Particle accelerationand gamma-ray emission from Starburst Galaxies

Enrico Peretti

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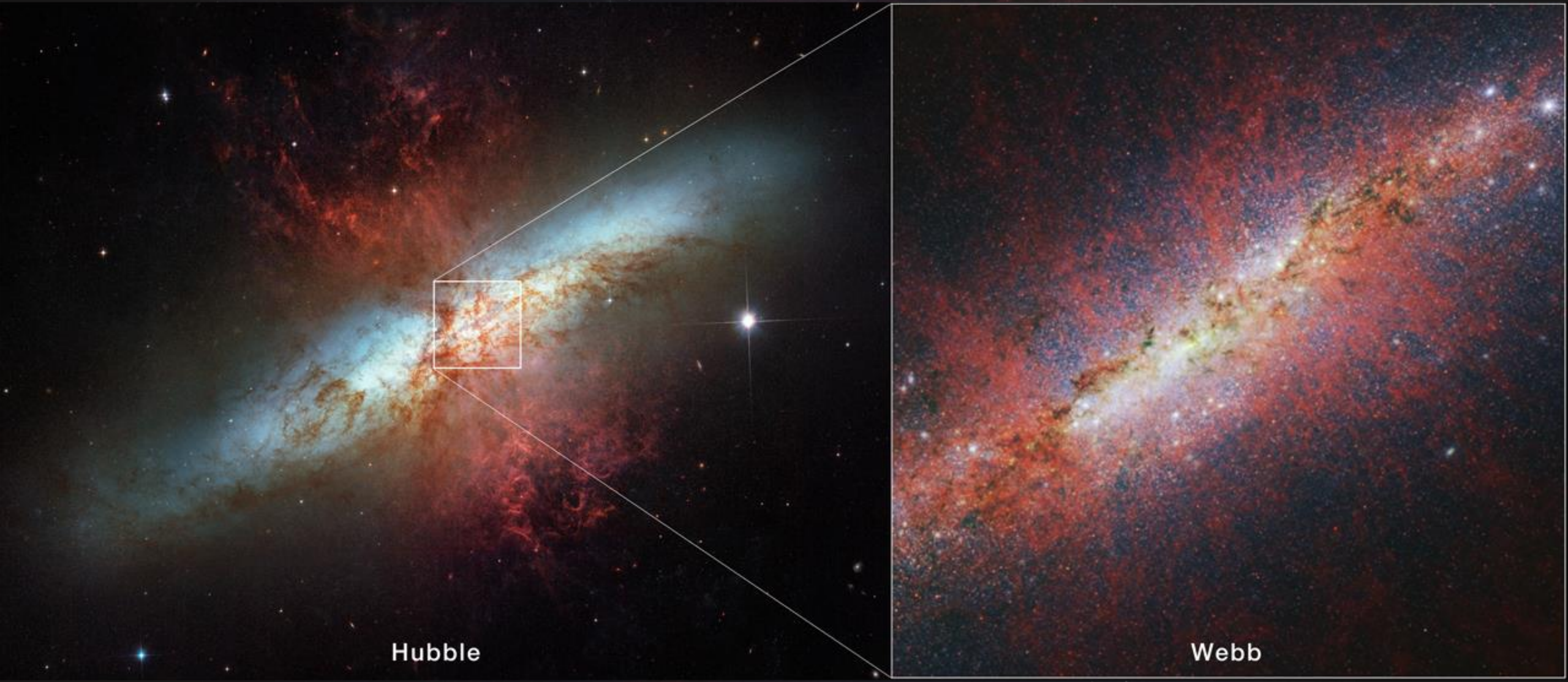
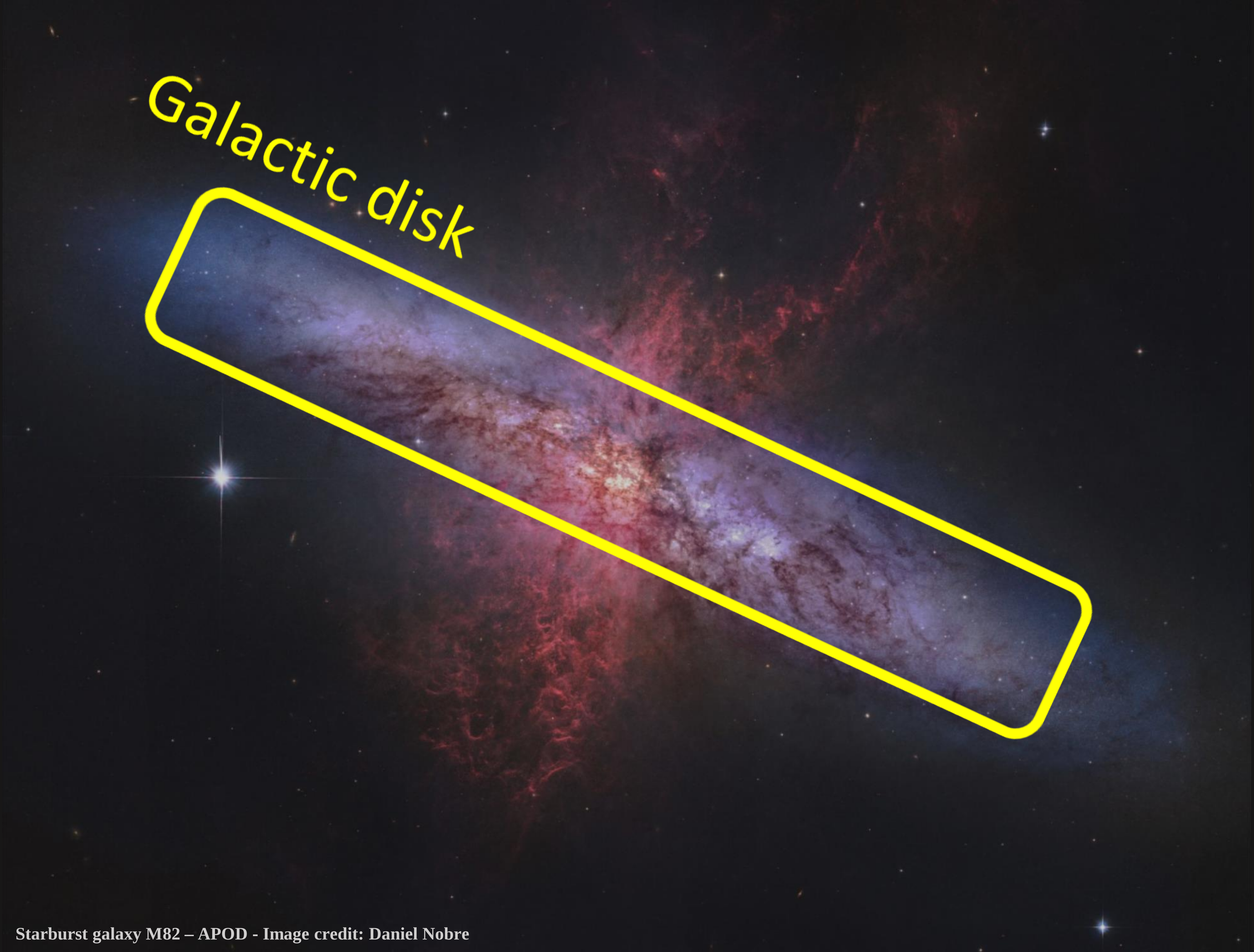
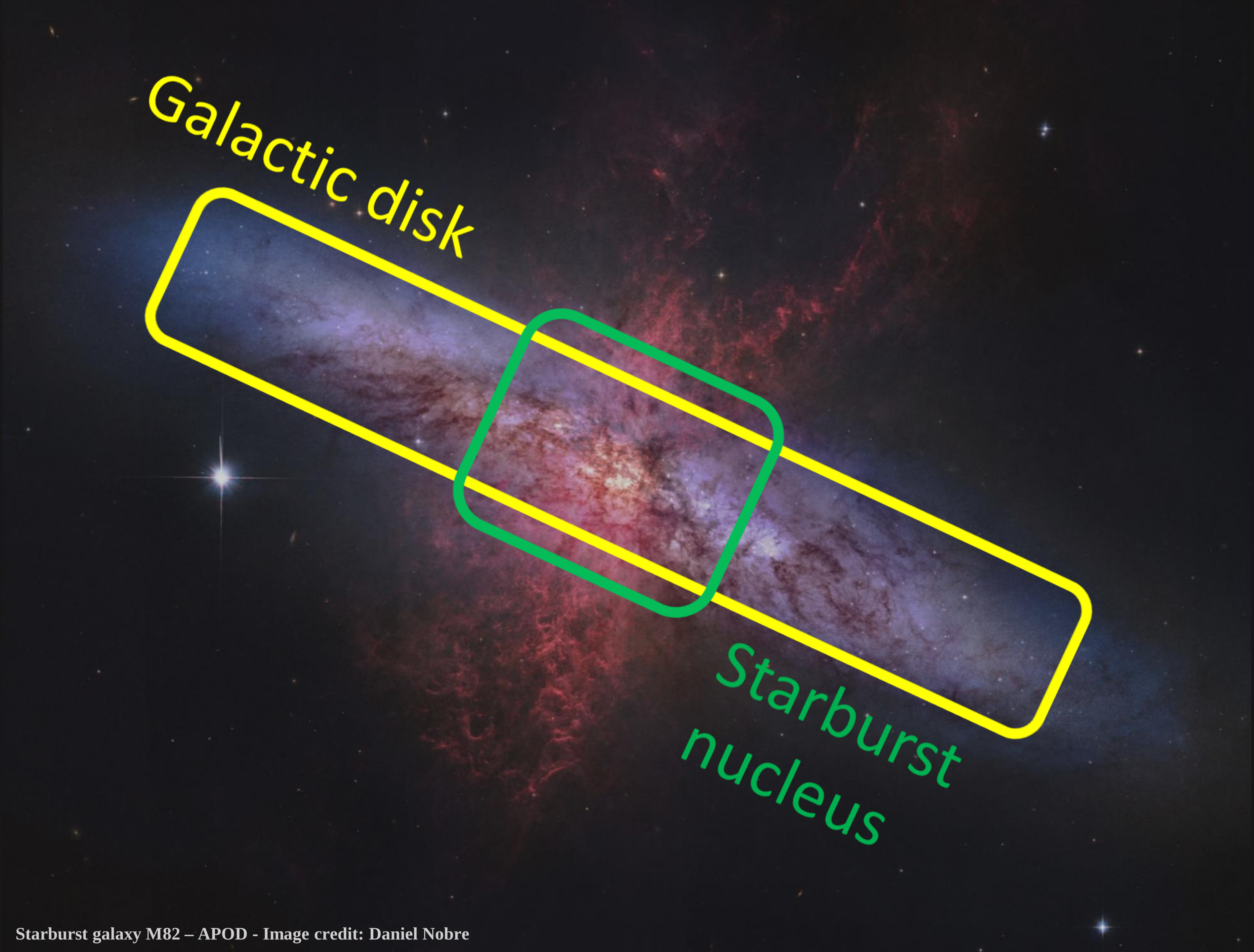


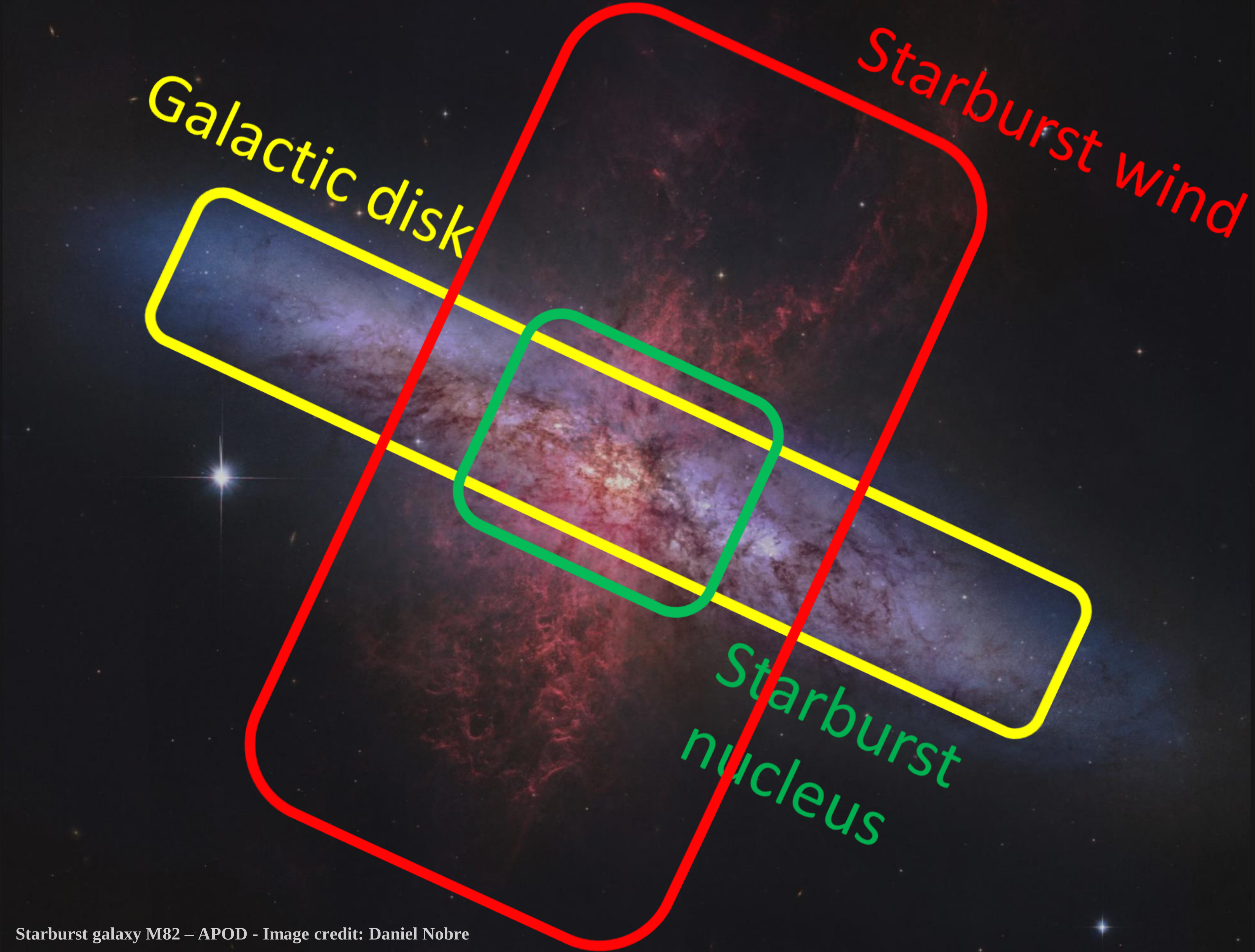
Starburst galaxy M82 – NASA, ESA, CSA, STScI, A. Bolatto



Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

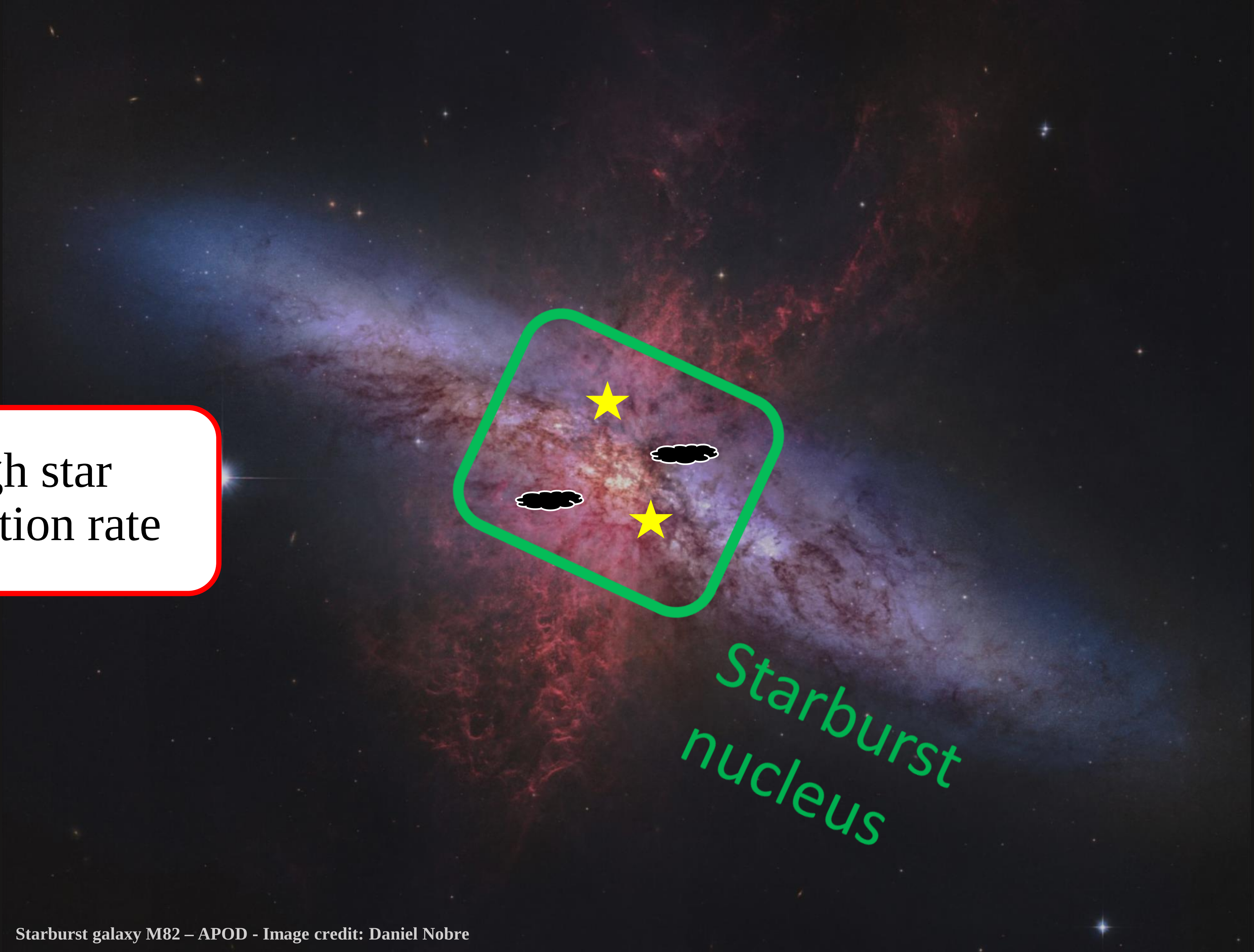


Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

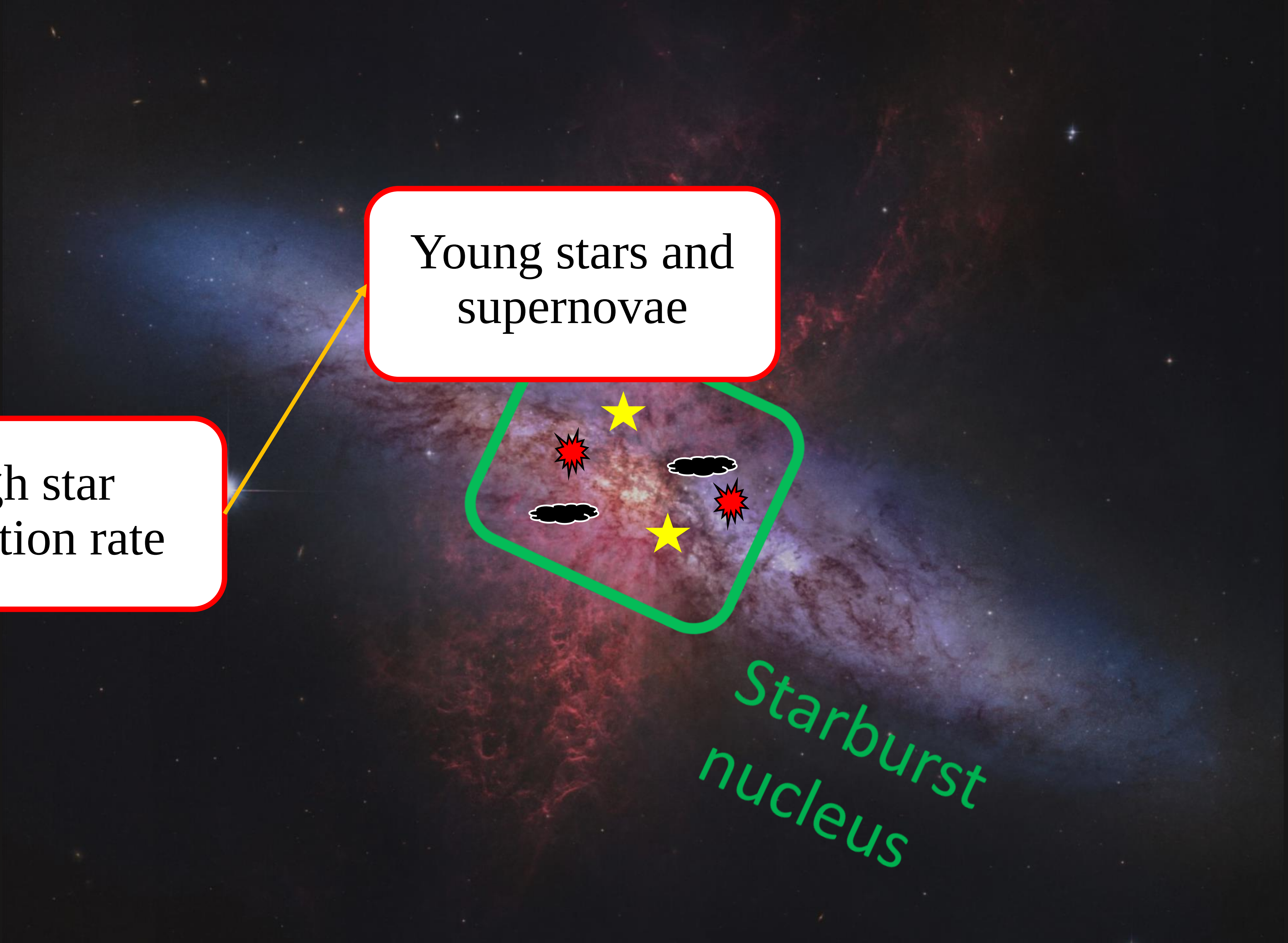


Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

High star formation rate



Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

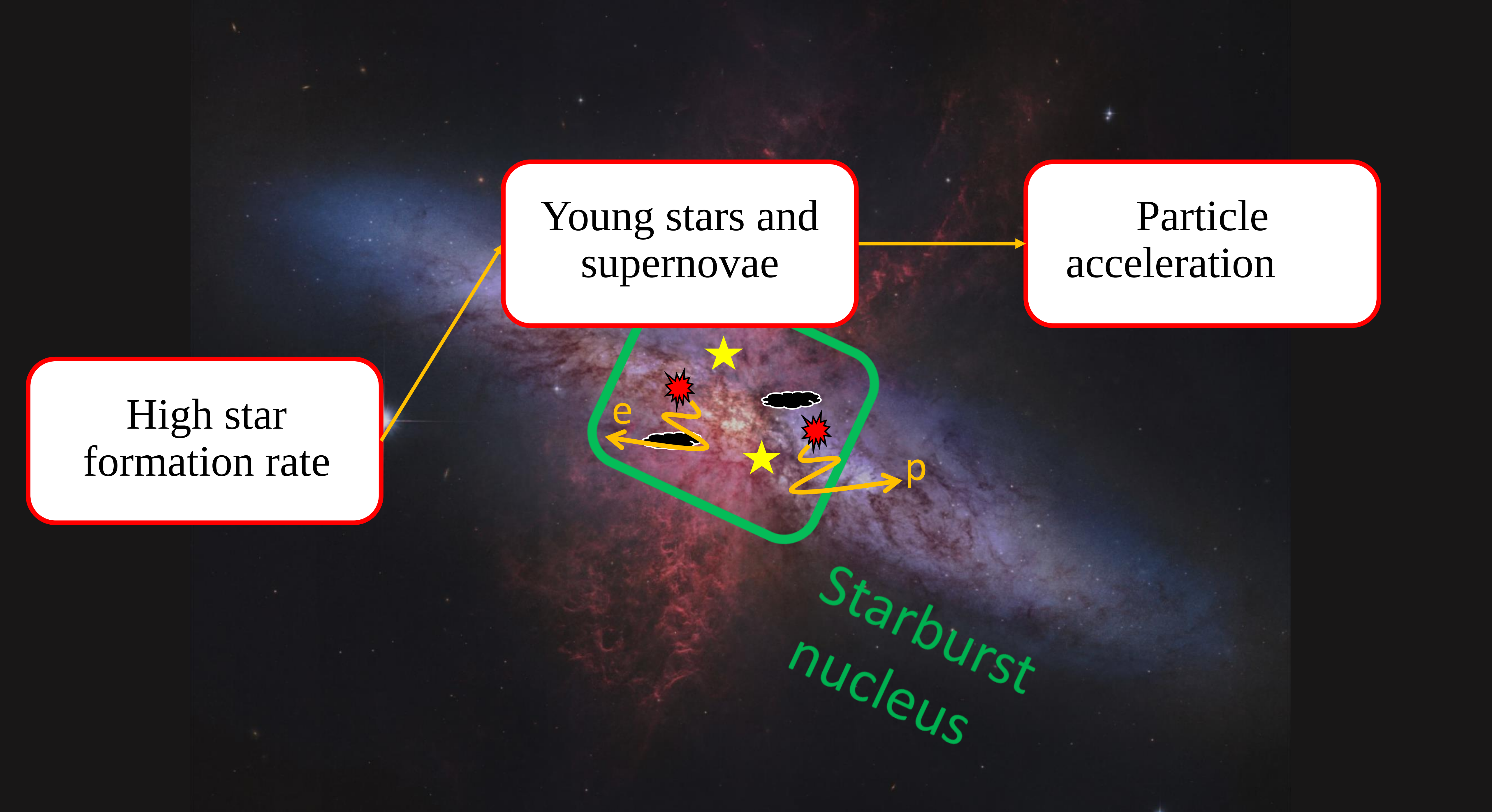


High star formation rate

Young stars and supernovae

Starburst nucleus

Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

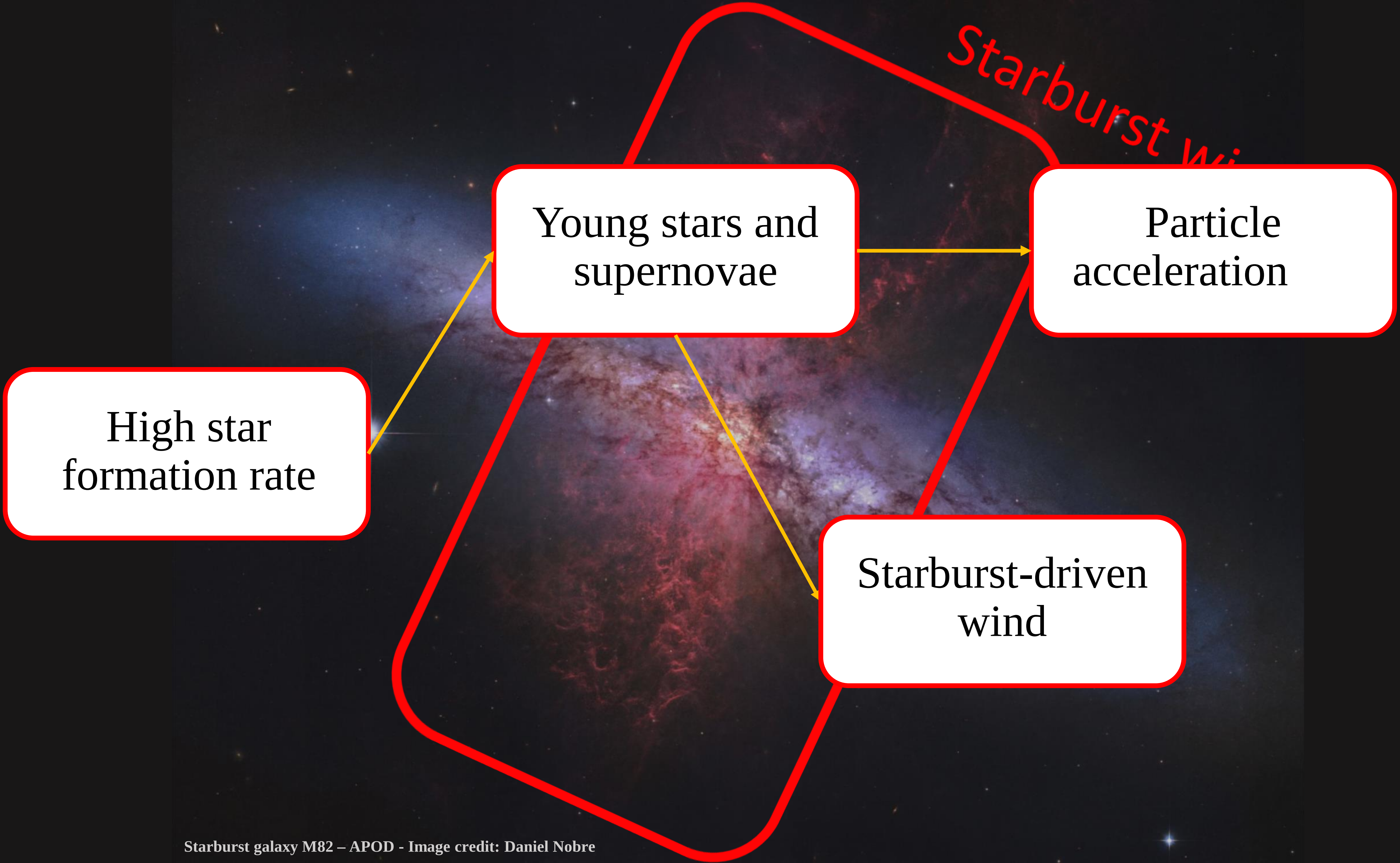


High star formation rate

Young stars and supernovae

Particle acceleration

Starburst galaxy M82 – APOD - Image credit: Daniel Nobre



Starburst wi

High star formation rate

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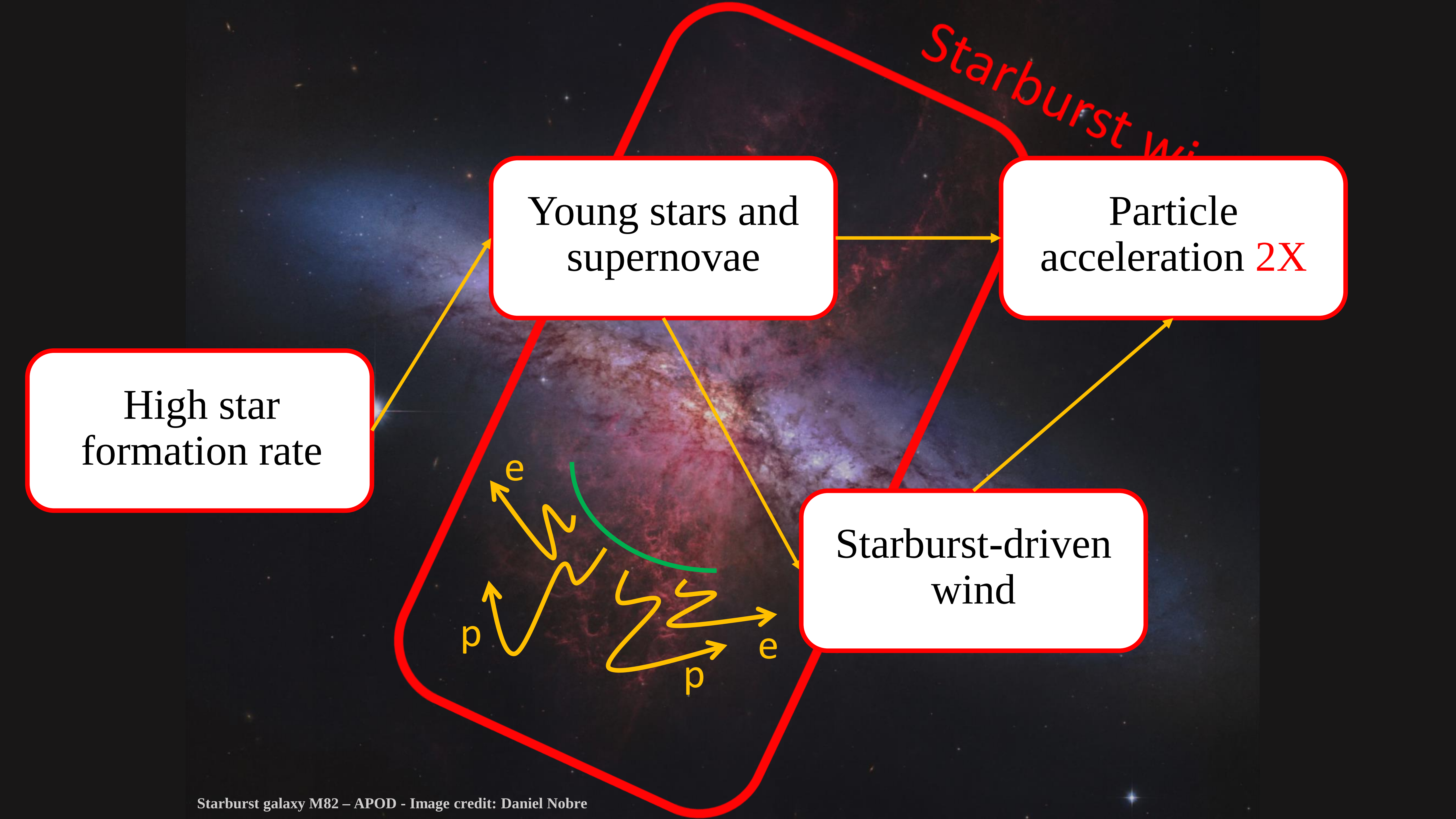
Particle acceleration

Starburst-driven wind

Starburst galaxy M82 – APOD - Image credit: Daniel Nobre



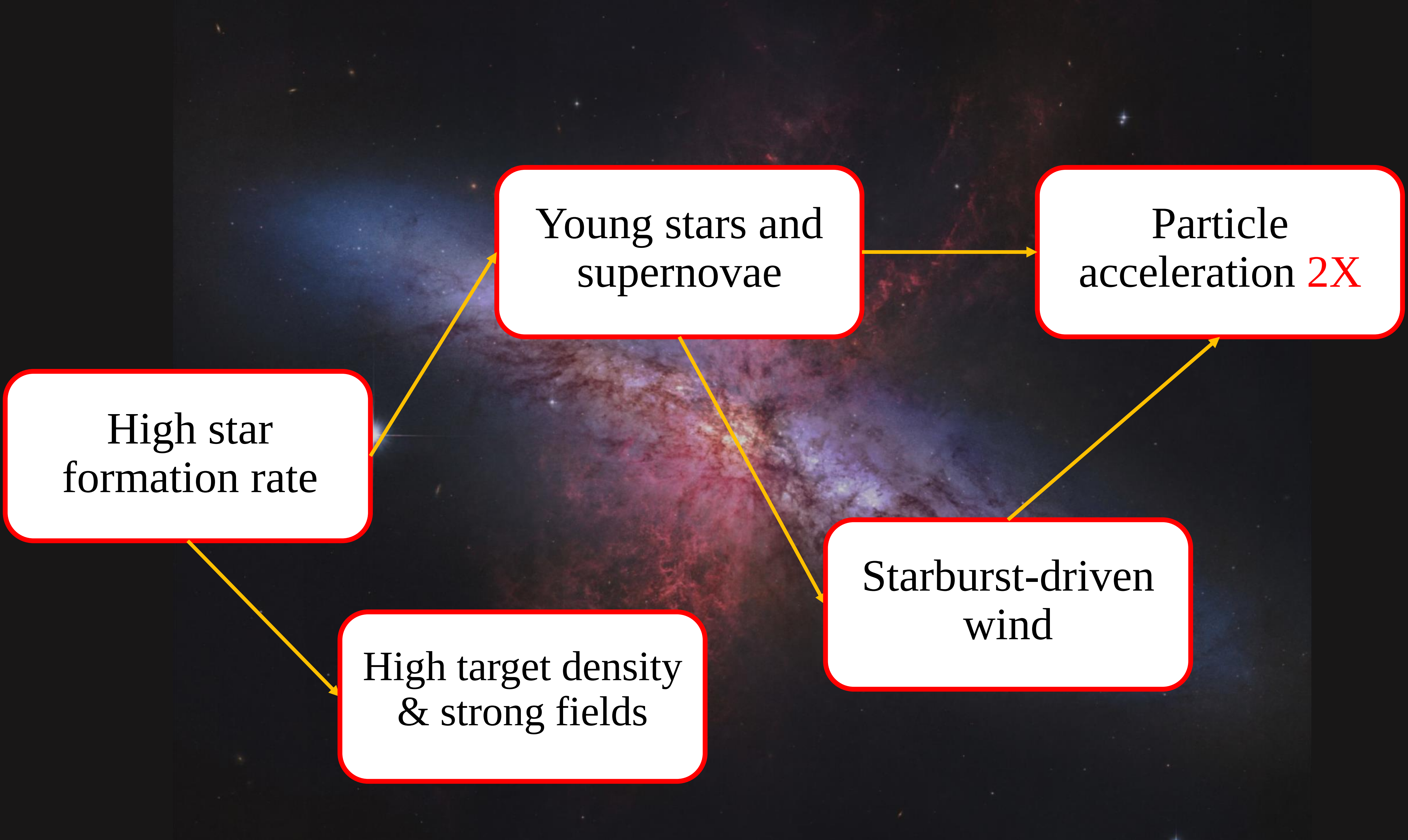
High star formation rate

Young stars and supernovae

Particle acceleration 2X

Starburst-driven wind

Starburst galaxy M82 – APOD - Image credit: Daniel Nobre



High star formation rate

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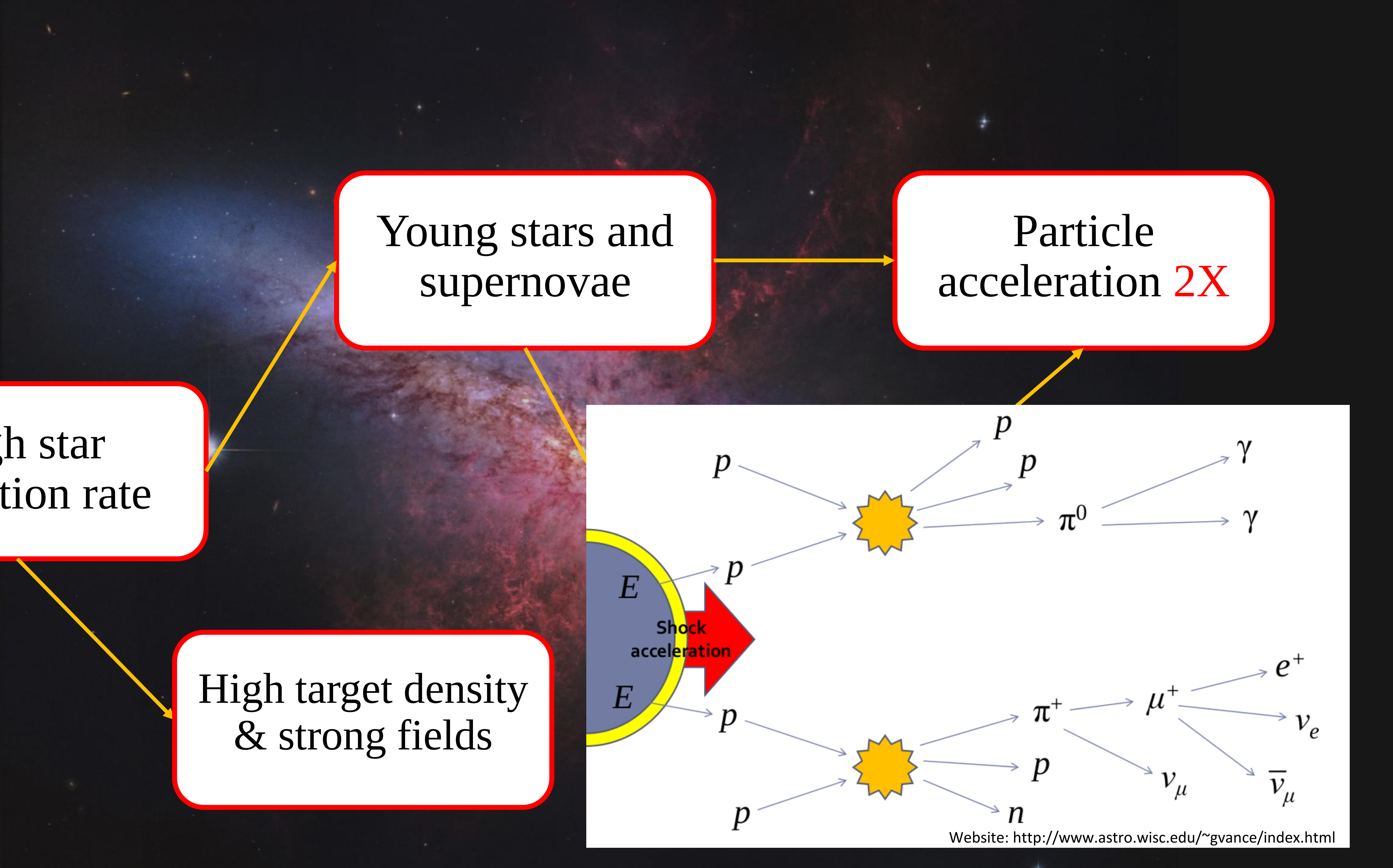
Starburst-driven wind

High target density & strong fields

Starburst galaxy M82 – APOD - Image credit: Daniel Nobre



Young stars and supernovae

Particle acceleration 2X

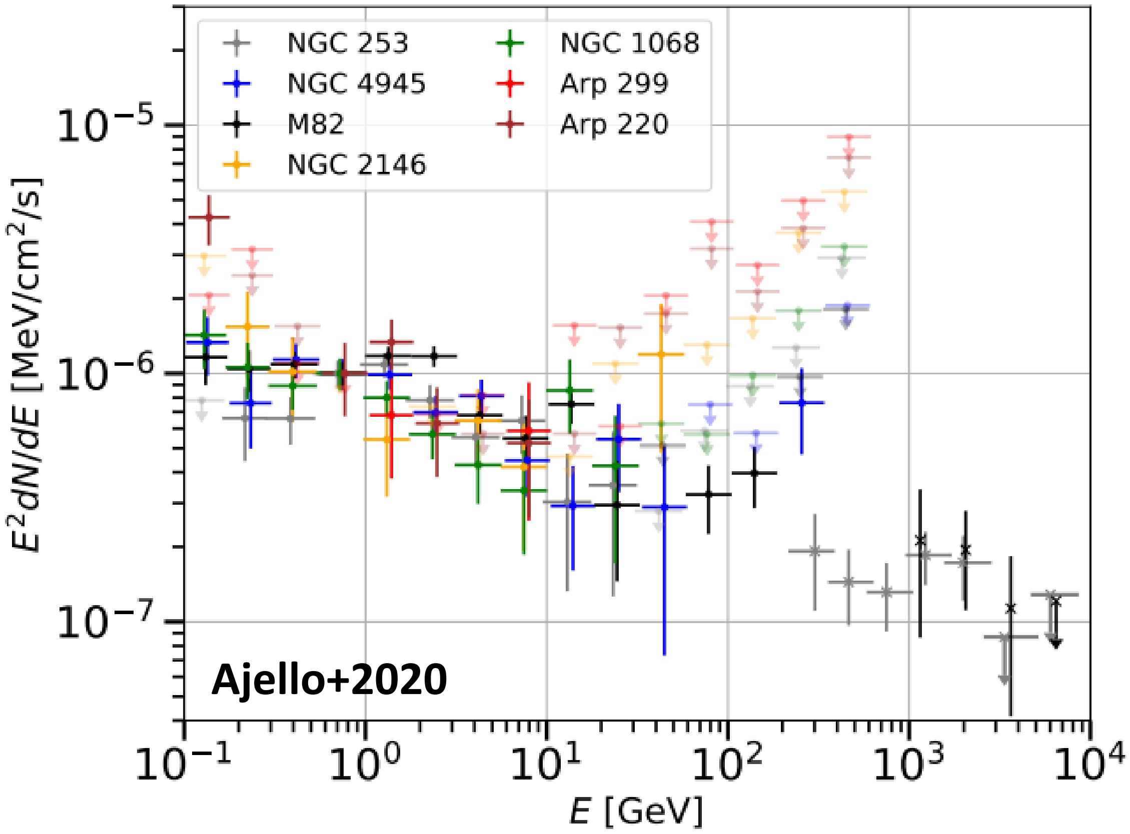
High star formation rate

High target density & strong fields

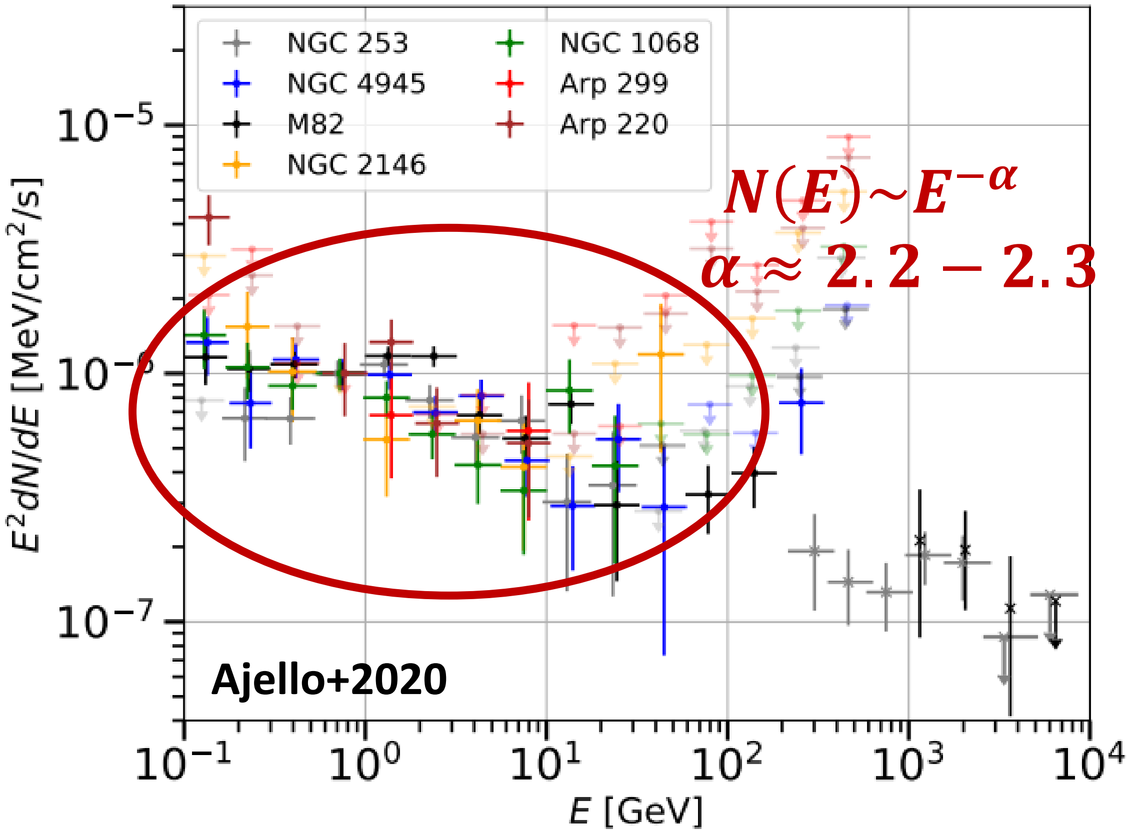
Website: http://www.astro.wisc.edu/~gvance/index.html

Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

Observation of Star-forming Galaxies - Gamma



Observation of Star-forming Galaxies - Gamma

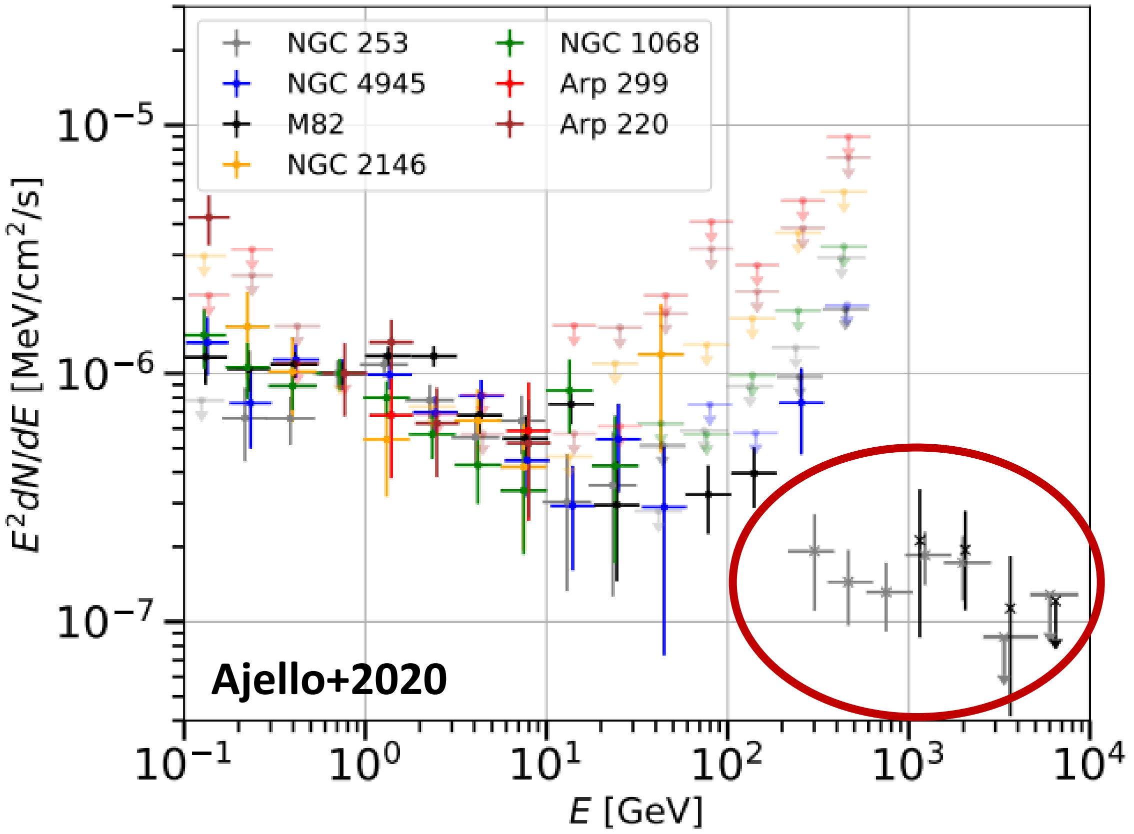


$$N(E) \sim E^{-\alpha}$$

$$\alpha \approx 2.2 - 2.3$$

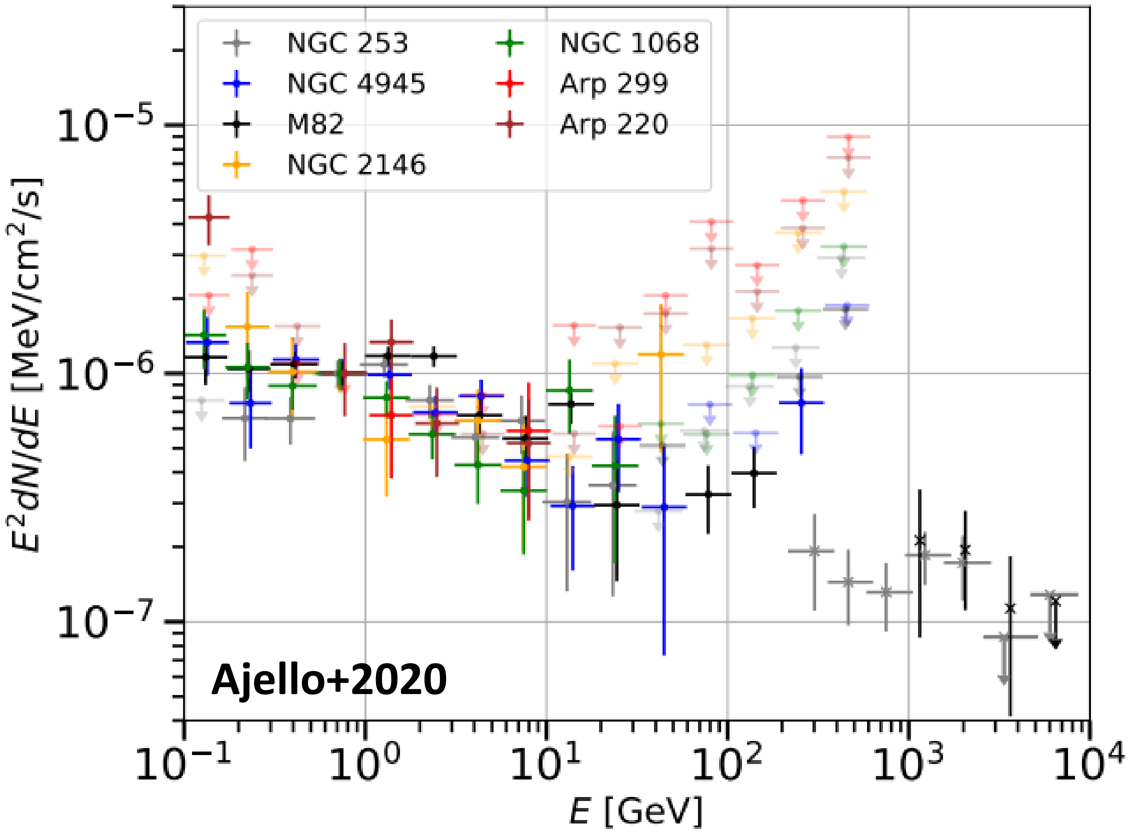
- Star-forming observed at GeV

Observation of Star-forming Galaxies - Gamma



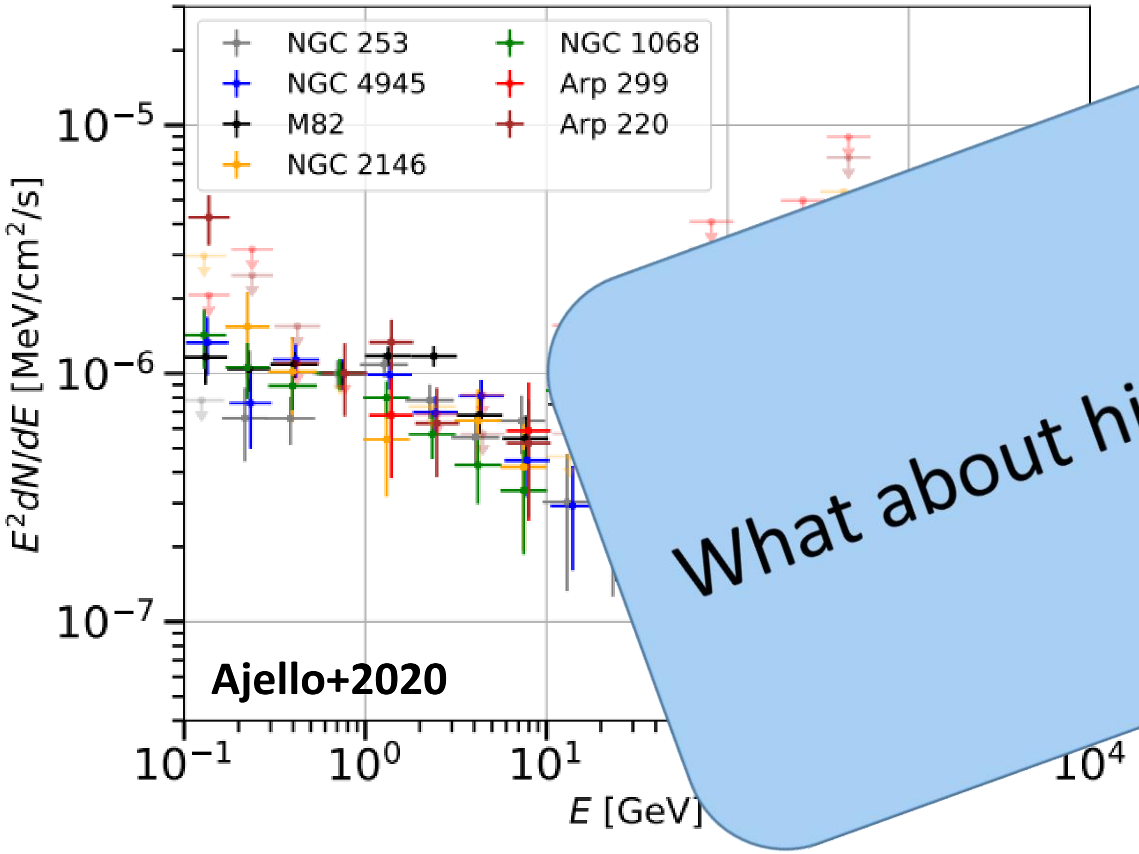
- Star-forming observed at GeV
- Most nearby at TeV (<4 Mpc)

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



Ajello+2020

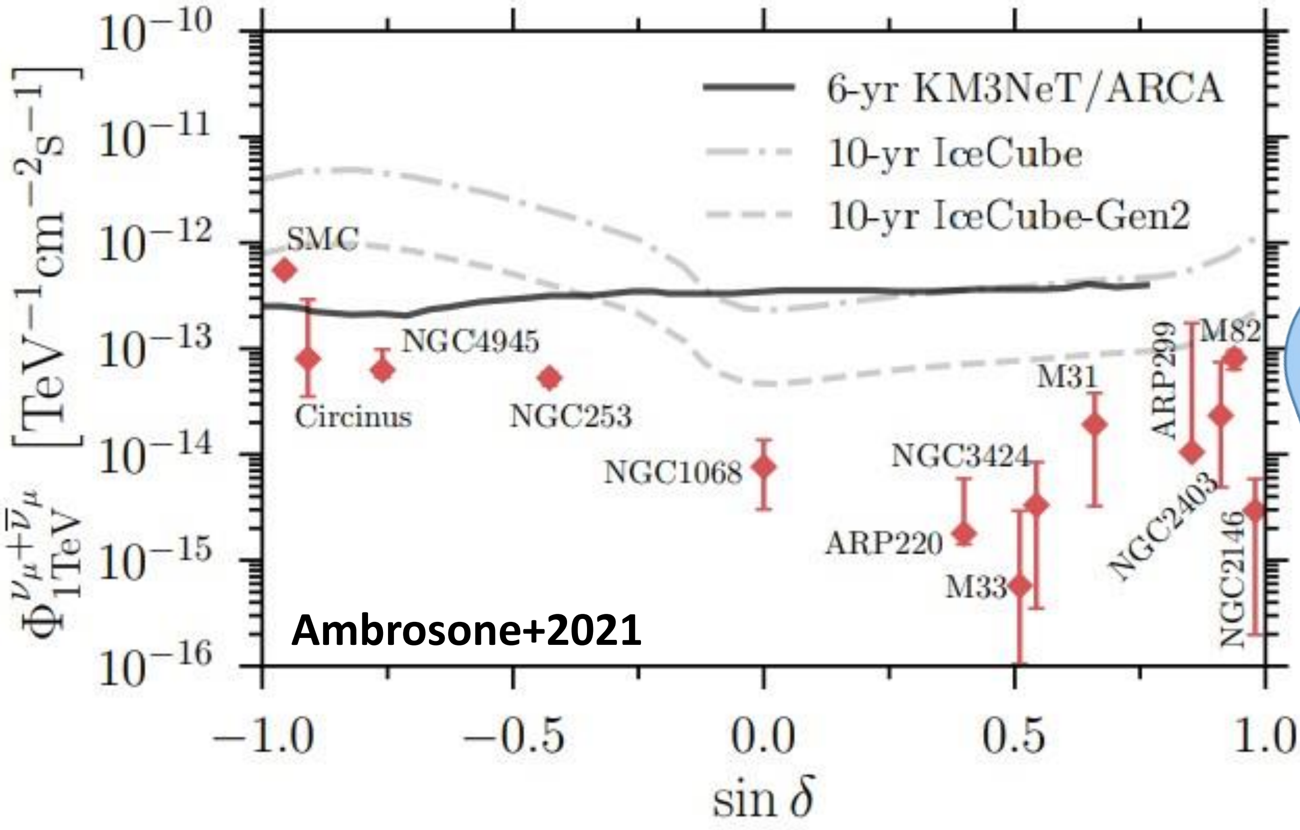
What about high-energy neutrinos?

observed at GeV

TeV (<4 Mpc)

distant: Arp 220 (77 Mpc)

Observation of Star-forming Galaxies - Neutrinos



Ambrosone+2021

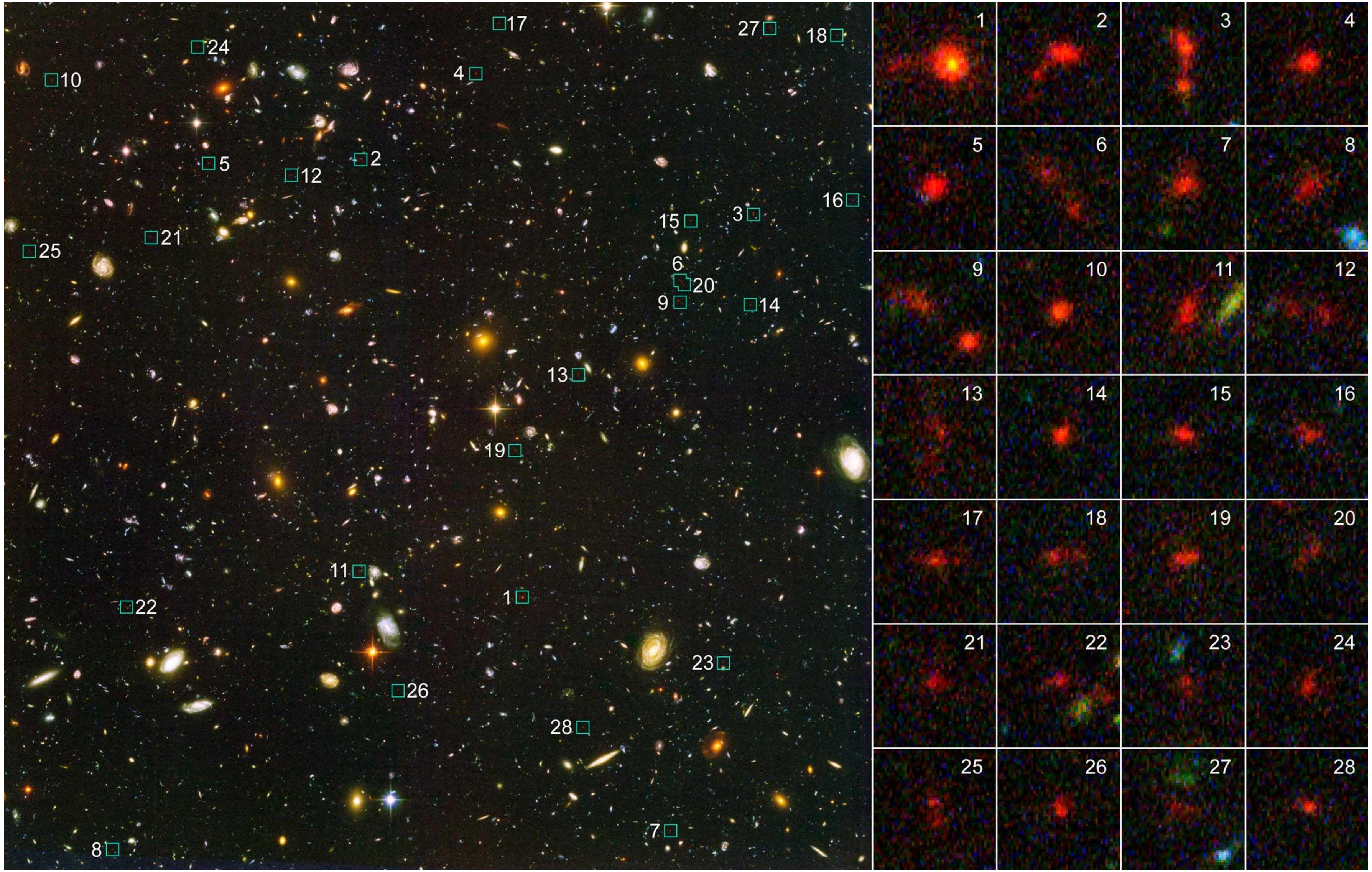
- Star-forming

Mpc)

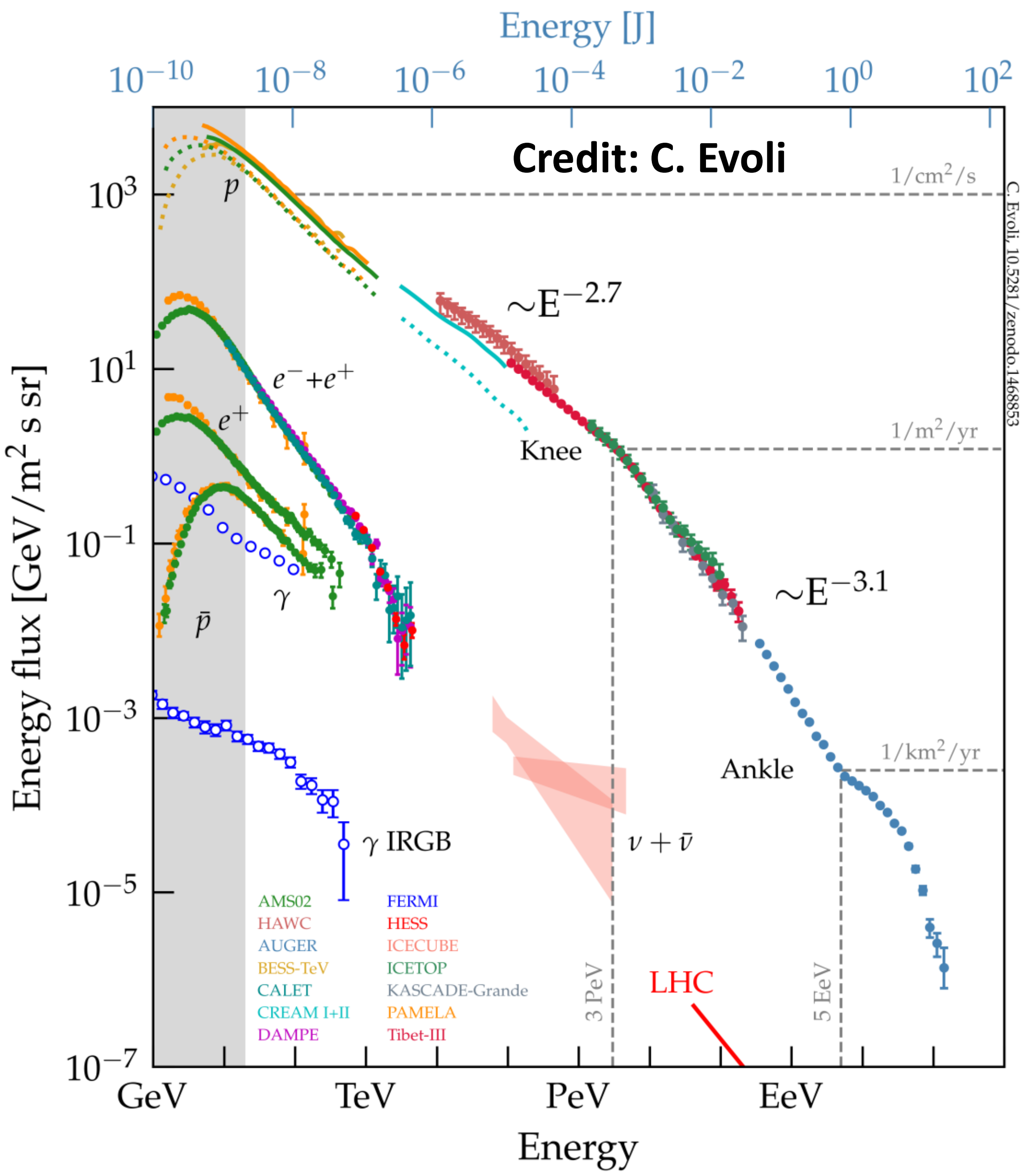
- S are currently undetected neutrino sources (*)

Just upper limits for now, but stay tuned for KM3NeT and upcoming observatories

Another reason to study Star-forming galaxies



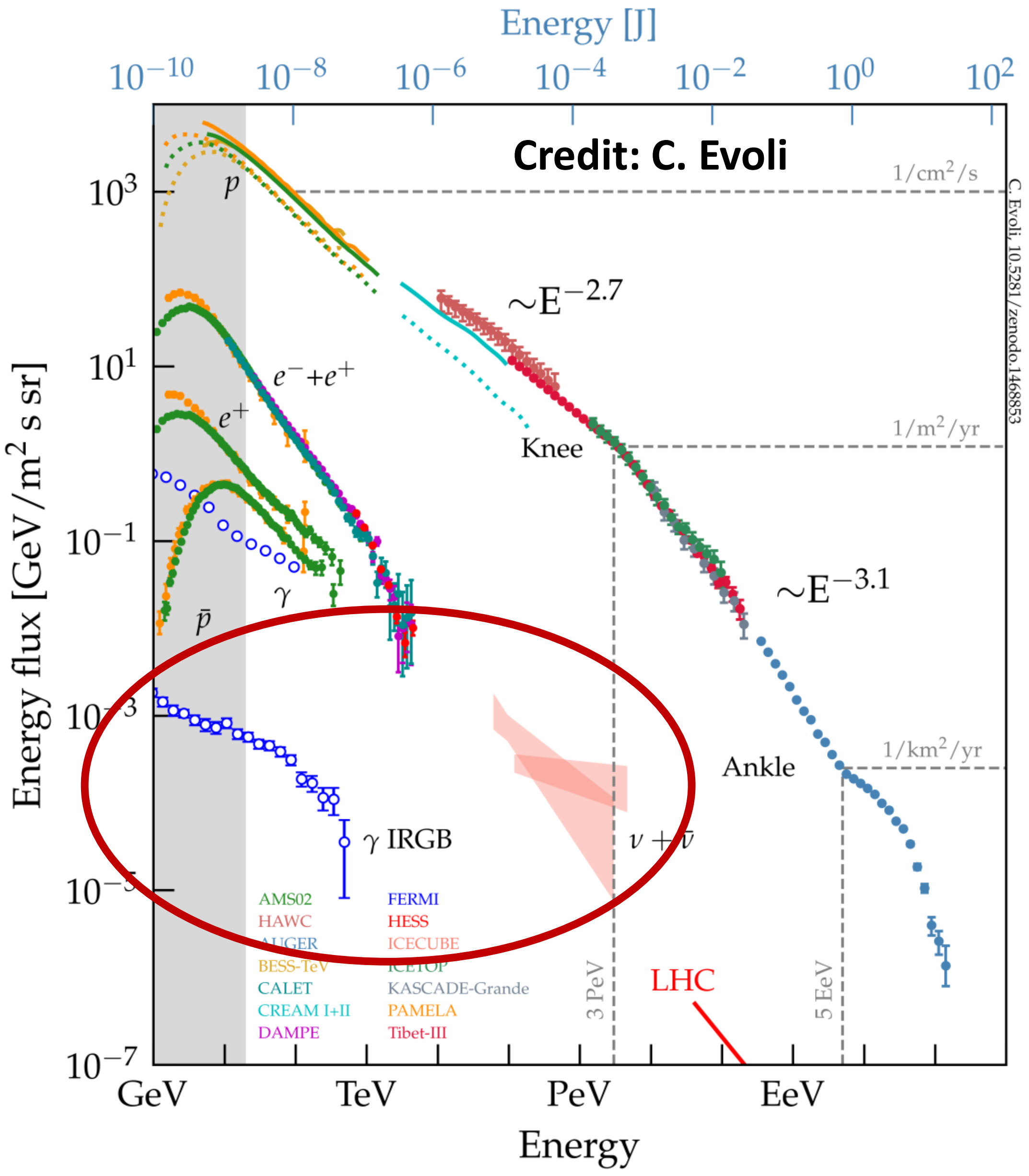
Diffuse radiation from Star-forming galaxies



Credit: C. Evoli

- SFGs are expected to shine on gamma rays and neutrinos

Diffuse radiation from Star-forming galaxies



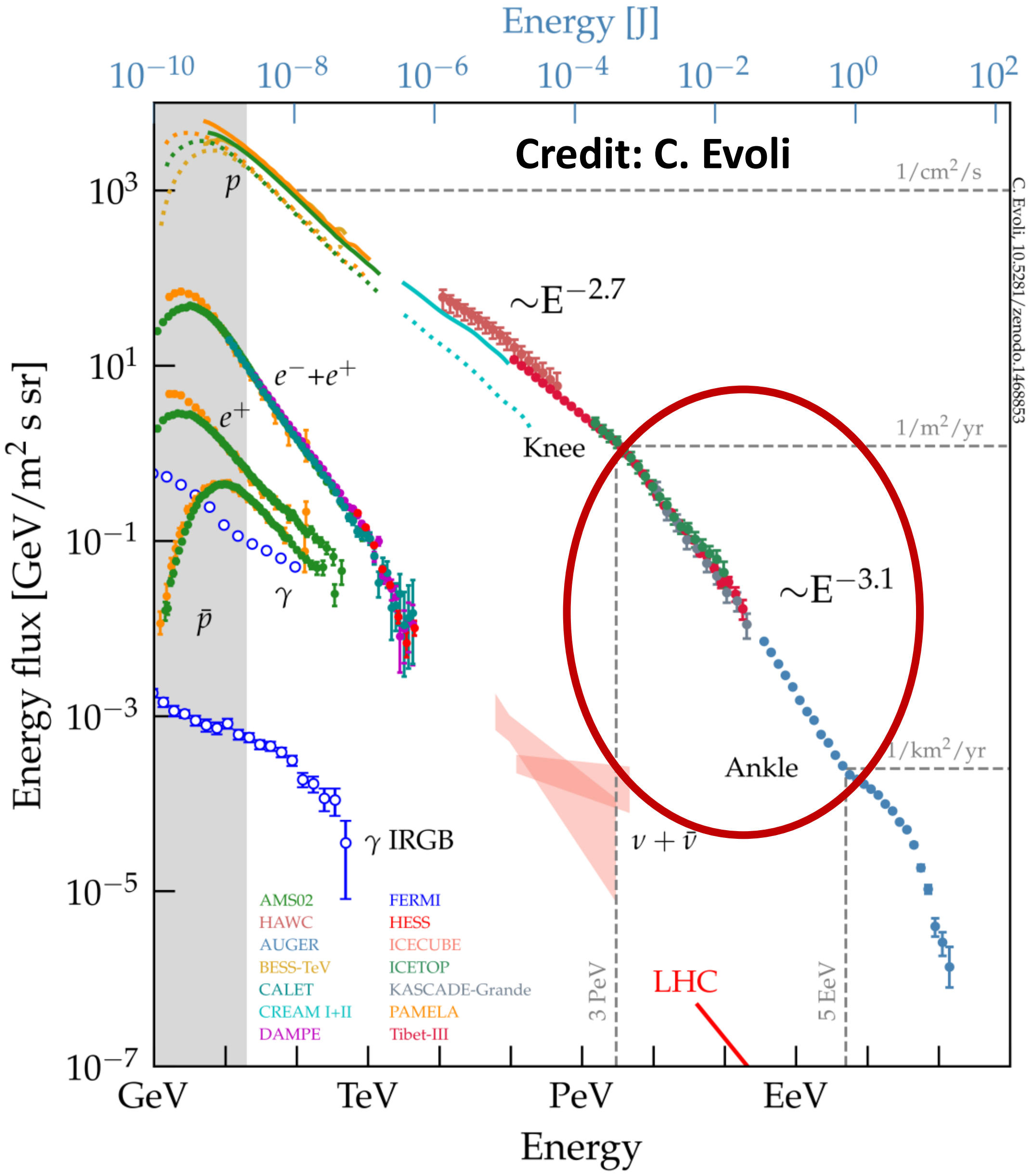
Credit: C. Evoli

C. Evoli, 10.5281/zenodo.1468853

- SFGs are expected to shine on gamma rays and neutrinos

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

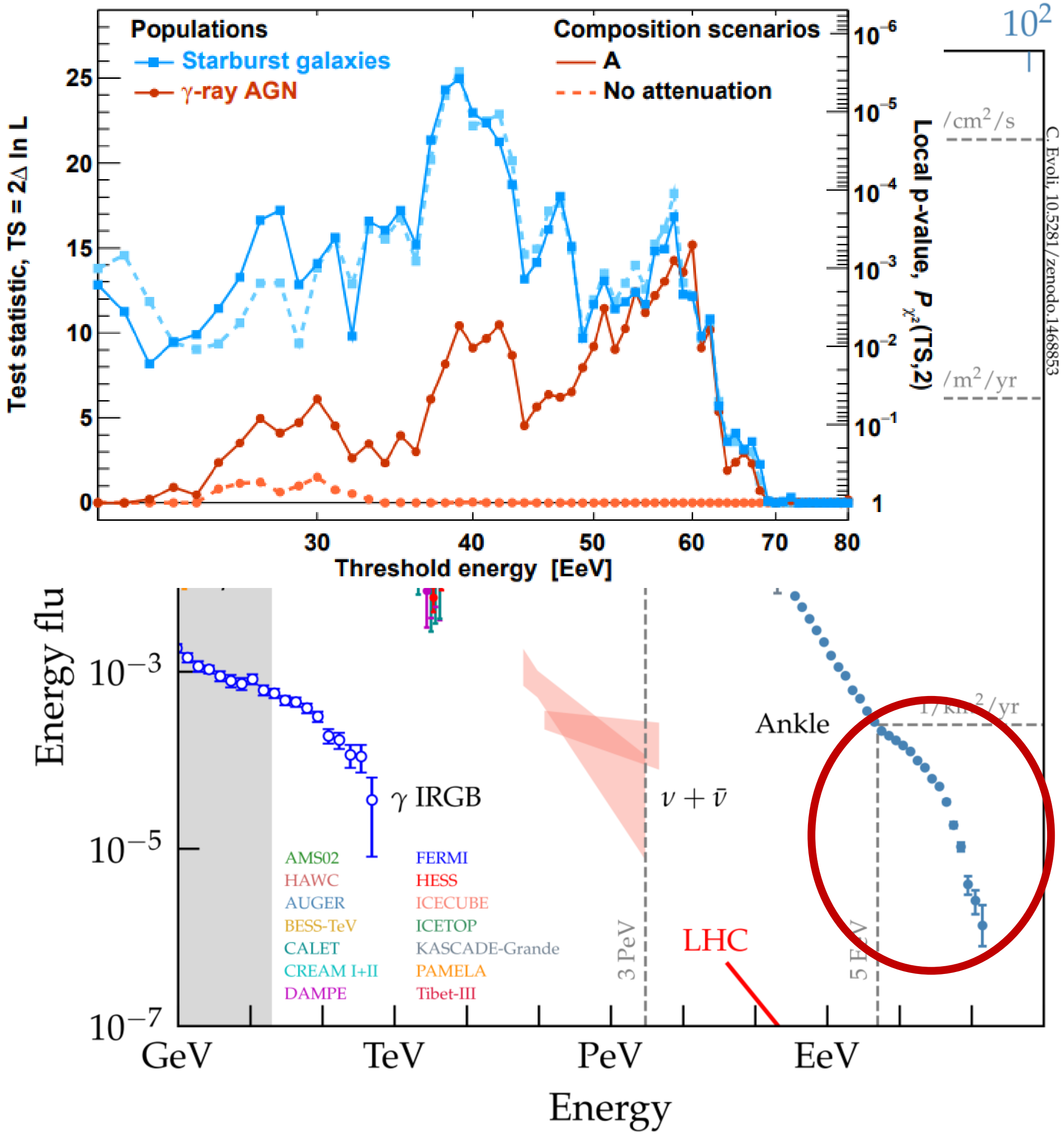
Diffuse radiation from Star-forming galaxies



- 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?

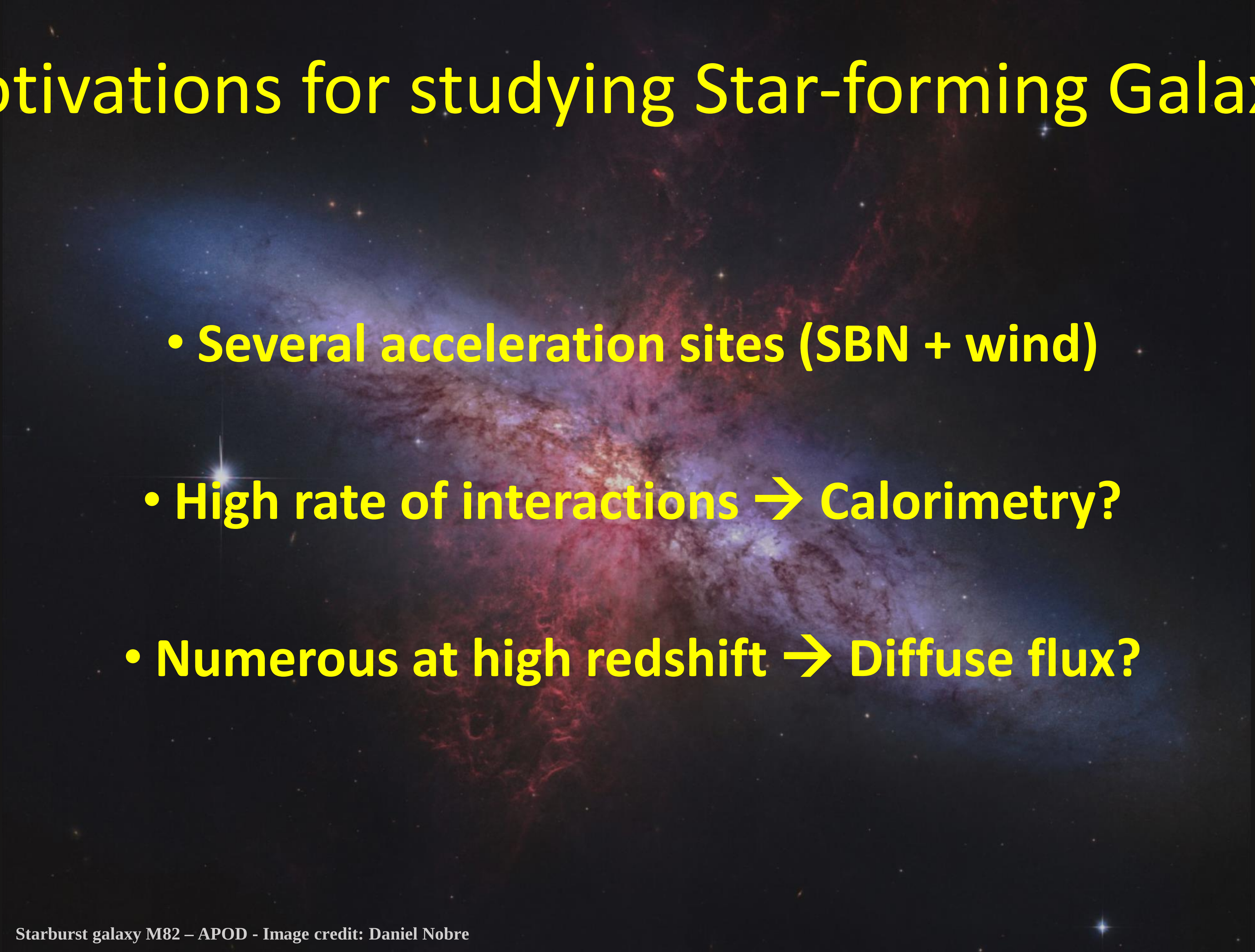
Diffuse radiation from Star-forming galaxies

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?

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

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

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Optical view of starburst regions

Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

Westmoquette+2020

Optical view of starburst regions

Westmoquette+2009

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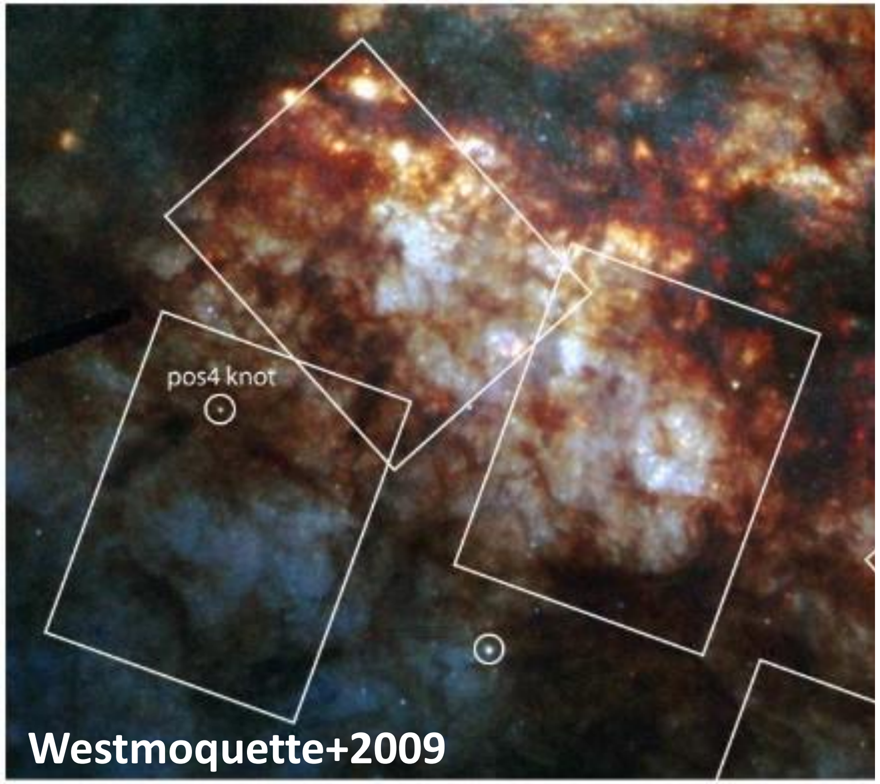
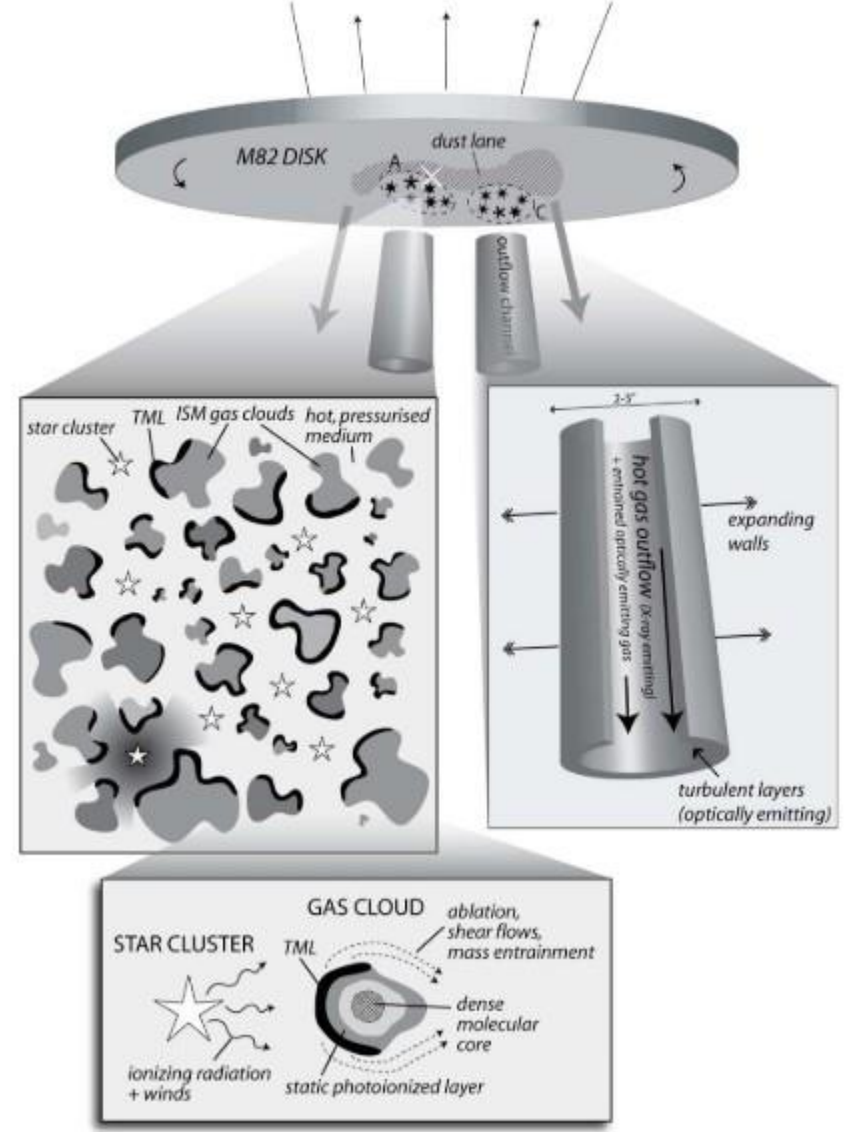
Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

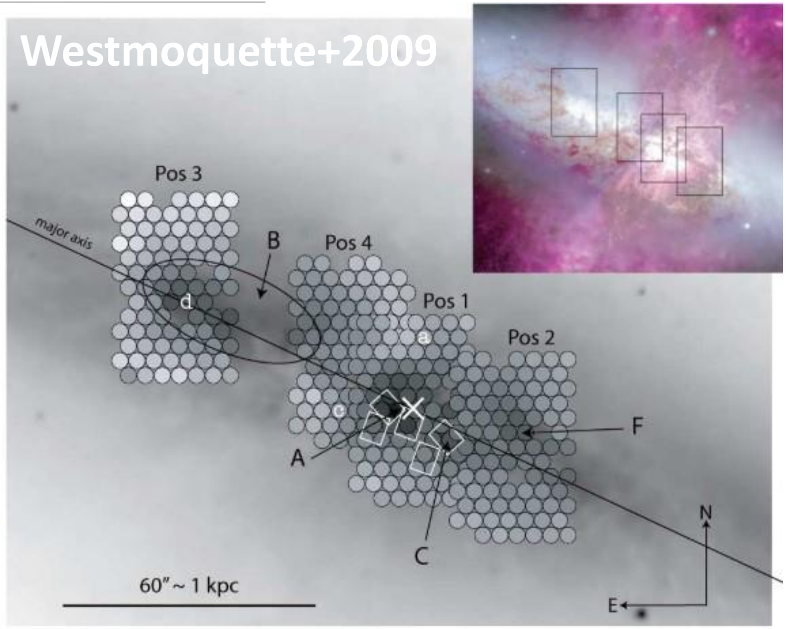
Optical view of starburst regions



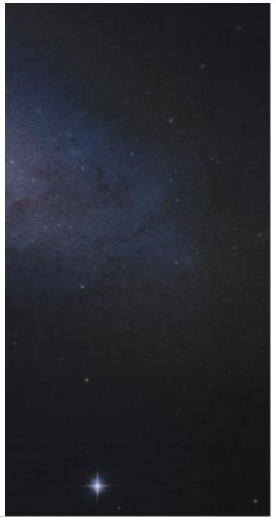
Westmoquette+2009



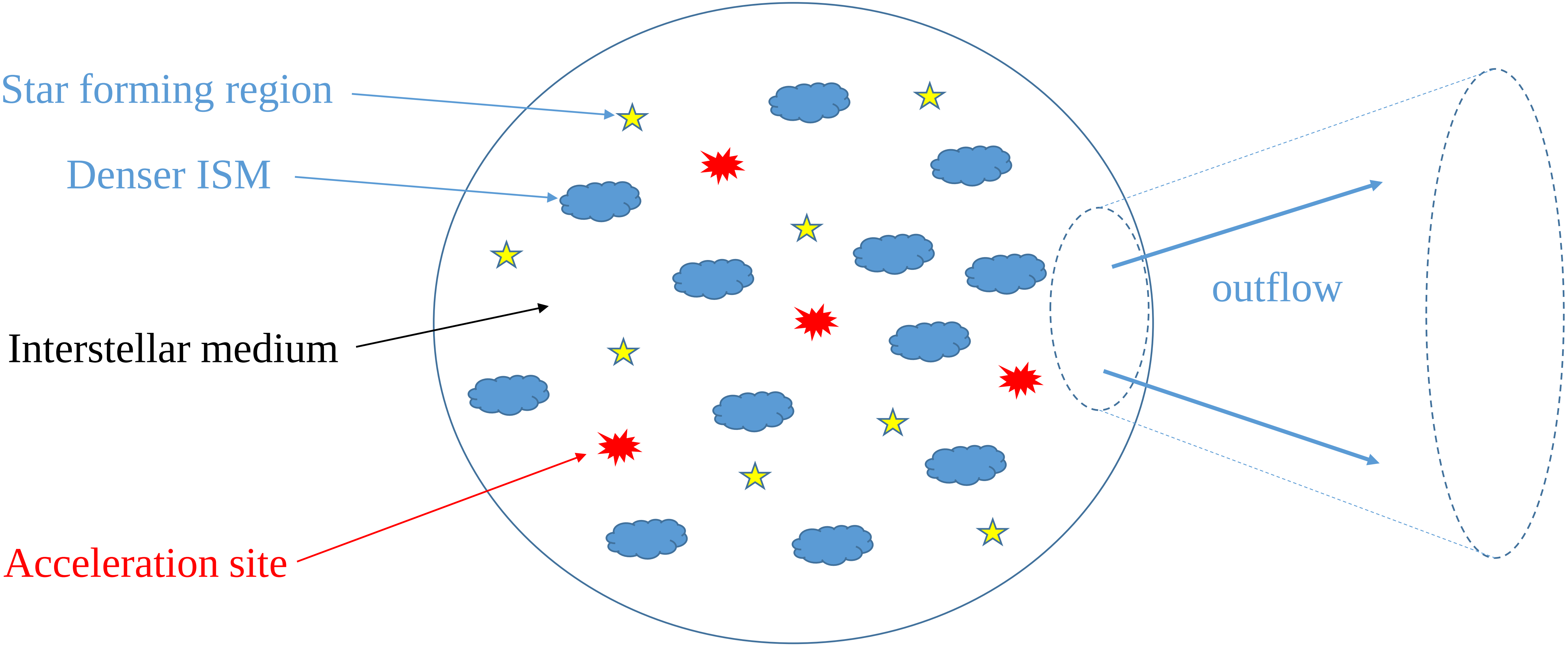
Westmoquette+2009




Starburst galaxy M82 – APO



Particle transport in starburst nuclei



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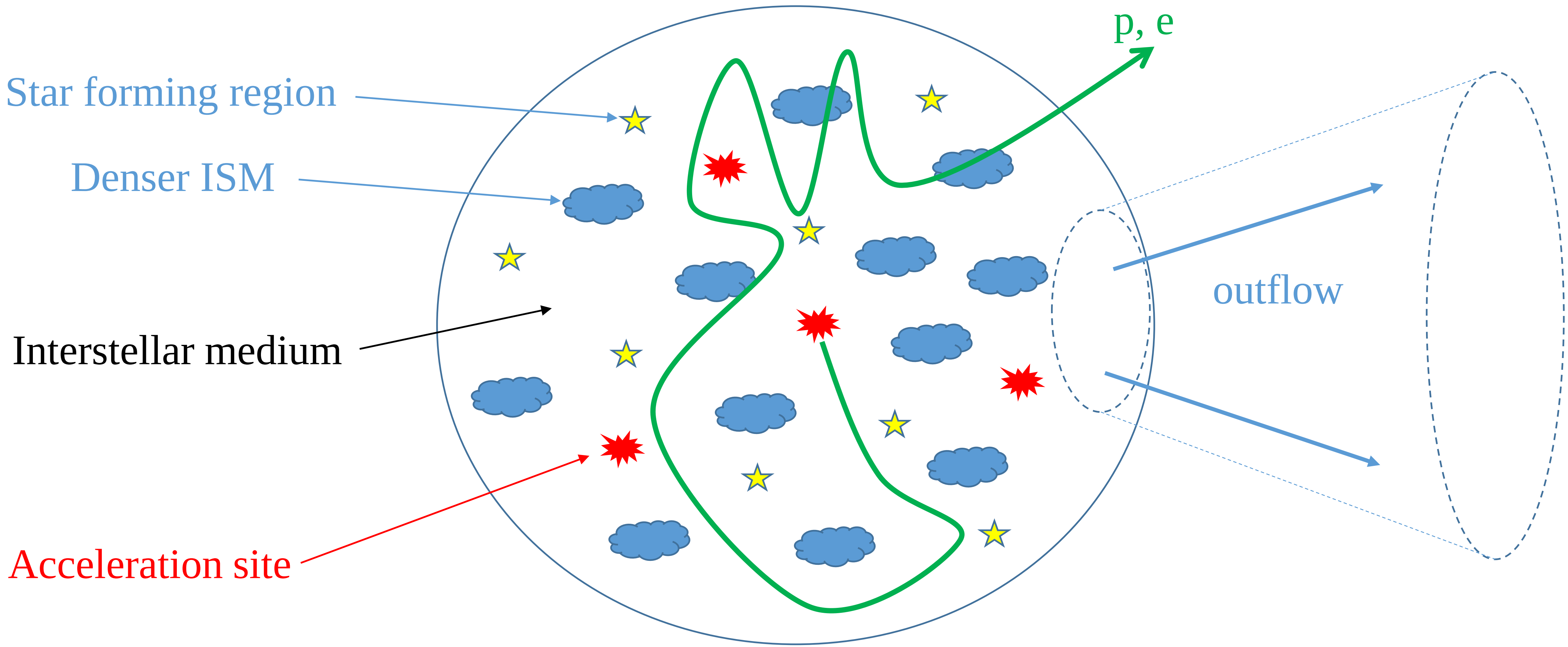

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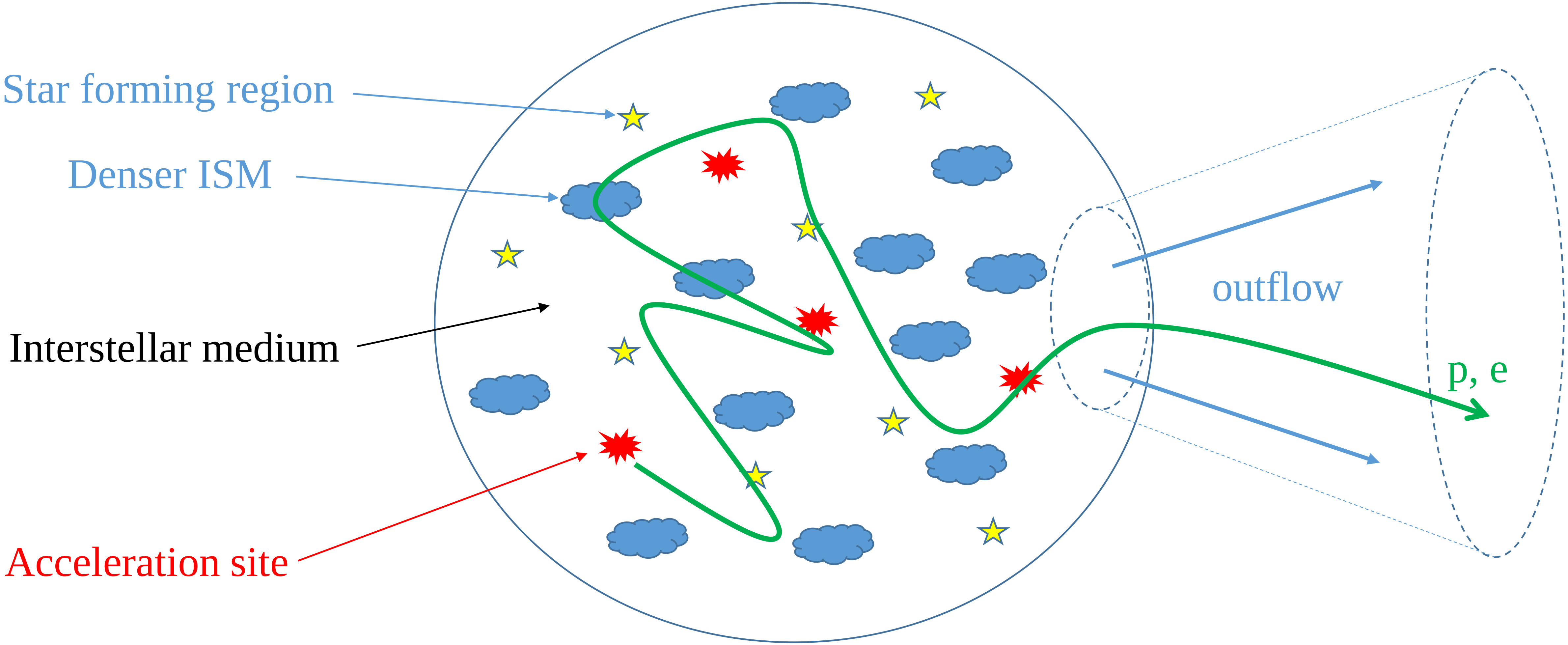

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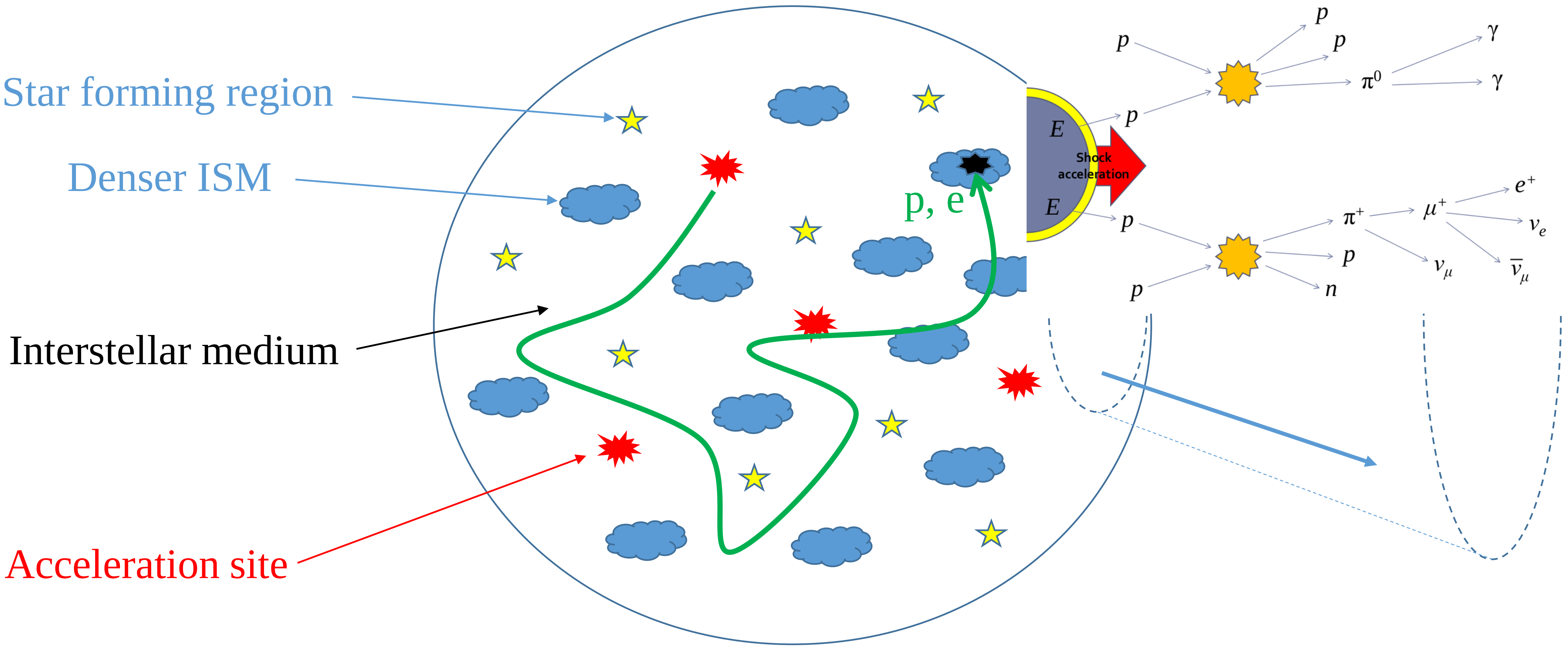
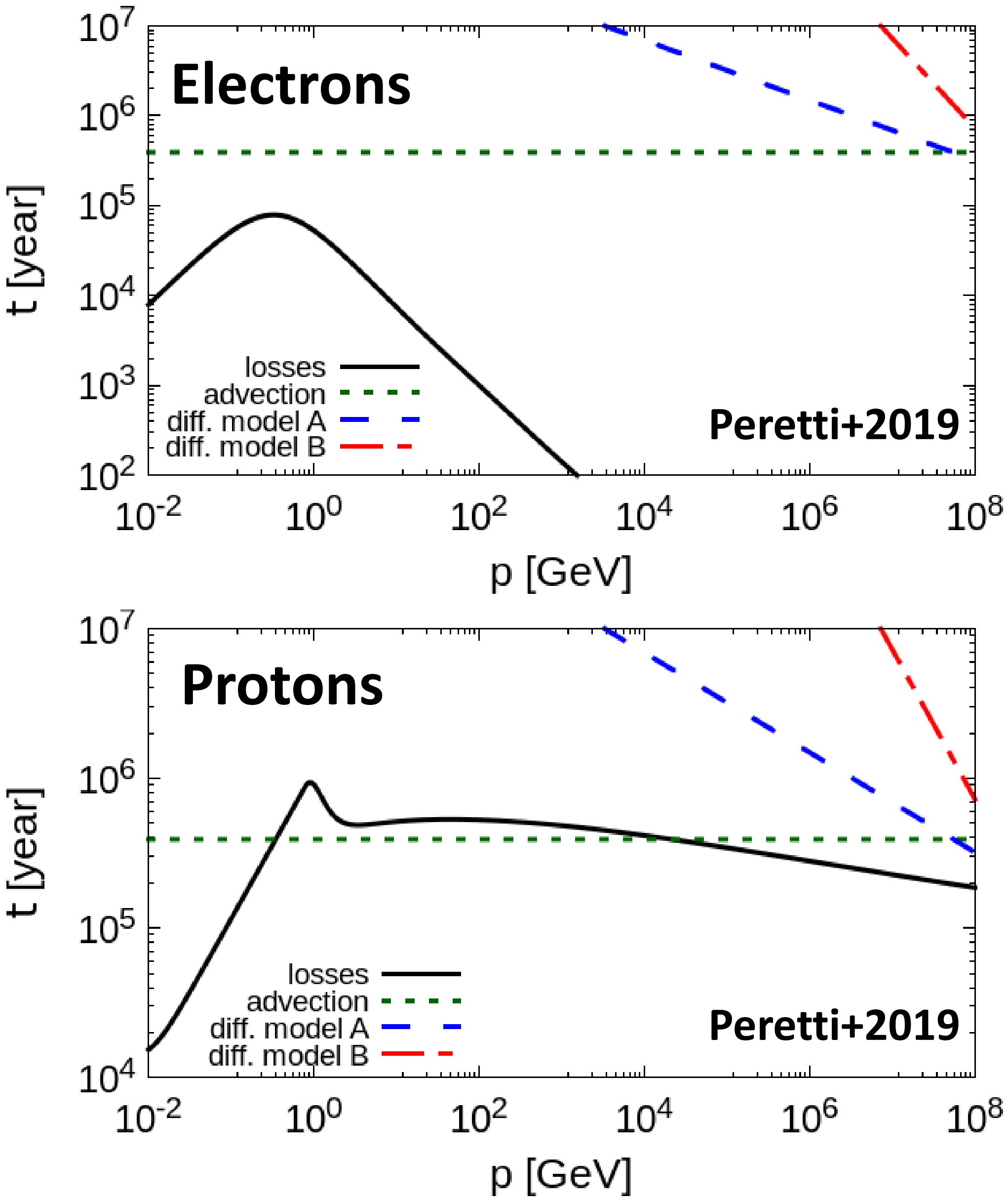


Modeling the transport in SBNi



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

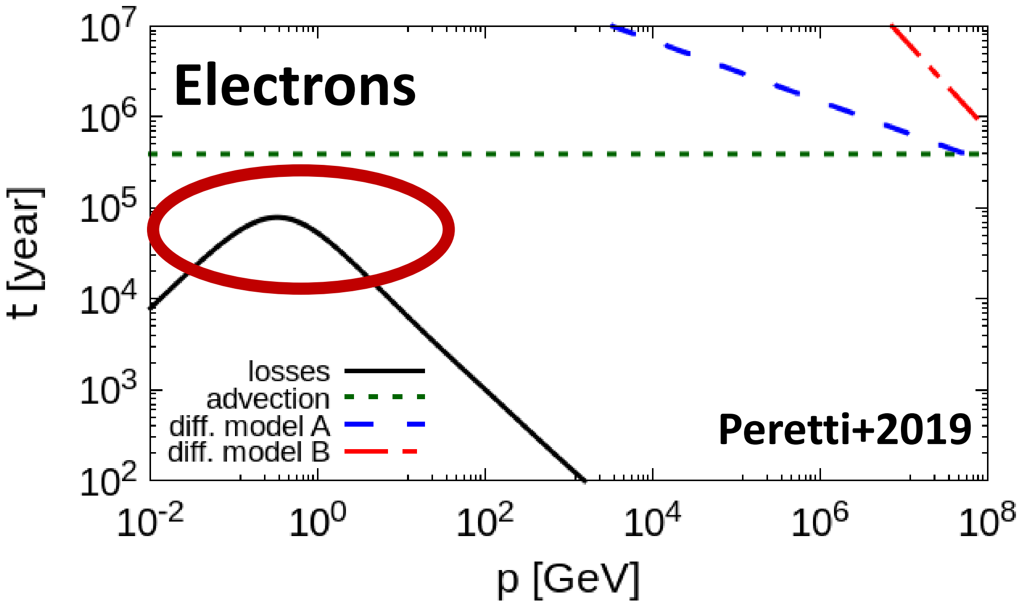
$$B \approx 10^{2}\ \mu G$$

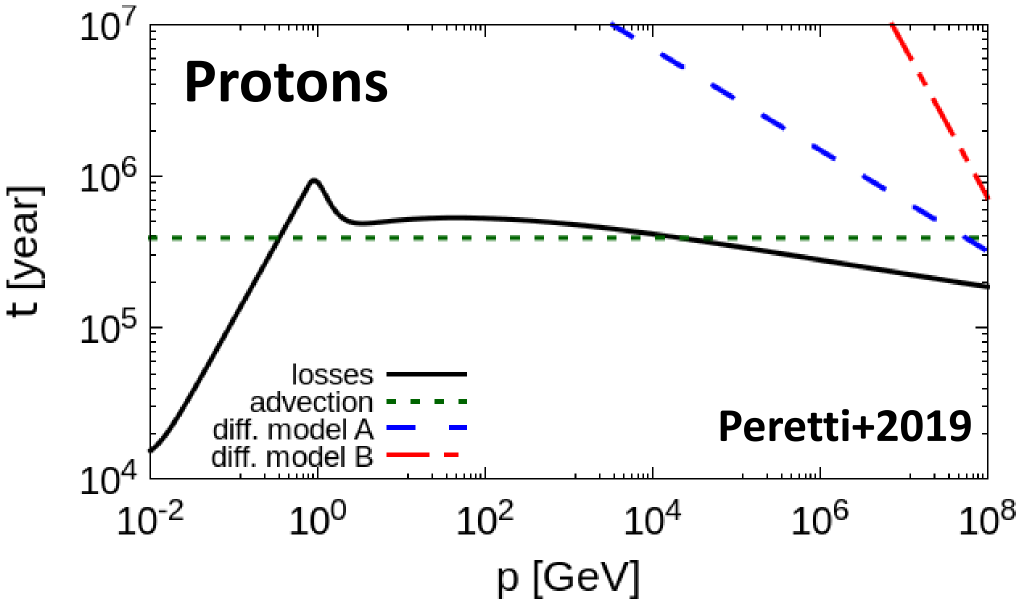
$$U_{RAD} \approx 10^{3}\ eV\ cm^{-3}$$

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

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

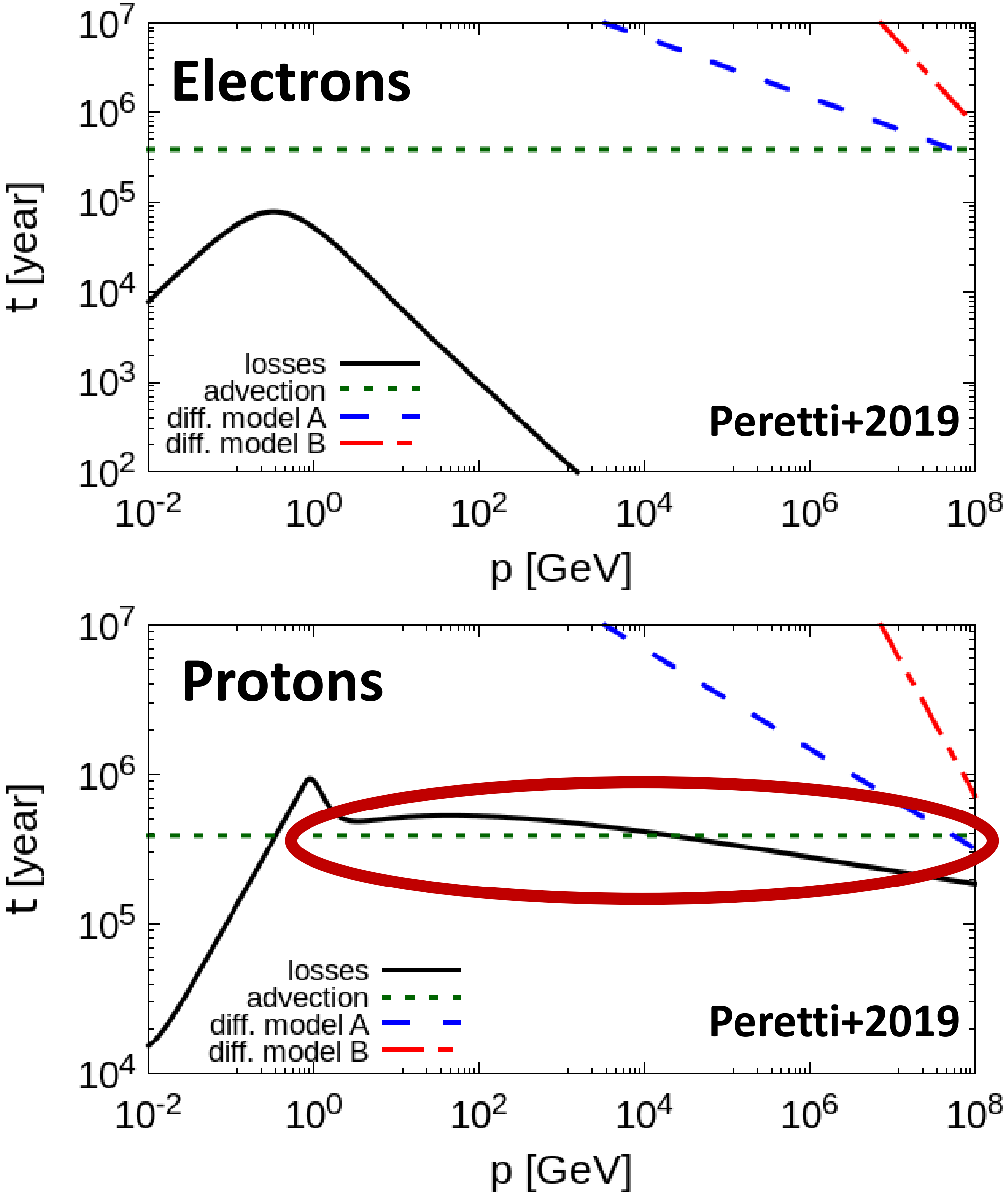
Modeling the transport in SBNi





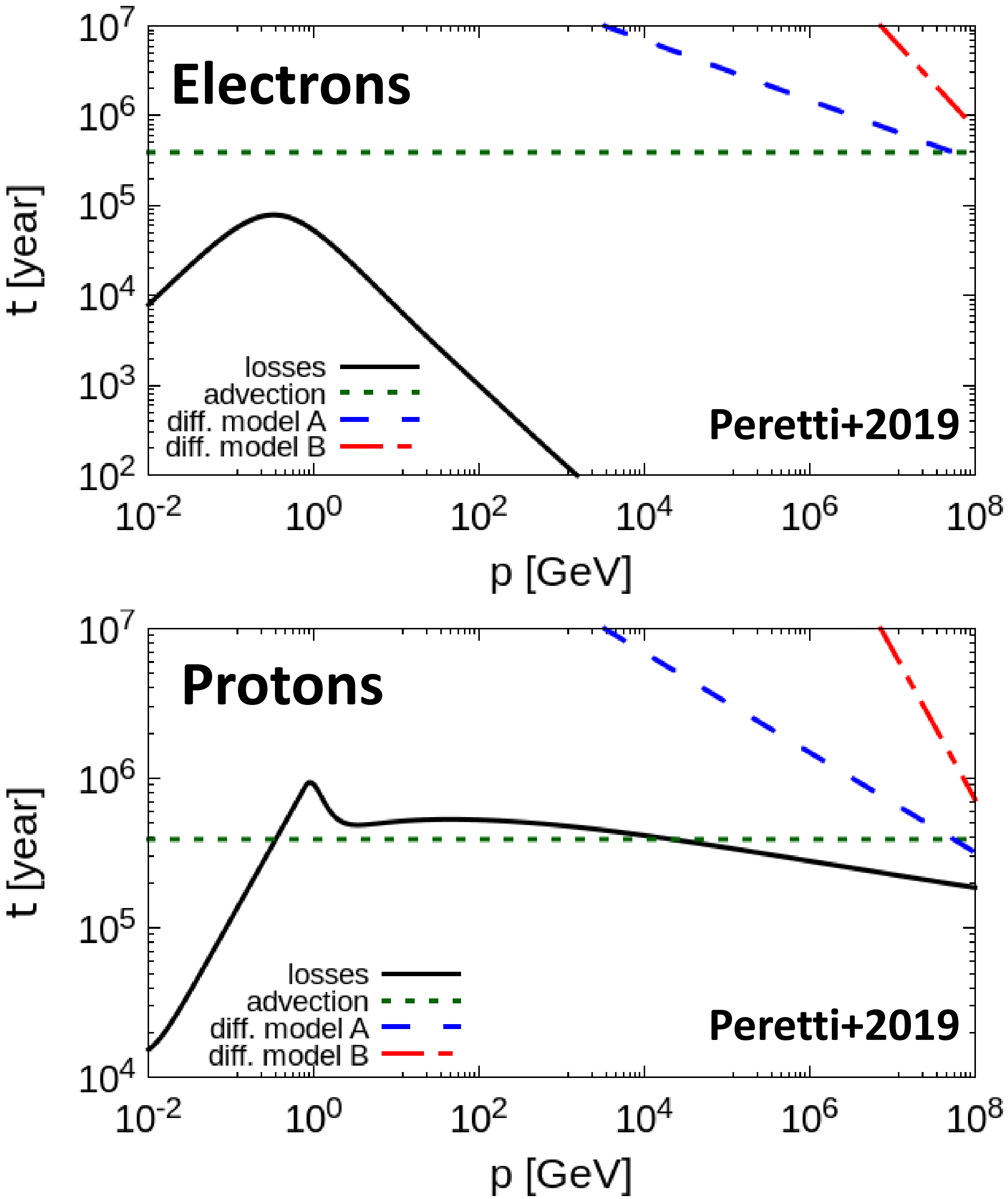
- Electrons are confined in SBNi

Modeling the transport in SBNi



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

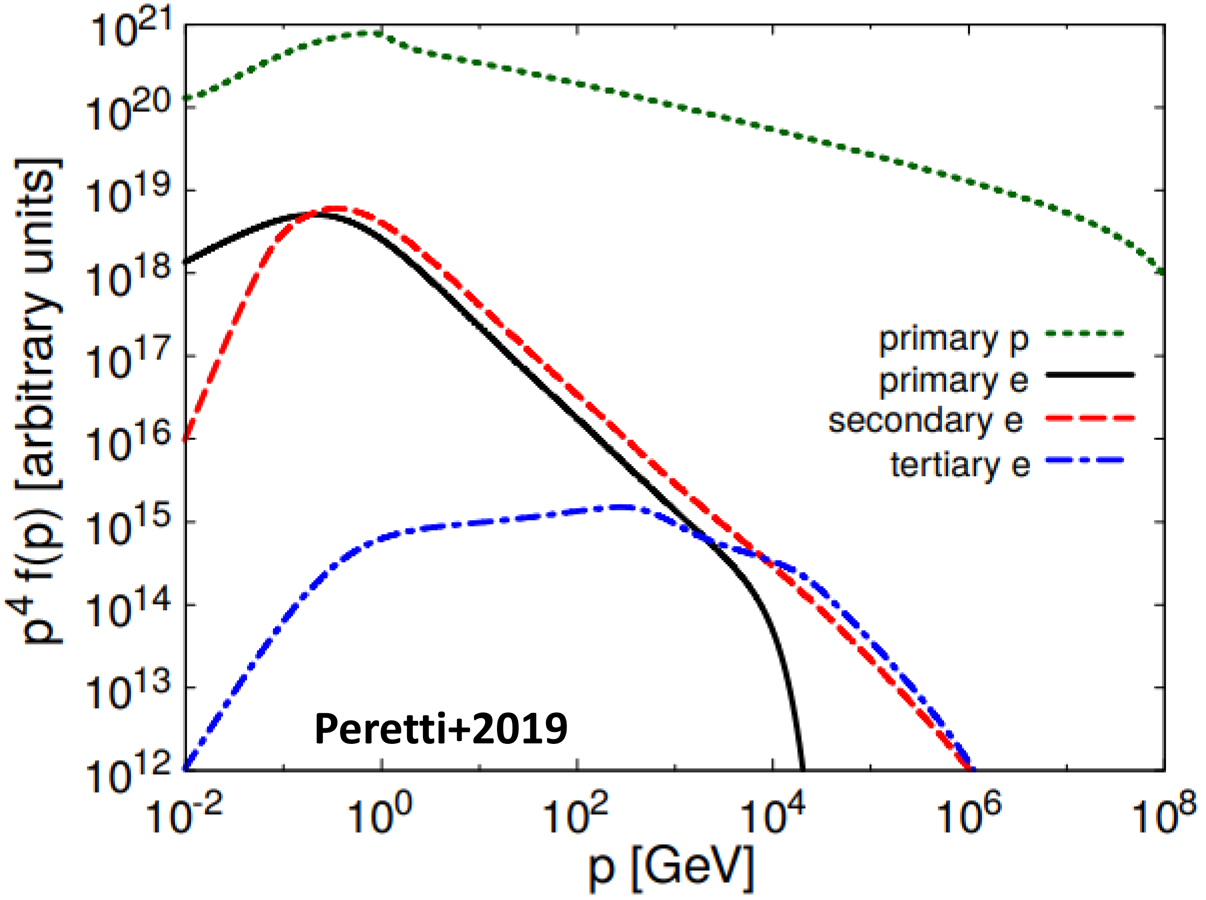
Modeling the transport in SBNi



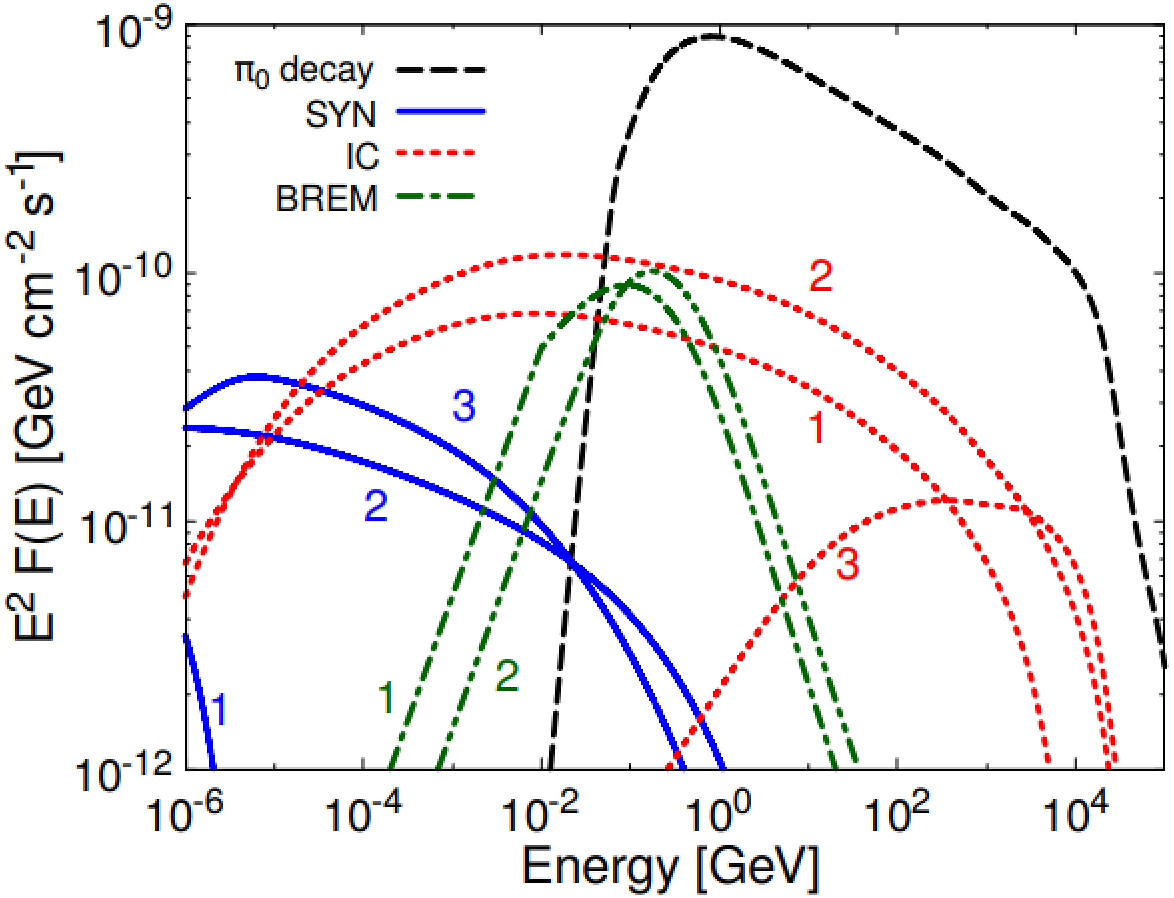
- Electrons are confined in SBNi
- Advection and losses regulate the transport of protons
- Particles experience all phases of the ISM

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

Particle and photon spectra in SBNi

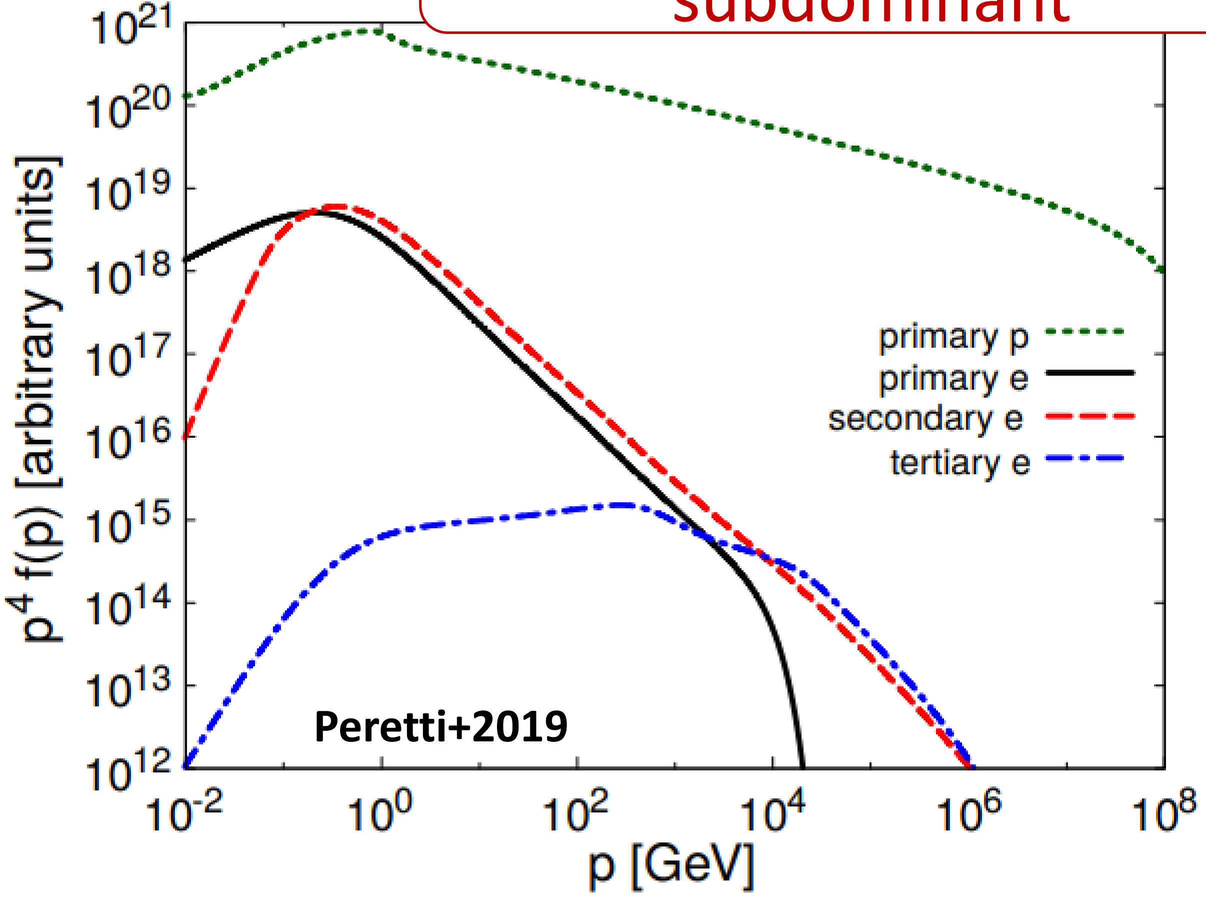


Peretti+2019



Particle and photon spectra in SBNi

Particle diffusion is subdominant



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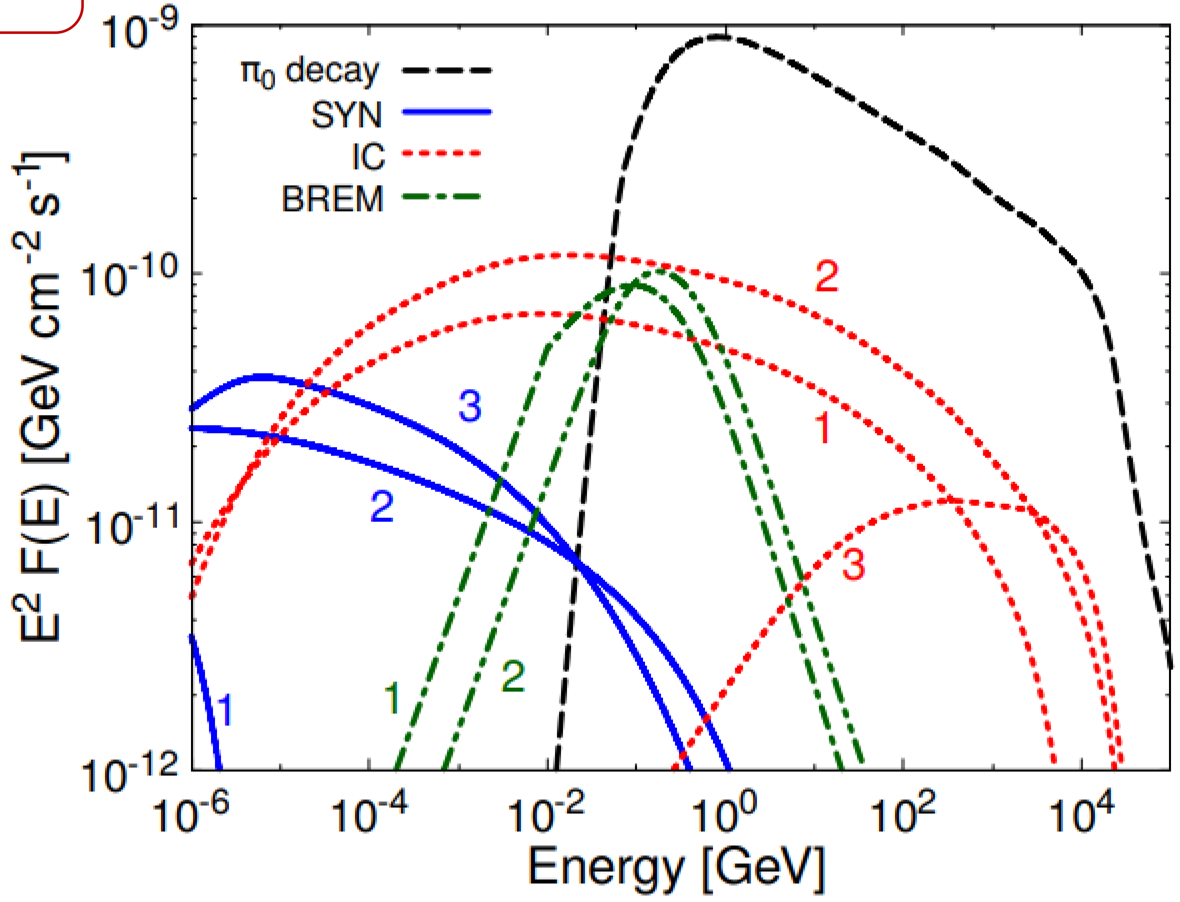
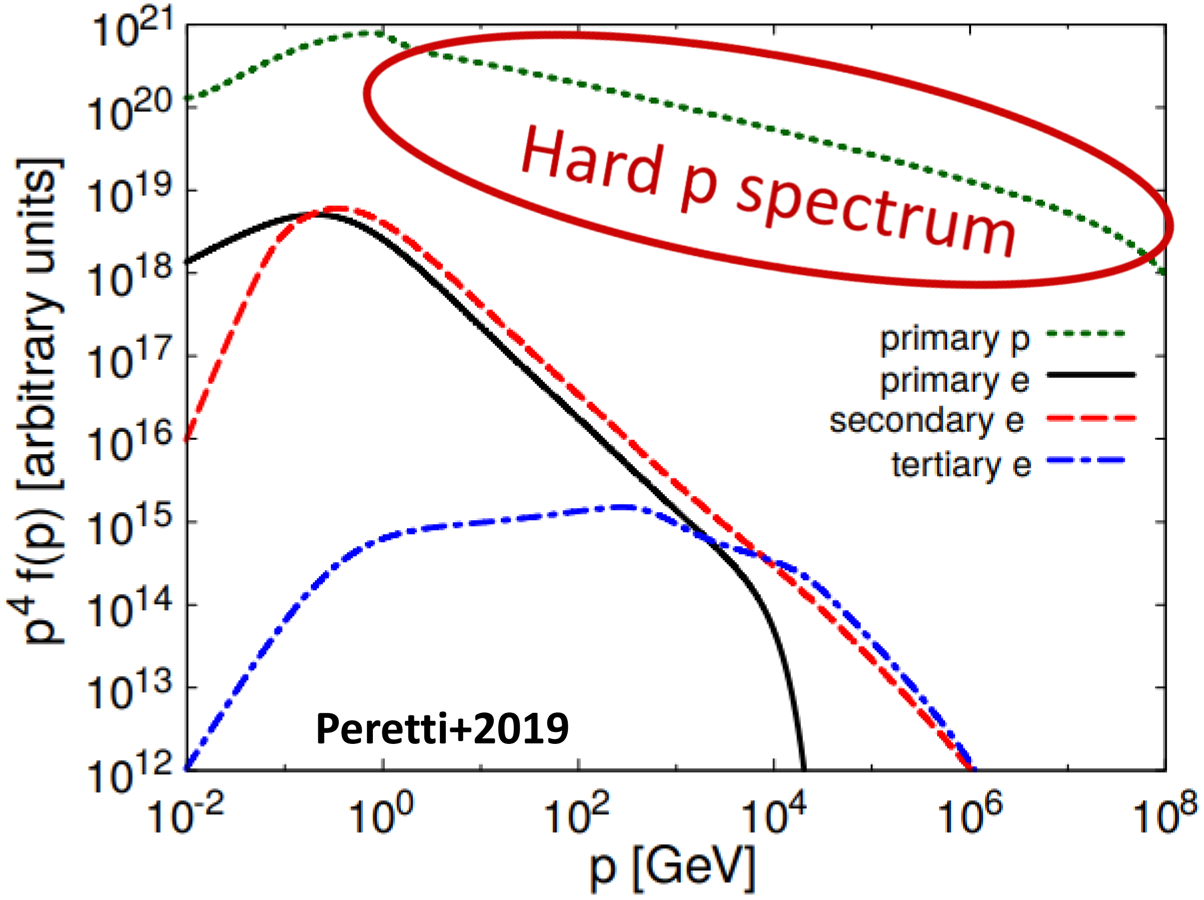


Particle and photon spectra in SBNi



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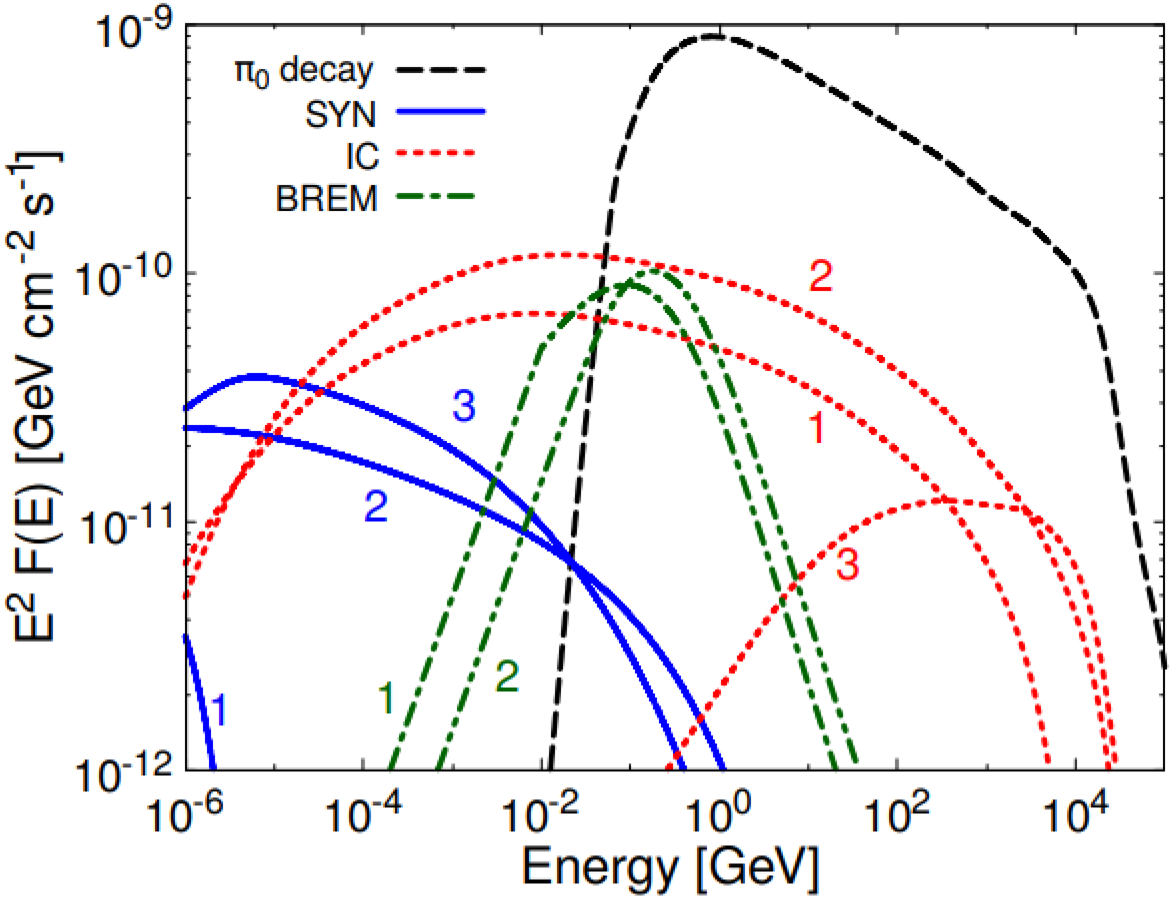
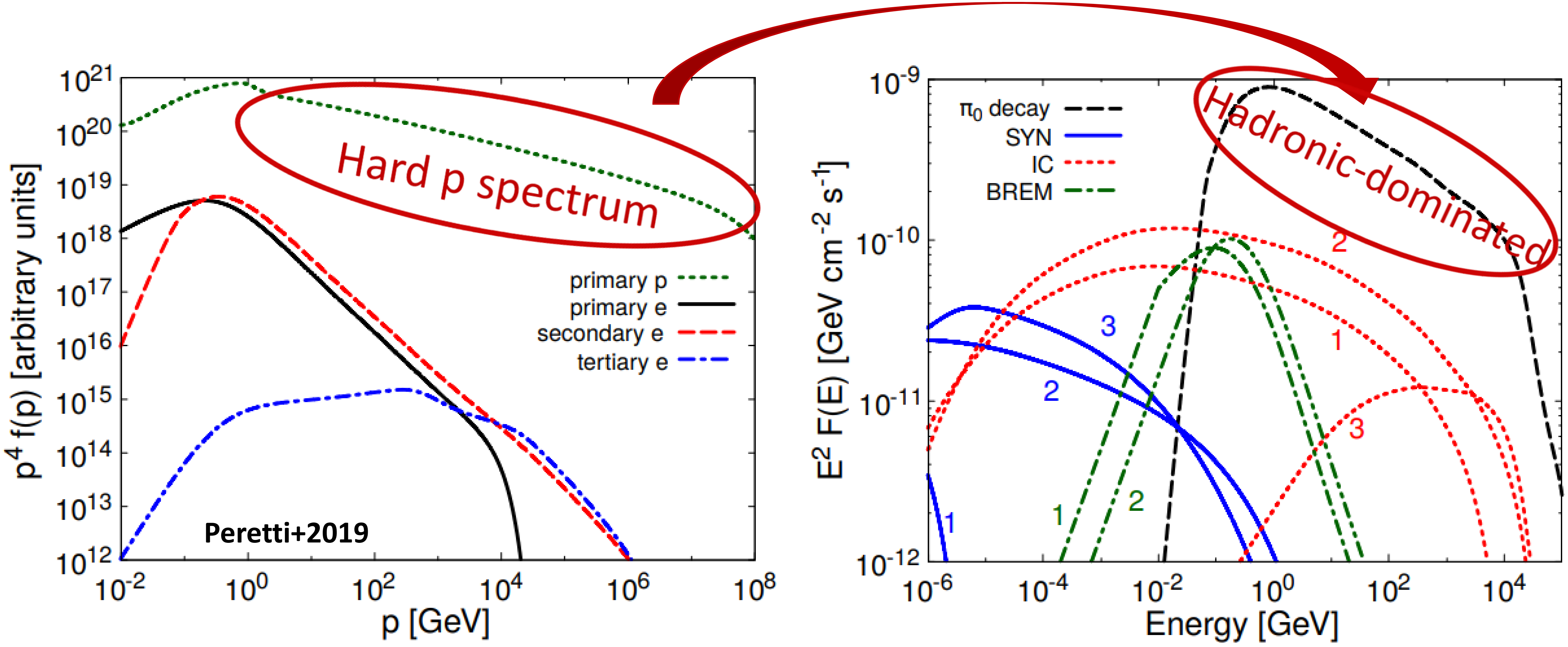


Particle and photon spectra in SBNi

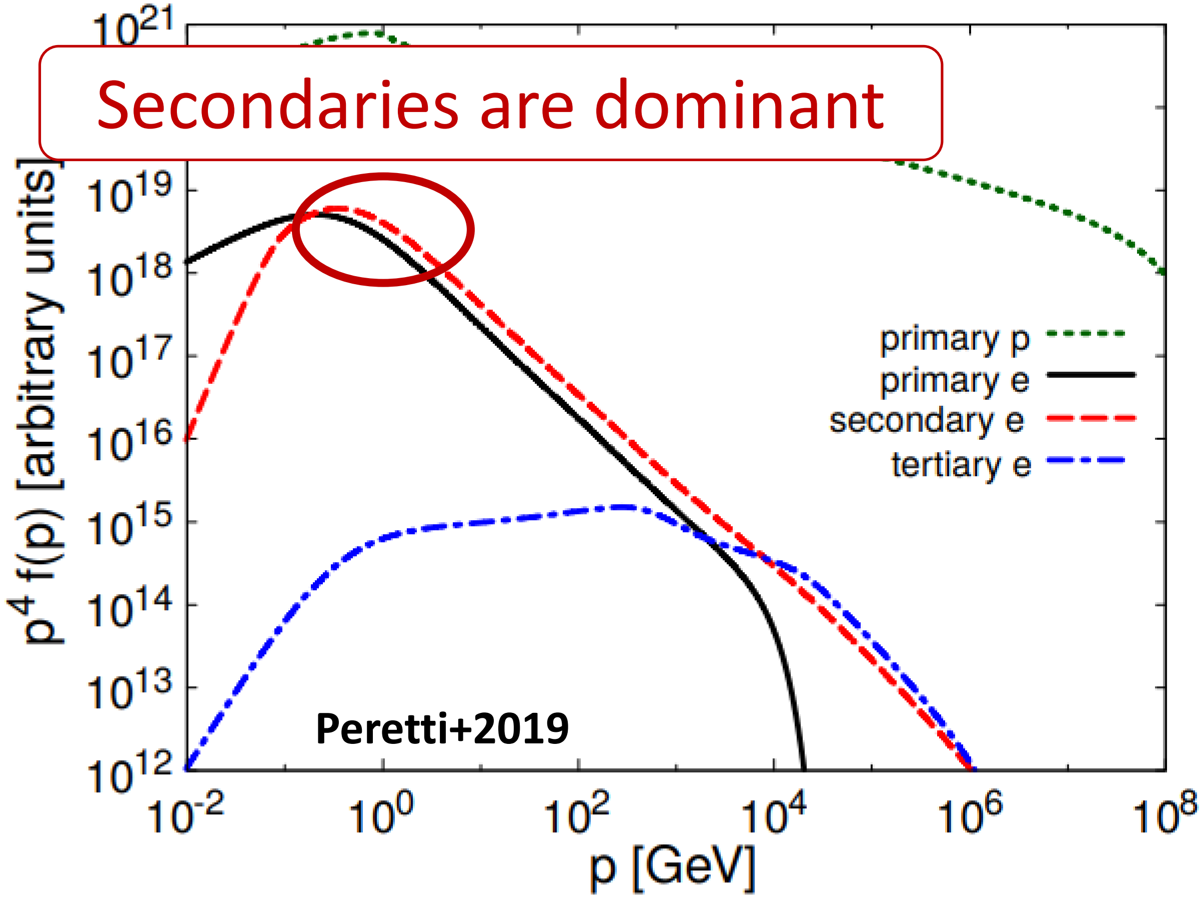


Hard p spectrum

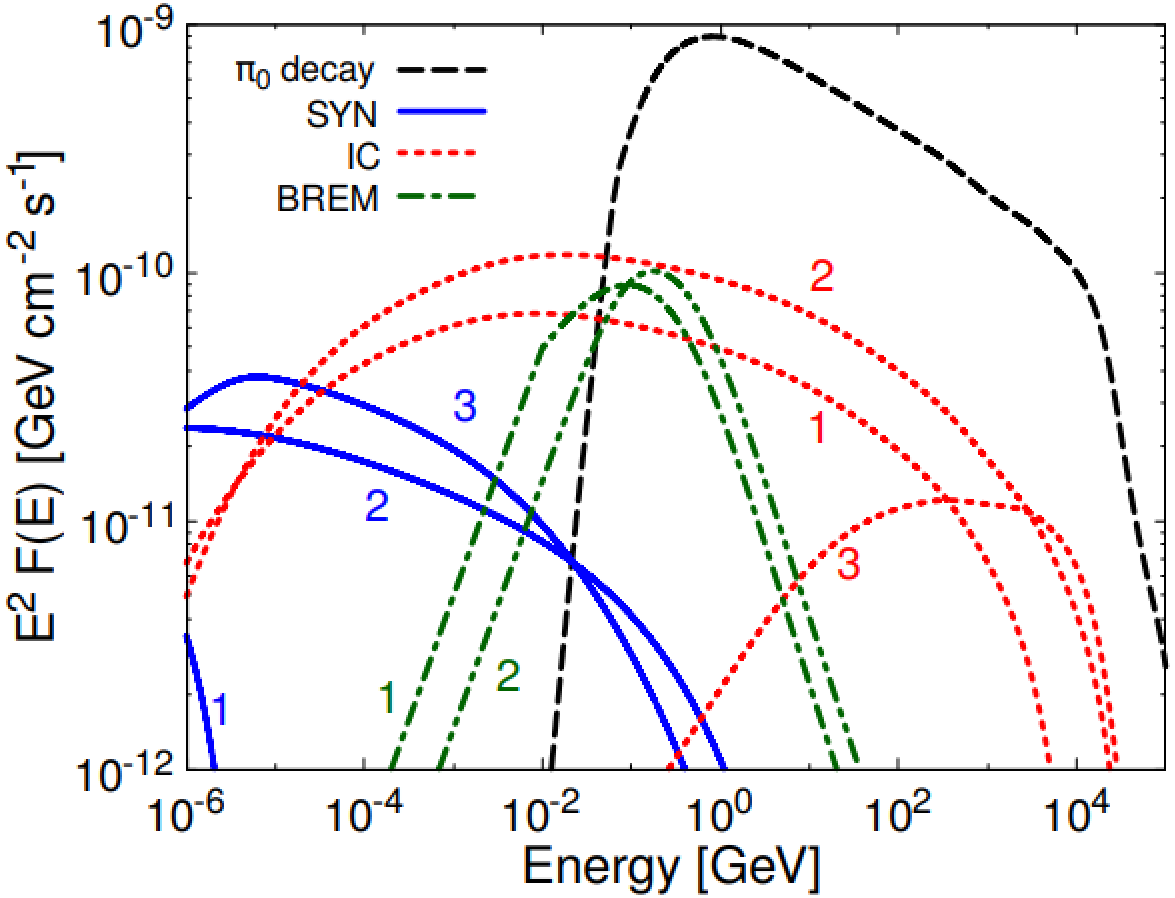
Hadronic-dominated

Peretti+2019

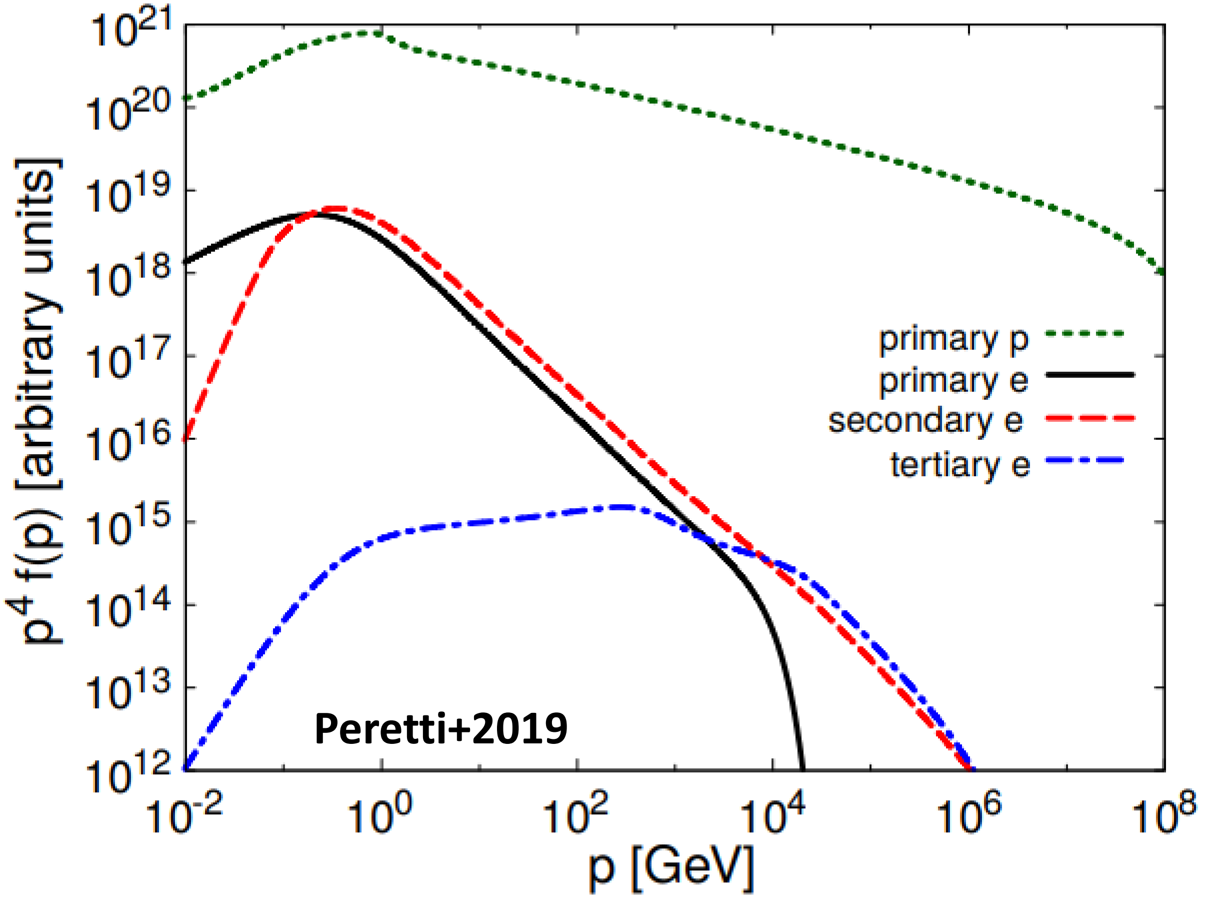
Particle and photon spectra in SBNi


Secondaries are dominant

Peretti+2019



Particle and photon spectra in SBNi



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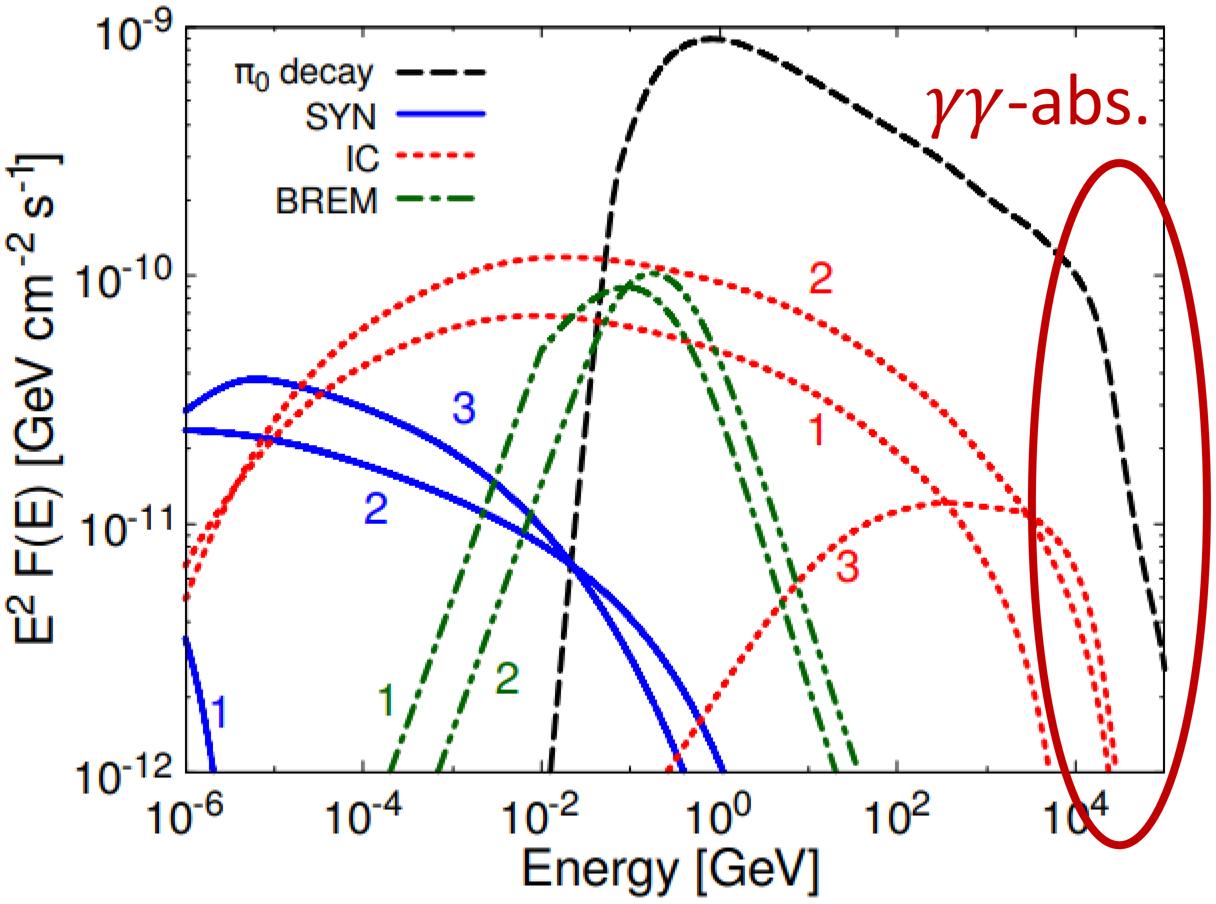
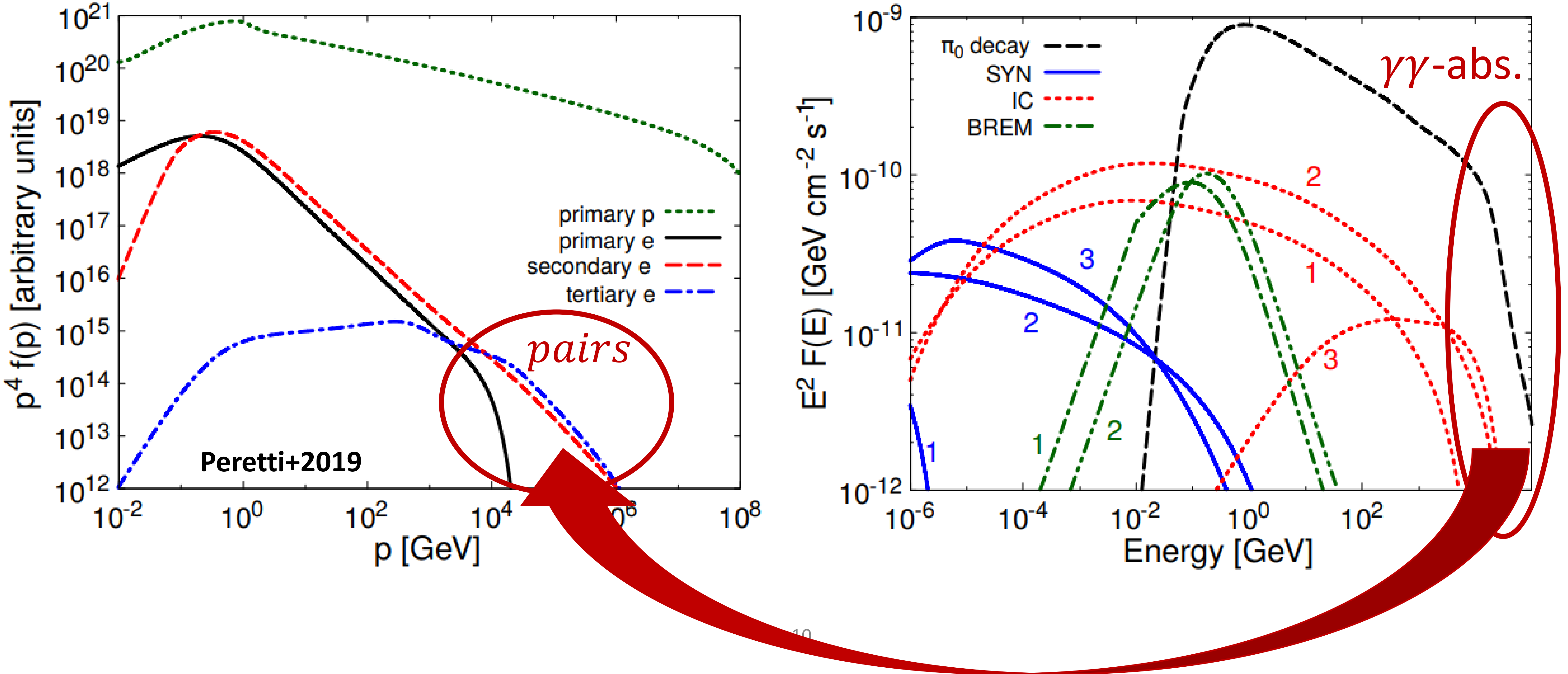
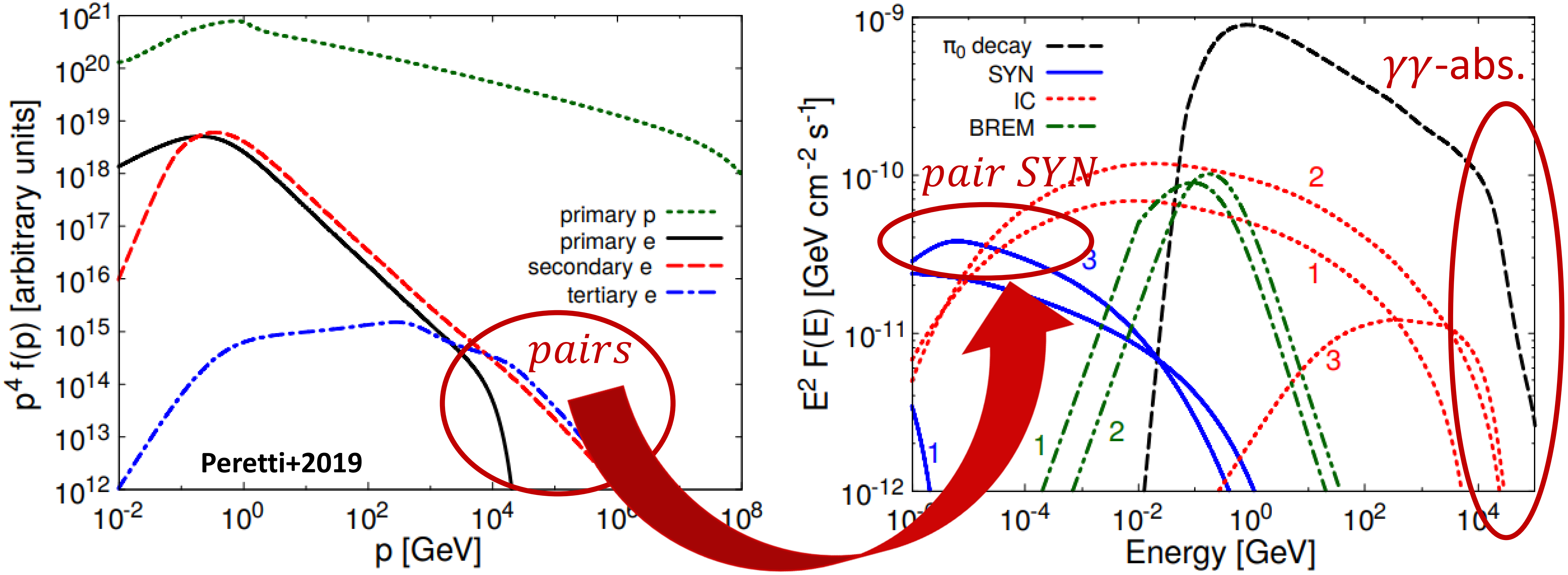


$\gamma\gamma$-abs.

Particle and photon spectra in SBNi

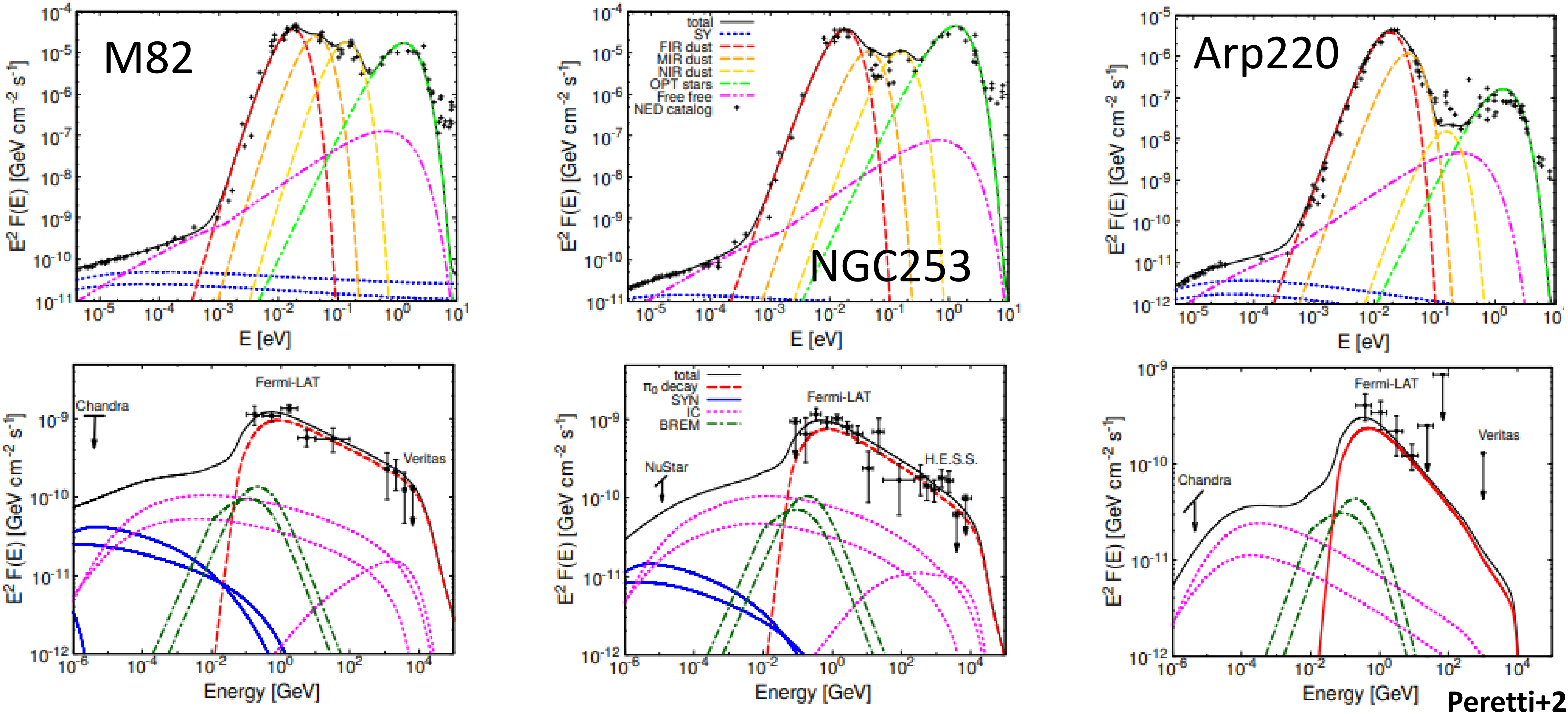


Particle and photon spectra in SBNi



Peretti+2019

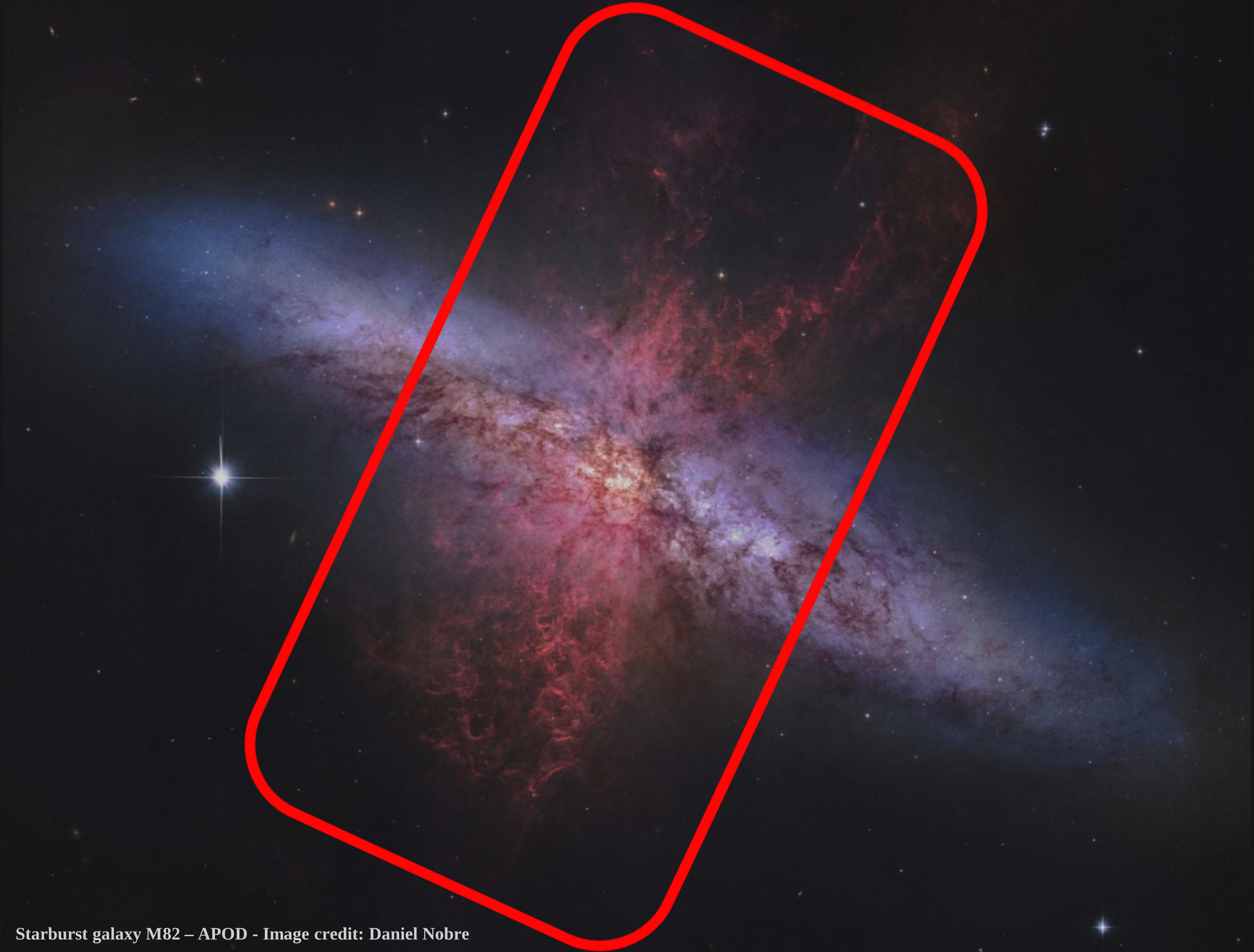
Modeling nearby SBGs



Peretti+2019

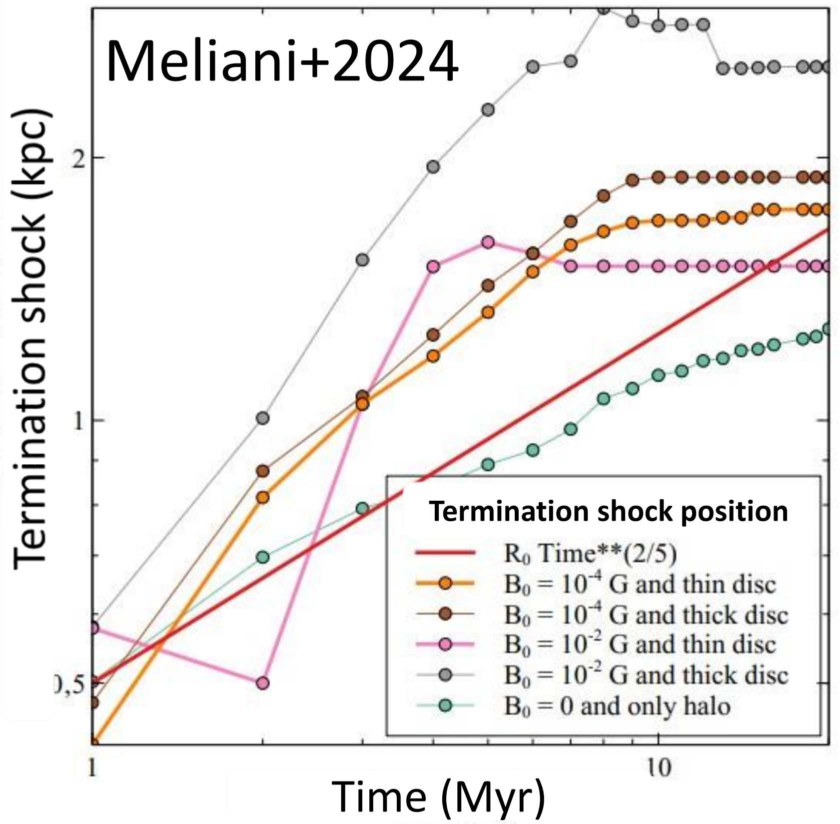
Outline

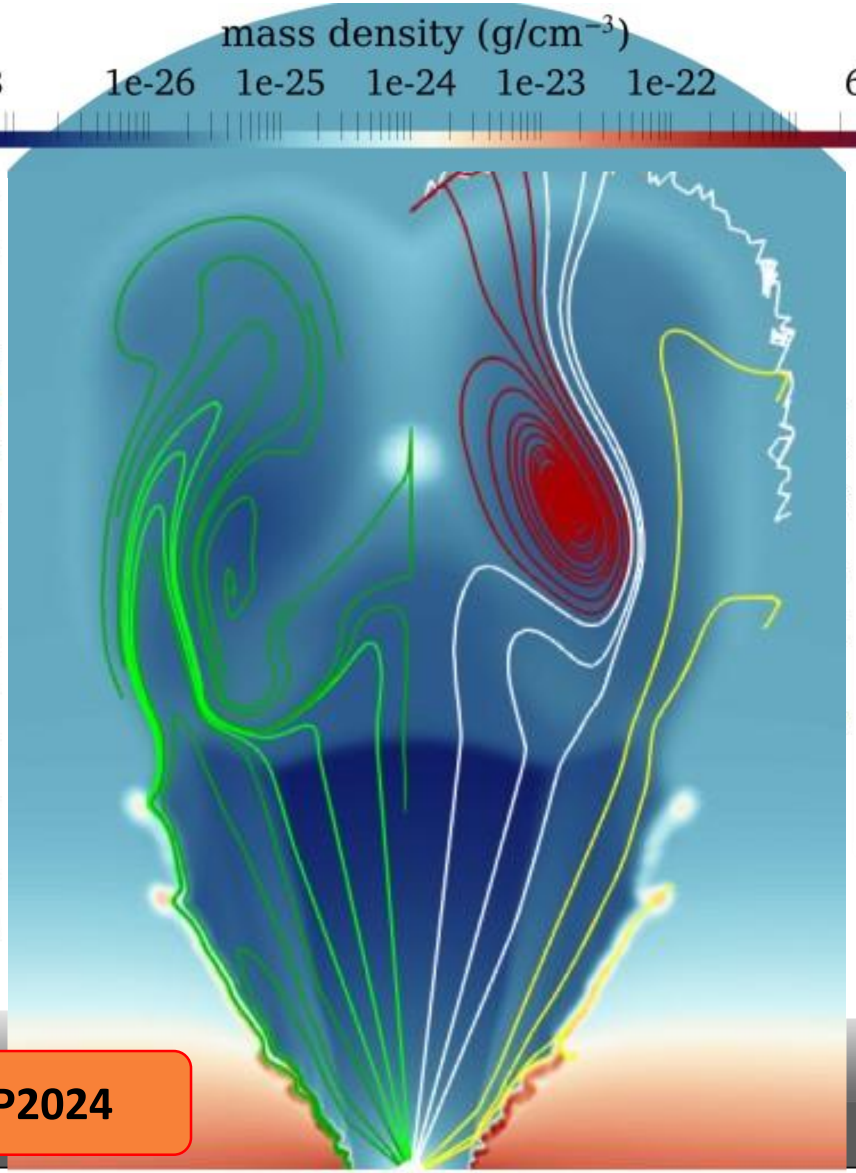
- Particle Transport in Starburst Nuclei
- Starburst-driven winds
- Multi-messenger diffuse flux

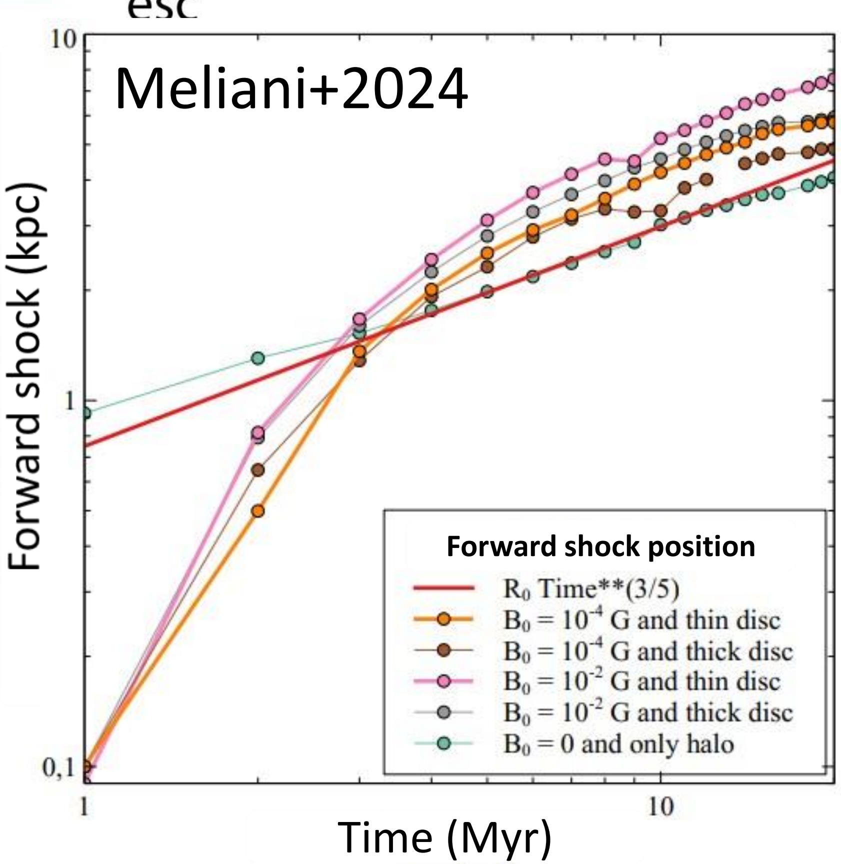


Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

Starburst-driven wind bubble

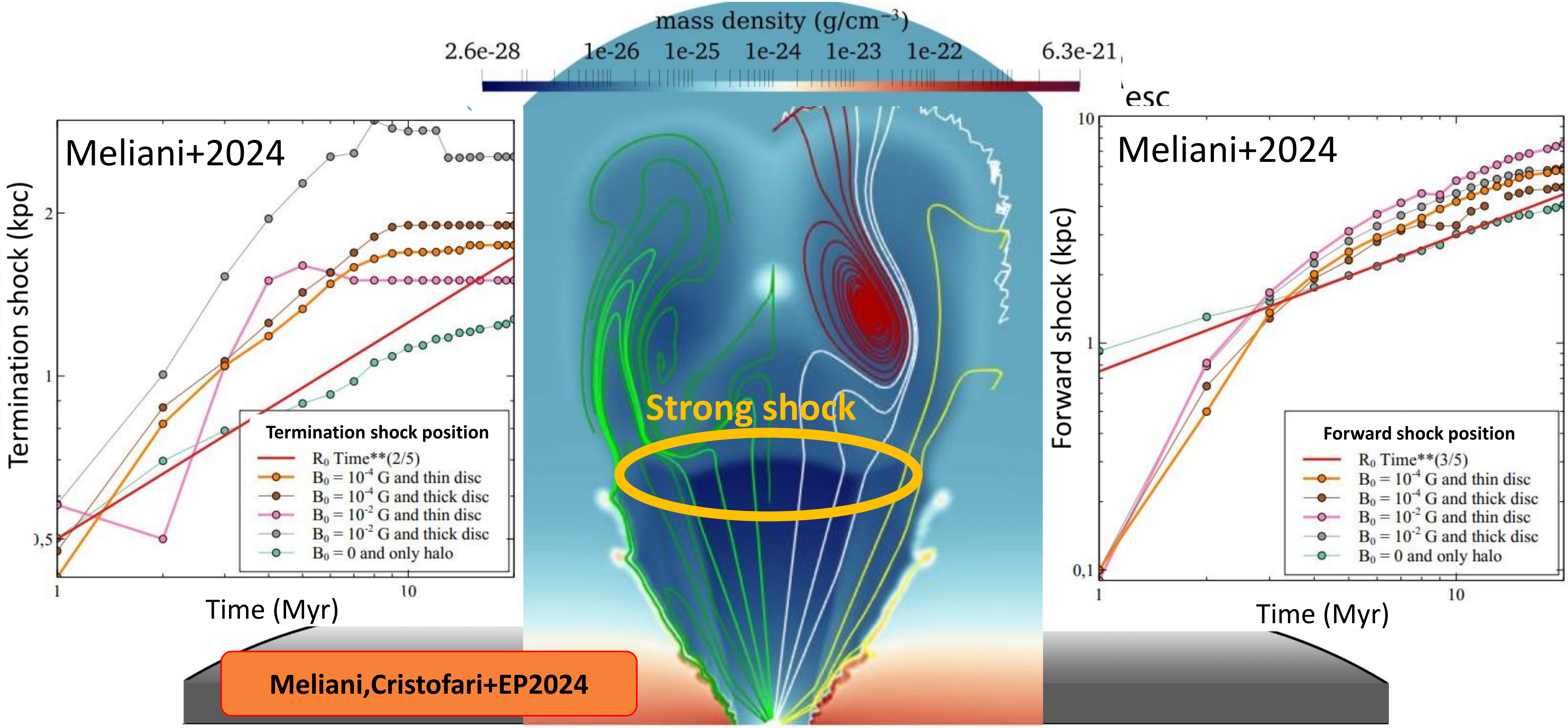






Meliani,Cristofari+EP2024

Starburst-driven wind bubble



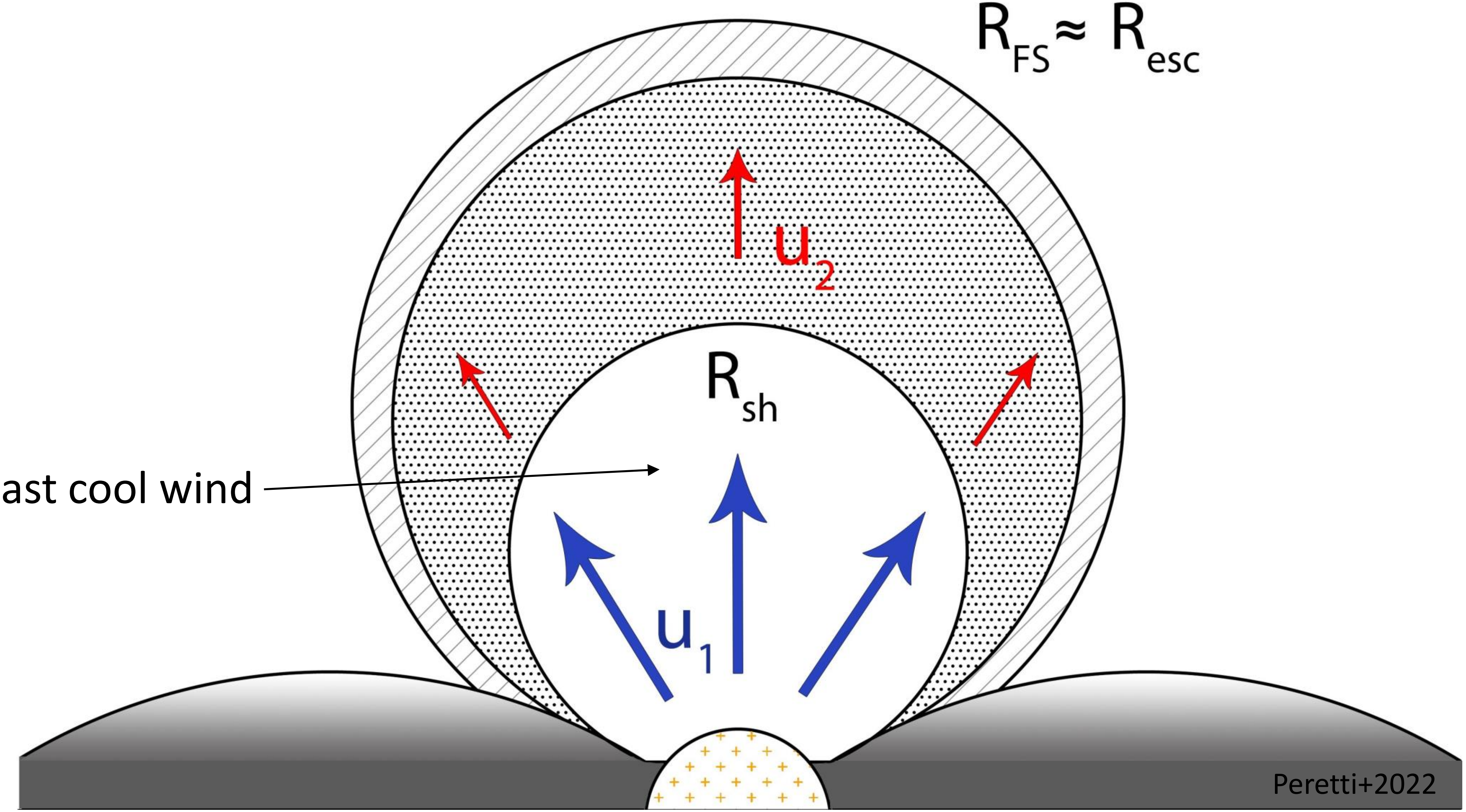
Meliani+2024

Strong shock

Meliani+2024

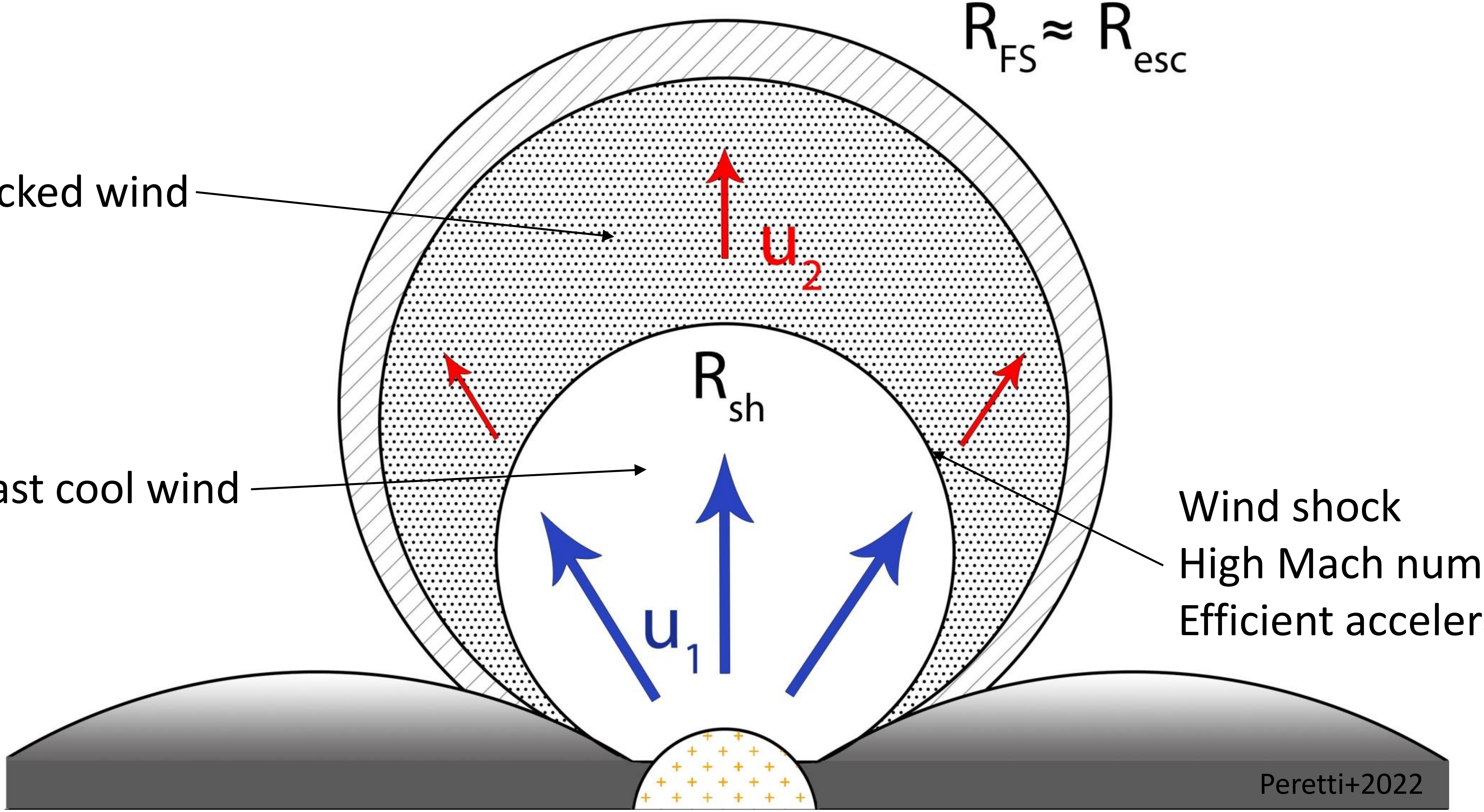
Meliani,Cristofari+EP2024

Acceleration and transport in starburst winds



Fast cool wind

Acceleration and transport in starburst winds



Hot shocked wind

Fast cool wind

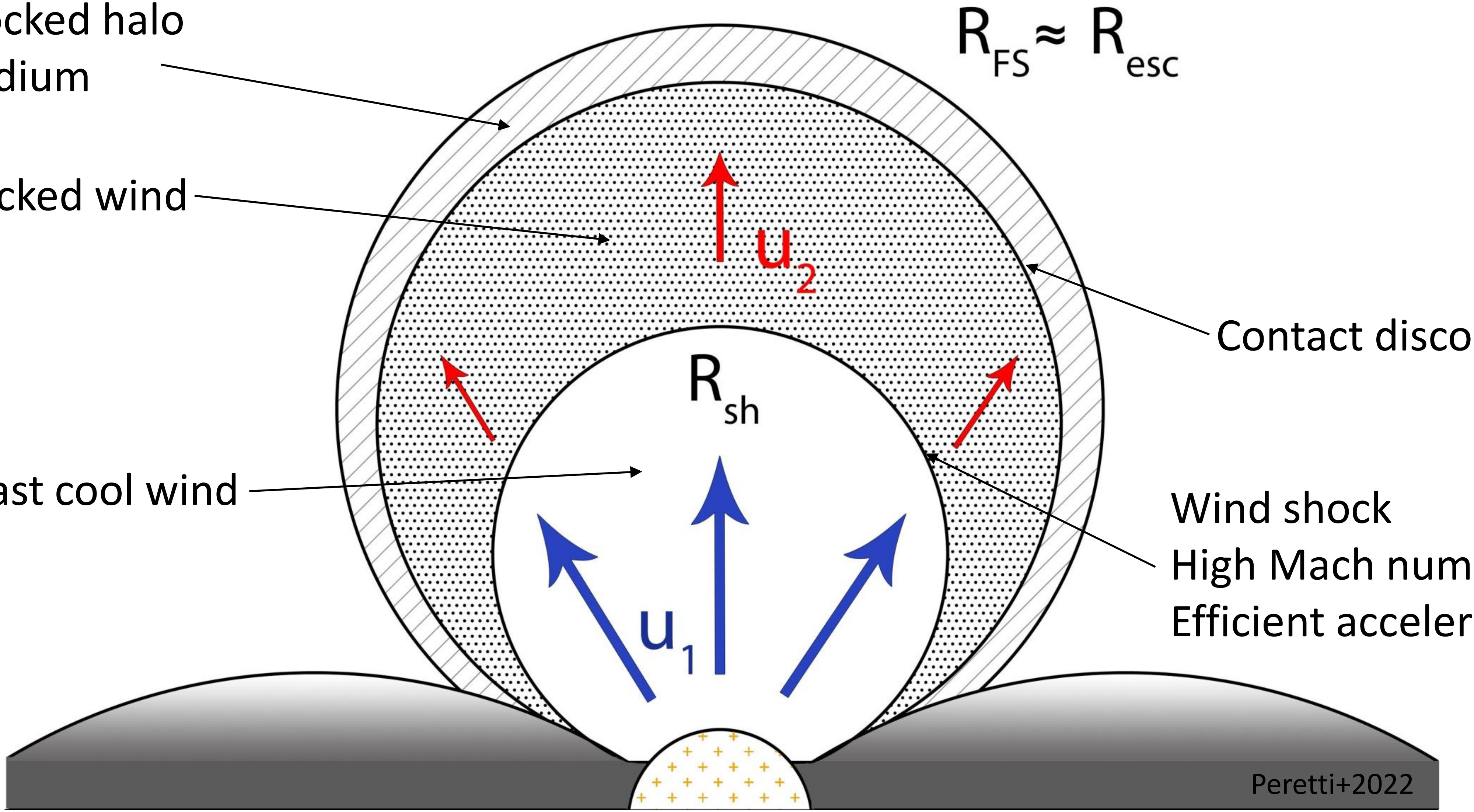
Wind shock

High Mach number (≥10)

Efficient acceleration

Peretti+2022

Acceleration and transport in starburst winds



Shocked halo medium

Hot shocked wind

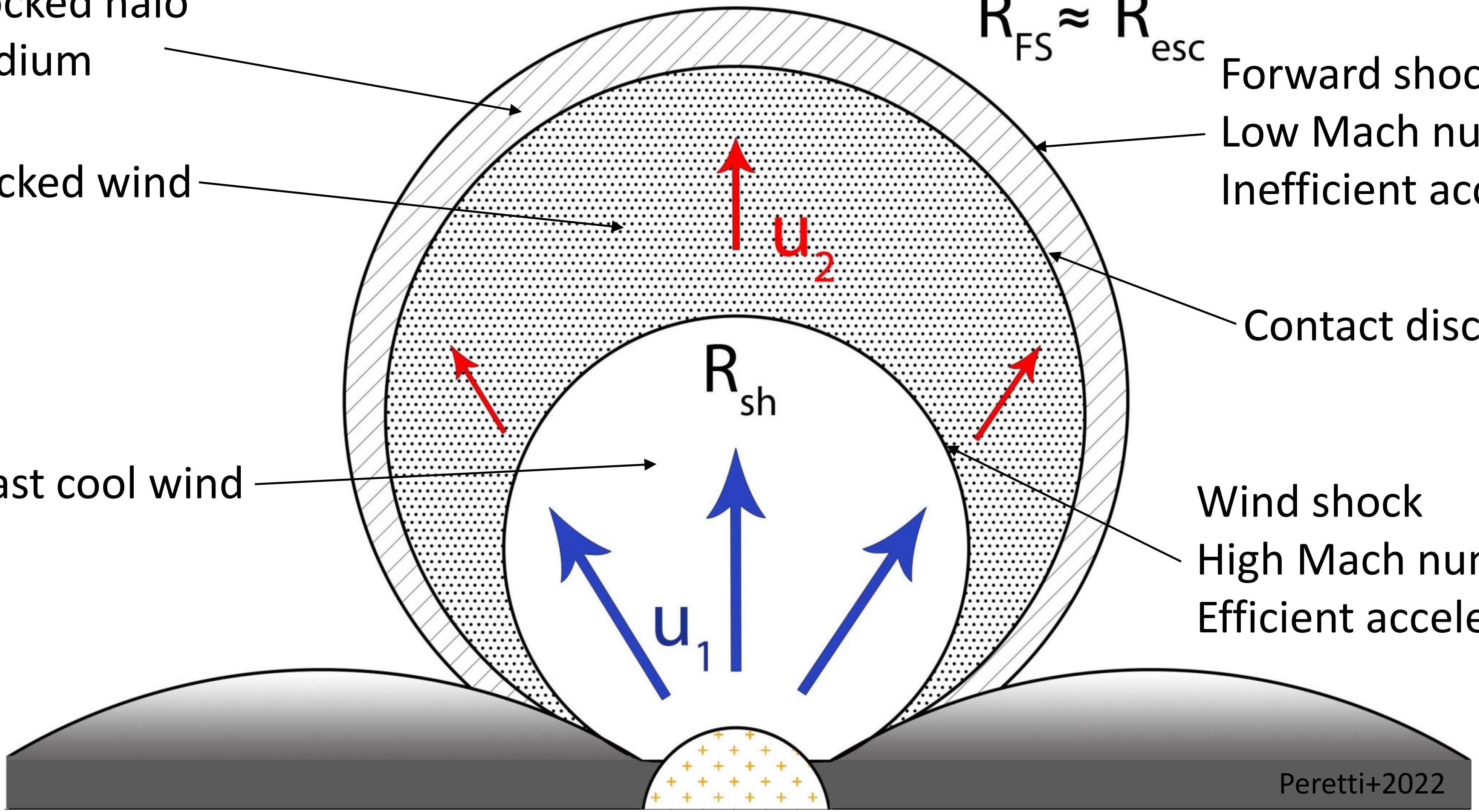
Contact discontinuity

Fast cool wind

Wind shock
High Mach number (≥10)
Efficient acceleration

Peretti+2022

Acceleration and transport in starburst winds



Shocked halo medium

Hot shocked wind

Fast cool wind

$R_{FS} \approx R_{esc}$

Forward shock
Low Mach number (<5)
Inefficient acceleration

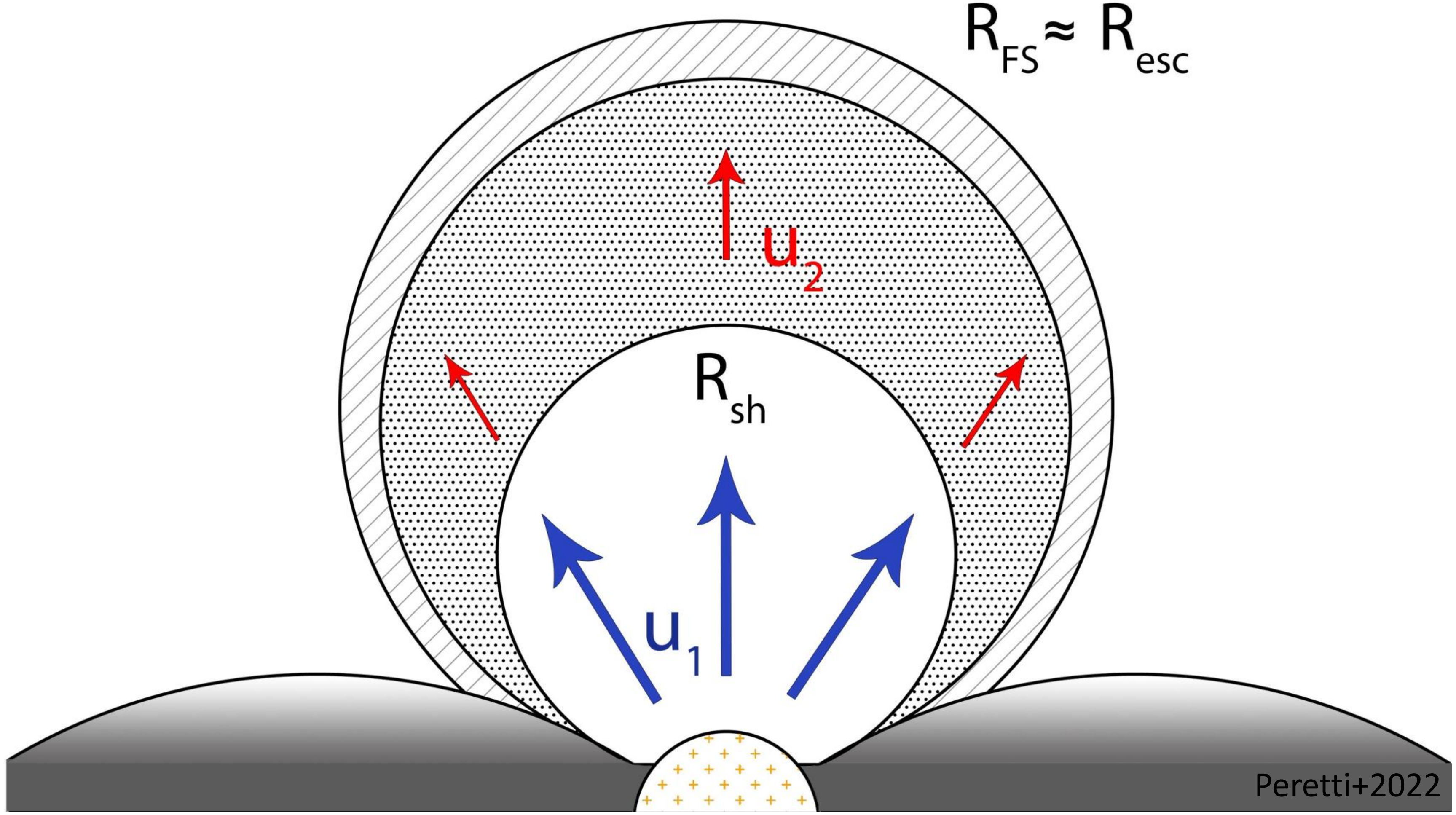
Contact discontinuity

Wind shock
High Mach number (≥10)
Efficient acceleration

Peretti+2022

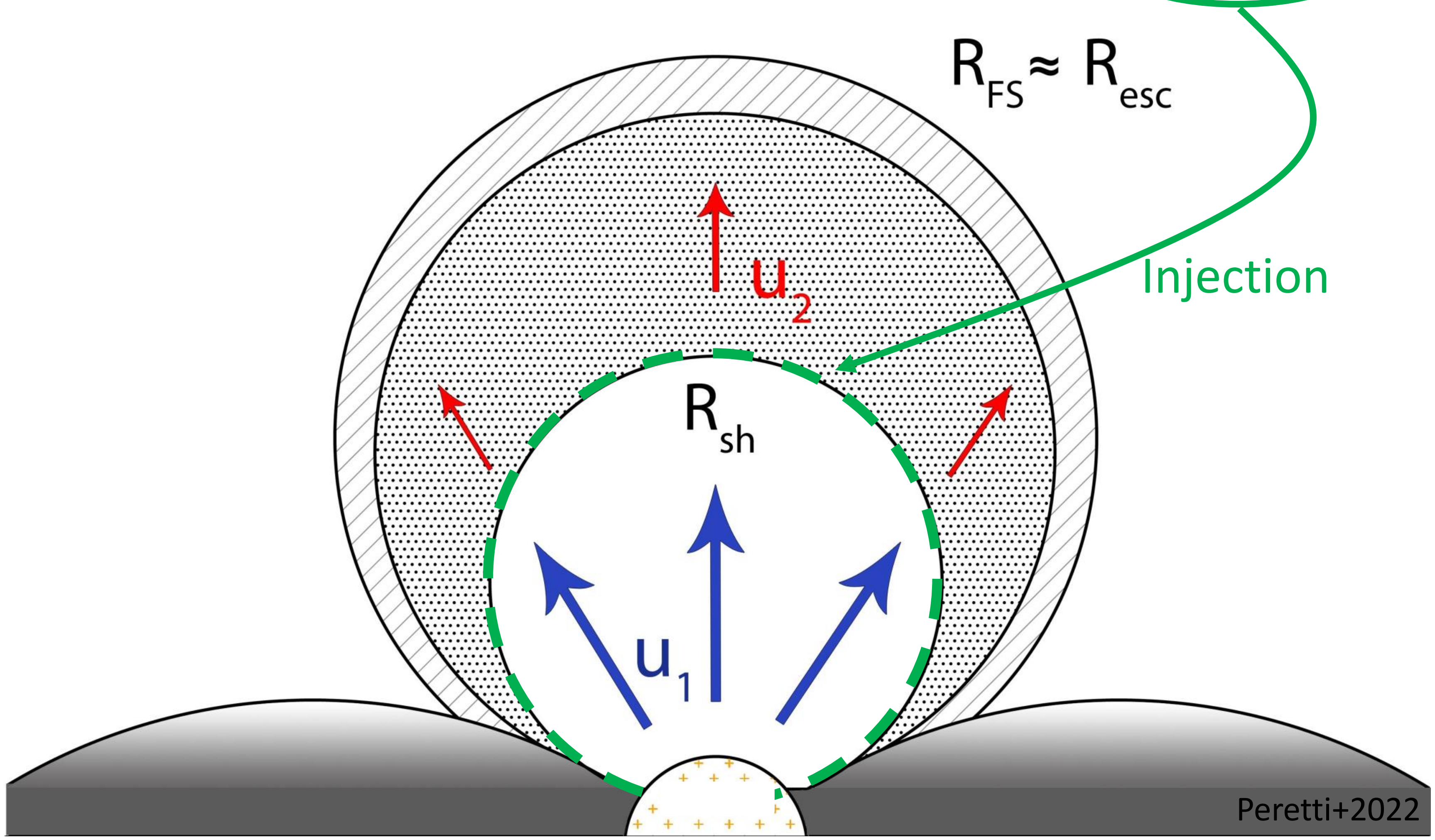
Transport model

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



Transport model

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

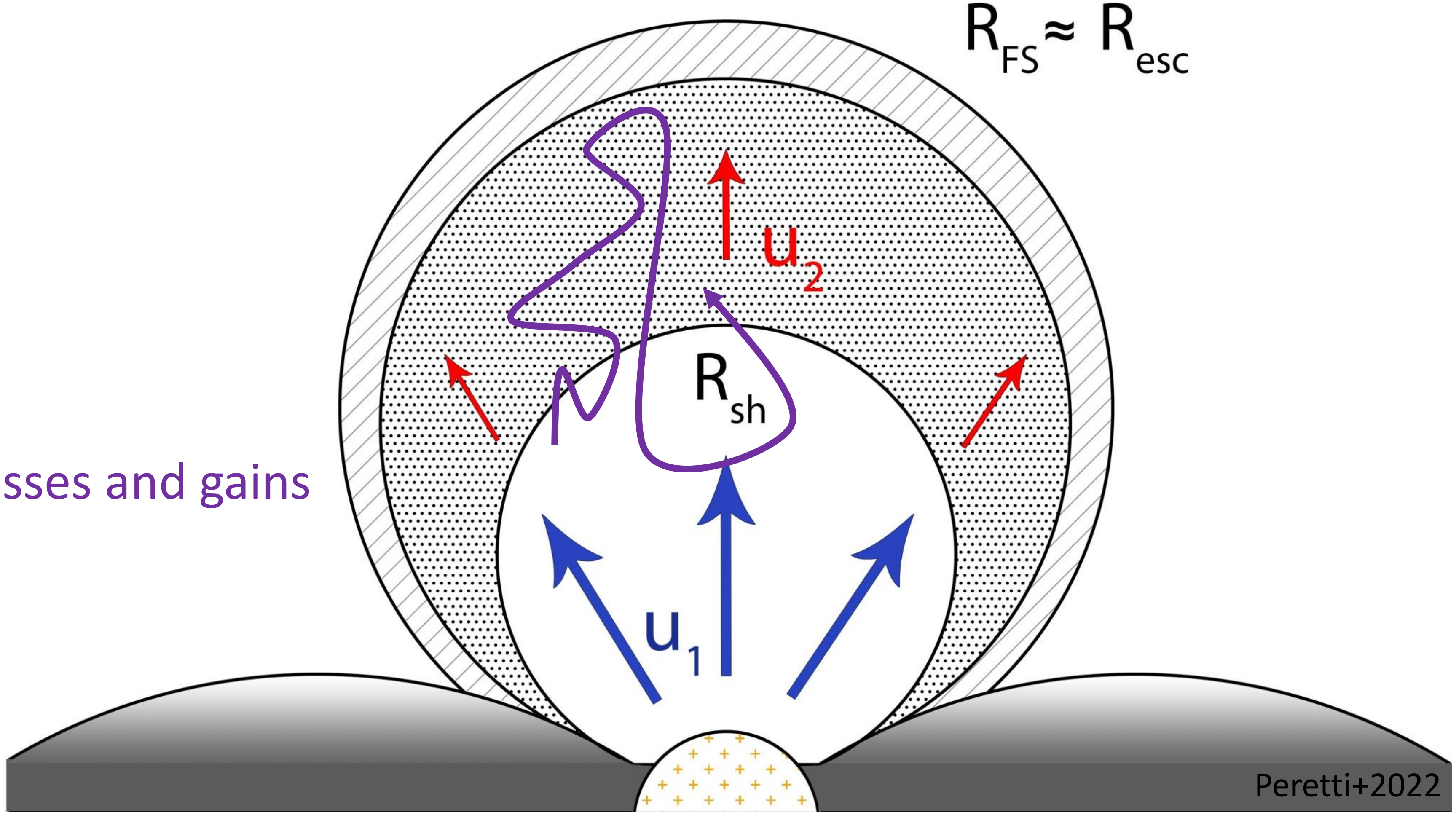


Peretti+2022

Transport model

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

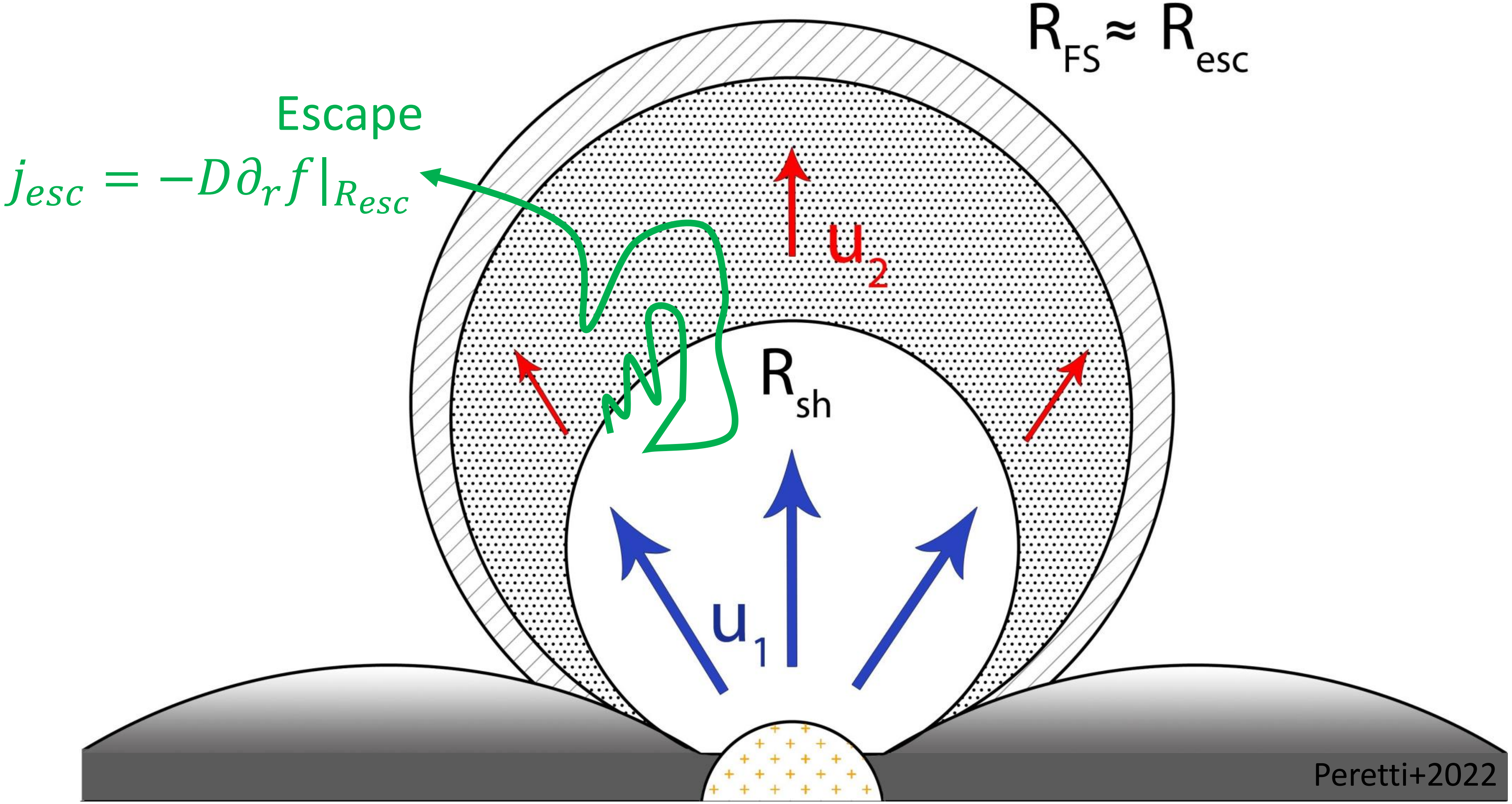
- Advection
- Diffusion
- Adiabatic losses and gains



Peretti+2022

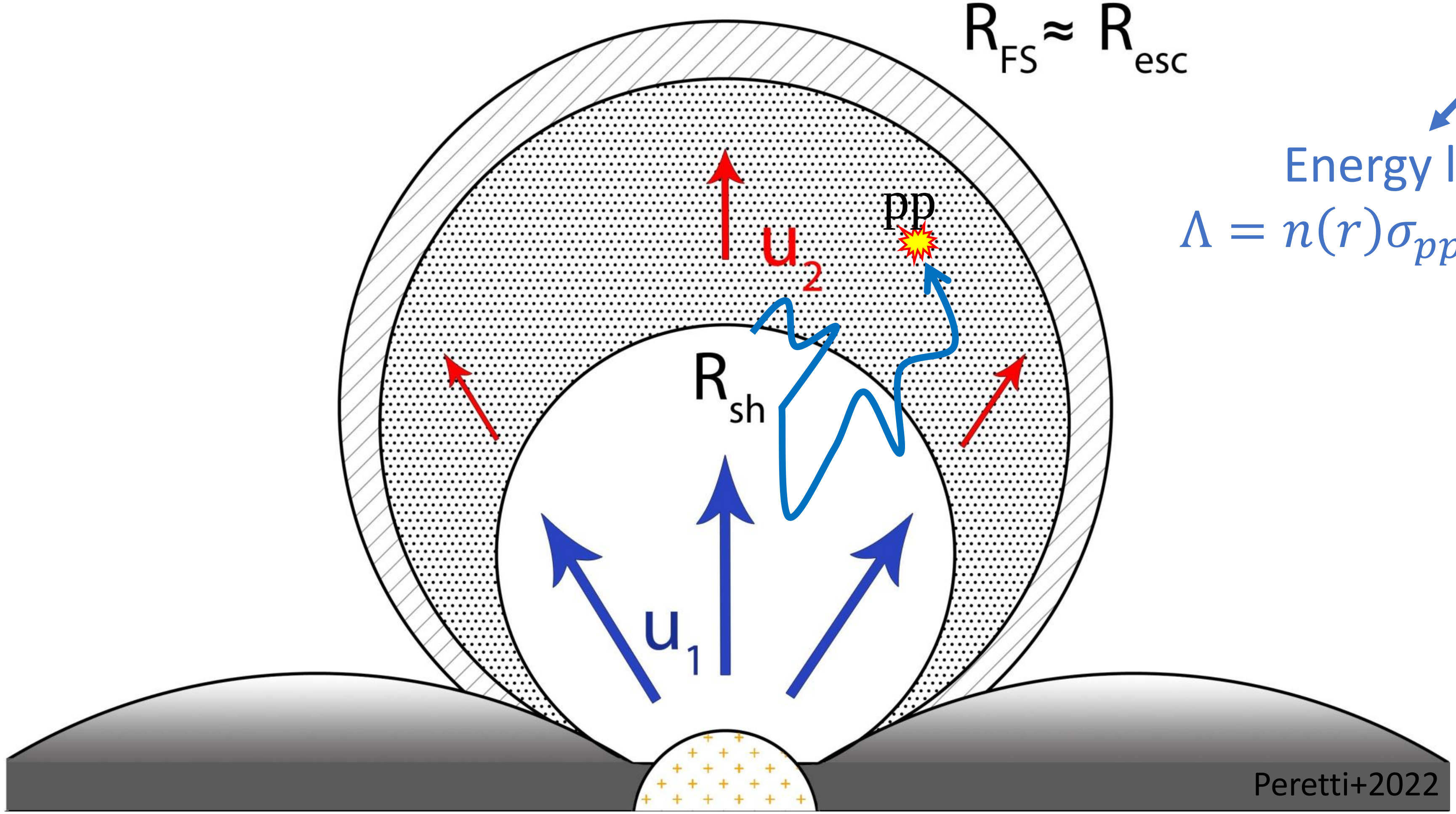
Transport model

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



Transport model

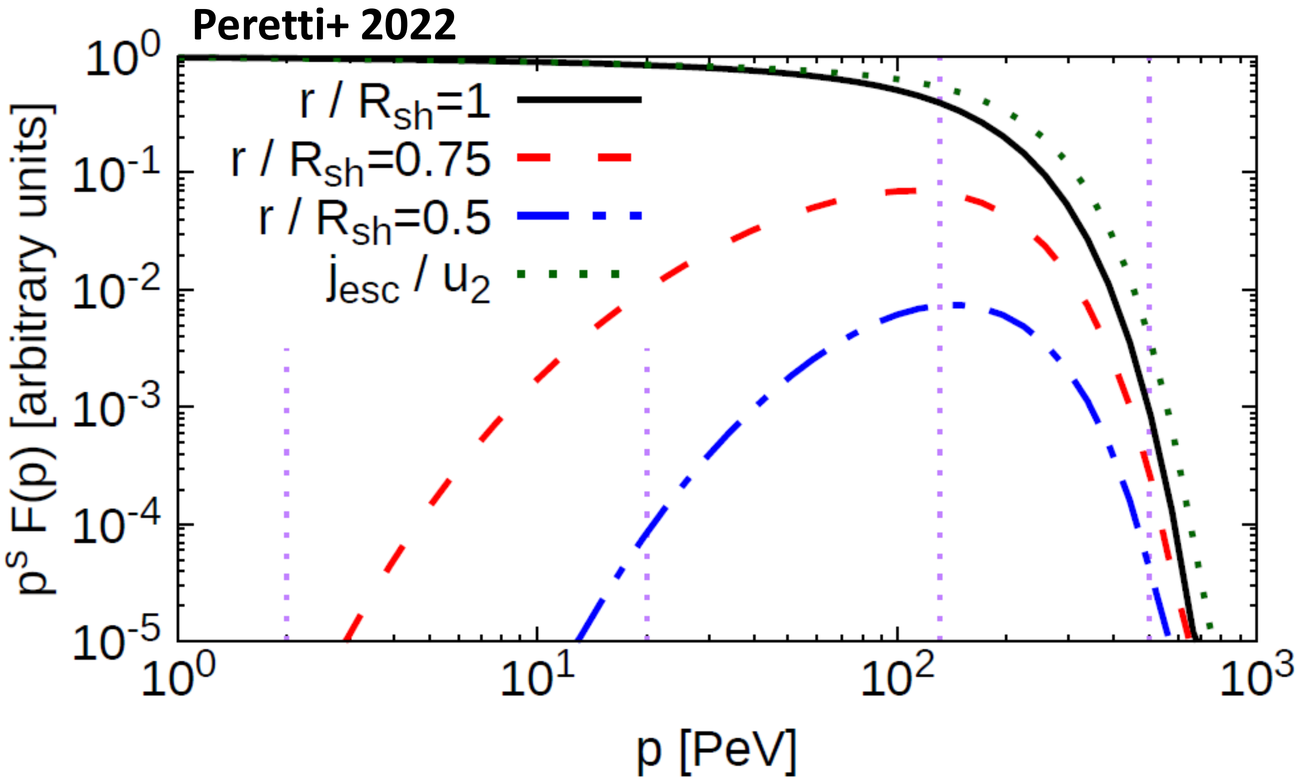
$$r^2 u(r)\partial_r f = \partial_r[r^2 D(r,p)\partial_r f] + \frac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p) - r^2\Lambda(r,p)$$



Energy losses

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

Particles in the system



Parameters

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

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

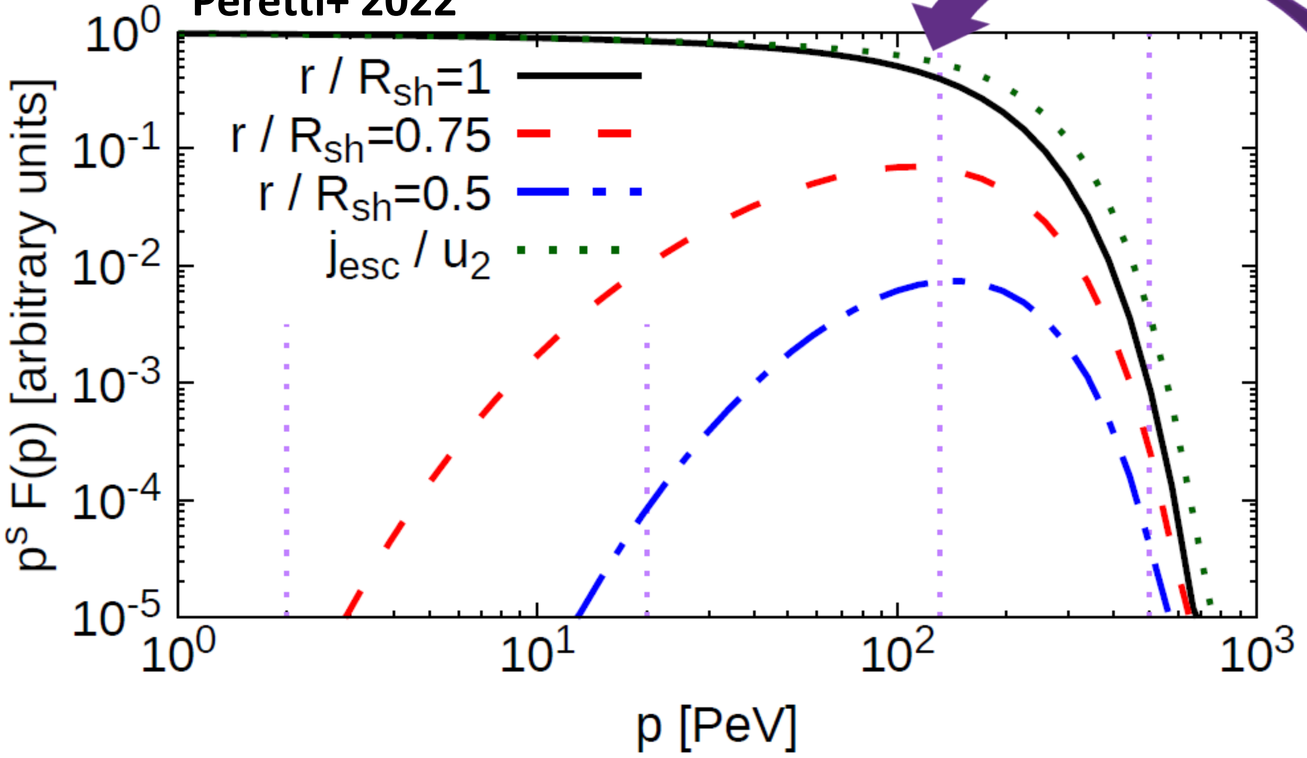
$R_{sh} = 12\ kpc$

$R_{FS} = 55\ kpc$

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

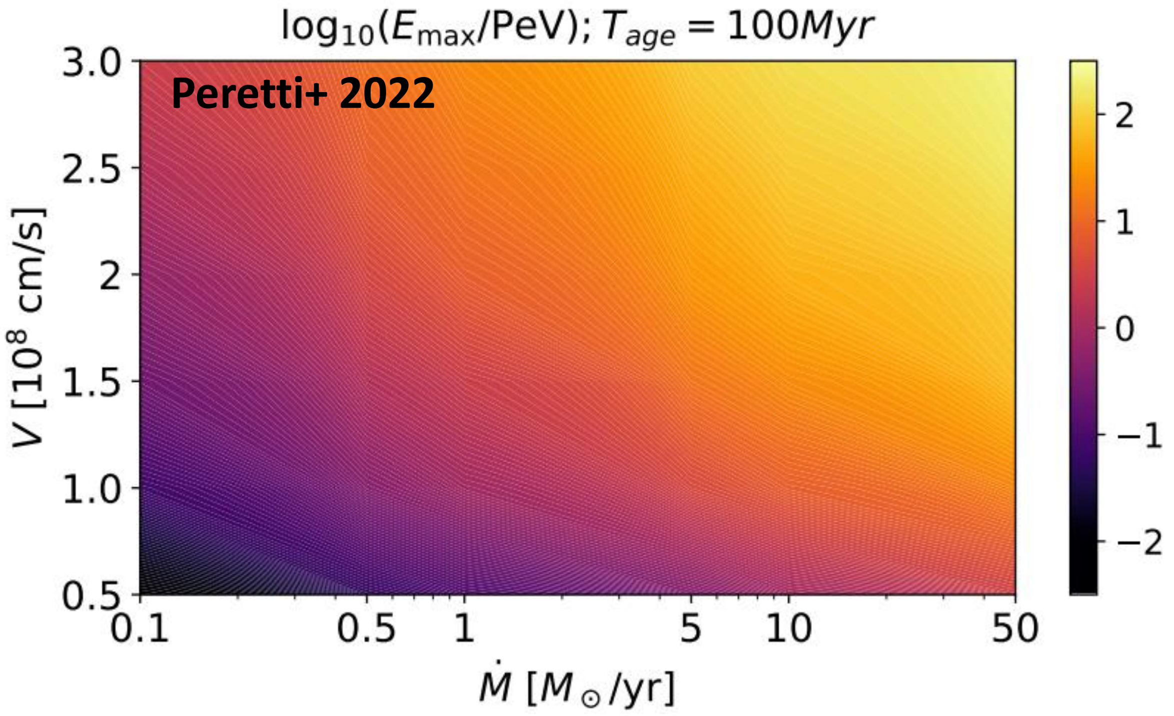
Particles in the system

Peretti+ 2022

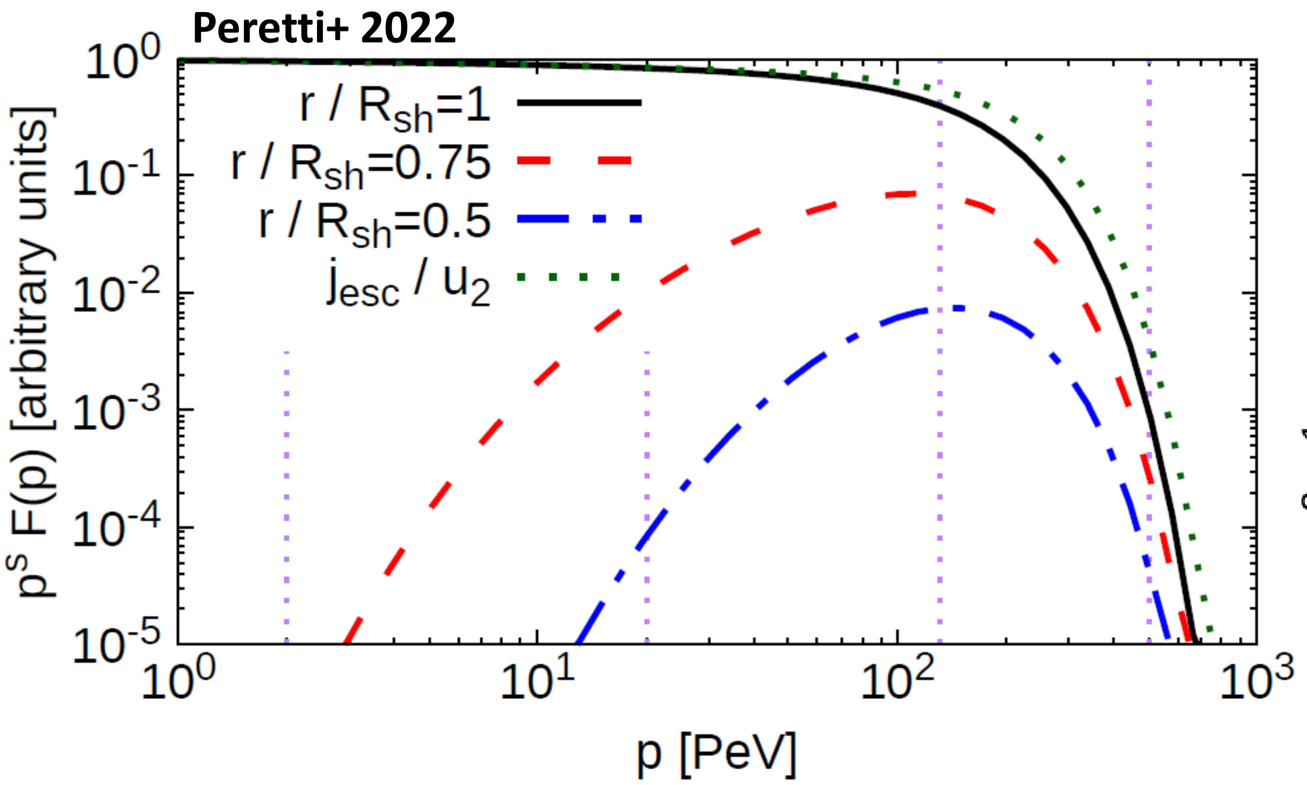


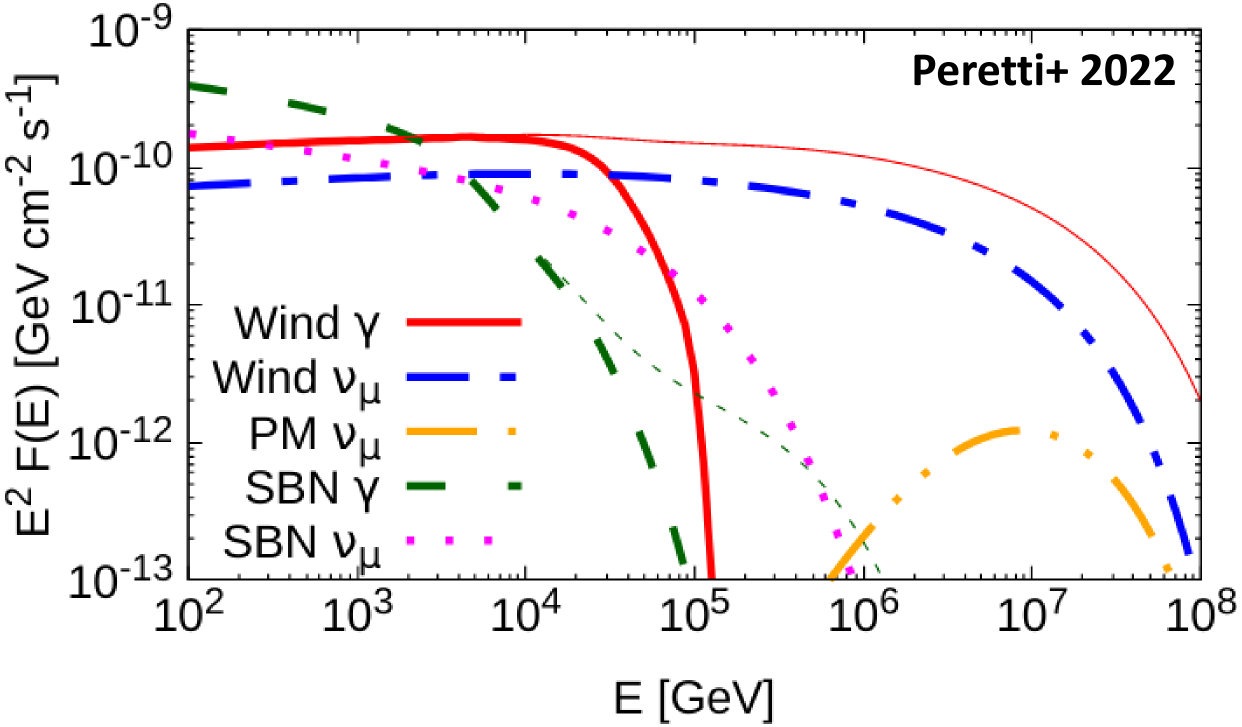
$$f_{sh}(p) \propto p^{-s} e^{-\Gamma_1(p)} e^{-\Gamma_2(p)}$$

- Maximum Energy → 10^2 PeV



High-Energy SED and neutrinos

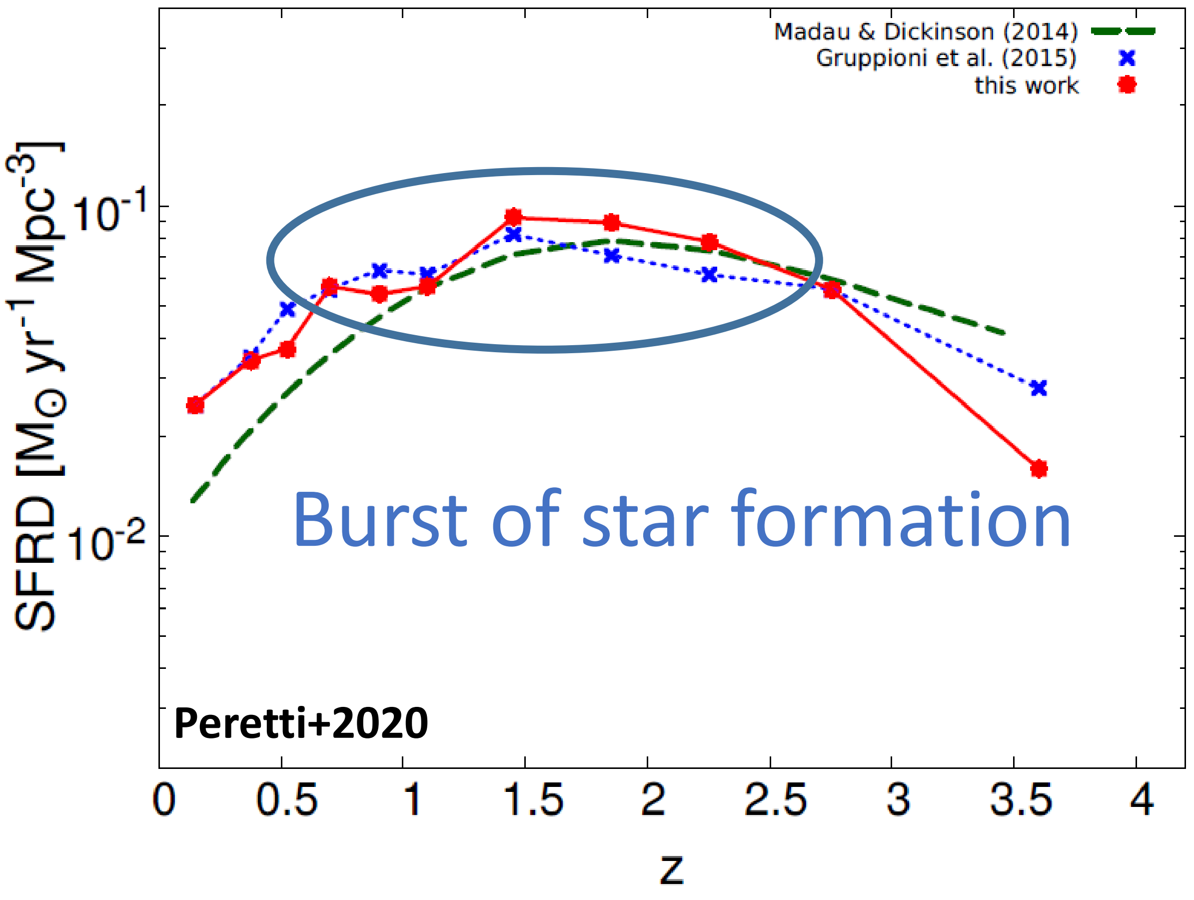




Outline

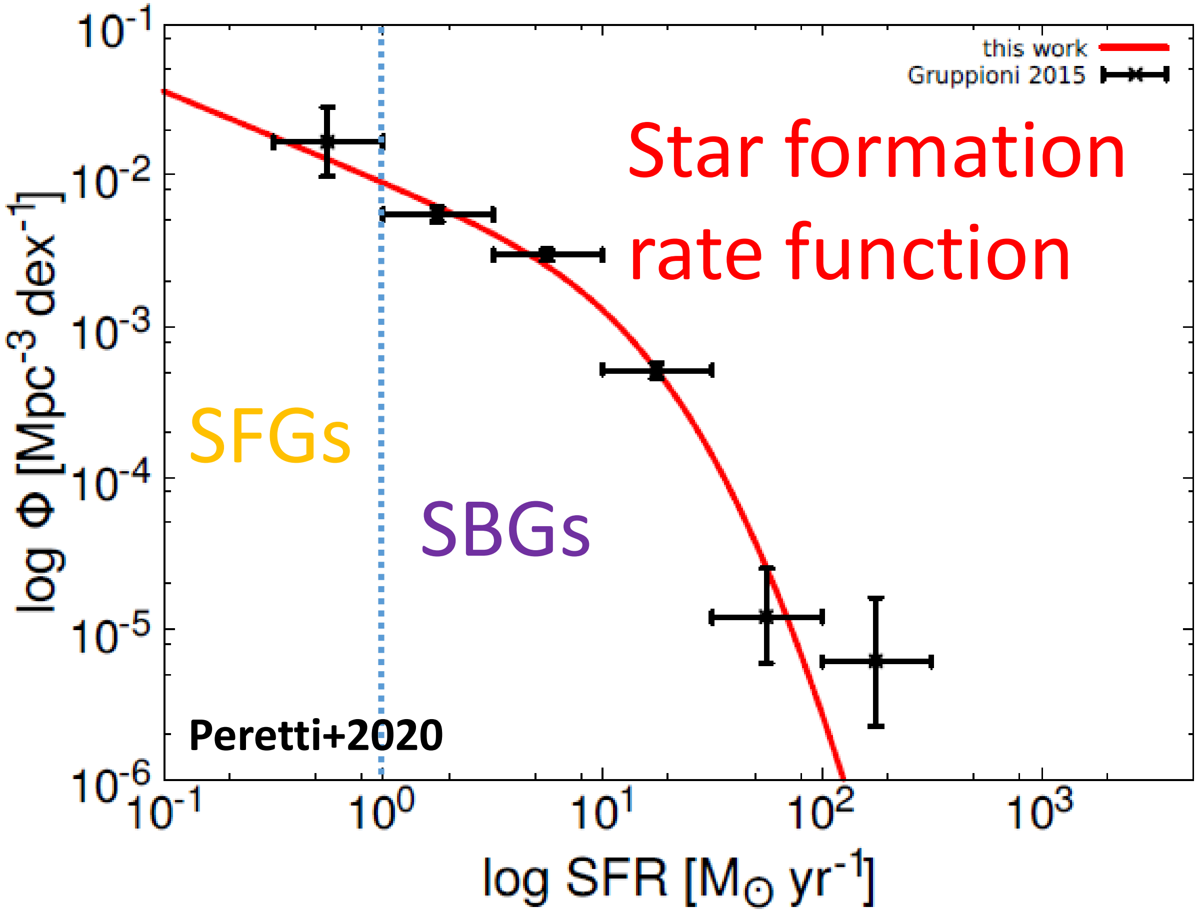
- Particle Transport in Starburst Nuclei
- Starburst-driven winds
- Multi-messenger diffuse flux

Starbursts as diffuse sources



Burst of star formation

Peretti+2020



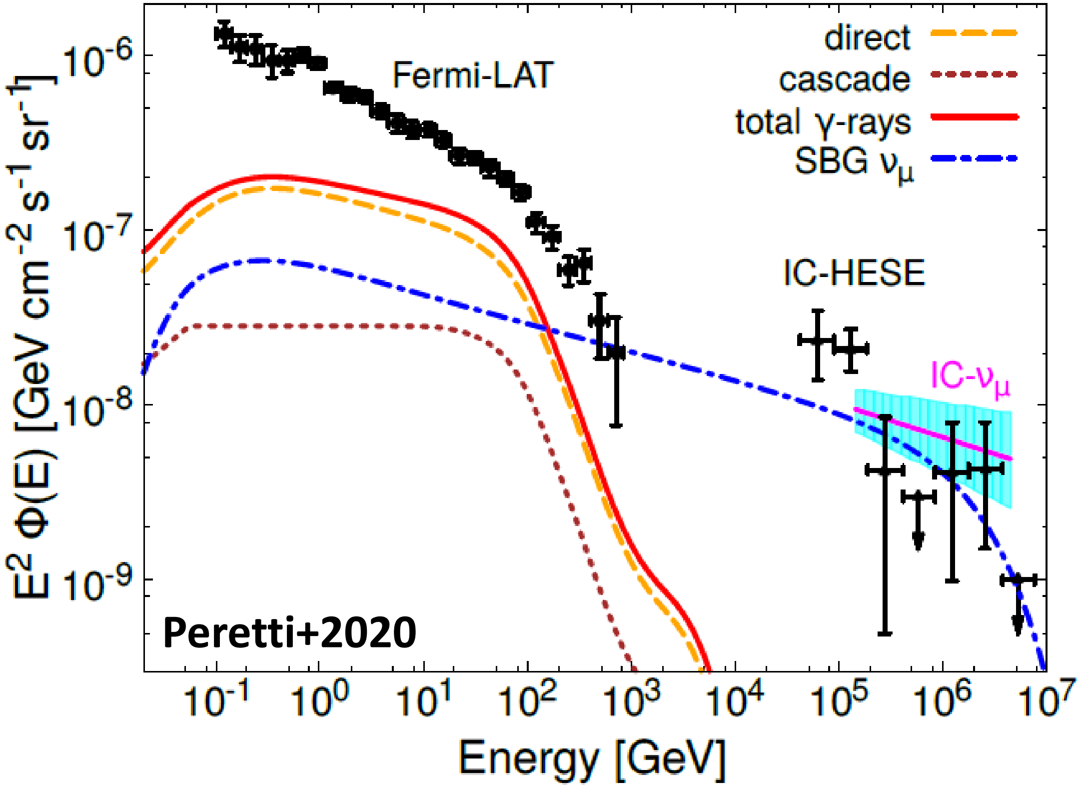
Star formation rate function

SFGs

SBGs

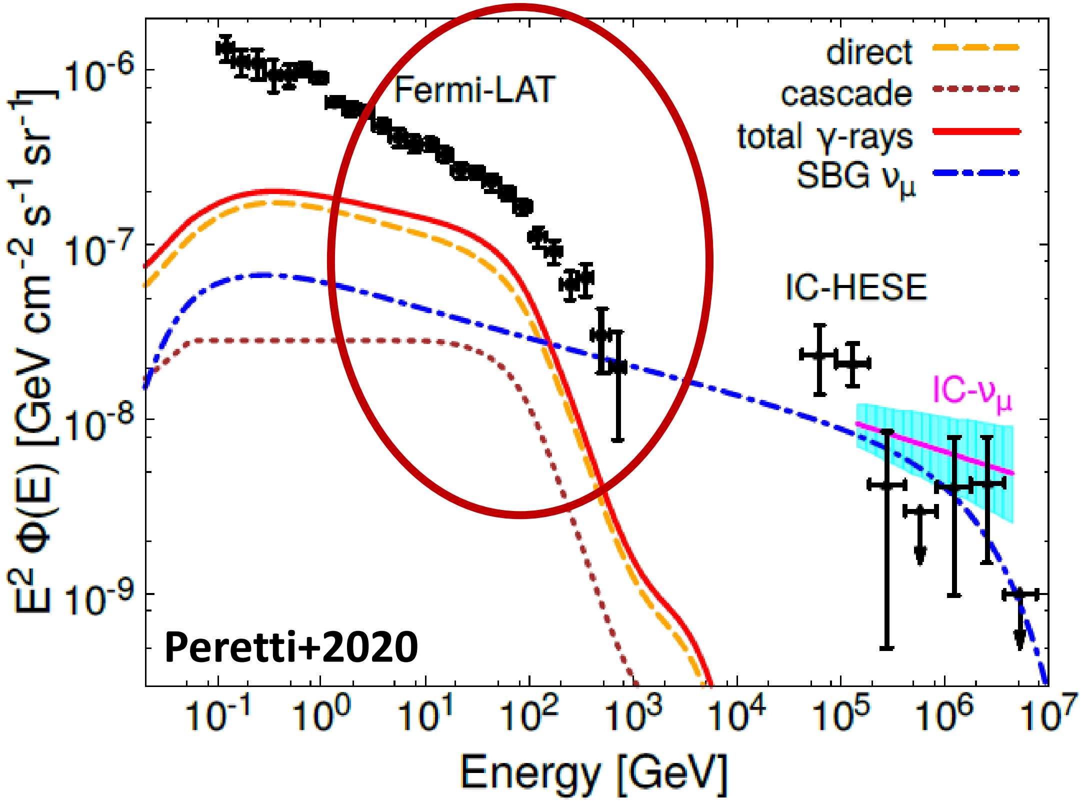
Peretti+2020

Diffuse emission from Starburst Galaxies



- SBNi only

Diffuse emission from Starburst Galaxies

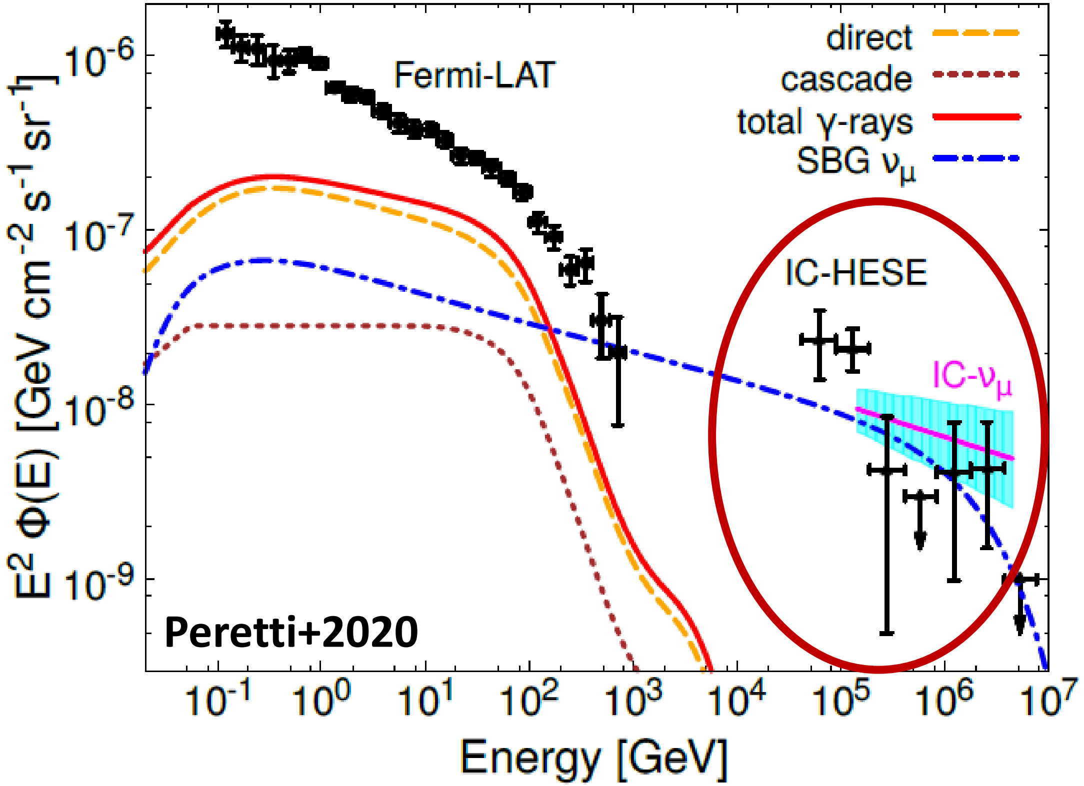


Peretti+2020

- SBNi only

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

Diffuse emission from Starburst Galaxies

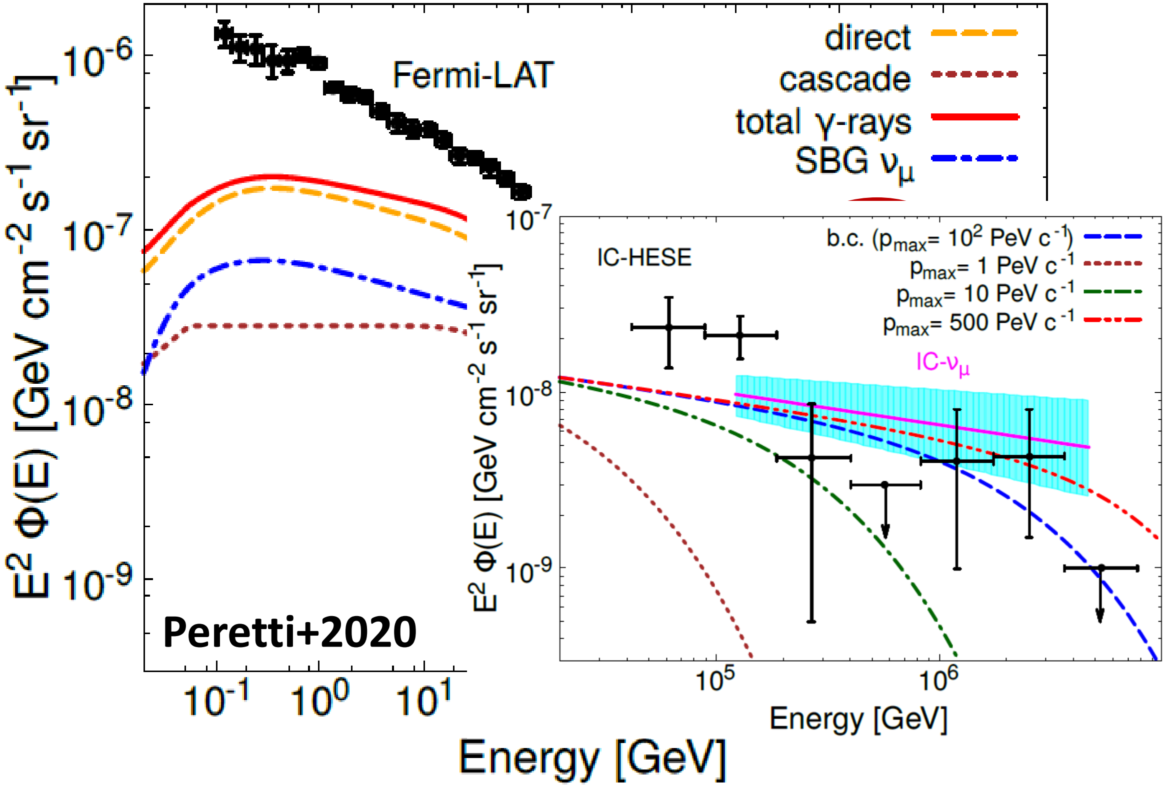


- SBNi only

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

- Neutrino flux at the level of IceCube measurment

Diffuse emission from Starburst Galaxies



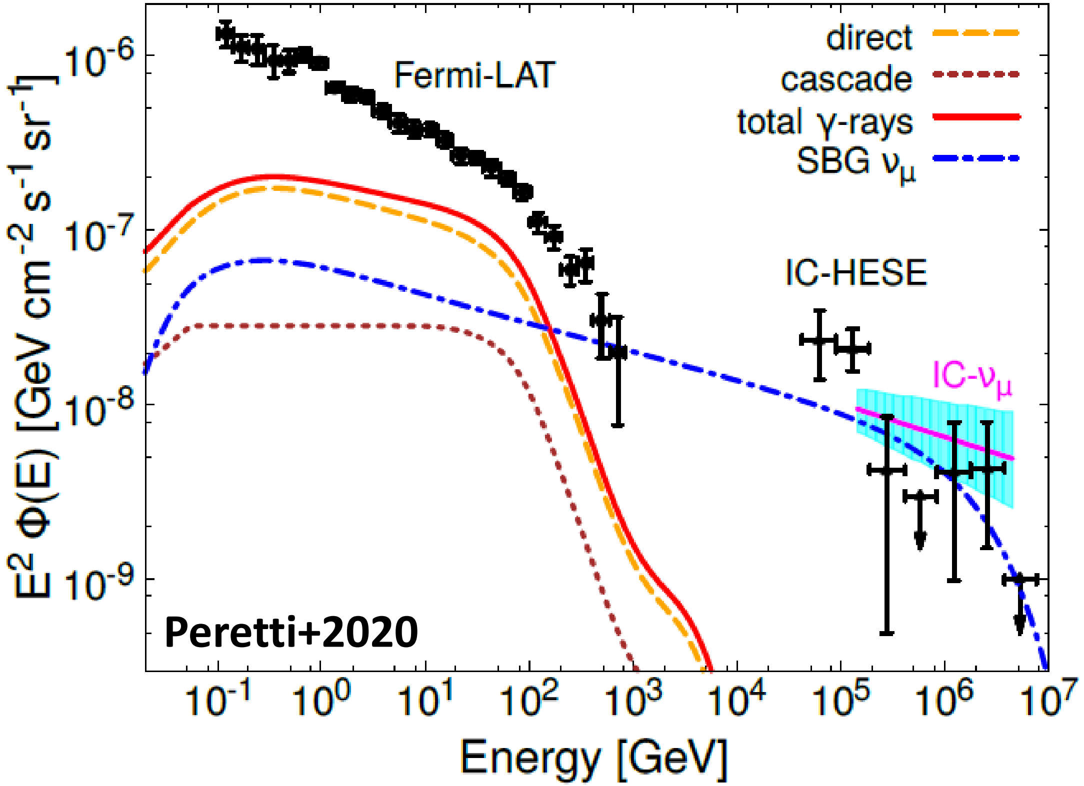
Peretti+2020

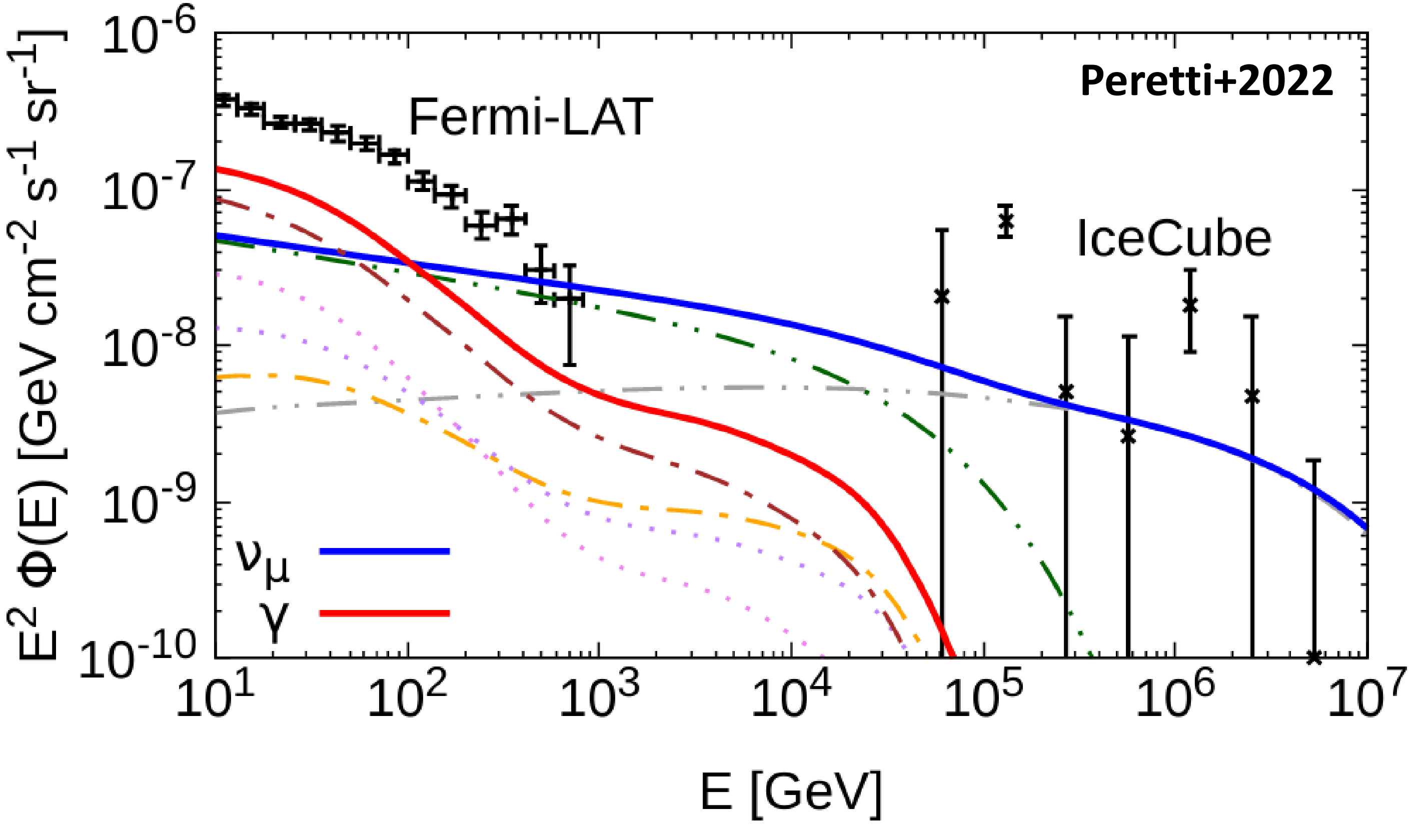
- SBNi only

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

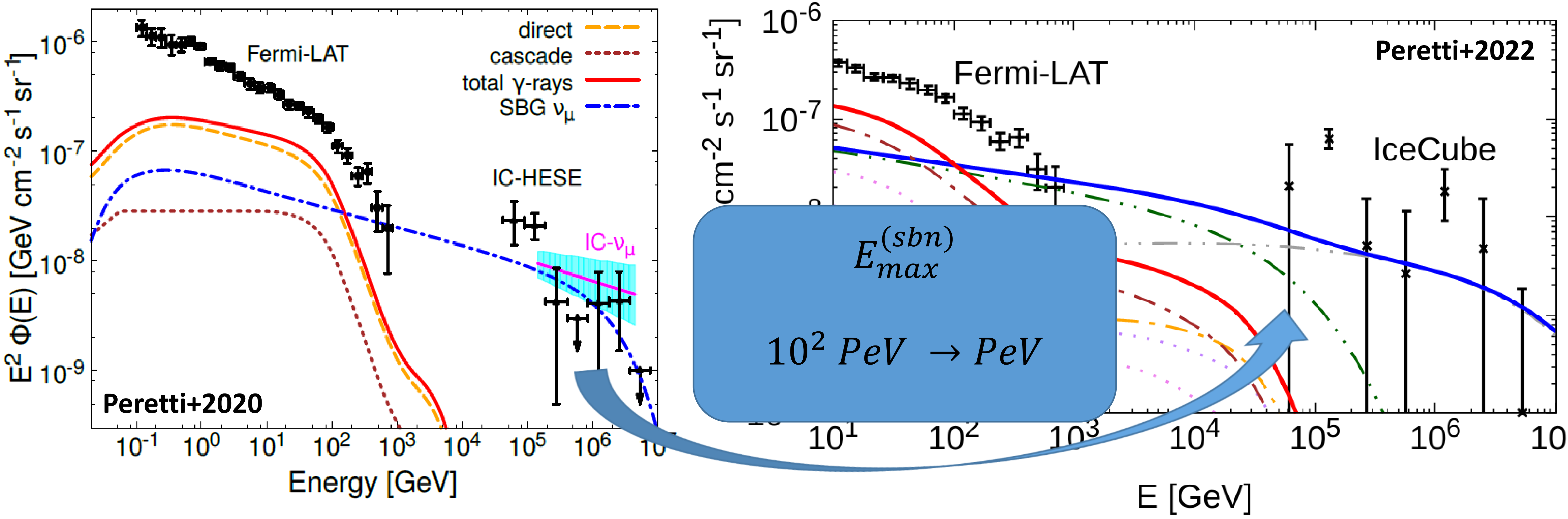
- Neutrino flux at the level of IceCube measurment

Diffuse emission from Starburst Winds





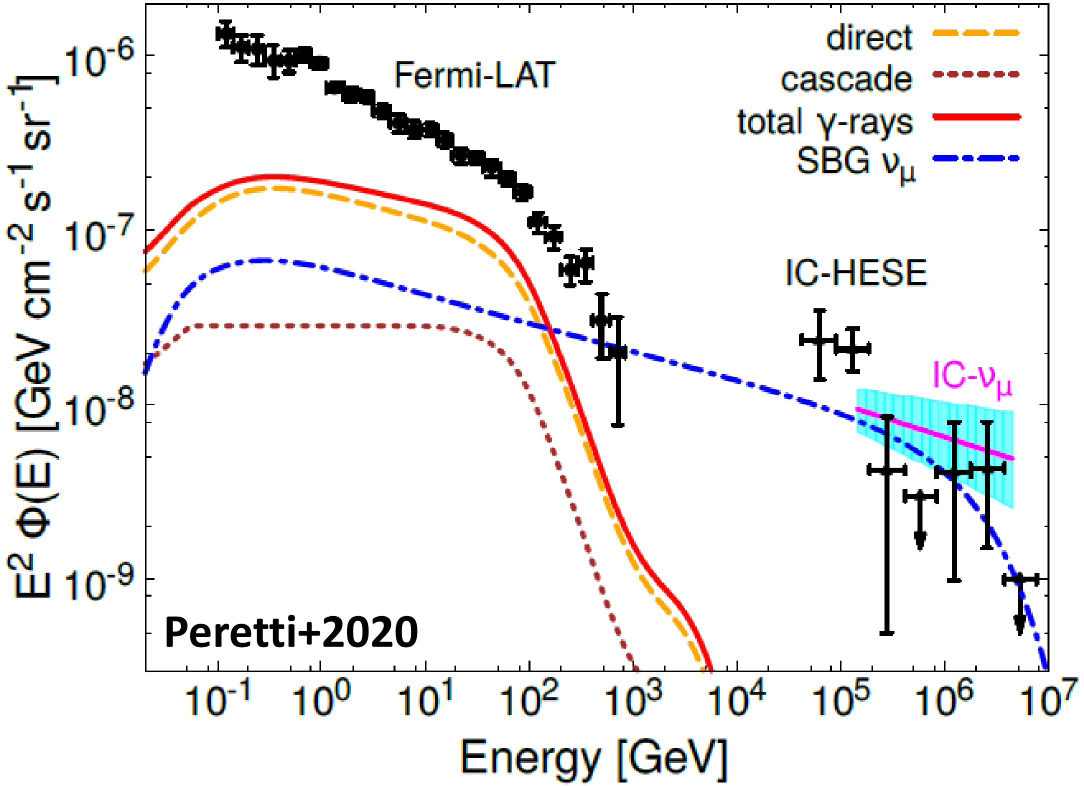
Diffuse emission from Starburst Winds

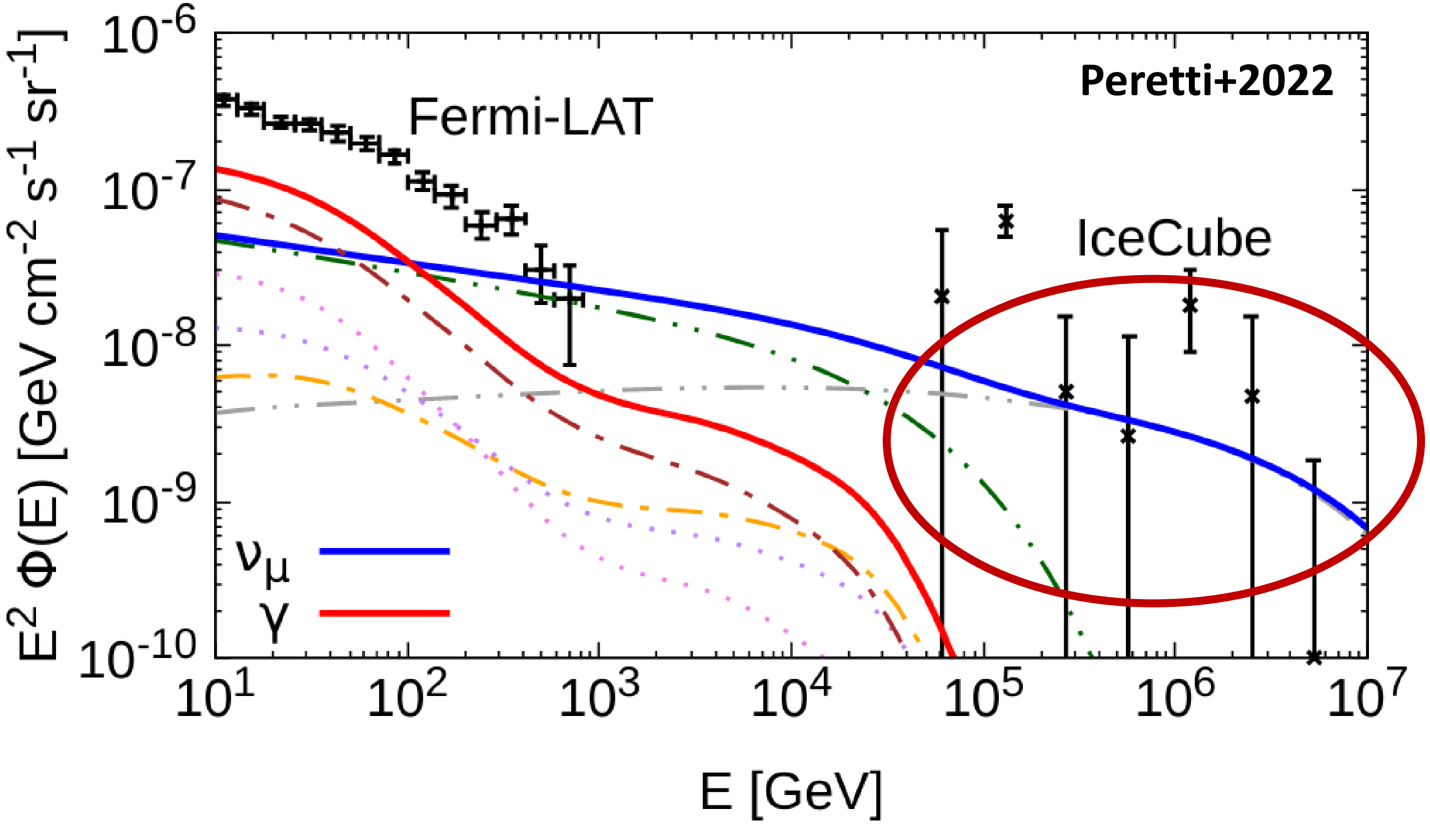


$E_{max}^{(sbn)}$

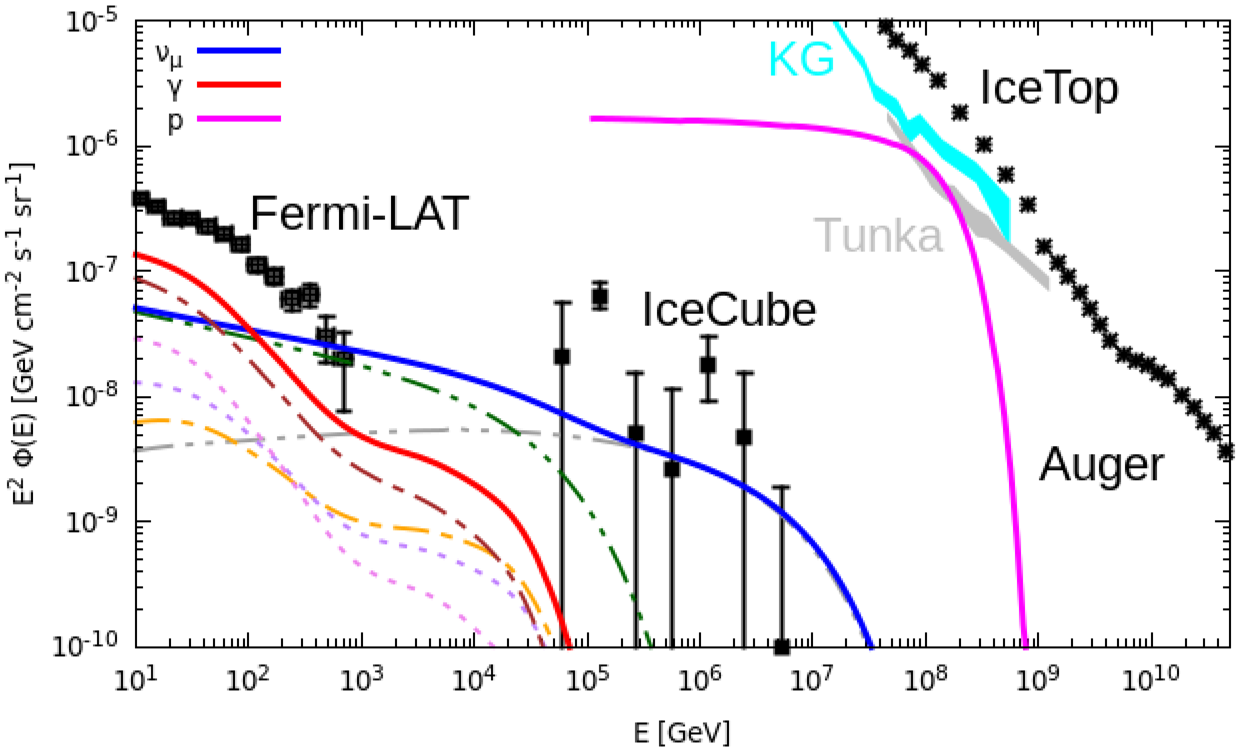
$10^2\ PeV \rightarrow PeV$

Diffuse emission from Starburst Winds

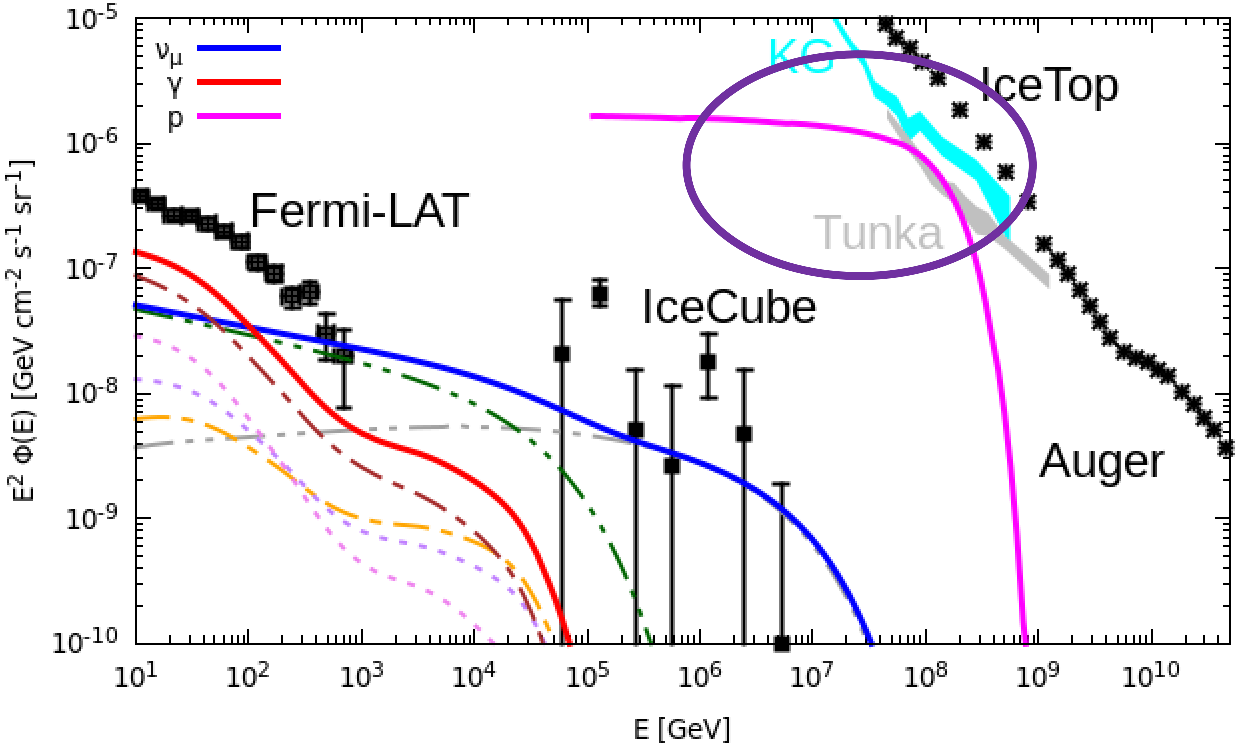




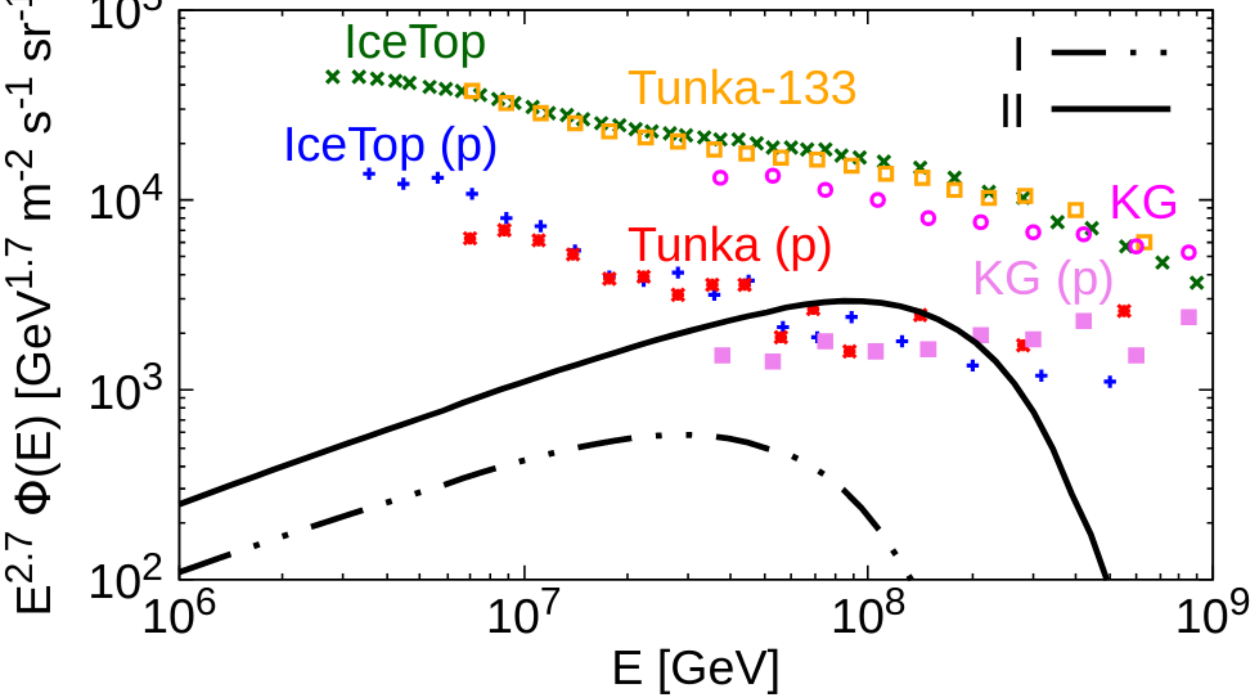
Multimessenger emission from Starburst Galaxies and their winds



Multimessenger emission from Starburst Galaxies and their winds



Peretti+2022



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

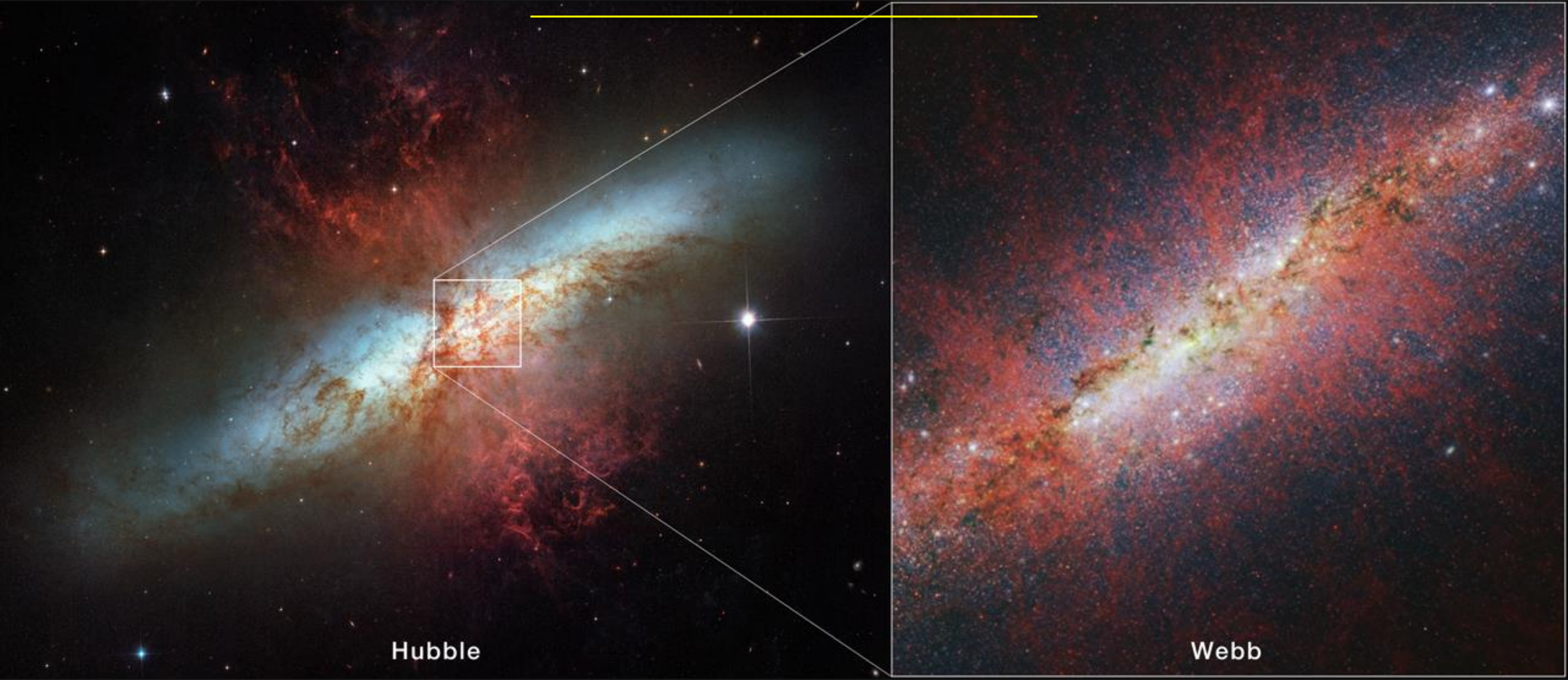
4. We expect γ-rays and neutrinos both from SBNi and SB-winds

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!

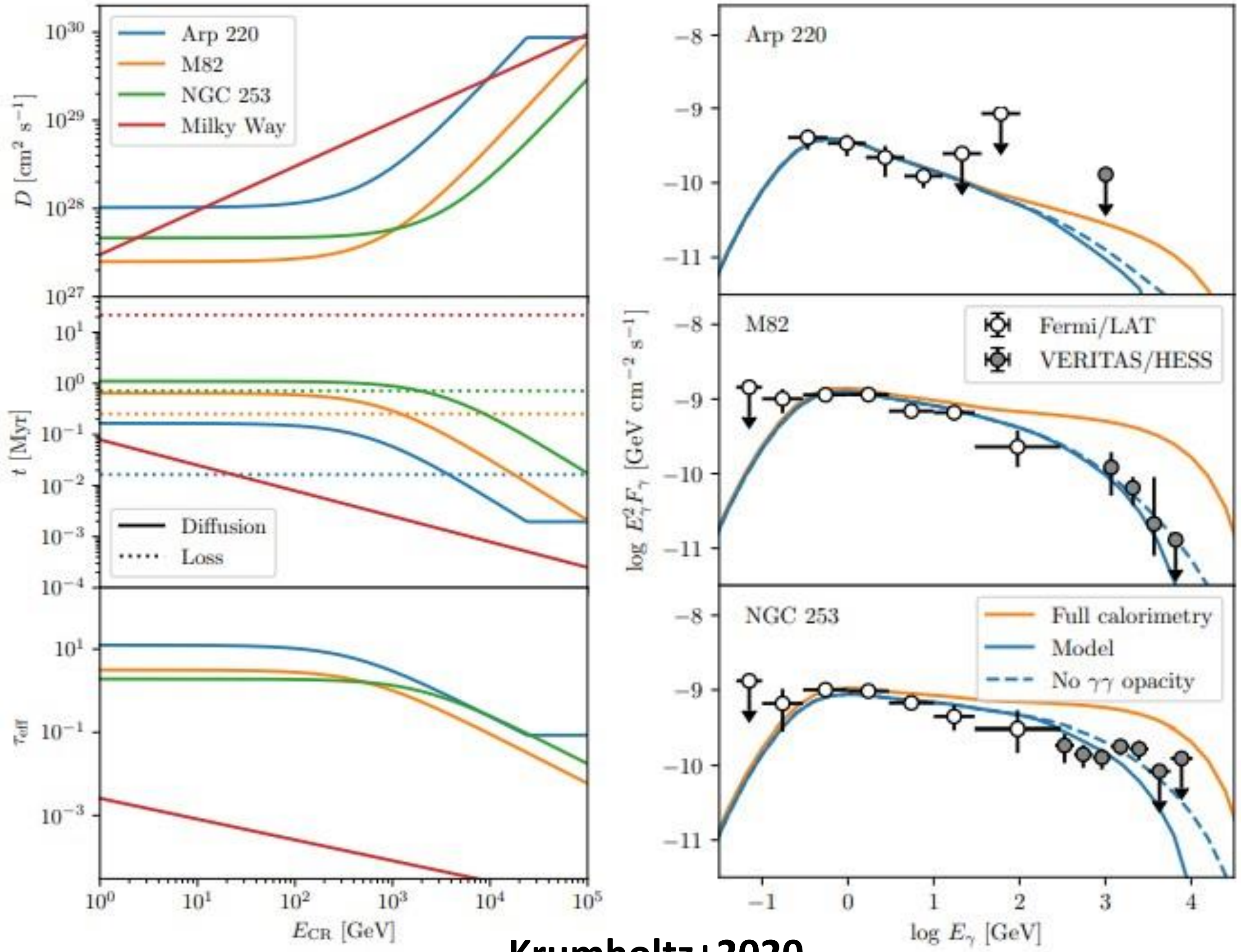


Starburst galaxy M82 – NASA, ESA, CSA, STScI, A. Bolatto

Back up

Open questions in the TeV band for Starburst Galaxies

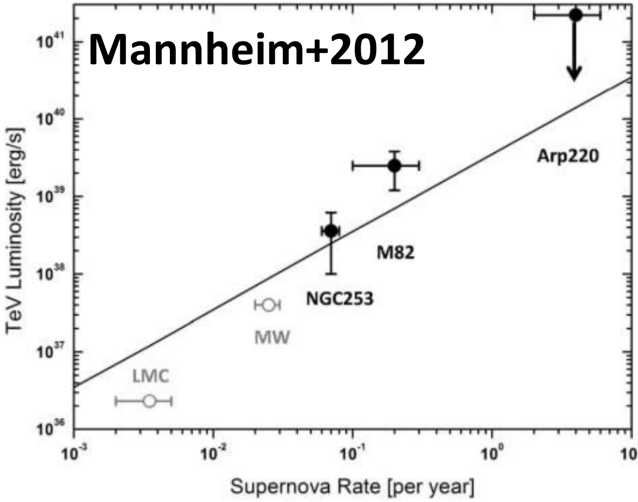
Microphysics

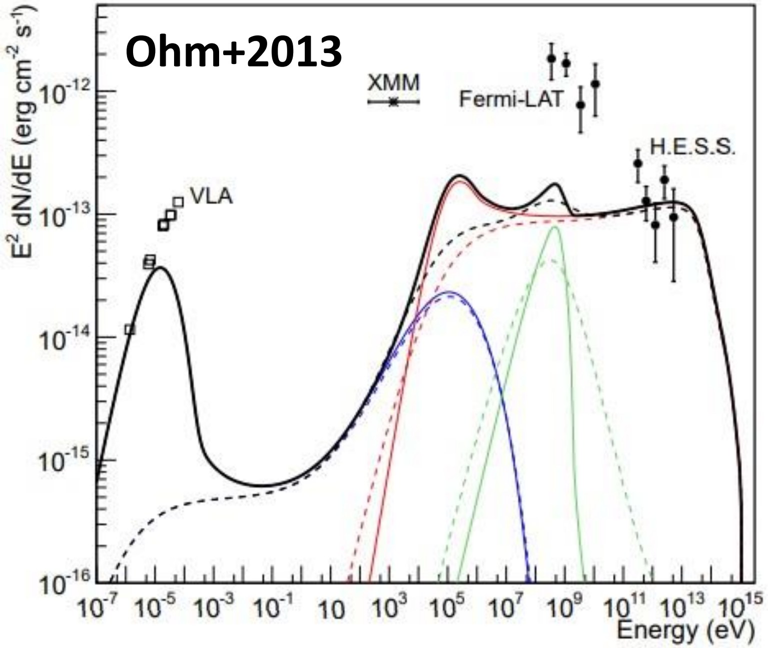


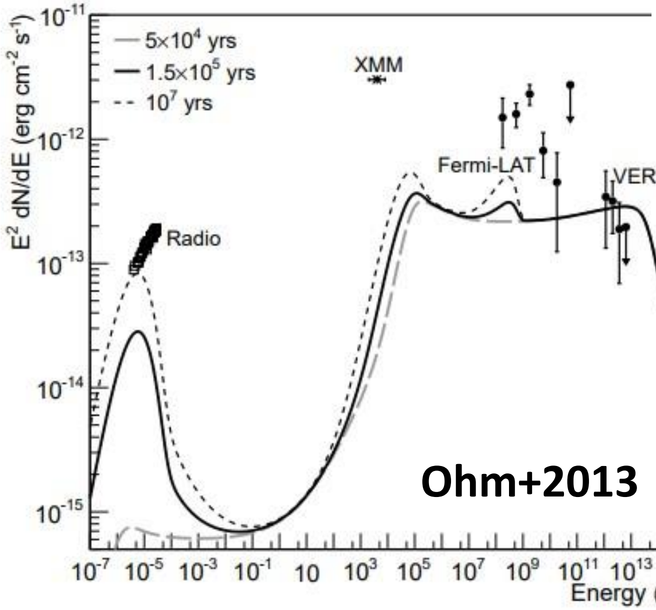
Krumholtz+2020

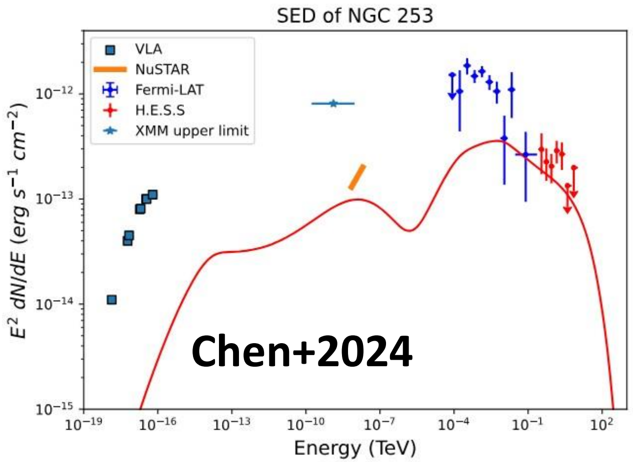
- The turbulence cascade might be suppressed by the ion-neutral damping
- In this scenario TeV particles are escaping efficiently

Pulsar wind nebulae and other pointlike sources







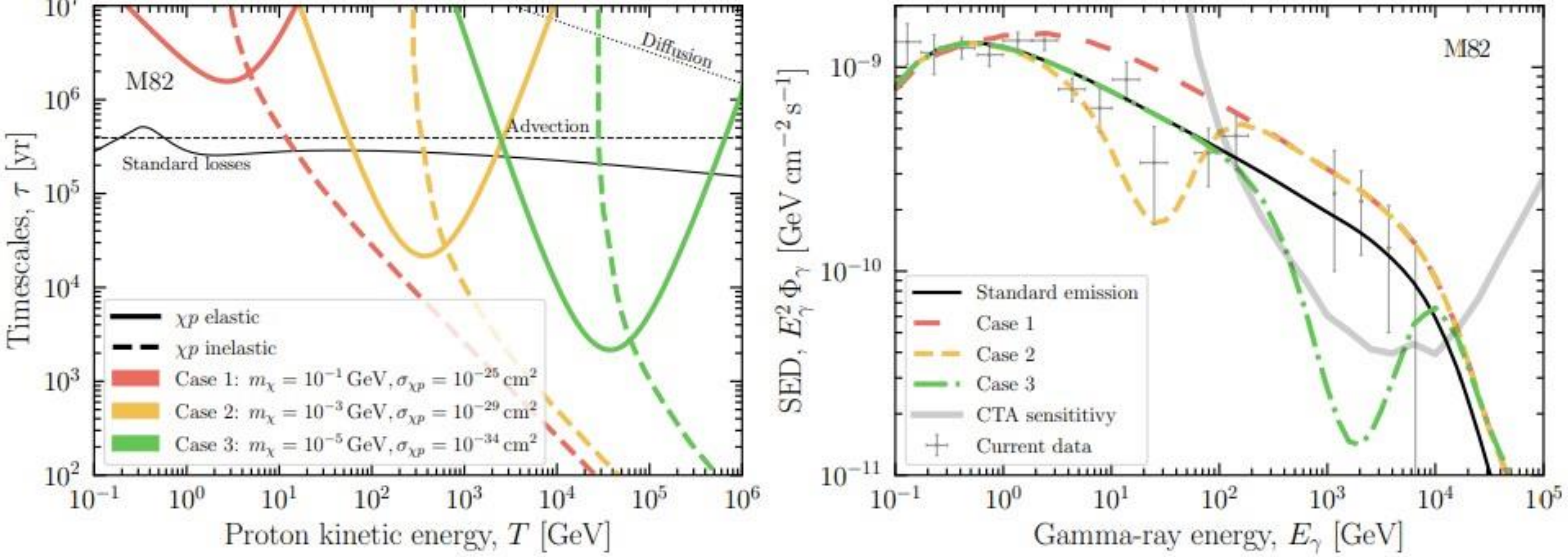


- The high supernova rate must necessarily result in a large number of emitting pulsar wind nebulae (PWNe)

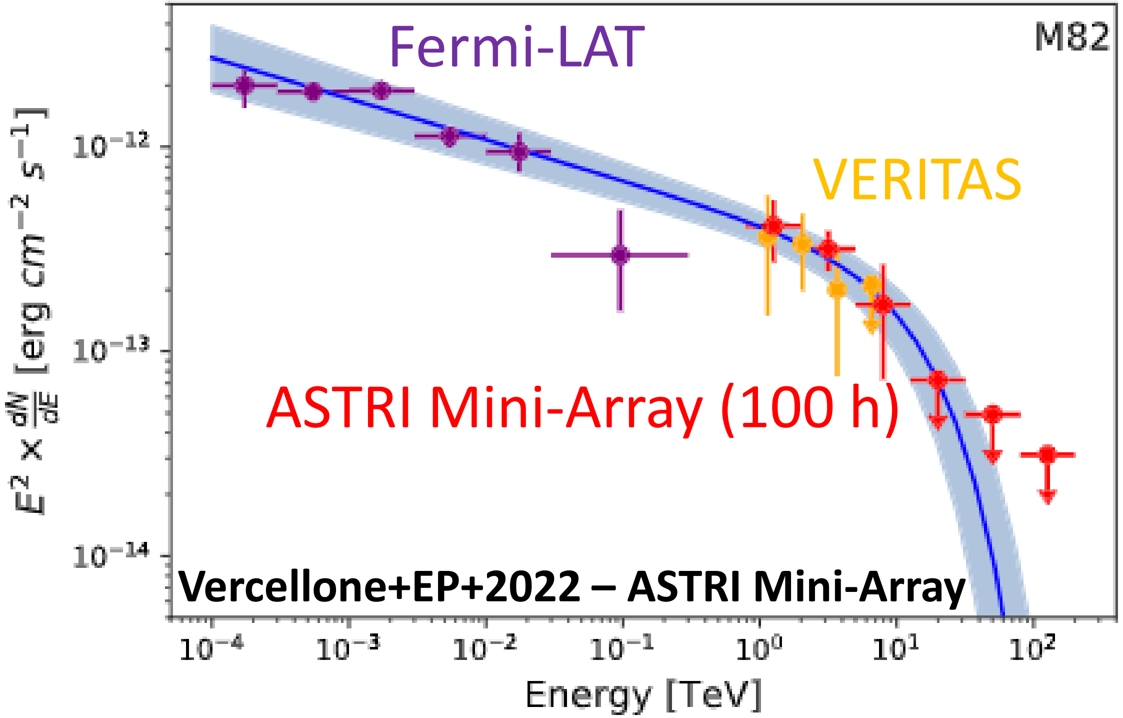
- The PWNe emission could dominate the gamma-ray flux in the TeV band

Constraining Dark Matter

Ambrosone+2023



Upcoming gamma-ray observations



Vercellone+EP+2022 – ASTRI Mini-Array

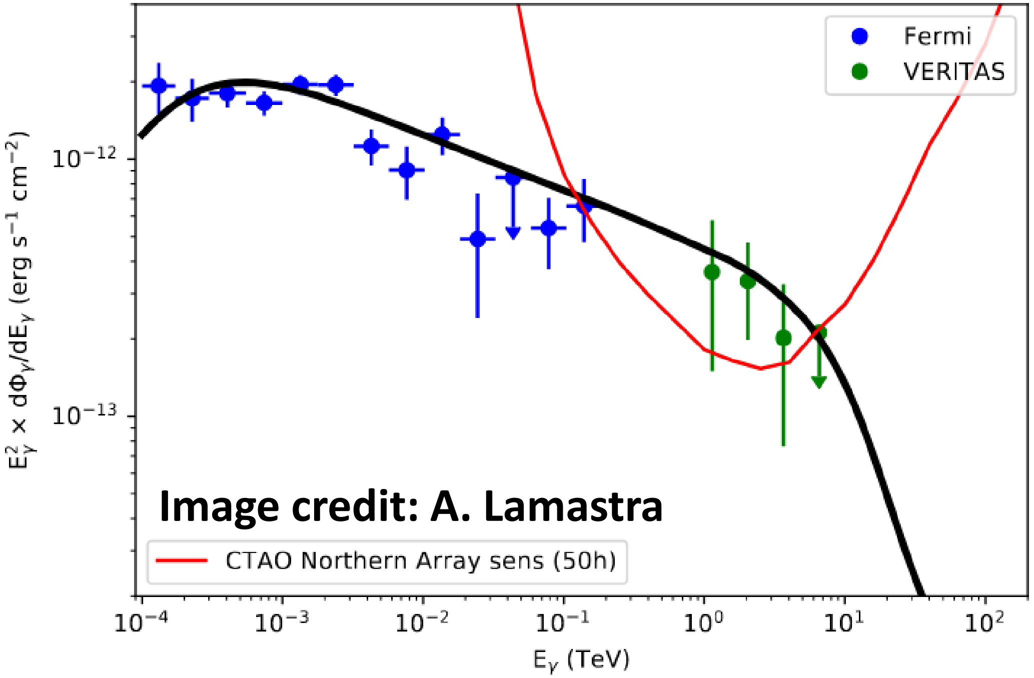
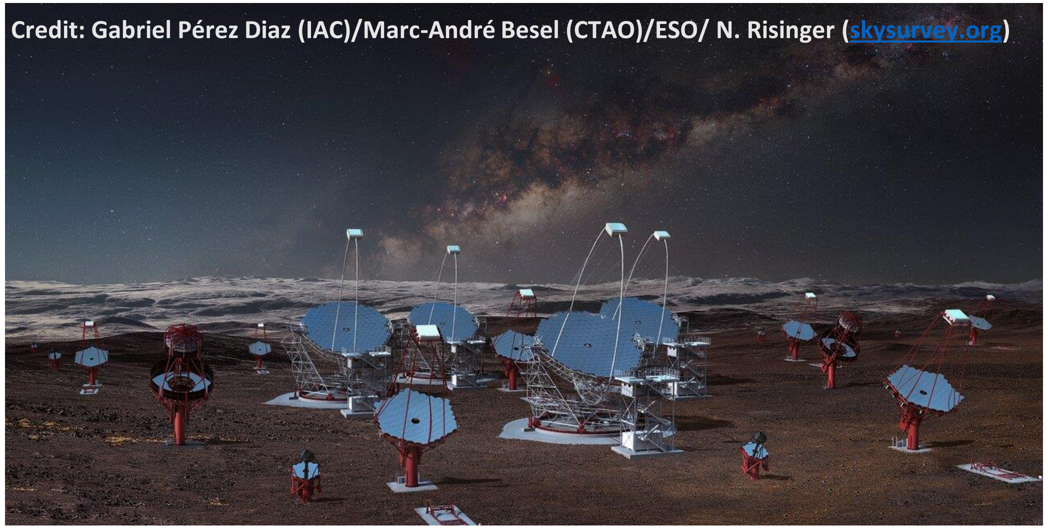


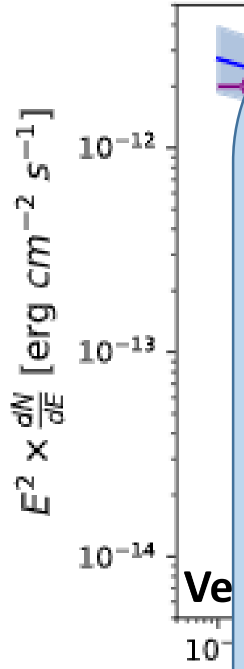
Image credit: A. Lamastra

Credit: Astri/Inaf

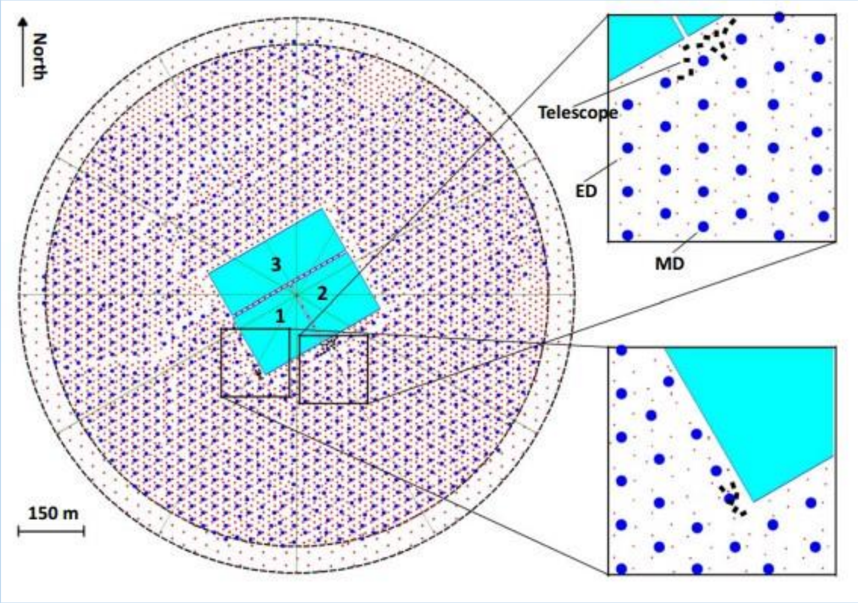


Credit: Gabriel Pérez Diaz (IAC)/Marc-André Besel (CTAO)/ESO/ N. Risinger (skysurvey.org)

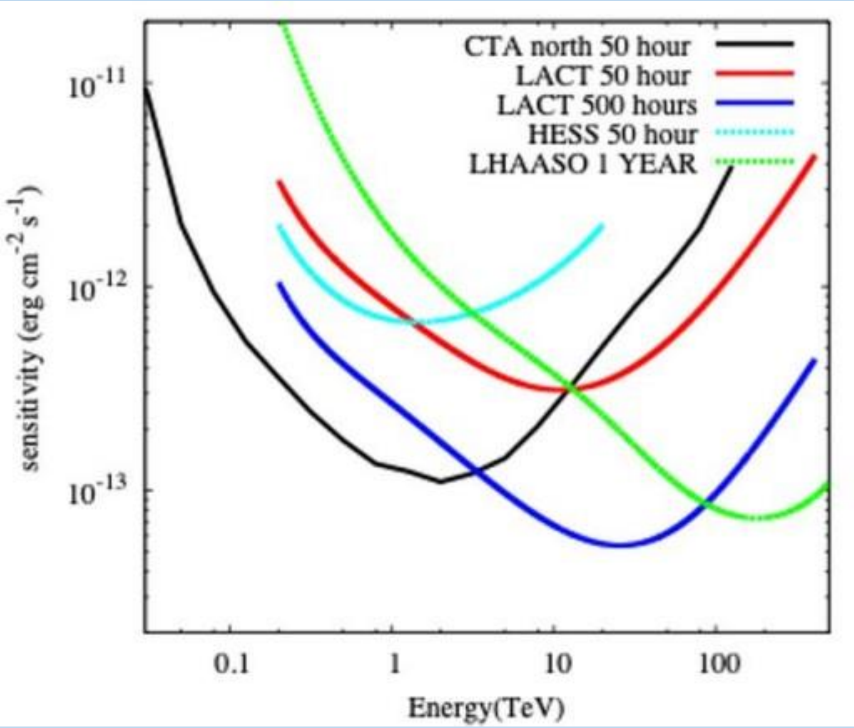
Upcoming gamma-ray observations



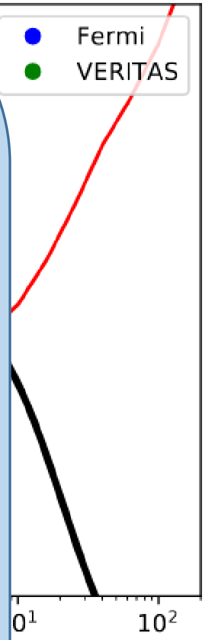
LHAASO and LACT

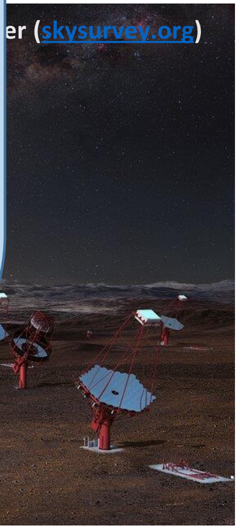


Aharonian+2021



Li+2023 (ICRC2023)666

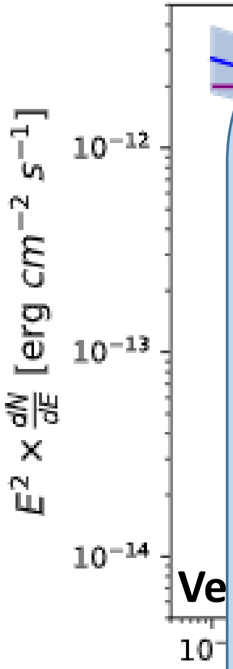




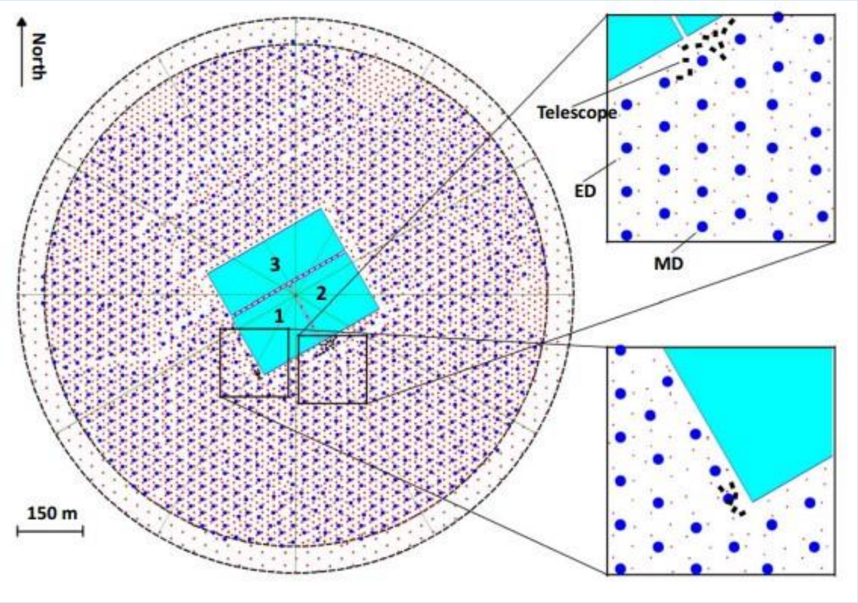
er (skysurvey.org)

Credit: Astri/Inaf

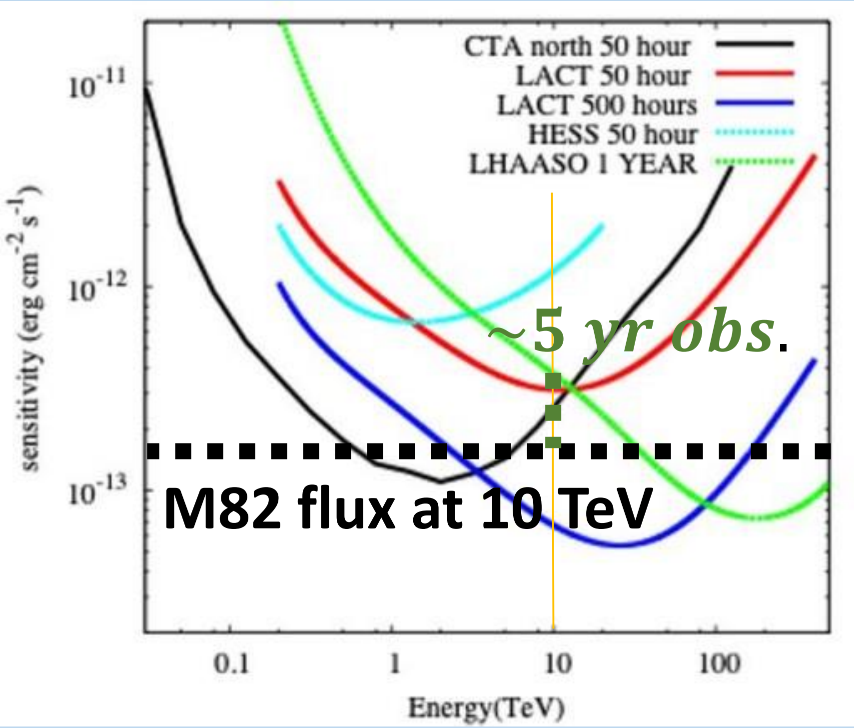
Upcoming gamma-ray observations



LHAASO and LACT



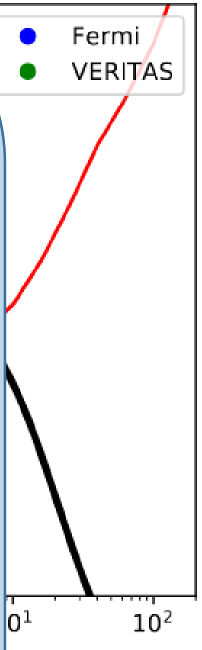
Aharonian+2021



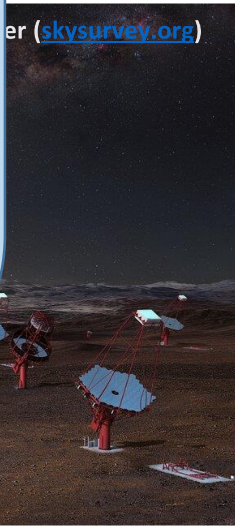
$\sim 5\ yr\ obs.$

M82 flux at 10 TeV

Li+2023 (ICRC2023)666

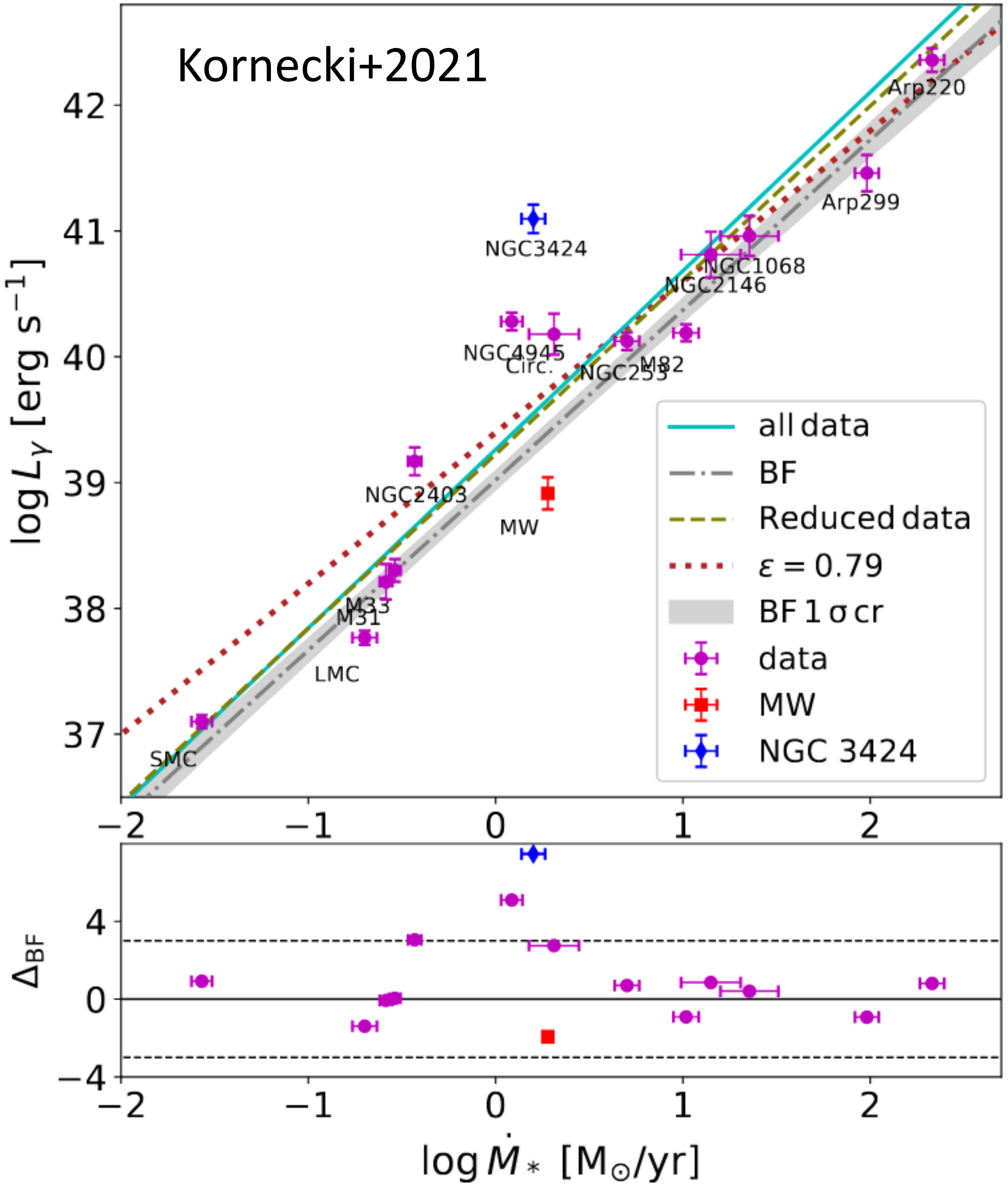


Credit: Astri/Inaf



er (skysurvey.org)

The starburst of NGC 1068

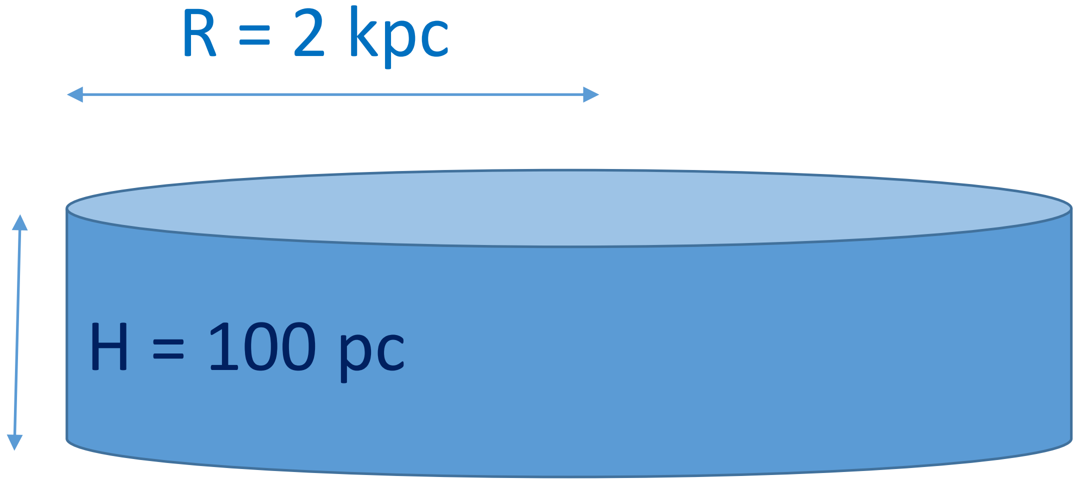


The starburst of NGC 1068

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

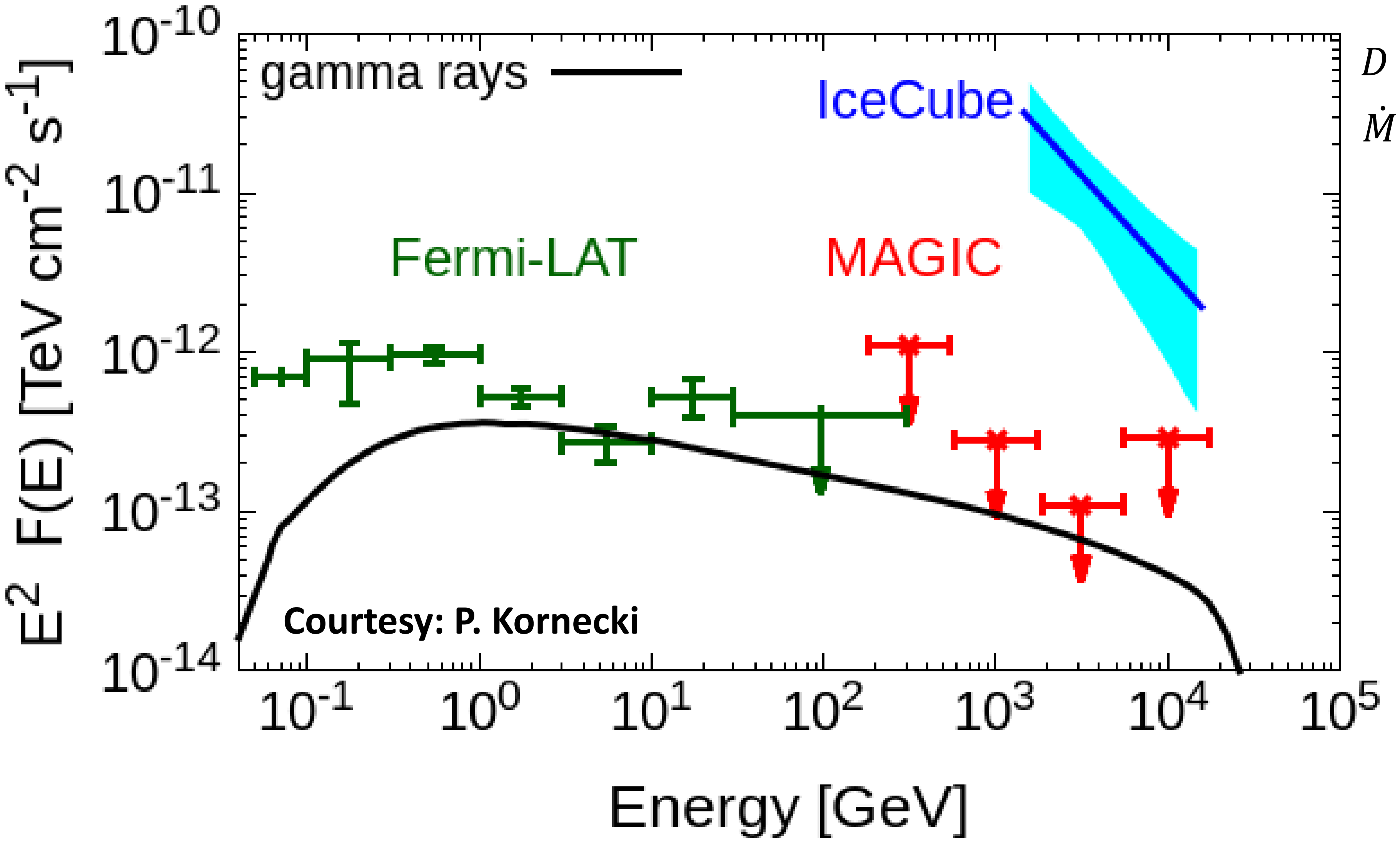
$$\tau_{diff}(GeV) \approx 10^5 \left(\frac{H}{10^2 pc}\right)^2 \left(\frac{D}{10^{28} cm^2/s}\right)^{-1} yr$$

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



Calorimetry is possible but not trivial

The starburst of NGC 1068

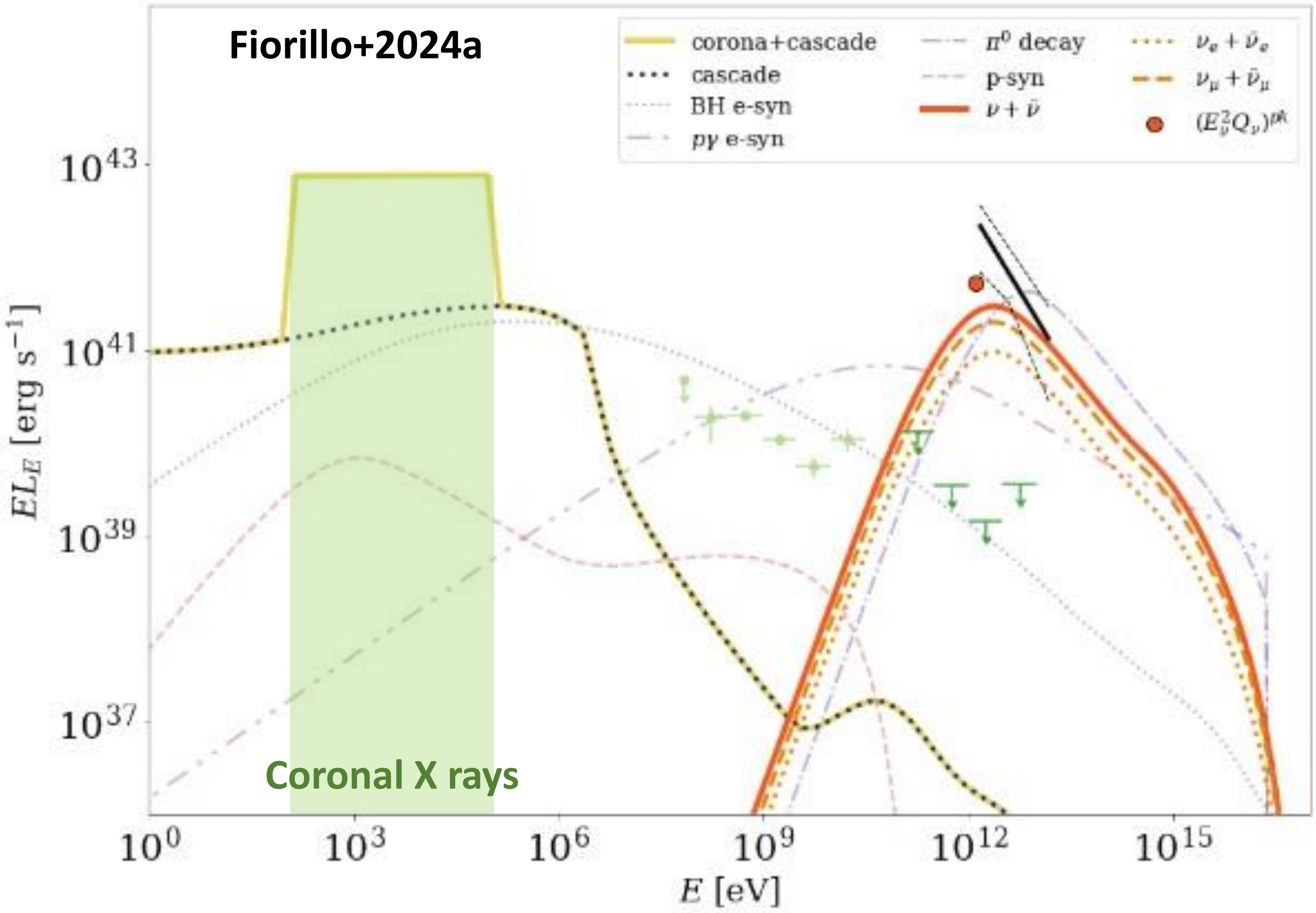


$D = 14.4\ Mpc$

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

The starburst of NGC 1068

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

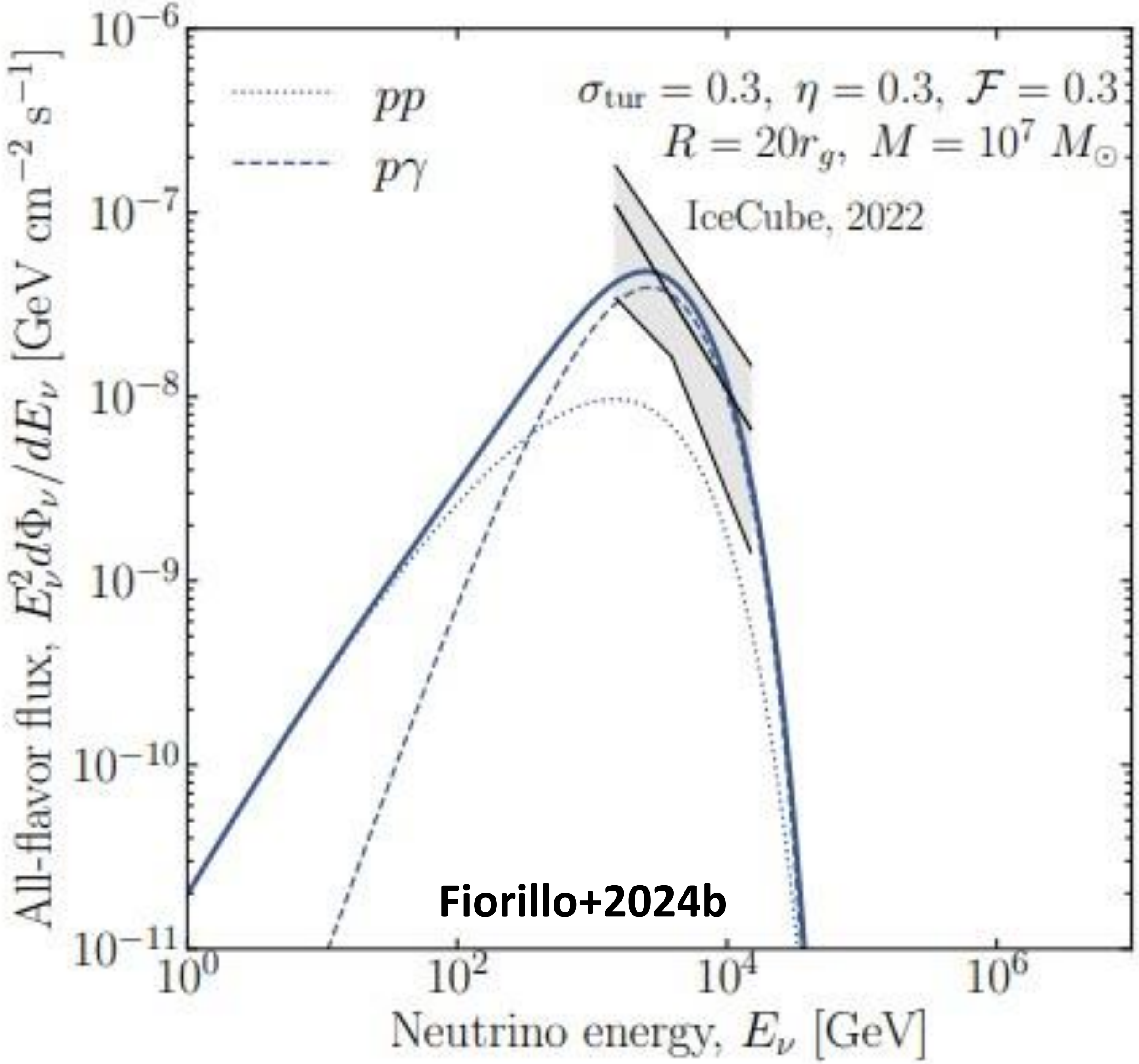


Fiorillo+2024a

Coronal X rays

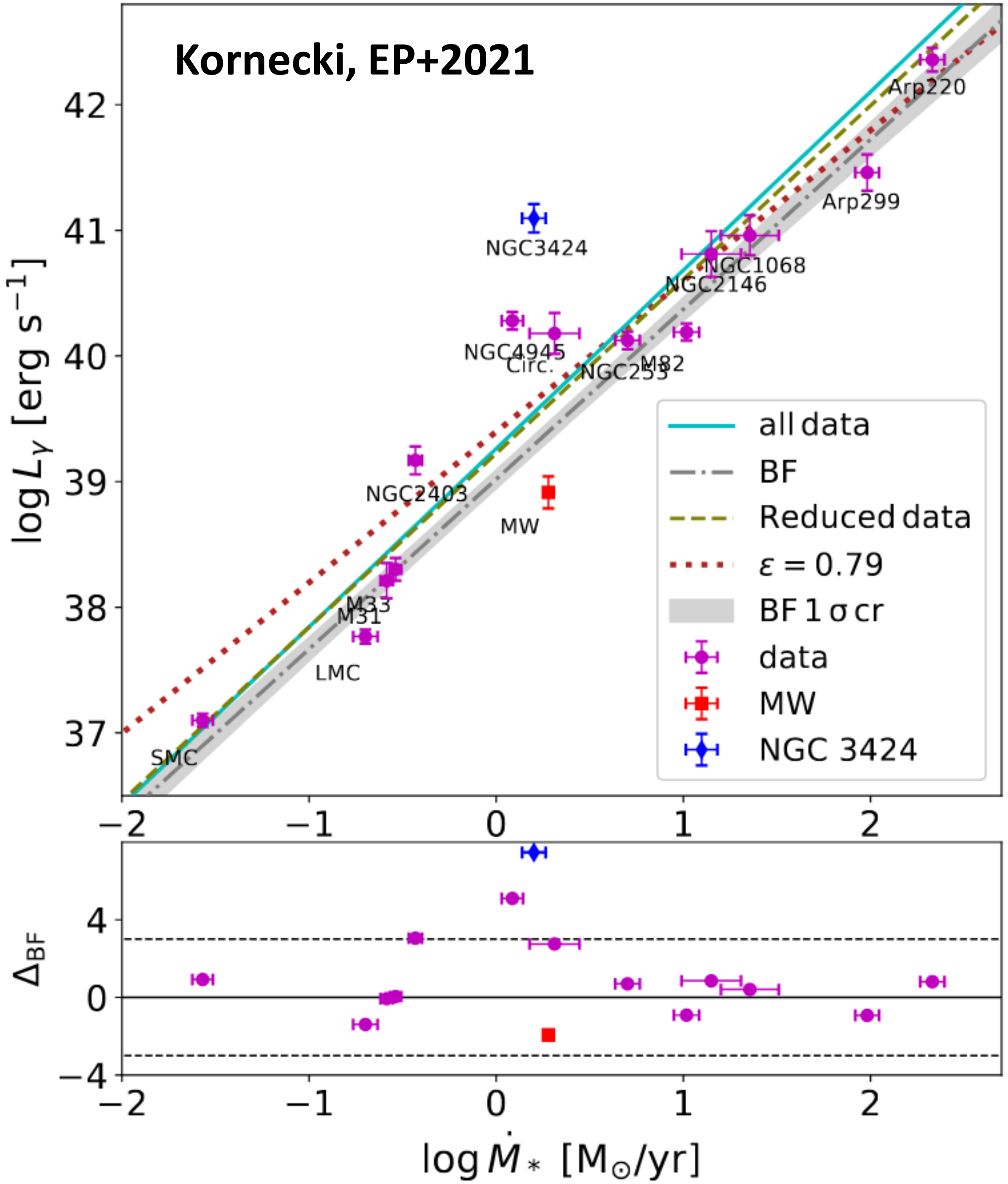
The starburst of NGC 1068

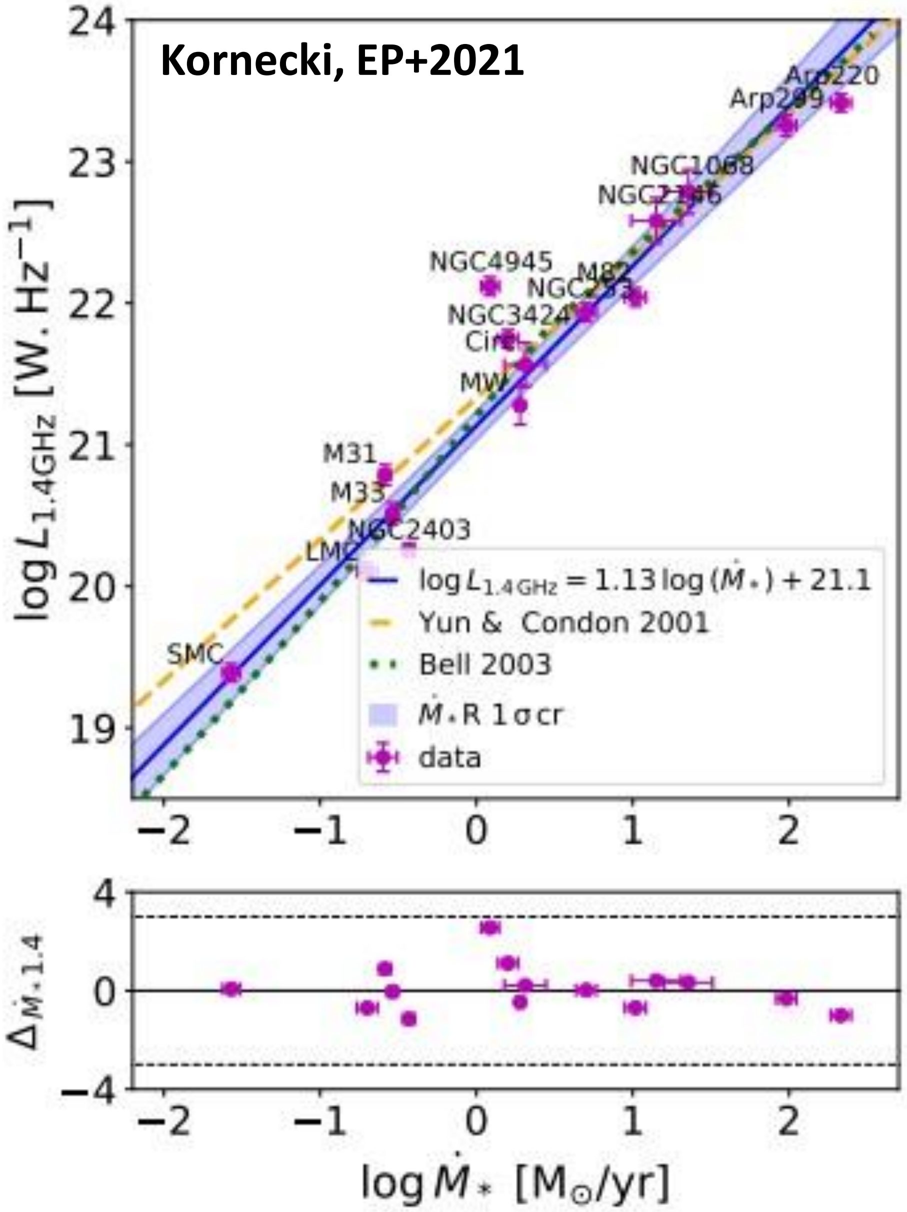
Acceleration via turbulence in a magnetized AGN corona surrounding the accreting SMBH



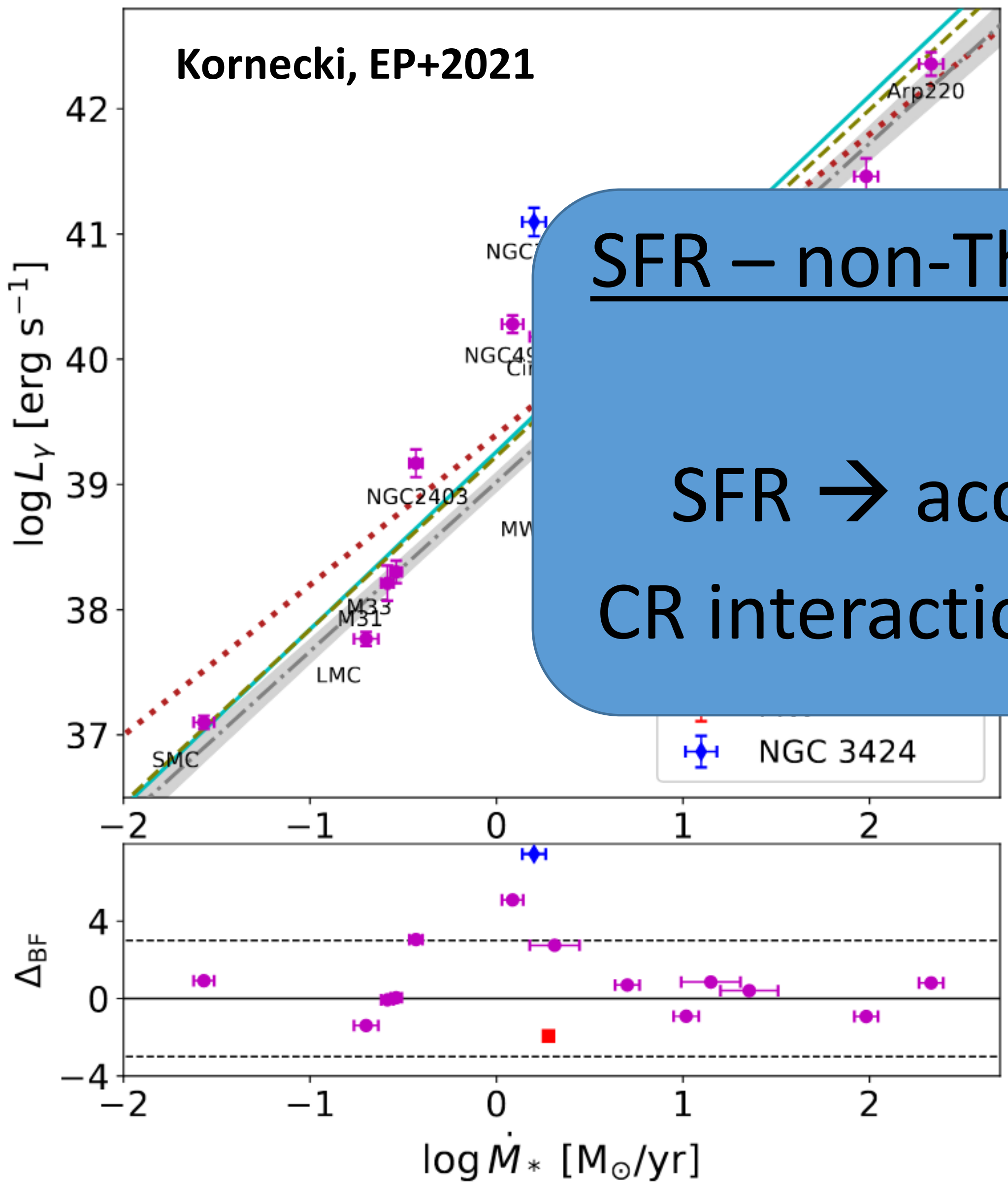
Fiorillo+2024b

Observation of Star-forming Galaxies - Correlations





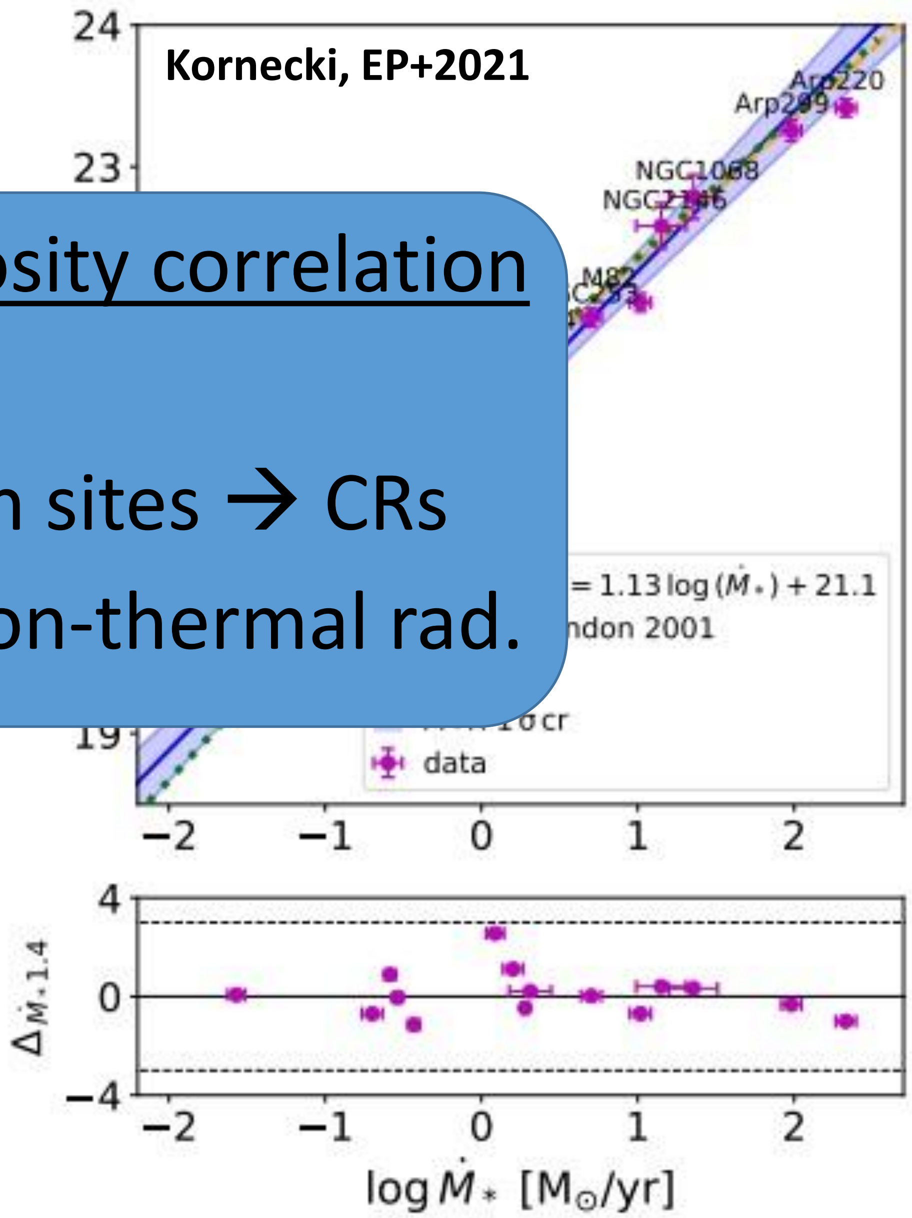
Observation of Star-forming Galaxies - Correlations



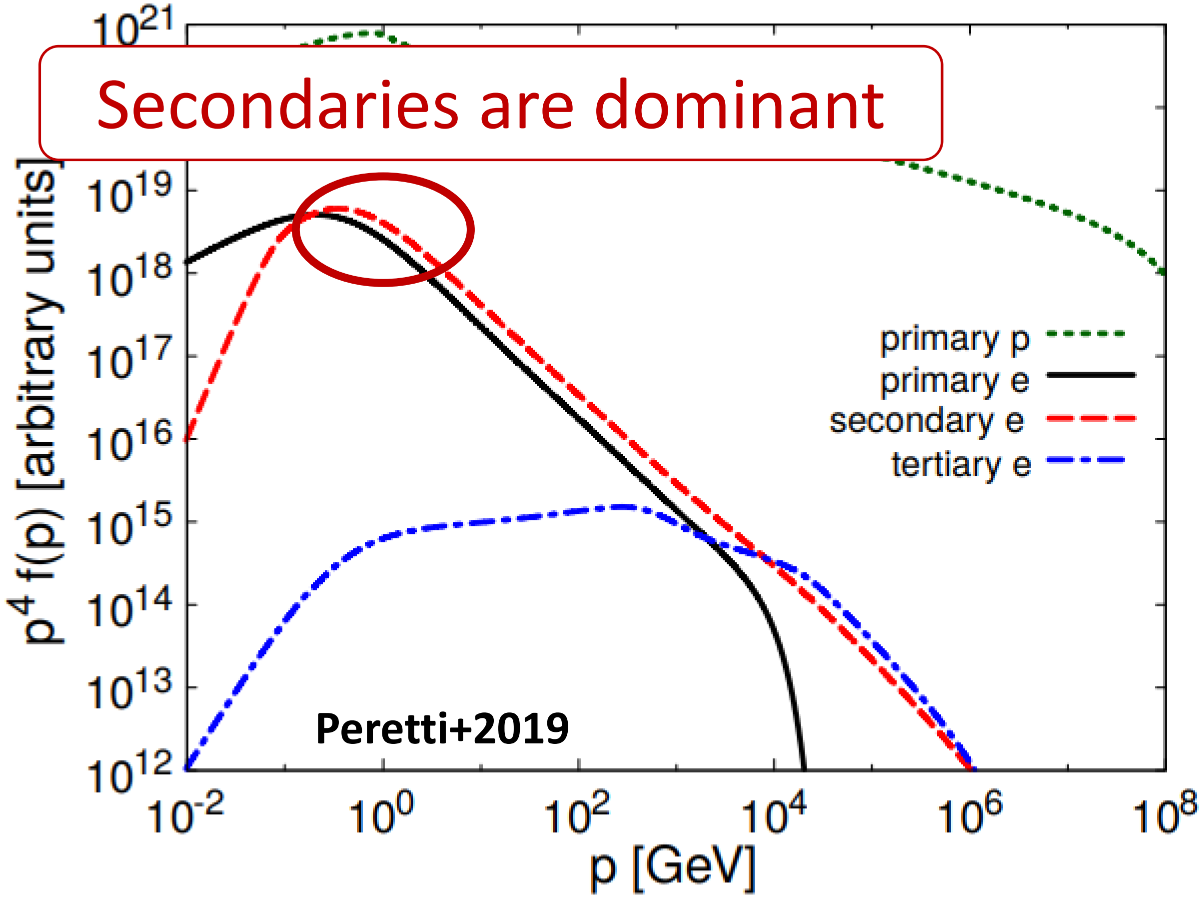
<u>SFR – non-Th. luminosity correlation</u>

SFR → acceleration sites → CRs

CR interactions → Non-thermal rad.

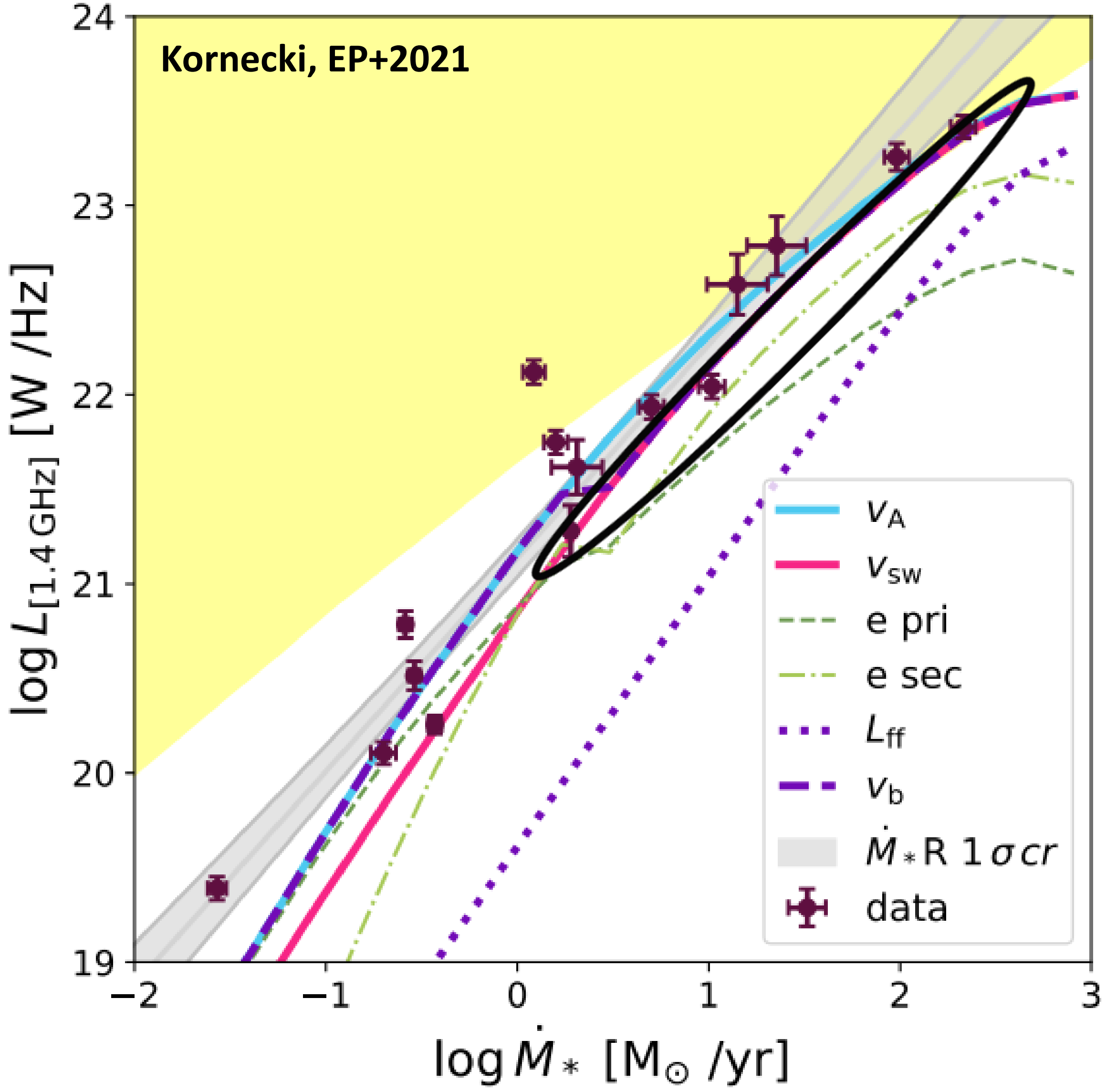


Particle and photon spectra in SBNi



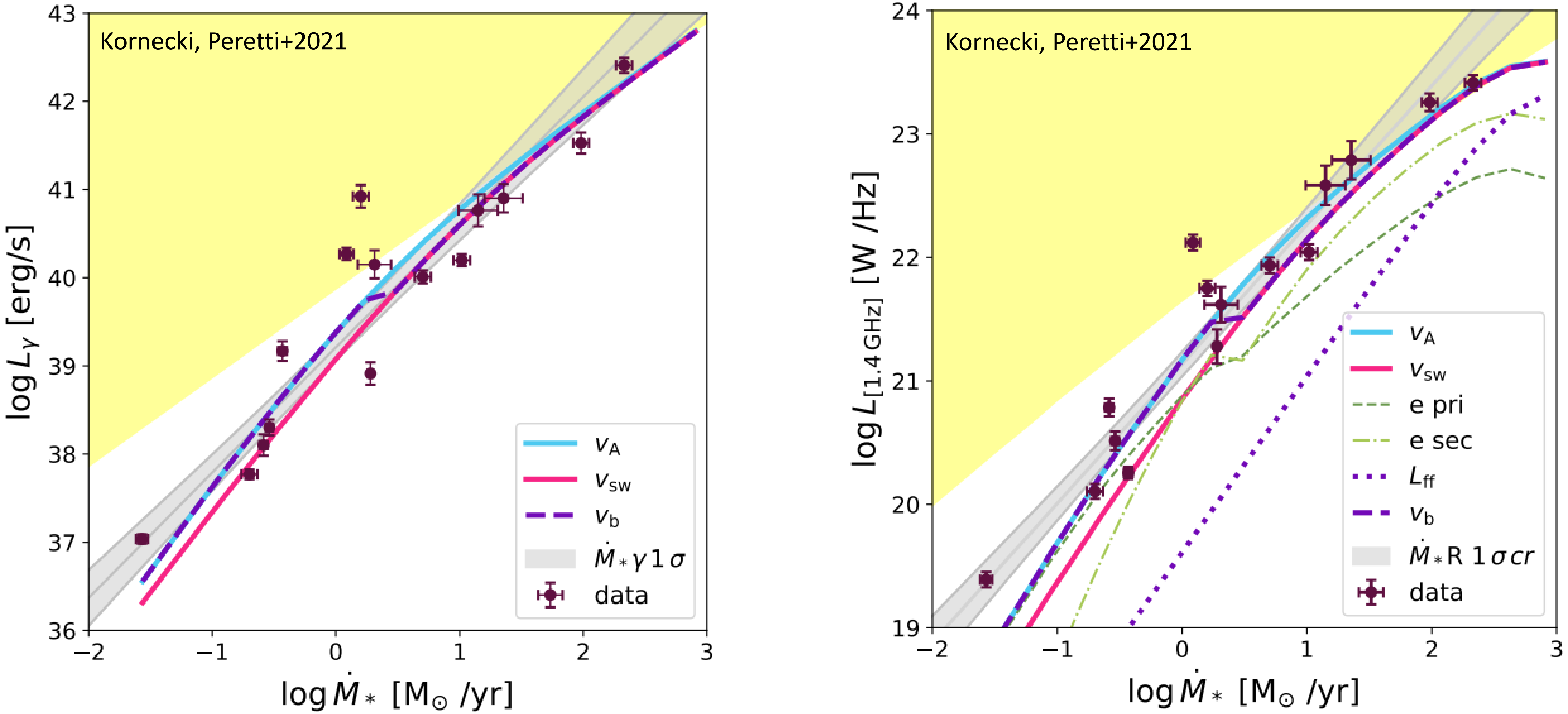
Secondaries are dominant

Peretti+2019

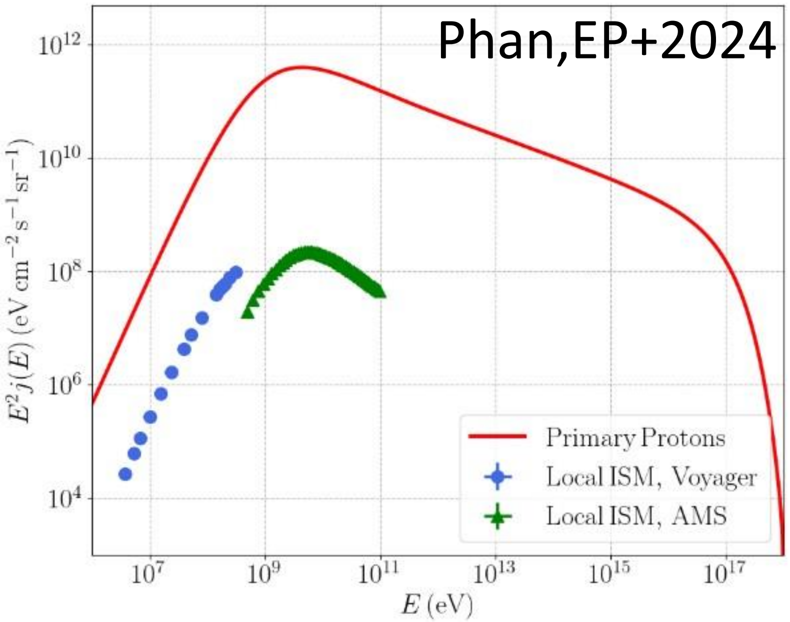


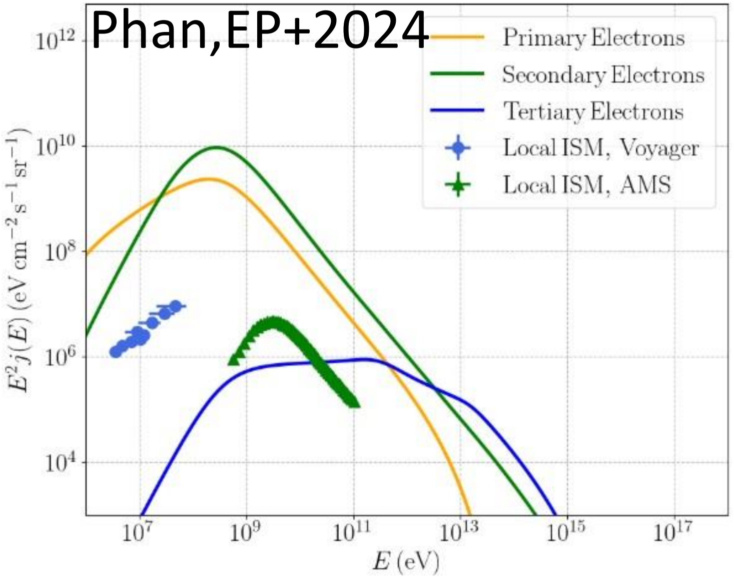
Kornecki, EP+2021

Leaky box model and L—SFR correlations

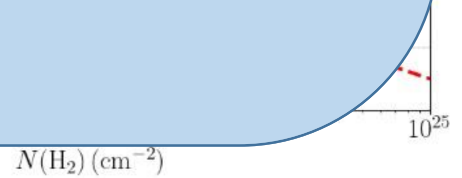


Cosmic rays in Starbursts vs Milky Way


Phan,EP+2024


Phan,EP+2024

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

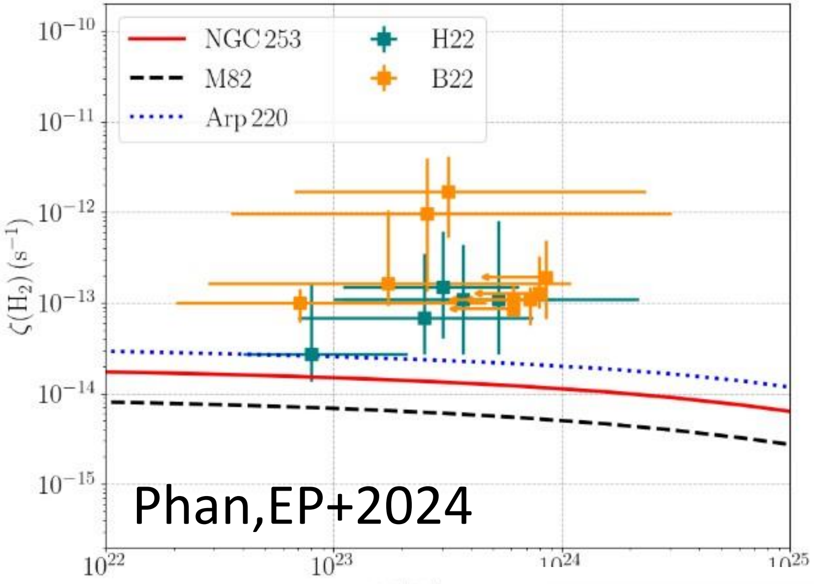


Ionization rate in starburst galaxies

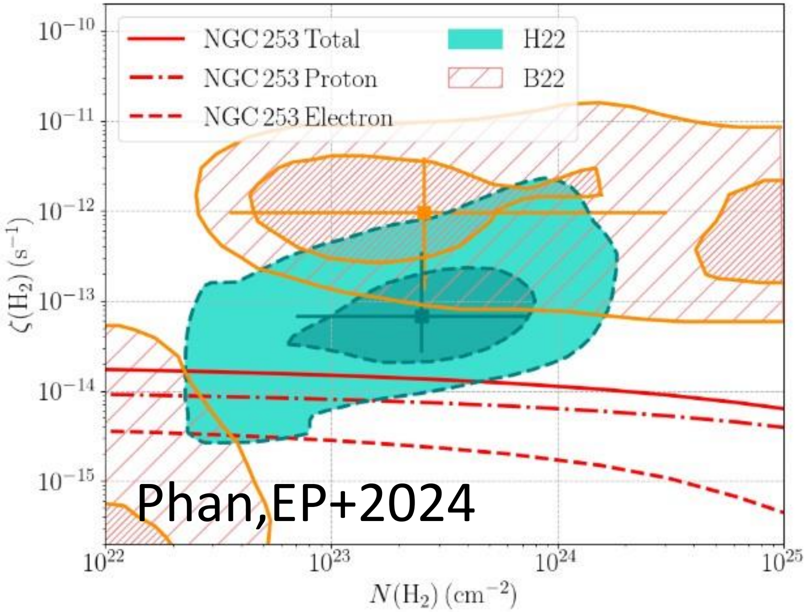
- Cosmic-ray density in starburst is orders of magnitude larger than in our Galaxy

- 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



Phan,EP+2024



Phan,EP+2024

Powering a starburst wind

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

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

Powering a starburst wind

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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

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

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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

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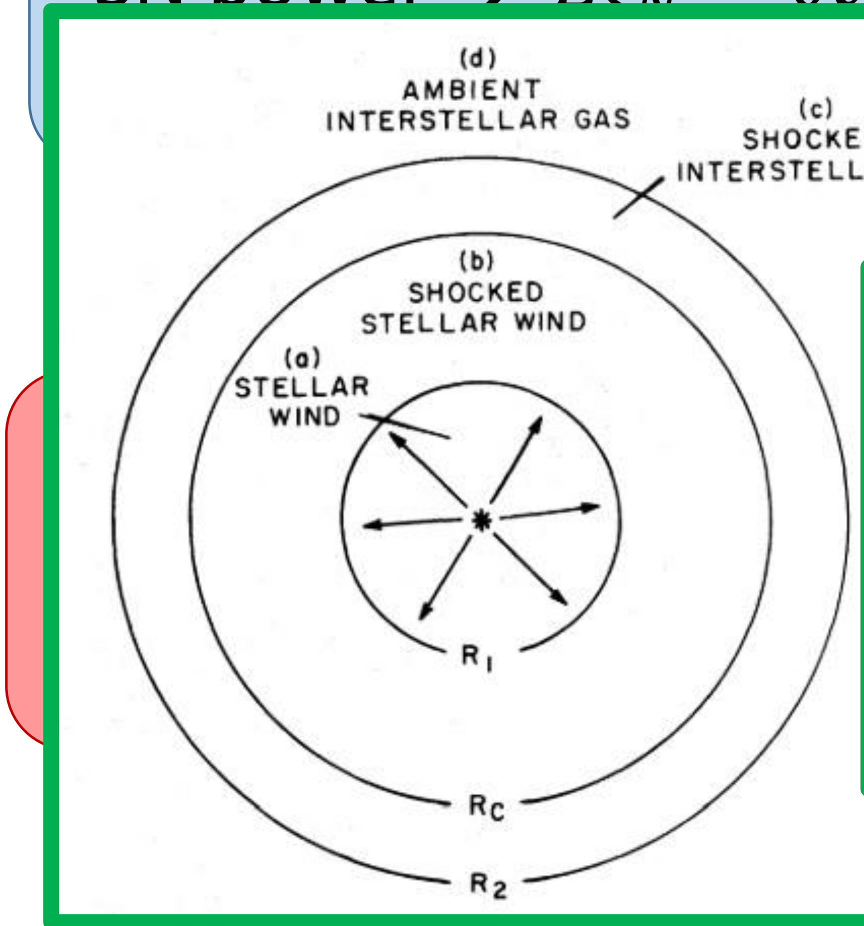
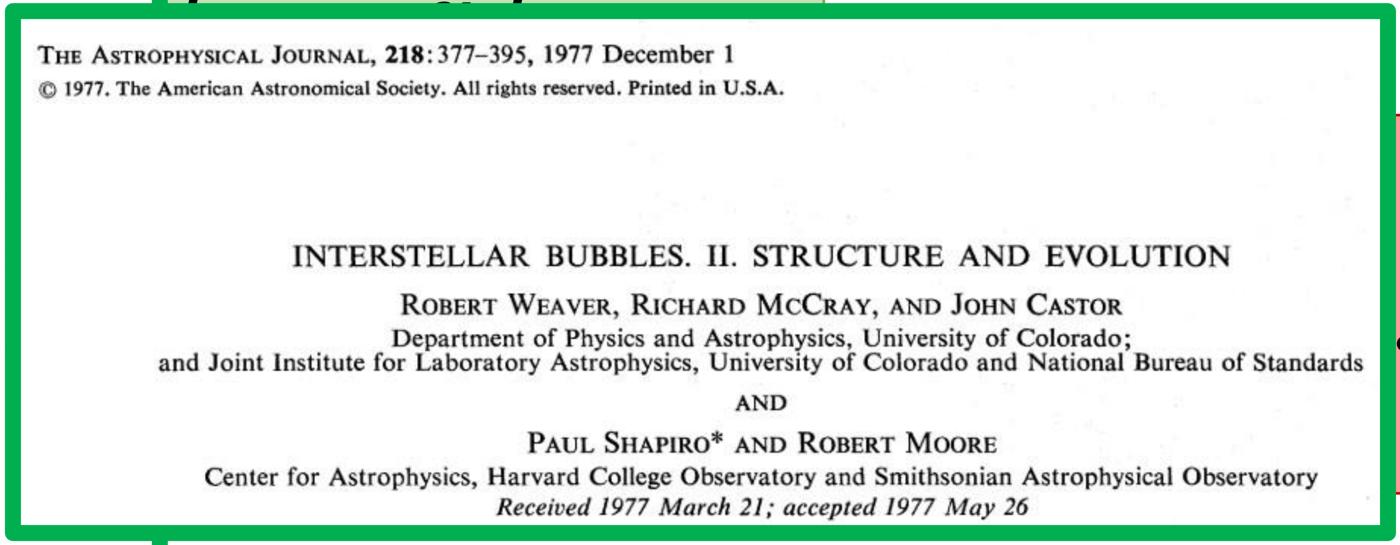


$\dot{E}\ \ \alpha\ \dot{E}$



THE ASTROPHYSICAL JOURNAL, **218**:377–395, 1977 December 1
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INTERSTELLAR BUBBLES. II. STRUCTURE AND EVOLUTION

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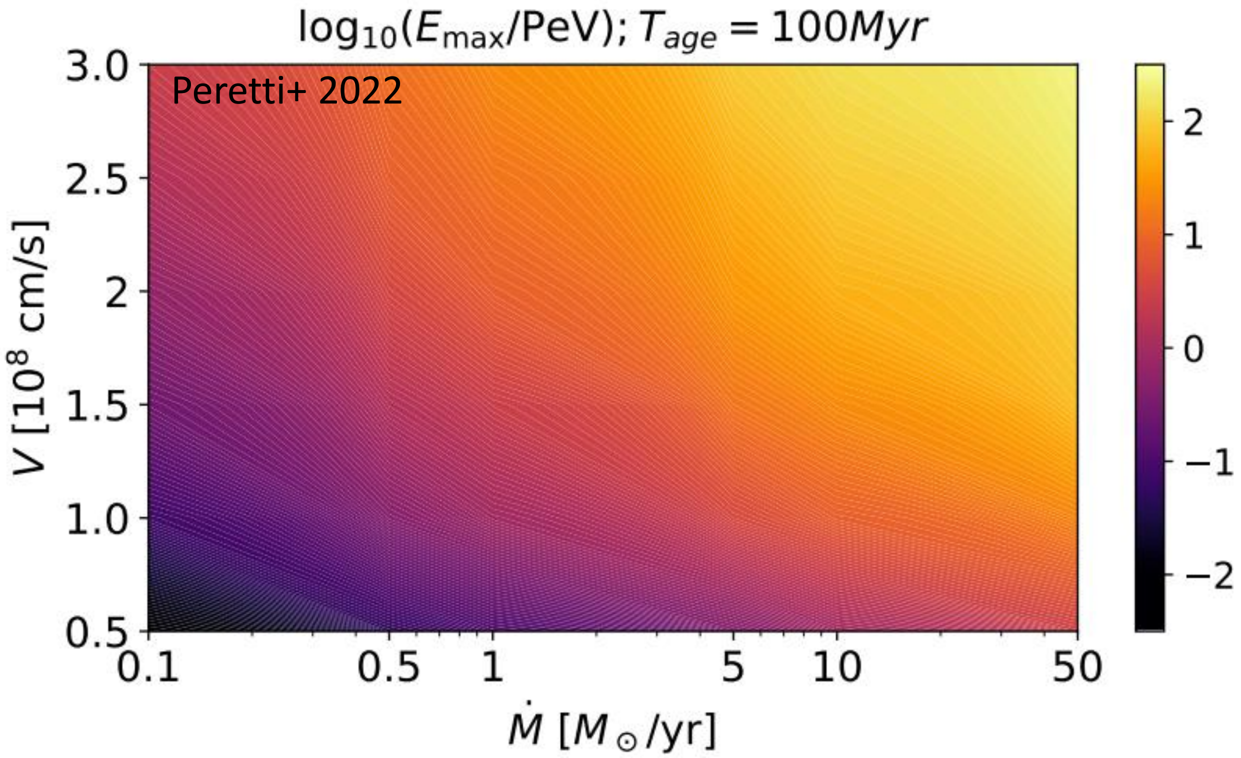
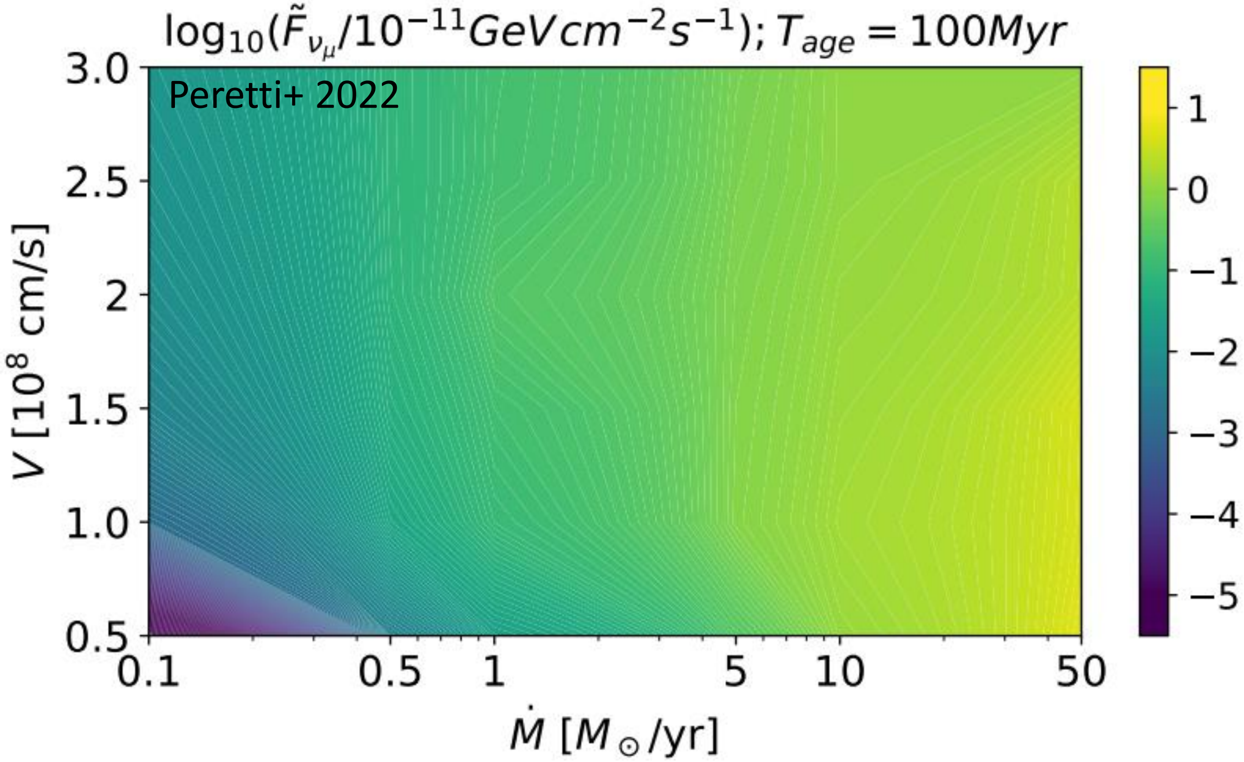
AND
PAUL SHAPIRO* AND ROBERT MOORE
Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory
Received 1977 March 21; accepted 1977 May 26

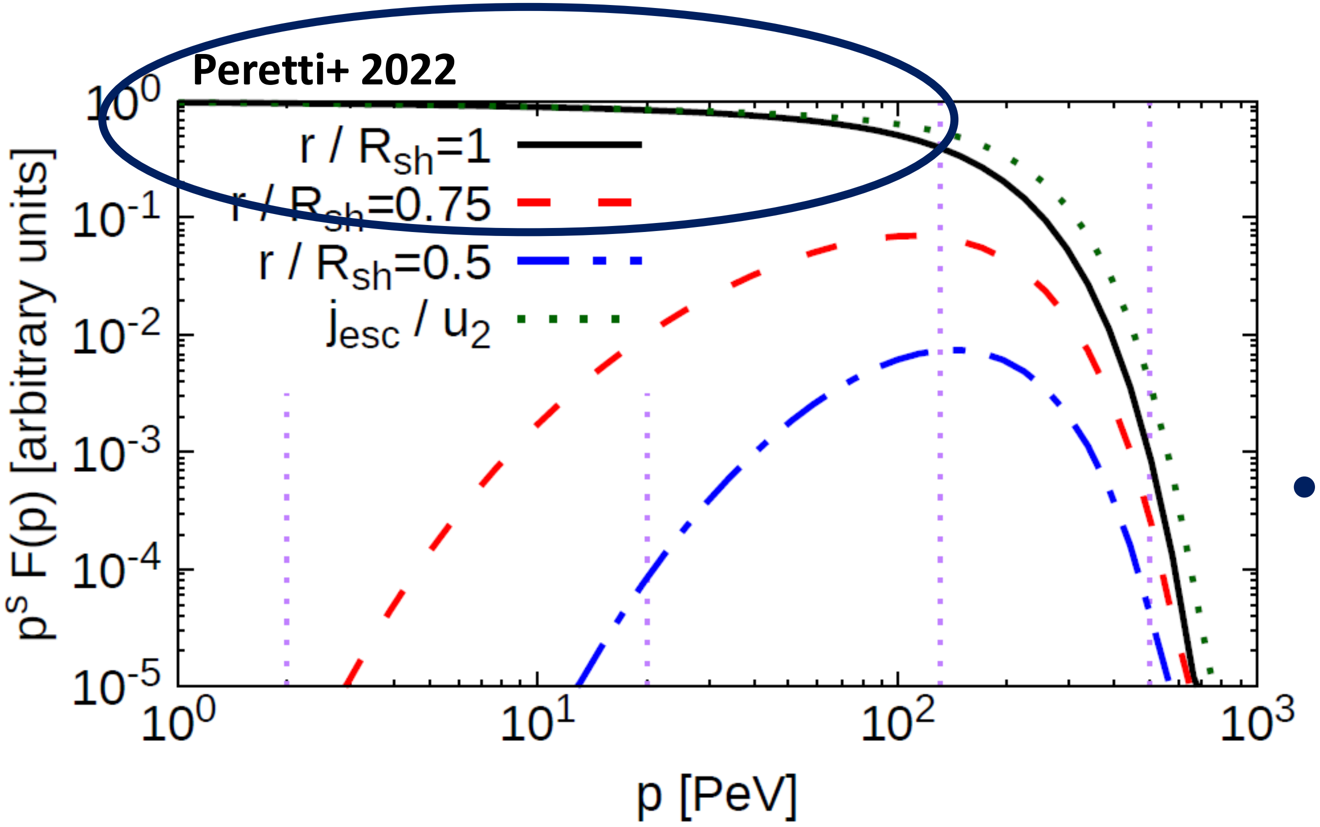
$g\ s^{-1}$

Maximum Energy & Luminosity in Winds





Particles in the system

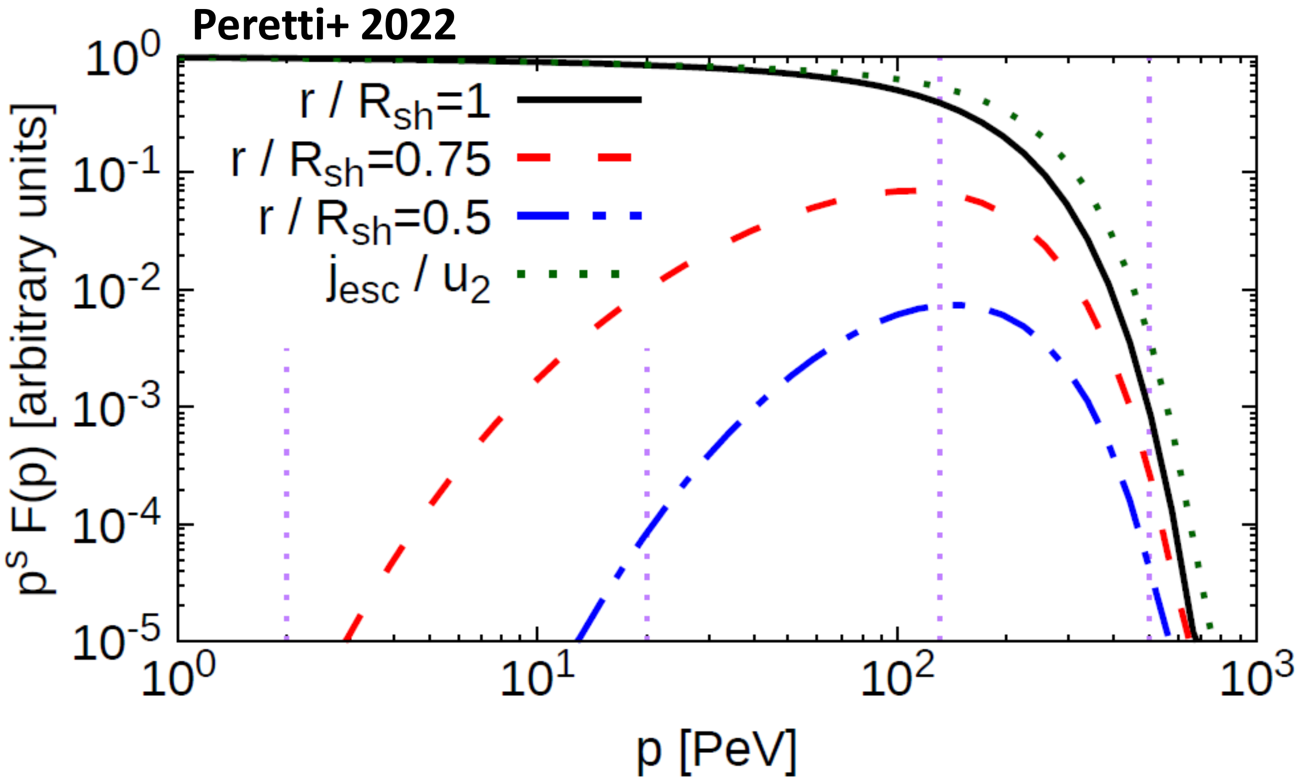


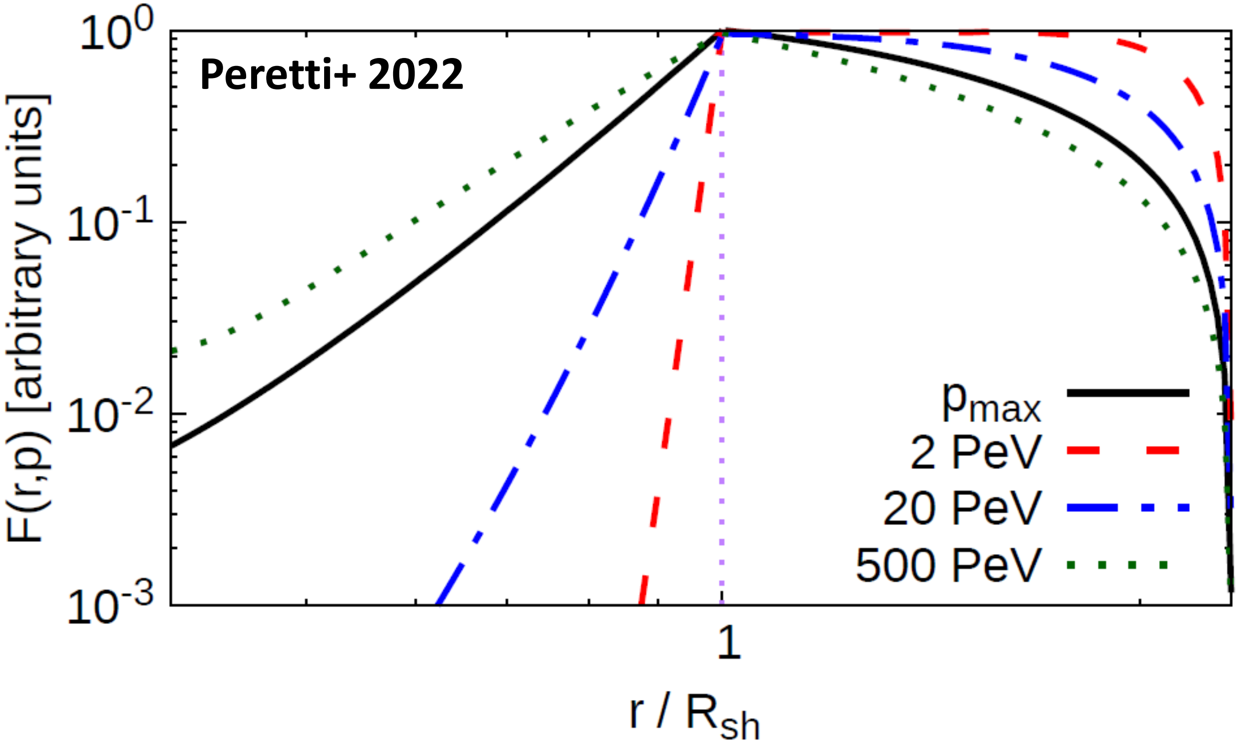
- Maximum Energy → 10^2 PeV

- Standard DSA valid at low Energy

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

Particles in the system

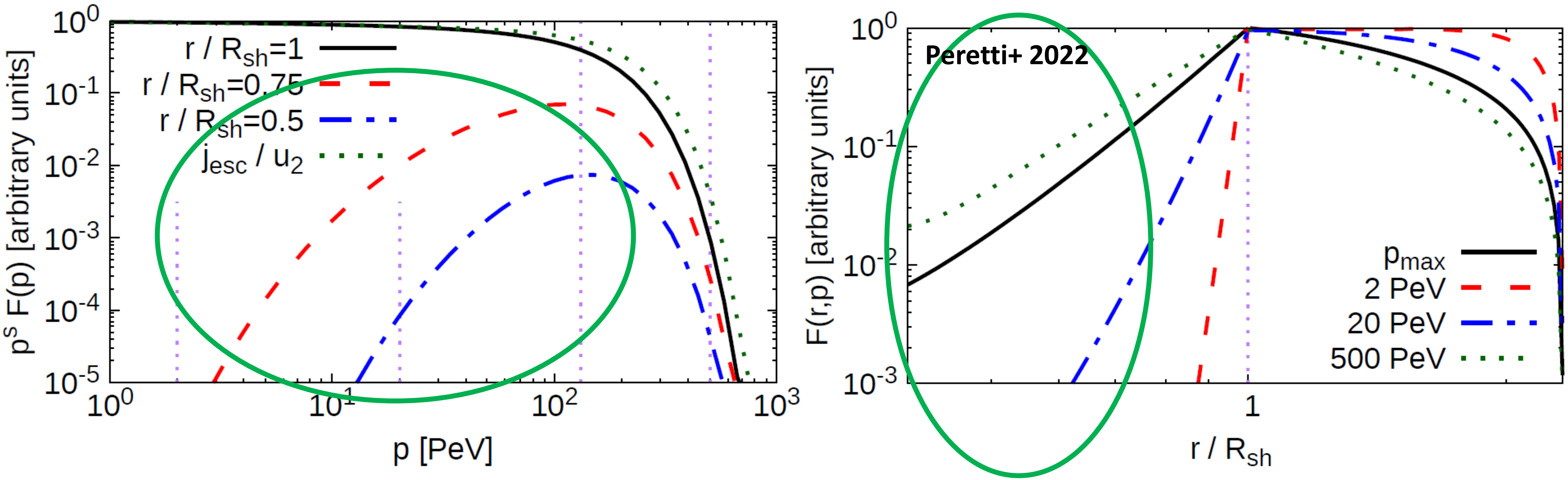




$$f_{sh}(p) \propto p^{-s} e^{-\Gamma_1(p)} e^{-\Gamma_2(p)}$$

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

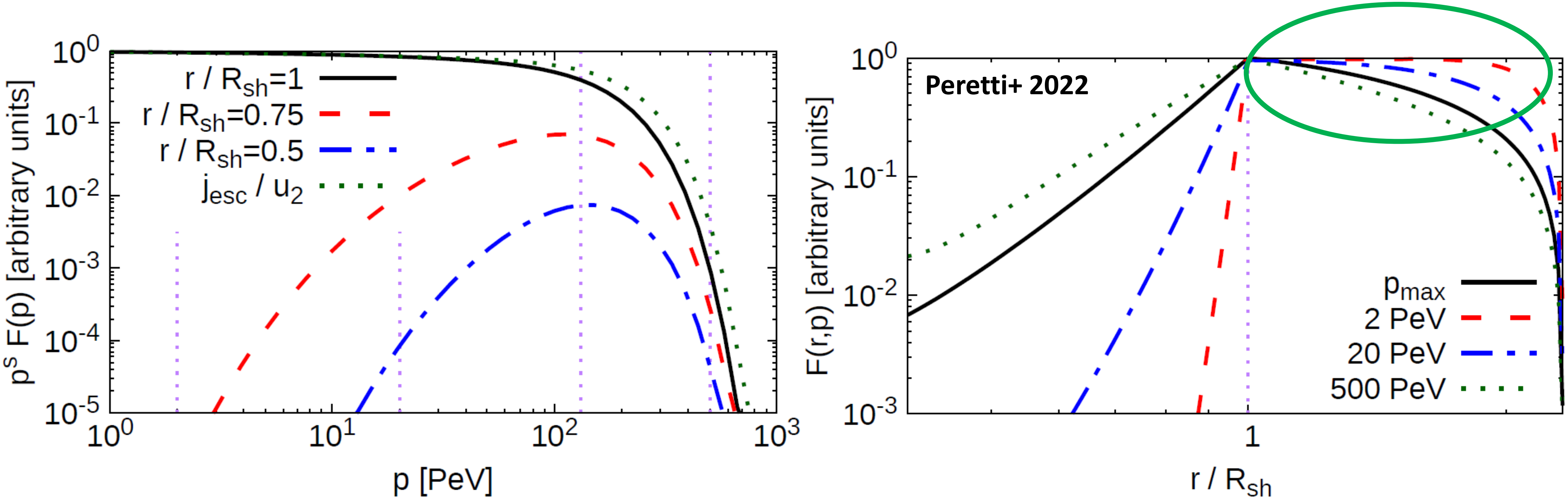
Particles in the system



Peretti+ 2022

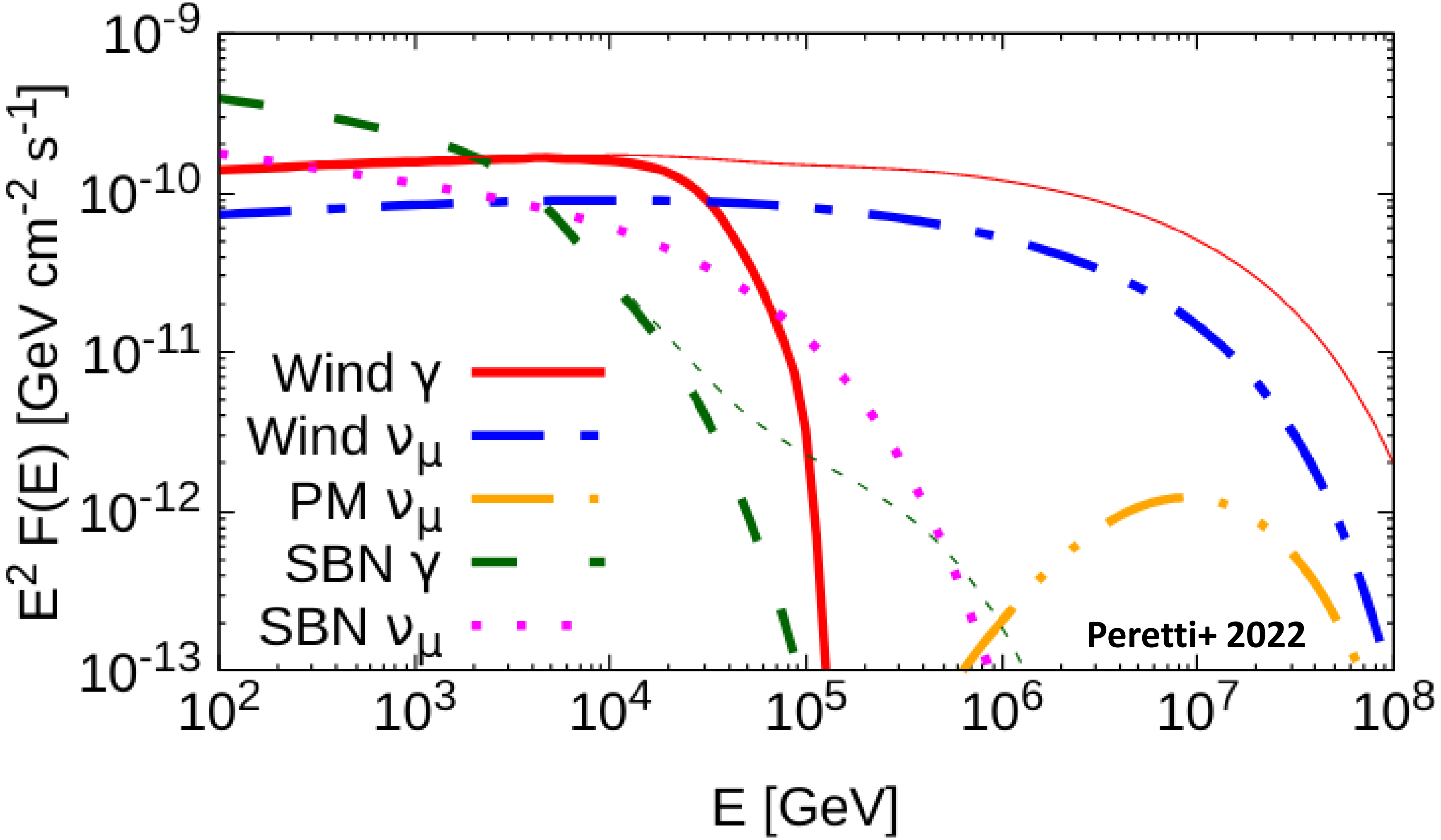
The wind suppresses the diffusion of particles back to the galaxy

Particles in the system

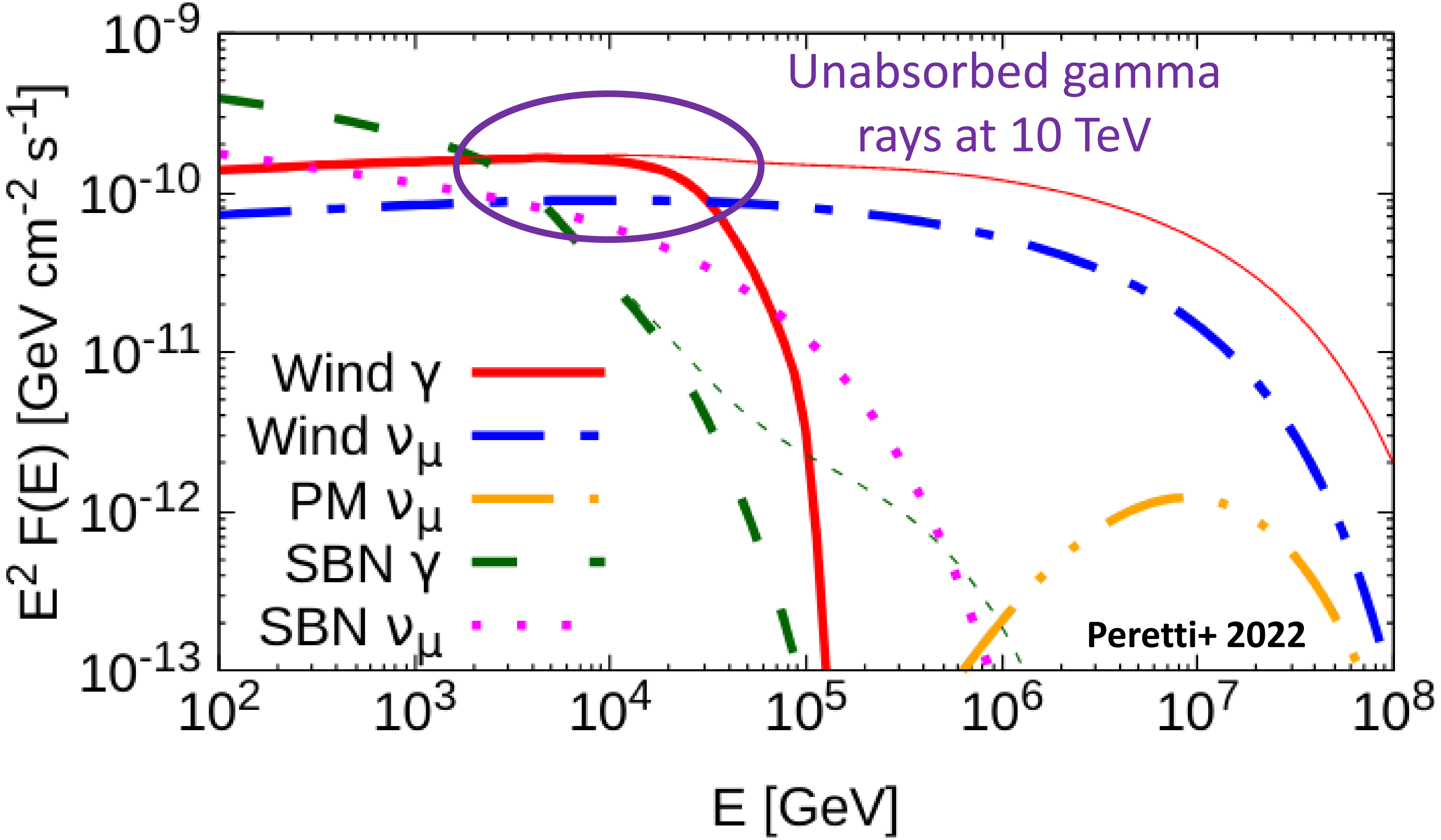


Particle distribution homogenized in
the downstream region

High-Energy SED and Neutrinos



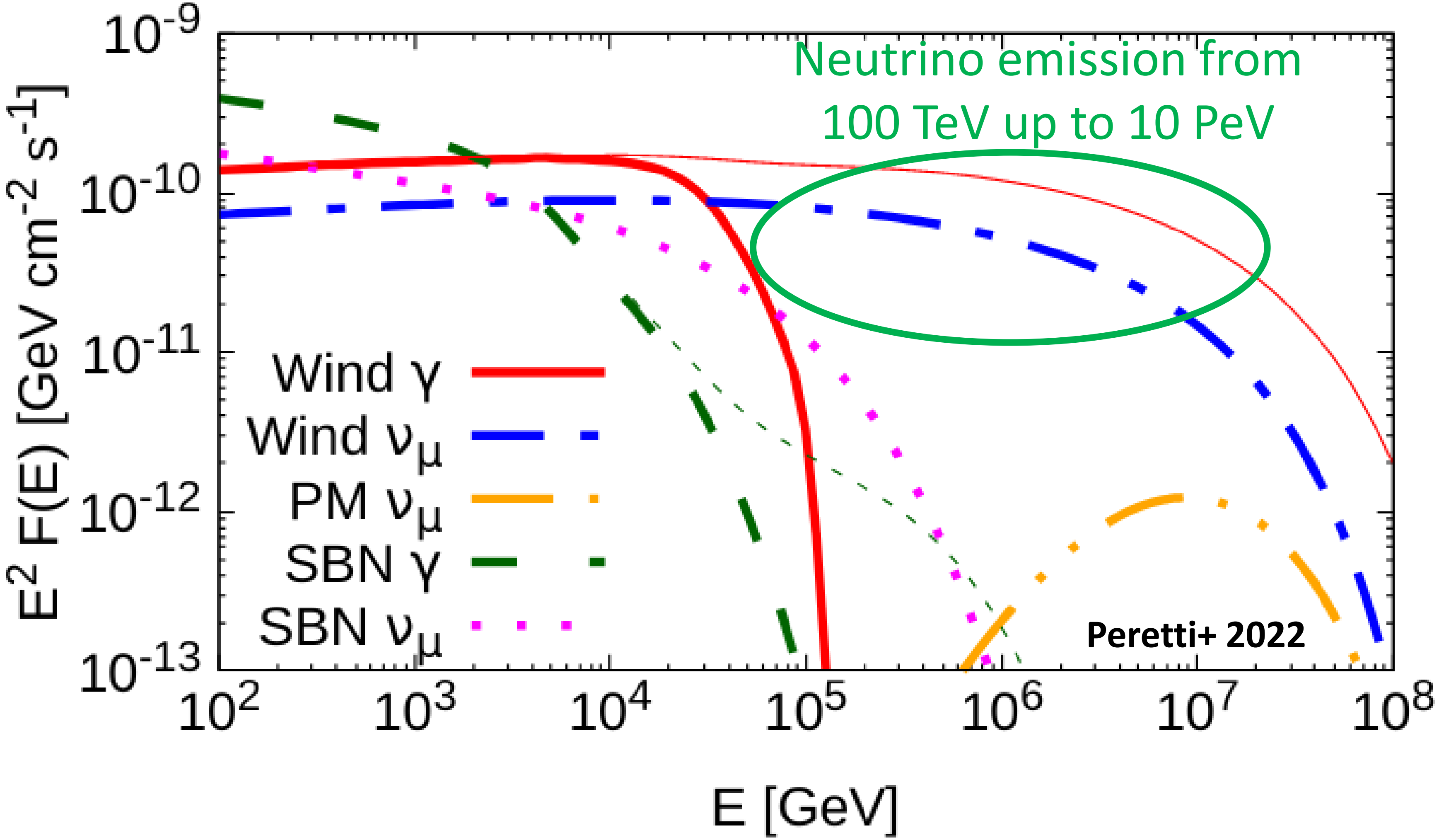
High-Energy SED and Neutrinos



Unabsorbed gamma rays at 10 TeV

Peretti+ 2022

High-Energy SED and Neutrinos



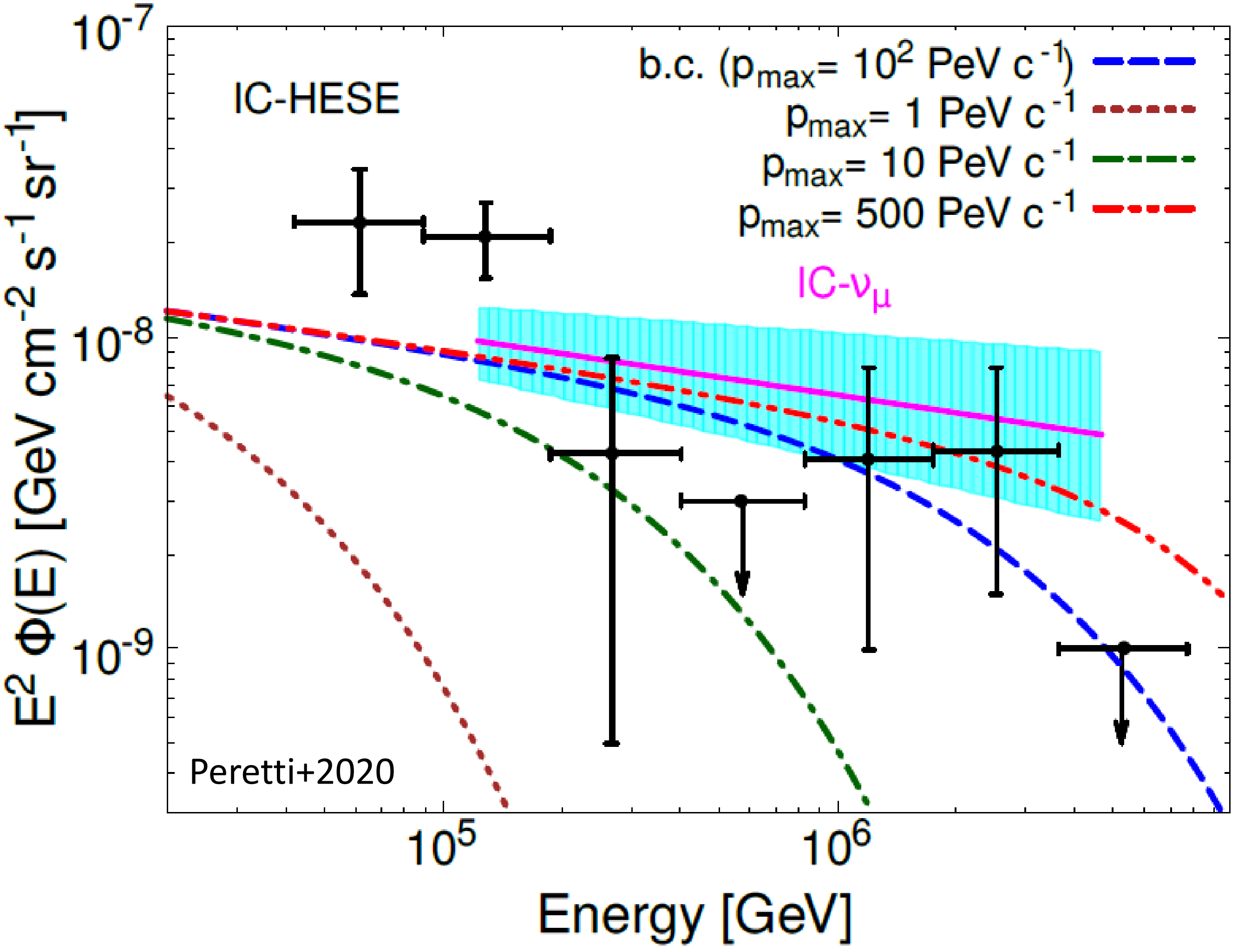
The issue of the maximum energy

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

SNR in case of Bohm diffusion:

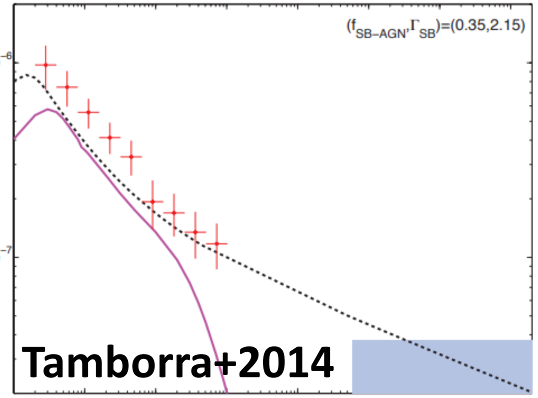
$$E_{max} = 30\ PeV\ \times R_3 u_4 B_{mG}$$

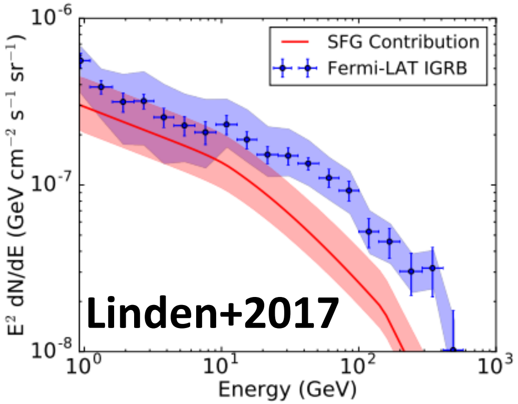
- Magnetic field amplification can allow reaching 10-100 PeV

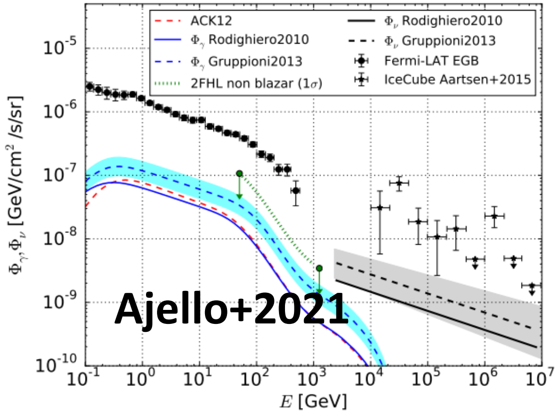


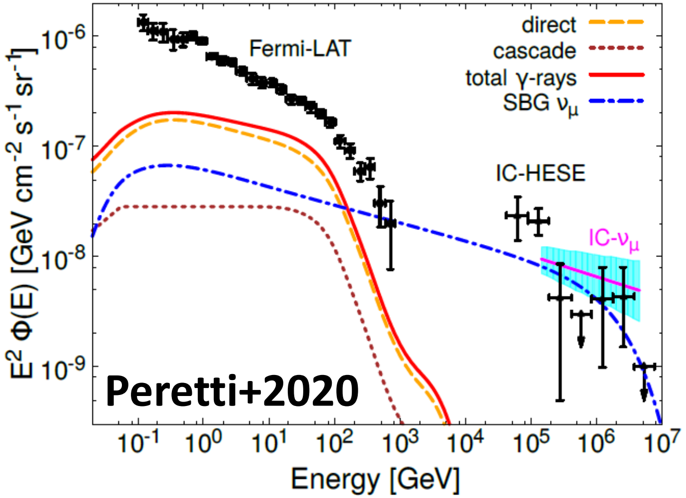
Peretti+2020

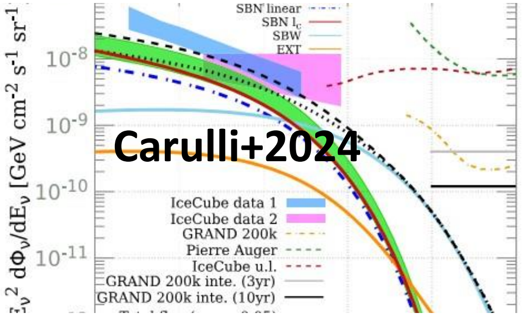
Starbursts in the last 10 years

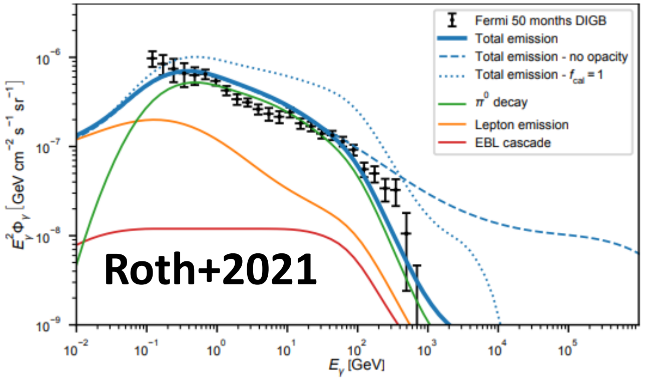

Tamborra+2014

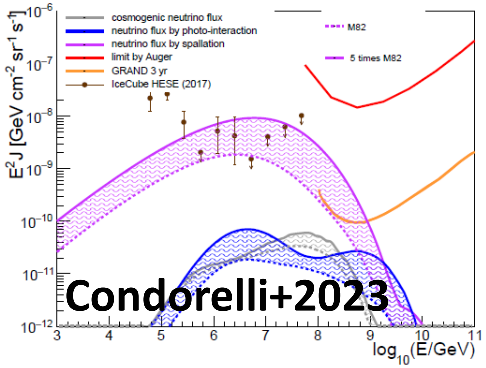

Linden+2017

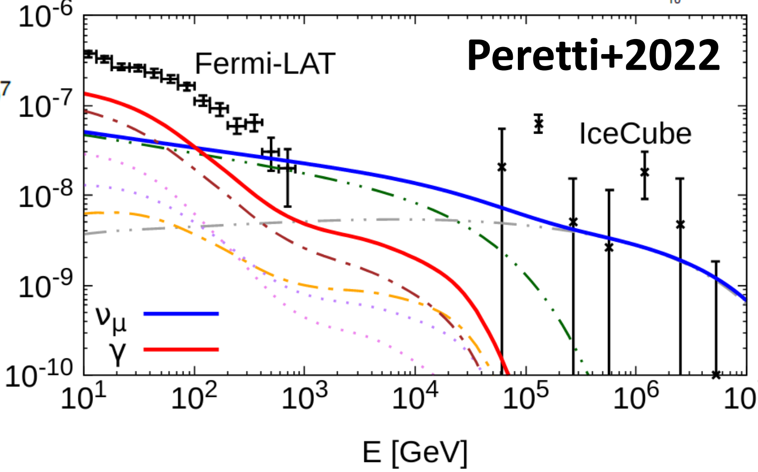

Ajello+2021

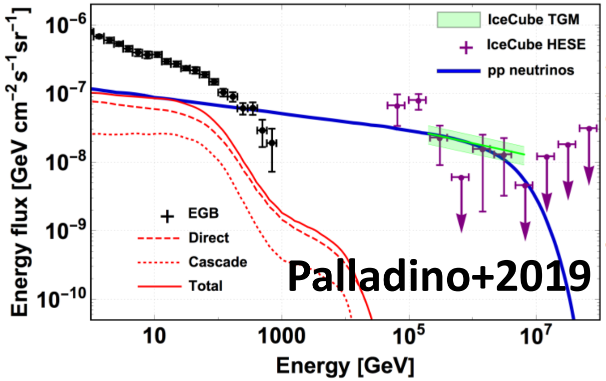

Peretti+2020

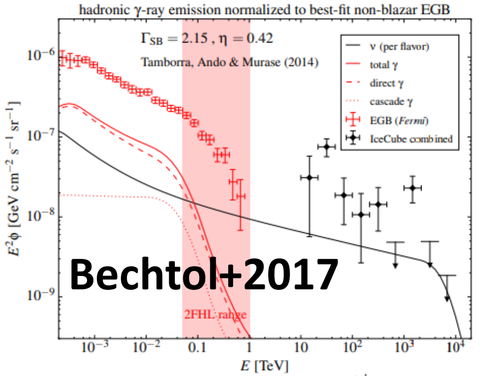

Carulli+2024

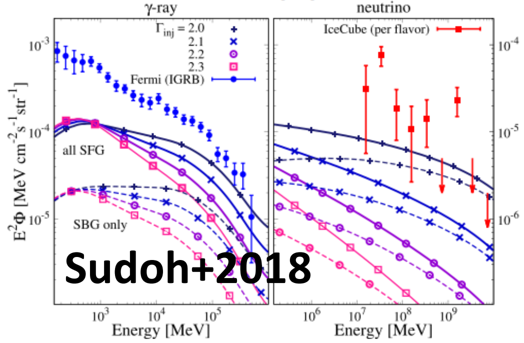

Roth+2021

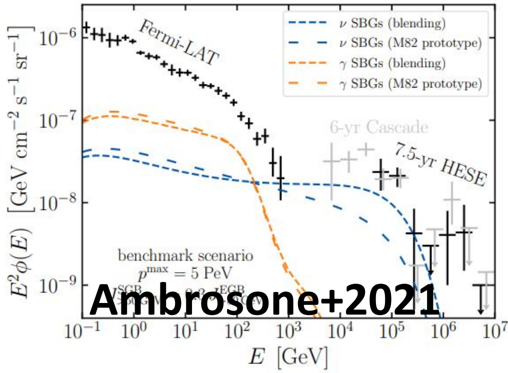

Condorelli+2023

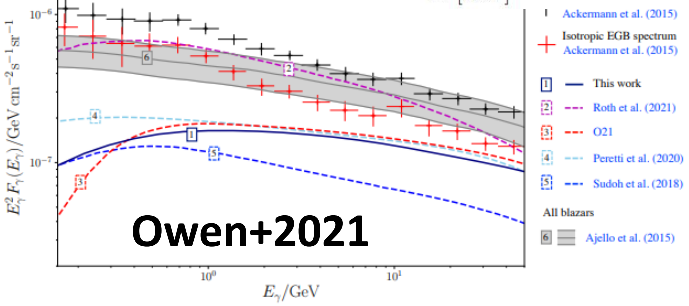

Peretti+2022


Palladino+2019


Bechtol+2017

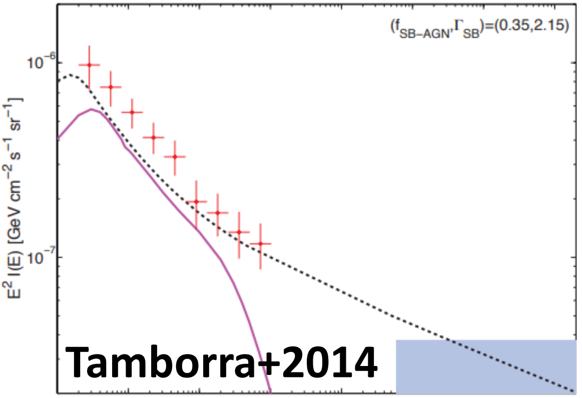

Sudoh+2018

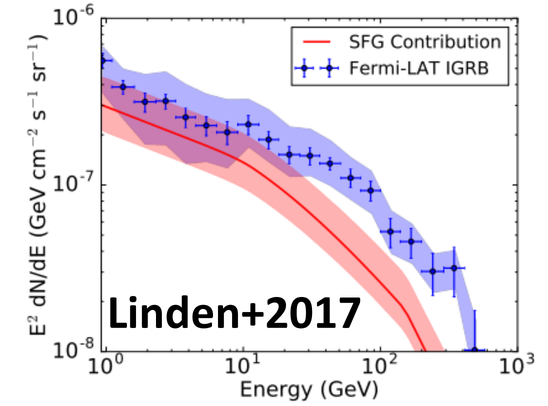

Ambrosone+2021

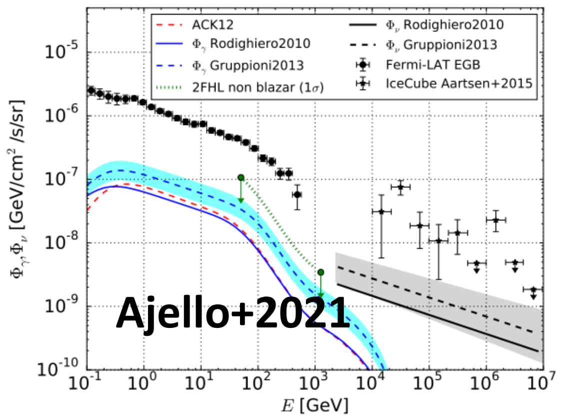

Owen+2021

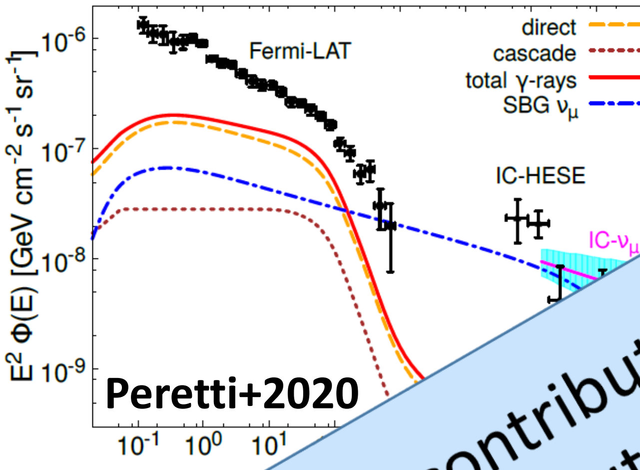
Starbursts in the last 10 years

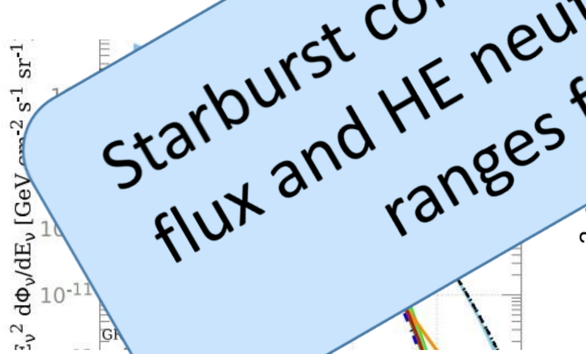
Starburst contribution to the diffuse γ-ray flux and HE neutrino flux beyond 100 TeV ranges from 1% up to 100%

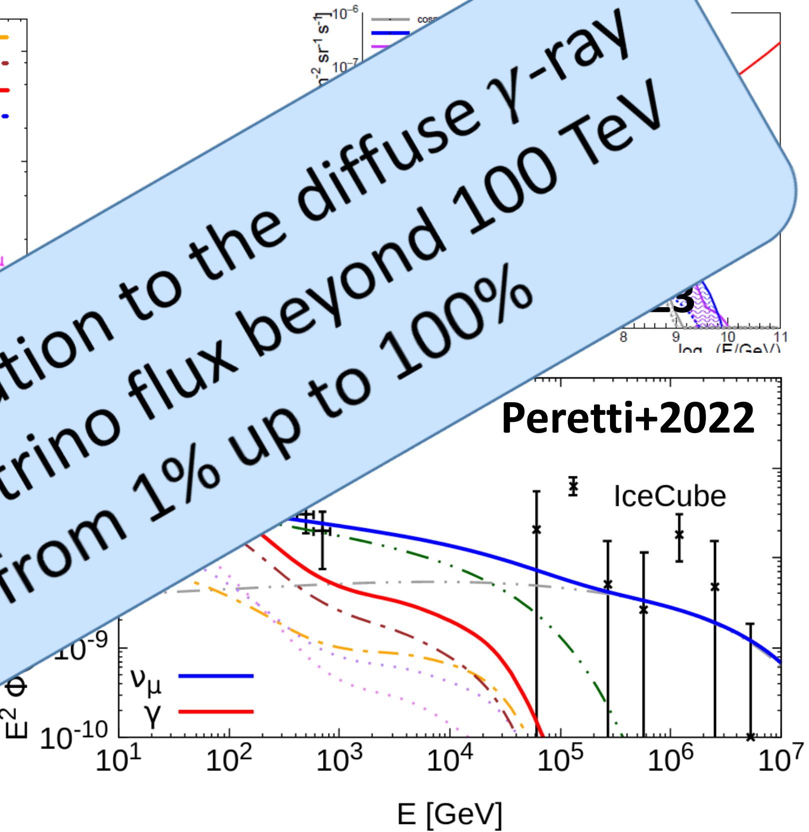


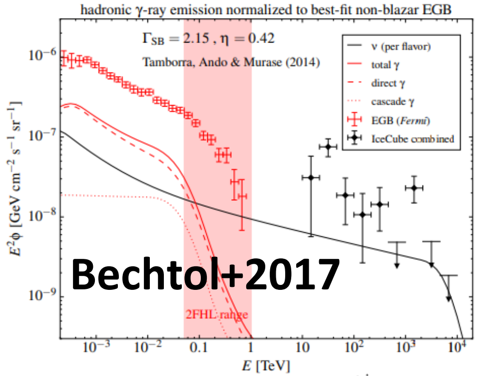


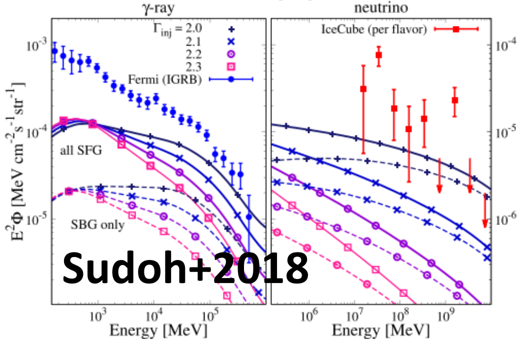


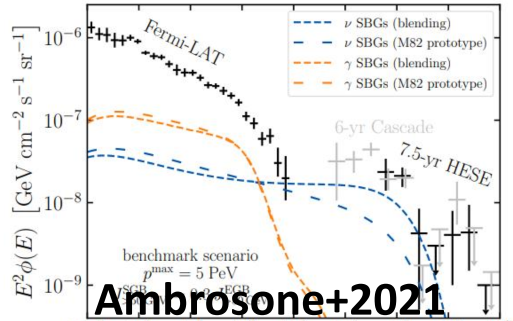


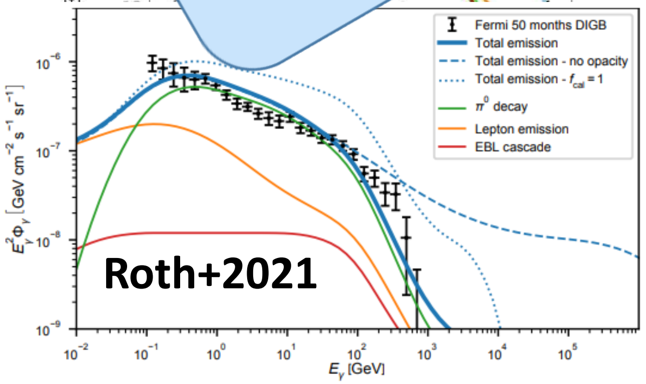


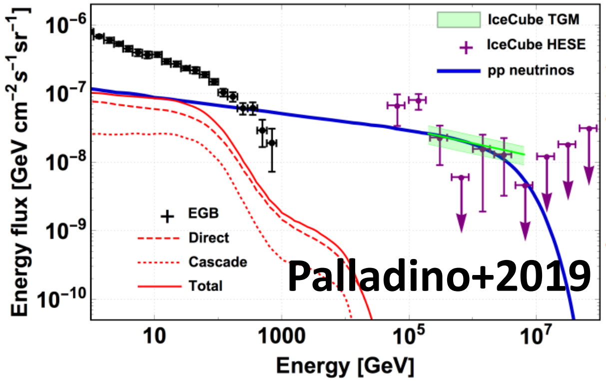


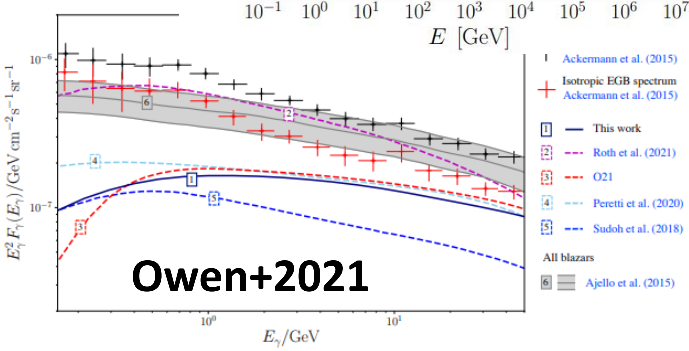




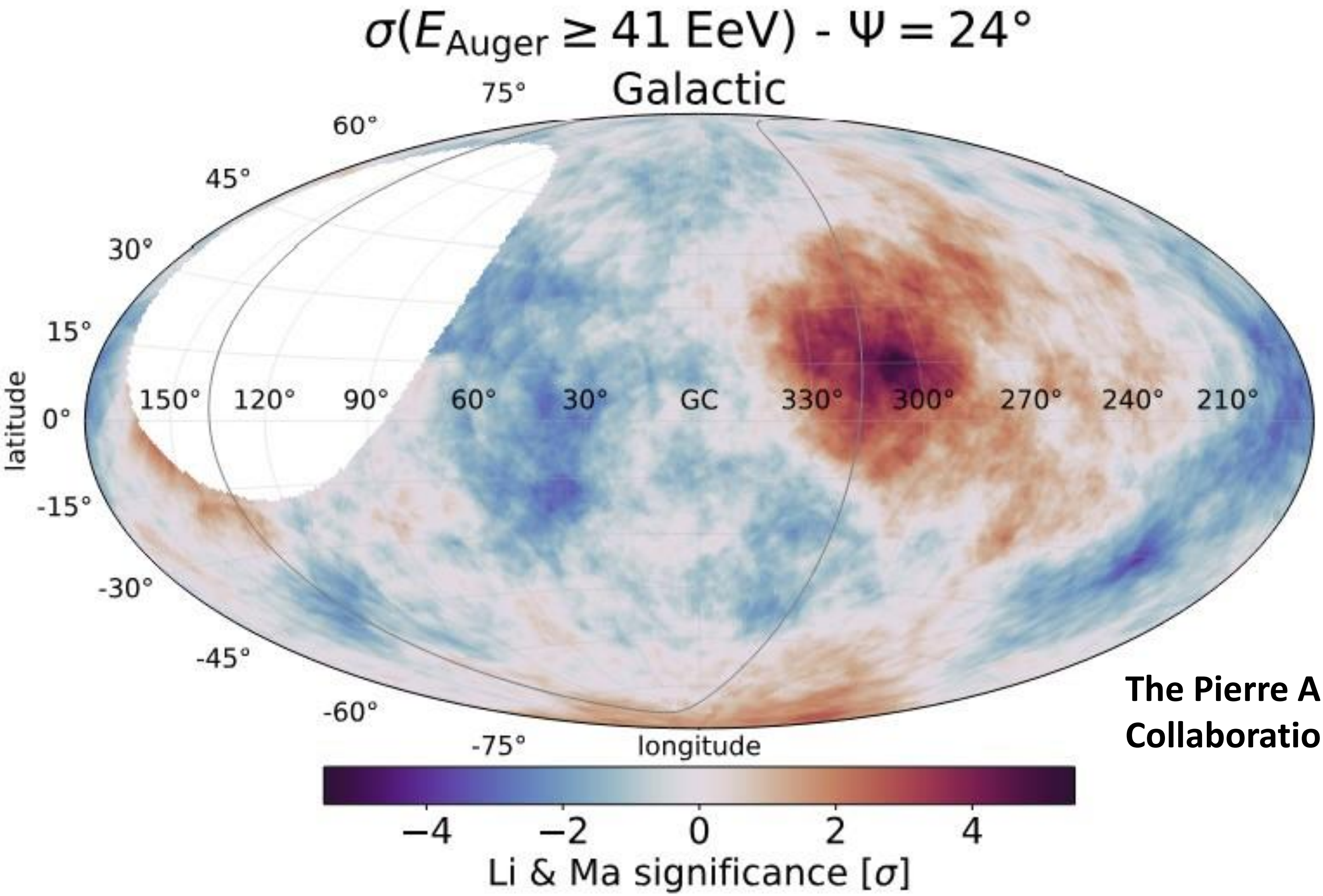






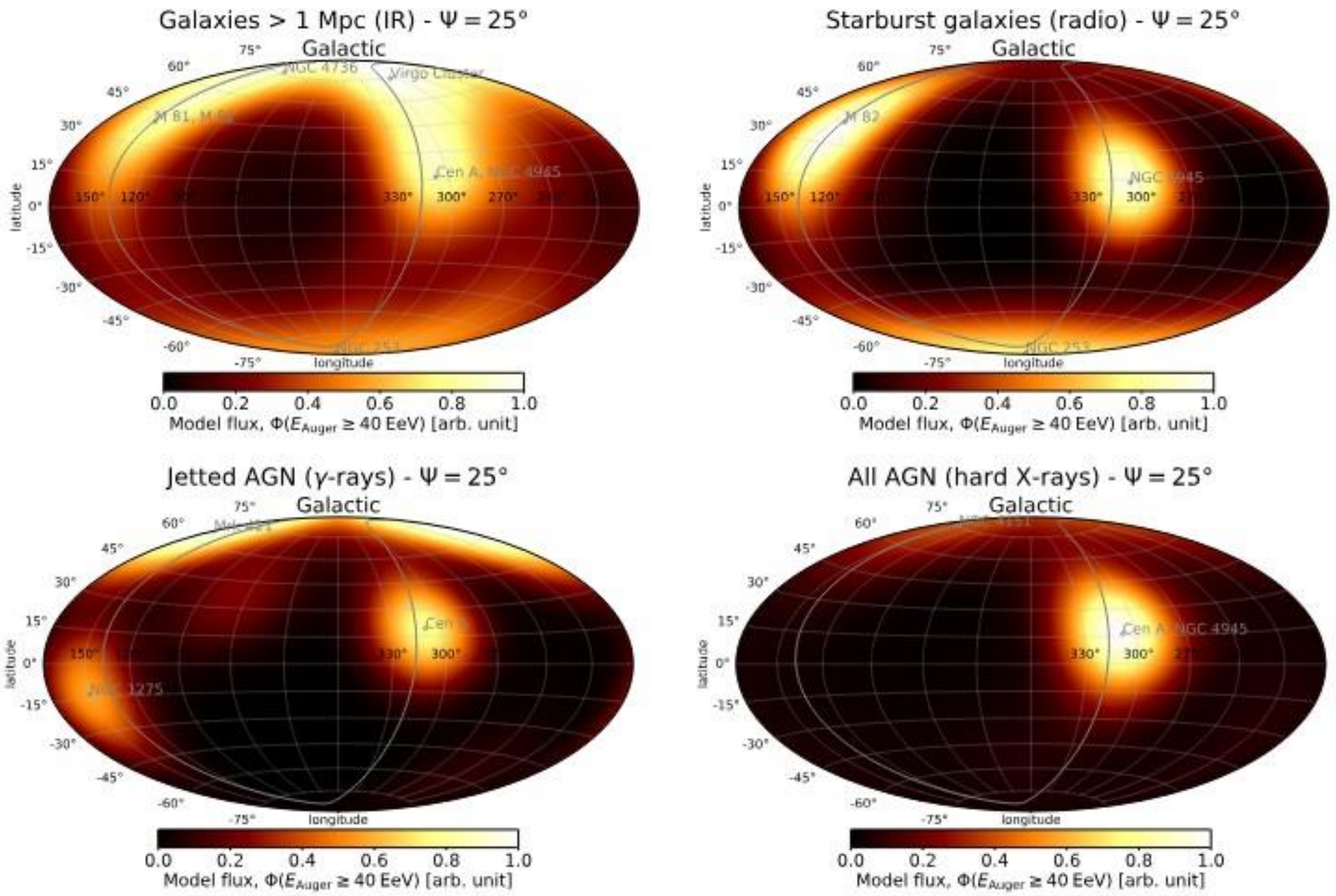


Starbursts and Ultra-High-Energy cosmic rays



The Pierre Auger Collaboration 2022

Starbursts and Ultra-High-Energy cosmic rays



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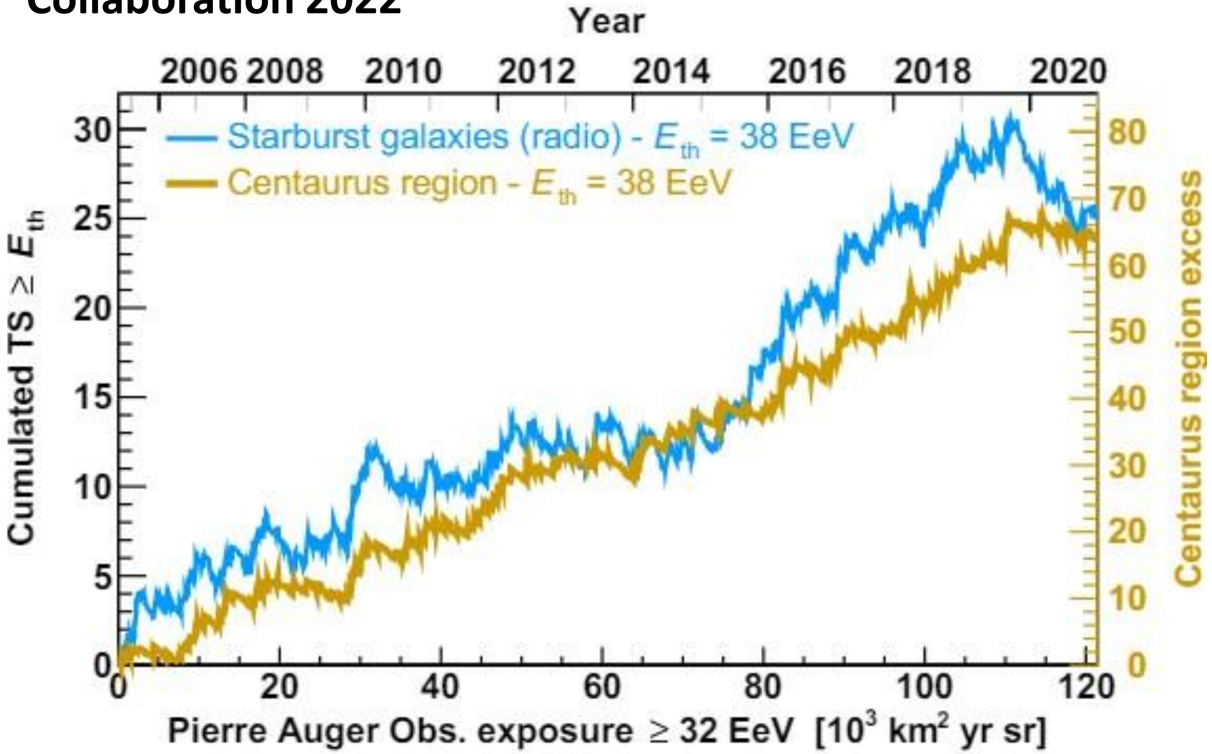

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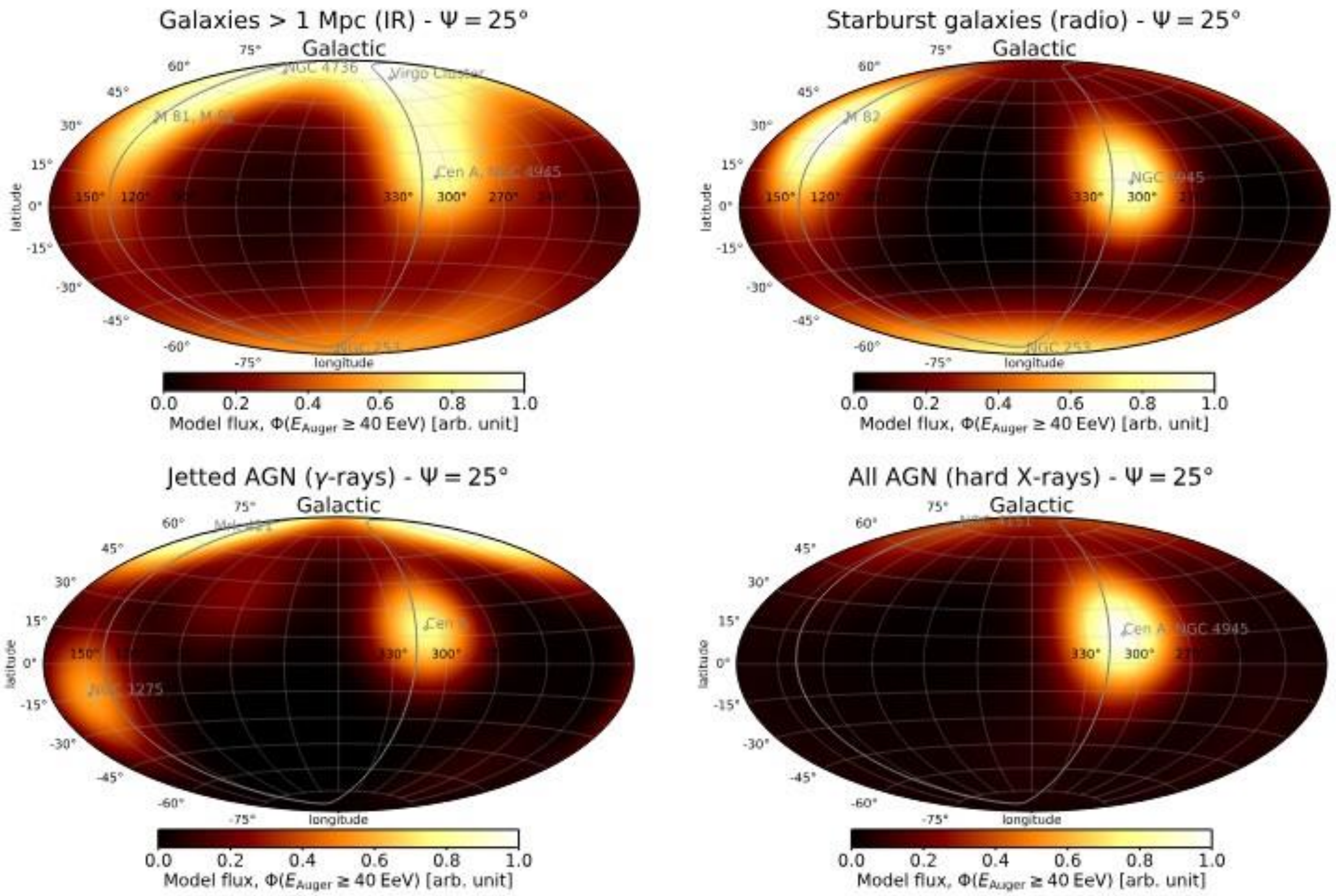

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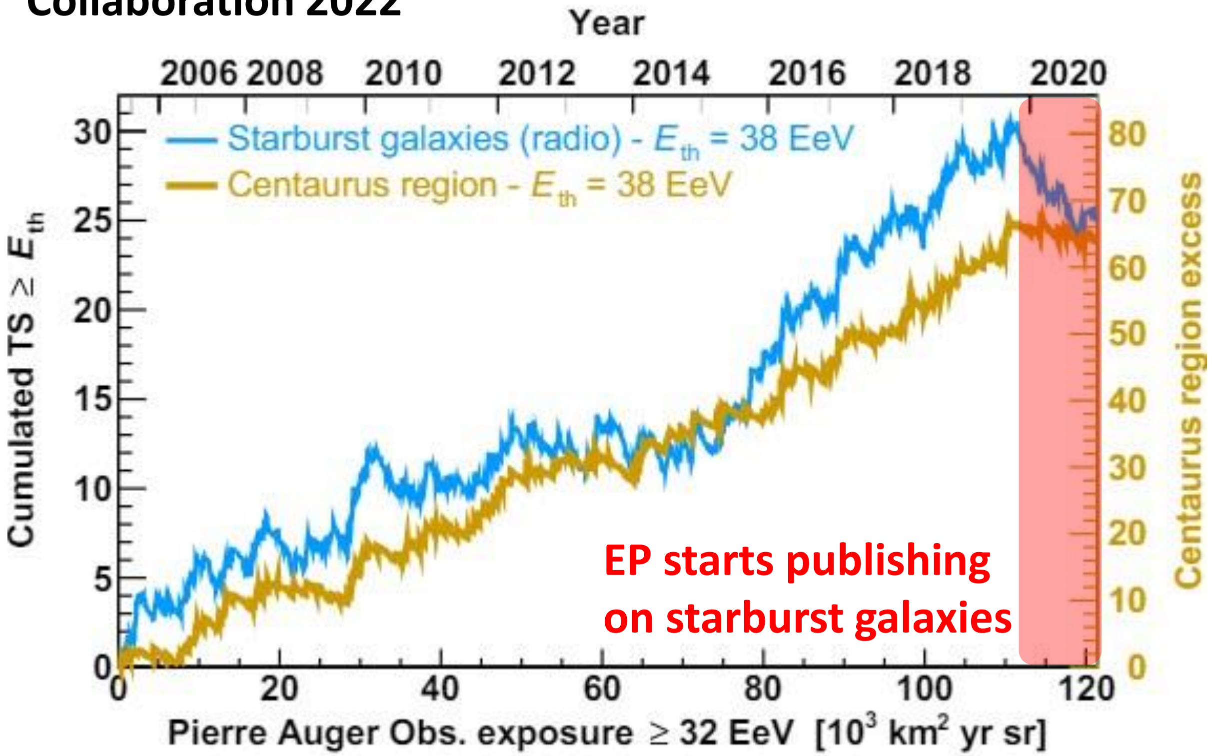
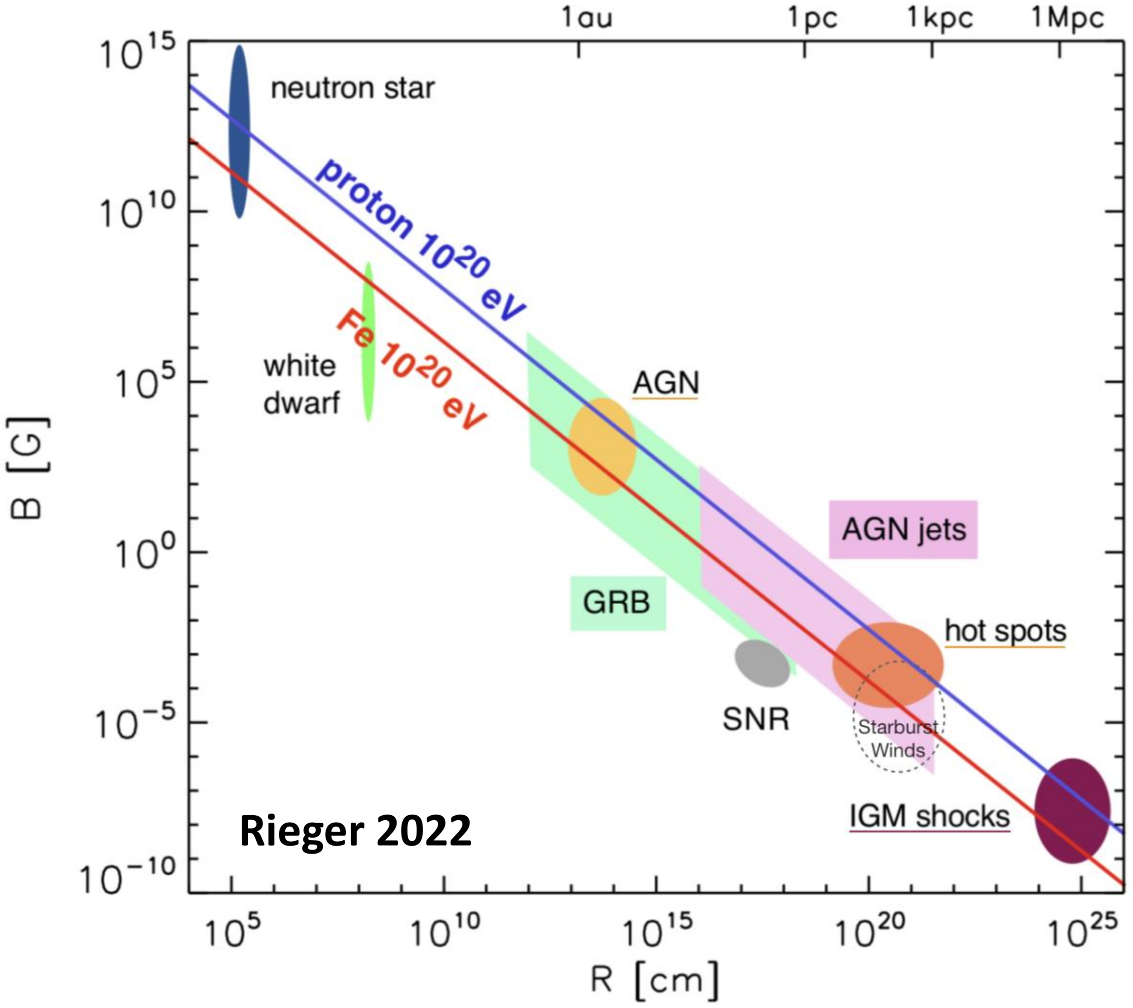


EP starts publishing on starburst galaxies

UHECR accelerators in starburst galaxies

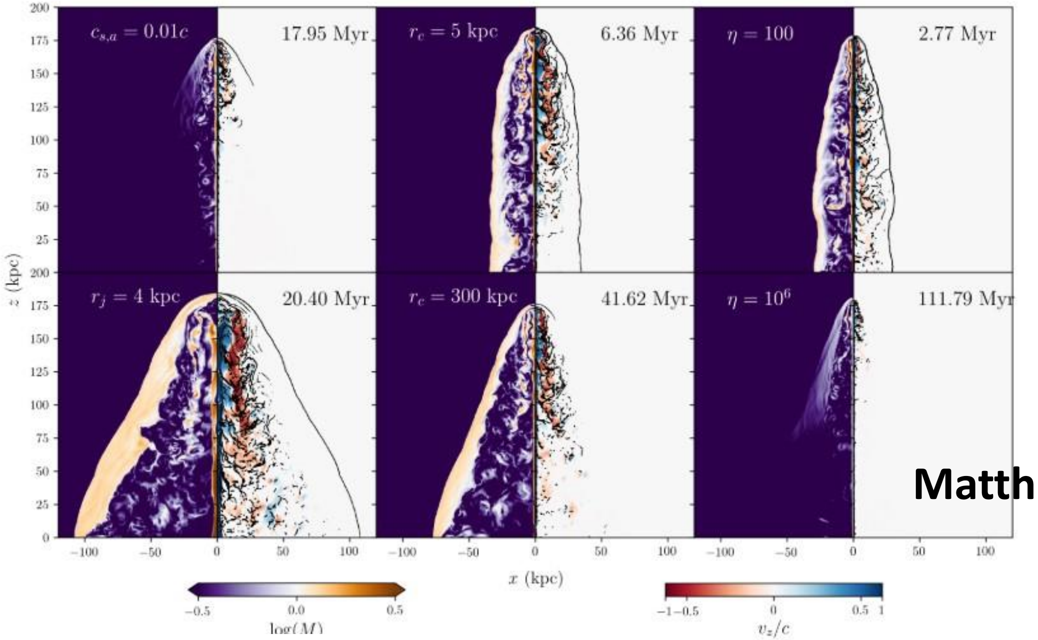
- Starburst winds could possibly exceed our prediction of DSA only and reach the limit allowed by Hillas

- 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

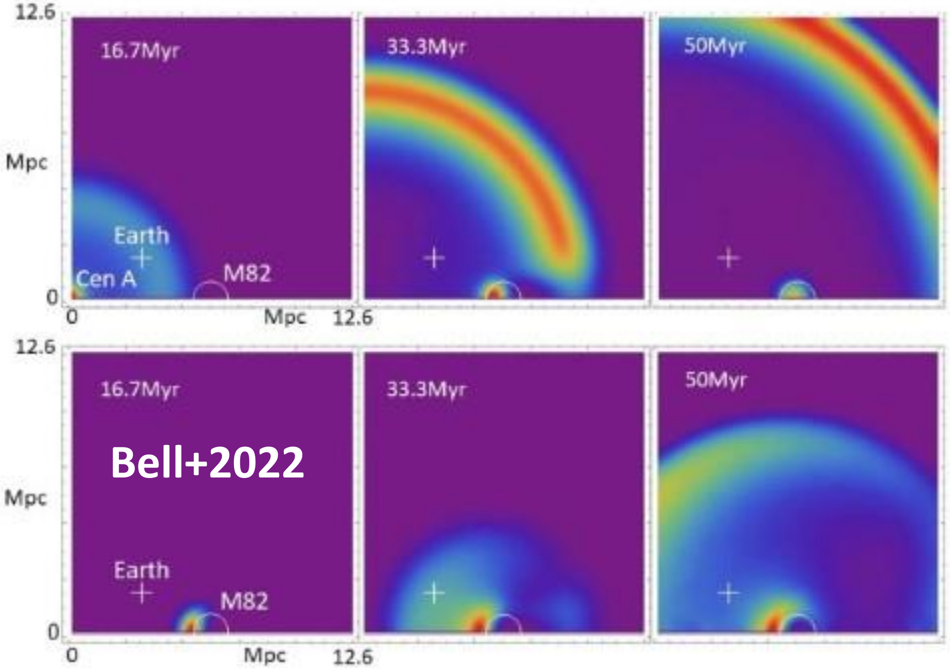


Rieger 2022

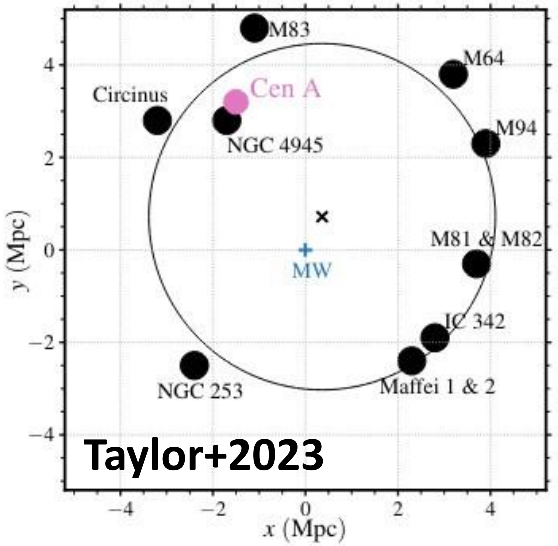
Alternative scenario: Echoes of Cen A activity



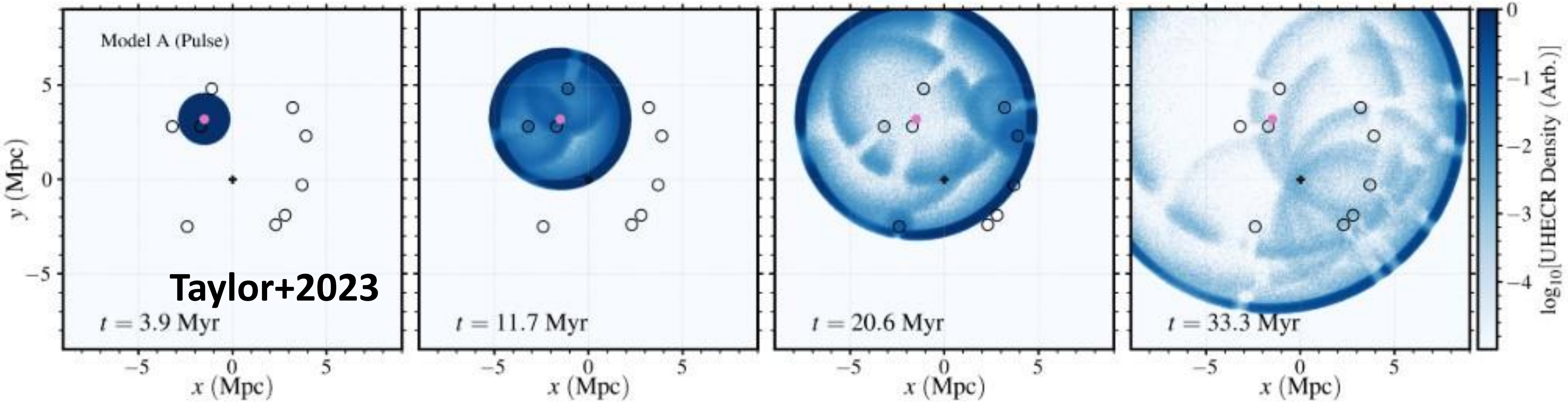
Matthews+2018



Bell+2022

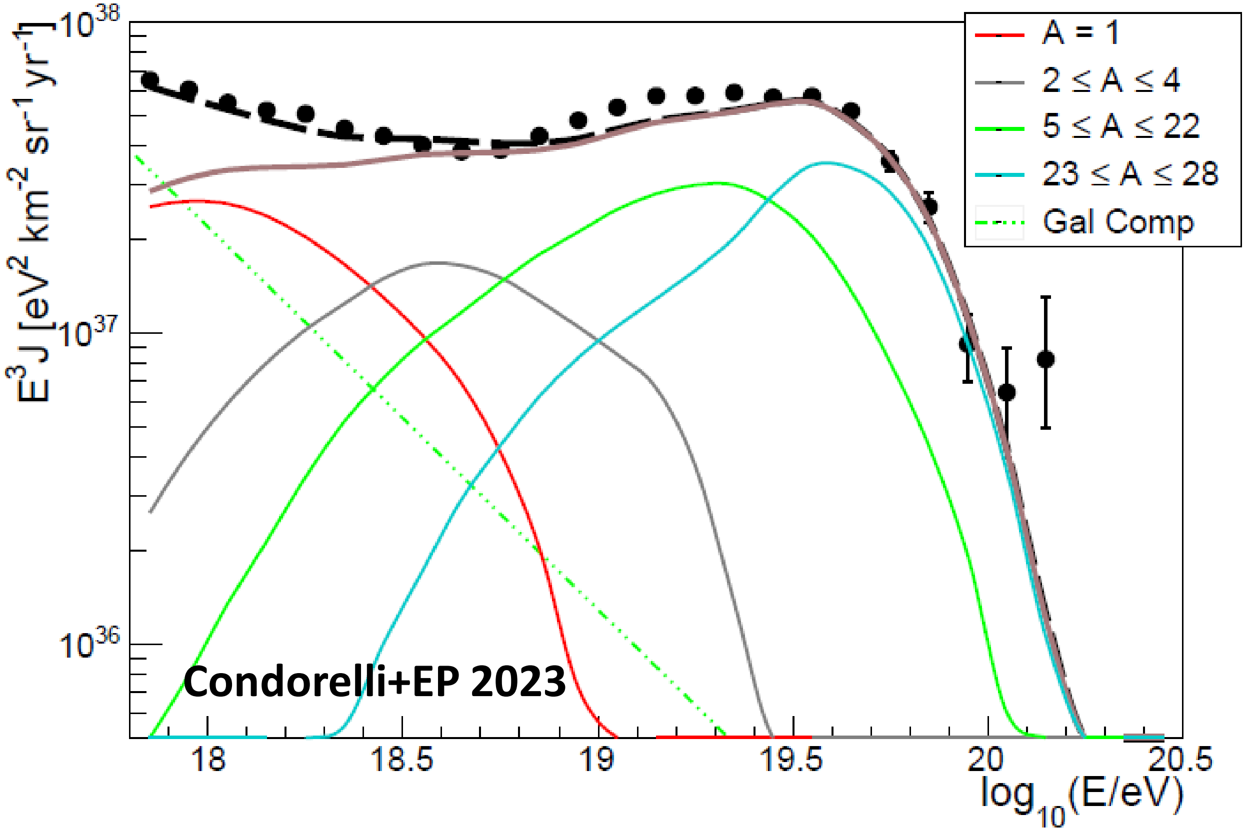


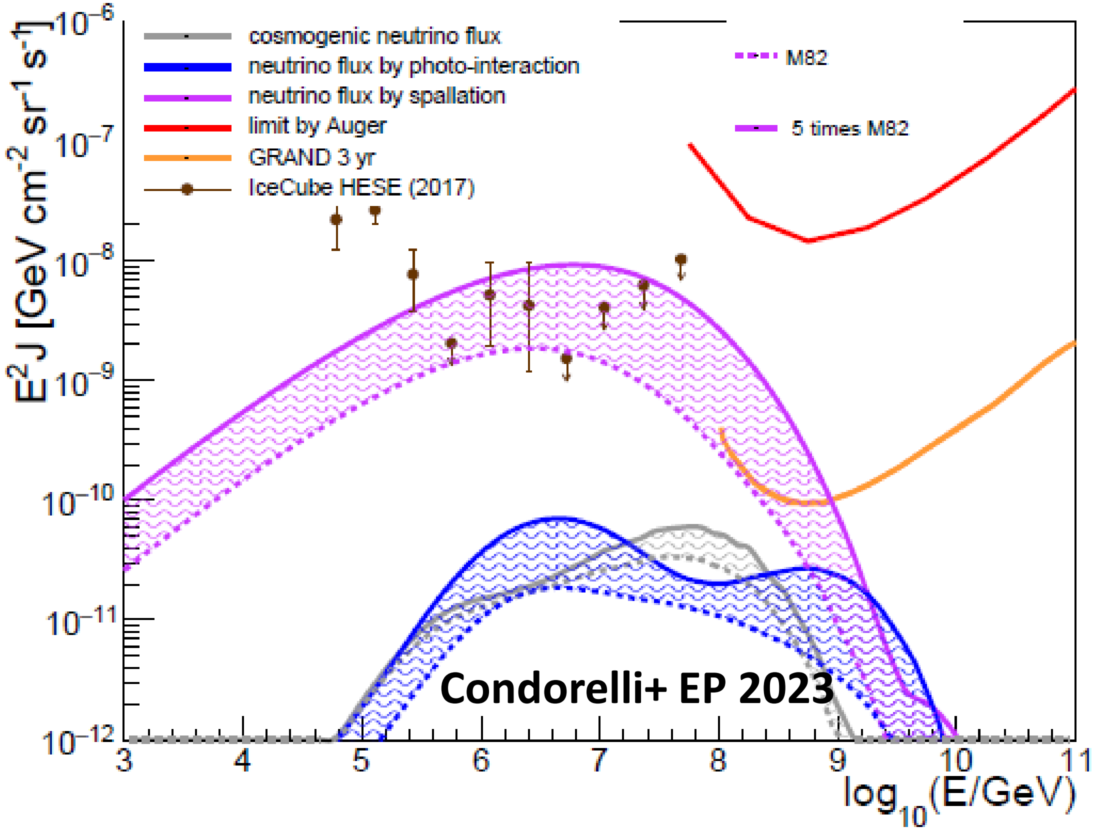
Taylor+2023



Taylor+2023

Ultra-High-Energy cosmic rays in starbursts


Condorelli+EP 2023


Condorelli+ EP 2023