Neutrino emission from Starburst Galaxies

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PhD Summer School on Neutrinos

Here, There & Everywhere

July 11-15, 2022
Niels Bohr Institute, Copenhagen

VILLUM FONDEN

UNIVERSITY OF COPENHAGEN

Niels Bohr Institutet

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

Neutrinos in starburst galaxies

- What is a starburst galaxy?

- What is the origin of neutrinos in starburst galaxies?

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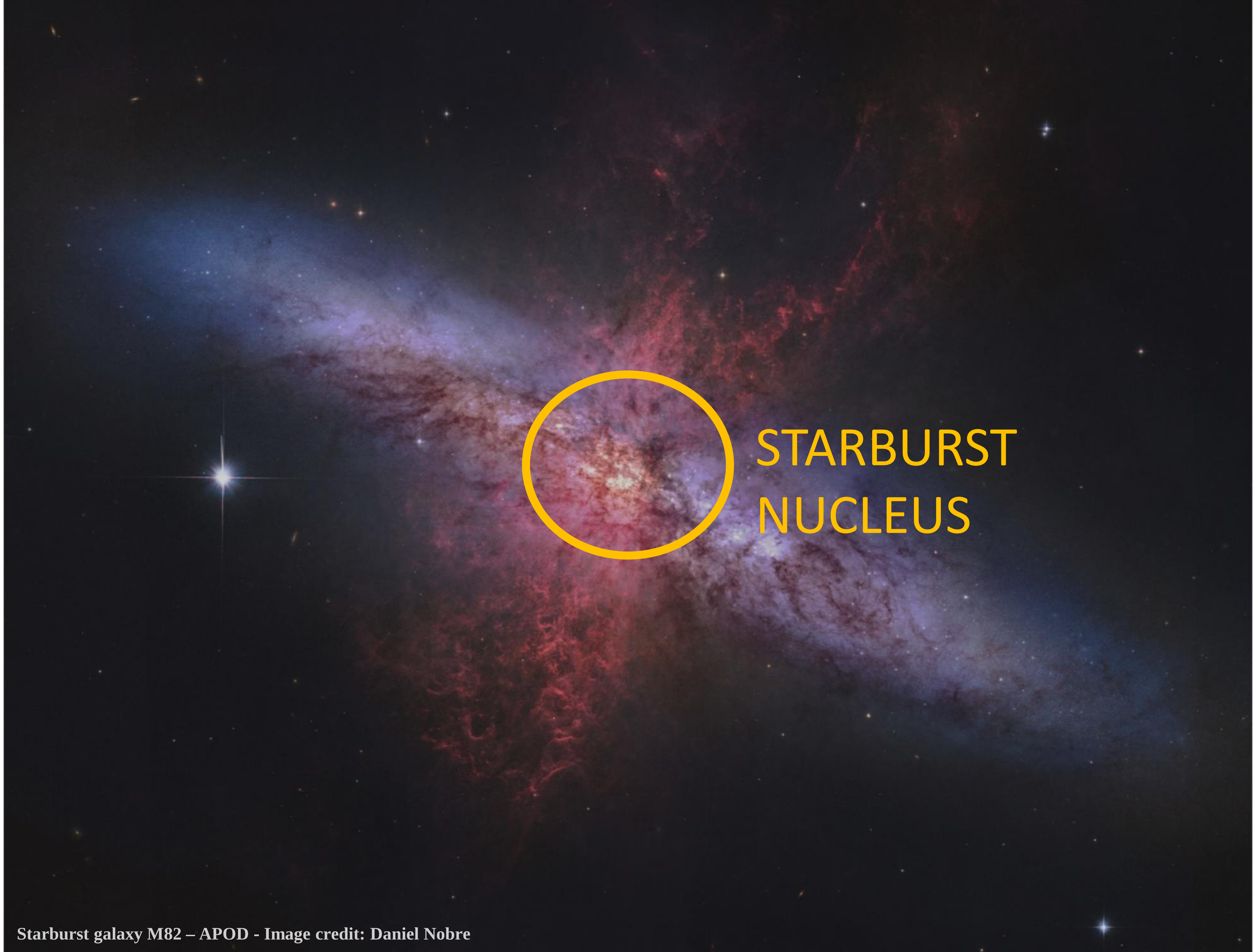
Starburst galaxy M82 – APOD - Image credit: Daniel Nobre



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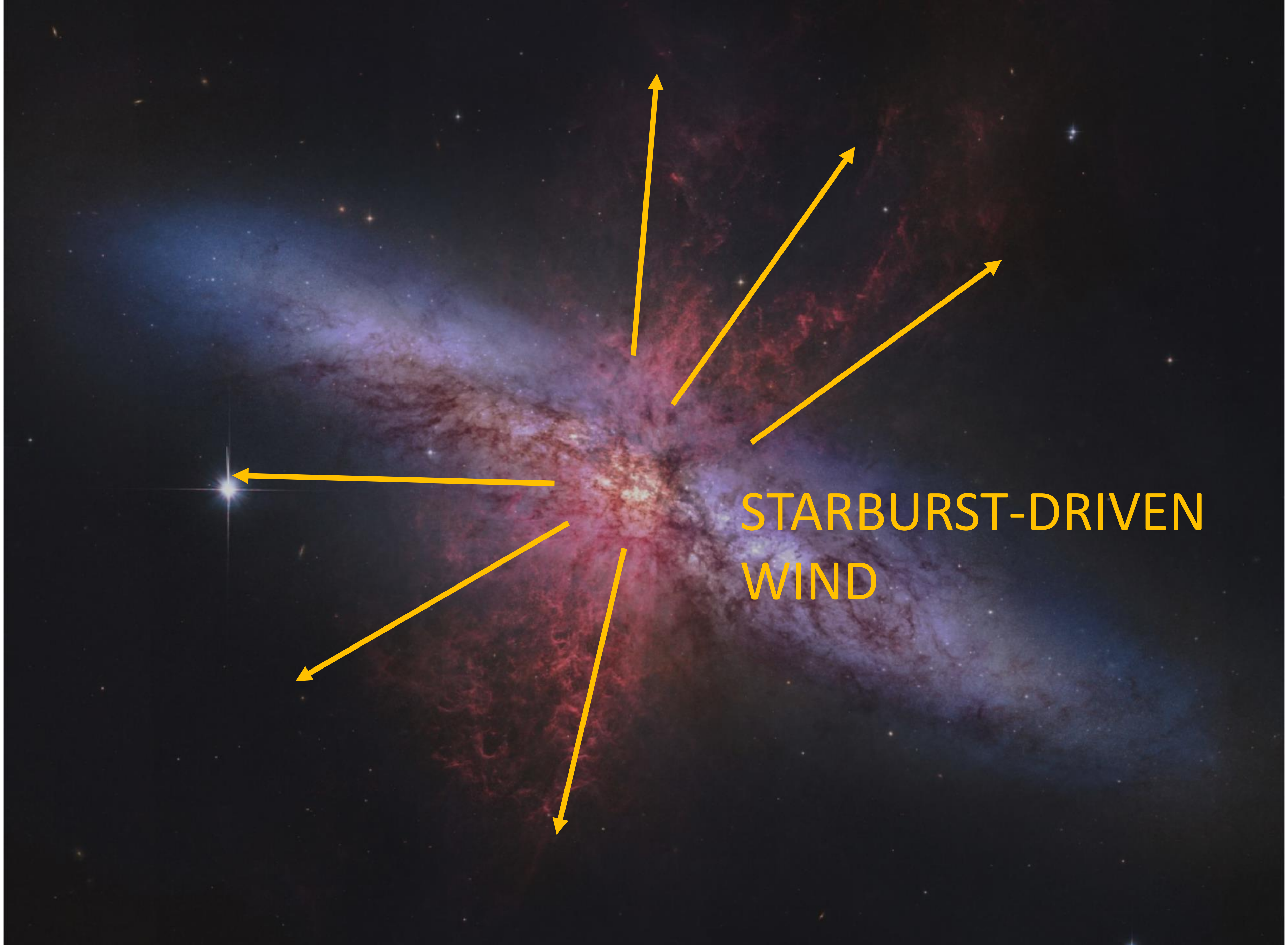

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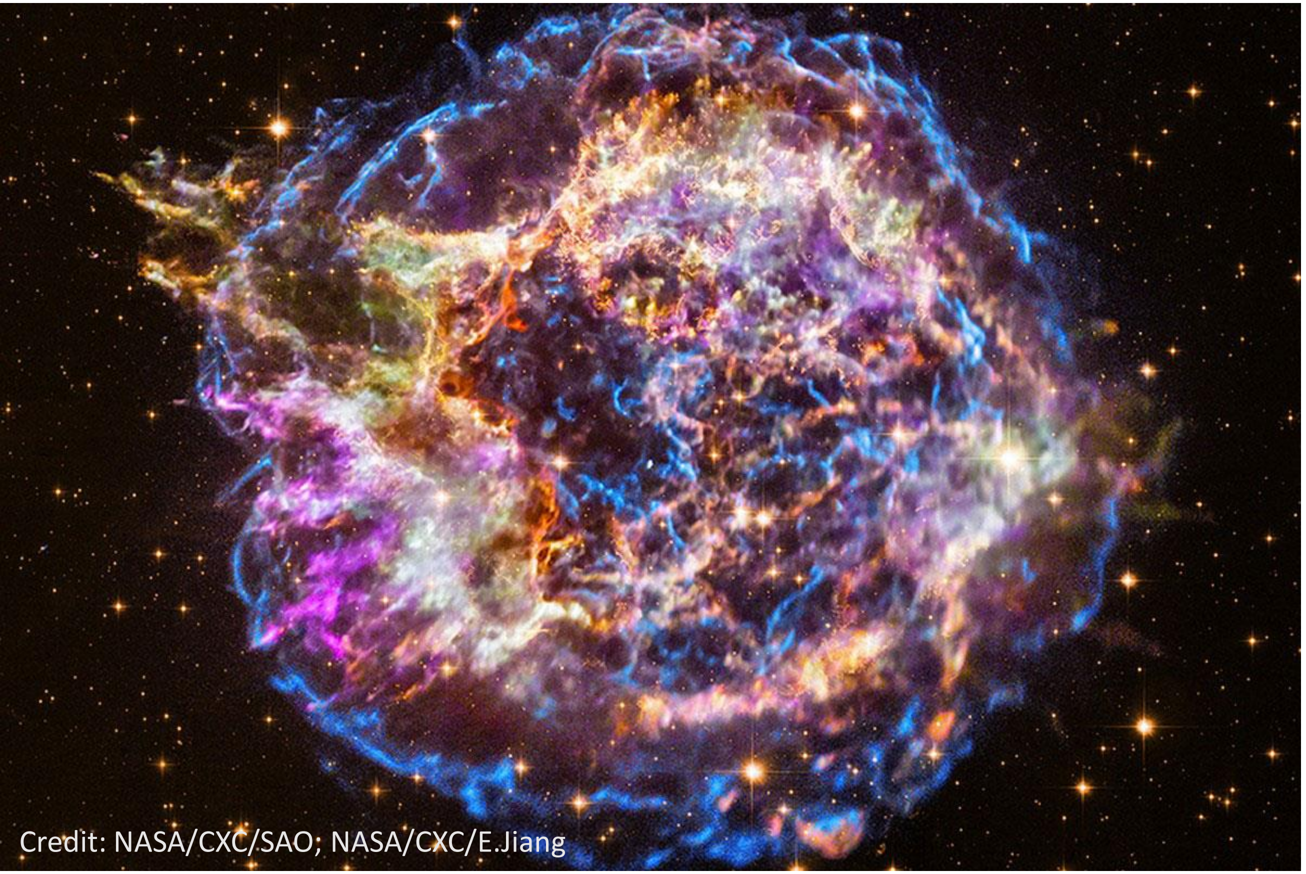
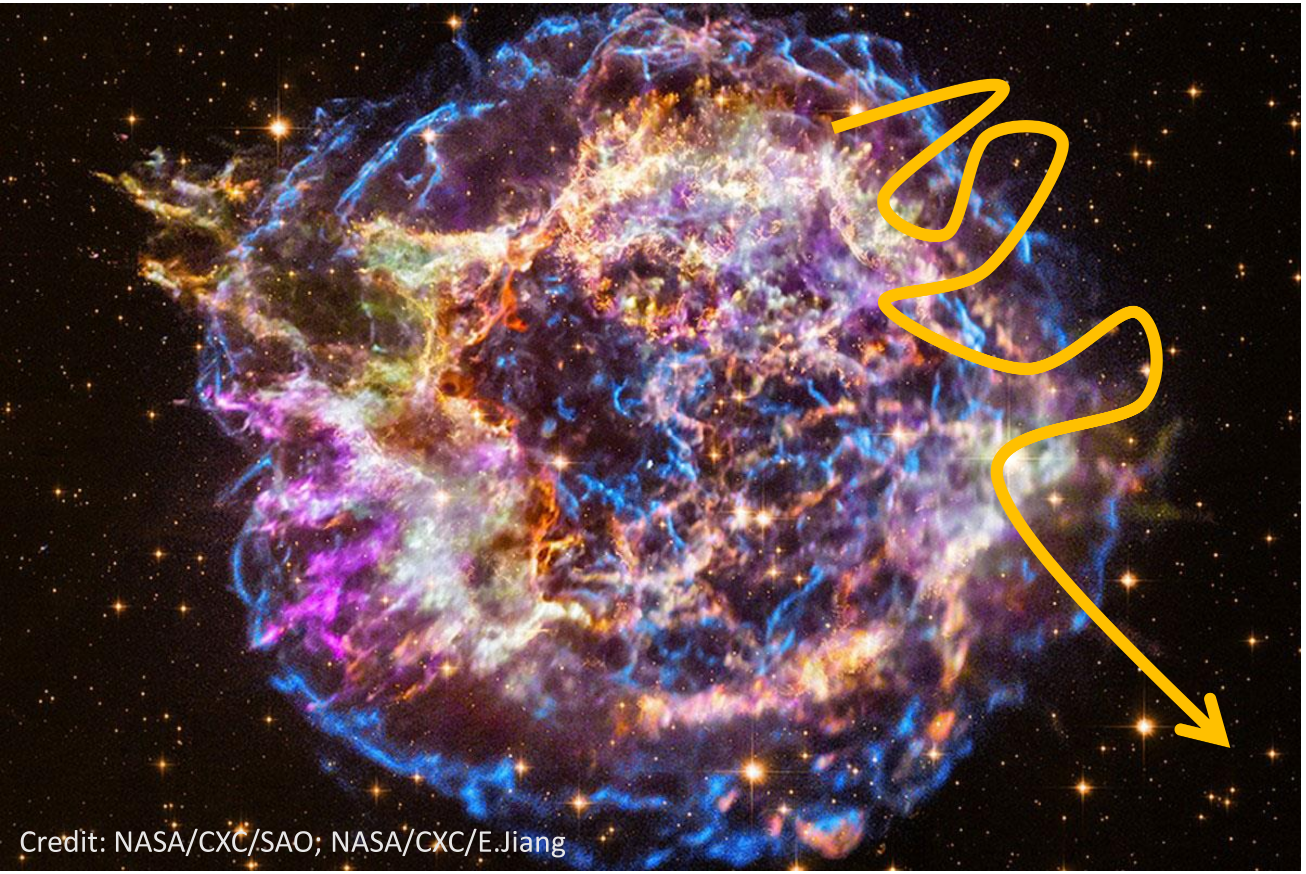
Supernova Remnants and DSA



Supernova remnants are shocks resulting from CCSNe and SN1a

Supernova Remnants and DSA



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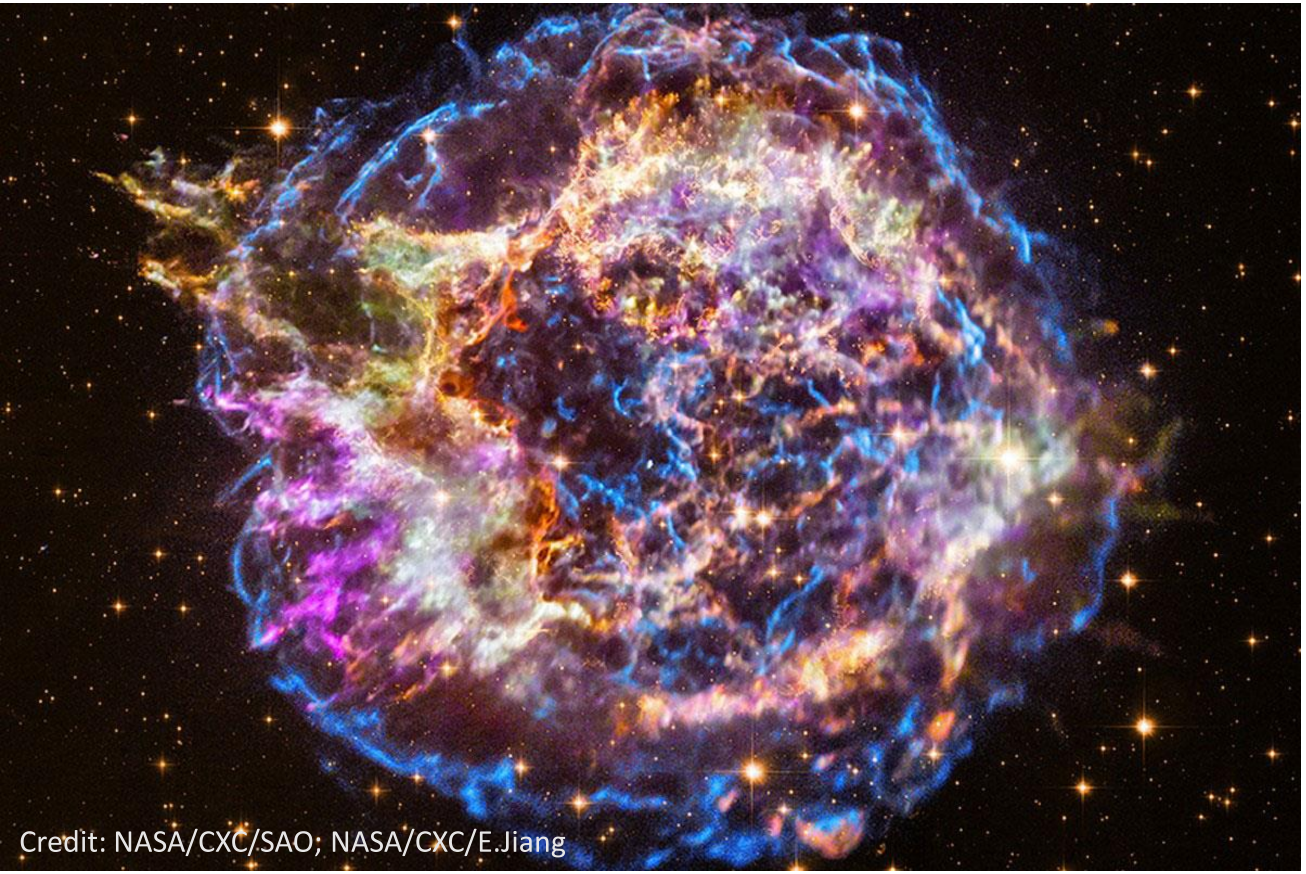
Supernova Remnants and DSA



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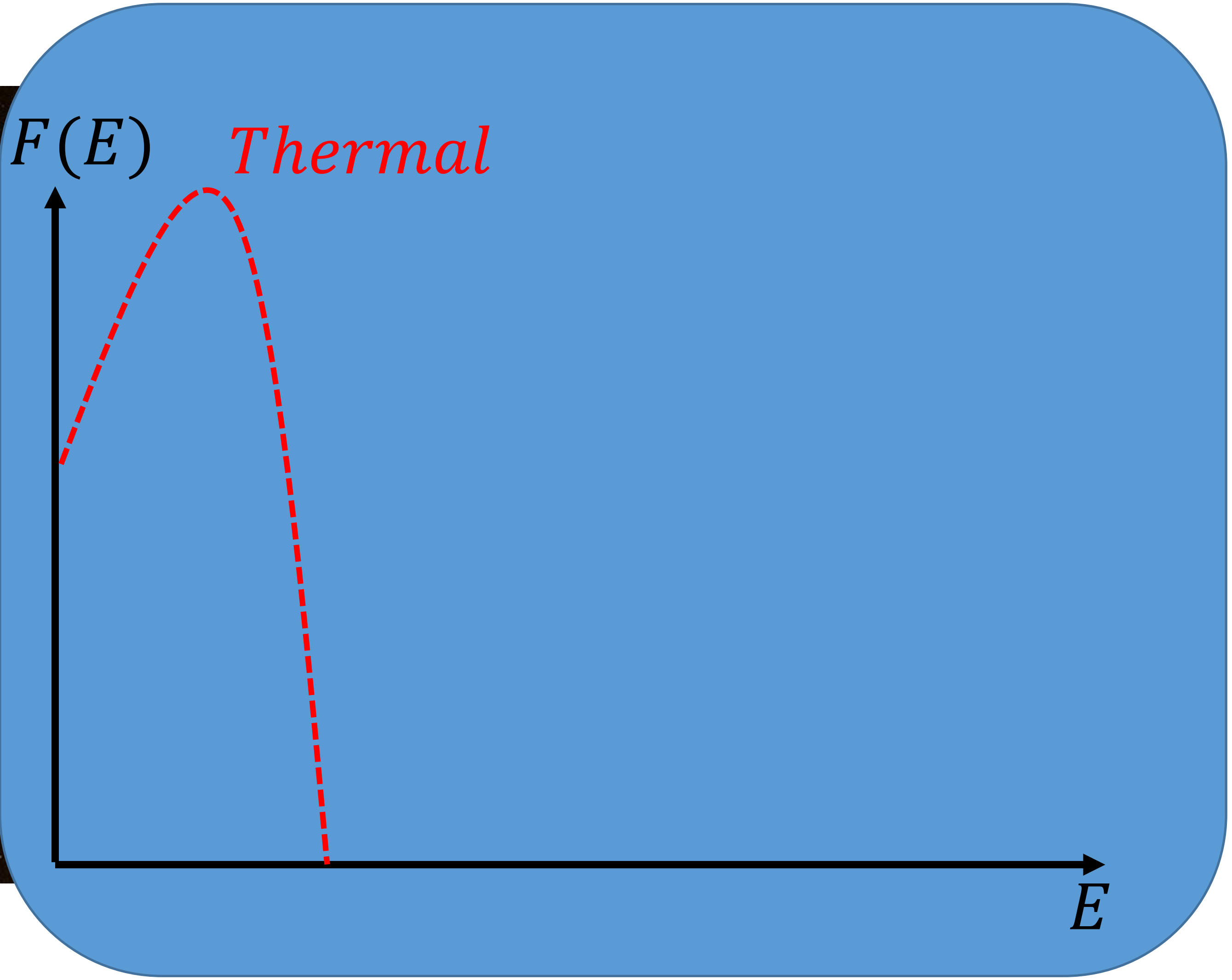

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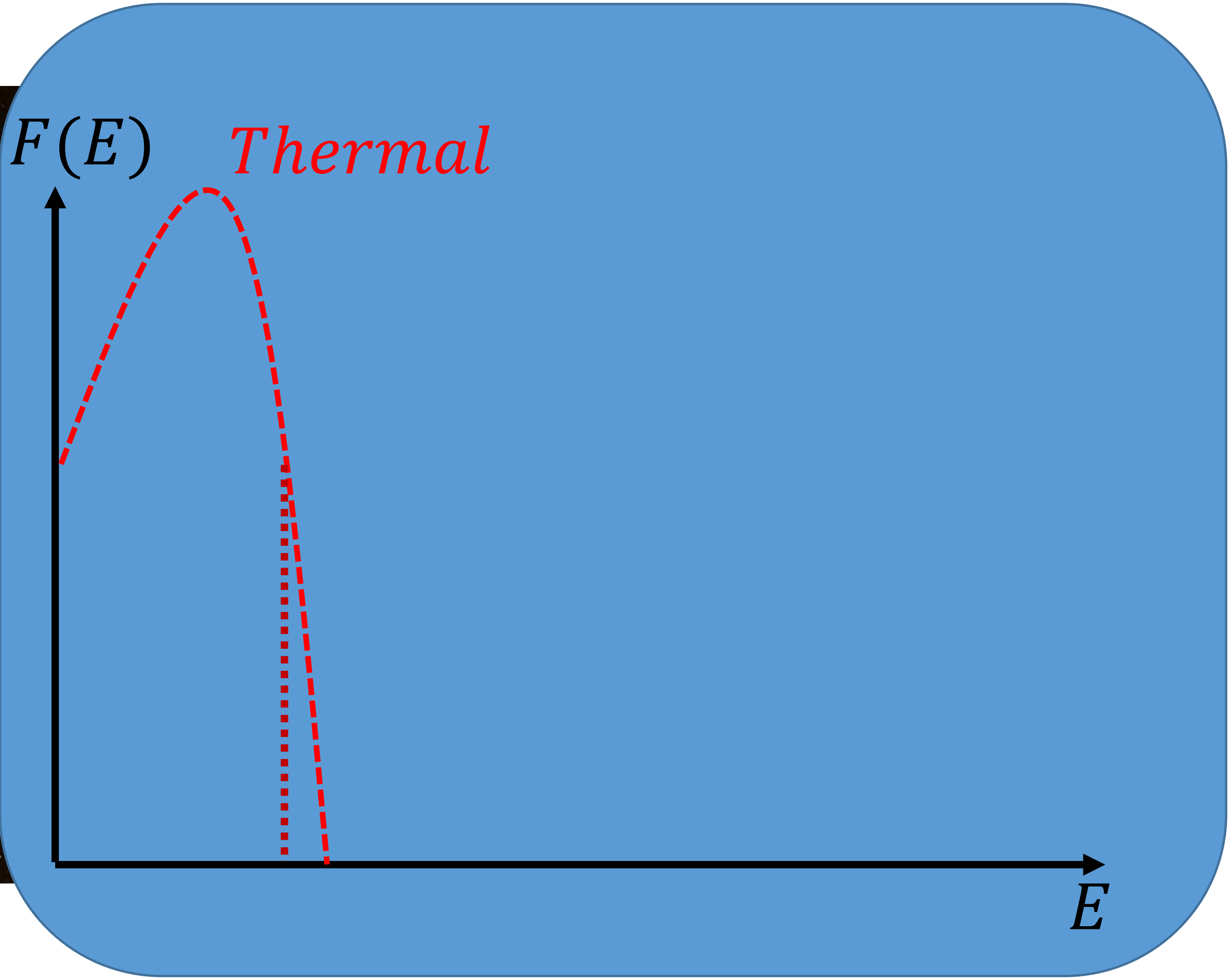

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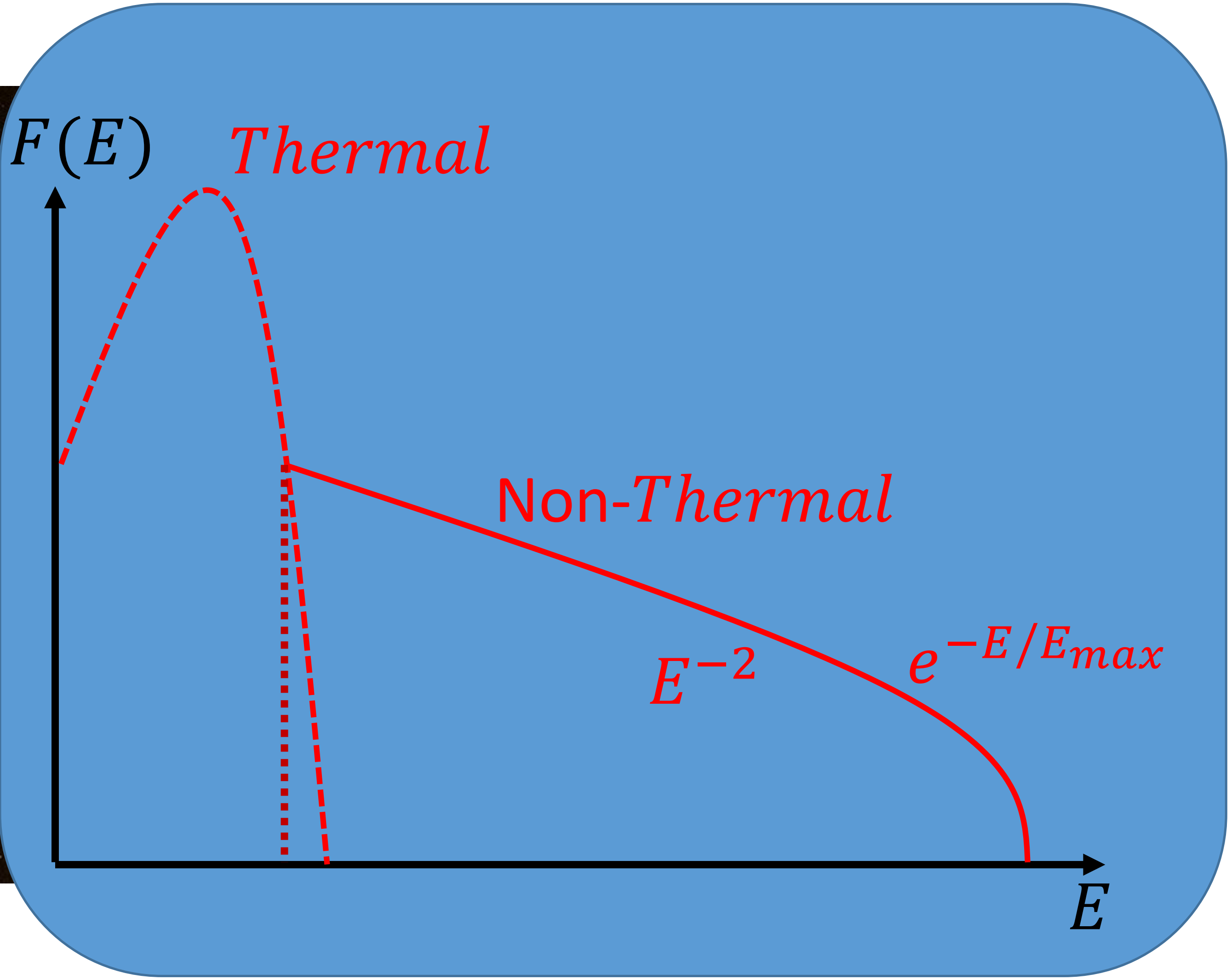

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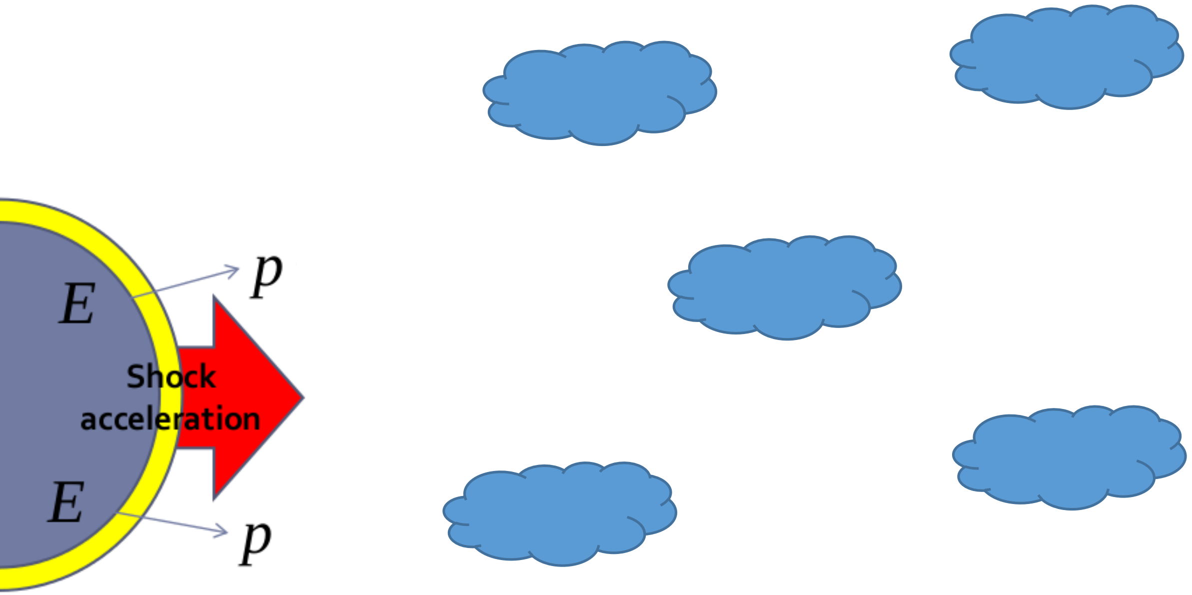
Inelastic collisions and hadronic byproducts

High energy protons can escape the accelerator



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

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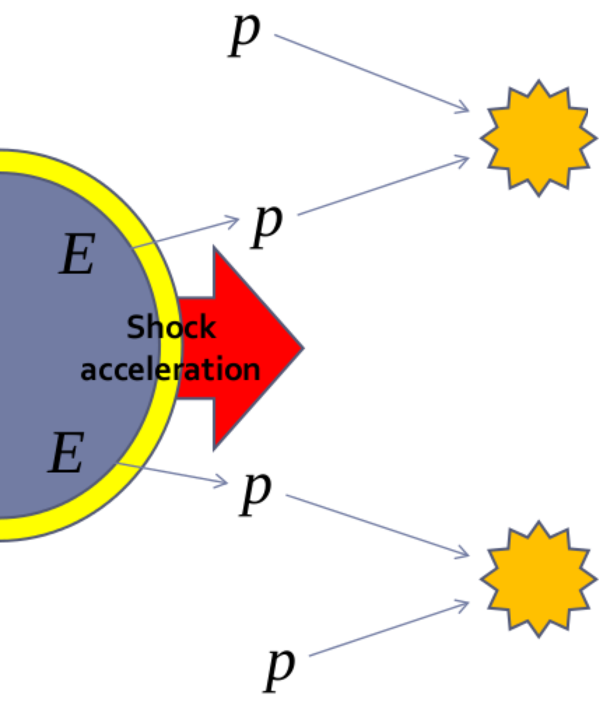

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- Escaping protons can interact with gas in the external medium

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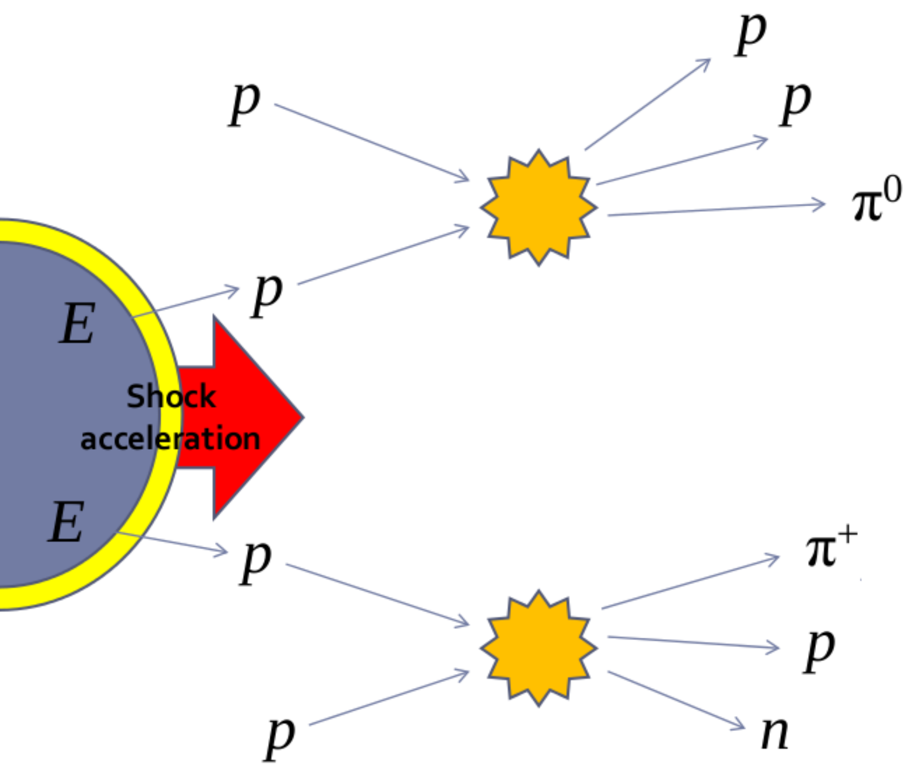

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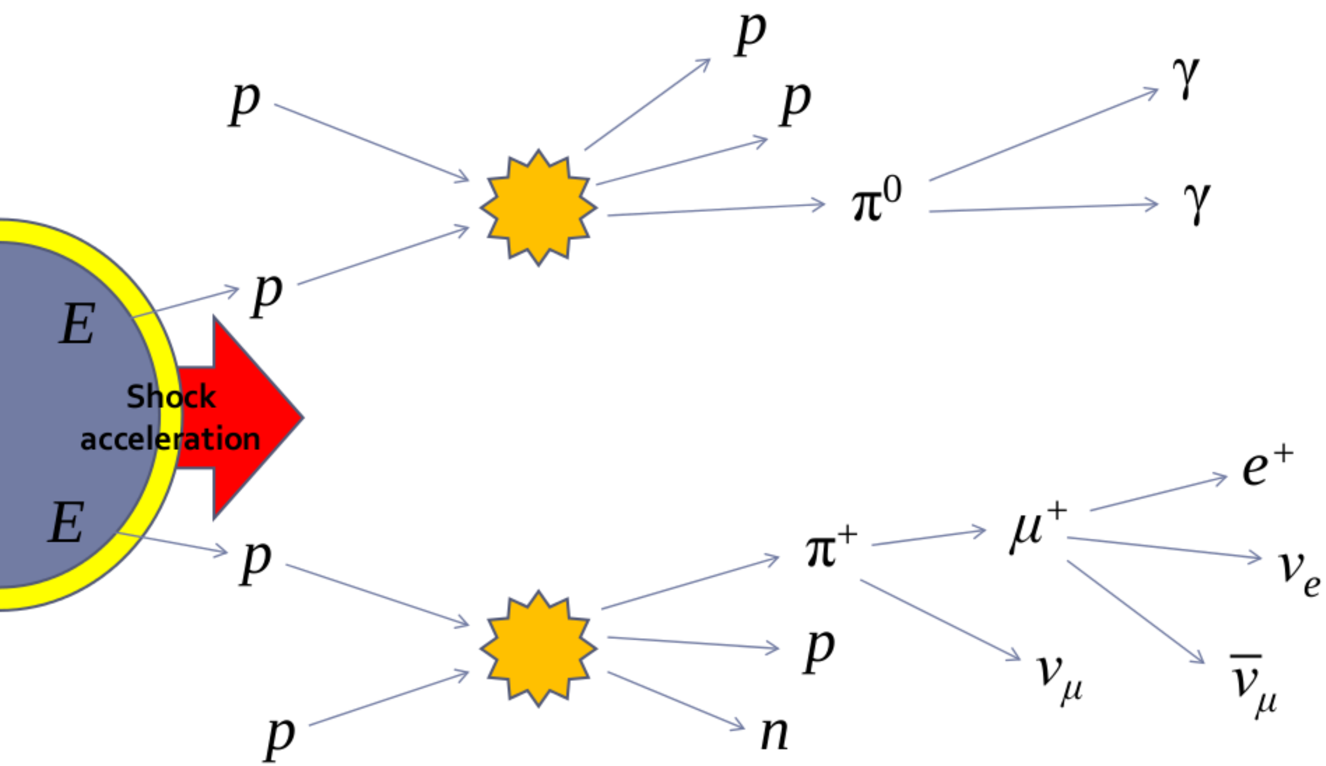

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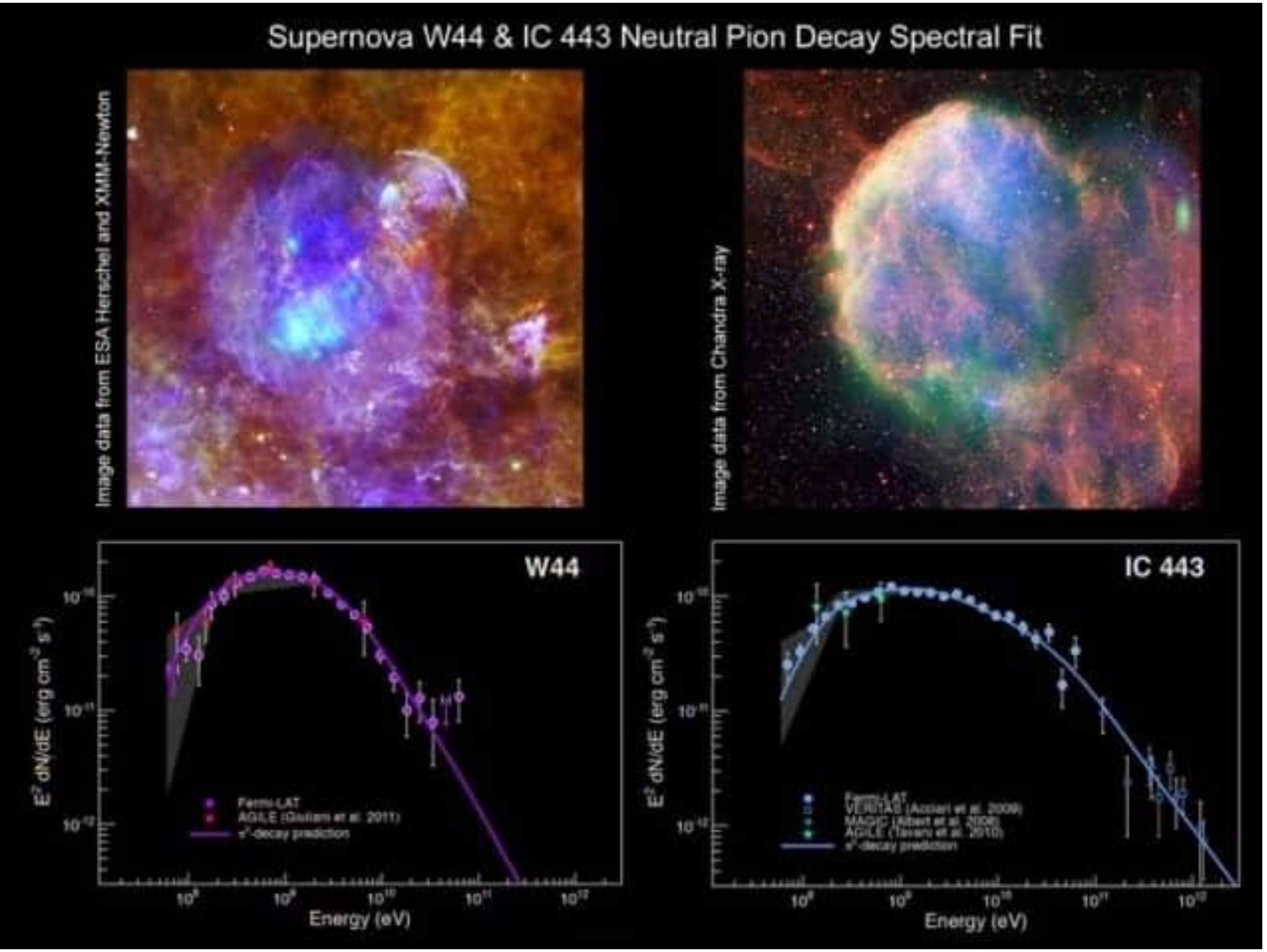

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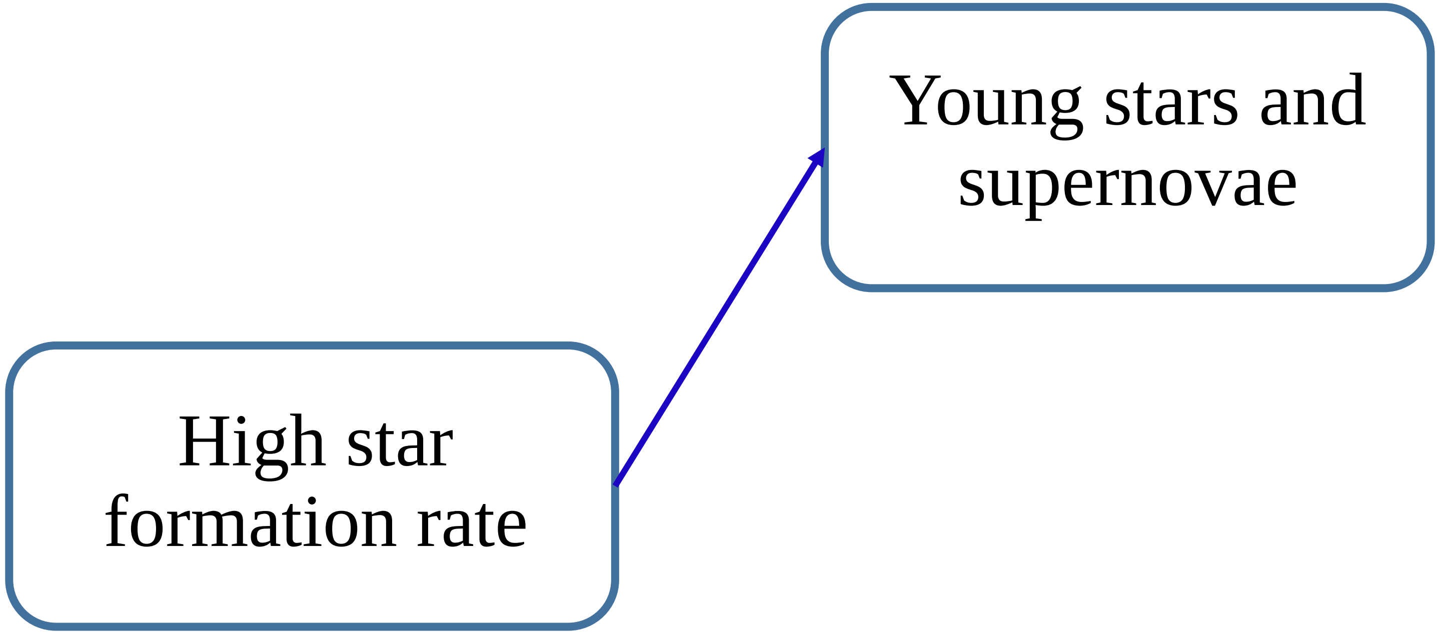
Why Starburst Galaxies?

High star
formation rate

Why Starburst Galaxies?



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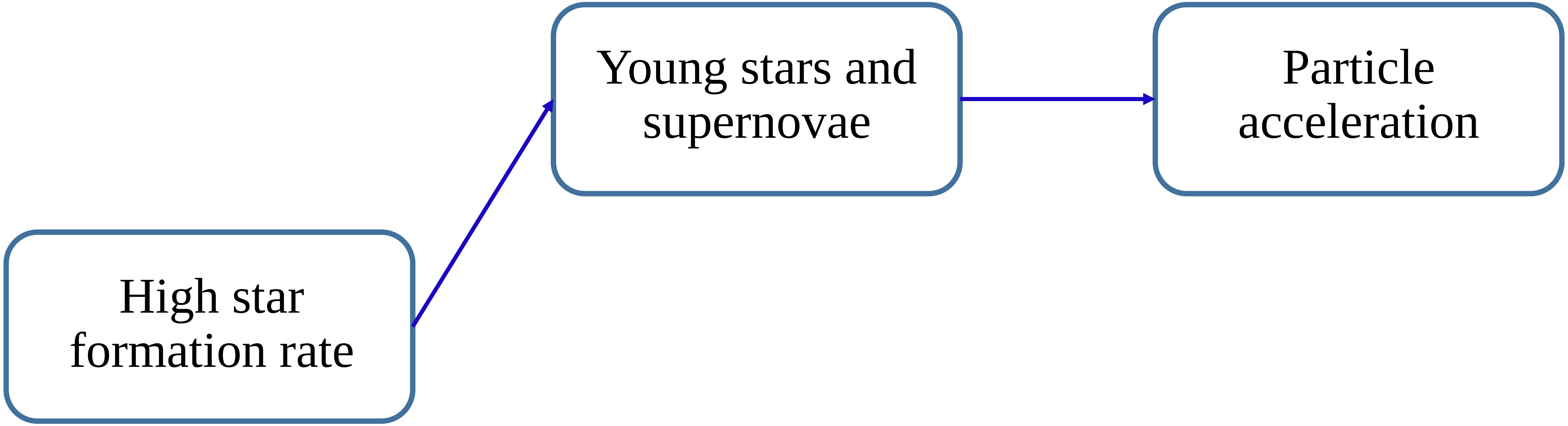

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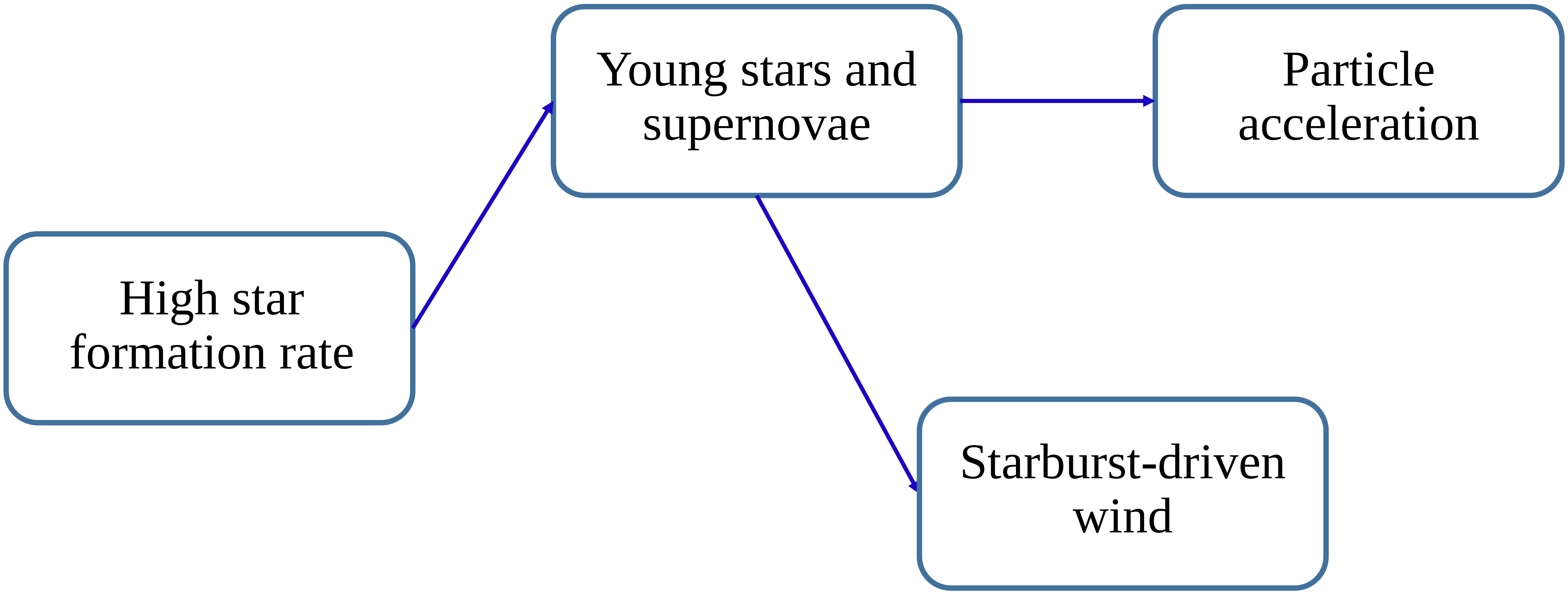

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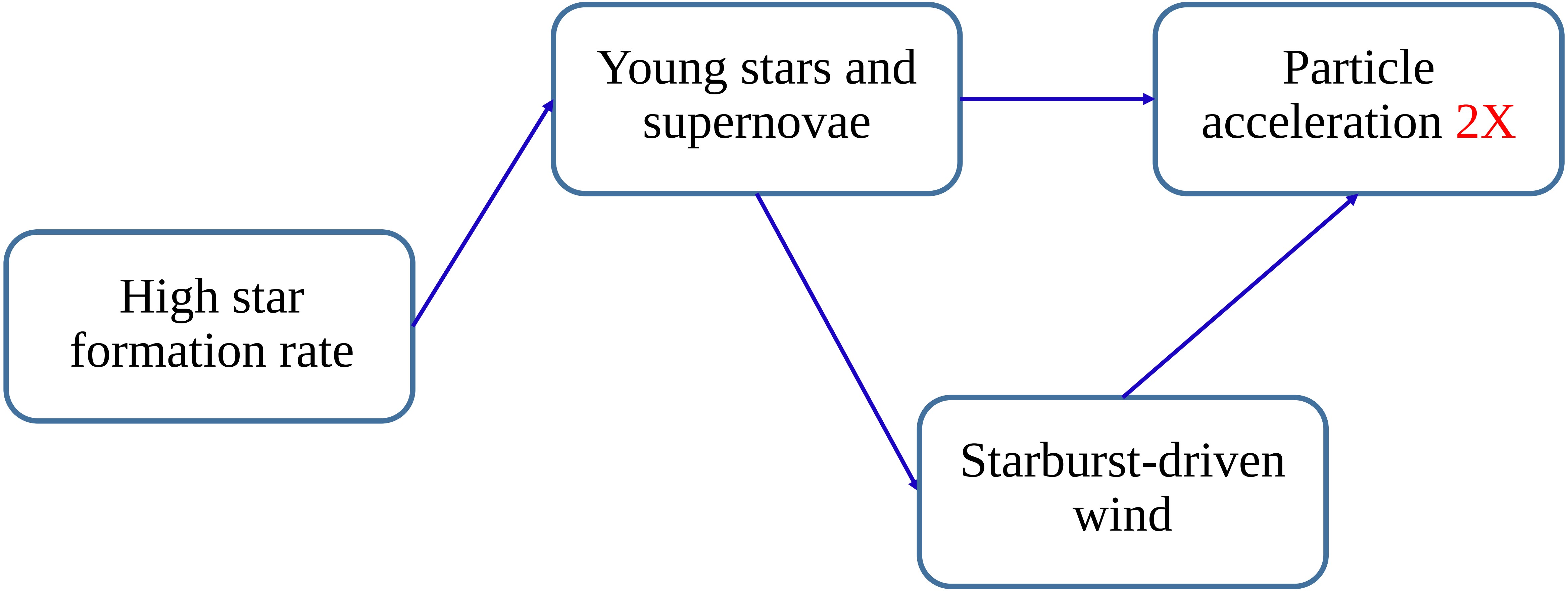

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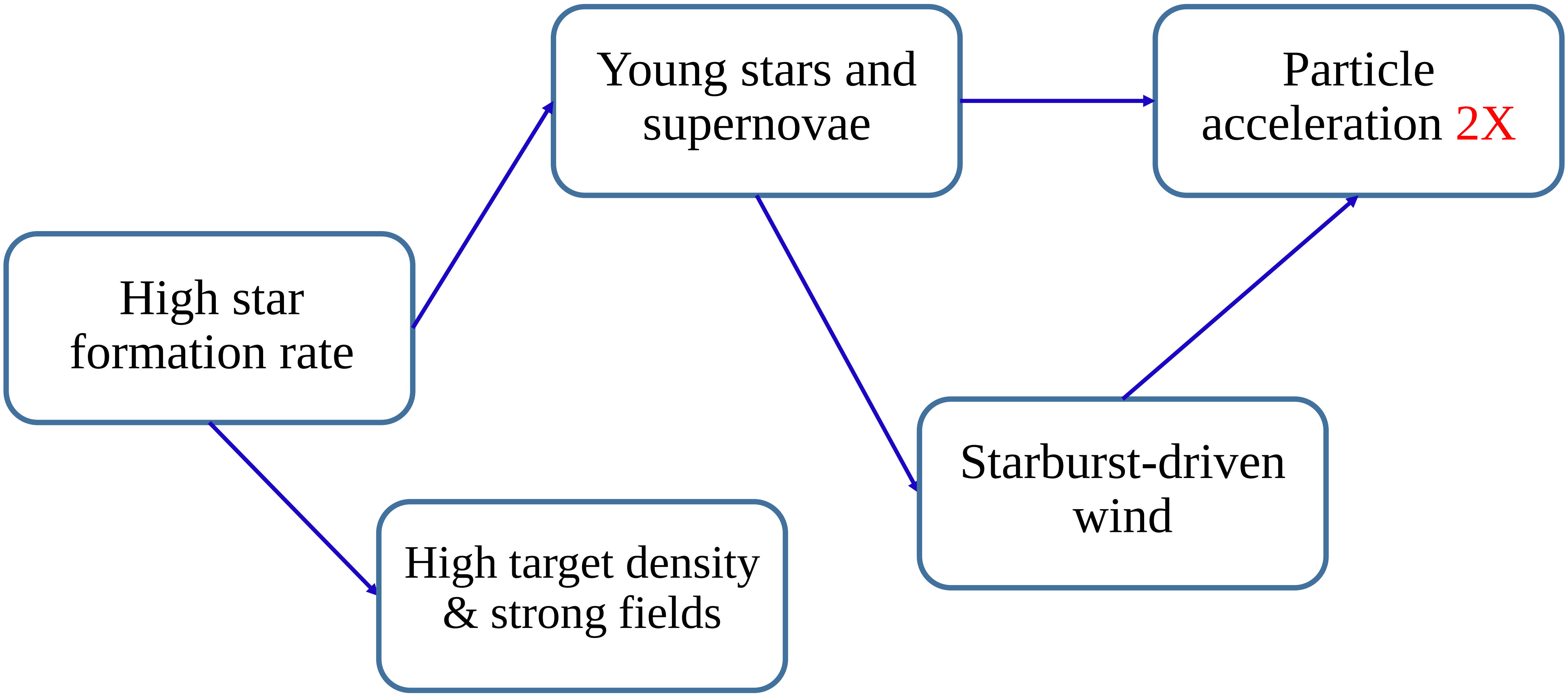

Why Starburst Galaxies?

Particle acceleration 2X

High target density & strong fields

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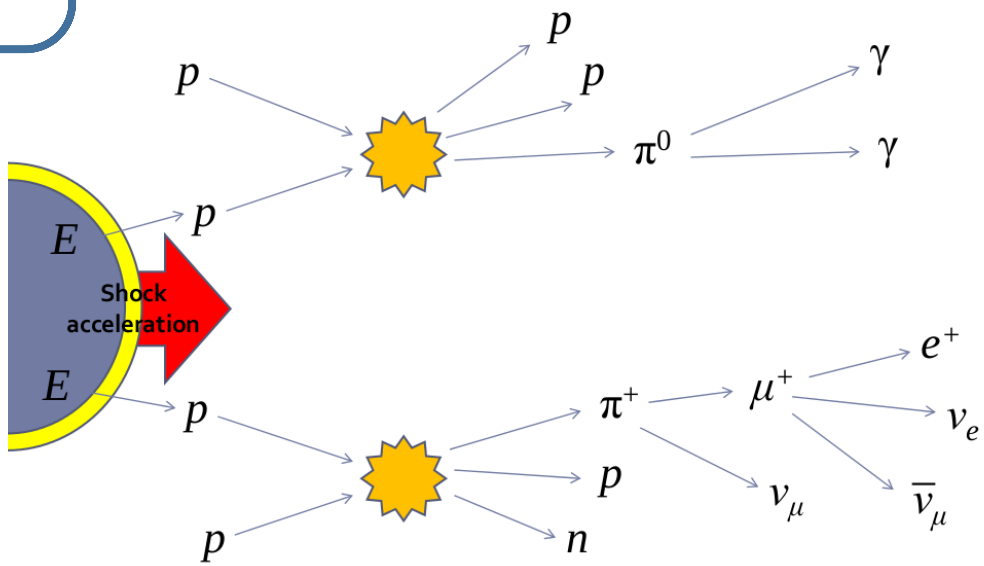
Particle acceleration 2X

Interactions

High target density & strong fields



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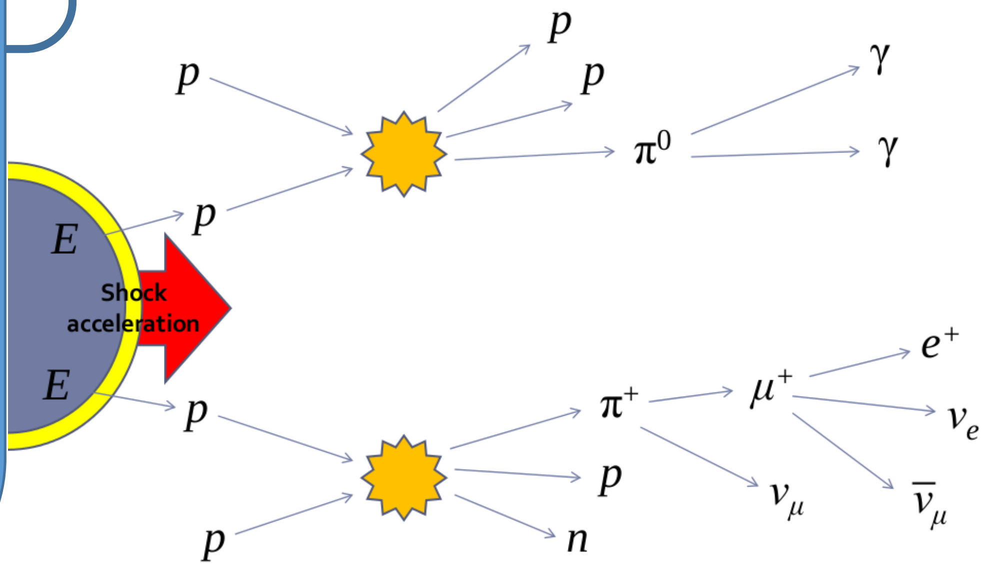
Why Starburst Galaxies?

From starburst galaxies we expect:

- High-energy neutrinos E>0.1 GeV
- Power-law distribution
- Maximum energy model dep.

Particle acceleration 2X



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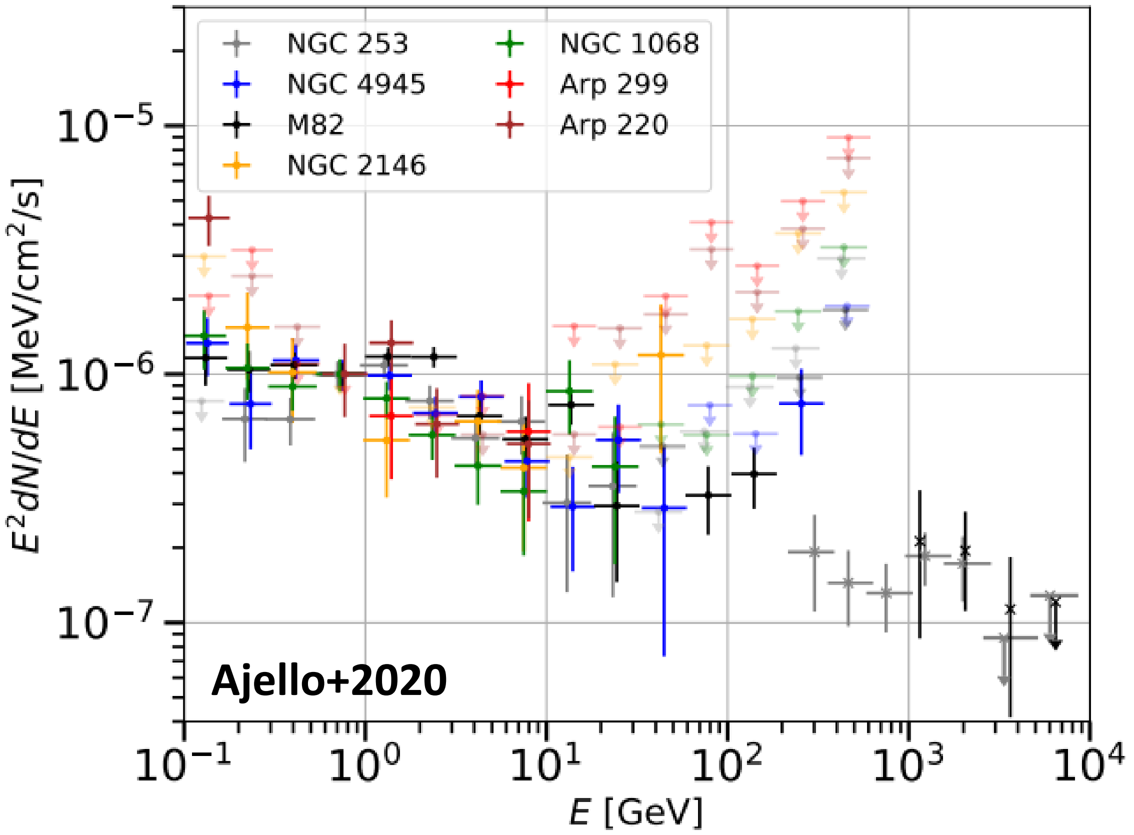
Observation of Starburst Galaxies - Gamma



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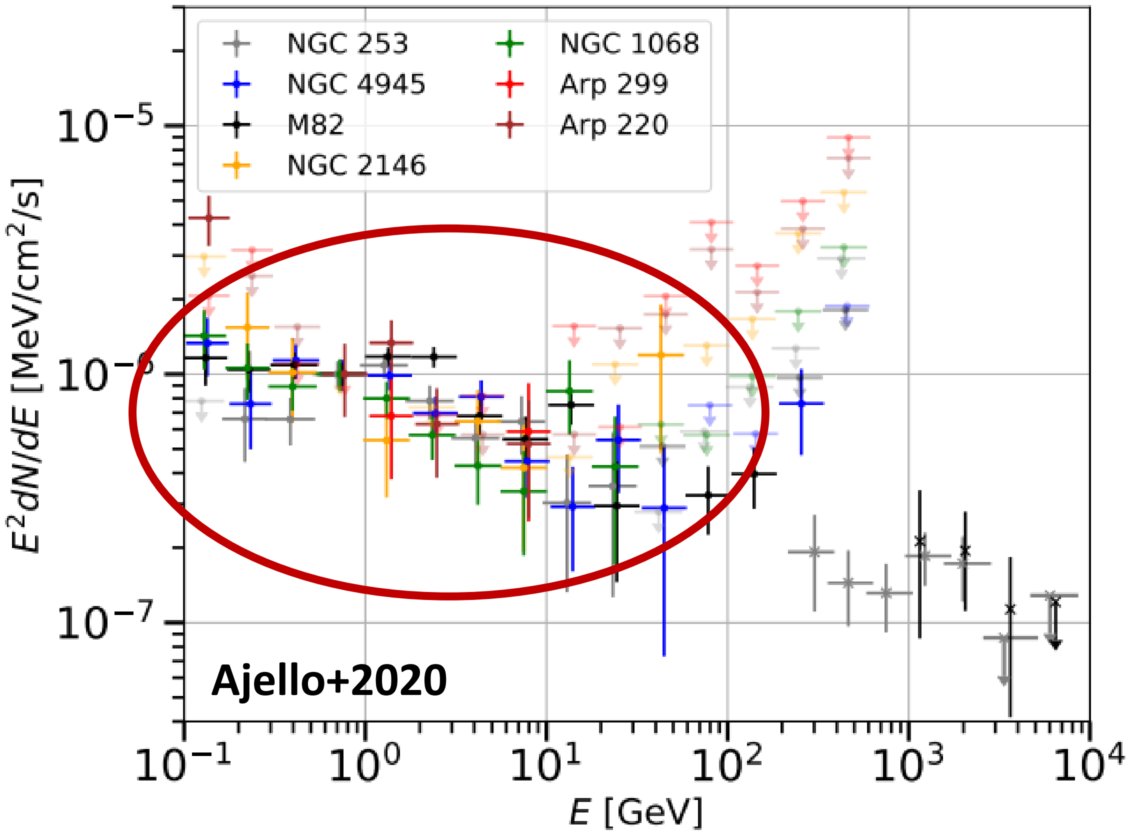

- Starbursts observed at GeV

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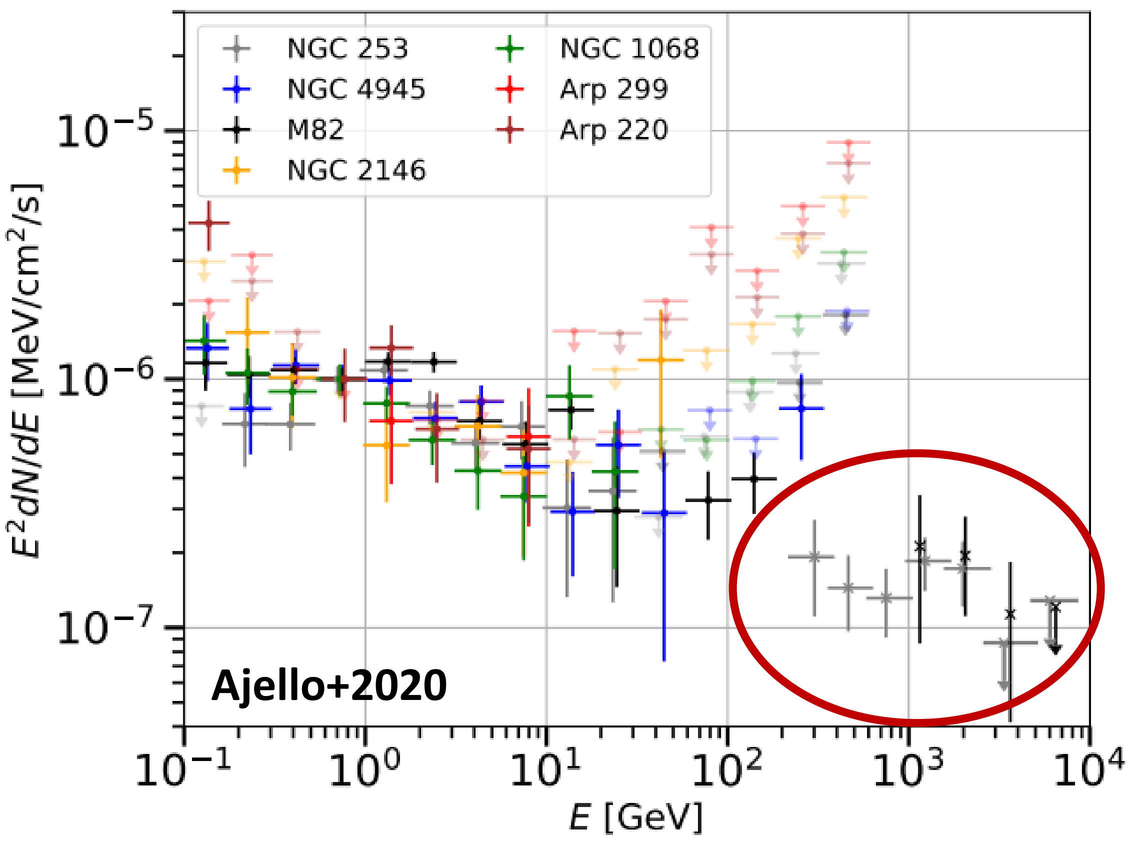

- Starbursts observed at GeV

- Most nearby observed at TeV (<4 Mpc)

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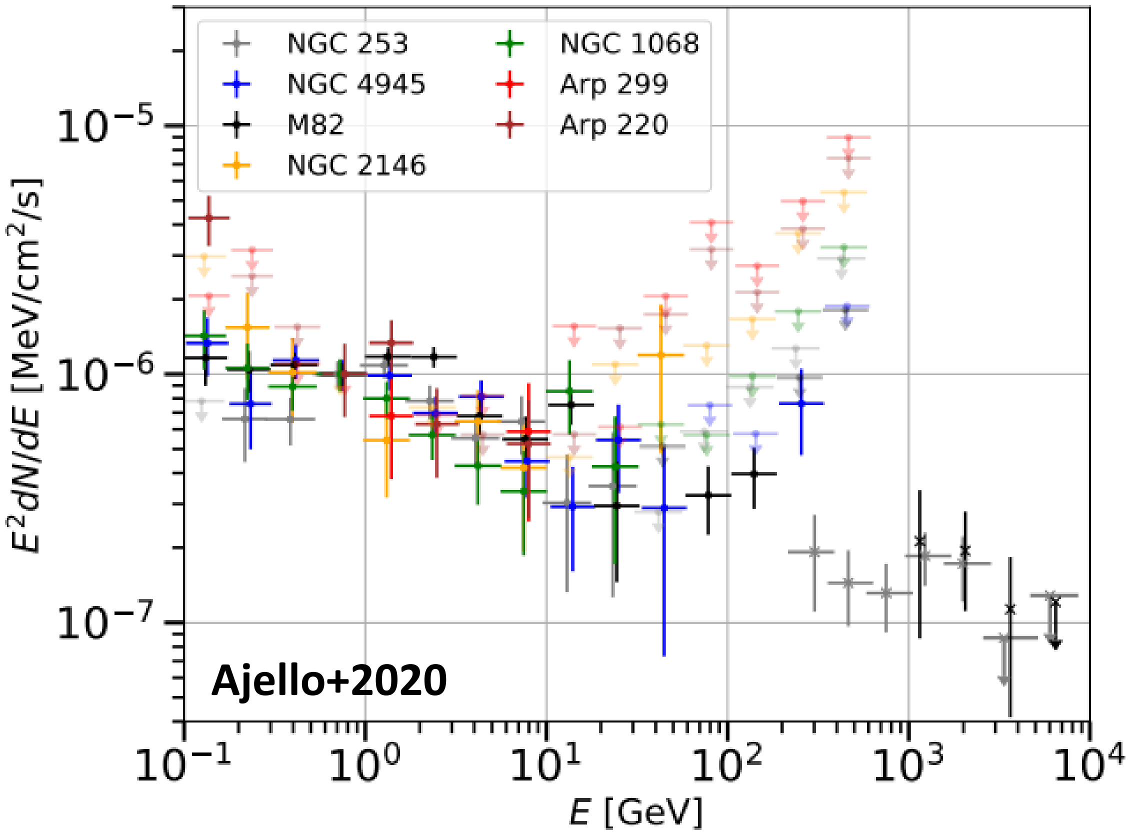
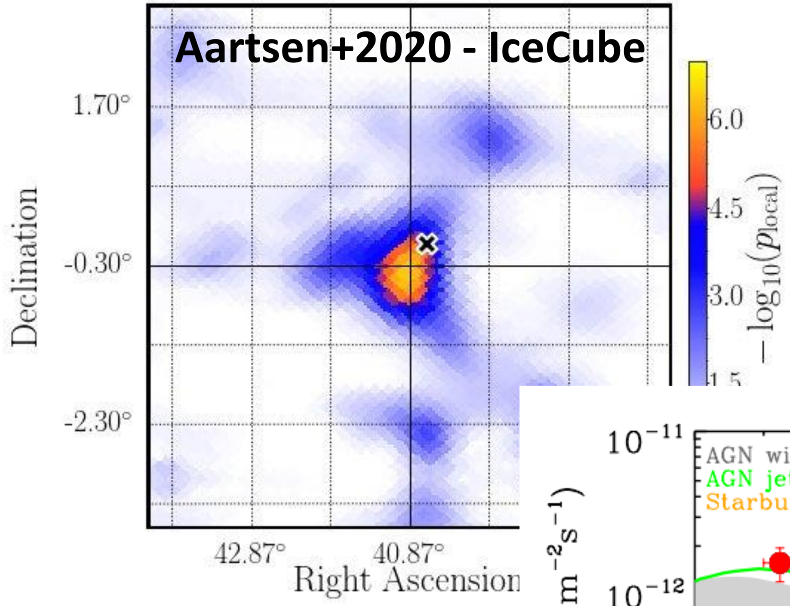
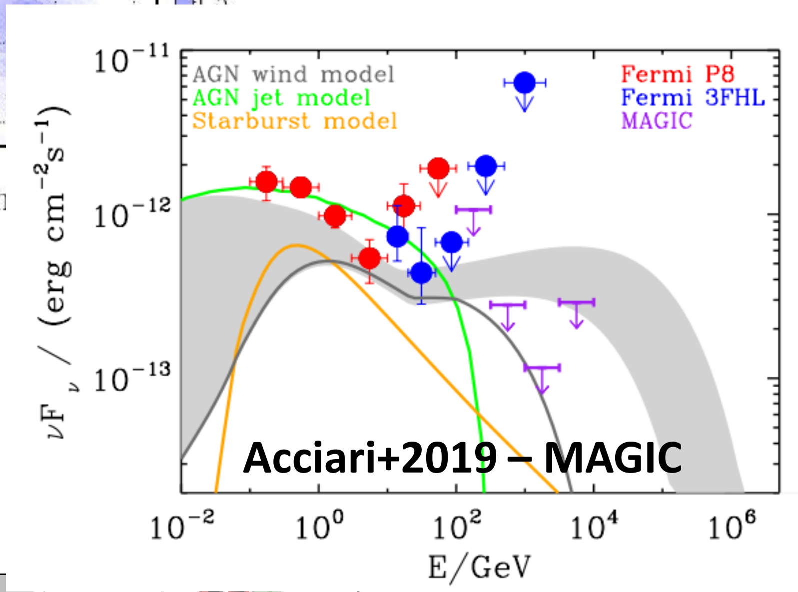
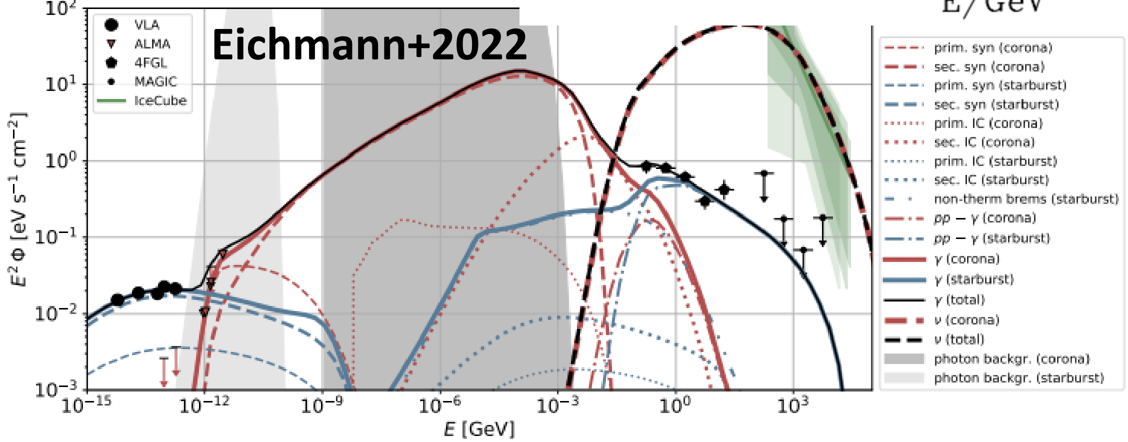


- Starbursts observed at GeV
- Most nearby observed at TeV (<4 Mpc)
- Most distant: Arp 220 (77 Mpc)

Observations - Neutrinos



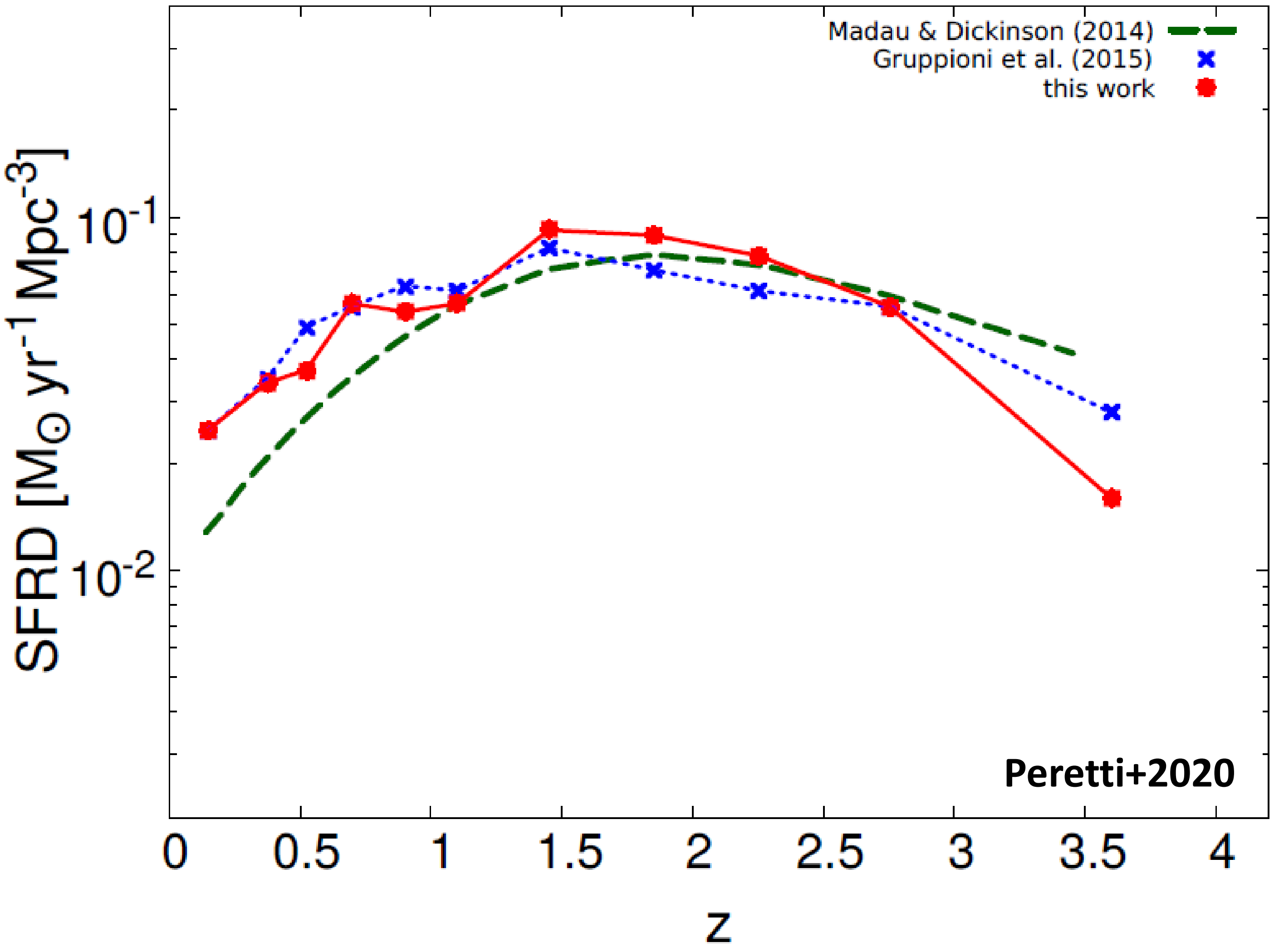




Indications of neutrino production at TeV the nearby NGC1068 while gamma is limited below 10^2 GeV

- Starburst emission?
- AGN jet? AGN wind?
- Other sources?

Another reason to study Starbursts



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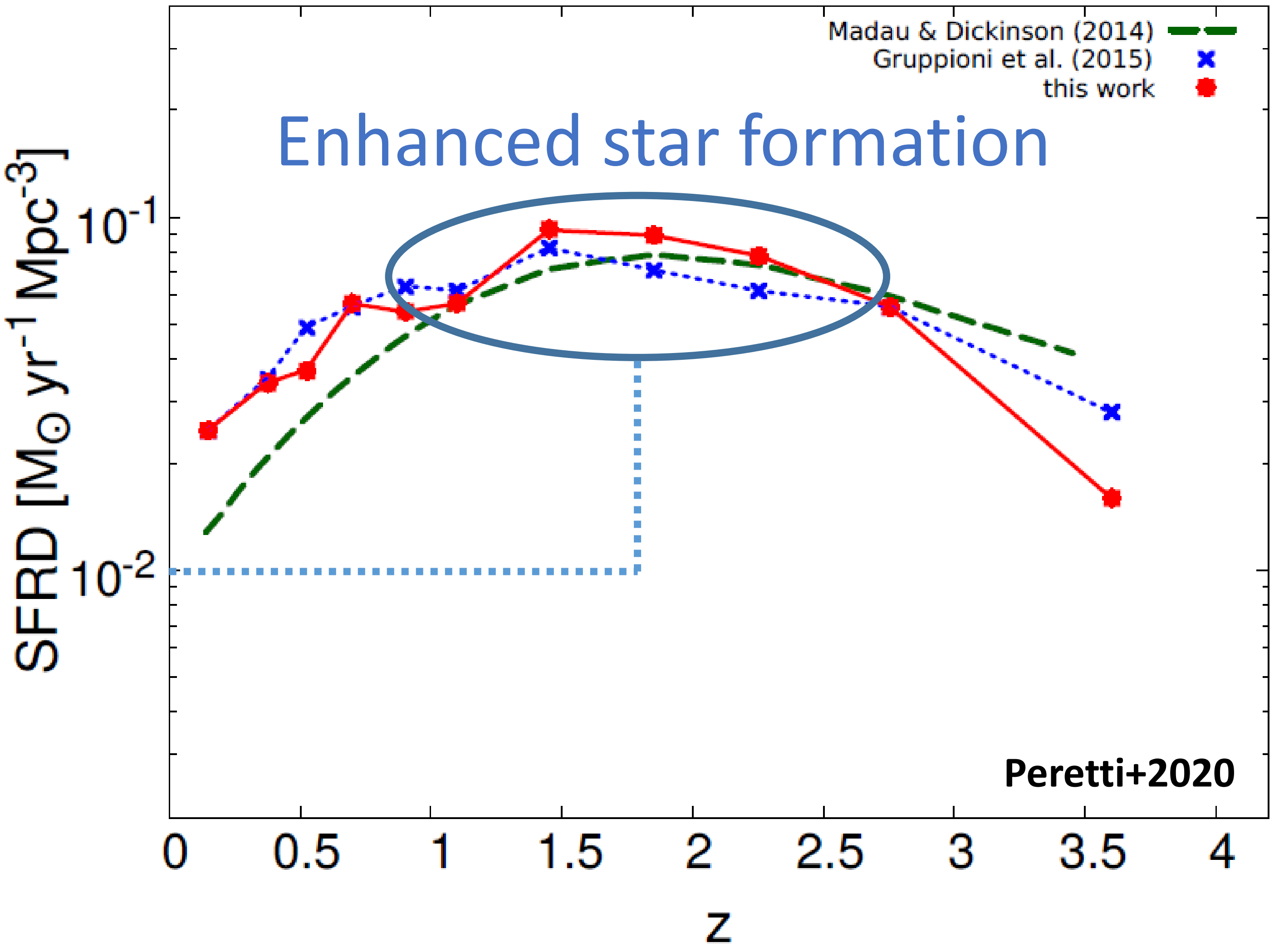
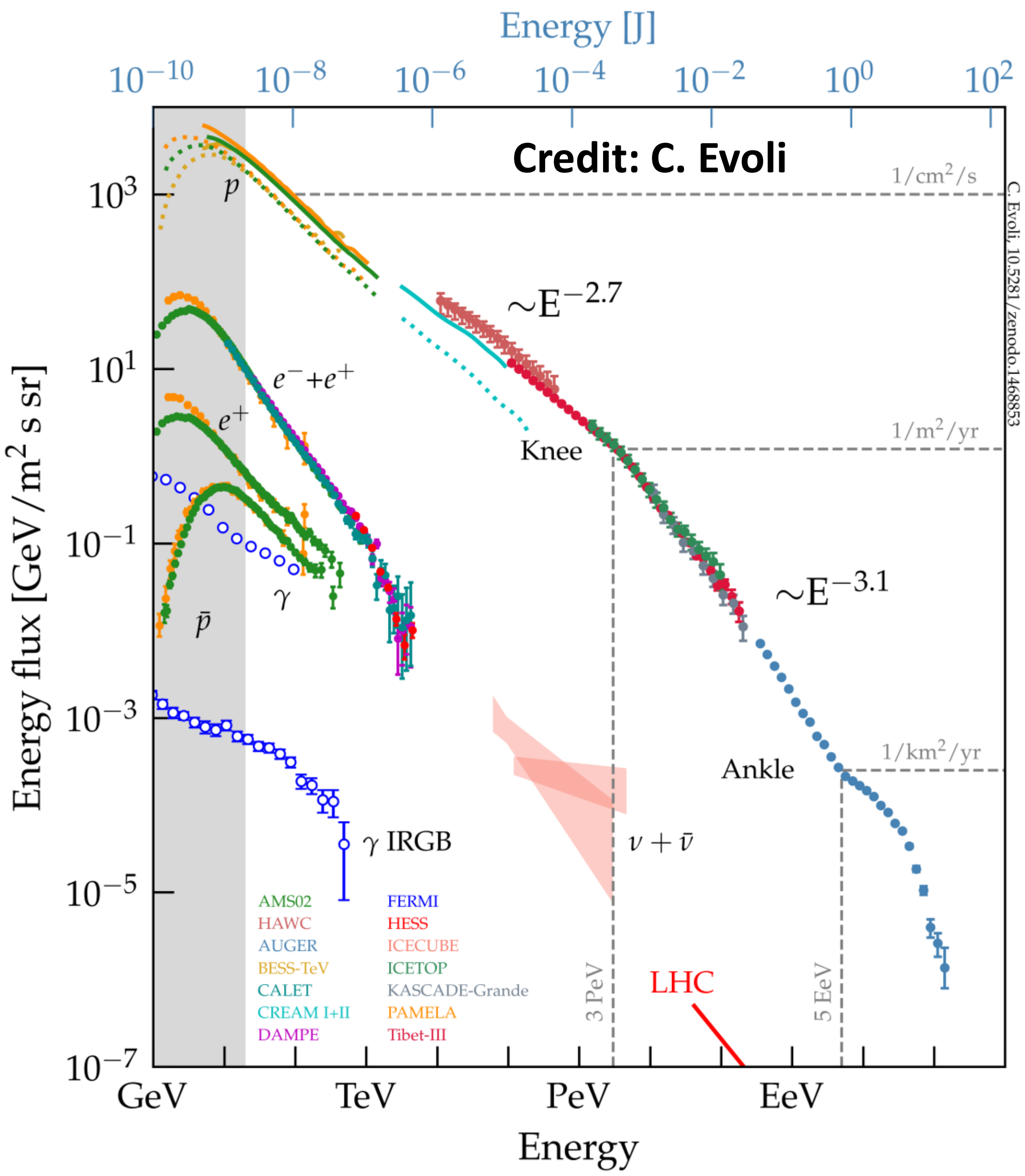
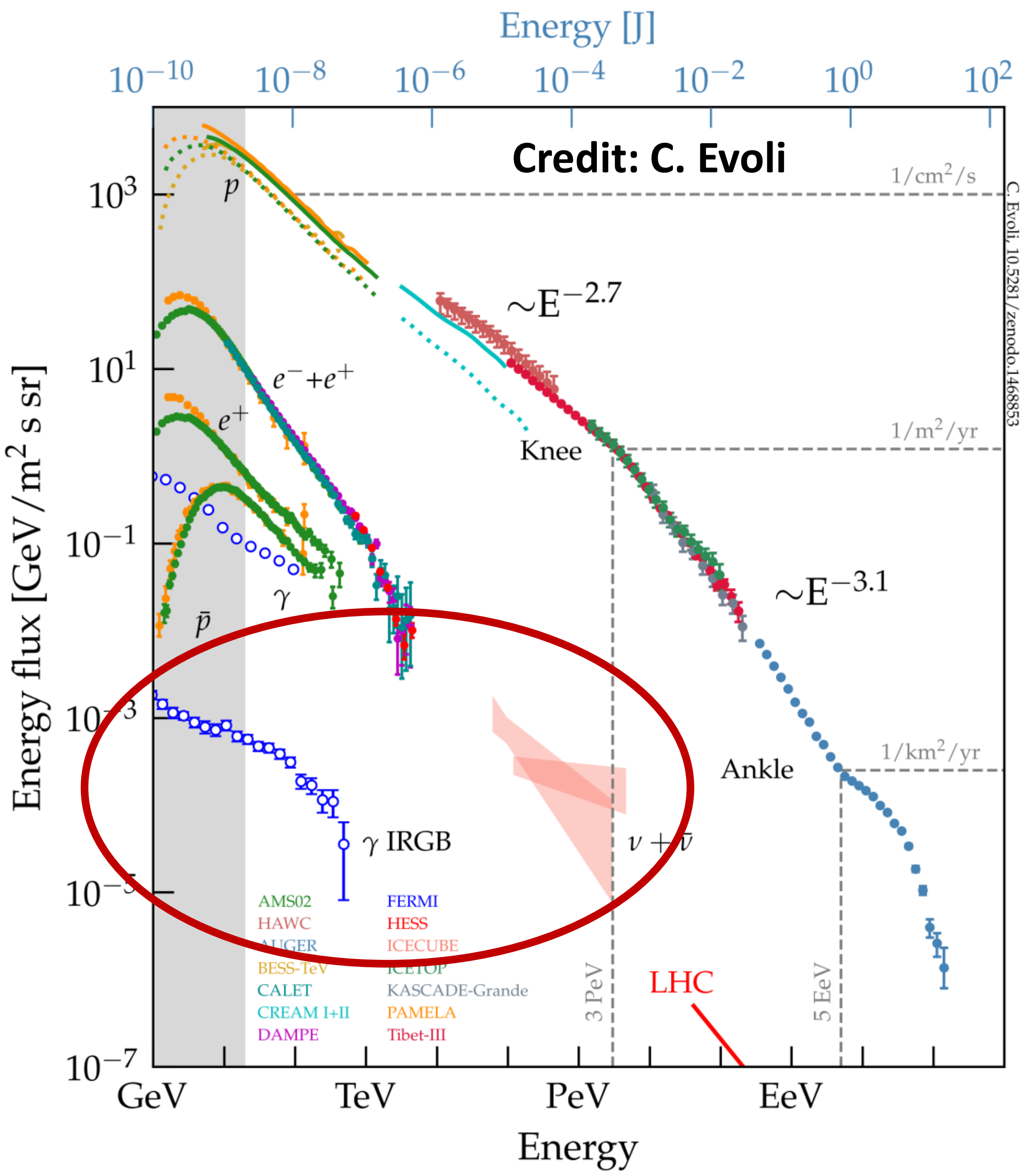


Diffuse radiation from starburst



Starbursts are expected to shine on gamma rays and neutrinos

Diffuse radiation from starburst



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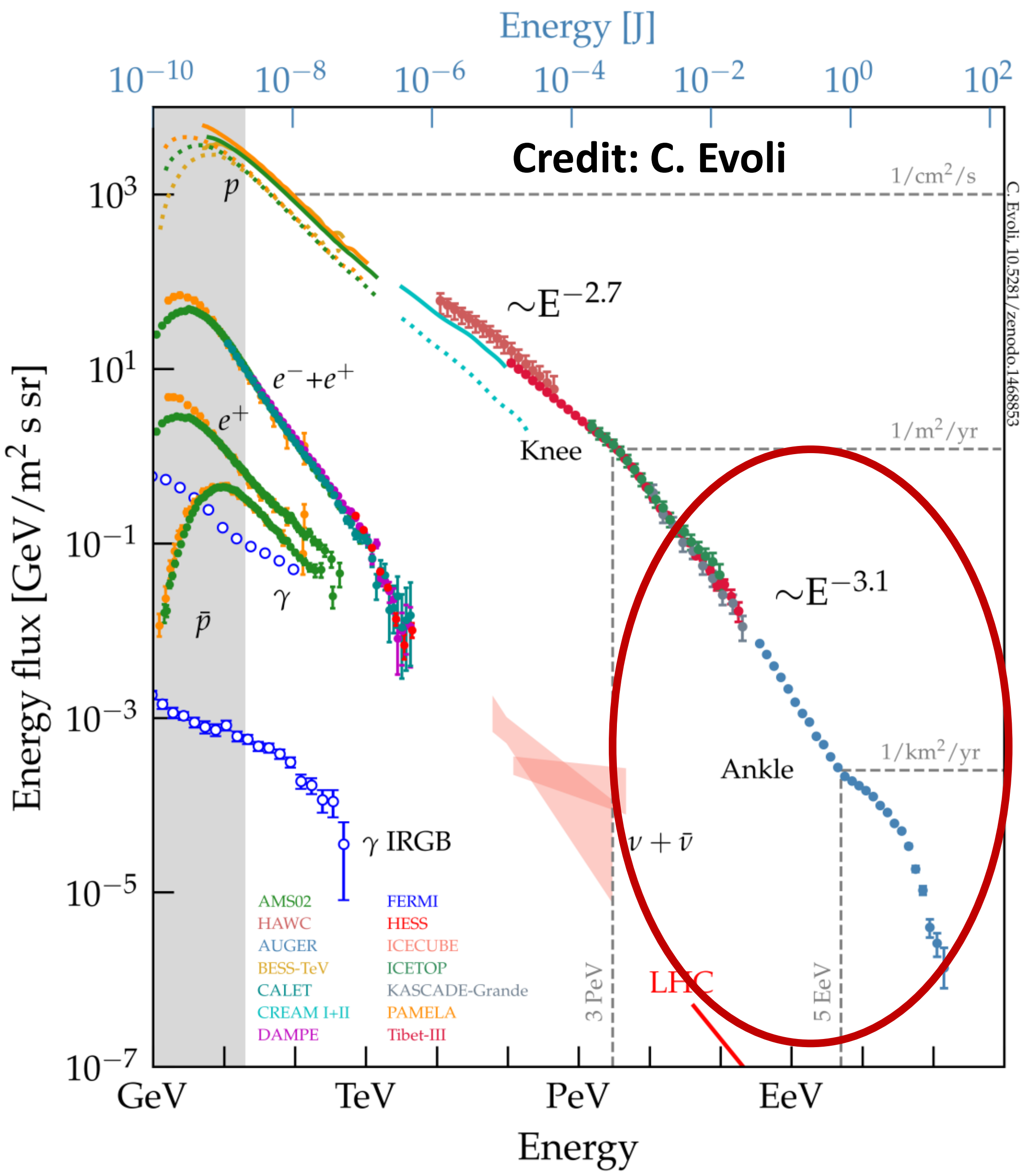
- At which level can they contribute to the observed diffuse fluxes?

Diffuse radiation from starburst



Starbursts 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?

Motivations for studying Starburst Galaxies

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

Outline

- Cosmic ray transport
- Particle Transport in Starburst Nuclei
- Diffuse emission from Starburst Galaxies

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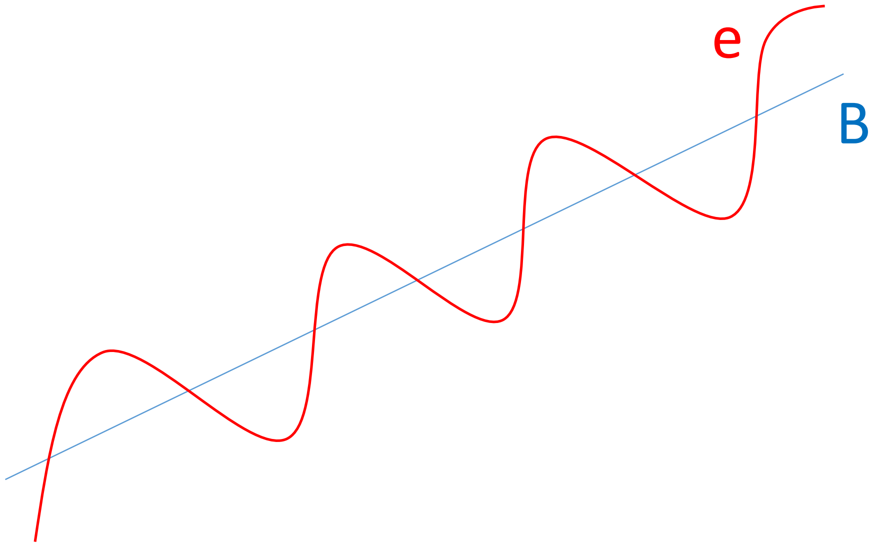
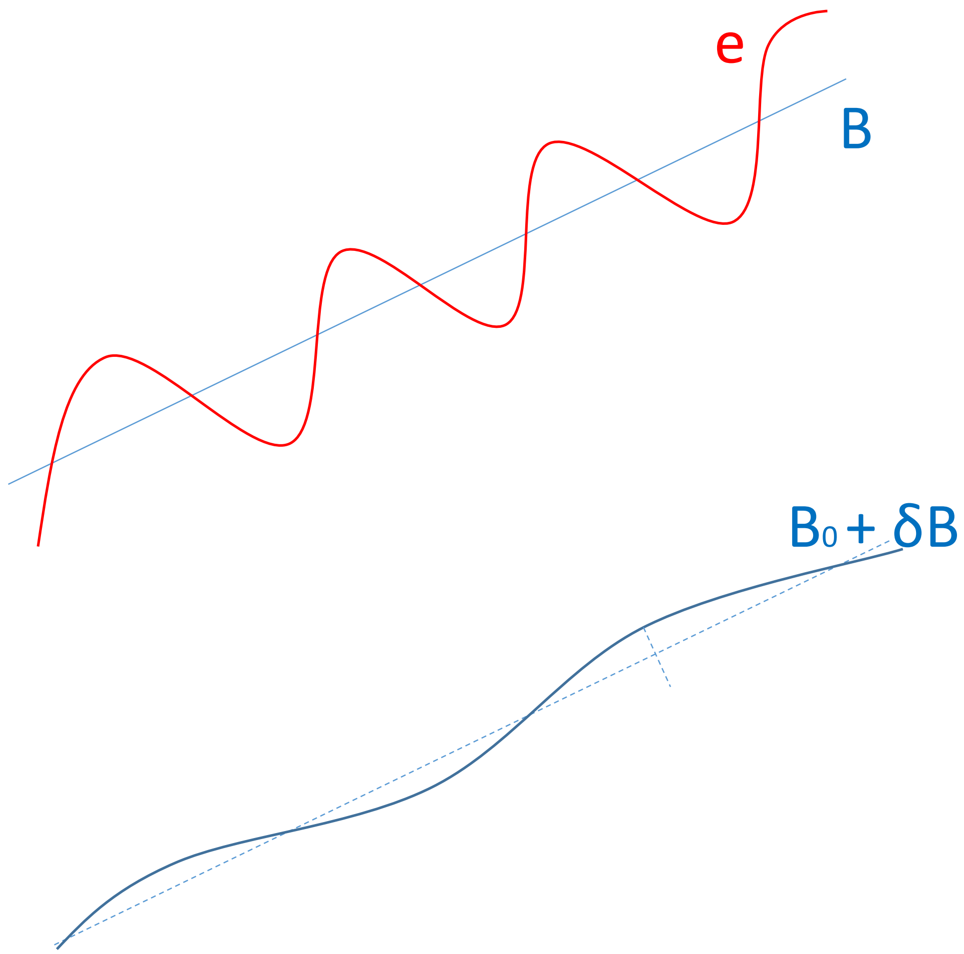
Physics of cosmic rays: Diffusion - 1



- Charged particles follow helical paths around magnetic field line in ideal conditions

Physics of cosmic rays: Diffusion - 1



- The ISM is a turbulent plasma

- The magnetic field is also turbulent (δB)

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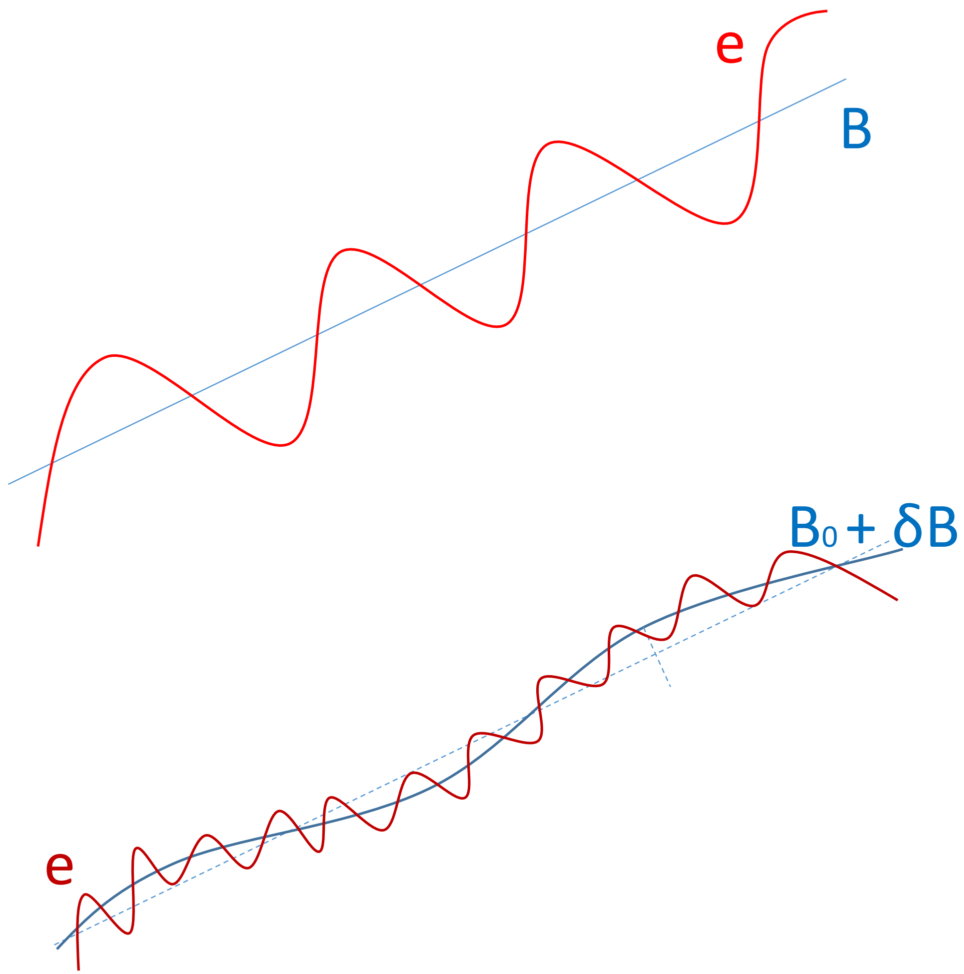

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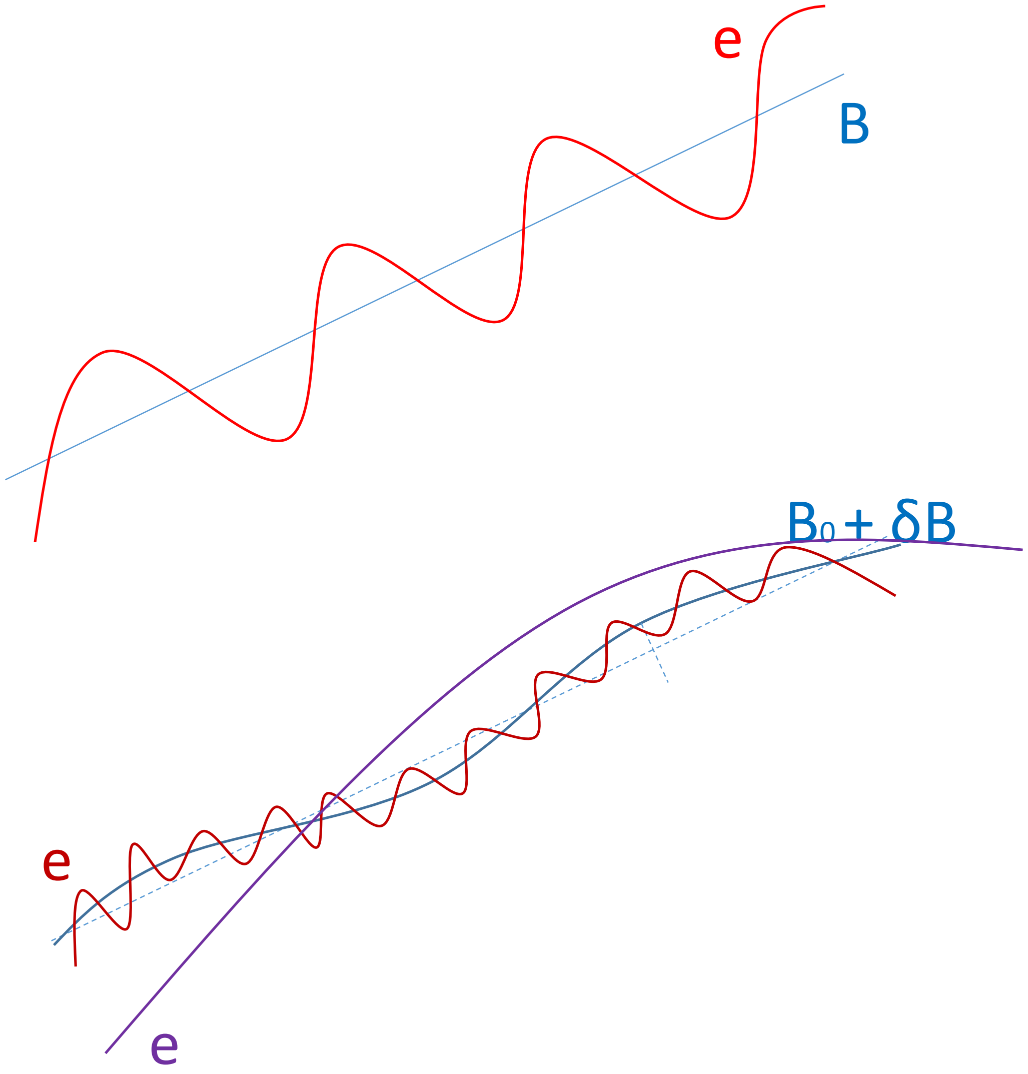

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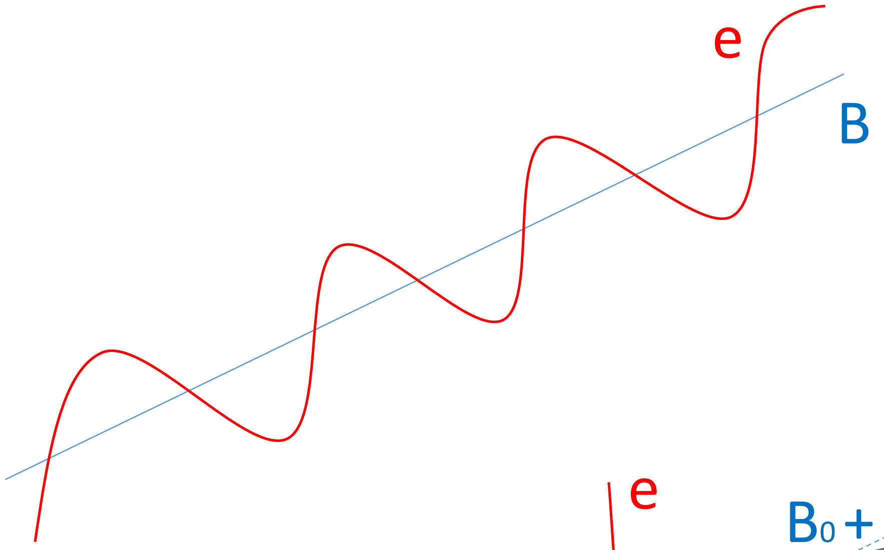

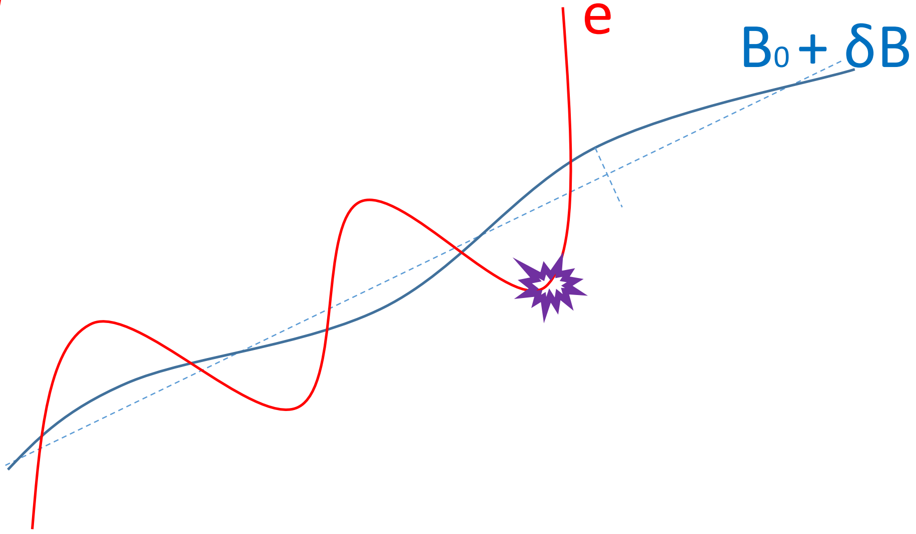

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- Particles pitch angle evolves in time when in presence of magnetic field disturbances

Helical motion→ Spatial diffusion

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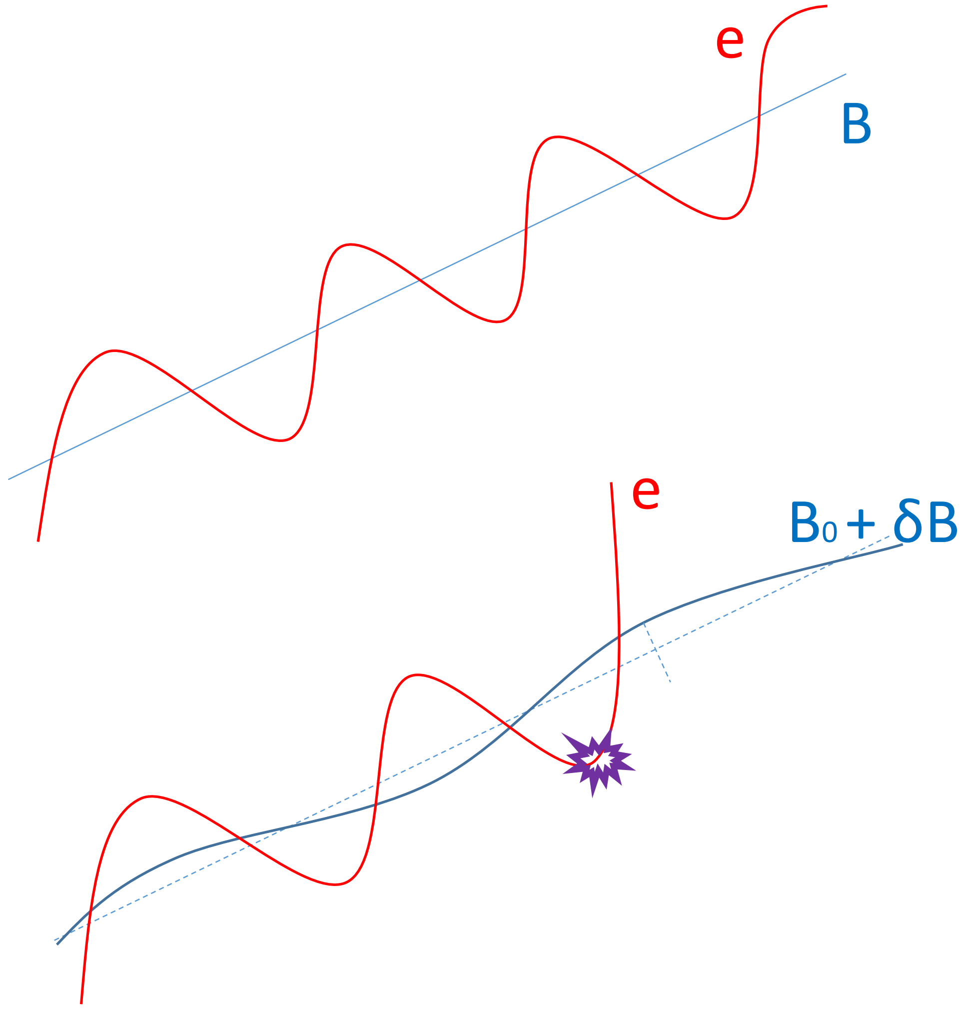

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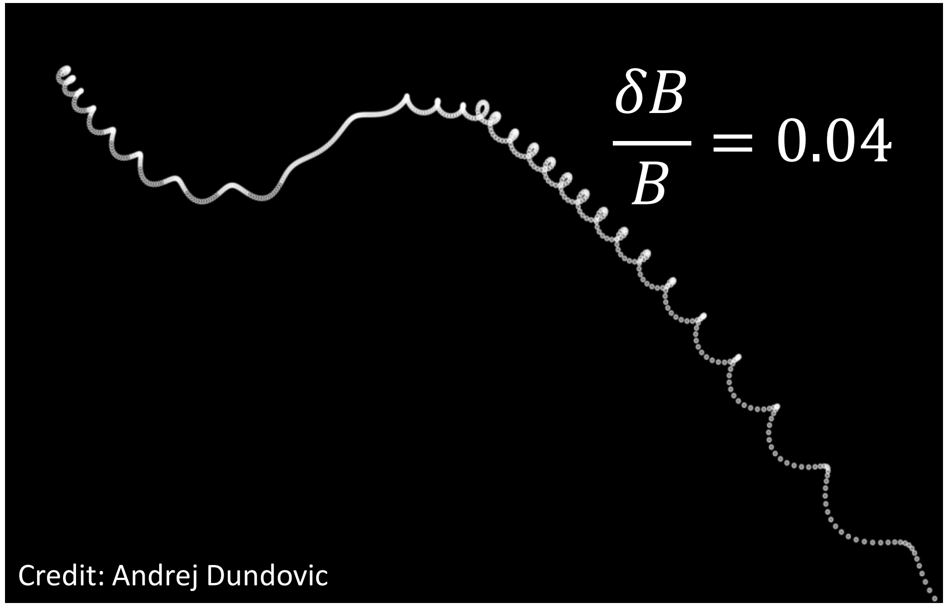
- Diffusion tensor/coefficient: $D(\vec{x},\vec{p})$

Physics of cosmic rays: Diffusion - 2



- Low turbulence environment allows to observe standard helical motions

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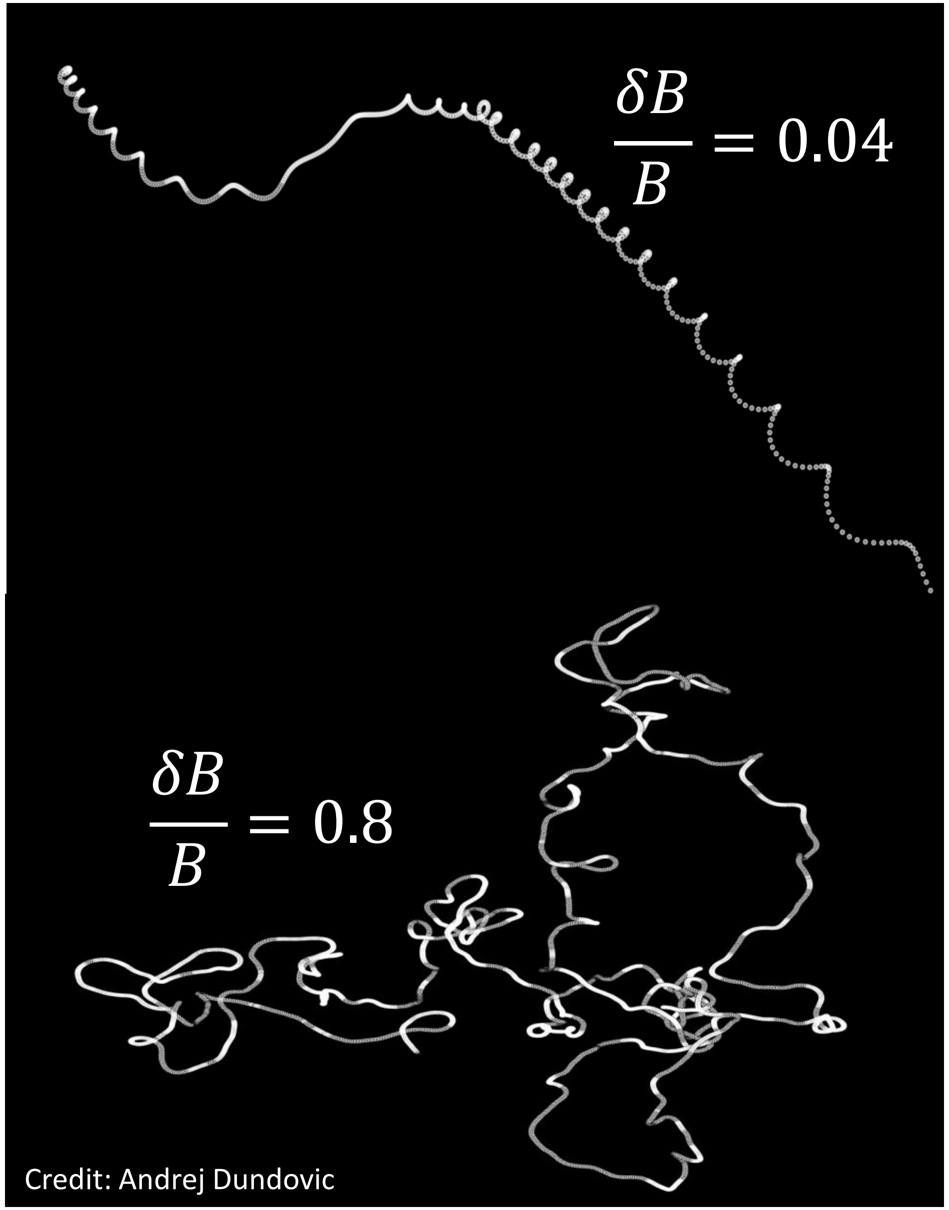

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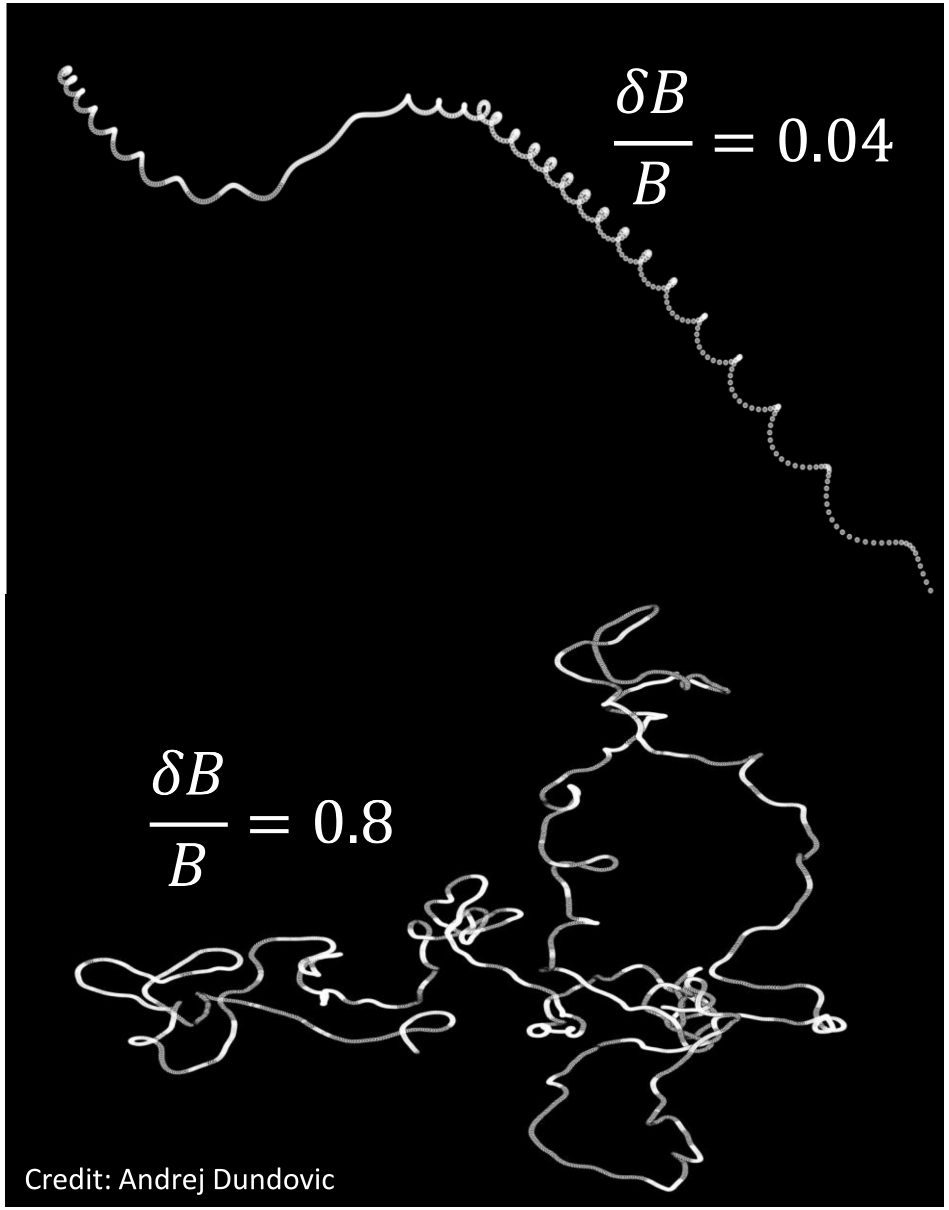

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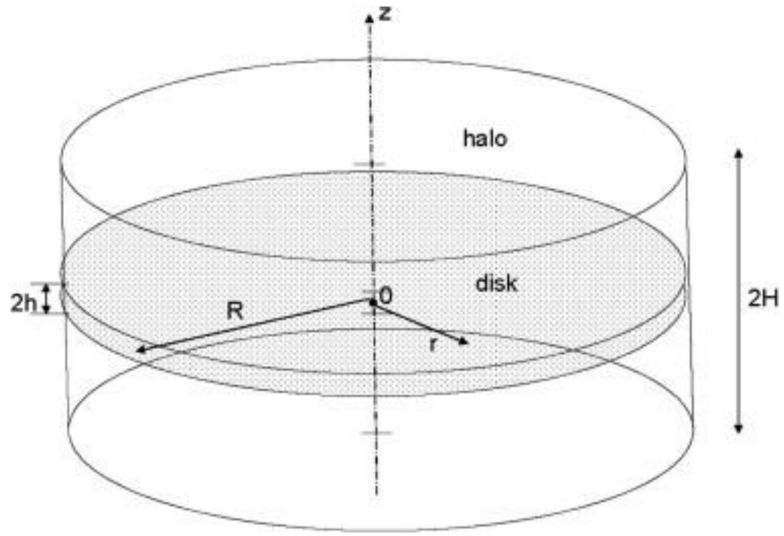

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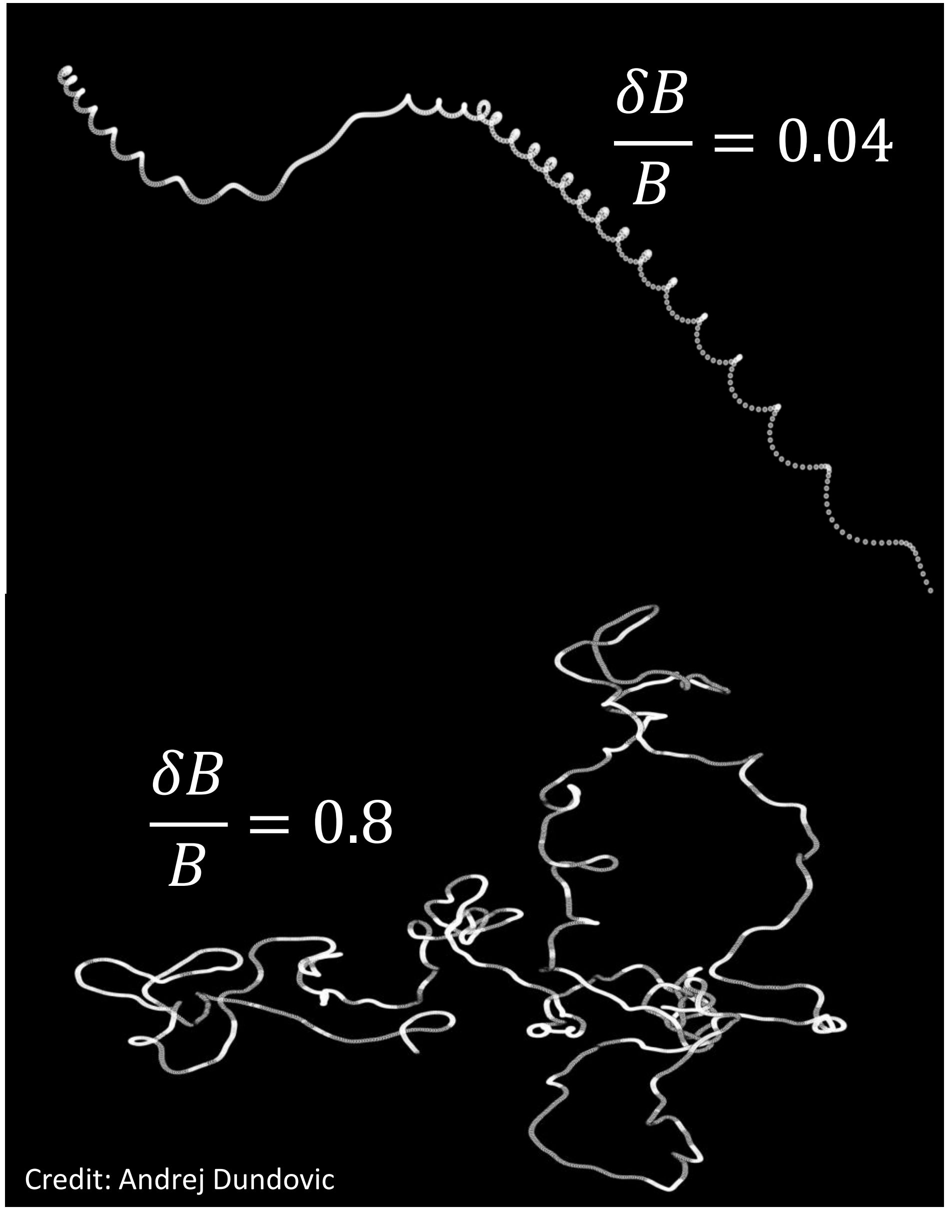

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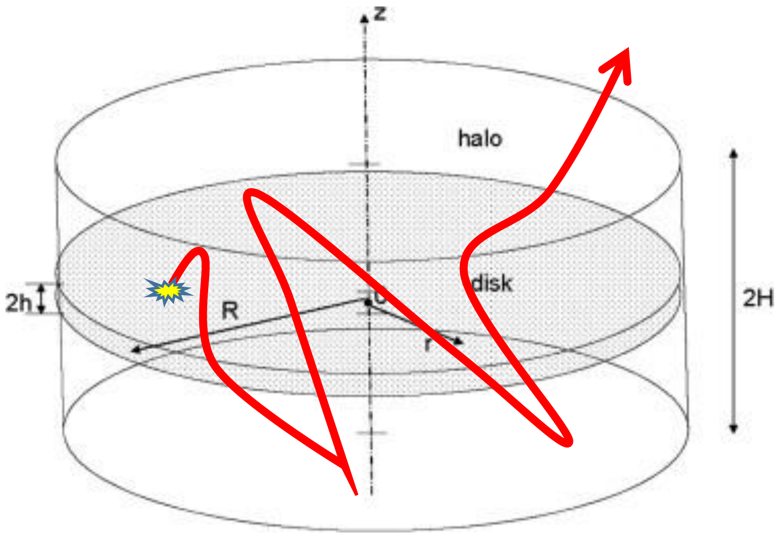
$$\tau_{diff}(E) \approx \frac{H^2}{D(E)}$$



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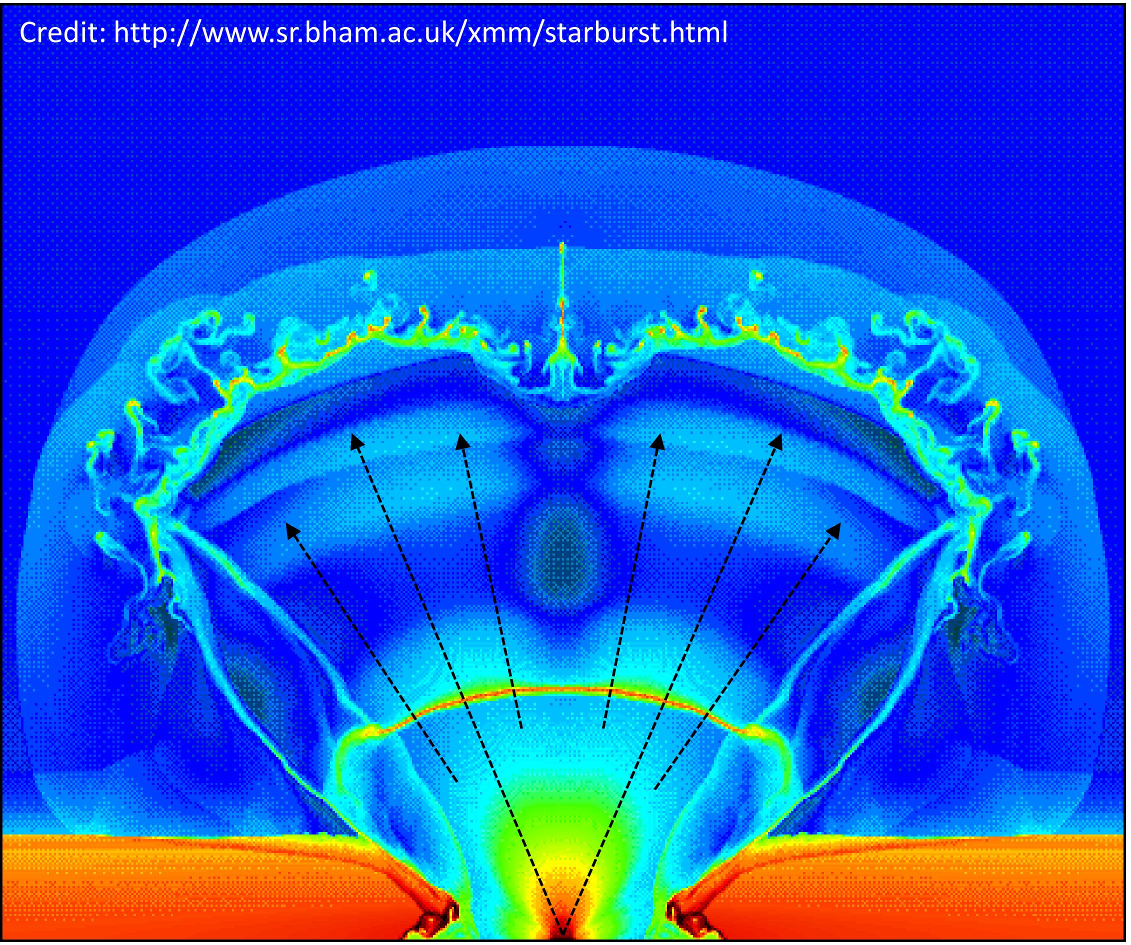
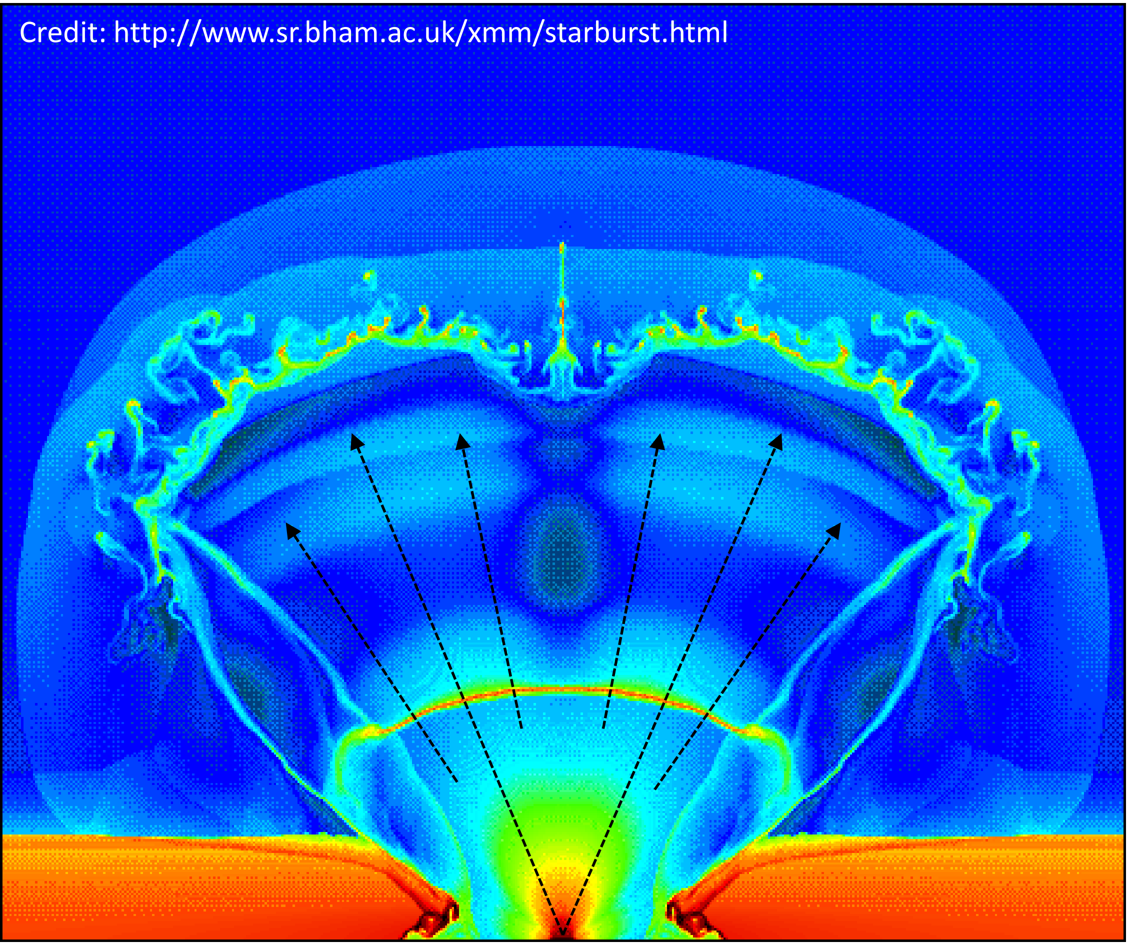


- The interstellar medium (ISM) can be characterized by large scale bulk motions

Physics of cosmic rays: Advection and Adb



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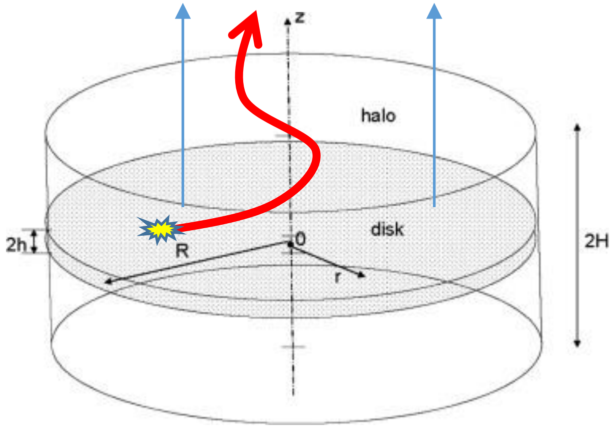
$$\tau_{adv} \approx \frac{H}{v}$$



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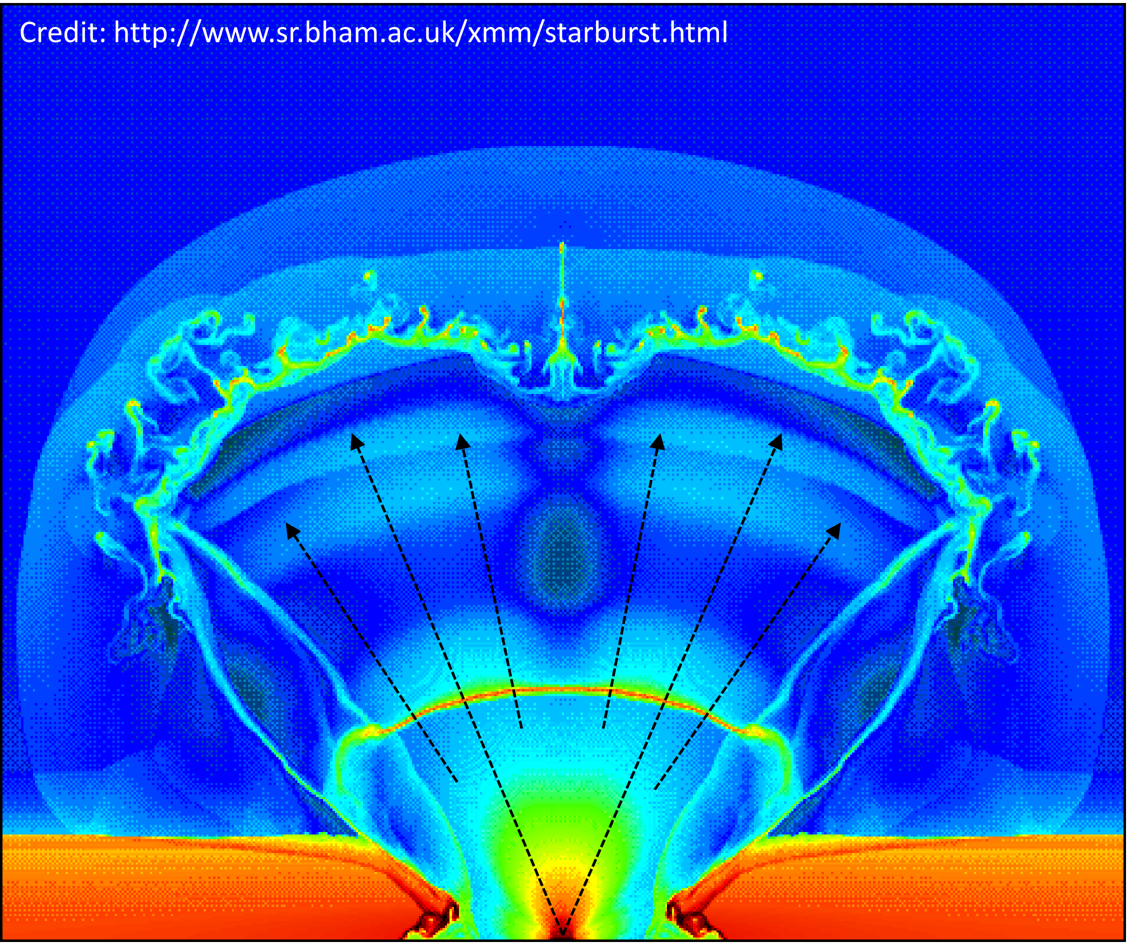

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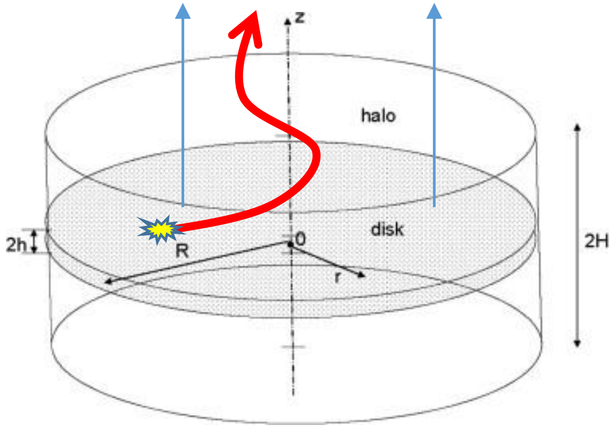

- CRs can lose or gain energy adiabatically

Physics of cosmic rays: E losses & radiative processes

- Ions (p): Ionization, Coulomb interaction, spallation (pp), Aγ (pγ)
- Electrons: Ionzation, synchrotron, bremsstrahlung, inverse Compton

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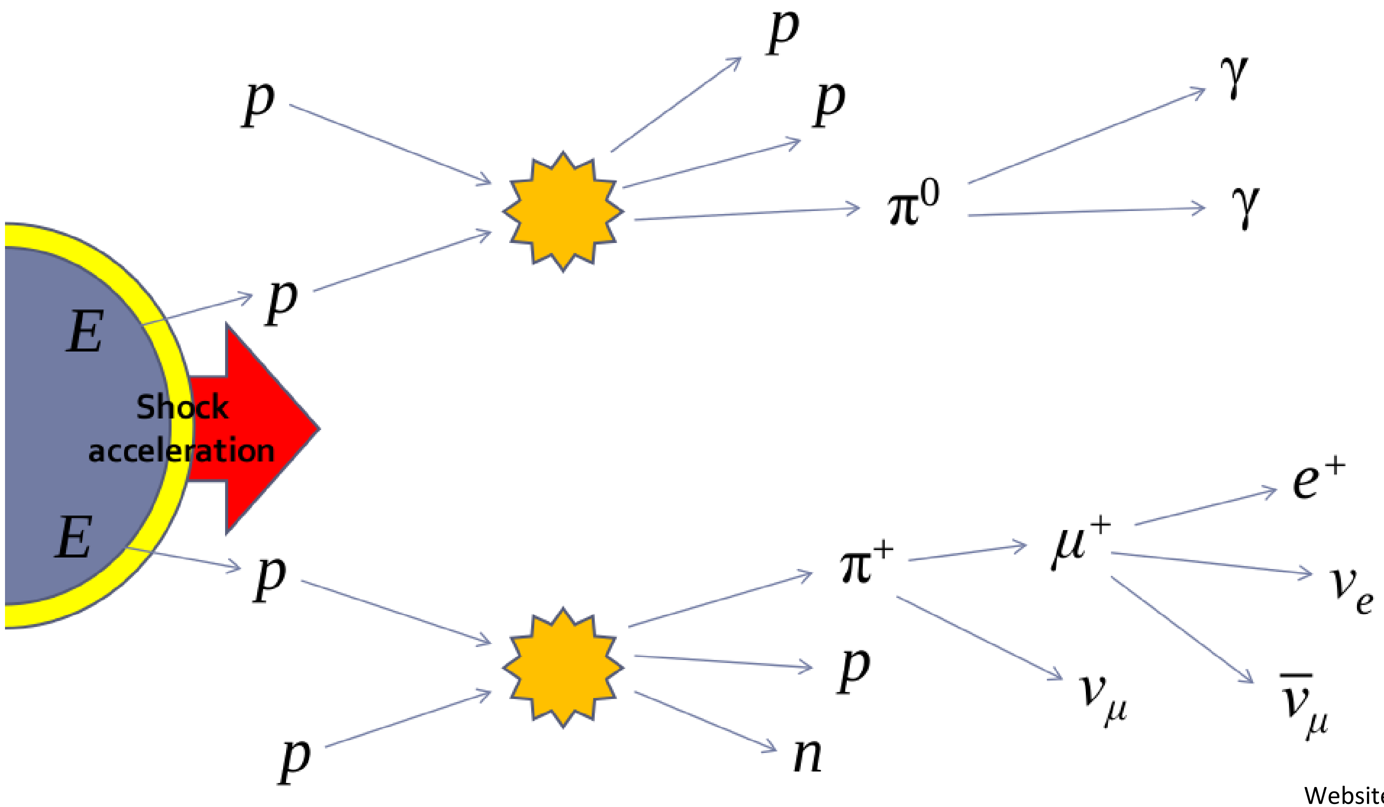

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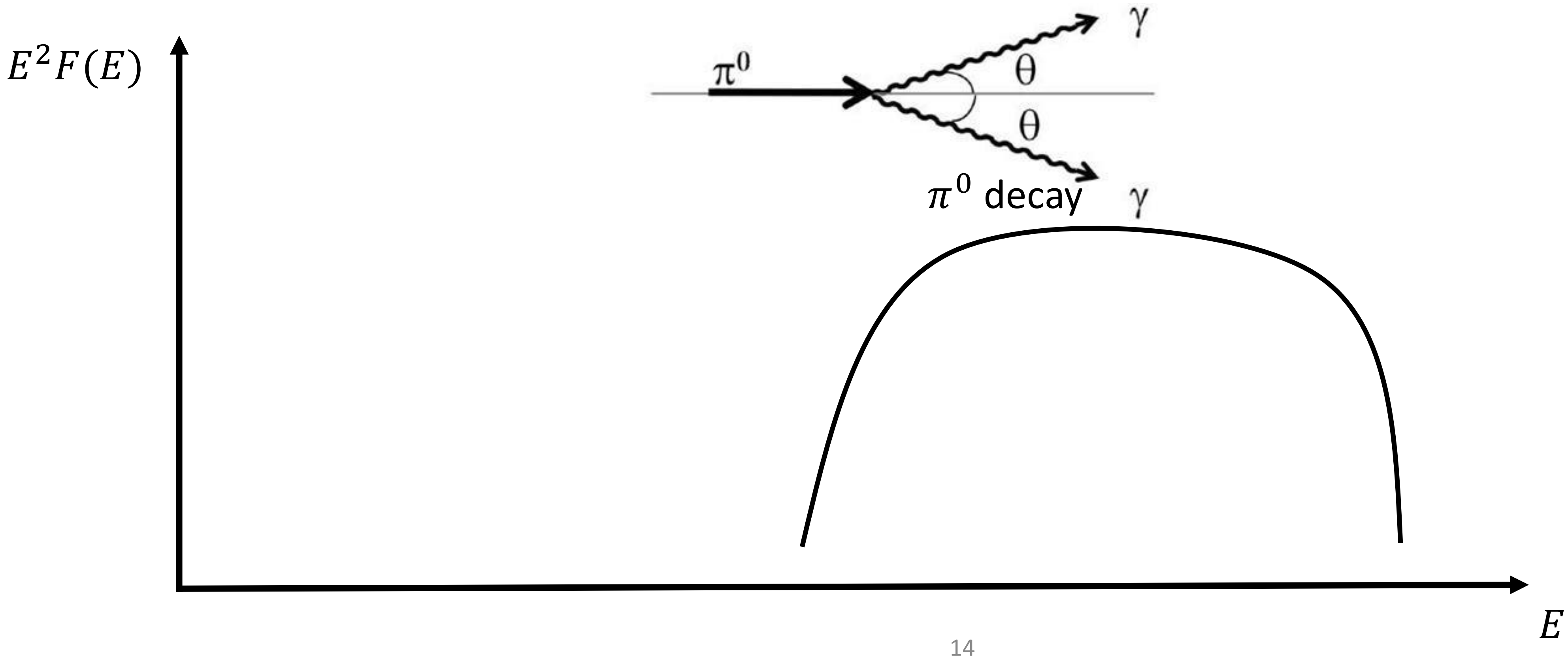

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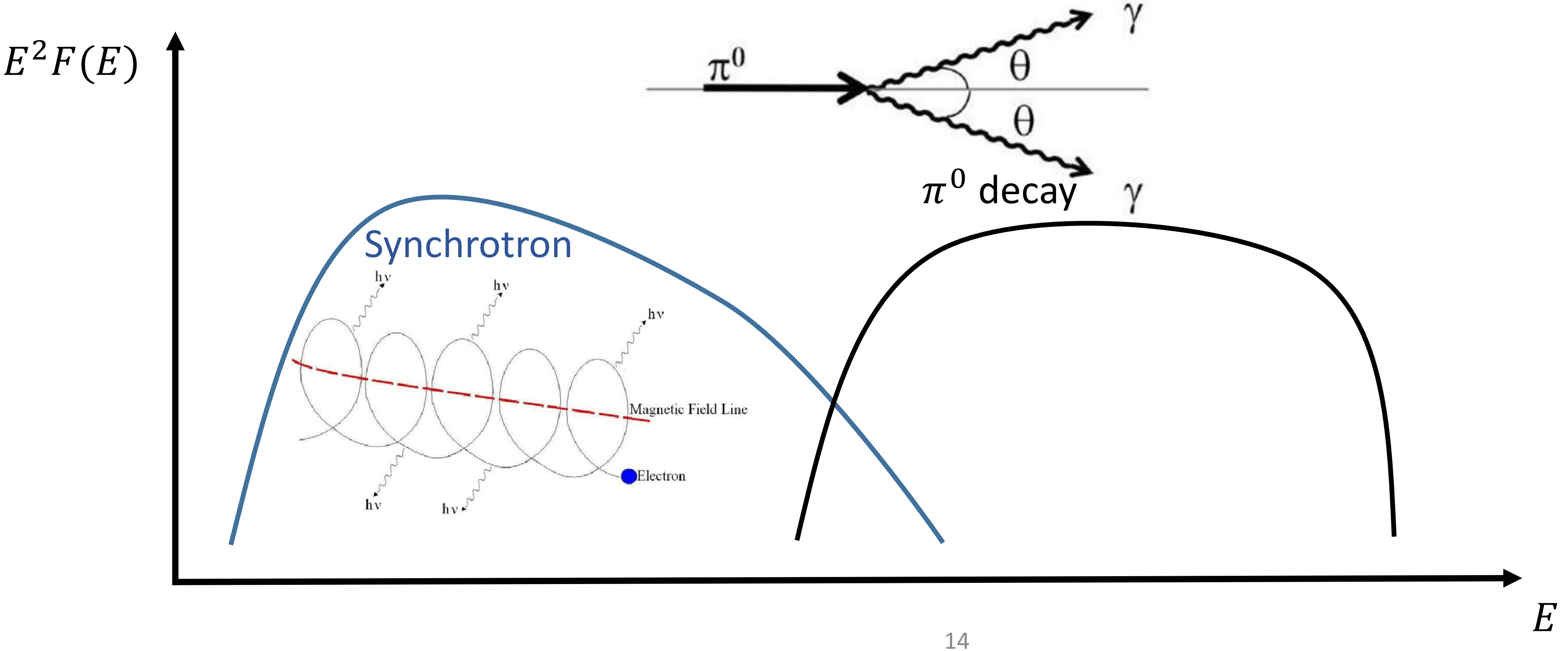

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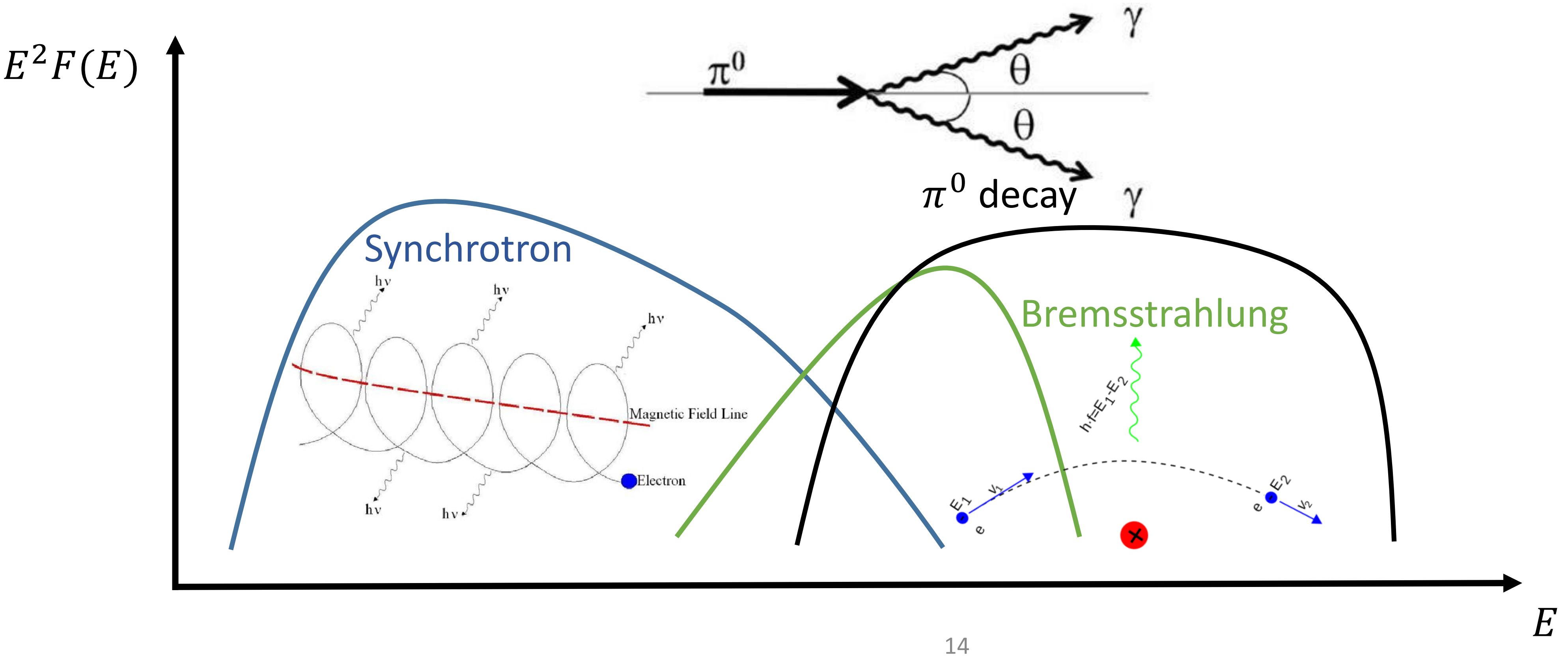

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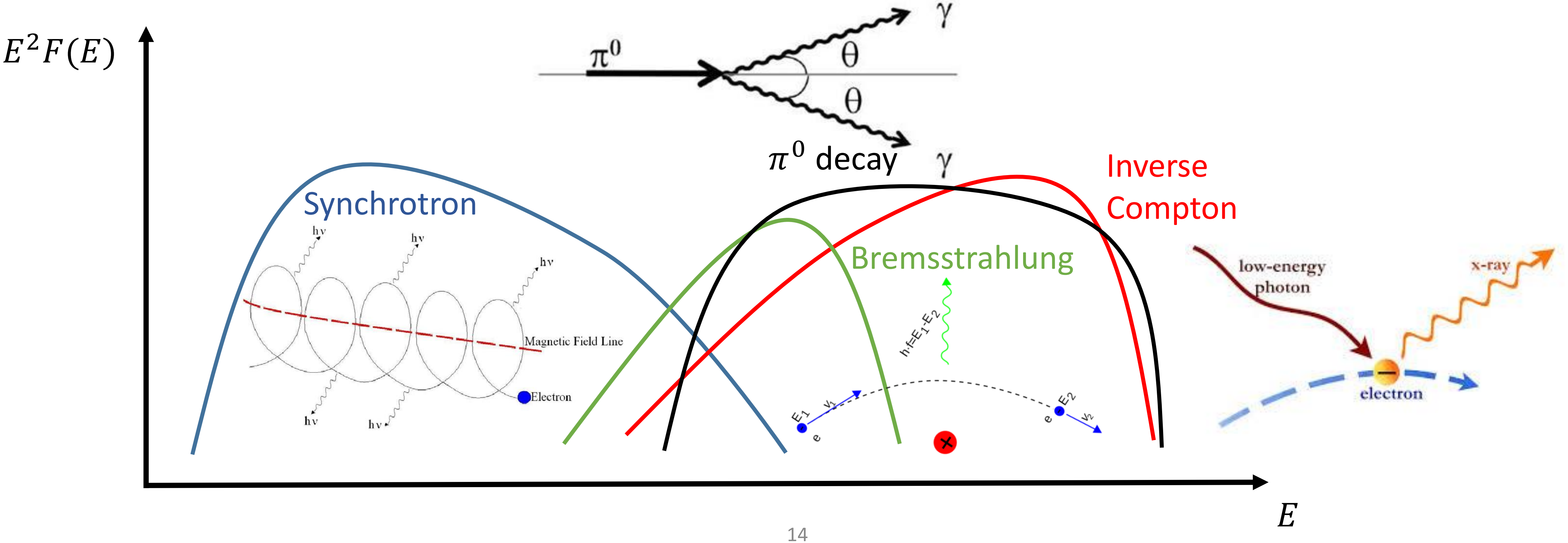

Physics of cosmic rays: E losses & radiative processes

- Ions (p): Ionization, Coulomb interaction, spallation (pp), Aγ (pγ)
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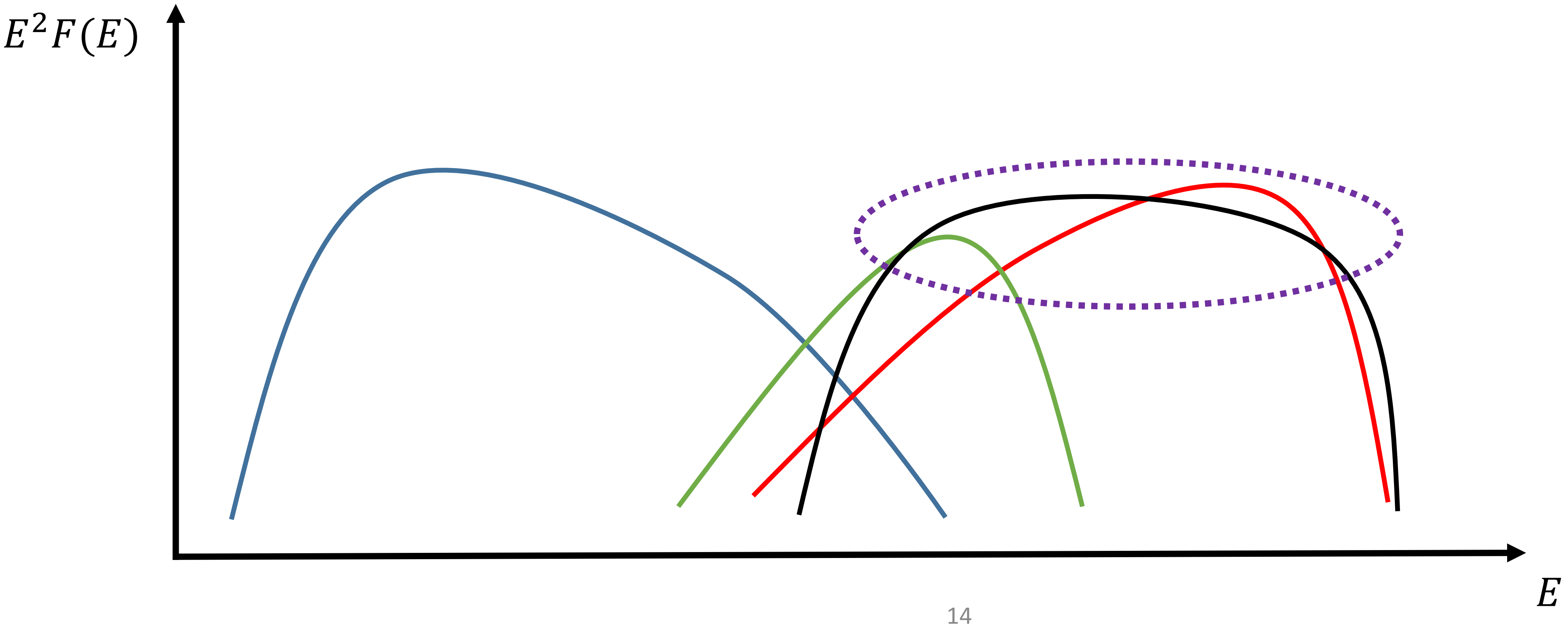

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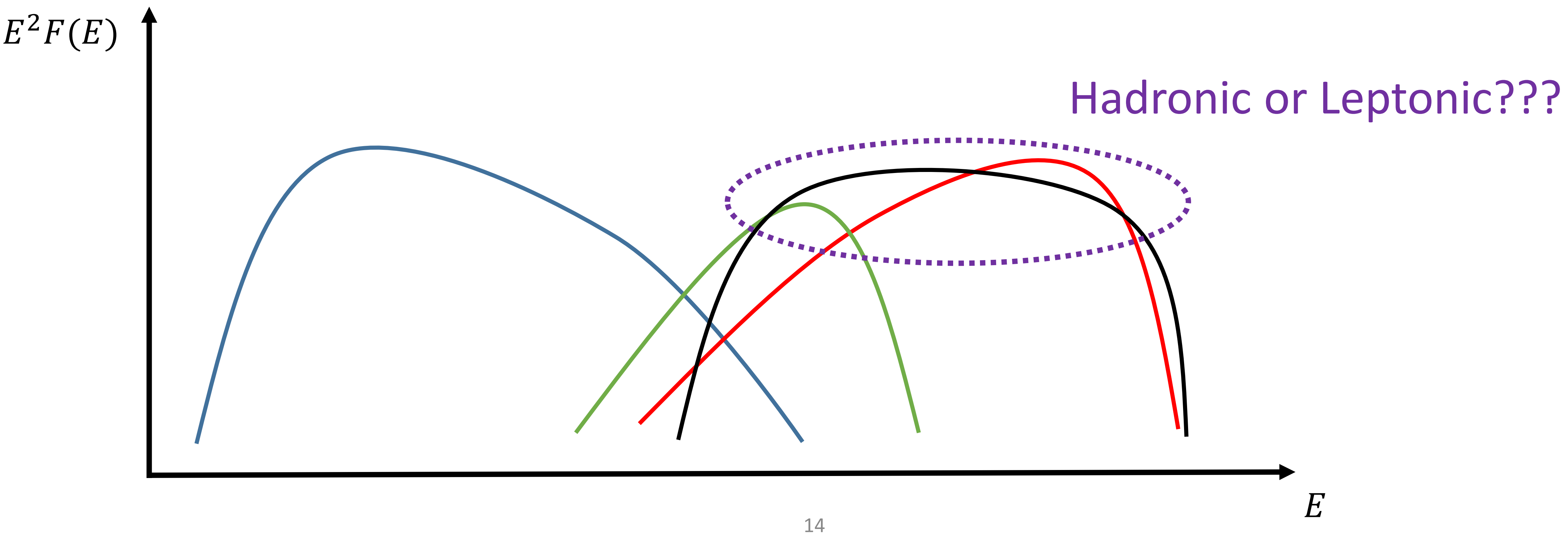


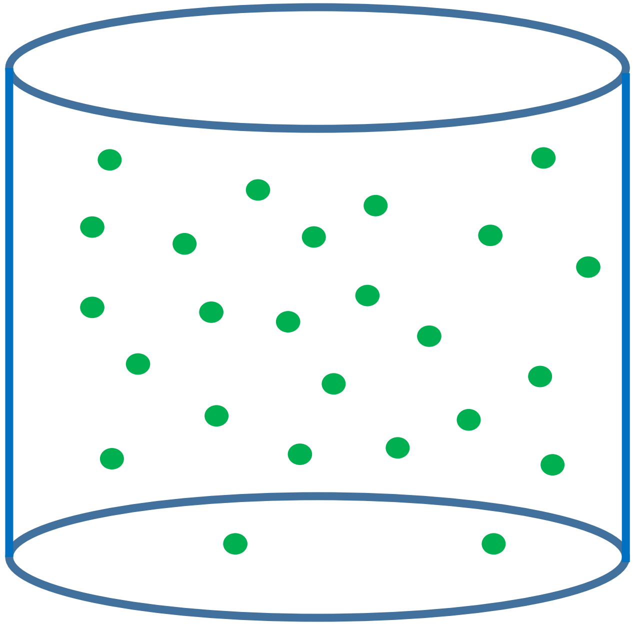
Physics of cosmic rays: E losses & radiative processes

- Ions (p): Ionization, Coulomb interaction, spallation (pp), Aγ (pγ)
- Electrons: Ionzation, synchrotron, bremsstrahlung, inverse Compton

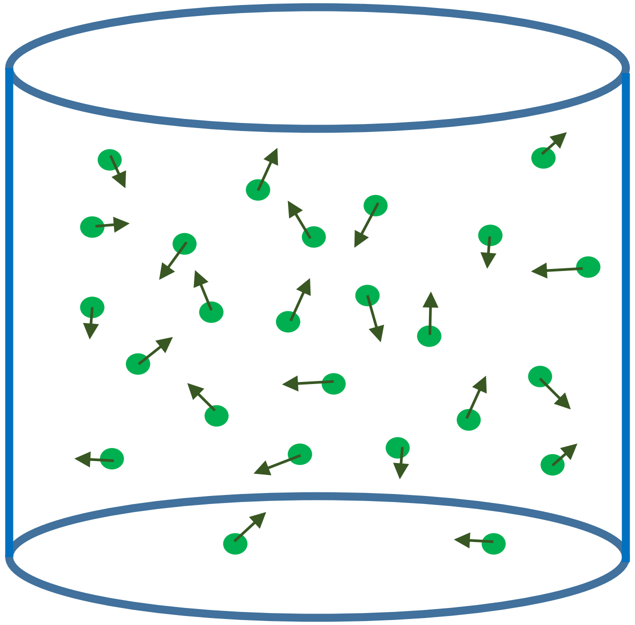
- E loss mechanism can be often associated to a typical rate/timescale which allows to model properly CR transport and possibly answer on the origin of an observed non-thermal spectrum

$$\tau_{loss}^{-1} \approx -\frac{1}{E}\left[\frac{\partial E}{\partial t}\right]$$

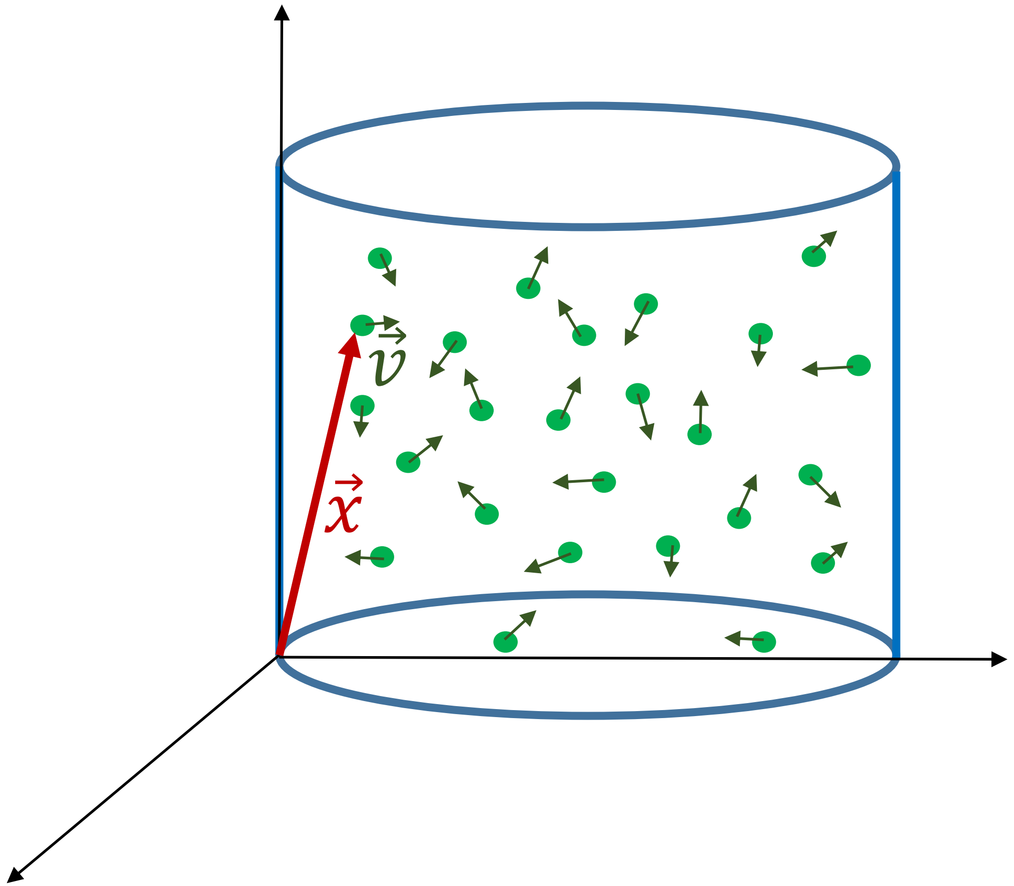
Physics of cosmic rays: Transport equation



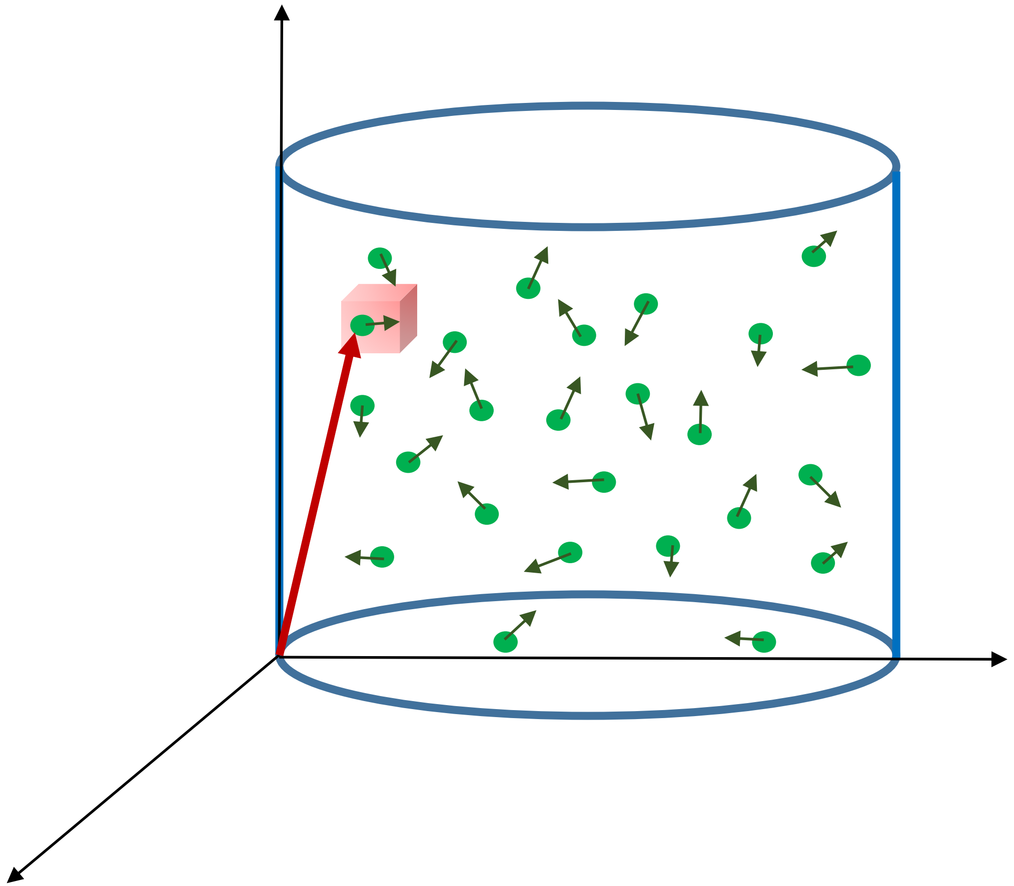
Physics of cosmic rays: Transport equation



Physics of cosmic rays: Transport equation

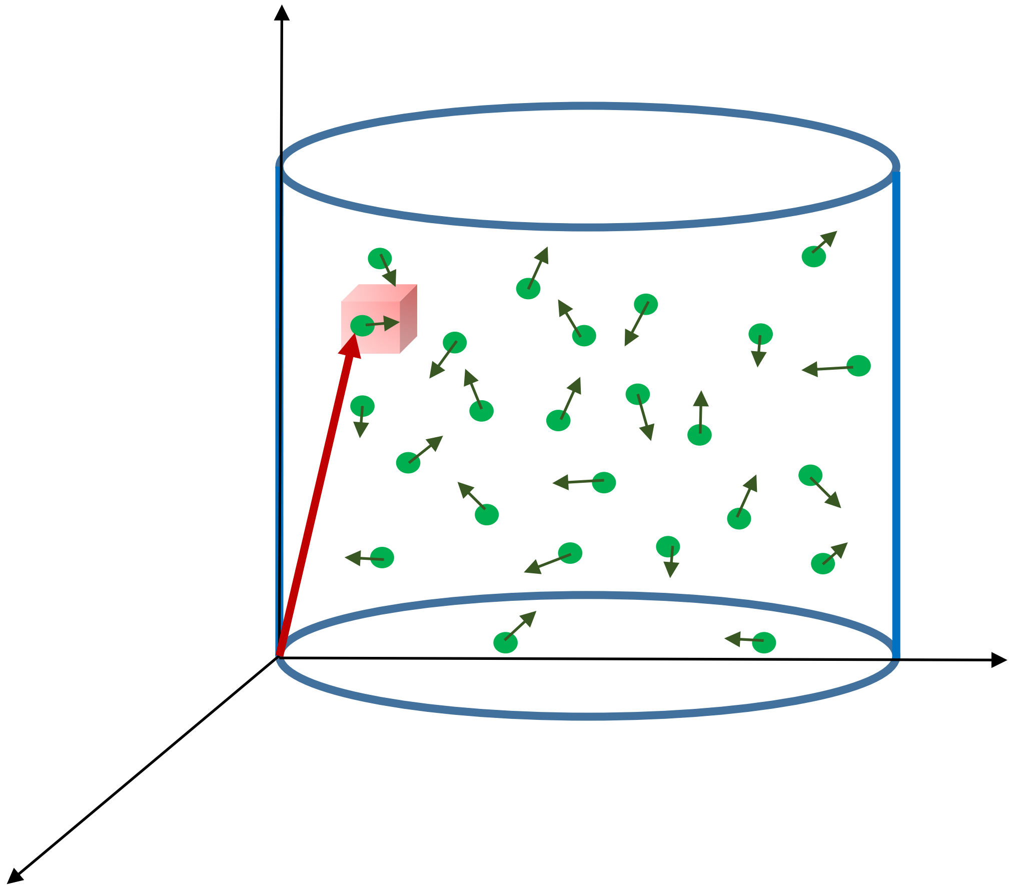


Physics of cosmic rays: Transport equation



Physics of cosmic rays: Transport equation

- Cosmic rays → phase space density → $f(t, \vec{x}, \vec{p}) = \frac{dN}{dV \cdot d^3p}$



Physics of cosmic rays: Transport equation

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$$Time\ evolution = \ Injection + diff. + adv. + adb. + loss.$$

Physics of cosmic rays: Transport equation

- Cosmic rays → phase space density → $f(t,\vec{x},\vec{p}) = \frac{dN}{dV \cdot d^3p}$

$$\frac{\partial f}{\partial t} = Q + \nabla \cdot [D \nabla f] - \vec{u} \cdot \nabla f + \frac{\nabla \cdot \vec{u}}{3} p \frac{\partial f}{\partial p} - L$$

Physics of cosmic rays: Transport equation

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- When the transport is stationary, homogeneous and isotropic:

Physics of cosmic rays: Transport equation

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- When the transport is stationary, homogeneous and isotropic:

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

Outline

- Cosmic ray transport
- Particle Transport in Starburst Nuclei
- Diffuse emission from Starburst Galaxies

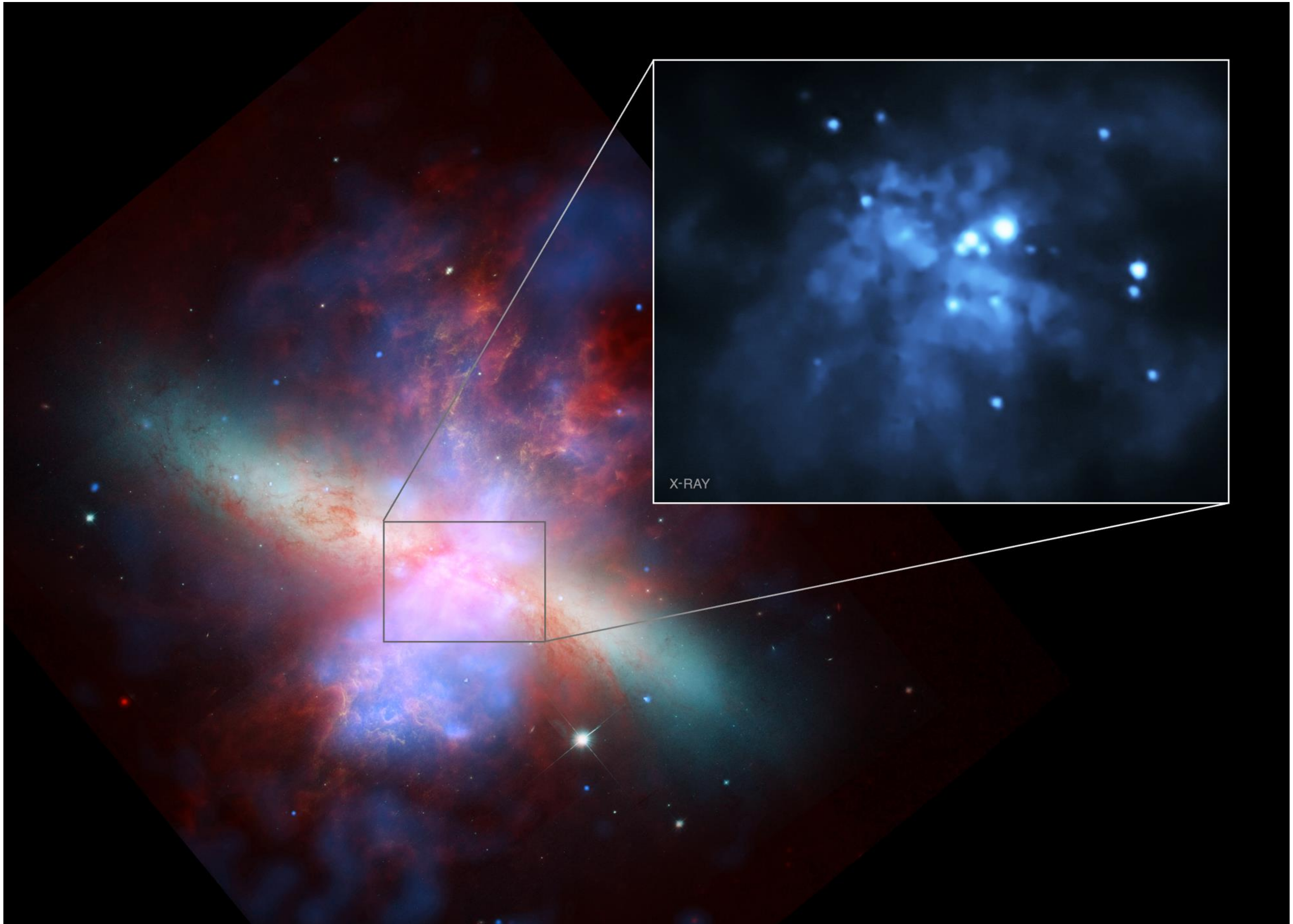
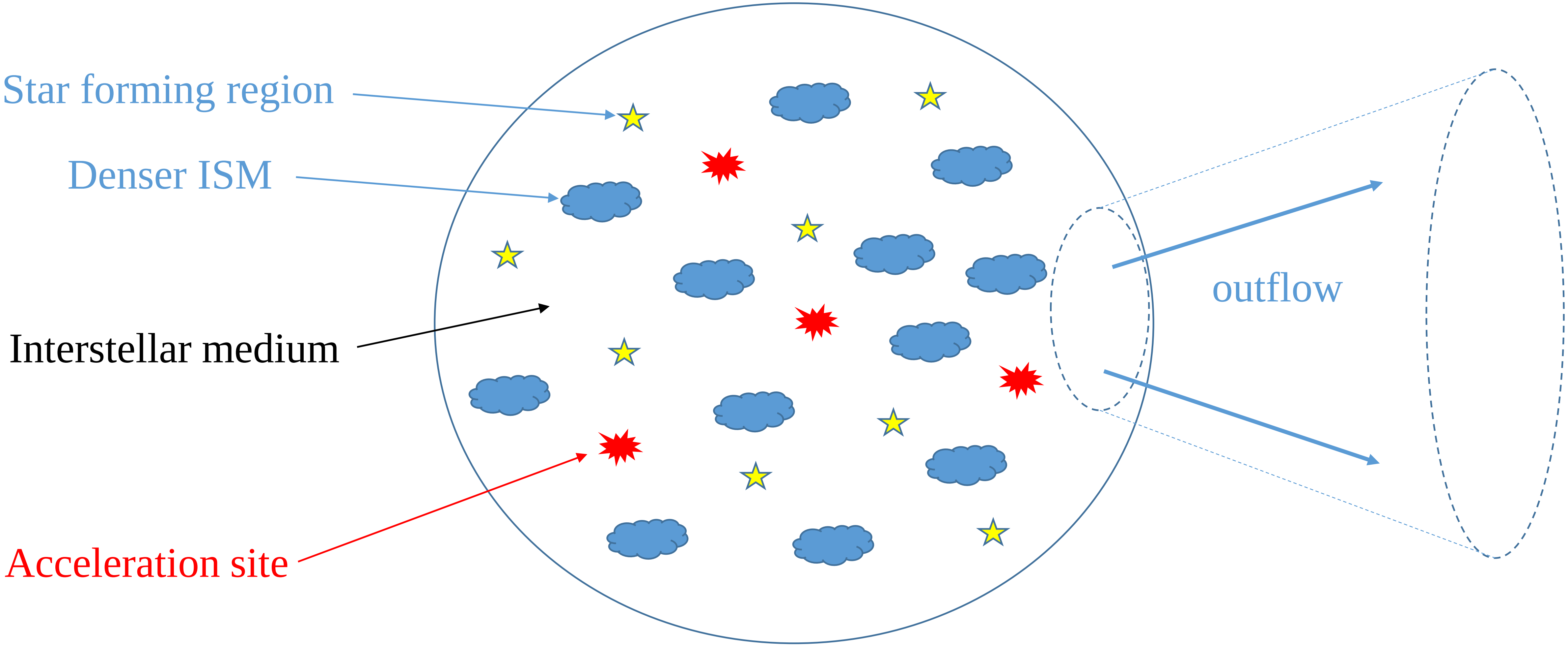


Image credit: X-ray: NASA/CXC/Tsinghua Univ./H. Feng et al.; Full-field: X-ray: NASA/CXC/JHU/D.Strickland; Optical: NASA/ESA/STScI/AURA/The Hubble Heritage Team; IR: NASA/JPL-Caltech/Univ. of AZ/C. Engelbracht

Particle transport in starburst nuclei



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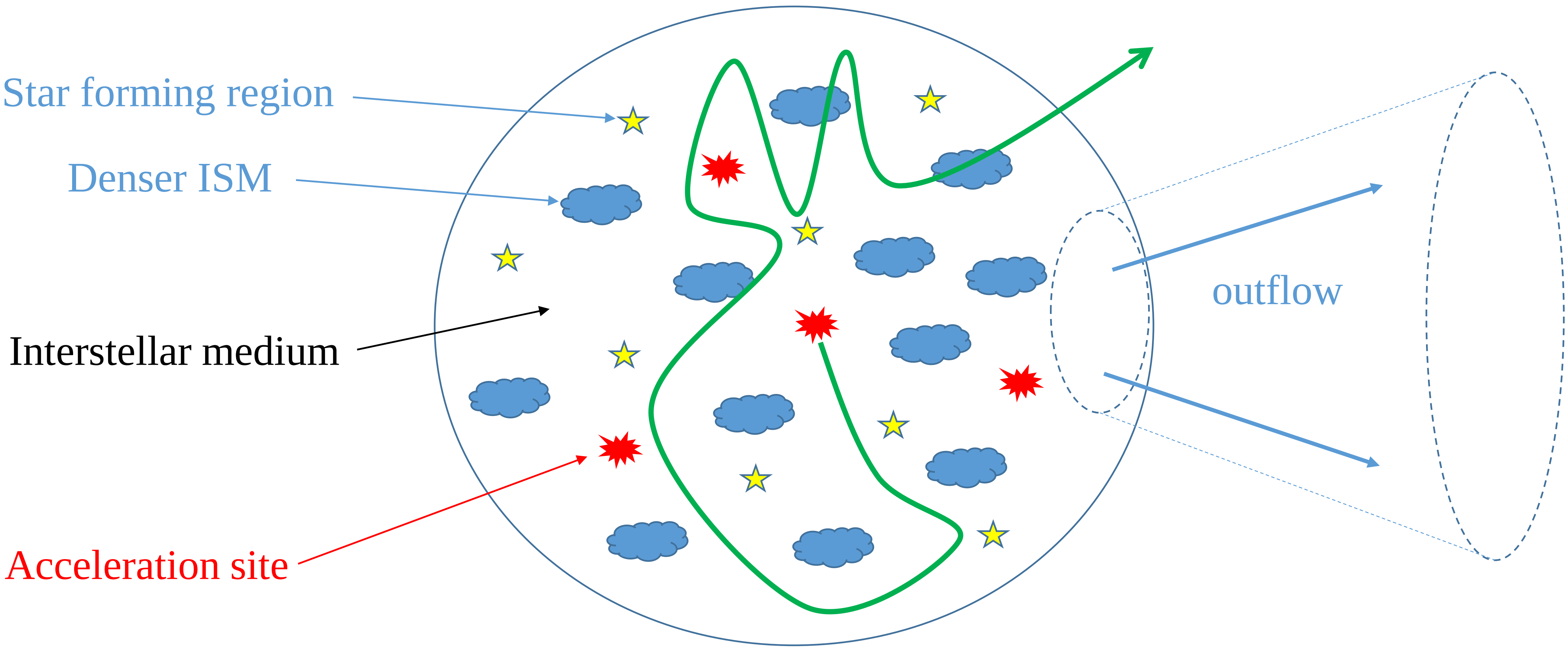
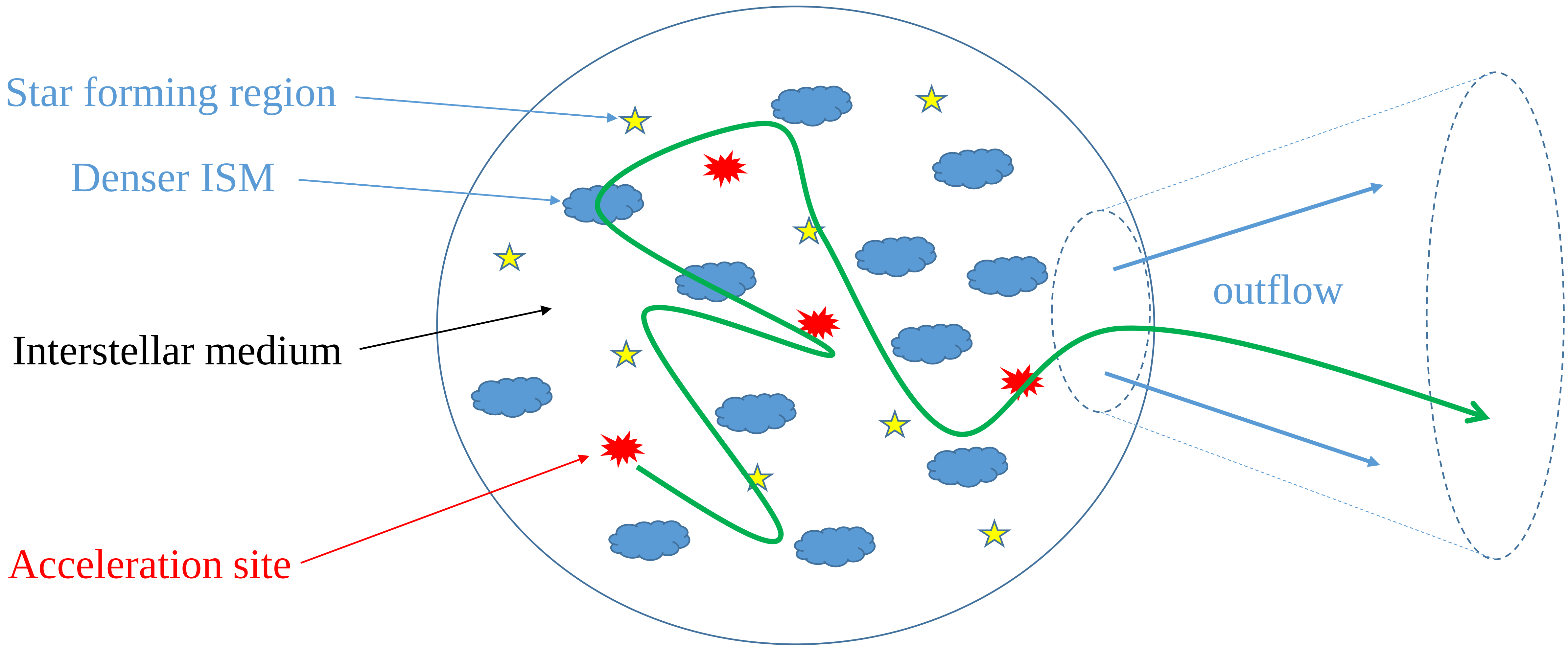


Particle transport in starburst nuclei



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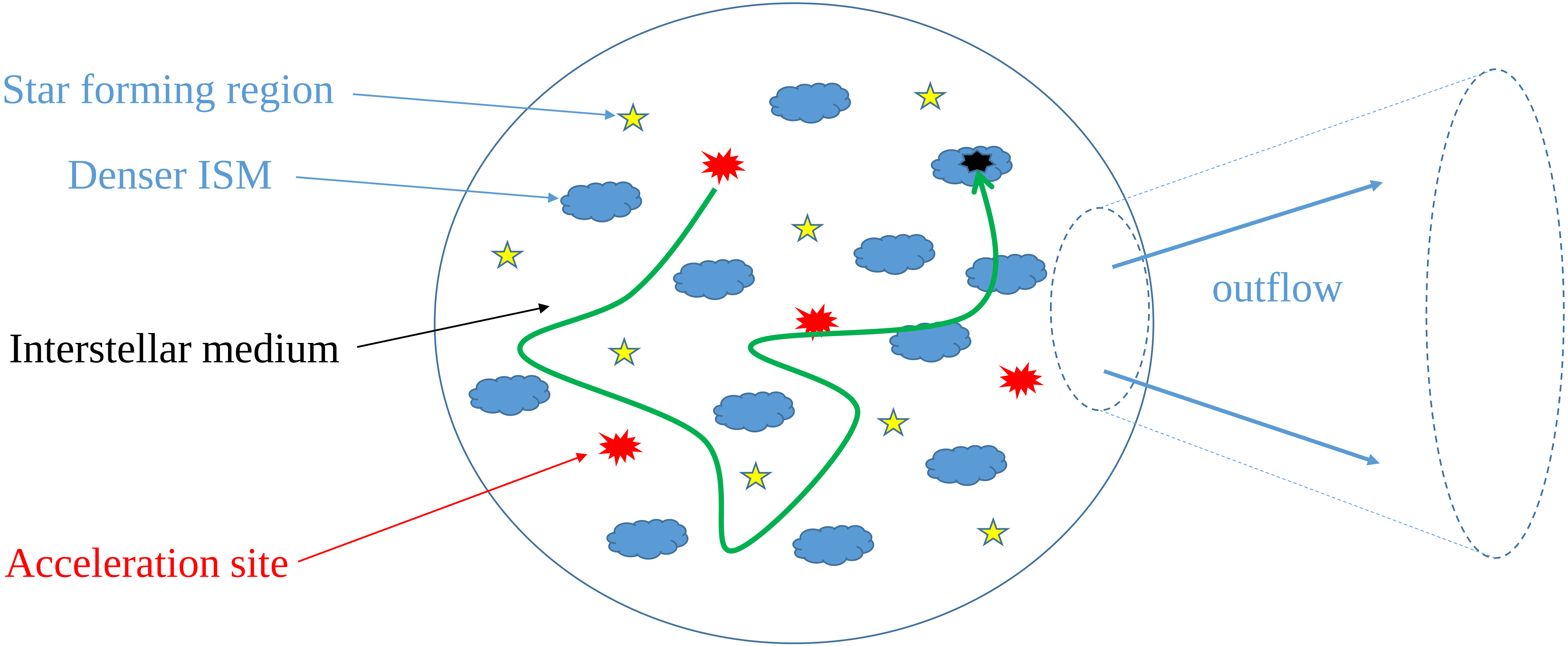
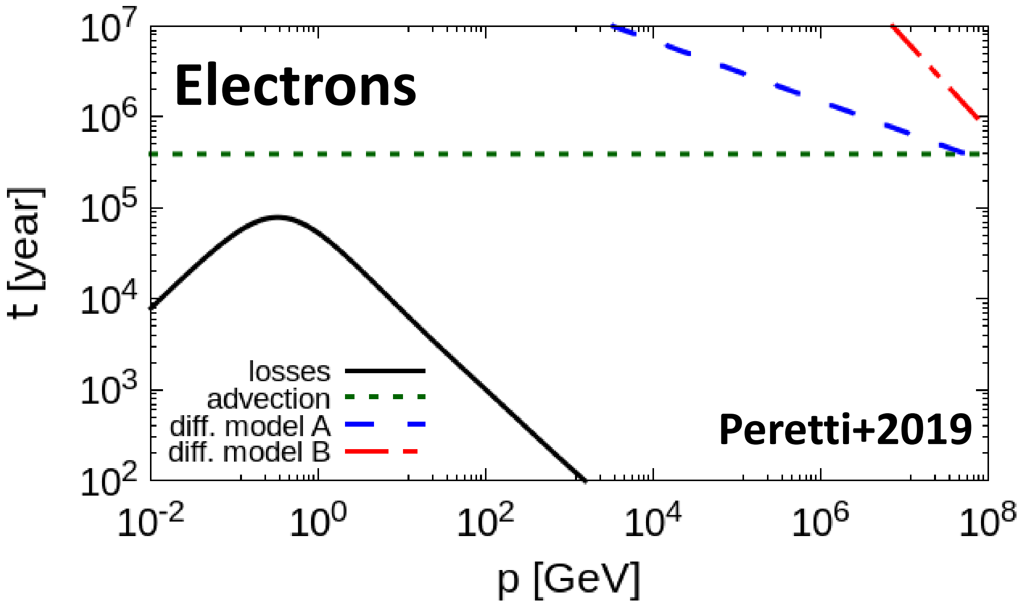
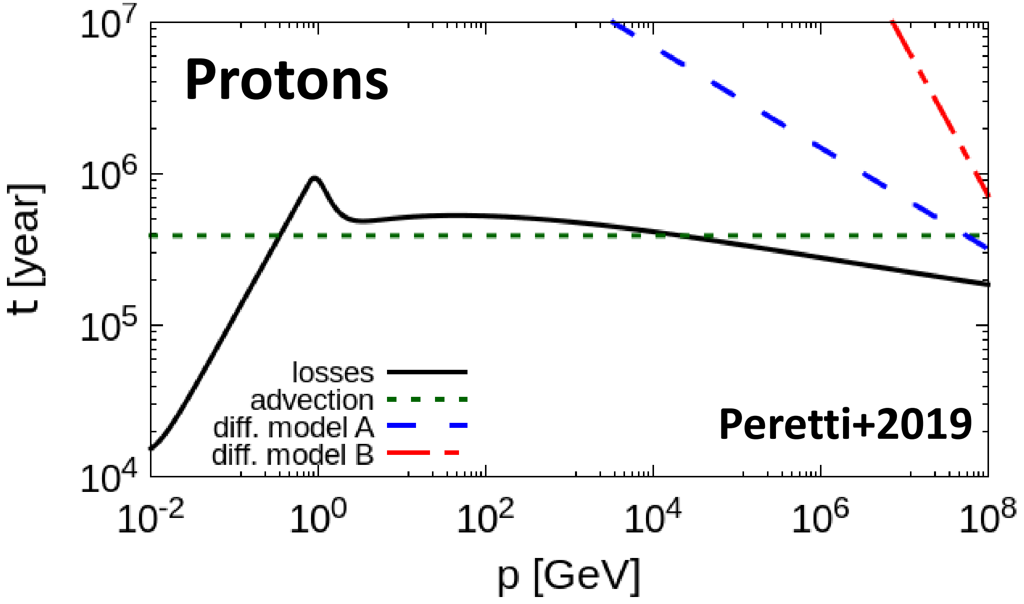


Modeling the transport in SBNi





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

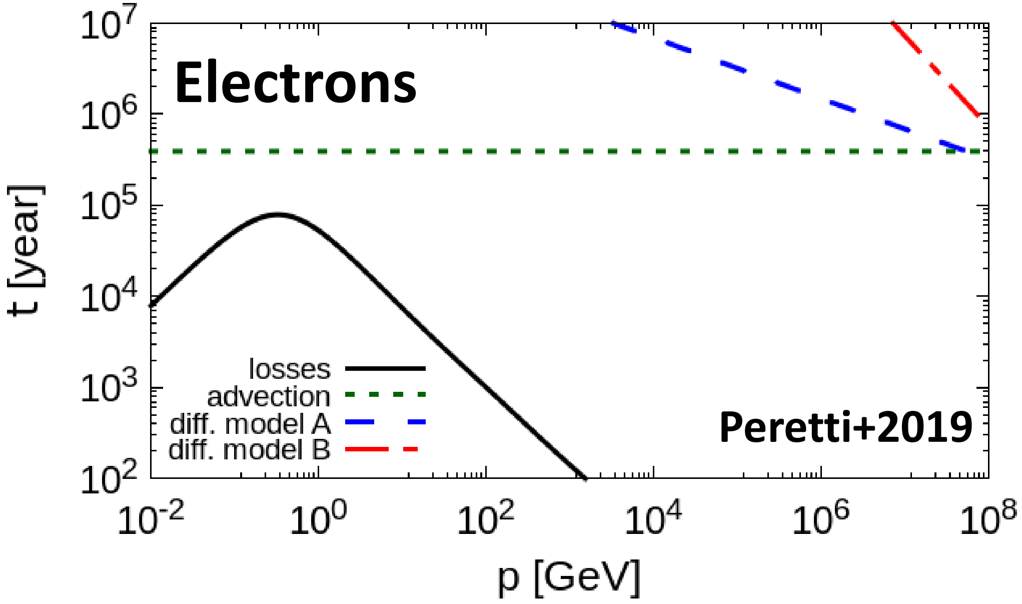
$$B \approx 10^2\ \mu G$$

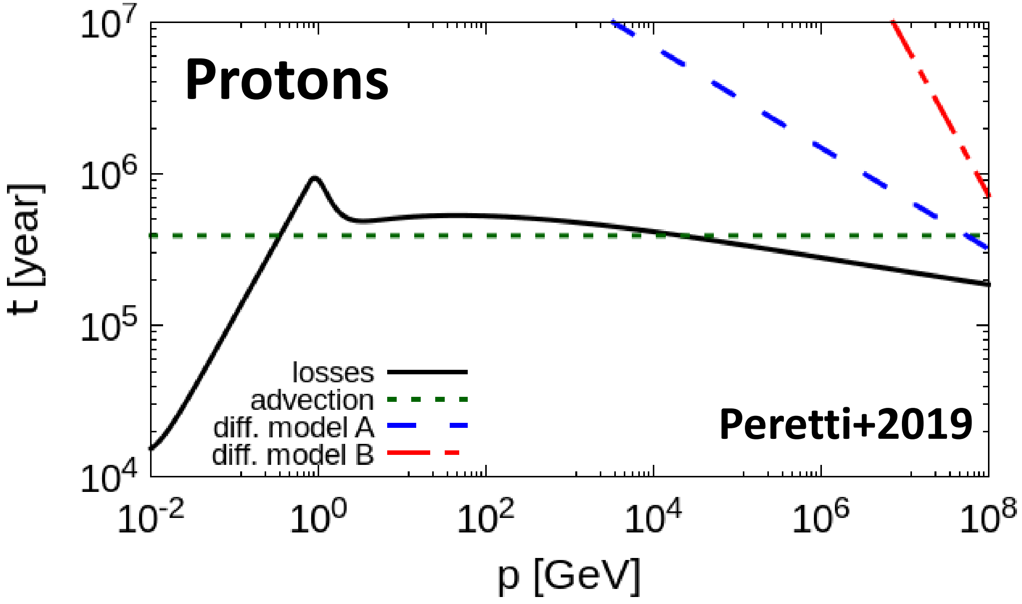
$$U_{RAD} \approx 10^3\ eV\ cm^{-3}$$

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

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

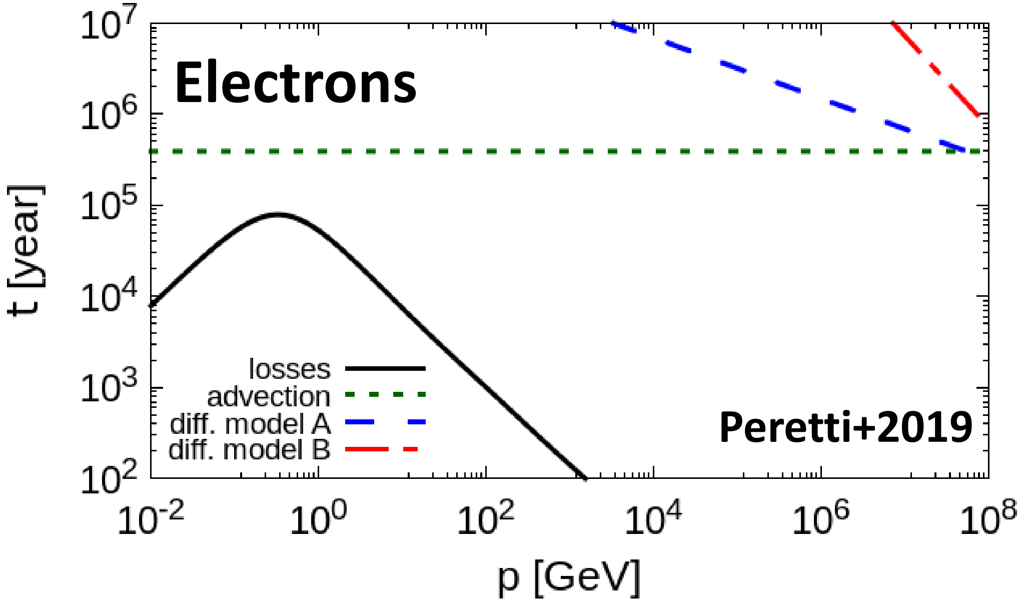
Modeling the transport in SBNi

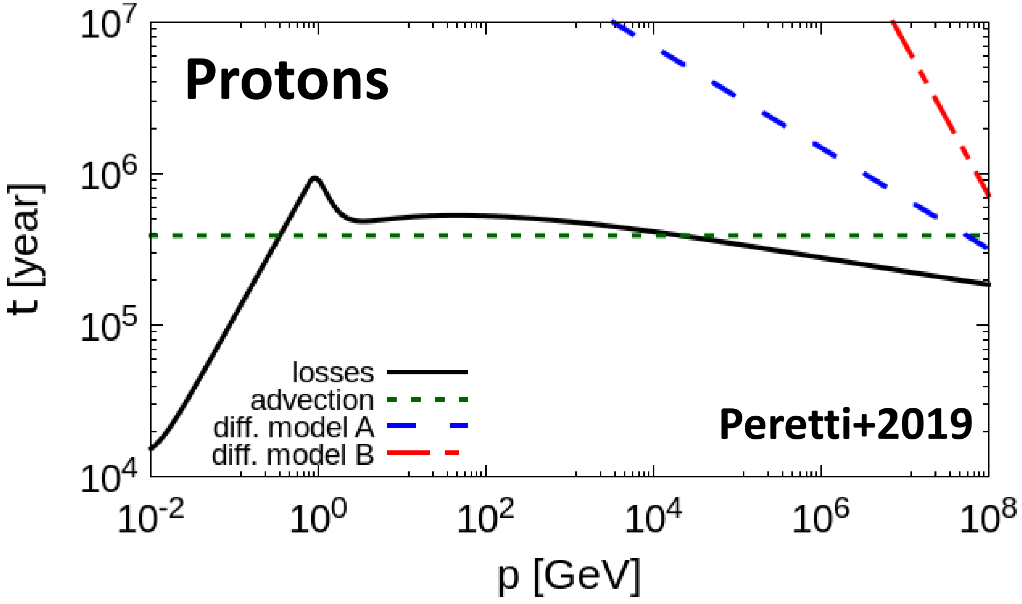




- Electrons are confined in SBNi

Modeling the transport in SBNi

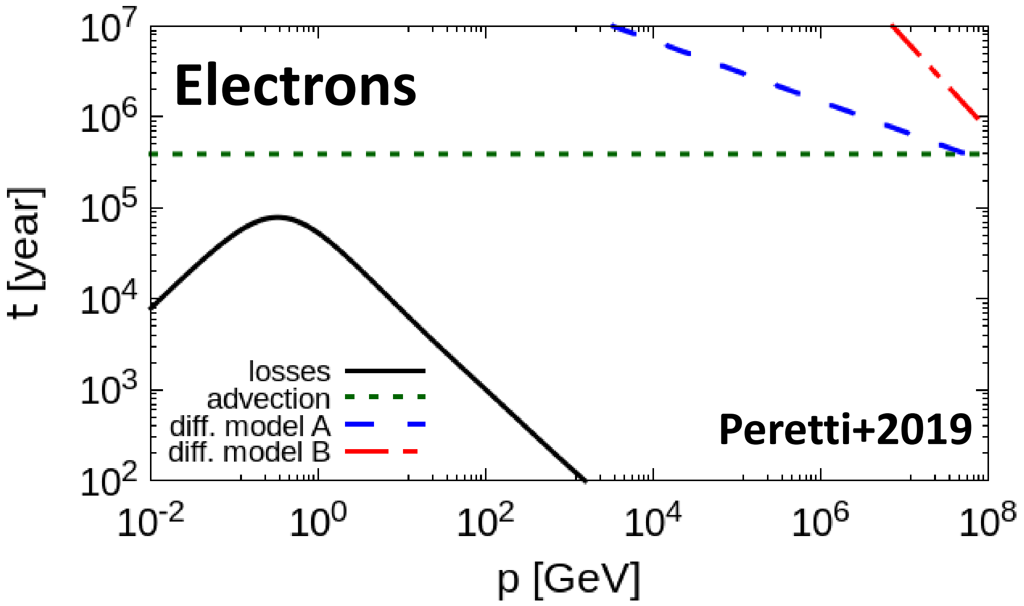


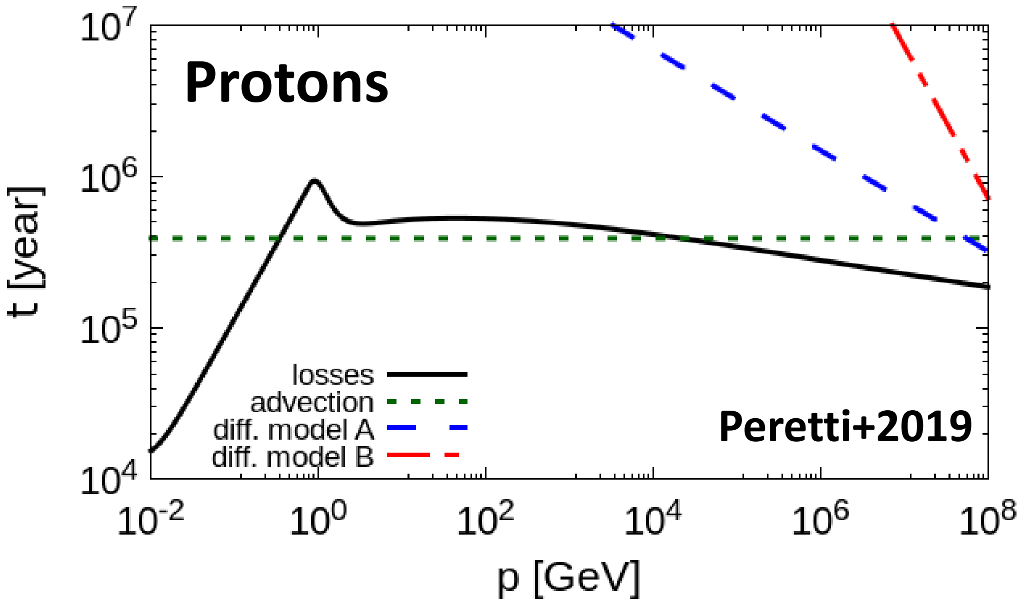


- Electrons are confined in SBNi

- Advection and losses regulate the transport of protons

Modeling the transport in SBNi

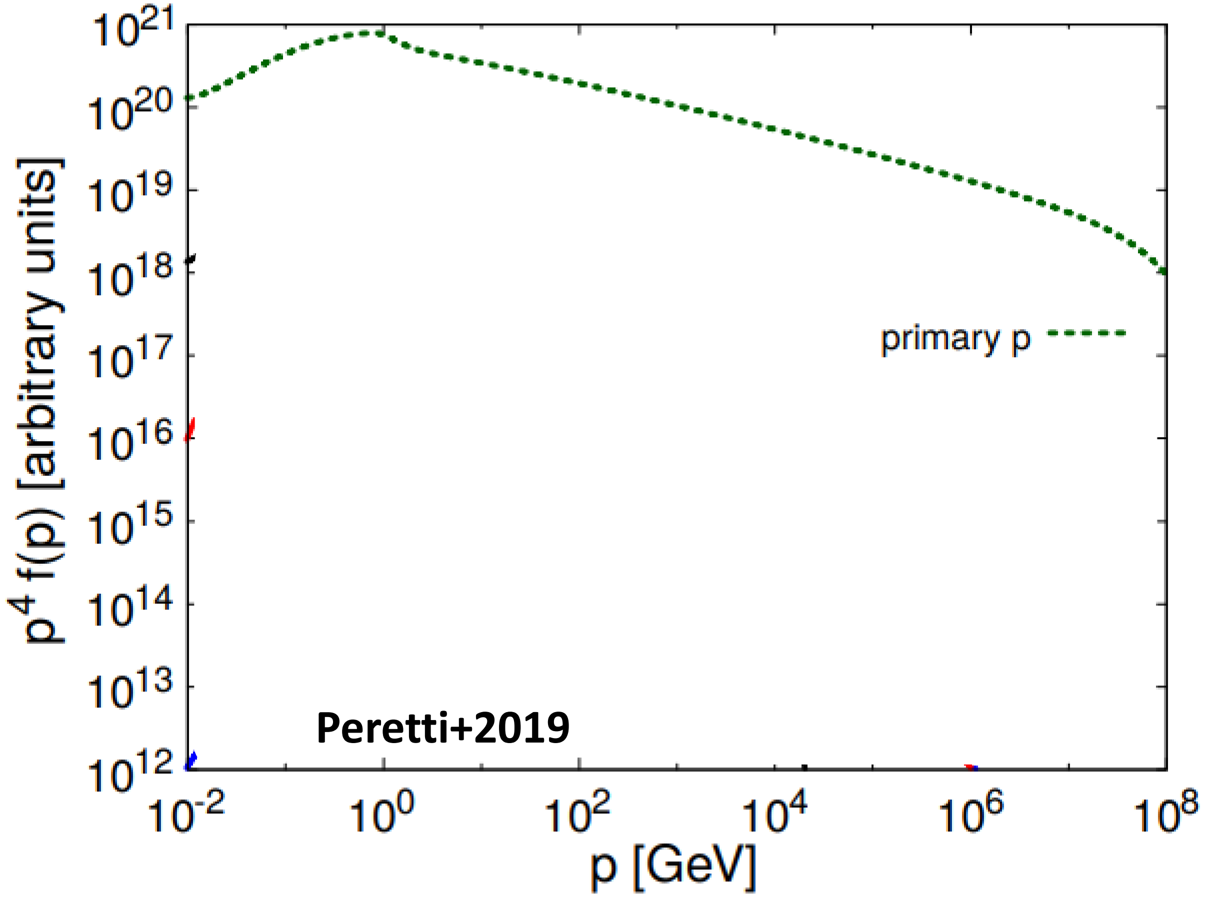


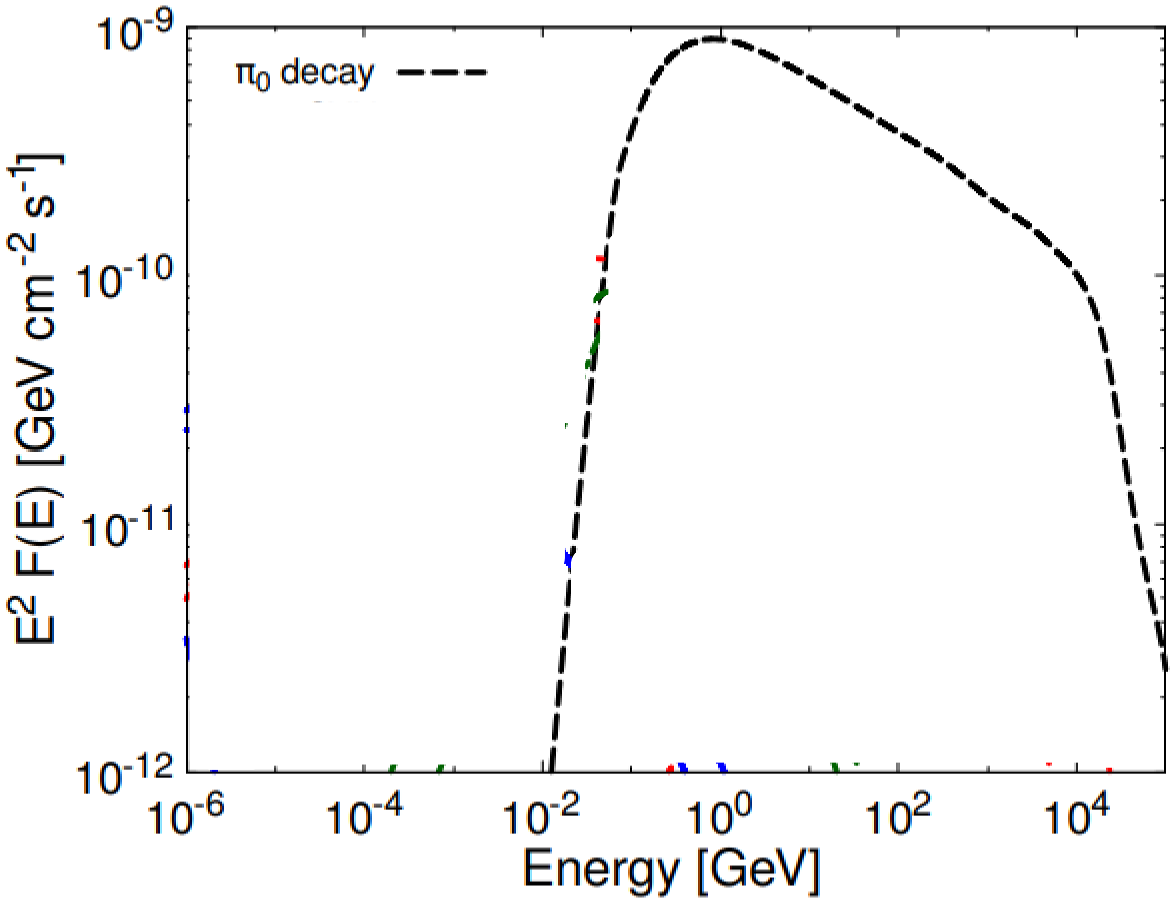


- Electrons are confined in SBNi
- Advection and losses regulate the transport of protons
- Particles experience all phases of the ISM

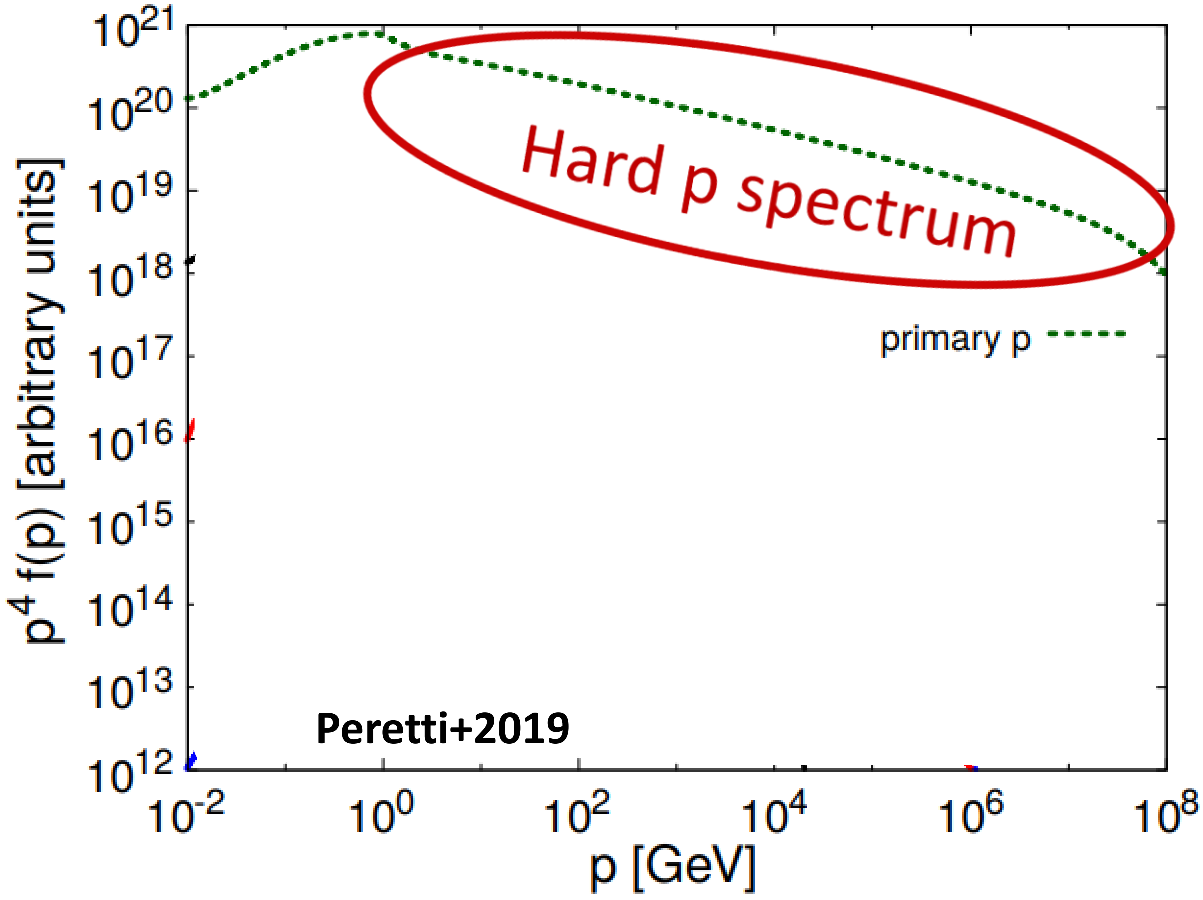
$$Q = \frac{f}{\tau_{loss}} + \frac{f}{\tau_{diff}} + \frac{f}{\tau_{adv}}$$

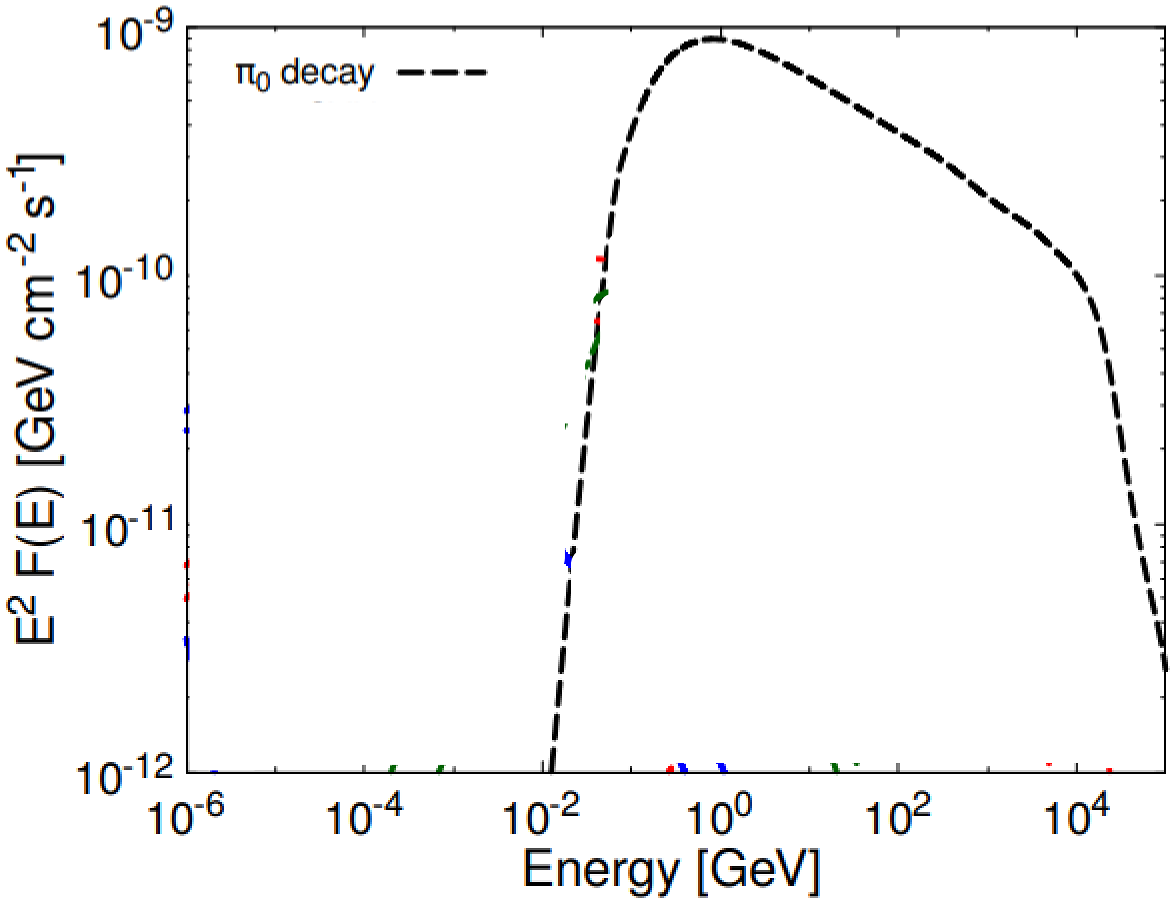
Particle and photon spectra in SBNi





Particle and photon spectra in SBNi





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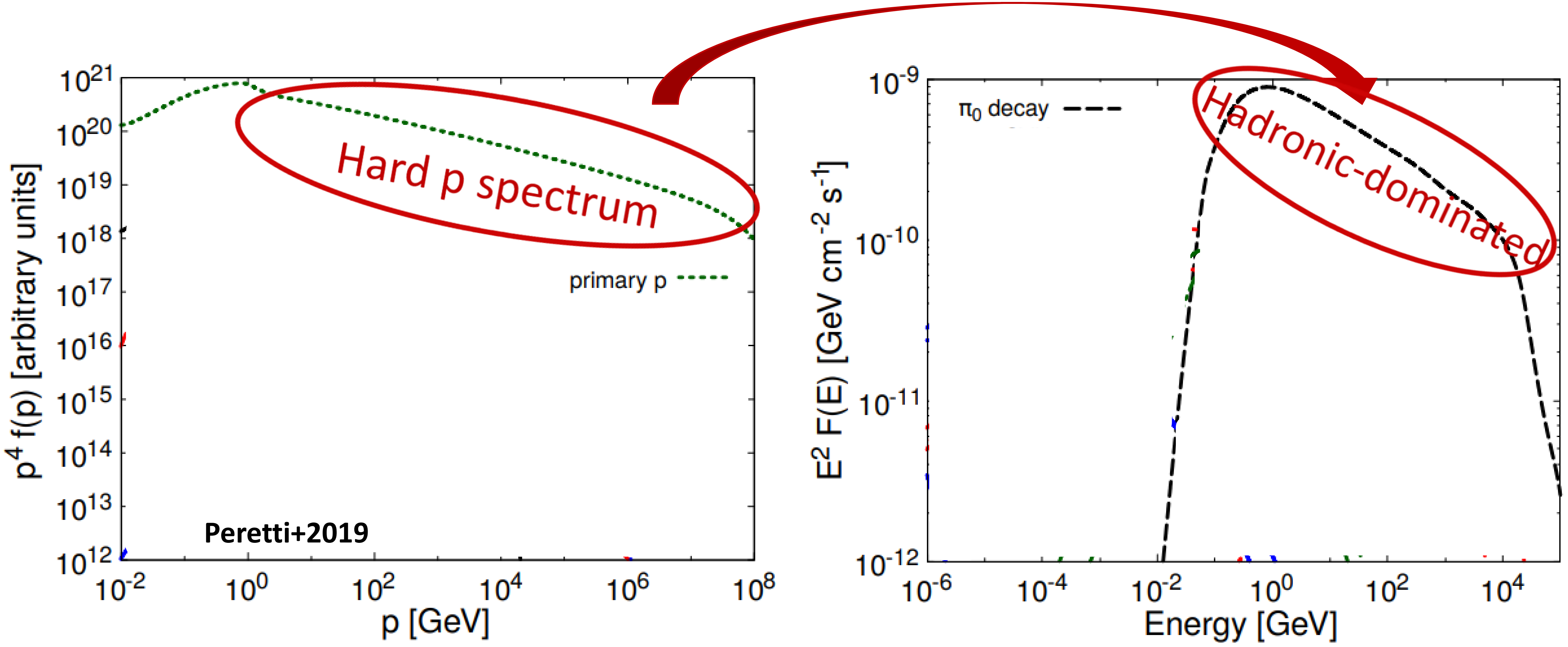

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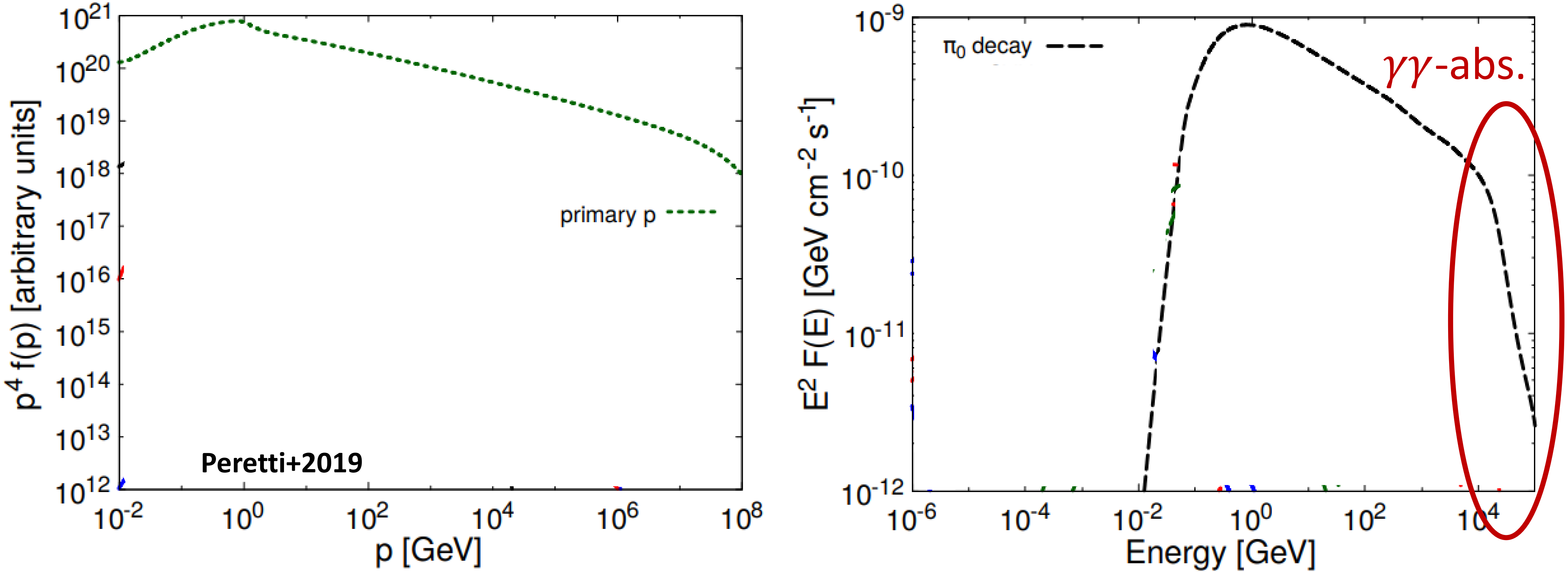

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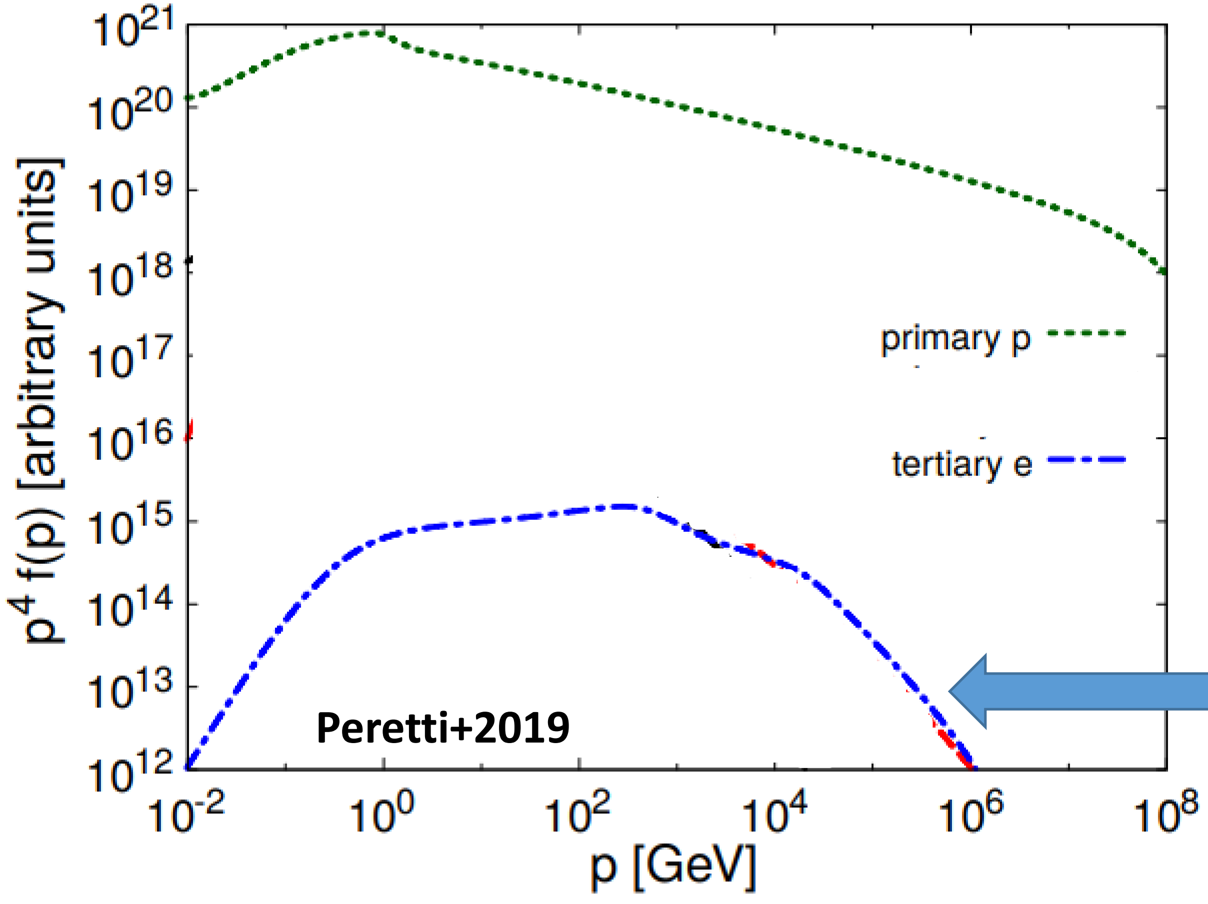

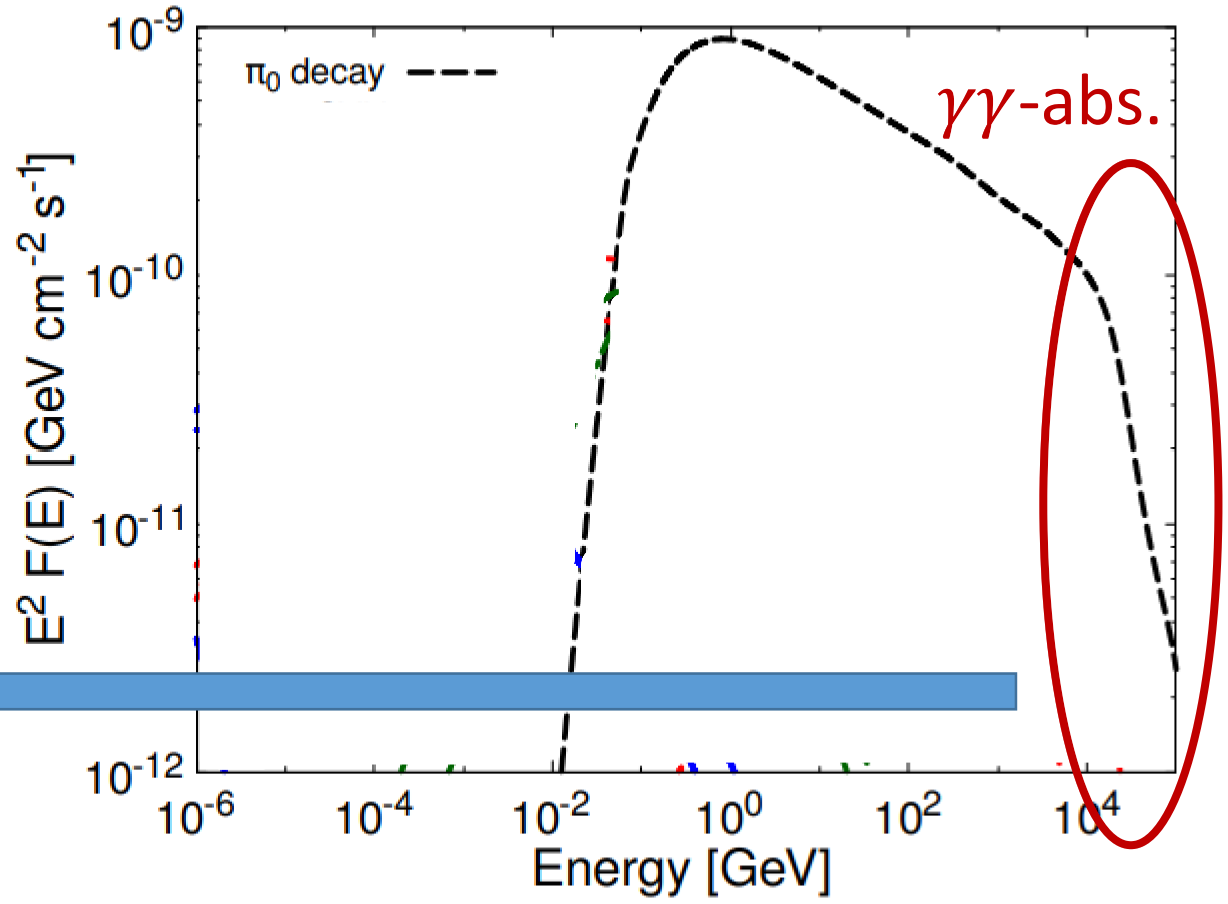

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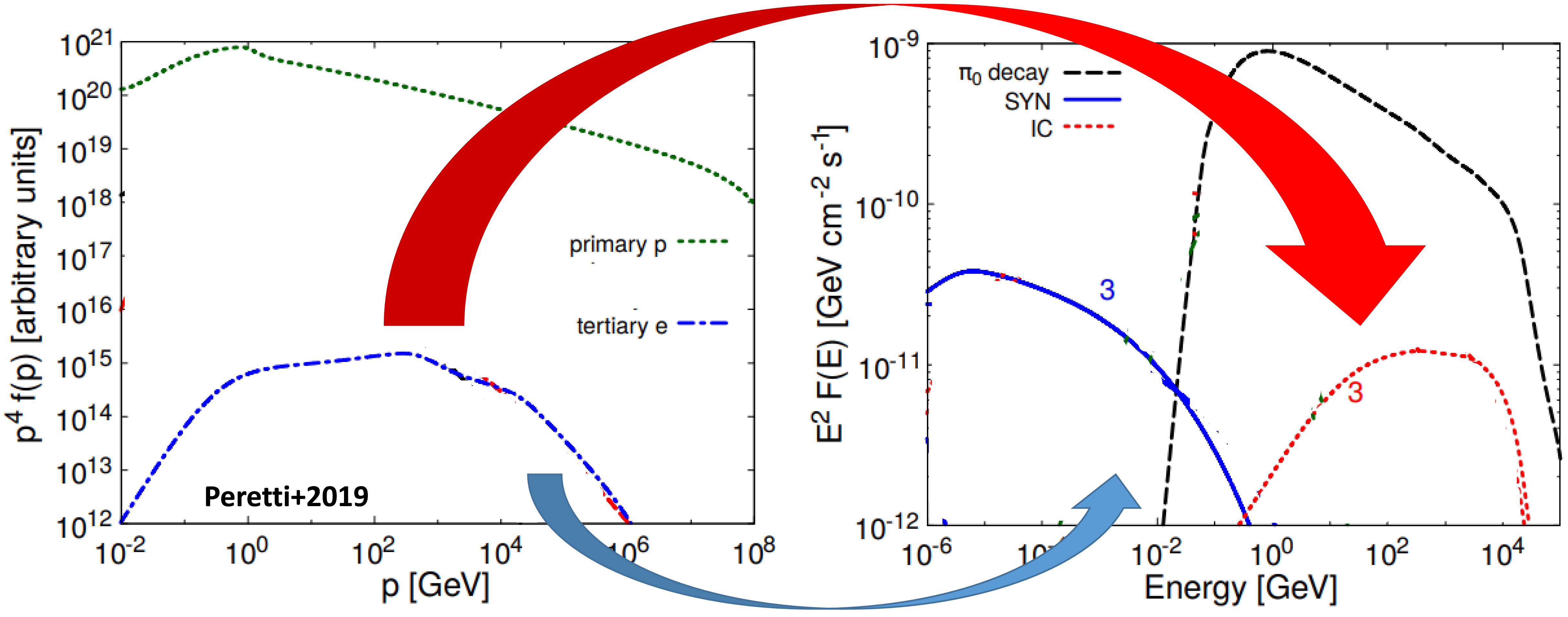

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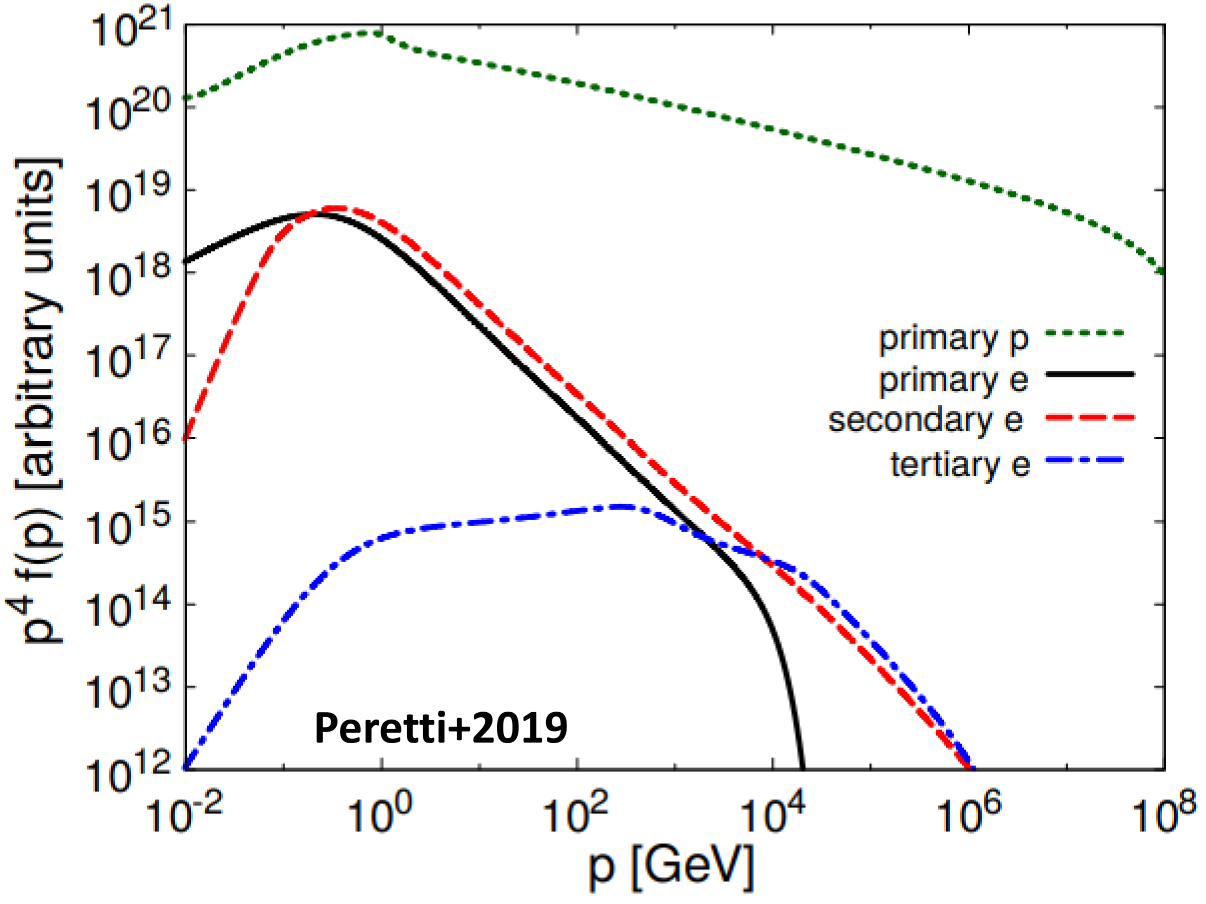

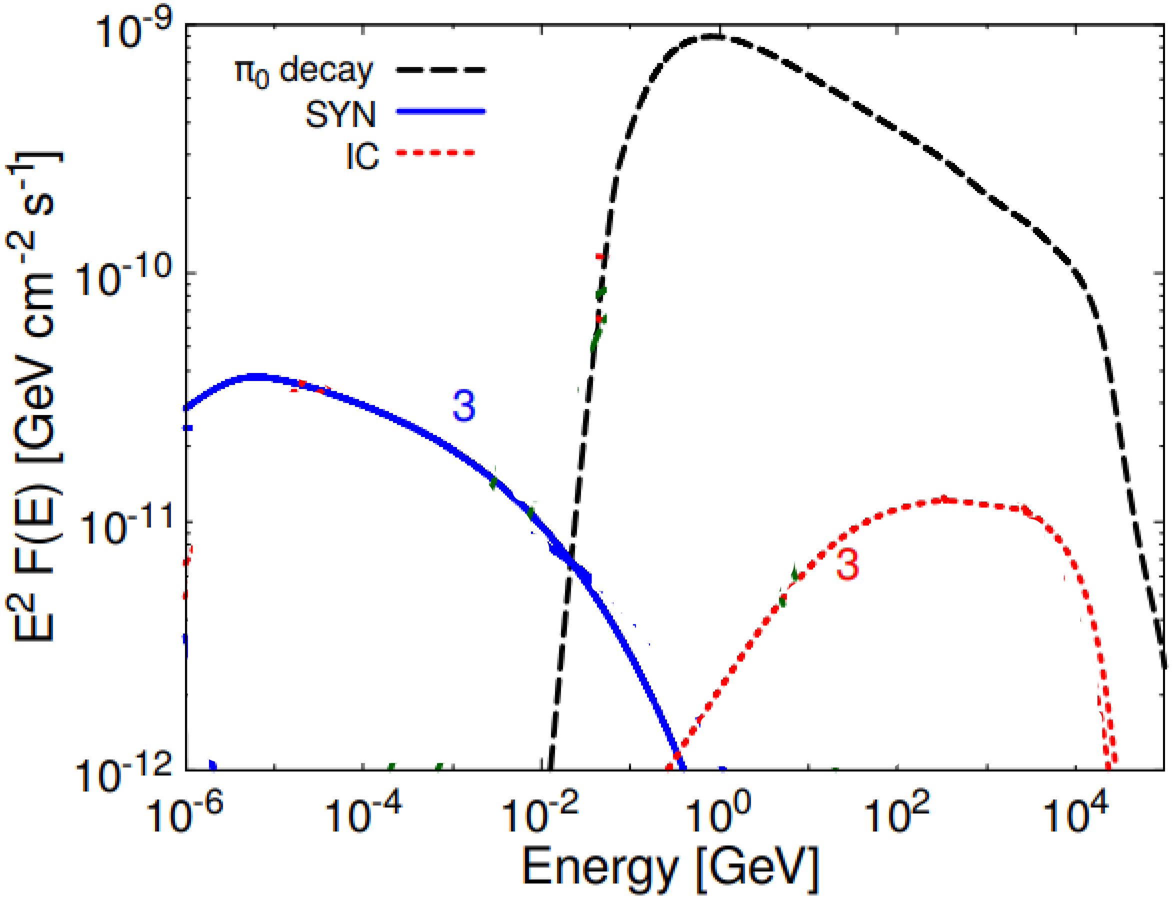

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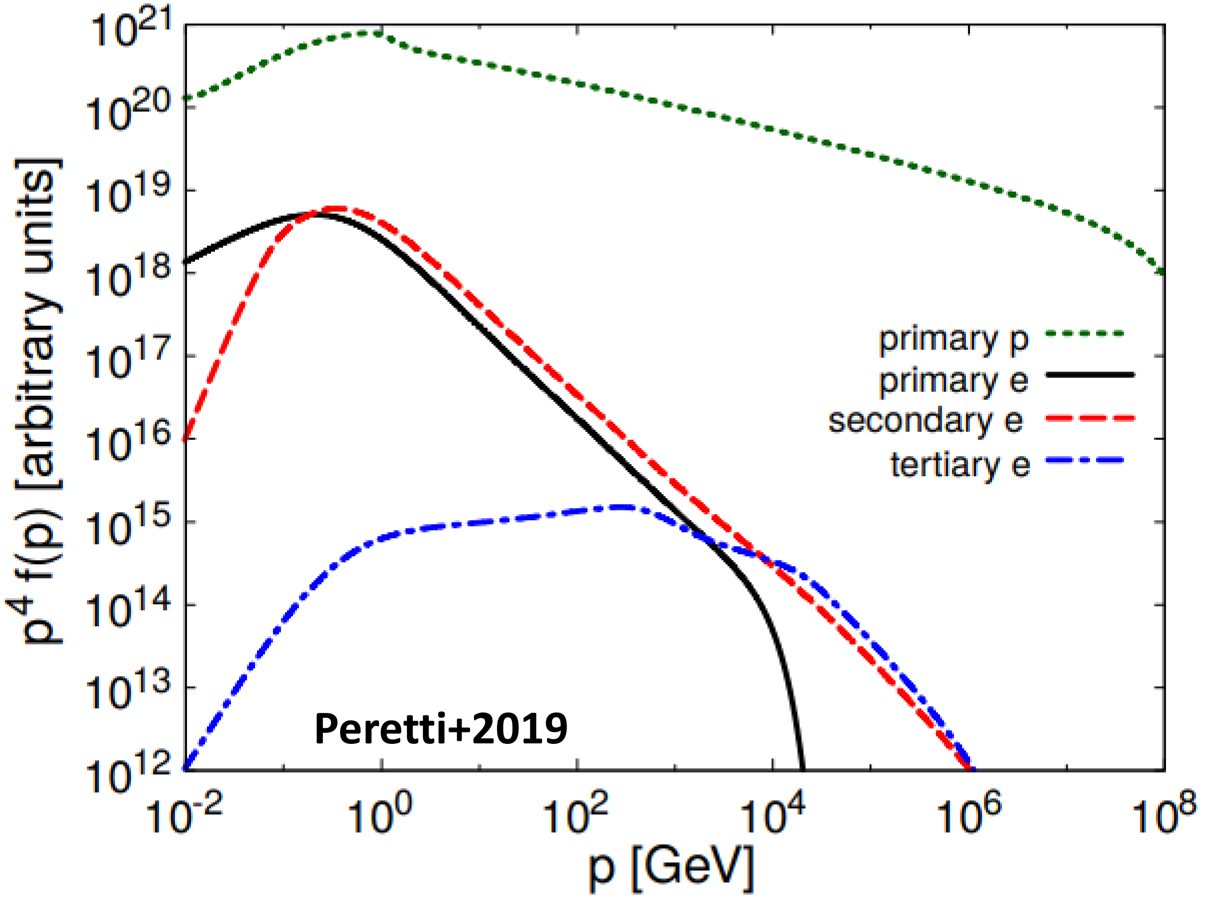
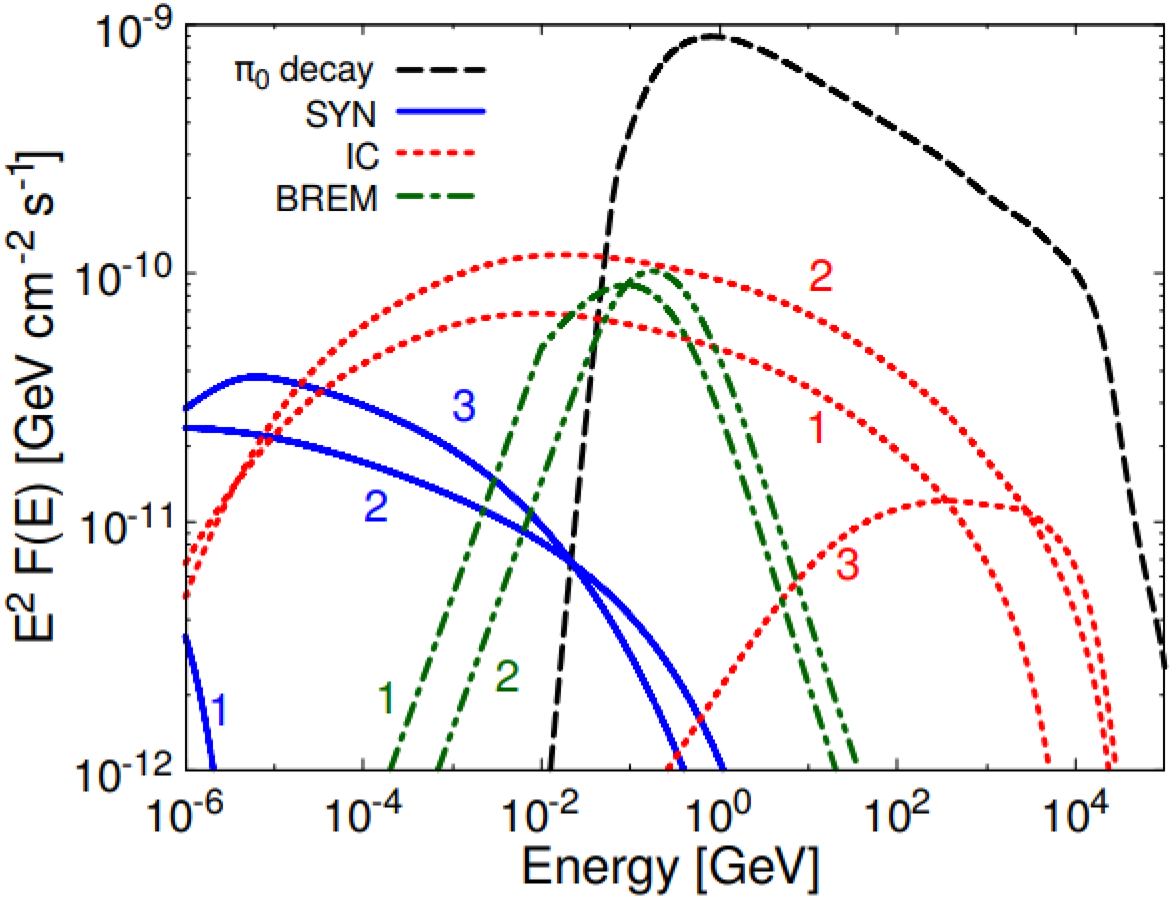
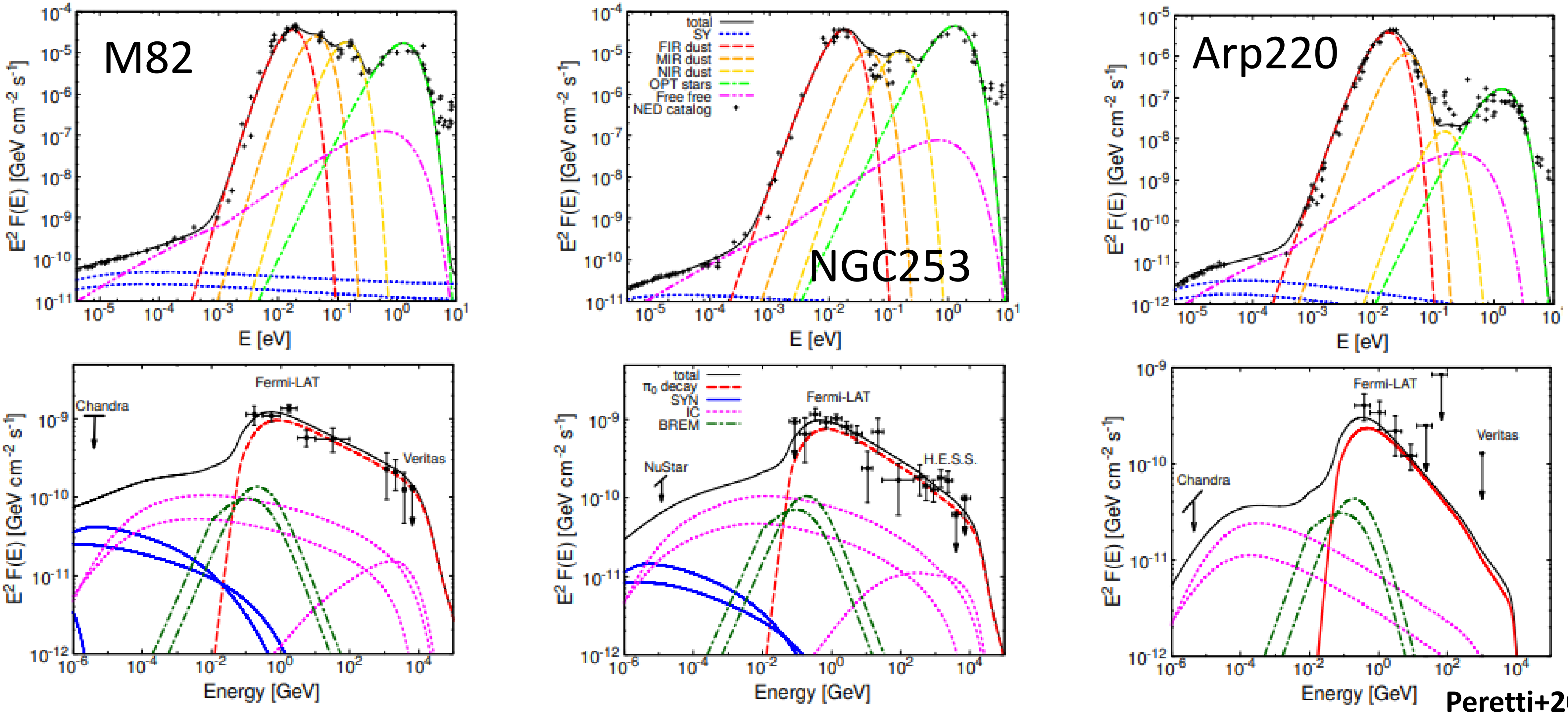




Modeling nearby SBGs

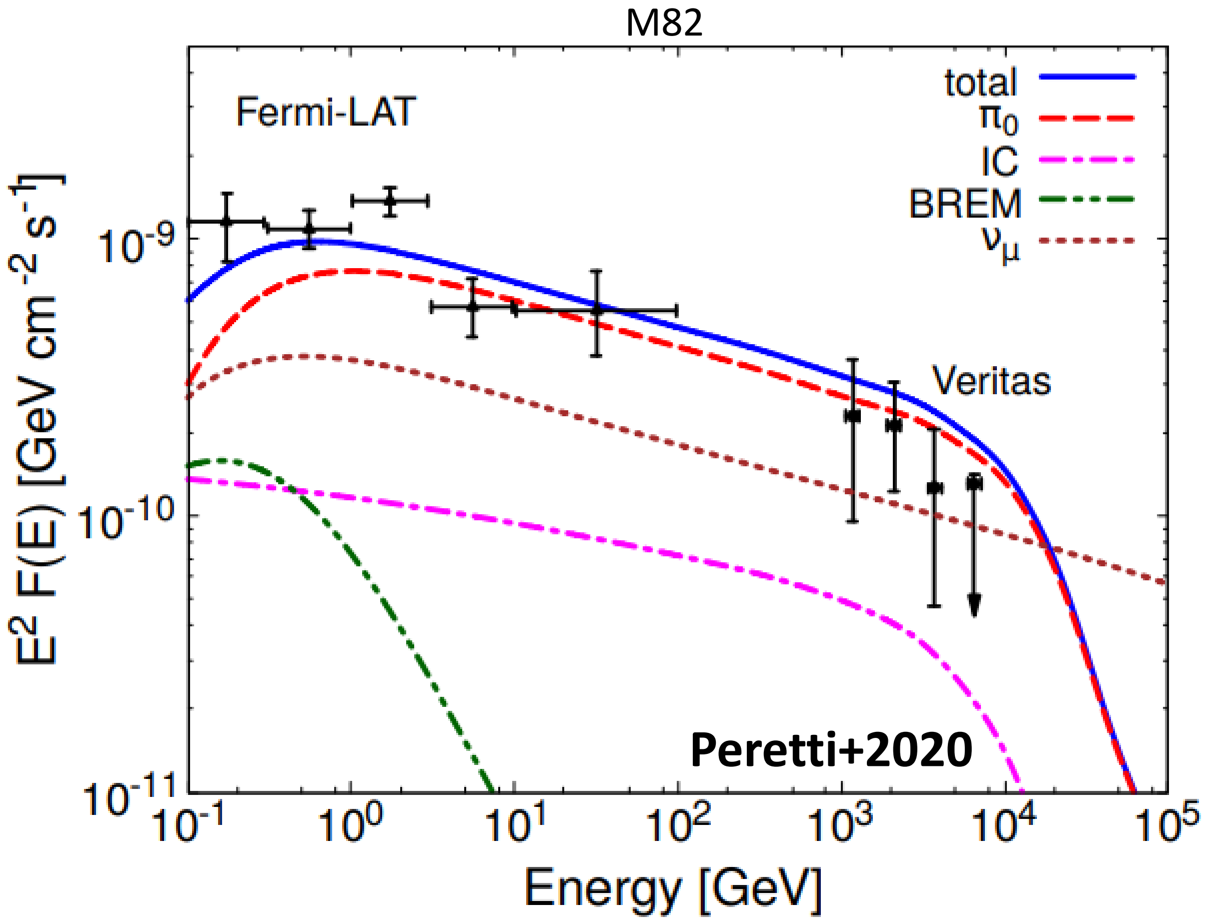


Peretti+2019

Gamma rays and neutrinos

- Cosmic-ray calorimeters are ideal neutrino factories

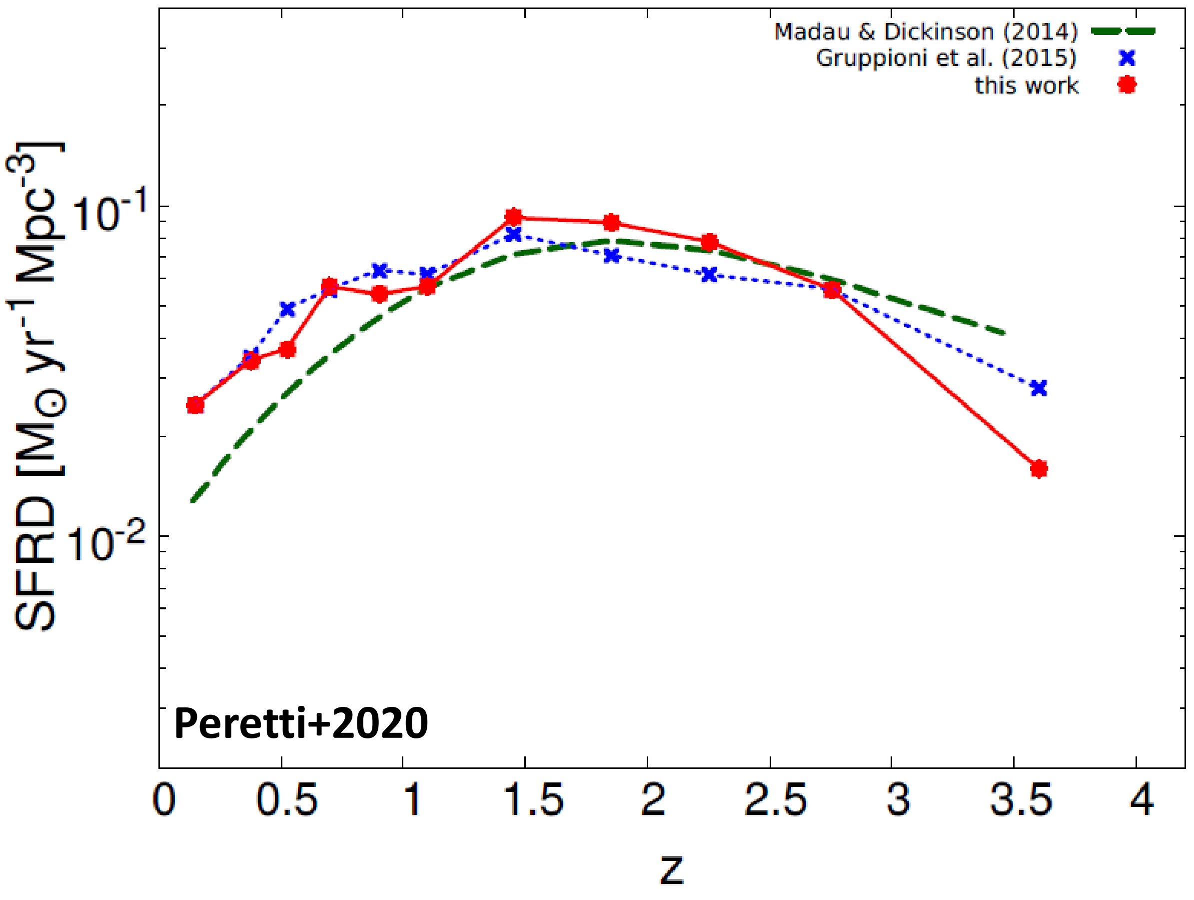
parameter	value
$p_{p,\max}$	10^2 PeV
α	4.2
R	0.25 kpc
D_L	3.9 Mpc
$\xi_{\rm CR}$	0.1
$\mathcal{R}_{\rm SN}$	0.06 $\rm yr^{-1}$
B	200 μG
$n_{\rm ISM}$	100 $\rm cm^{-3}$
$v_{\rm wind}$	700 km/s
$U_{\rm rad}$	2500 $\rm eV/cm^3$

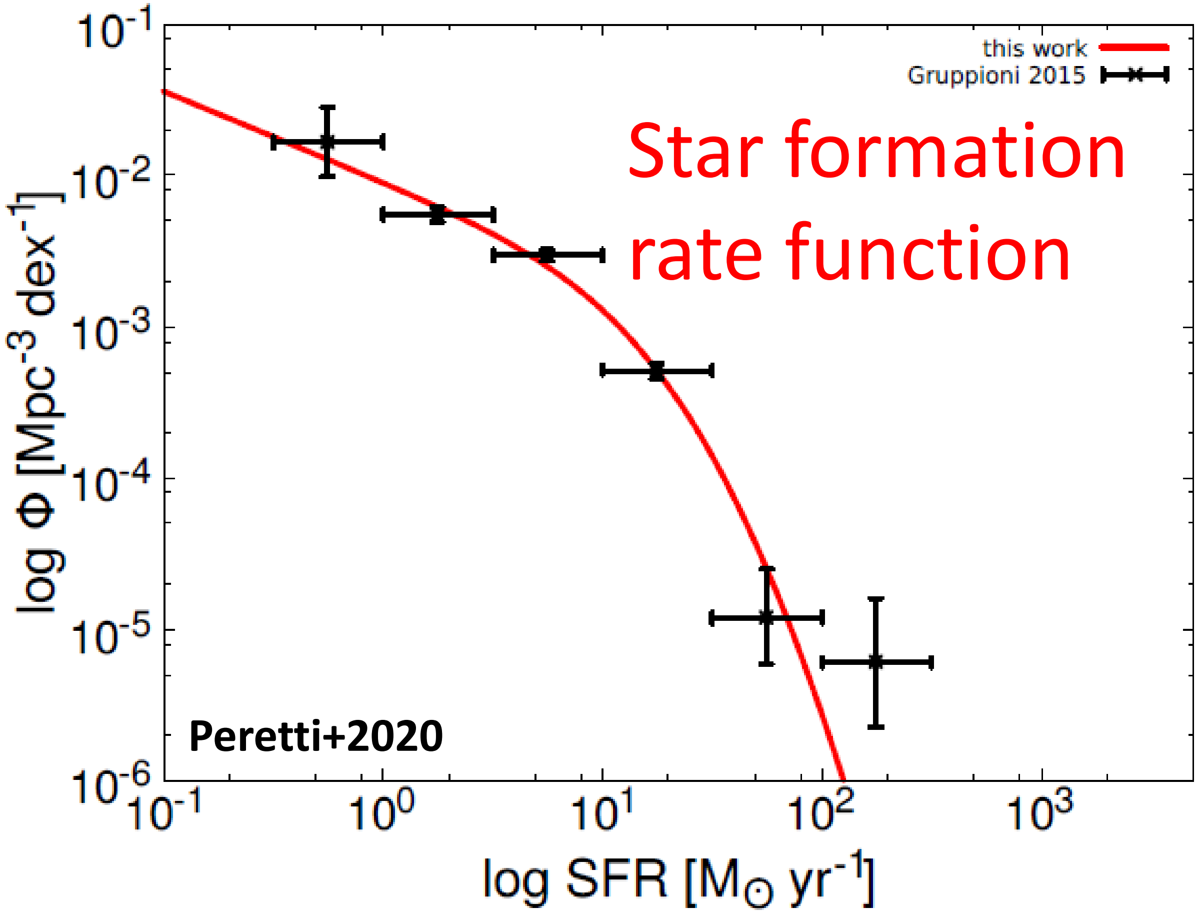


Outline

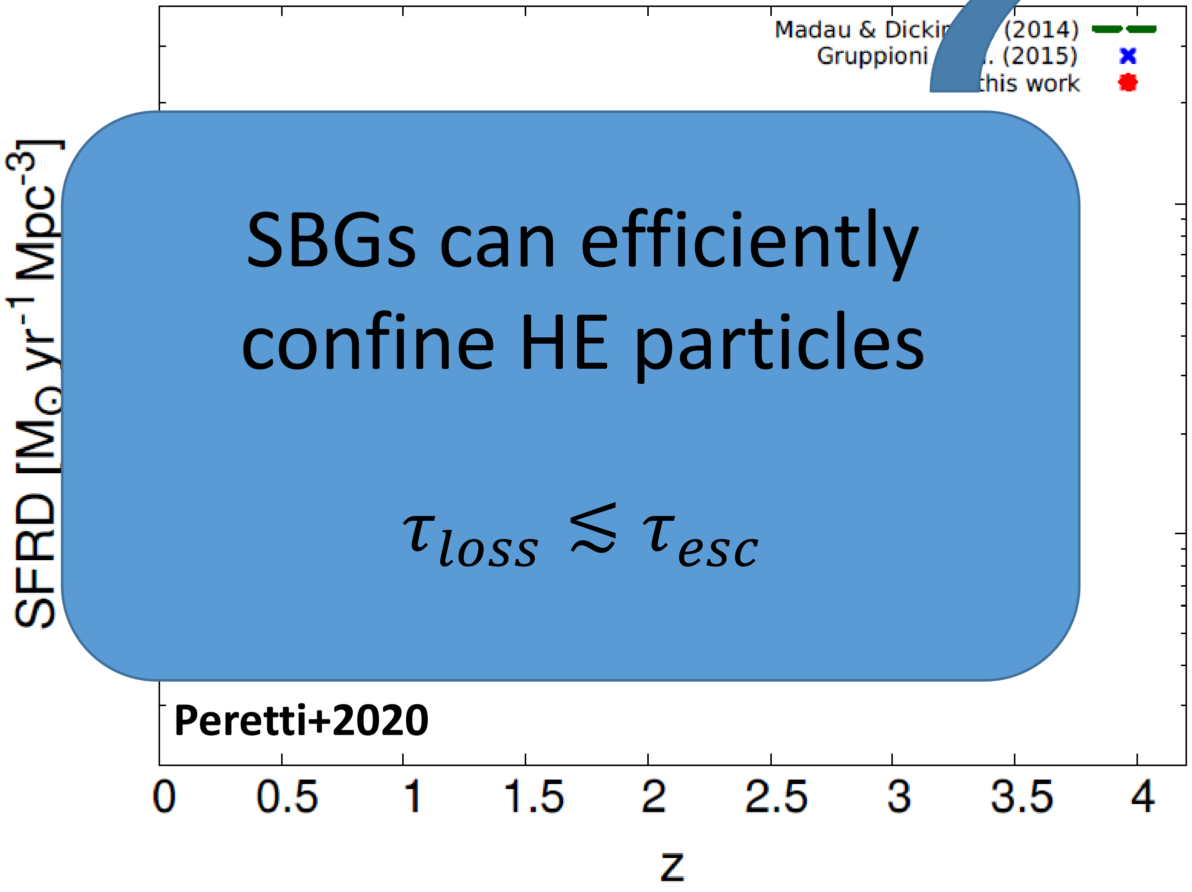
- Cosmic ray transport
- Particle Transport in Starburst Nuclei
- Diffuse emission from Starburst Galaxies

Counting Starburst Galaxies



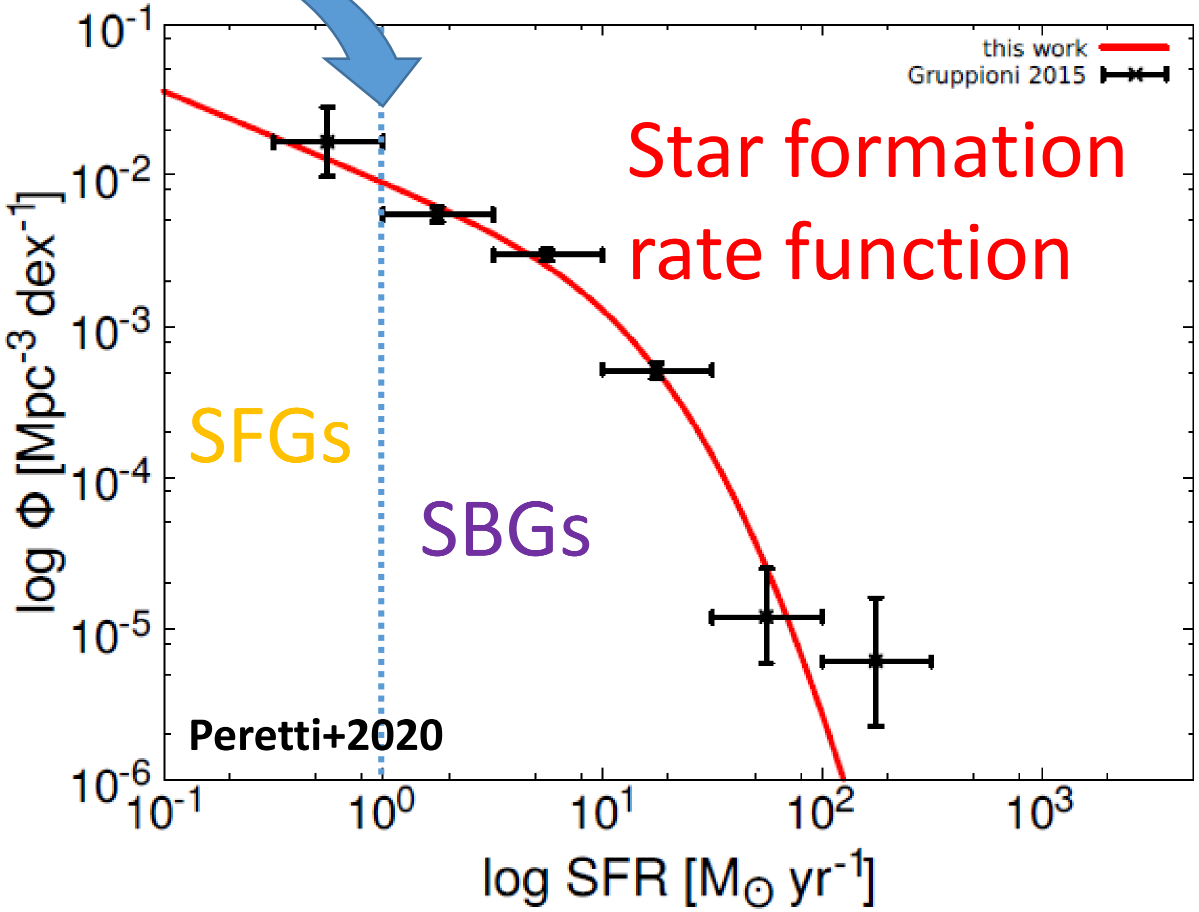


Counting Starburst Galaxies

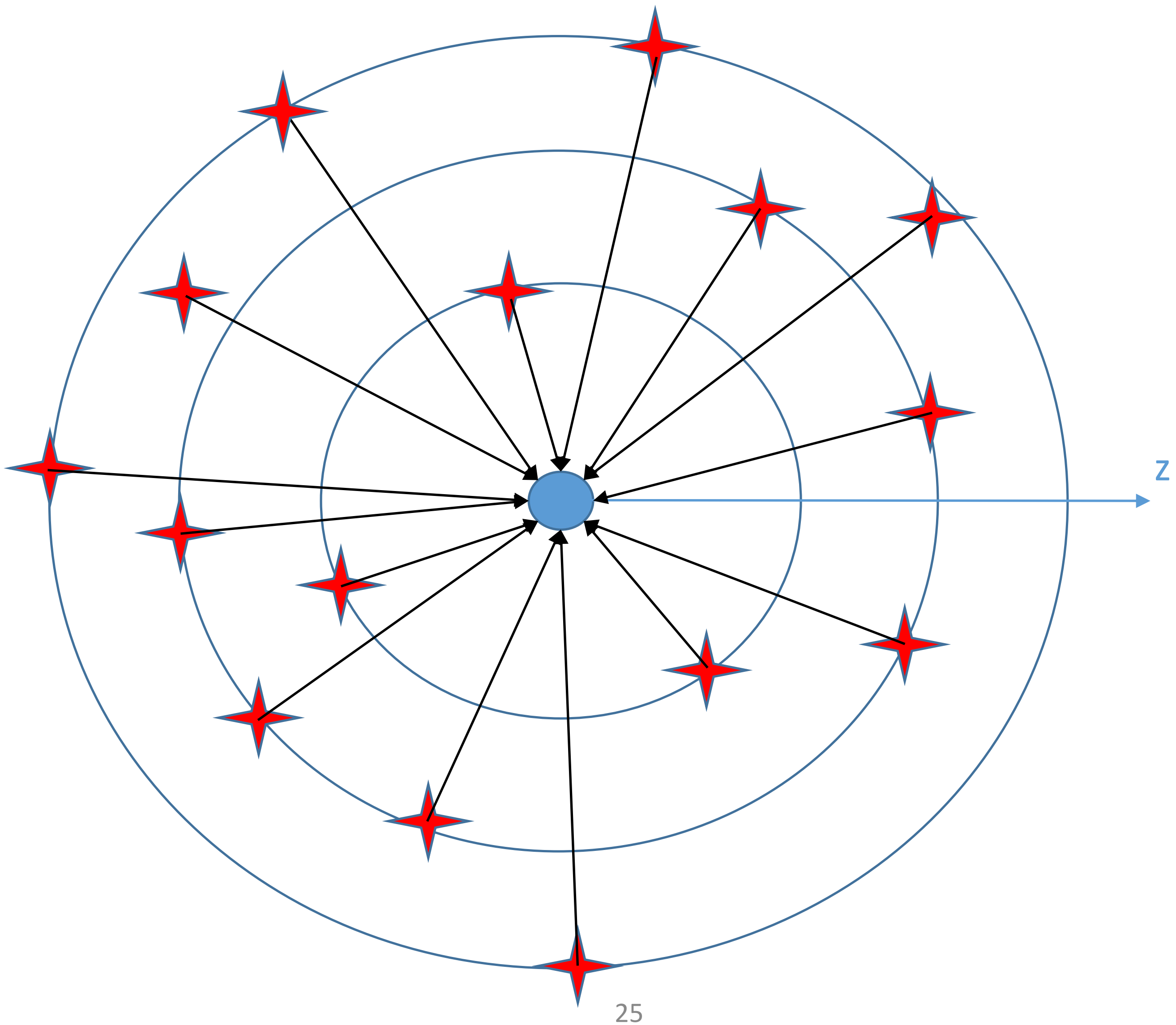


SBGs can efficiently confine HE particles

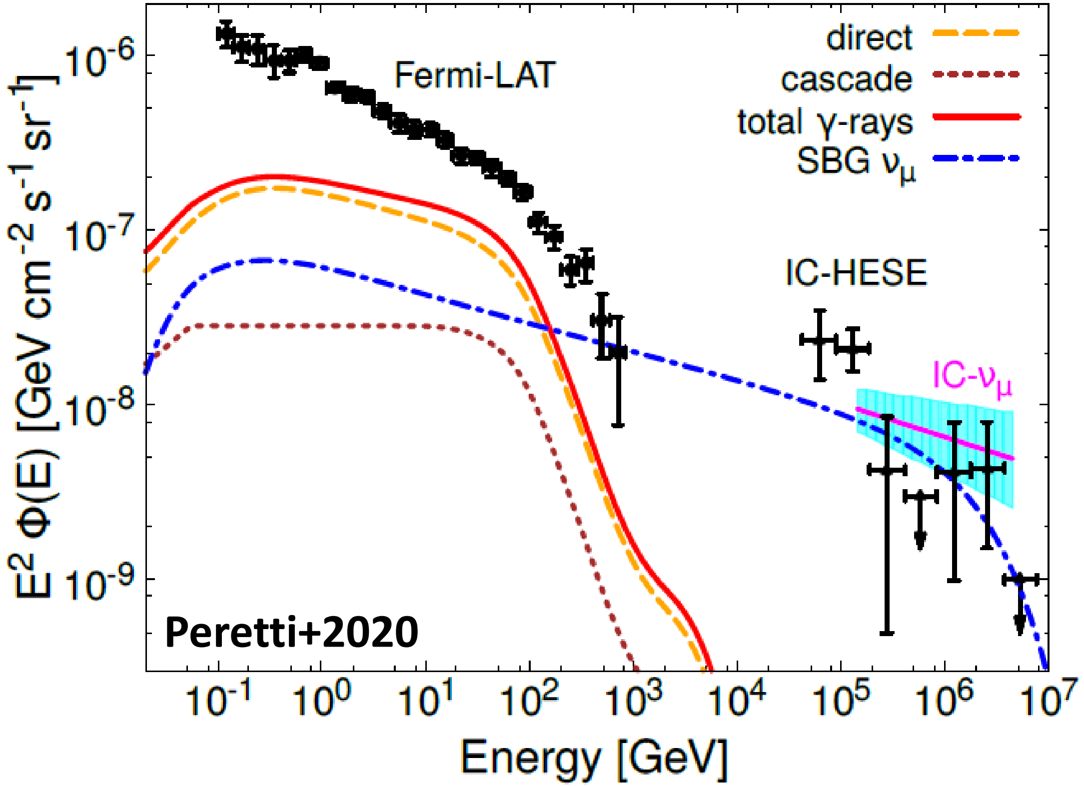
$$\tau_{loss} \lesssim \tau_{esc}$$



Starbursts as diffuse sources

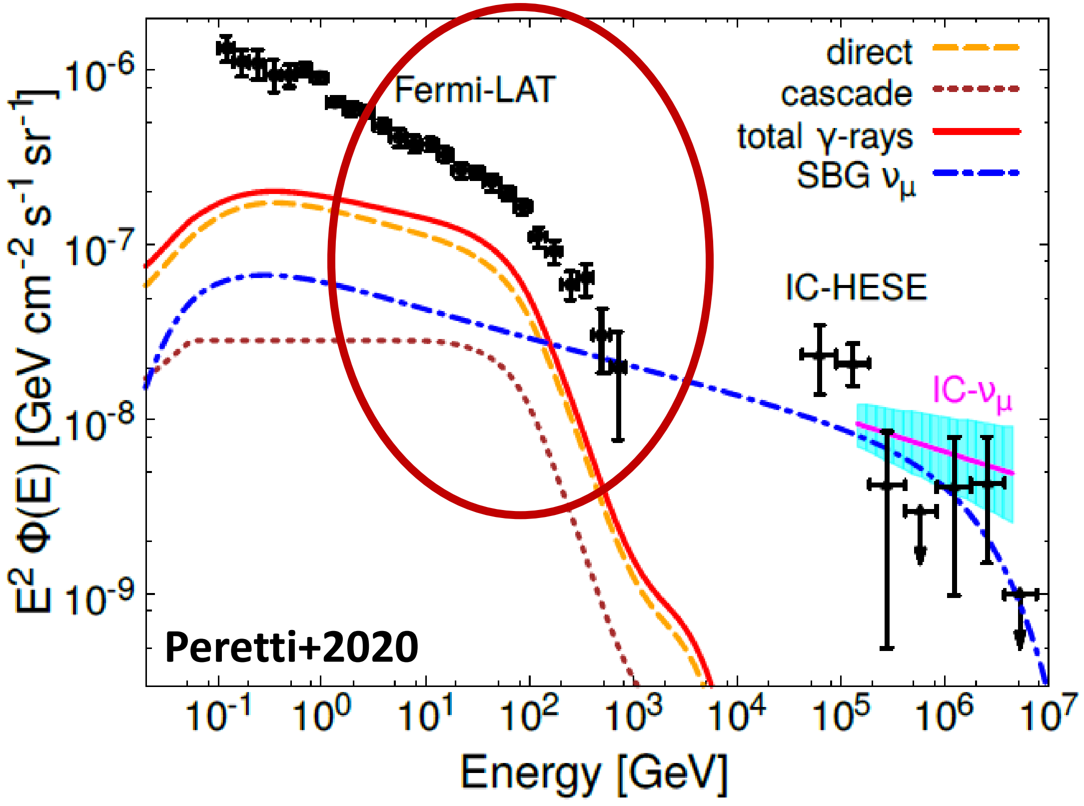


Diffuse emission from Starburst Galaxies



- SBNi only

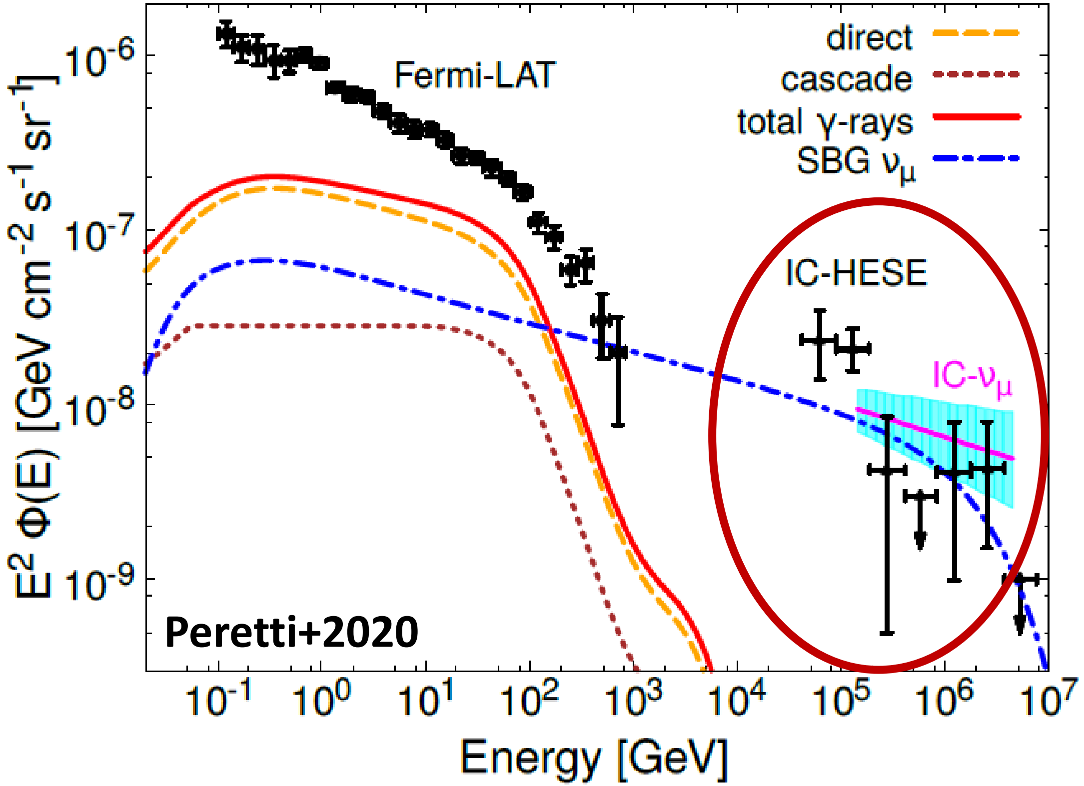
Diffuse emission from Starburst Galaxies



- 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 measurment

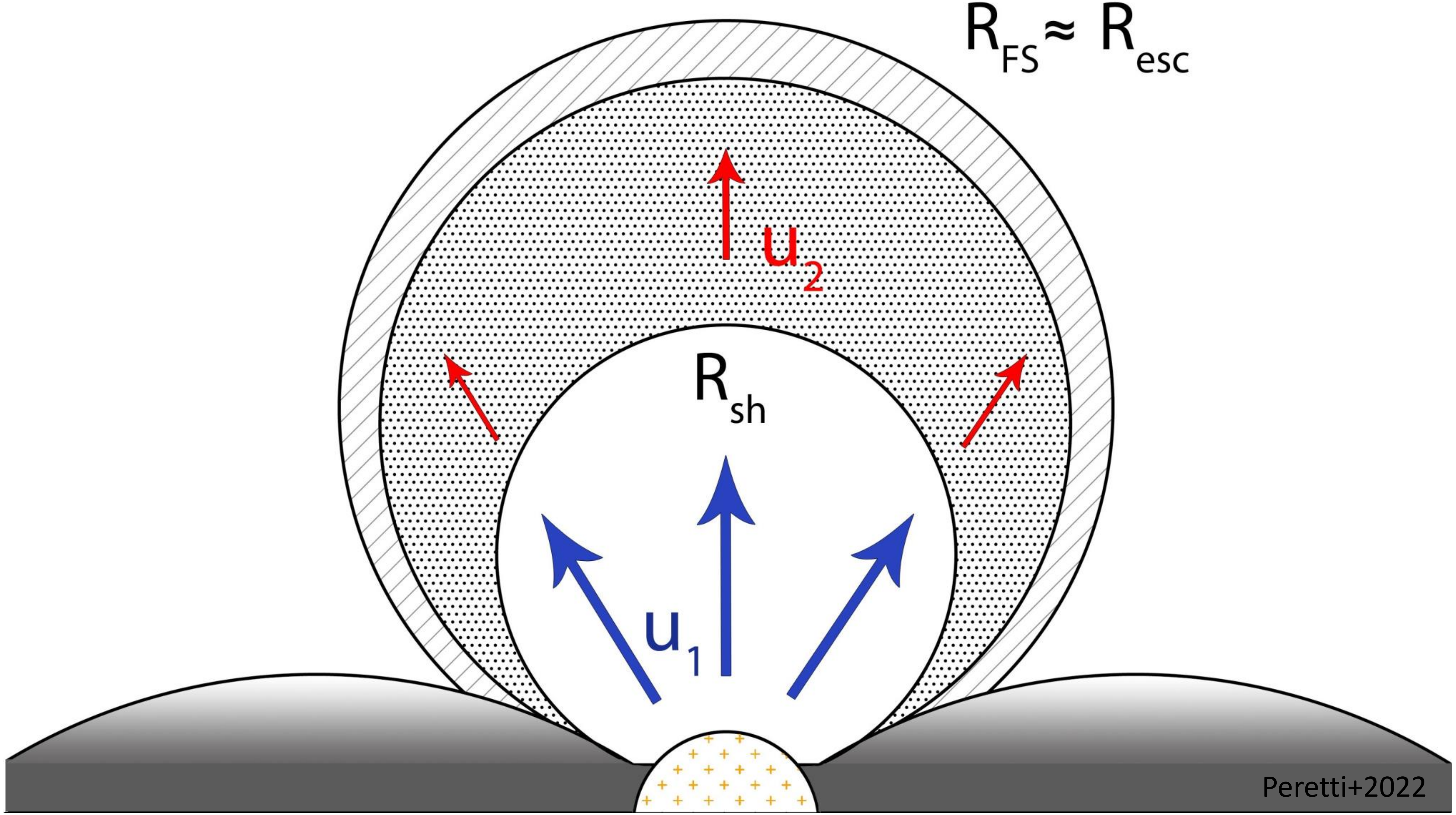
Take home messages

- Starburst galaxies can approach calorimeteric conditions
- We expect gamma rays and neutrino from Starburst Nuclei
- Starburst Nuclei can provide a sizeable contribution to the multimessenger diffuse flux (gamma rays, neutrinos)

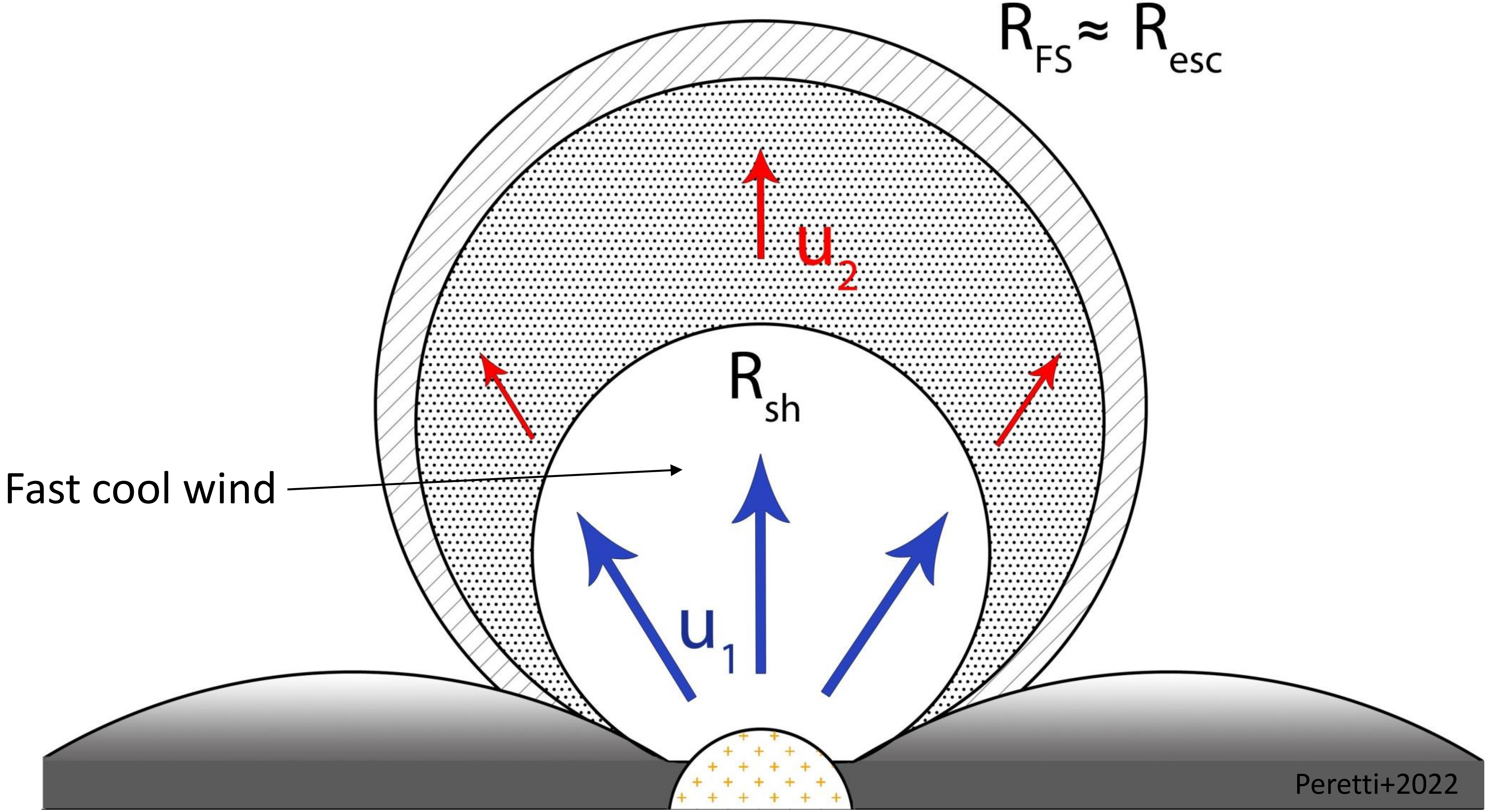
Thanks for your attention!

Back up

Acceleration and transport in starburst winds



Acceleration and transport in starburst winds



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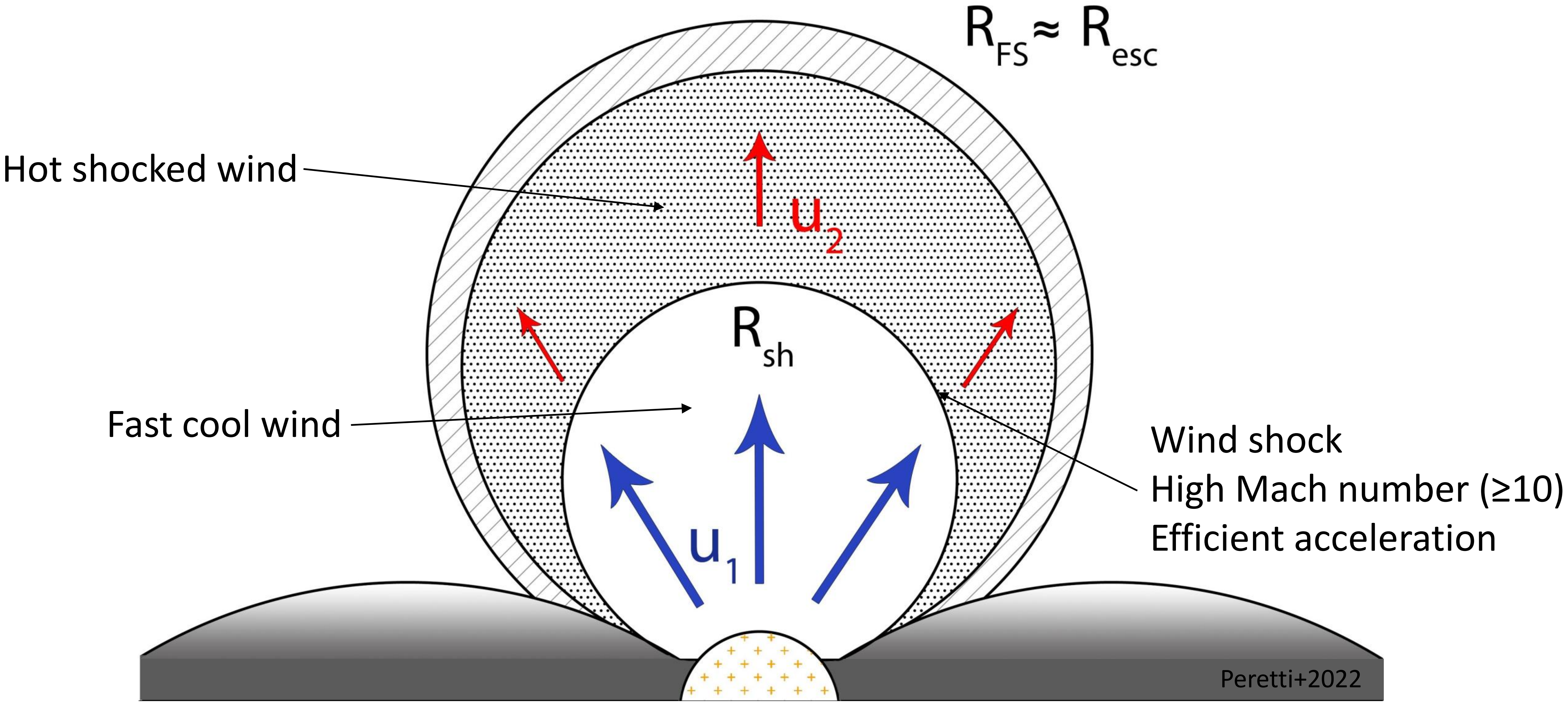
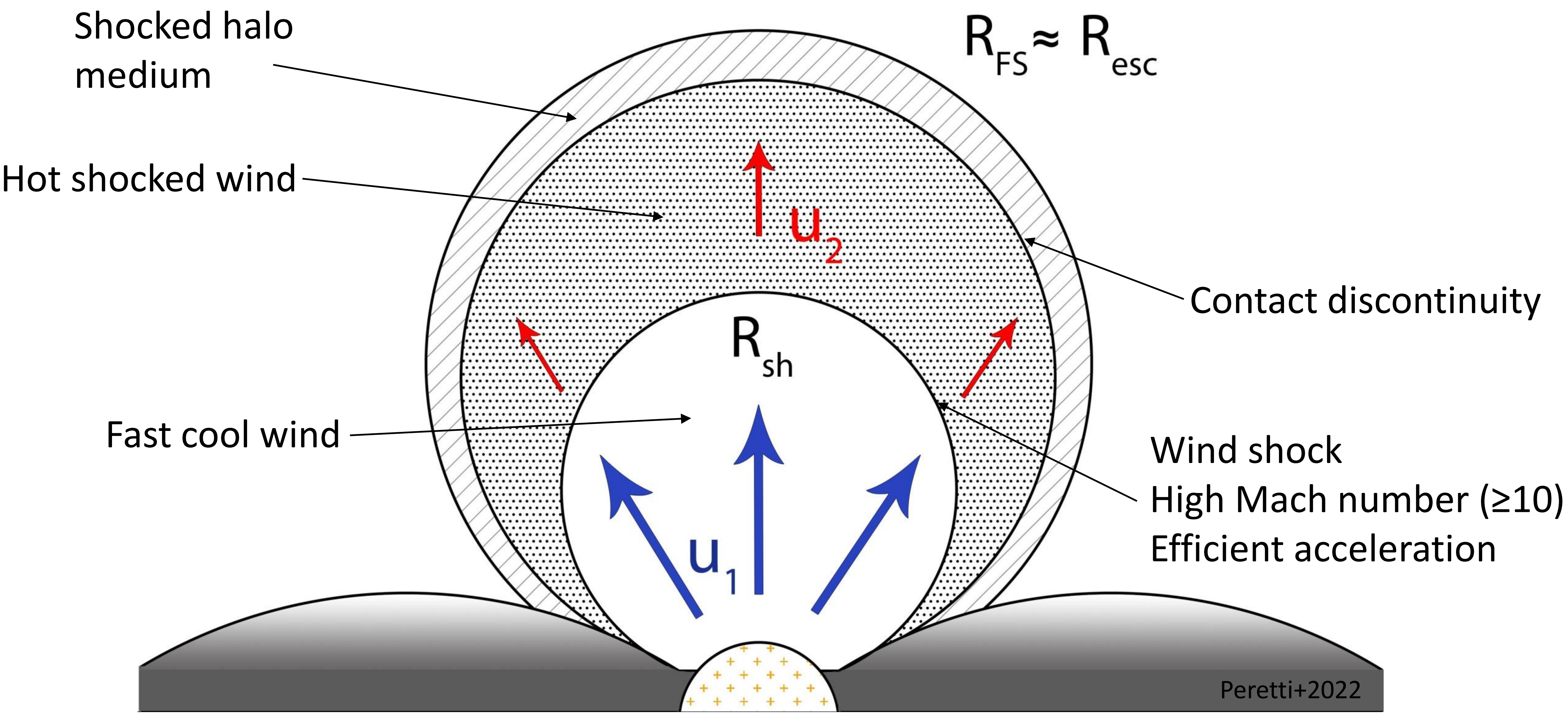


Acceleration and transport in starburst winds



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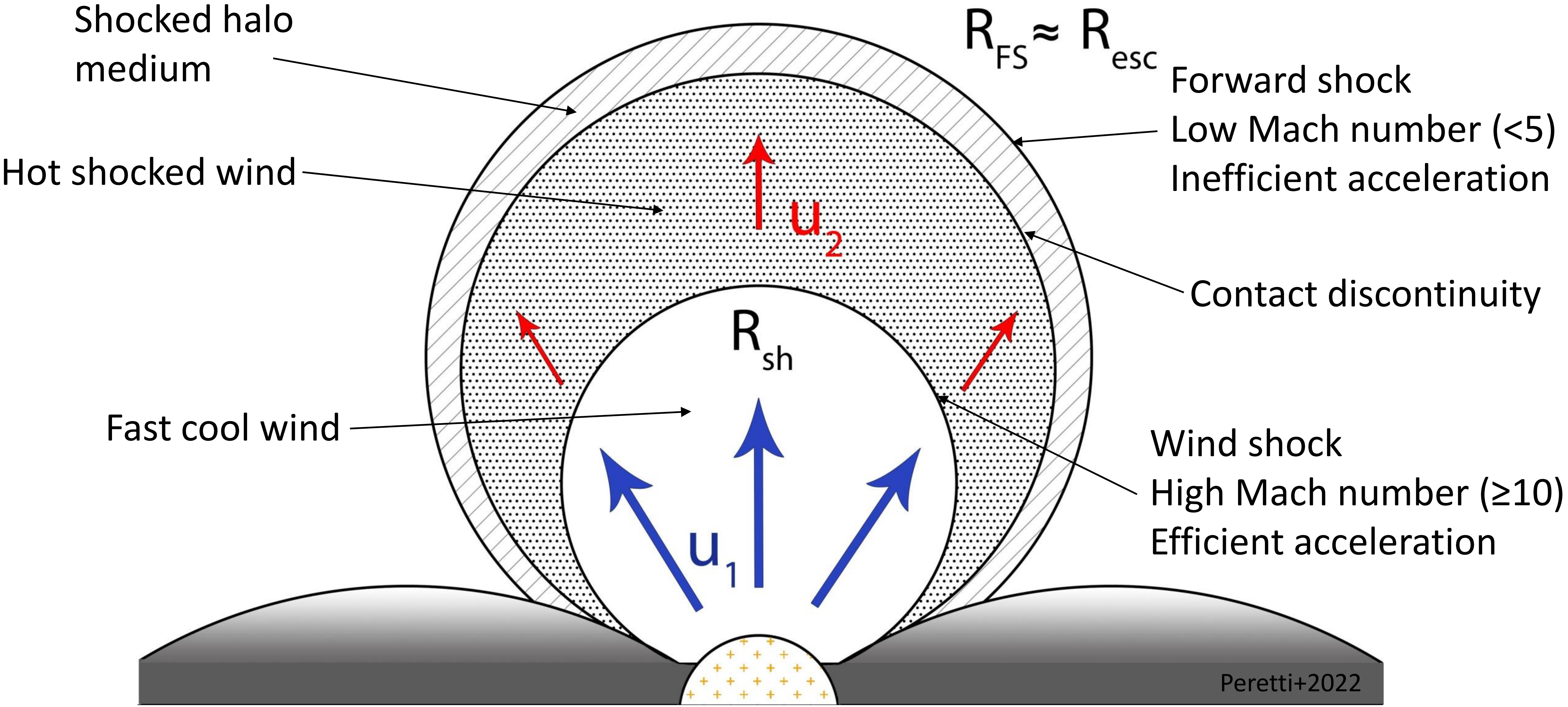
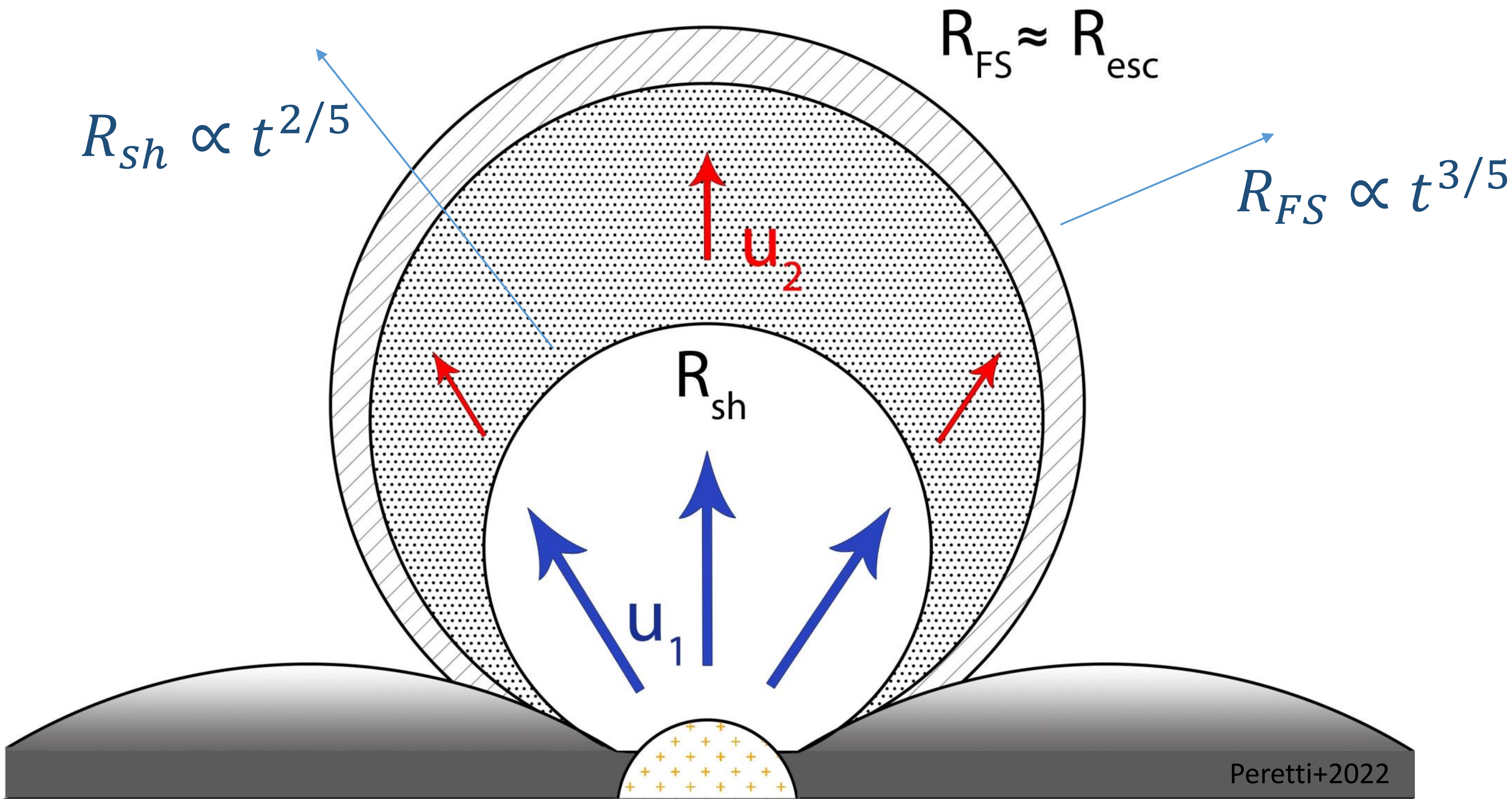
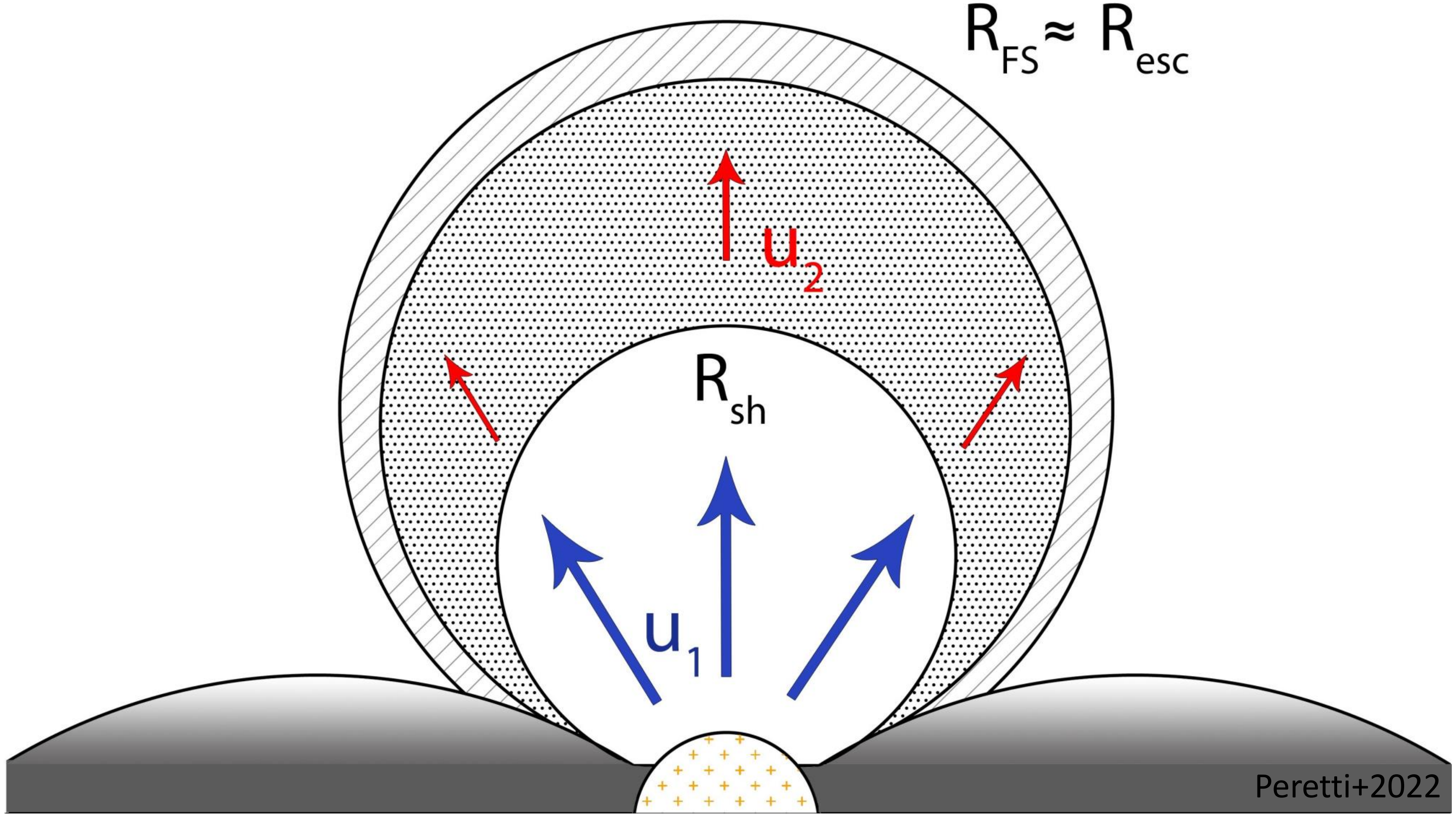


Acceleration and transport in starburst winds



Transport model

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



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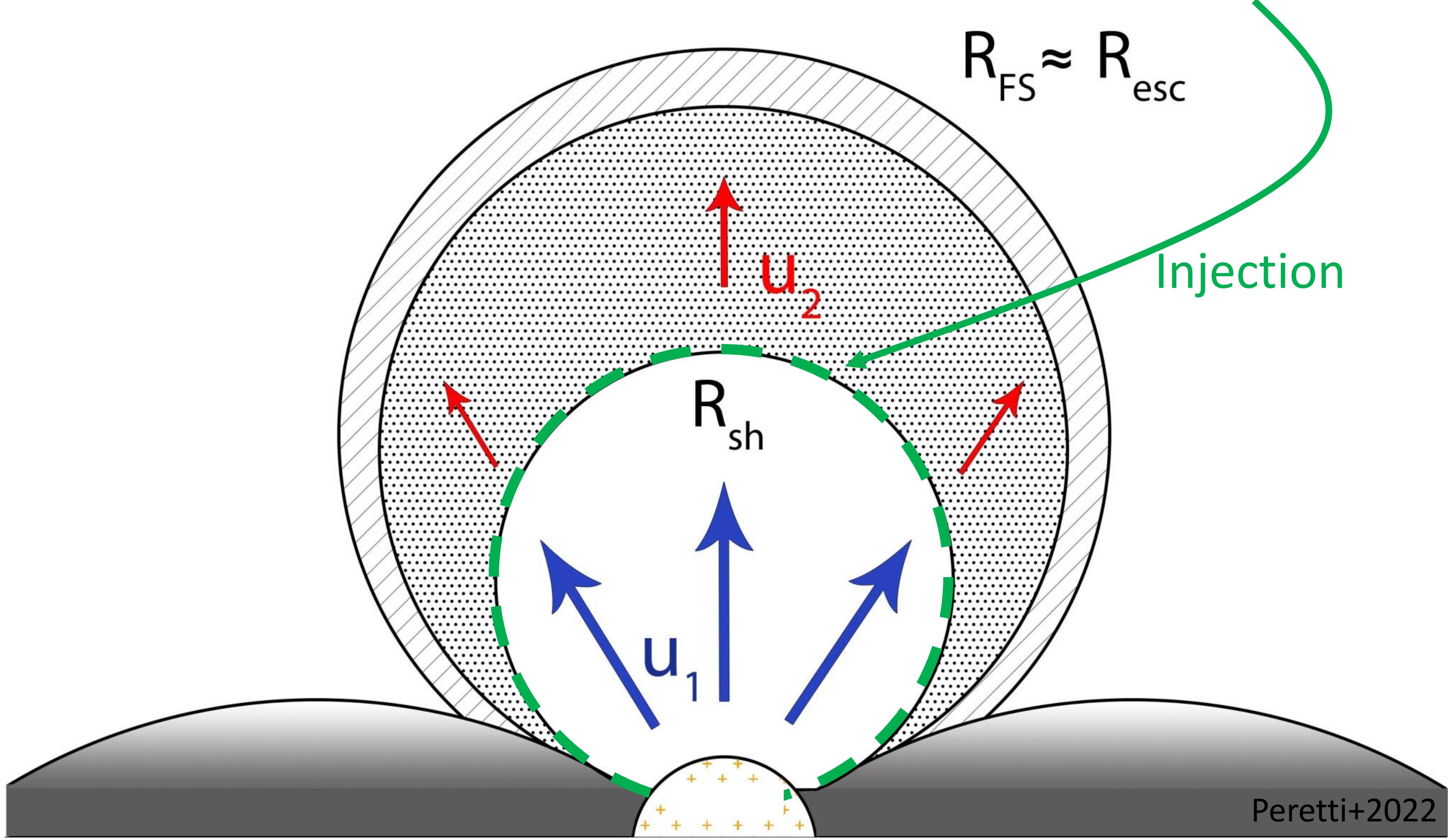

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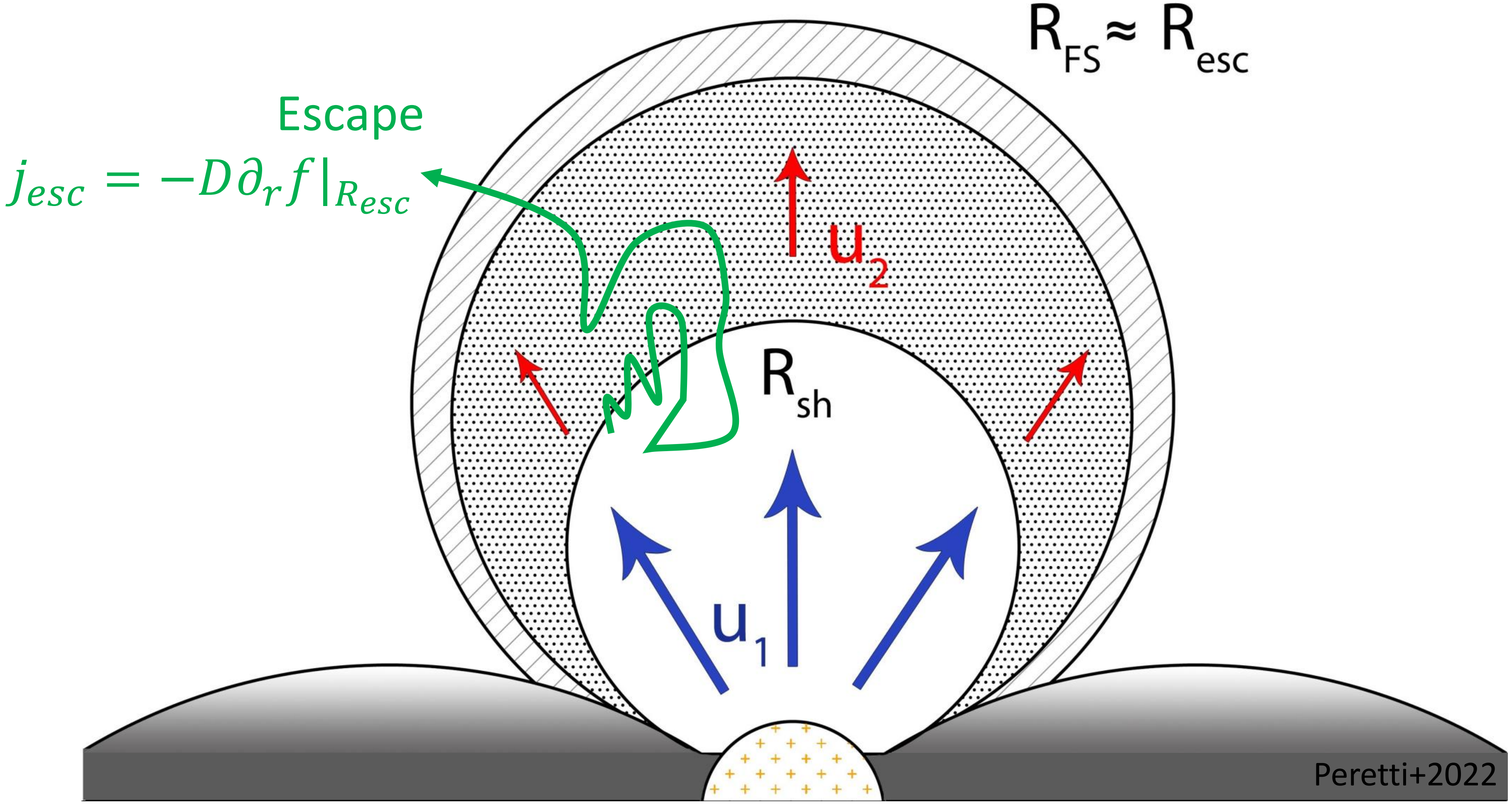

Transport model

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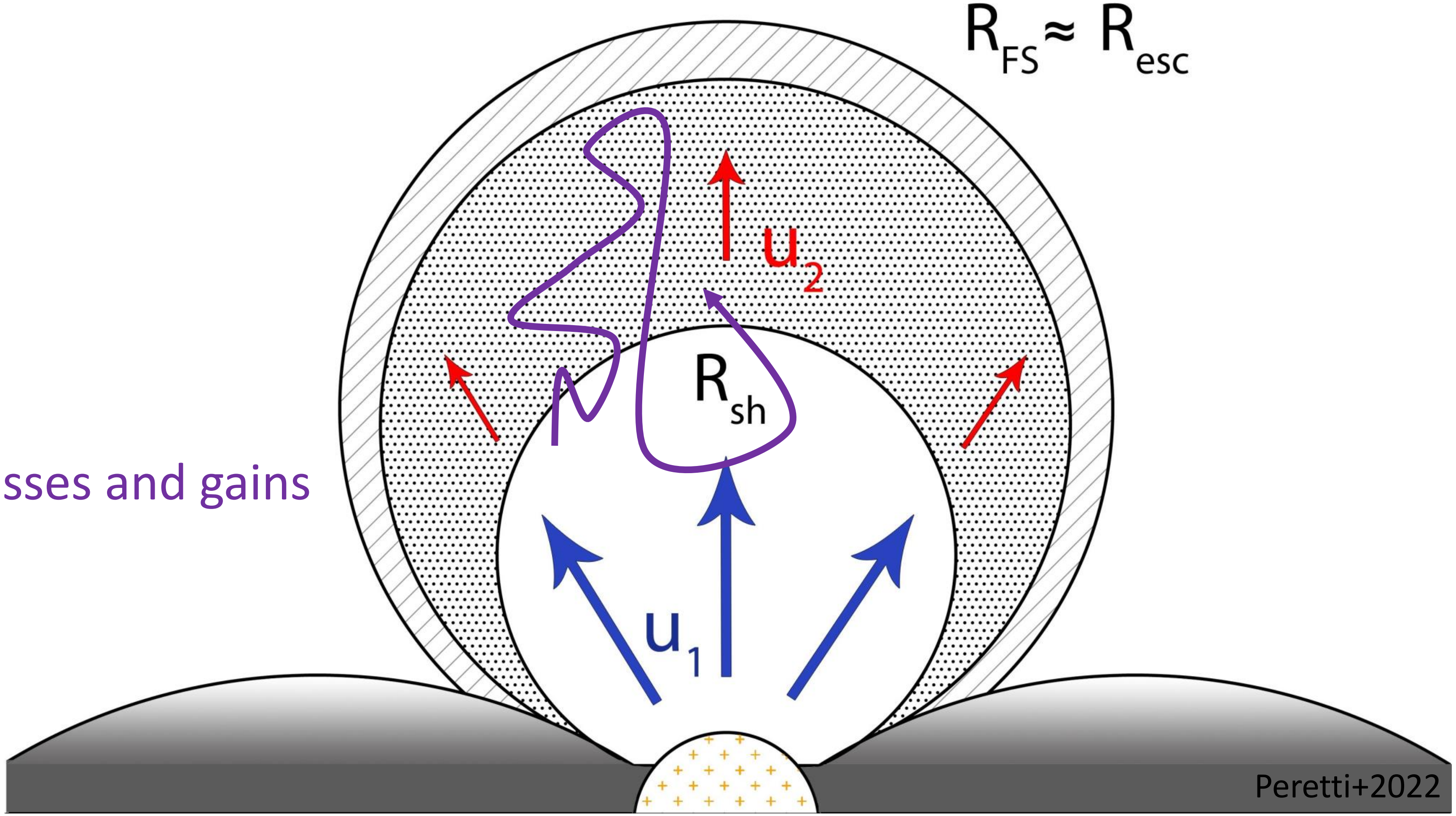
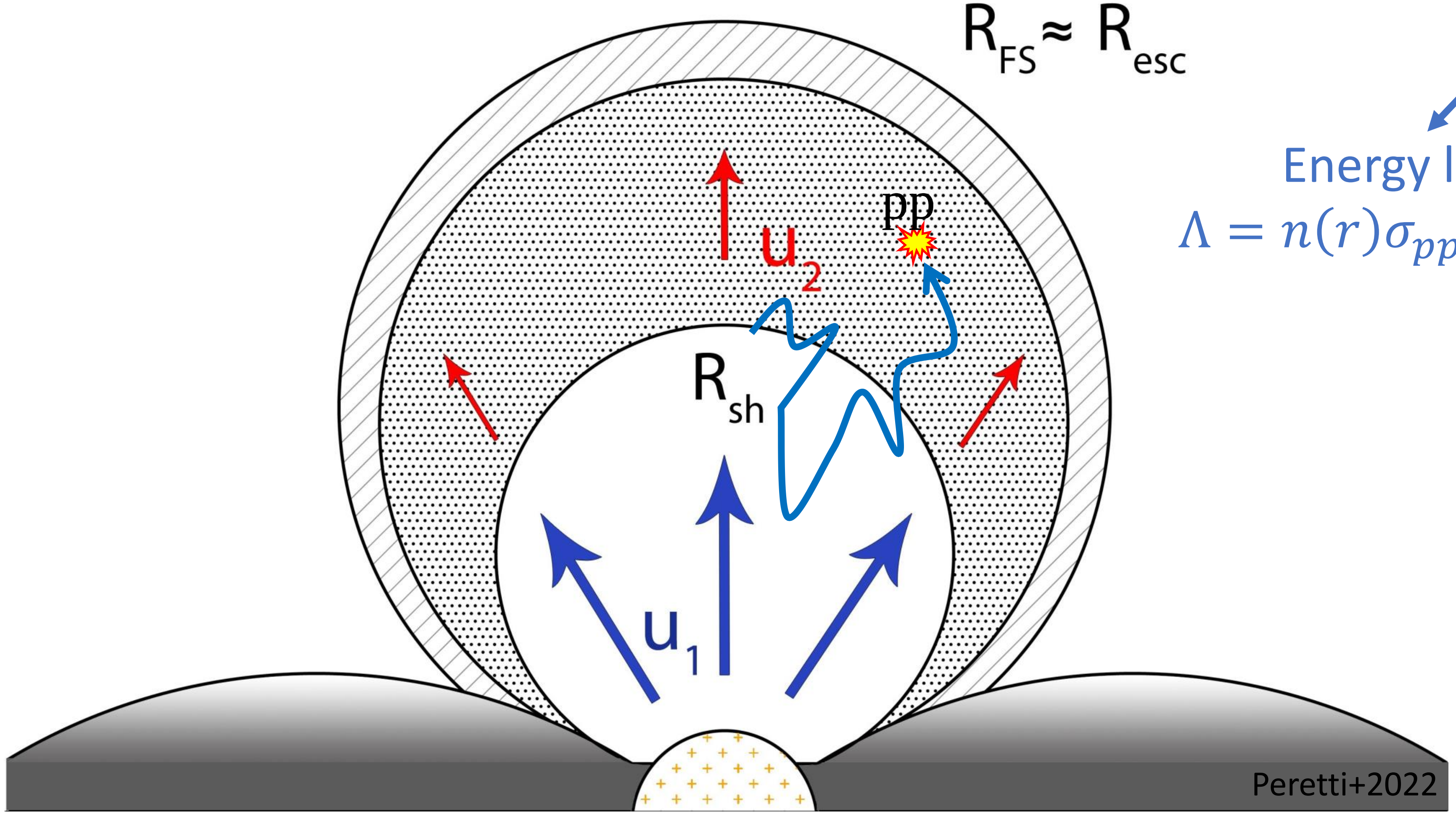
- Advection
- Diffusion
- Adiabatic losses and gains



Transport model

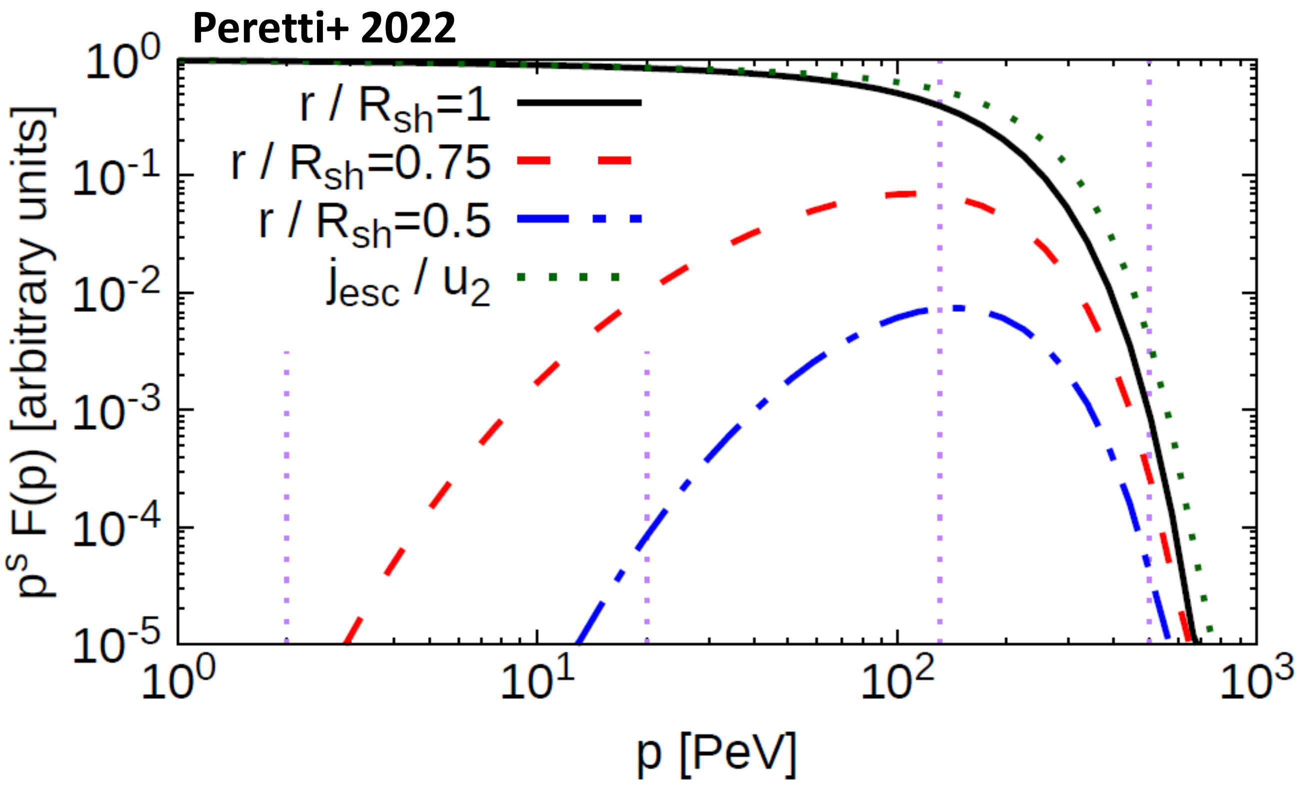
$$r^2 u(r)\partial_r f = \partial_r[r^2 D(r,p)\partial_r f] + \frac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p) - r^2\Lambda(r,p)$$



Energy losses

$$\Lambda = n(r)\sigma_{pp}(p)v(p)f$$

Particles in the system



Parameters

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

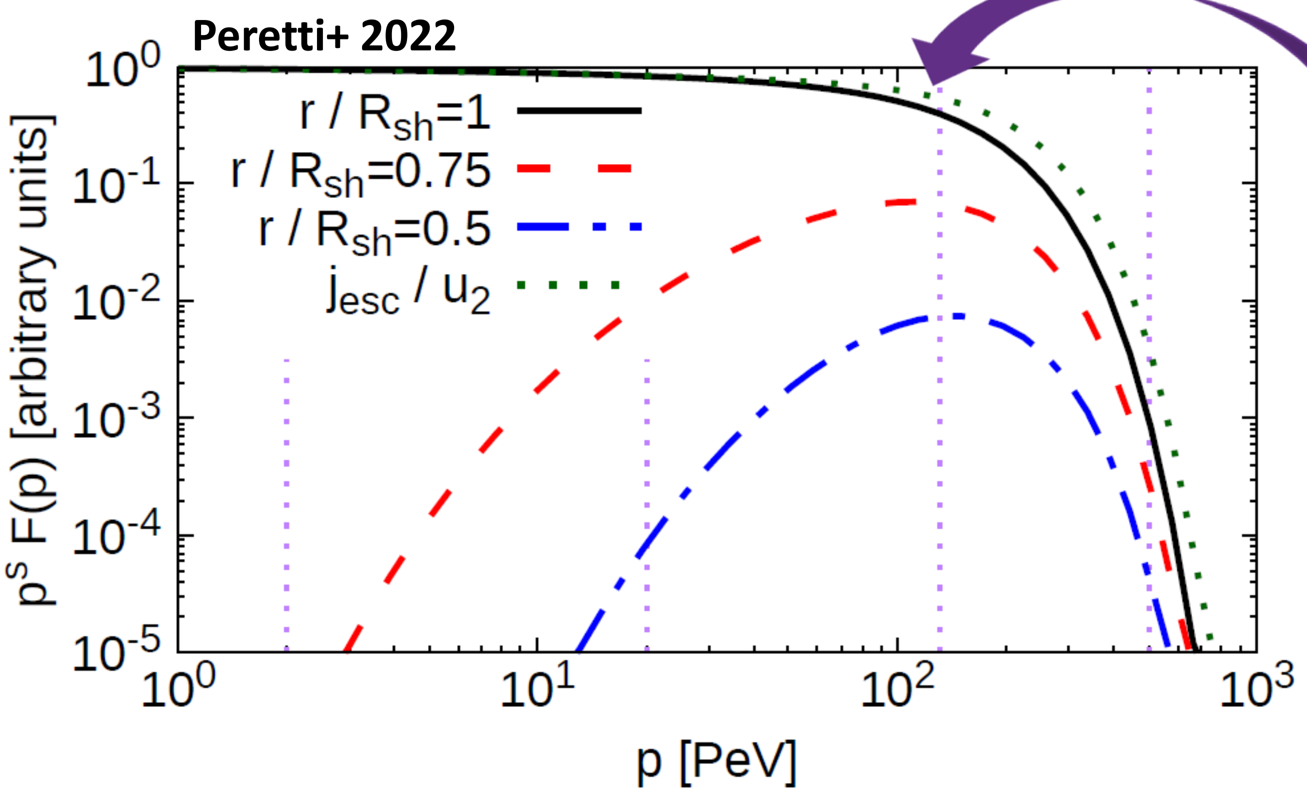
$V_{\infty} = 3000\ km\ \ s^{-1}$

$R_{sh} = 12\ kpc$

$R_{FS} = 55\ kpc$

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

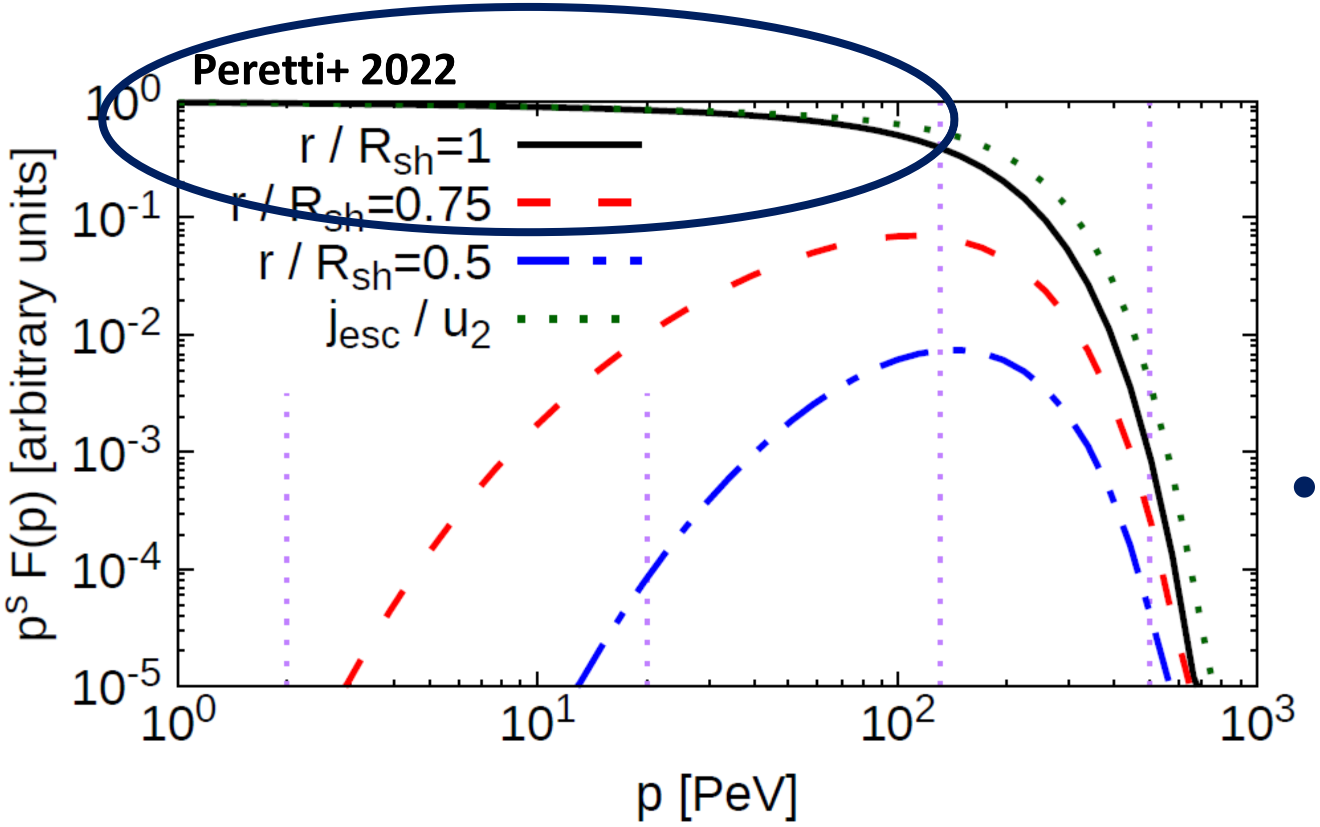
Particles in the system



- Maximum Energy → 10^2 PeV

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

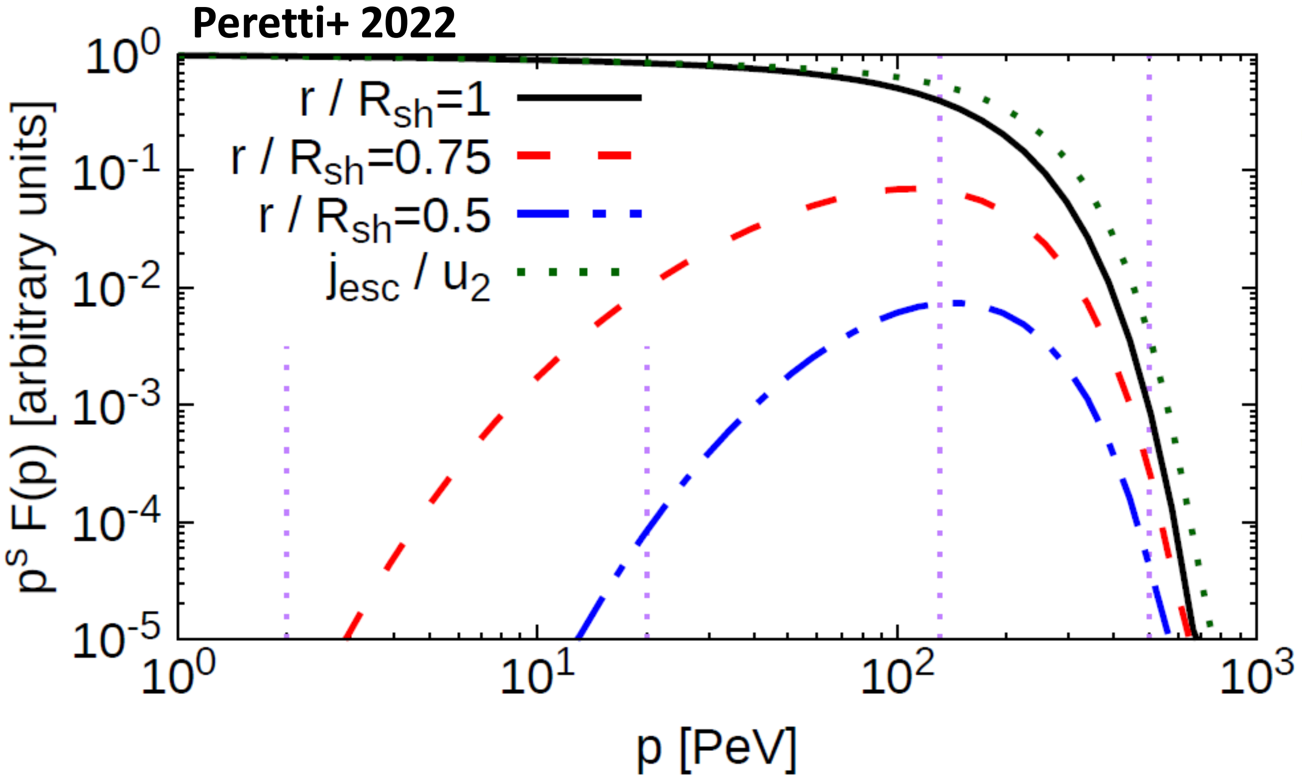
Particles in the system

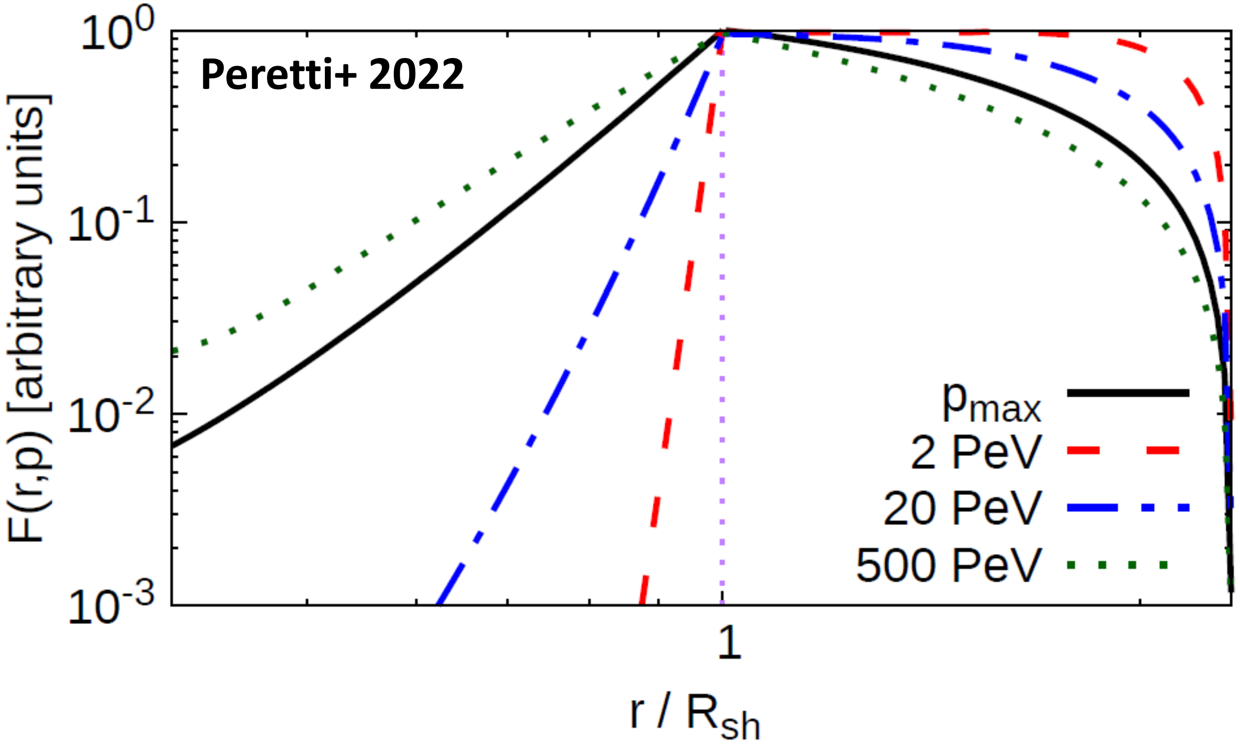


- Maximum Energy → 10^2 PeV
- Standard DSA valid at low Energy

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

Particles in the system

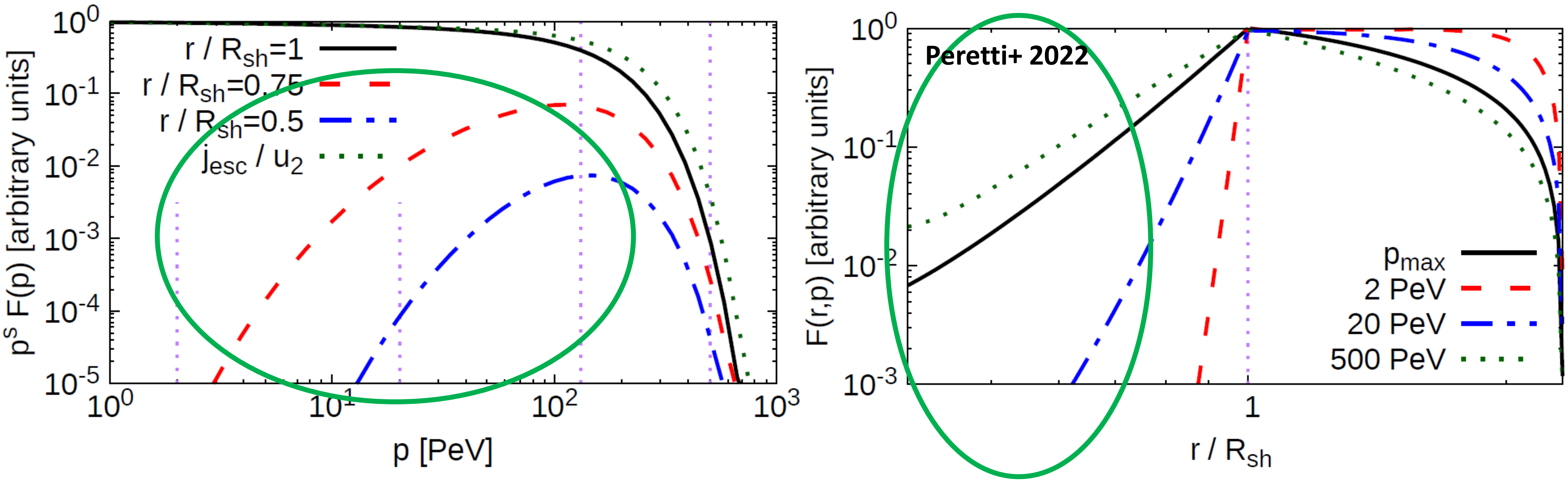




$$f_{sh}(p) \propto p^{-s} e^{-\Gamma_1(p)} e^{-\Gamma_2(p)}$$

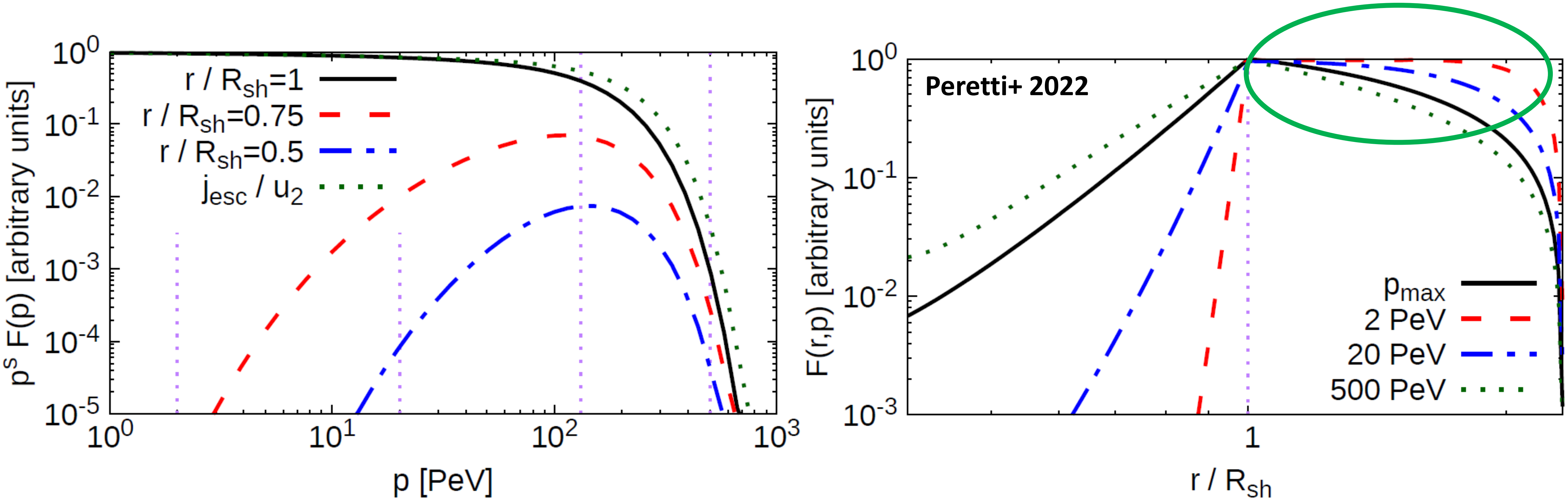
$$f_u(r,p) = f_{sh}(p)\, e^{-\int_r^{R_{sh}} \left(\frac{u_{eff}}{D}\right) dr'}$$

Particles in the system



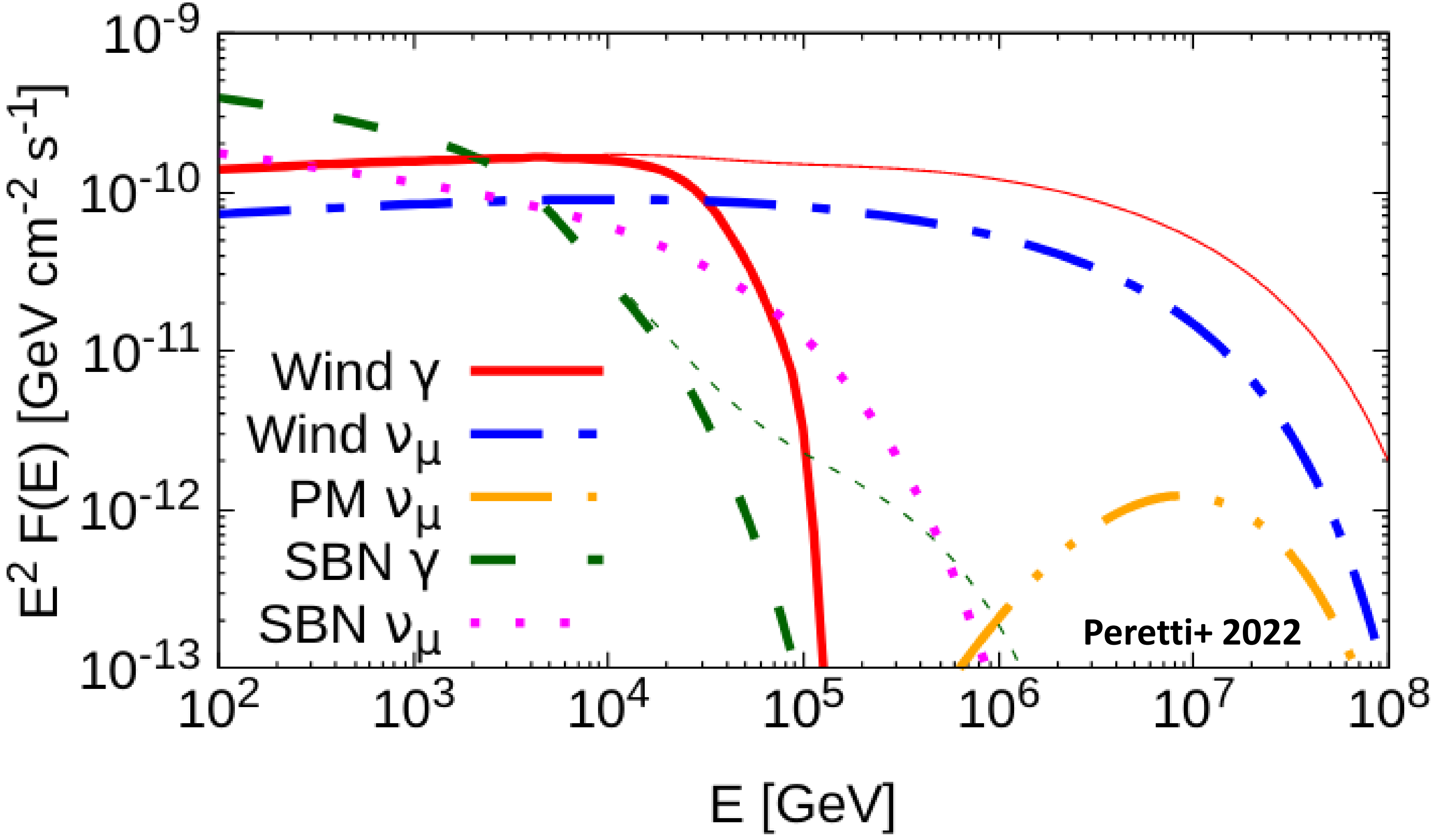
The wind suppresses the diffusion of particles back to the galaxy

Particles in the system

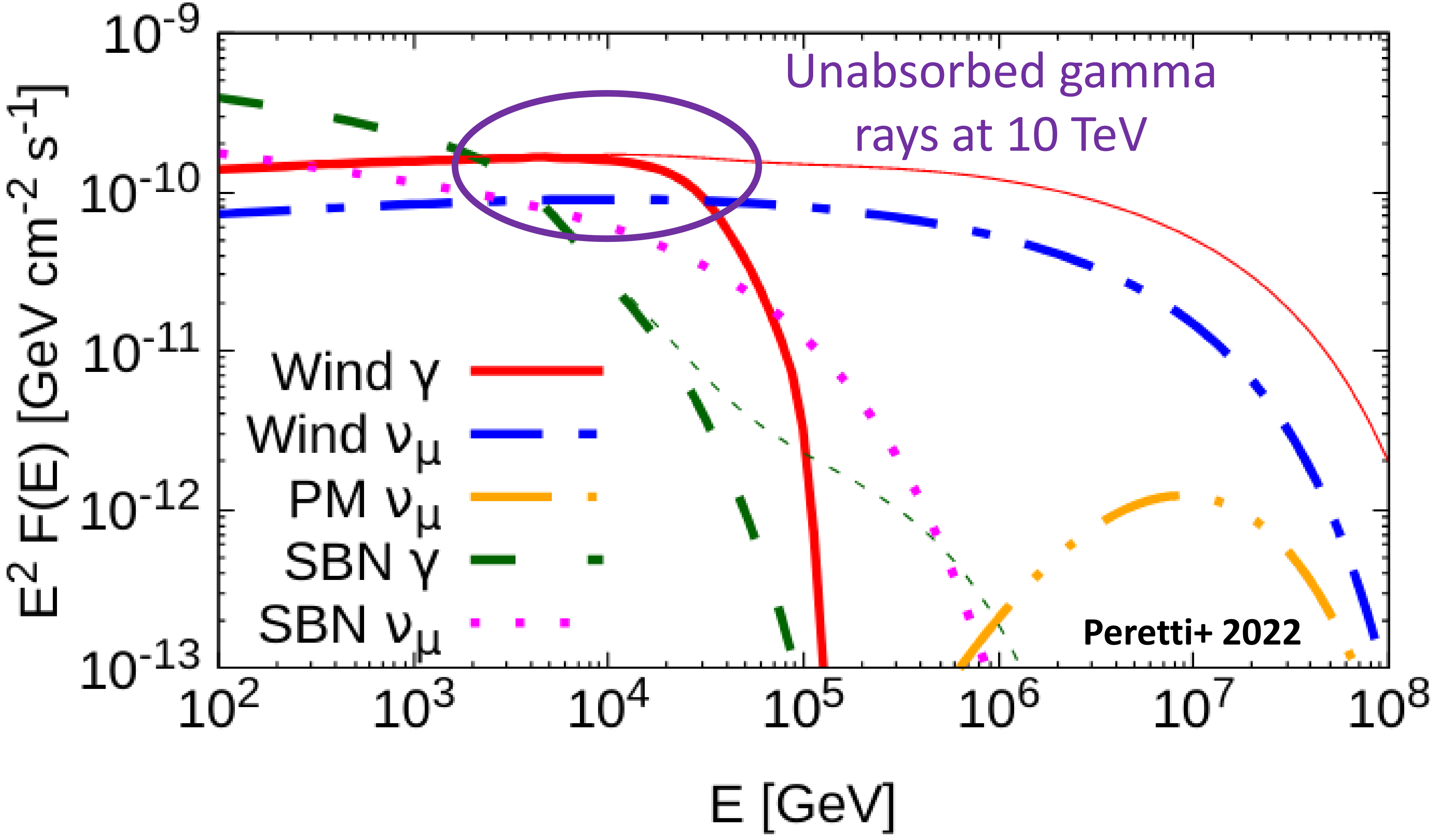


Particle distribution homogenized in the downstream region

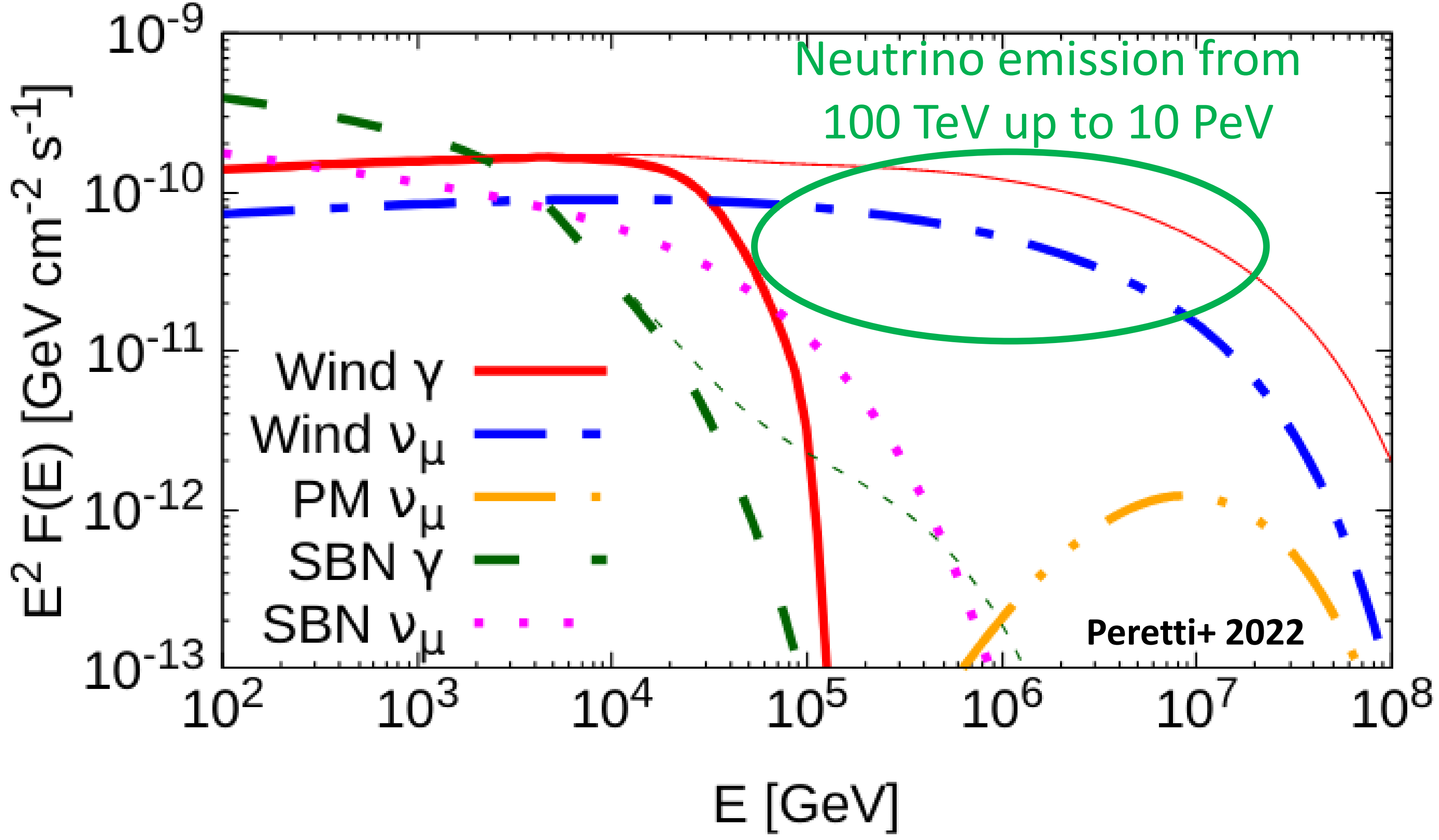
High-Energy SED and Neutrinos



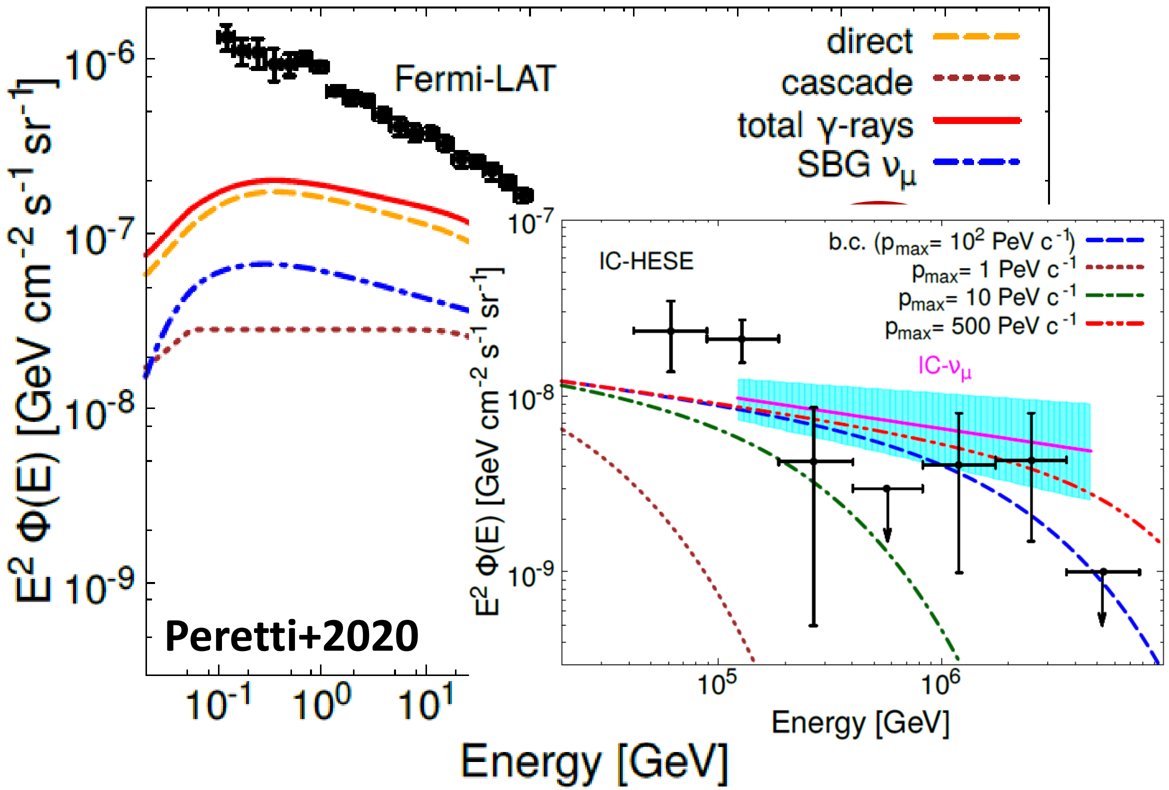
High-Energy SED and Neutrinos



High-Energy SED and Neutrinos

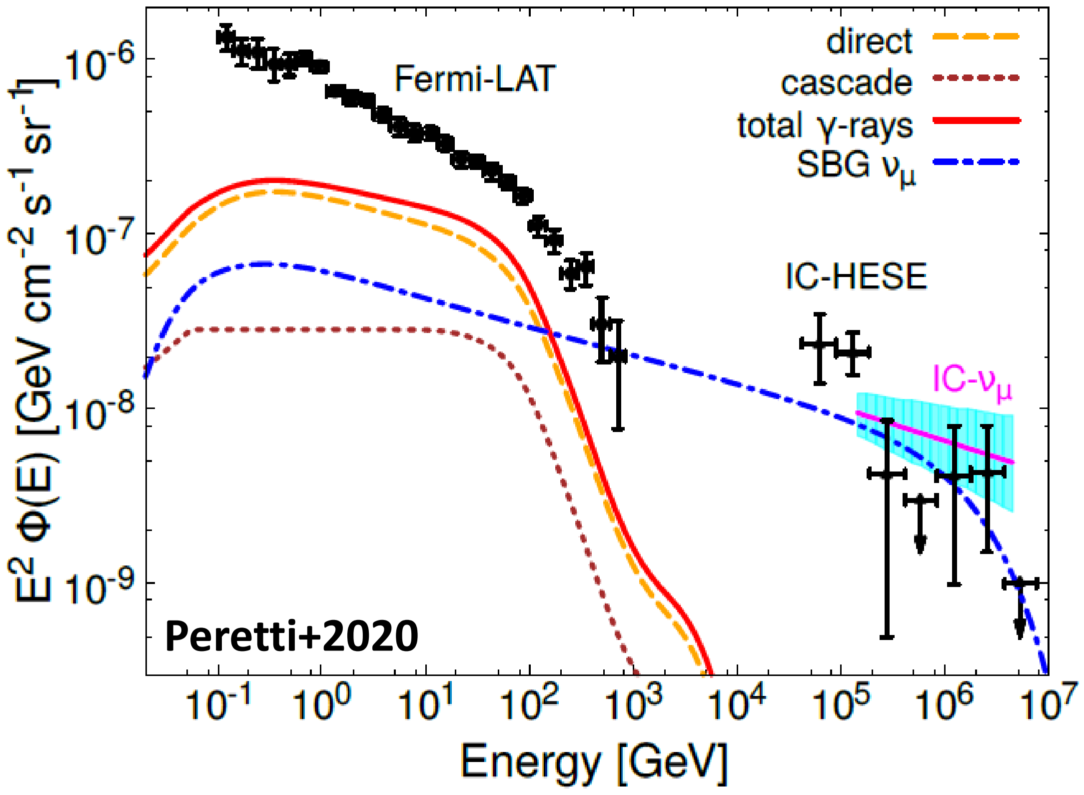


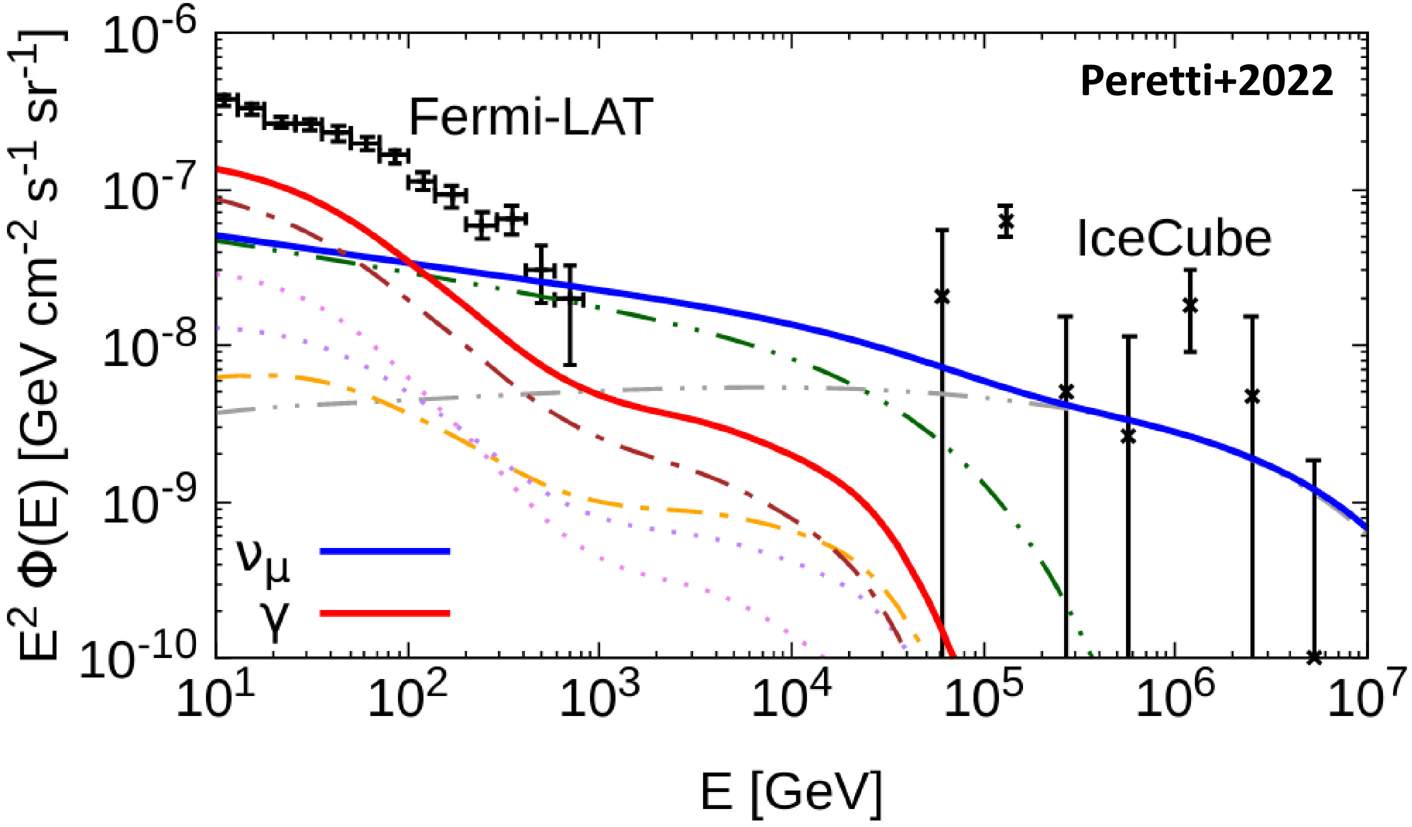
Diffuse emission from Starburst Galaxies



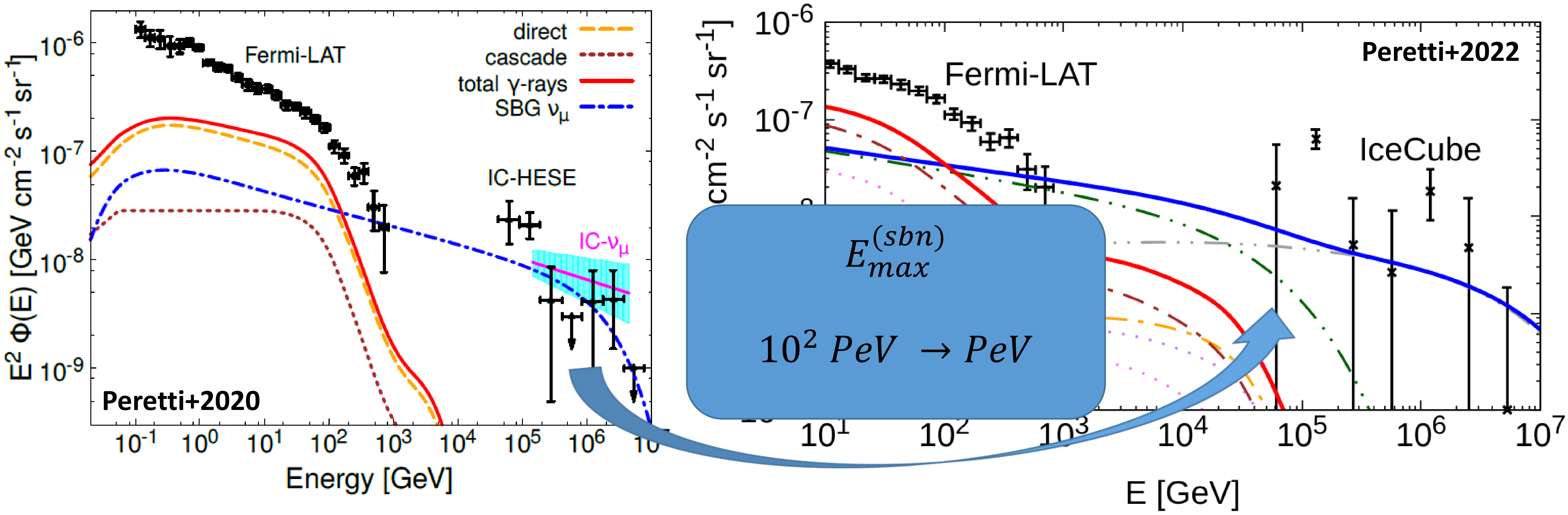
- SBNi only
- Sizeable contribution to the diffuse flux observed by Fermi-LAT
- Neutrino flux at the level of IceCube measurment

Diffuse emission from Starburst Galaxies





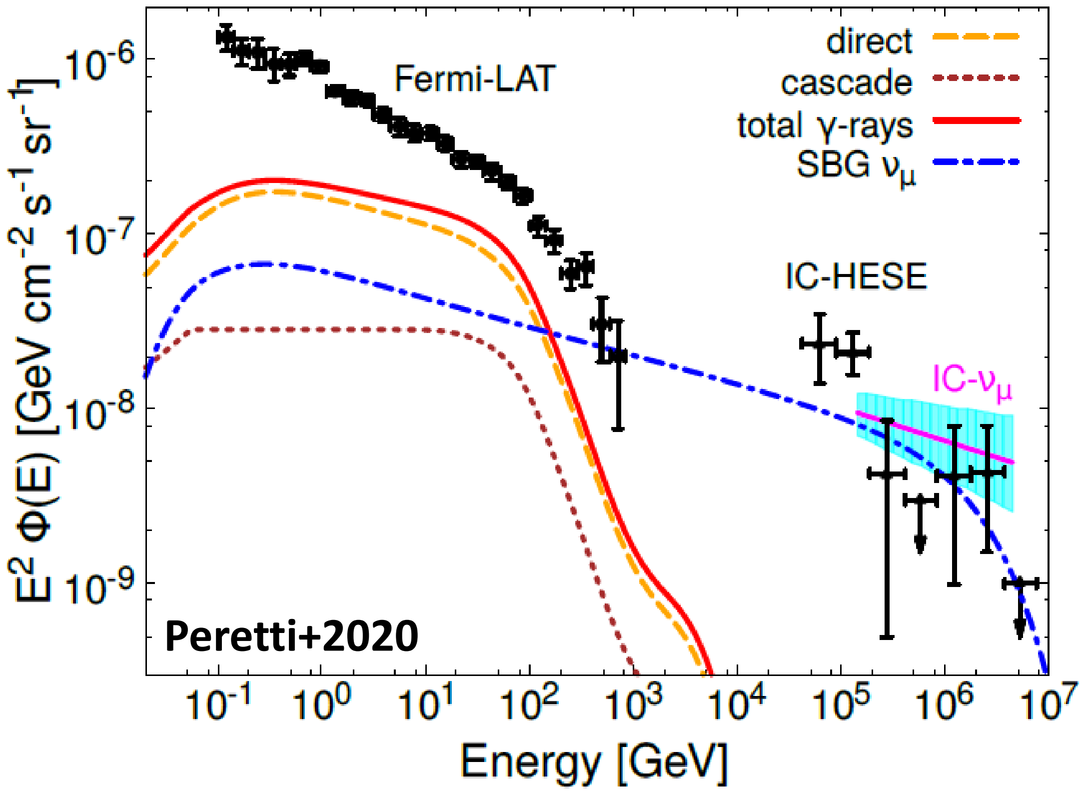
Diffuse emission from Starburst Galaxies

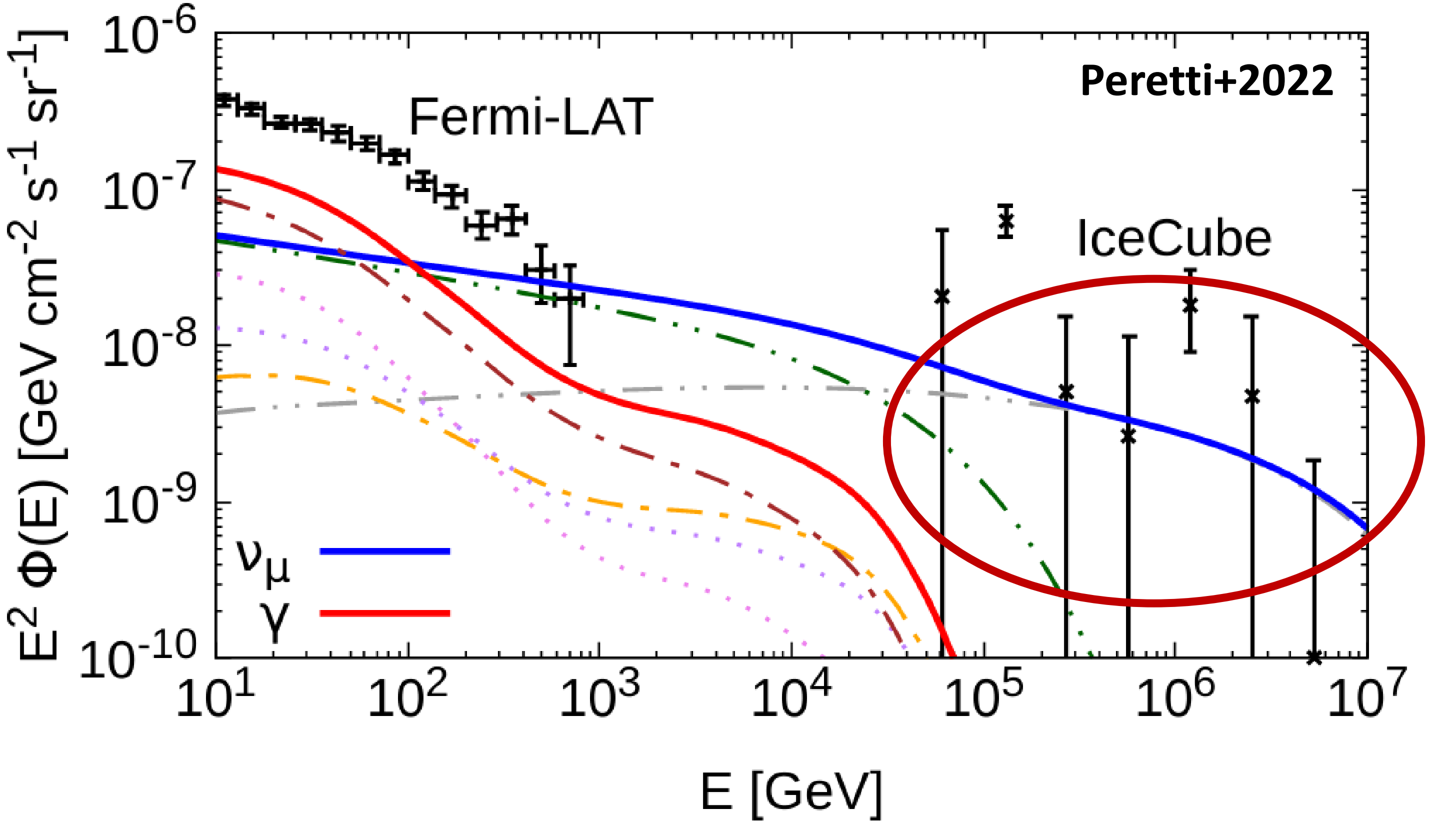


$E_{max}^{(sbn)}$

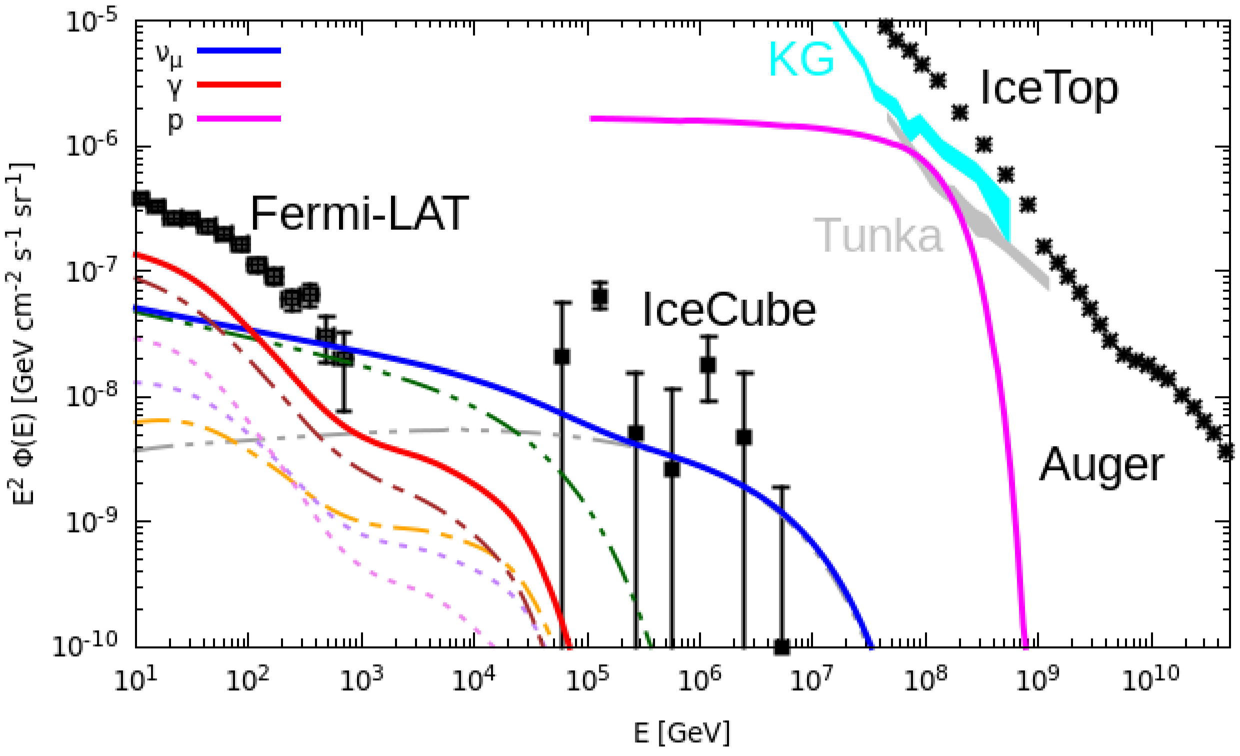
$10^2\ PeV \ \rightarrow PeV$

Diffuse emission from Starburst Galaxies

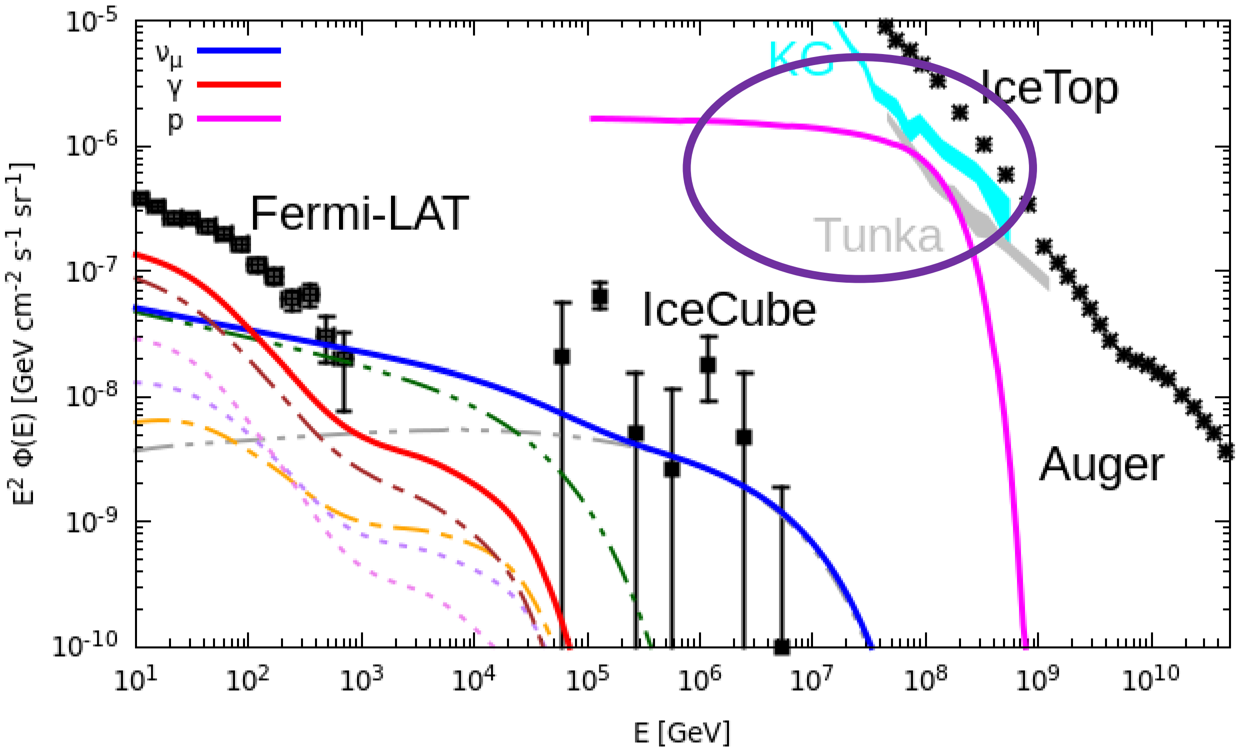


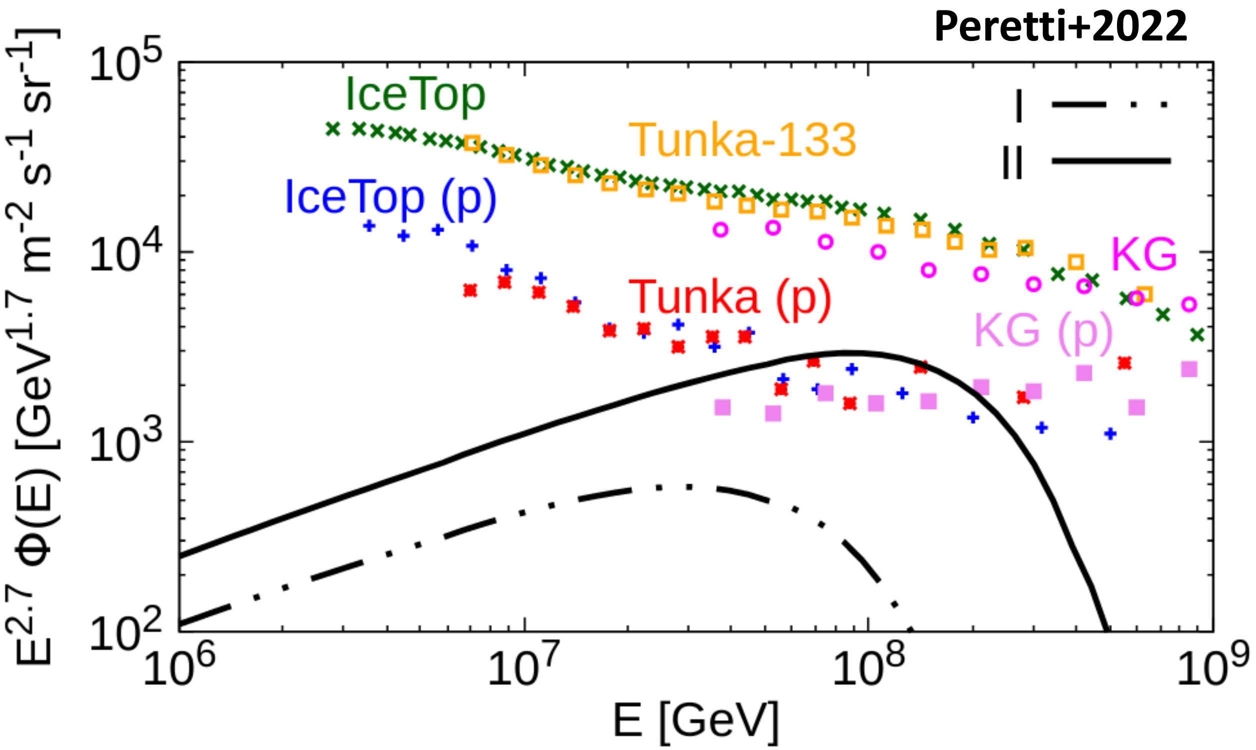


Multimessenger emission from Starburst Galaxies

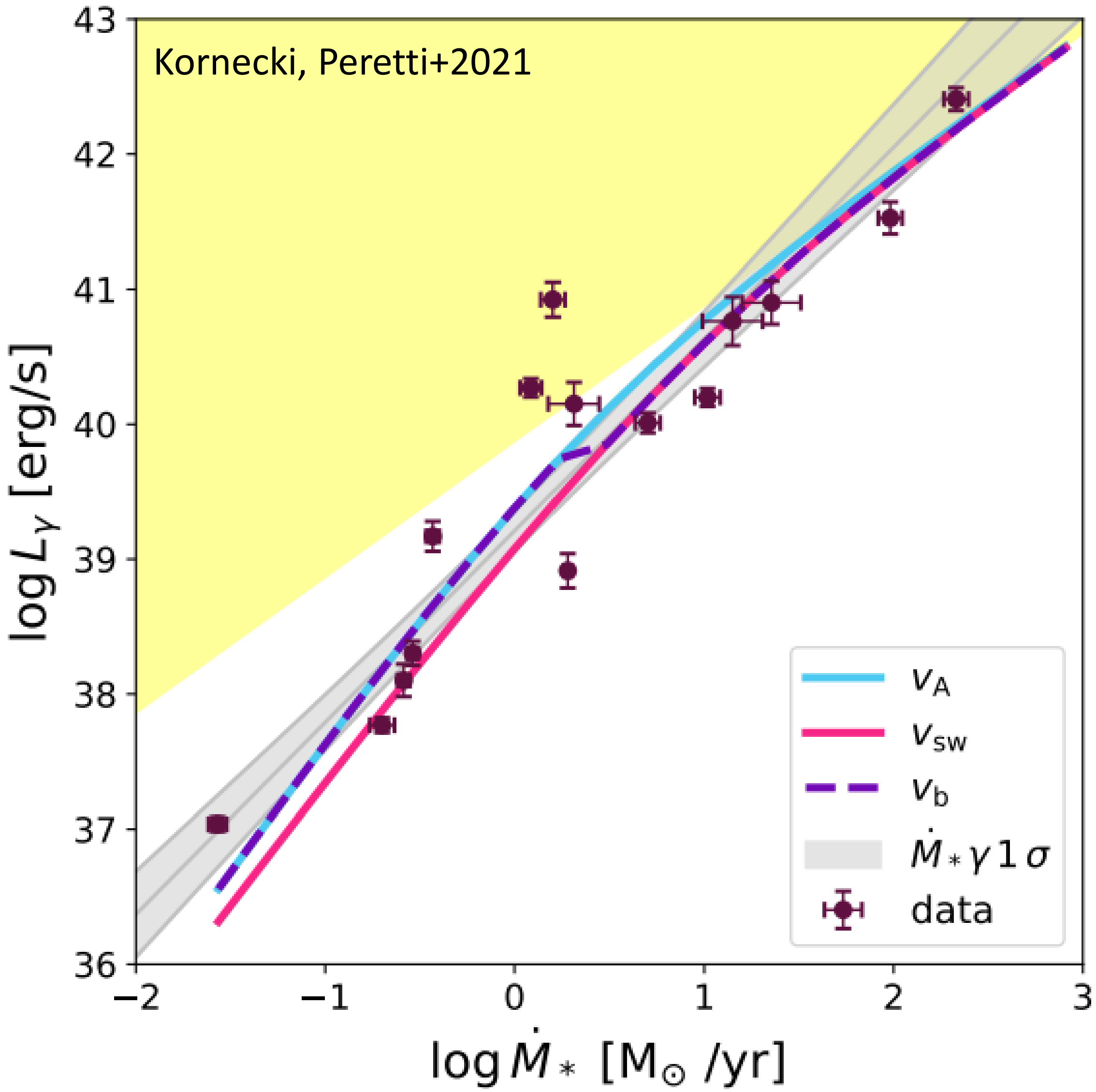


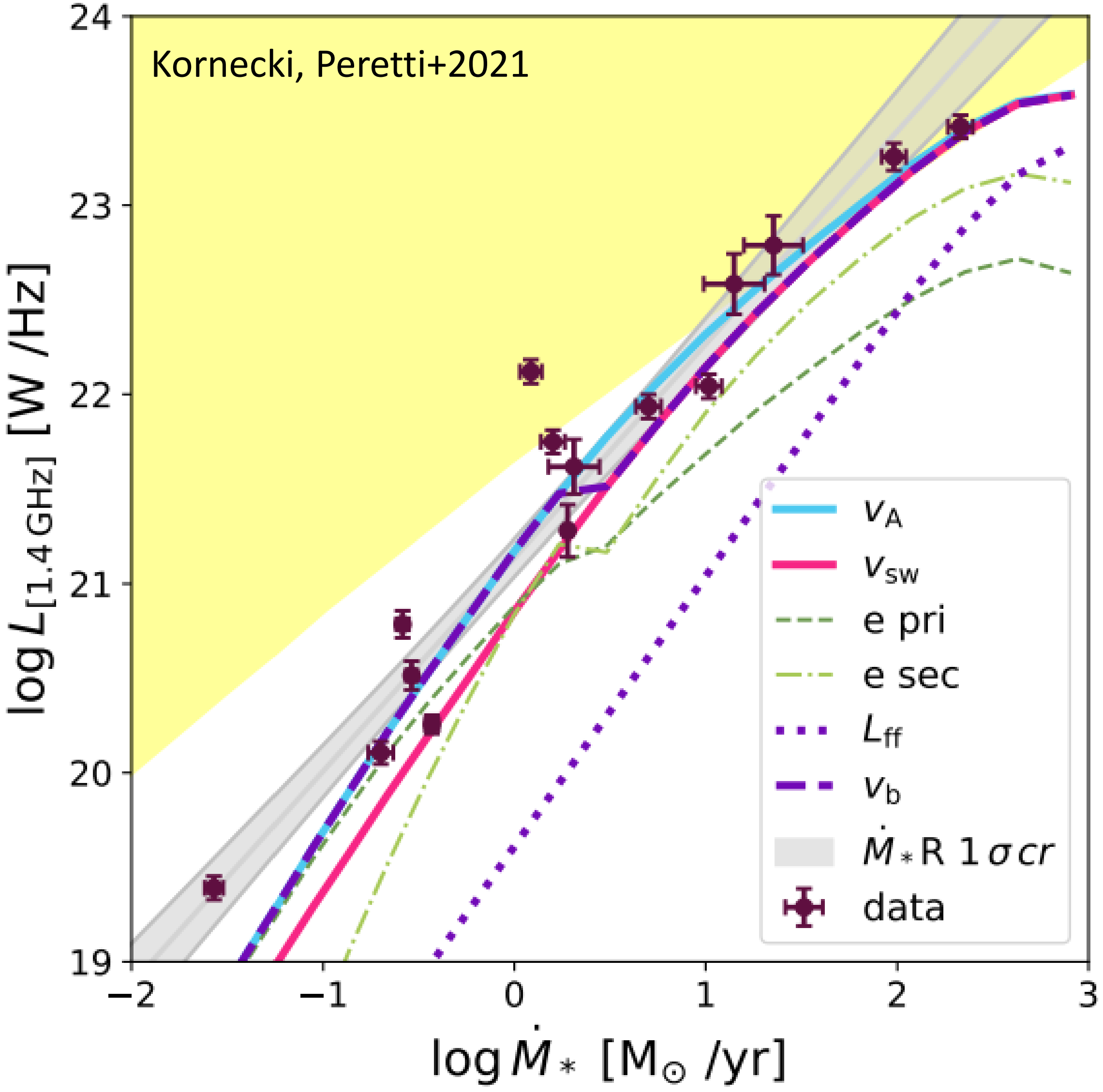
Multimessenger emission from Starburst Galaxies



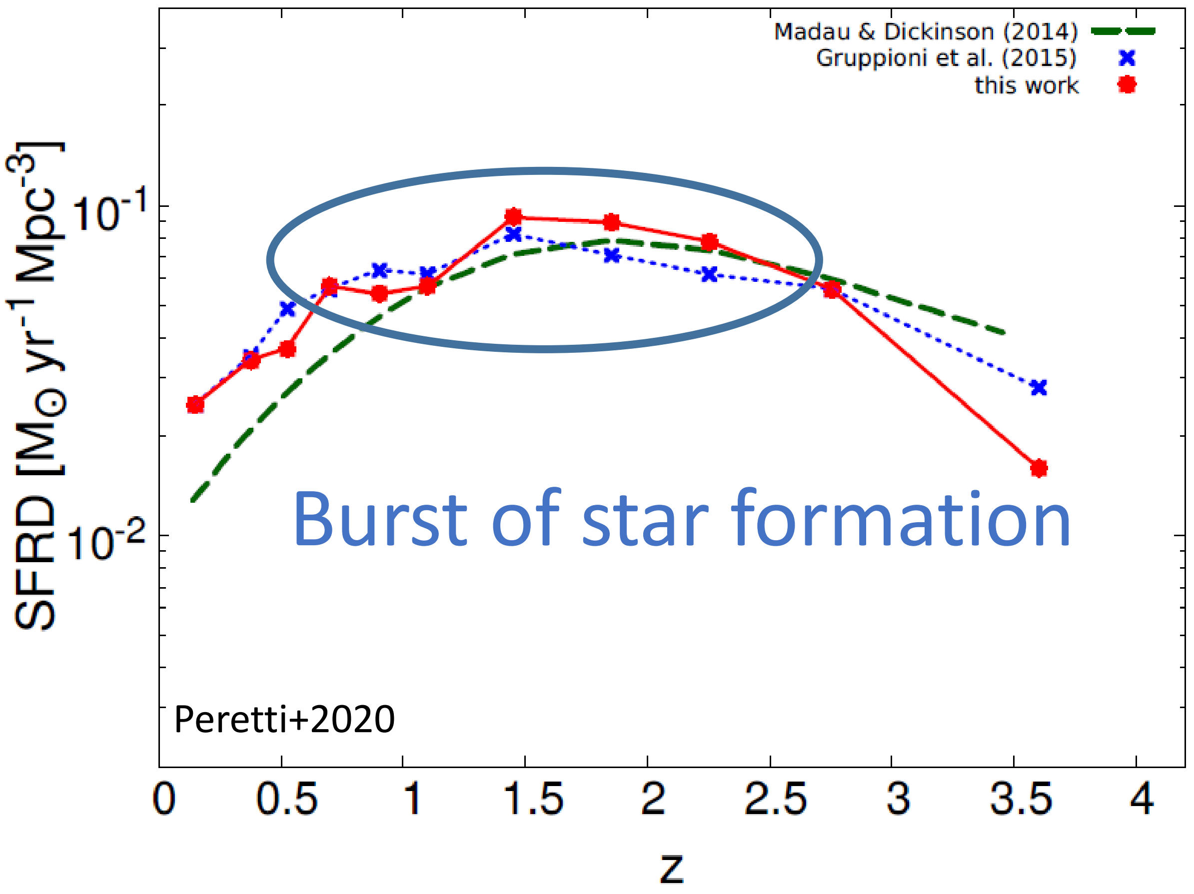


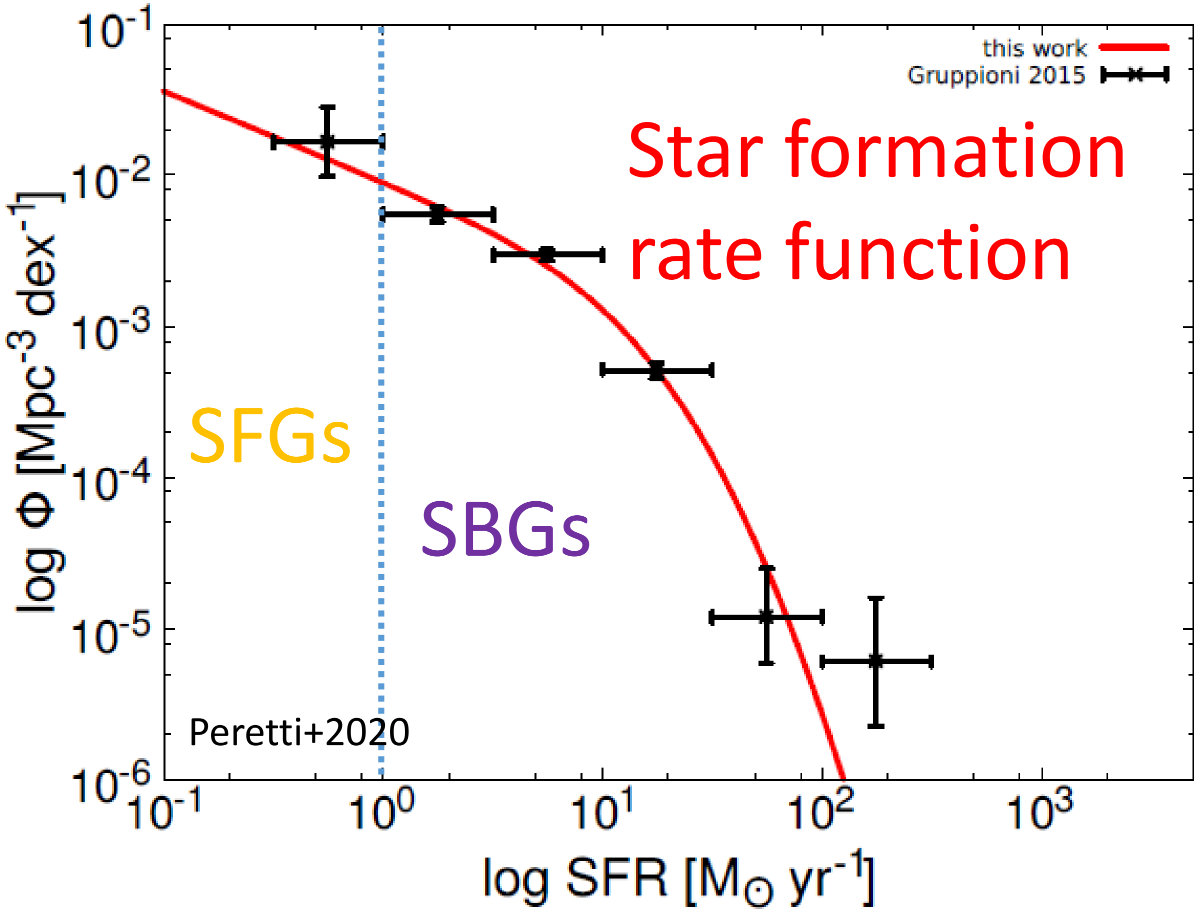
Leaky box model and L—SFR correlations





Starbursts as diffuse sources





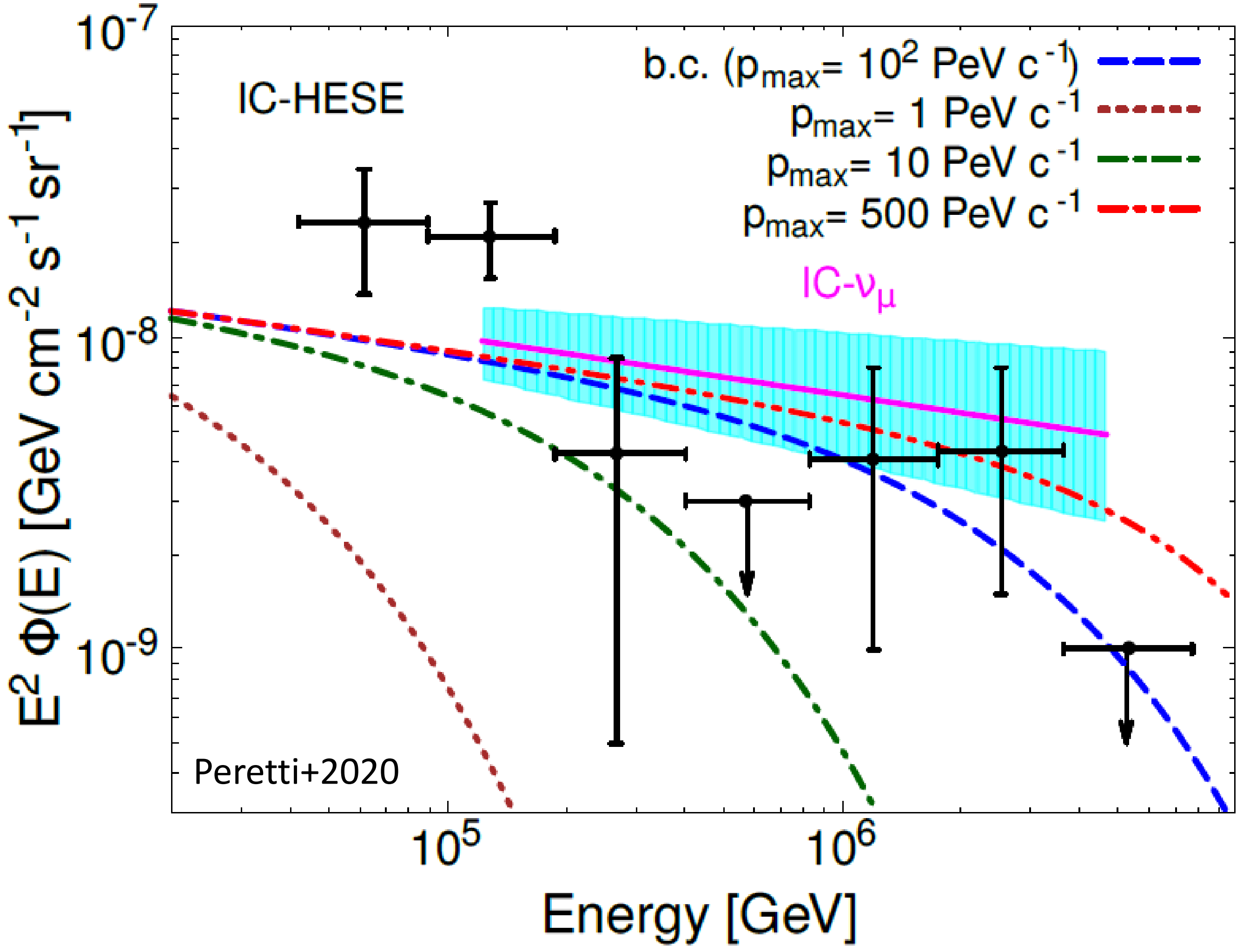
The issue of the maximum energy

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

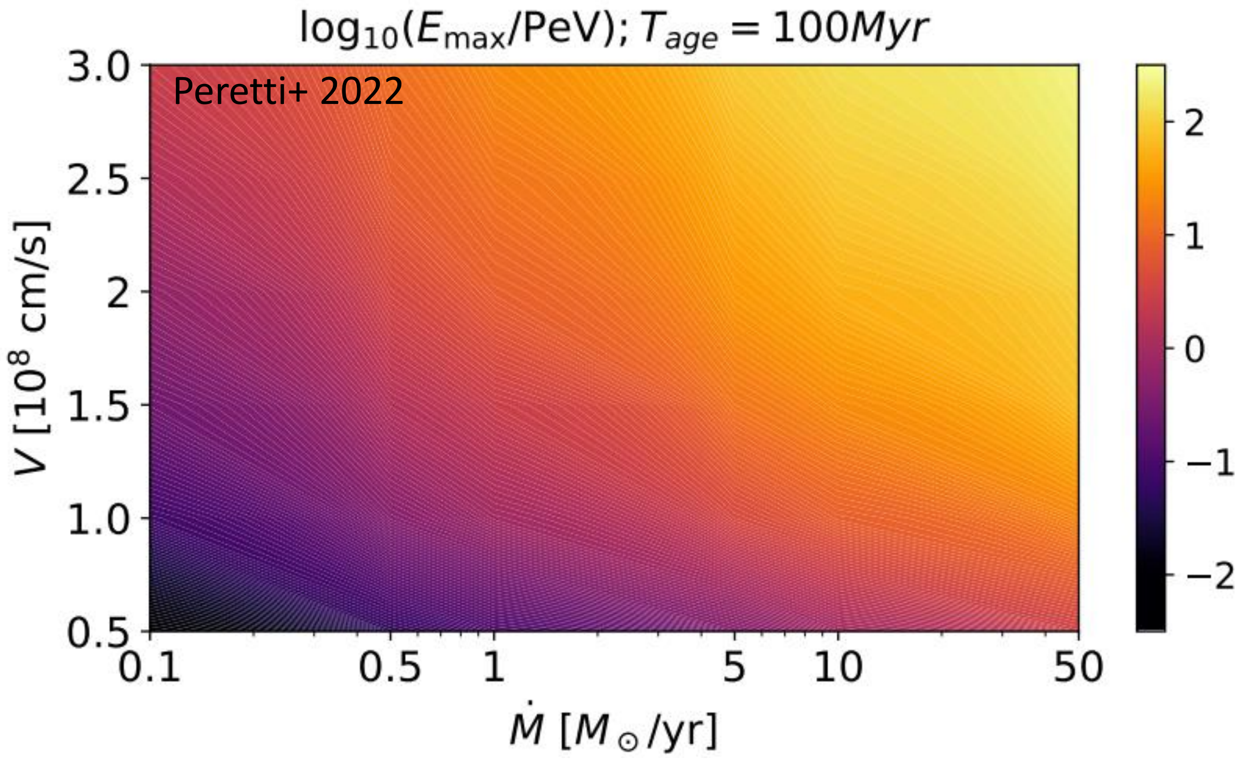
SNR in case of Bohm diffusion:

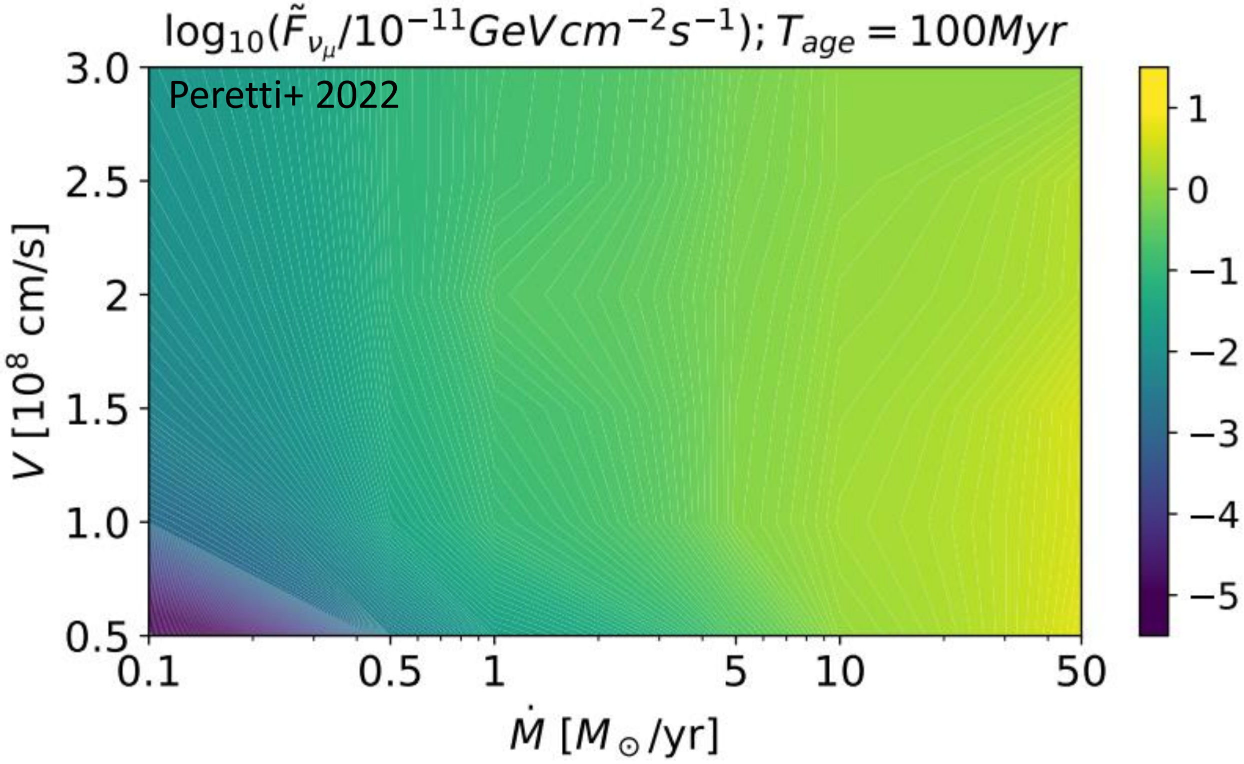
$$E_{max} = 30\ PeV\ \times R_3 u_4 B_{mG}$$

- Magnetic field amplification can allow reaching 10-100 PeV

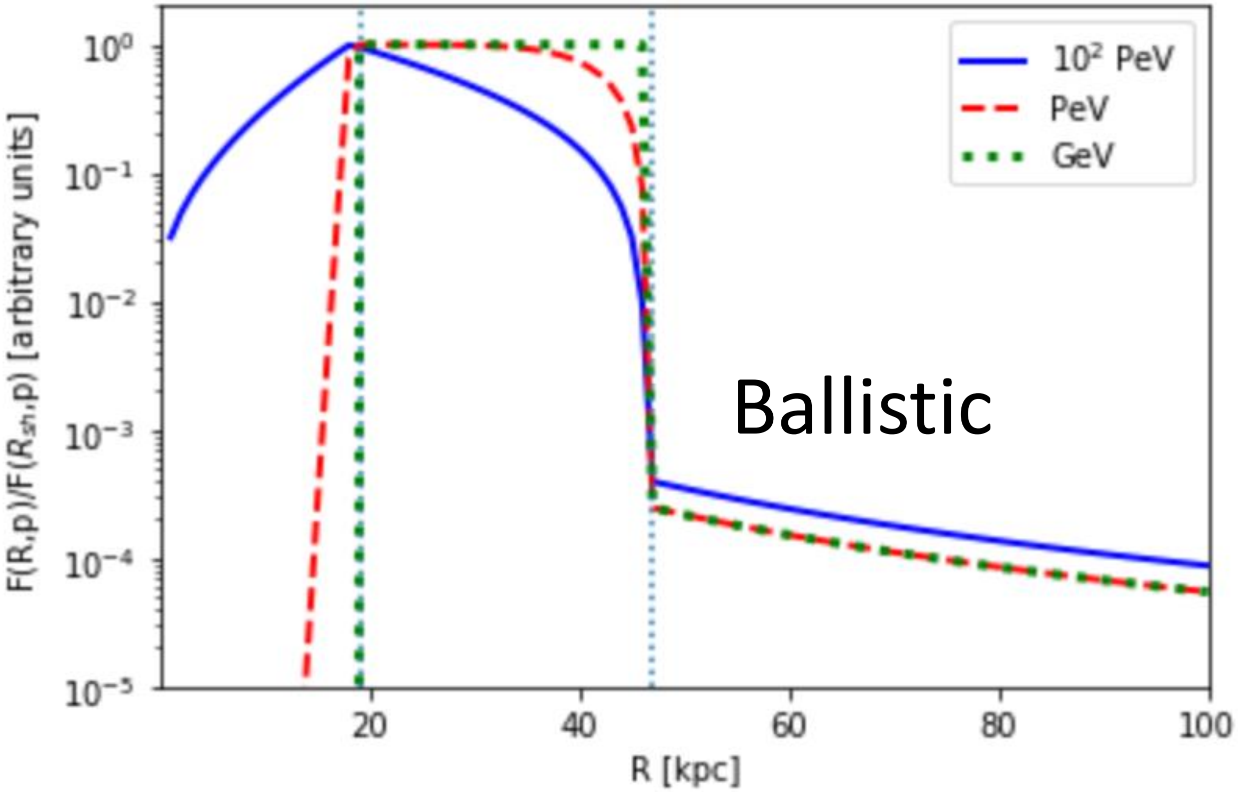


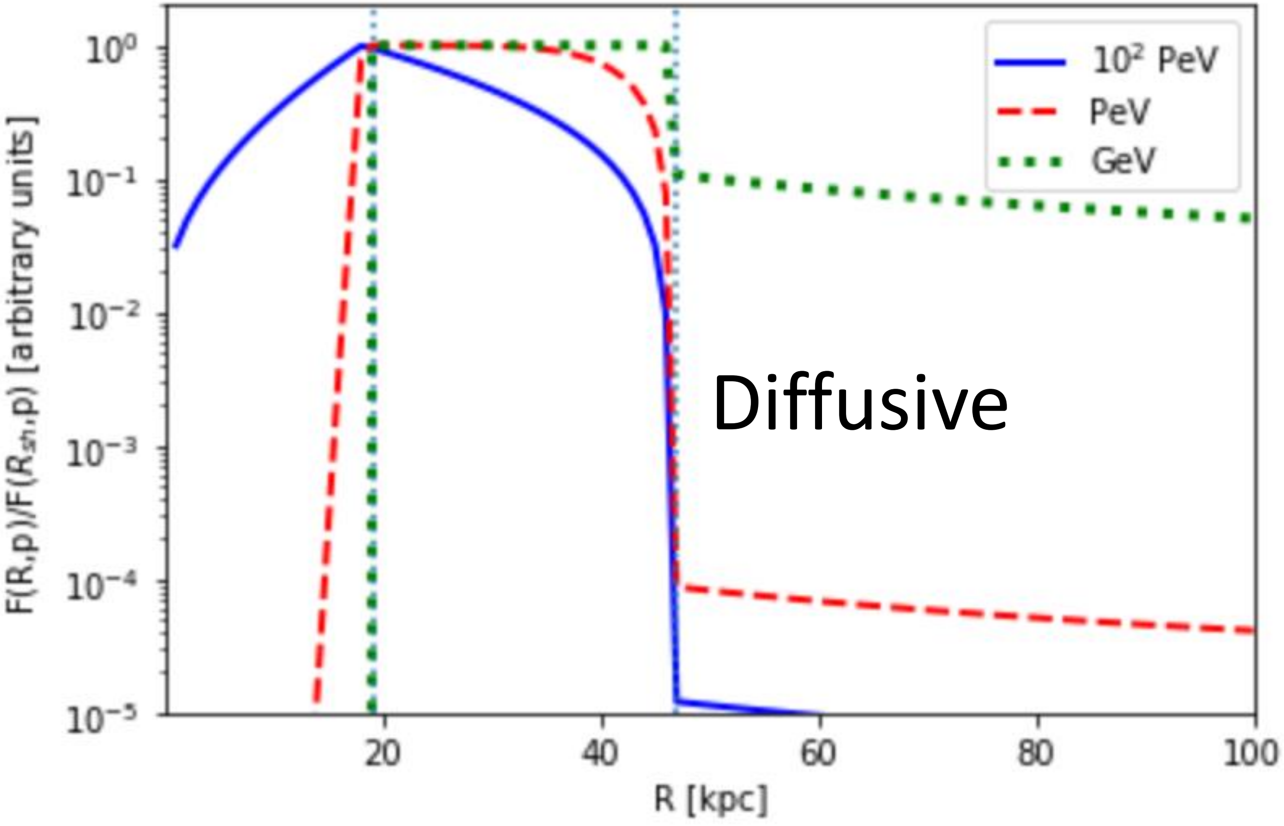
Maximum Energy & Luminosity



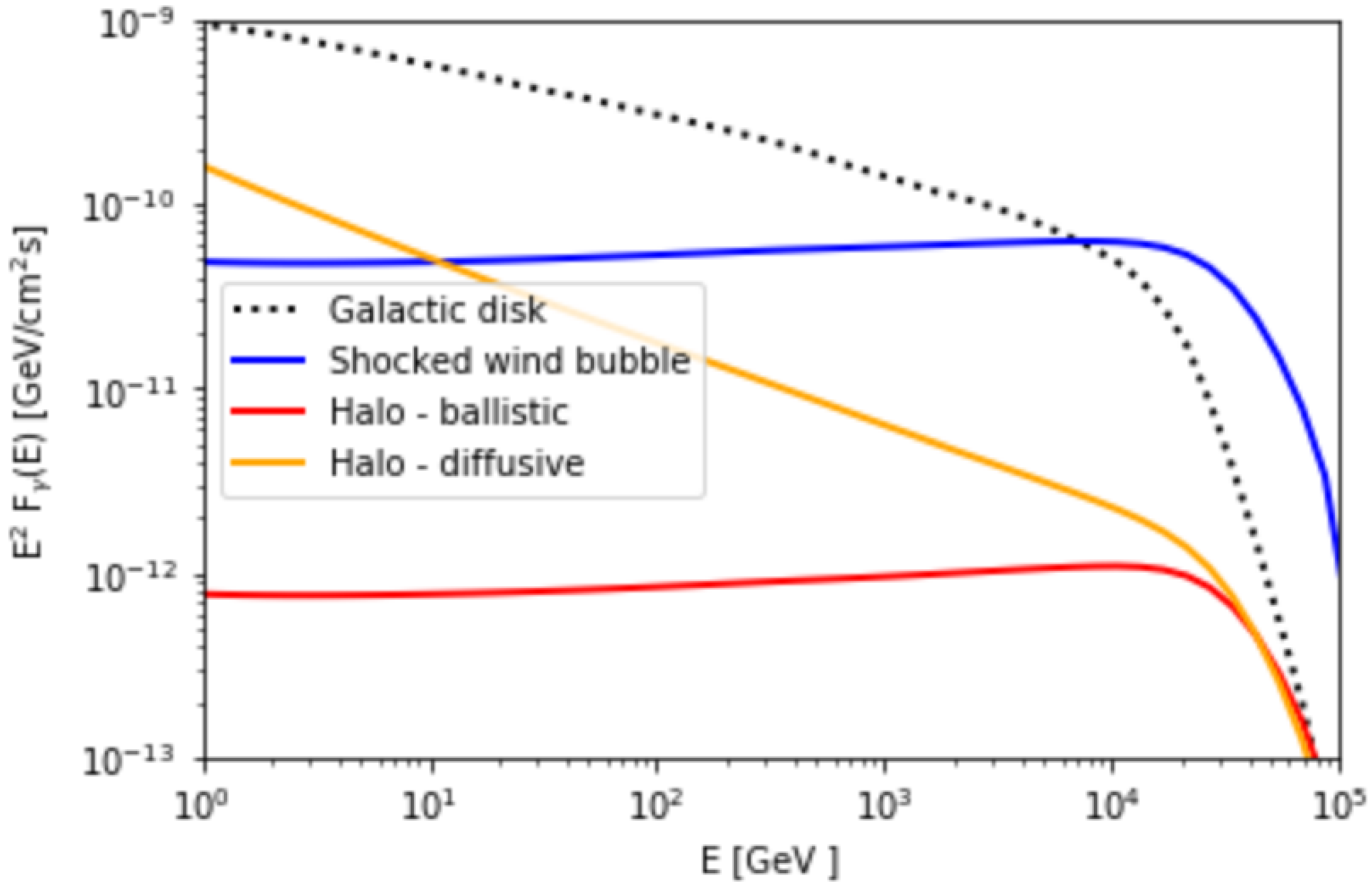


Starburst halo

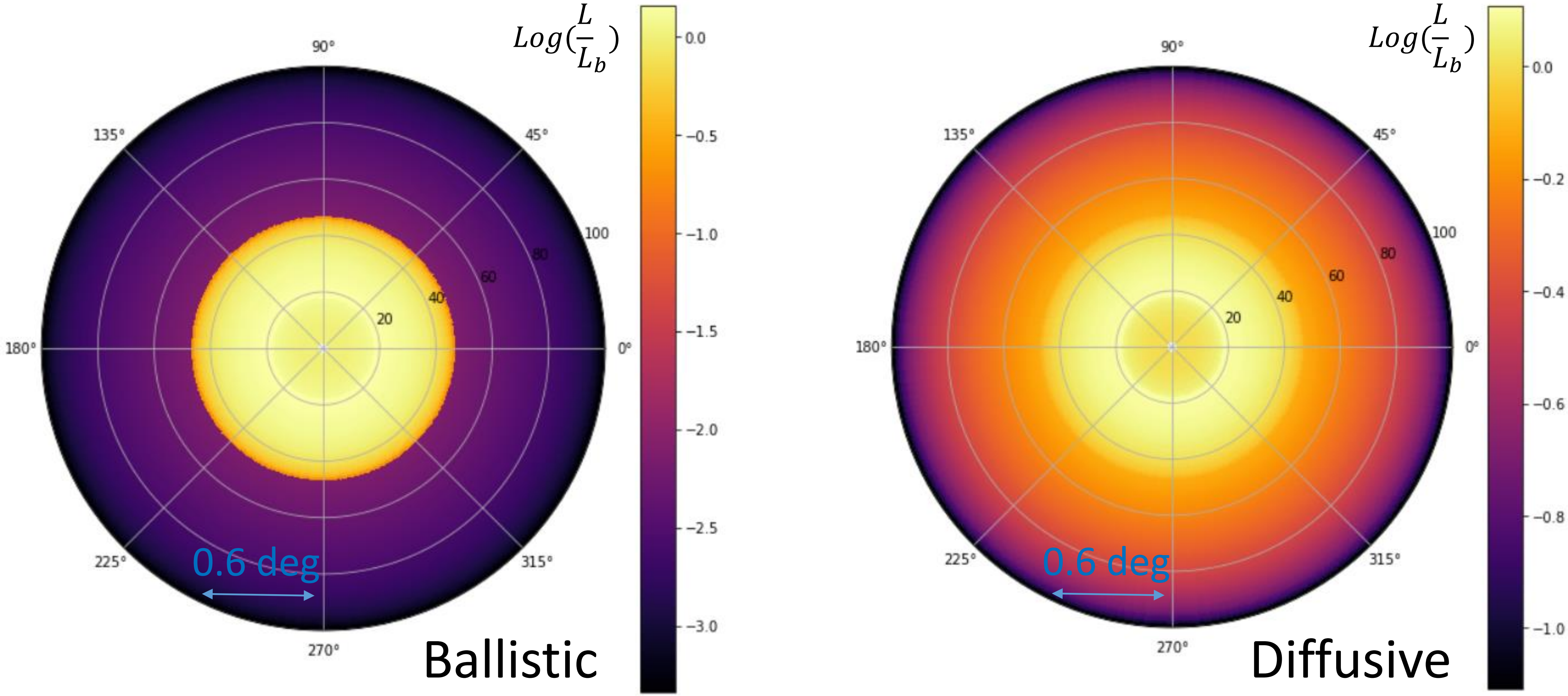




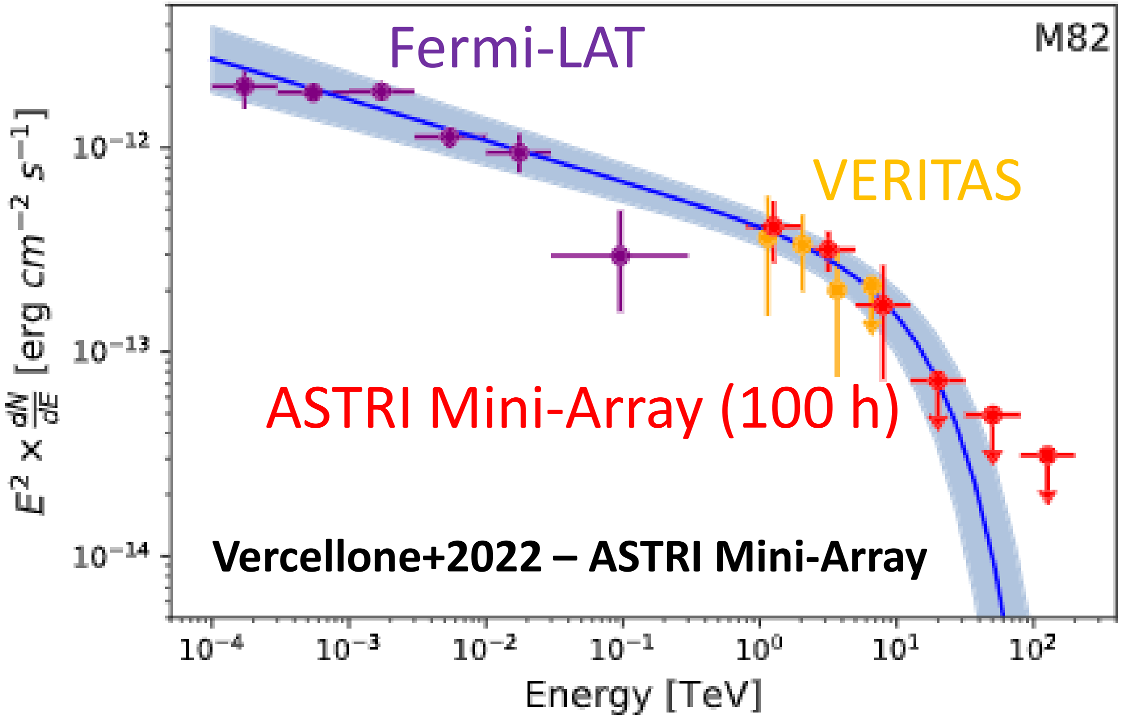
Starburst halo

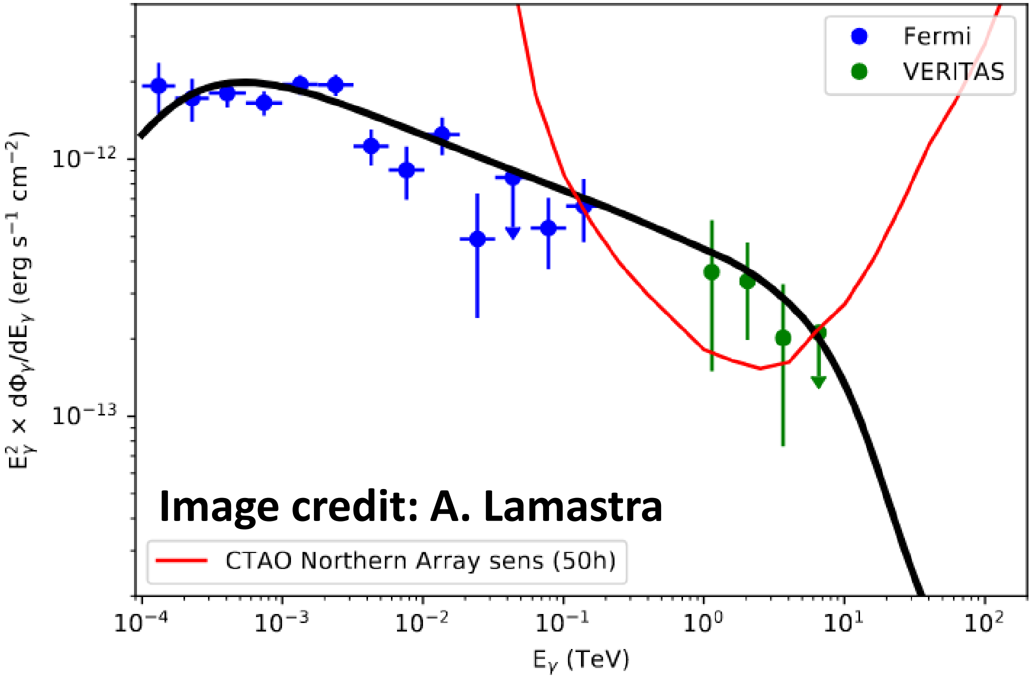


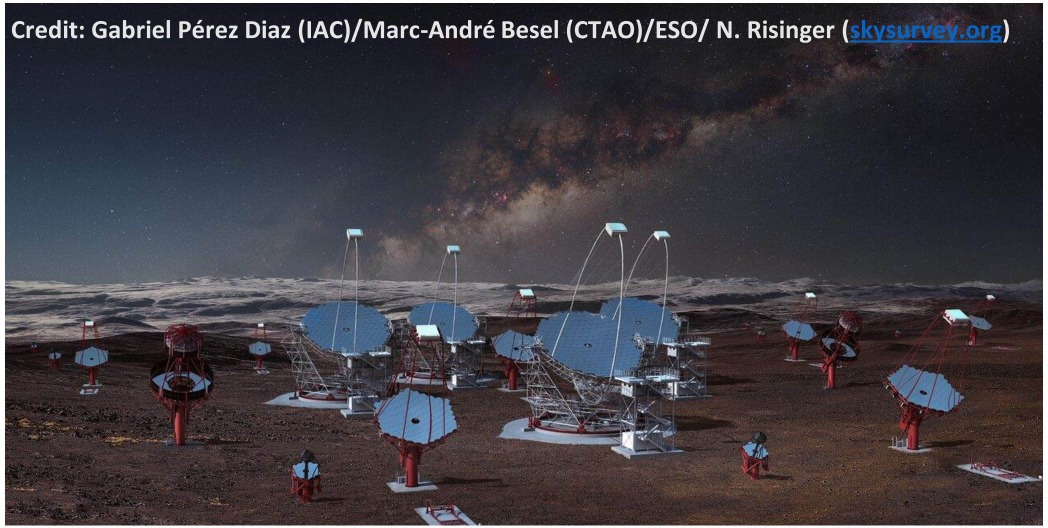
Tracing the emission in the wind bubble – 1 GeV



Upcoming gamma-ray observations







Outlook and open questions

- Transport and diffusion: neutral medium?

Outlook and open questions

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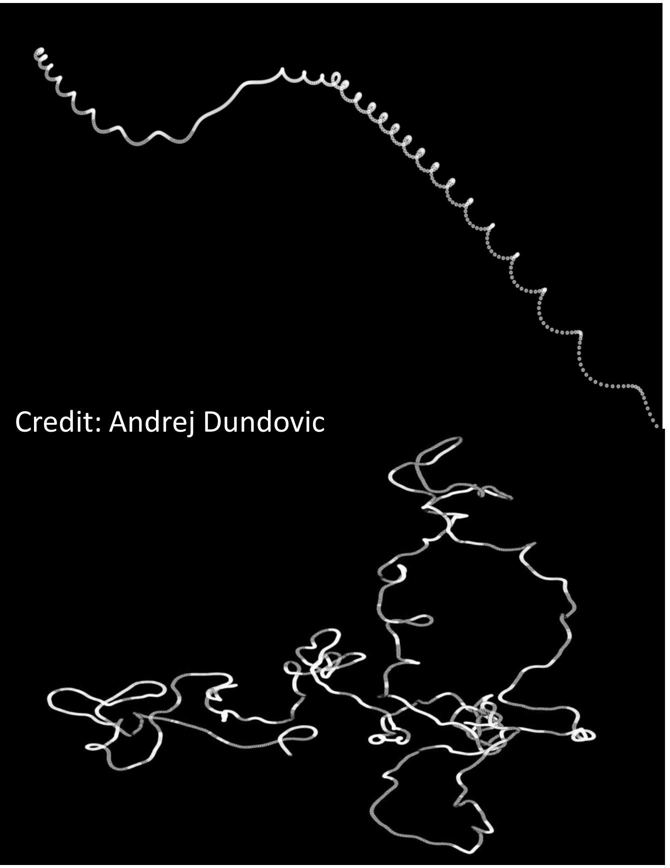
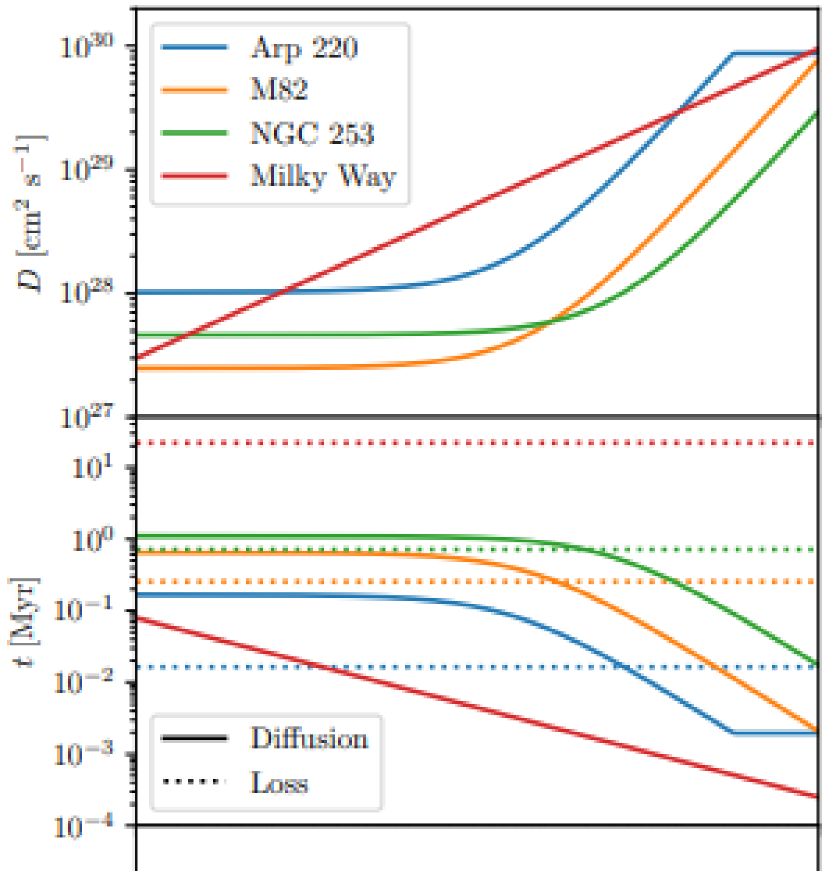

Credit: Andrej Dundovic

Krumholtz+2020



Outlook and open questions

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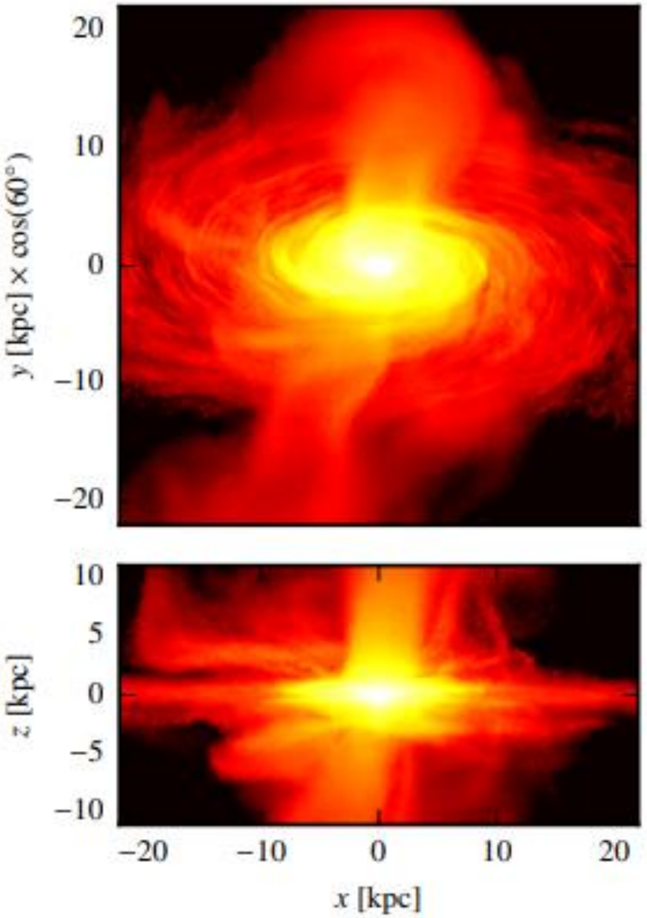
- What happens in the wind bubble?

Outlook and open questions

Werhahn+2021



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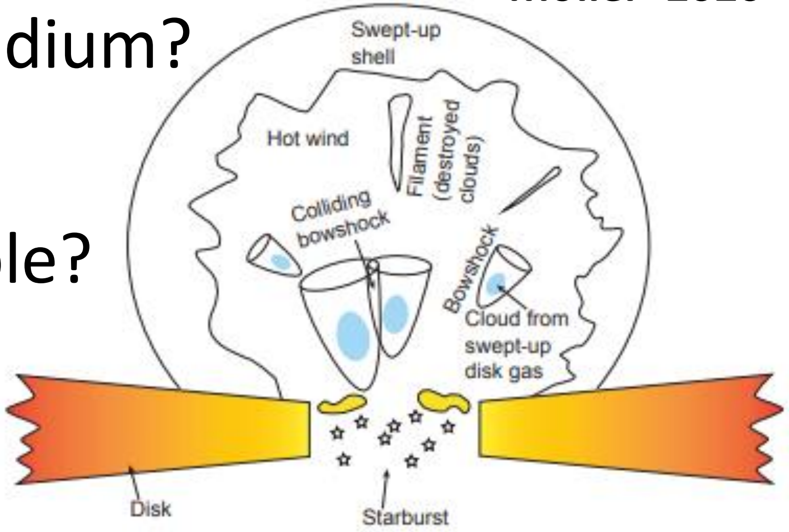
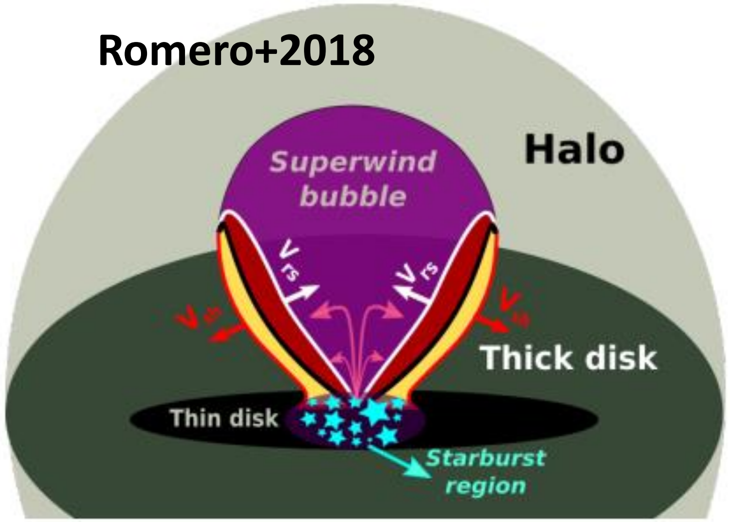
Müller+2020



Romero+2018



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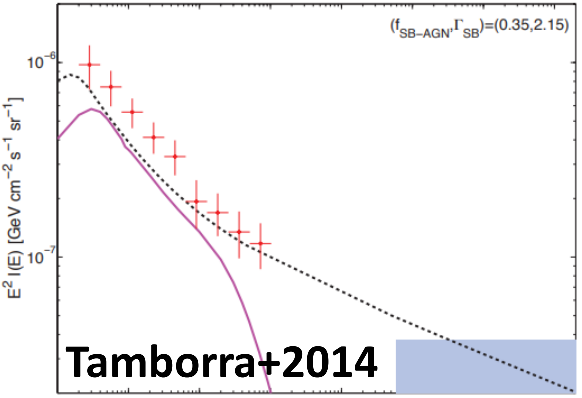

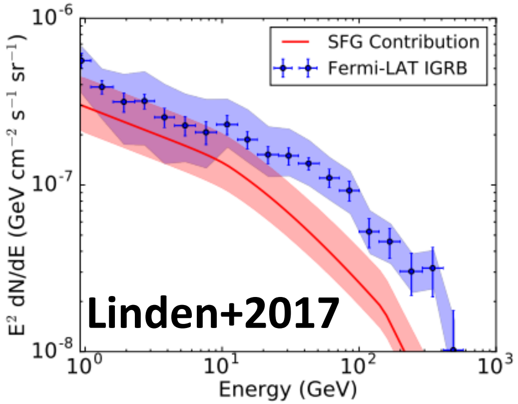

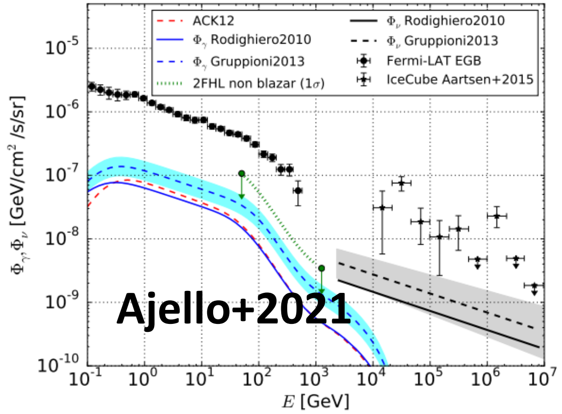

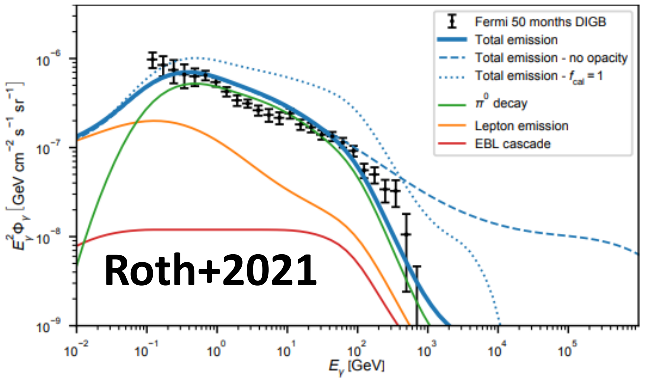

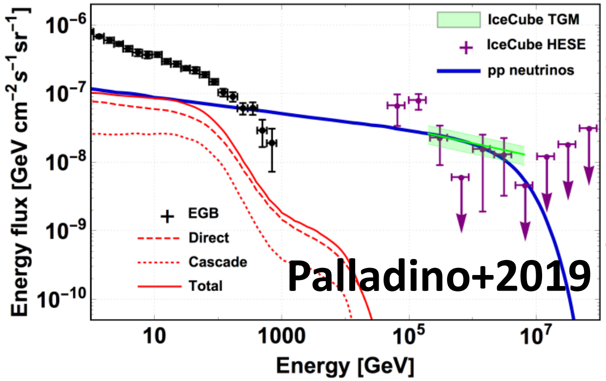

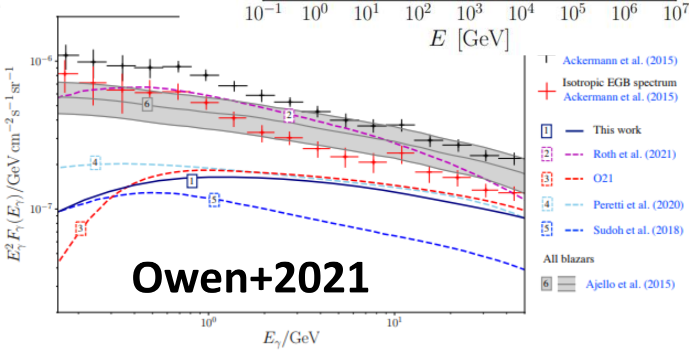

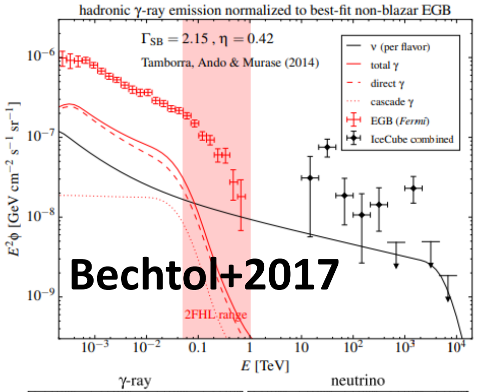

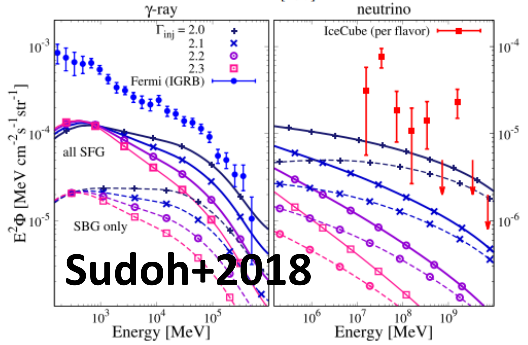

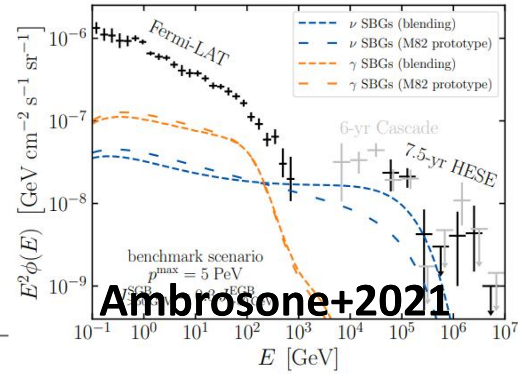

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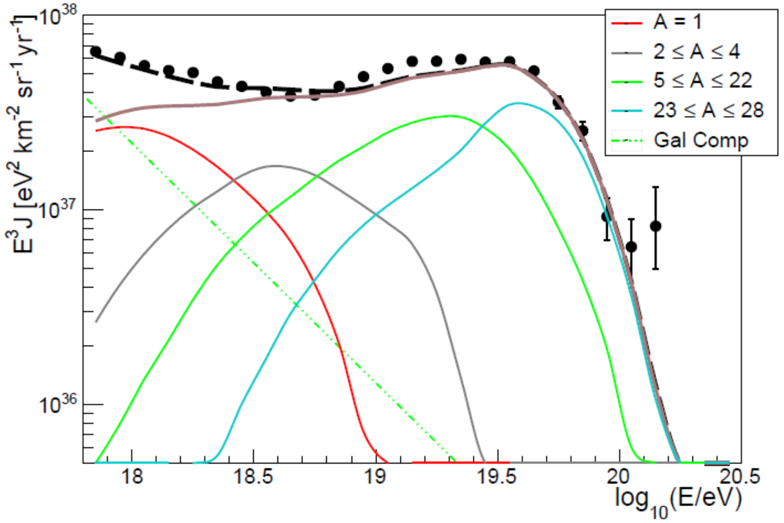
Outlook and open questions

Condorelli+2022 in prep.



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