Particle acceleration, propagation and radiation in Starburst Galaxies

Enrico Peretti

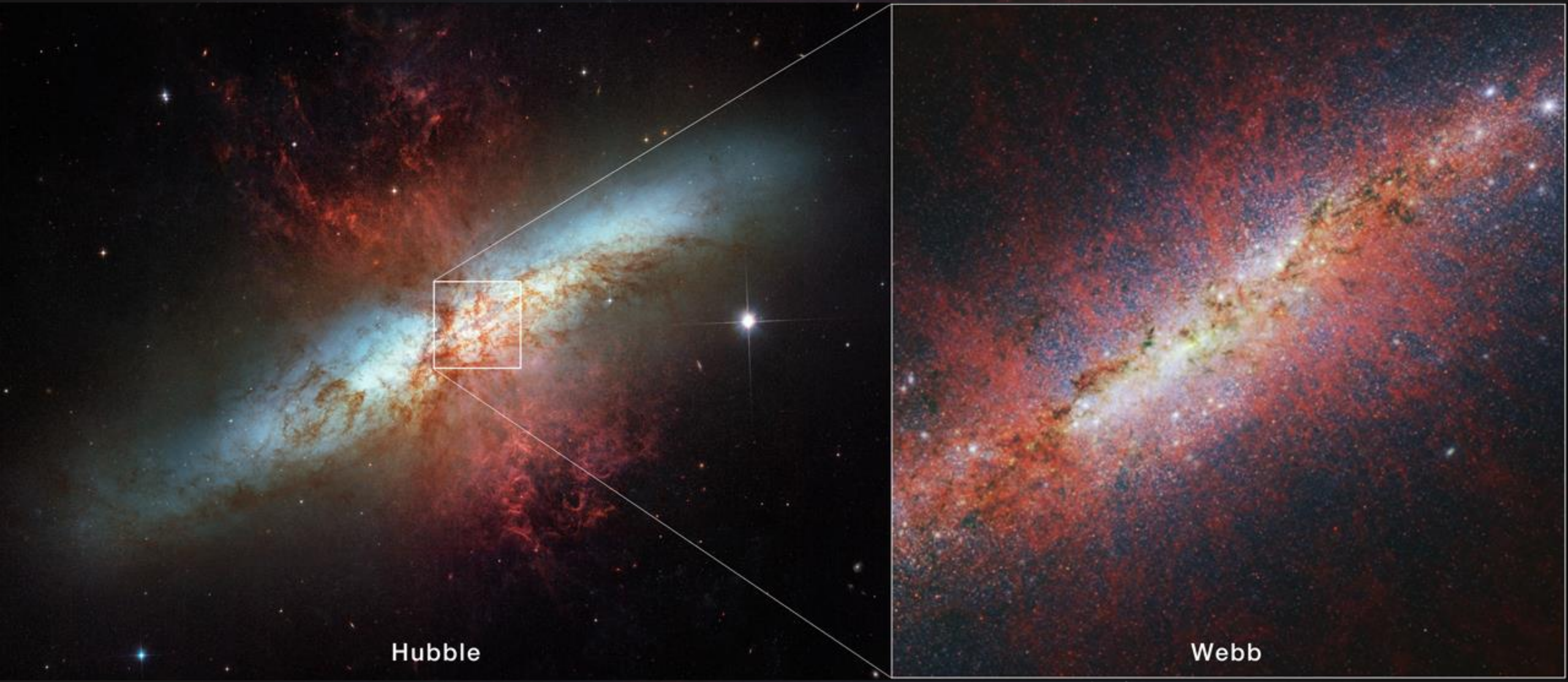
enrico.peretti.science@gmail.com

May 1 2024 – The Extreme Non-Thermal Universe: CDY Initiative

cnrs

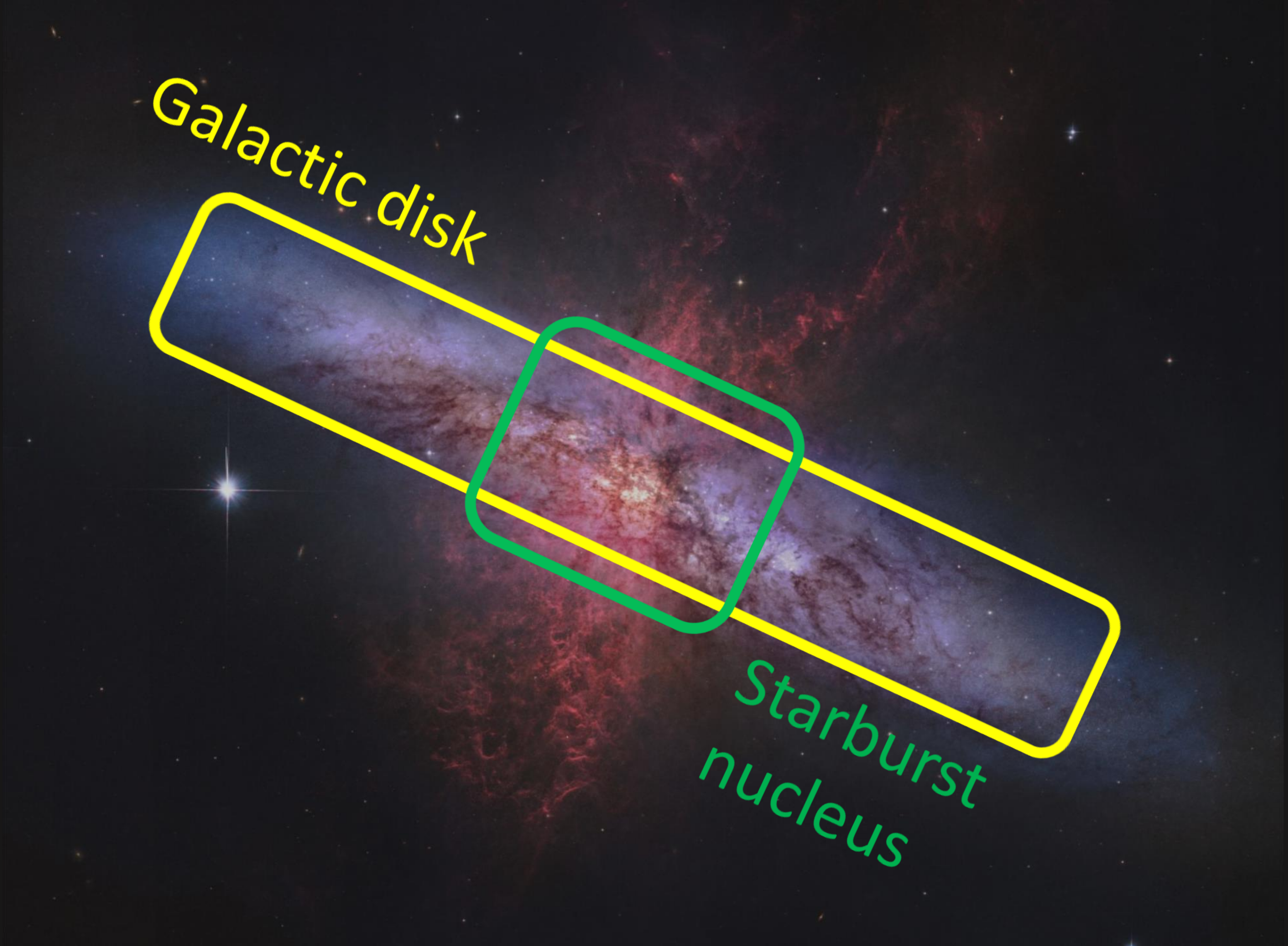
Université Paris Cité

APC

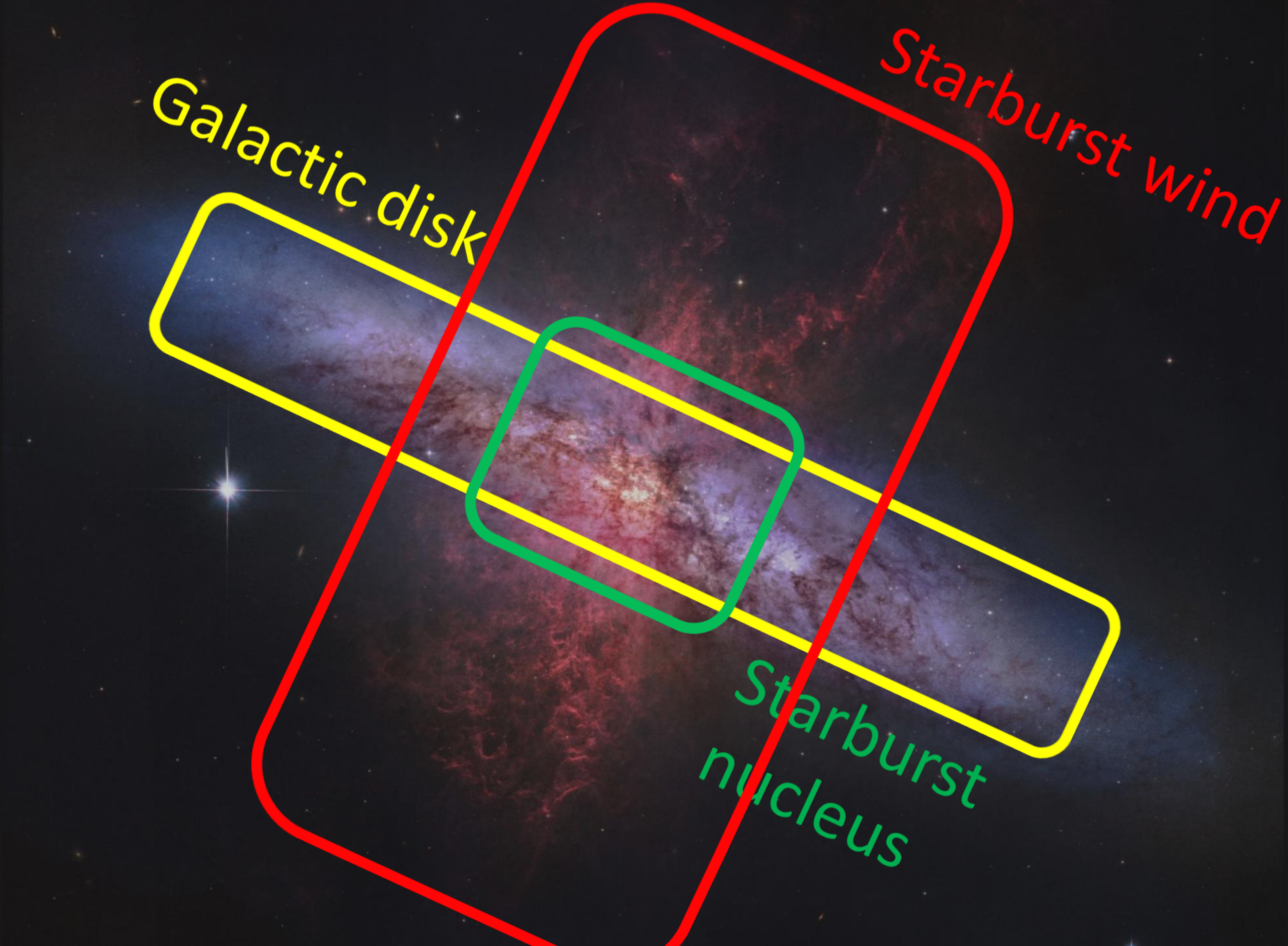


Starburst galaxy M82 – NASA, ESA, CSA, STScI, A. Bolatto

Starburst galaxy M82 – APOD - Image credit: Daniel Nobre



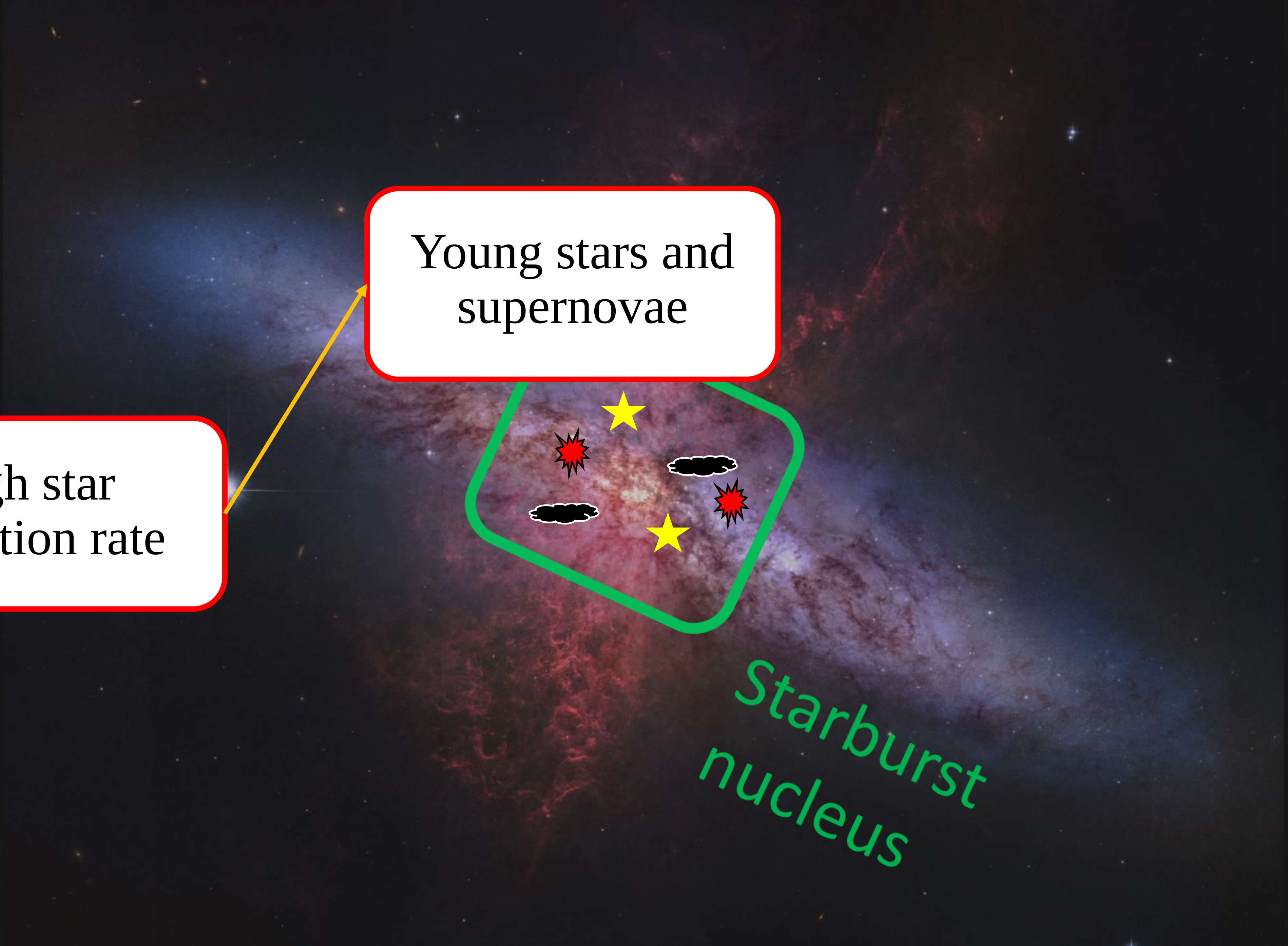
Starburst galaxy M82 – APOD - Image credit: Daniel Nobre



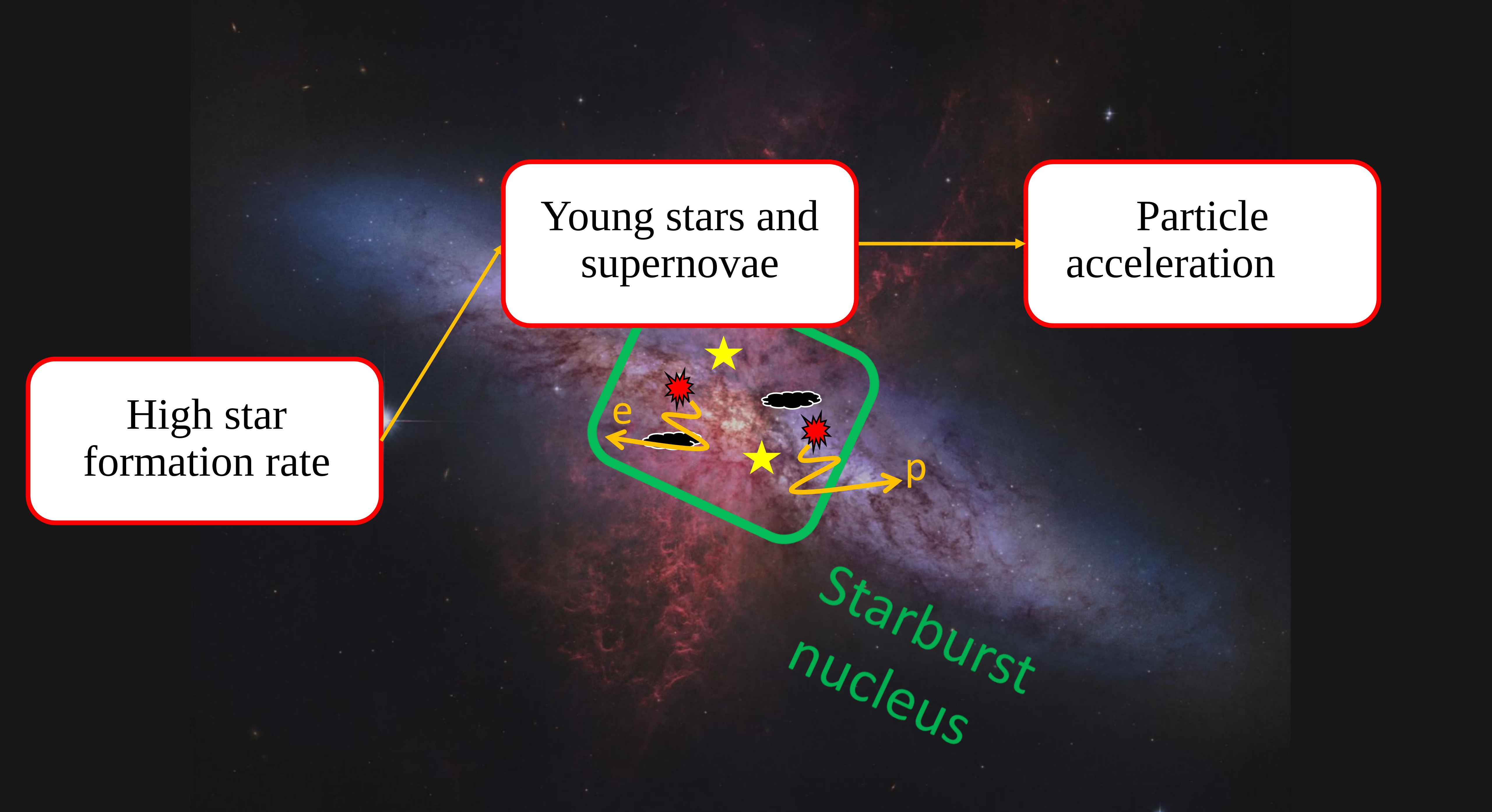
Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

High star formation rate

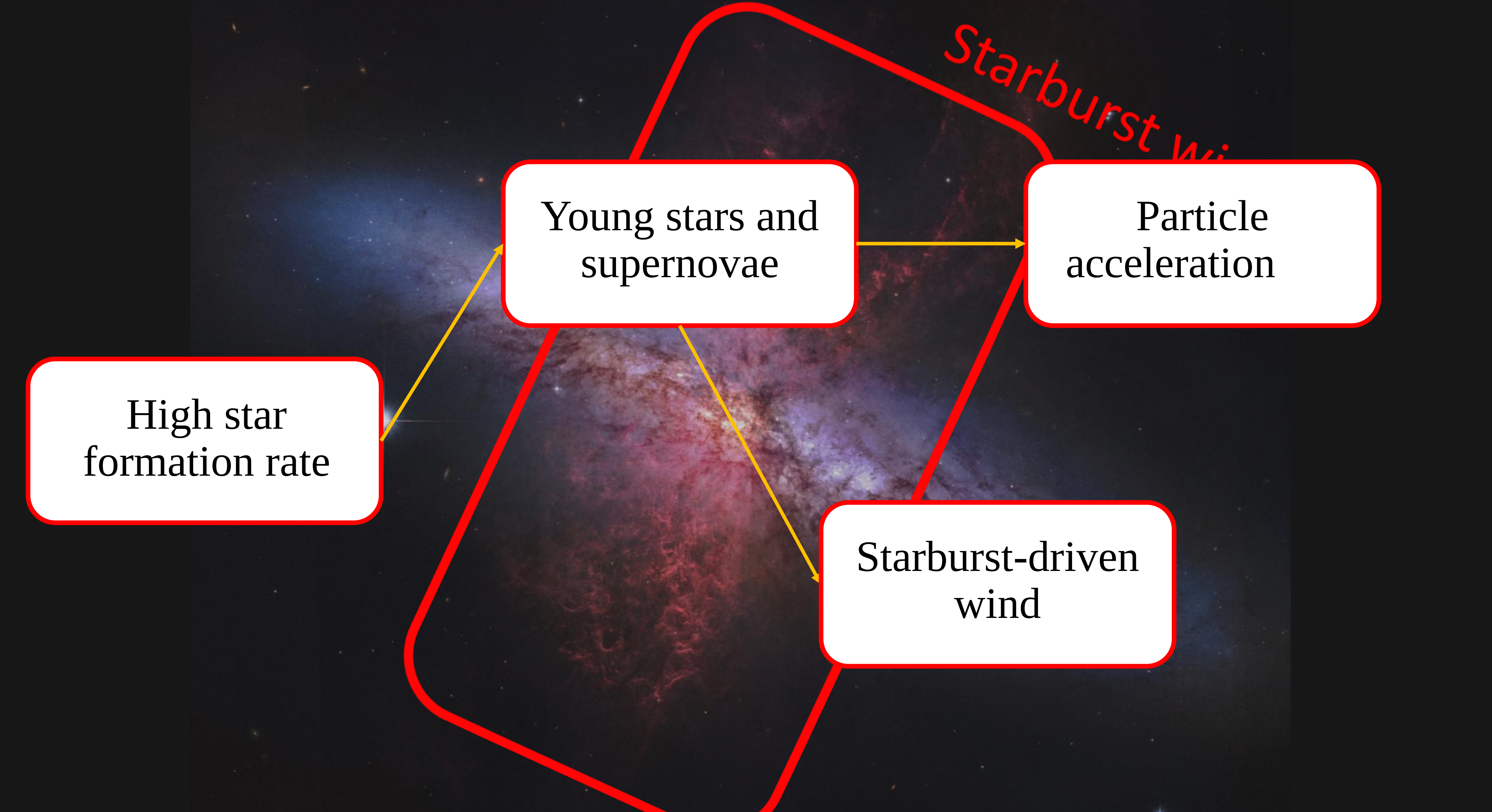
Starburst galaxy M82 – APOD - Image credit: Daniel Nobre



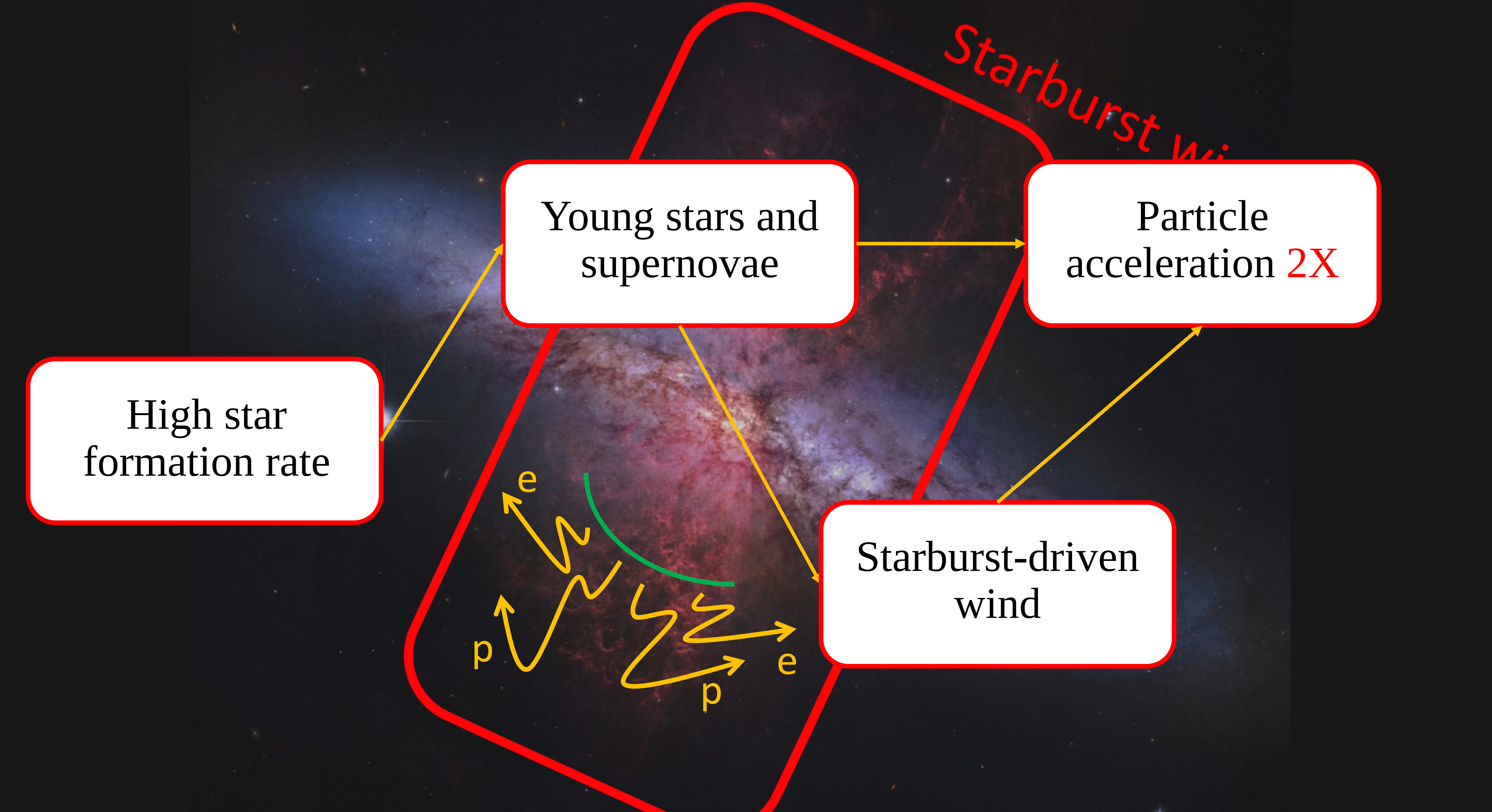
Starburst galaxy M82 – APOD - Image credit: Daniel Nobre



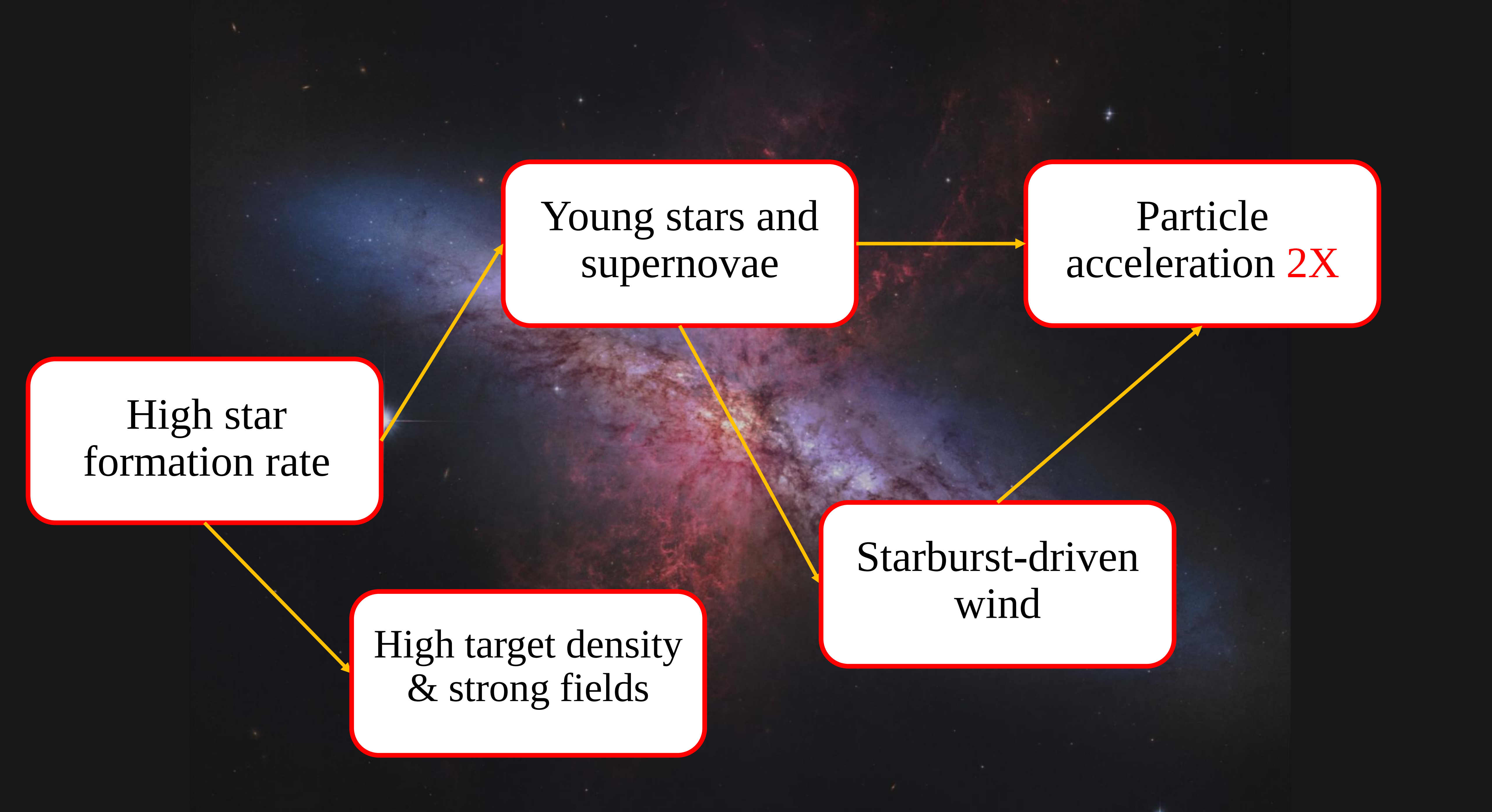
Starburst galaxy M82 – APOD - Image credit: Daniel Nobre



Starburst galaxy M82 – APOD - Image credit: Daniel Nobre



Starburst galaxy M82 – APOD - Image credit: Daniel Nobre



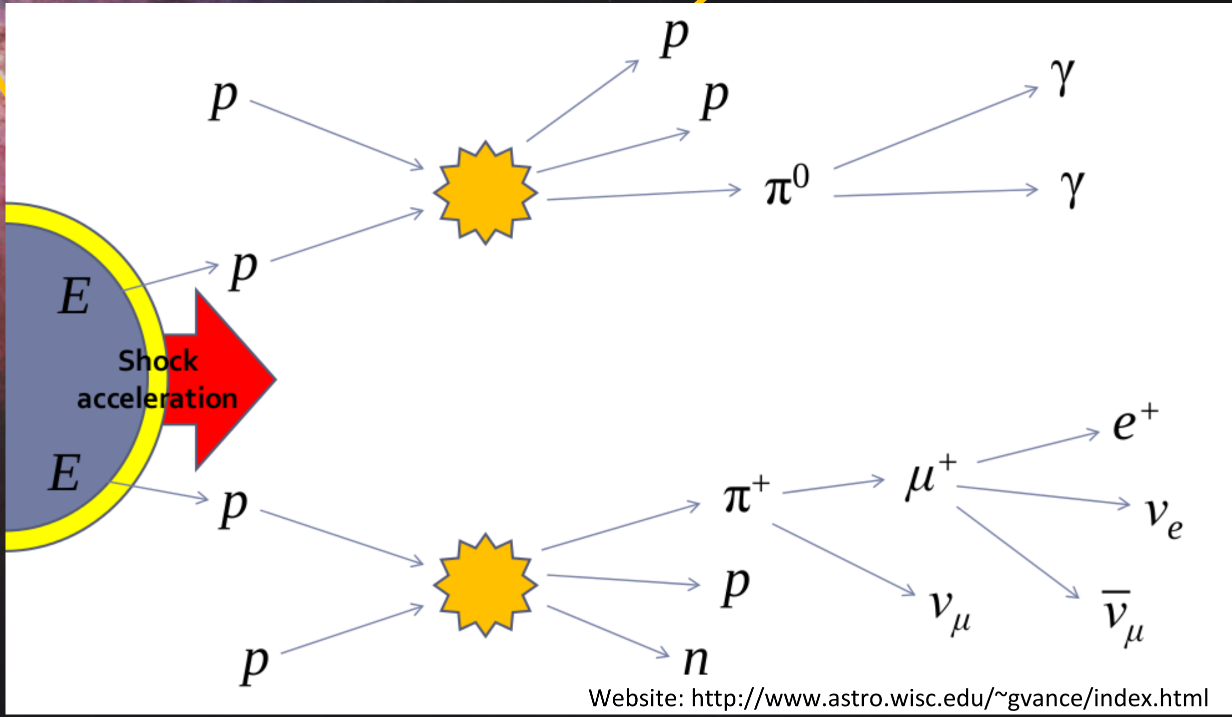
Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

High star formation rate

Young stars and supernovae

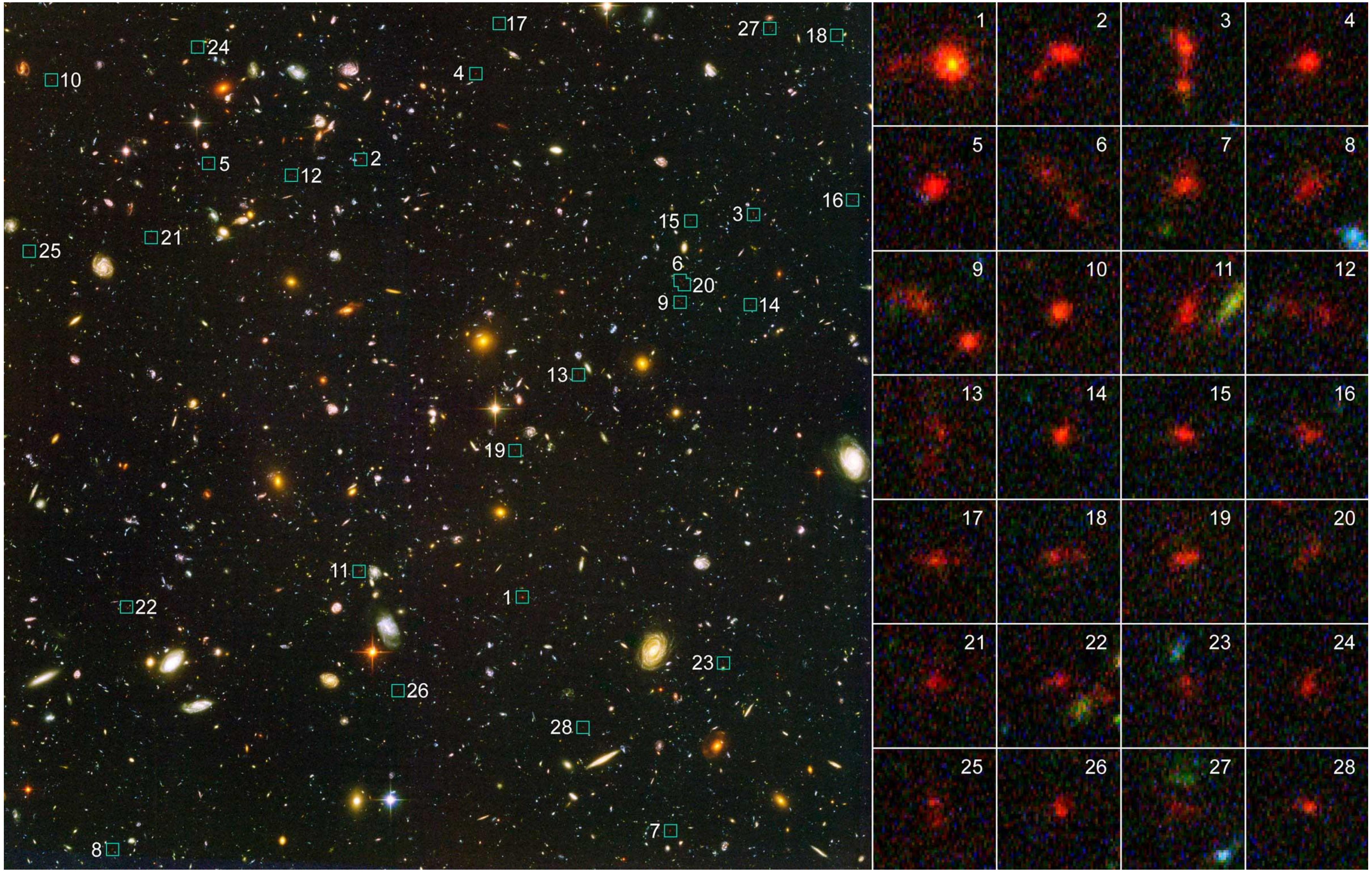
Particle acceleration 2X

High target density & strong fields

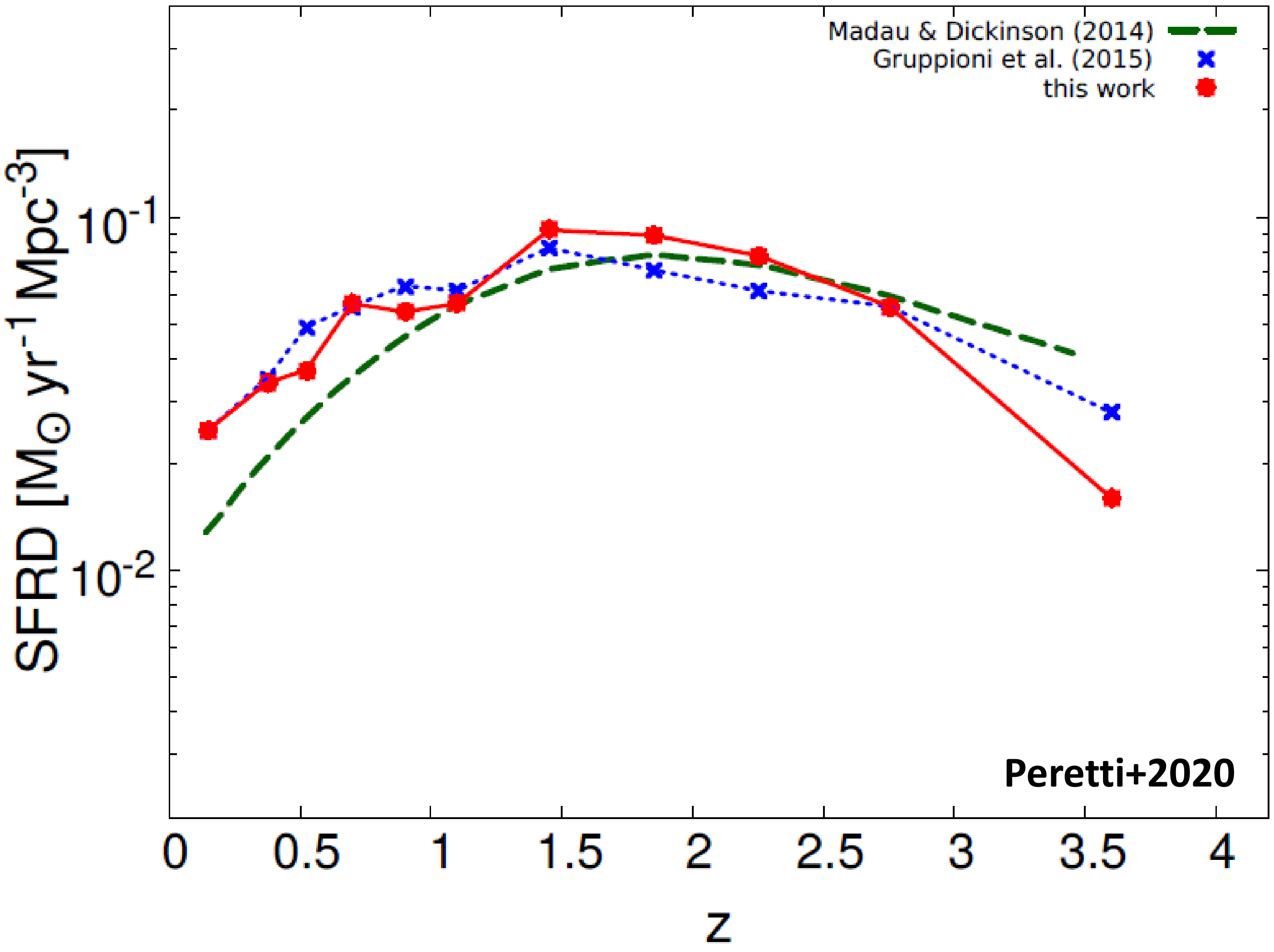


Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

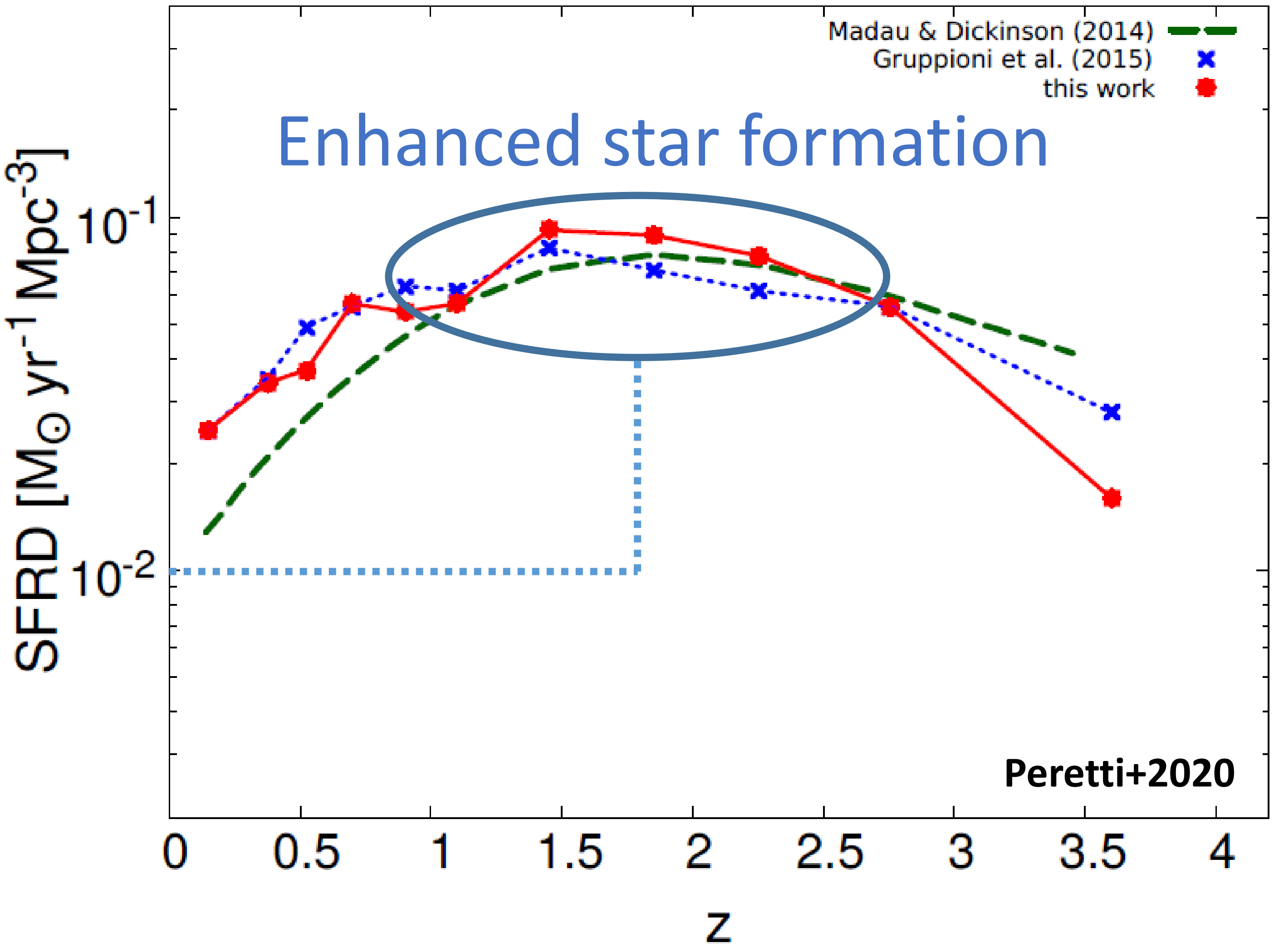
Another reason to study Star-forming galaxies



Another reason to study Star-forming galaxies

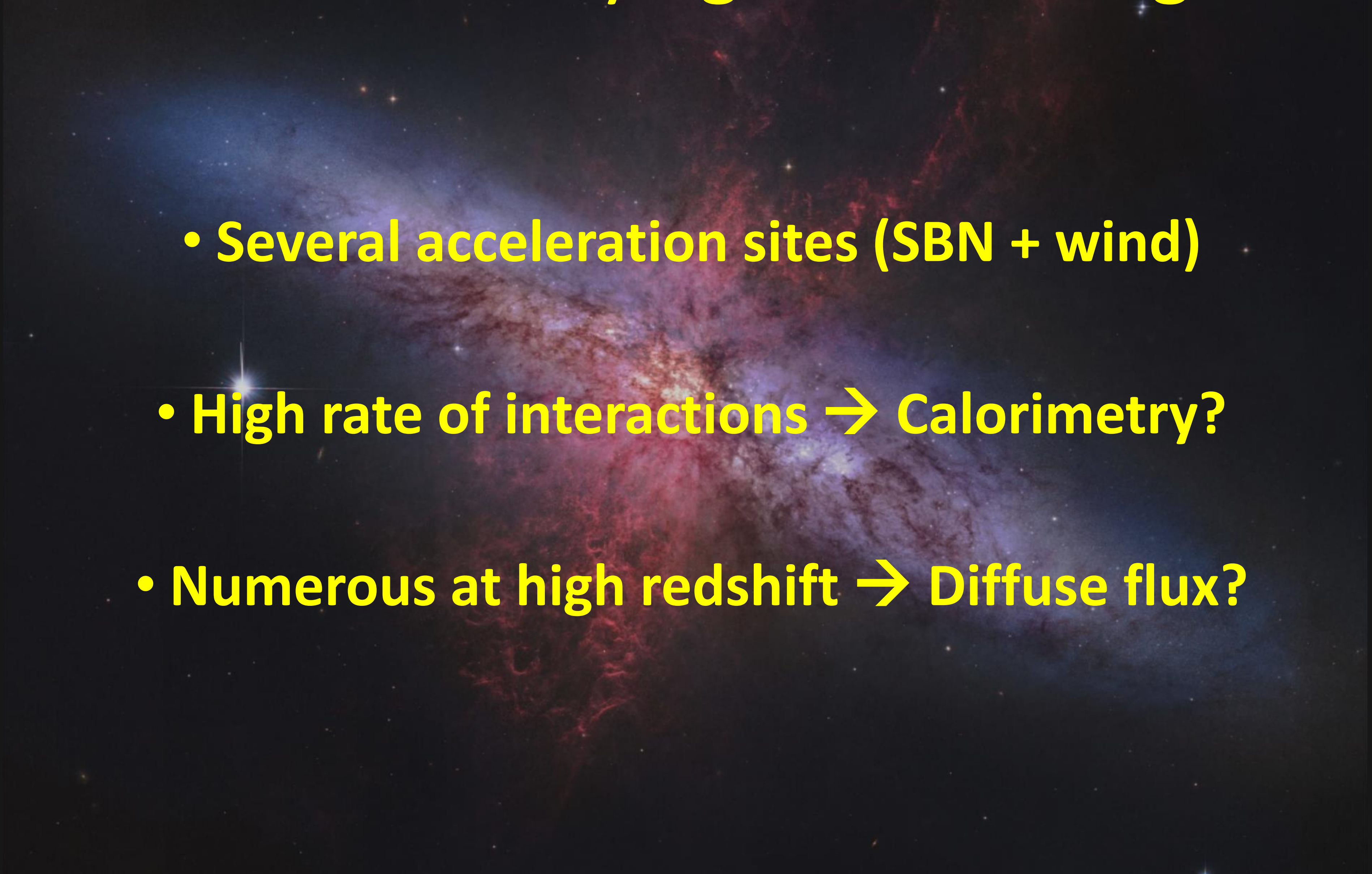


Another reason to study Star-forming galaxies



Motivations for studying Star-forming Galaxies

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



Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

Outline

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

Outline

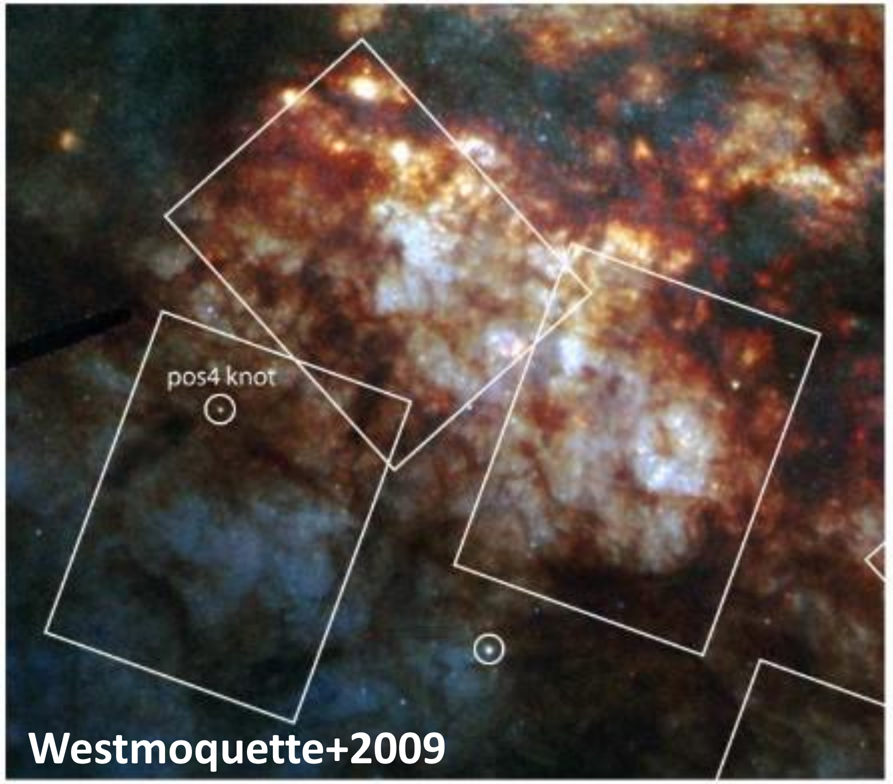
- Observations of Star-forming galaxies
- Particle Transport in Starburst Nuclei
- Starburst-driven winds
- Multi-messenger diffuse flux

Optical view of starburst regions

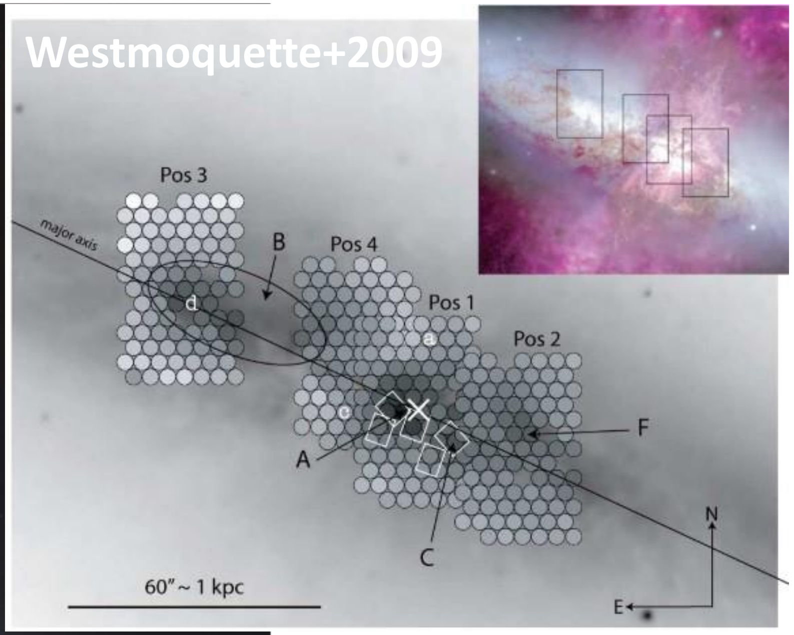
Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

Westmoquette+2020

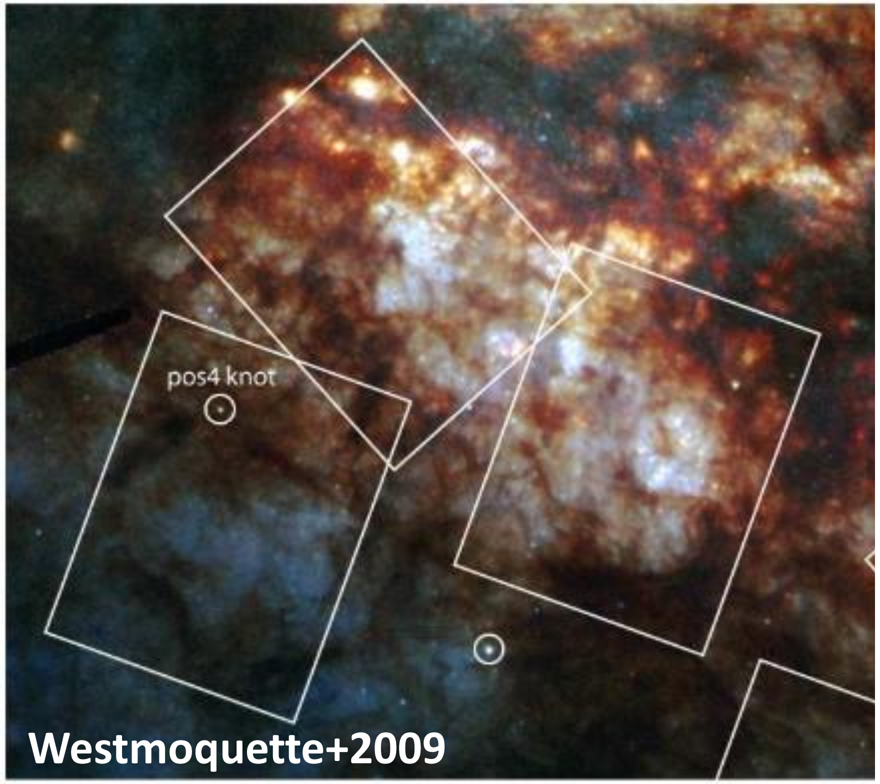
Optical view of starburst regions



Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

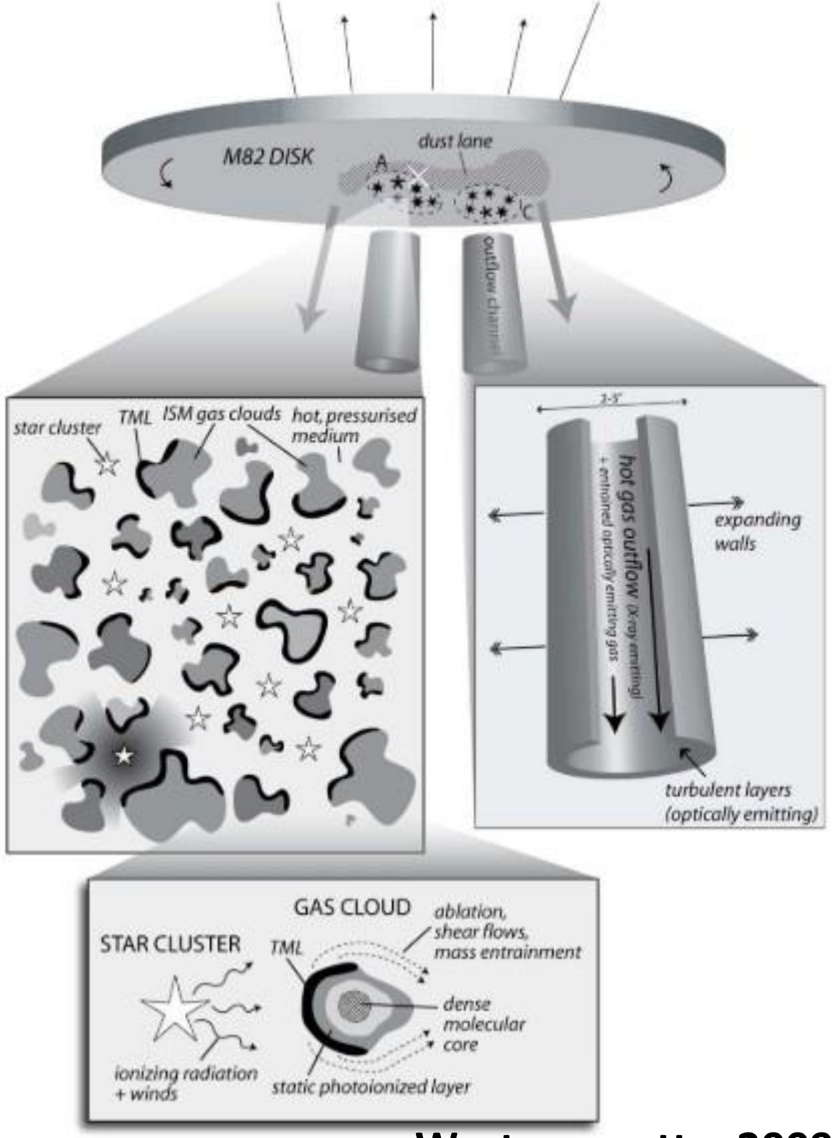


Optical view of starburst regions

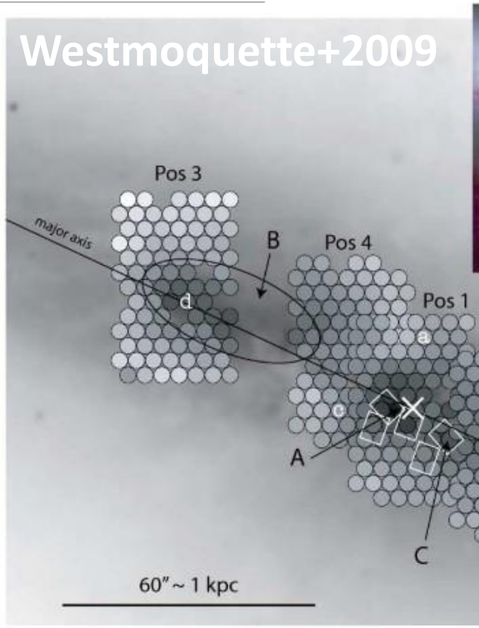


Westmoquette+2009

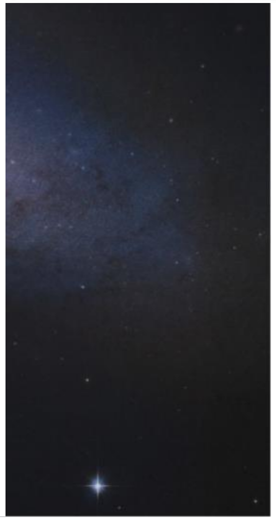
Starburst galaxy M82 – APO



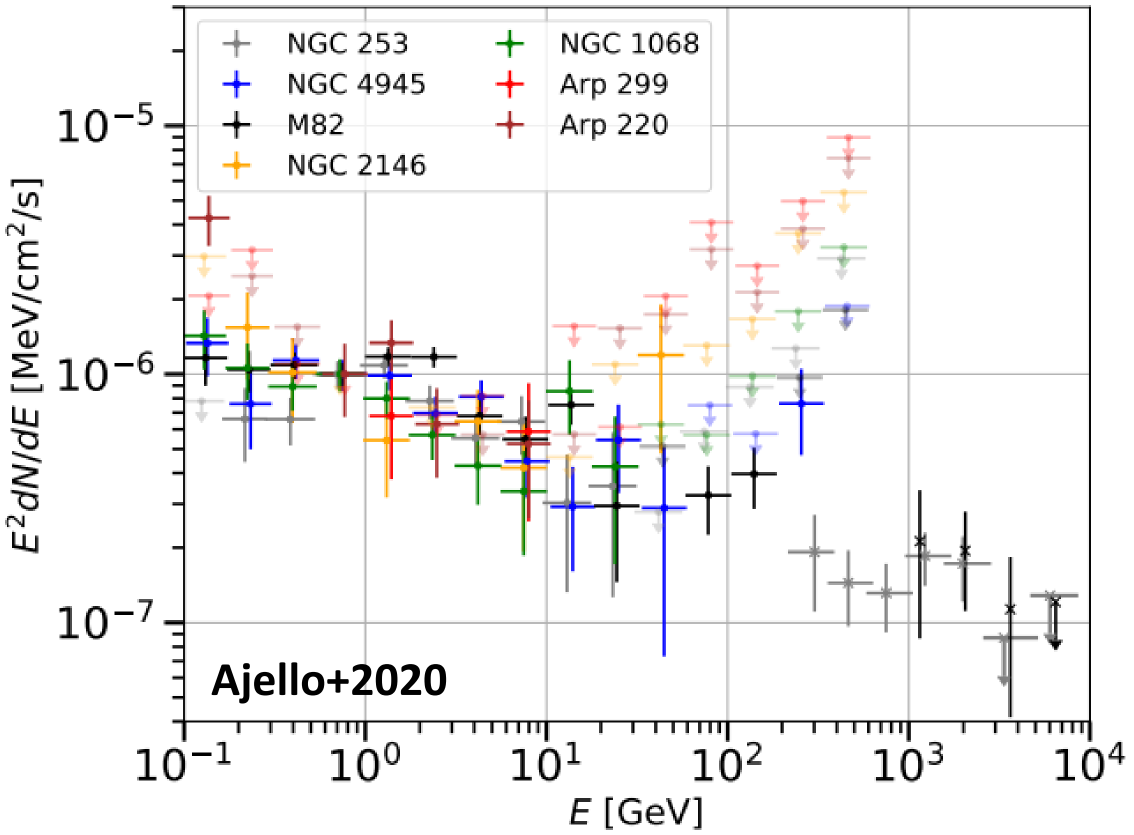
Westmoquette+2009



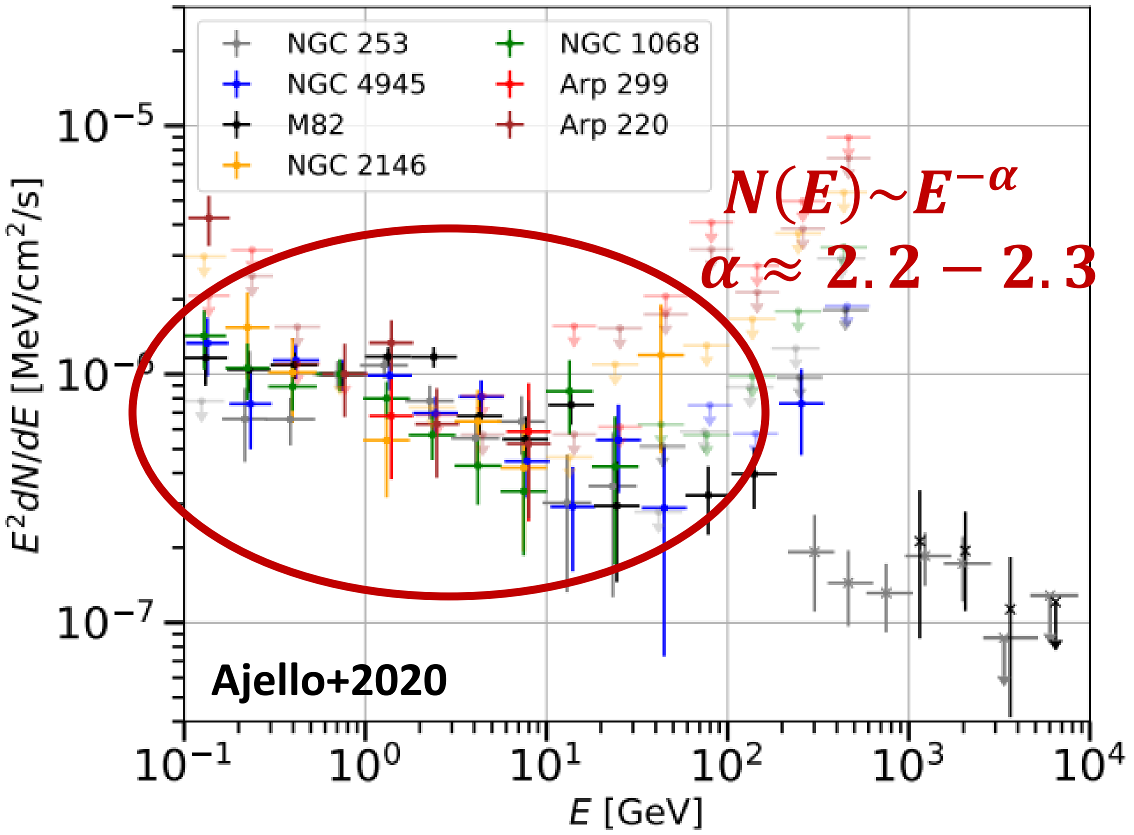
Westmoquette+2009



Observation of Star-forming Galaxies - Gamma

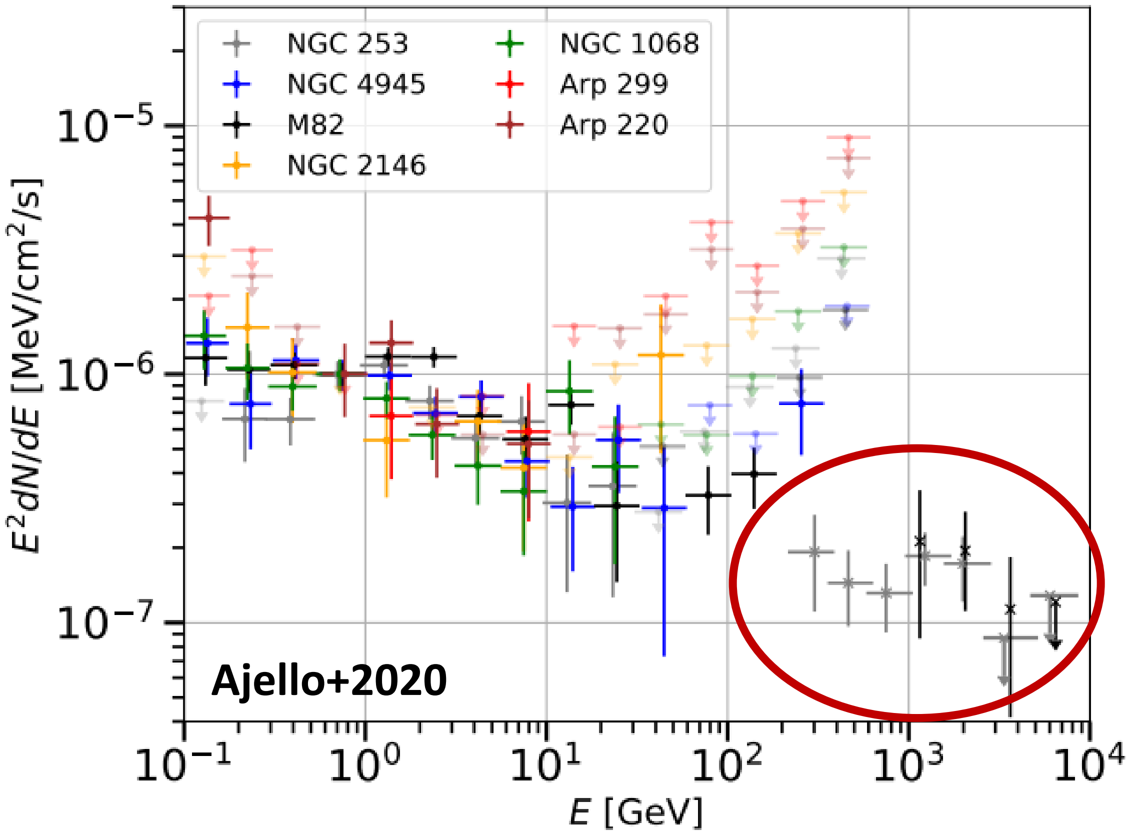


Observation of Star-forming Galaxies - Gamma



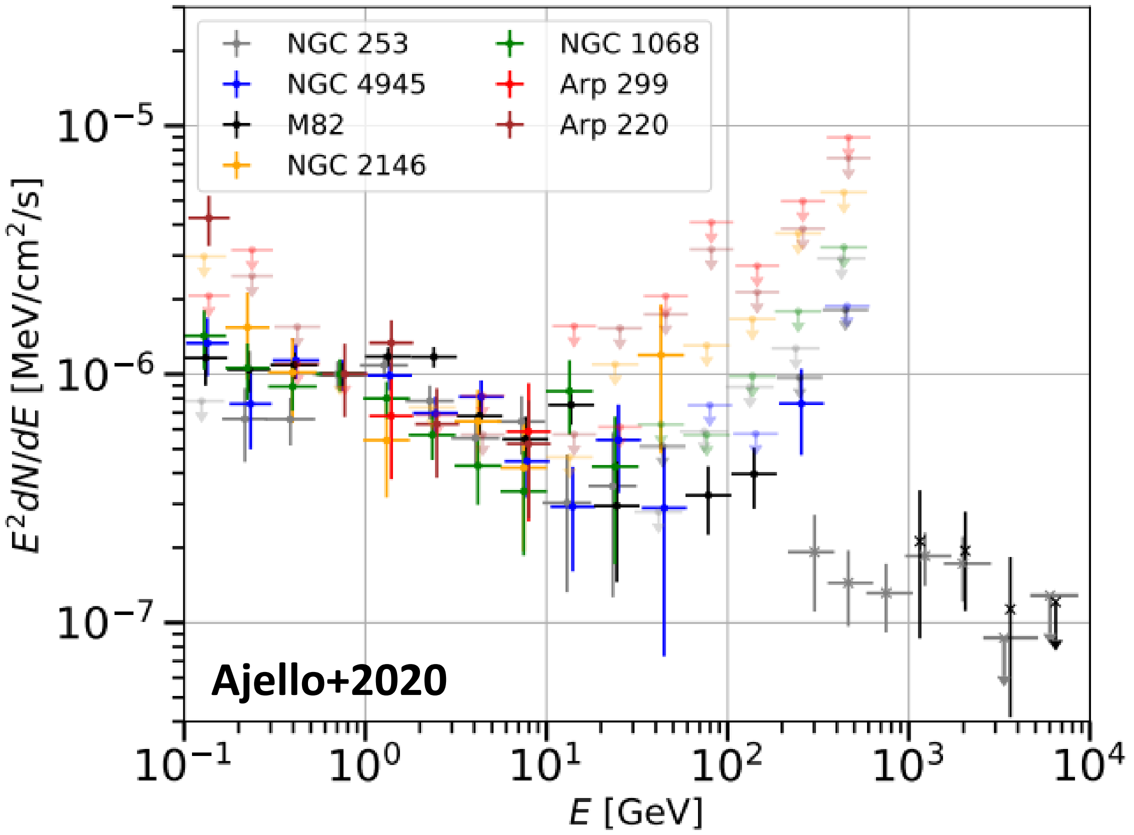
- Star-forming observed at GeV

Observation of Star-forming Galaxies - Gamma



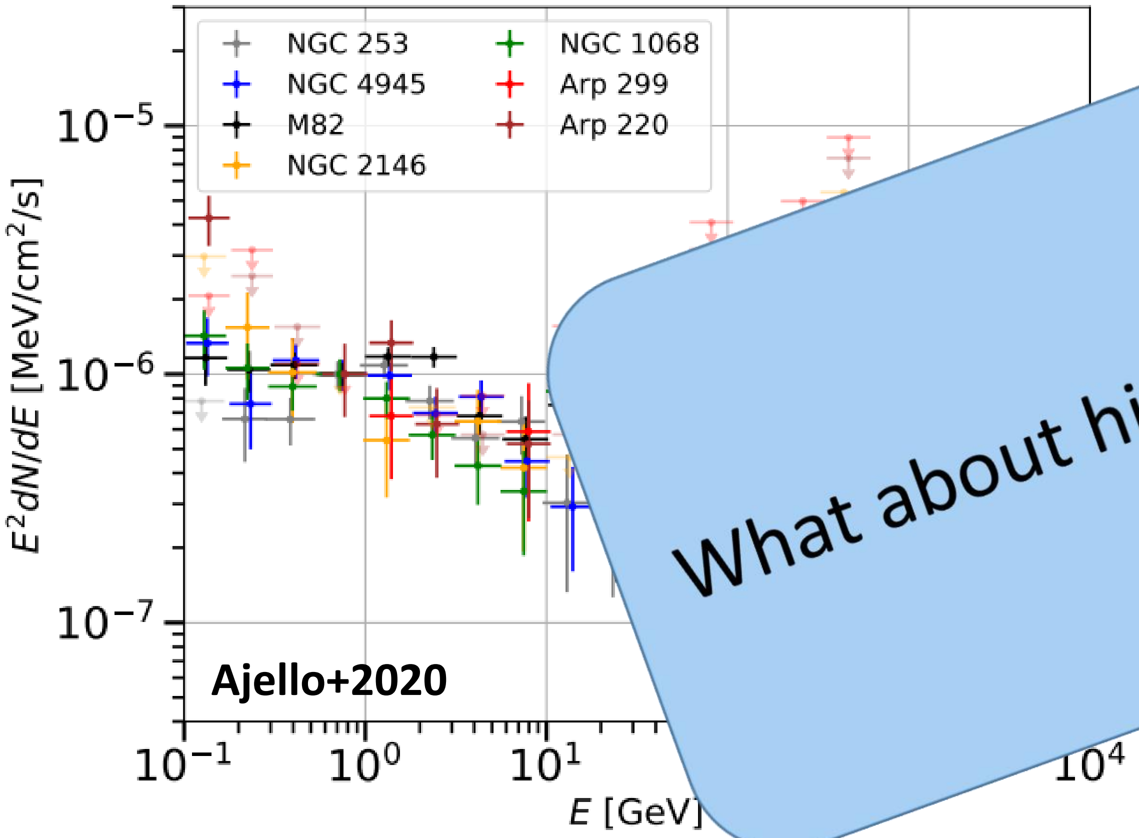
- Star-forming observed at GeV
- Most nearby at TeV (<4 Mpc)

Observation of Star-forming Galaxies - Gamma



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

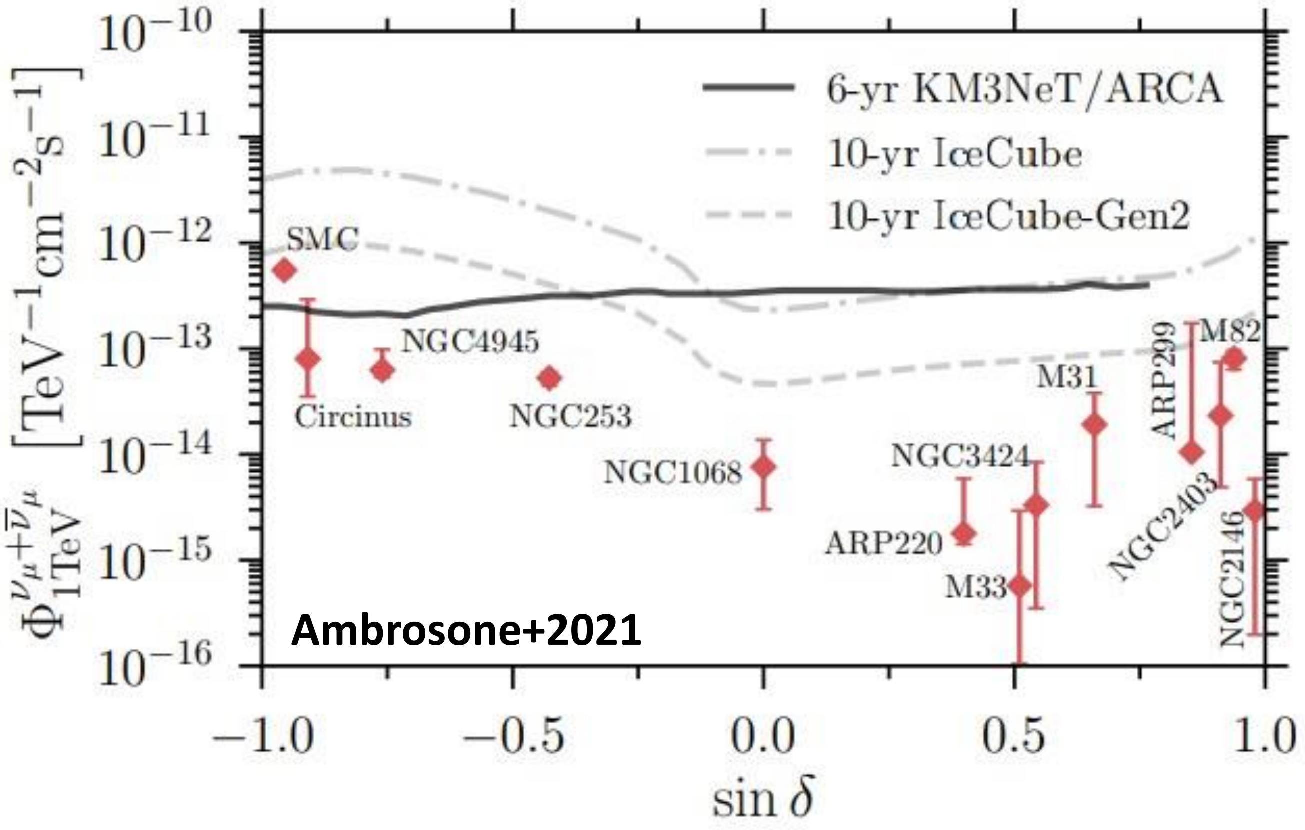
Observation of Star-forming Galaxies - Gamma



- …bserved at GeV
- …TeV (<4 Mpc)
- …distant: Arp 220 (77 Mpc)

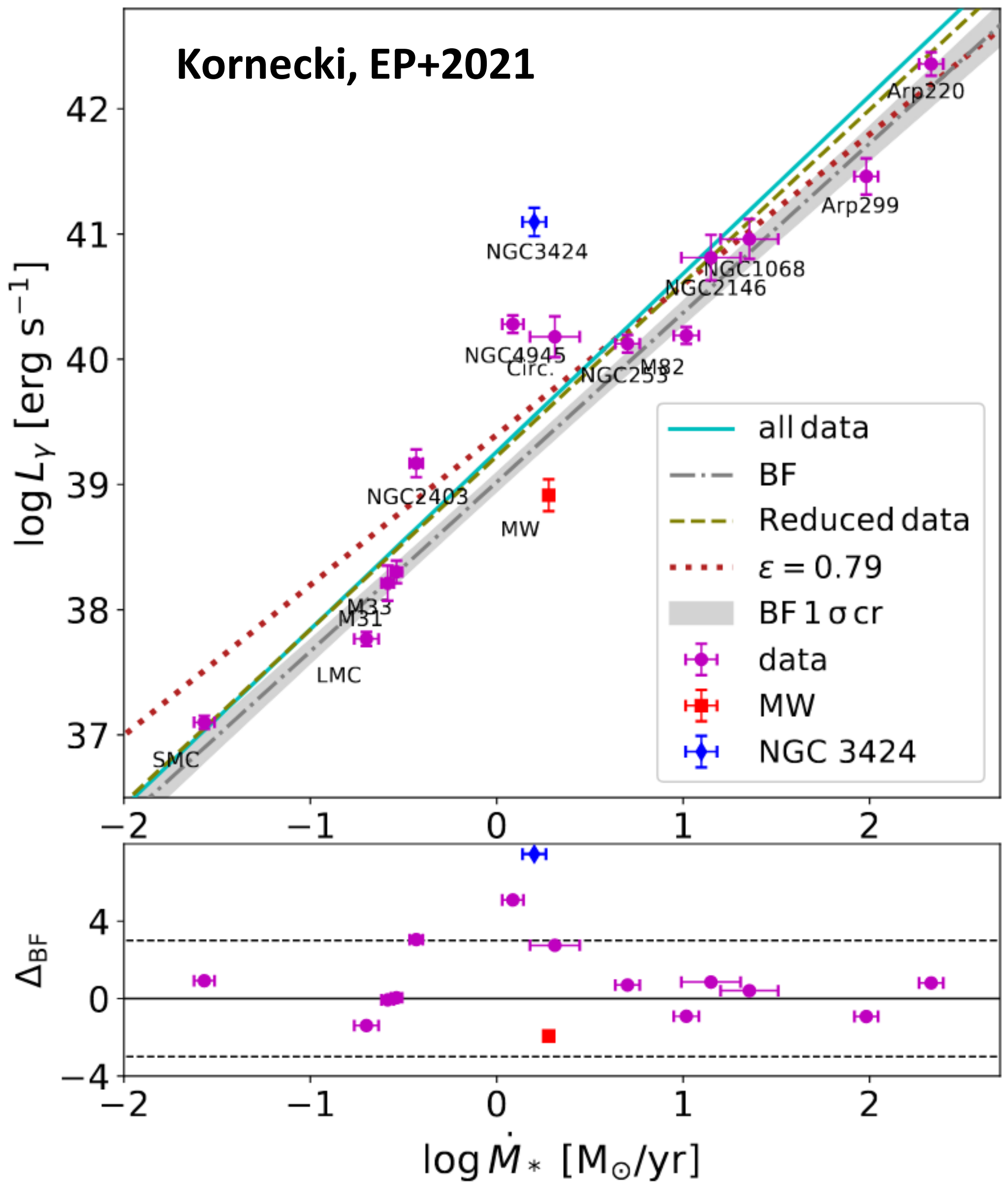
What about high-energy neutrinos?

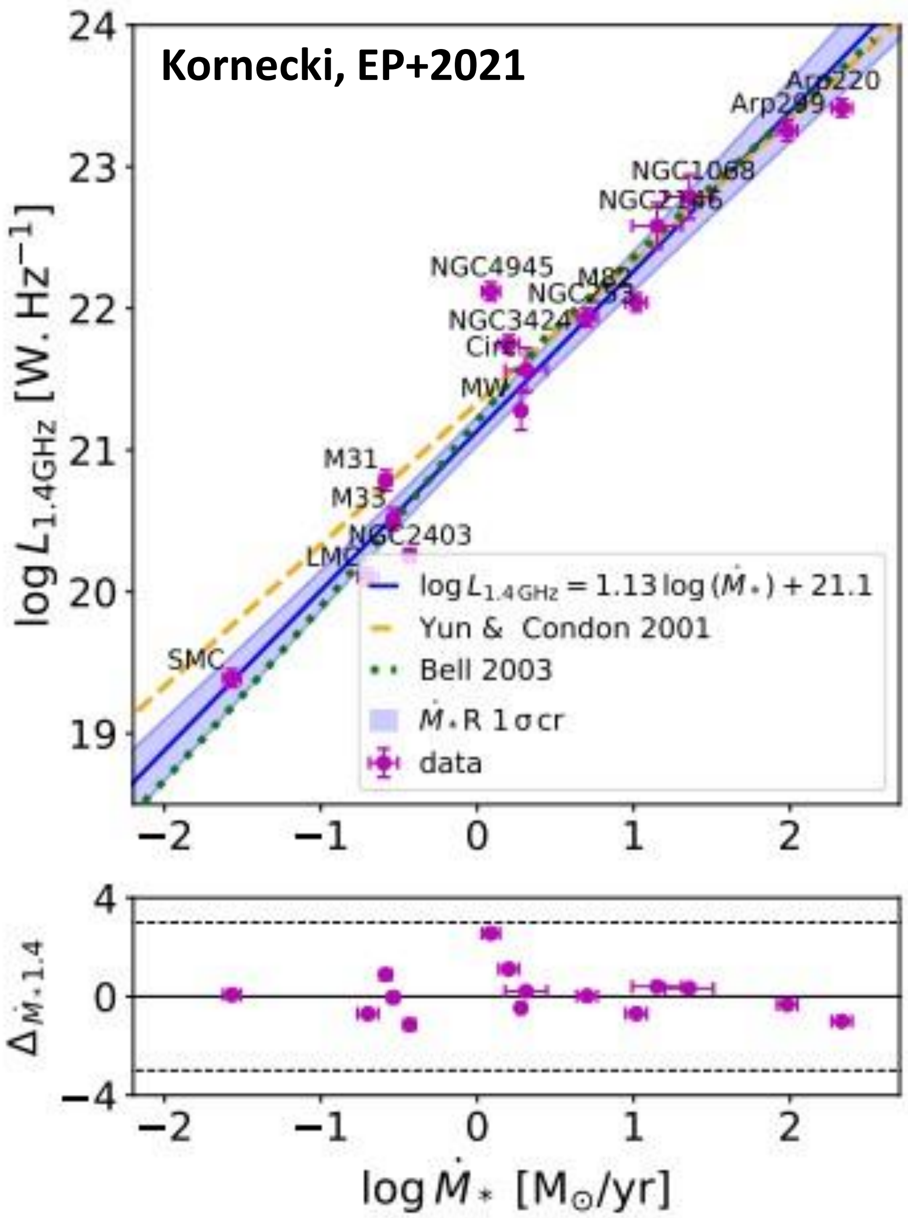
Observation of Star-forming Galaxies - Neutrinos



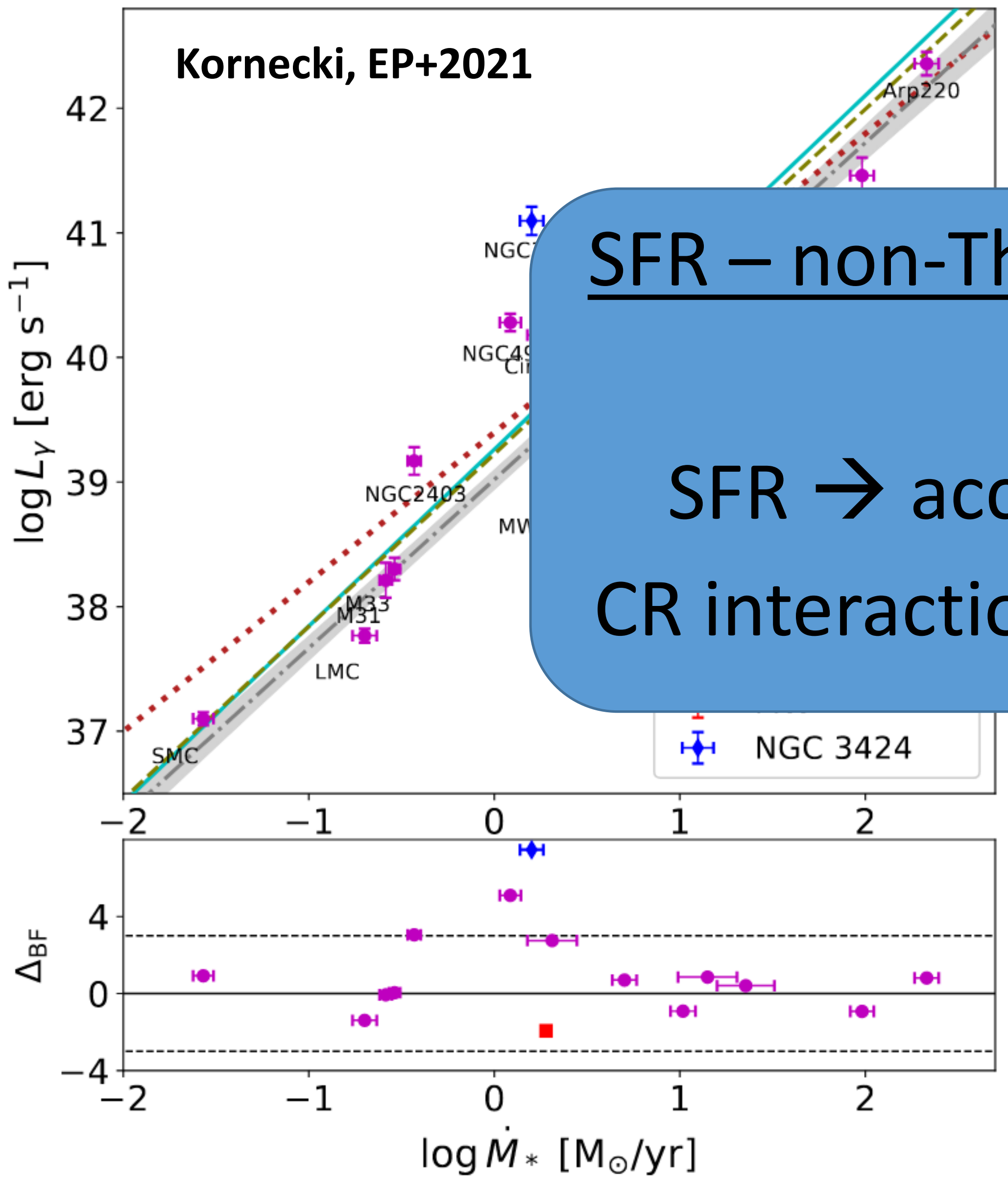
- Star-forming observed at GeV
- Most nearby at TeV (<4 Mpc)
- Most distant: Arp 220 (77 Mpc)
- SBGs are currently undetected neutrino sources (*)

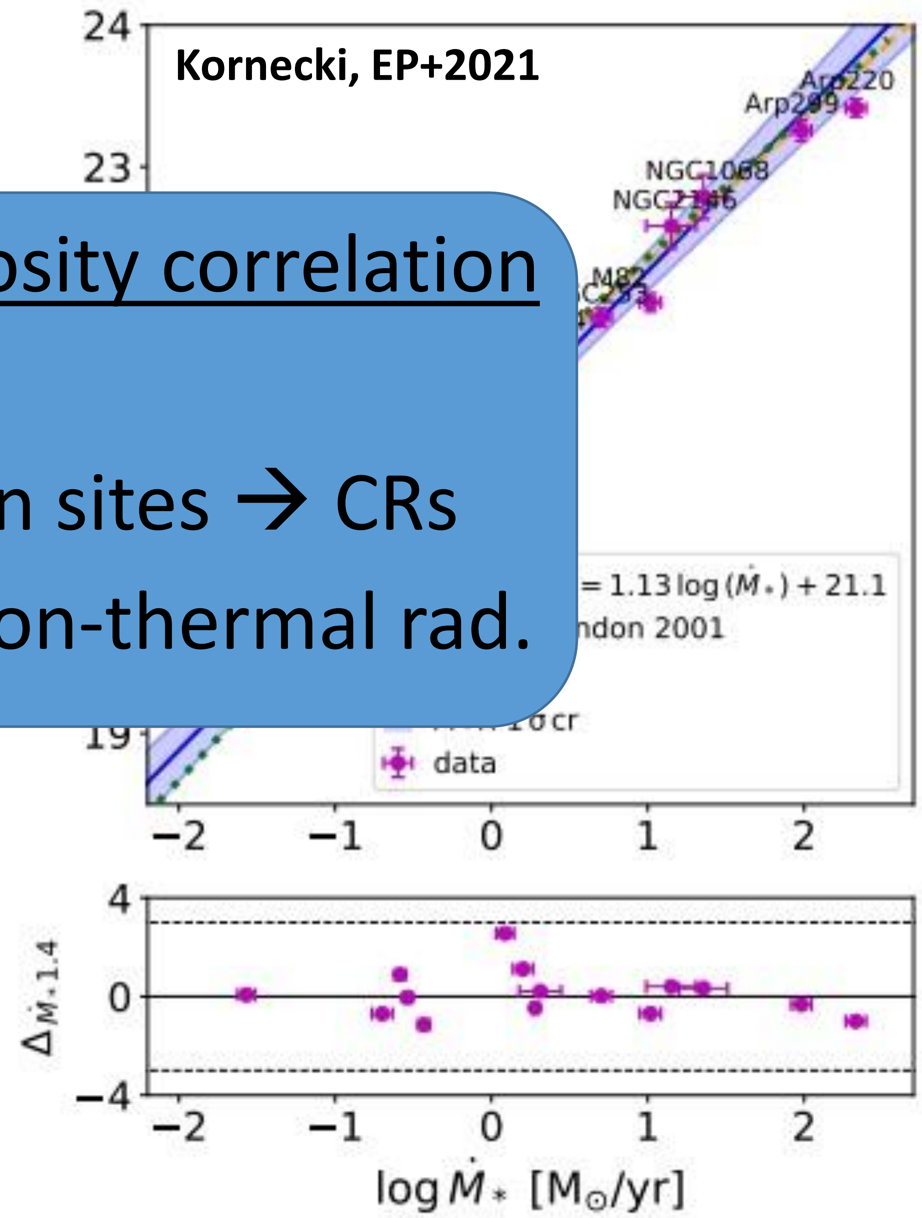
Observation of Star-forming Galaxies - Correlations





Observation of Star-forming Galaxies - Correlations



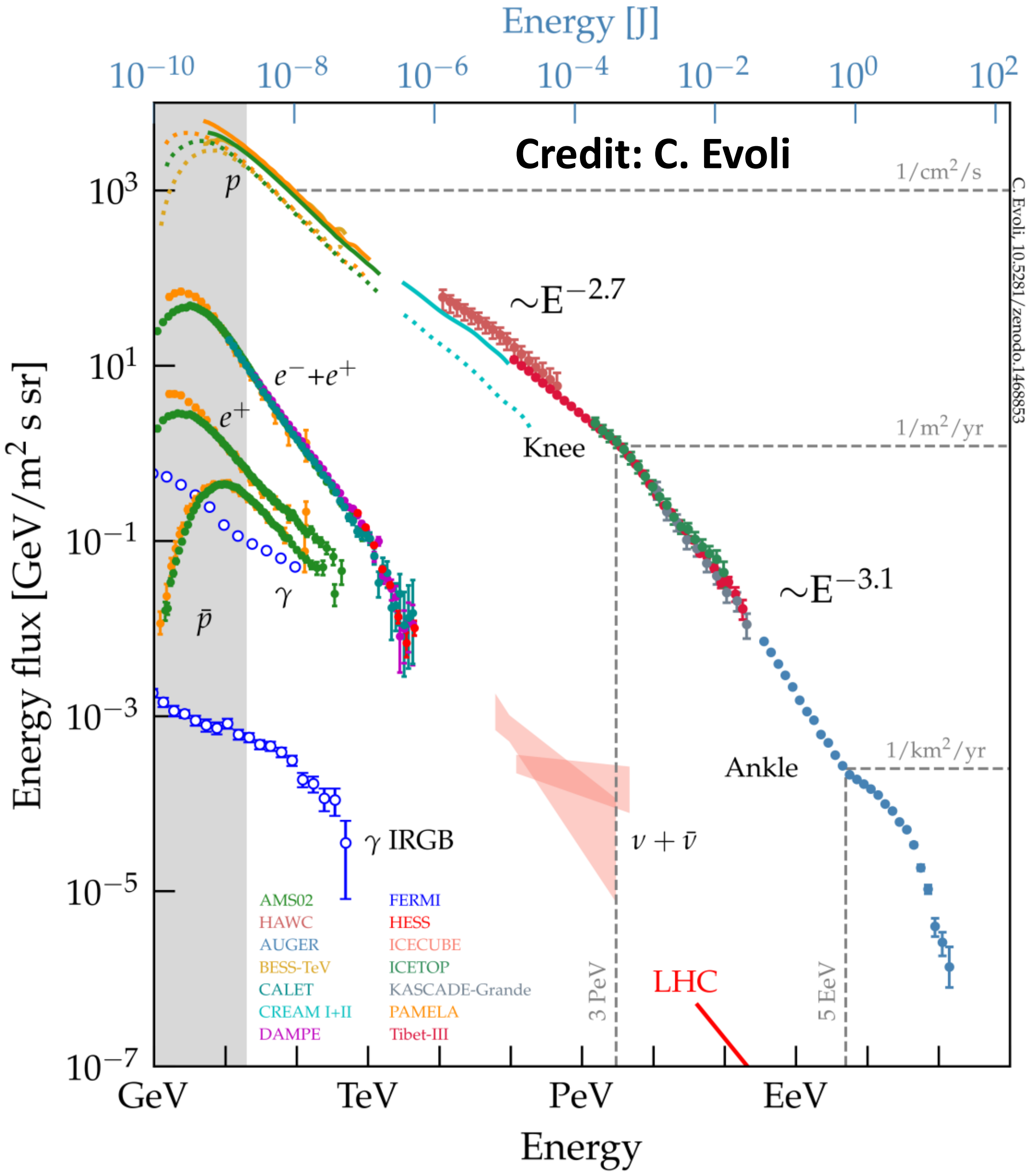


<u>SFR – non-Th. luminosity correlation</u>

SFR → acceleration sites → CRs

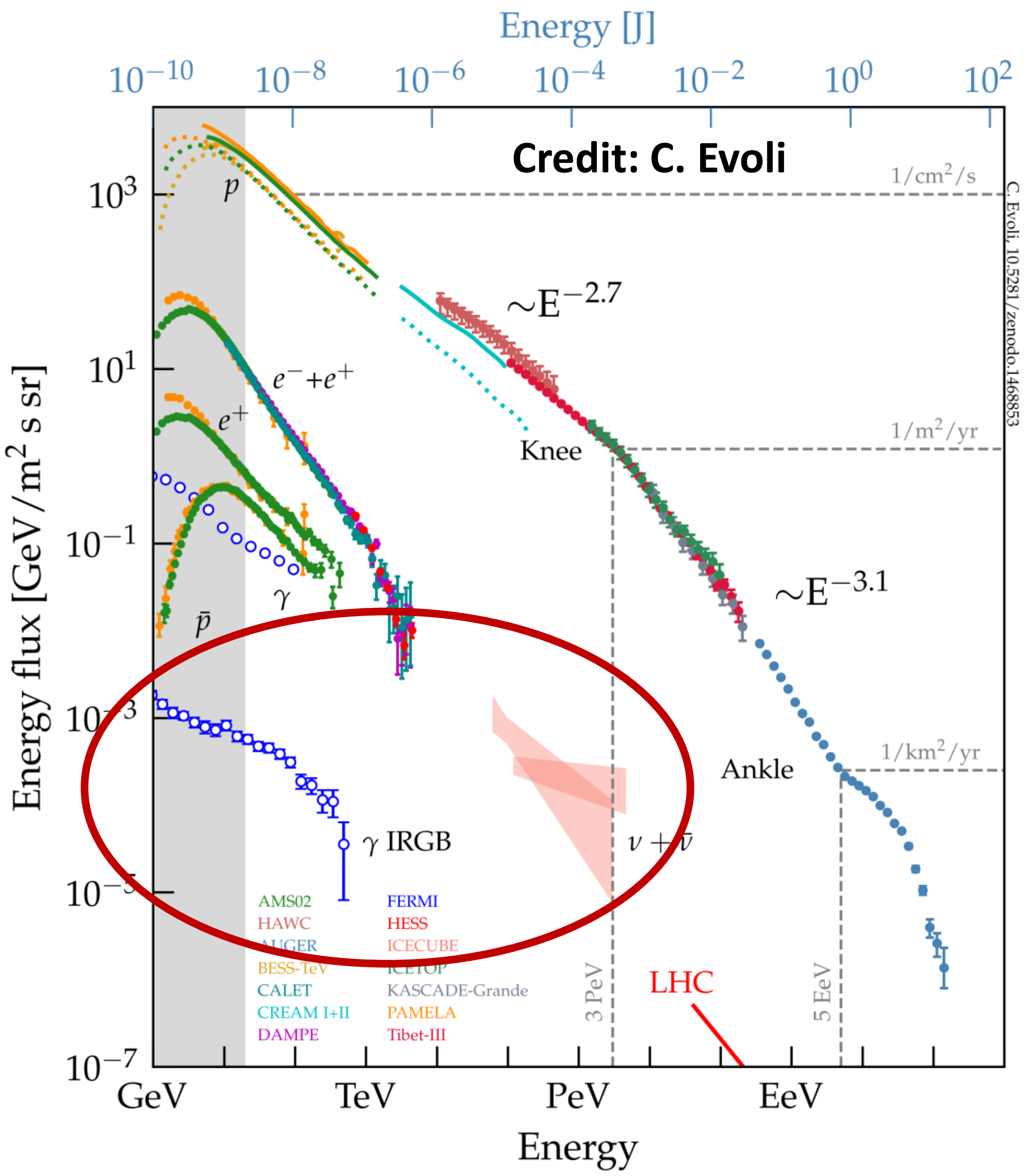
CR interactions → Non-thermal rad.

Diffuse radiation from Star-forming galaxies



- SFGs are expected to shine on gamma rays and neutrinos

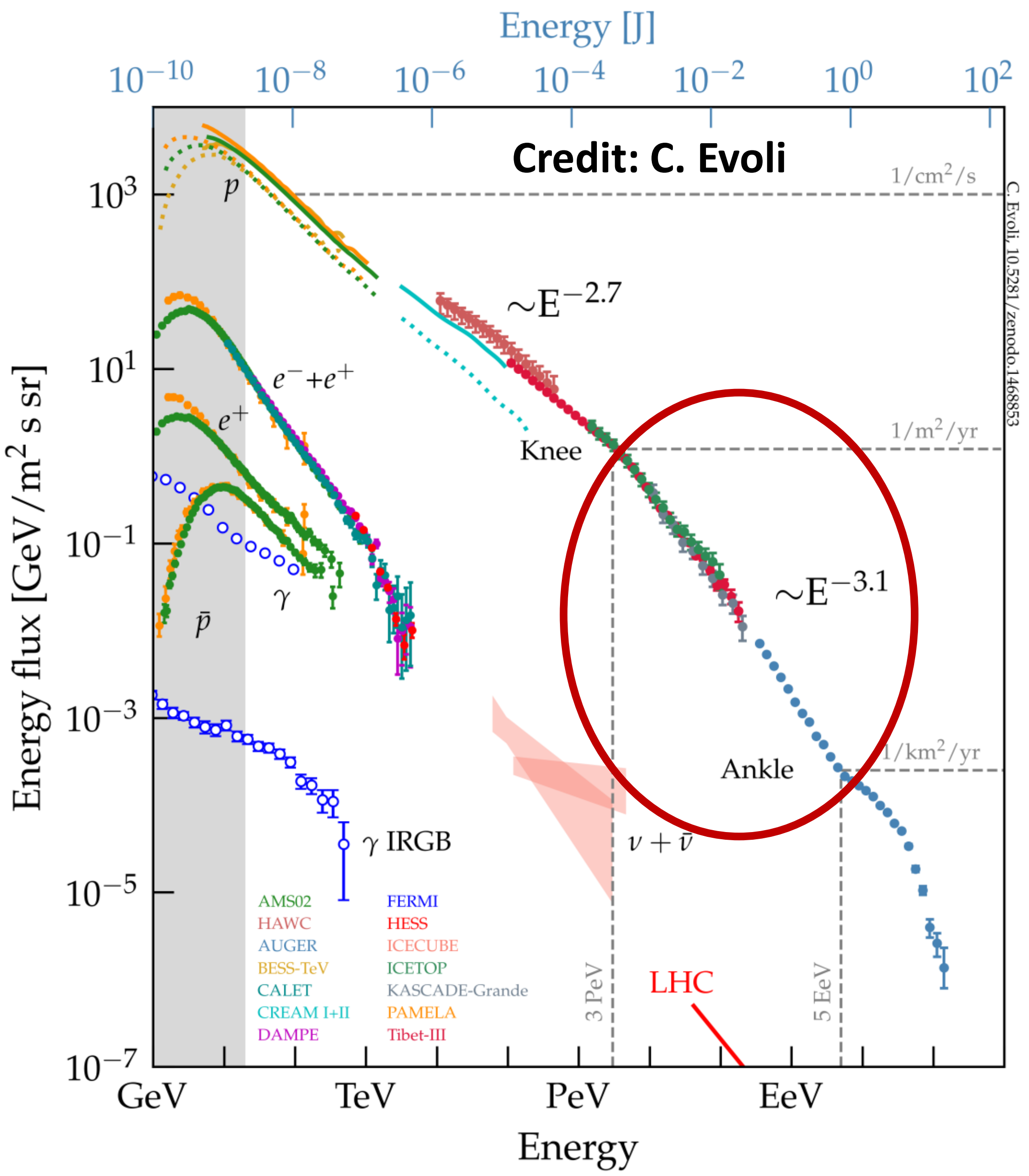
Diffuse radiation from Star-forming galaxies



- SFGs are expected to shine on gamma rays and neutrinos

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

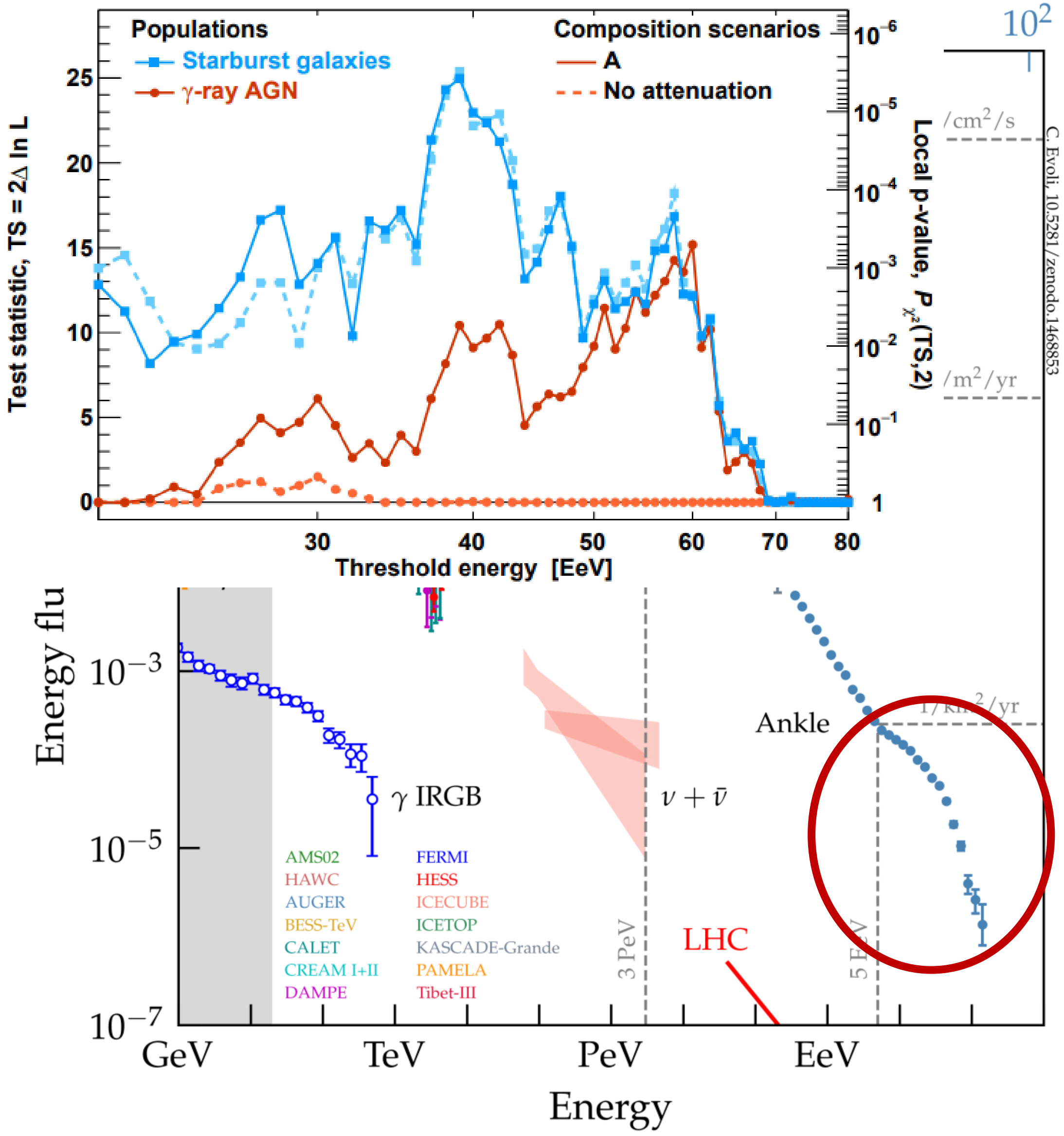
Diffuse radiation from Star-forming galaxies



- 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?

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
- Particle Transport in Starburst Nuclei
- Starburst-driven winds
- Multi-messenger diffuse flux

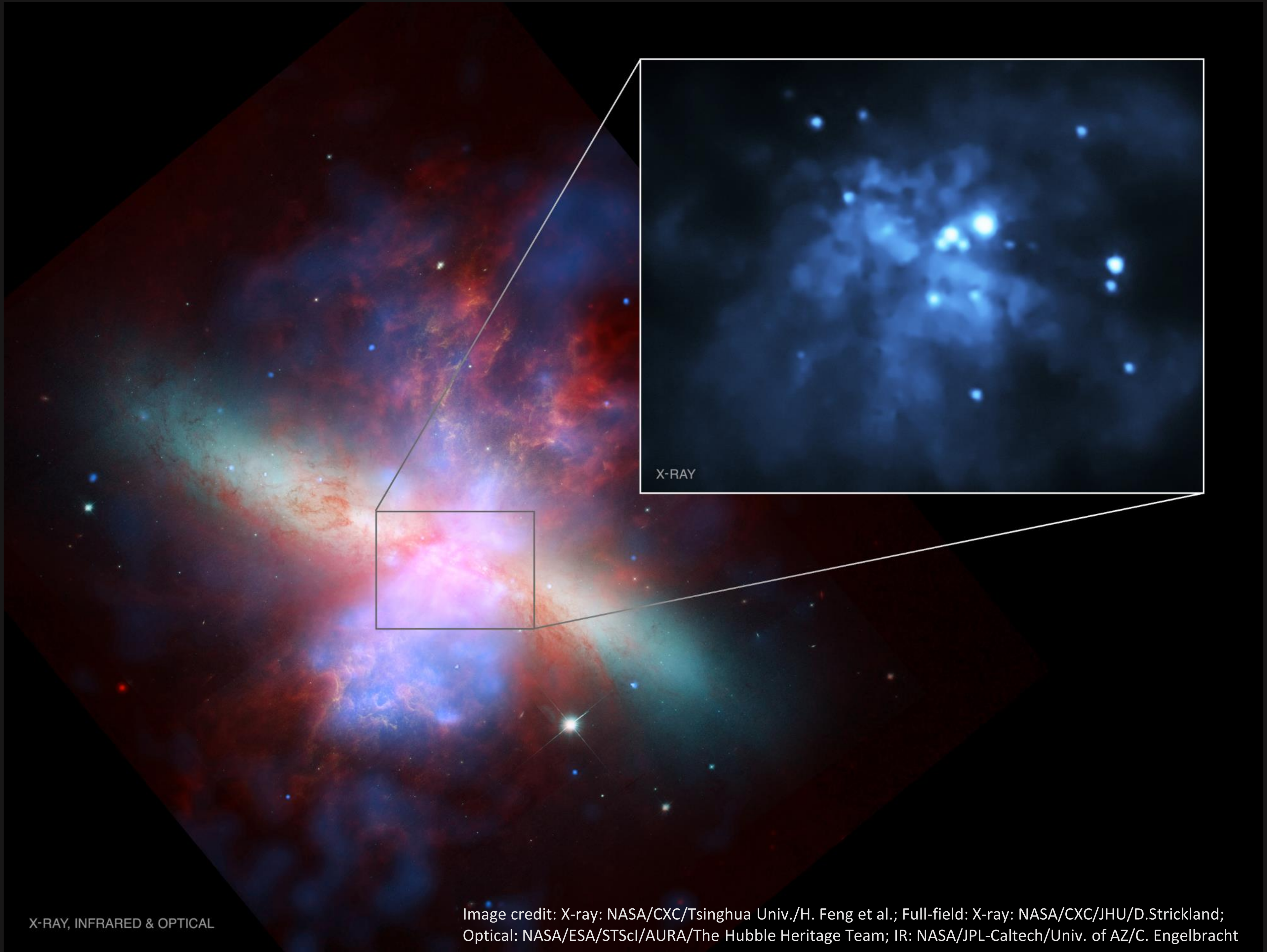
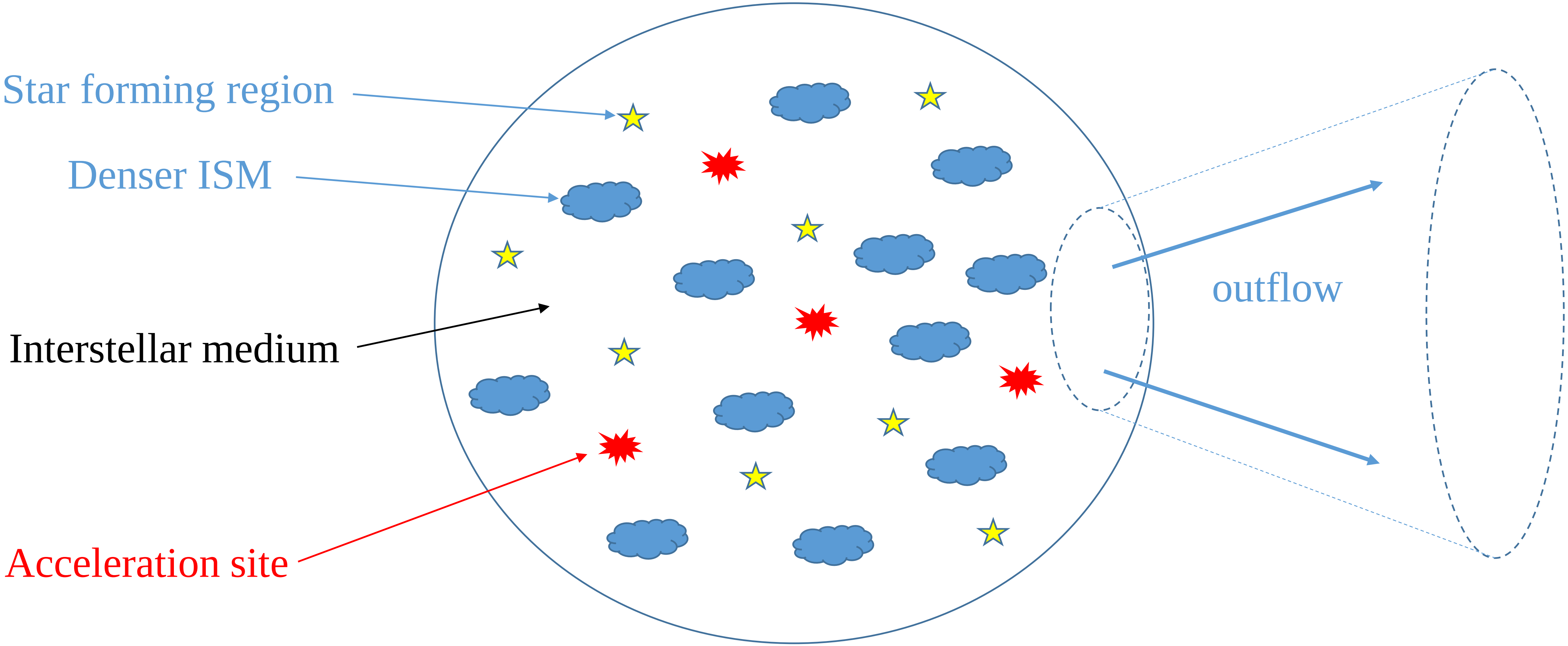
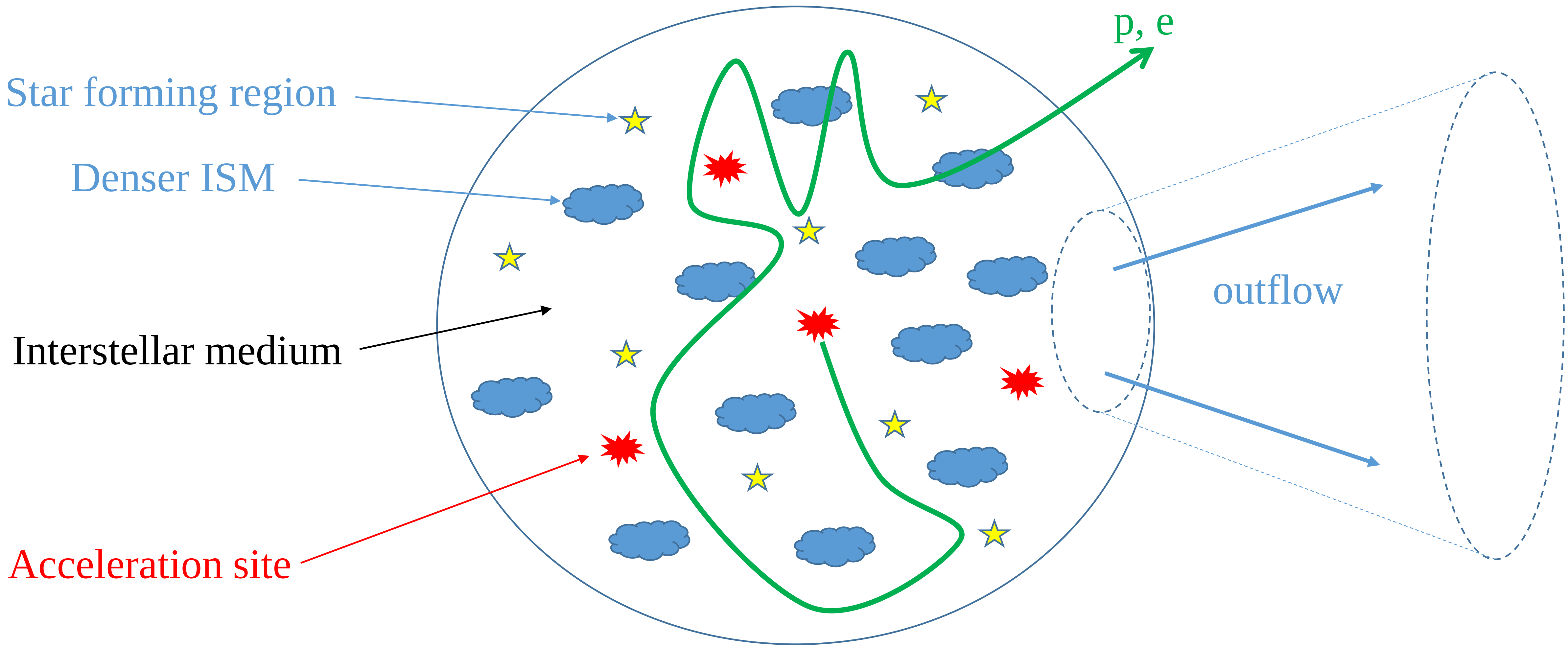


Image credit: X-ray: NASA/CXC/Tsinghua Univ./H. Feng et al.; Full-field: X-ray: NASA/CXC/JHU/D.Strickland; Optical: NASA/ESA/STScI/AURA/The Hubble Heritage Team; IR: NASA/JPL-Caltech/Univ. of AZ/C. Engelbracht

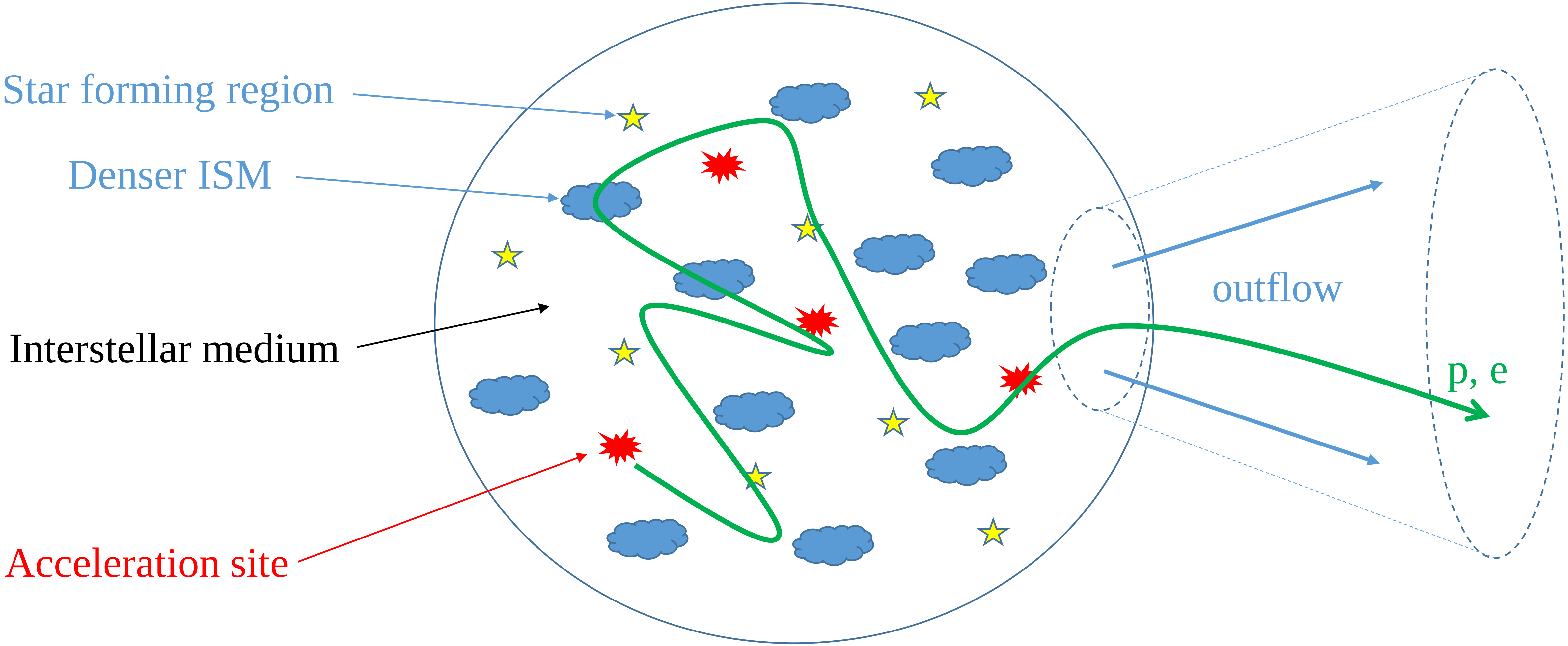
Particle transport in starburst nuclei



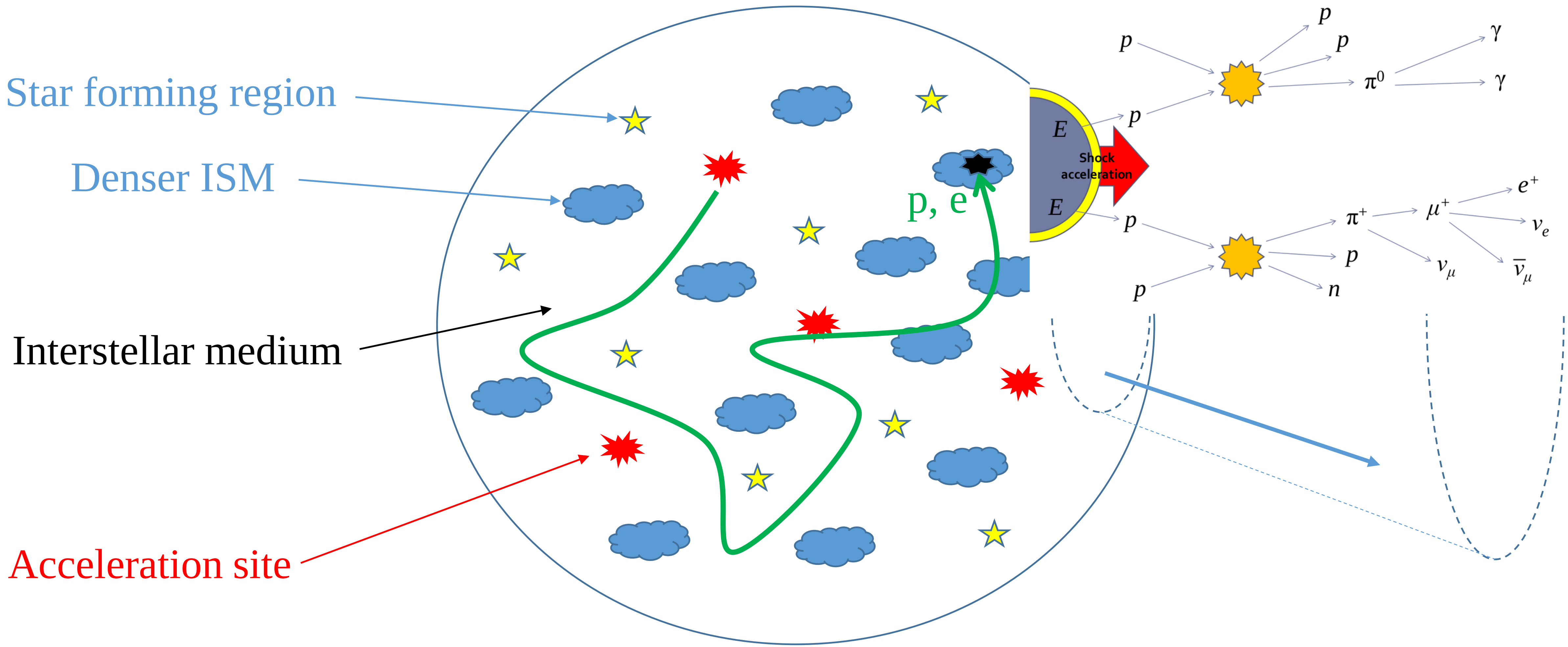
Particle transport in starburst nuclei



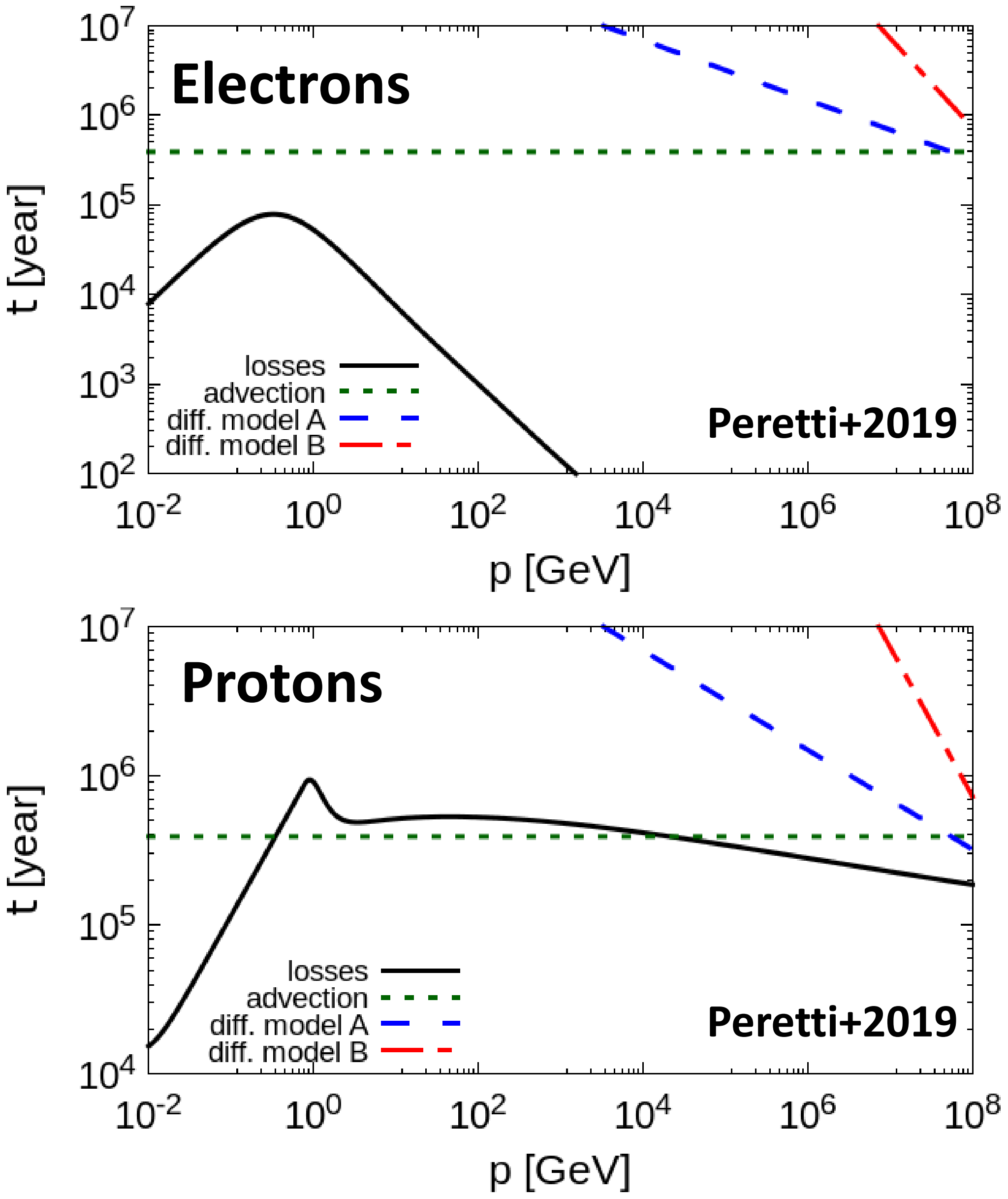
Particle transport in starburst nuclei



Particle transport in starburst nuclei



Modeling the transport in SBNi



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

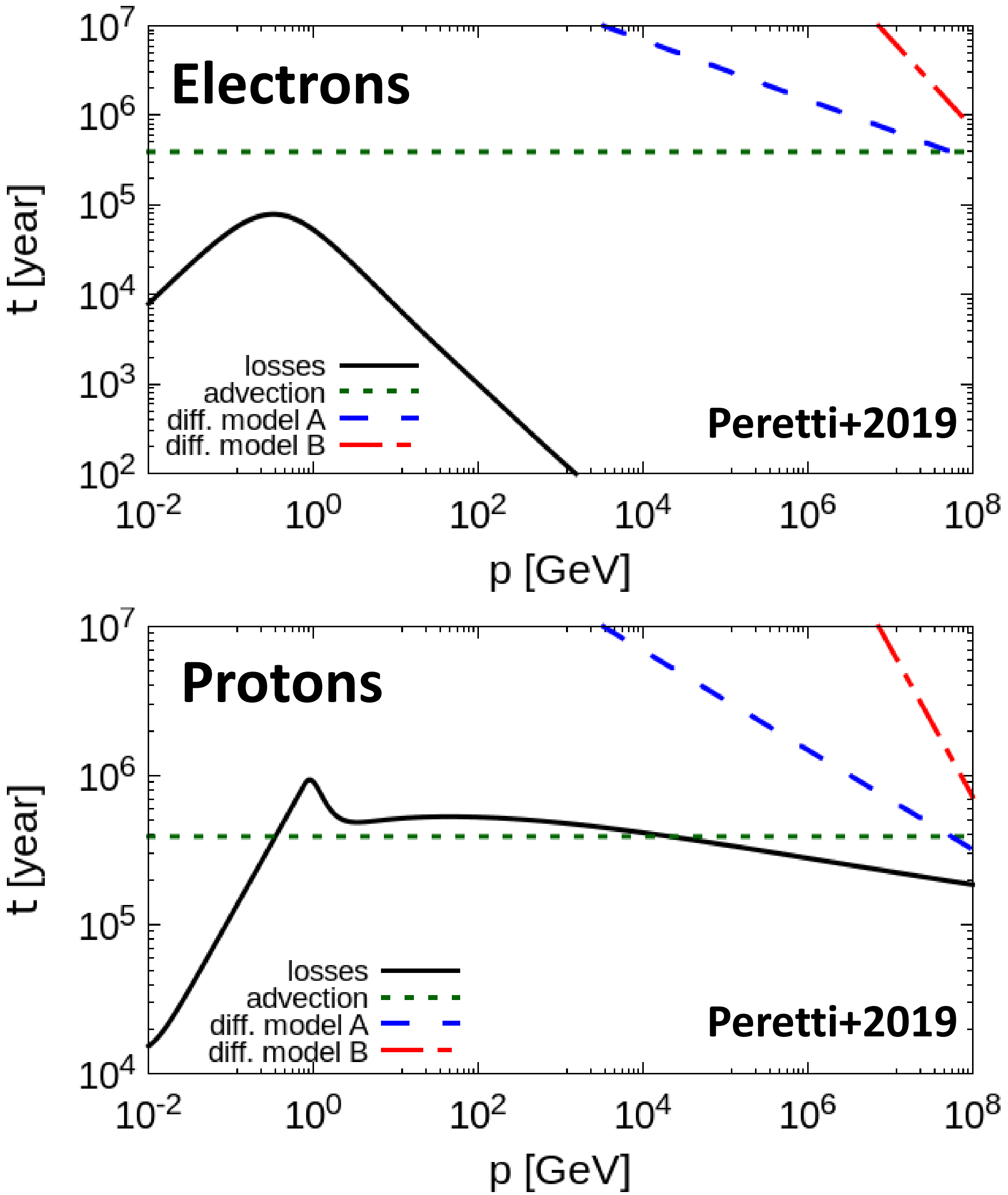
$$B \approx 10^2\ \mu G$$

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

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

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

Modeling the transport in SBNi



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

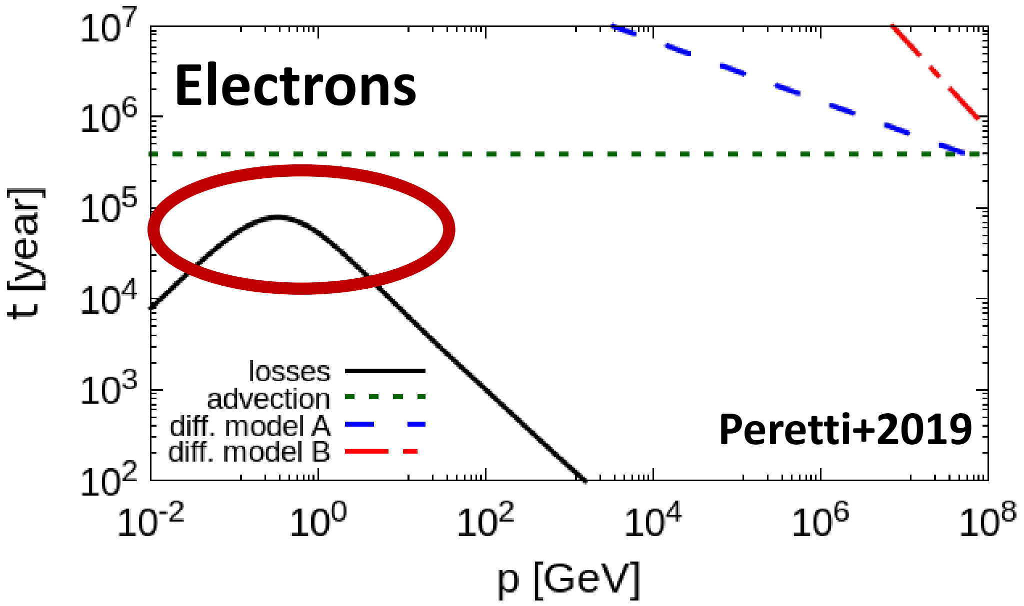
$B \approx 10^2\ \mu G$

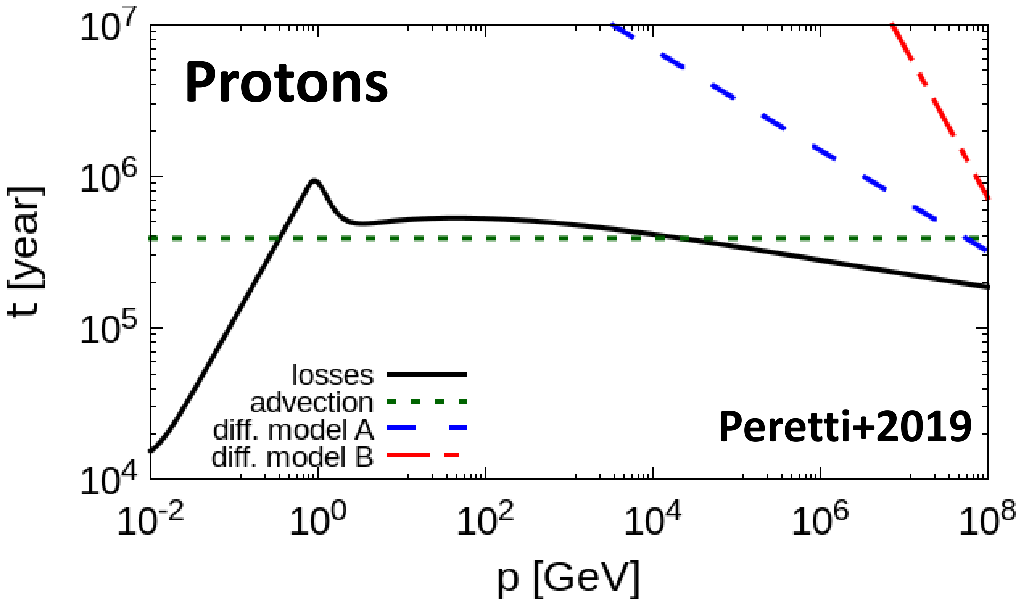
$U_{RAD} \approx 10^3\ eV\ cm^{-3}$

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

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

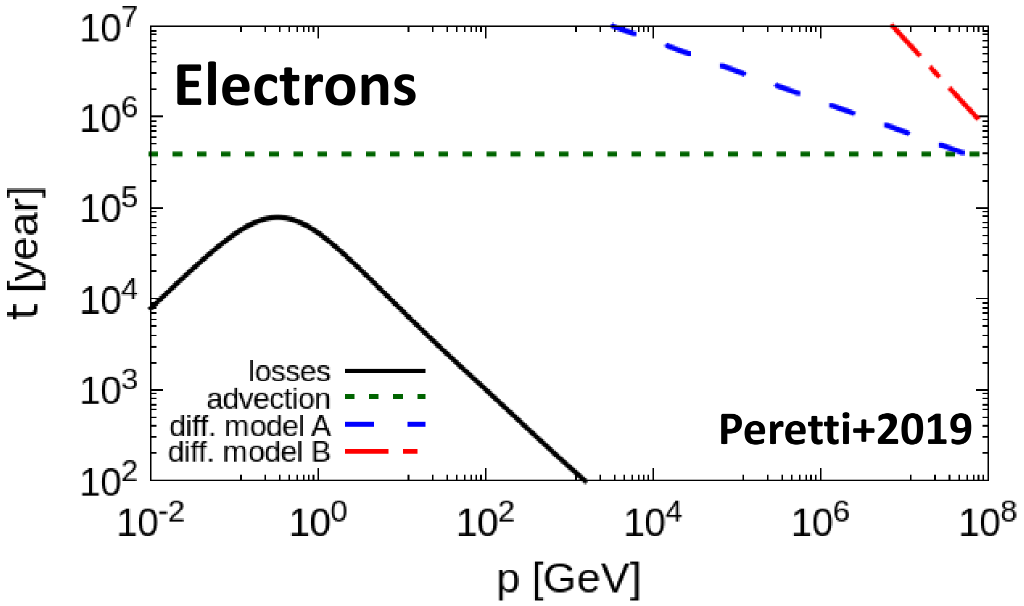
Modeling the transport in SBNi

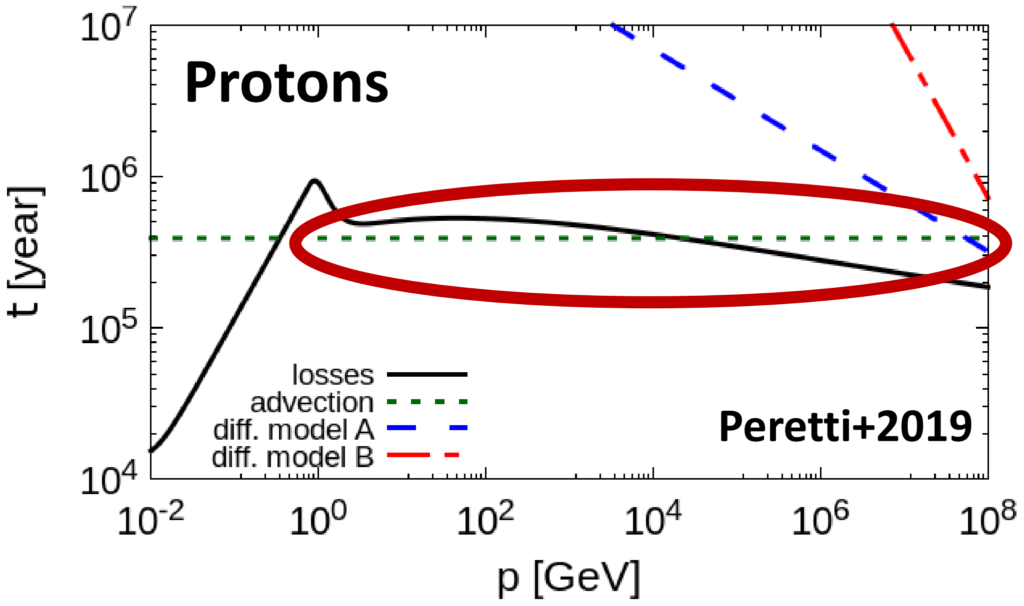




- Electrons are confined in SBNi

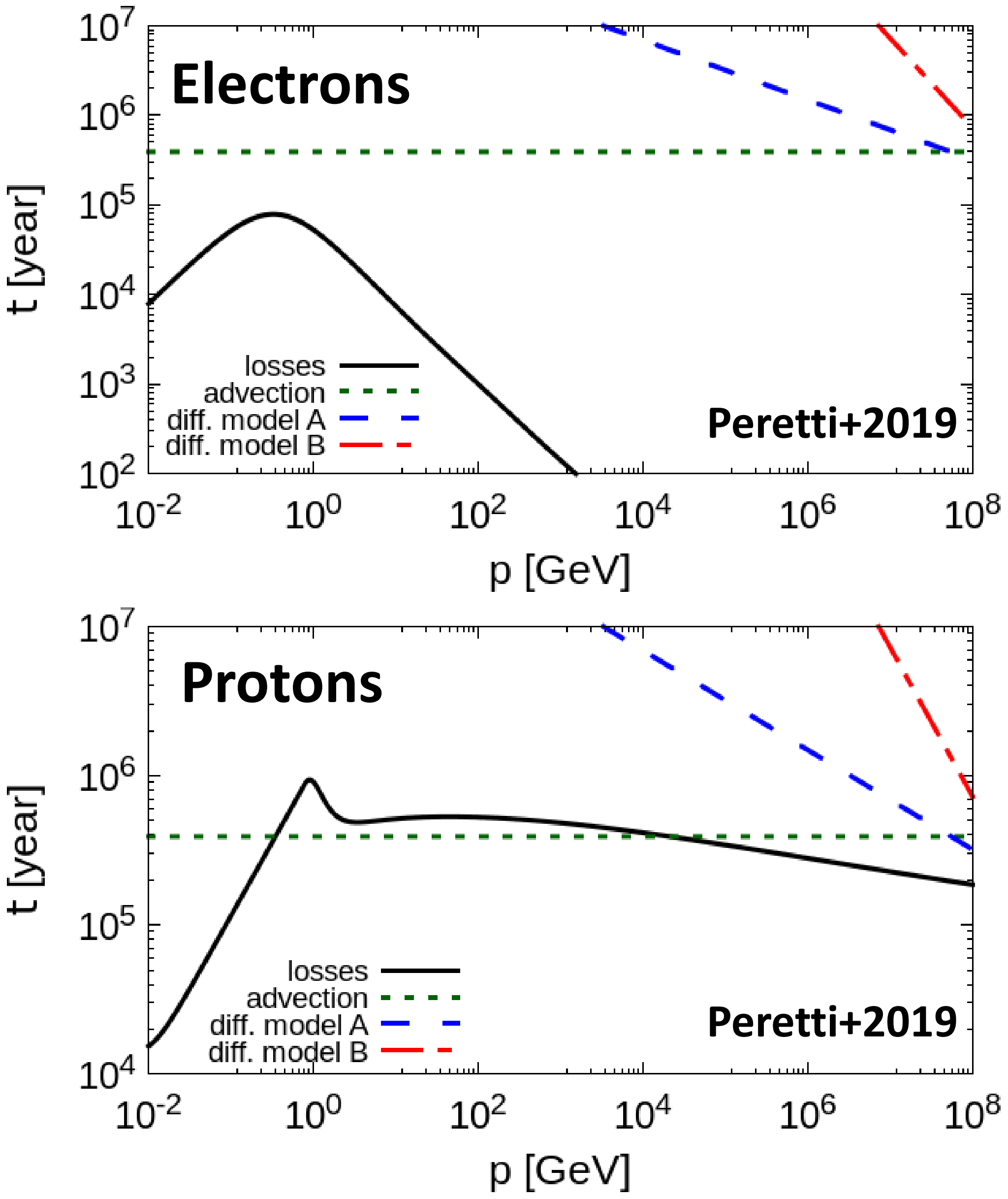
Modeling the transport in SBNi





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

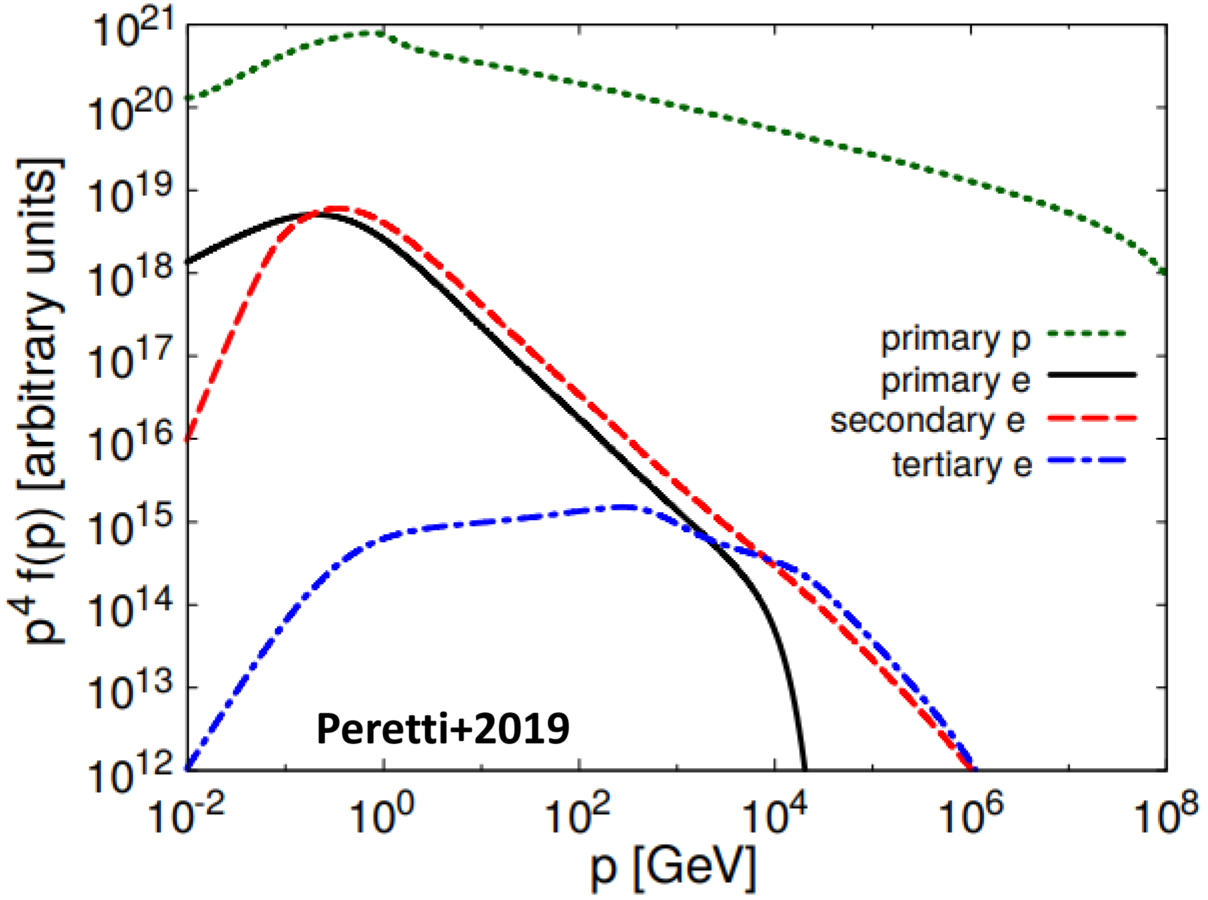
Modeling the transport in SBNi

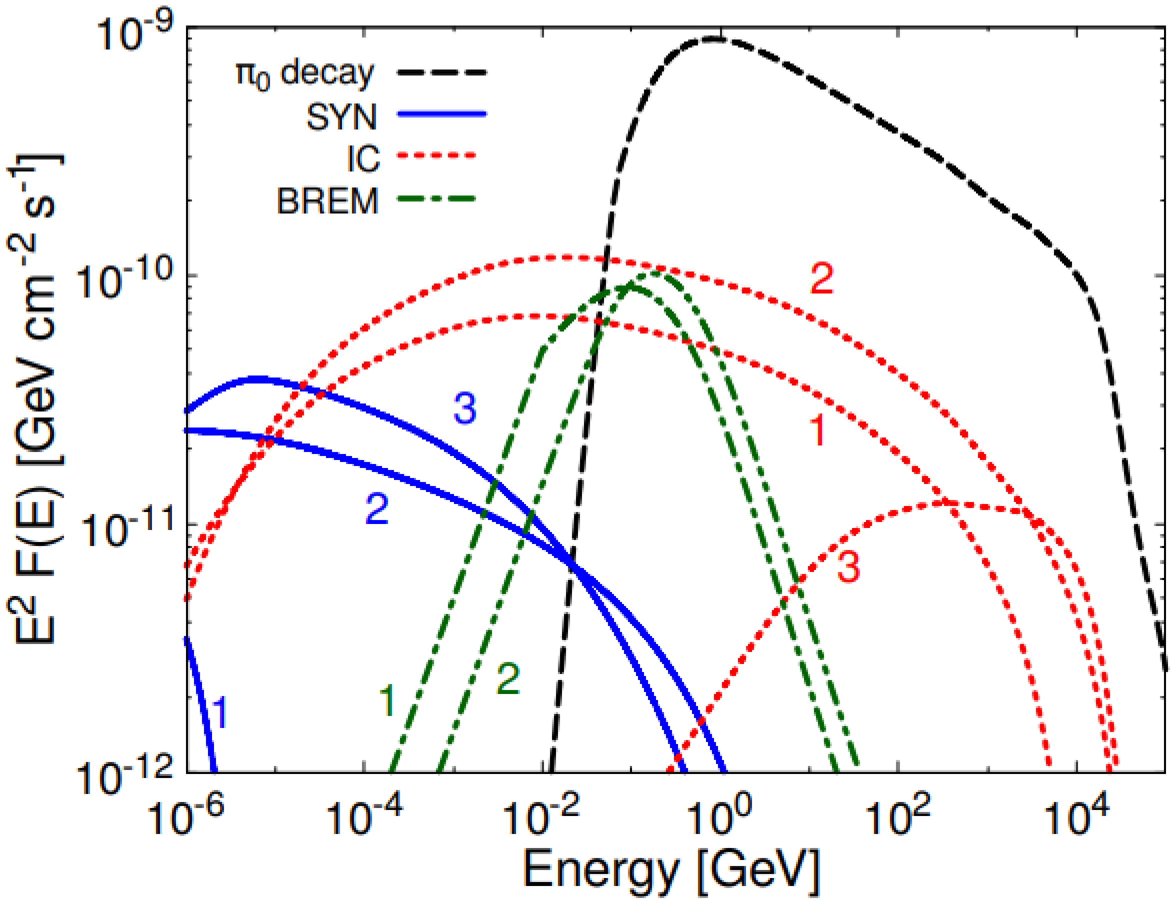


- Electrons are confined in SBNi
- Advection and losses regulate the transport of protons
- Particles experience all phases of the ISM

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

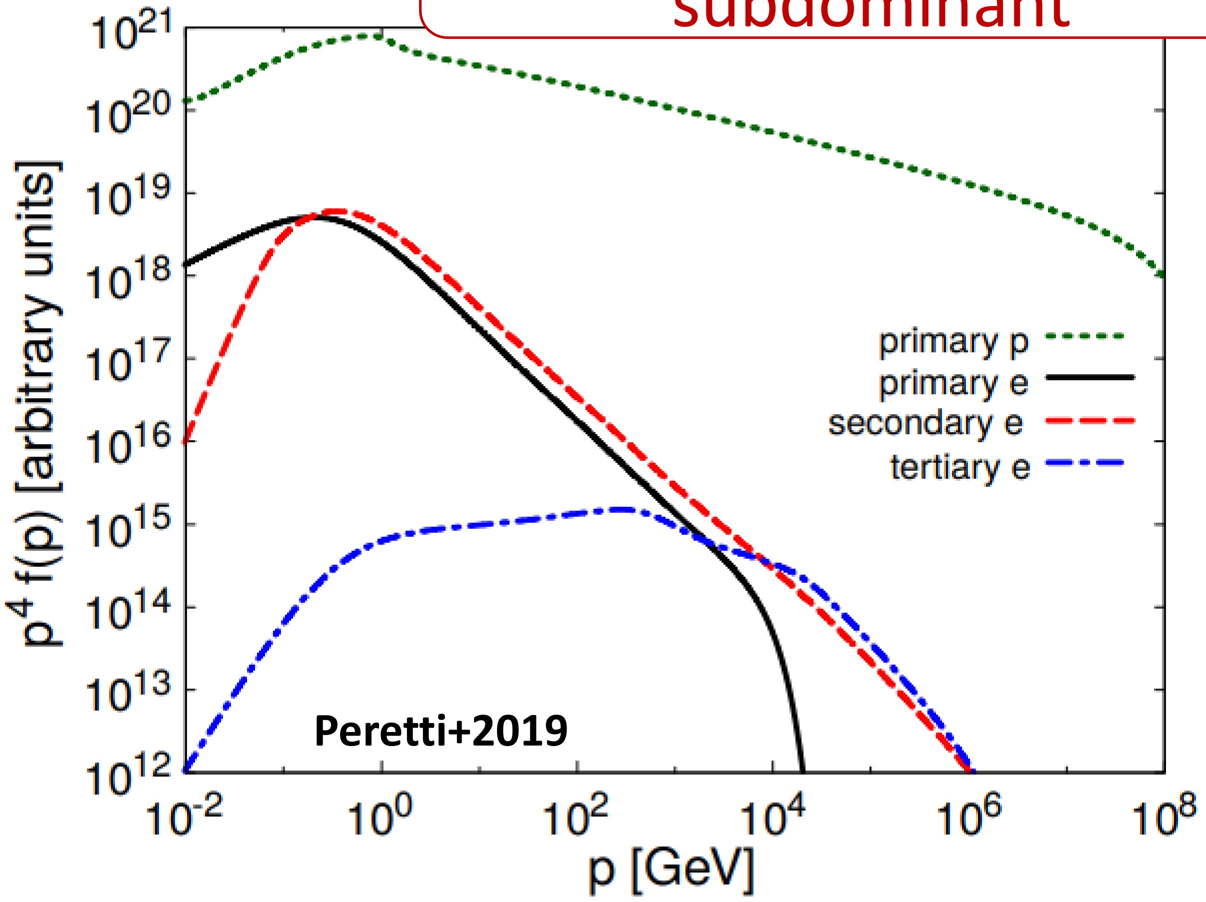
Particle and photon spectra in SBNi

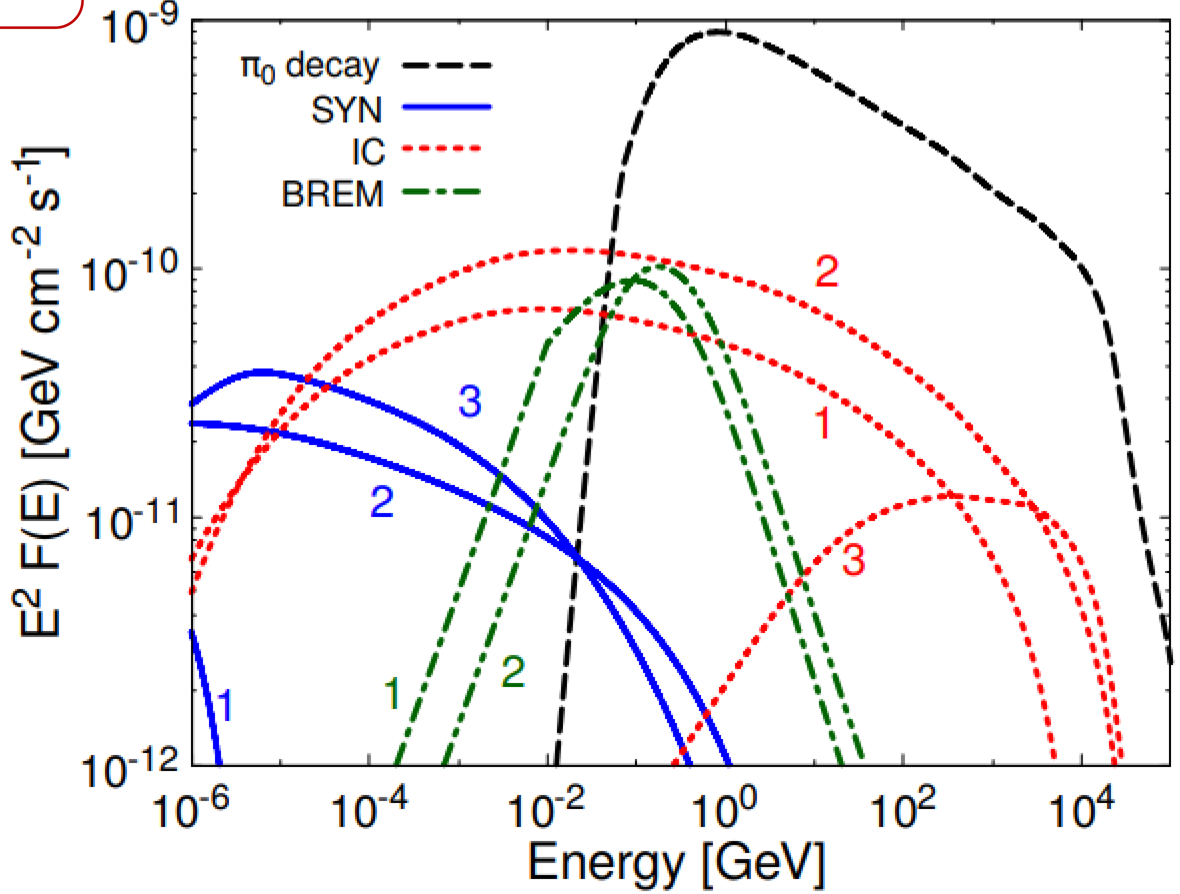




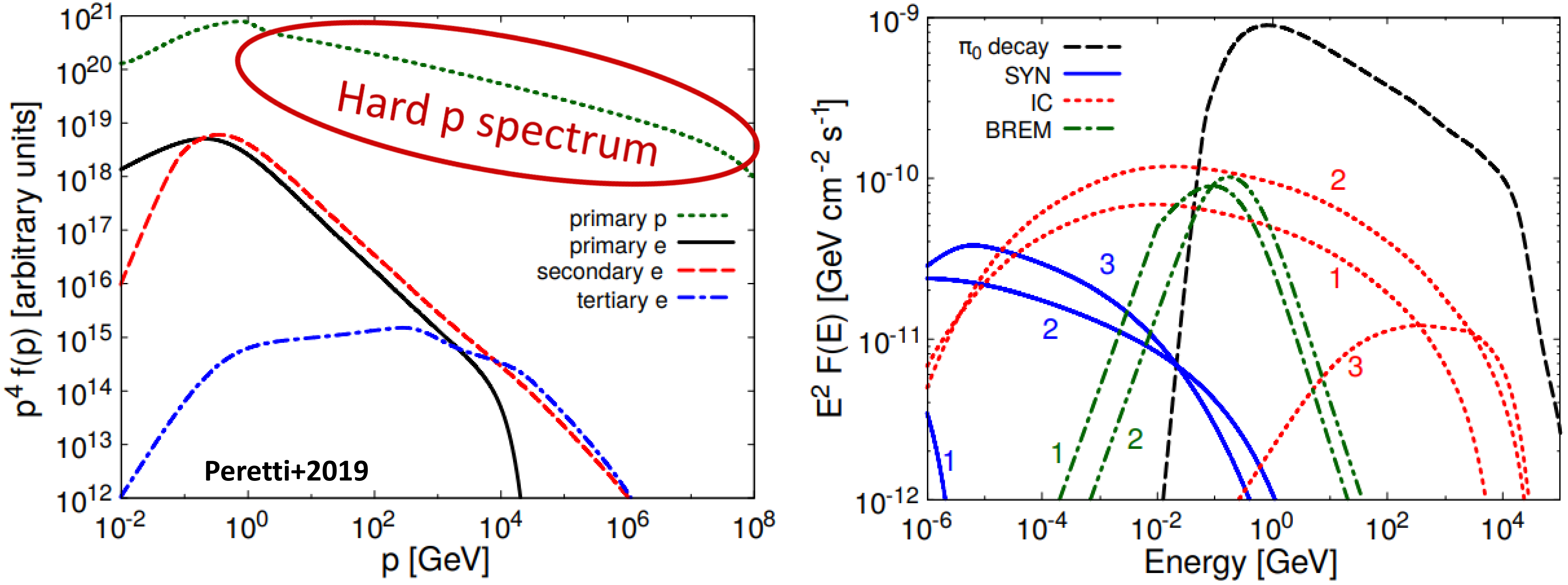
Particle and photon spectra in SBNi

Particle diffusion is subdominant

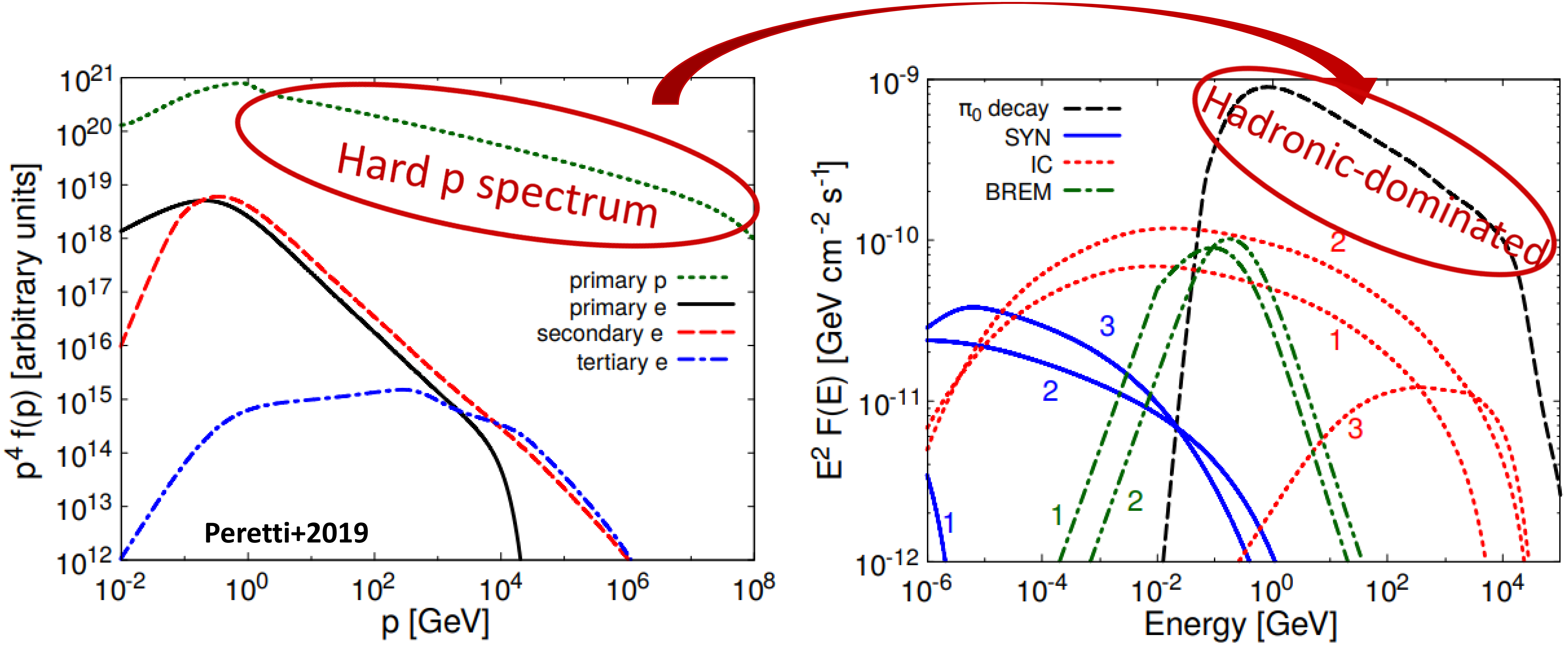




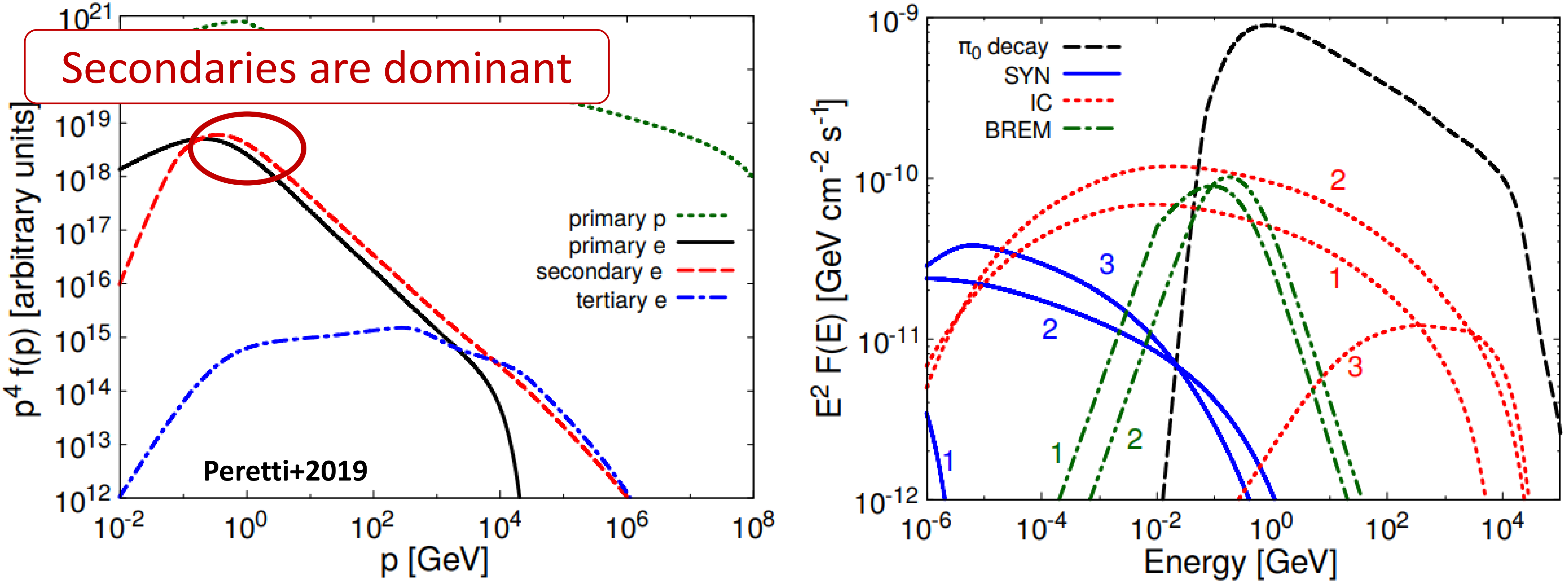
Particle and photon spectra in SBNi



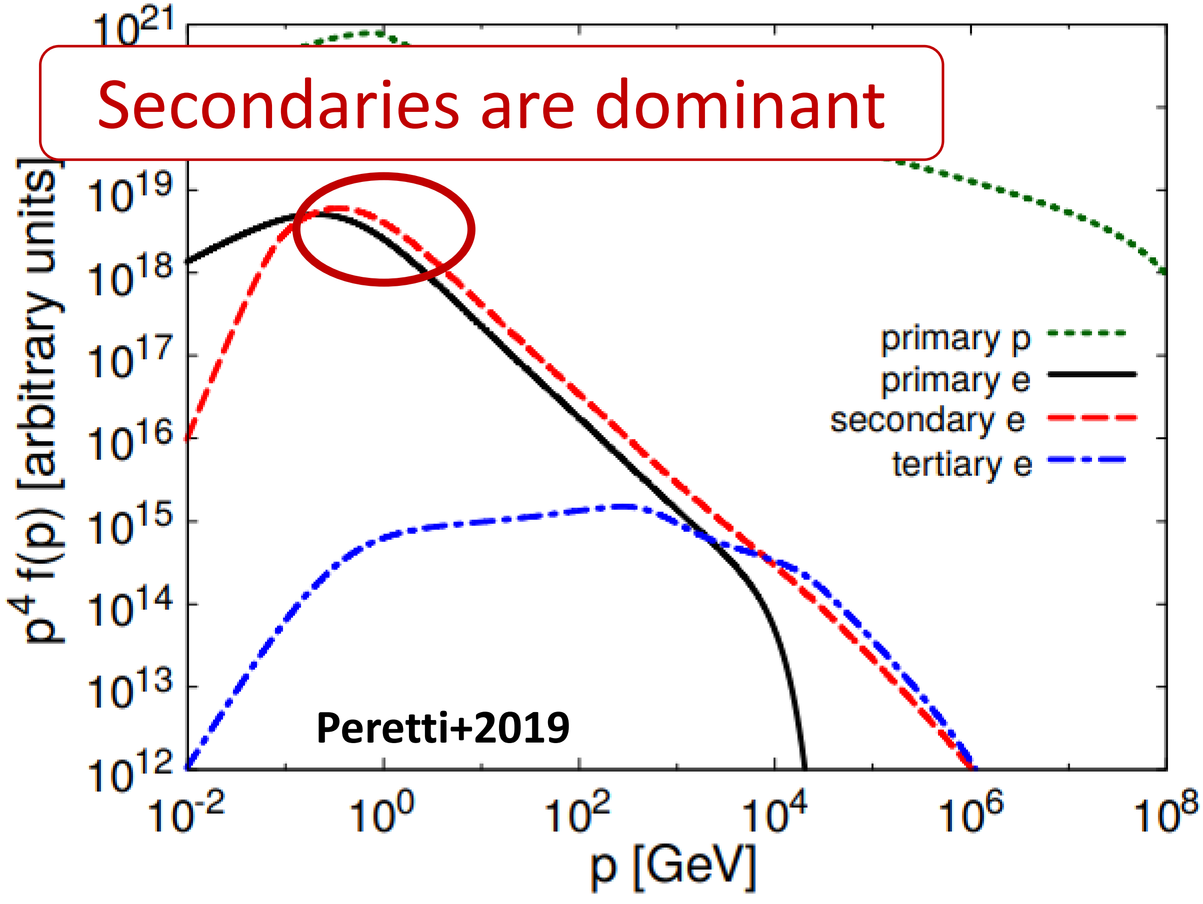
Particle and photon spectra in SBNi

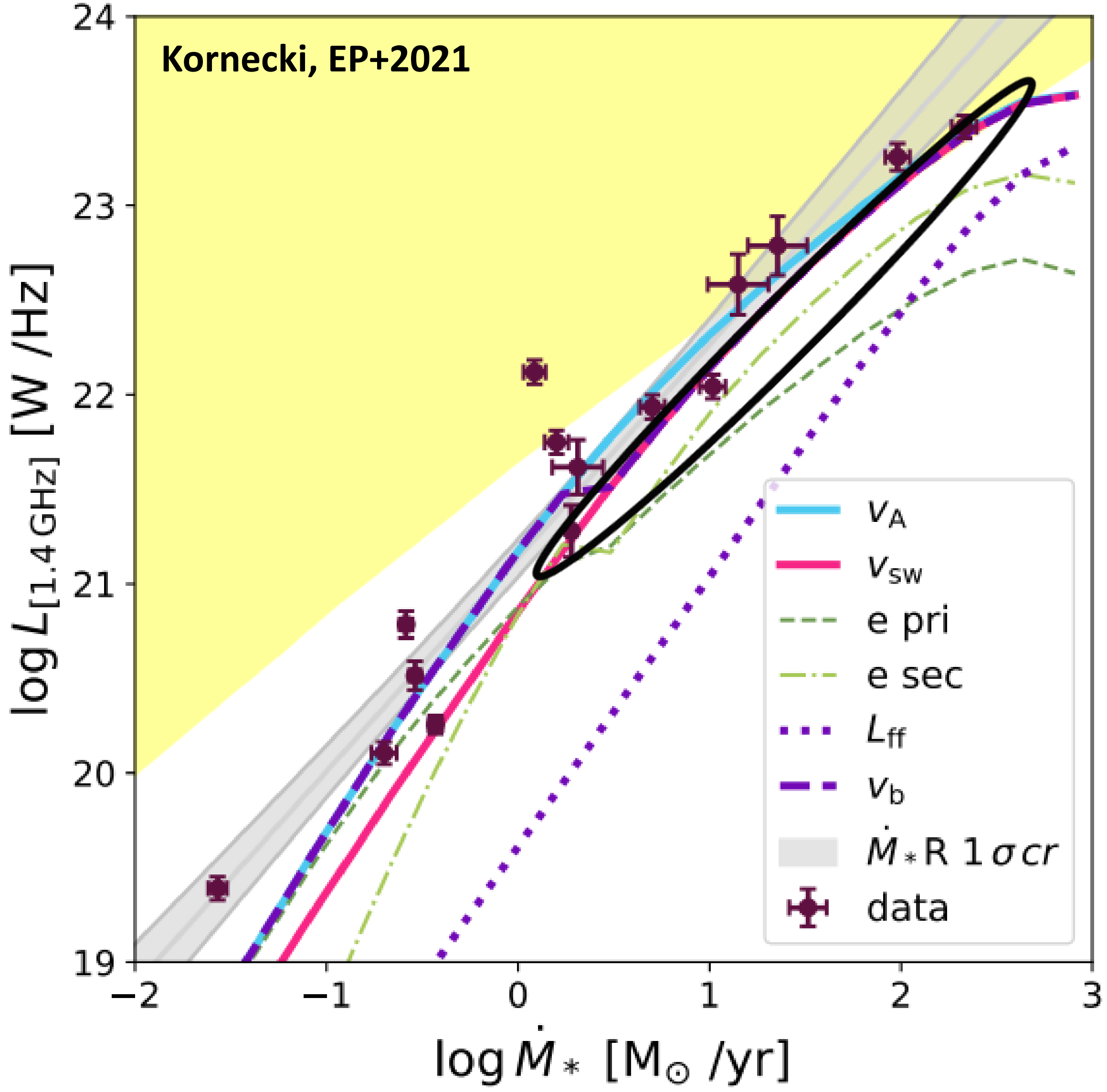


Particle and photon spectra in SBNi

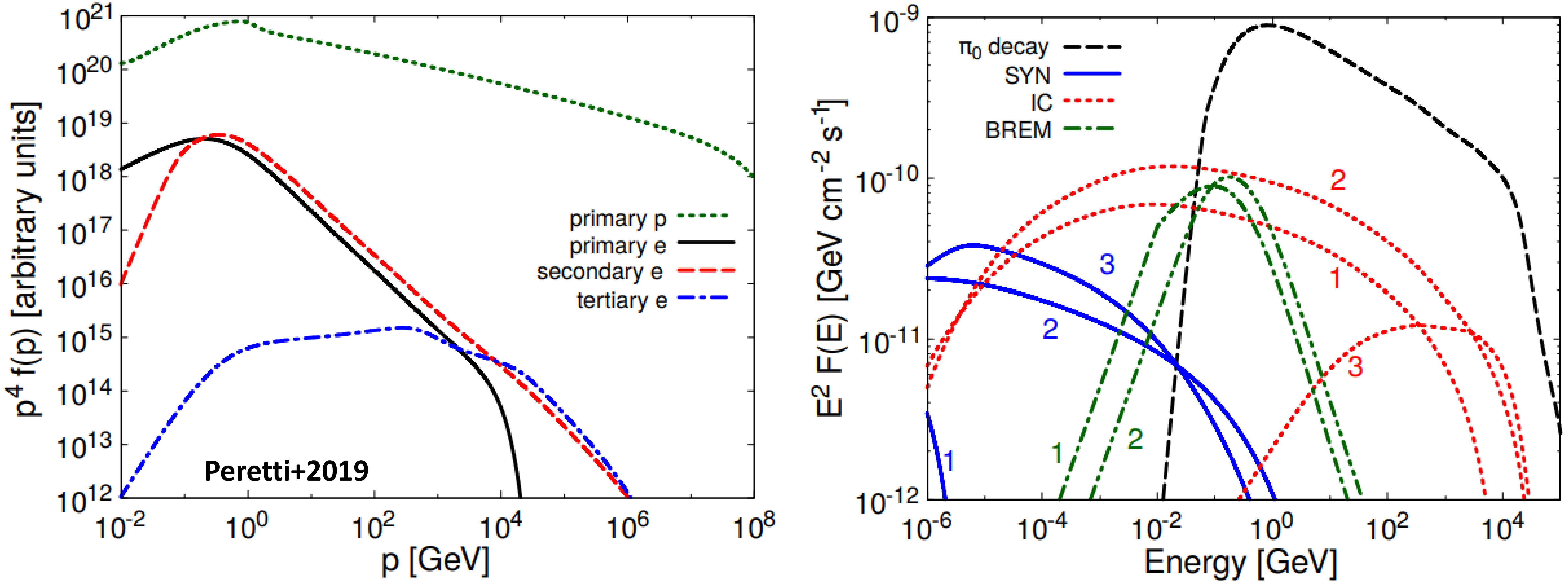


Particle and photon spectra in SBNi

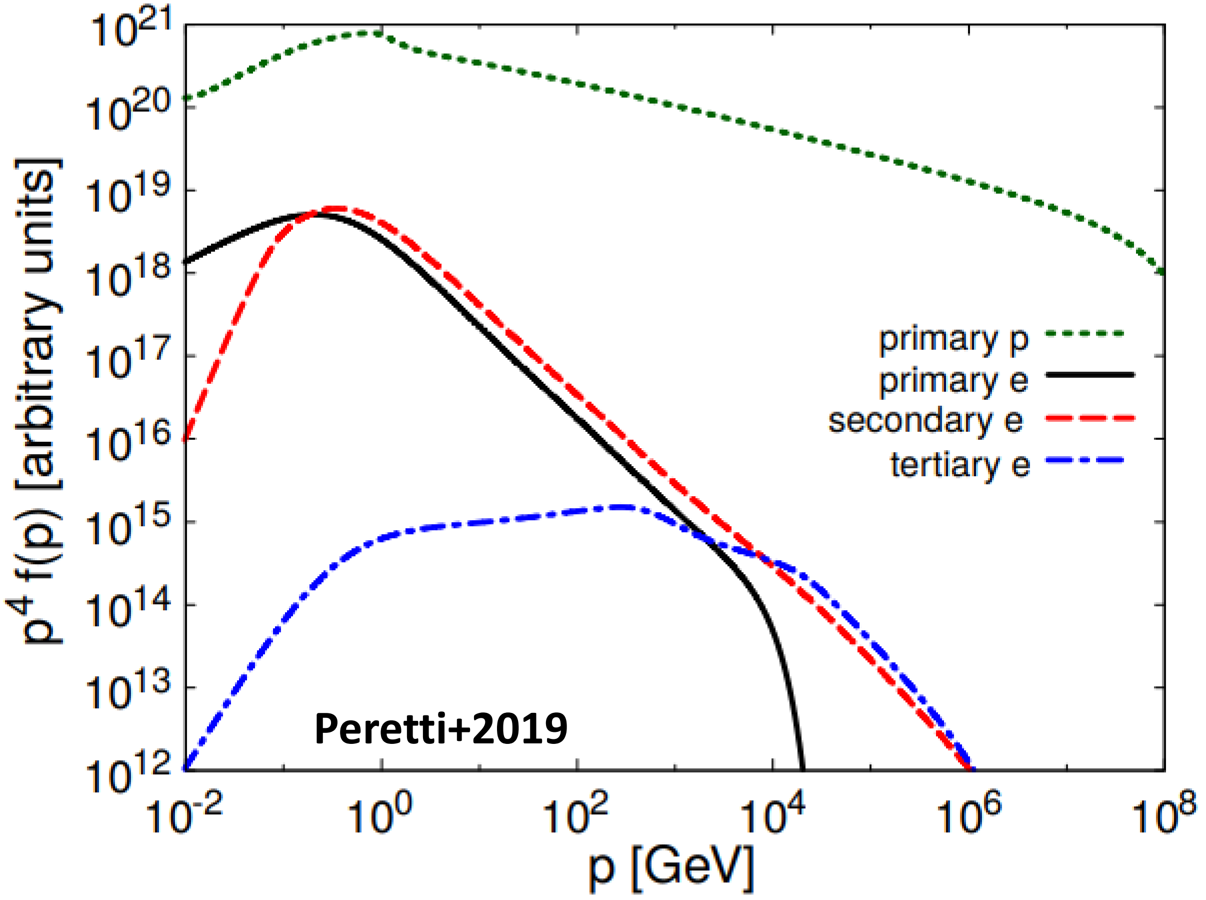


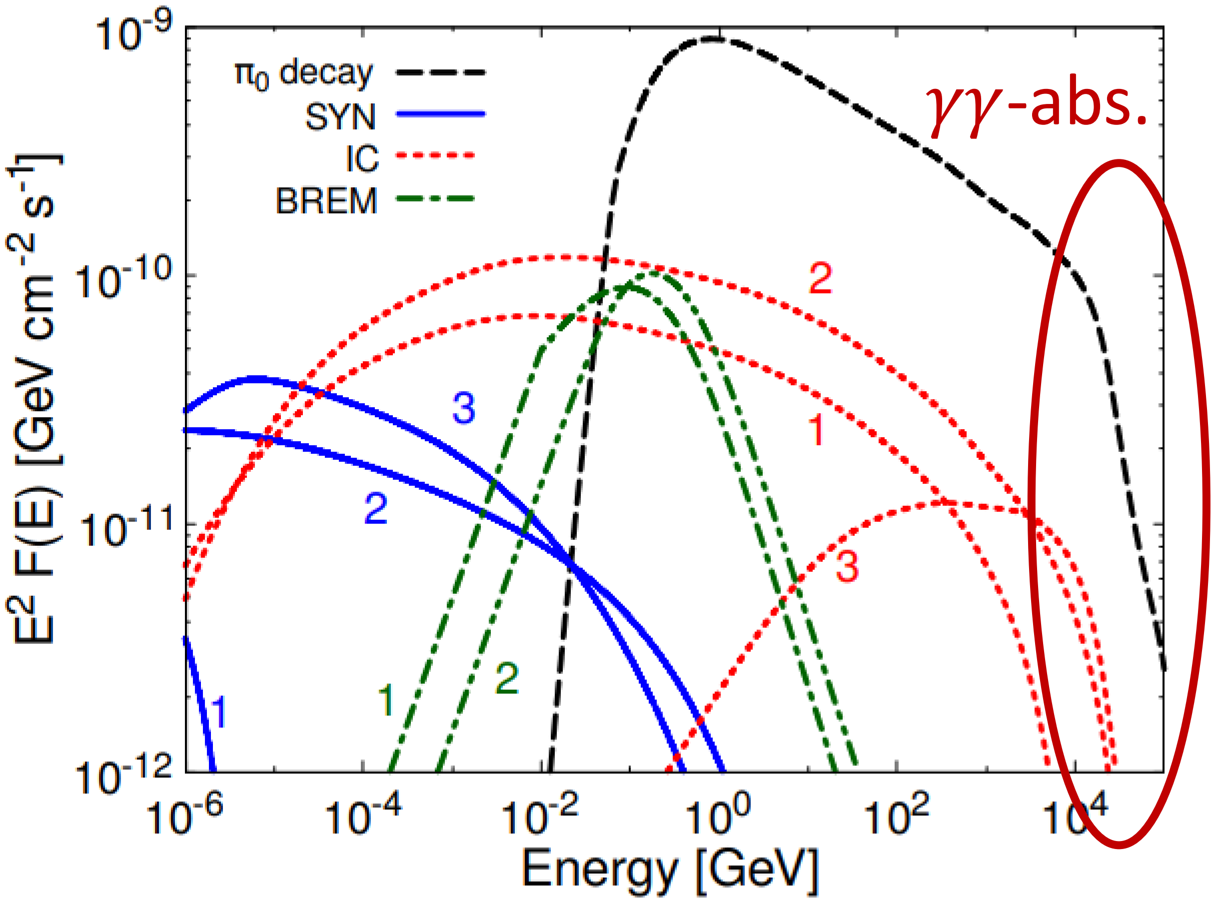


Particle and photon spectra in SBNi

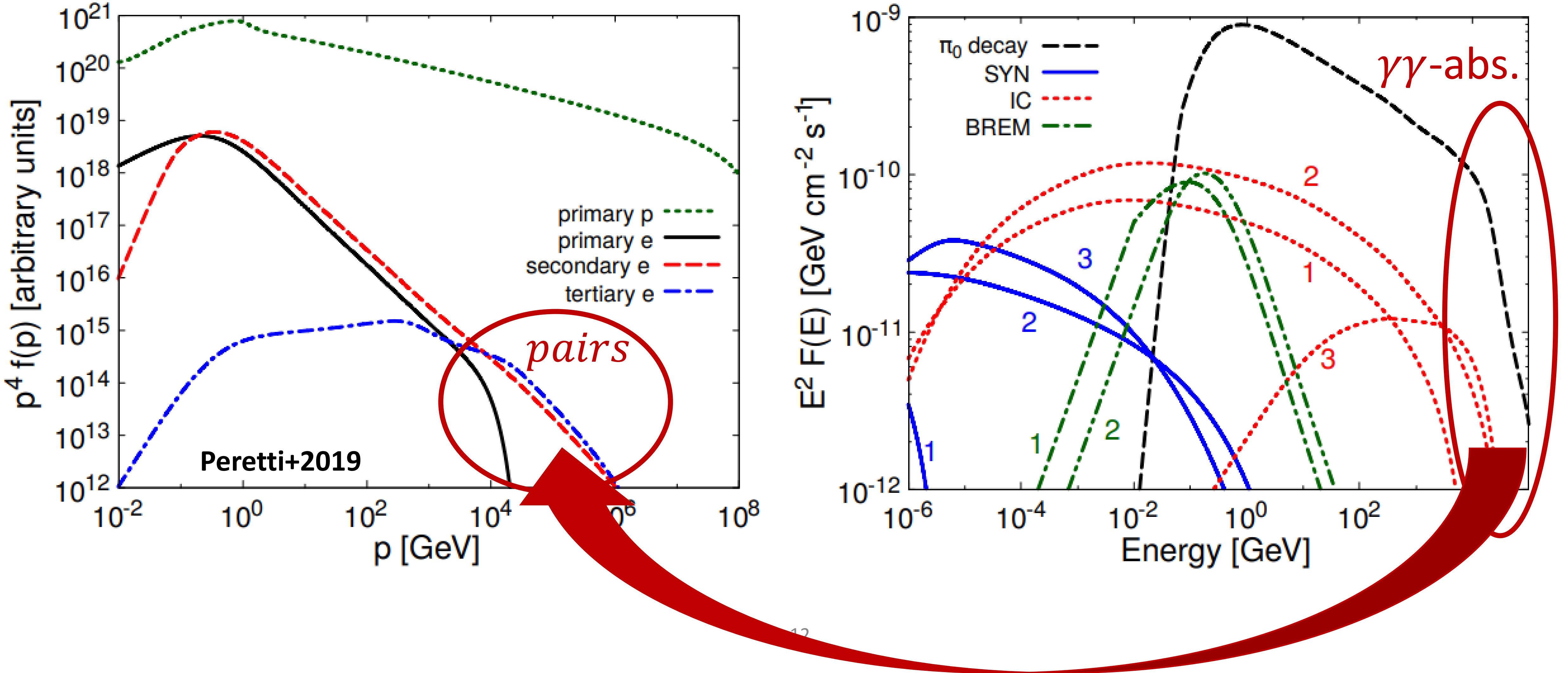


Particle and photon spectra in SBNi

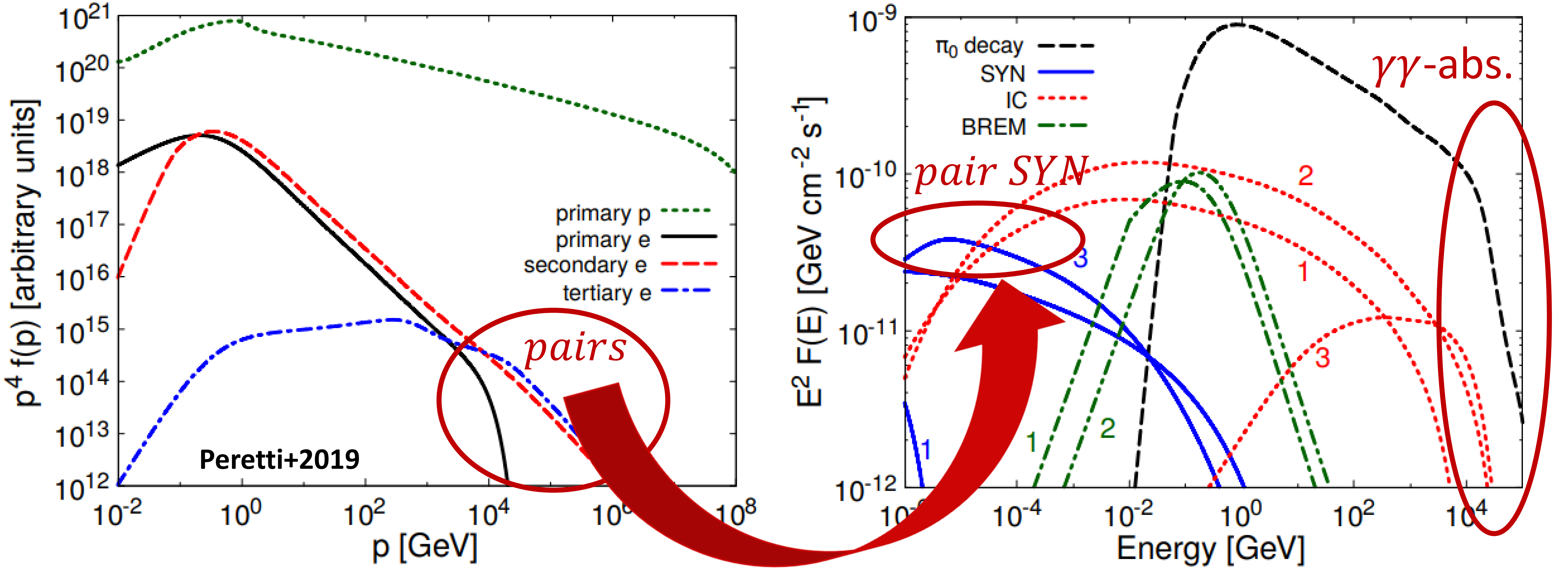




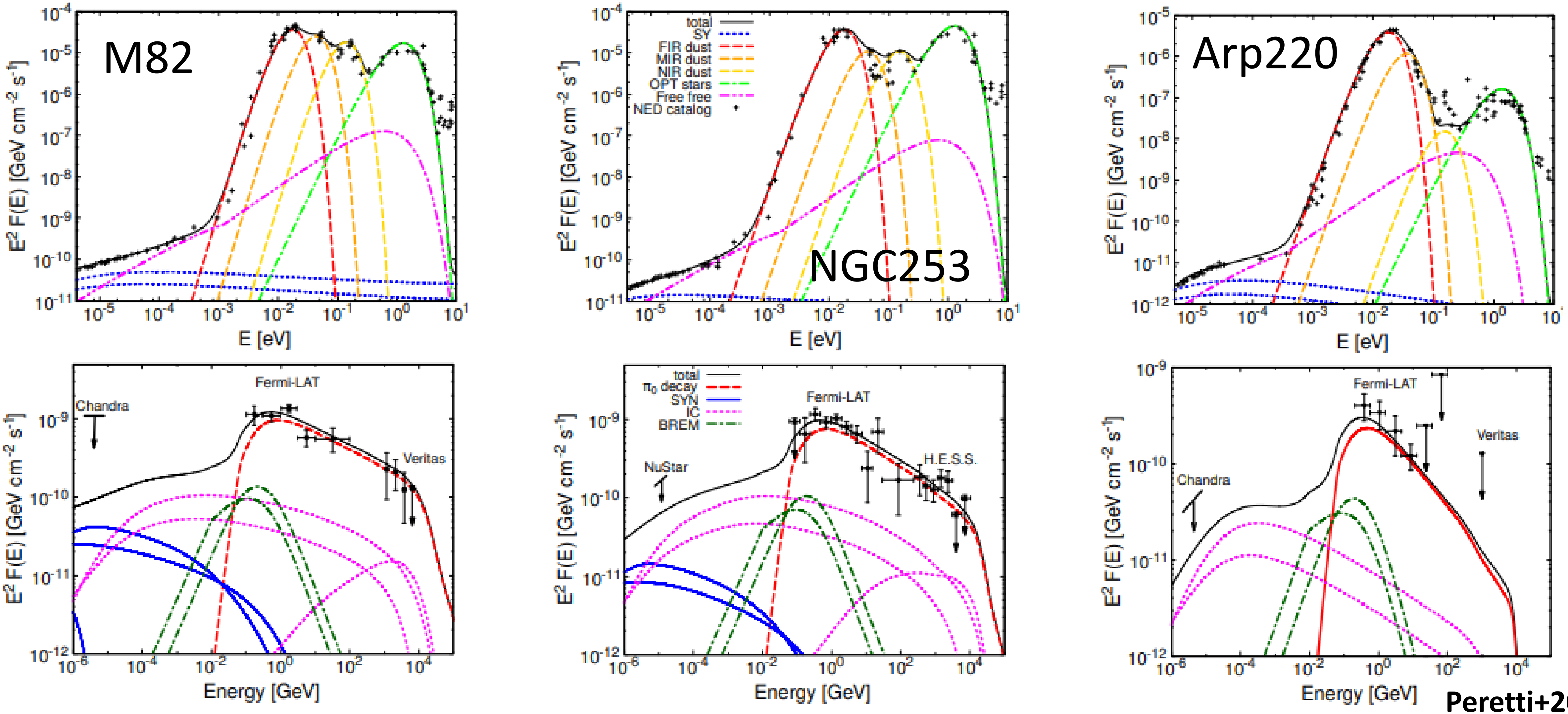
Particle and photon spectra in SBNi



Particle and photon spectra in SBNi

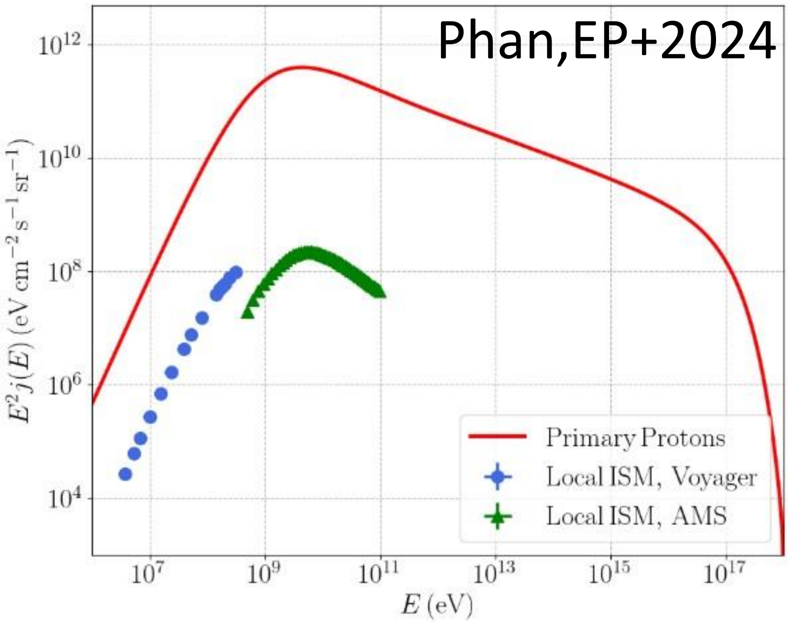


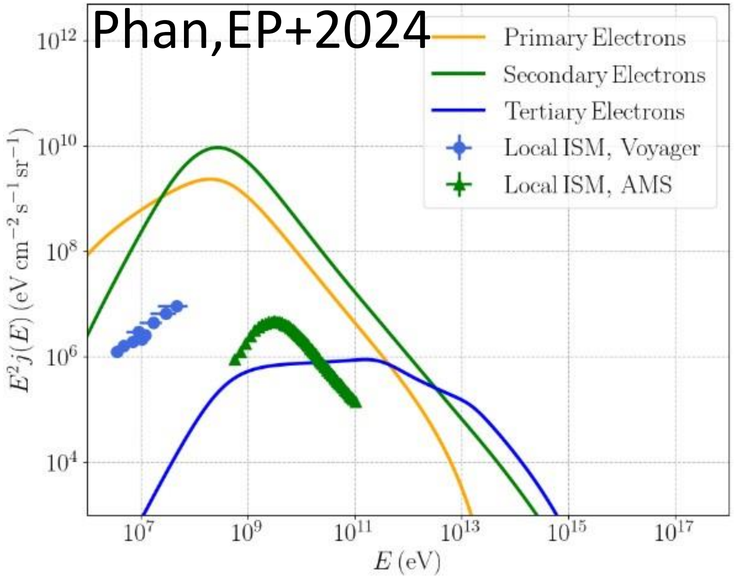
Modeling nearby SBGs



Peretti+2019

Cosmic rays in Starbursts vs Milky Way





- Cosmic-ray density in starburst is orders of magnitude larger than in our Galaxy

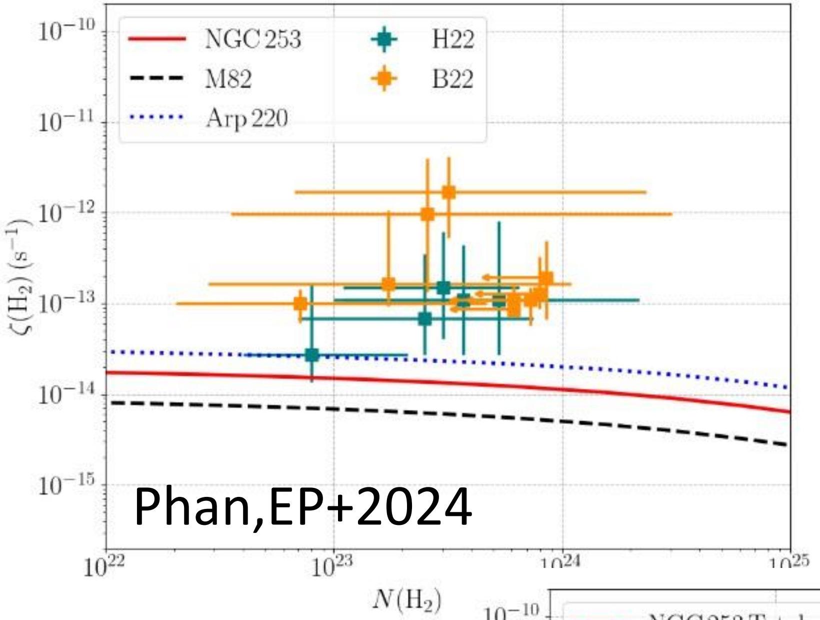
$N(H_2)$ (cm^{-2})

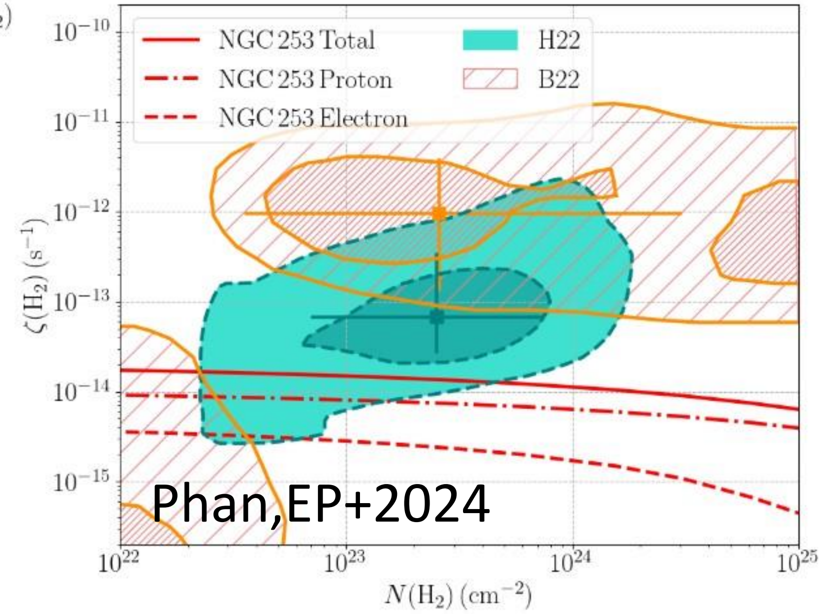
Ionization rate in starburst galaxies

- Cosmic-ray density in starburst is orders of magnitude larger than in our Galaxy

- The cosmic-ray induced ionization rate (H_3O^+, SO, HCN) while being «close» to observations appears sistematically smaller →

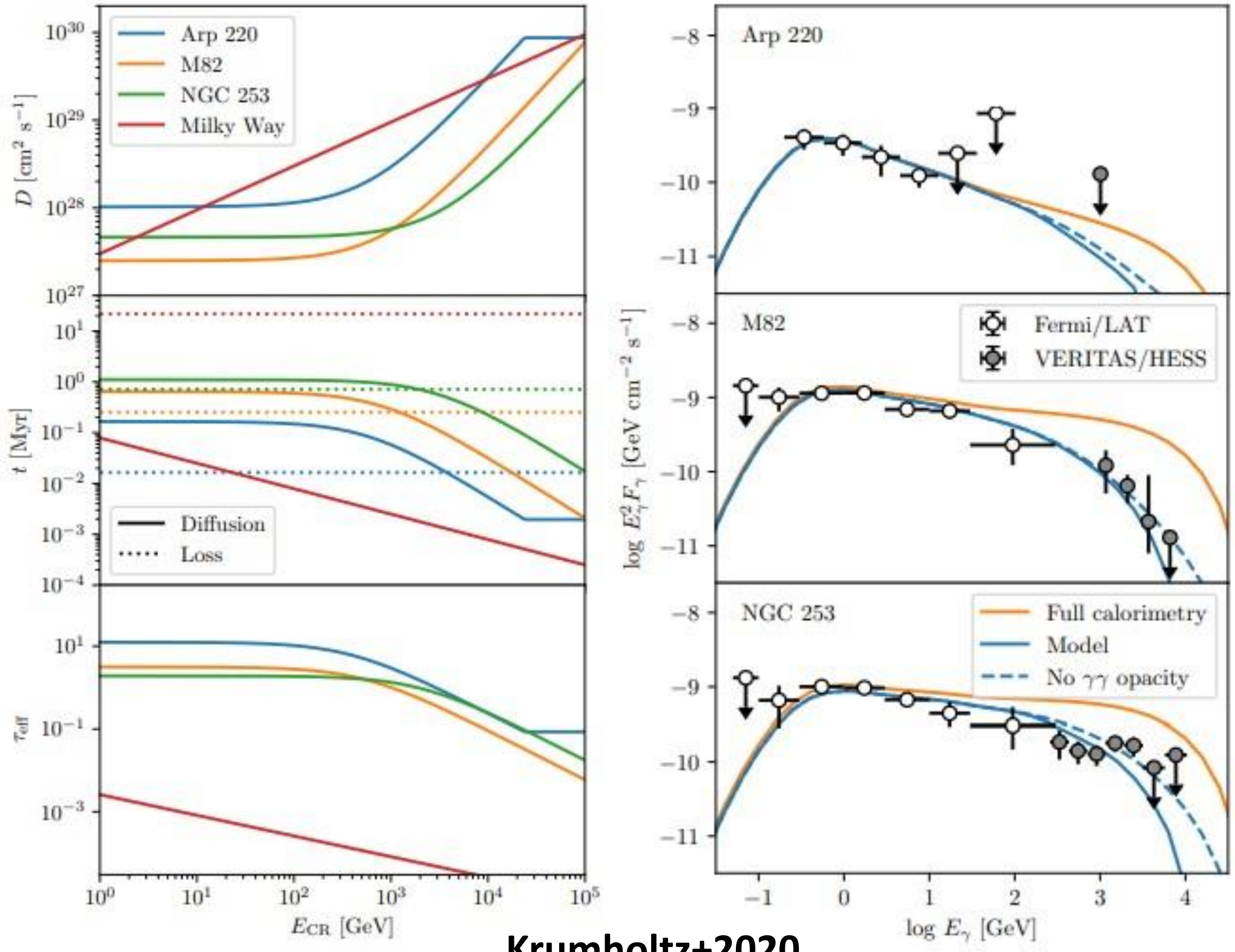
  1. One-zone model limitation
  2. Chem. model uncertainties
  3. Gas mass and rate of SNe
  4. Local sources of MeV CRs





Open questions in the TeV band for Starburst Galaxies

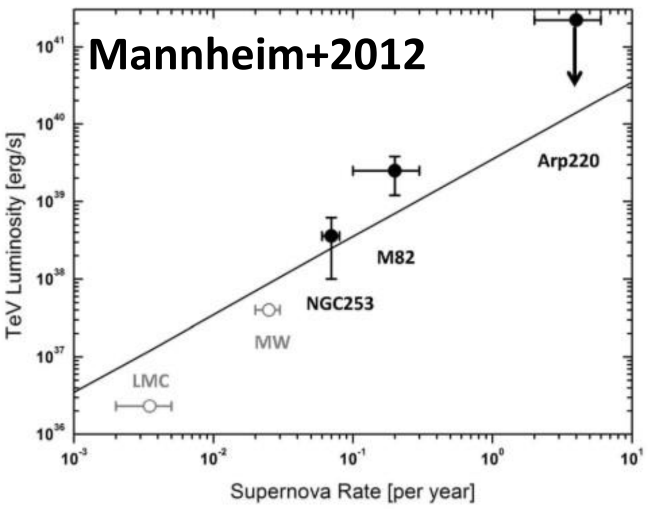
Microphysics

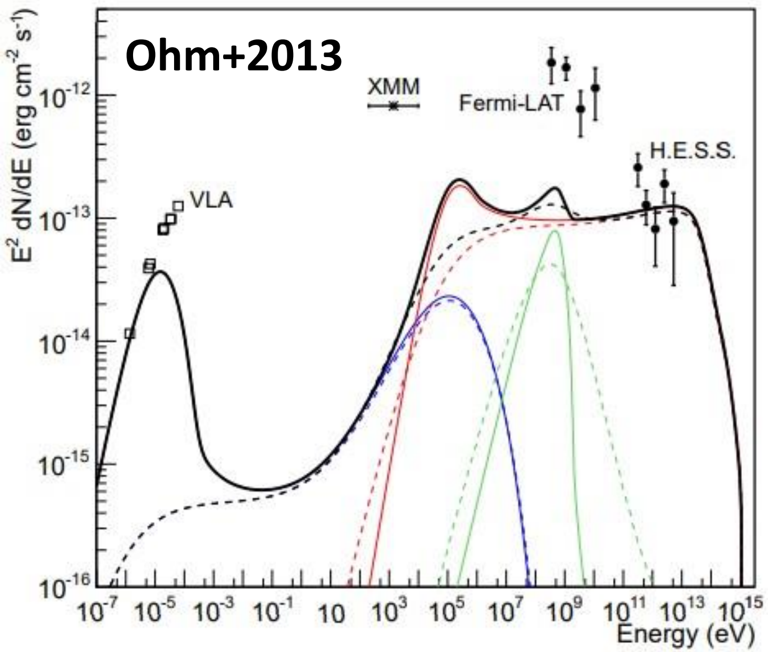


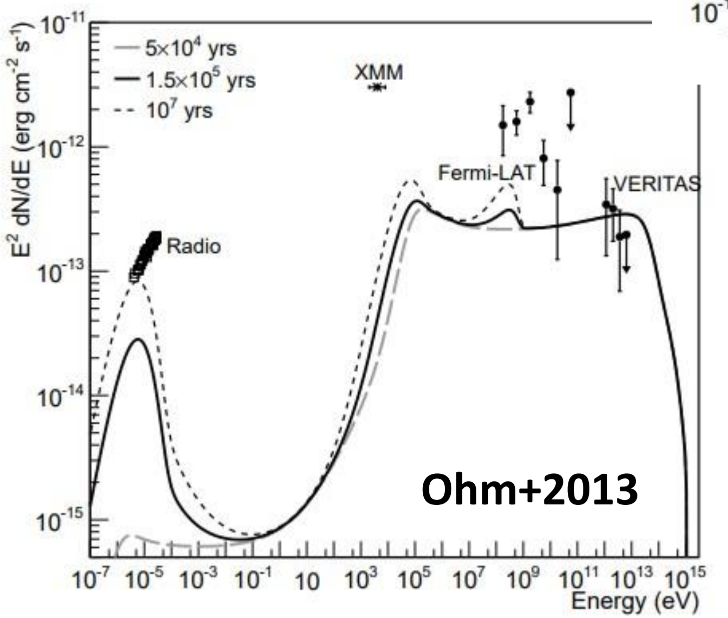
Krumholtz+2020

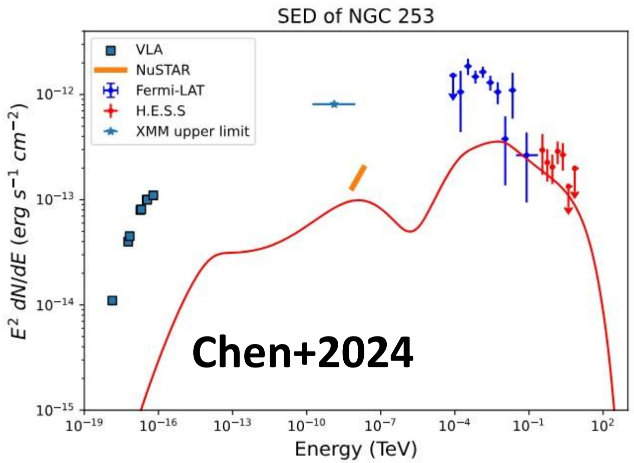
- The turbulence cascade might be suppressed by the ion-neutral damping
- In this scenario TeV particles are escaping efficiently

Pulsar wind nebulae and other pointlike sources





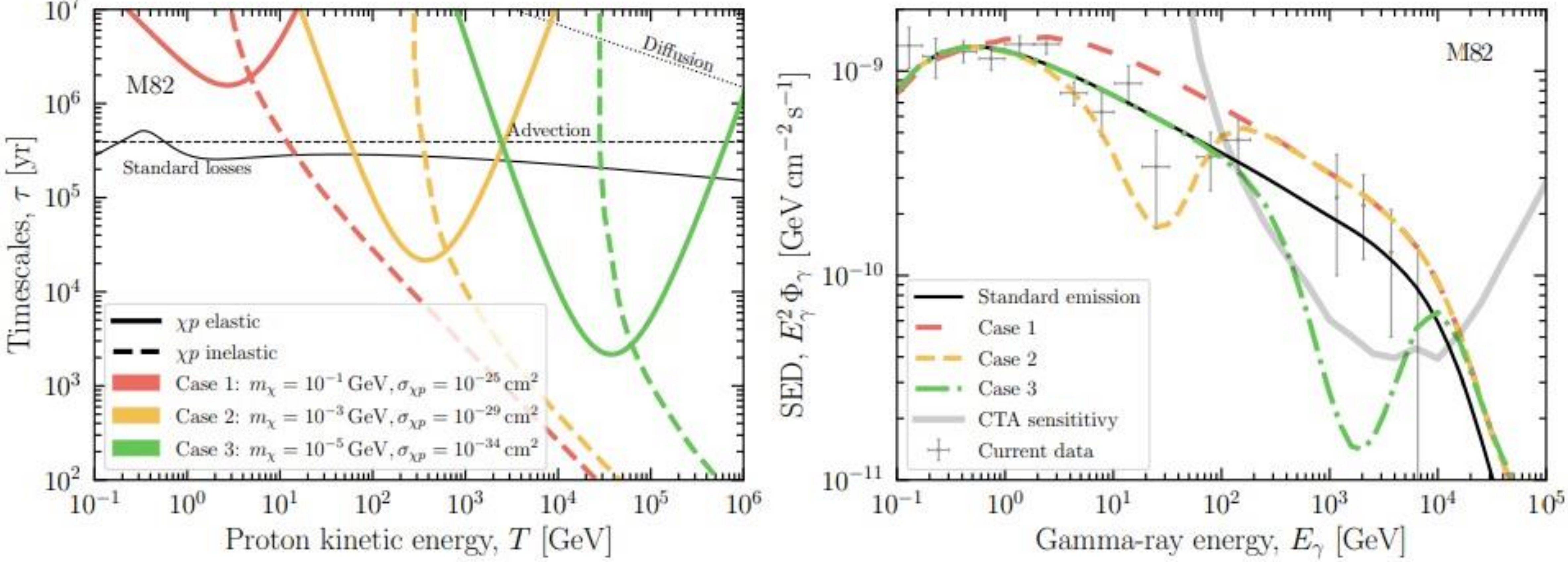




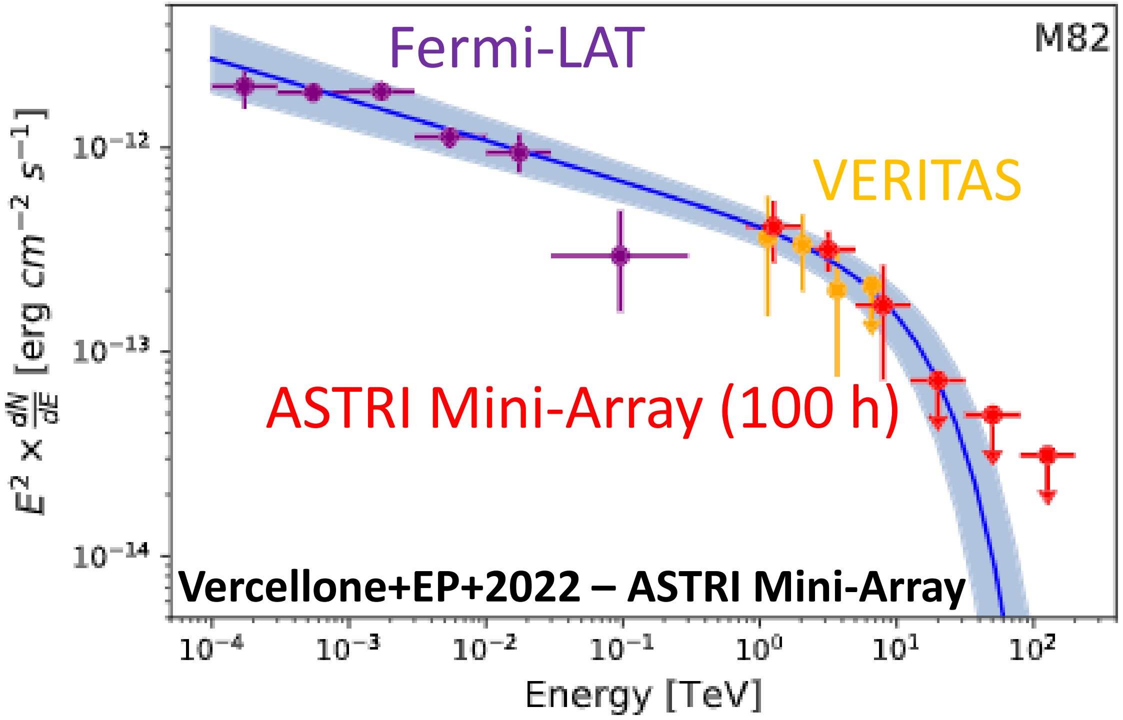
- The high supernova rate must necessarily result in a large number of emitting pulsar wind nebulae (PWNe)
- The PWNe emission could dominate the gamma-ray flux in the TeV band

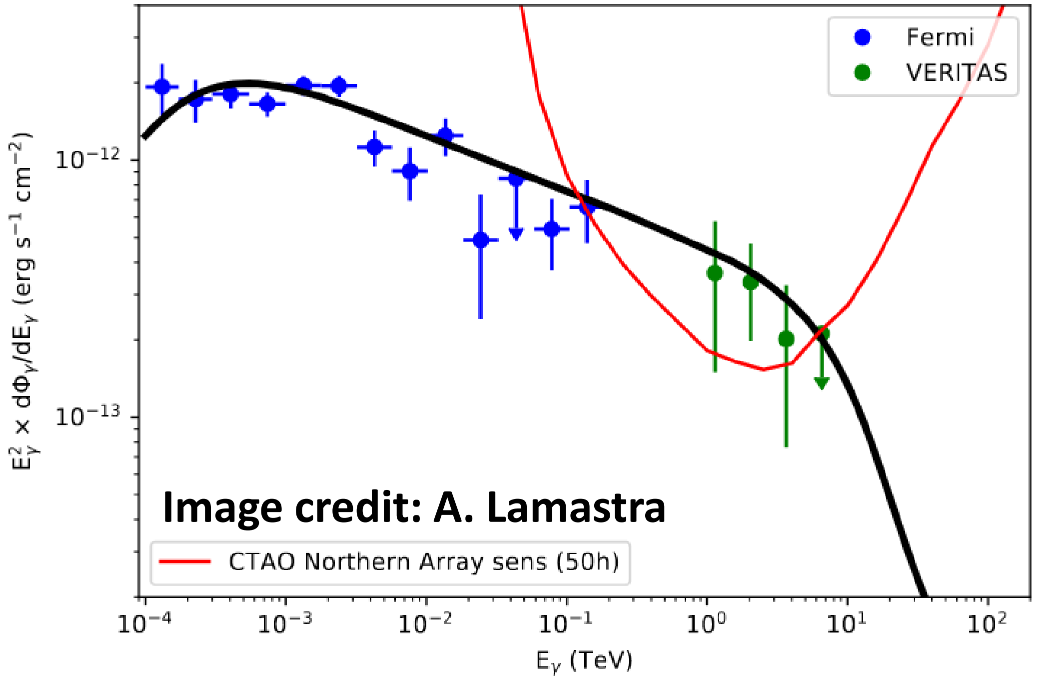
Constraining Dark Matter

Ambrosone+2023

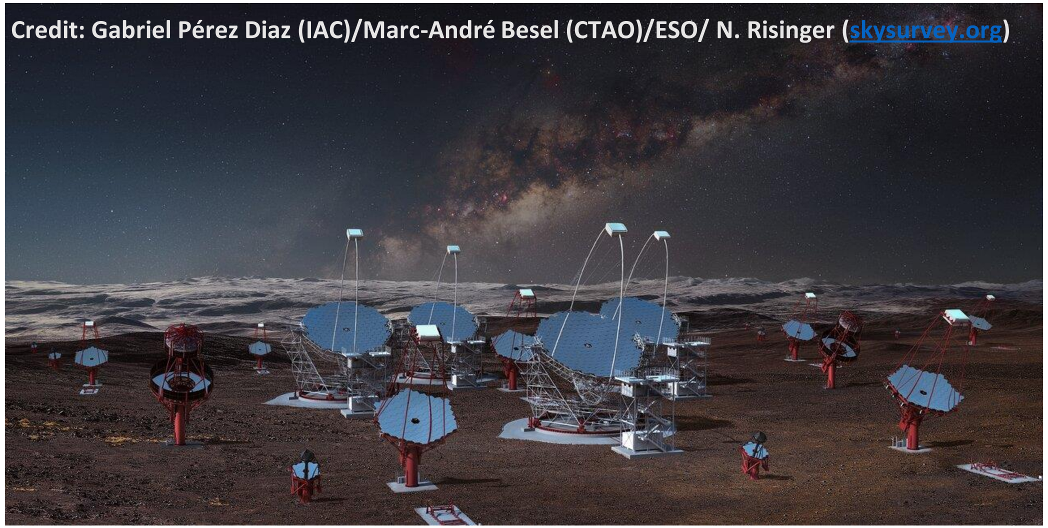


Upcoming gamma-ray observations

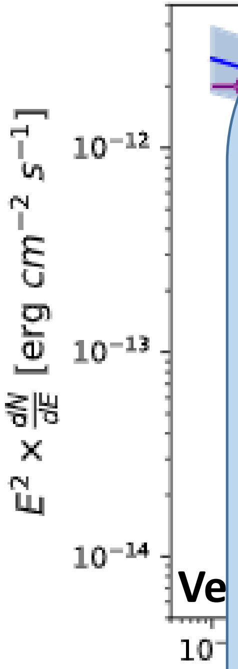




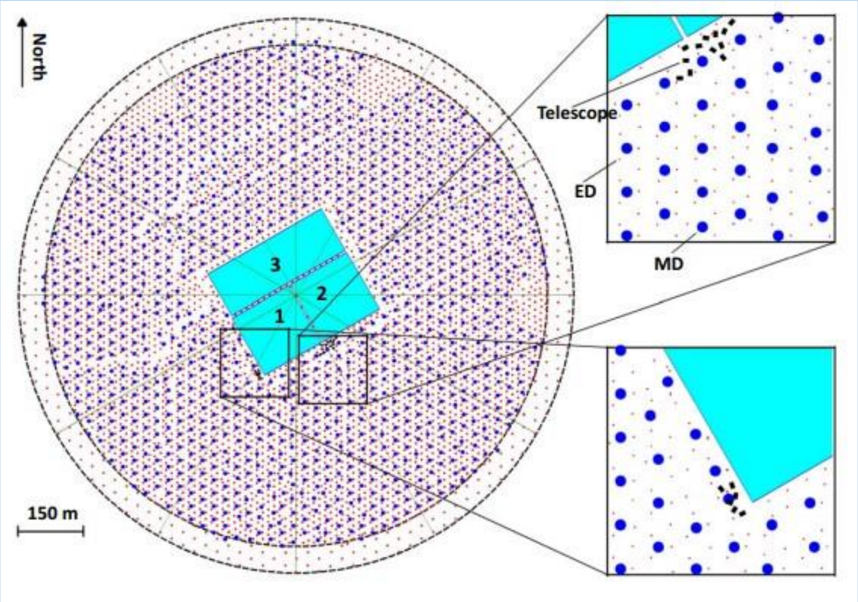
Credit: Astri/Inaf



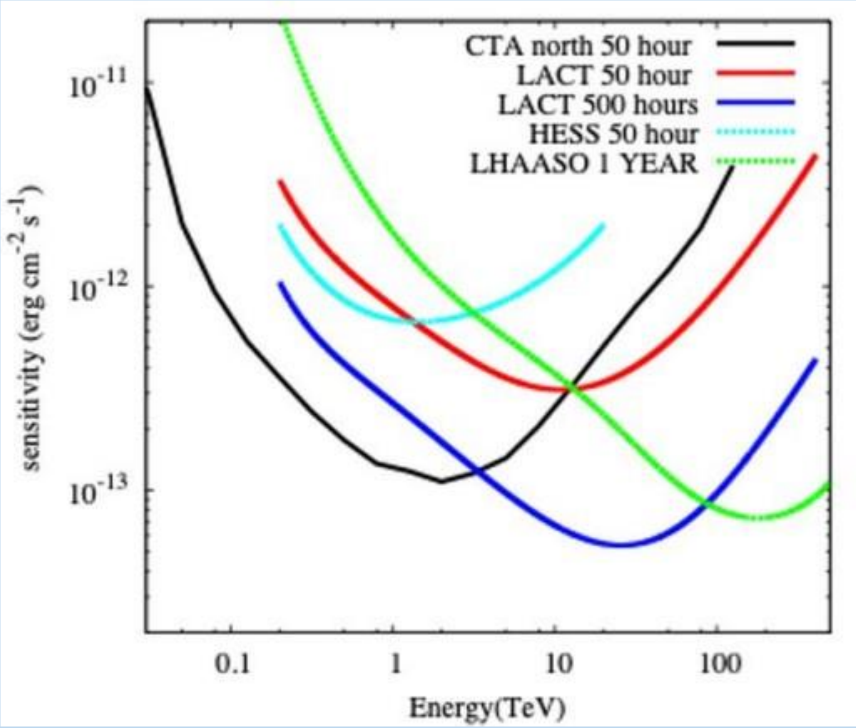
Upcoming gamma-ray observations



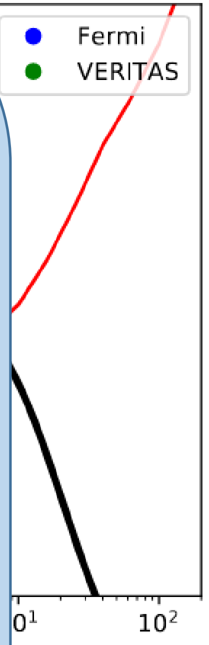
LHAASO and LACT



Aharonian+2021

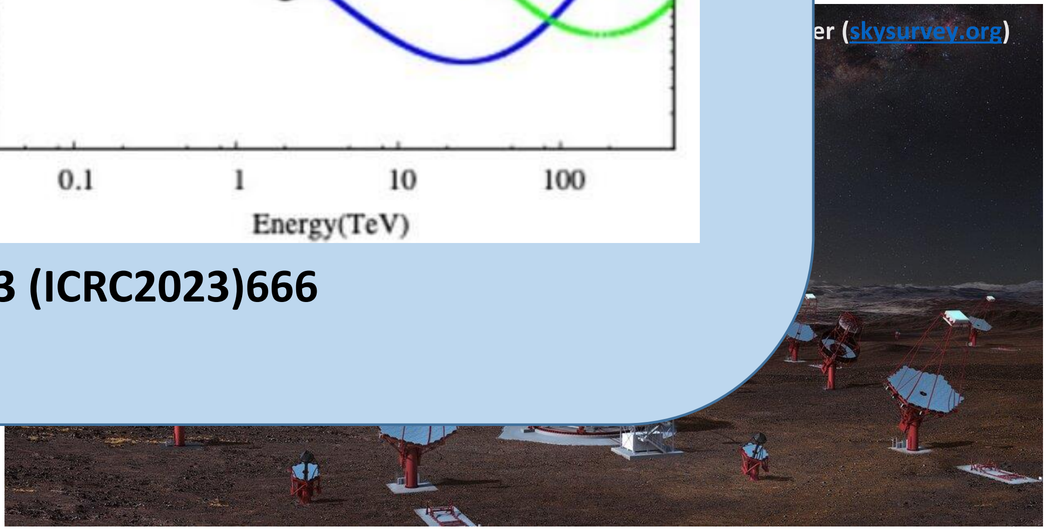


Li+2023 (ICRC2023)666



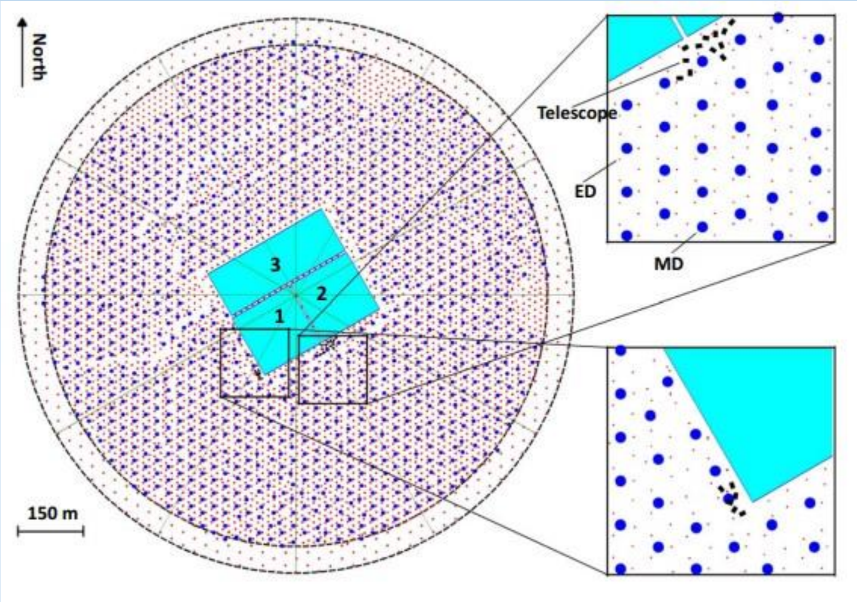
er (skysurvey.org)

Credit: Astri/Inaf

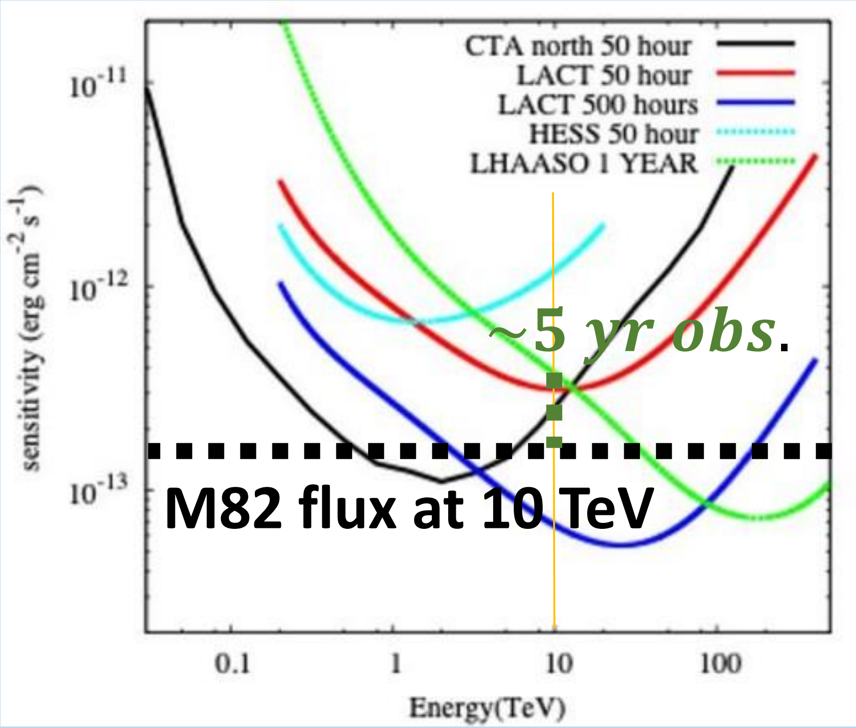


Upcoming gamma-ray observations

LHAASO and LACT

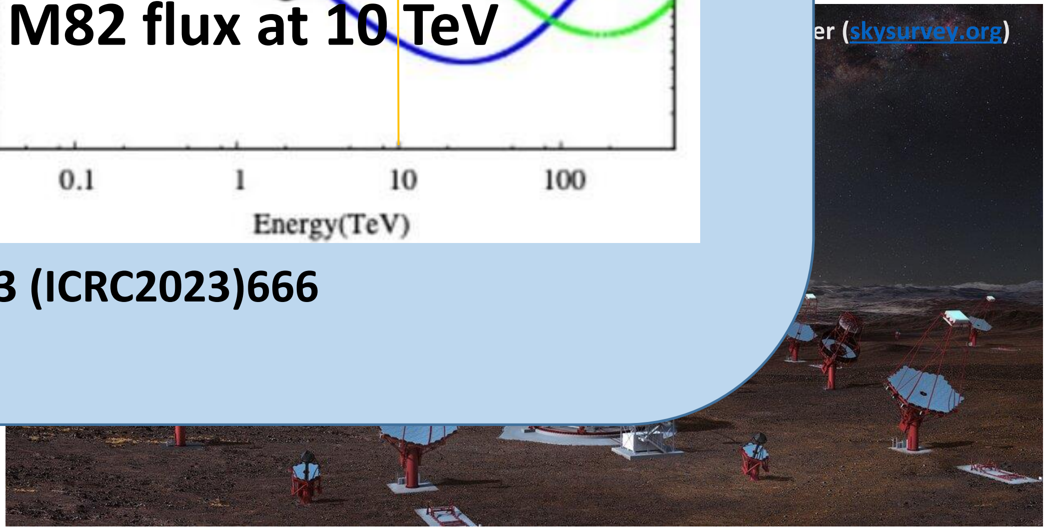


Aharonian+2021



Li+2023 (ICRC2023)666

Credit: Astri/Inaf



Outline

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

Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

Powering a starburst wind

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

Powering a starburst wind

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

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

Powering a starburst wind

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

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

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

Powering a starburst wind

SN power → $\dot{E}_{SN} = \mathcal{R}_{SN}\,\mathcal{E}_{SN} = 3.2\ \cdot 10^{42}\,\mathcal{r}_2\,SFR_1\,\mathcal{E}_{SN,51}\,erg\ s^{-1}$

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

Powering a starburst wind

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

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

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

Powering a starburst wind

SN power → $\dot{E}_{SN} = \mathcal{R}_{SN}\,\mathcal{E}_{SN} = 3.2\ \cdot 10^{42}\,\mathcal{r}_2\,SFR_1\,\mathcal{E}_{SN,51}\,erg\ s^{-1}$

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

Powering a starburst wind

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

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

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

Powering a starburst wind

SN power → $\dot{E}_{SN} = \mathcal{R}_{SN}\, \mathcal{E}_{SN} = 3.2 \cdot$

Letter | Published: 05 September 1985

Wind from a starburst galaxy nucleus

R. A. Chevalier & A. W. Clegg

Nature **317**, 44–45 (1985) | Cite this article

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

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

Powering a starburst wind

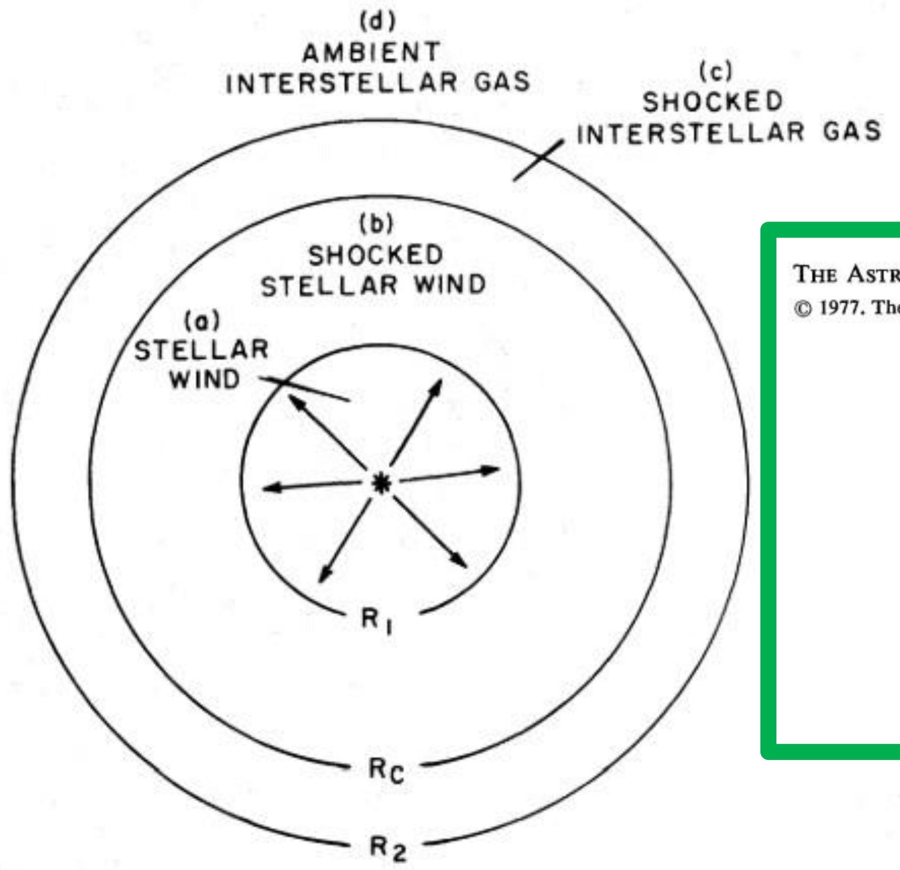
SN power → $\dot{E}_{SN} = \mathcal{R}_{SN}\,\mathcal{E}_{SN} = 3.2 \cdot$

Letter | Published: 05 September 1985

Wind from a starburst galaxy nucleus

R. A. Chevalier & A. W. Clegg

Nature **317**, 44–45 (1985) | Cite this article



$\dot{E}$ ... $\dot{E}$

THE ASTROPHYSICAL JOURNAL, **218**:377–395, 1977 December 1

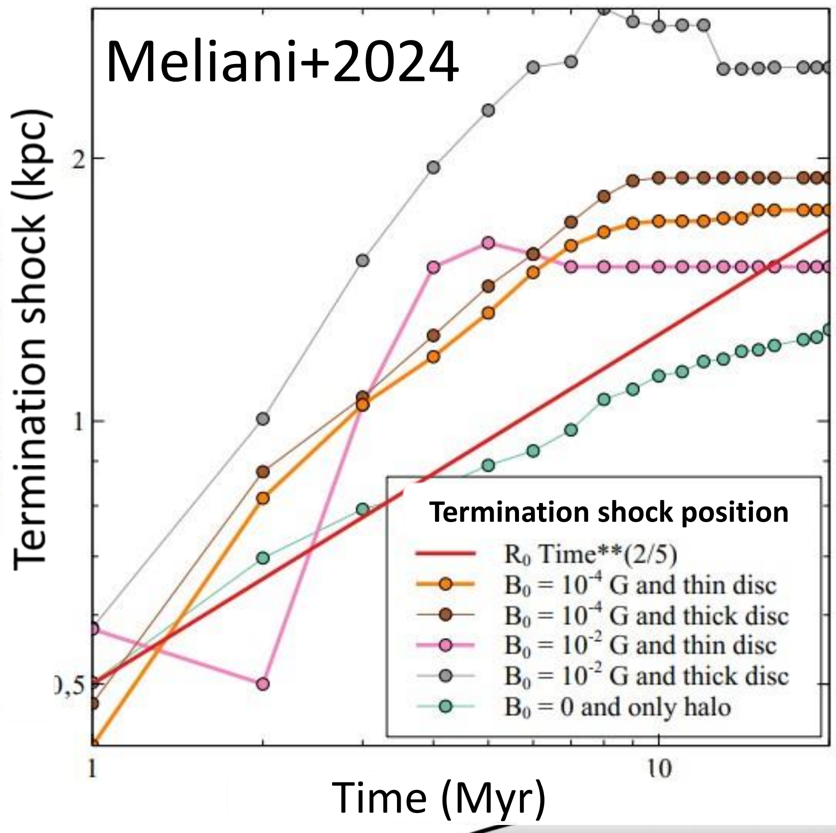
INTERSTELLAR BUBBLES. II. STRUCTURE AND EVOLUTION

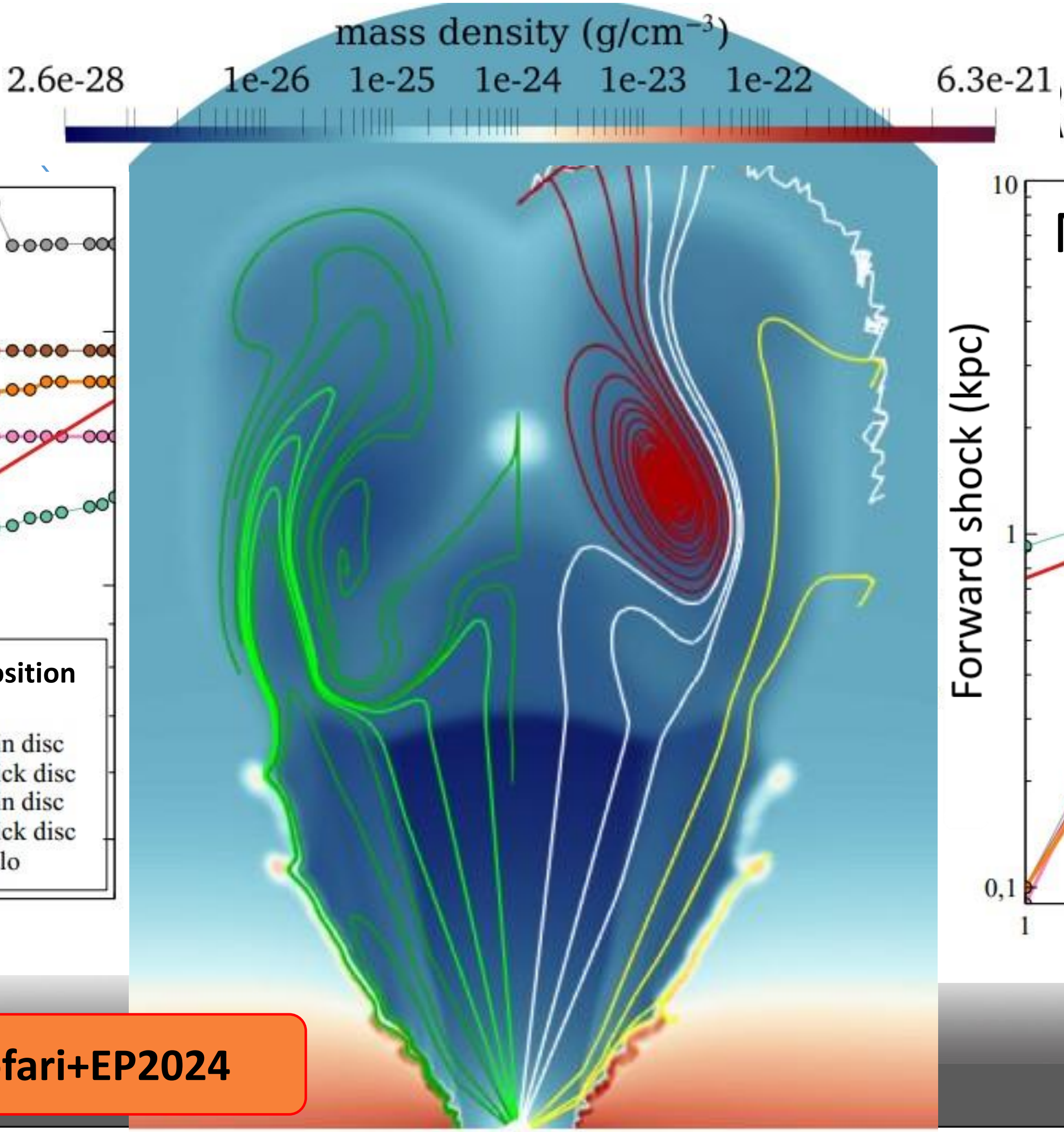
ROBERT WEAVER, RICHARD MCCRAY, AND JOHN CASTOR
Department of Physics and Astrophysics, University of Colorado;
and Joint Institute for Laboratory Astrophysics, University of Colorado and National Bureau of Standards
AND
PAUL SHAPIRO* AND ROBERT MOORE
Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory
Received 1977 March 21; accepted 1977 May 26

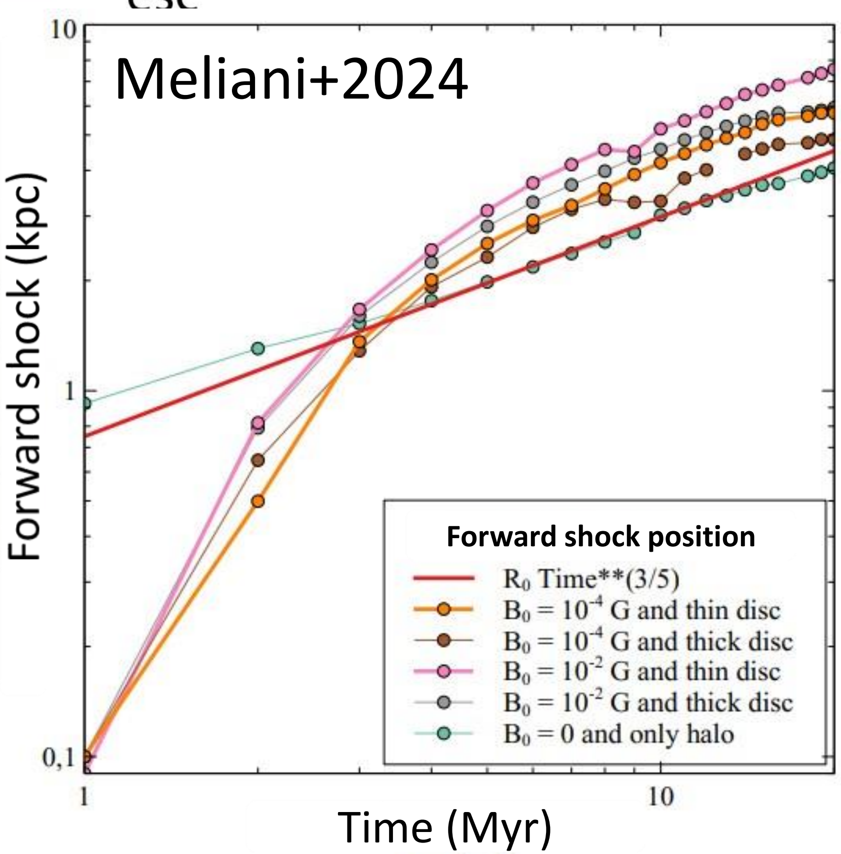
$g\ s^{-1}$

Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

Starburst-driven wind bubble



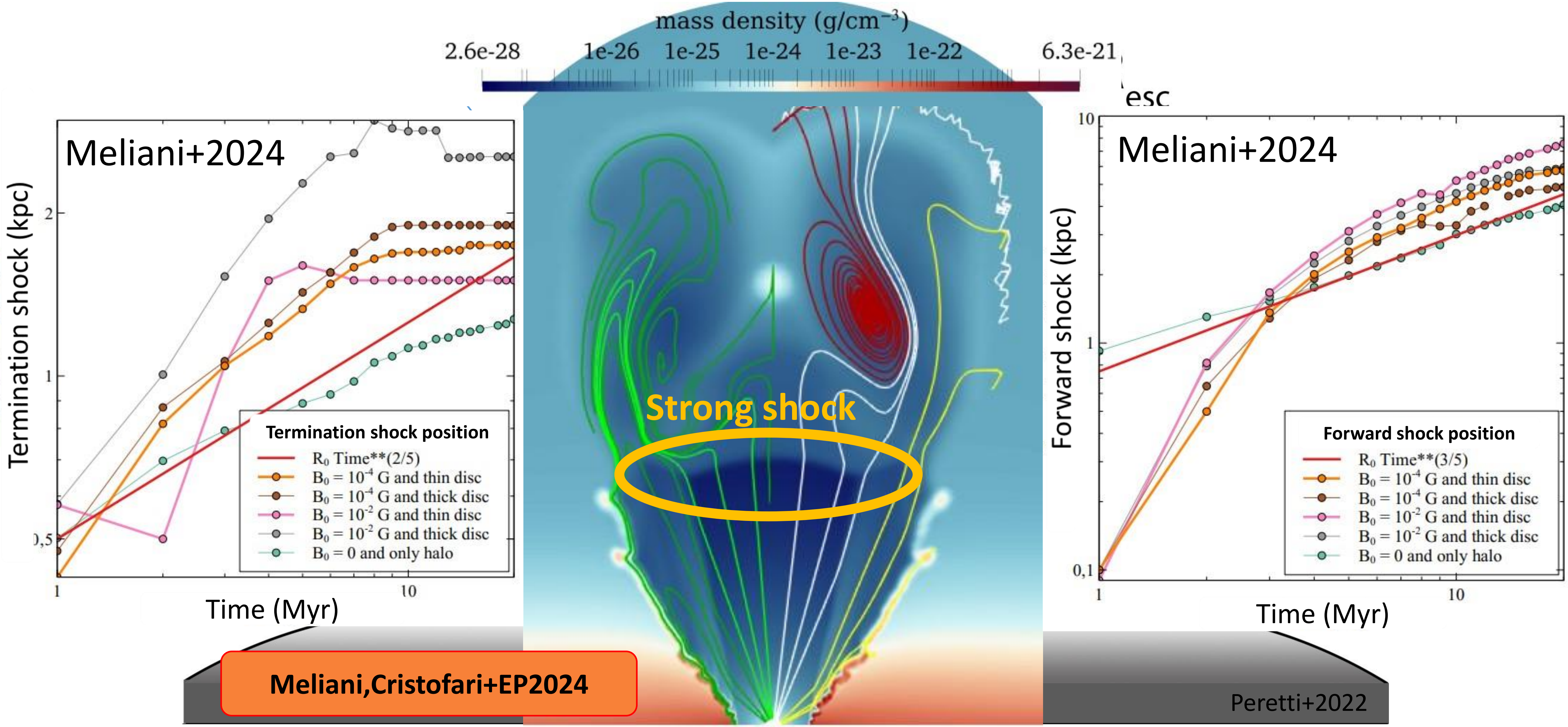




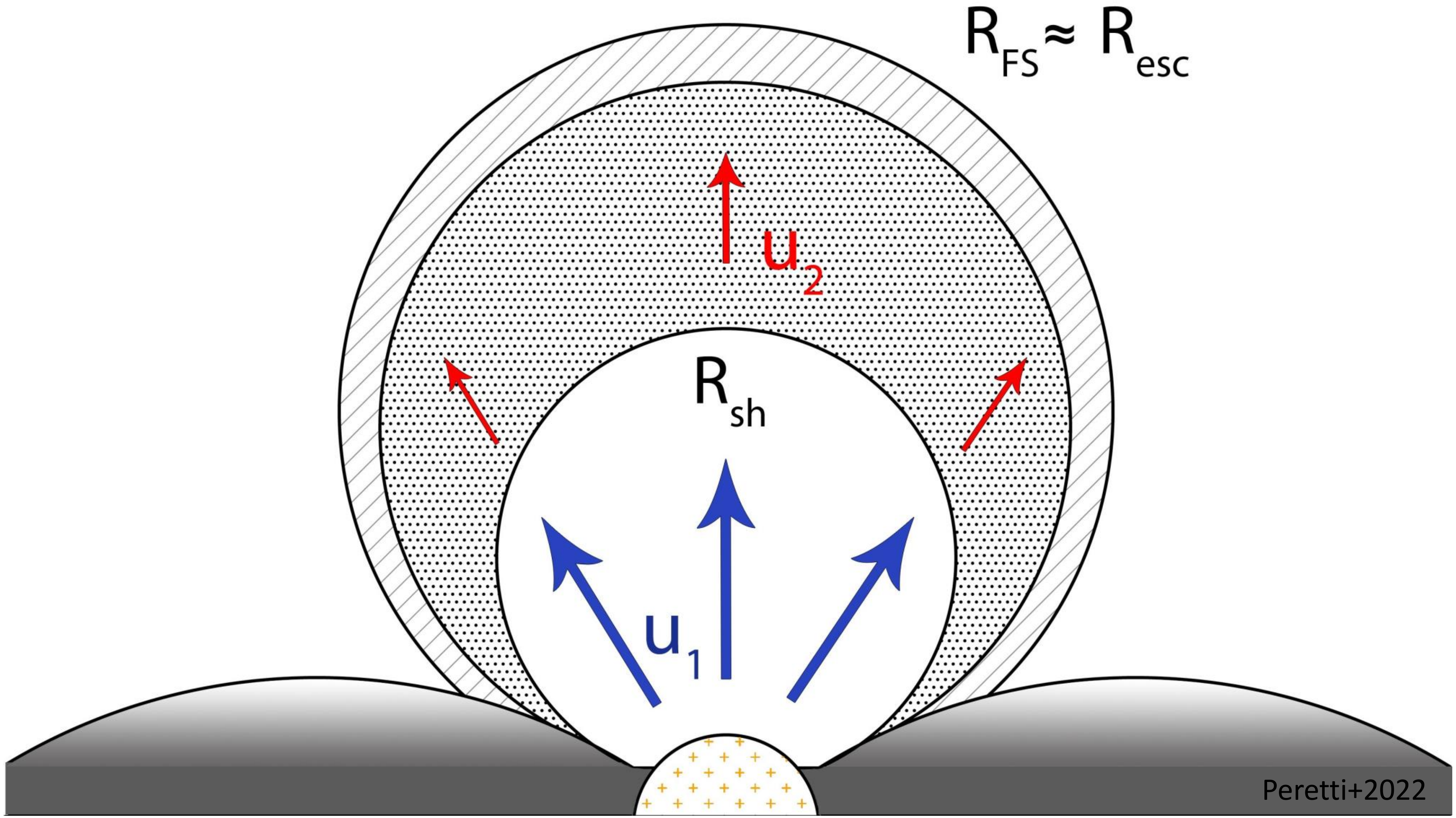
Meliani,Cristofari+EP2024

Peretti+2022

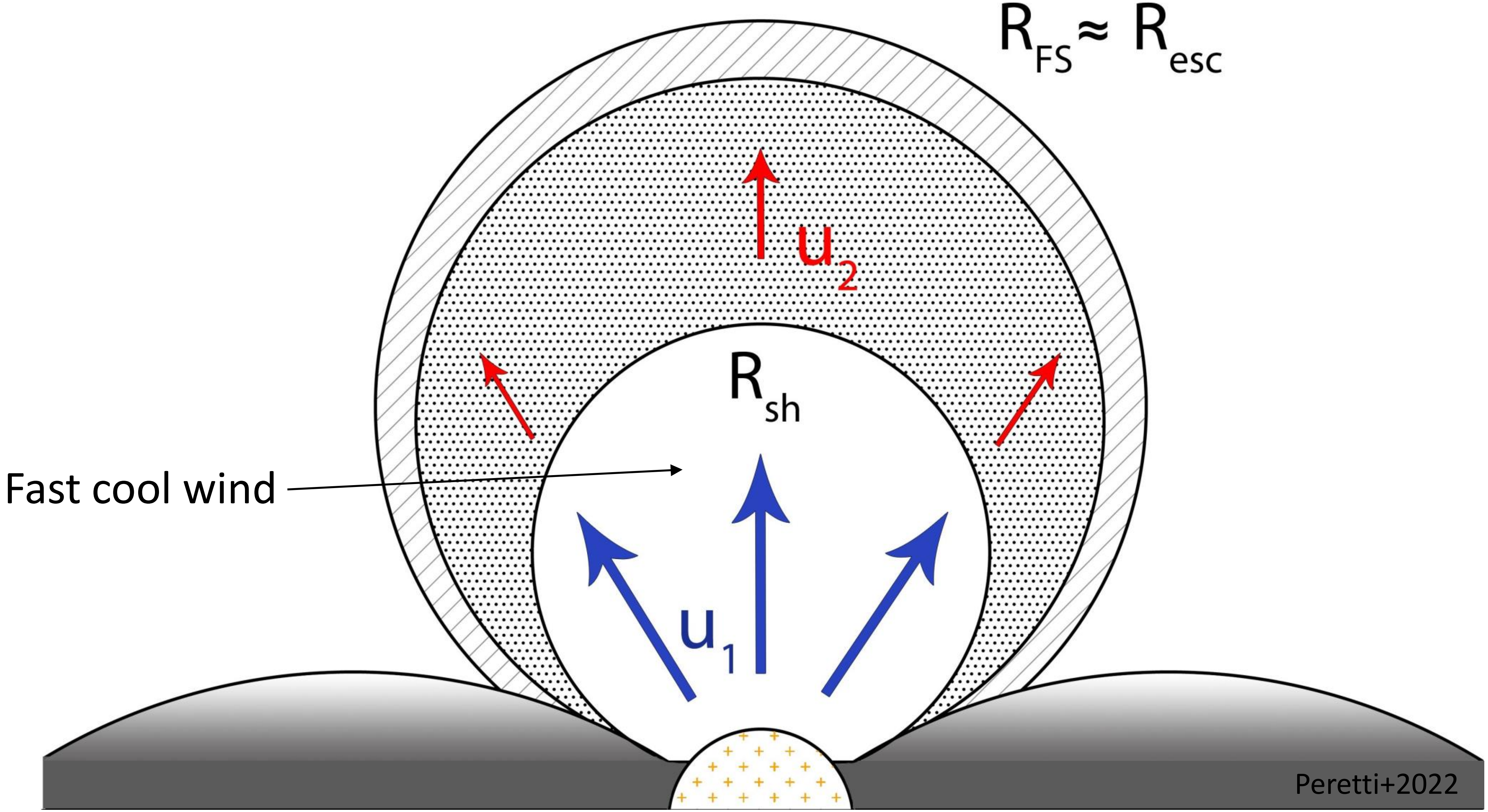
Starburst-driven wind bubble



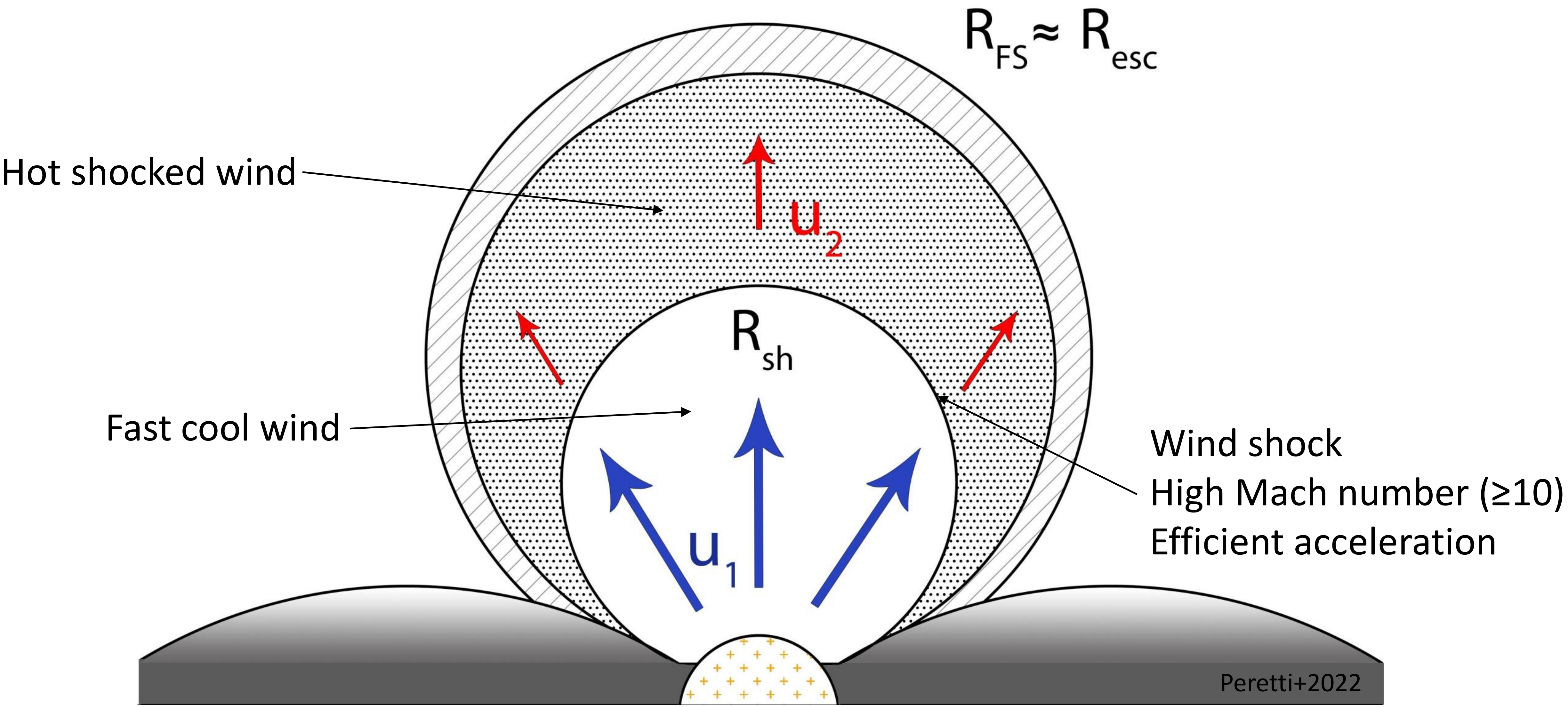
Starburst-driven wind bubble



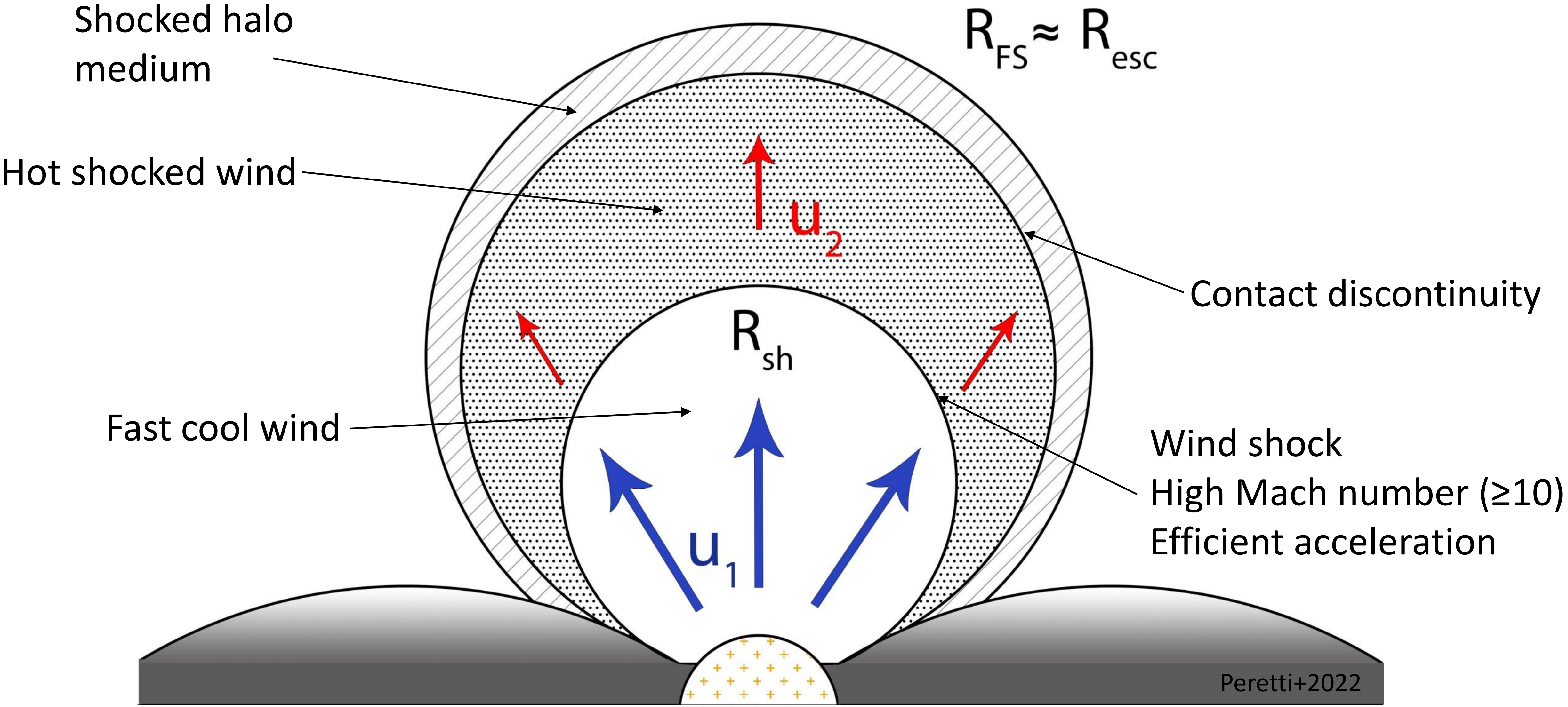
Acceleration and transport in starburst winds



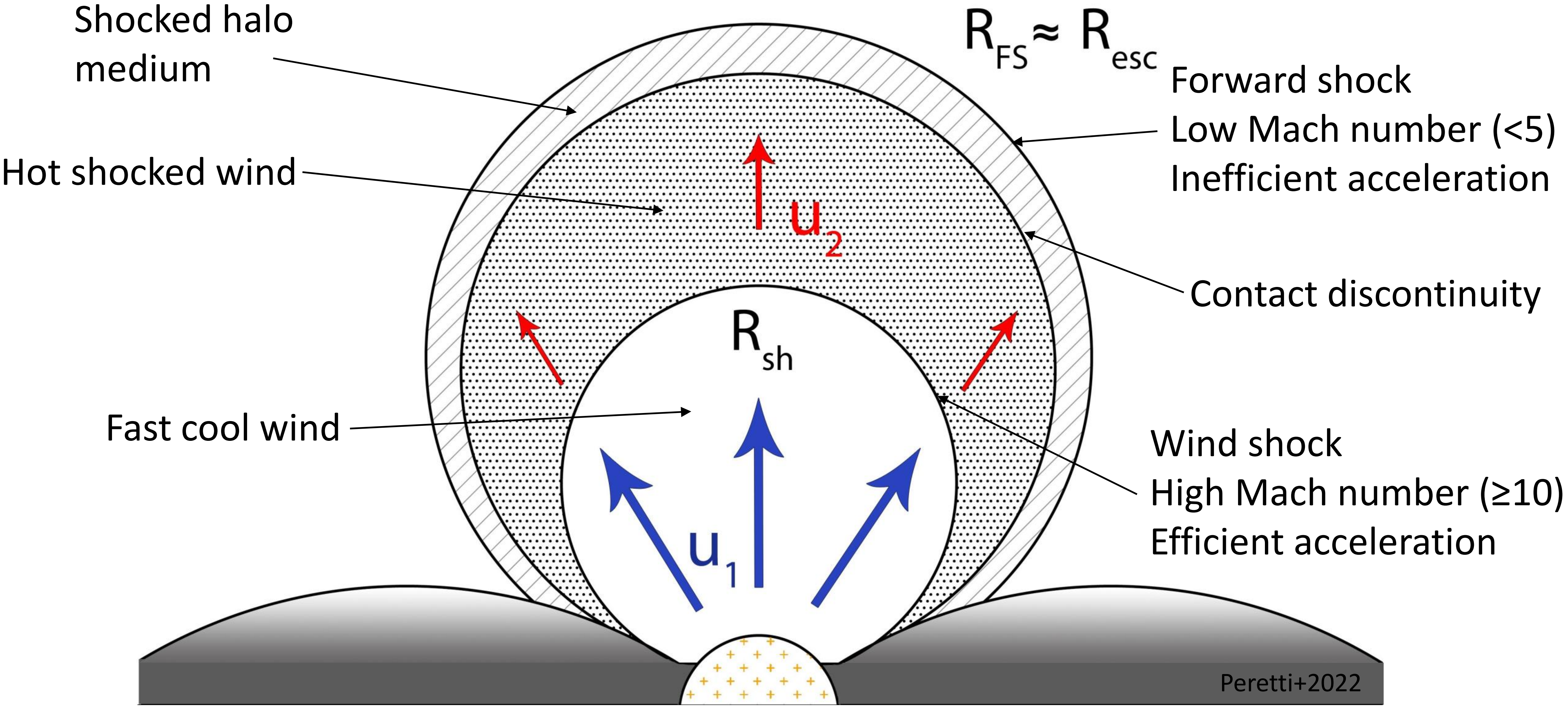
Acceleration and transport in starburst winds



Acceleration and transport in starburst winds

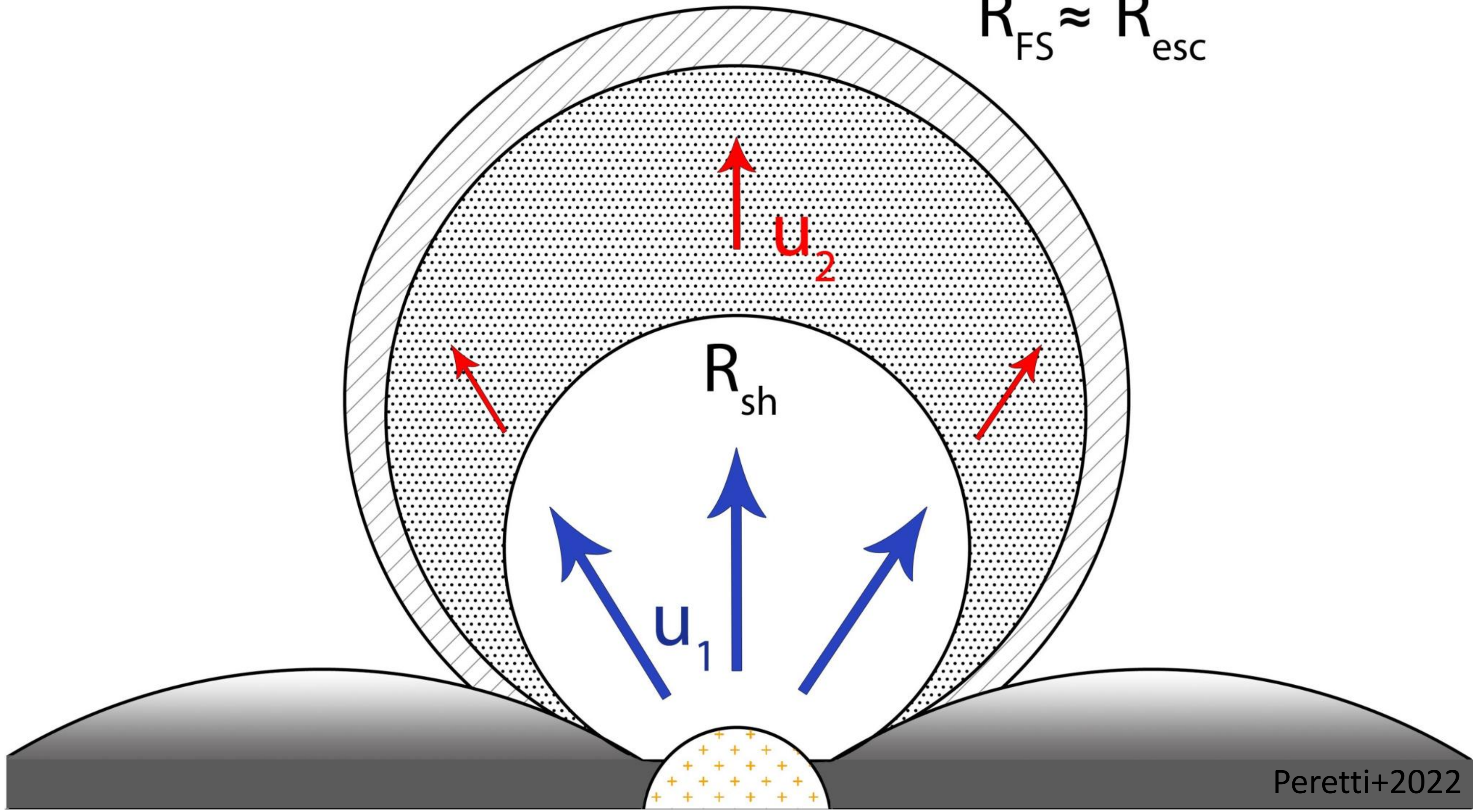


Acceleration and transport in starburst winds



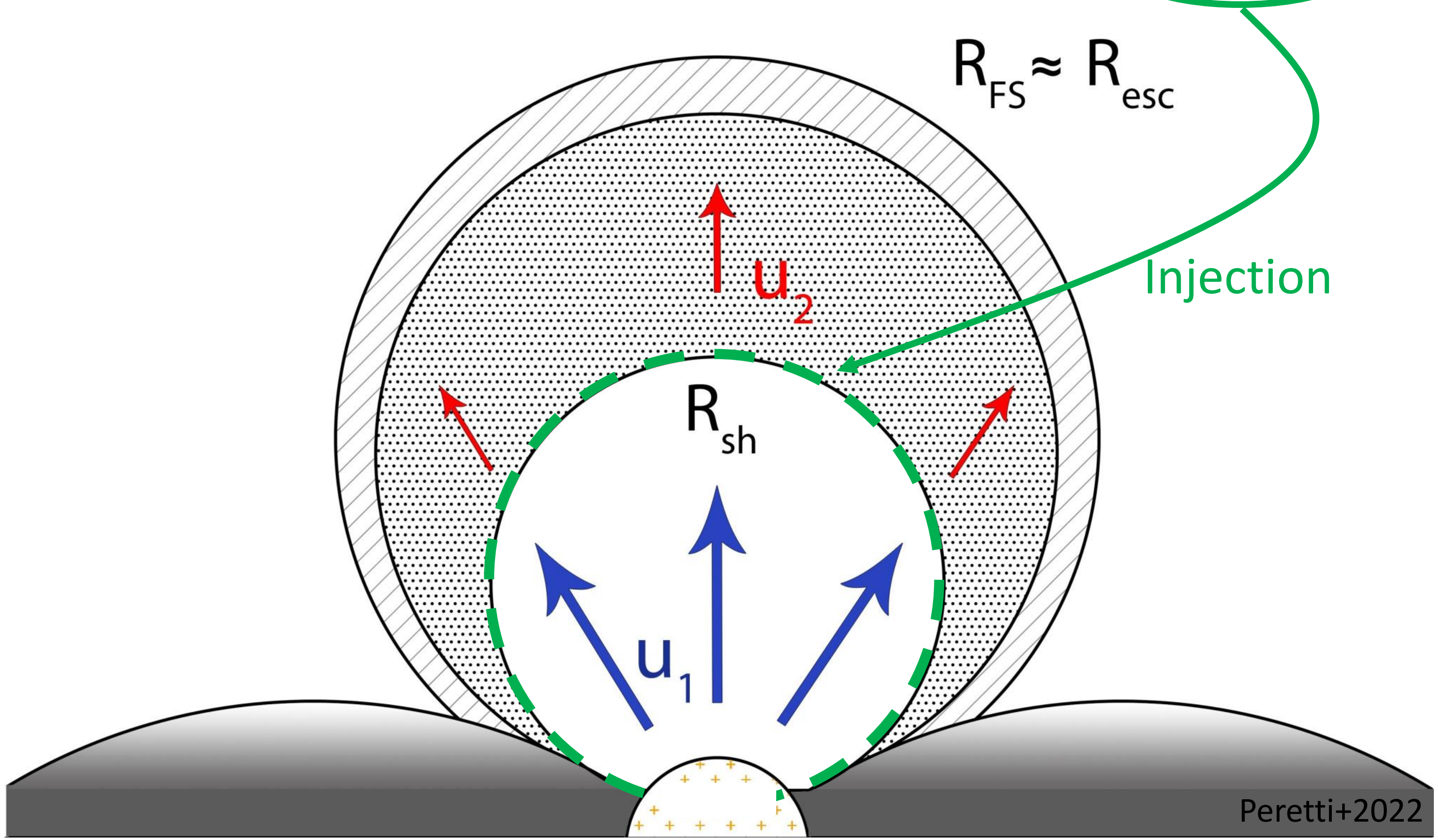
Transport model

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



Transport model

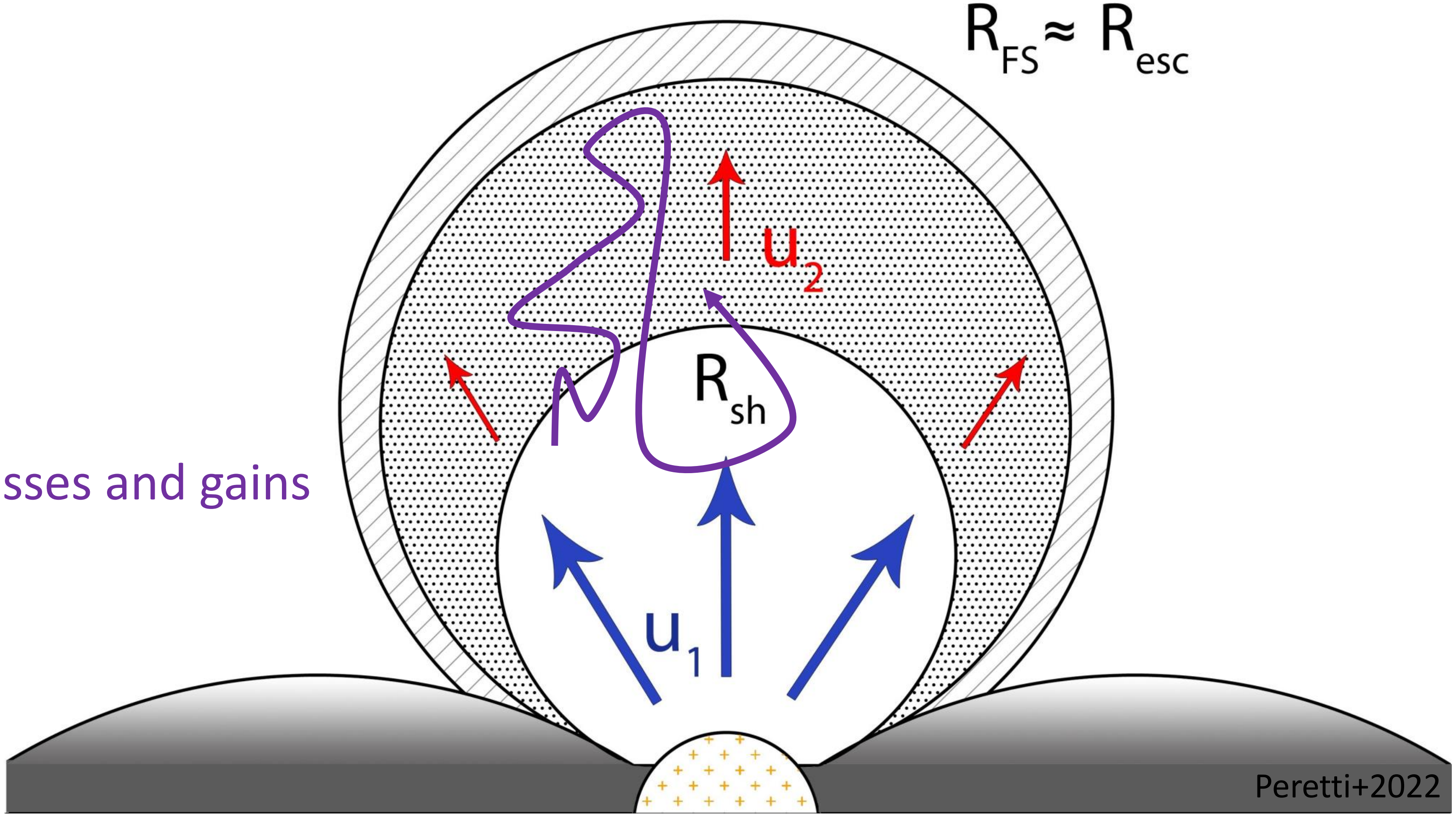
$$r^2 u(r)\partial_r f = \partial_r[r^2 D(r,p)\partial_r f] + \frac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p) - r^2\Lambda(r,p)$$



Transport model

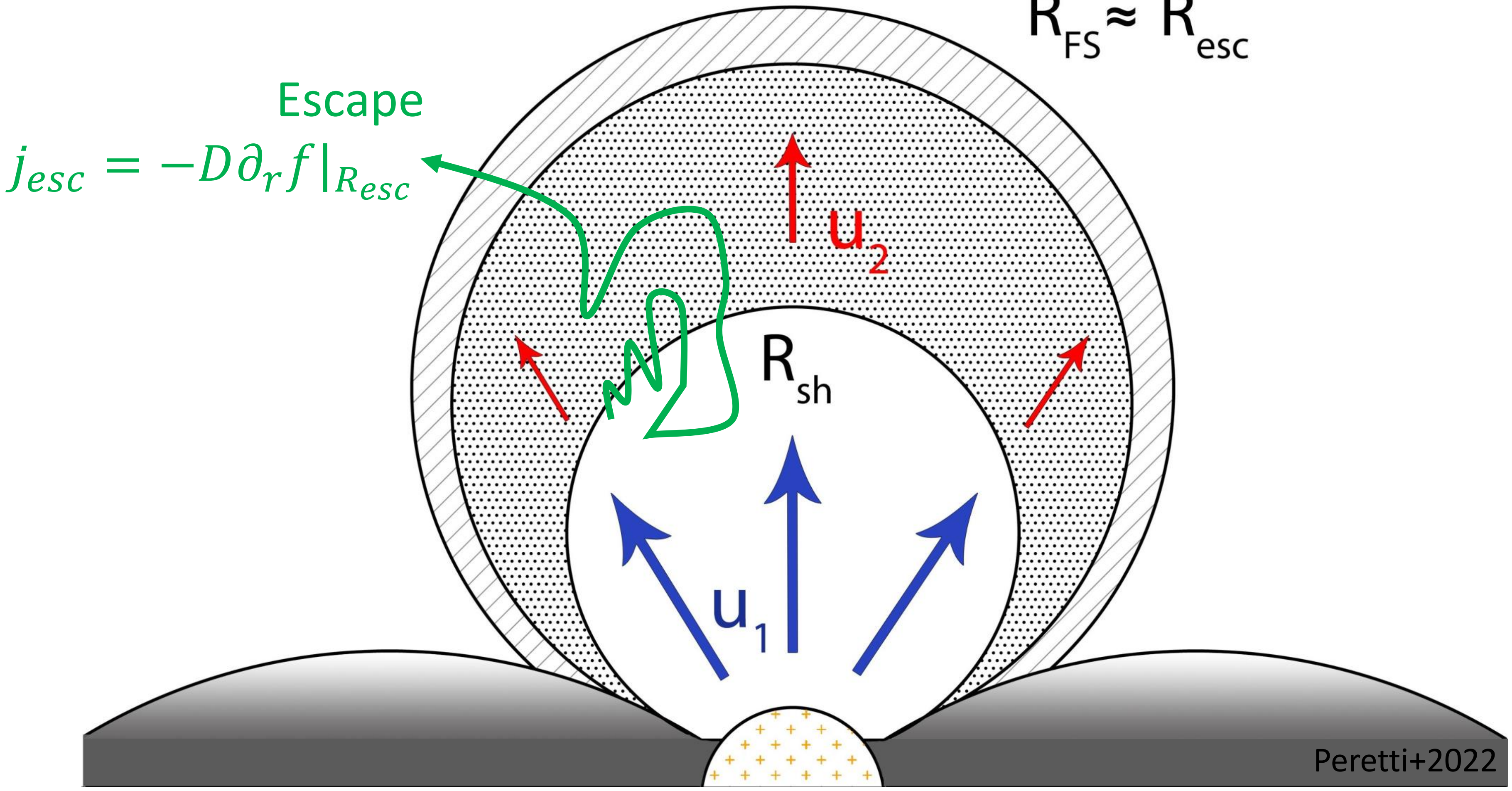
$$r^2 u(r)\partial_r f = \partial_r[r^2 D(r,p)\partial_r f] + \frac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p) - r^2 \Lambda(r,p)$$

- Advection
- Diffusion
- Adiabatic losses and gains



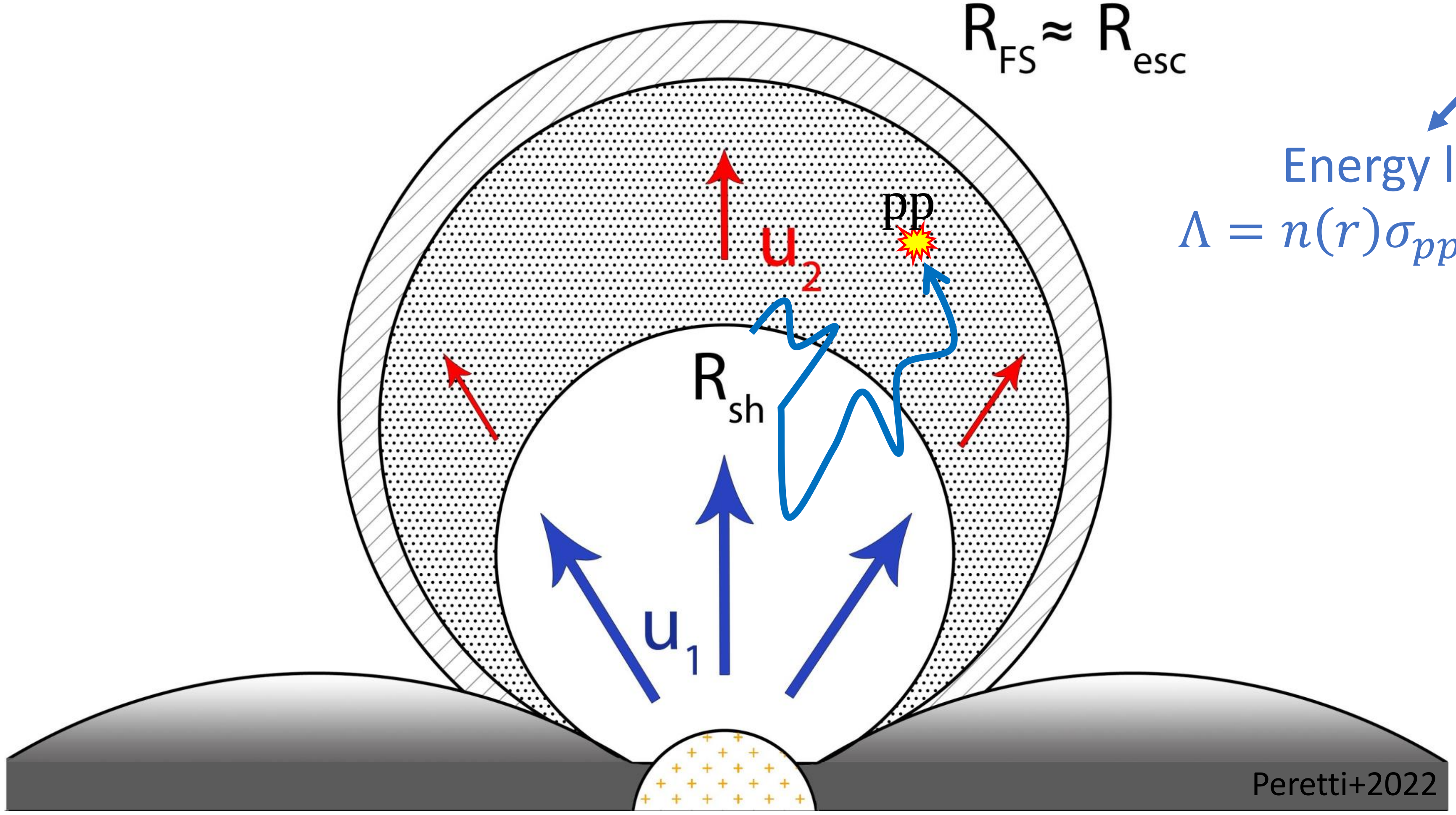
Transport model

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



Transport model

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

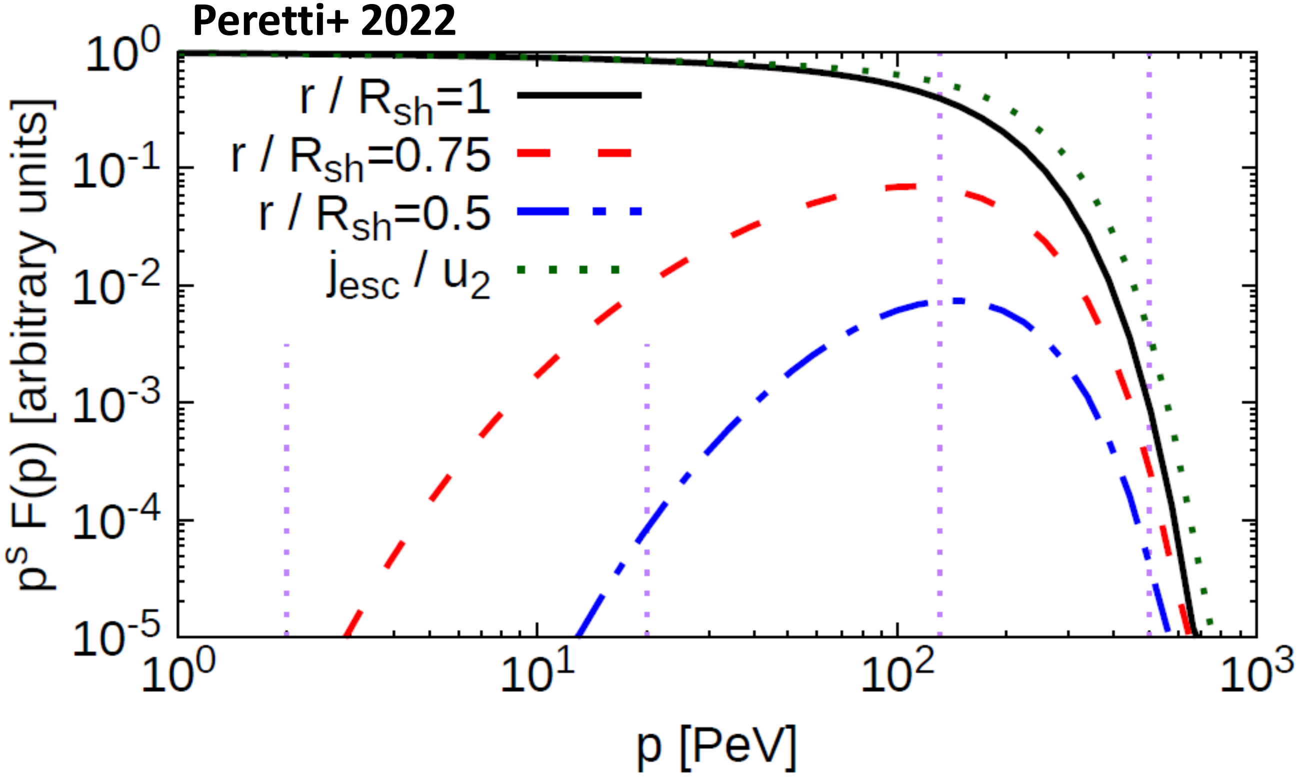


Energy losses

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

Particles in the system

Peretti+ 2022



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

Parameters

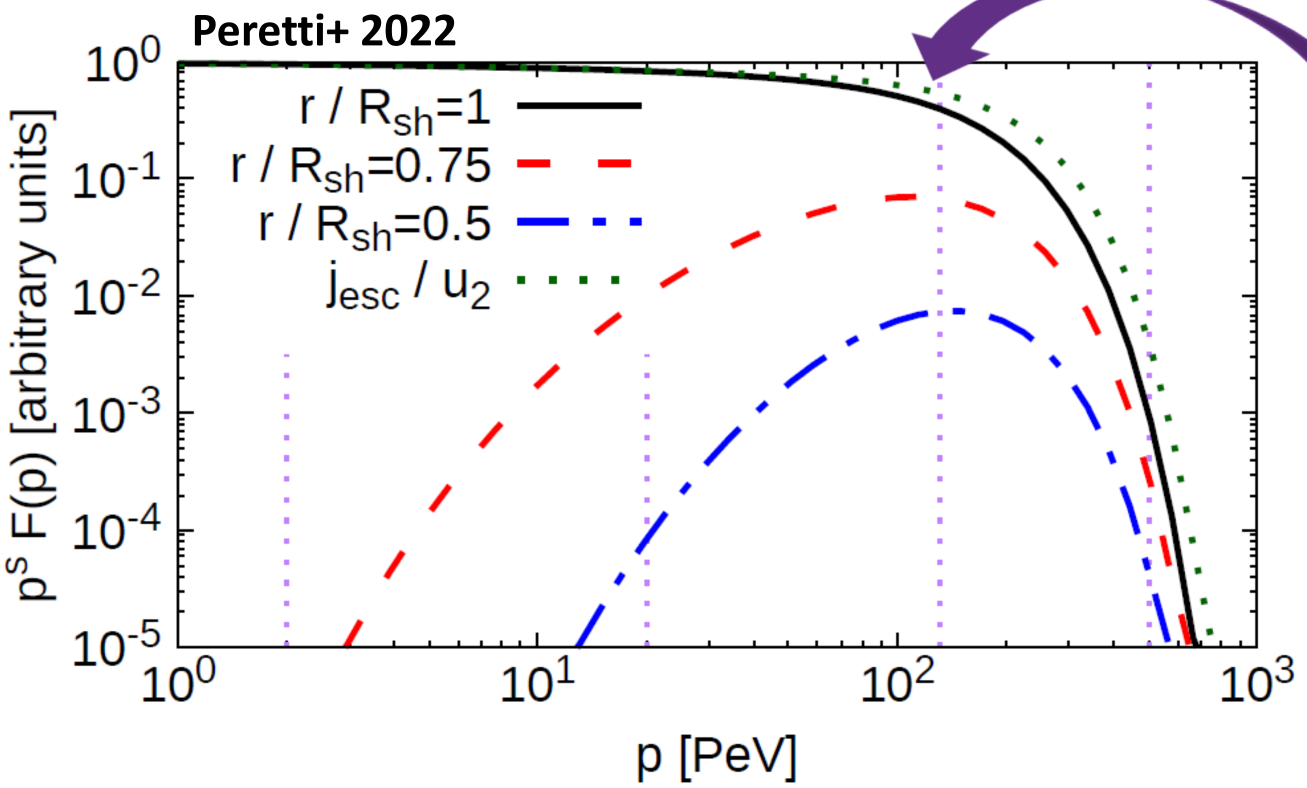
$\dot{M} = 10\, M_{\odot}\, yr^{-1}$

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

$R_{sh} = 12\, kpc$

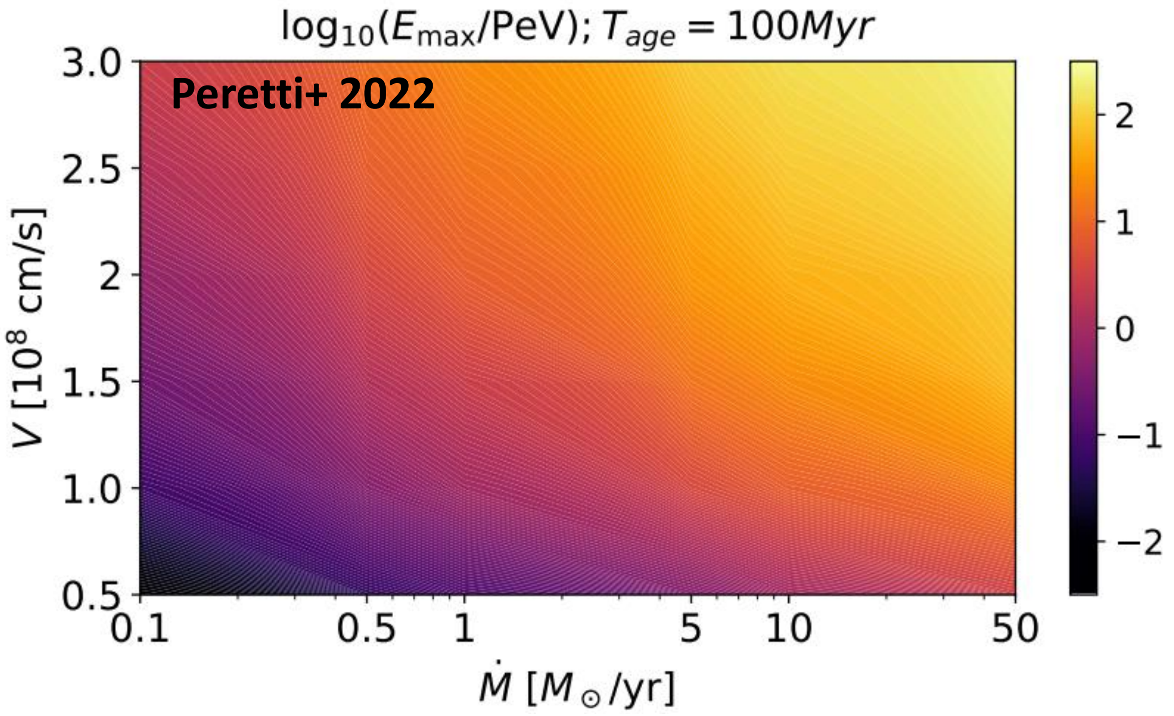
$R_{FS} = 55\, kpc$

Particles in the system

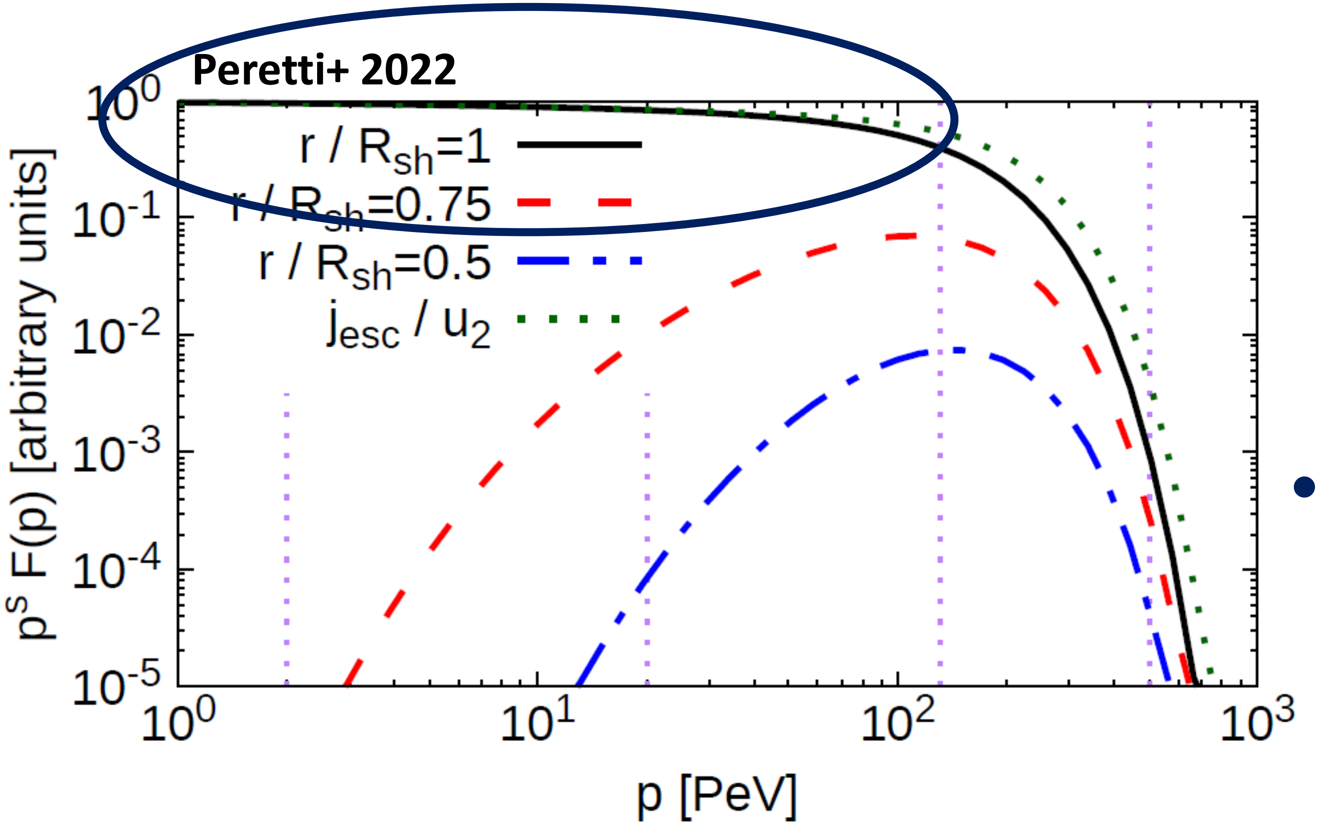


$$f_{sh}(p) \propto p^{-s} e^{-\Gamma_1(p)} e^{-\Gamma_2(p)}$$

- Maximum Energy → 10^2 PeV



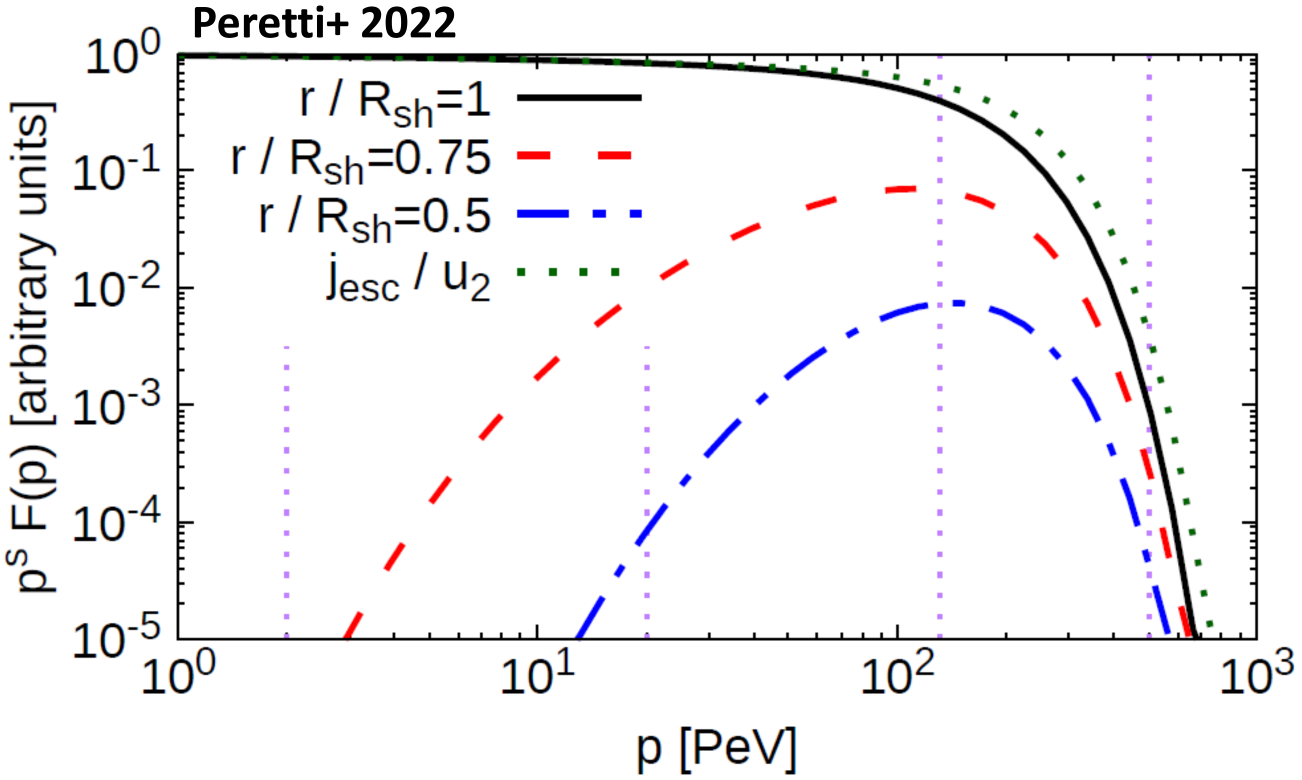
Particles in the system

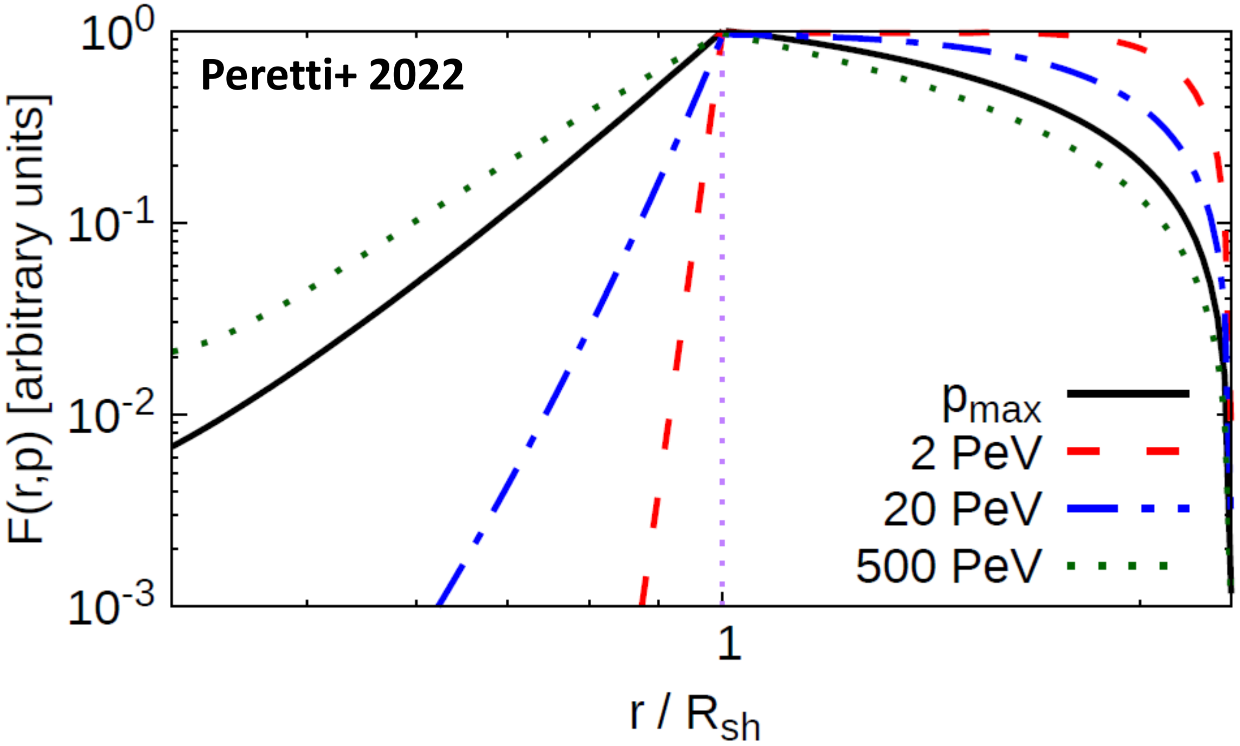


- Maximum Energy → 10^2 PeV
- Standard DSA valid at low Energy

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

Particles in the system

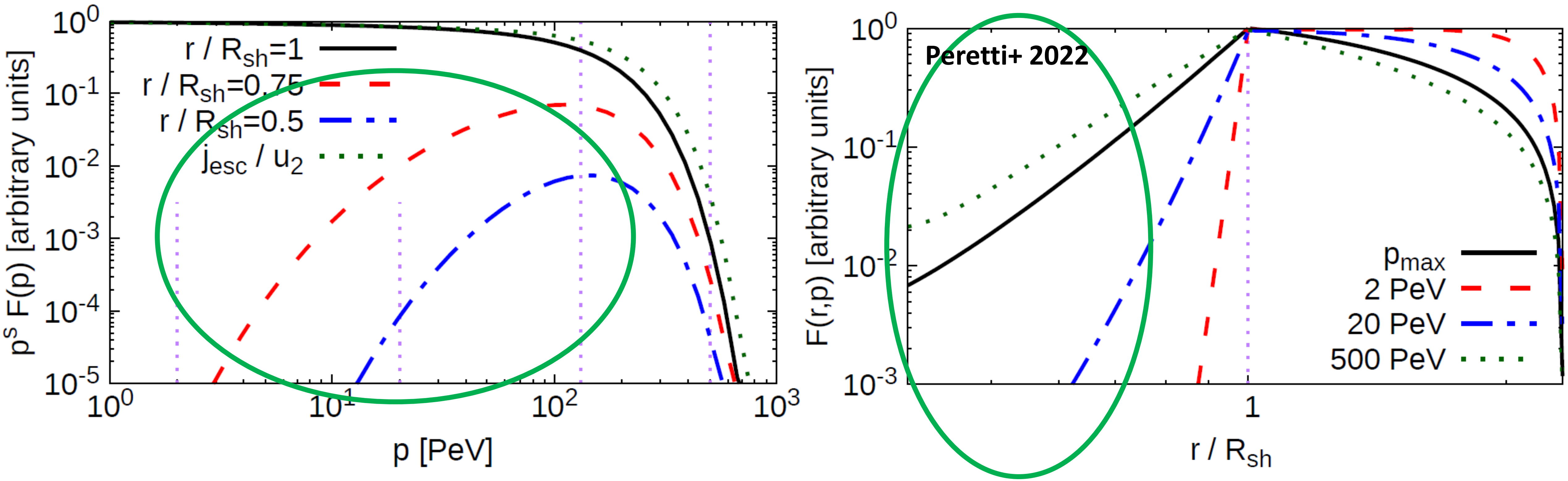




$$f_{sh}(p) \propto p^{-s} e^{-\Gamma_1(p)} e^{-\Gamma_2(p)}$$

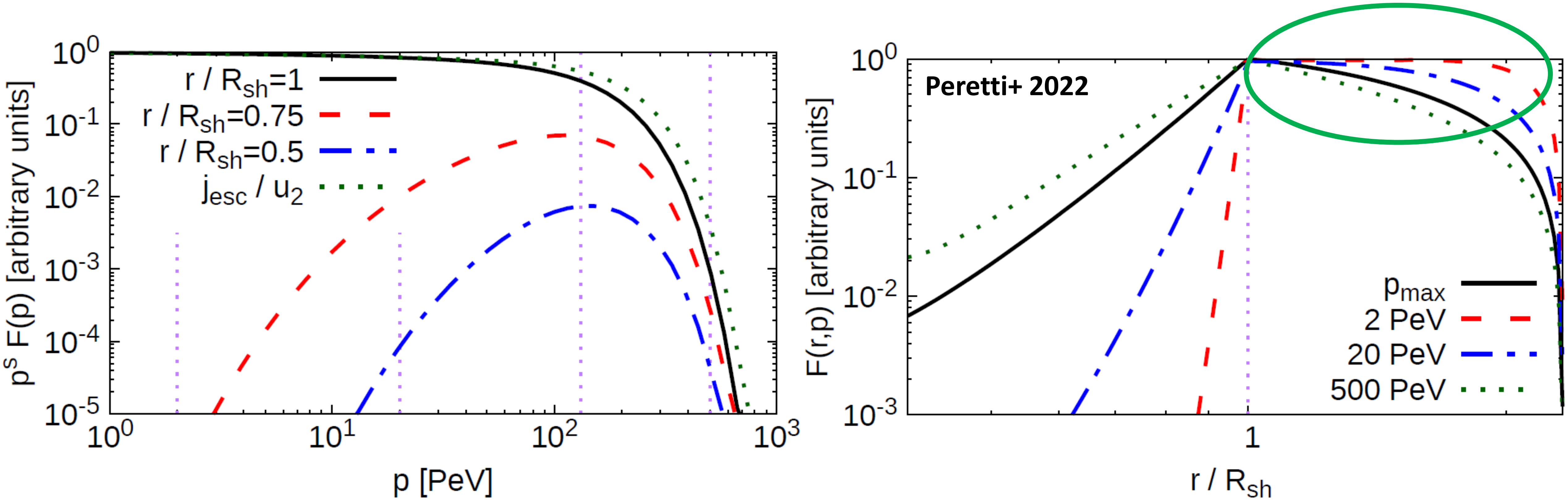
$$f_u(r,p) = f_{sh}(p)\, e^{-\int_r^{R_{sh}} \left(\frac{u_{eff}}{D}\right) dr'}$$

Particles in the system



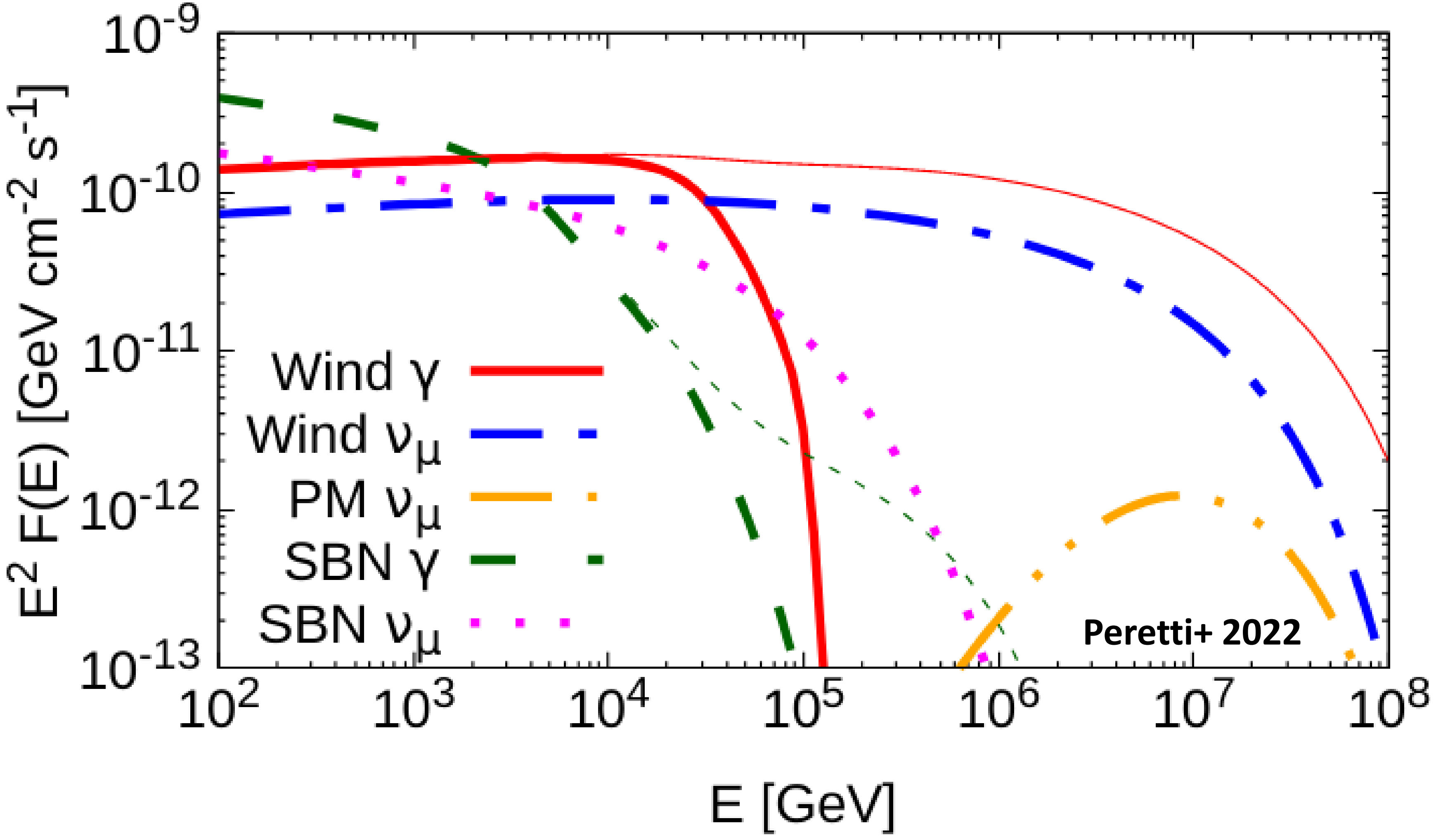
The wind suppresses the diffusion of particles back to the galaxy

Particles in the system

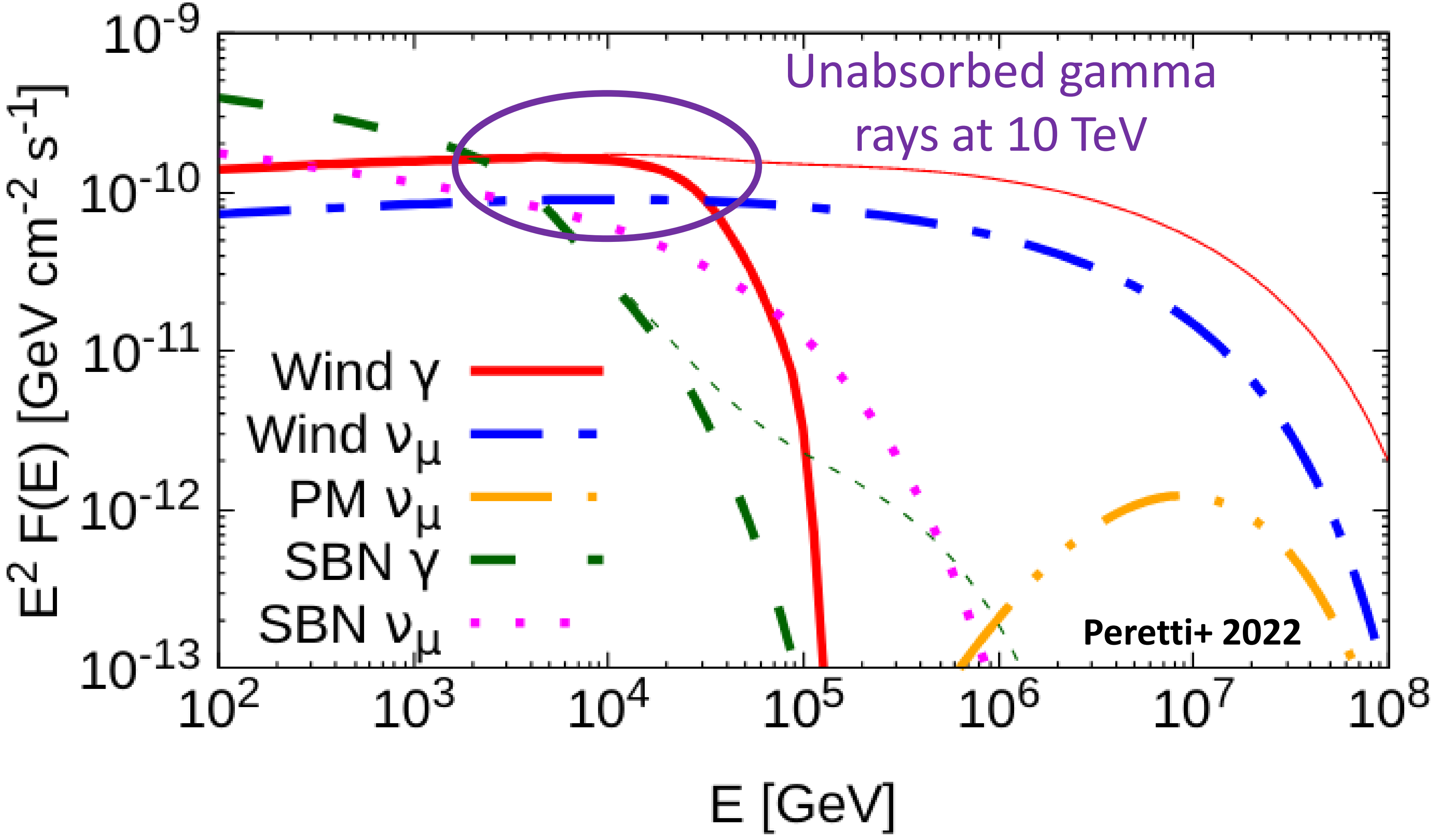


Particle distribution homogenized in
the downstream region

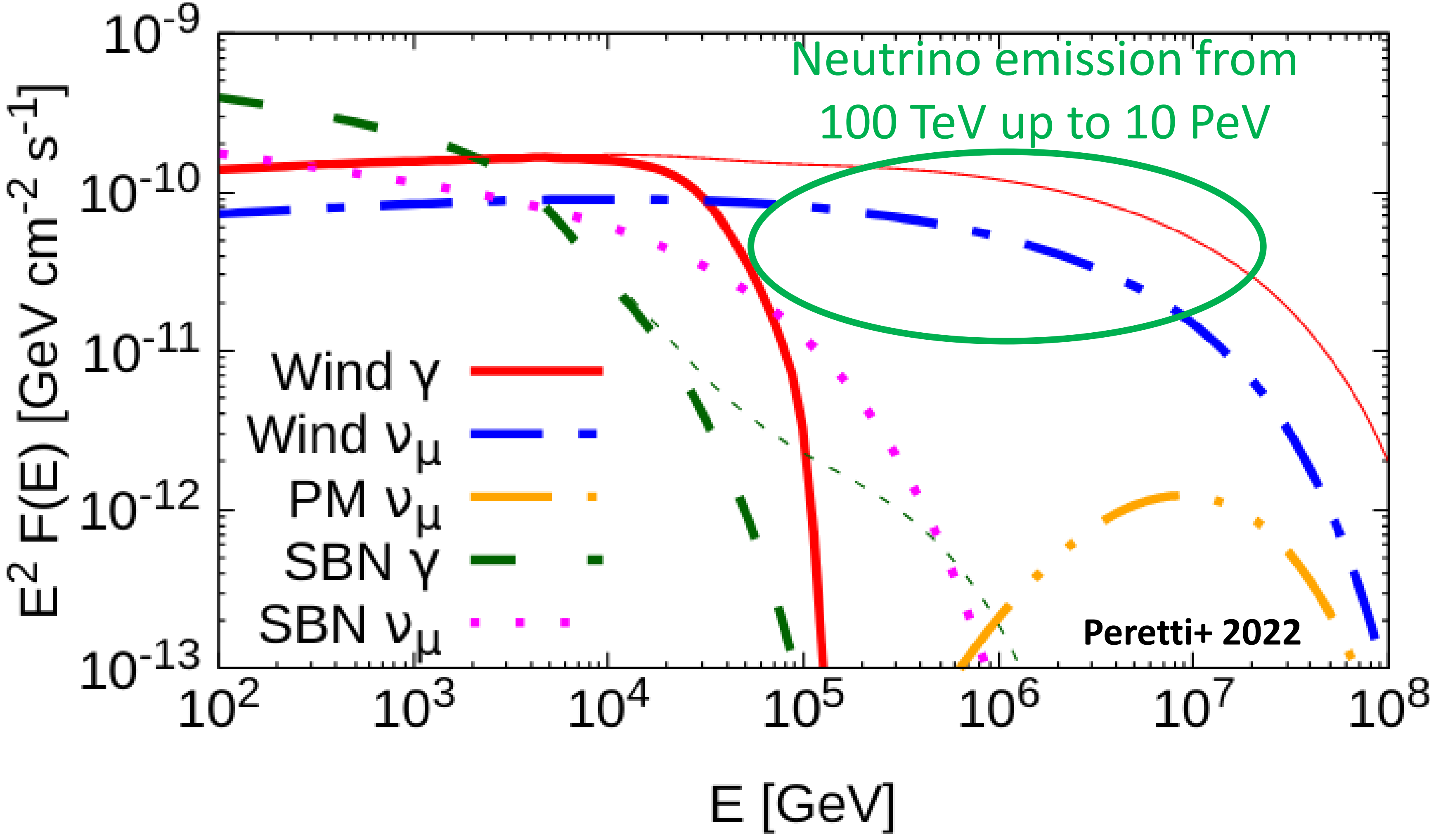
High-Energy SED and Neutrinos



High-Energy SED and Neutrinos



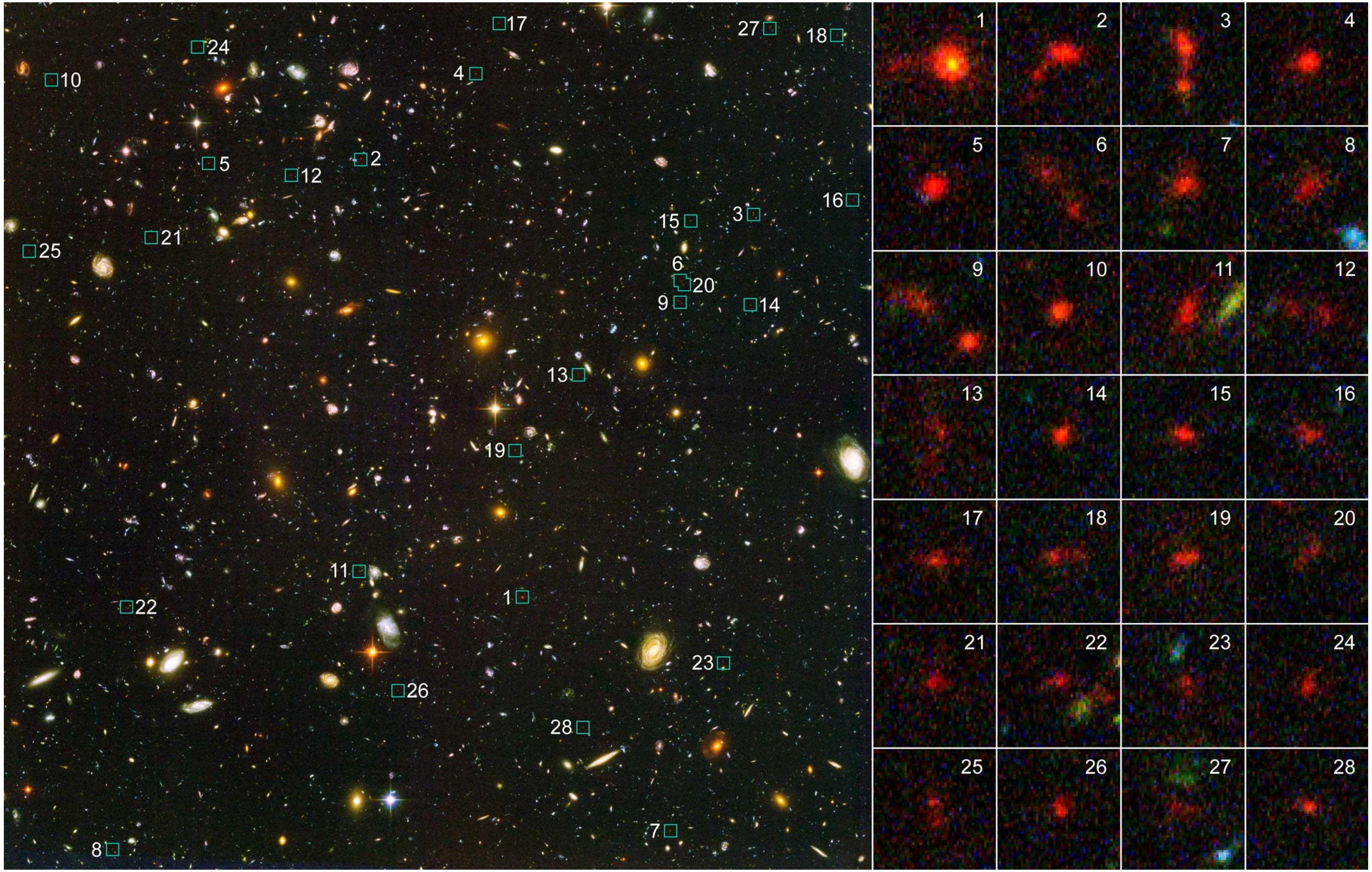
High-Energy SED and Neutrinos



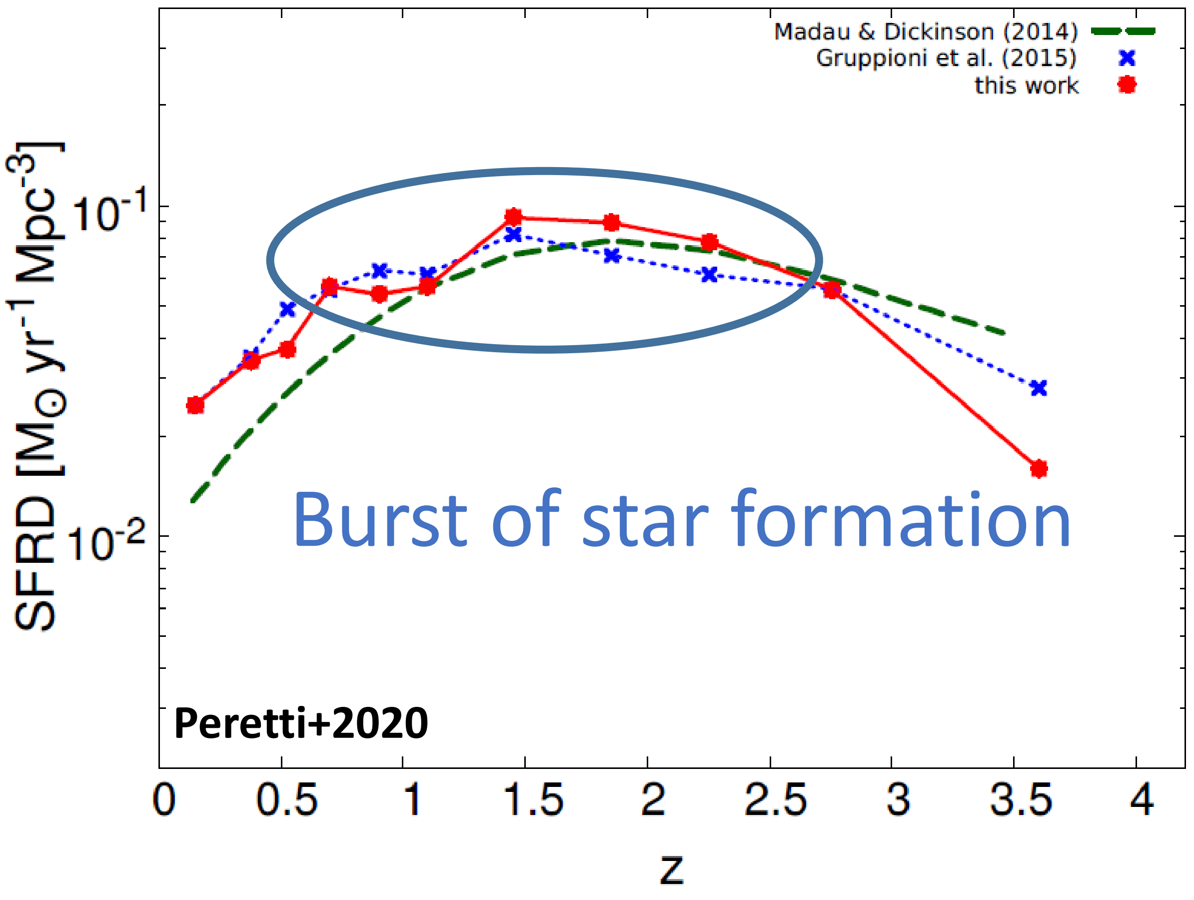
Outline

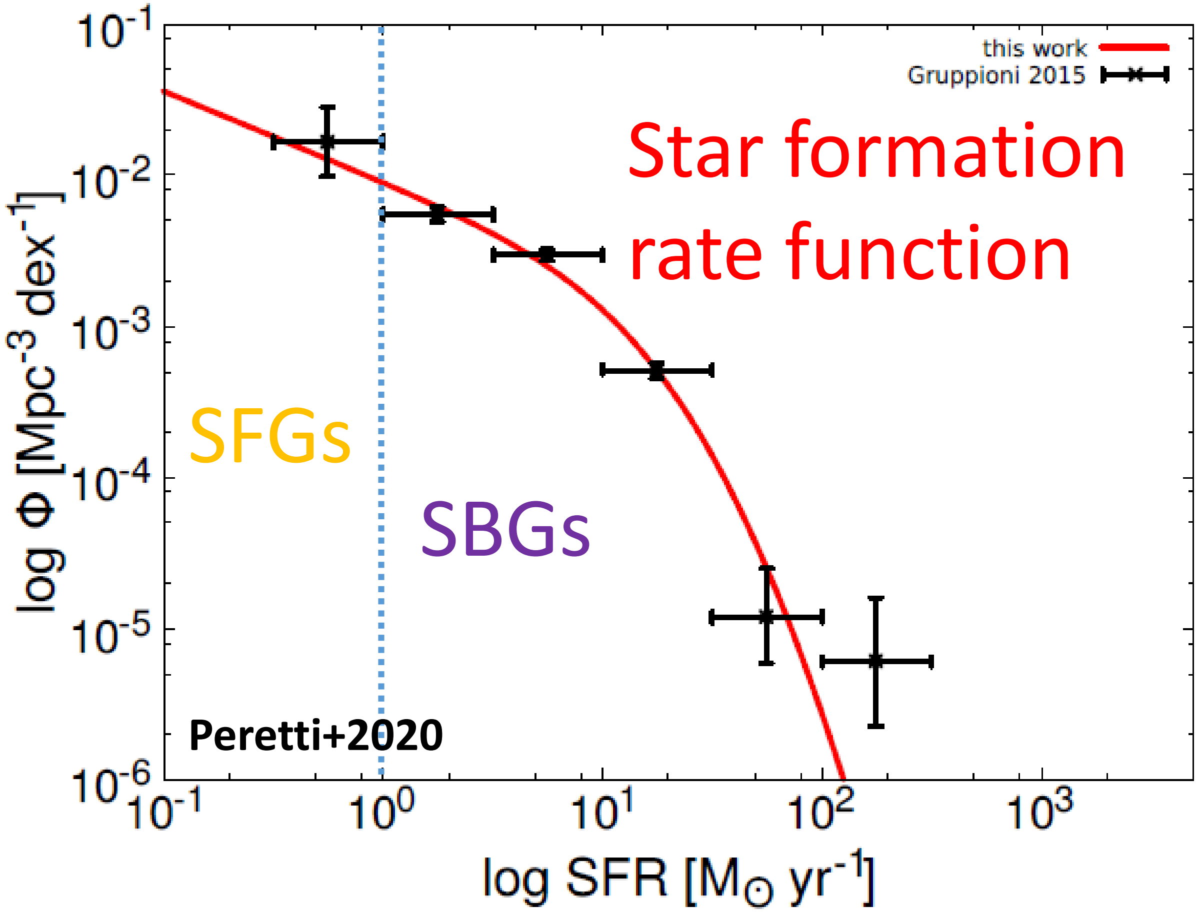
- Observations of Star-forming galaxies
- Particle Transport in Starburst Nuclei
- Starburst-driven winds
- Multi-messenger diffuse flux

Diffuse emission from starbursts

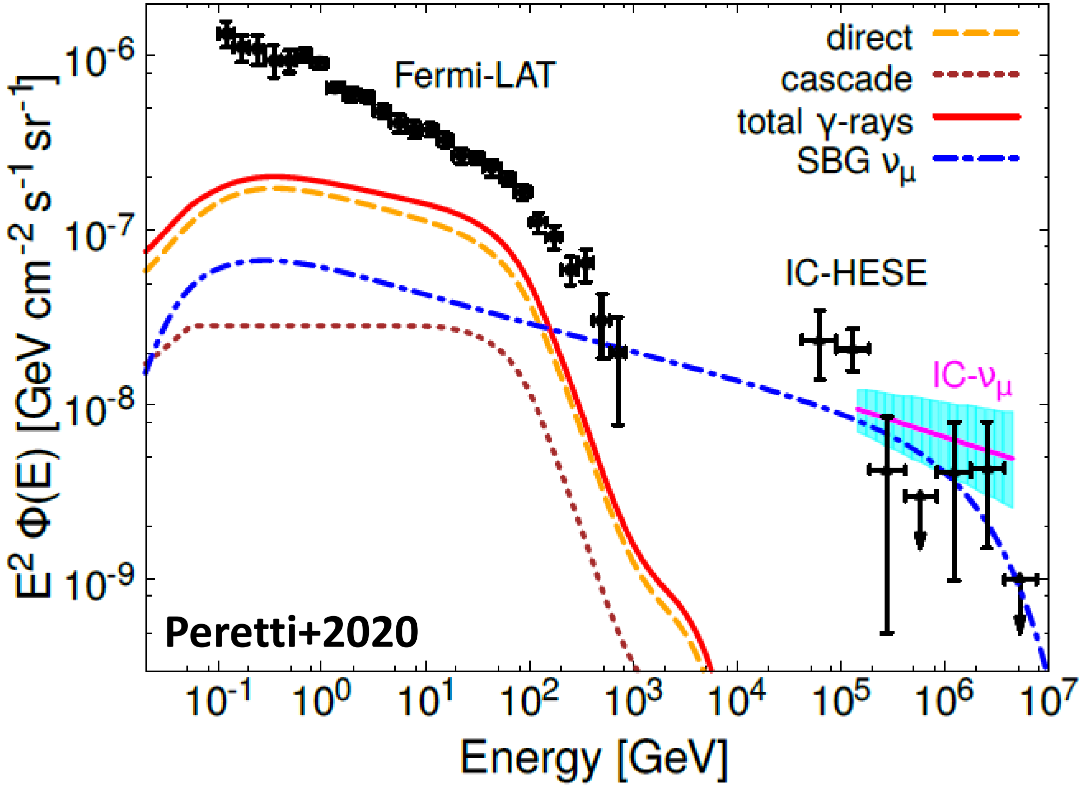


Starbursts as diffuse sources



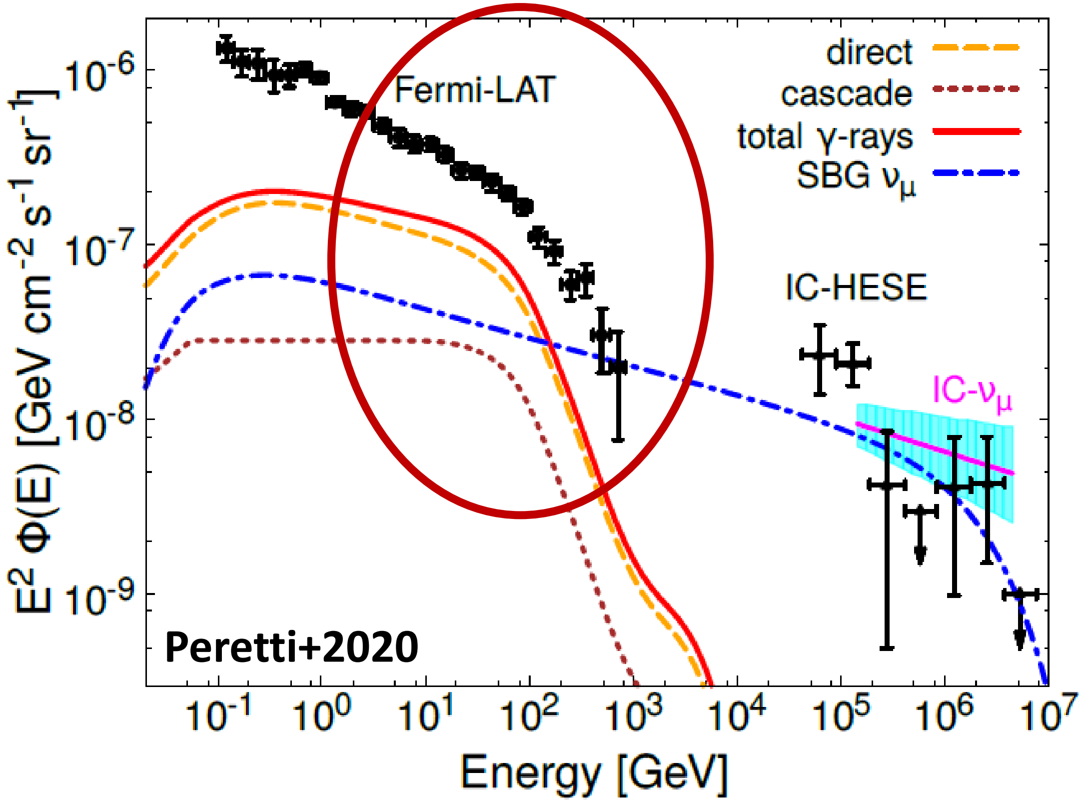


Diffuse emission from Starburst Galaxies



- SBNi only

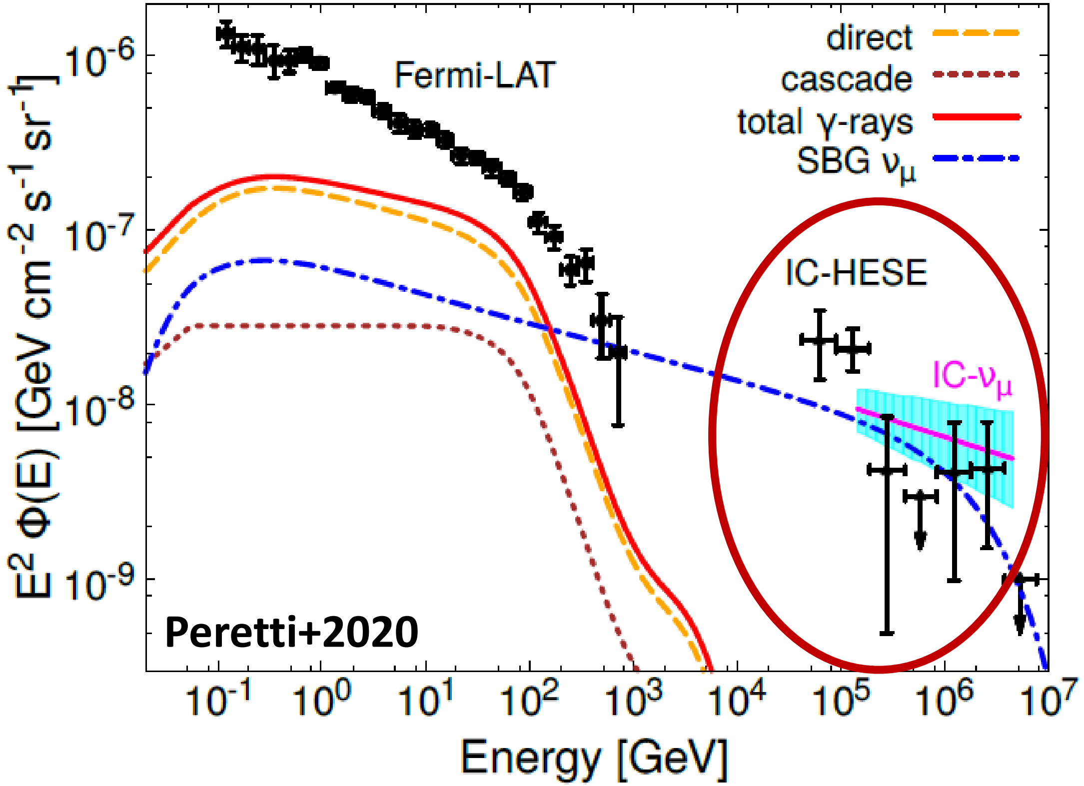
Diffuse emission from Starburst Galaxies



- SBNi only

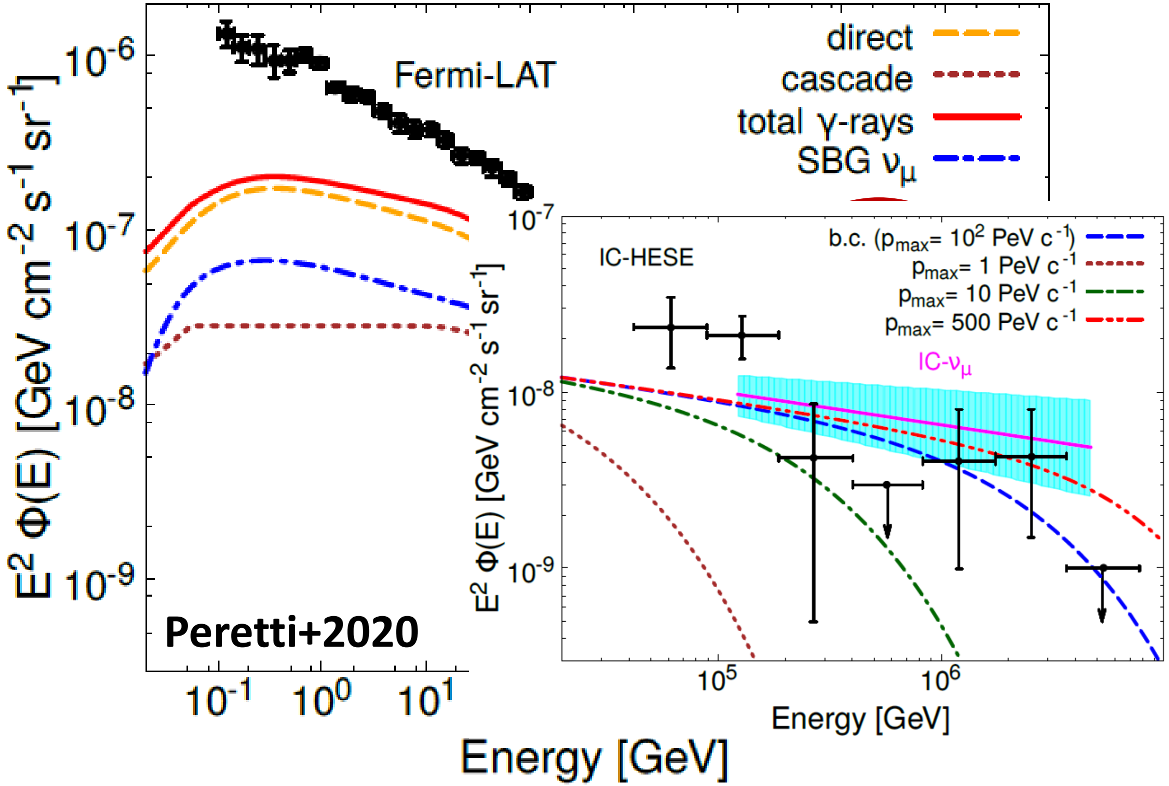
- Sizeable contribution to the diffuse flux observed by Fermi-LAT

Diffuse emission from Starburst Galaxies



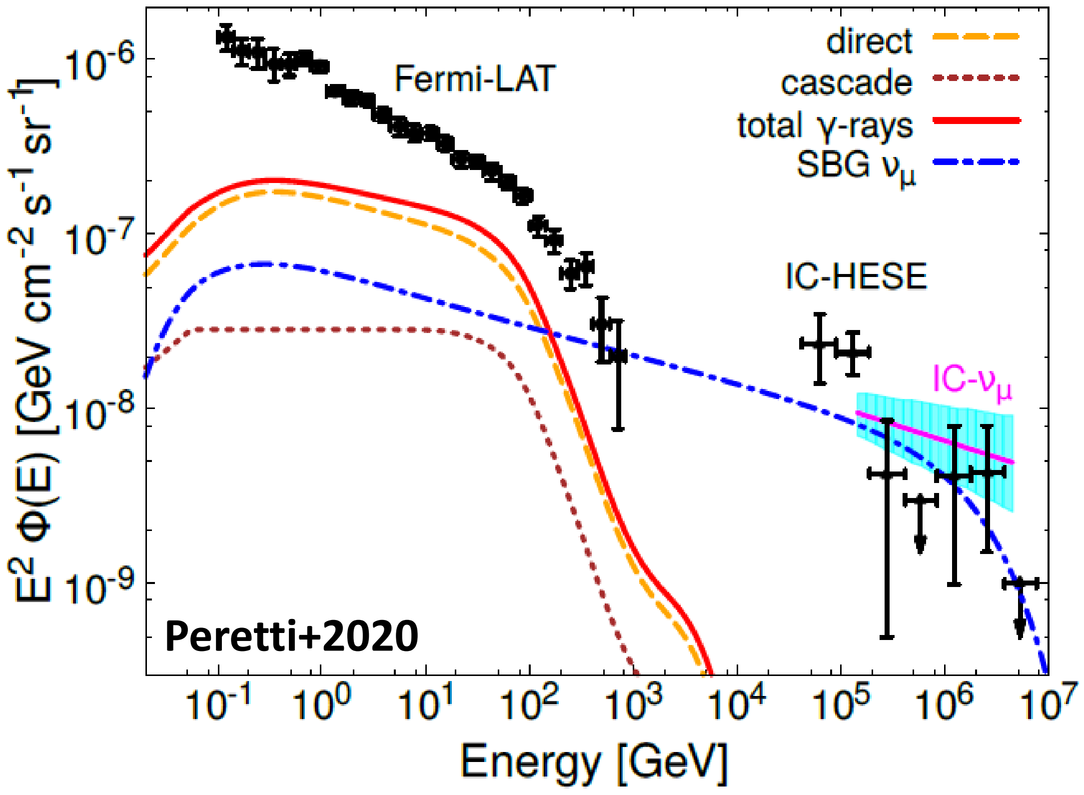
- SBNi only
- Sizeable contribution to the diffuse flux observed by Fermi-LAT
- Neutrino flux at the level of IceCube measurment

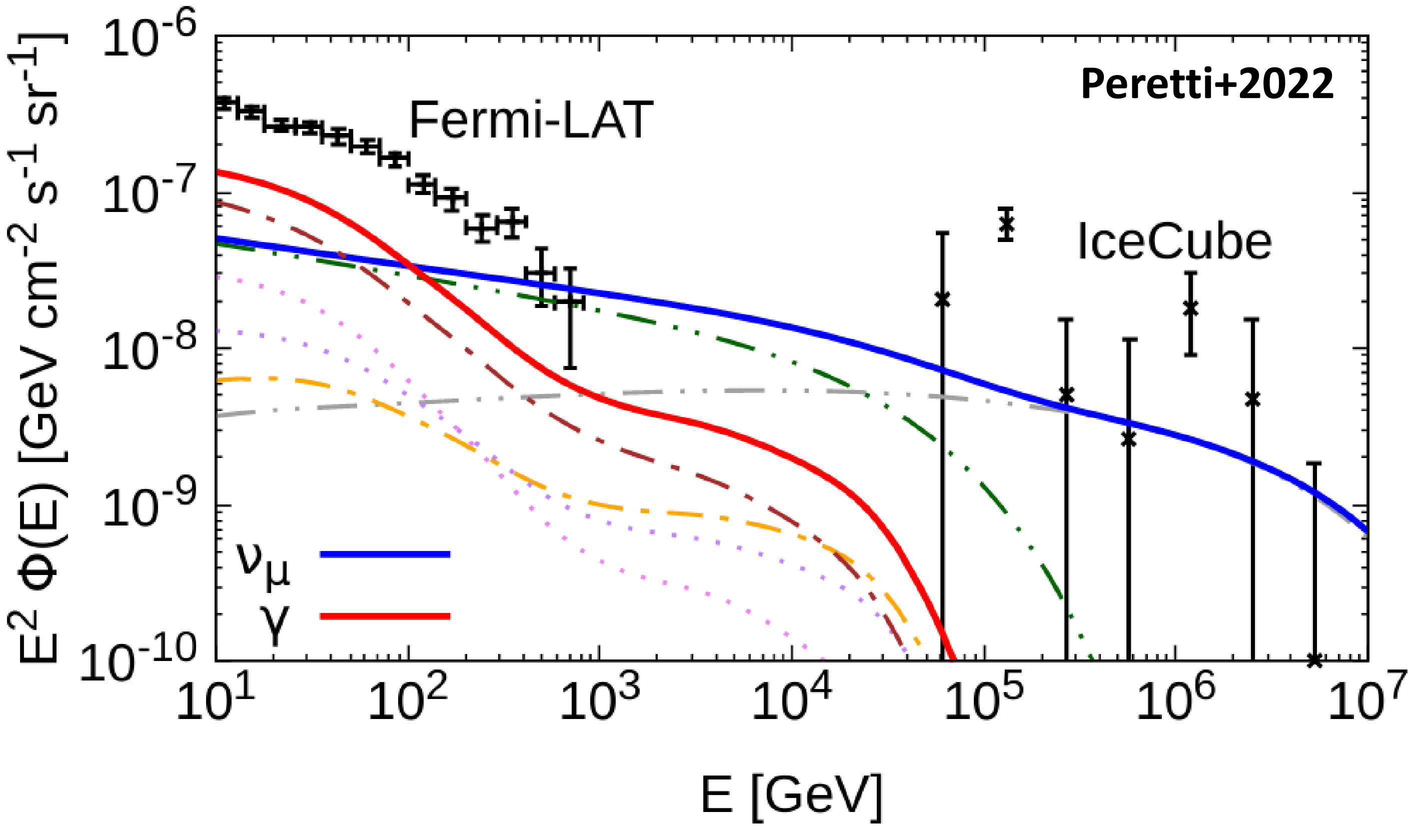
Diffuse emission from Starburst Galaxies



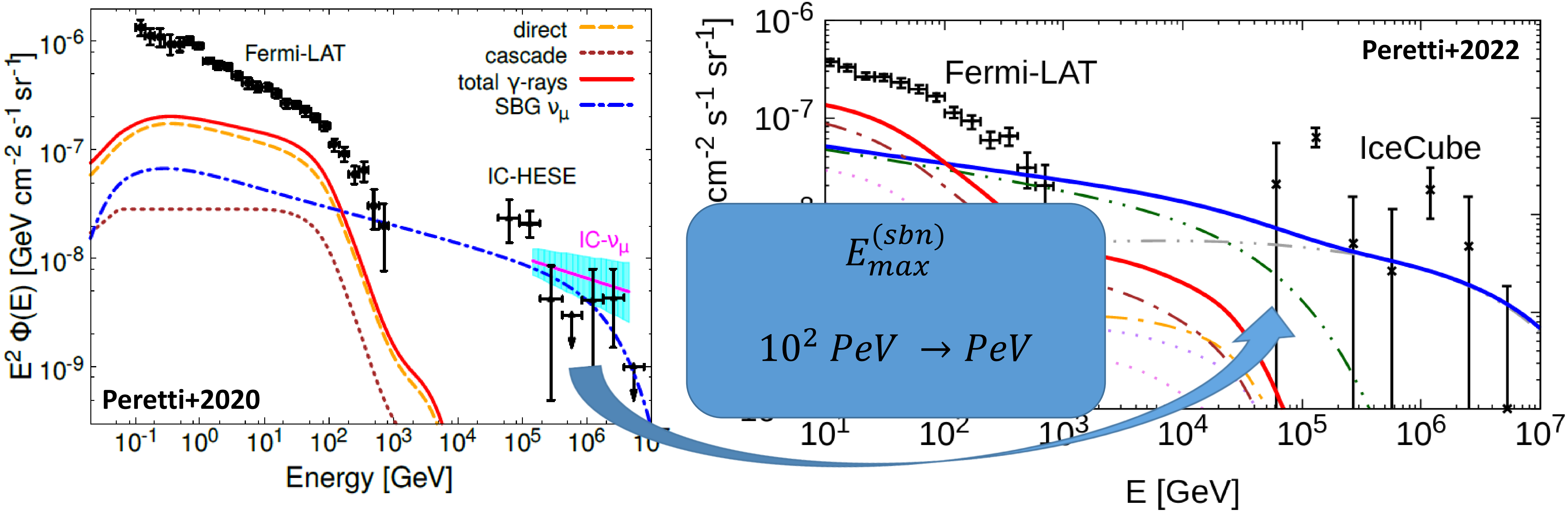
- SBNi only
- Sizeable contribution to the diffuse flux observed by Fermi-LAT
- Neutrino flux at the level of IceCube measurment

Diffuse emission from Starburst Winds

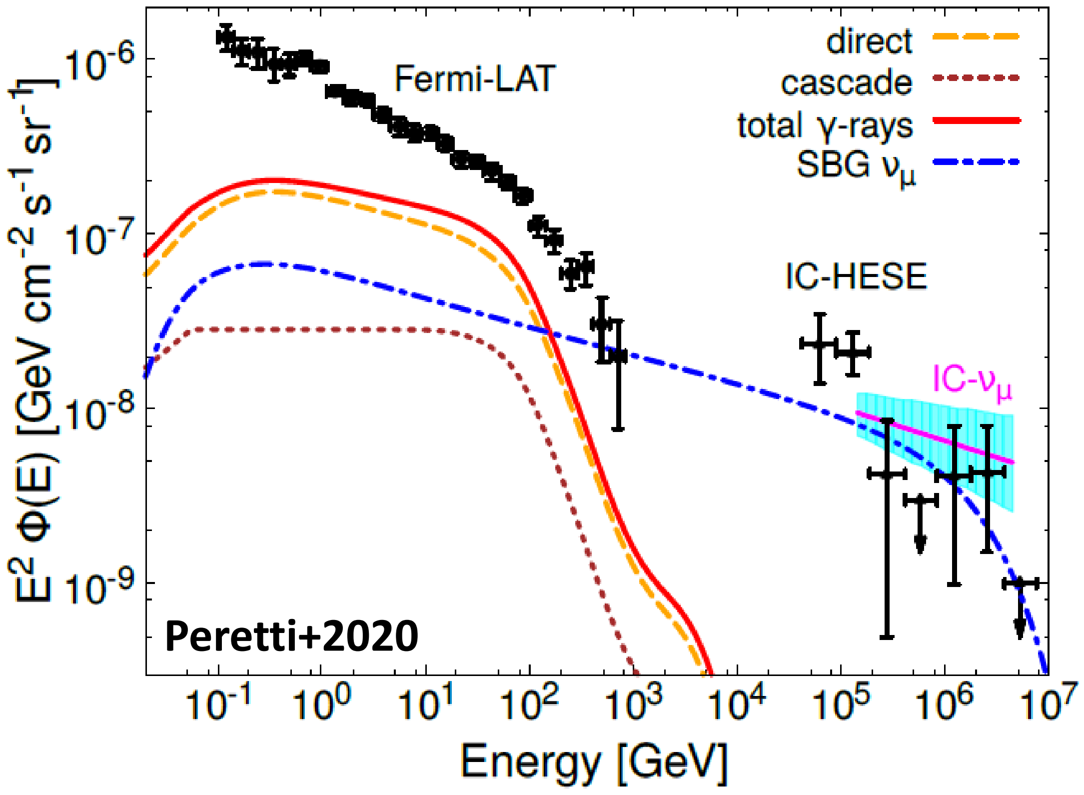


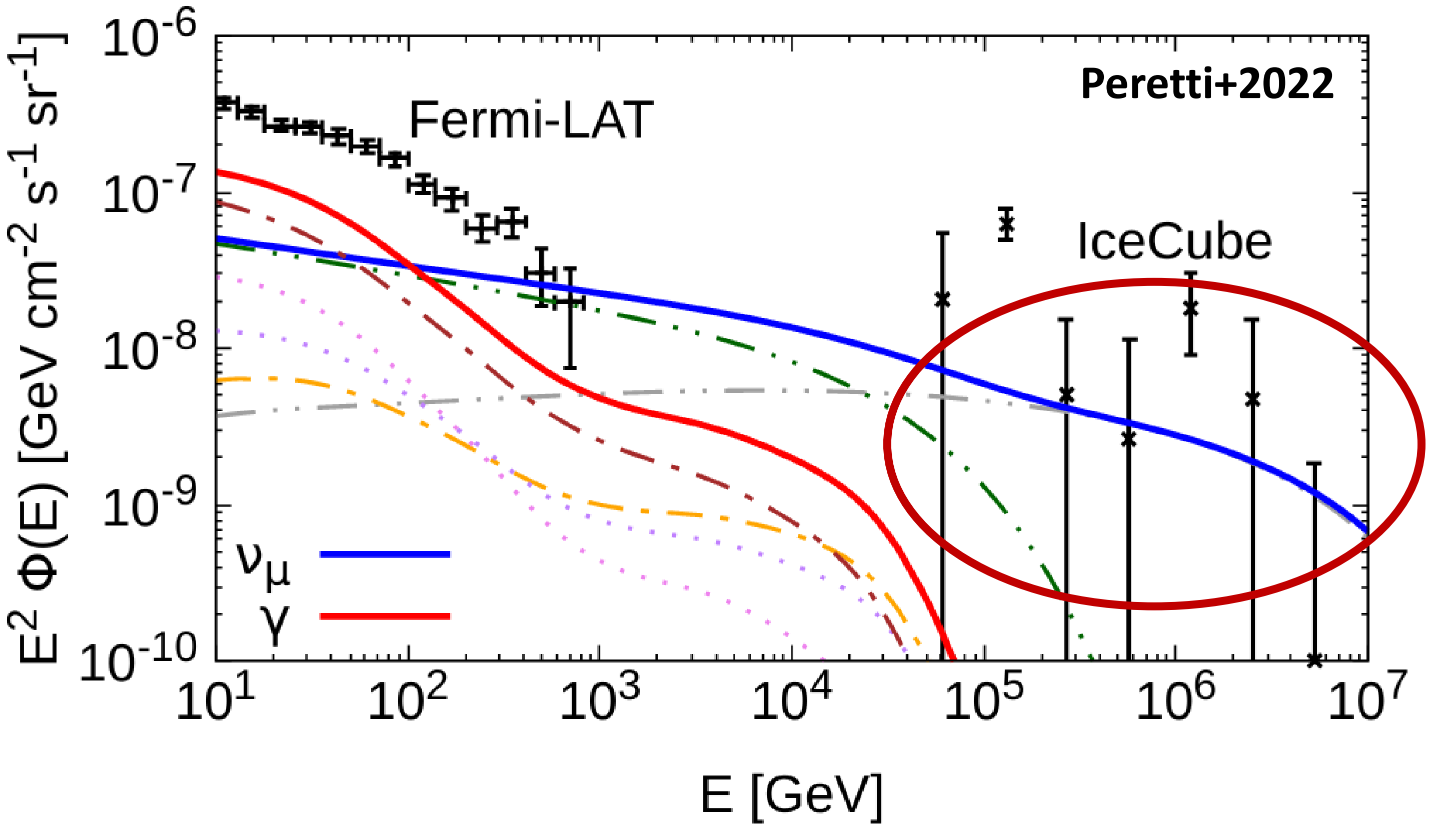


Diffuse emission from Starburst Winds

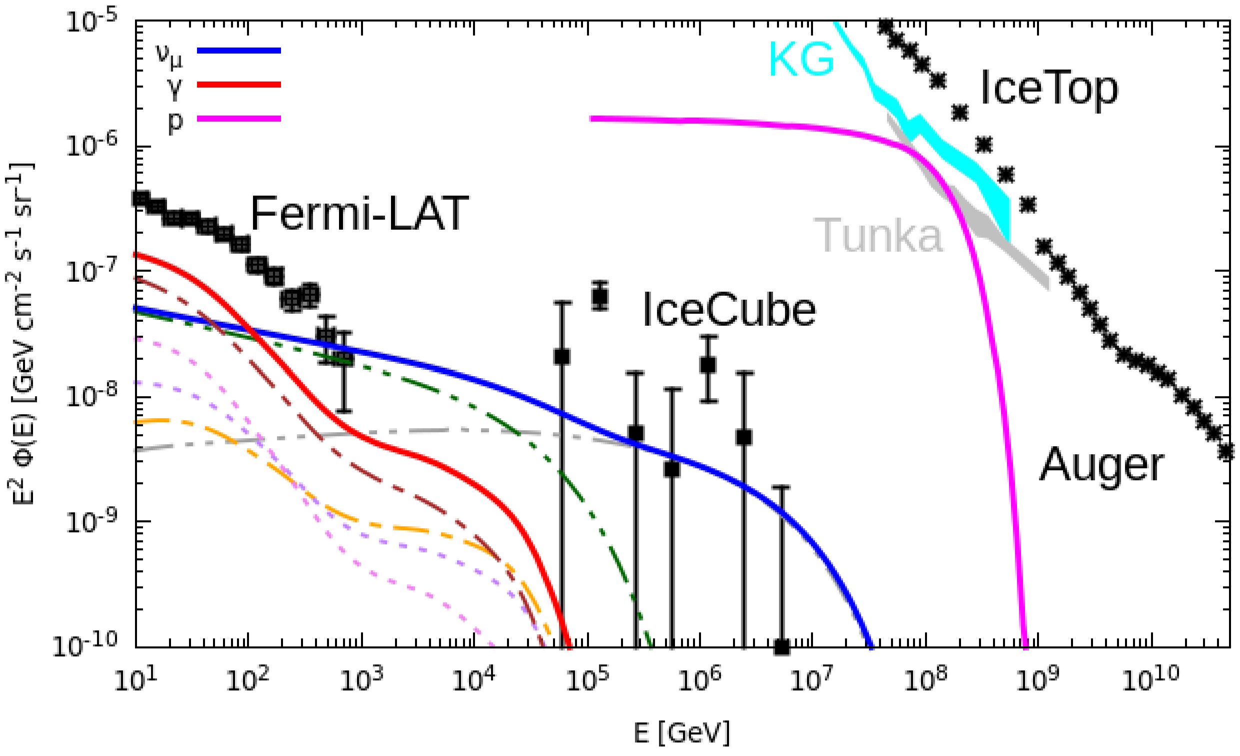


Diffuse emission from Starburst Winds

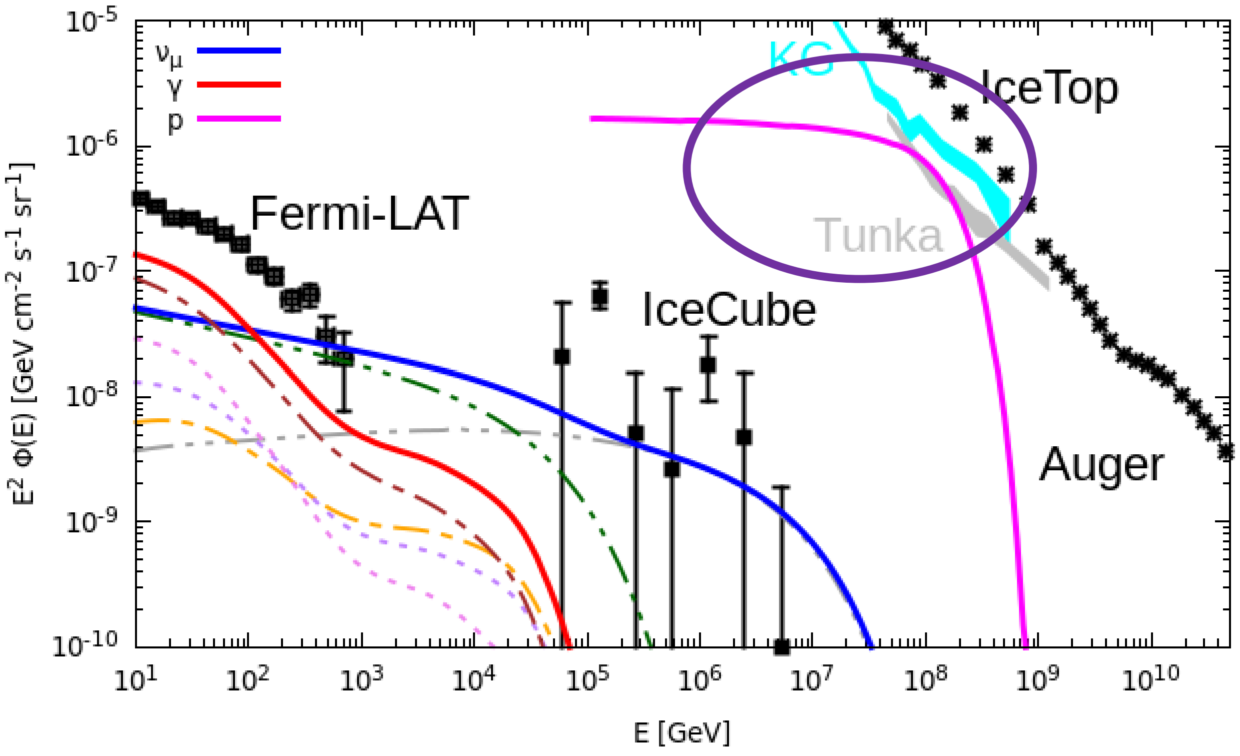


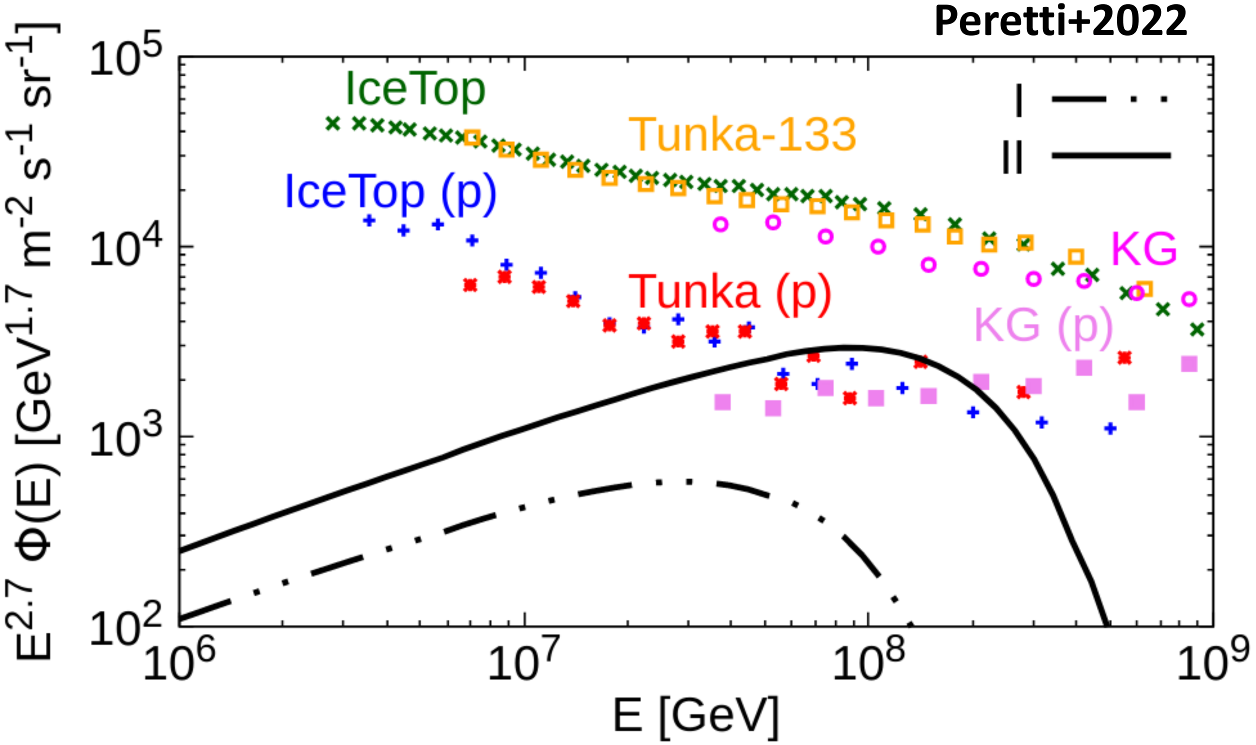


Multimessenger emission from Starburst Galaxies and their winds

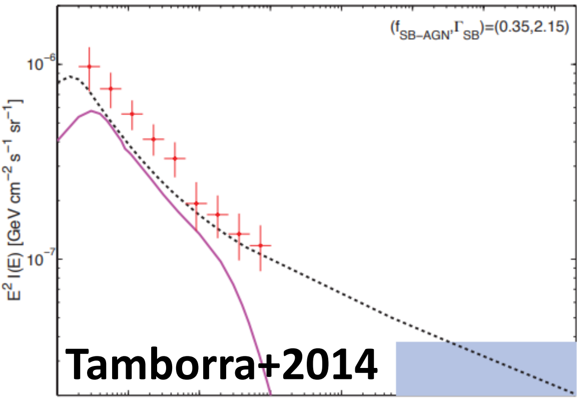


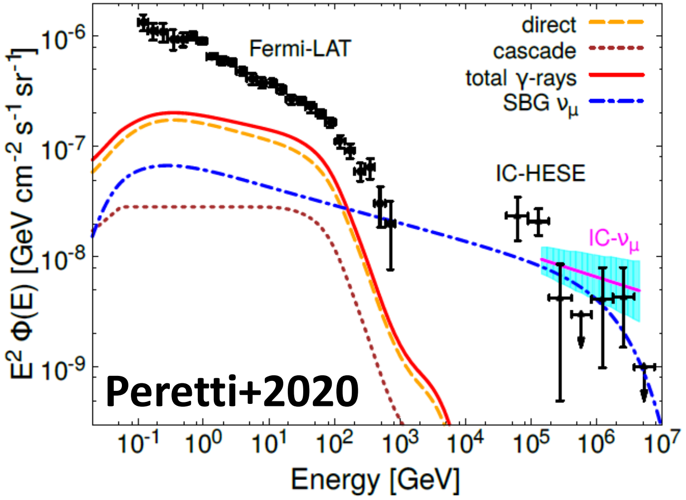
Multimessenger emission from Starburst Galaxies and their winds

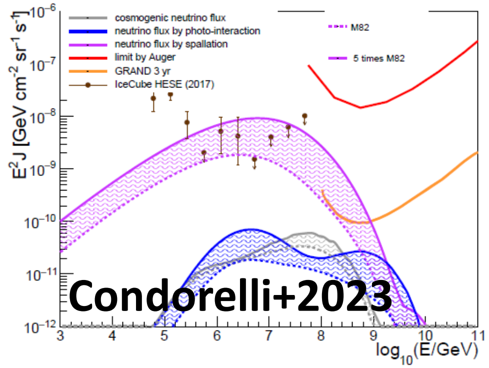


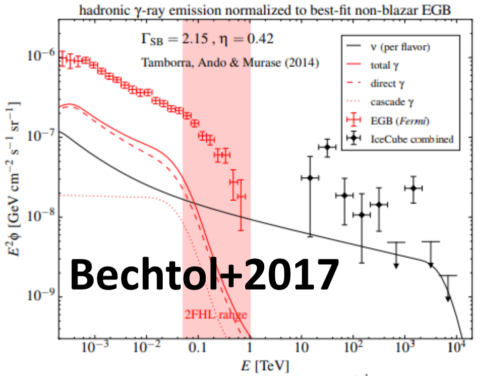


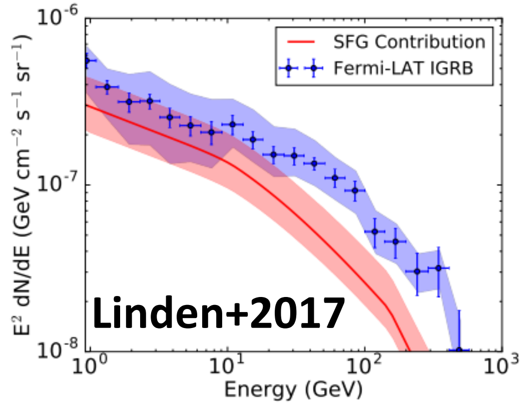
Starbursts in the last 10 years

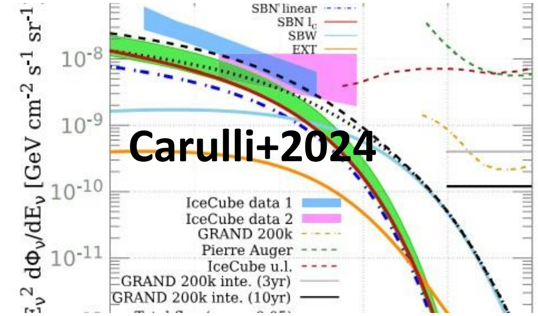


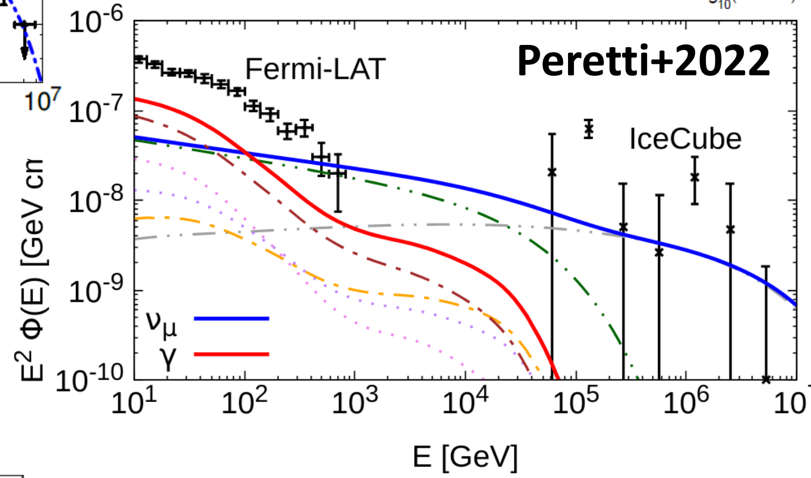


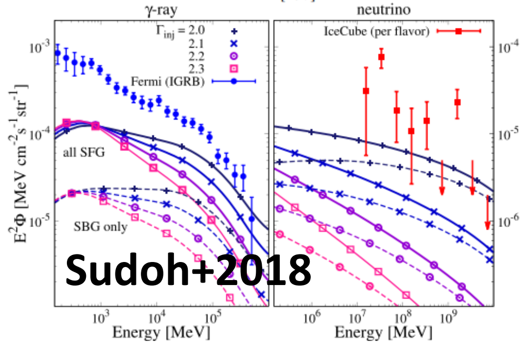


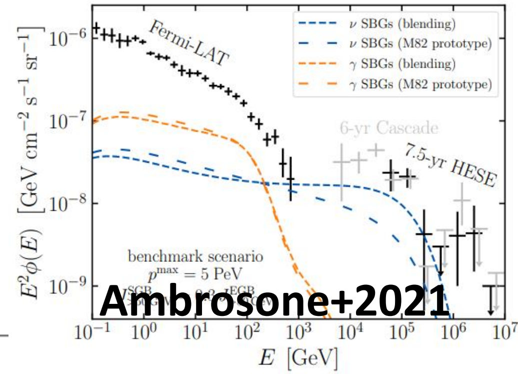


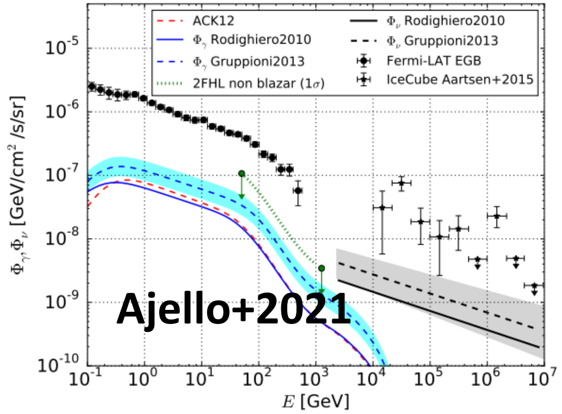


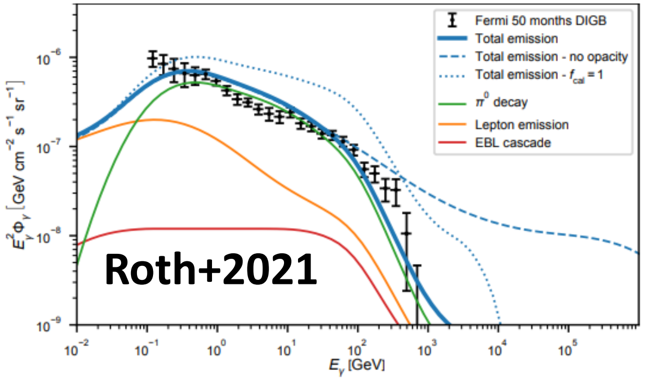


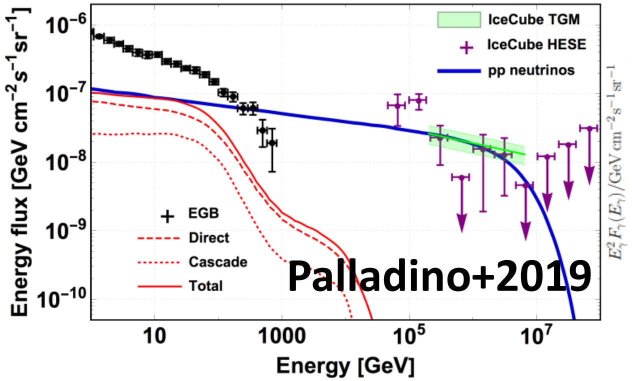


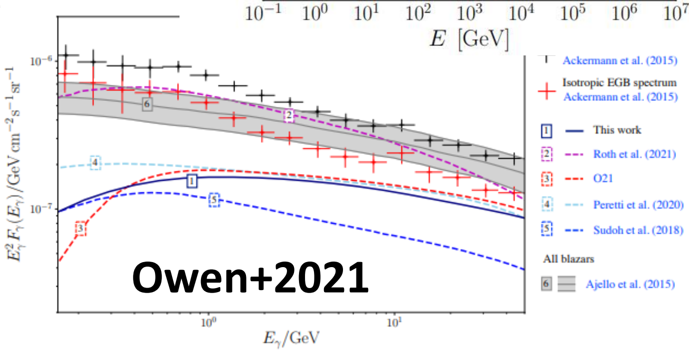




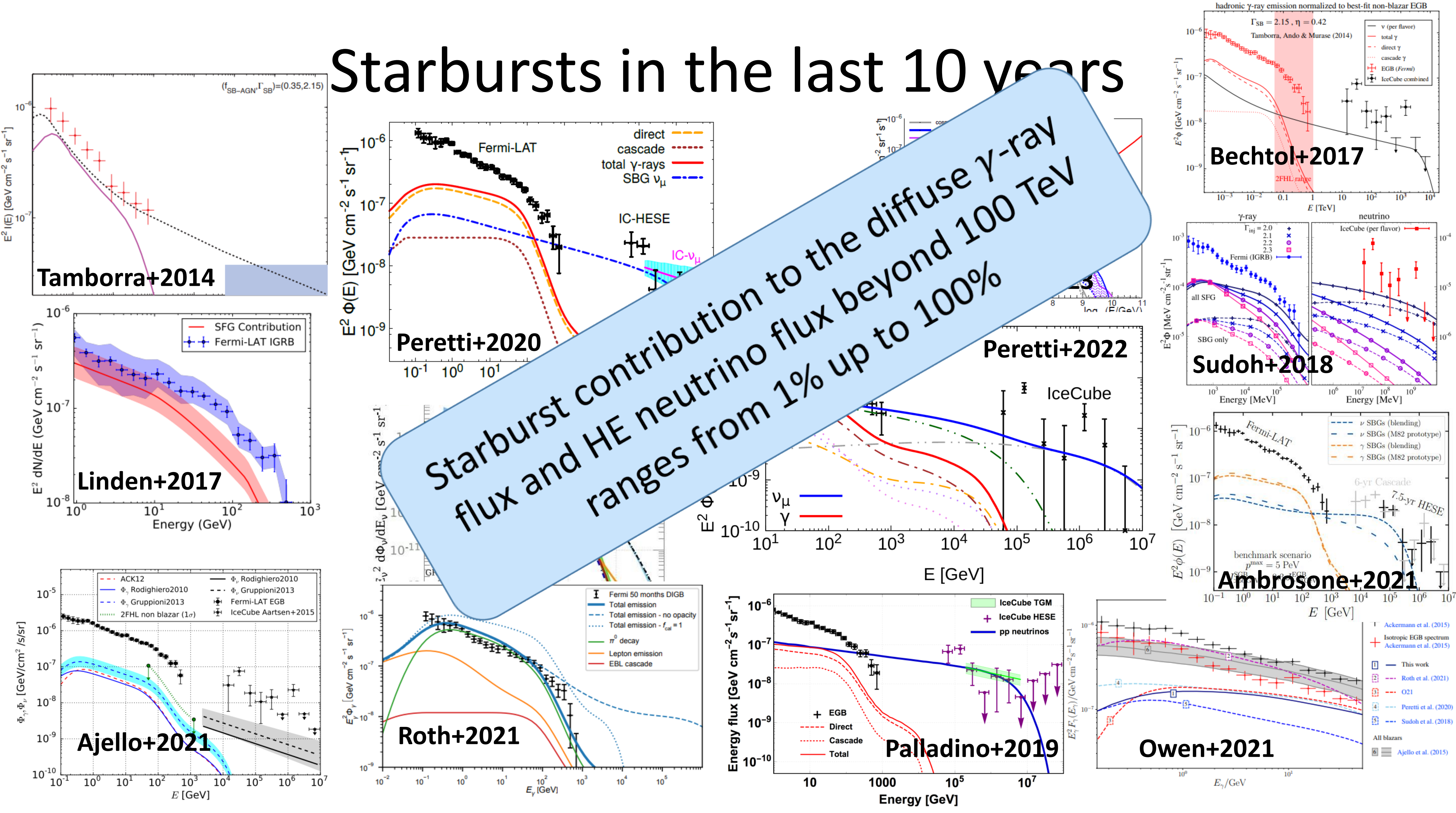




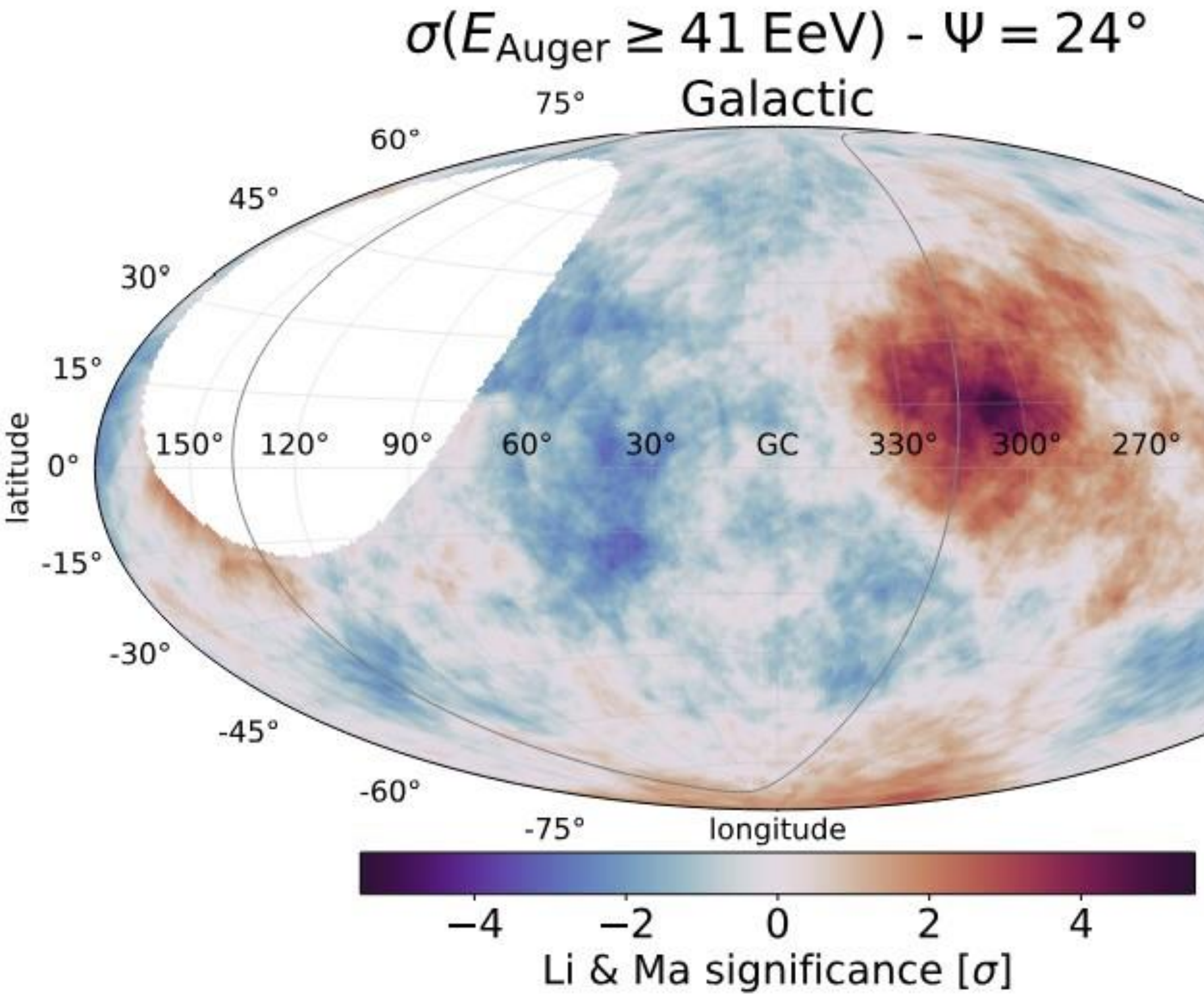




Starbursts in the last 10 years

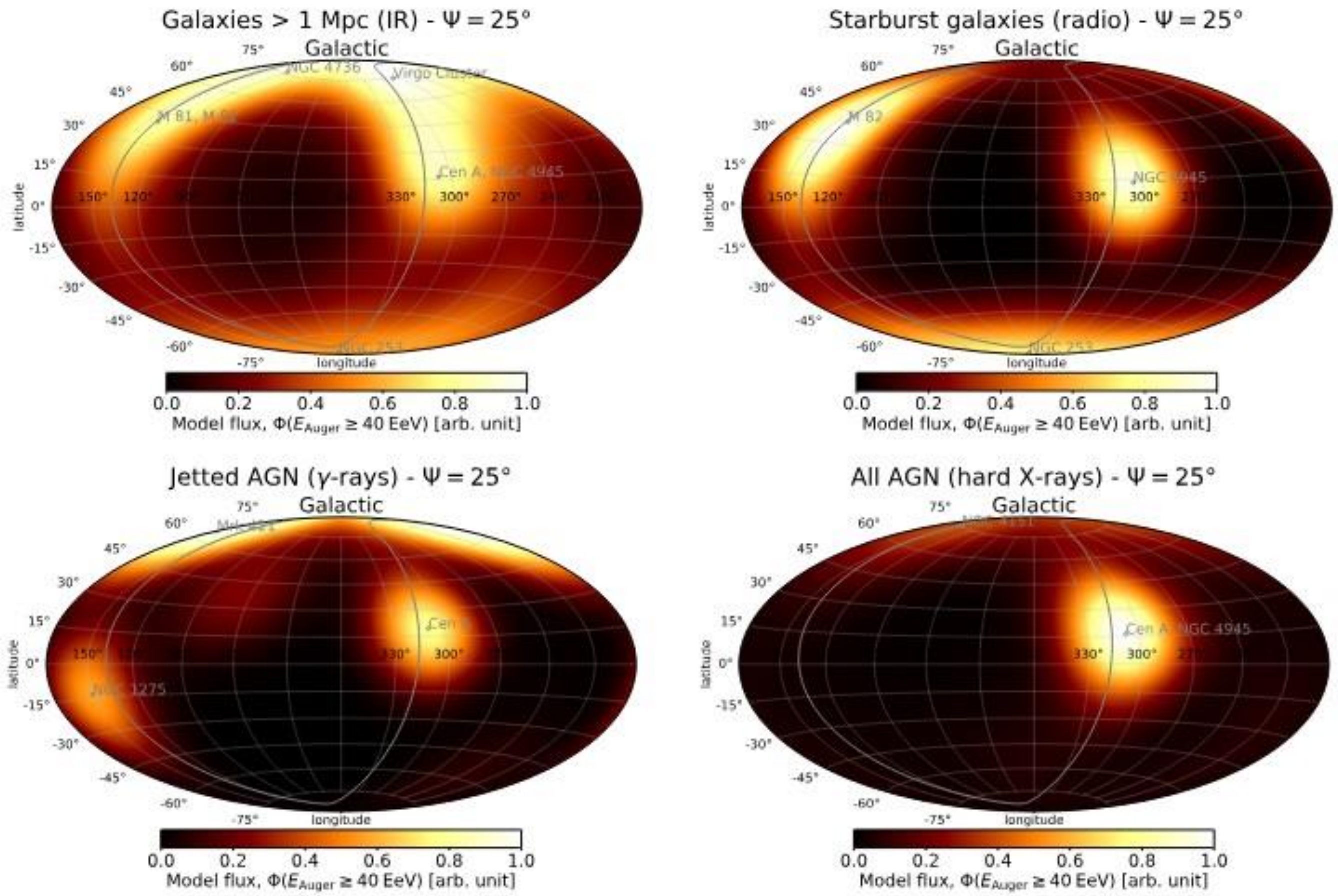


Starbursts and Ultra-High-Energy cosmic rays

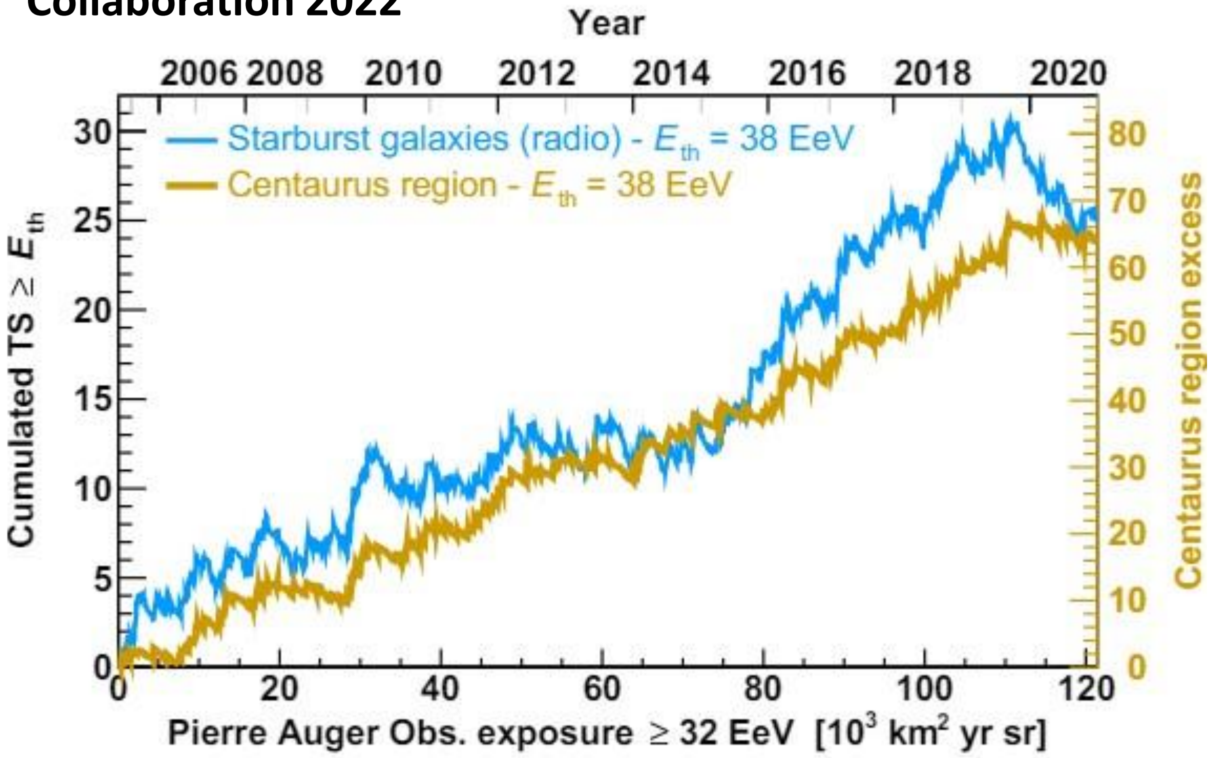


The Pierre Auger Collaboration 2022

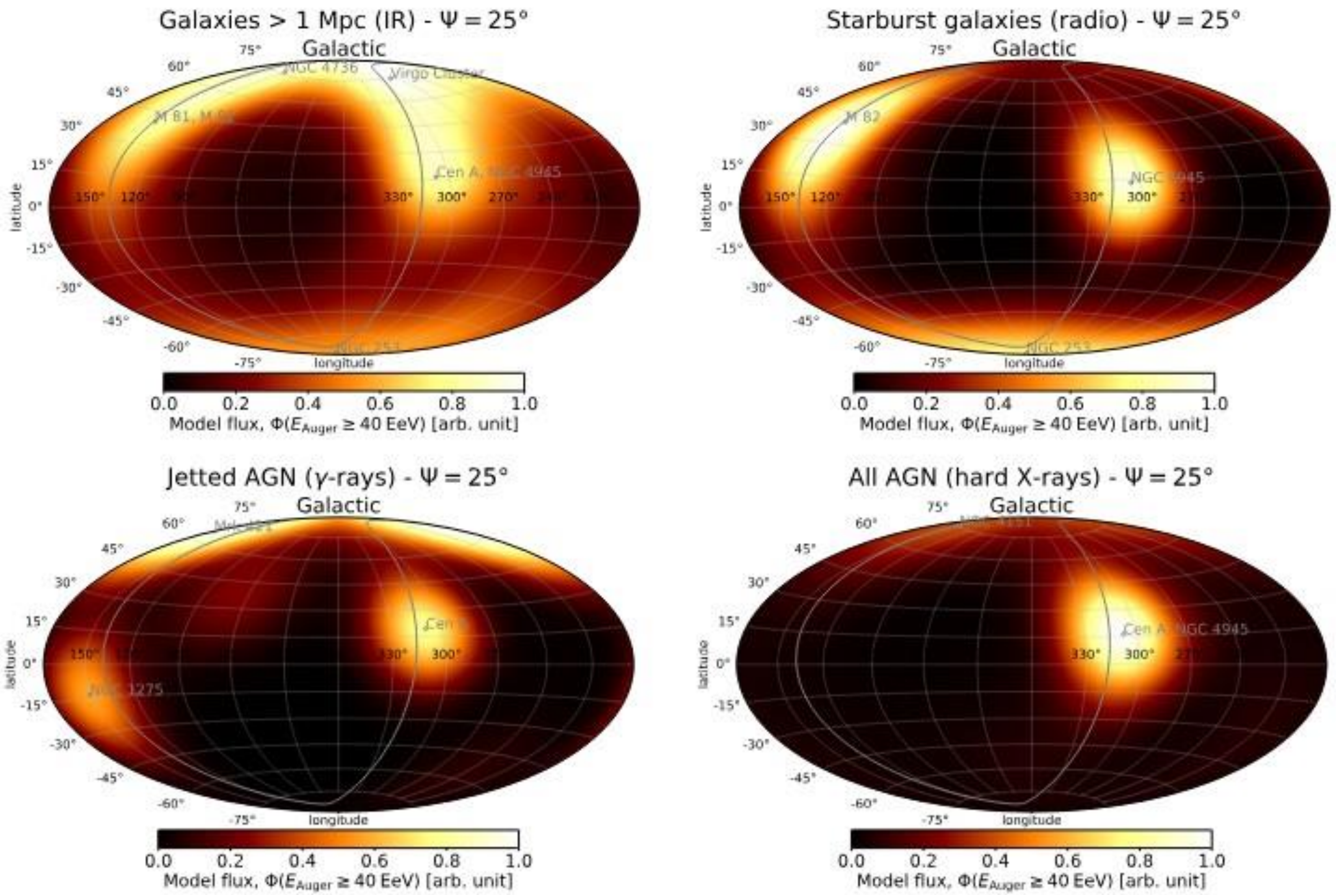
Starbursts and Ultra-High-Energy cosmic rays



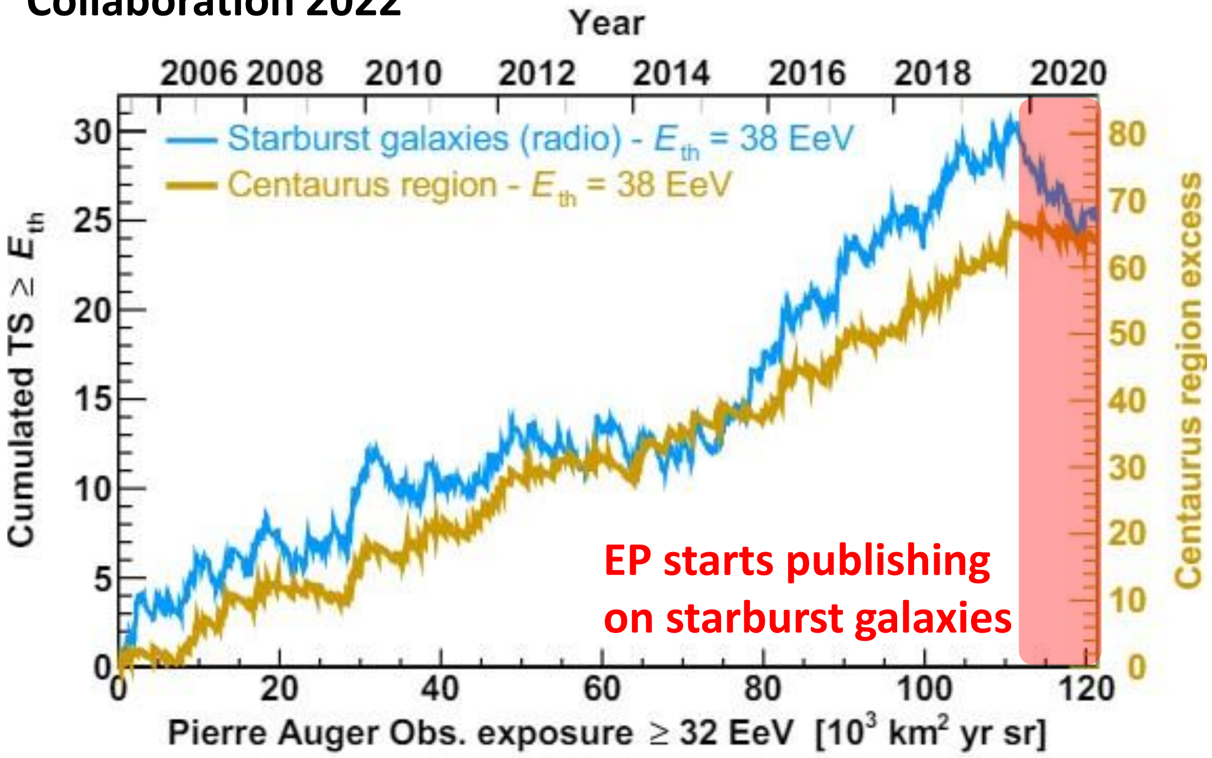
The Pierre Auger Collaboration 2022



Starbursts and Ultra-High-Energy cosmic rays



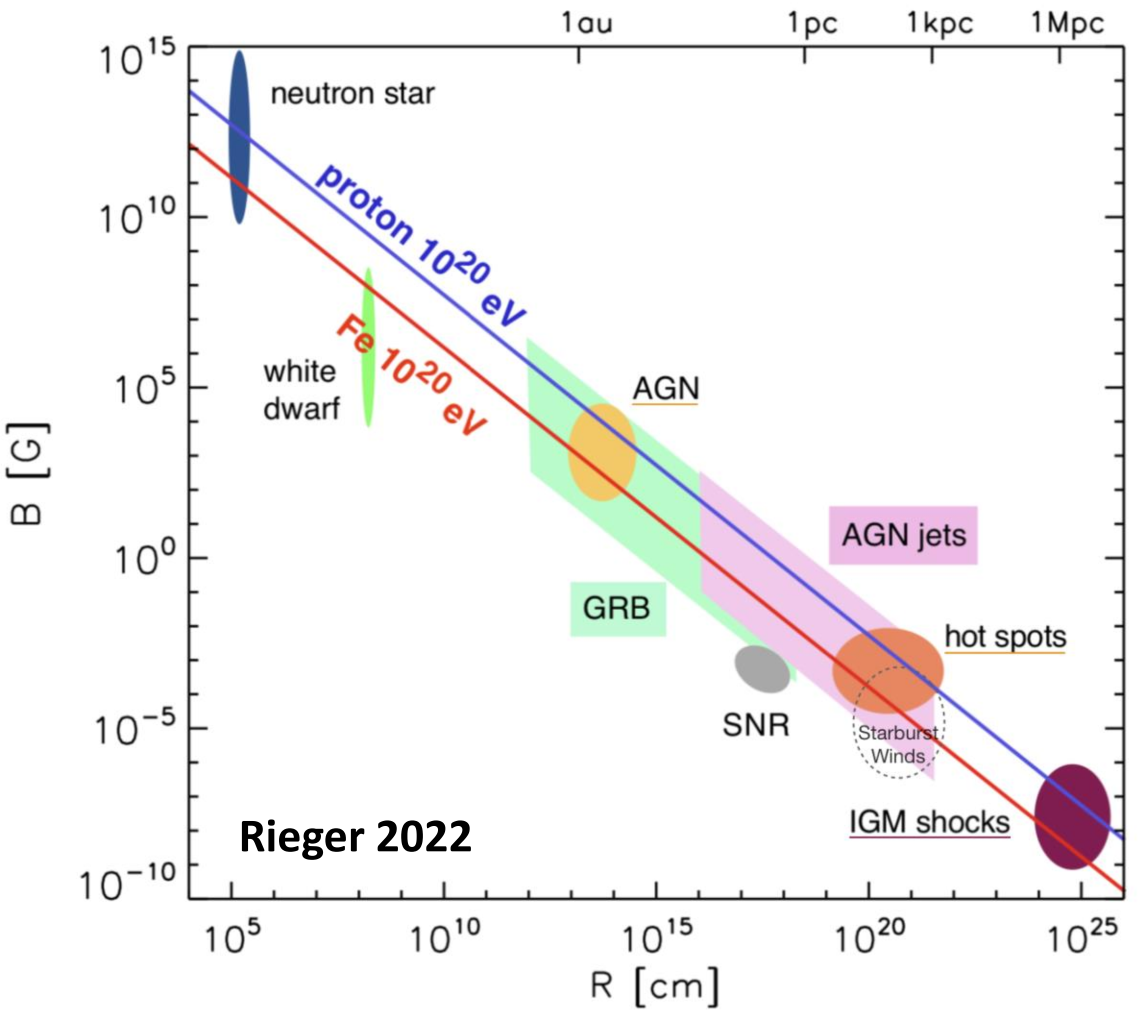
The Pierre Auger Collaboration 2022



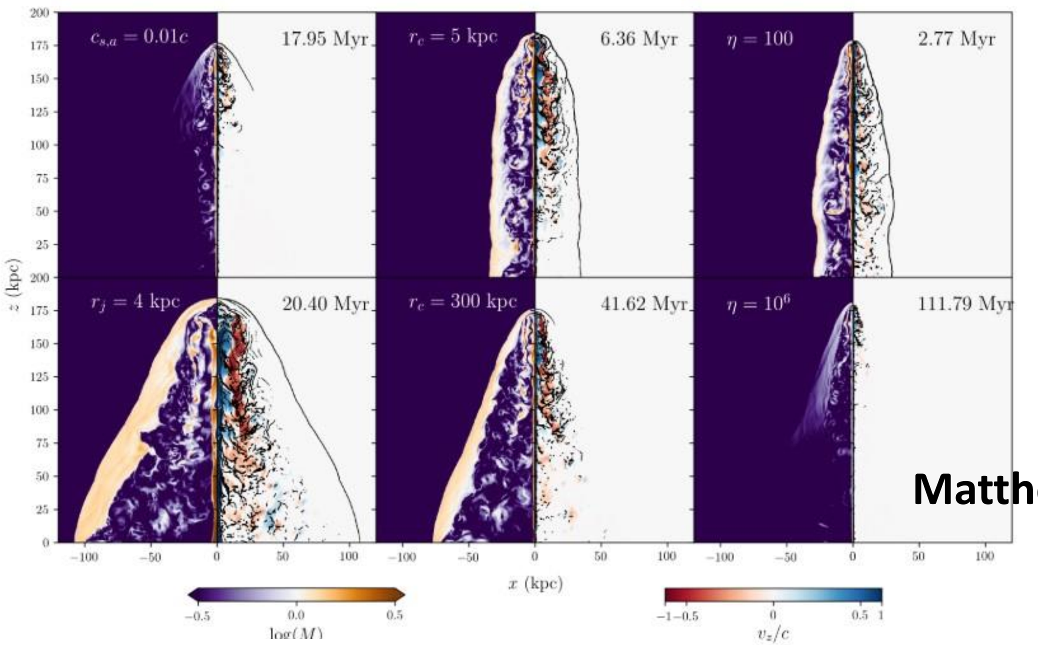
UHECR accelerators in starburst galaxies

- Starburst winds could possibly exceed our prediction of DSA only and reach the limit allowed by Hillas

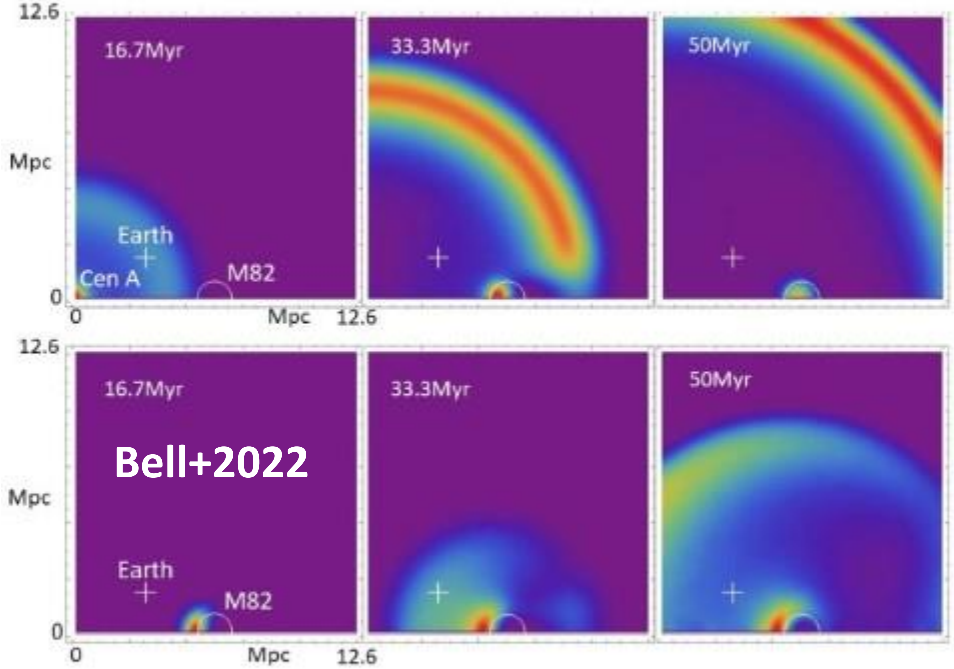
- Sub-galactic-sized objects such as Gamma-Ray Bursts might be the sources as they are more likely to happen where the star formation is higher



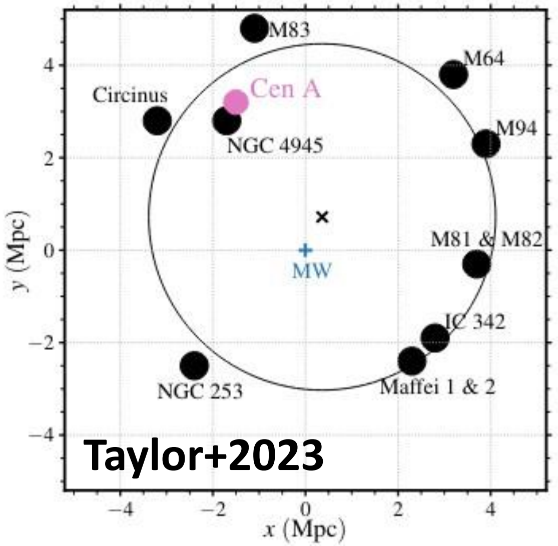
Alternative scenario: Echoes of Cen A activity



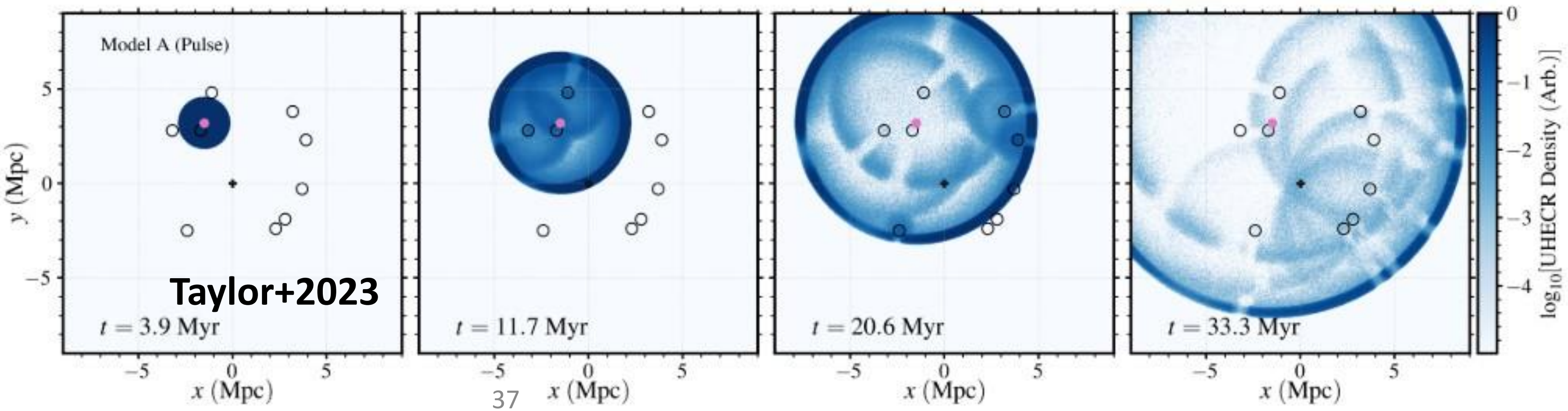
Matthews+2018



Bell+2022

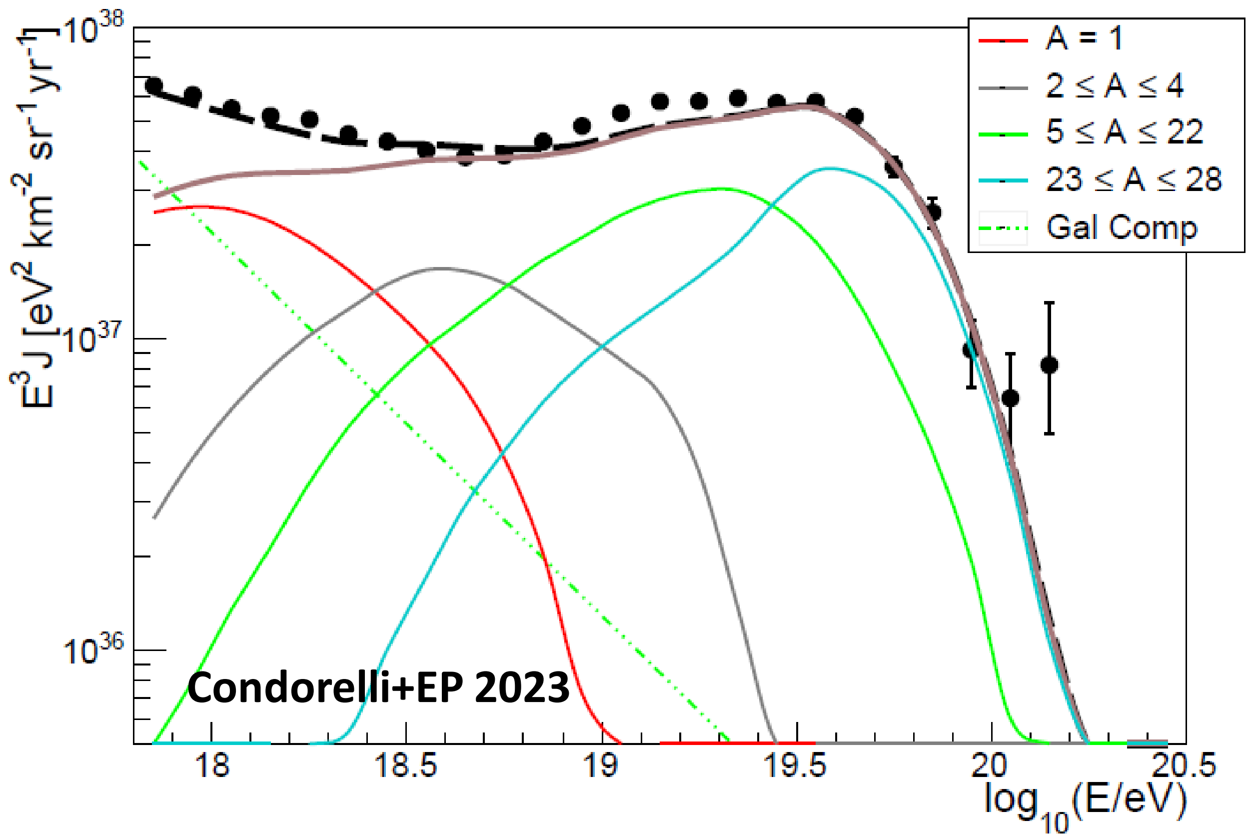


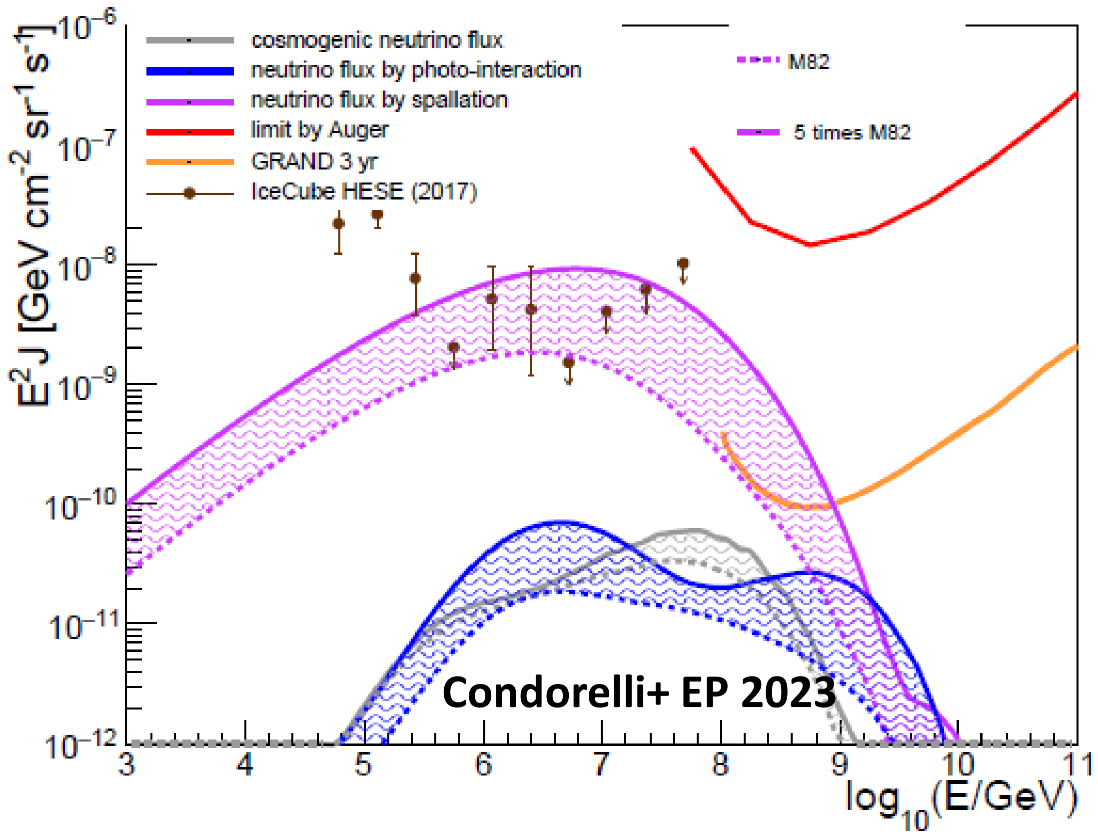
Taylor+2023



Taylor+2023

Ultra-High-Energy cosmic rays in starbursts

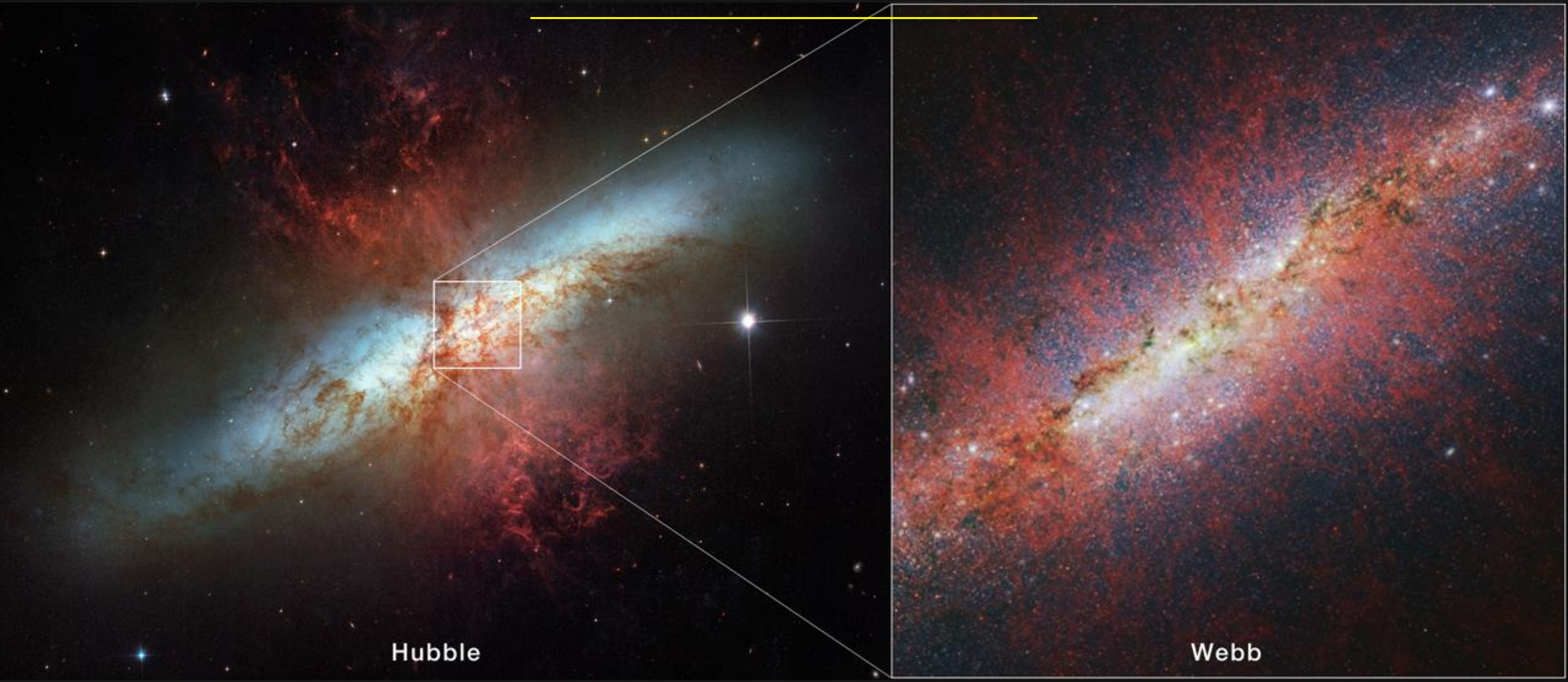




Take home messages

1. Star forming galaxies (SFGs) are cosmic-ray factories
2. Starburst nuclei (SBNi) can approach calorimeteric conditions
3. Starburst winds can accelerate cosmic rays up to 100 PV in rigidity through DSA
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 → promising observation perspectives!
7. Are SBGs the sources of UHECRs?

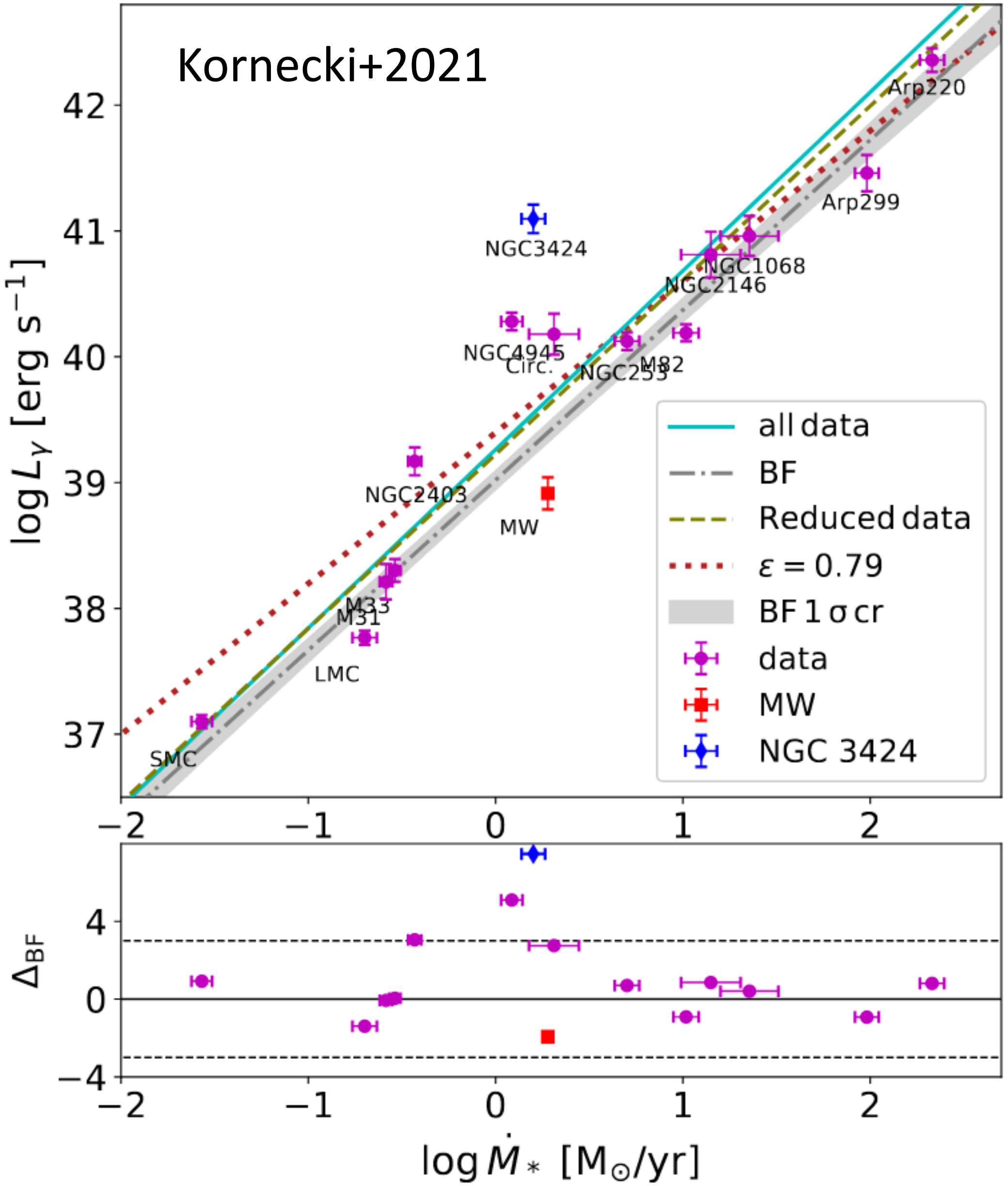
THANK YOU!



Starburst galaxy M82 – NASA, ESA, CSA, STScI, A. Bolatto

Back up

The starburst of NGC 1068



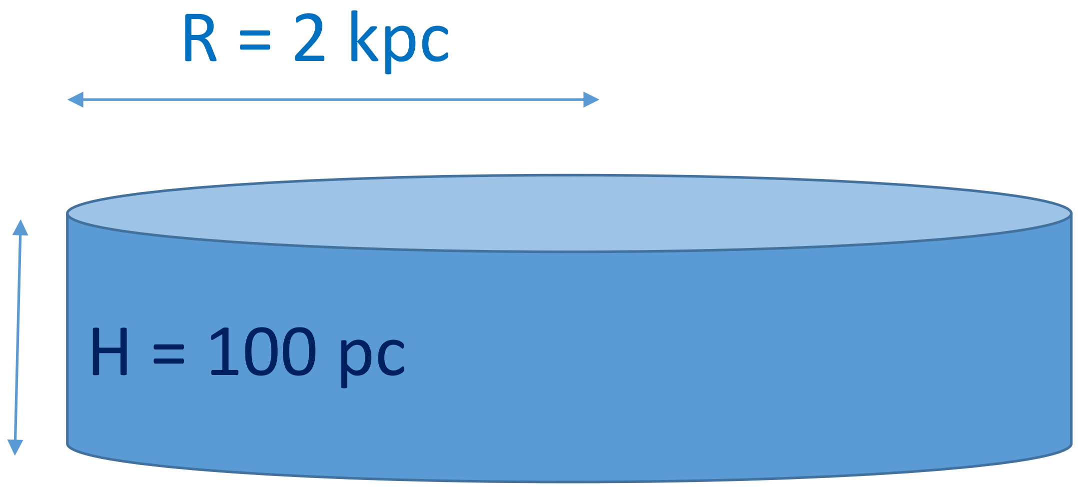
B-vi

The starburst of NGC 1068

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

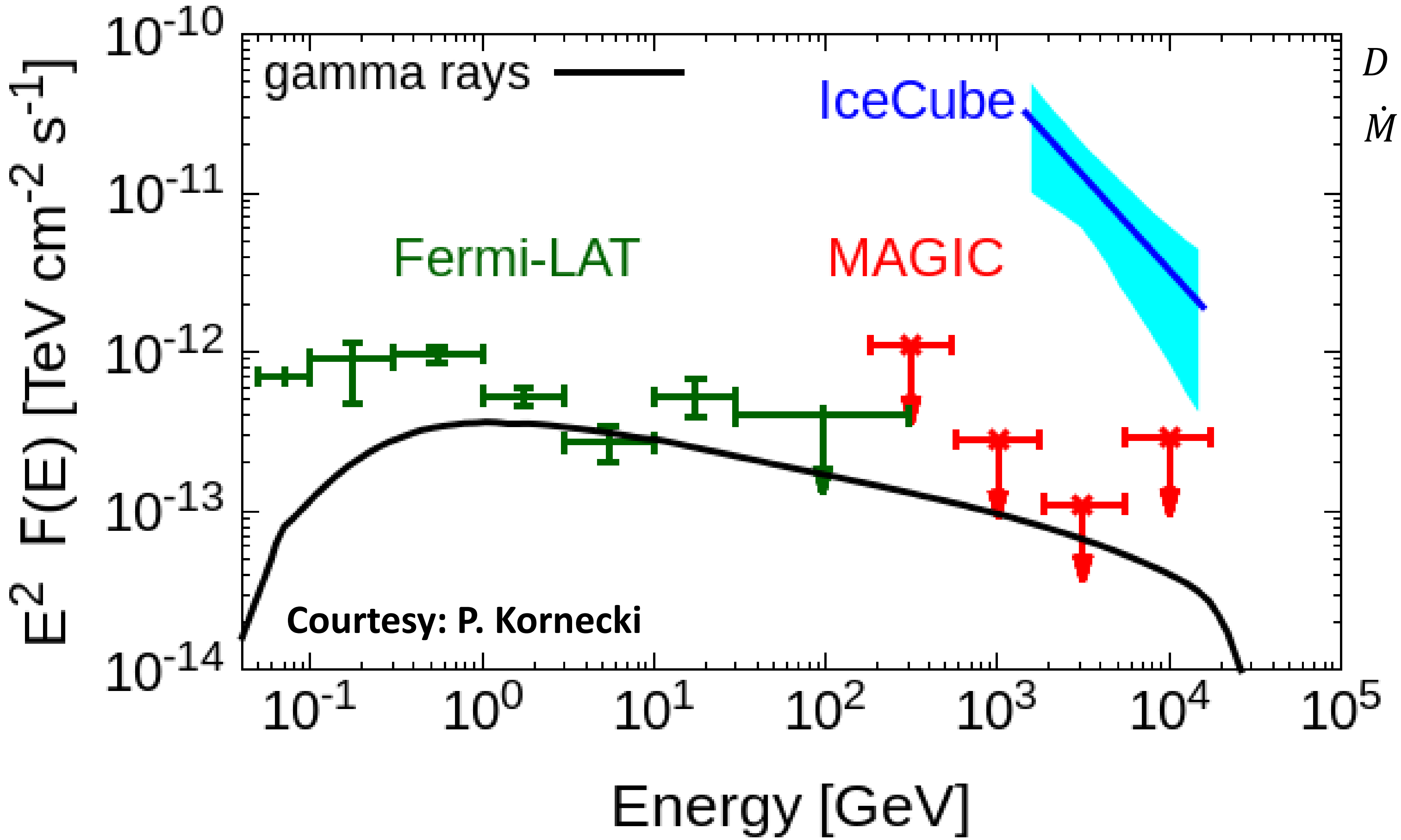
$$\tau_{diff}(GeV) \approx 10^5 \left(\frac{H}{10^2 pc}\right)^2 \left(\frac{D}{10^{28} cm^2/s}\right)^{-1} yr$$

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



Calorimetry is possible but not trivial

The starburst of NGC 1068

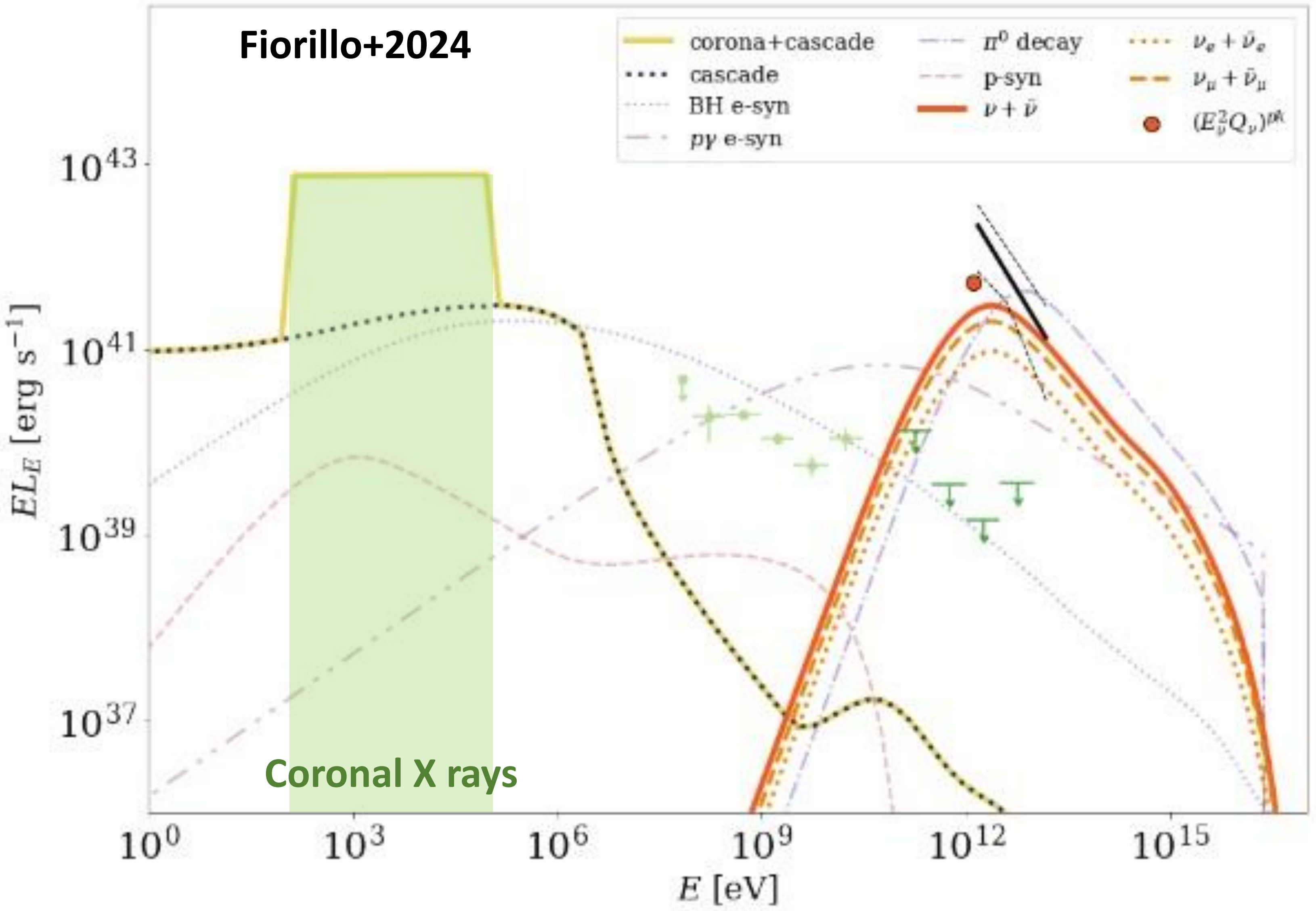


$D = 14.4\ Mpc$

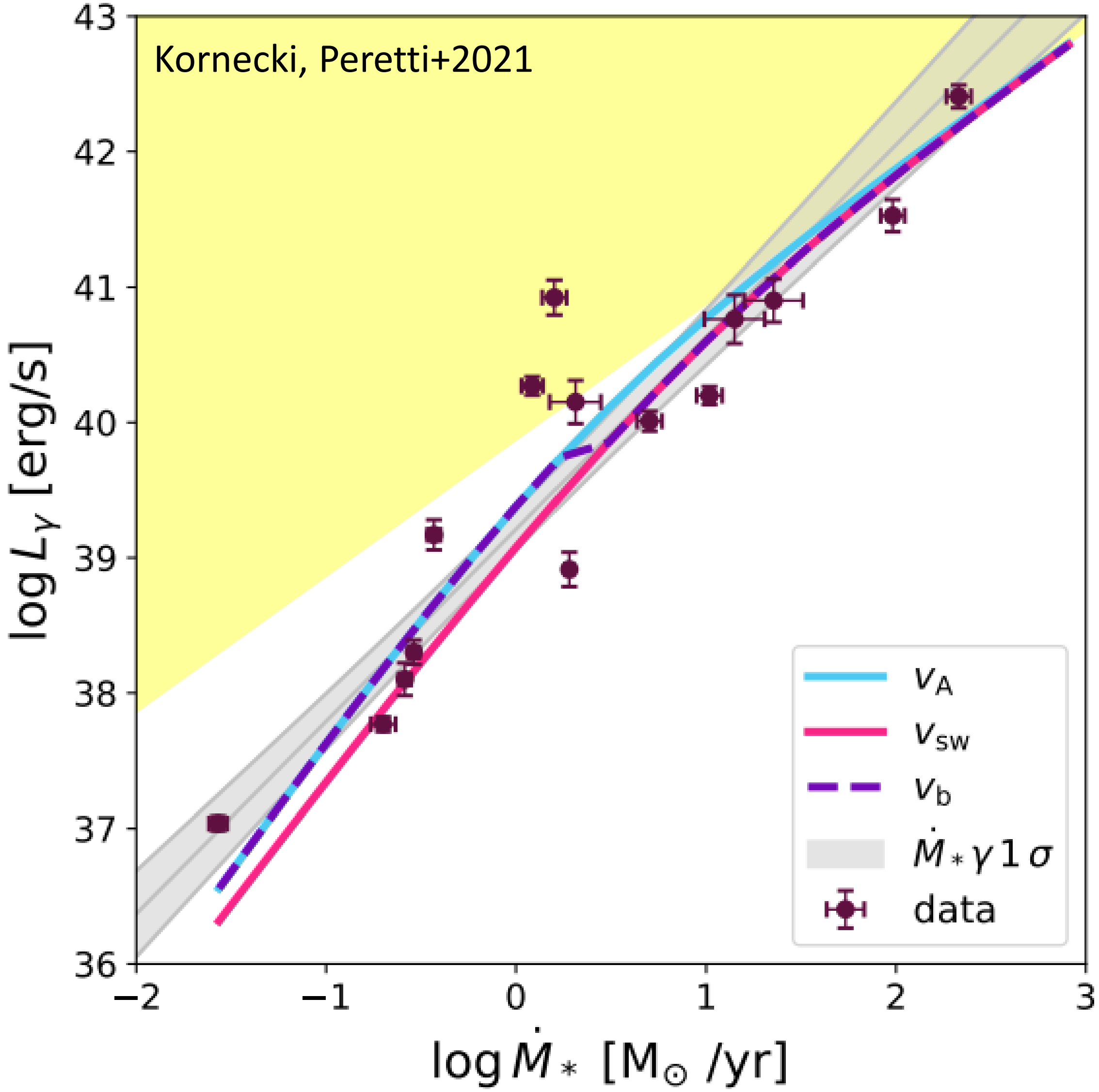
$\dot{M} \approx 20\ M_{\odot} yr^{-1}$

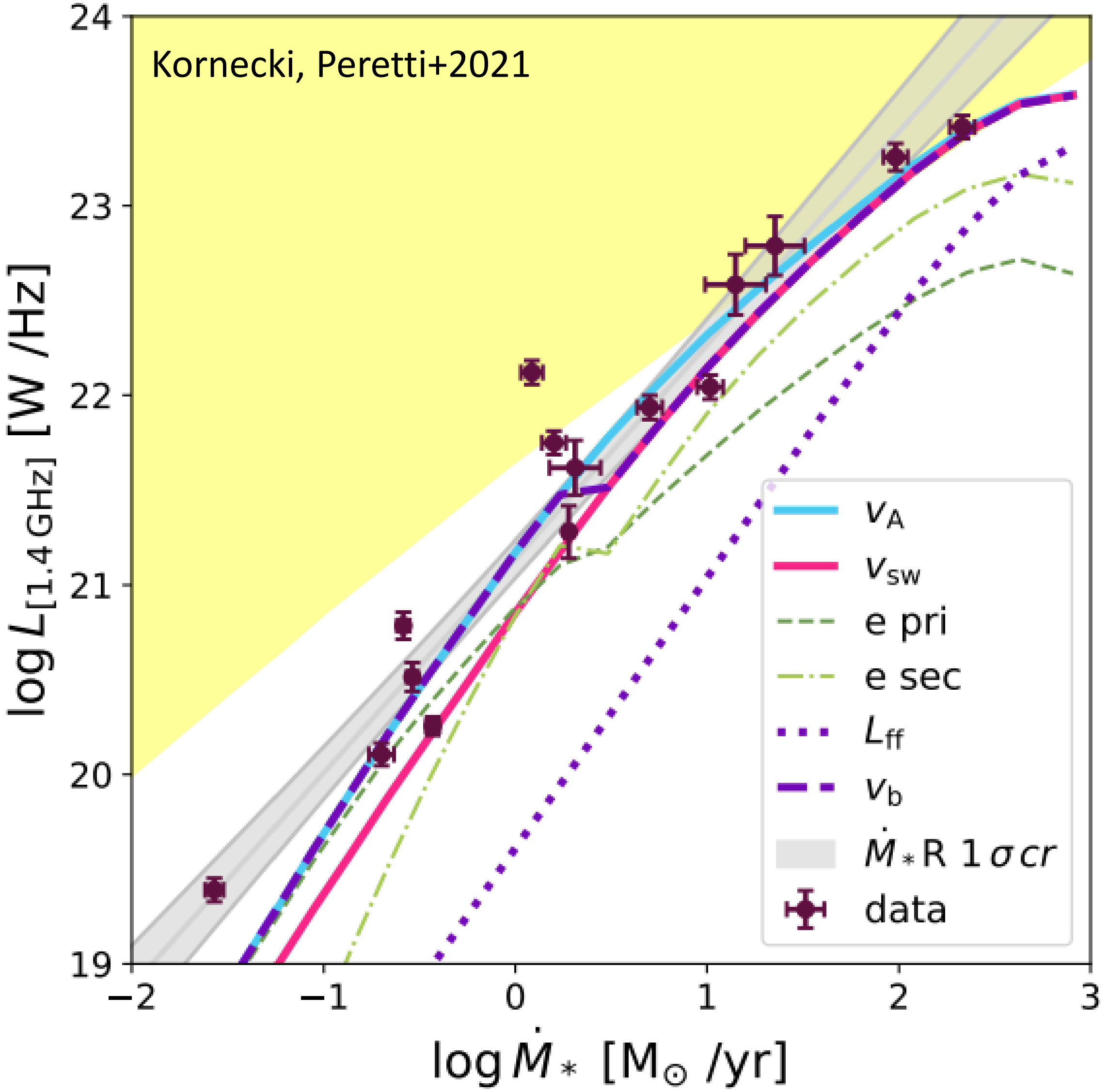
The starburst of NGC 1068

Acceleration via relativivistic magnetic reconnection in a compact AGN corona surrounding the accreting SMBH



Leaky box model and L—SFR correlations





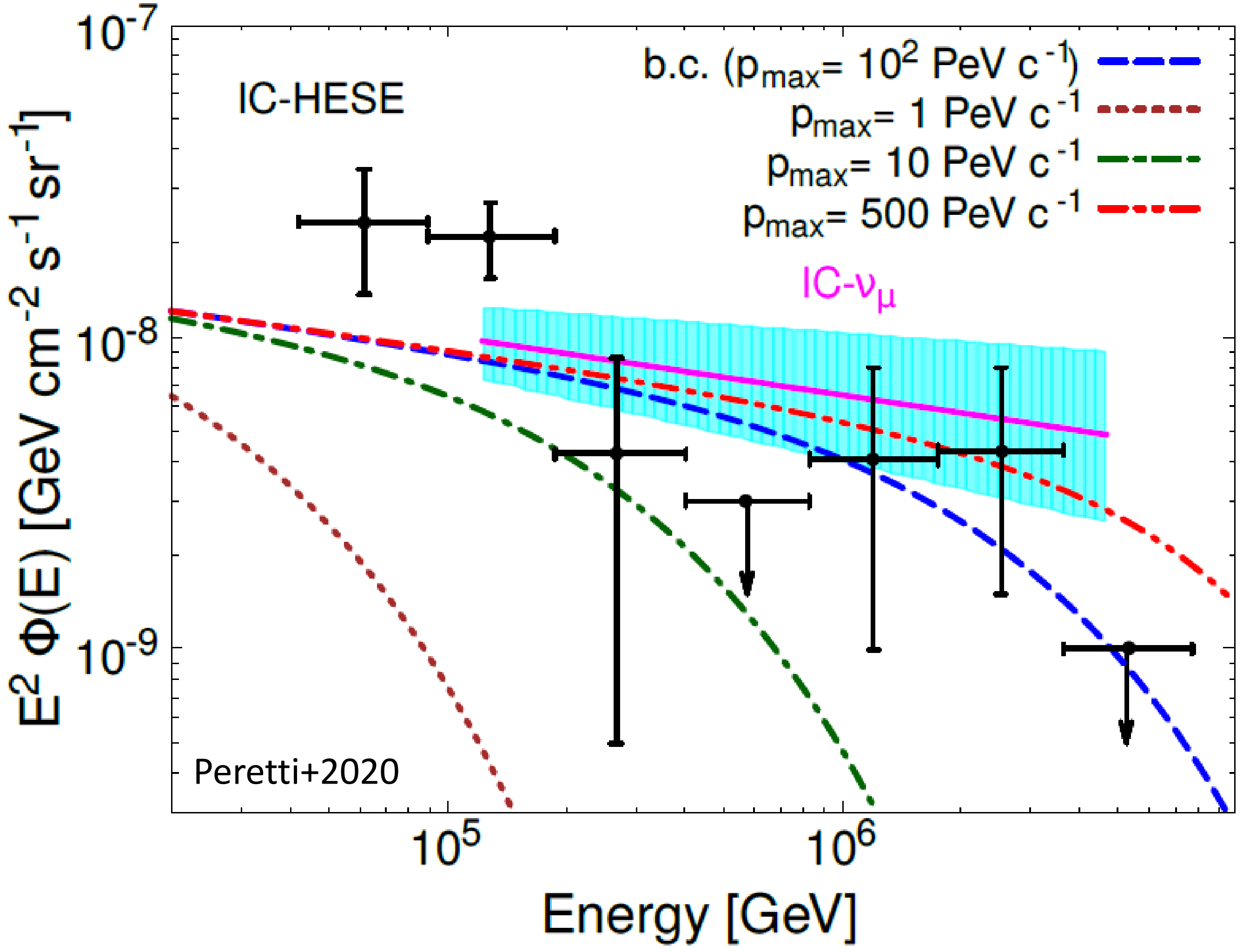
The issue of the maximum energy

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

SNR in case of Bohm diffusion:

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

- Magnetic field amplification can allow reaching 10-100 PeV



Maximum Energy & Luminosity