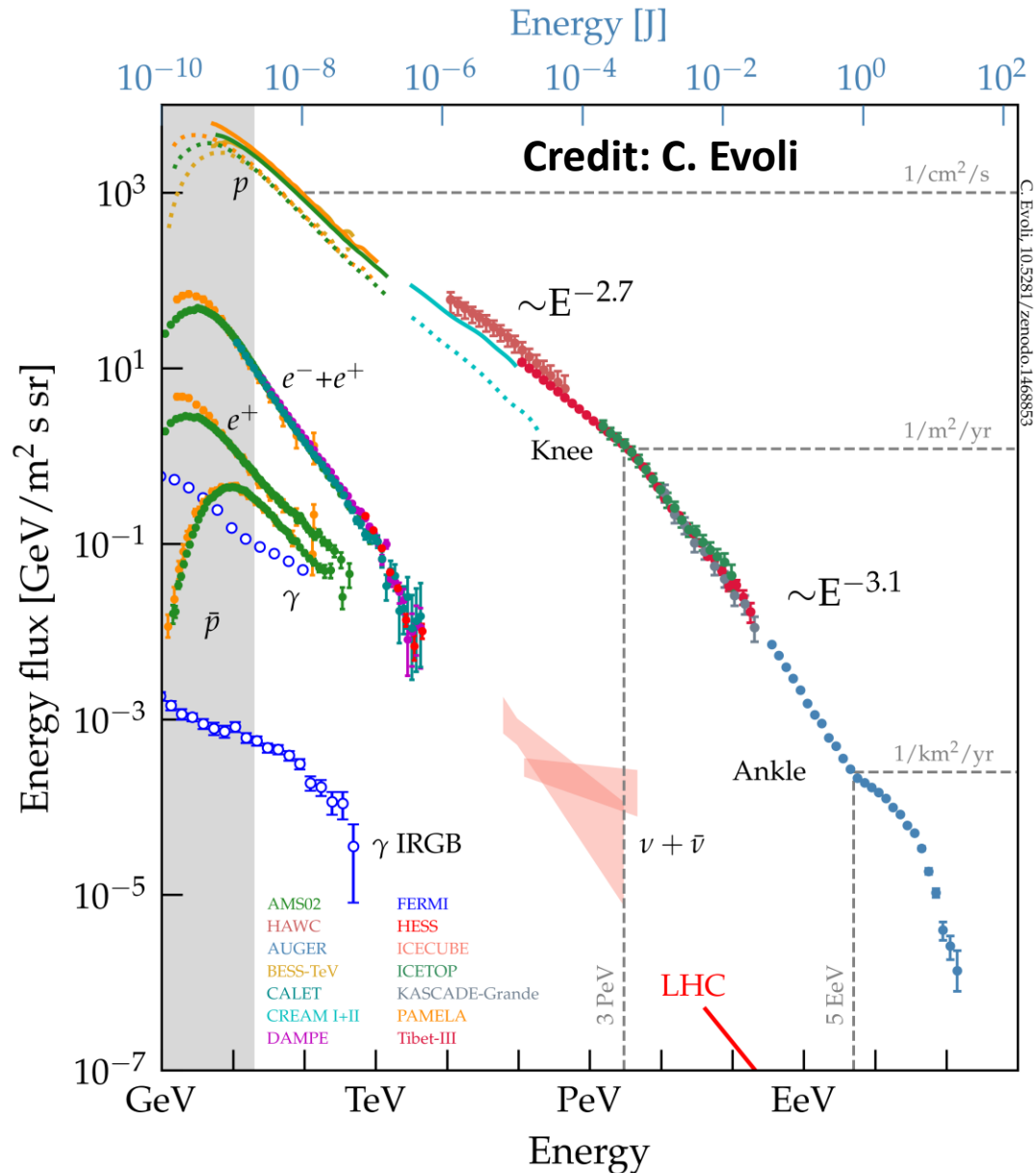
SFR – non-Th. luminosity correlation

SFR → acceleration sites → CRs
 CR interactions → Non-thermal rad.

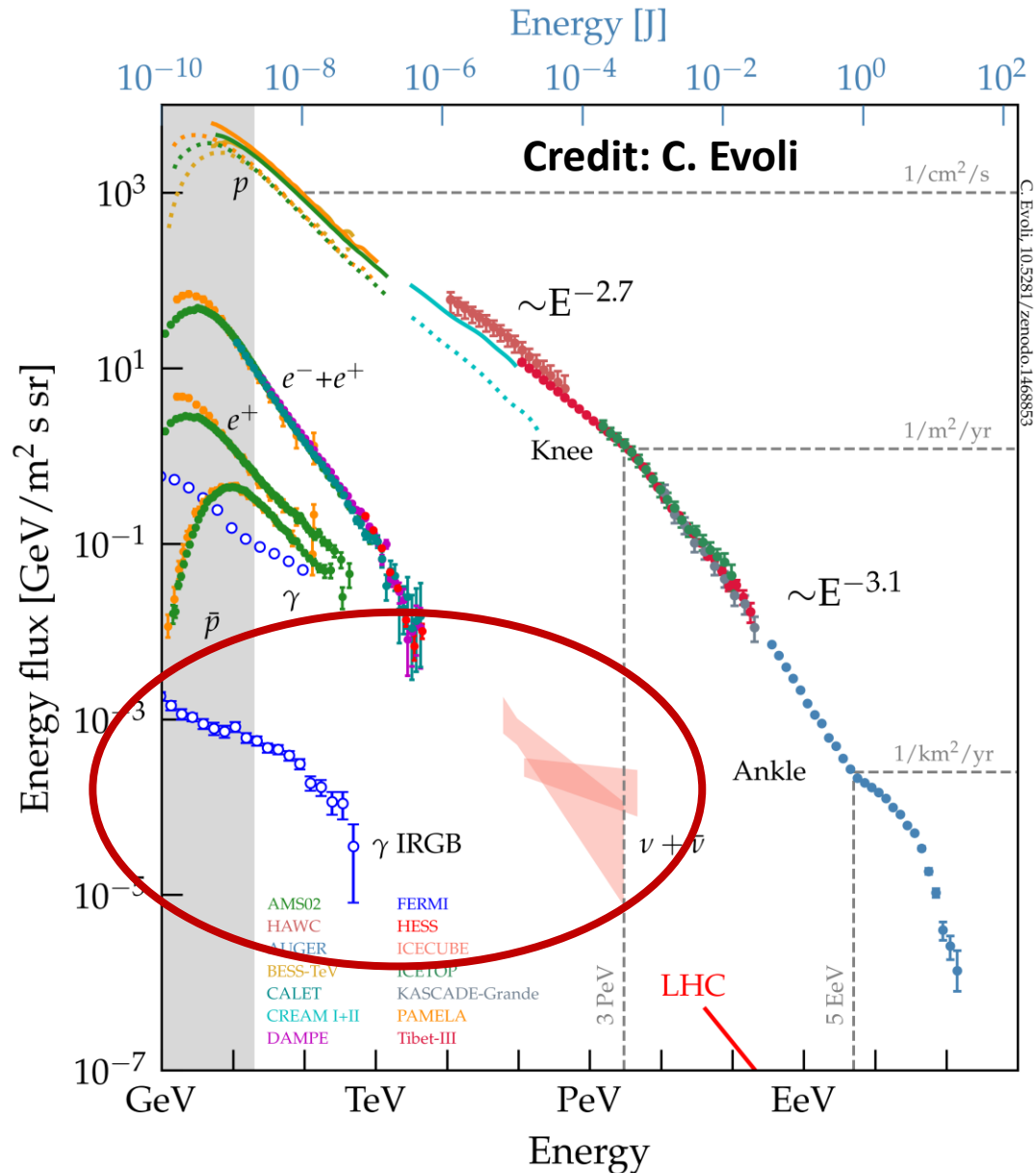


Diffuse radiation from Star-forming galaxies

- SFGs are expected to shine on gamma rays and neutrinos



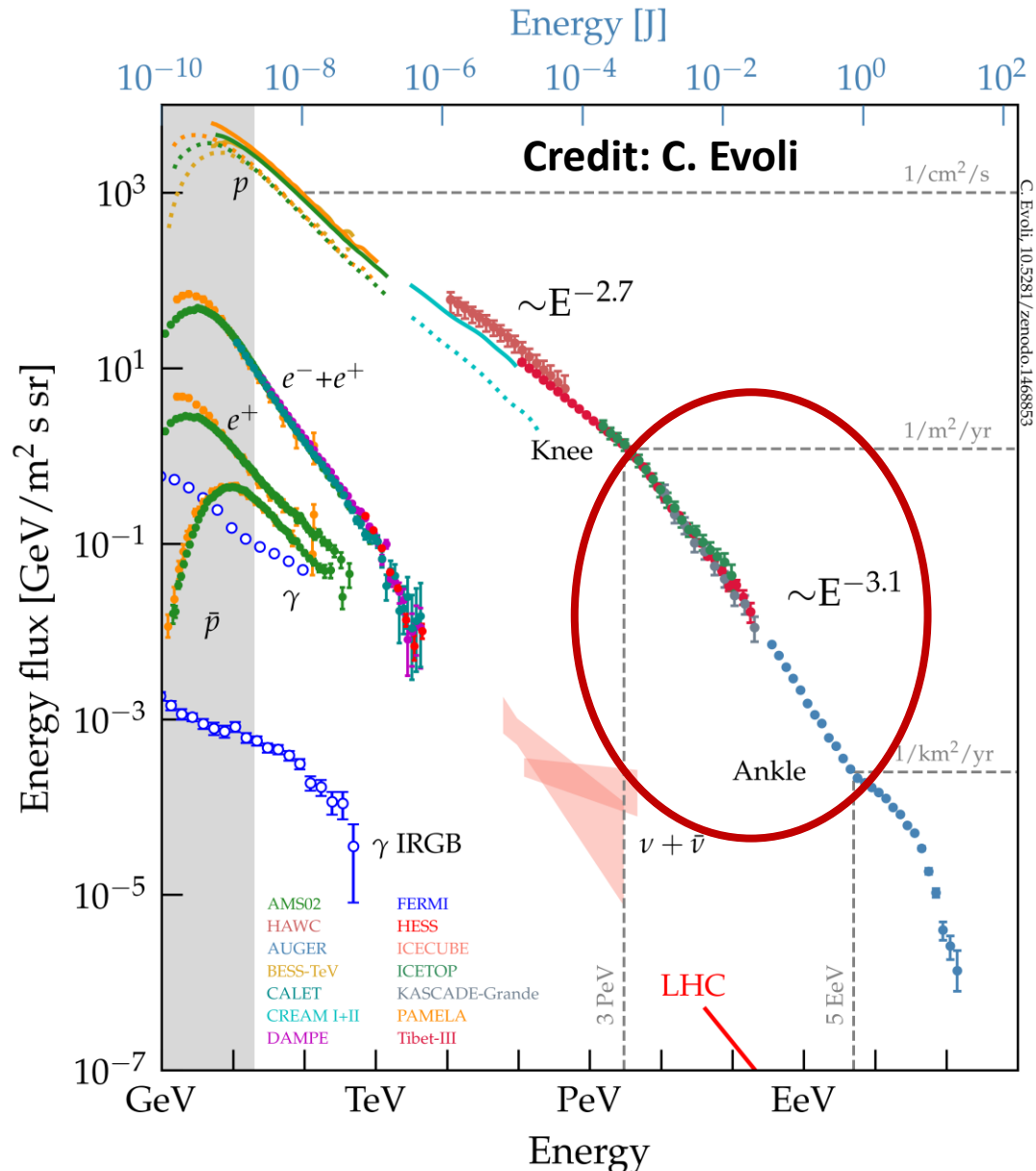
Diffuse radiation from Star-forming galaxies



- SFGs are expected to shine on gamma rays and neutrinos

- At which level can they contribute to the observed diffuse fluxes?

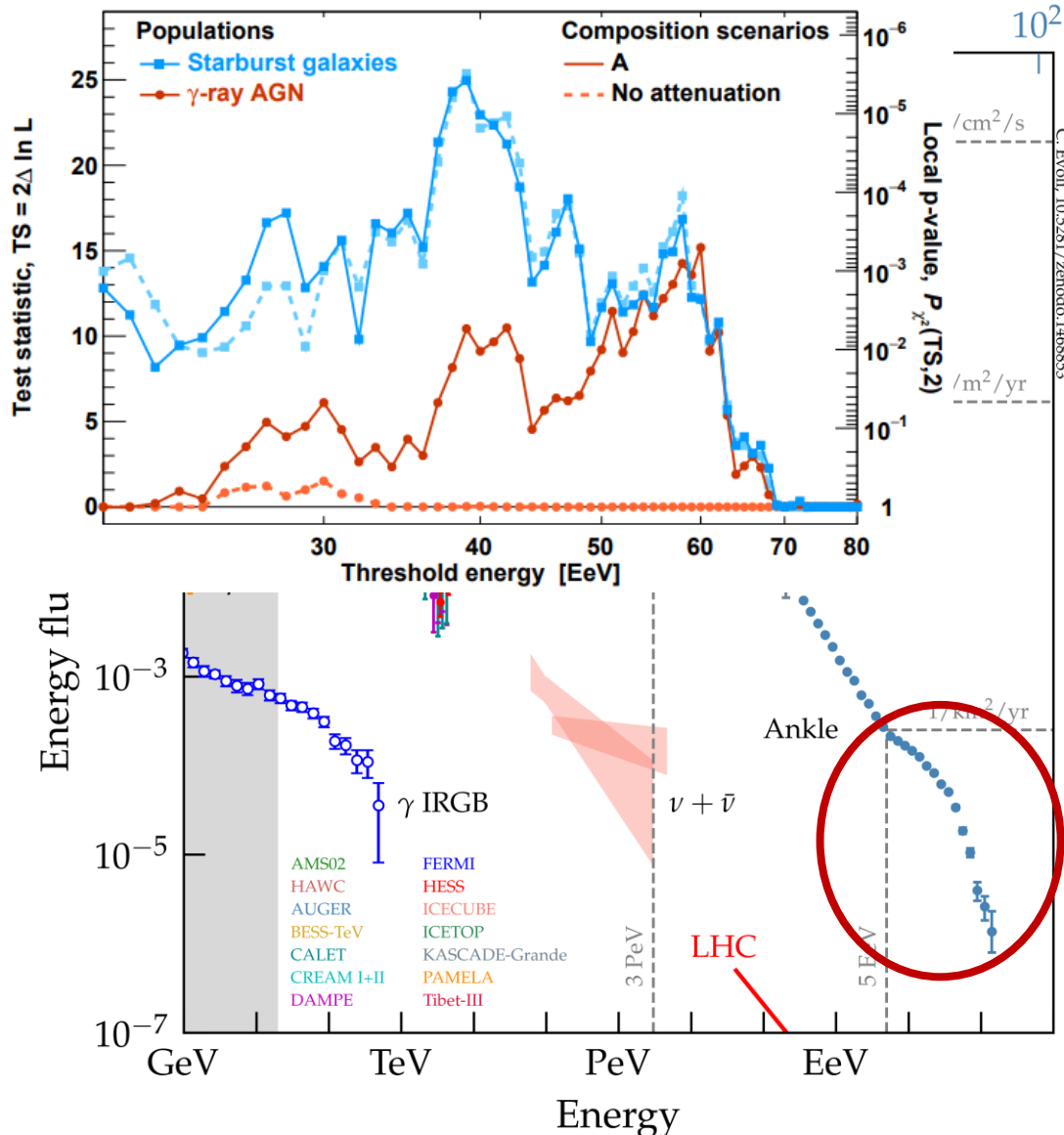
Diffuse radiation from Star-forming galaxies



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- At which level can they contribute to the observed diffuse fluxes?
- Can they contribute to the CR flux at some level?

Diffuse radiation from Star-forming galaxies

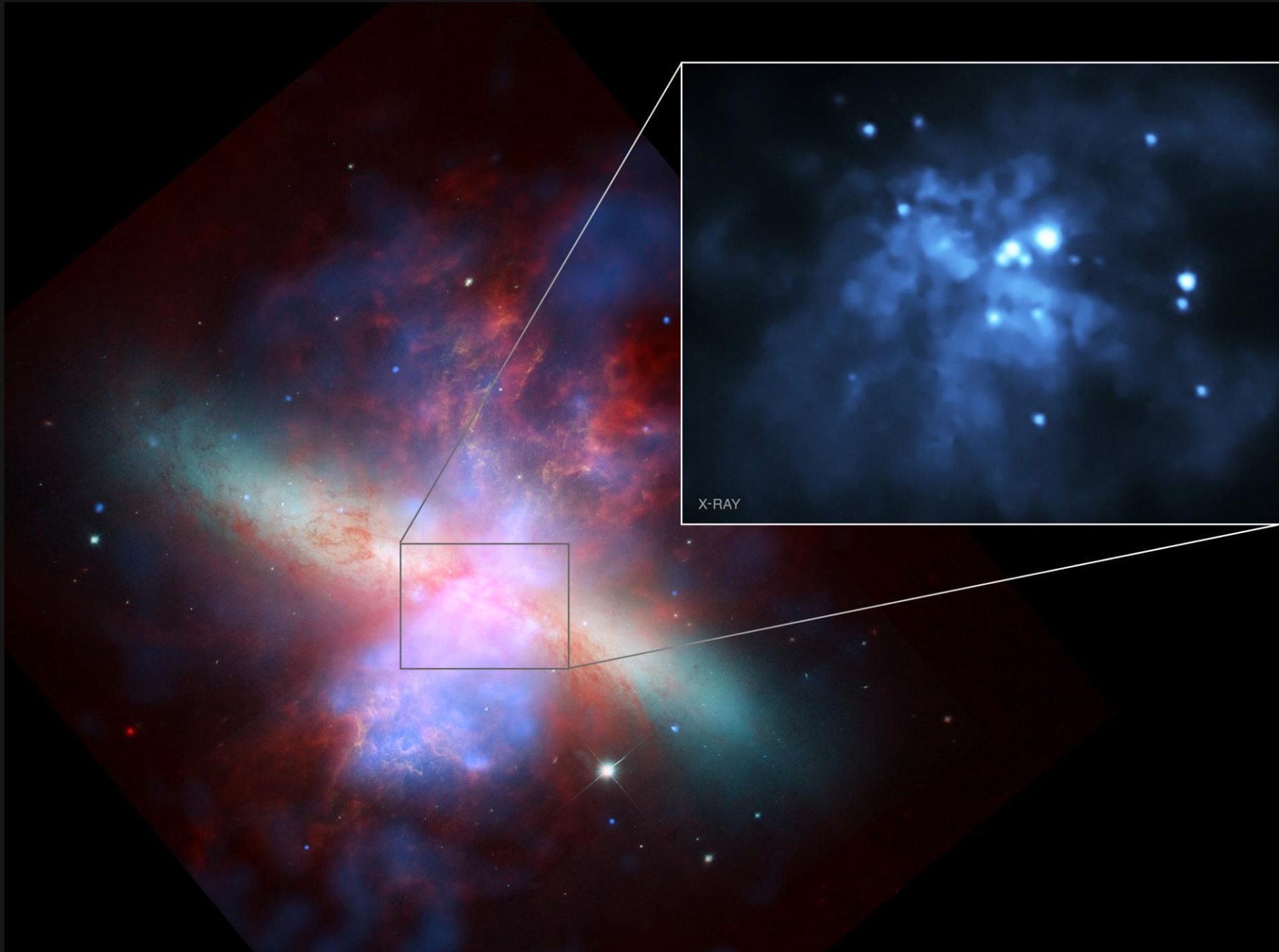
Aab+2018 - PAO



- SFGs are expected to shine on gamma rays and neutrinos
- At which level can they contribute to the observed diffuse fluxes?
- Can they contribute to the CR flux at some level?
- SFGs and UHECRs?

Outline

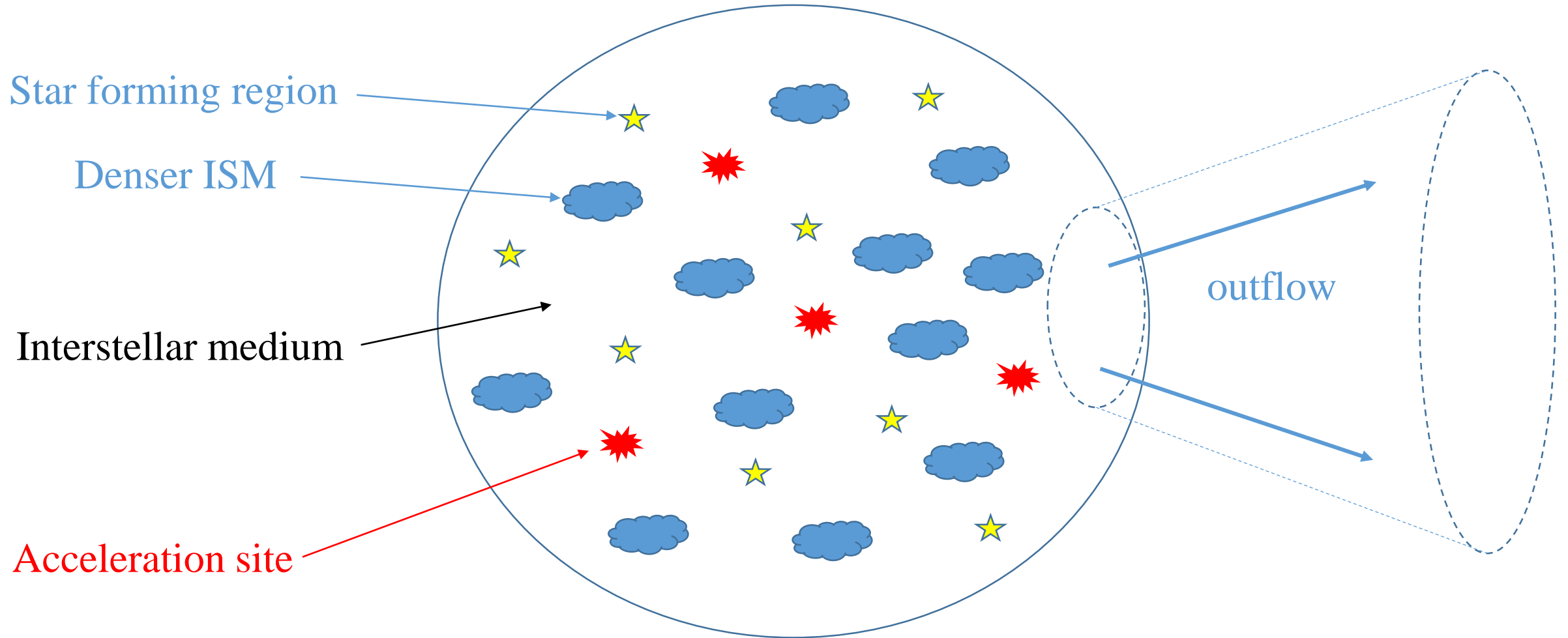
- Observations of Star-forming galaxies
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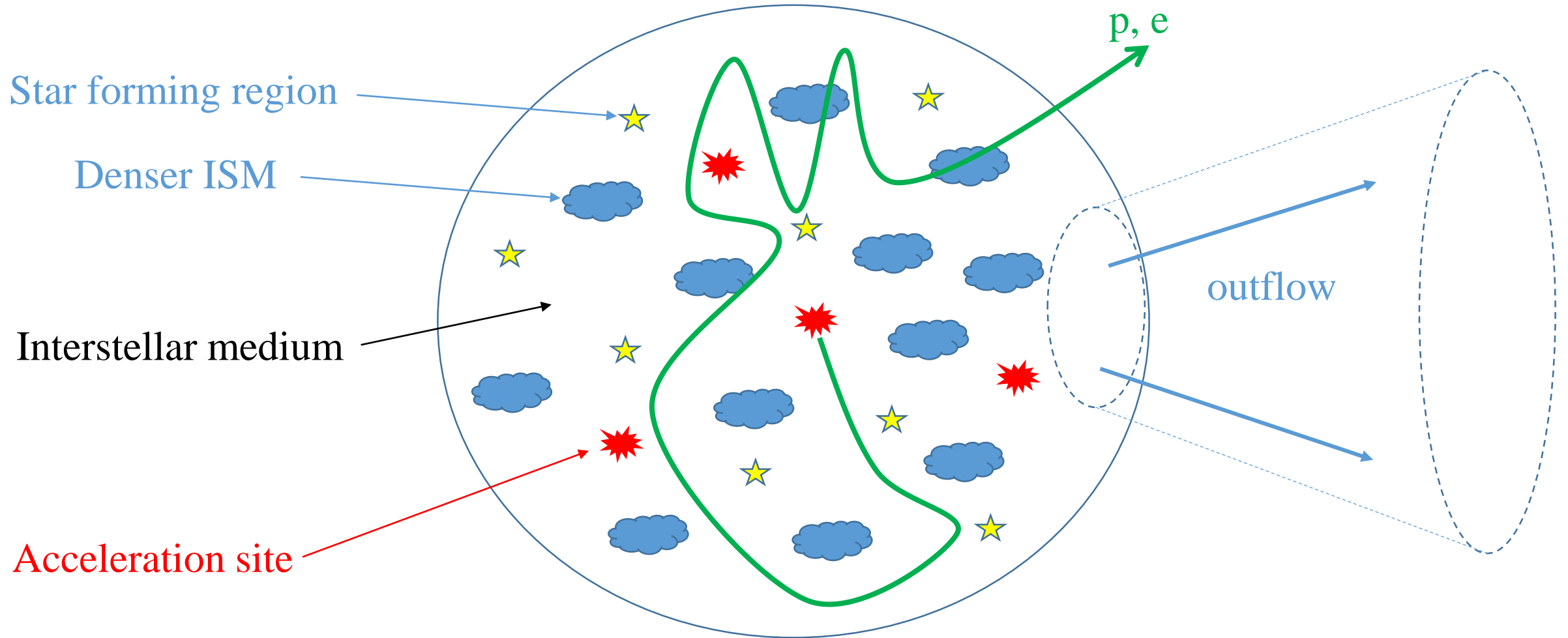
X-RAY, INFRARED & OPTICAL

Image credit: X-ray: NASA/CXC/Tsinghua Univ./H. Feng et al.; Full-field: X-ray: NASA/CXC/JHU/D.Strickland;
Optical: NASA/ESA/STScI/AURA/The Hubble Heritage Team; IR: NASA/JPL-Caltech/Univ. of AZ/C. Engelbracht

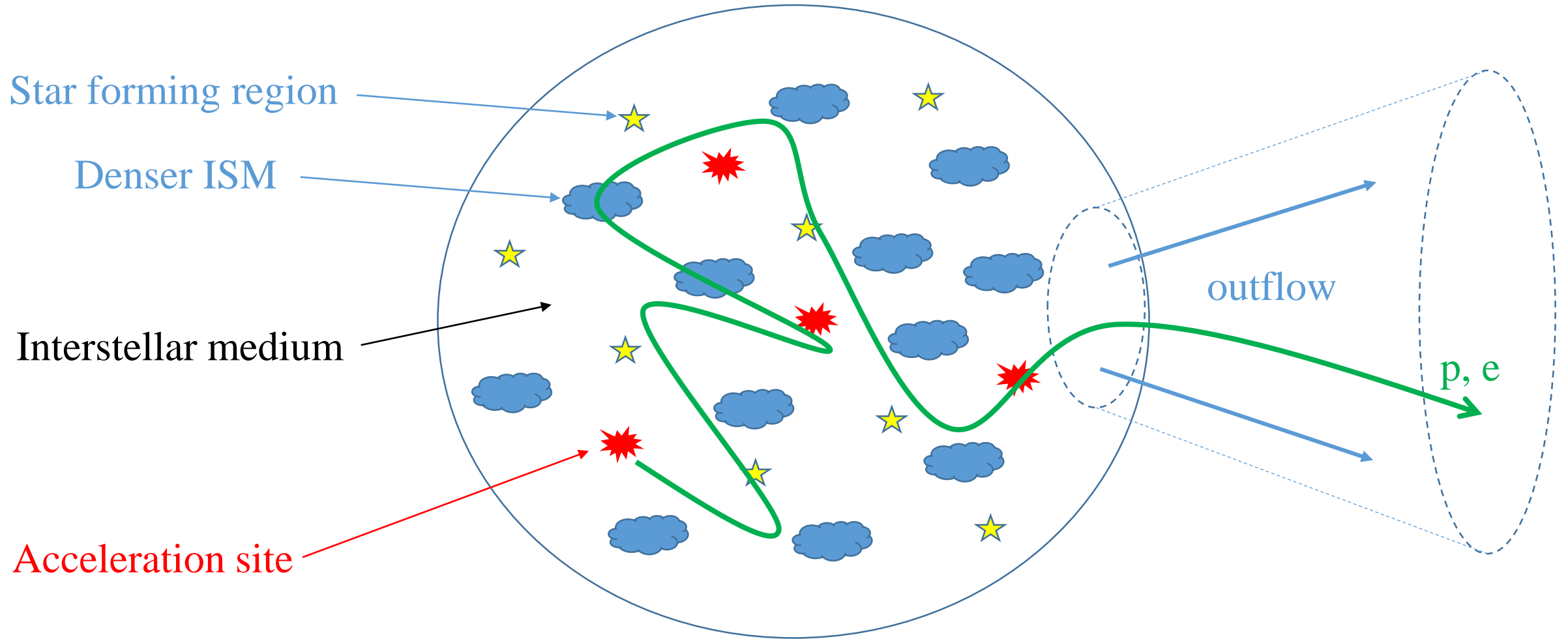
Particle transport in starburst nuclei



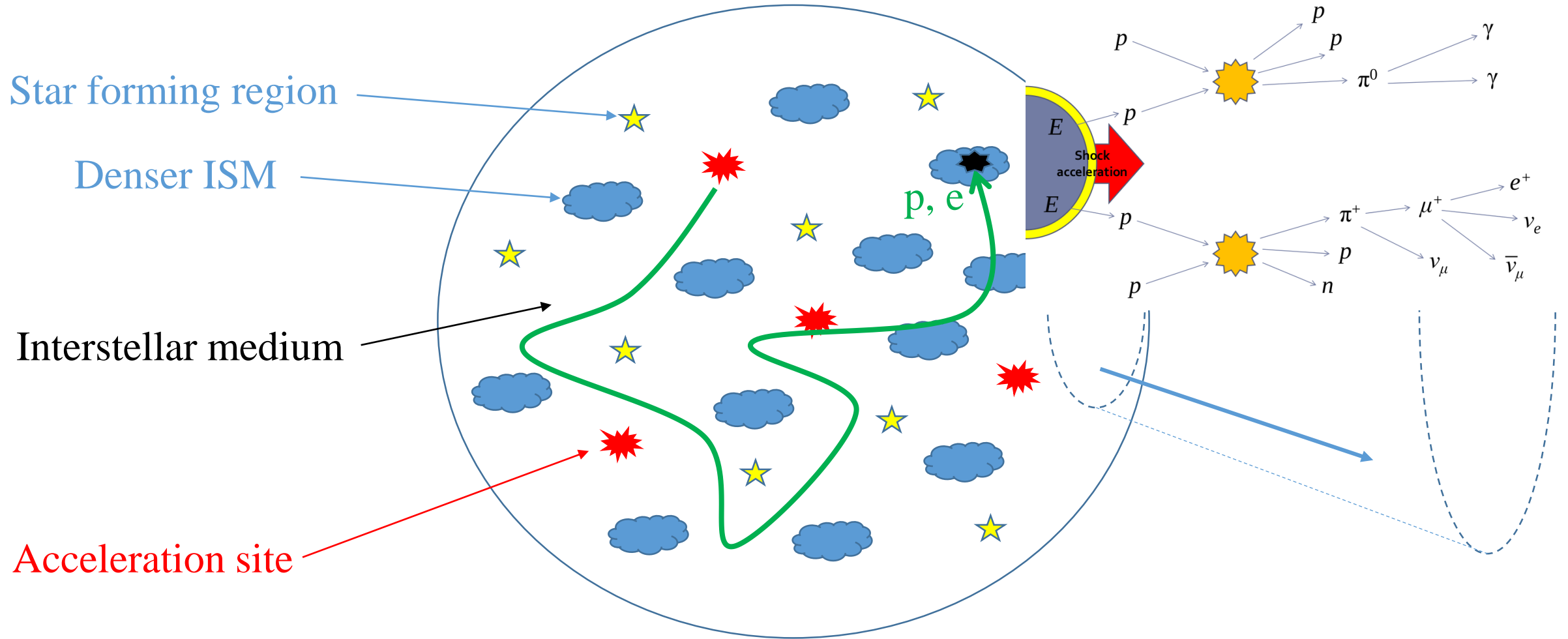
Particle transport in starburst nuclei



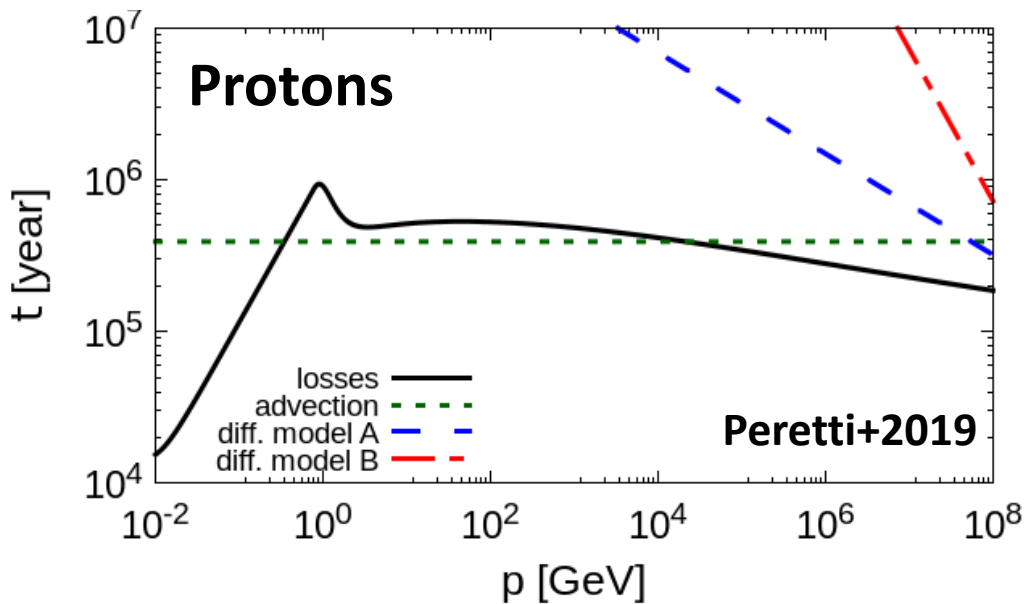
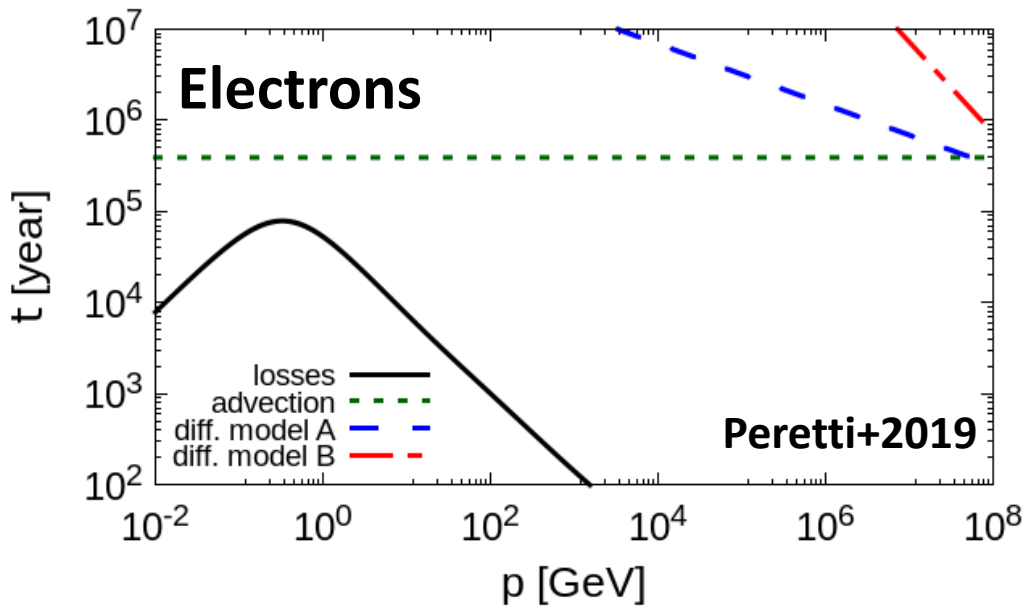
Particle transport in starburst nuclei



Particle transport in starburst nuclei



Modeling the transport in SBNi



$$n \approx 10^2 \text{ cm}^{-3}$$

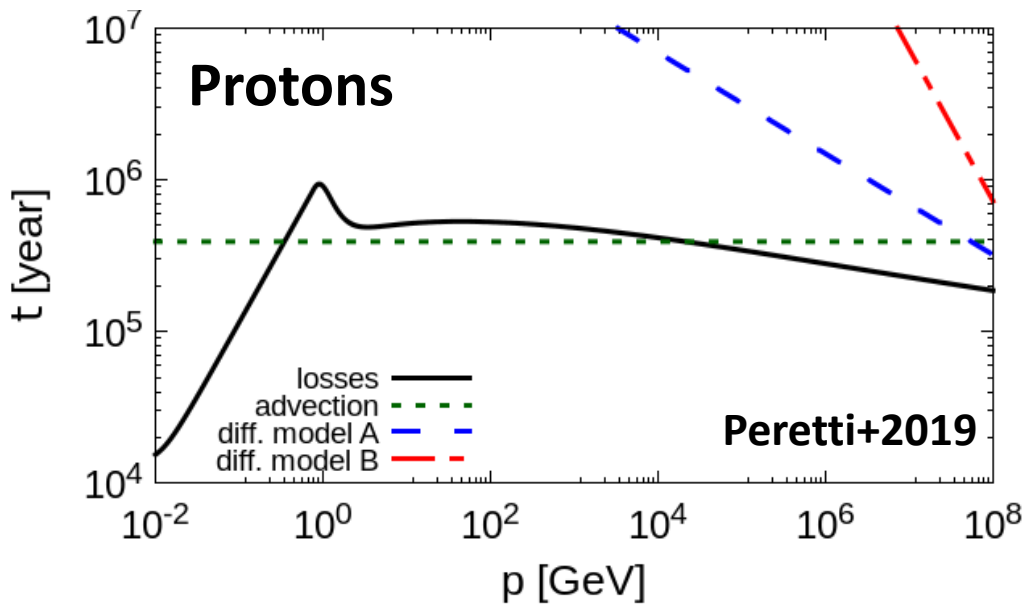
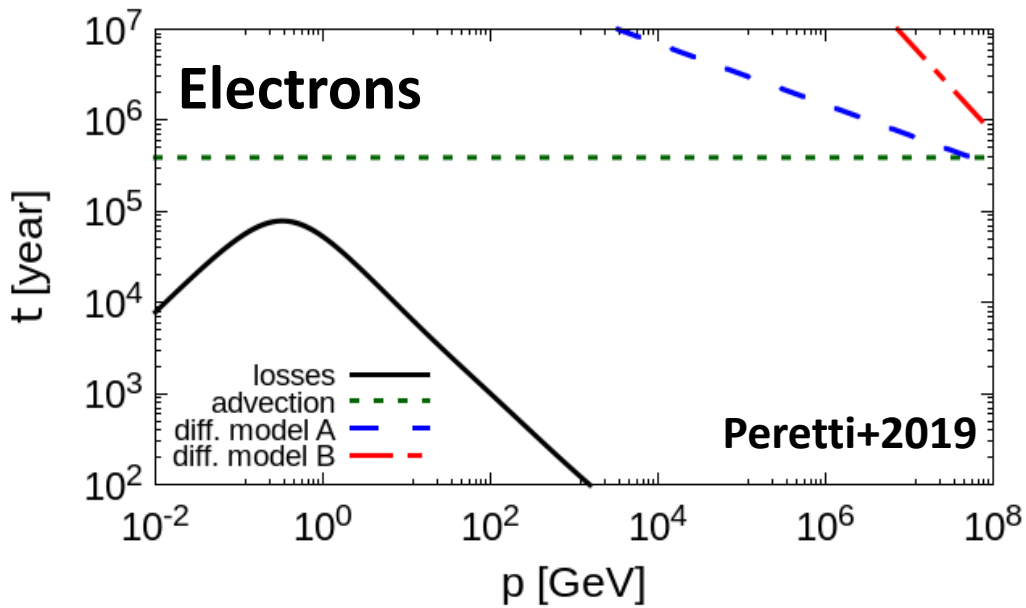
$$B \approx 10^2 \mu\text{G}$$

$$U_{\text{RAD}} \approx 10^3 \text{ eV cm}^{-3}$$

$$v \approx 10^2 \text{ km s}^{-1}$$

Turbulence is injected at a given coherence length and cascades down to smaller scales \rightarrow Quasi linear theory

Modeling the transport in SBNi



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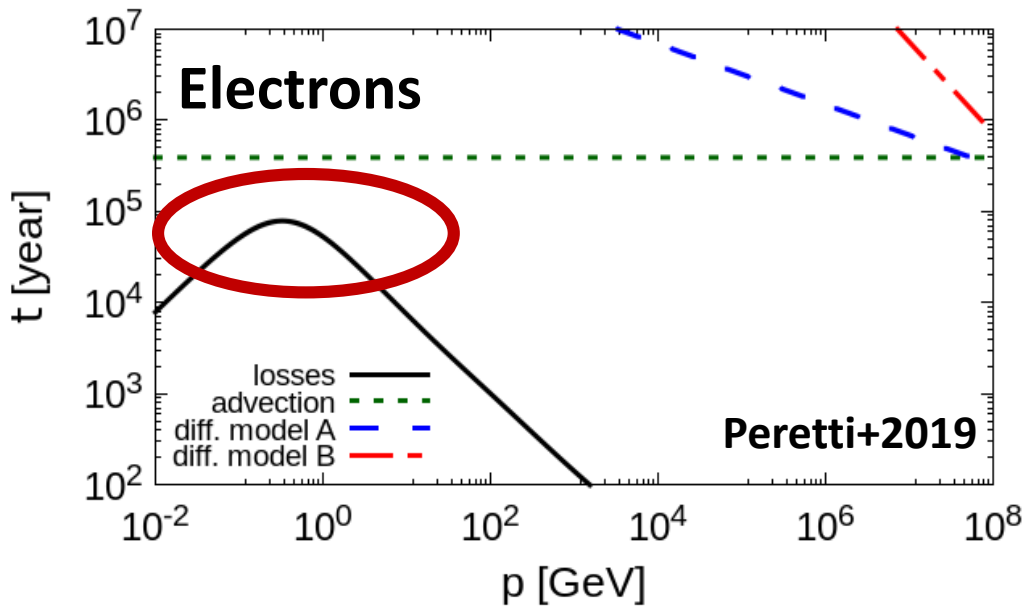
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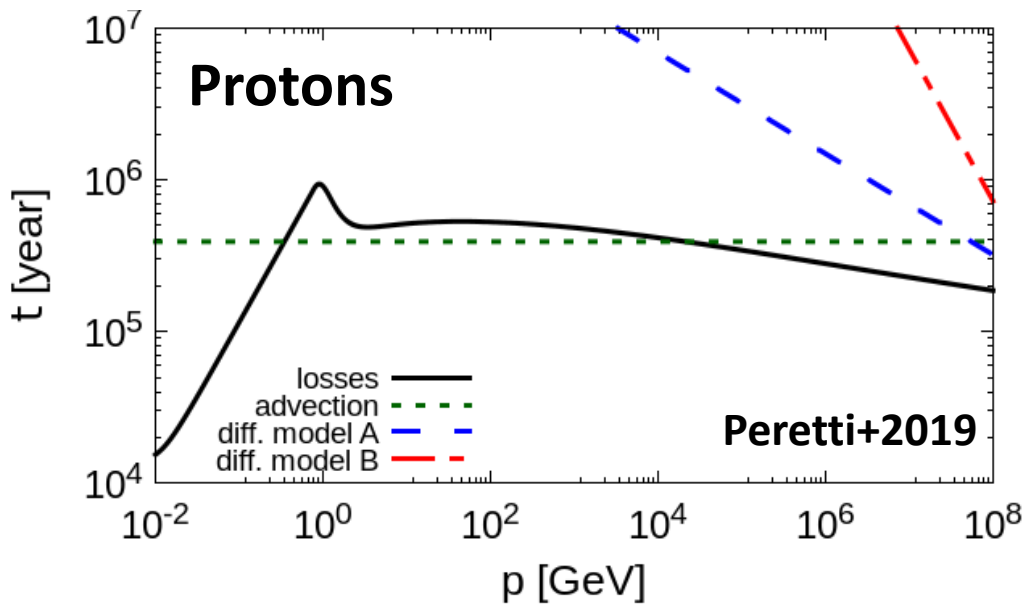
$$v \approx 10^2 \text{ km s}^{-1}$$

$$D(p) \approx \frac{c}{3} r_L^{2-\delta} l_c^{\delta-1}$$

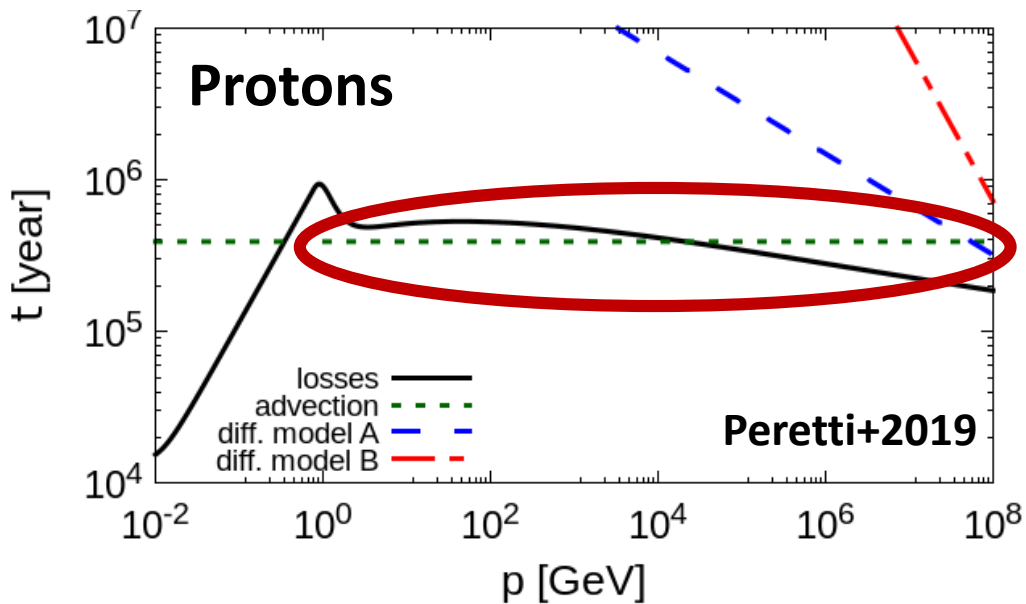
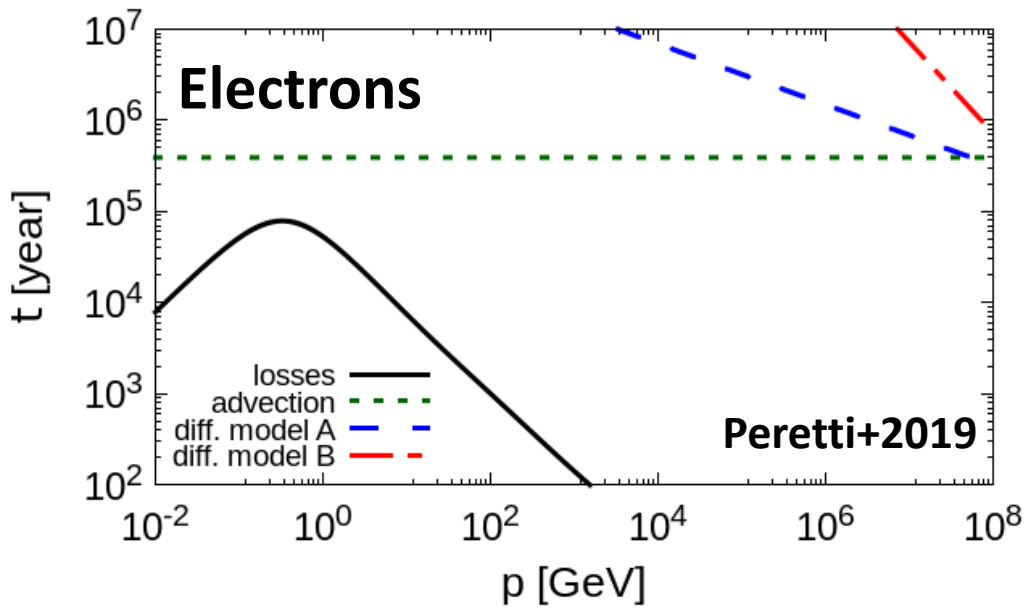
Modeling the transport in SBNi



- Electrons are confined in SBNi

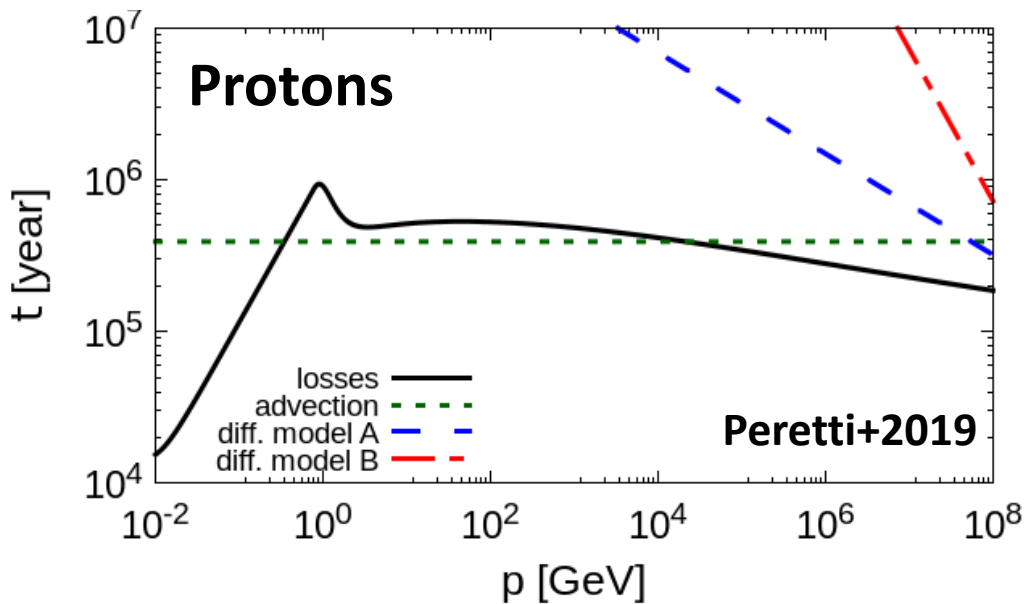
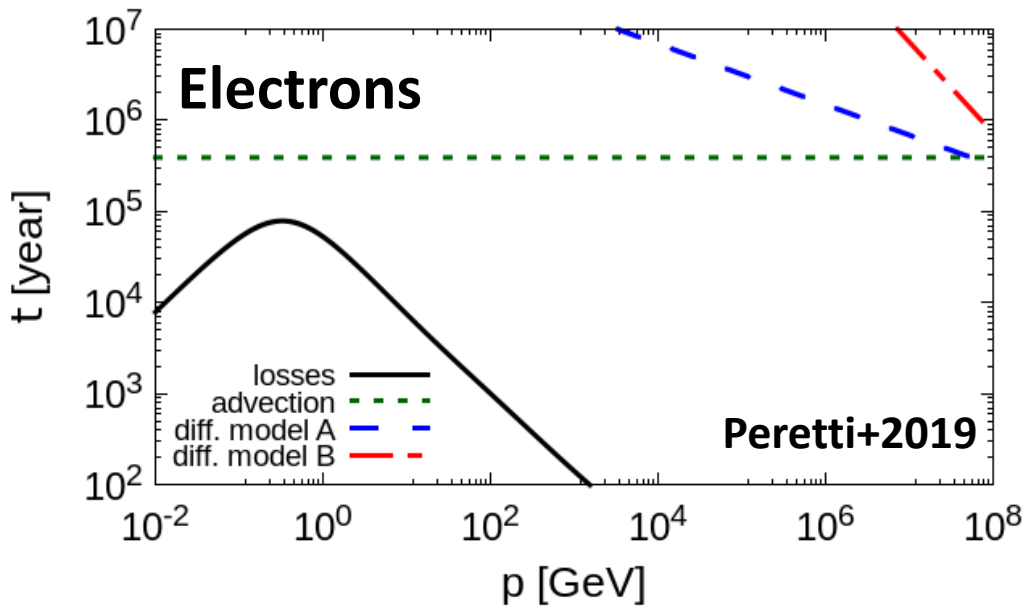


Modeling the transport in SBNi



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

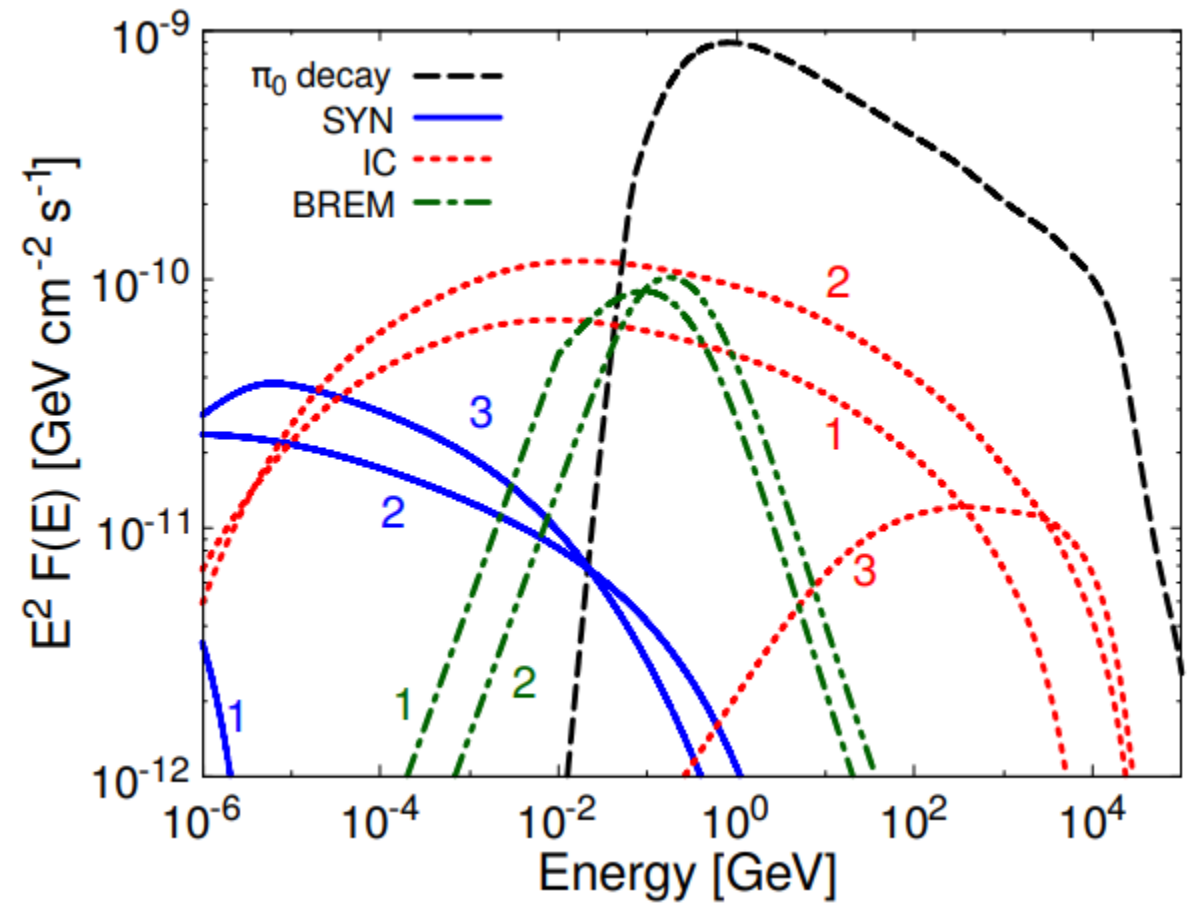
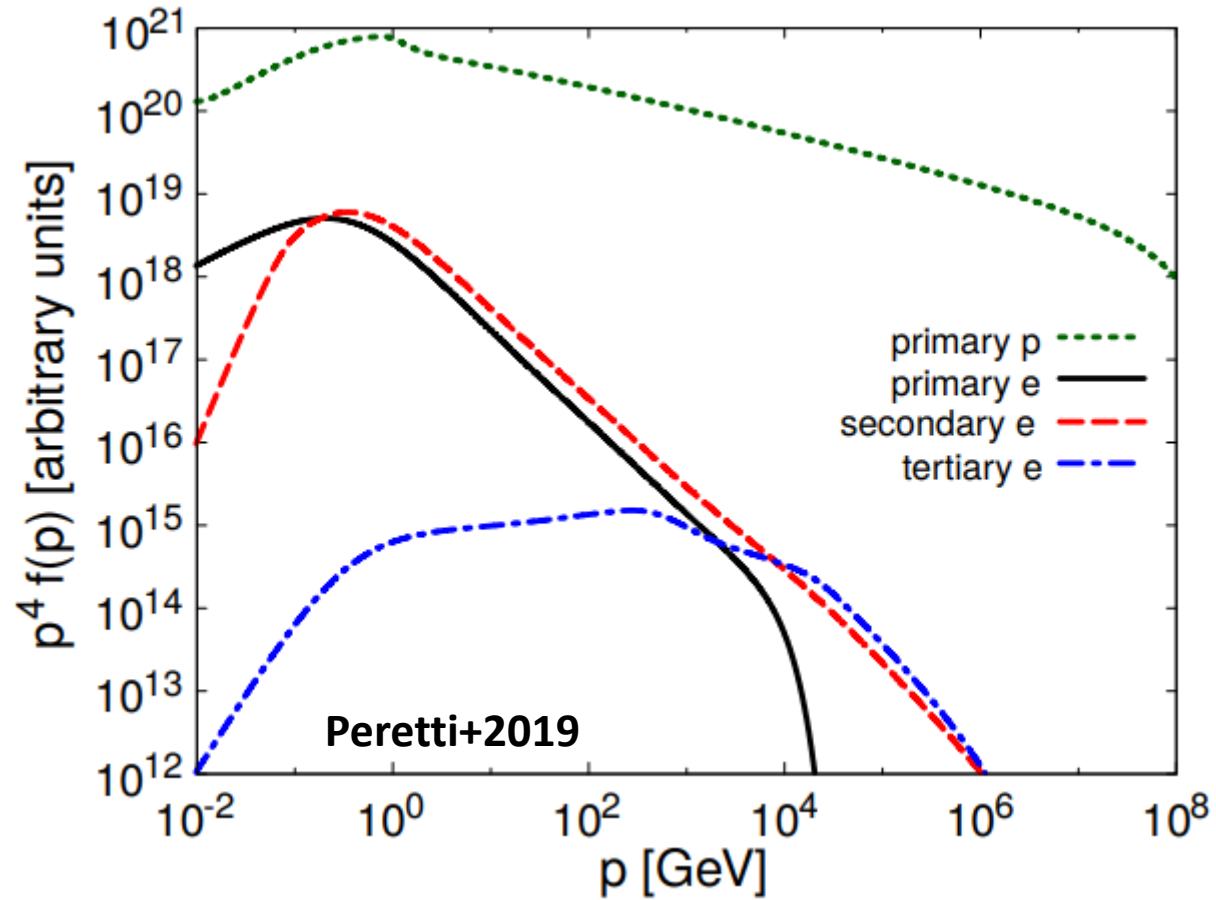
Modeling the transport in SBNi



- Electrons are confined in SBNi
- Advection and losses regulate the transport of protons
- Particles experience all phases of the ISM

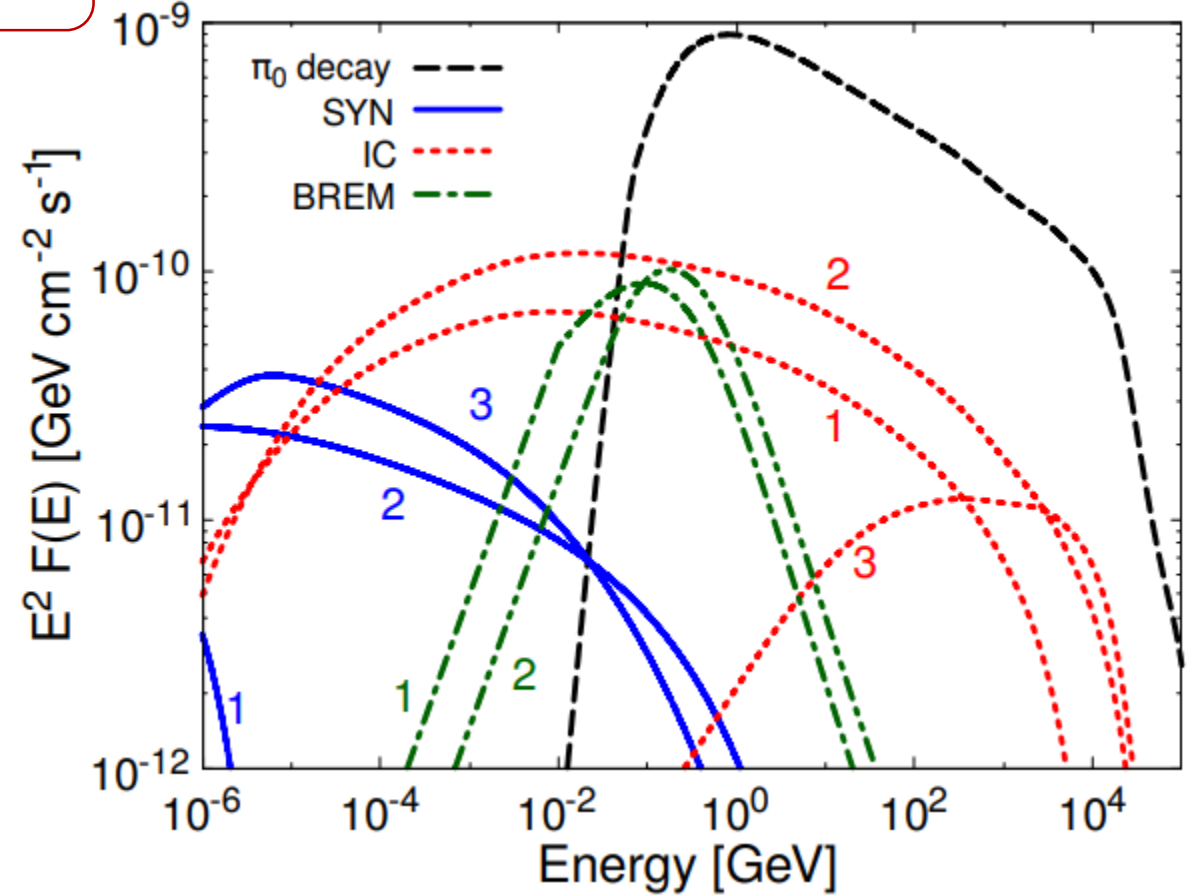
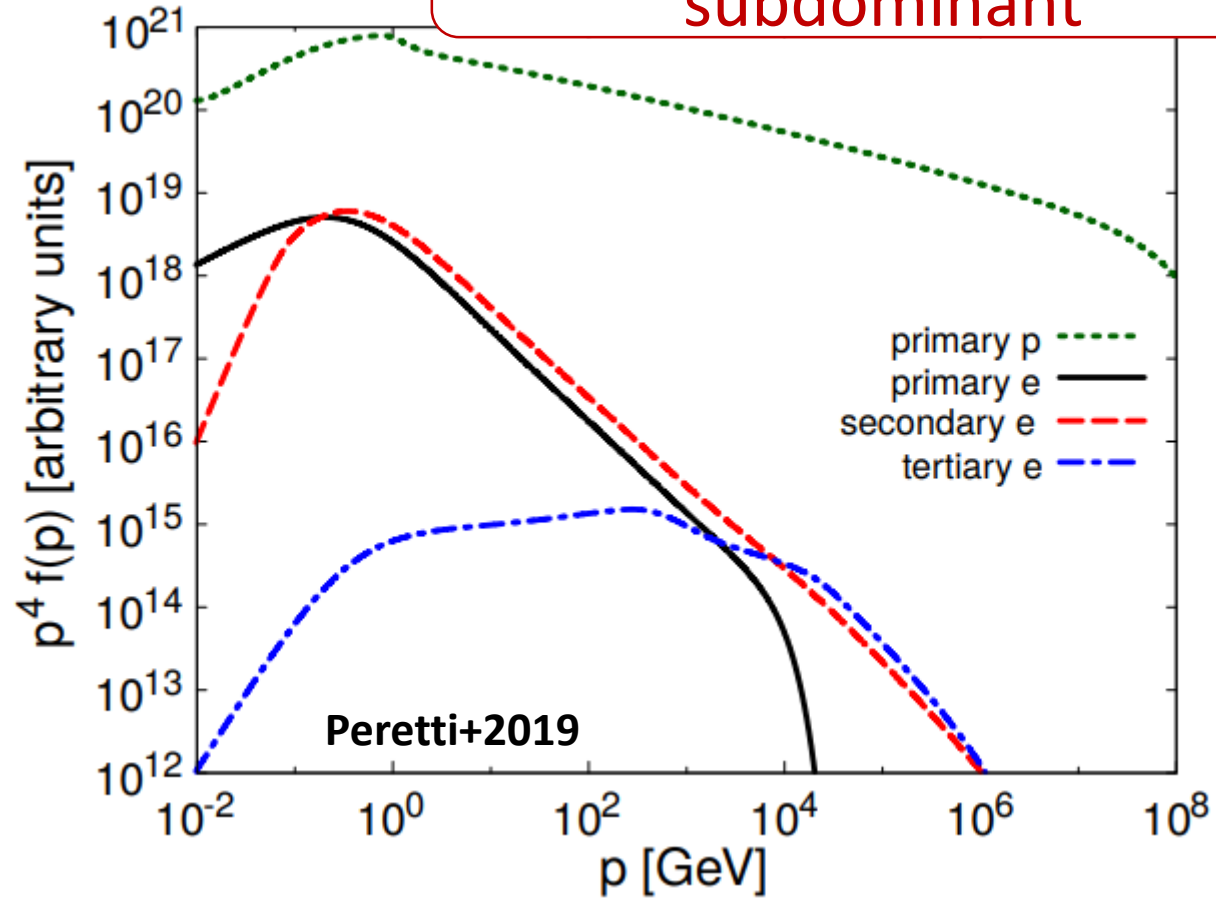
$$Q = \frac{f}{\tau_{loss}} + \frac{f}{\tau_{diff}} + \frac{f}{\tau_{adv}}$$

Particle and photon spectra in SBNi

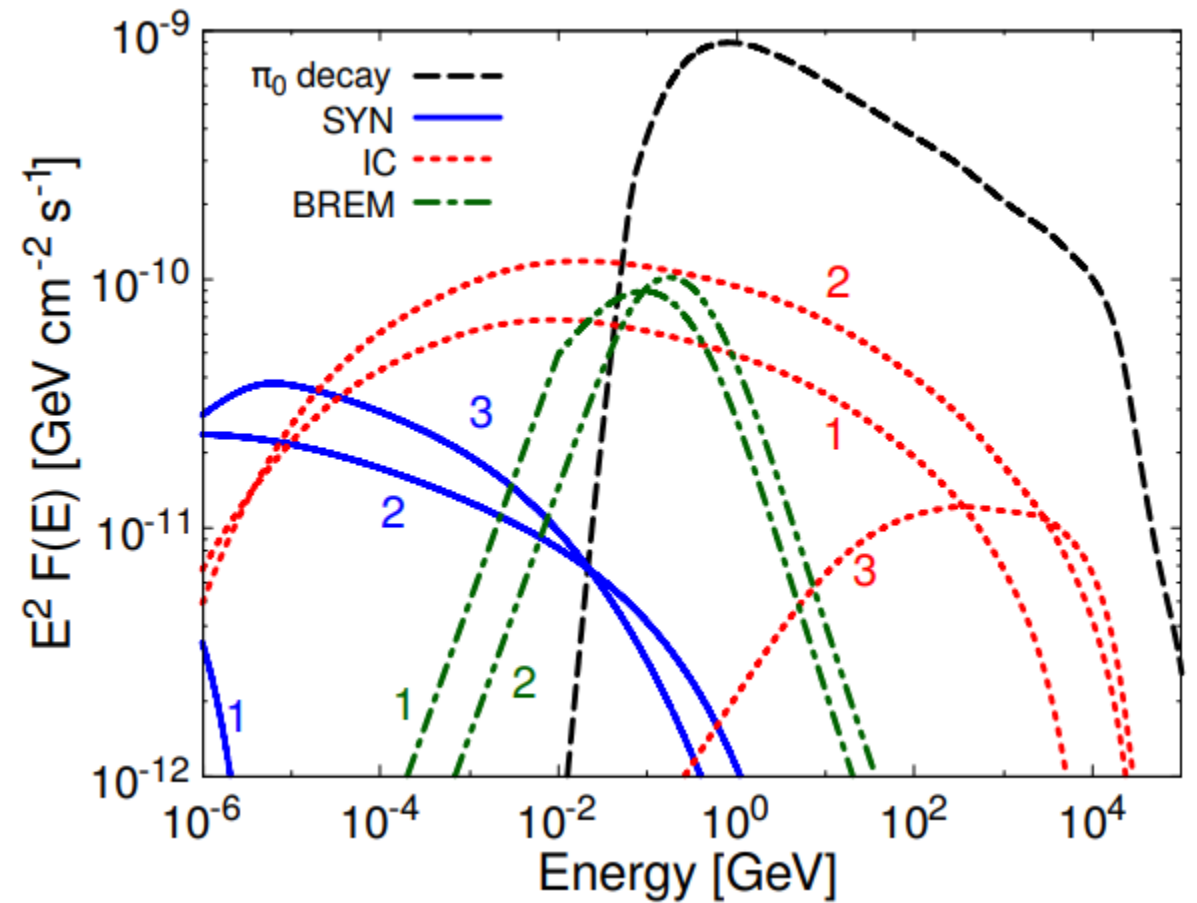
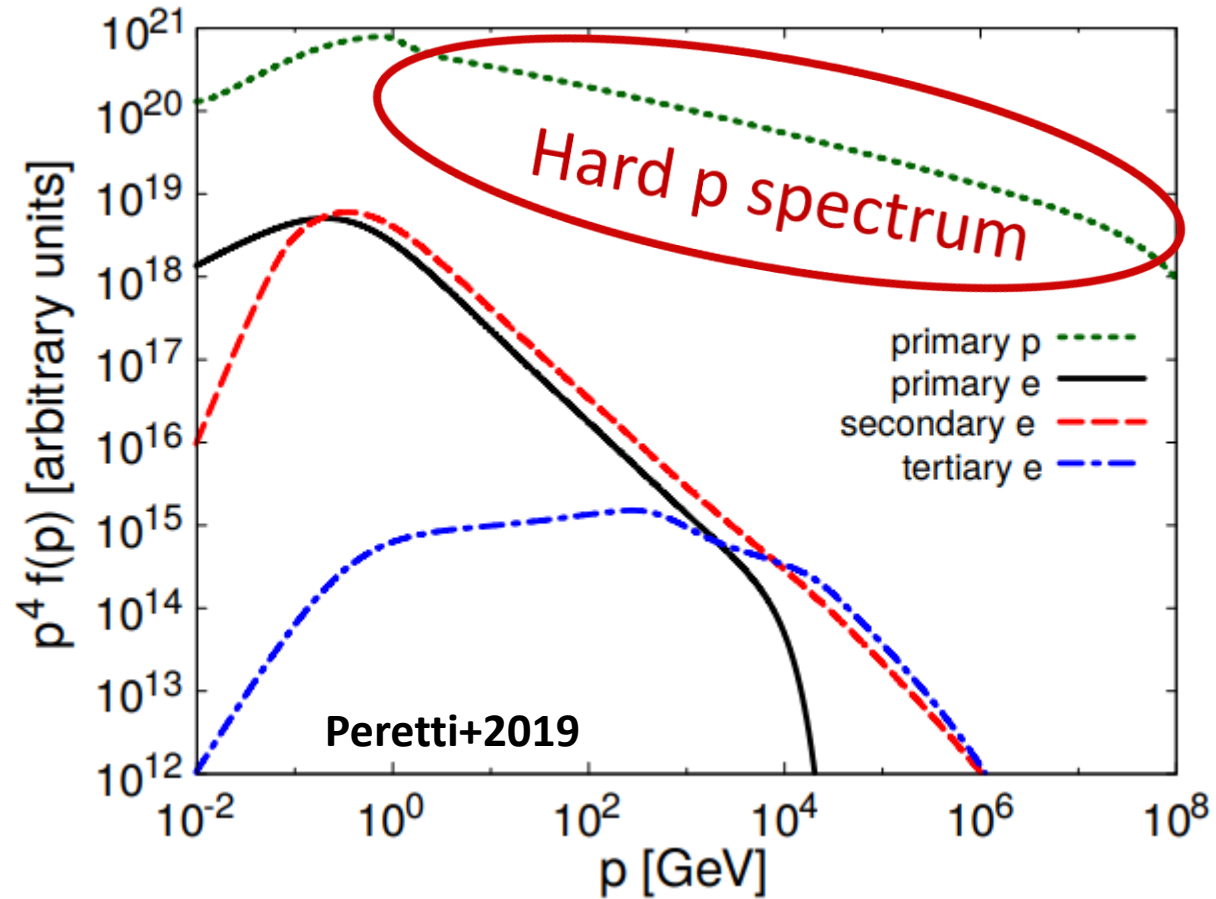


Particle and photon spectra in SBNi

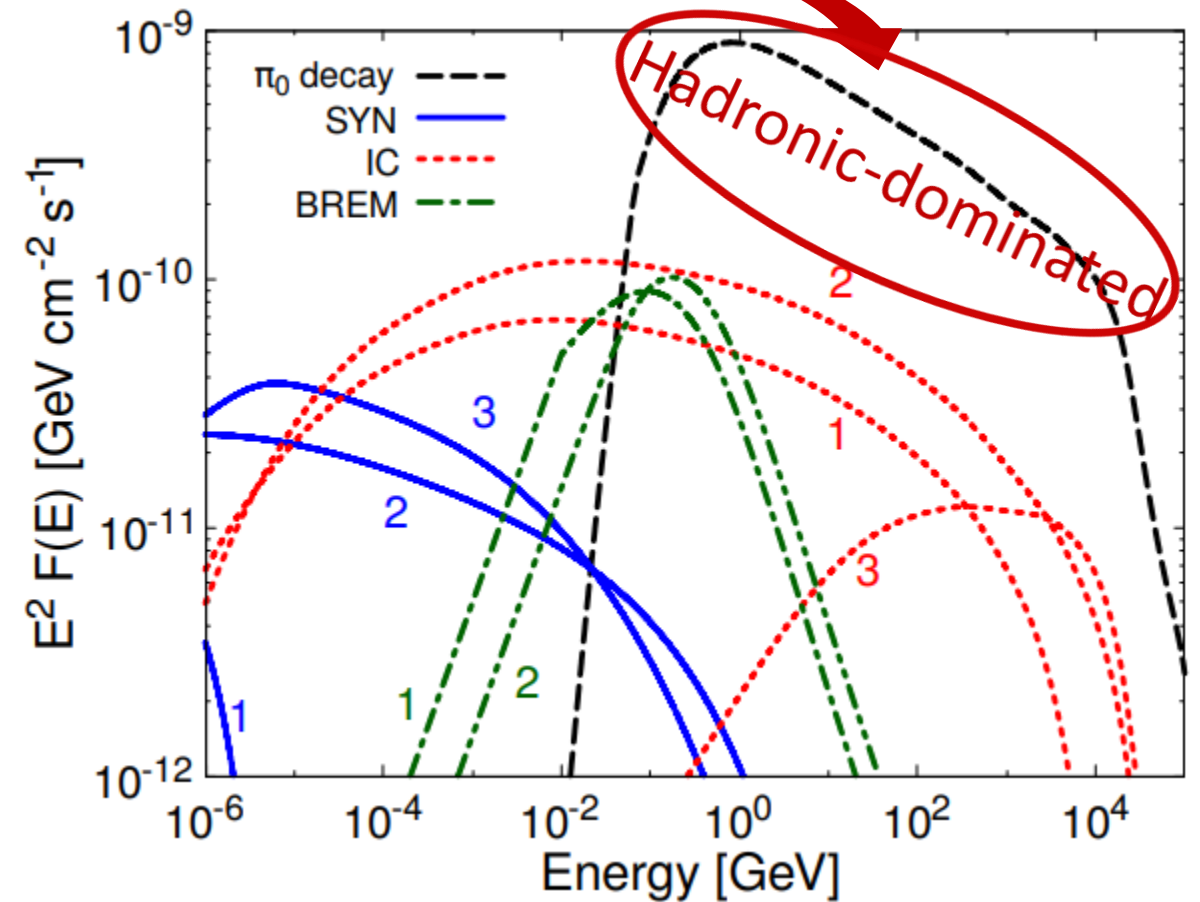
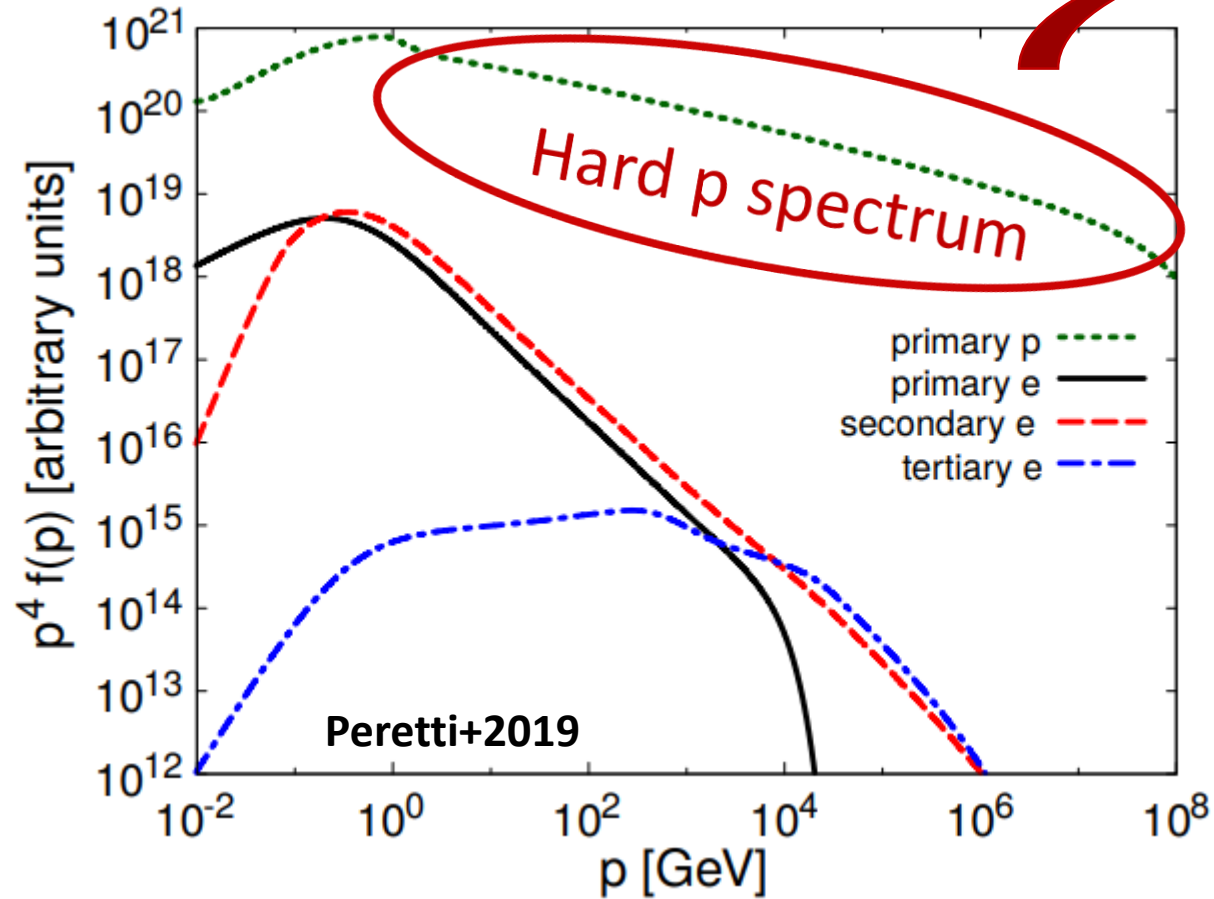
Particle diffusion is
subdominant



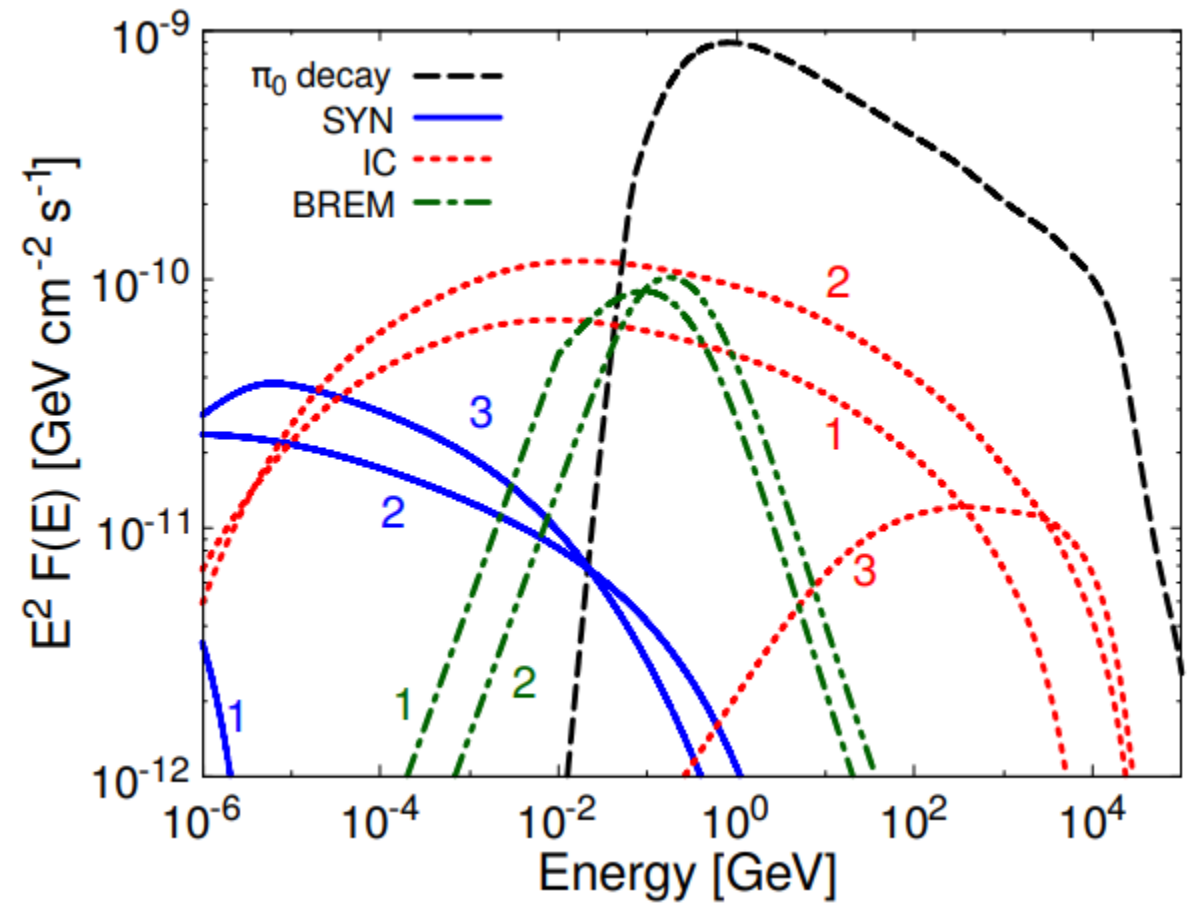
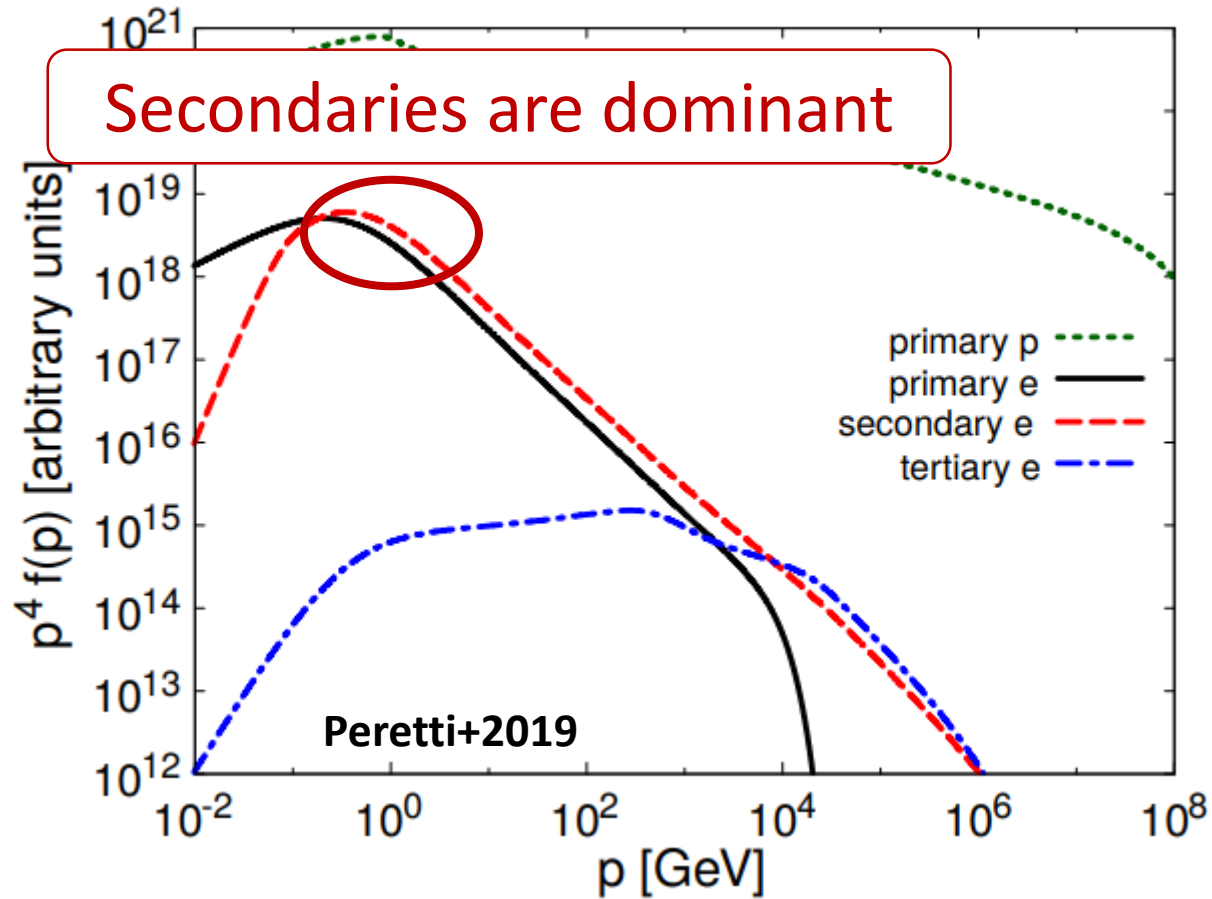
Particle and photon spectra in SBNi



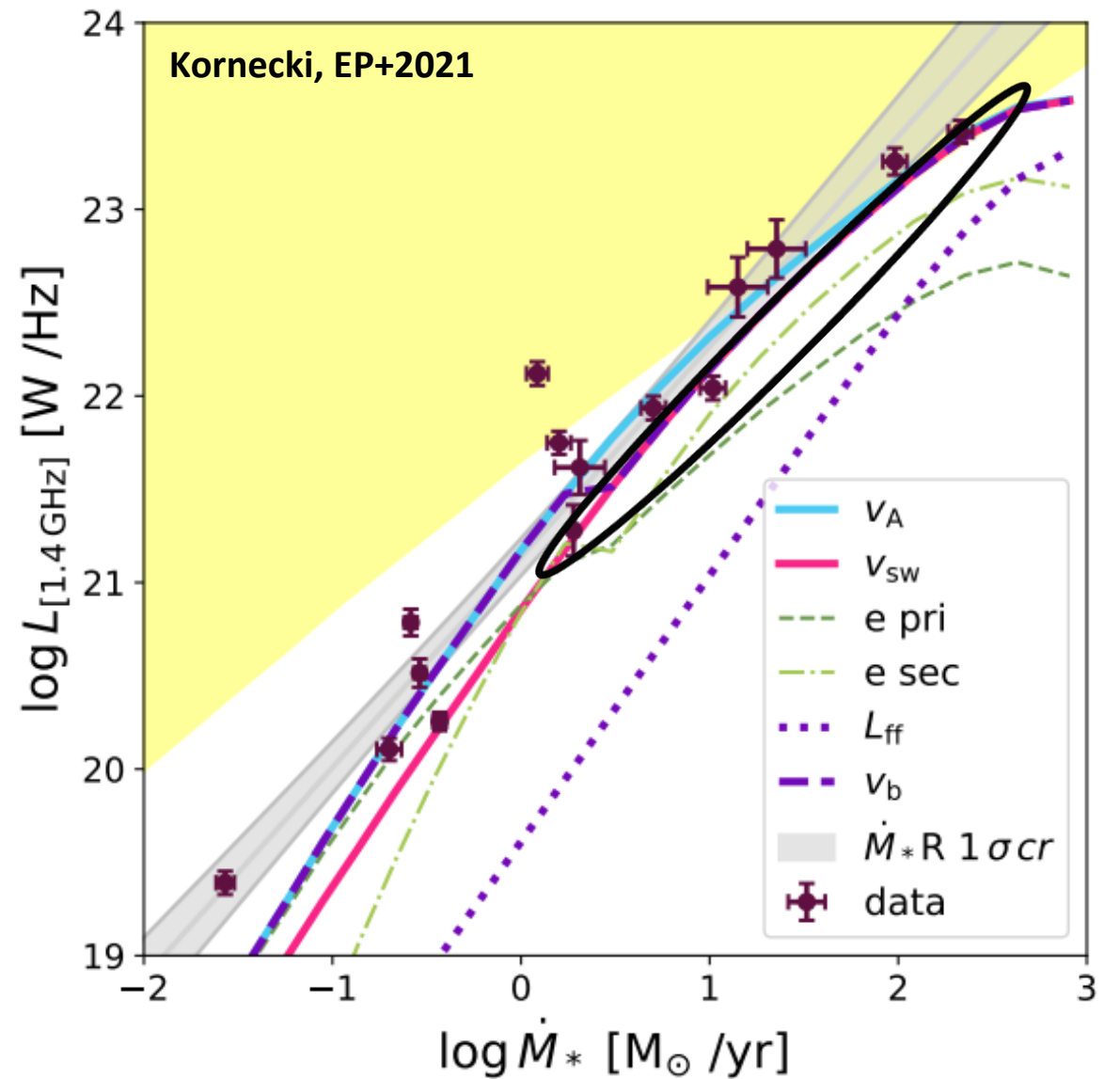
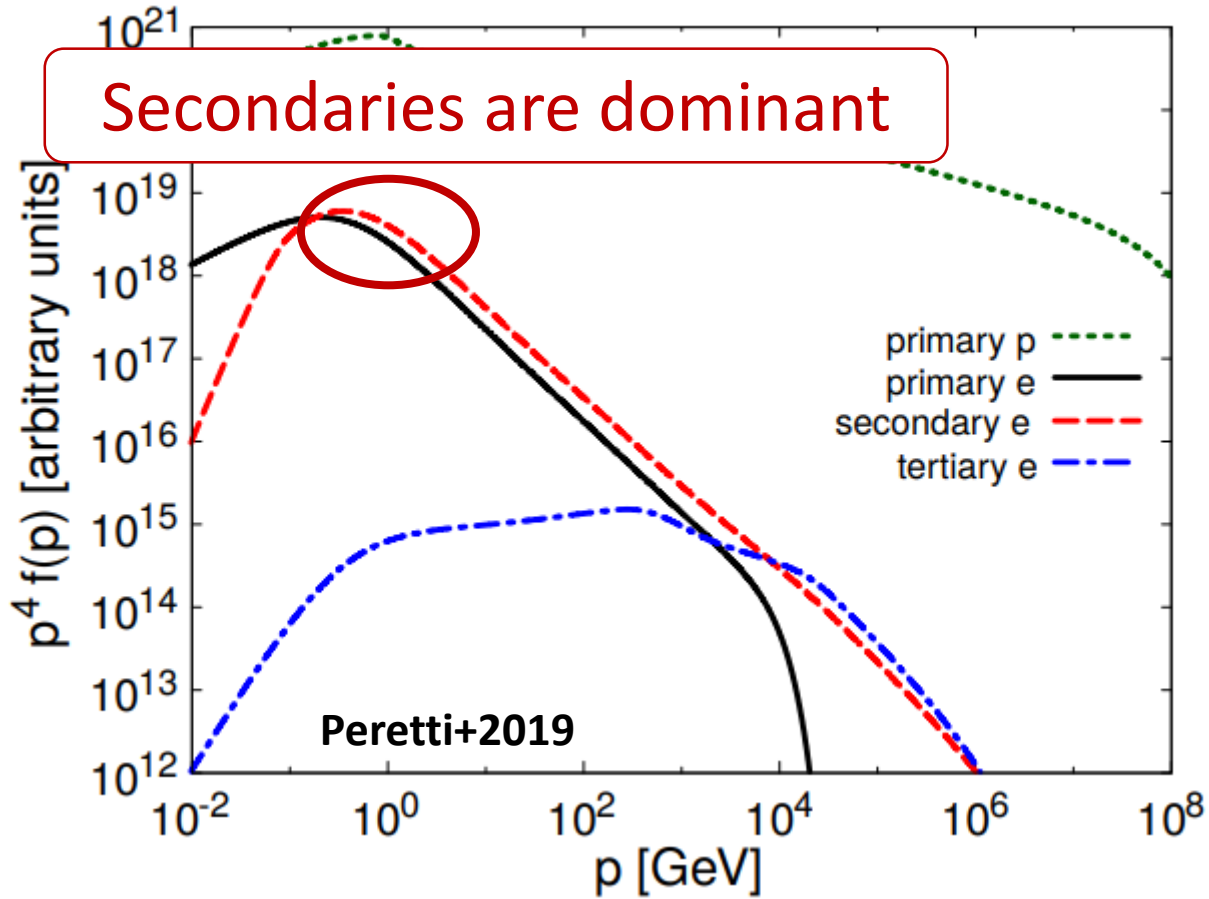
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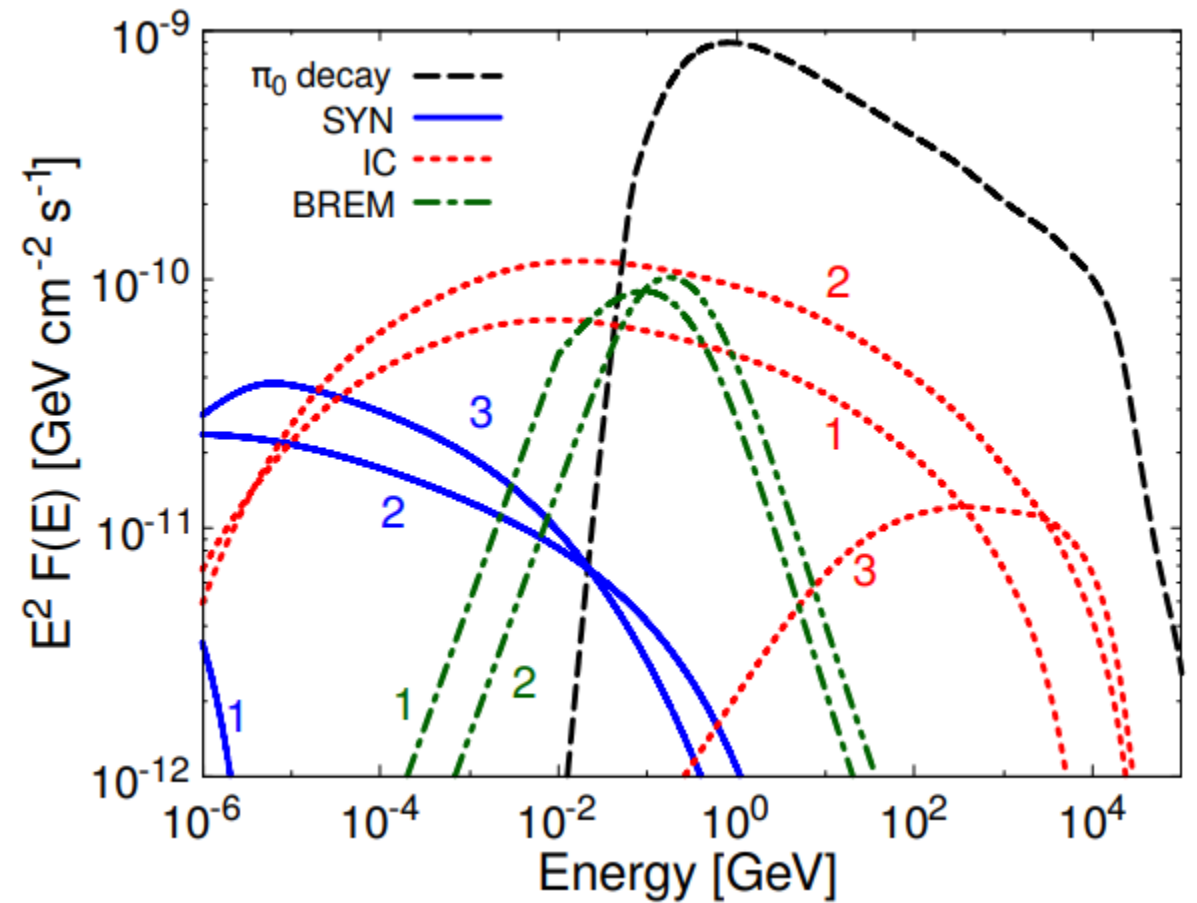
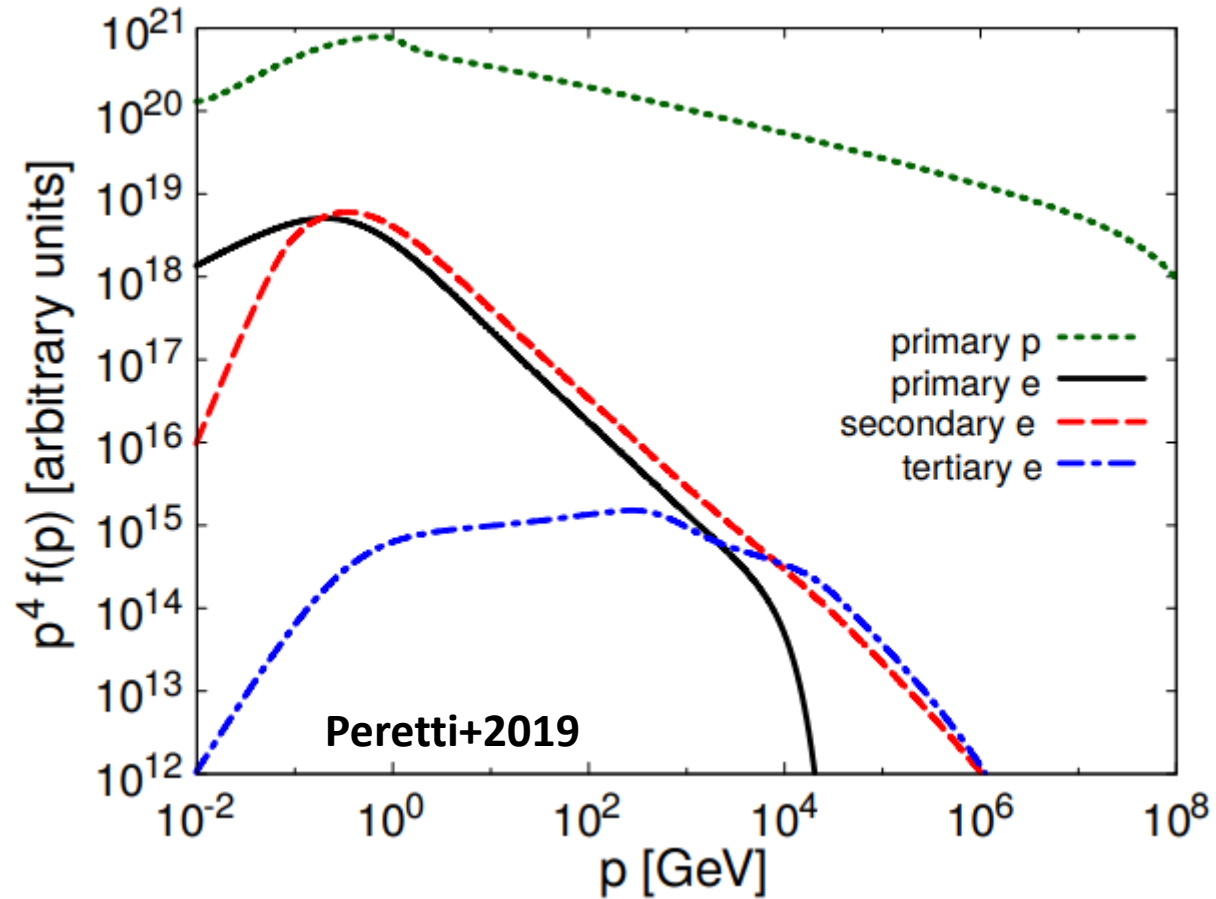
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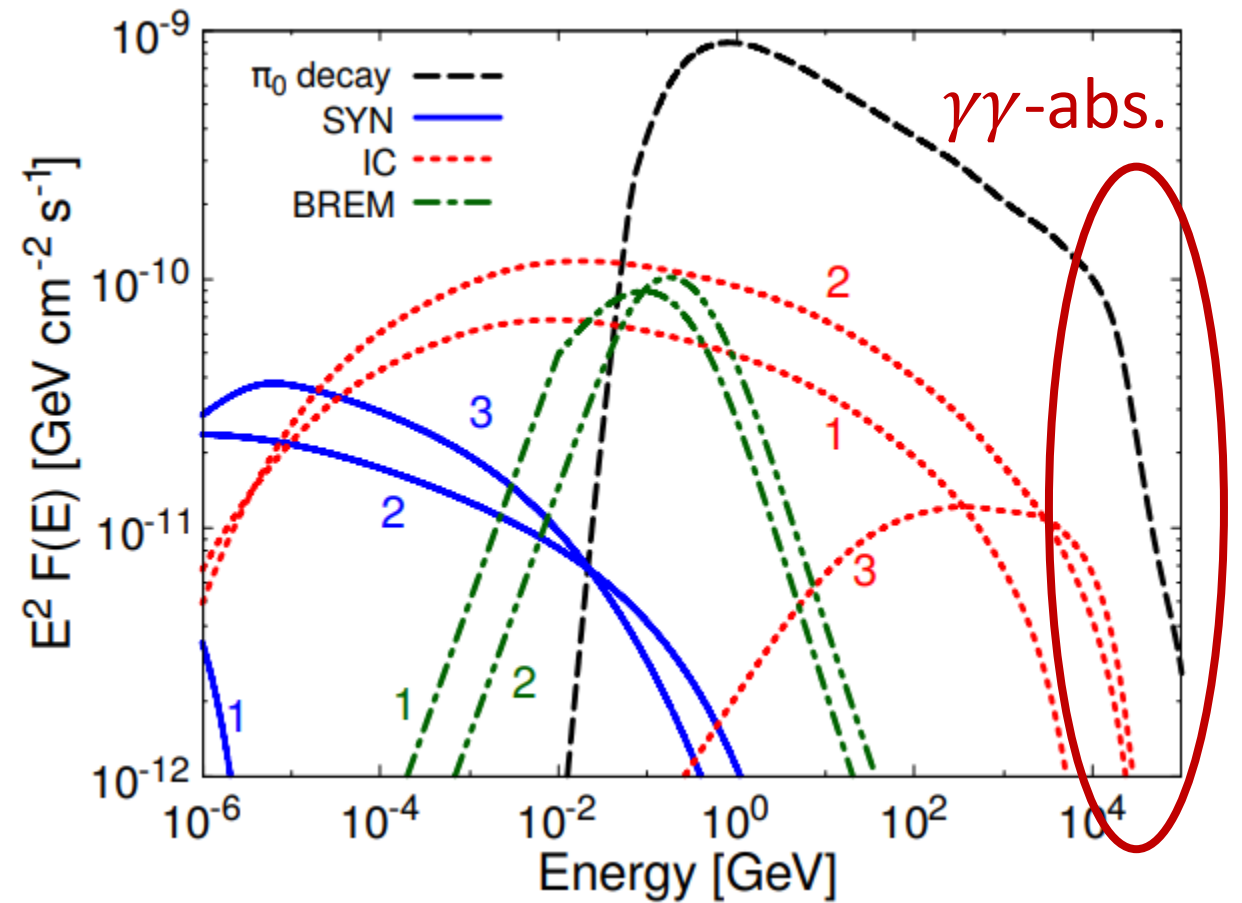
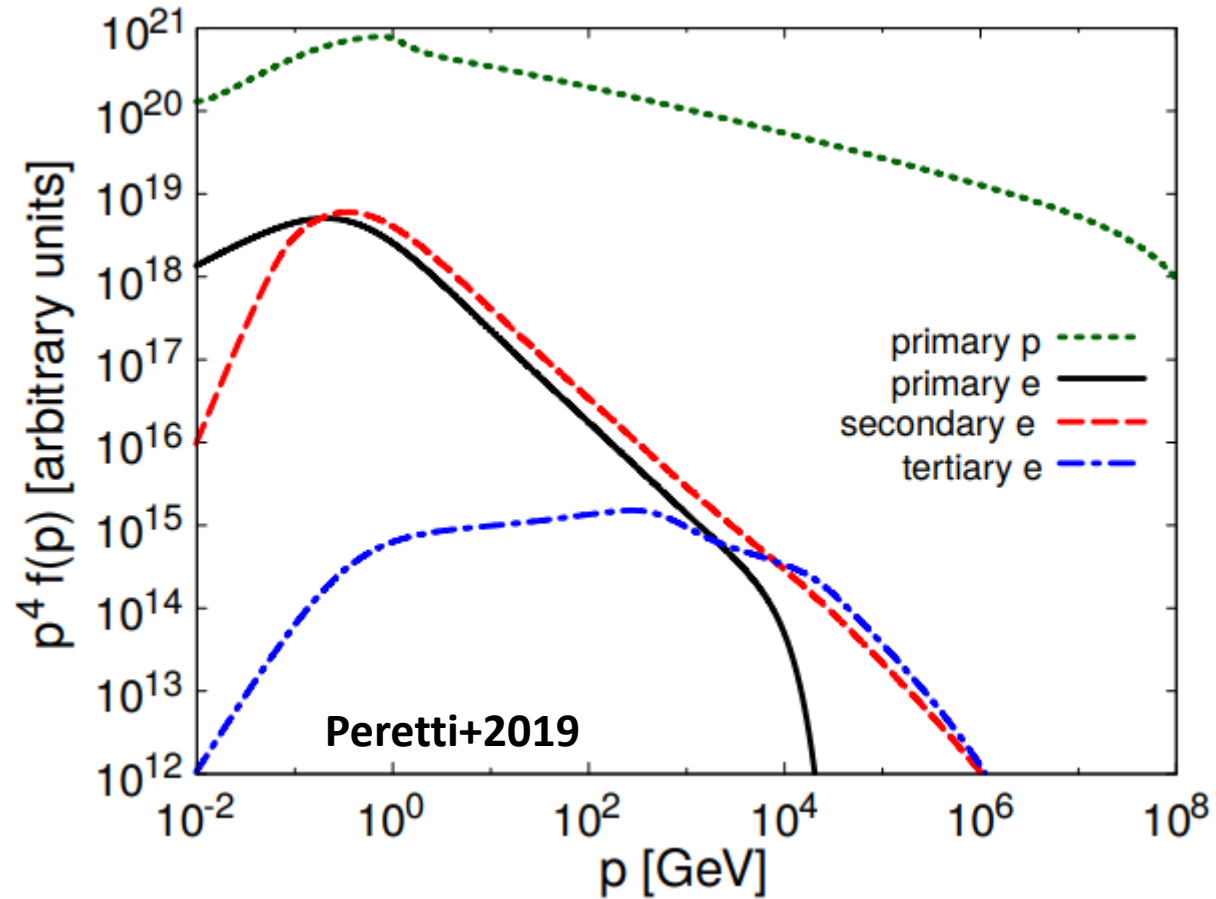
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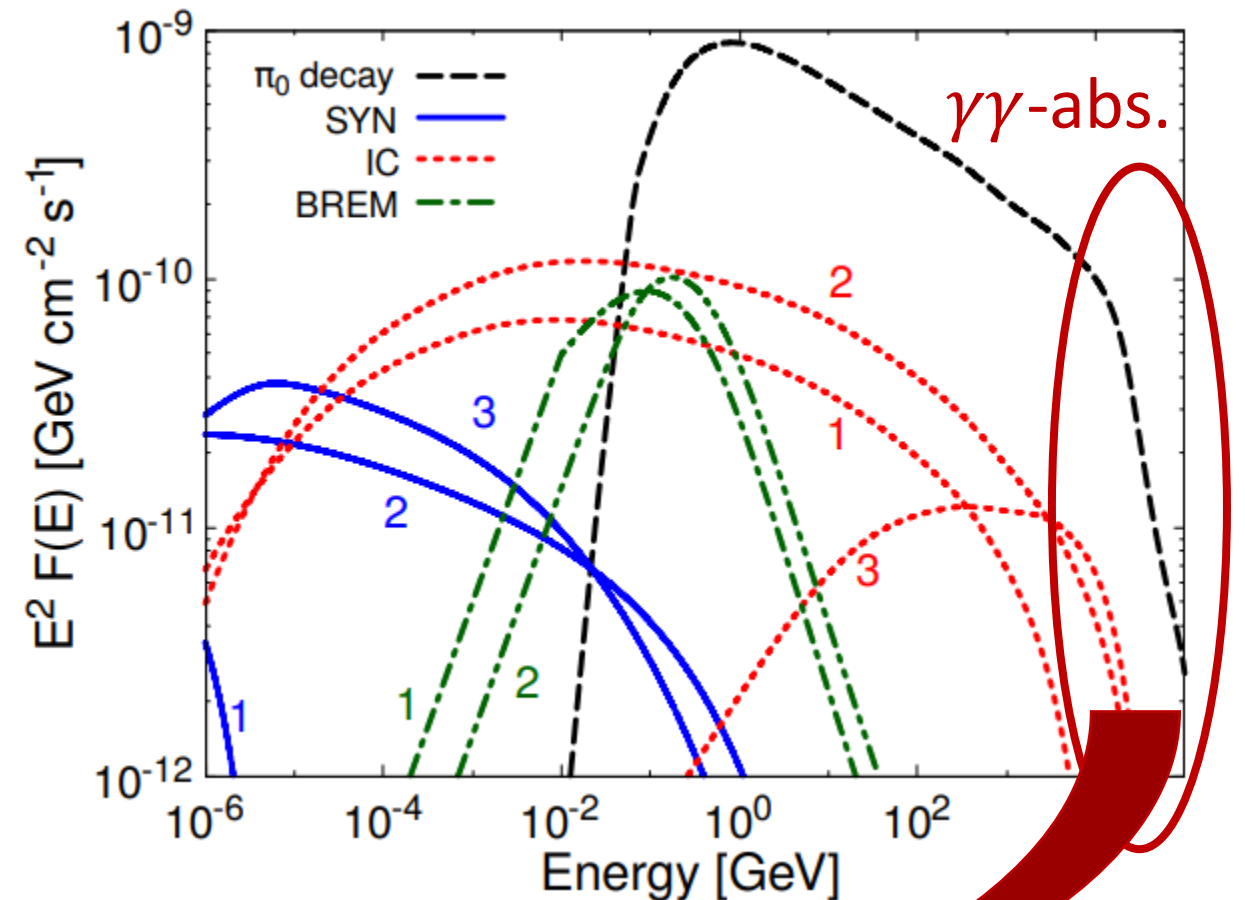
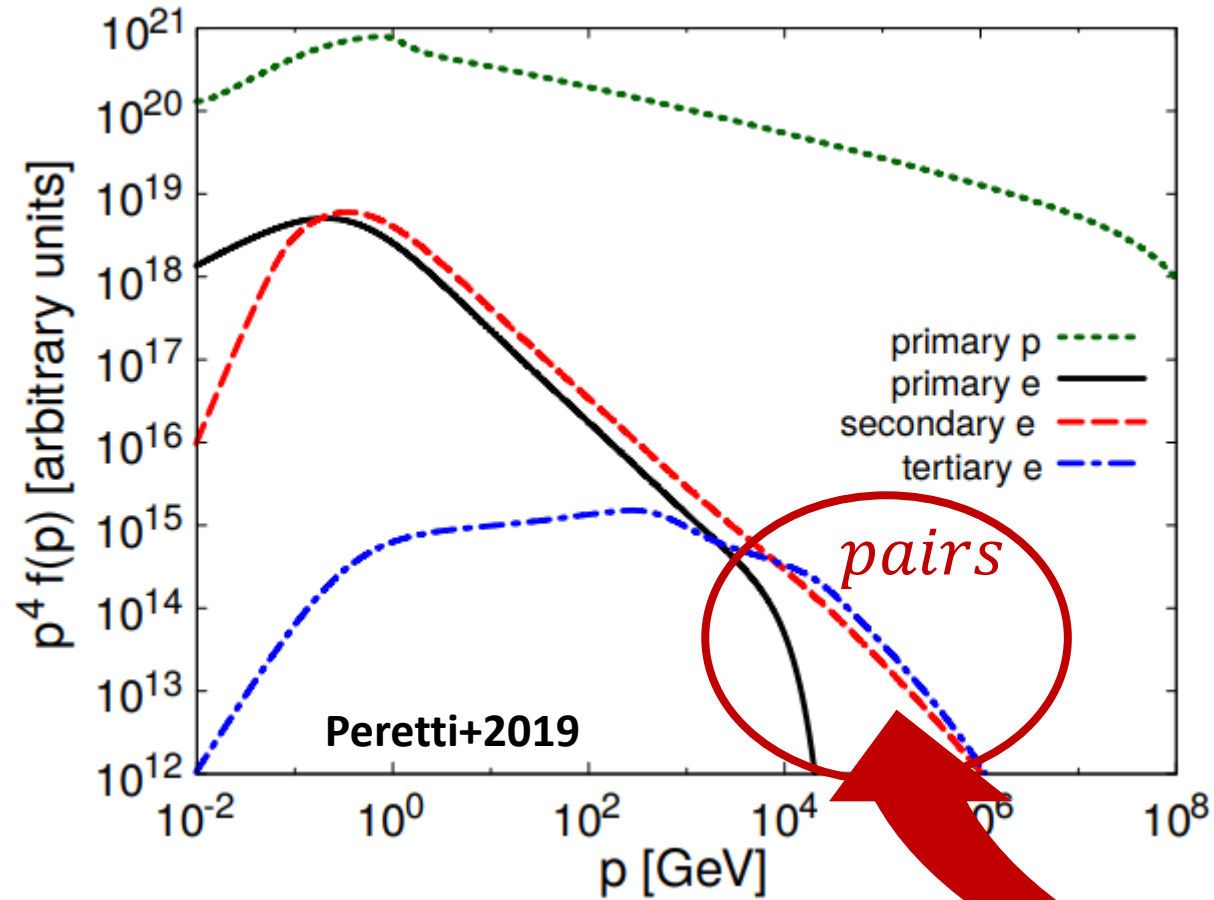
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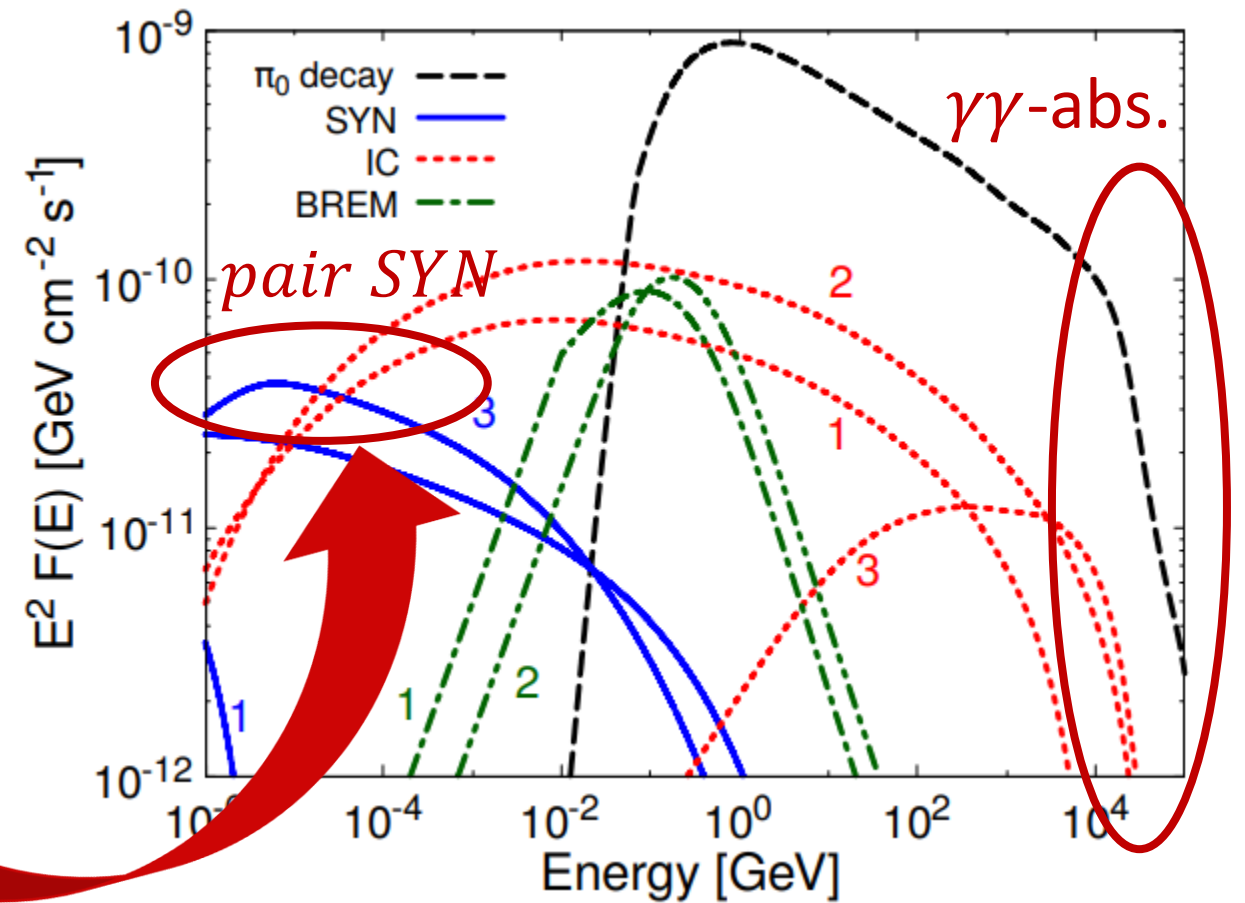
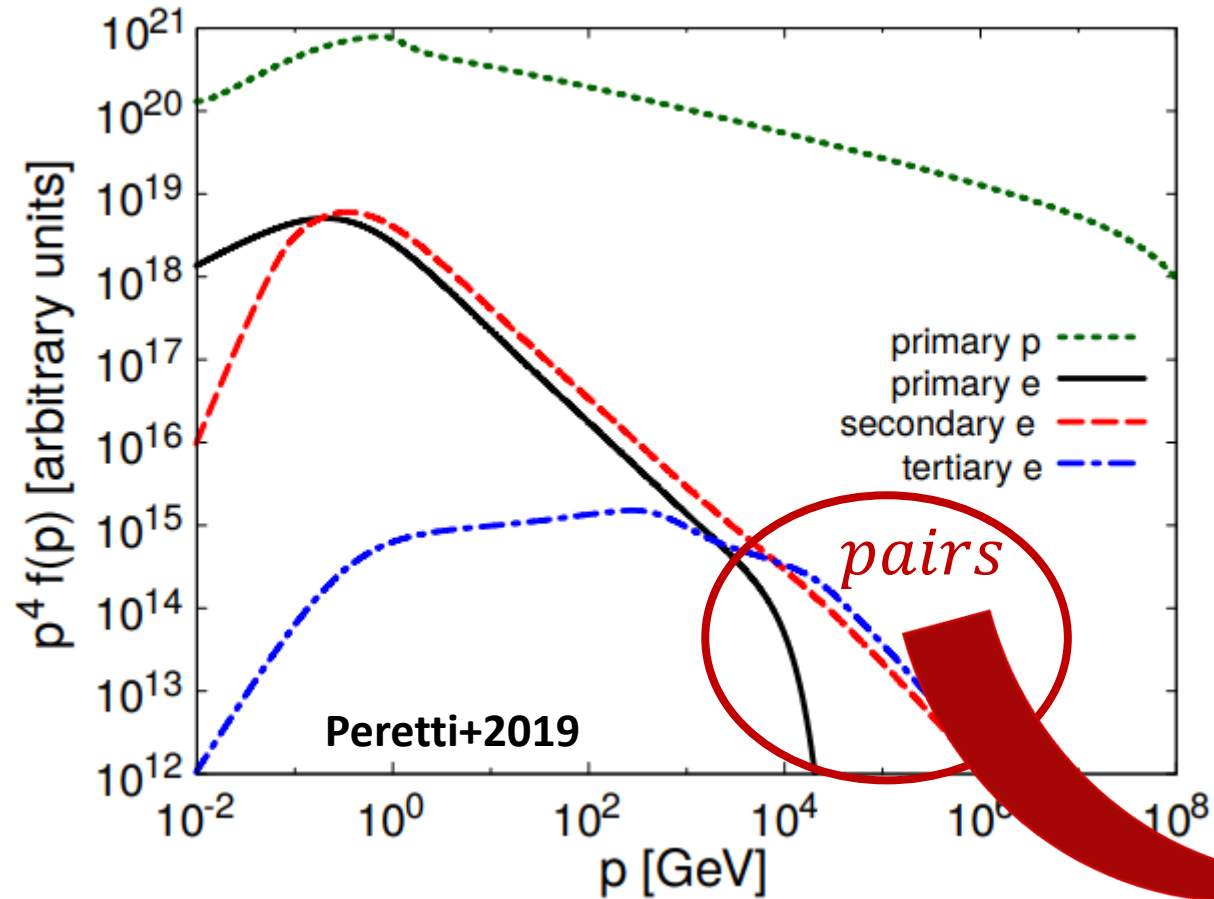
Particle and photon spectra in SBNi



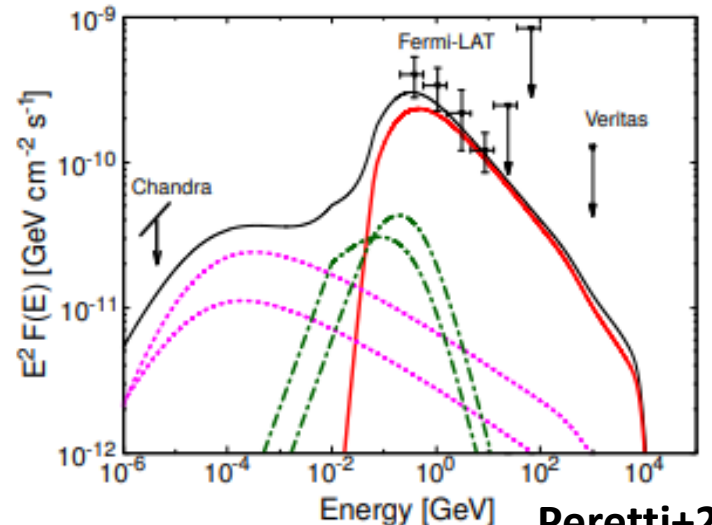
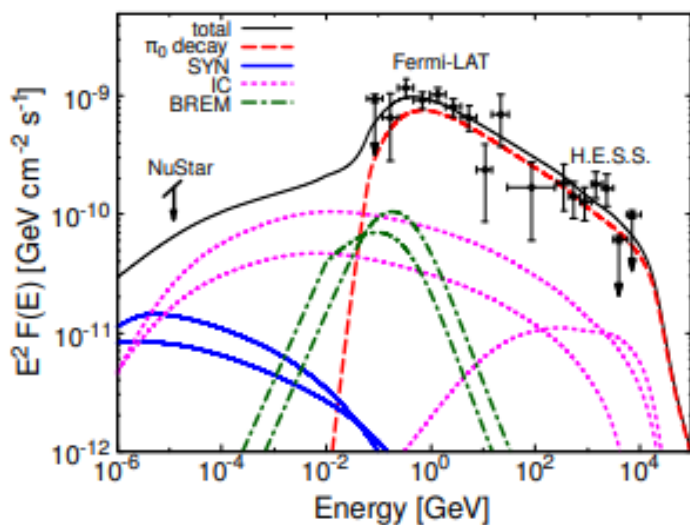
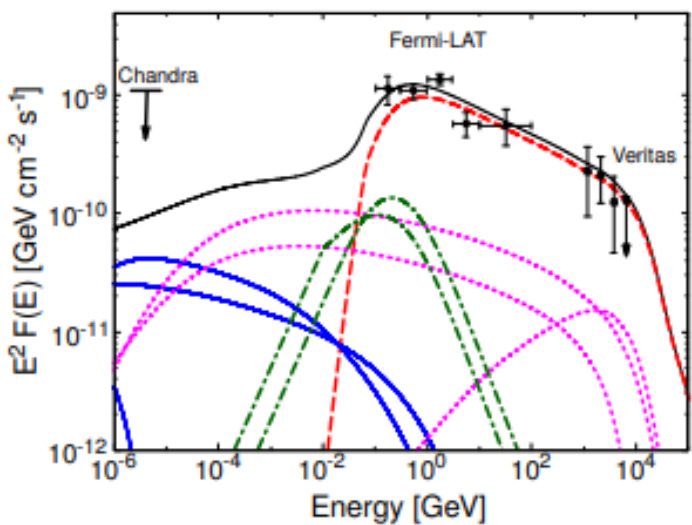
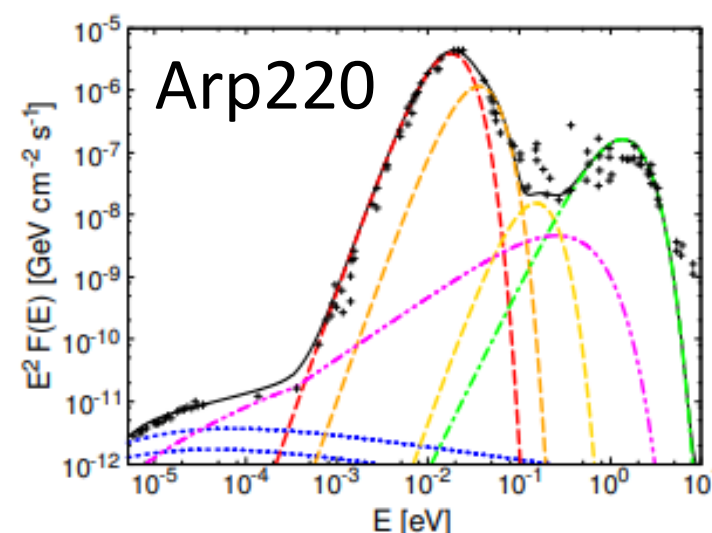
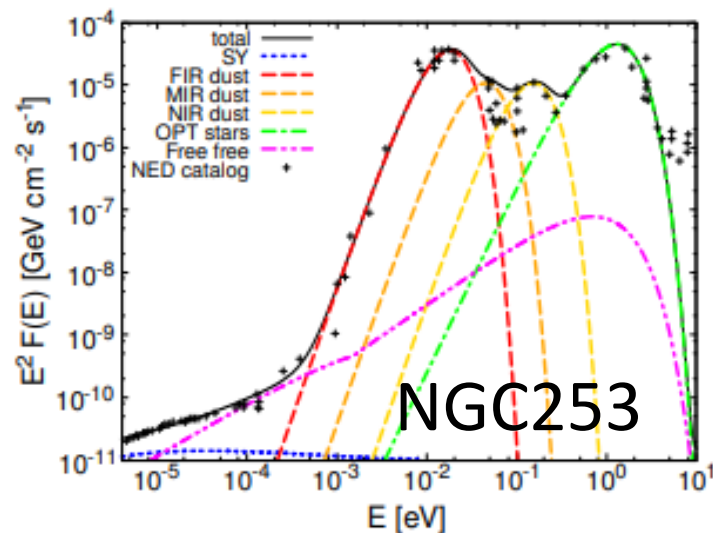
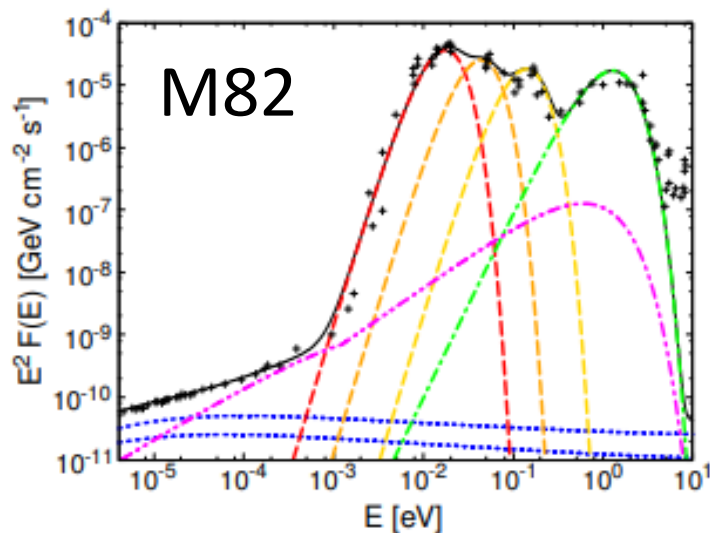
Particle and photon spectra in SBNi



Particle and photon spectra in SBNi

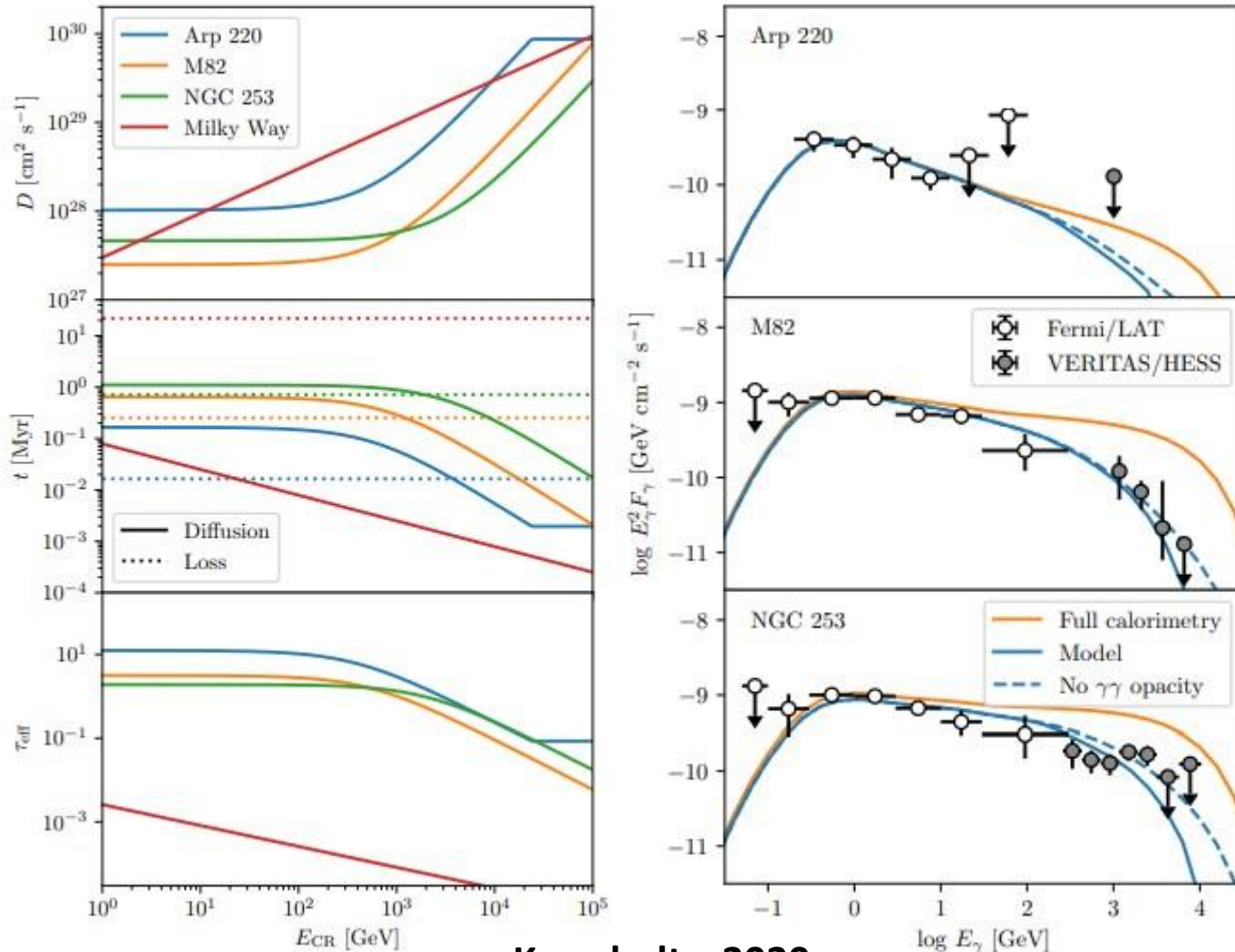


Modeling nearby SBGs



Peretti+2019

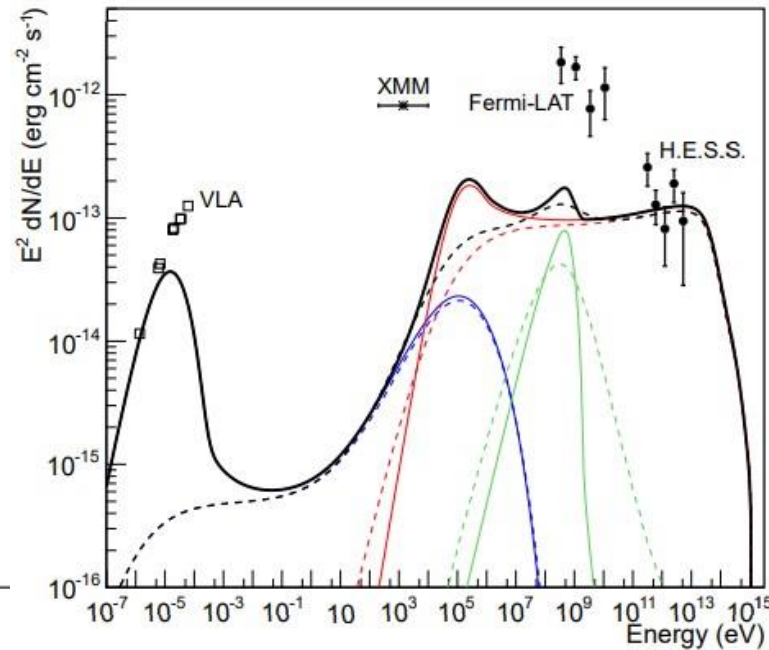
Open questions in the TeV band - Turbulence



Krumholtz+2020

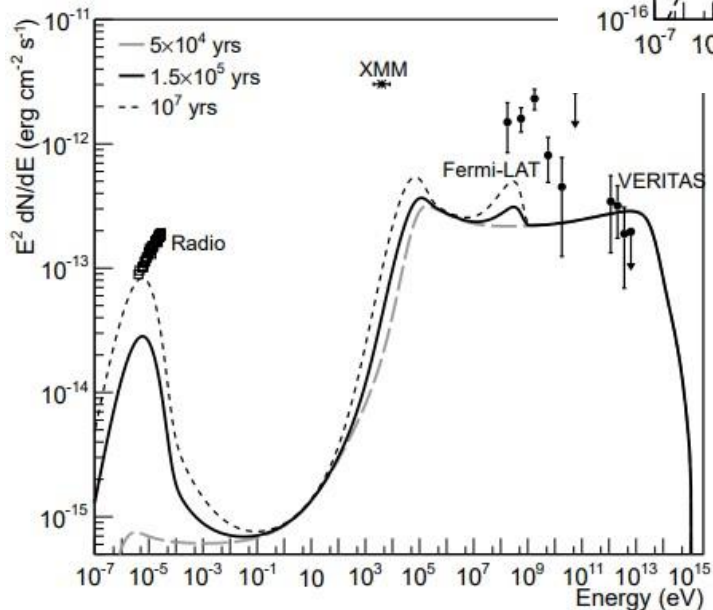
- The turbulence cascade might be suppressed by the ion-neutral damping
- In this scenario TeV particles are escaping efficiently

Open questions in the TeV band – Pulsar winds



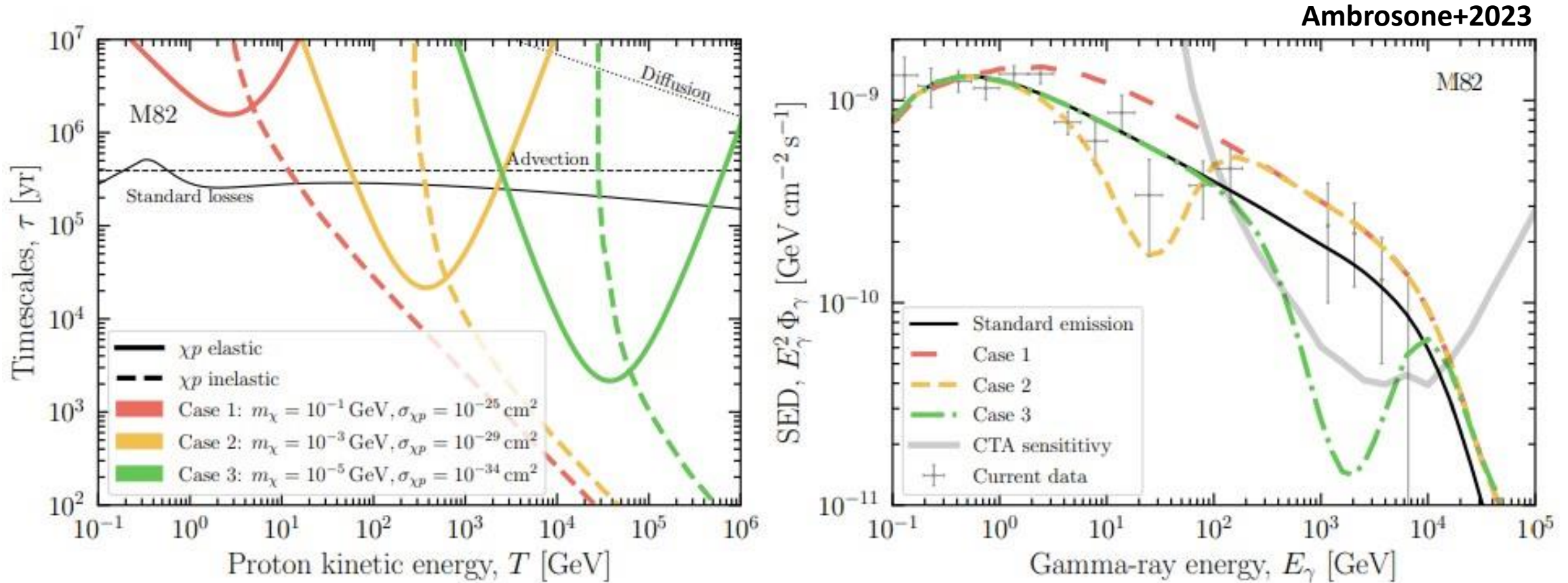
- The high supernova rate must necessarily result in a large number of emitting pulsar wind nebulae (PWNe)

Ohm+2013
(see also Mannheim+2010)

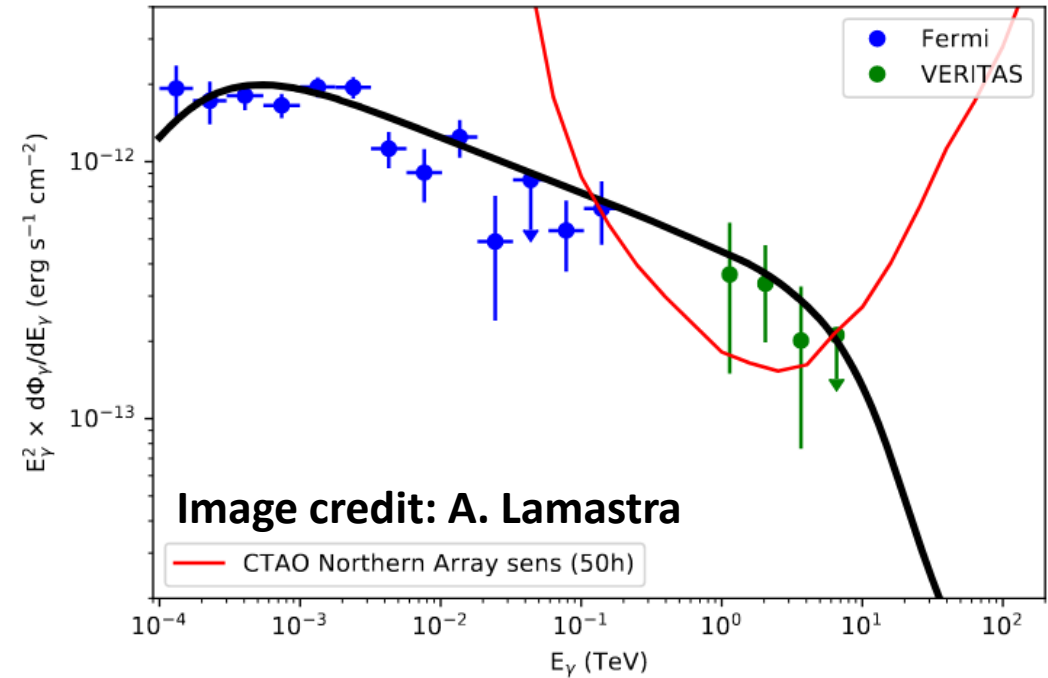
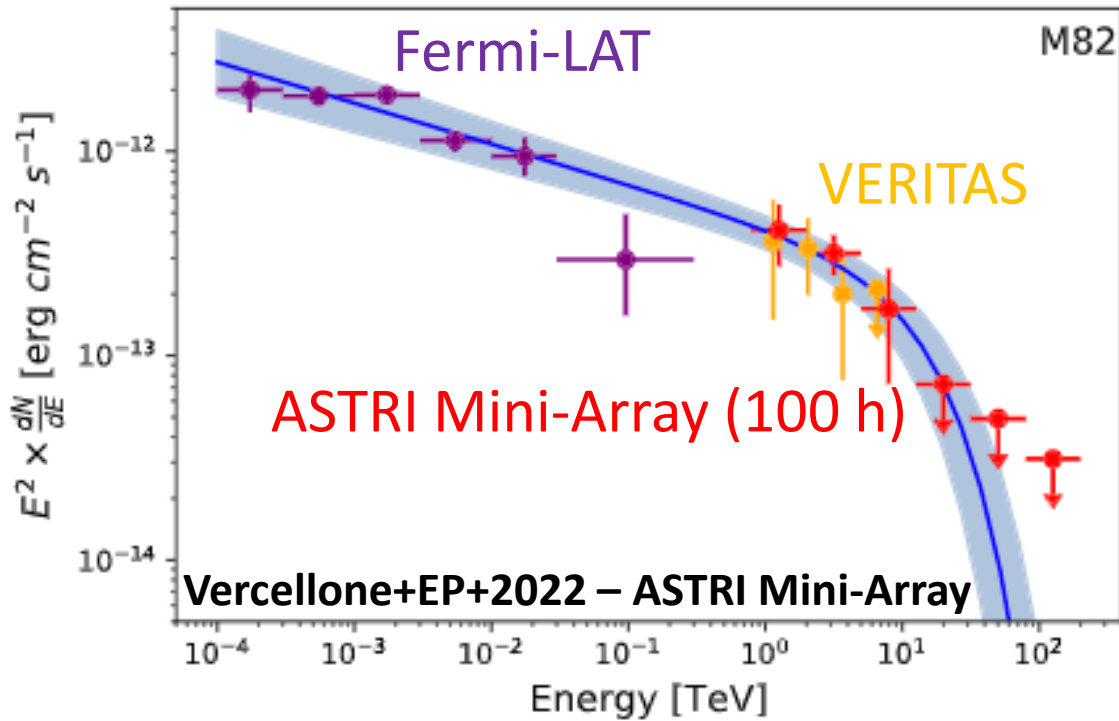


- The PWNe emission could dominate the gamma-ray flux in the TeV band

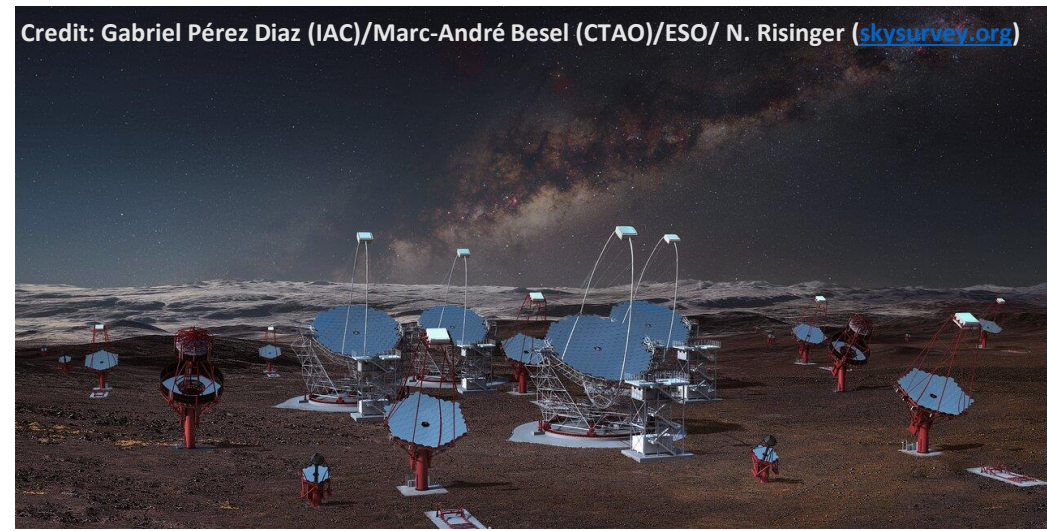
Open questions in the TeV band – Dark Matter



Upcoming gamma-ray observations

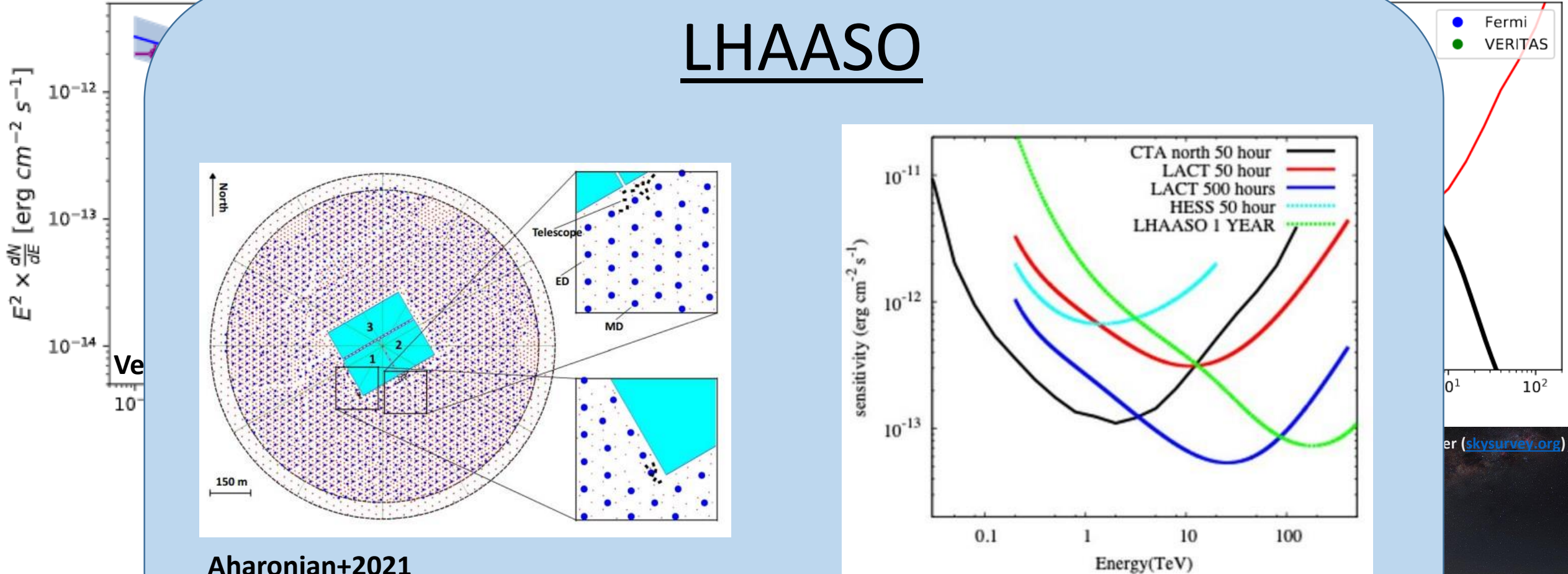


Credit: Astri/Inaf



Upcoming gamma-ray observations

LHAASO



Aharonian+2021

Li+2023 (ICRC2023)666

Outline

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 - Starburst-driven winds
- Multi-messenger diffuse flux



Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

Powering a starburst wind

Star formation rate $\rightarrow SFR = 10 SFR_1 M_{\odot} yr^{-1}$

Powering a starburst wind

Star formation rate $\rightarrow SFR = 10 SFR_1 M_{\odot} yr^{-1}$

Supernova rate $\rightarrow \mathcal{R}_{SN} = 10^{-2} r_2 SFR = 10^{-1} r_2 SFR_1 yr^{-1}$

Powering a starburst wind

Star formation rate $\rightarrow SFR = 10 SFR_1 M_{\odot} yr^{-1}$

Supernova rate $\rightarrow \mathcal{R}_{SN} = 10^{-2} r_2 SFR = 10^{-1} r_2 SFR_1 yr^{-1}$

SN power $\rightarrow \dot{E}_{SN} = \mathcal{R}_{SN} \mathcal{E}_{SN} = 3.2 \cdot 10^{42} r_2 SFR_1 \mathcal{E}_{SN,51} erg s^{-1}$

Powering a starburst wind

$$\text{SN power} \rightarrow \dot{E}_{SN} = \mathcal{R}_{SN} \mathcal{E}_{SN} = 3.2 \cdot 10^{42} r_2 SFR_1 \mathcal{E}_{SN,51} \text{ erg s}^{-1}$$

$$\text{Mass loss rate} \rightarrow \dot{M} = \beta SFR = 1 \beta_{-1} SFR_1 M_{\odot} \text{ yr}^{-1}$$

Powering a starburst wind

$$\text{SN power} \rightarrow \dot{E}_{SN} = \mathcal{R}_{SN} \mathcal{E}_{SN} = 3.2 \cdot 10^{42} r_2 SFR_1 \mathcal{E}_{SN,51} \text{ erg s}^{-1}$$

$$\text{Mass loss rate} \rightarrow \dot{M} = \beta SFR = 1 \beta_{-1} SFR_1 M_{\odot} \text{ yr}^{-1}$$

$$\text{Typical wind speed} \rightarrow V_w = 3000 V_{w,3000} \text{ km s}^{-1}$$

Powering a starburst wind

$$\text{SN power} \rightarrow \dot{E}_{SN} = \mathcal{R}_{SN} \mathcal{E}_{SN} = 3.2 \cdot 10^{42} r_2 SFR_1 \mathcal{E}_{SN,51} \text{ erg s}^{-1}$$

$$\text{Wind power} \rightarrow \dot{E}_w = \frac{1}{2} \dot{M} V_w^2 = 2.9 \cdot 10^{42} \beta_{-1} SFR_1 V_{w,3000}^2 \text{ erg s}^{-1}$$

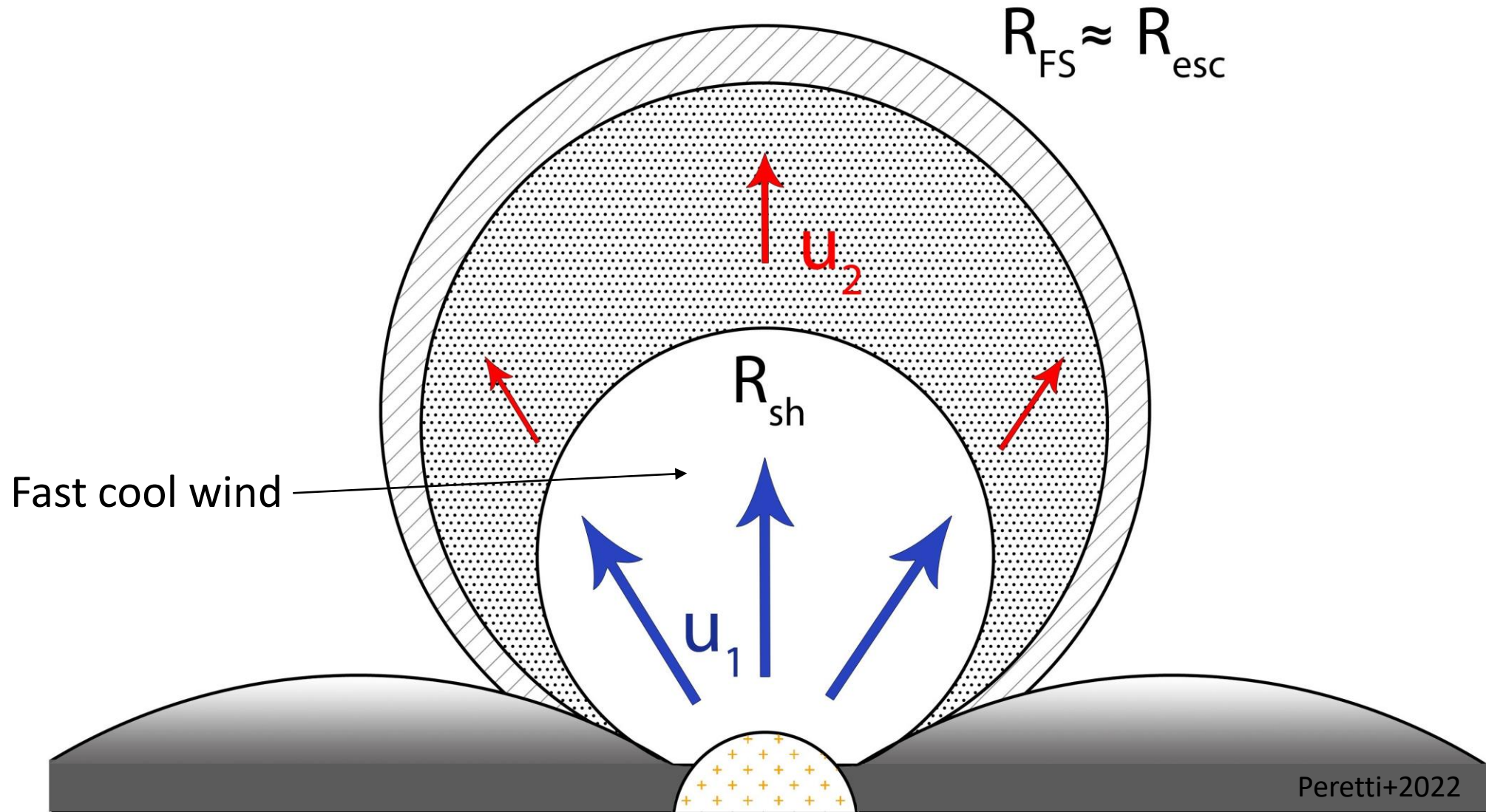
Powering a starburst wind

$$\text{SN power} \rightarrow \dot{E}_{SN} = \mathcal{R}_{SN} \mathcal{E}_{SN} = 3.2 \cdot 10^{42} r_2 SFR_1 \mathcal{E}_{SN,51} \text{ erg s}^{-1}$$

$$\dot{E}_w = \alpha \dot{E}_{SN}$$

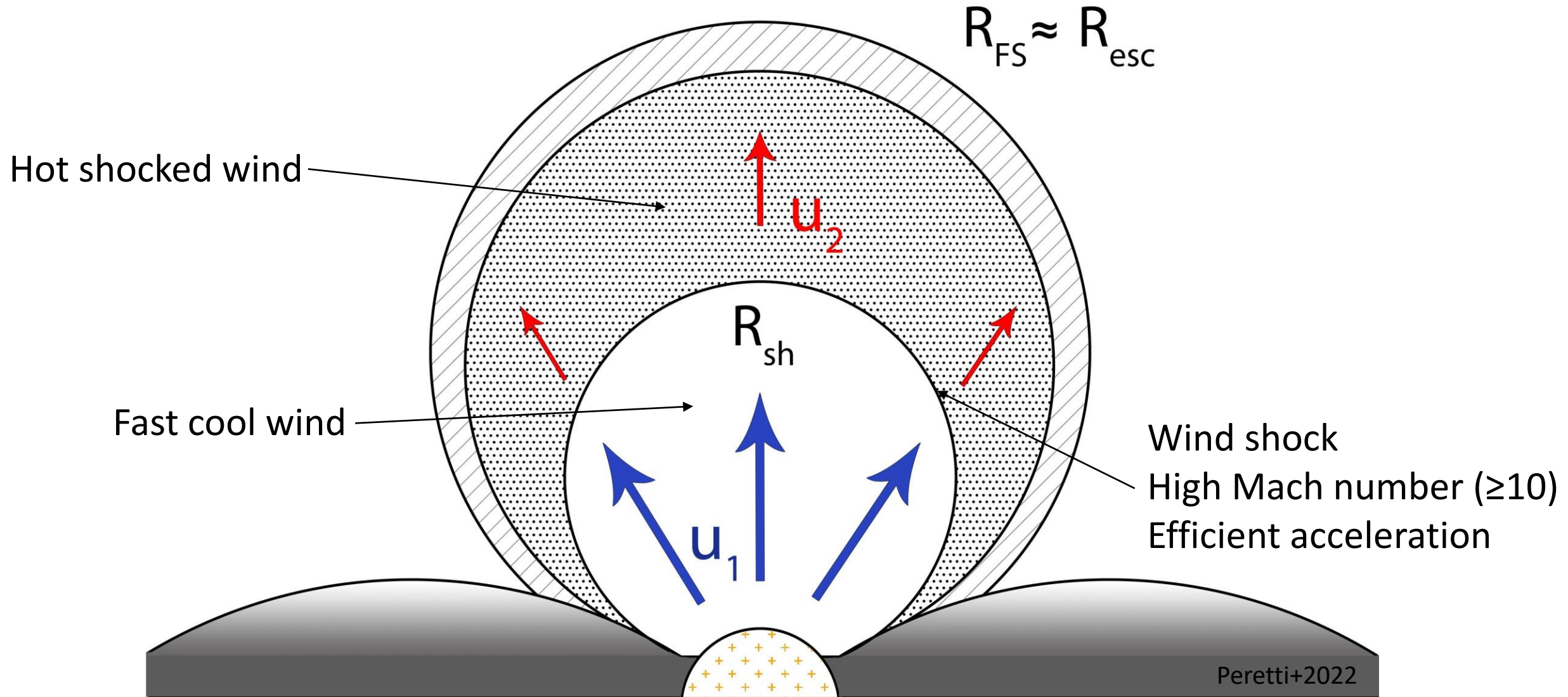
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Acceleration and transport in starburst winds

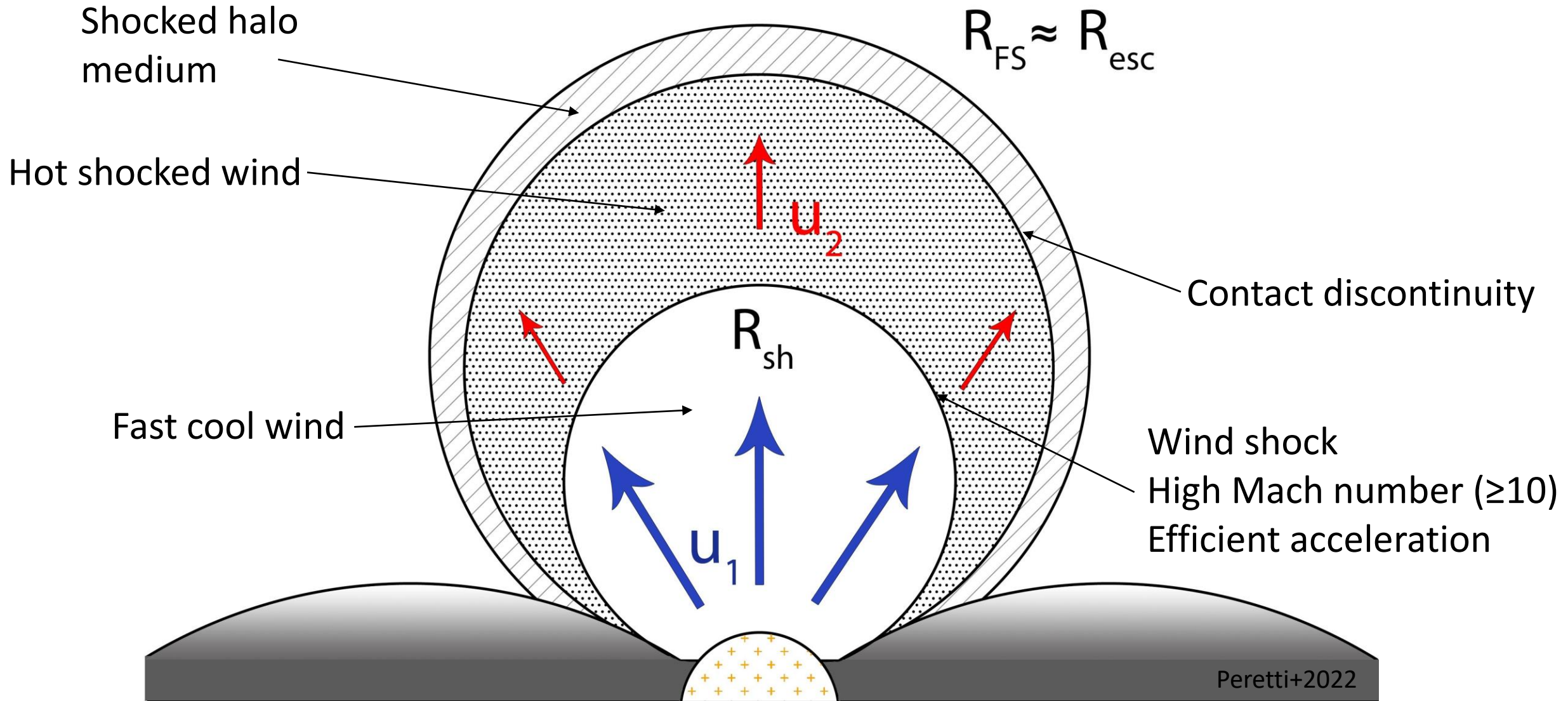


Peretti+2022

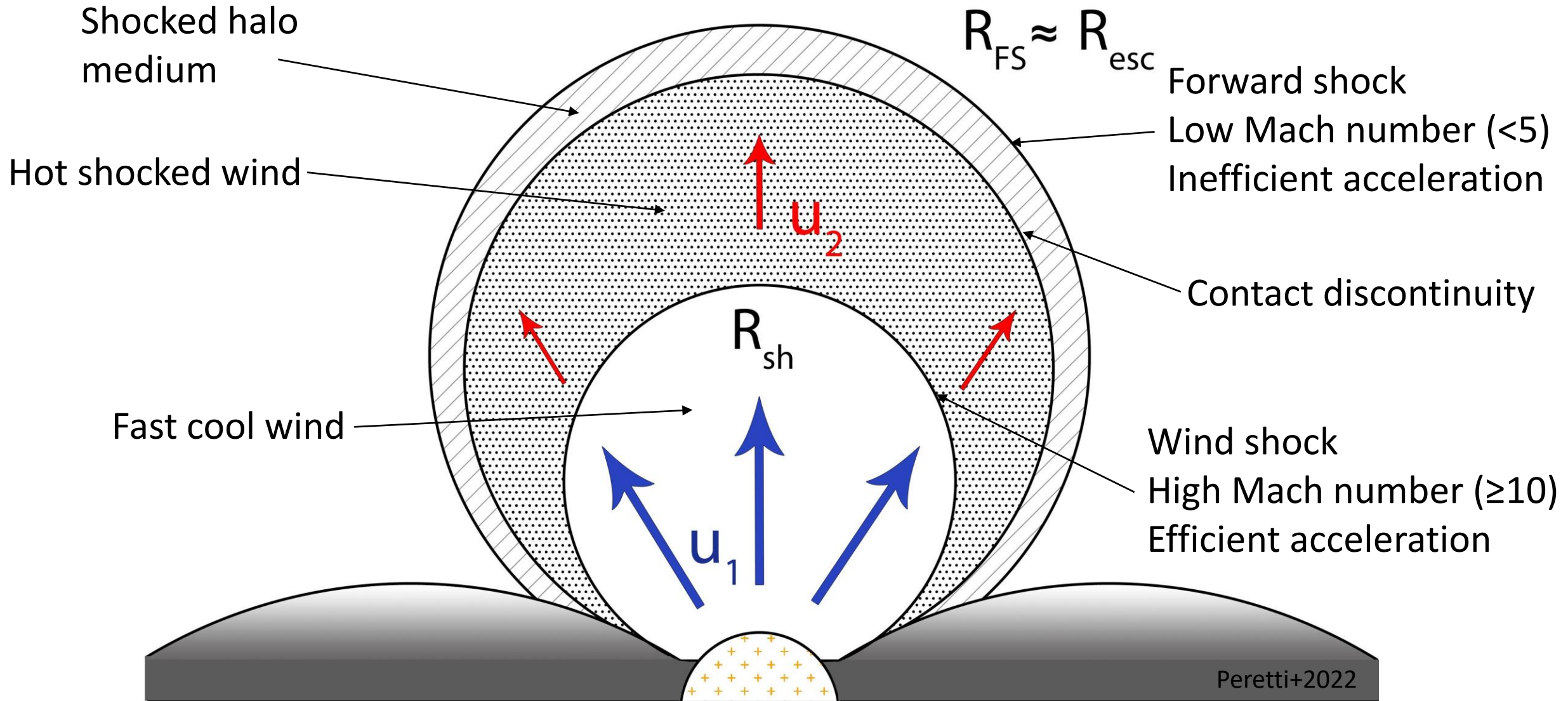
Acceleration and transport in starburst winds



Acceleration and transport in starburst winds

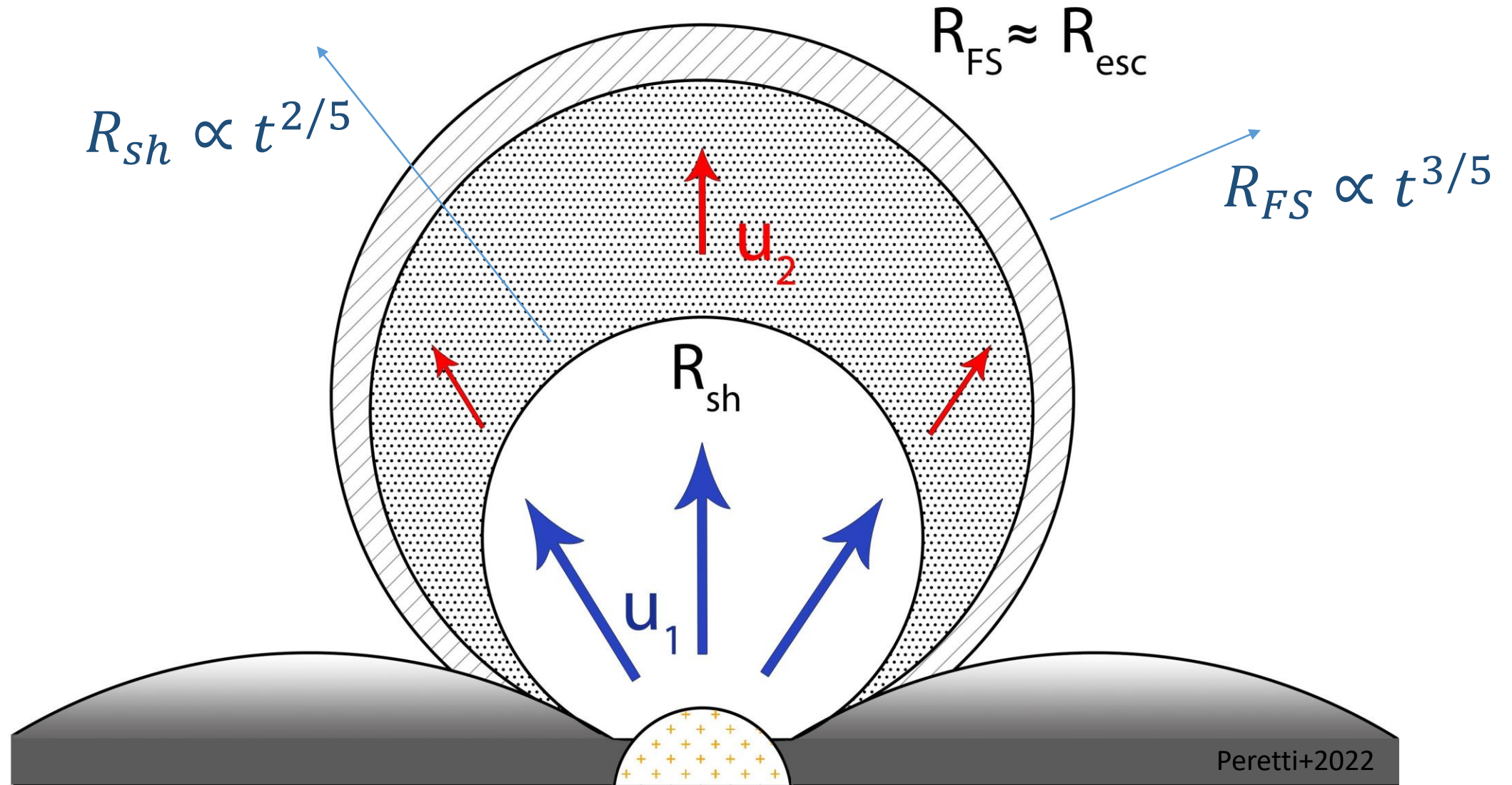


Acceleration and transport in starburst winds



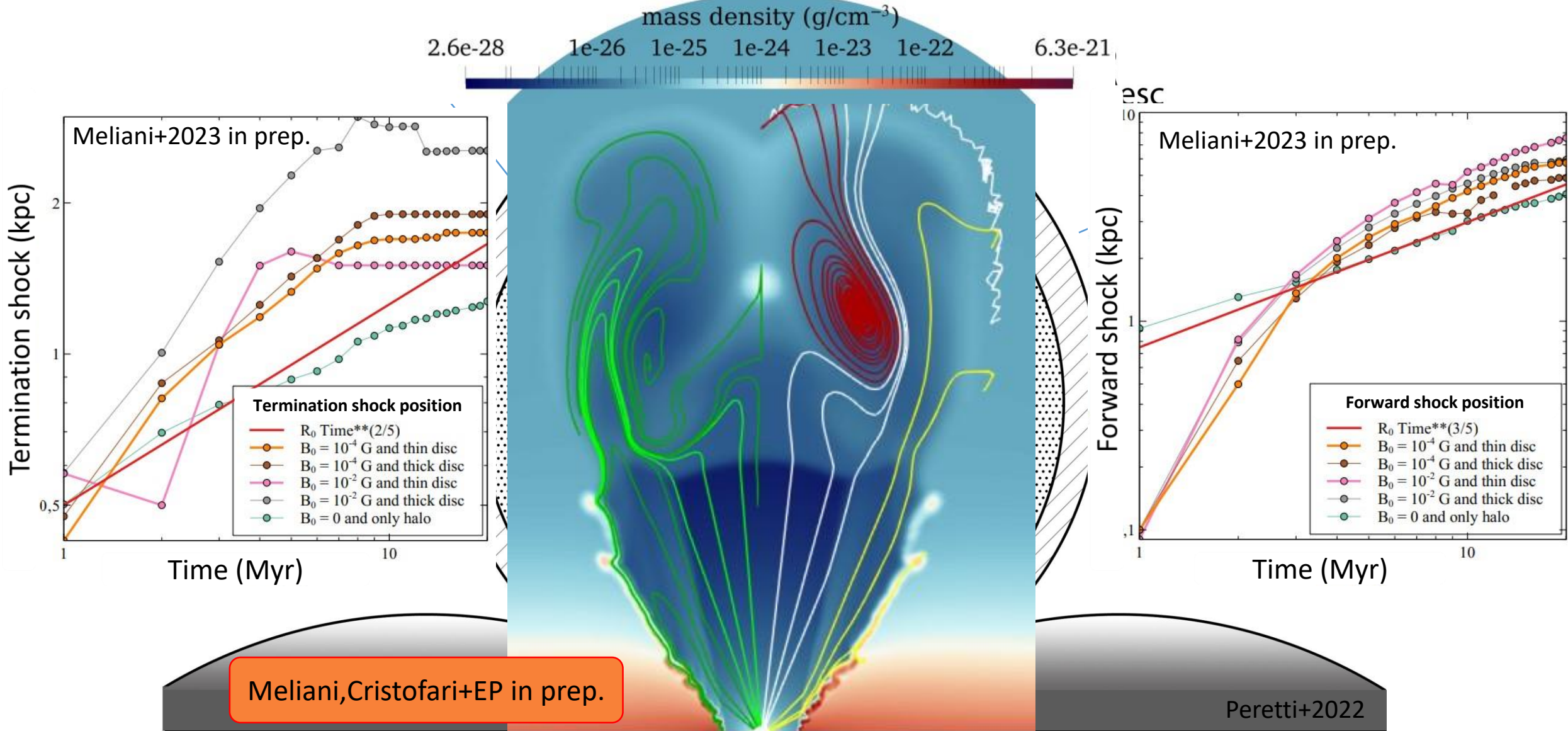
Peretti+2022

Acceleration and transport in starburst winds



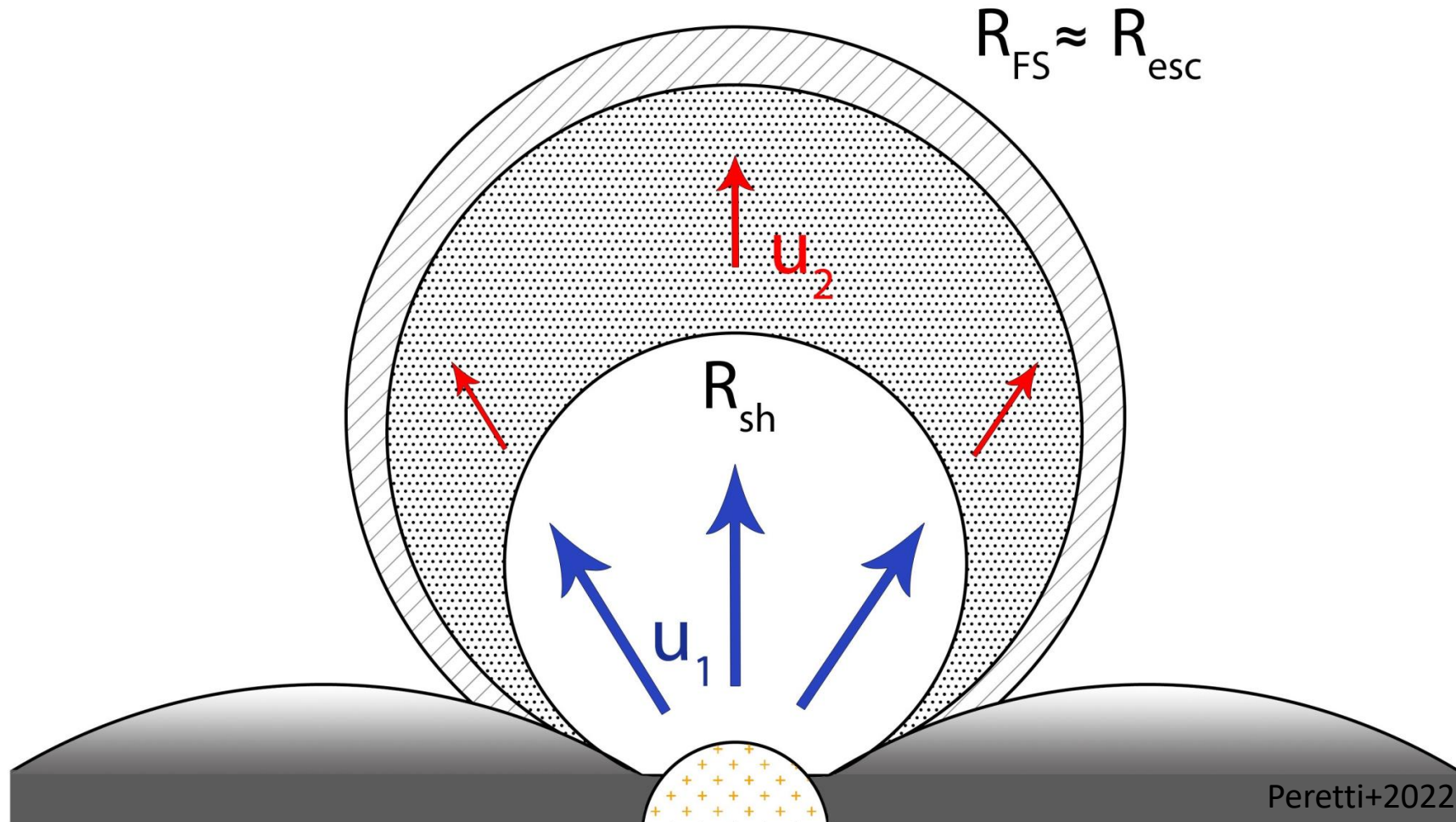
Peretti+2022

Acceleration and transport in starburst winds



Transport model

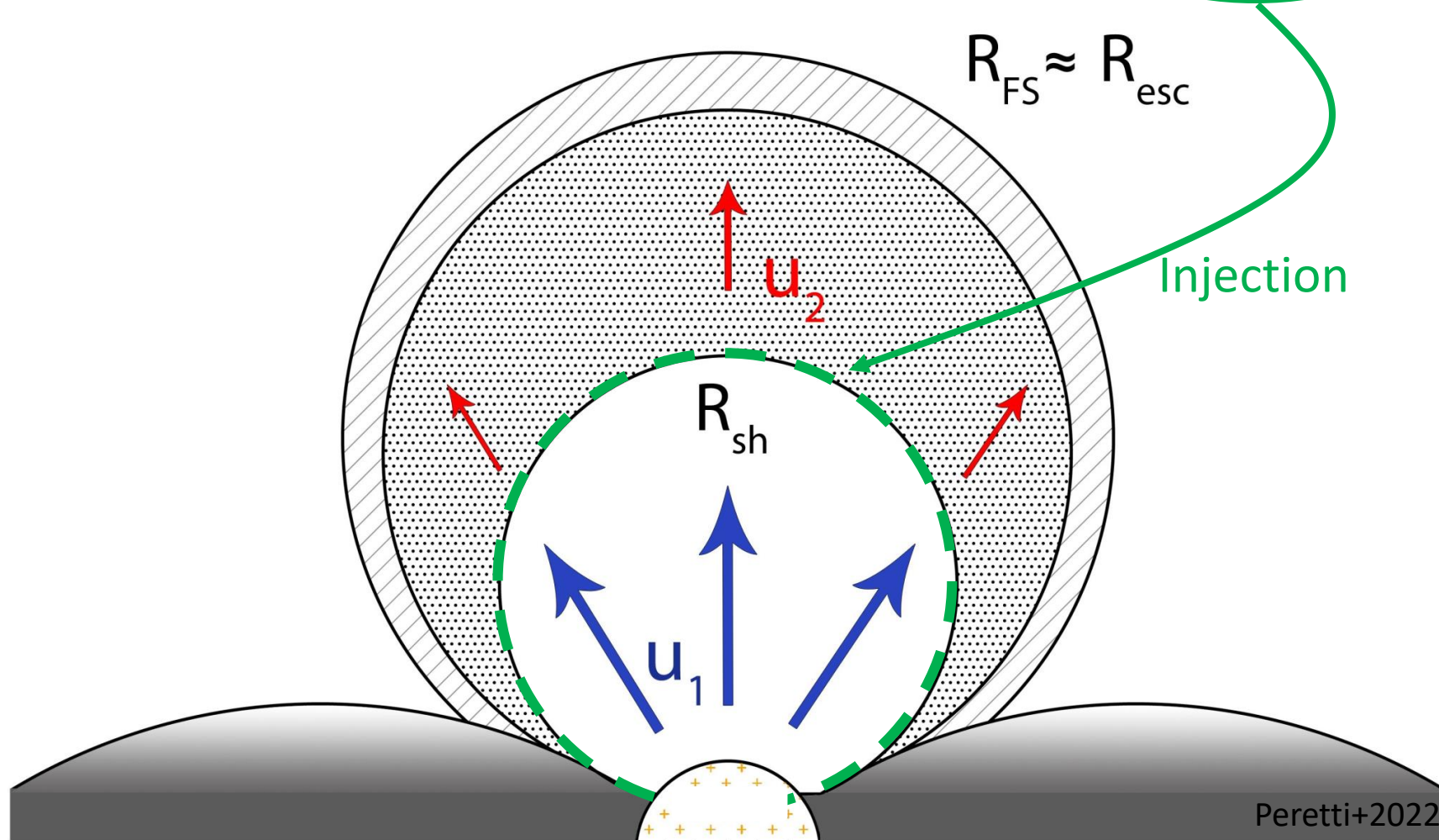
$$r^2 u(r) \partial_r f = \partial_r [r^2 D(r, p) \partial_r f] + \frac{1}{3} \partial_r [r^2 u(r)] p \partial_p f + r^2 Q(r, p) - r^2 \Lambda(r, p)$$



Peretti+2022

Transport model

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

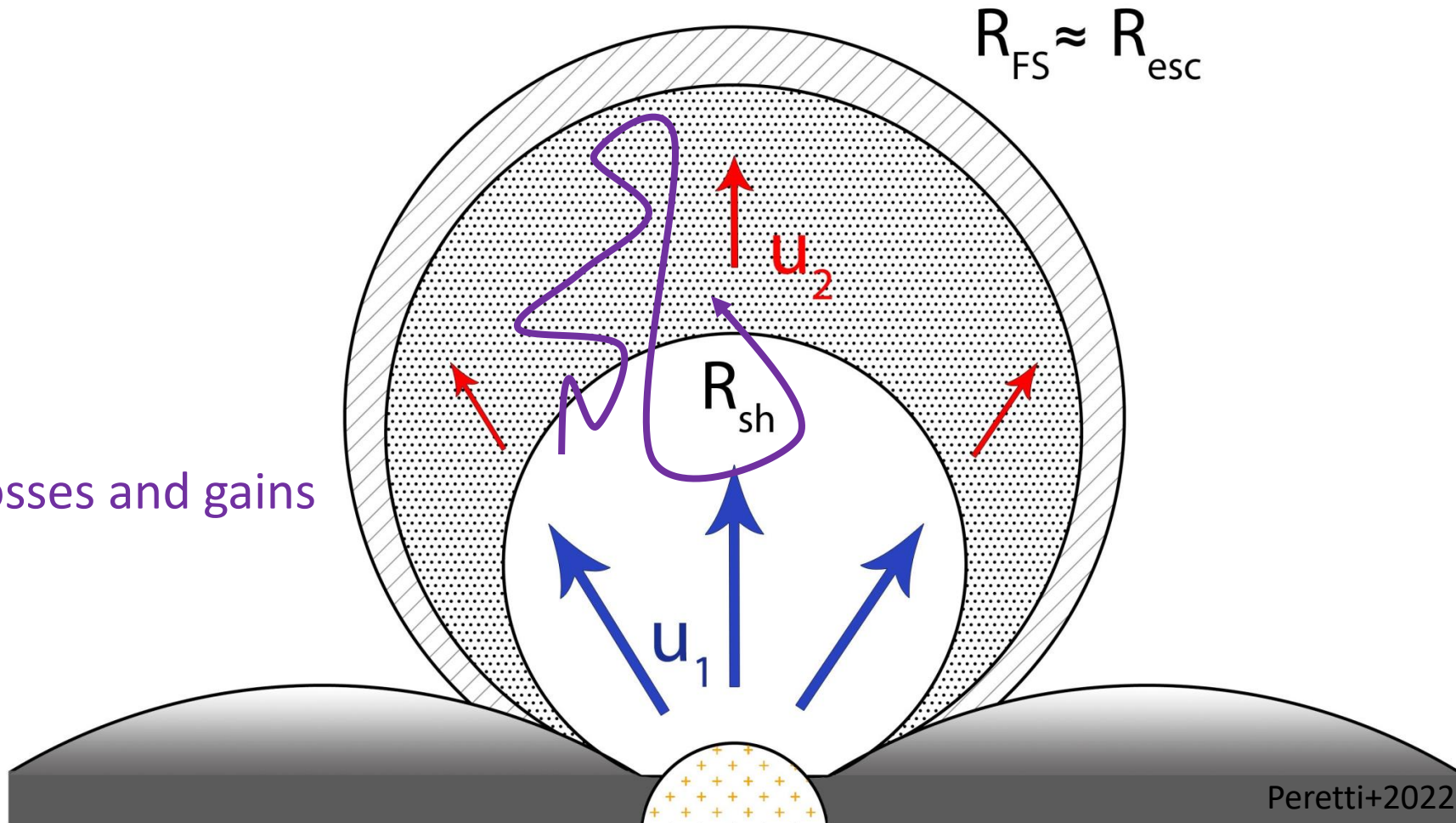


Peretti+2022

Transport model

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

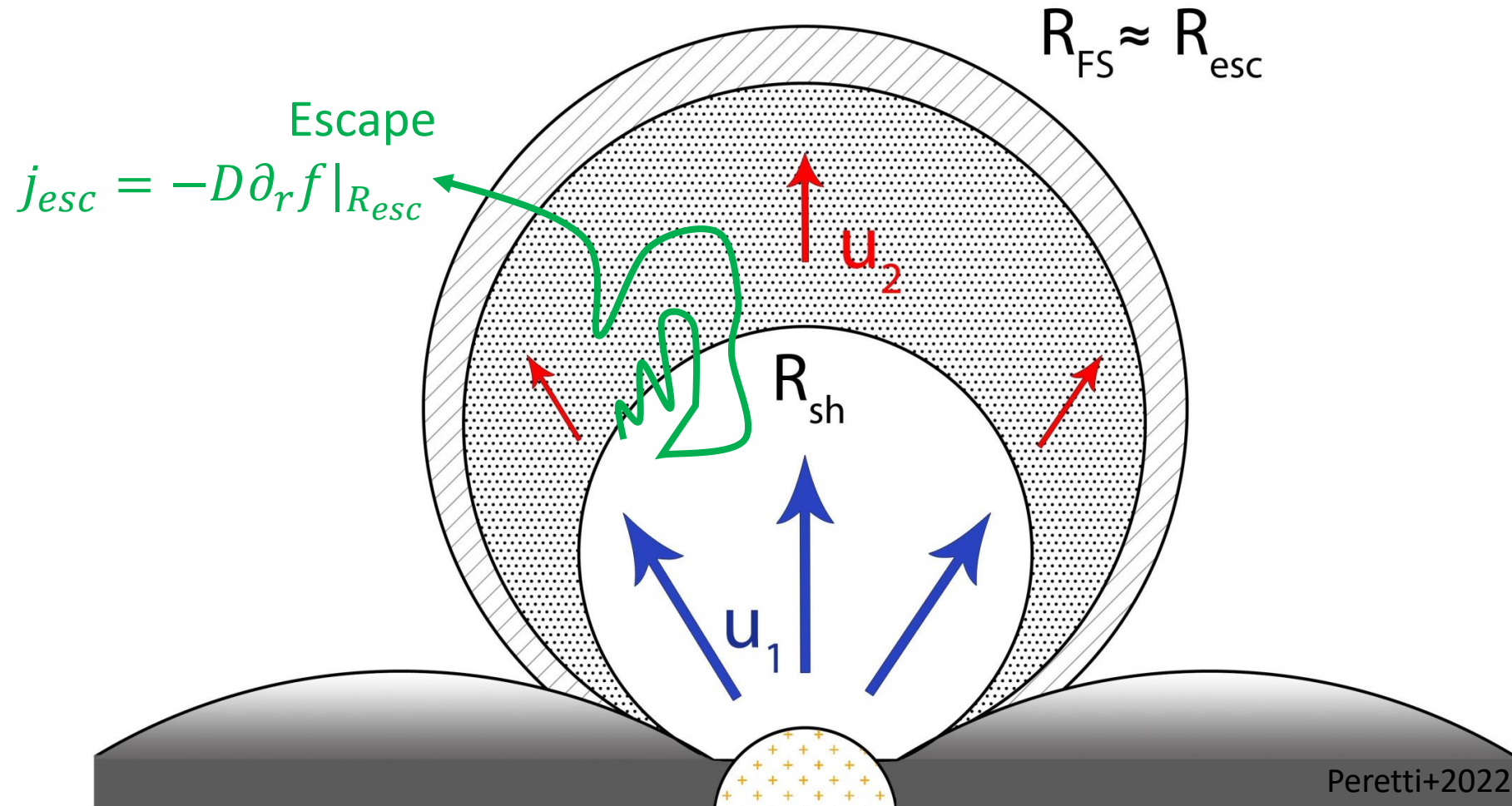
- Advection
- Diffusion
- Adiabatic losses and gains



Peretti+2022

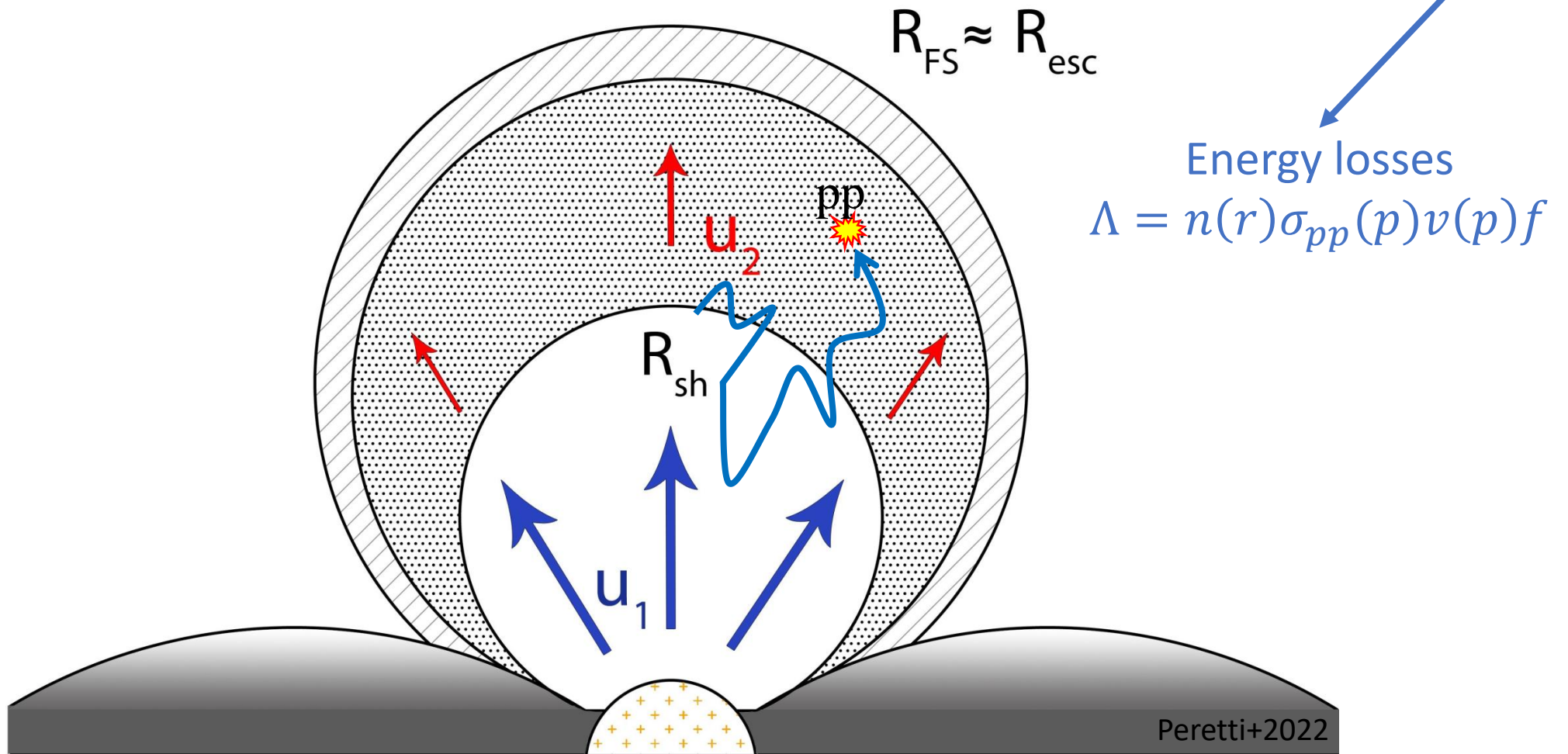
Transport model

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



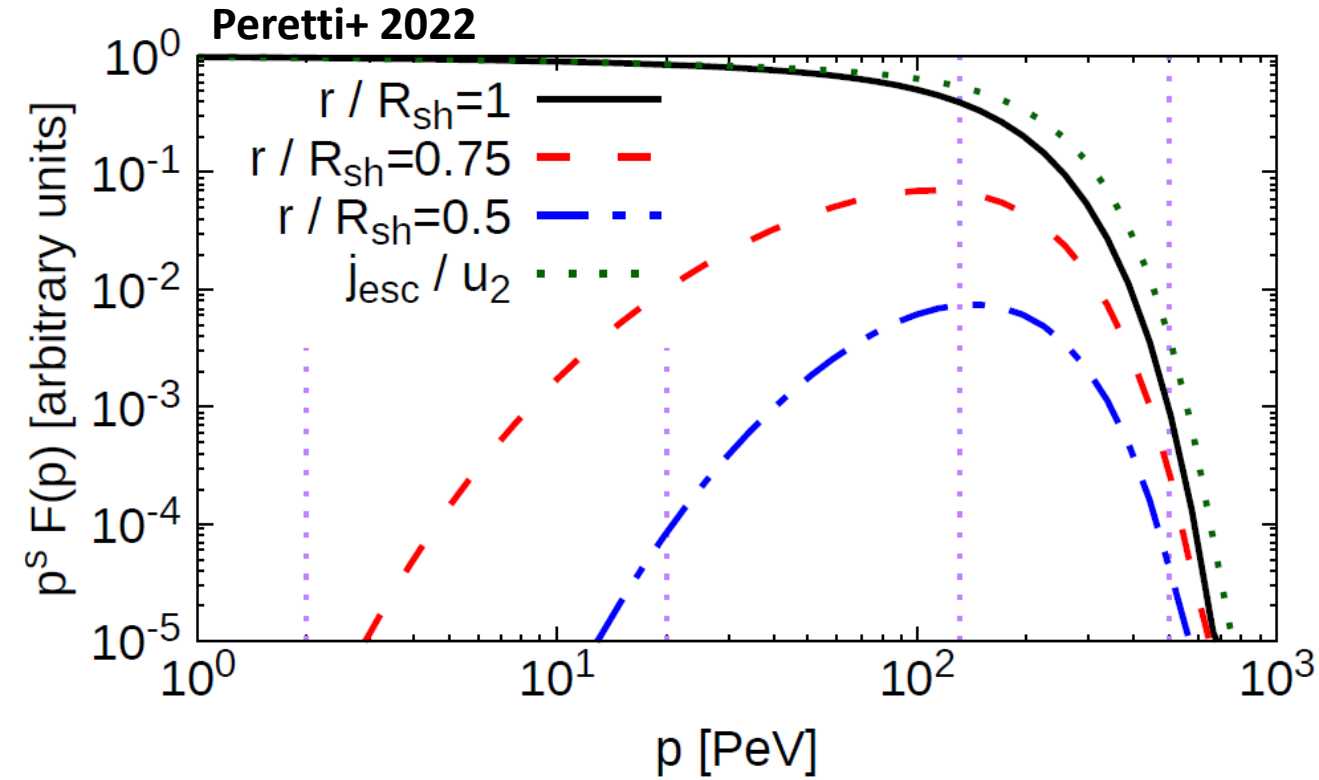
Transport model

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



Peretti+2022

Particles in the system



Parameters

$$\dot{M} = 10 M_{\odot} \text{ yr}^{-1}$$

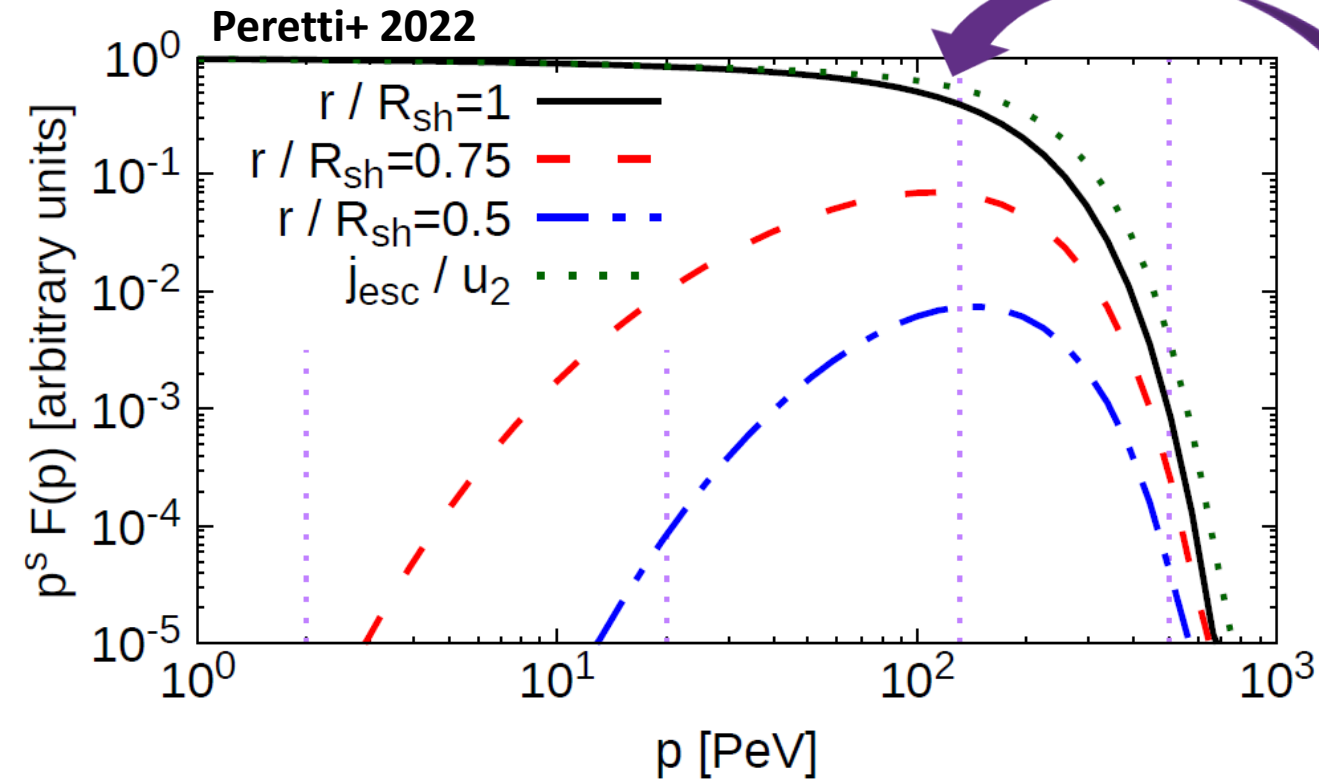
$$V_{\infty} = 3000 \text{ km s}^{-1}$$

$$R_{sh} = 12 \text{ kpc}$$

$$R_{FS} = 55 \text{ kpc}$$

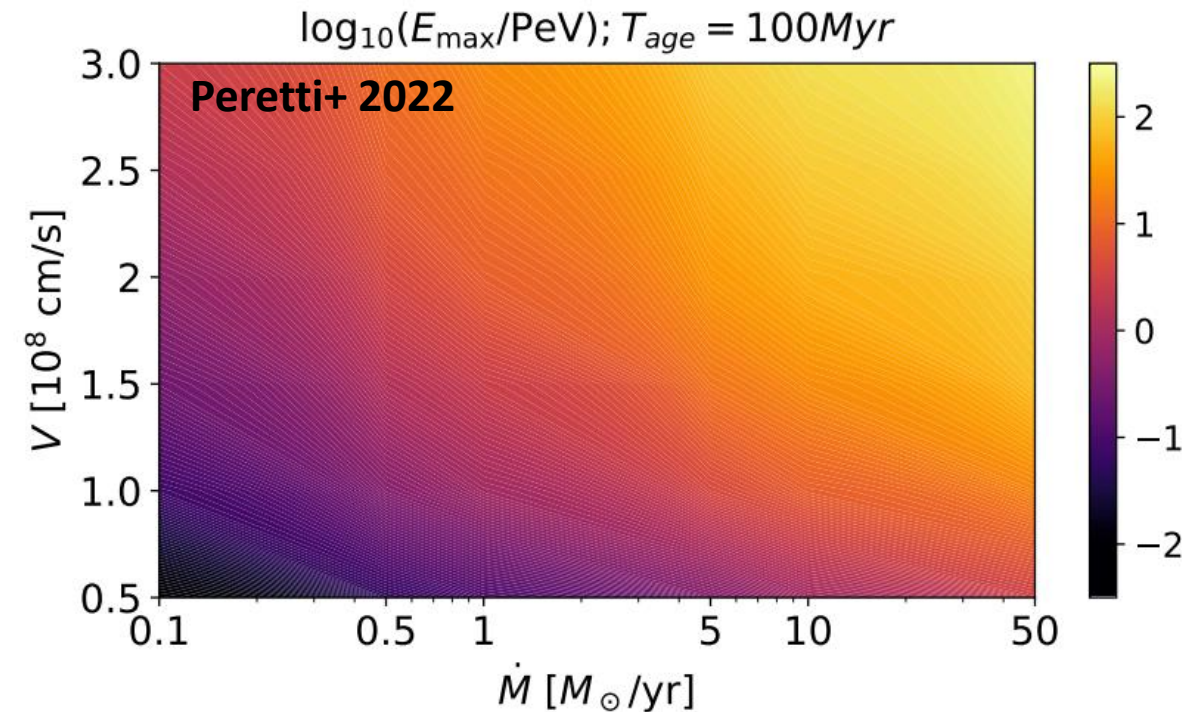
$$f_{sh}(p) \propto p^{-s} e^{-\Gamma_1(p)} e^{-\Gamma_2(p)}$$

Particles in the system

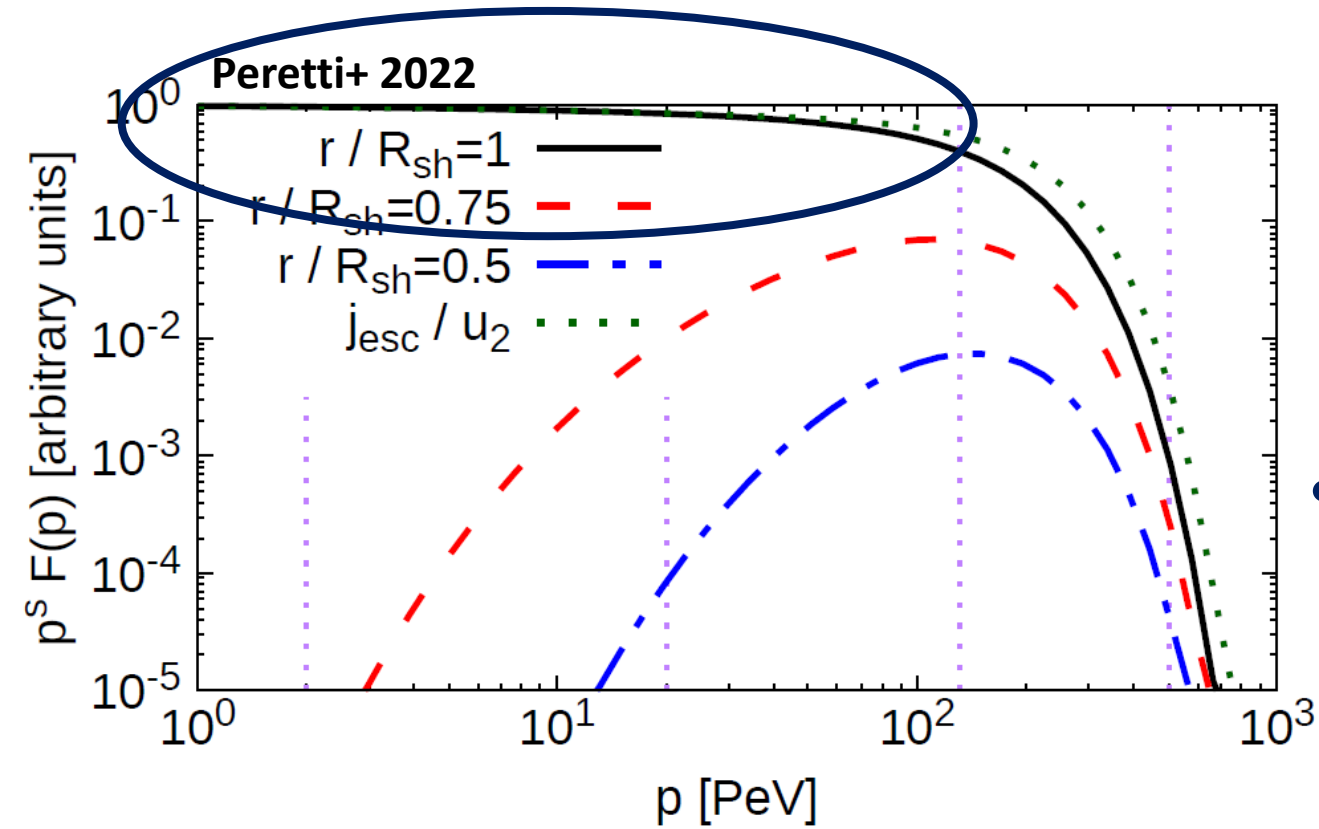


- Maximum Energy $\rightarrow 10^2$ PeV

$$f_{sh}(p) \propto p^{-s} e^{-\Gamma_1(p)} e^{-\Gamma_2(p)}$$



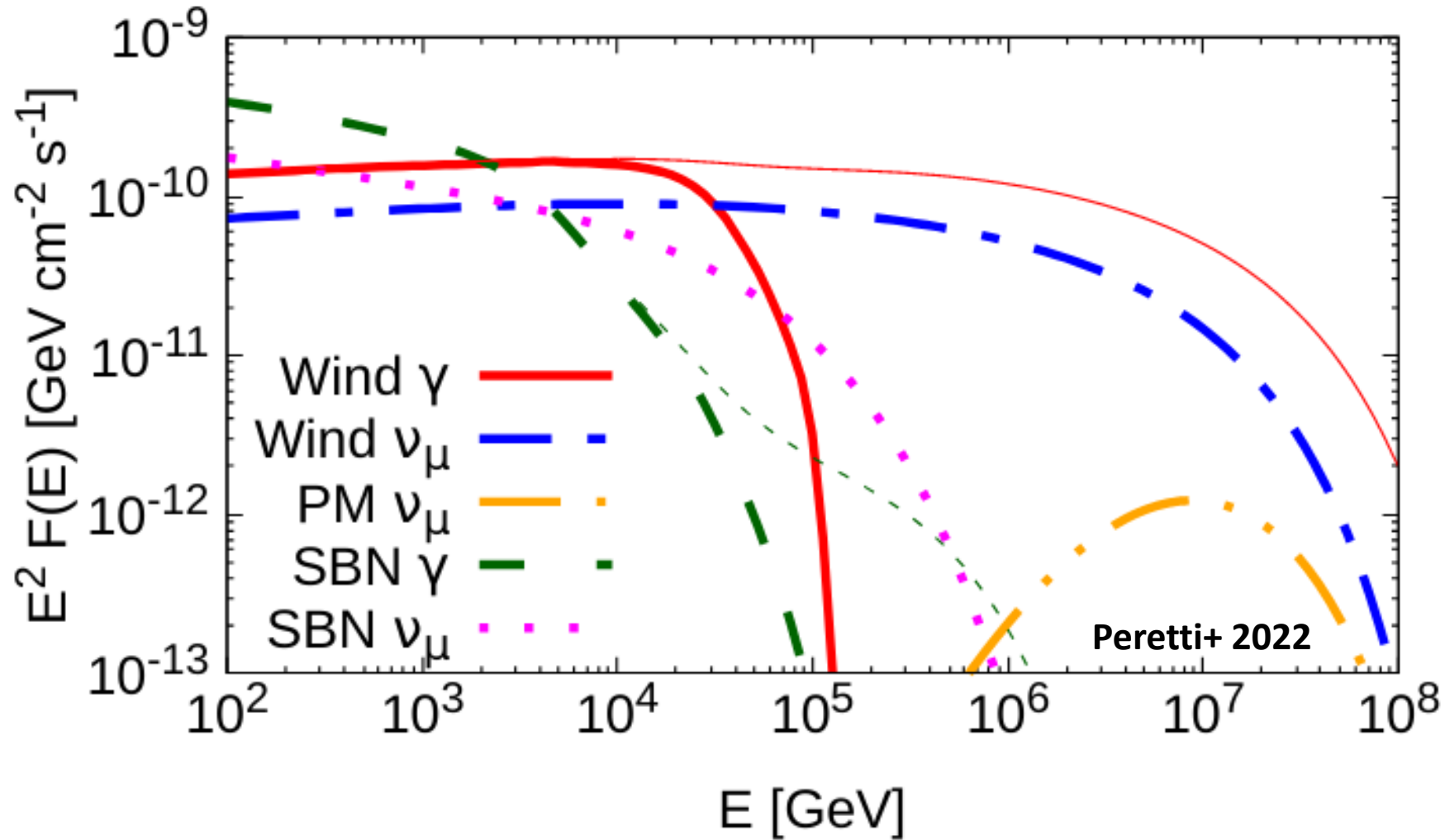
Particles in the system



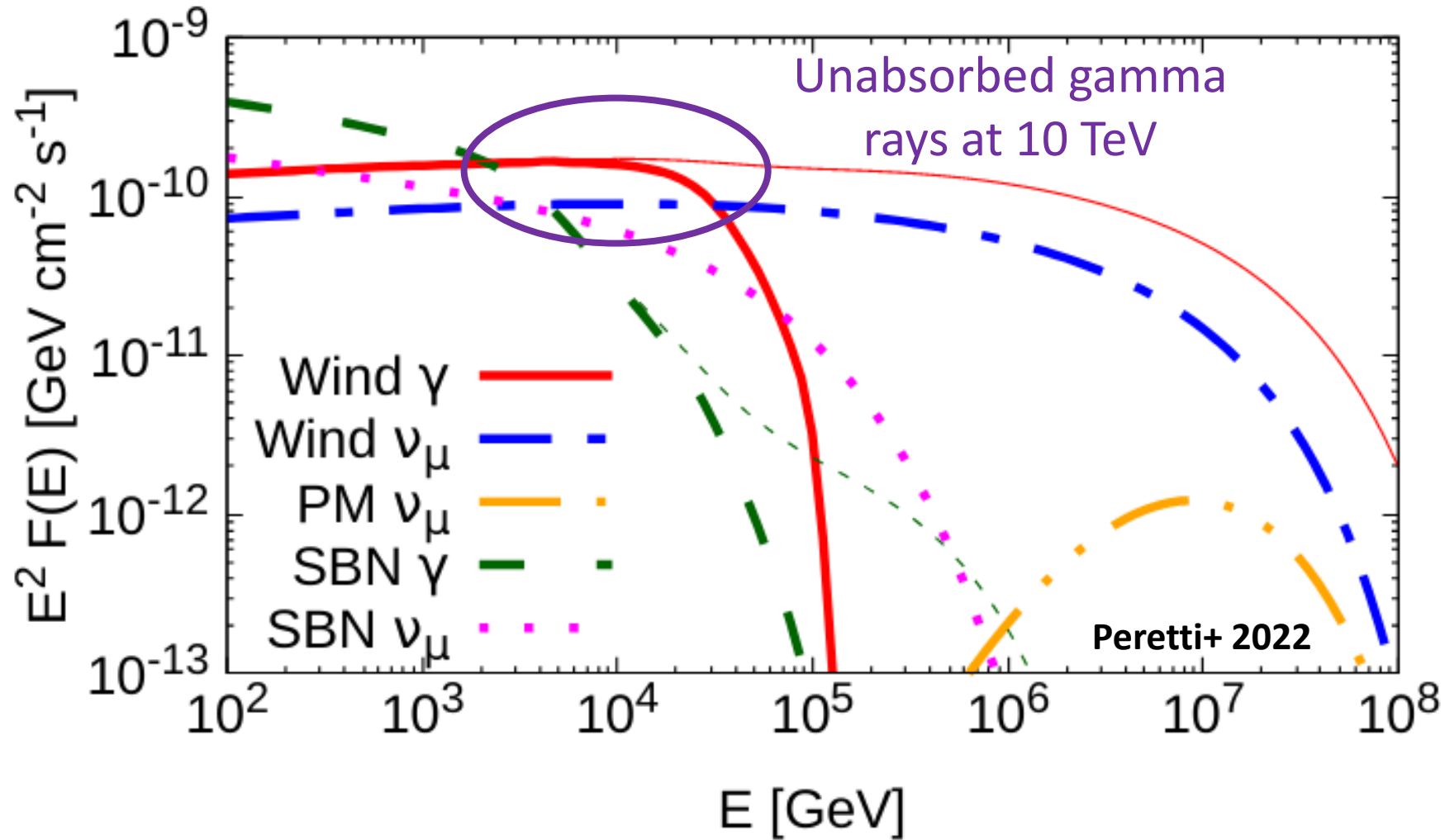
- Maximum Energy $\rightarrow 10^2$ PeV
- Standard DSA valid at low Energy

$$f_{sh}(p) \propto p^{-s} e^{-\Gamma_1(p)} e^{-\Gamma_2(p)}$$

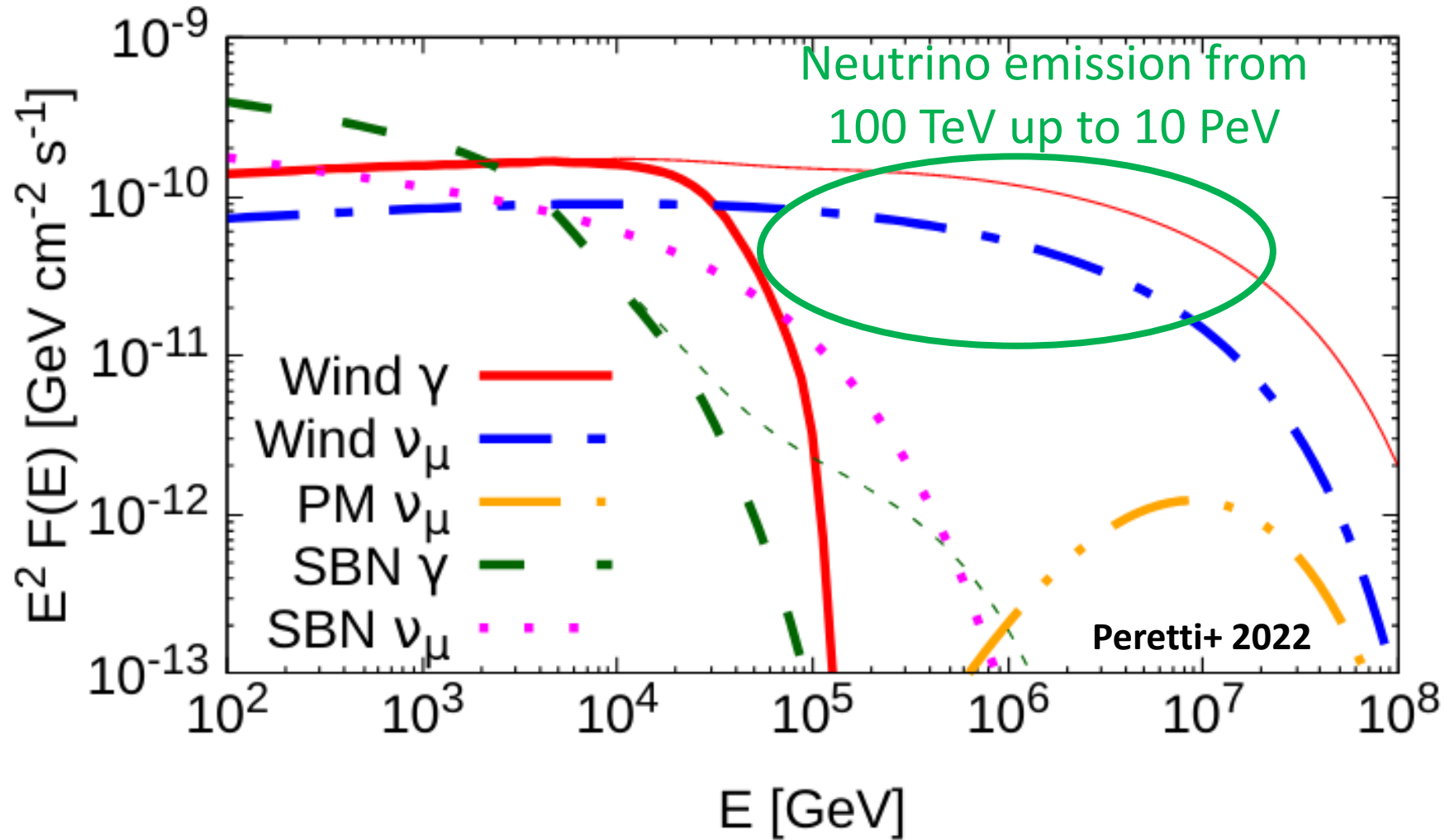
High-Energy SED and Neutrinos



High-Energy SED and Neutrinos



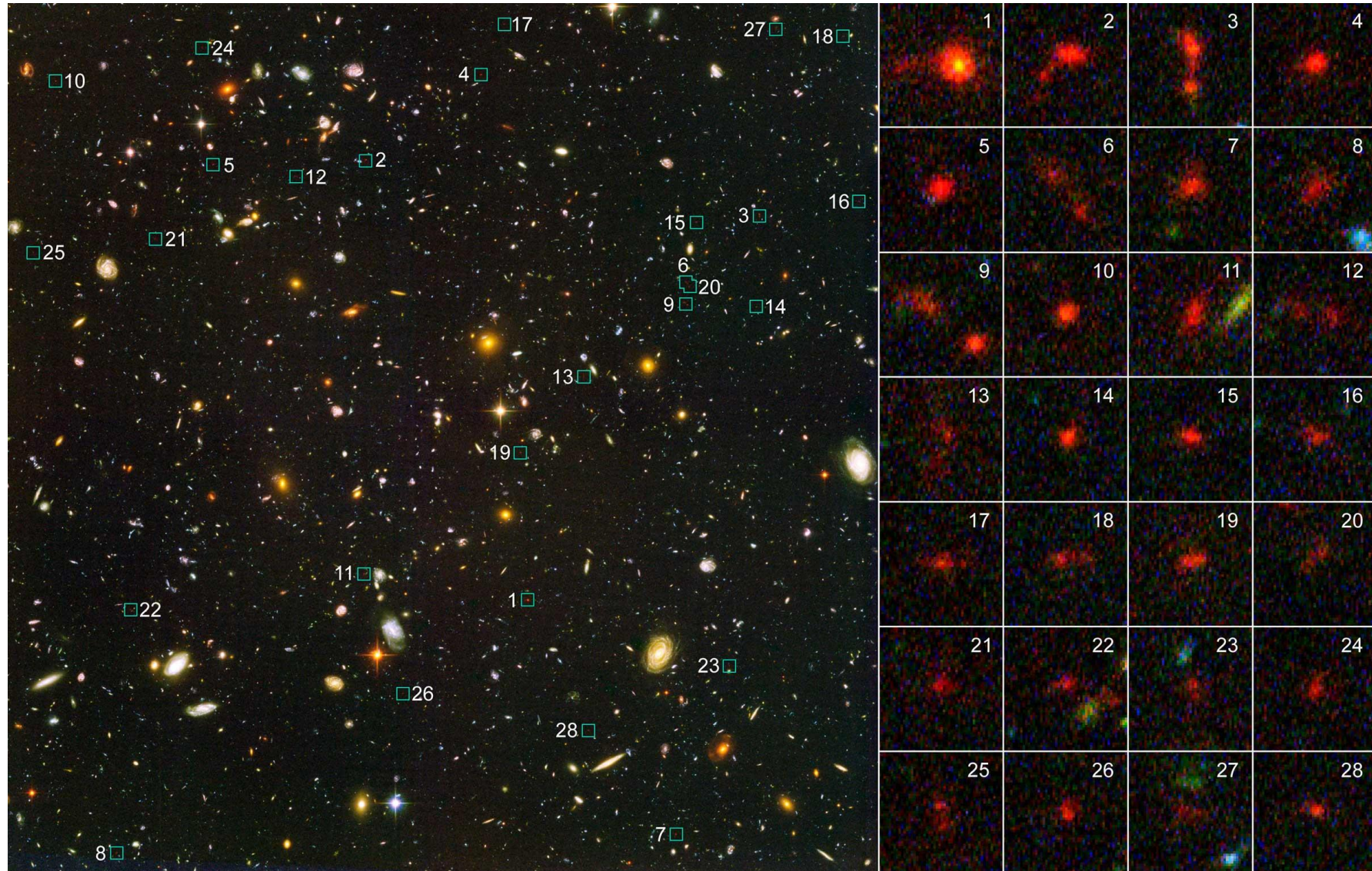
High-Energy SED and Neutrinos



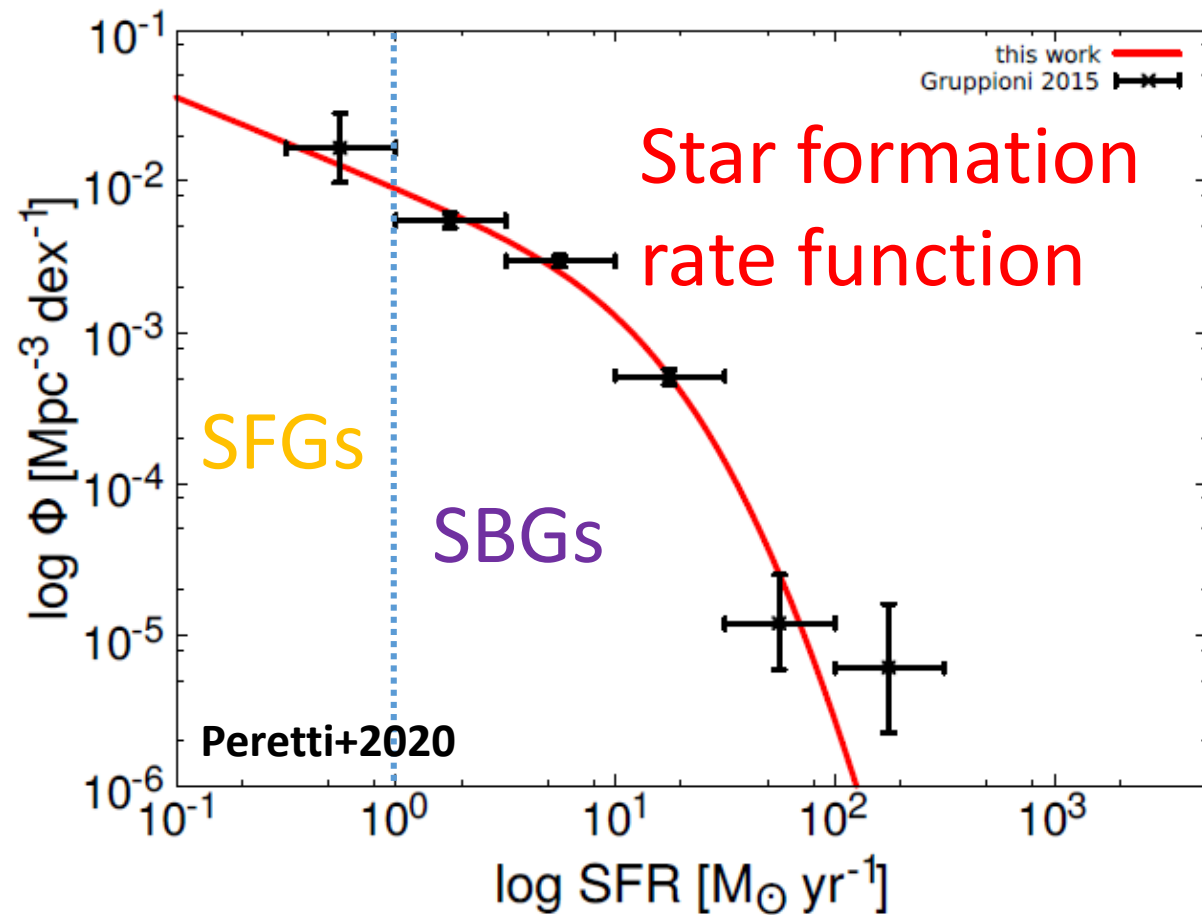
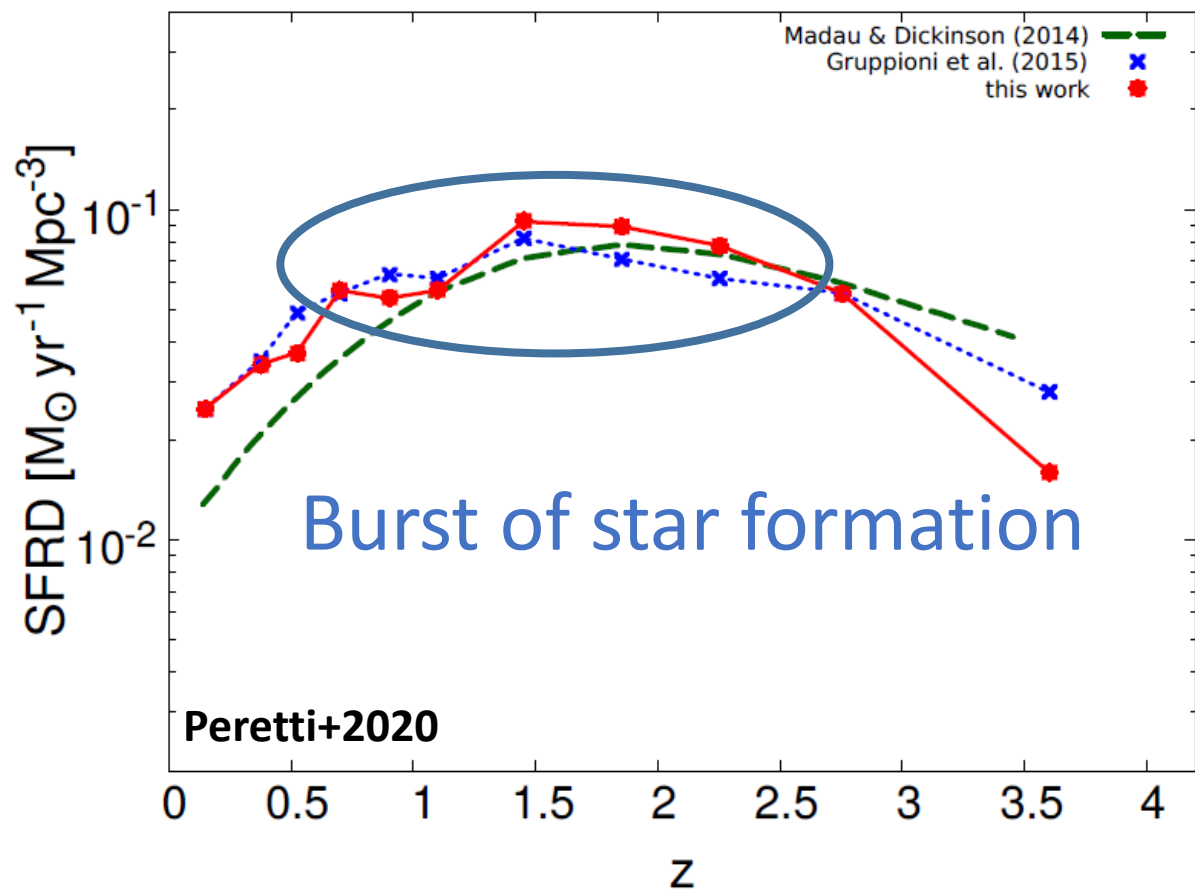
Outline

- Observations of Star-forming galaxies
- Particle Transport in Starburst Nuclei
 - Starburst-driven winds
- Multi-messenger diffuse flux

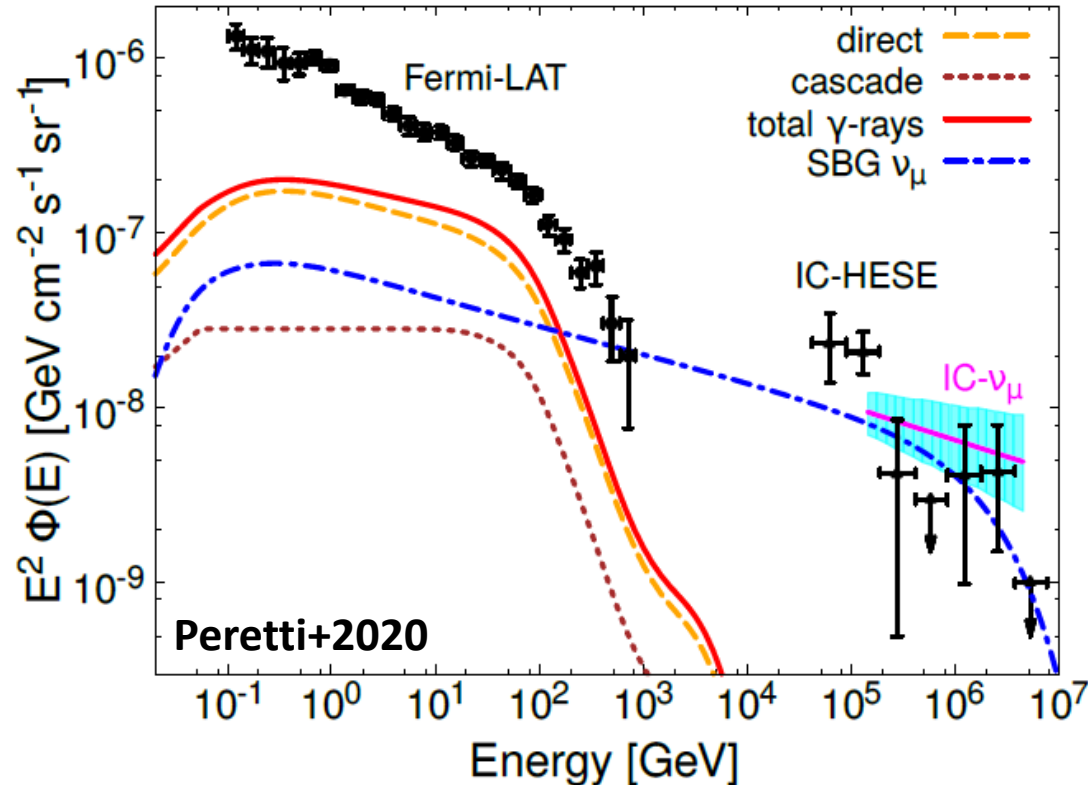
Diffuse emission from starbursts



Starbursts as diffuse sources

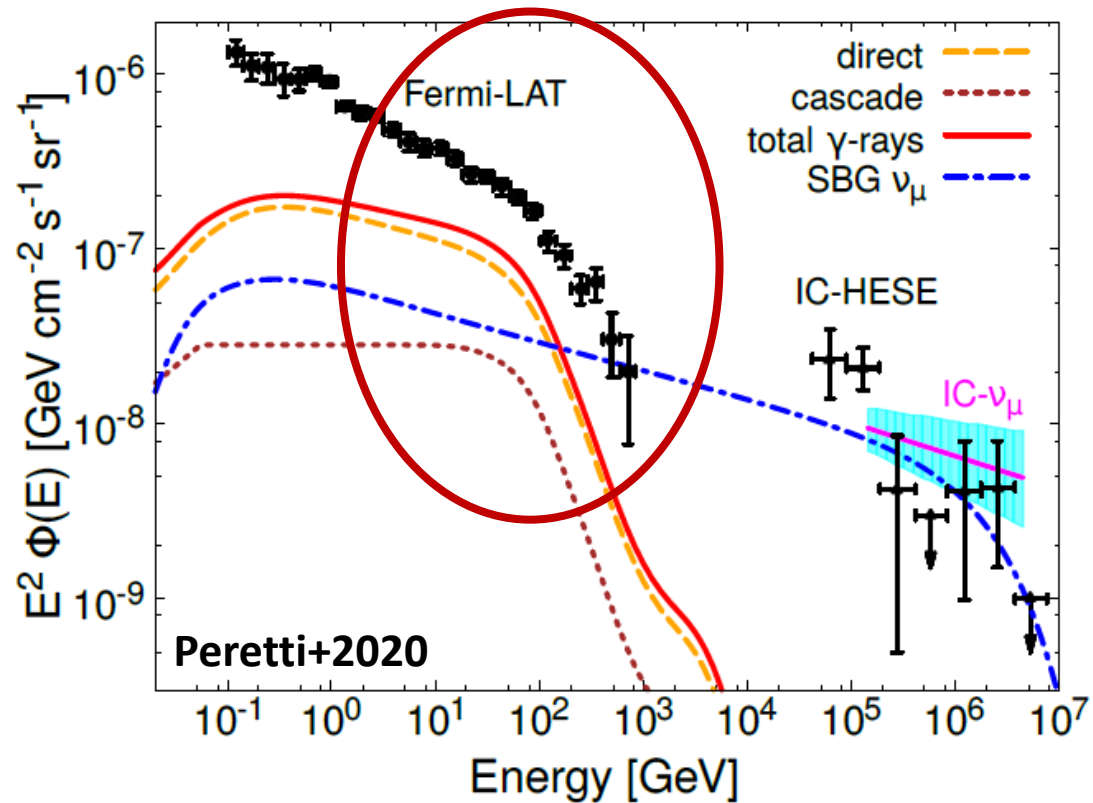


Diffuse emission from Starburst Galaxies



- SBNi only

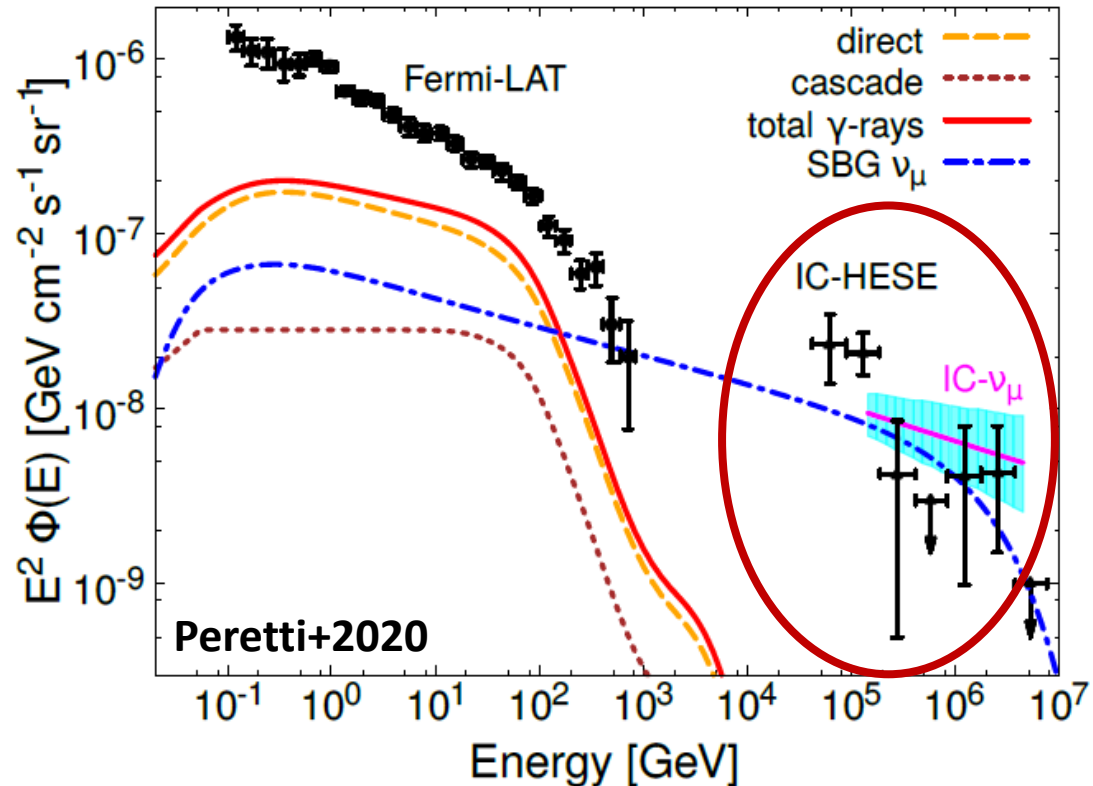
Diffuse emission from Starburst Galaxies



- SBNi only

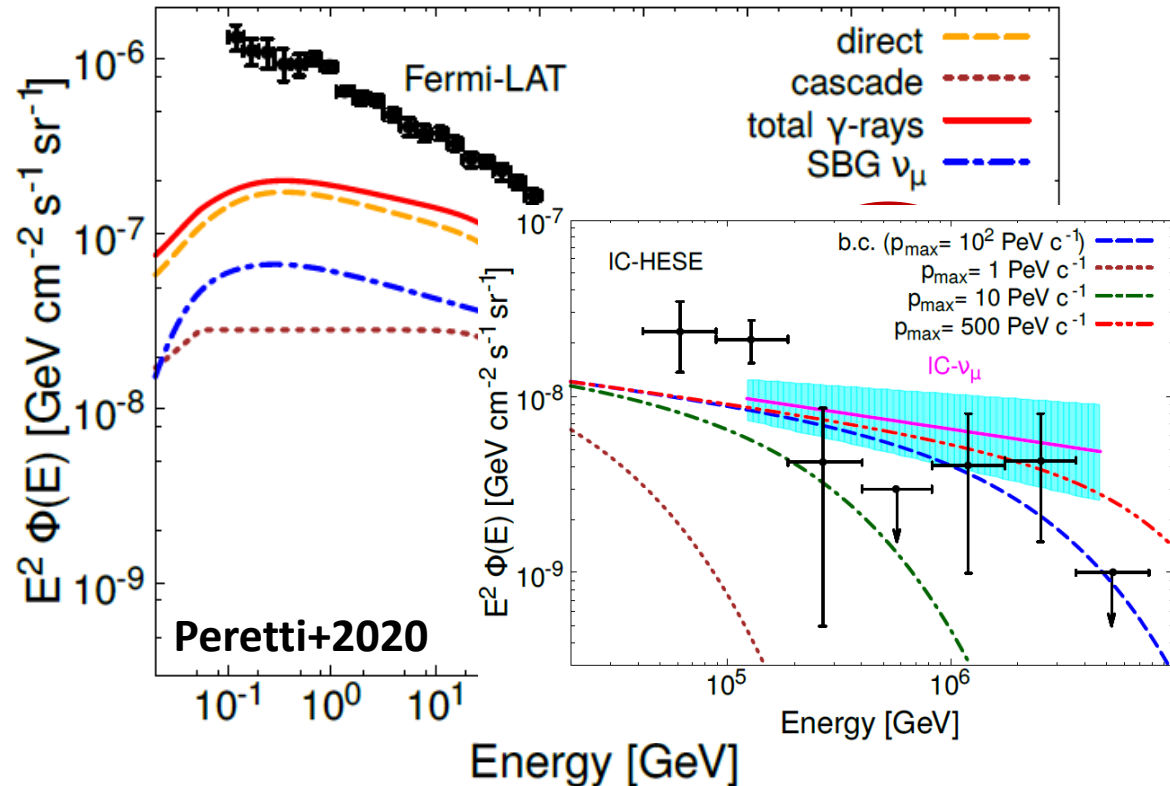
- Sizeable contribution to the diffuse flux observed by Fermi-LAT

Diffuse emission from Starburst Galaxies



- SBNi only
- Sizeable contribution to the diffuse flux observed by Fermi-LAT
- Neutrino flux at the level of IceCube measurement

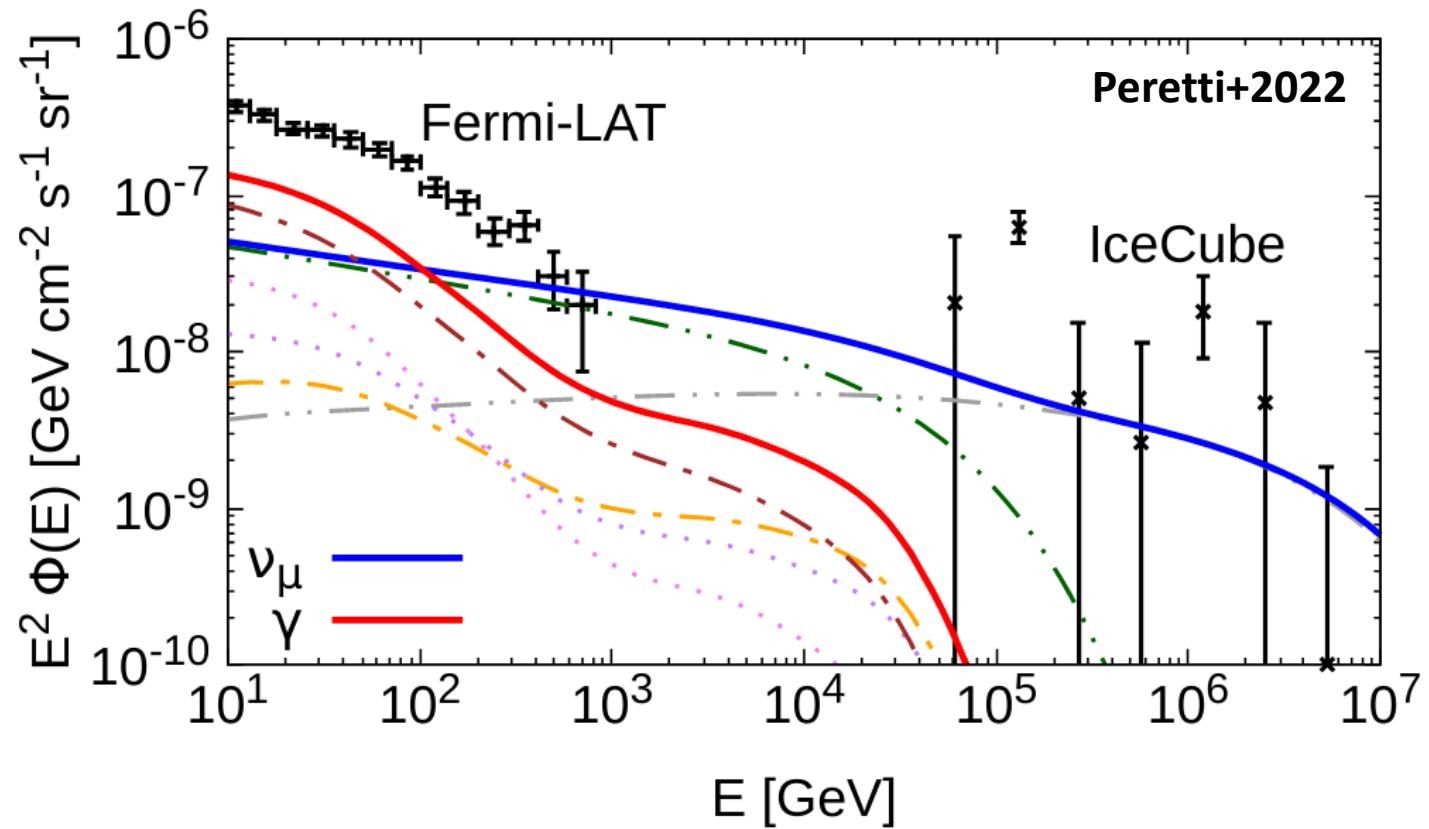
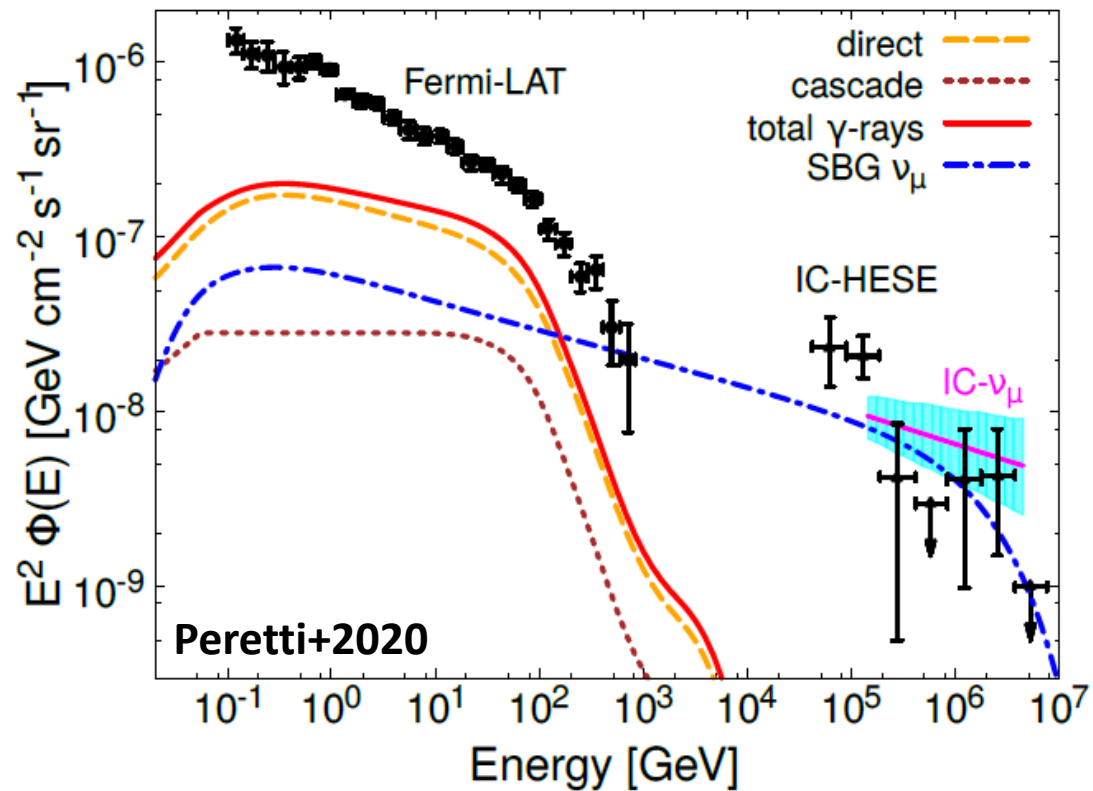
Diffuse emission from Starburst Galaxies



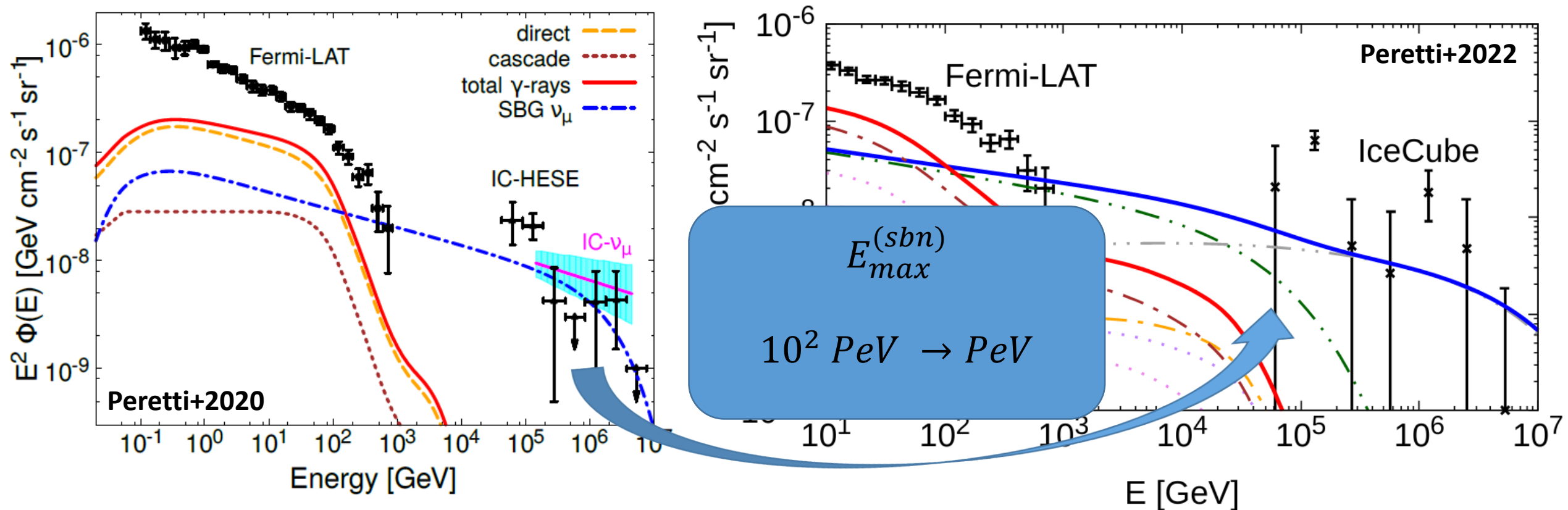
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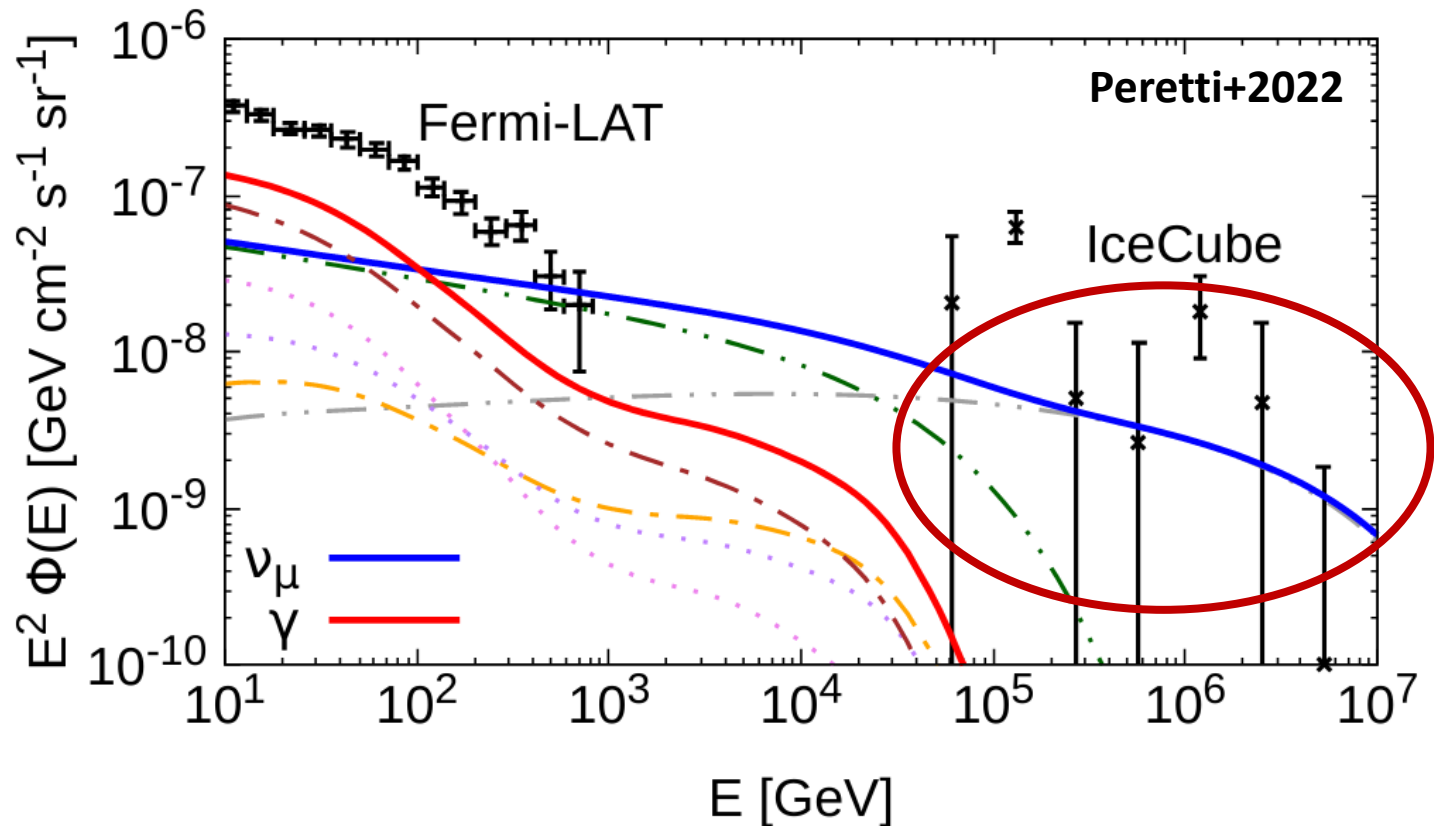
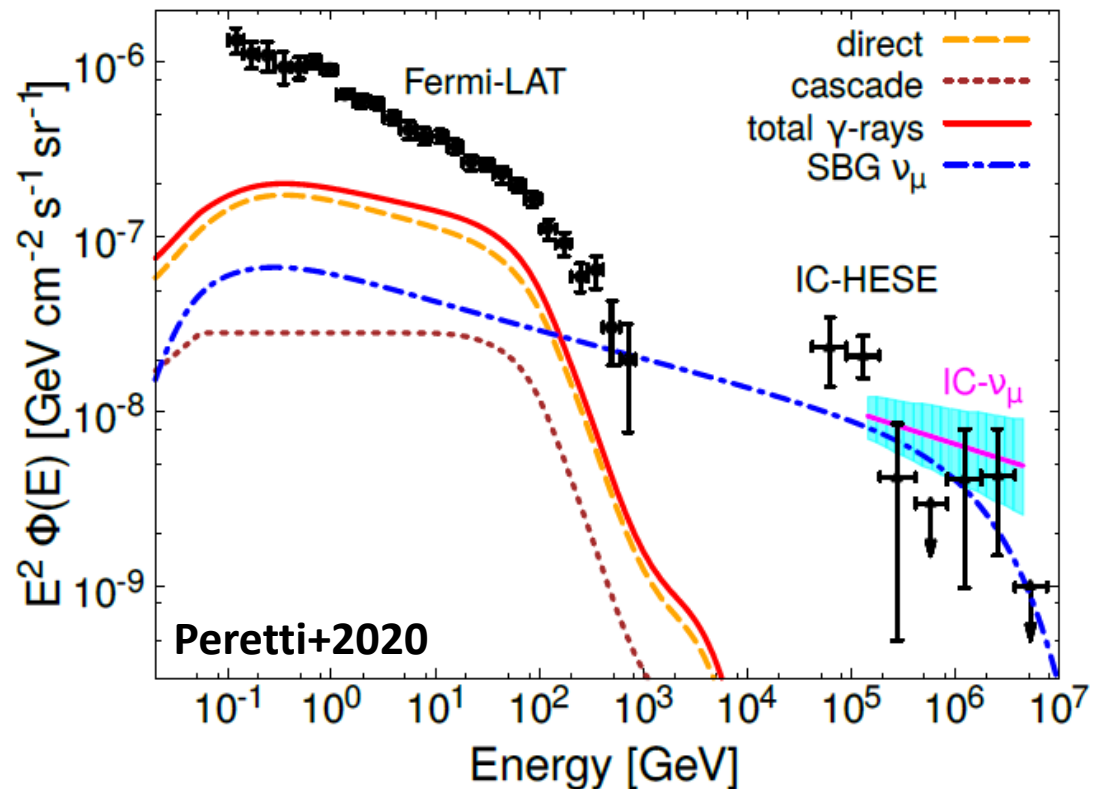
Diffuse emission from Starburst Galaxies



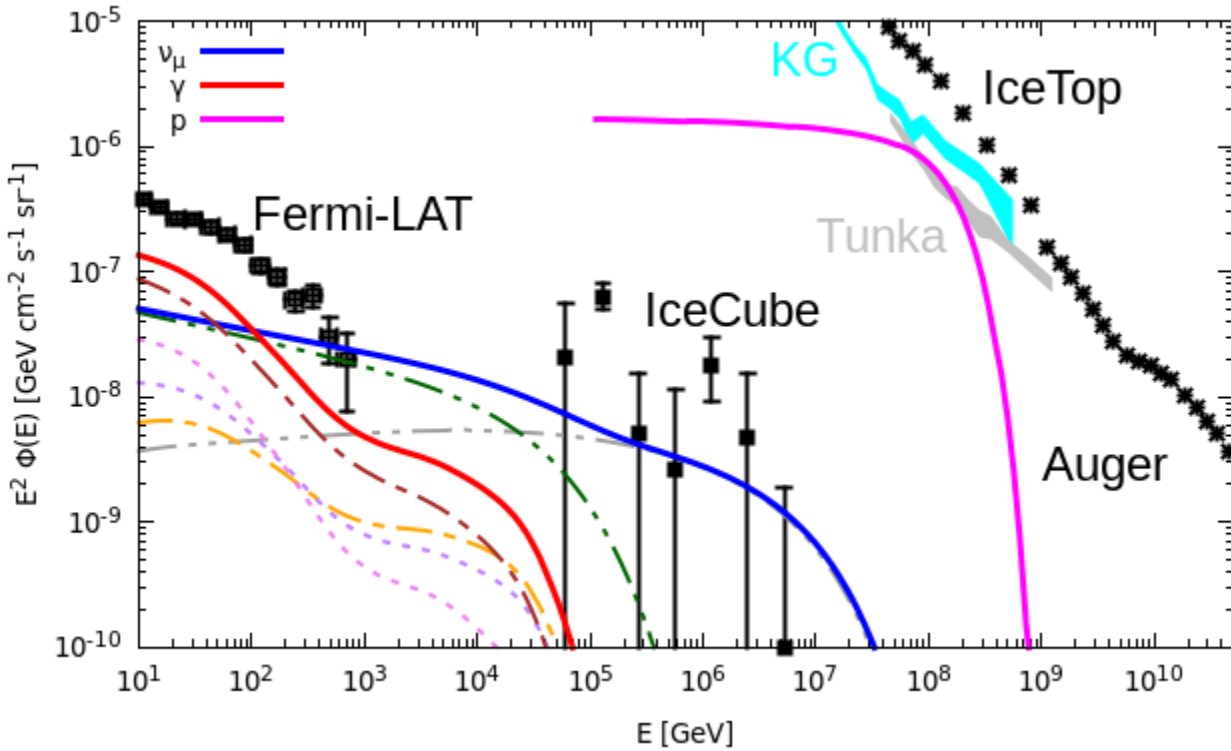
Diffuse emission from Starburst Galaxies



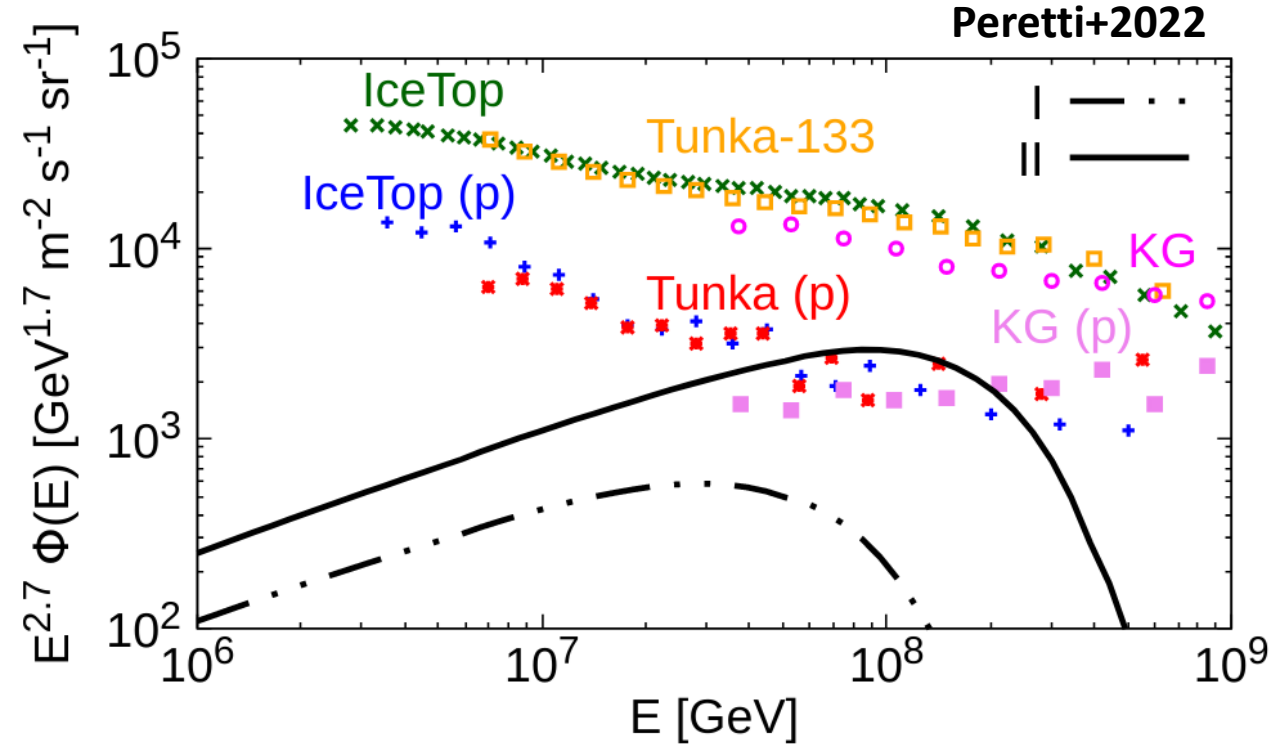
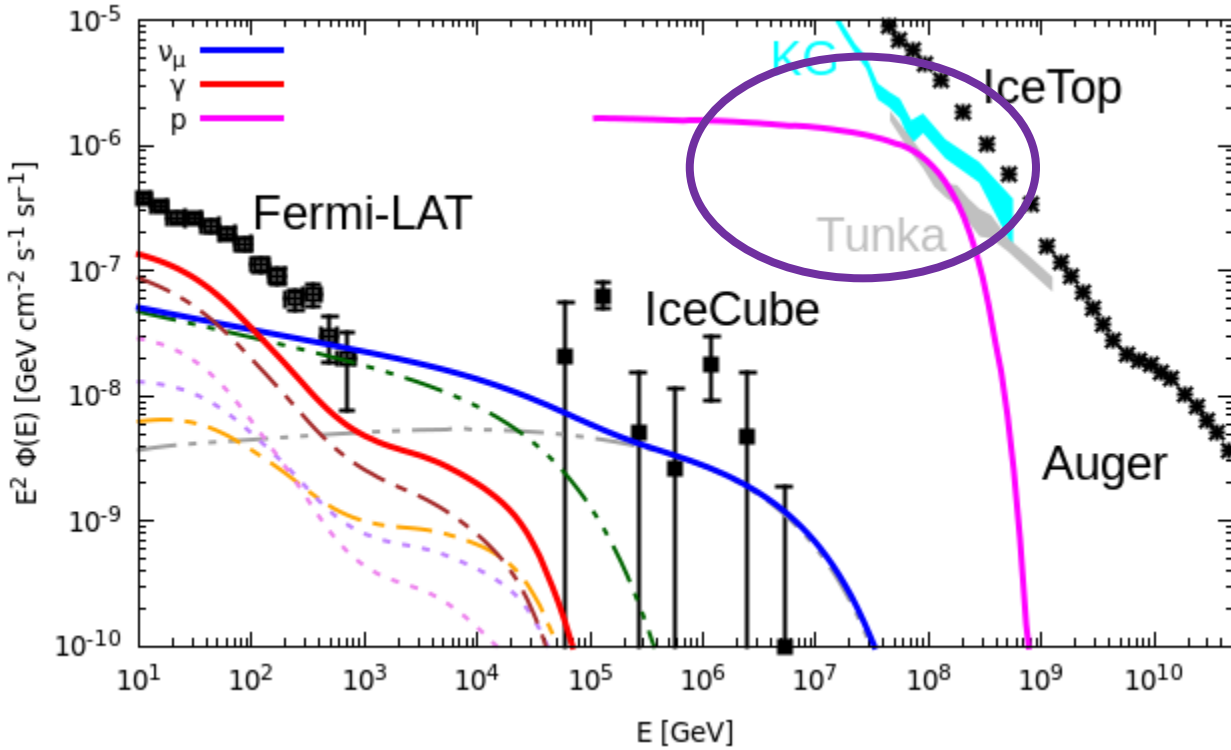
Diffuse emission from Starburst Galaxies



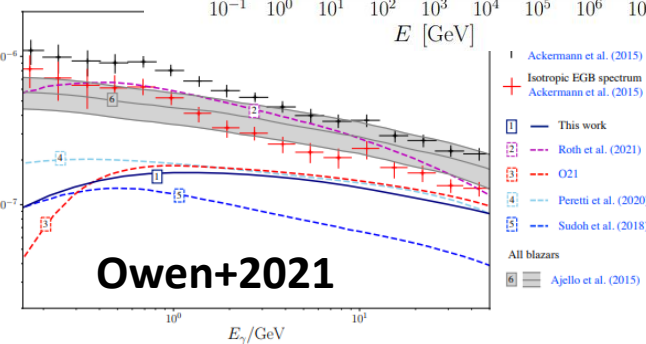
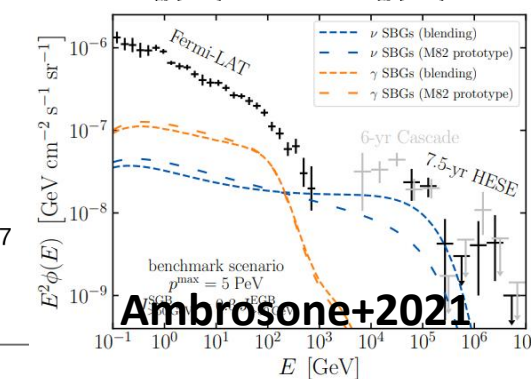
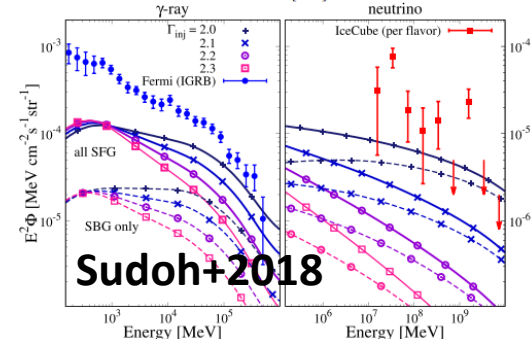
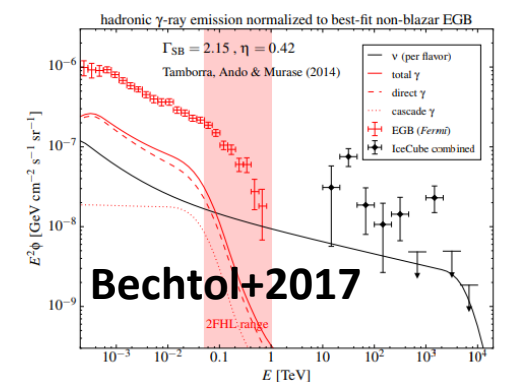
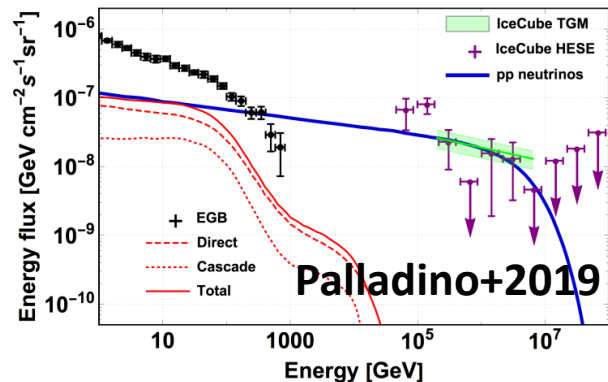
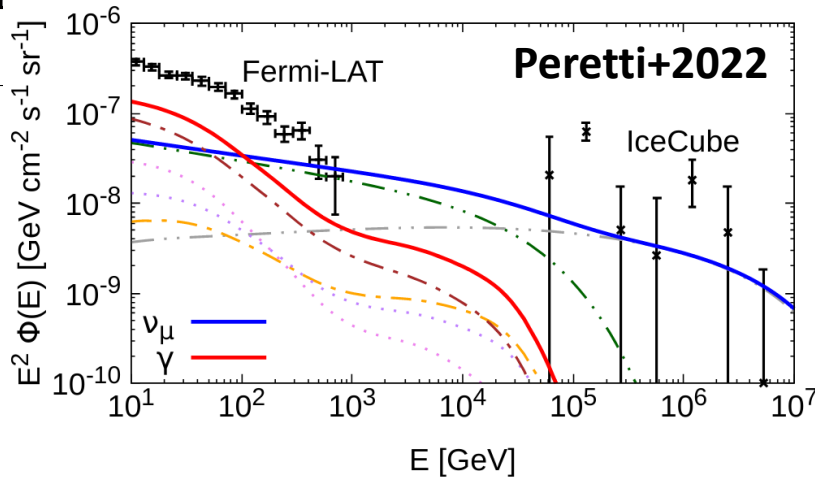
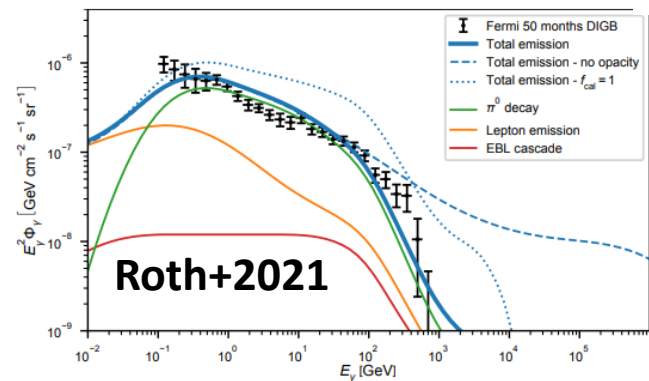
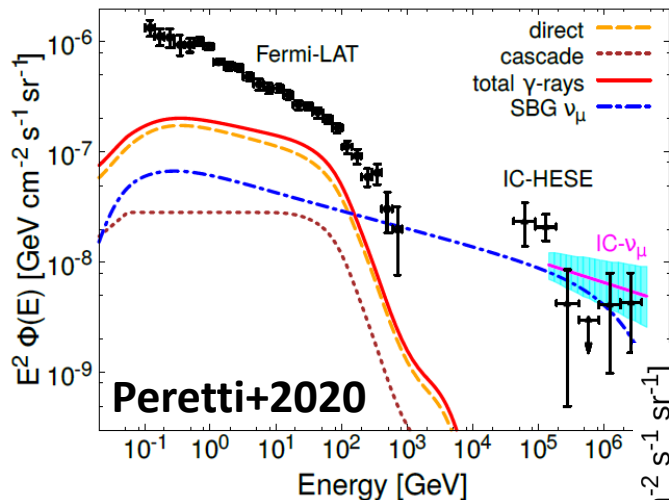
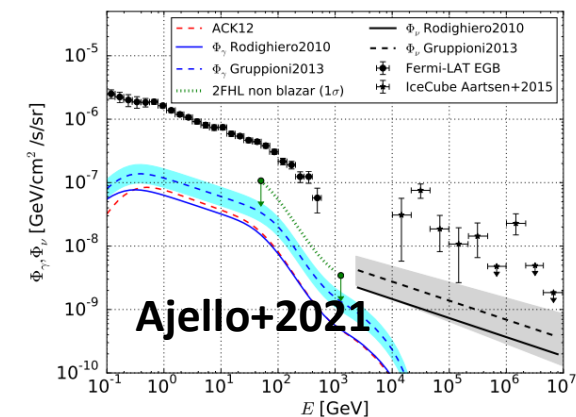
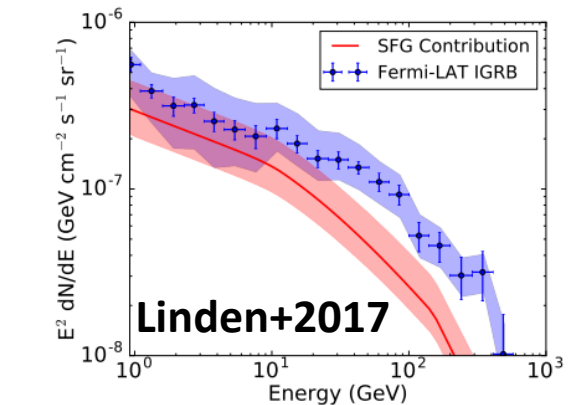
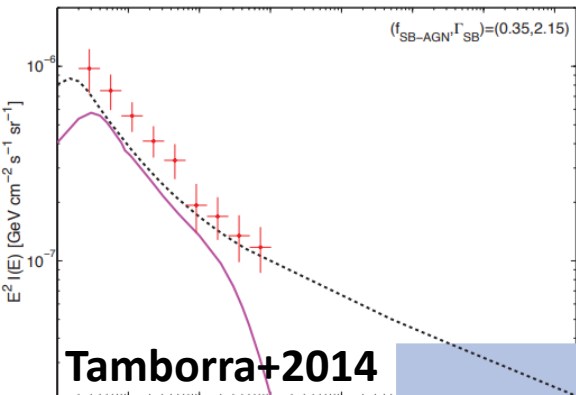
Multimessenger emission from Starburst Galaxies



Multimessenger emission from Starburst Galaxies

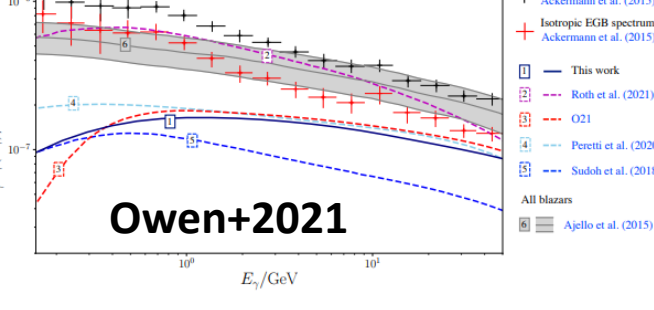
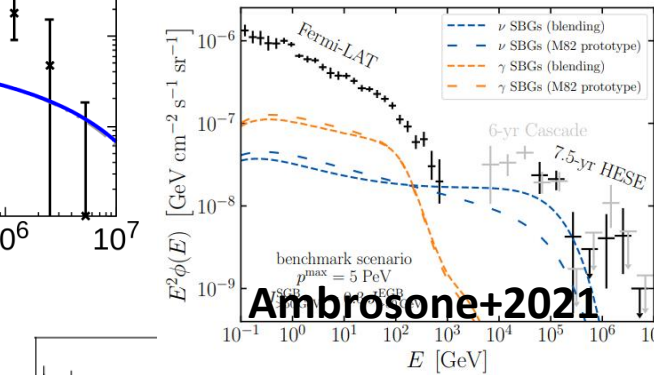
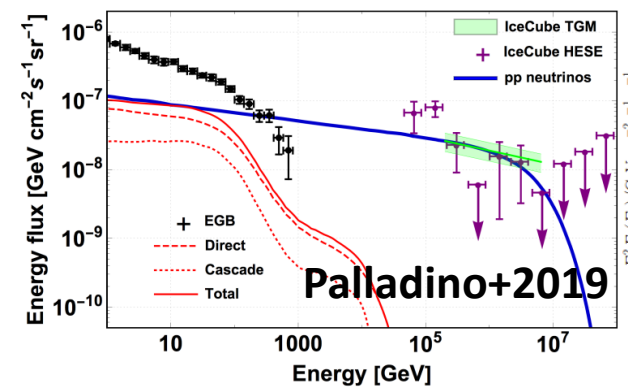
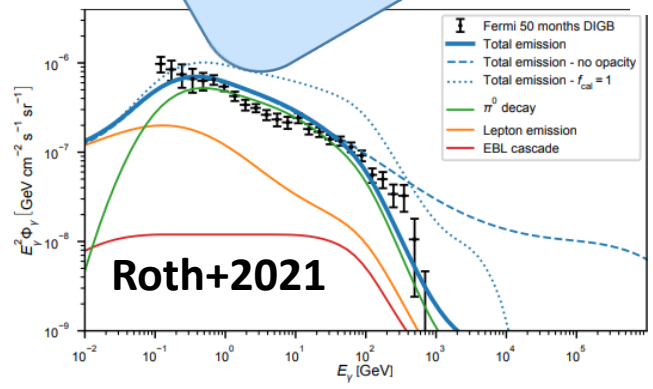
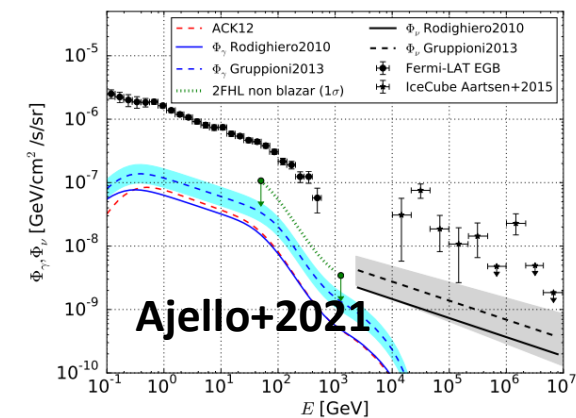
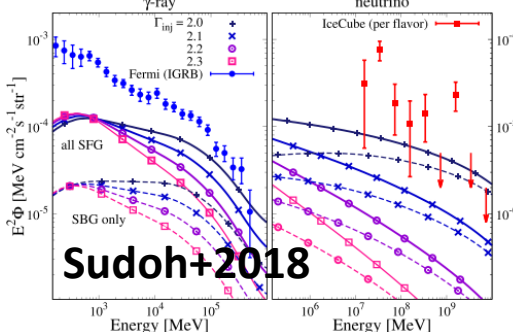
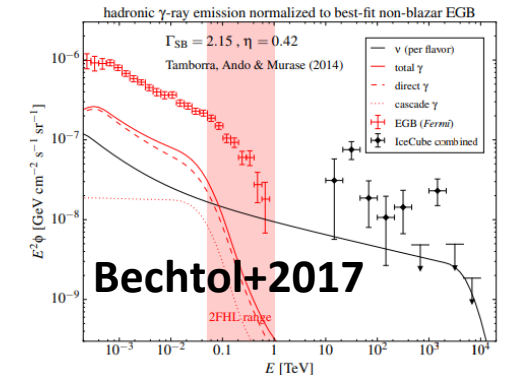
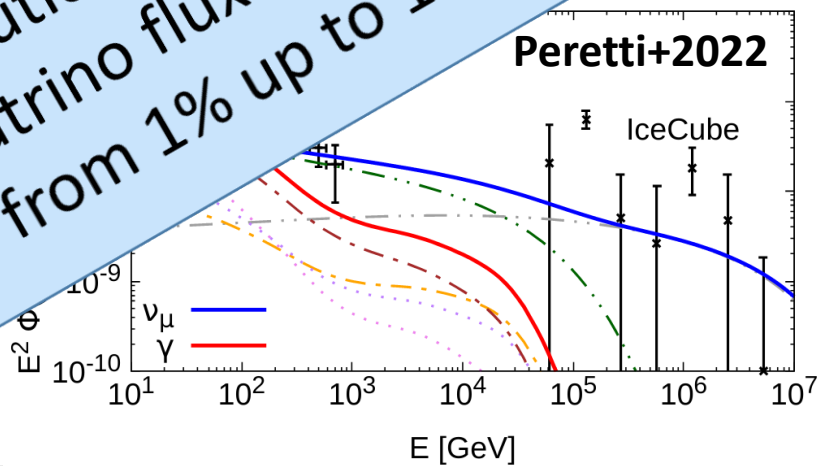
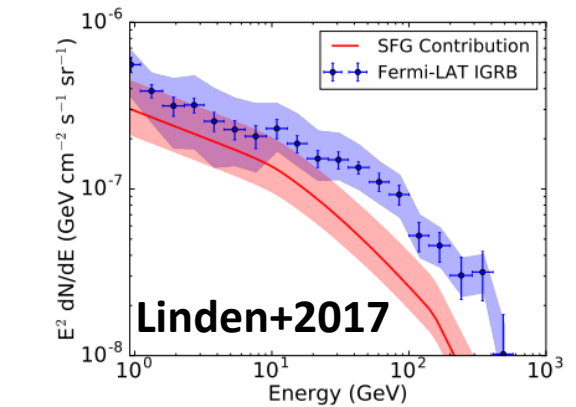
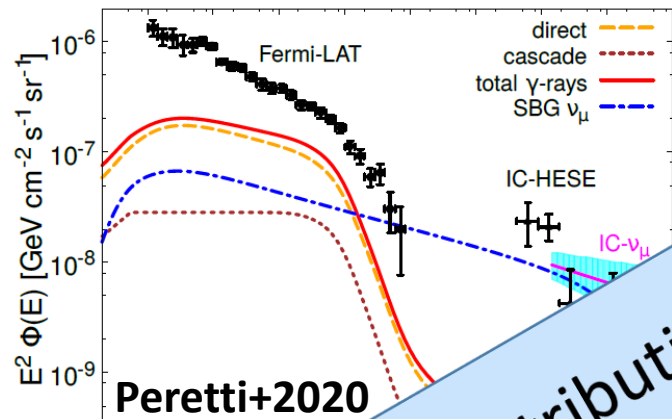
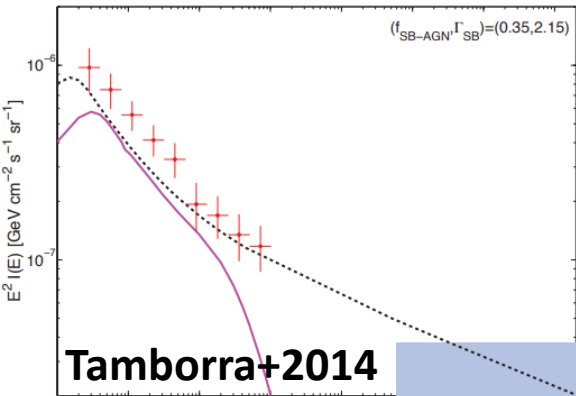


Starbursts in the last 10 years



Starbursts in the last 10 years

Starburst contribution to the diffuse γ -ray flux and HE neutrino flux beyond 100 TeV ranges from 1% up to 100%



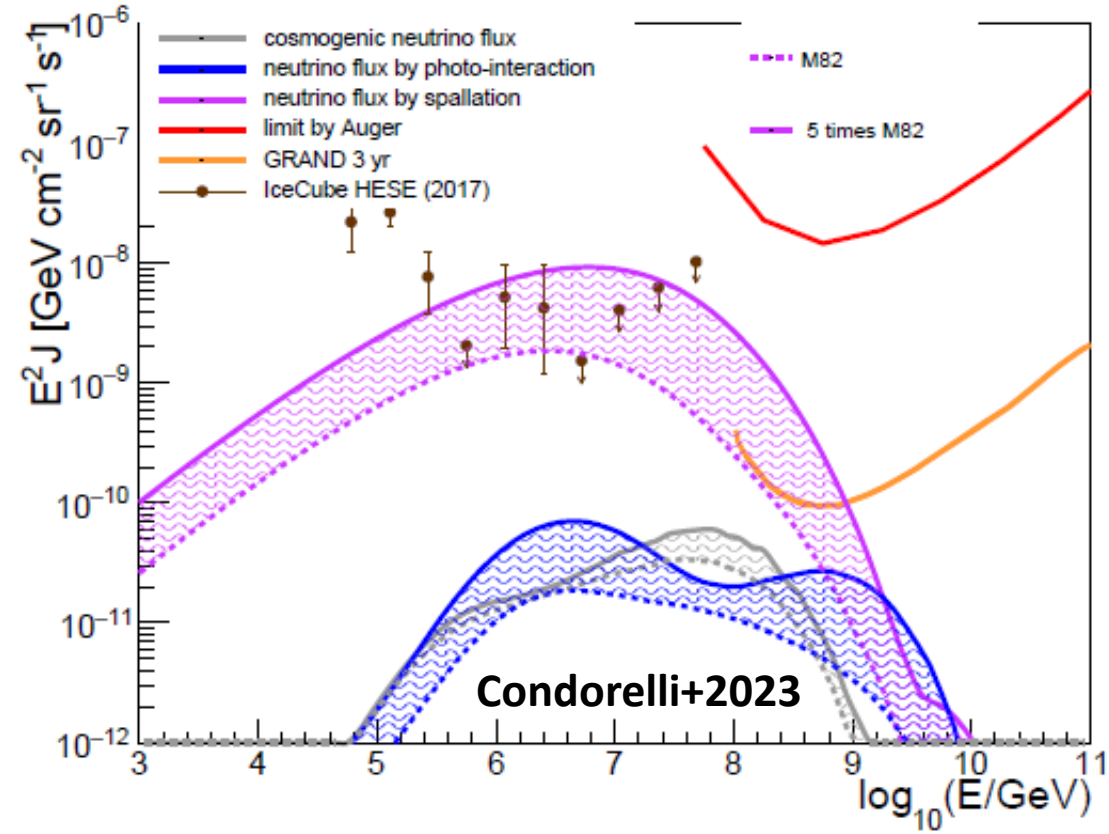
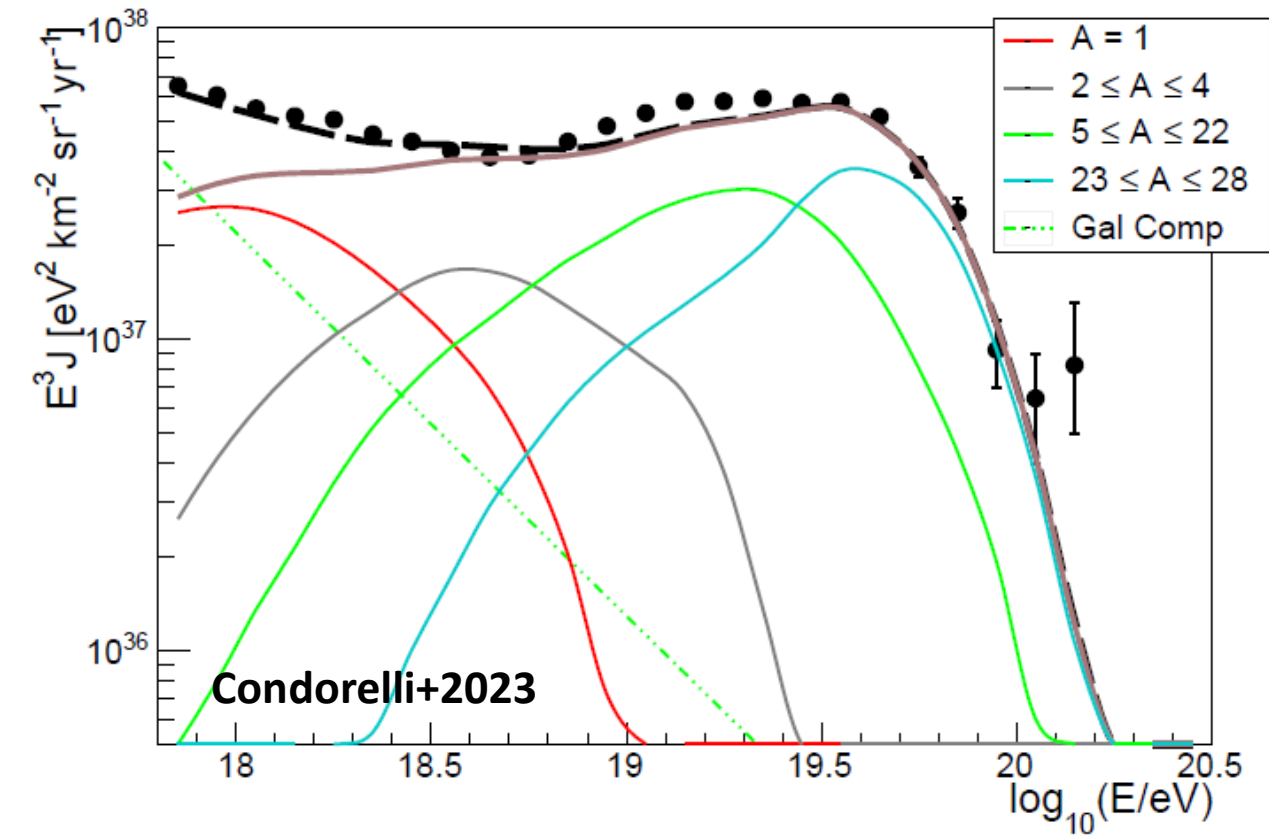
Take home messages

1. Star forming galaxies (SFGs) are cosmic-ray factories
2. Starburst nuclei (SBNi) can approach calorimetric conditions
3. Starburst winds can accelerate cosmic rays up to 100 PV in rigidity
4. We expect γ -rays and neutrinos both from SBNi and SB-winds
5. SFGs can provide a sizeable contribution to the multi-messenger diffuse flux
6. New observatories \rightarrow promising observation perspectives!

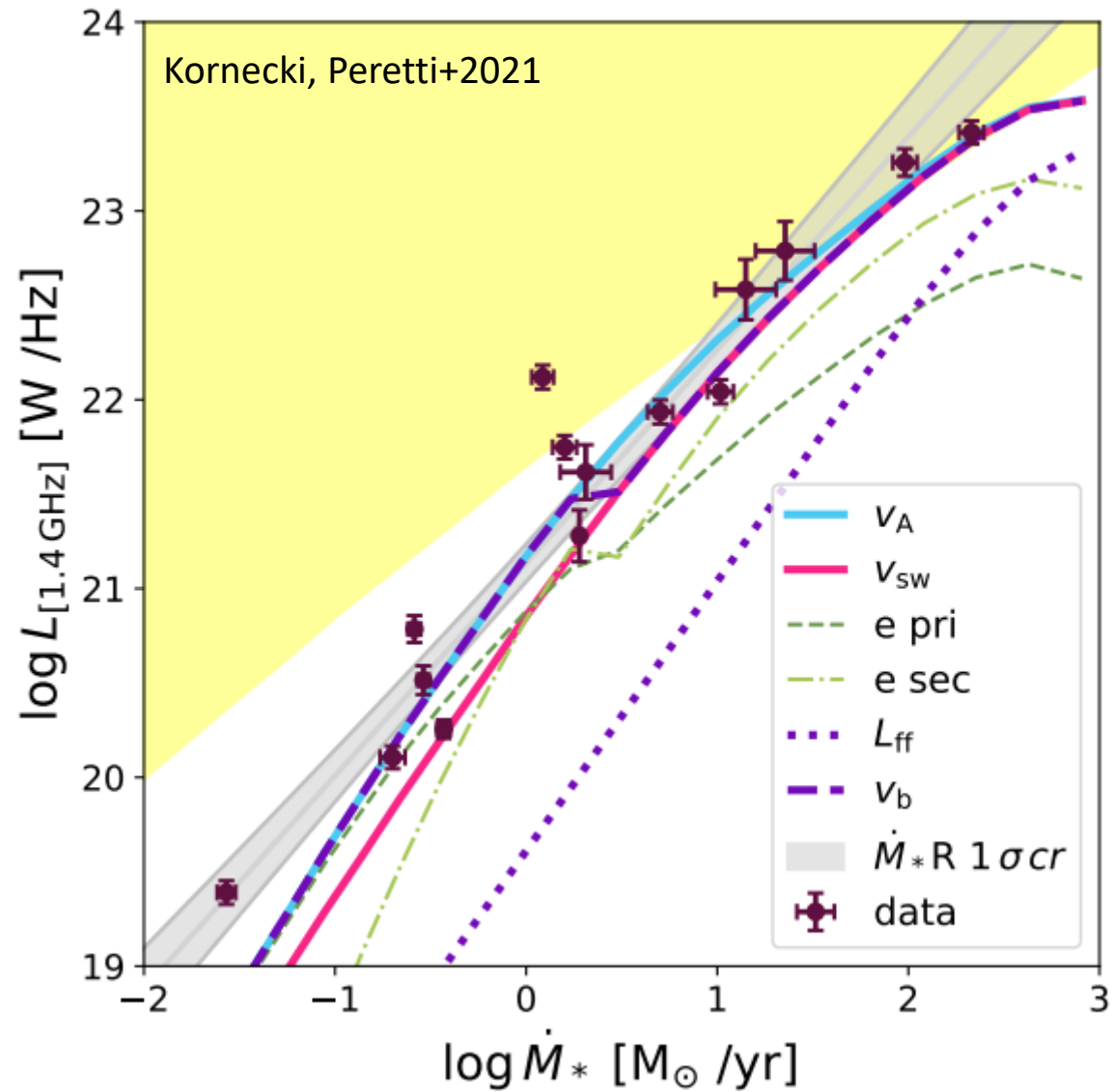
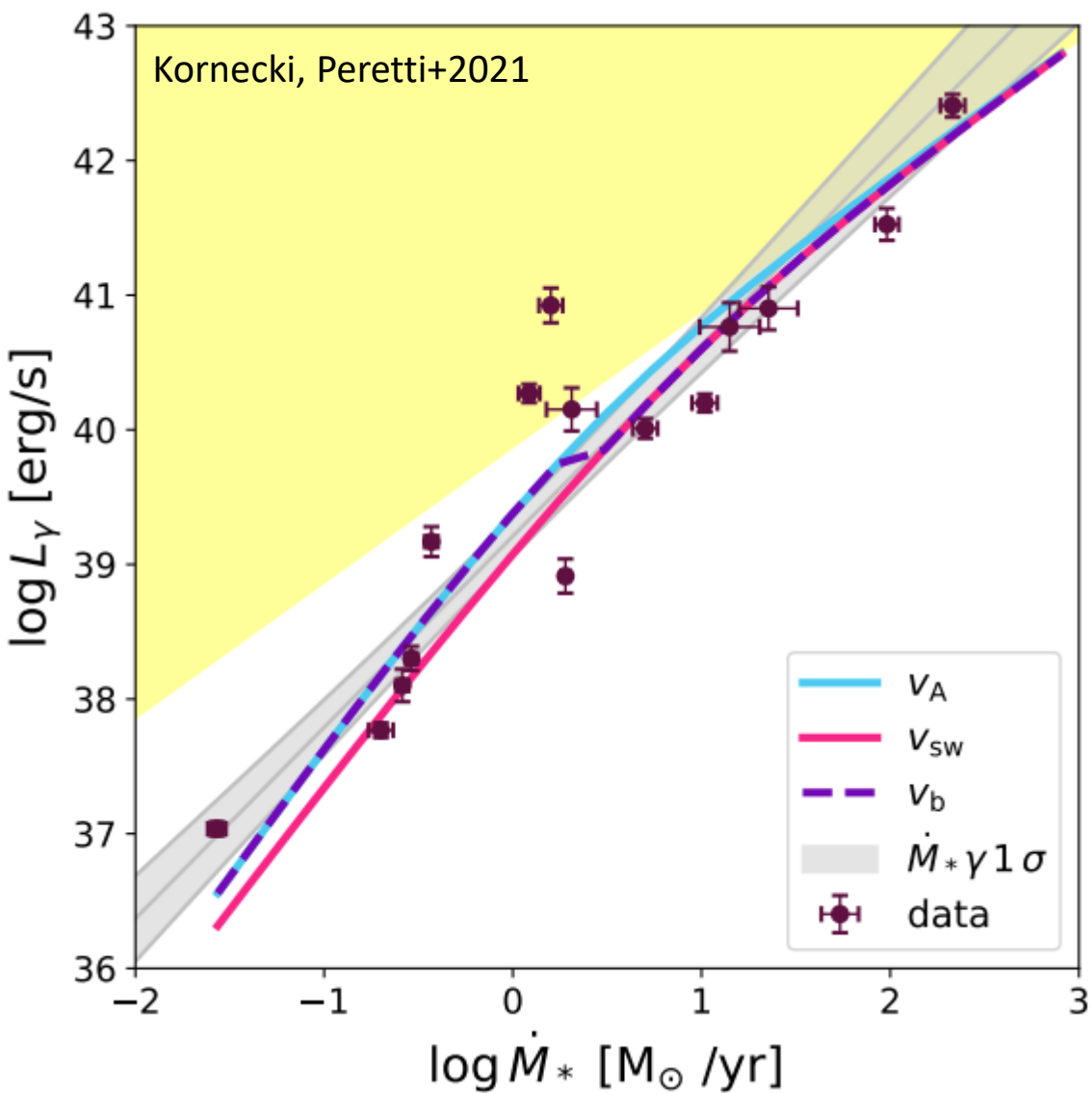
THANK YOU!

Back up

Starburst and the UHECRs



Leaky box model and L—SFR correlations



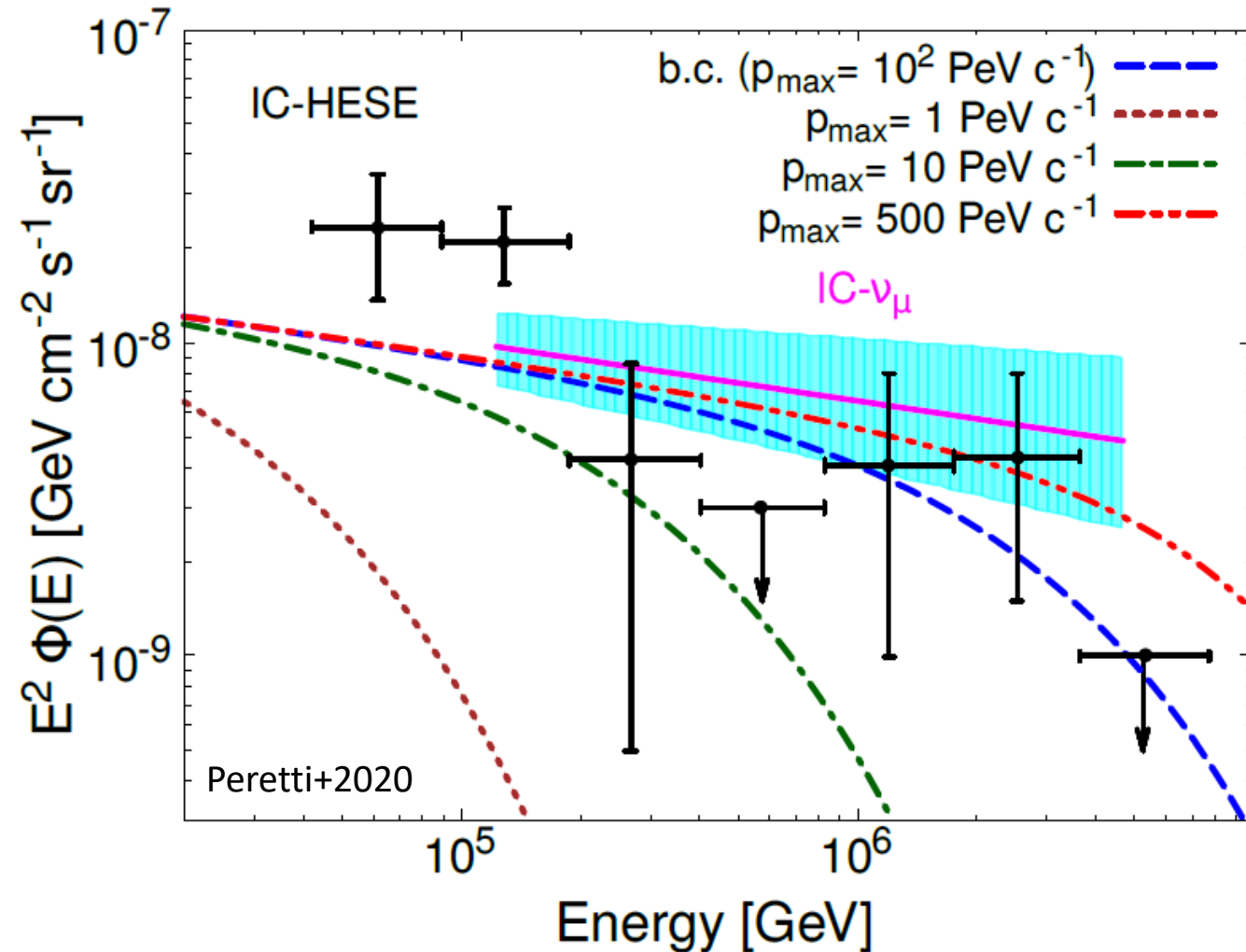
The issue of the maximum energy

Starburst contribution to IceCube neutrinos strongly depends on the maximum energy achievable in SBNI

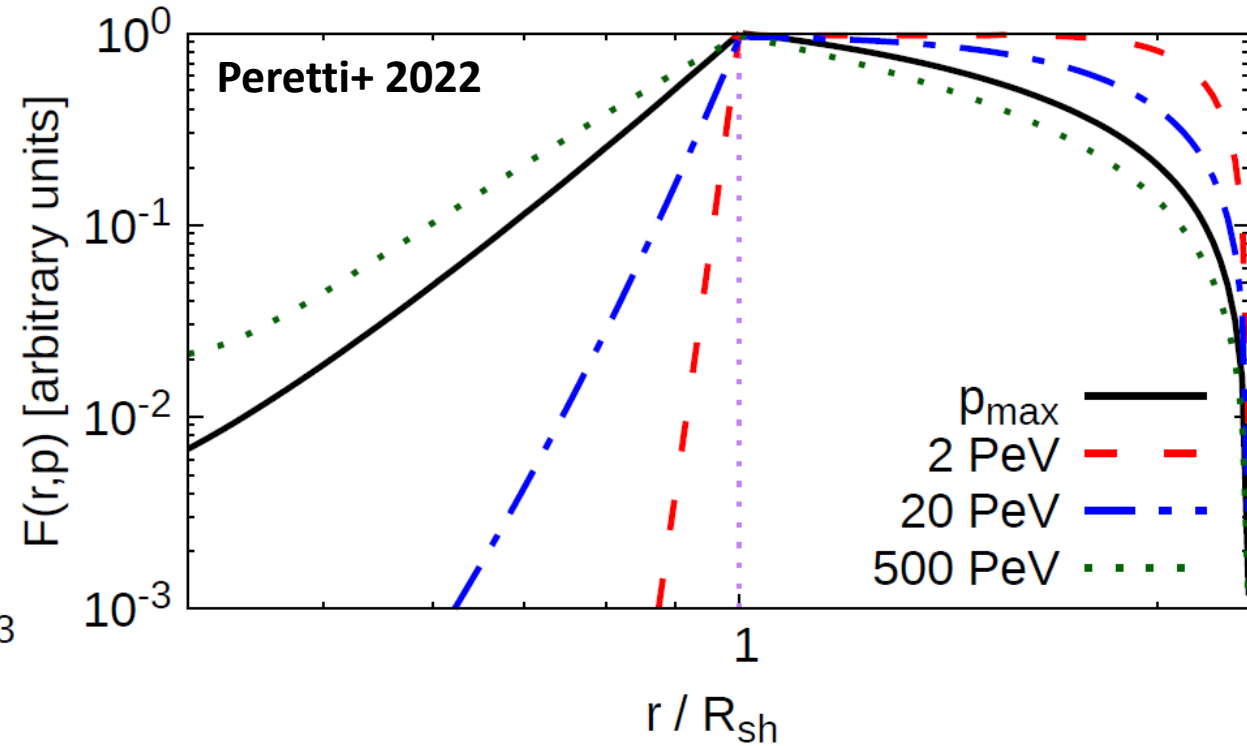
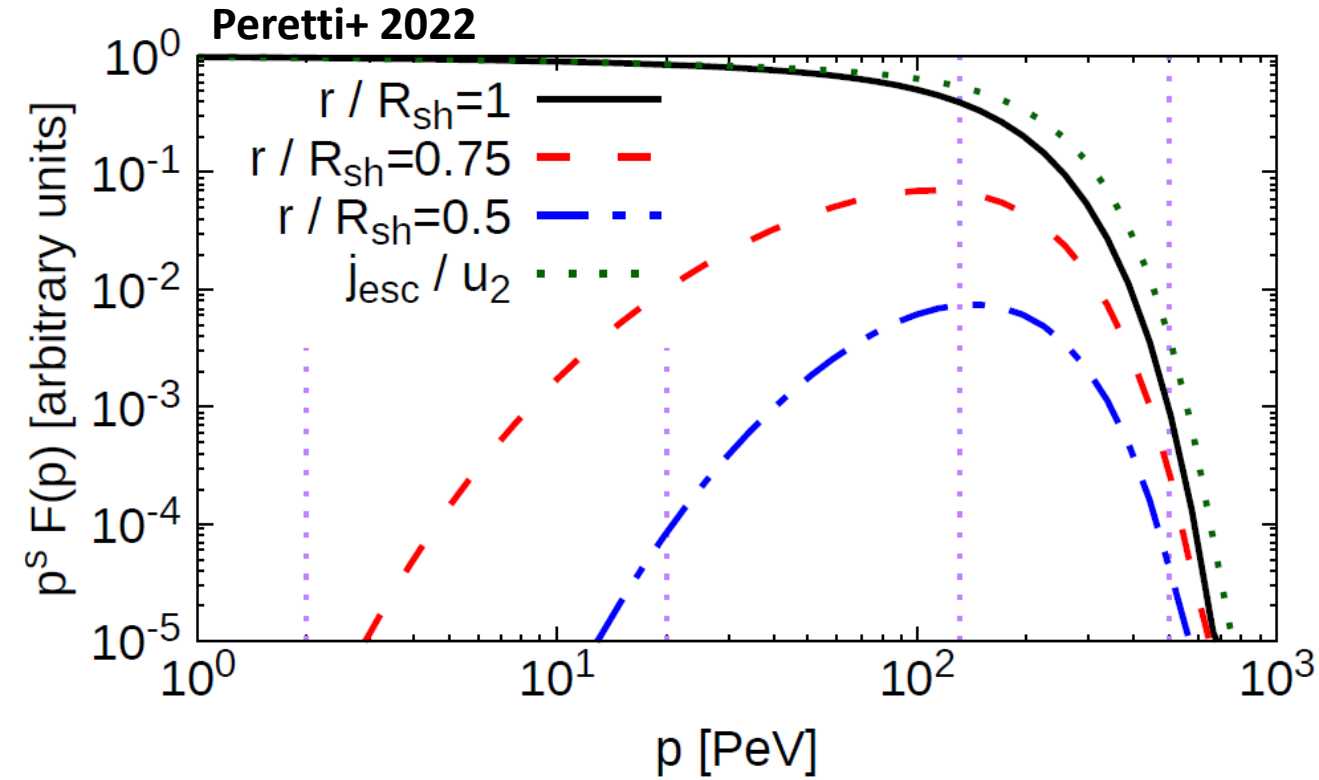
SNR in case of Bohm diffusion:

$$E_{max} = 30 \text{ PeV} \times R_3 u_4 B_{mG}$$

- Magnetic field amplification can allow reaching 10-100 PeV



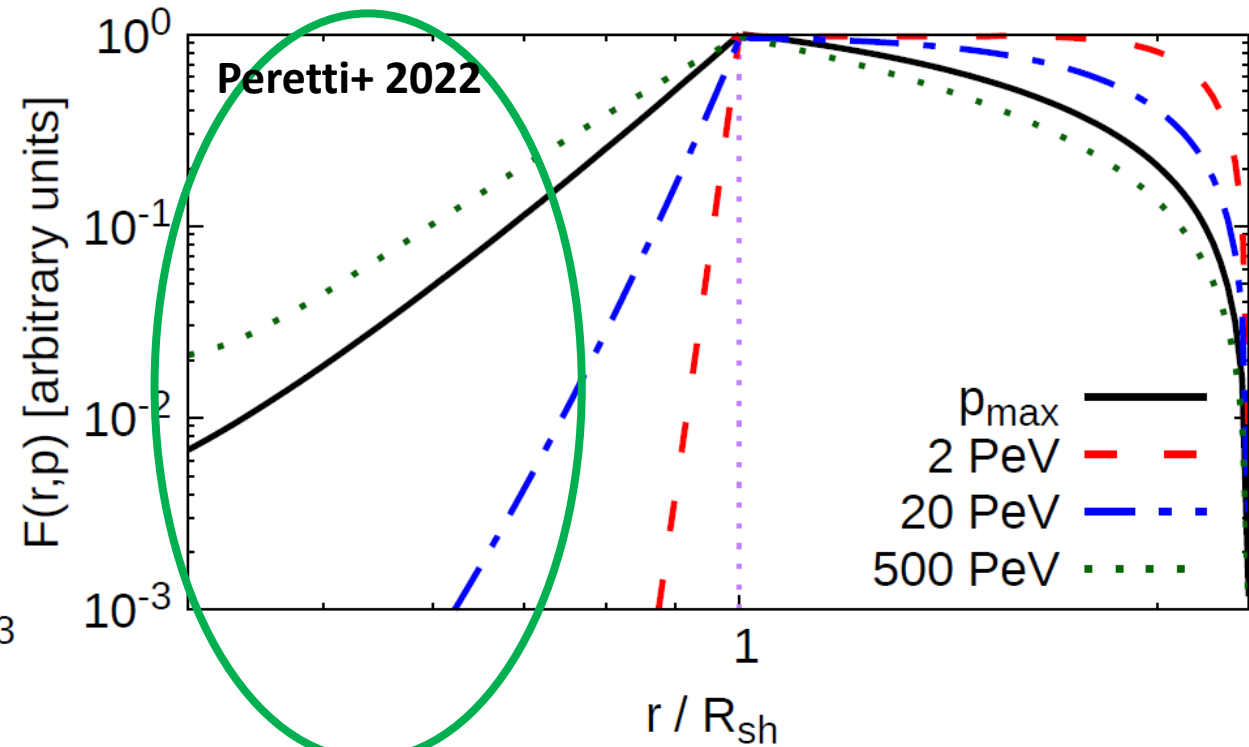
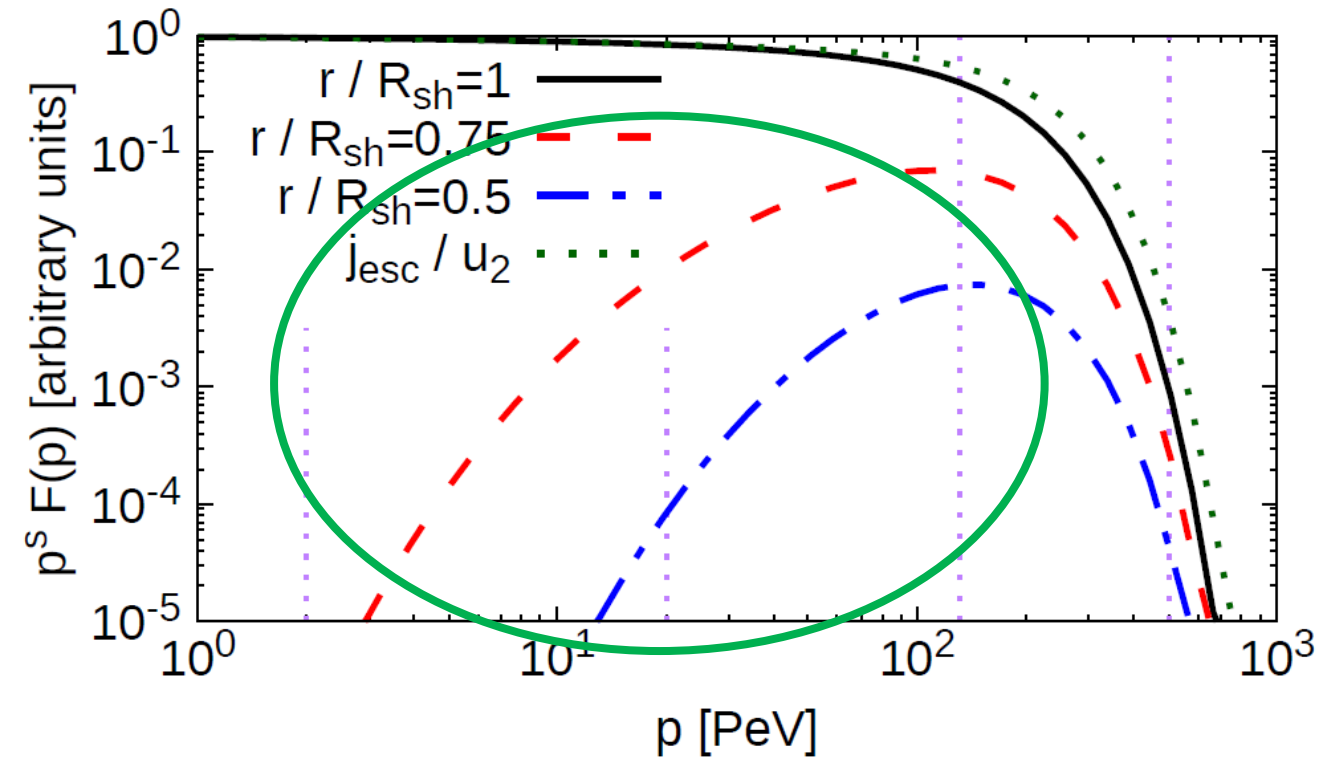
Particles in the system



$$f_{sh}(p) \propto p^{-s} e^{-\Gamma_1(p)} e^{-\Gamma_2(p)}$$

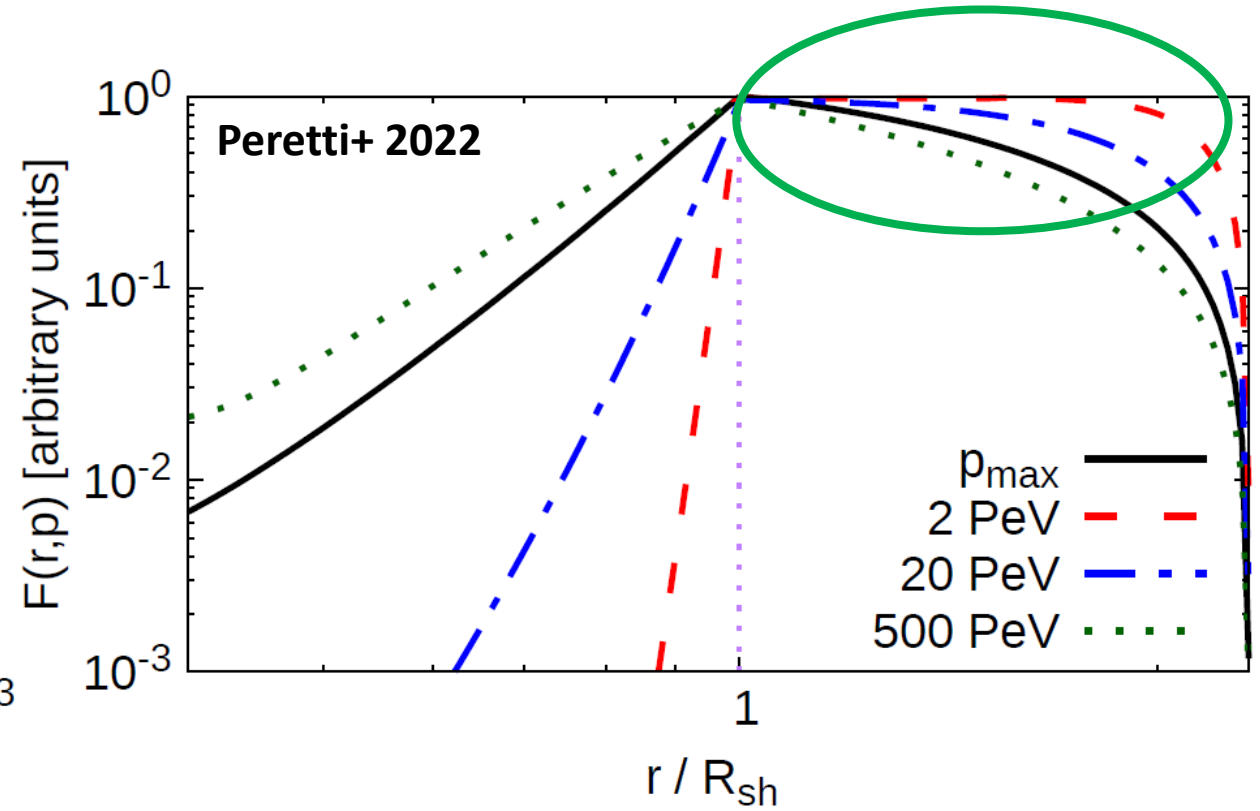
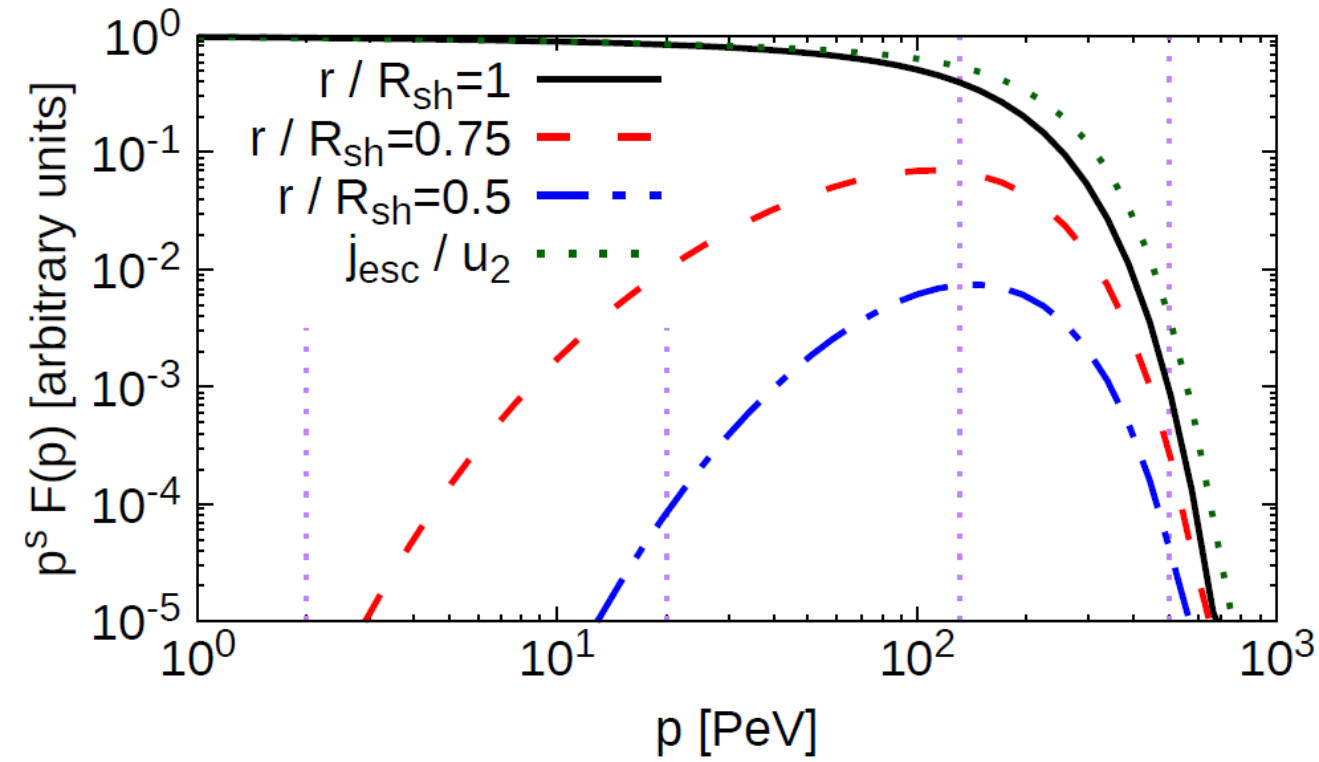
$$f_u(r,p) = f_{sh}(p) e^{-\int_r^{R_{sh}} \left(\frac{u_{eff}}{D}\right) dr'}$$

Particles in the system



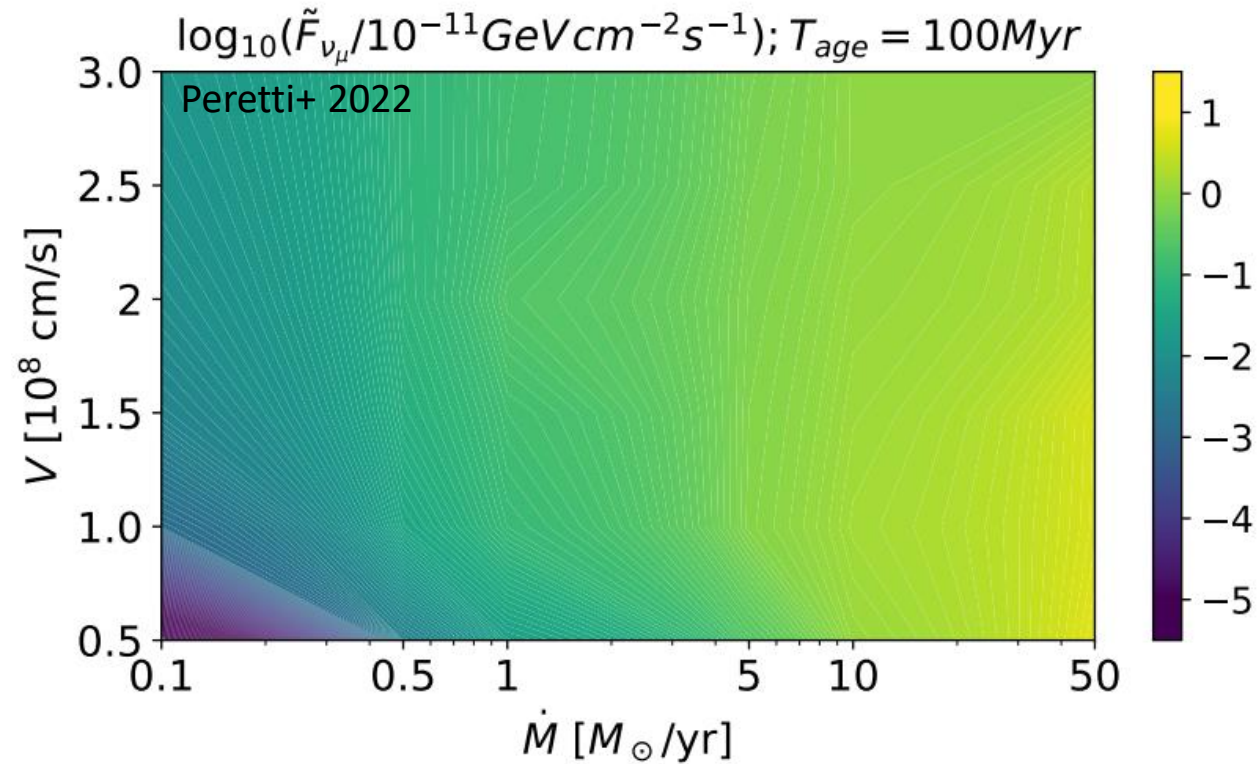
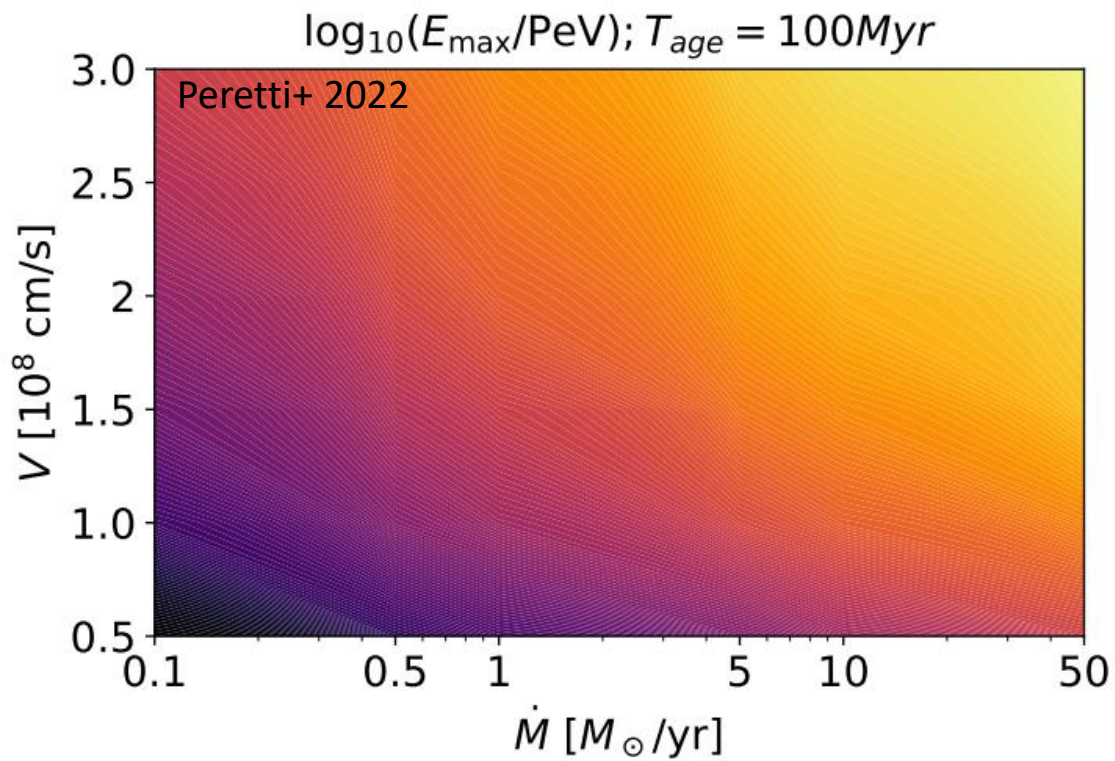
The wind suppresses the diffusion of particles back to the galaxy

Particles in the system



Particle distribution homogenized in the downstream region

Maximum Energy & Luminosity

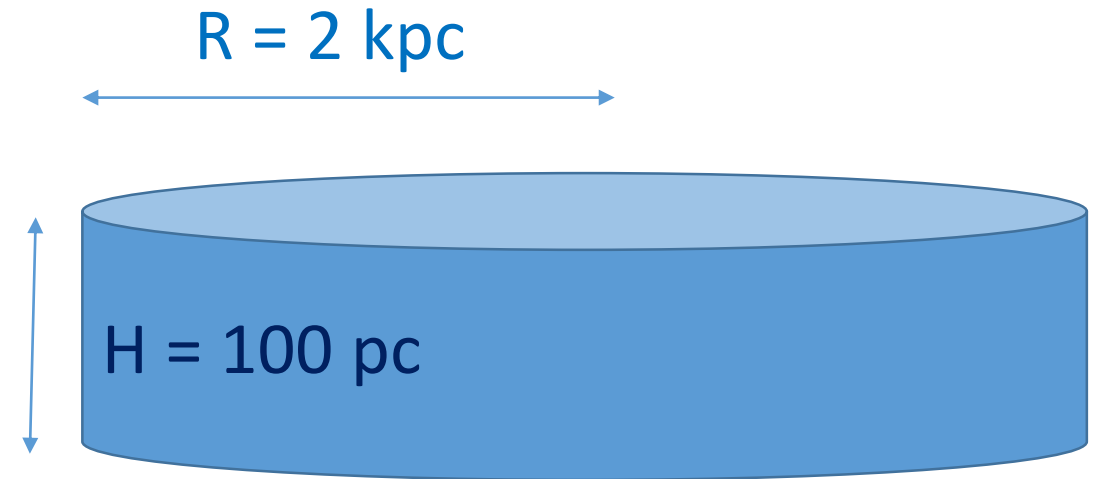


The starburst of NGC 1068

$$\tau_{pp}(GeV) \approx 5 \cdot 10^5 \left(\frac{n}{10^2 cm^{-3}} \right)^{-1} yr$$

$$\tau_{diff}(GeV) \approx 10^5 \left(\frac{H}{10^2 pc} \right)^2 \left(\frac{D}{10^{28} cm^2/s} \right)^{-1} yr$$

$$\tau_{adv}(GeV) \approx 10^6 \left(\frac{H}{10^2 pc} \right) \left(\frac{u}{10^2 km/s} \right)^{-1} yr$$



Calorimetry is possible but not trivial

The starburst of NGC 1068

