High-Energy emissions from Starburst Galaxies and AGN

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May 14 2024 – 4th EuCAPT Annual Symposium

Université Paris Cité

Why should we care about something happening outside our Galaxy?

Multimessenger picture of the Cosmos

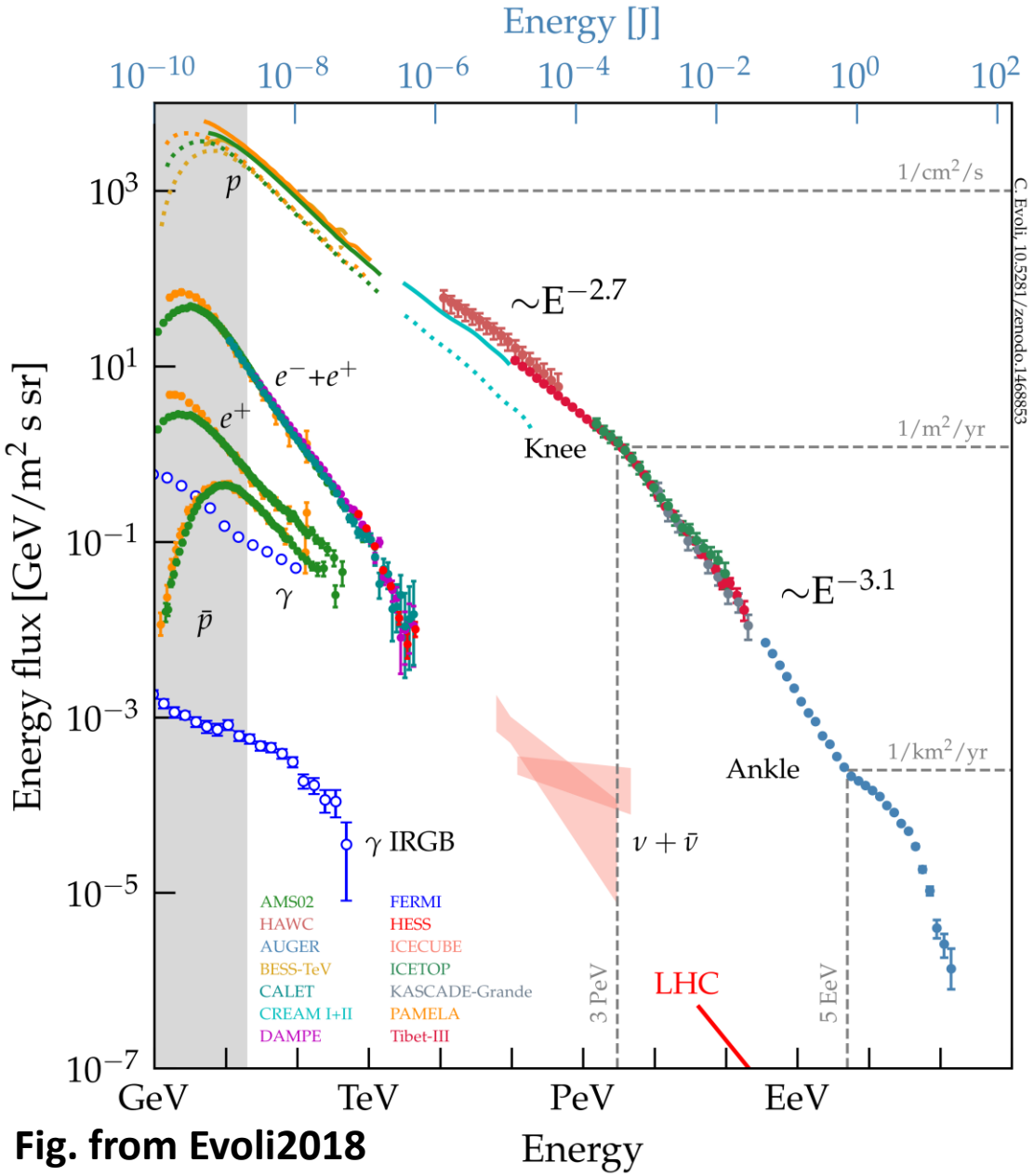

Fig. from Evoli2018

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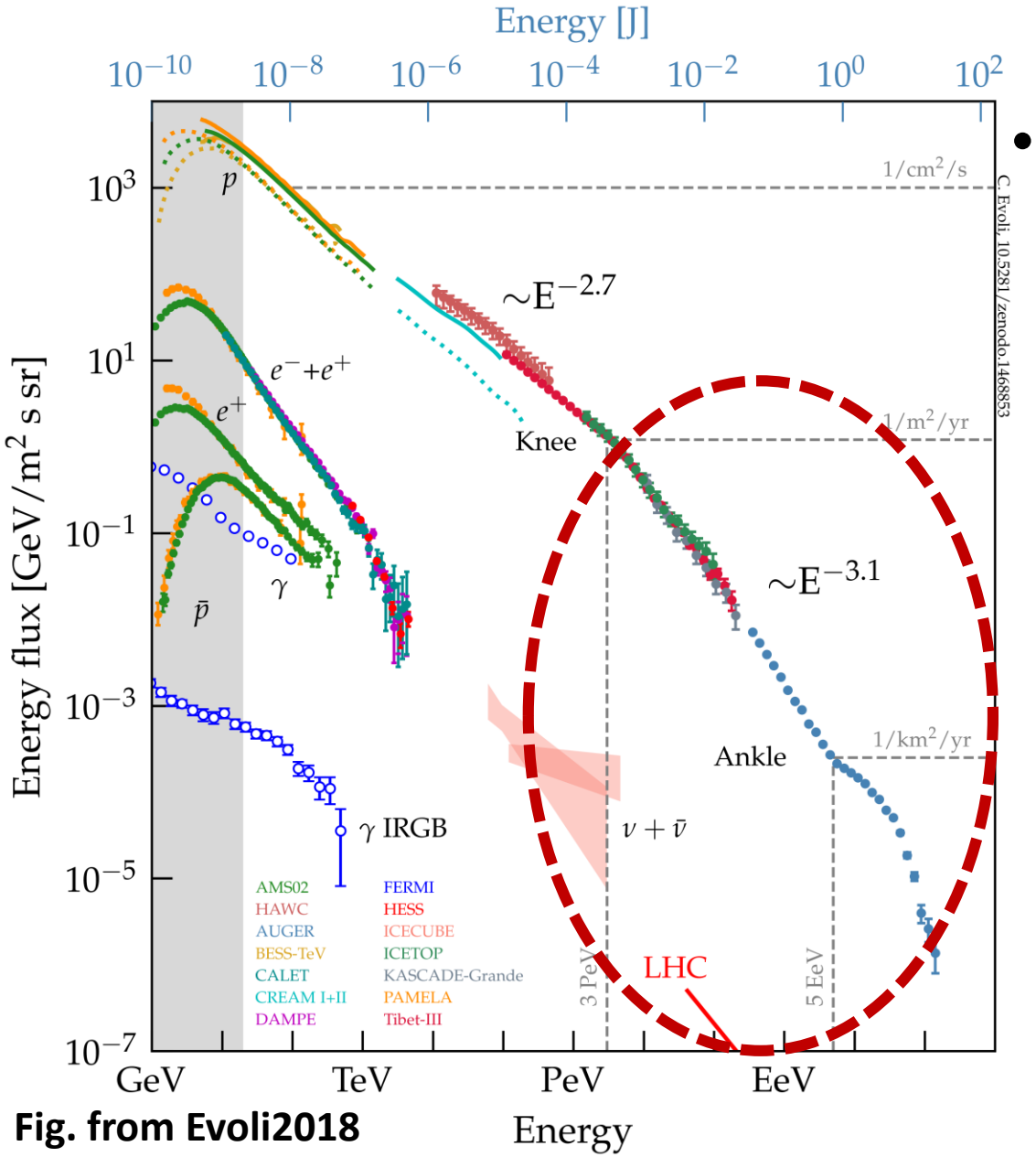

Fig. from Evoli2018

- No cosmic rays source beyond PV has been observed so far

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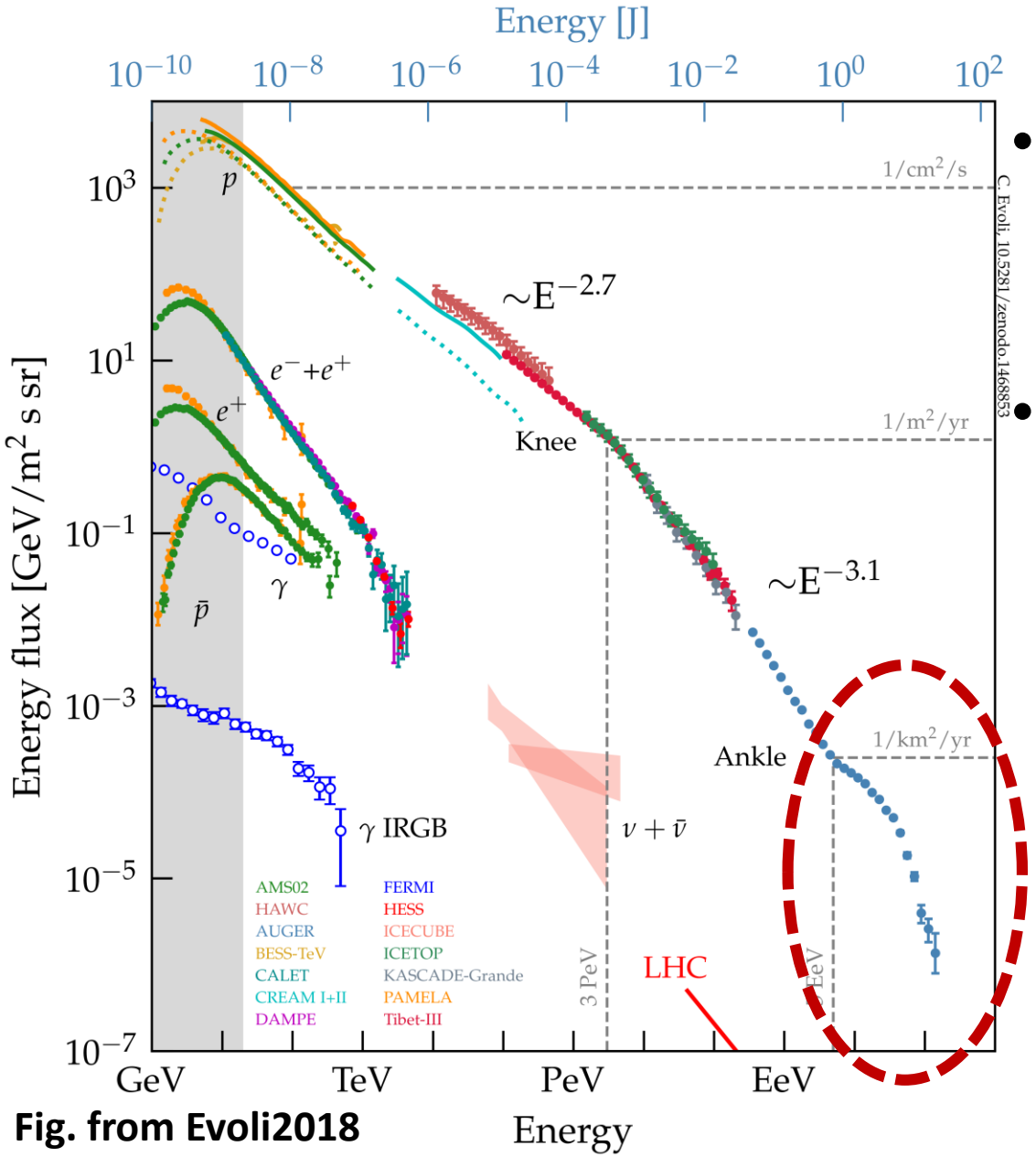

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- The Galactic magnetic field ($B \approx \mu G$) cannot confine particles of energy much larger than EeV – $r_L(EeV) \approx 1\ kpc\ B_{-6}^{-1}$

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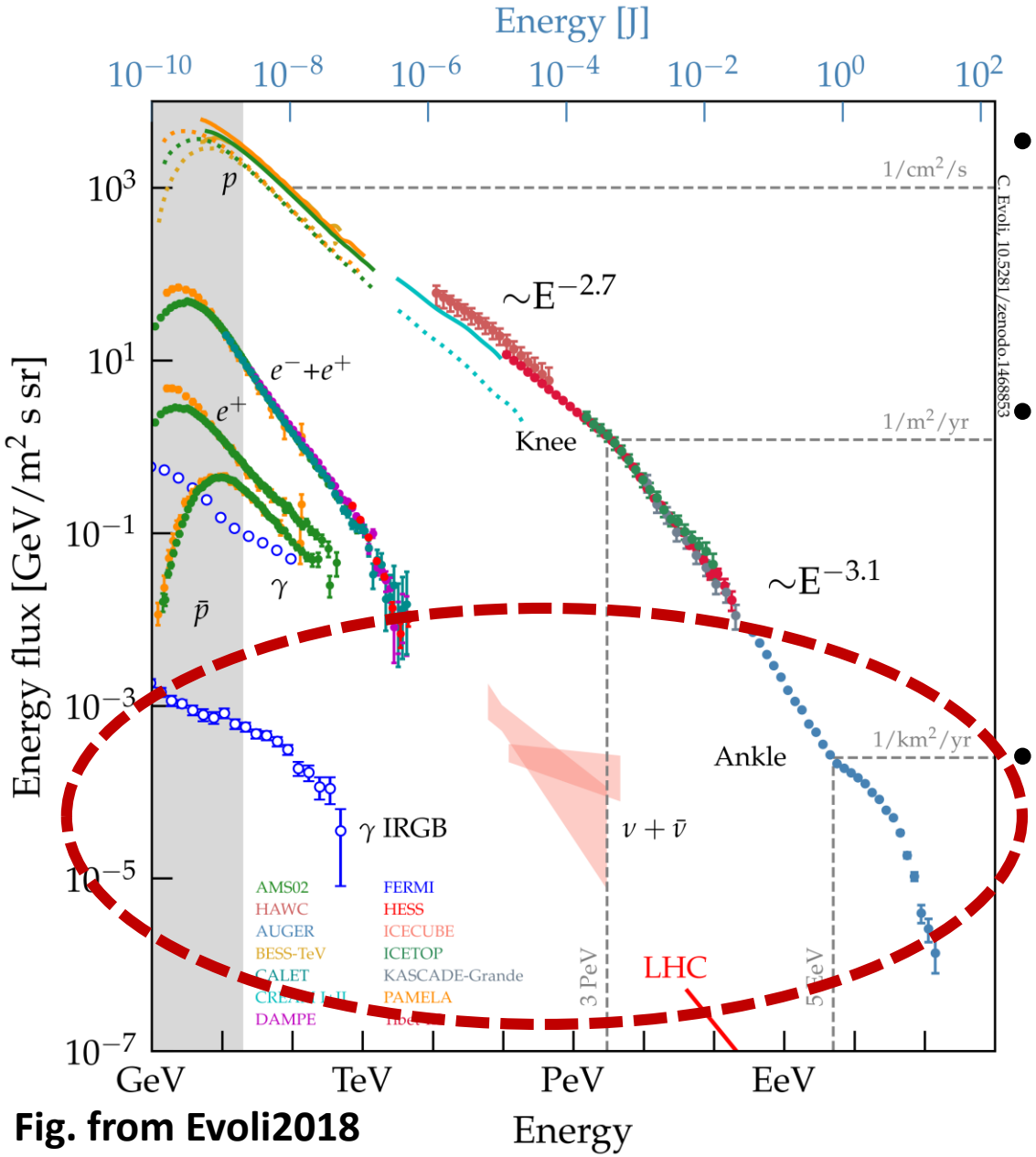

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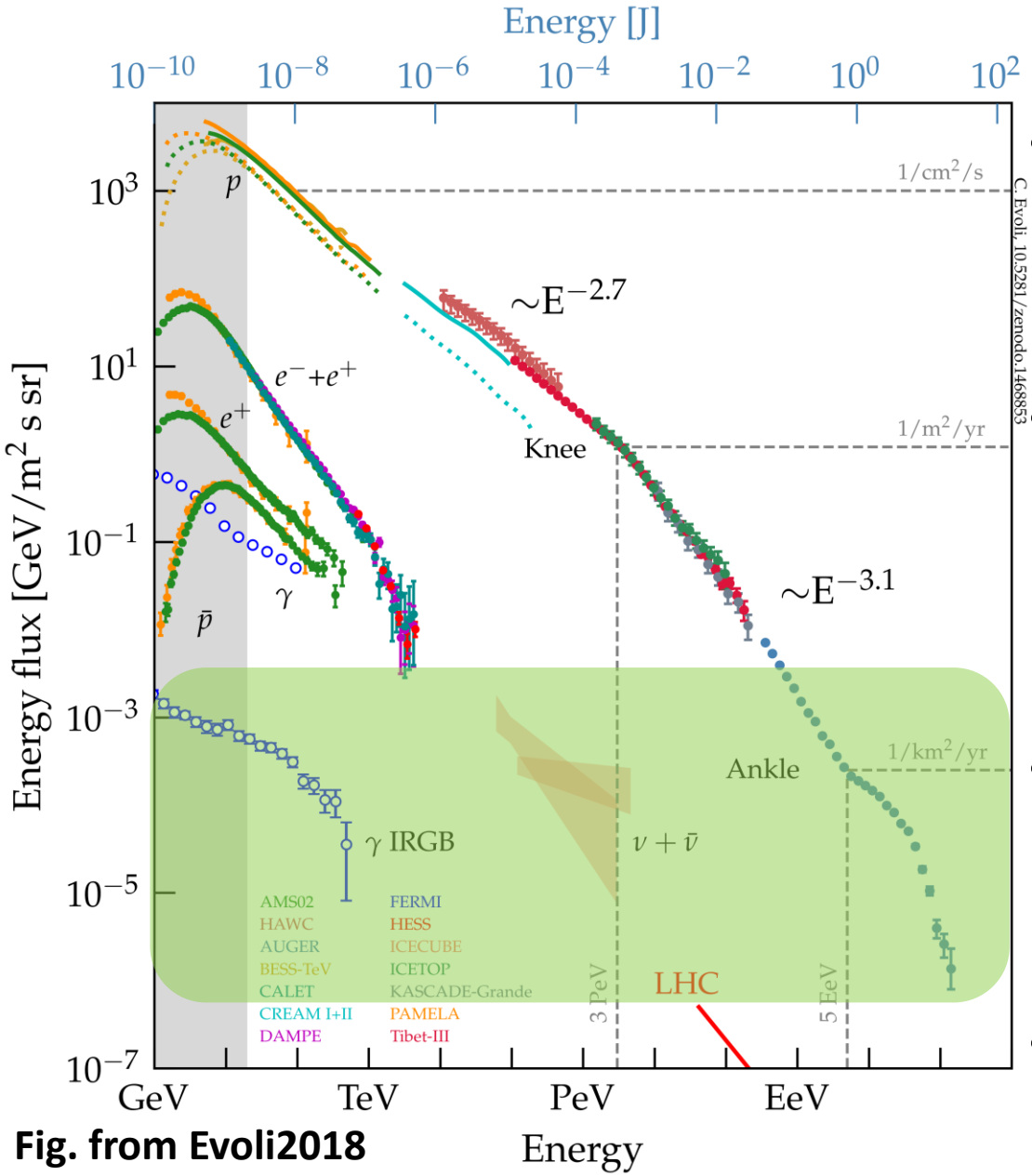

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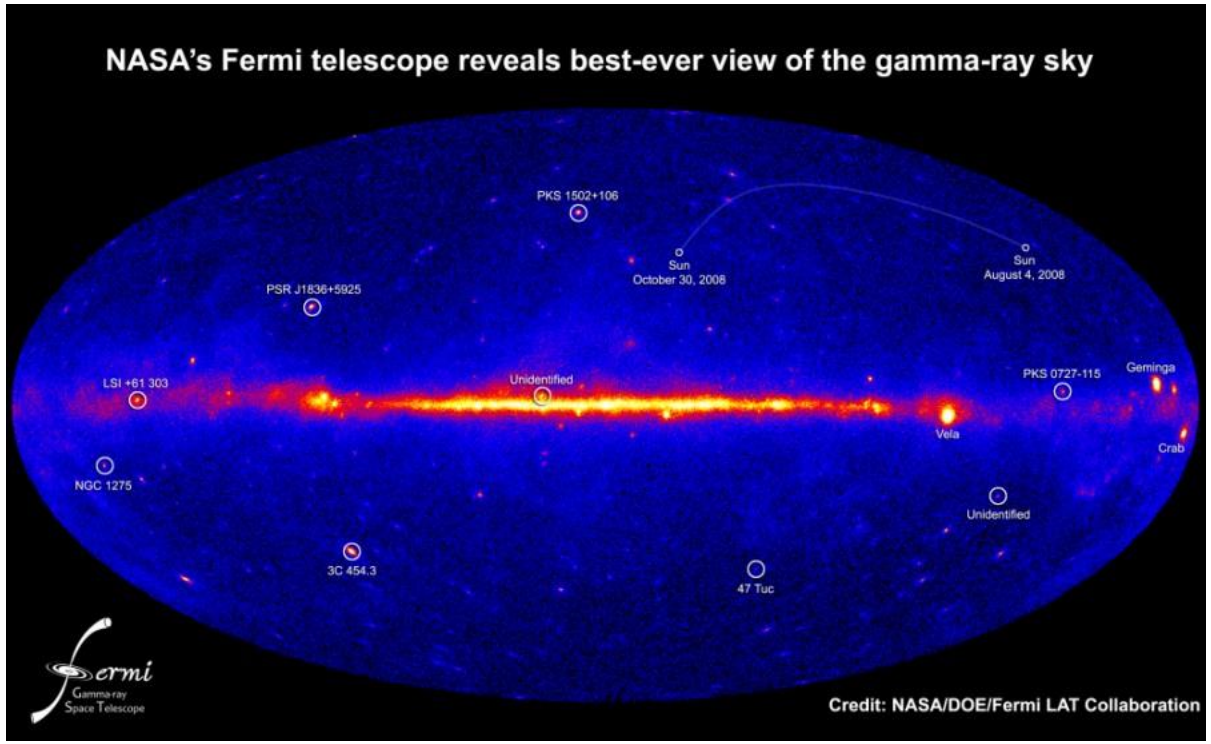
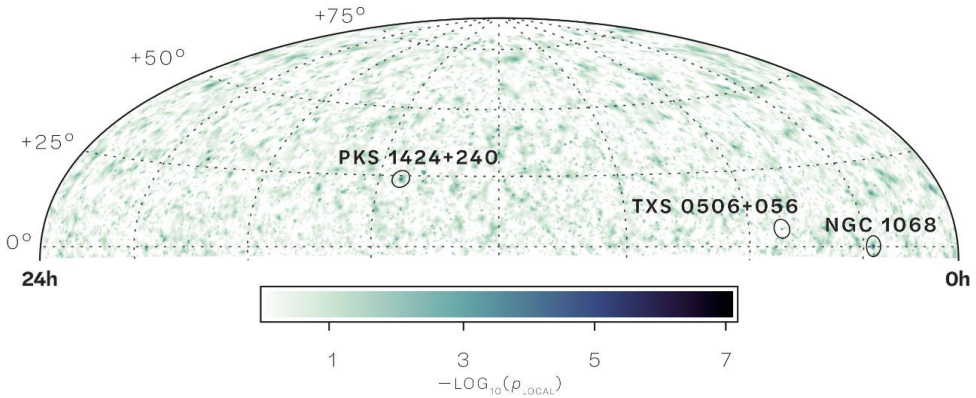
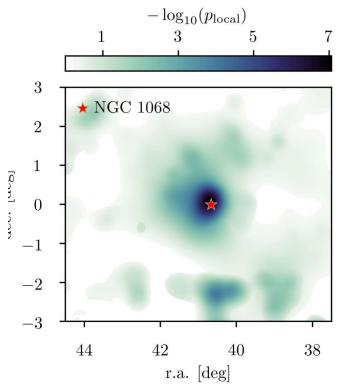
- Are they produced by a single source class?

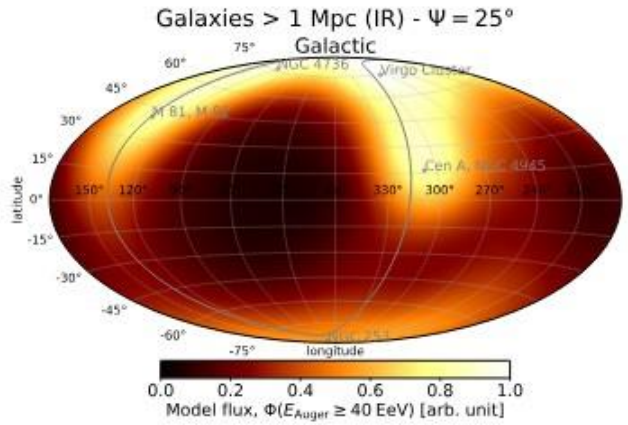
What is the origin of the most energetic multi-messenger cosmic radiation?

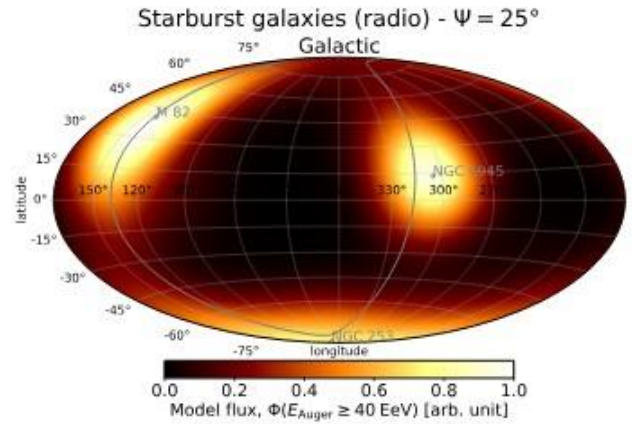
Powerful extra-galactic sources: AGN and SBGs

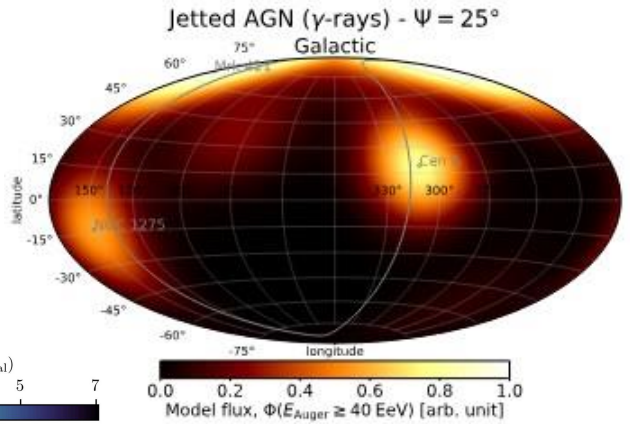


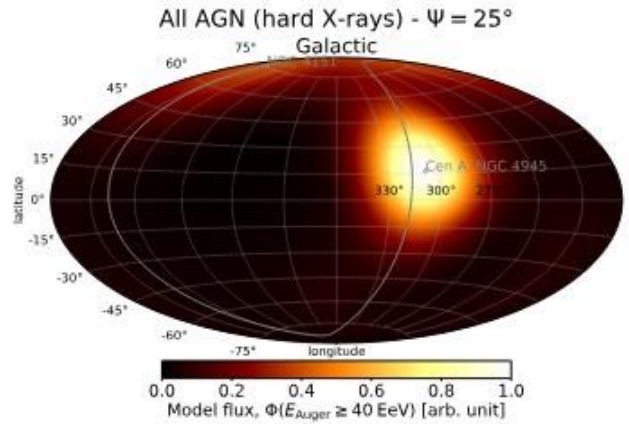










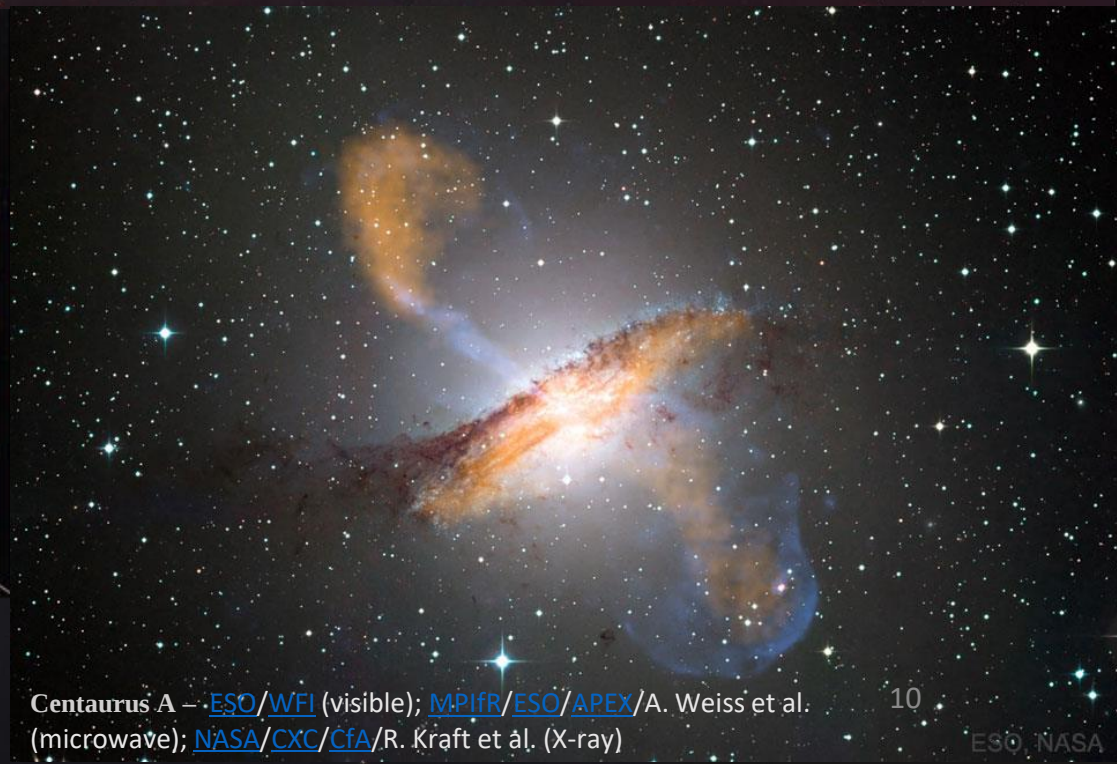


The Pierre Auger Collaboration 2022

Fig.s from (IceCube collab.), Abbasi+2022

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

Hubble



Centaurus A – ESO/WFI (visible); MPIfR/ESO/APEX/A. Weiss et al. (microwave); NASA/CXC/CfA/R. Kraft et al. (X-ray)

ESO, NASA

Non-Jetted AGN

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Active Galaxies

Starburst Galaxy

Hubble

Jetted AGN

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- Several sites with shocks
- Gas acting as target material

Starburst Galaxy

Hubble

- Several sites with shocks
- Strong radiation fields
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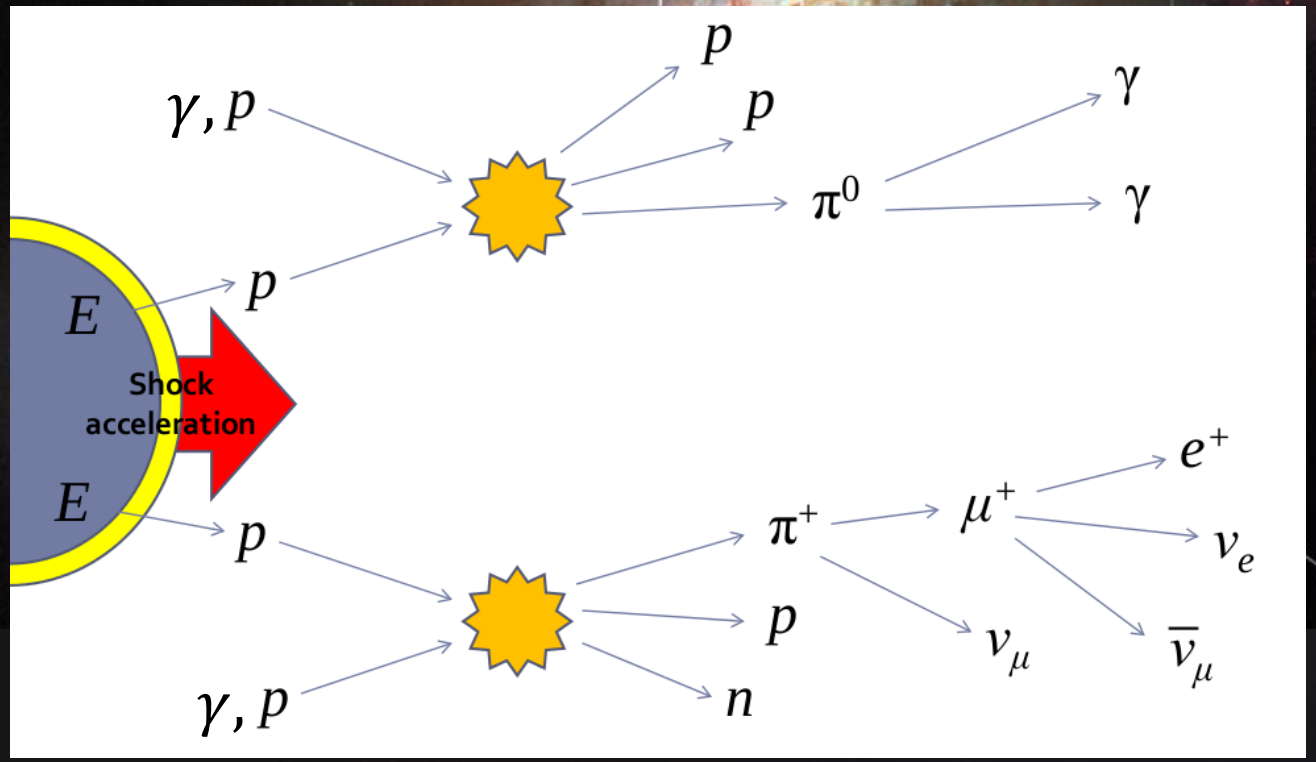

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ESO, NASA

Outline

- Starburst nulei
- Starburst and AGN winds
- AGN coronae
- Multi-messenger diffuse flux

STARBURST NUCLEI

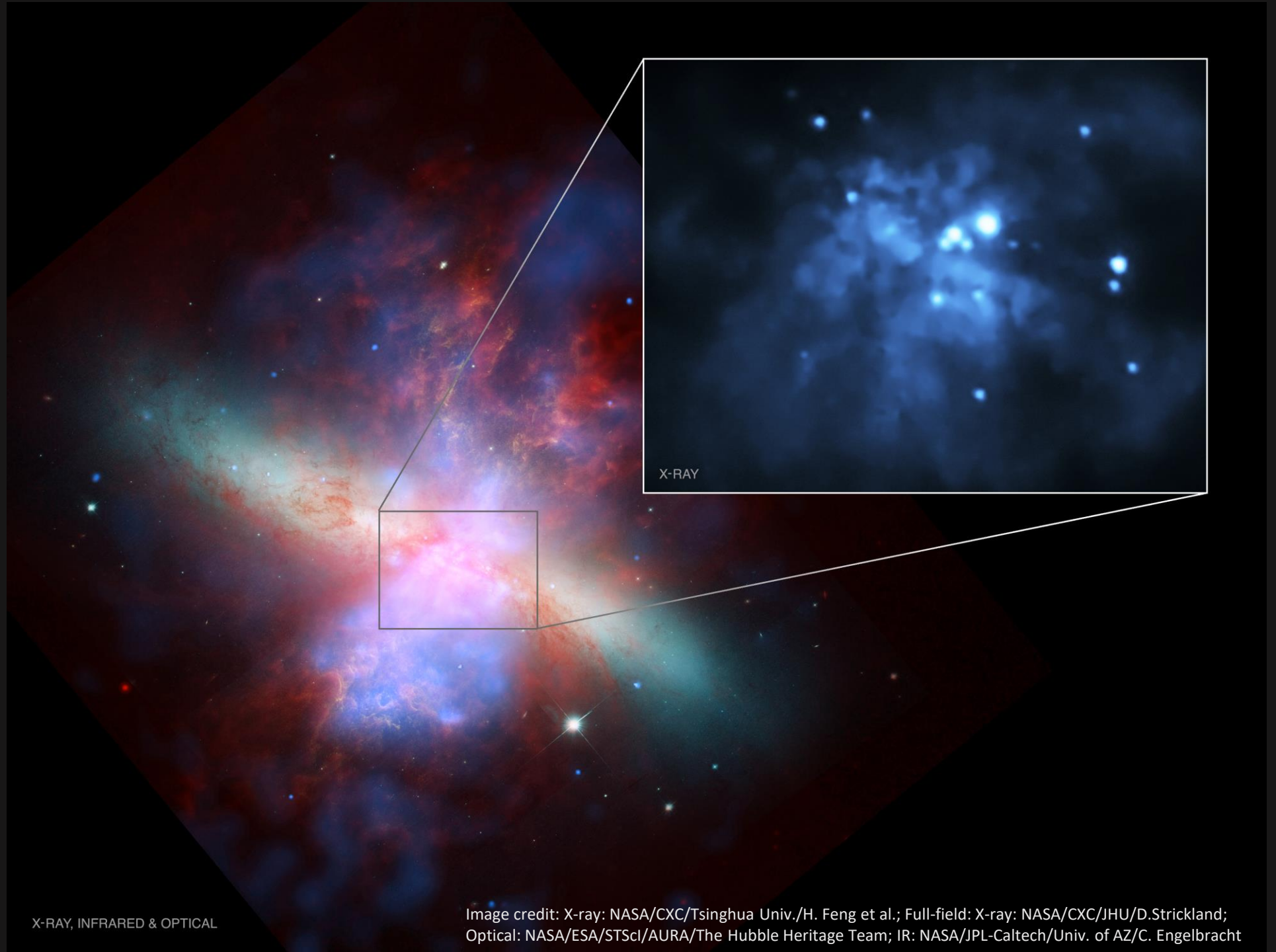
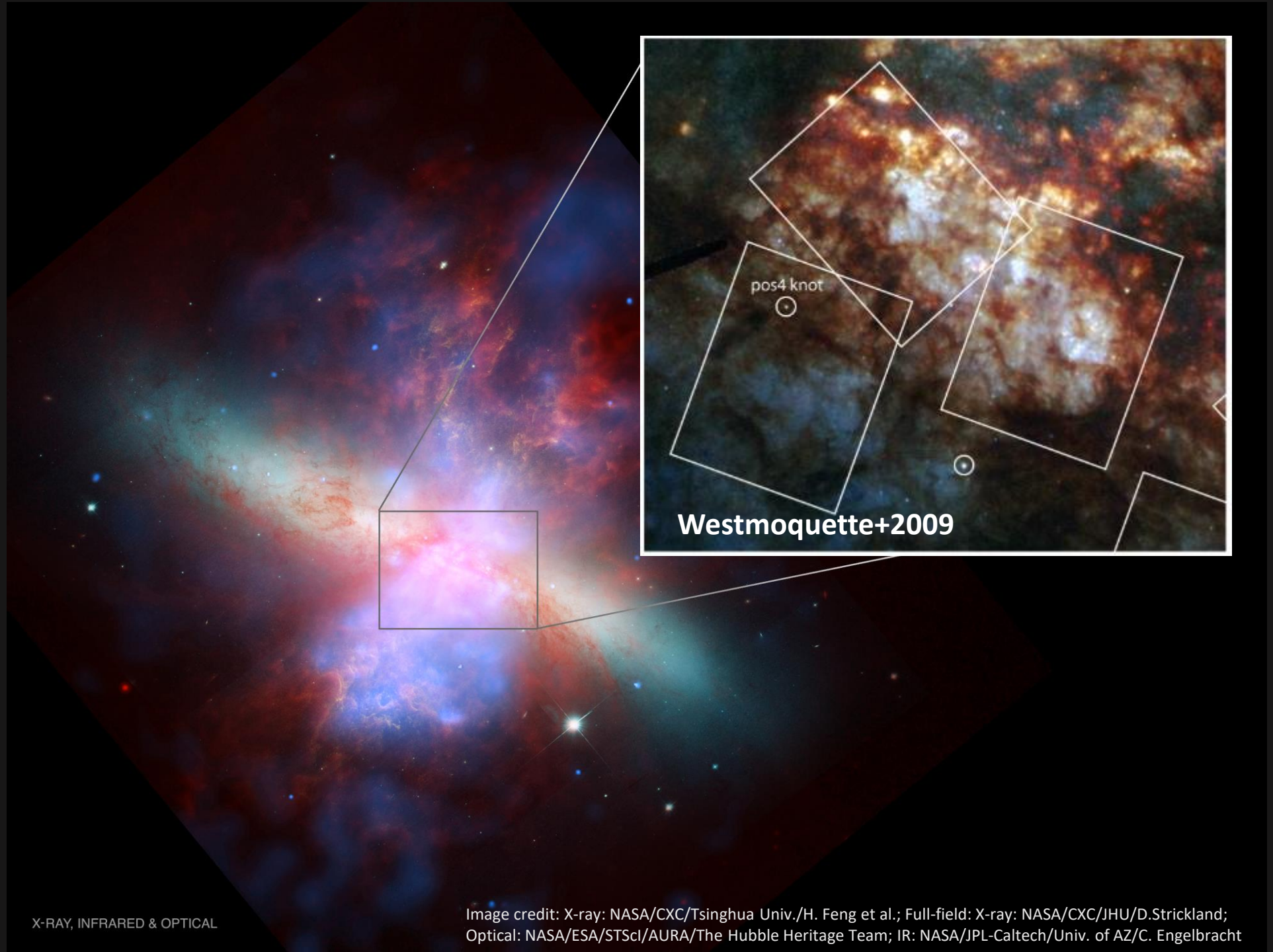


Image credit: X-ray: NASA/CXC/Tsinghua Univ./H. Feng et al.; Full-field: X-ray: NASA/CXC/JHU/D.Strickland; Optical: NASA/ESA/STScI/AURA/The Hubble Heritage Team; IR: NASA/JPL-Caltech/Univ. of AZ/C. Engelbracht



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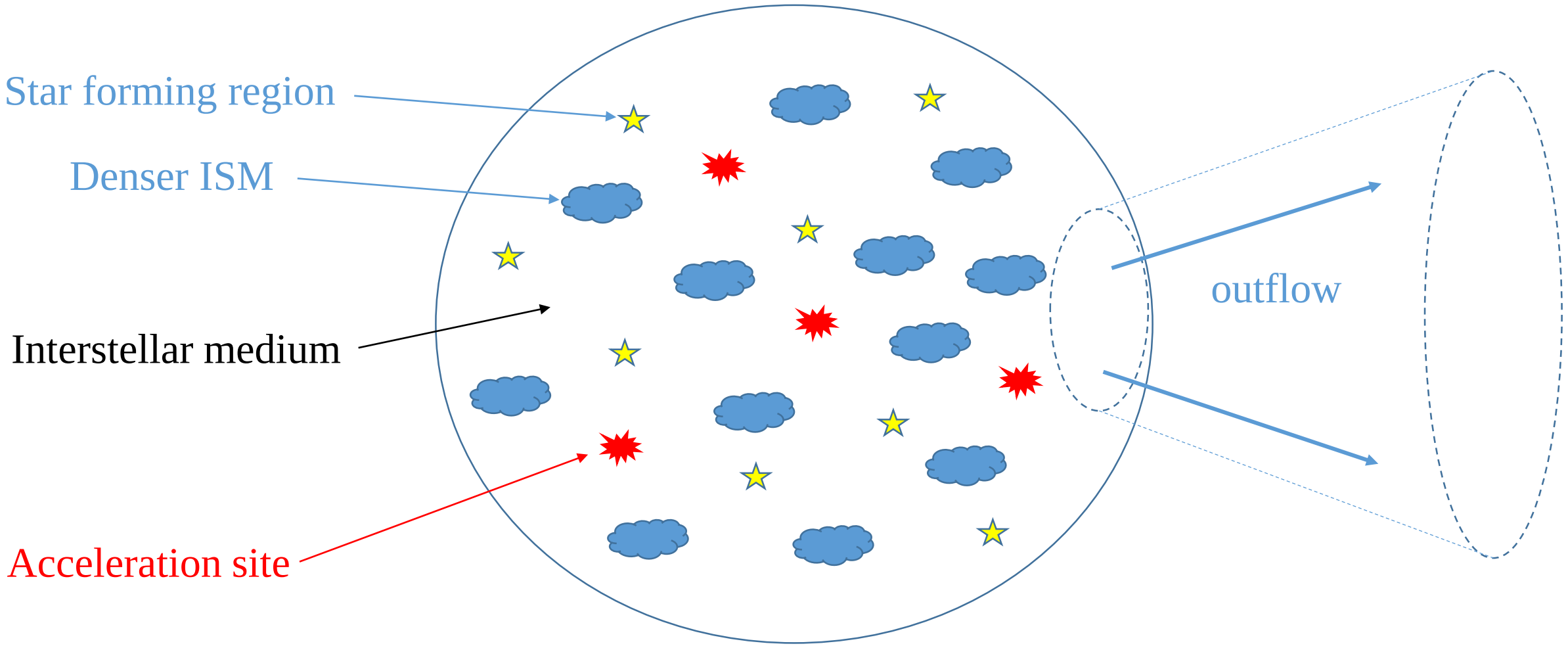
Particle transport in starburst nuclei



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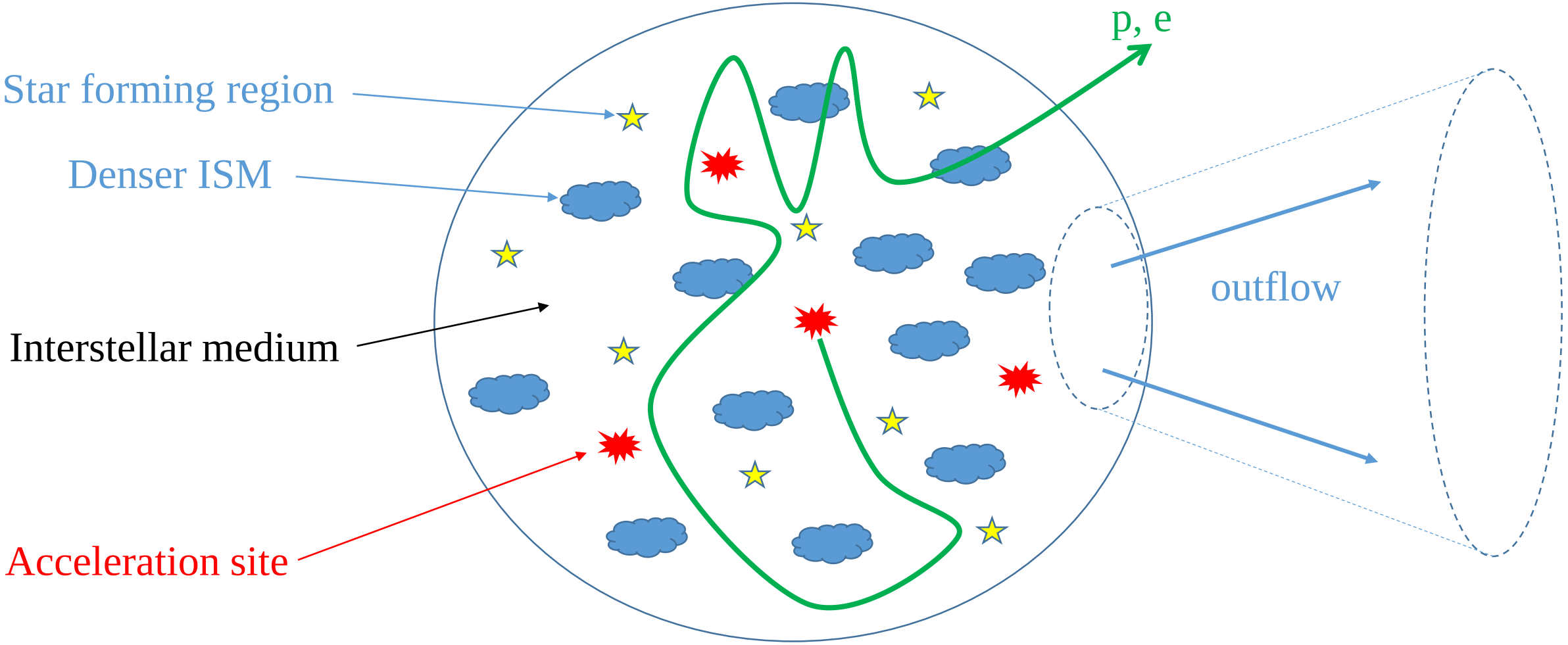

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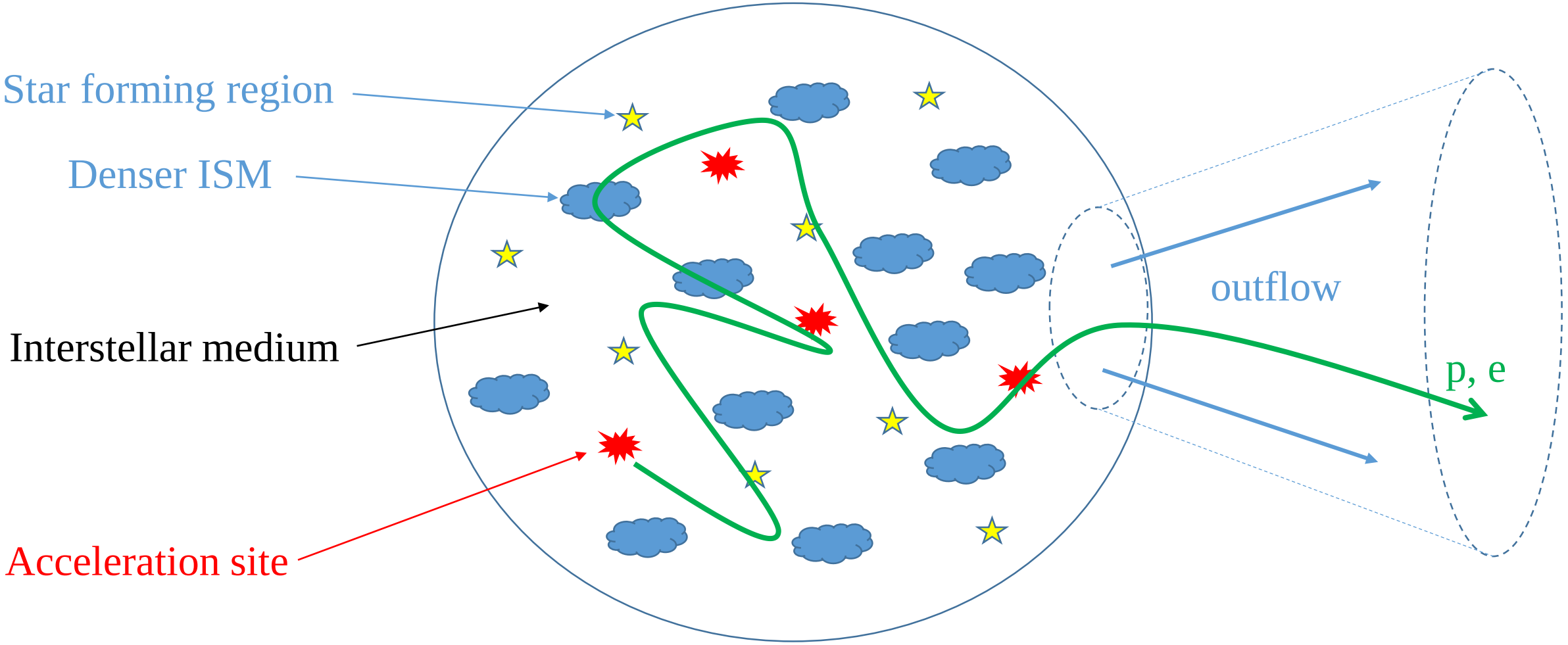

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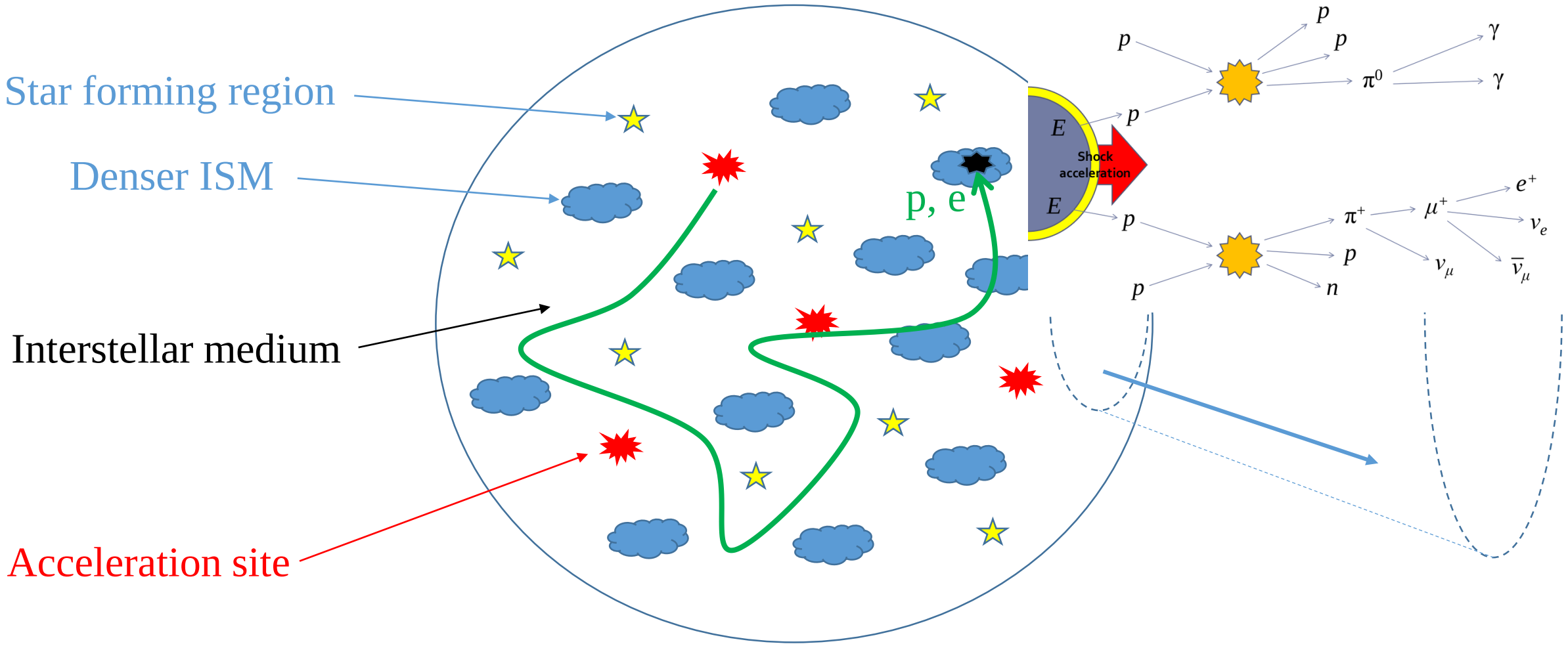
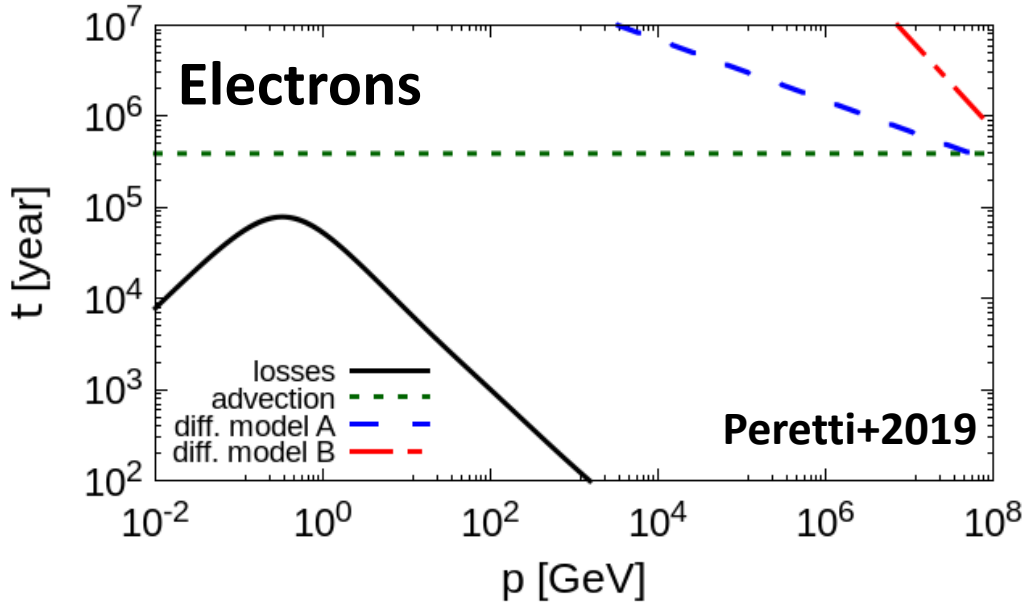
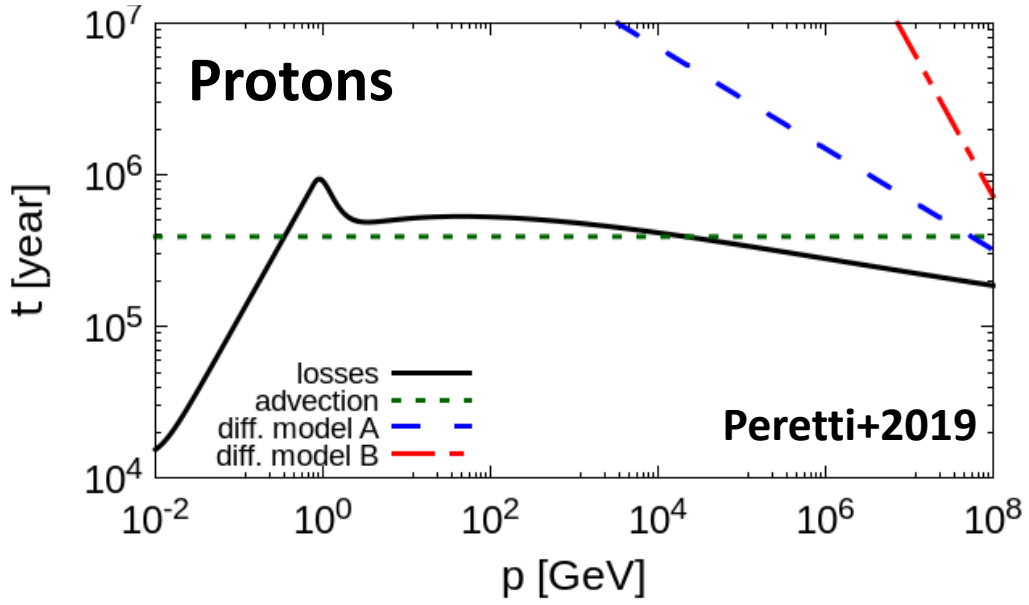


Modeling the transport in SBNi





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

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

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

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

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

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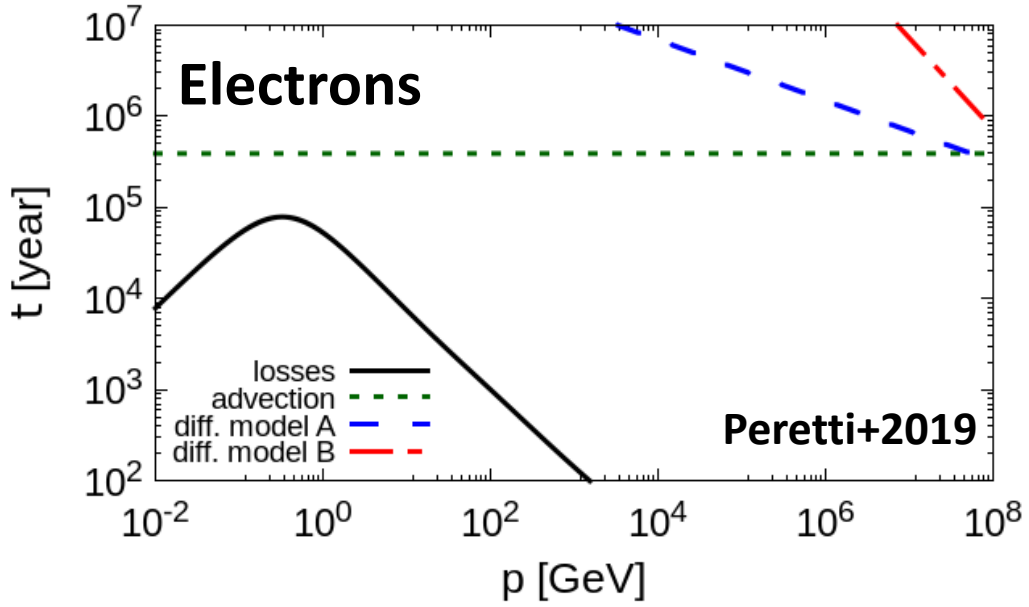

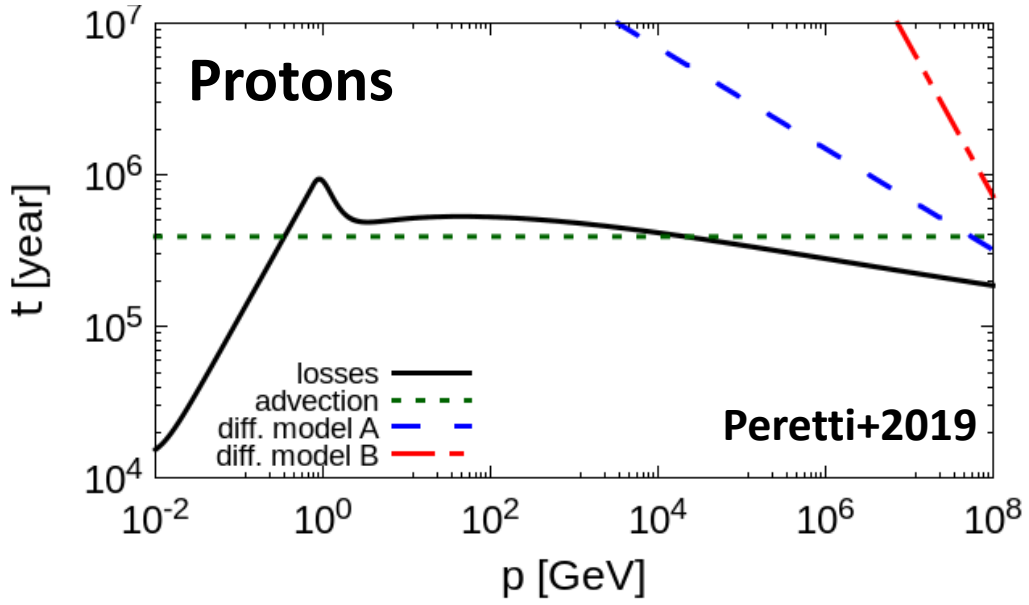

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$$D(p) \approx \frac{c}{3}\, r_L^{2-\delta}\, l_c^{\delta-1}$$

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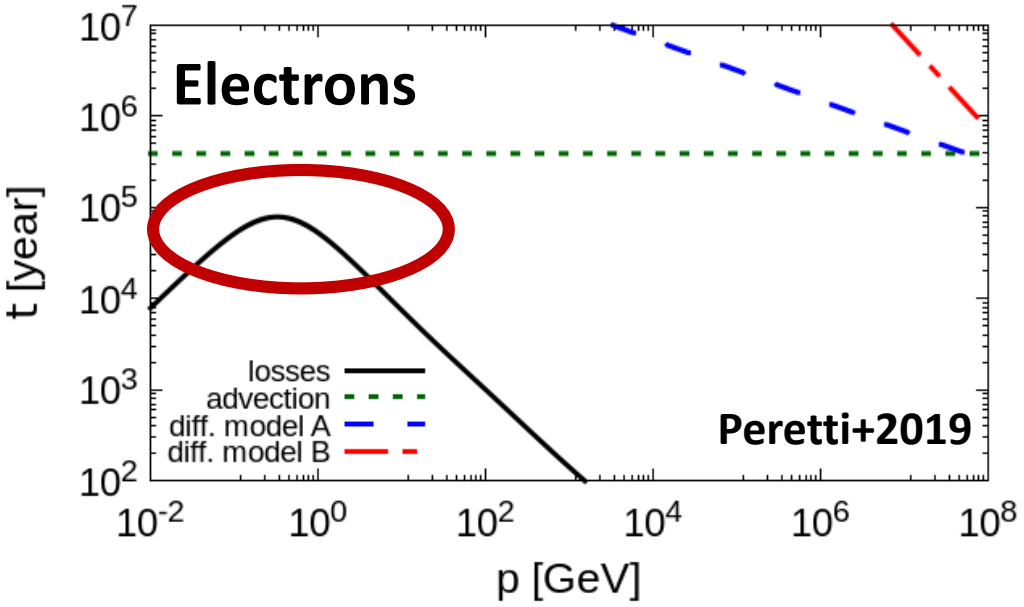
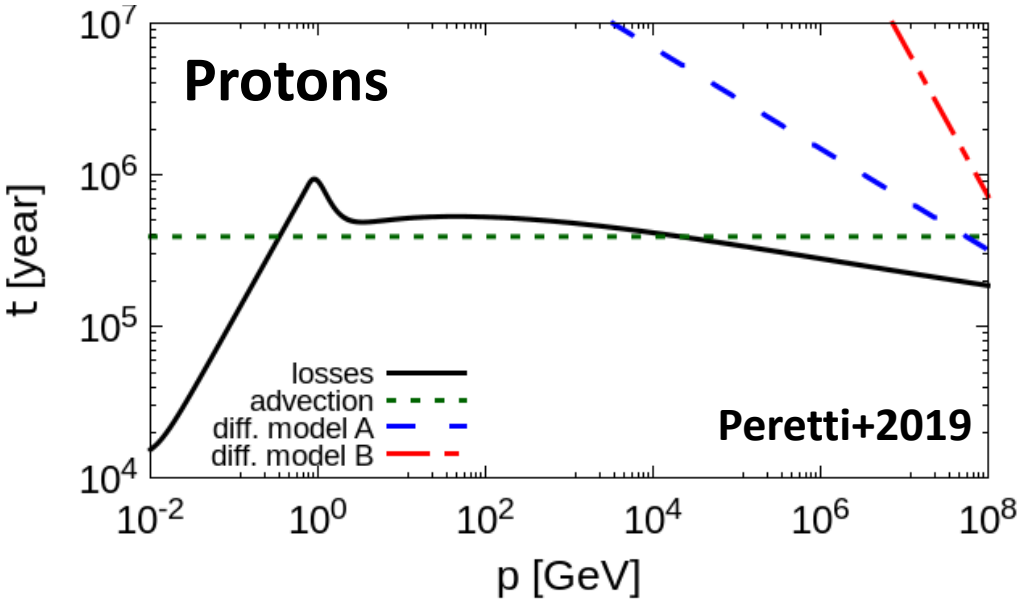
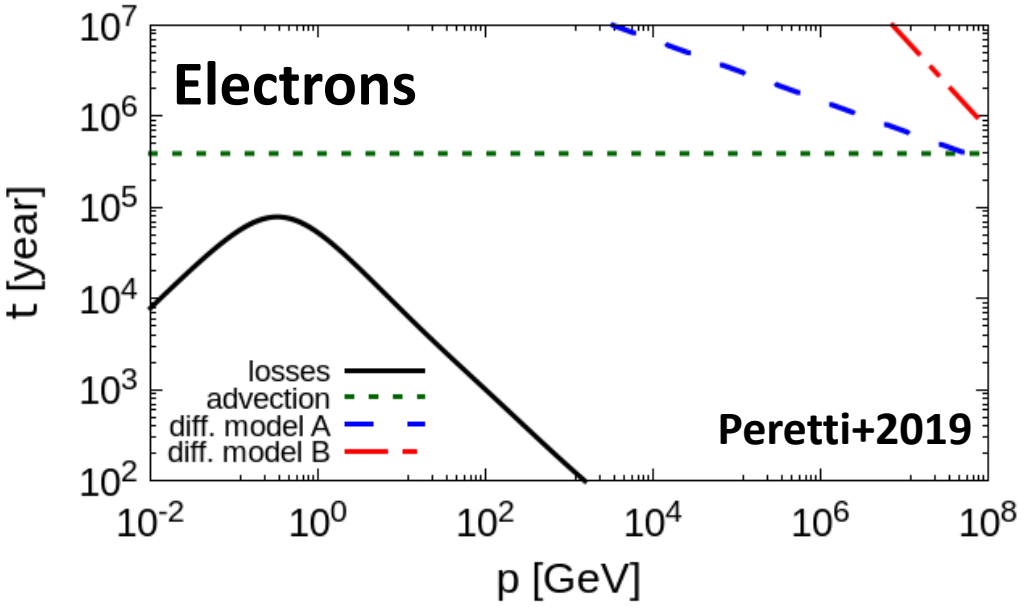
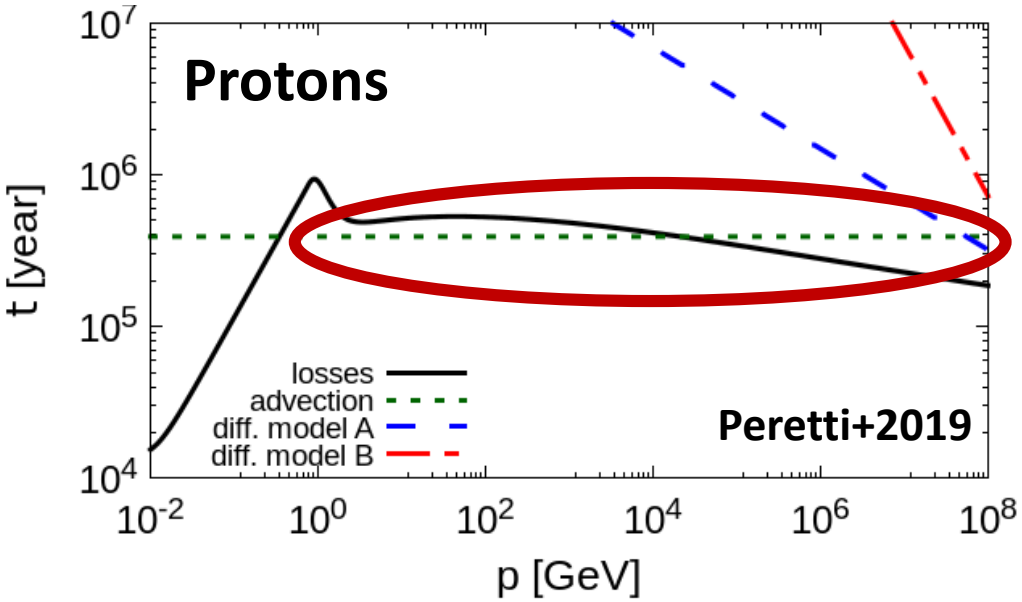




- Electrons are confined in SBNi

Modeling the transport in SBNi





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

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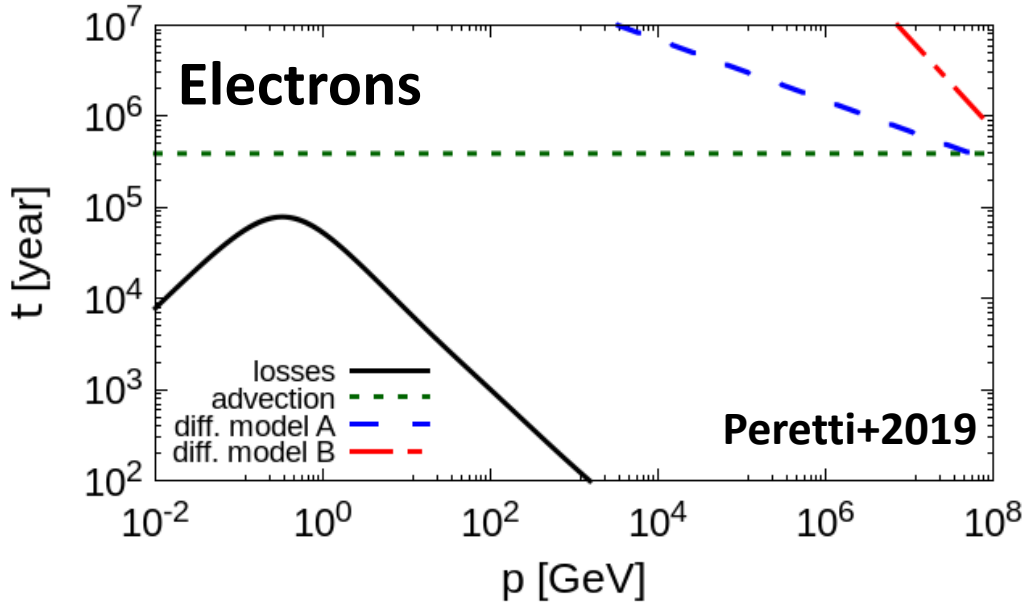
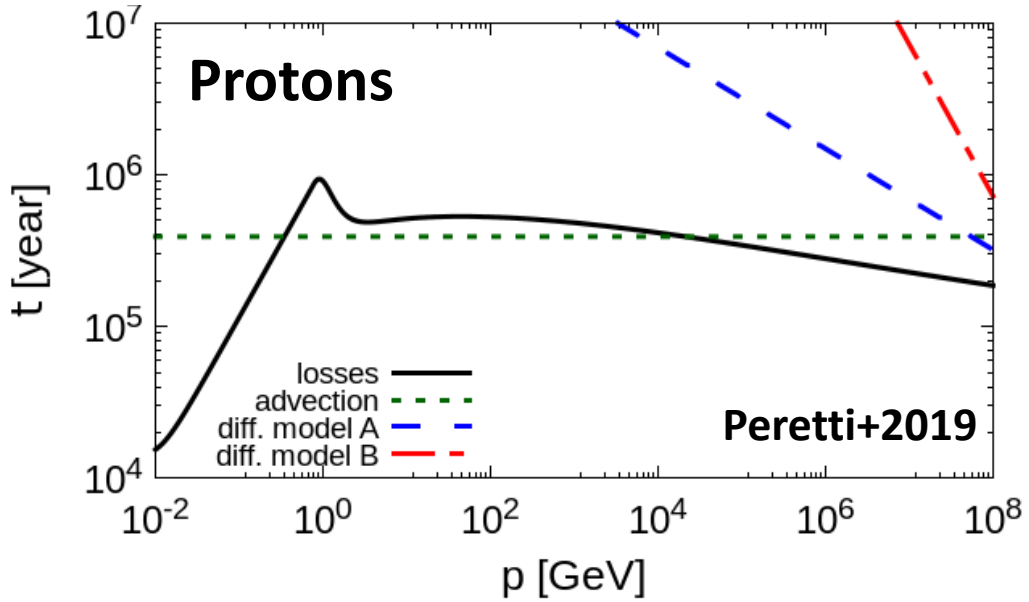
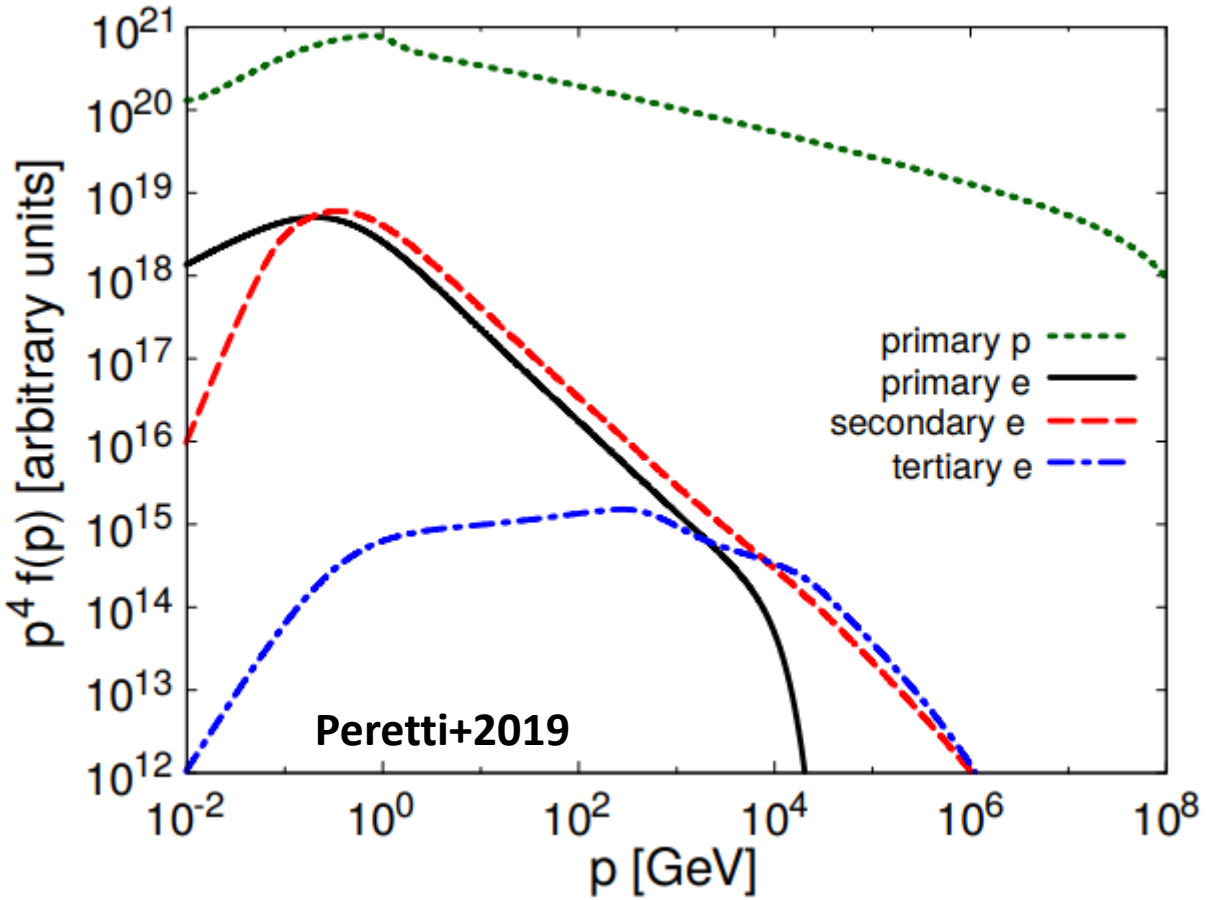


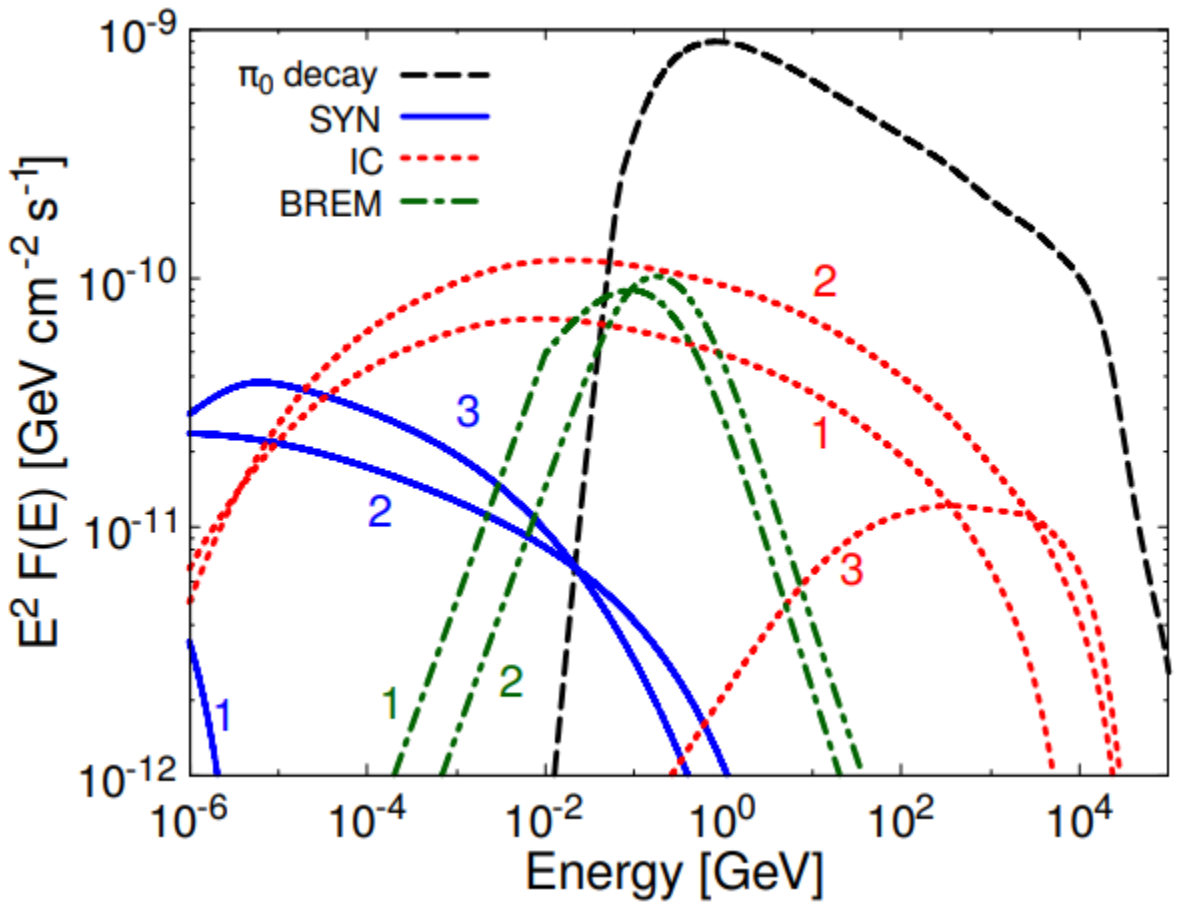


- Electrons are confined in SBNi
- Advection and losses regulate the transport of protons
- Particles experience all phases of the ISM

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

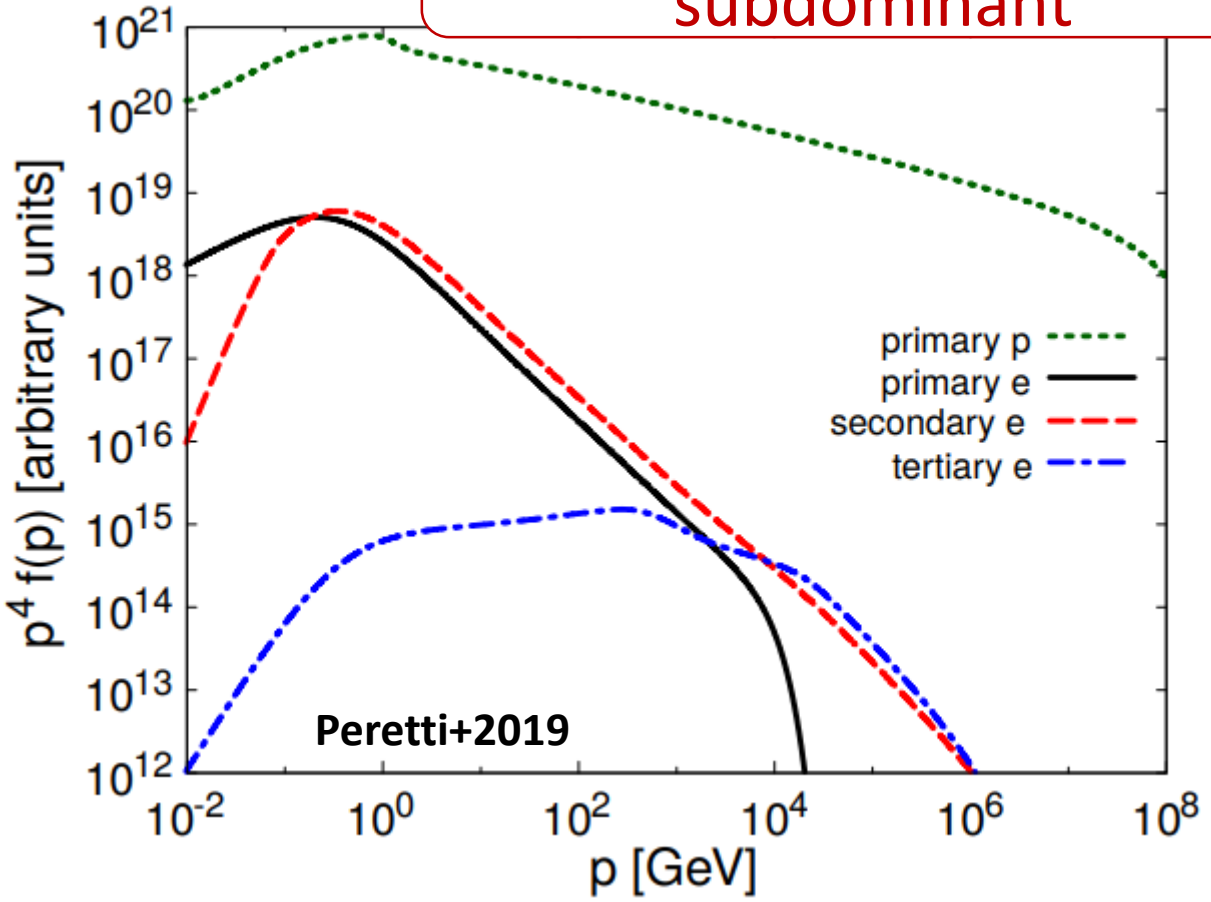
Particle and photon spectra in SBNi

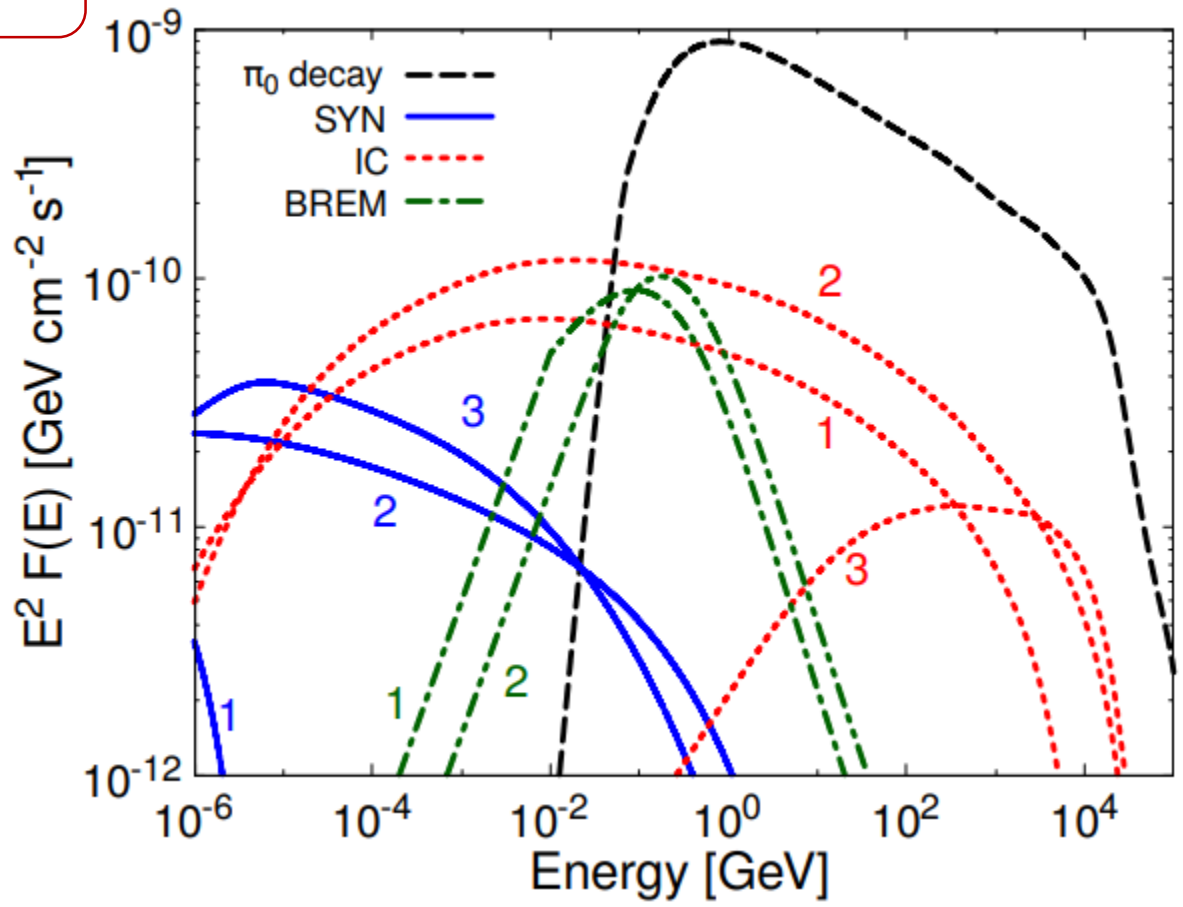




Particle and photon spectra in SBNi

Particle diffusion is subdominant





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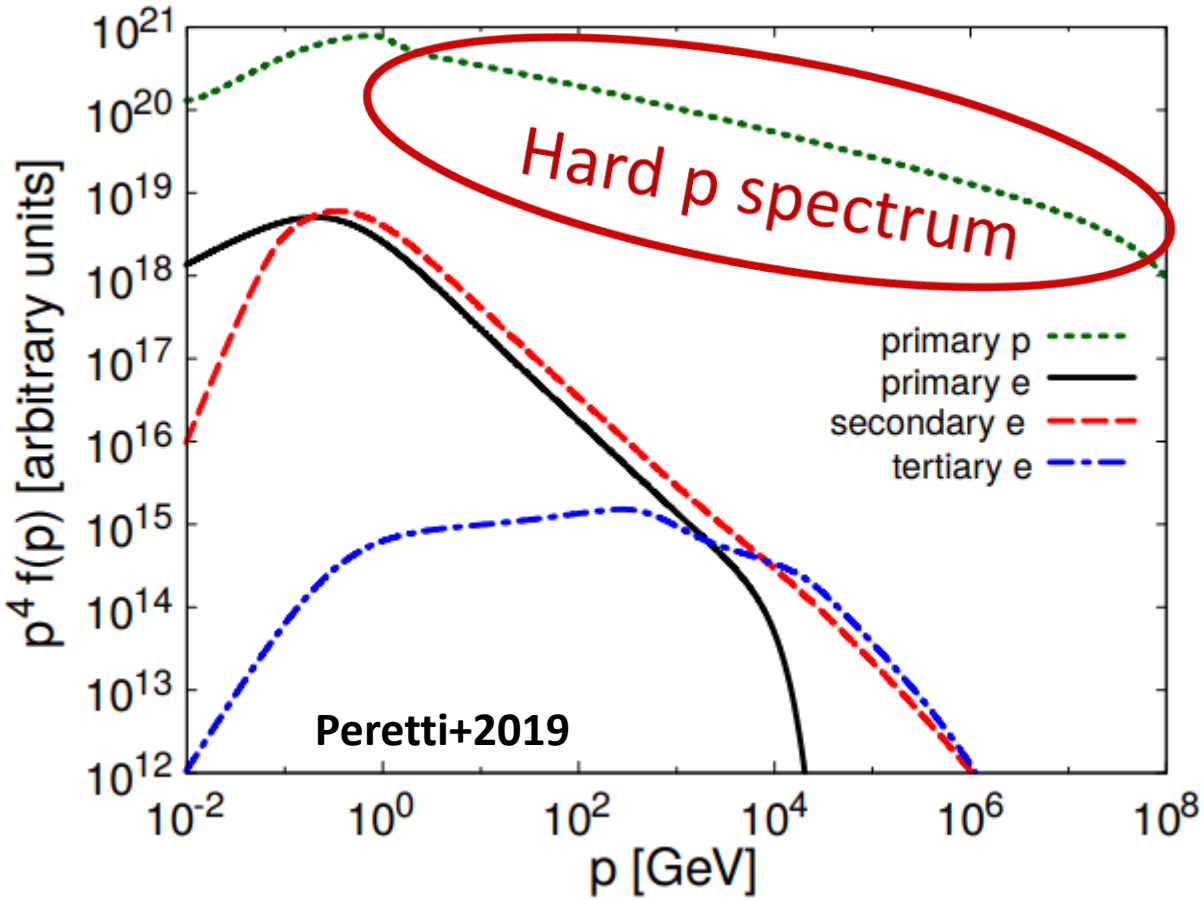

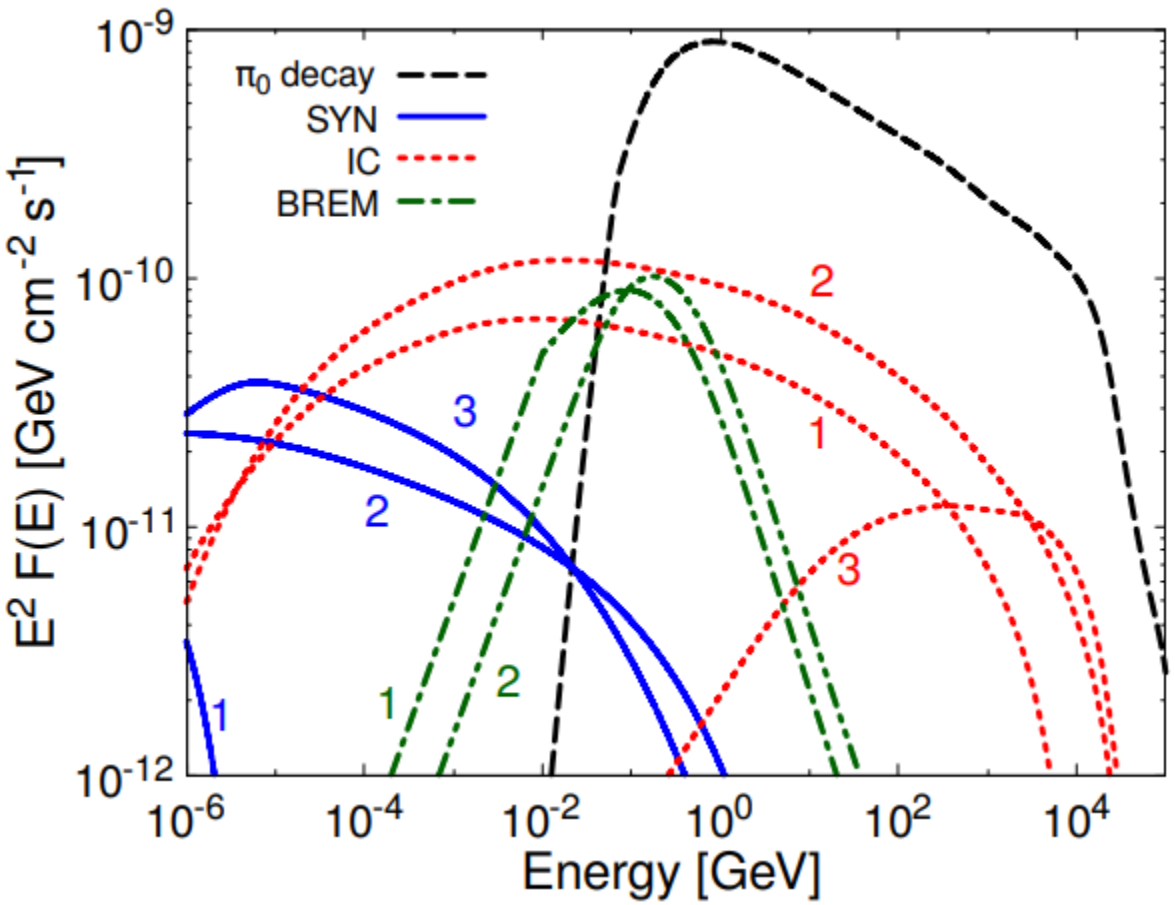

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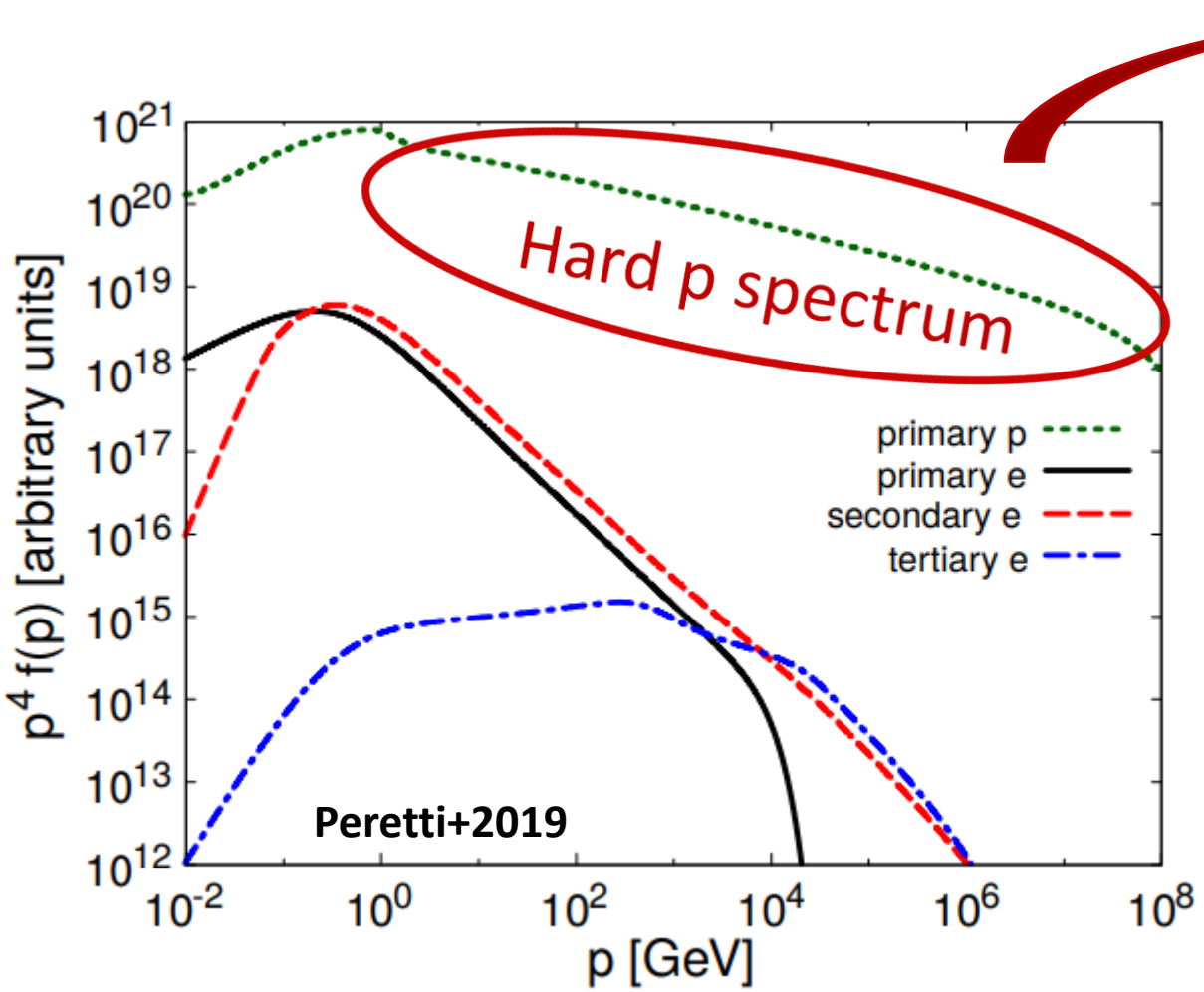
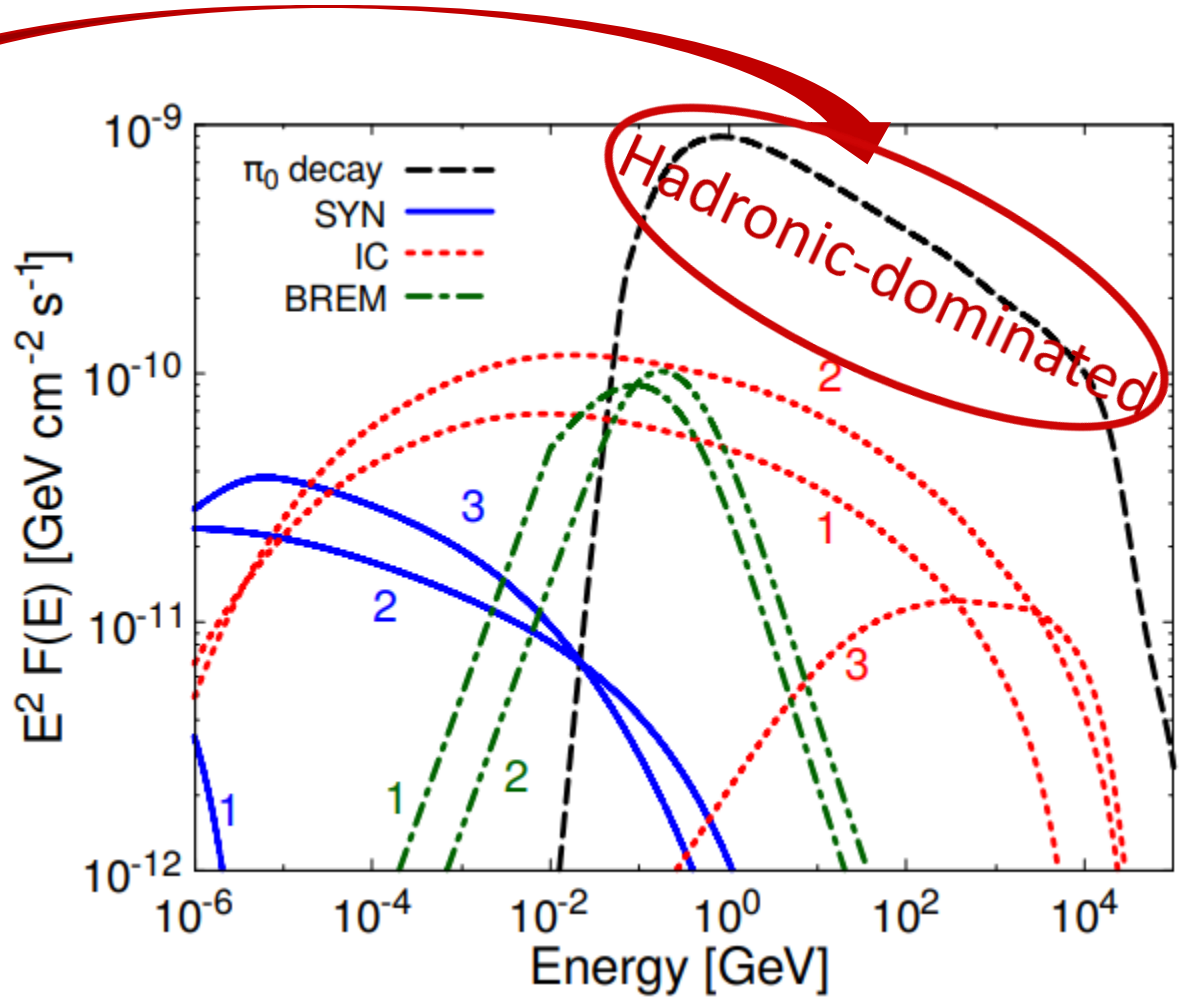
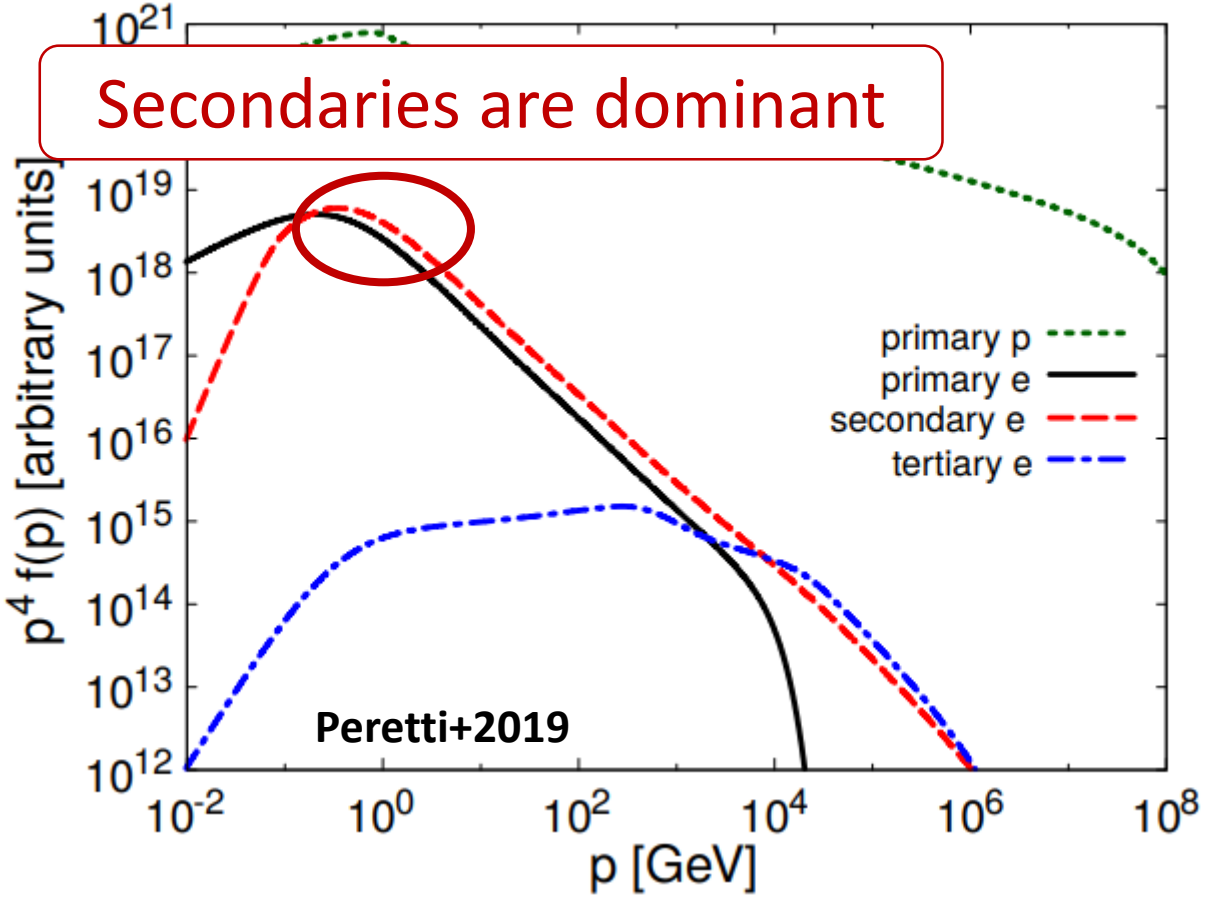
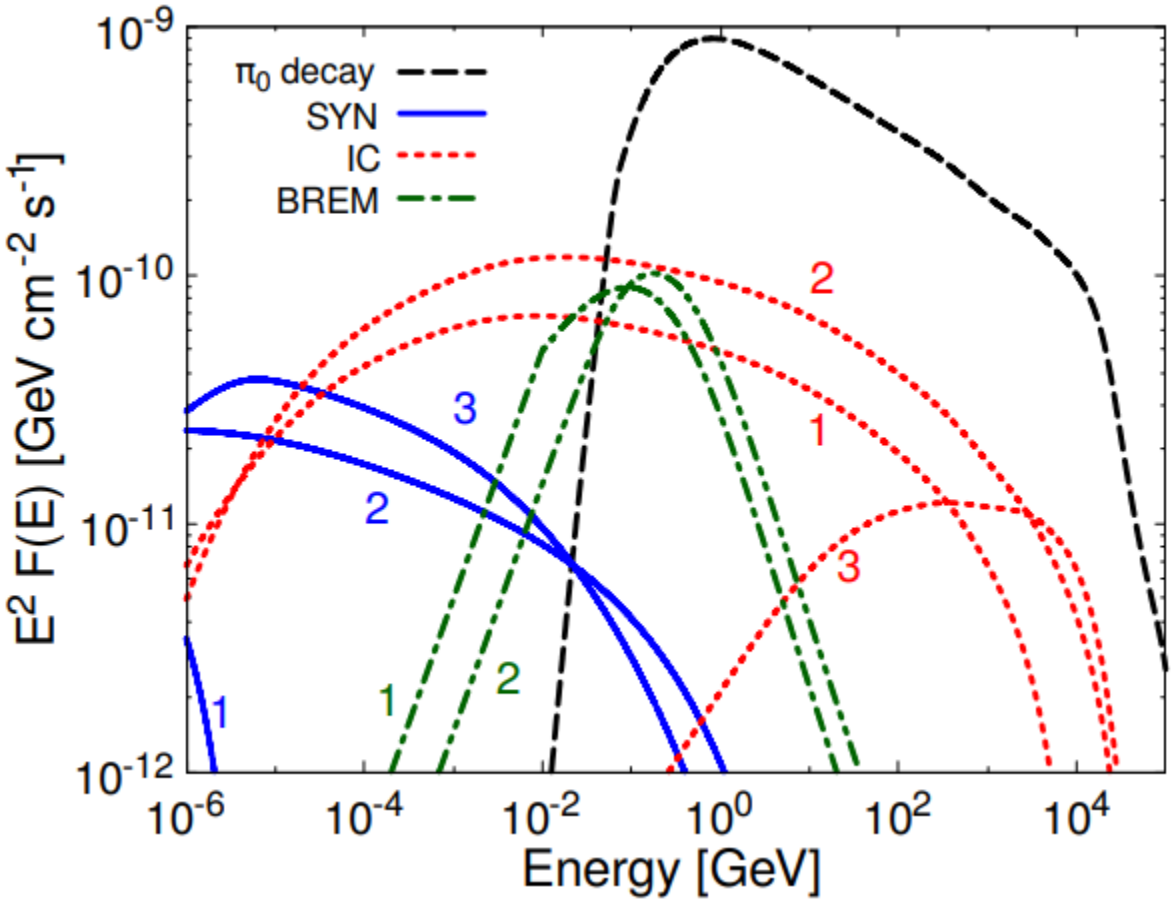




Particle and photon spectra in SBNi

Secondaries are dominant





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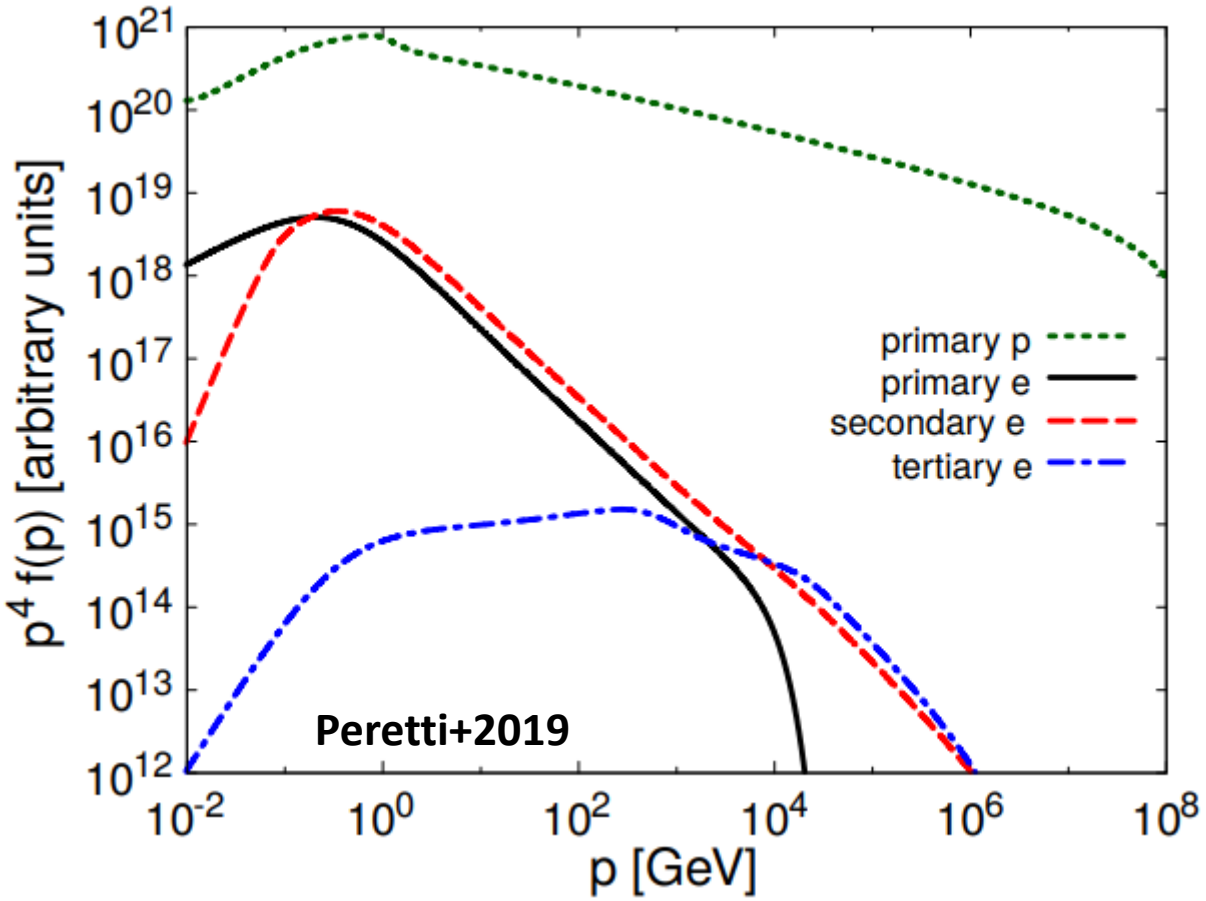

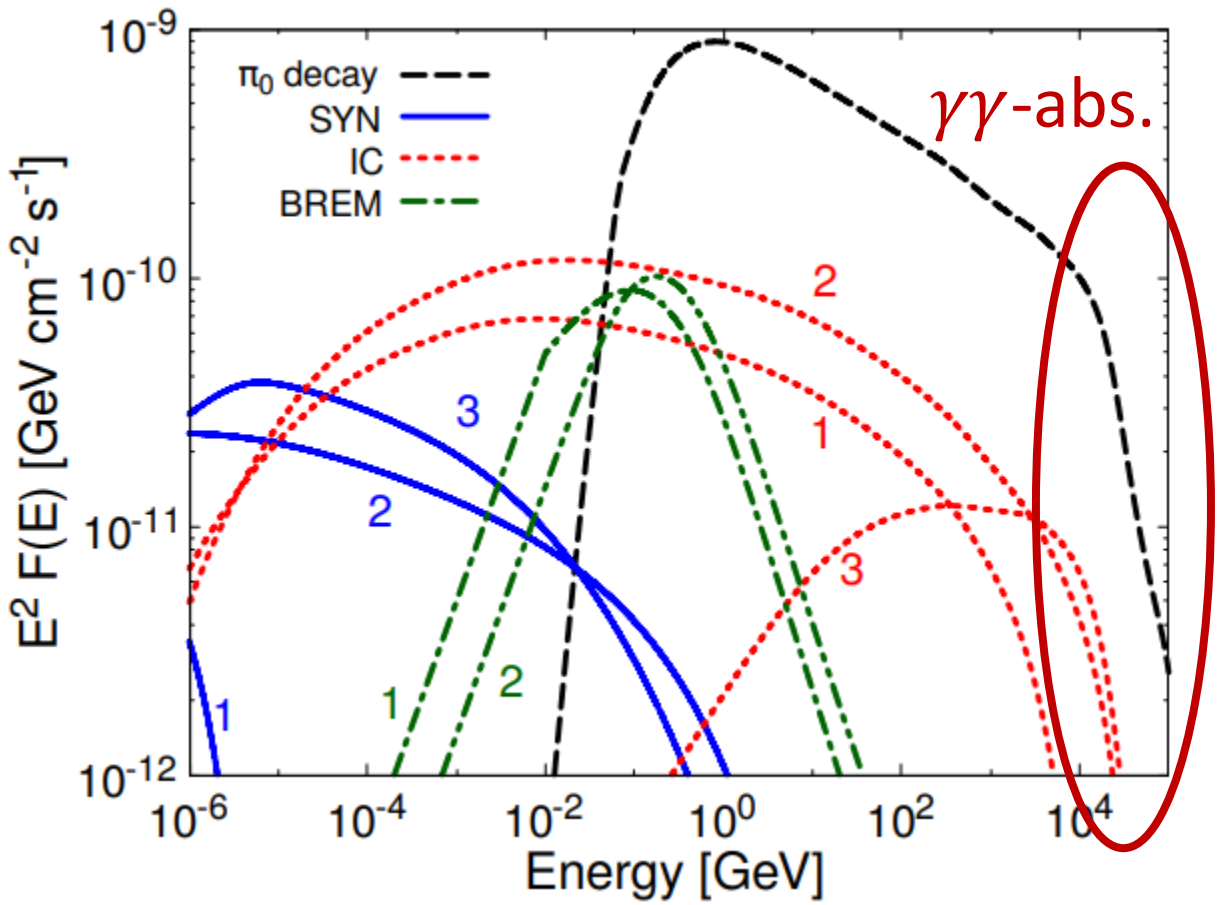

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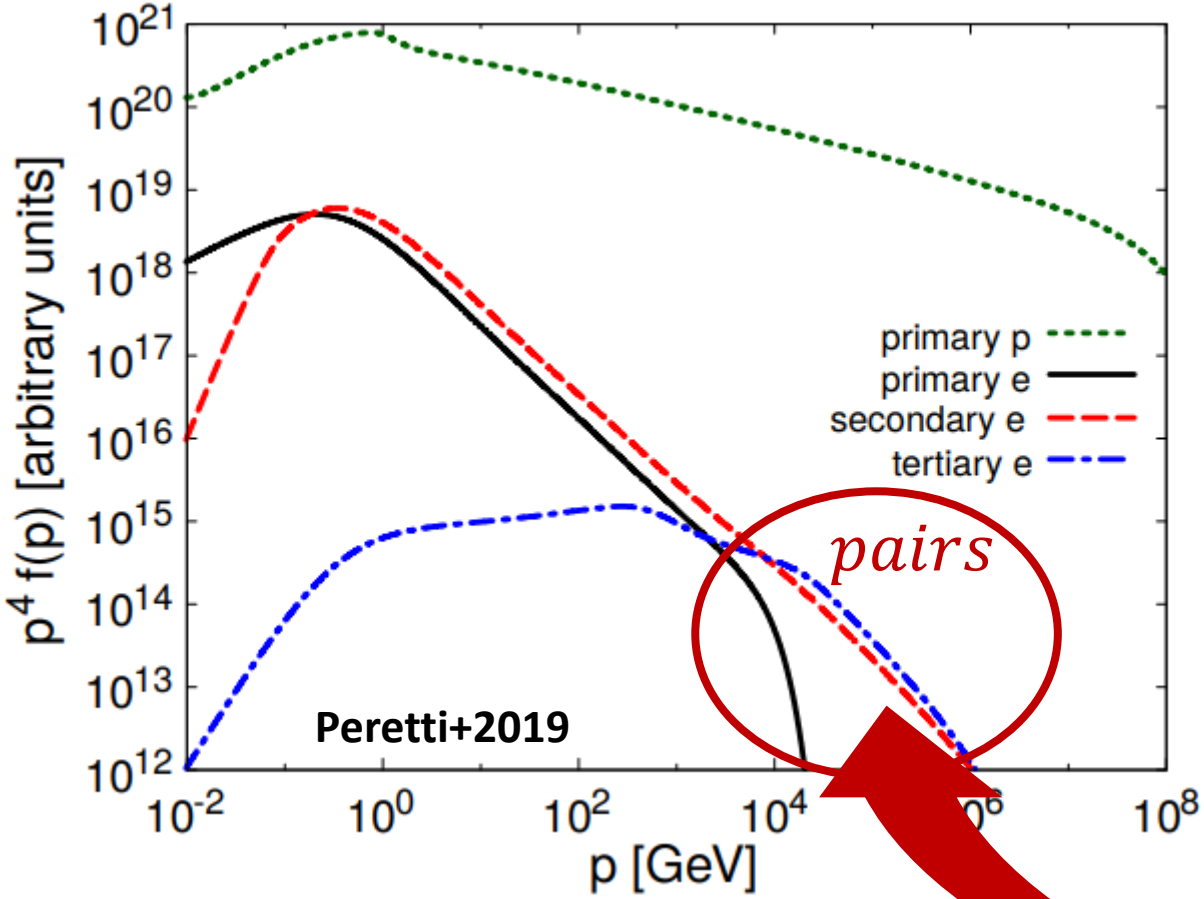

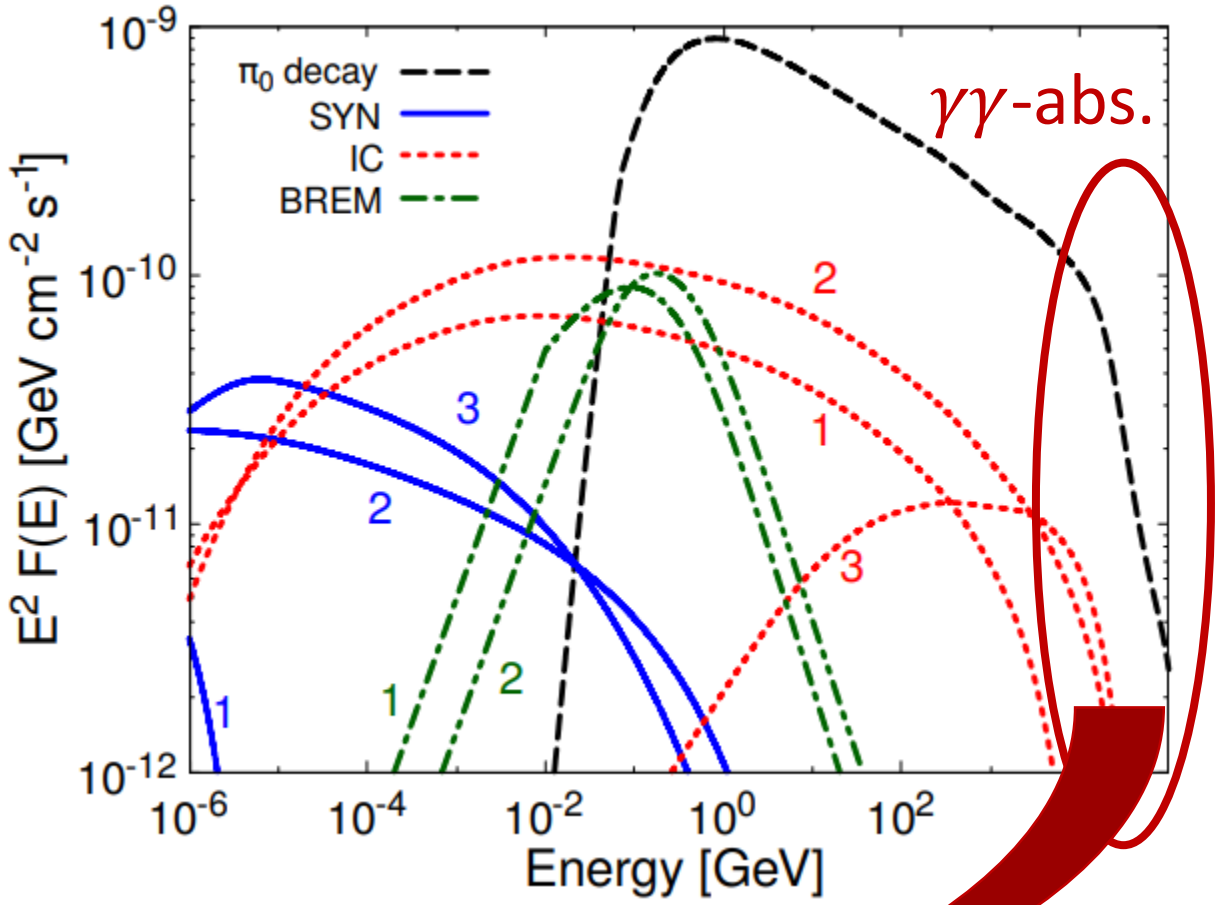

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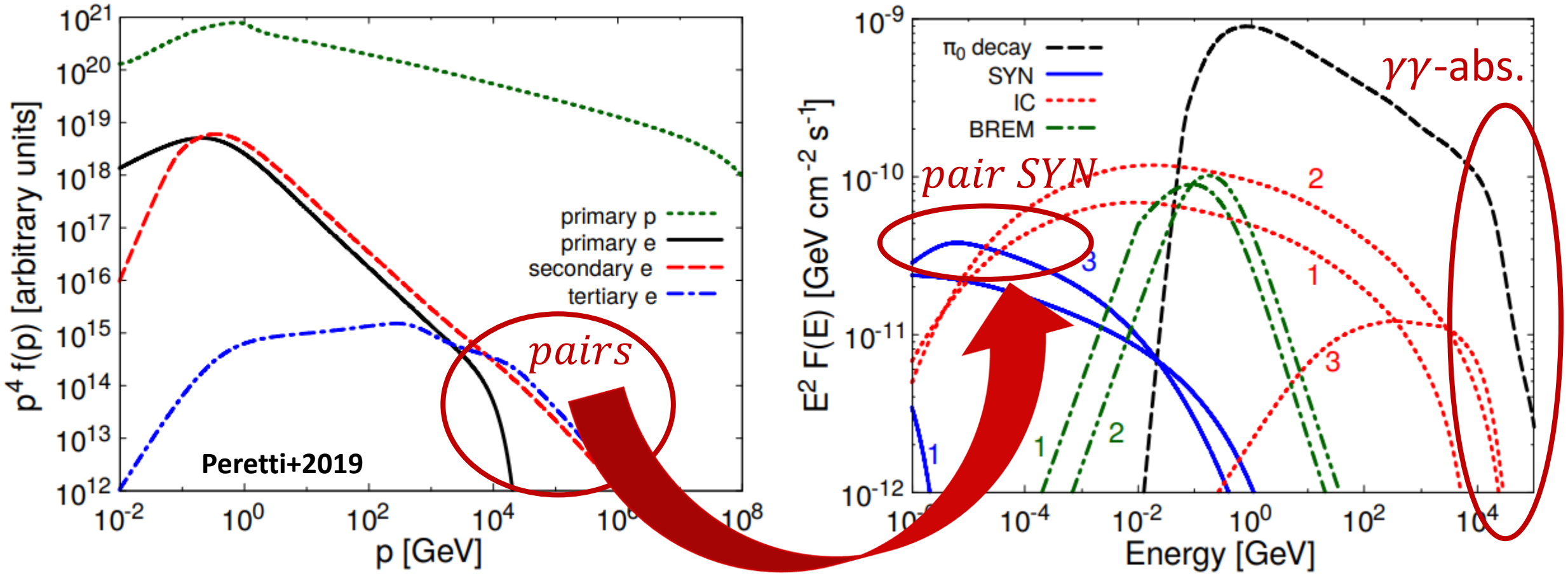
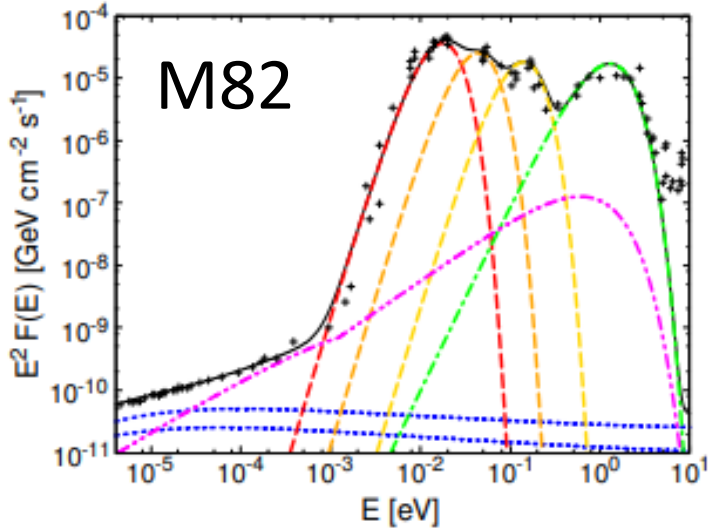
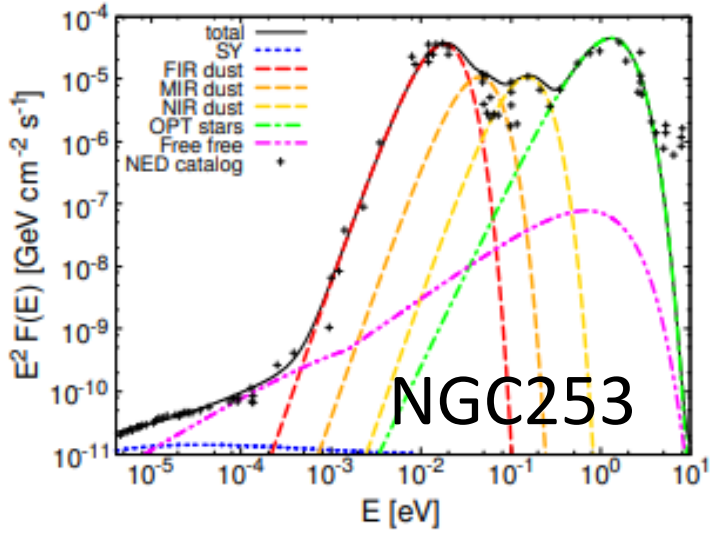
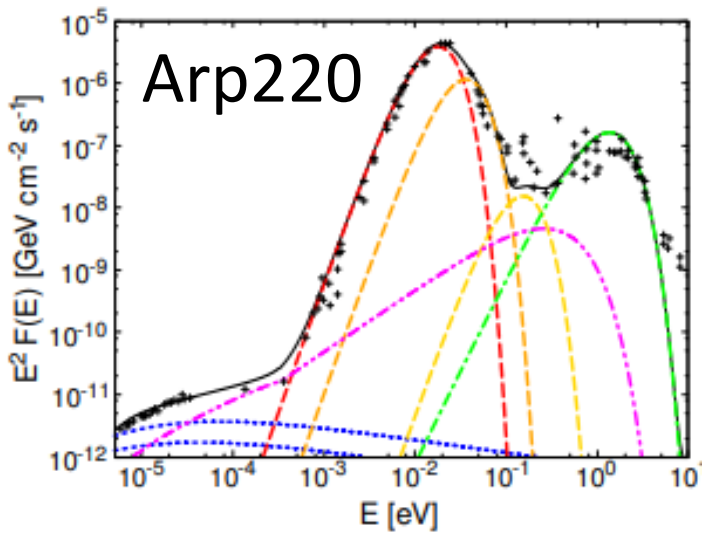
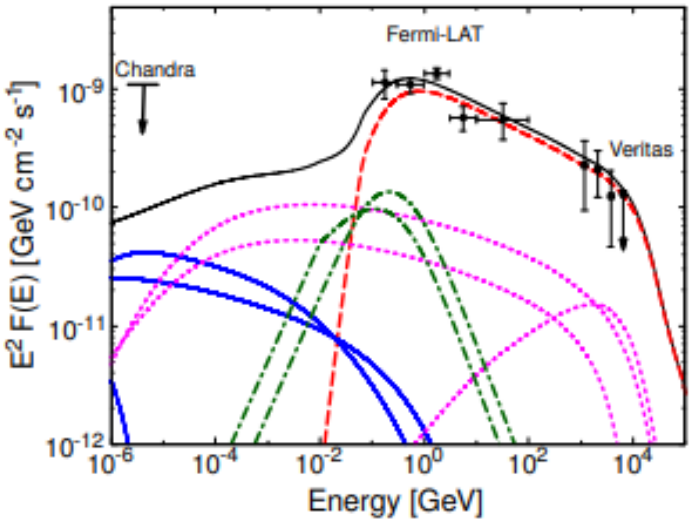


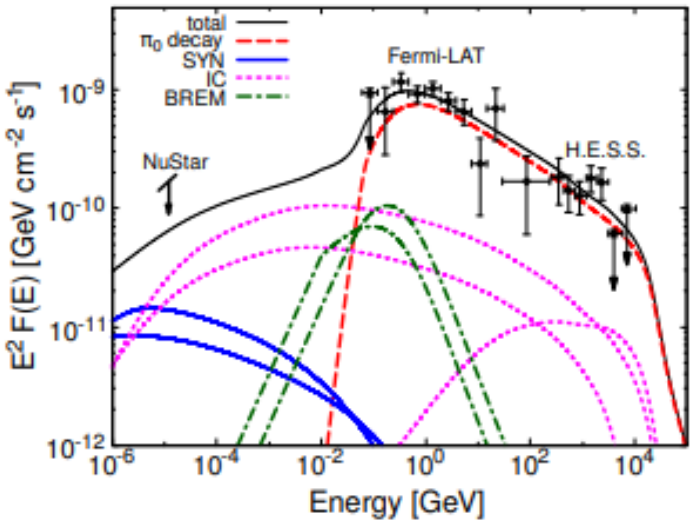
Modeling nearby SBGs

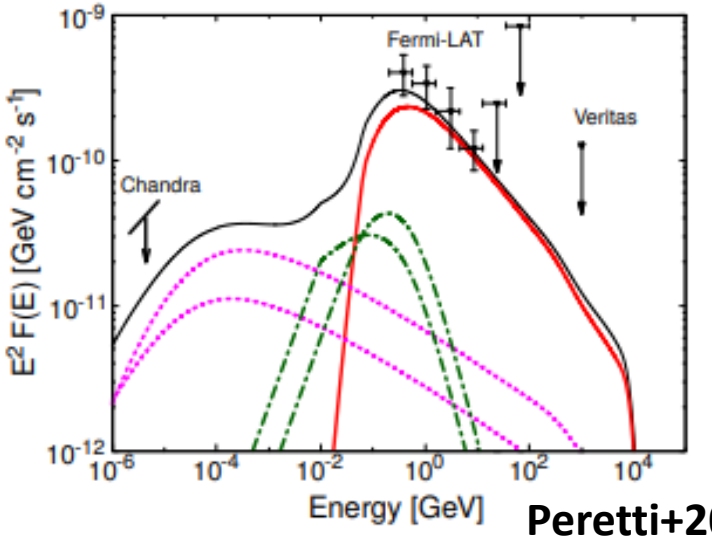












Peretti+2019

Starburst and AGN winds

(Extra-)galactic winds

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

JOURNAL ARTICLE

Electromagnetic extraction of energy from Kerr black holes FREE

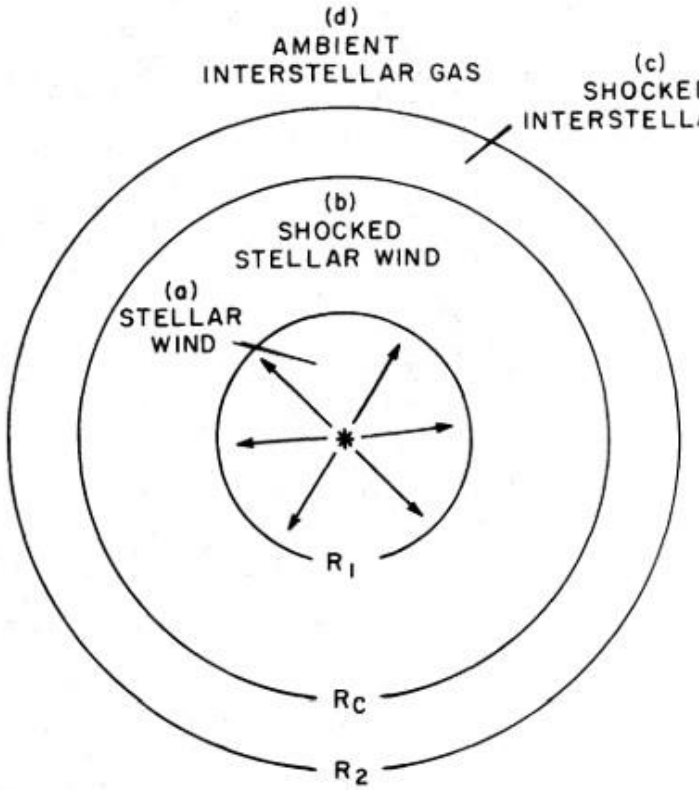
R. D. Blandford, R. L. Znajek

Monthly Notices of the Royal Astronomical Society, Volume 179, Issue 3, July 1977, Pages 433–456, https://doi.org/10.1093/mnras/179.3.433

Hydromagnetic flows from accretion discs and the production of radio jets FREE

R. D. Blandford, D. G. Payne

Monthly Notices of the Royal Astronomical Society, Volume 199, Issue 4, August 1982, Pages 883–903, https://doi.org/10.1093/mnras/199.4.883



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

Scales and power

AGN:

$V_\infty \approx 10^2 - 10^5 \mathrm{km/s}$

$\dot{M} \approx 10^{-3} - 10^3 M_\odot/\mathrm{yr}$

$R_{sh} \approx 10^{-1} pc - 10\ \mathrm{kpc}$

Starbursts:

$V_\infty \approx 10^3 \mathrm{km/s}$

$\dot{M} \approx 10^{-2} - 10^2 M_\odot/\mathrm{yr}$

$R_{sh} \approx 1 - 10\ \mathrm{kpc}$

Scales and power

$L_{kin} \approx 10^{41} - 10^{43}\ erg\ /s$

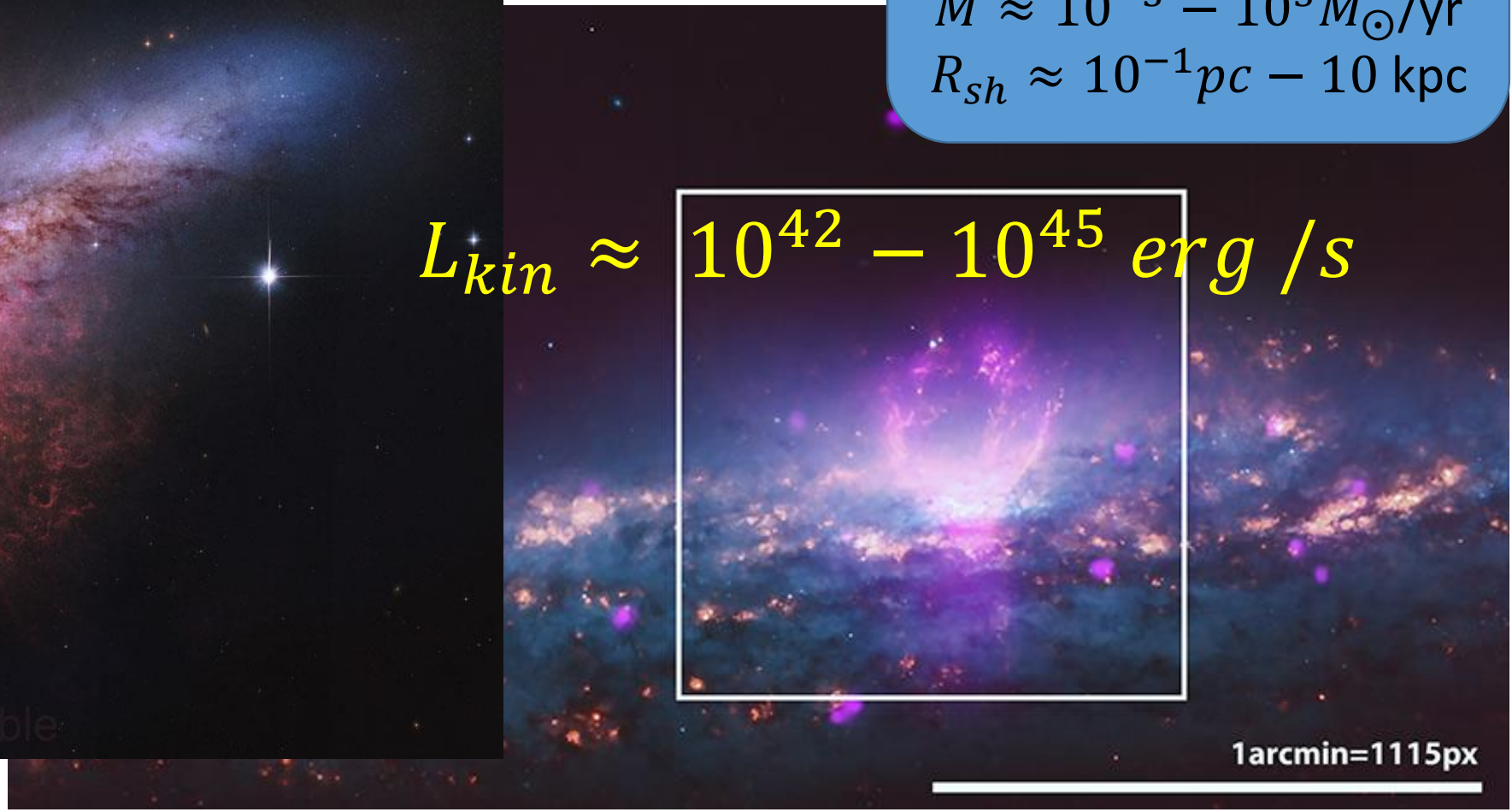
Starbursts:

$V_\infty \approx 10^3$km/s
$\dot{M} \approx 10^{-2} - 10^2 M_\odot$/yr
$R_{sh} \approx 1 - 10$ kpc

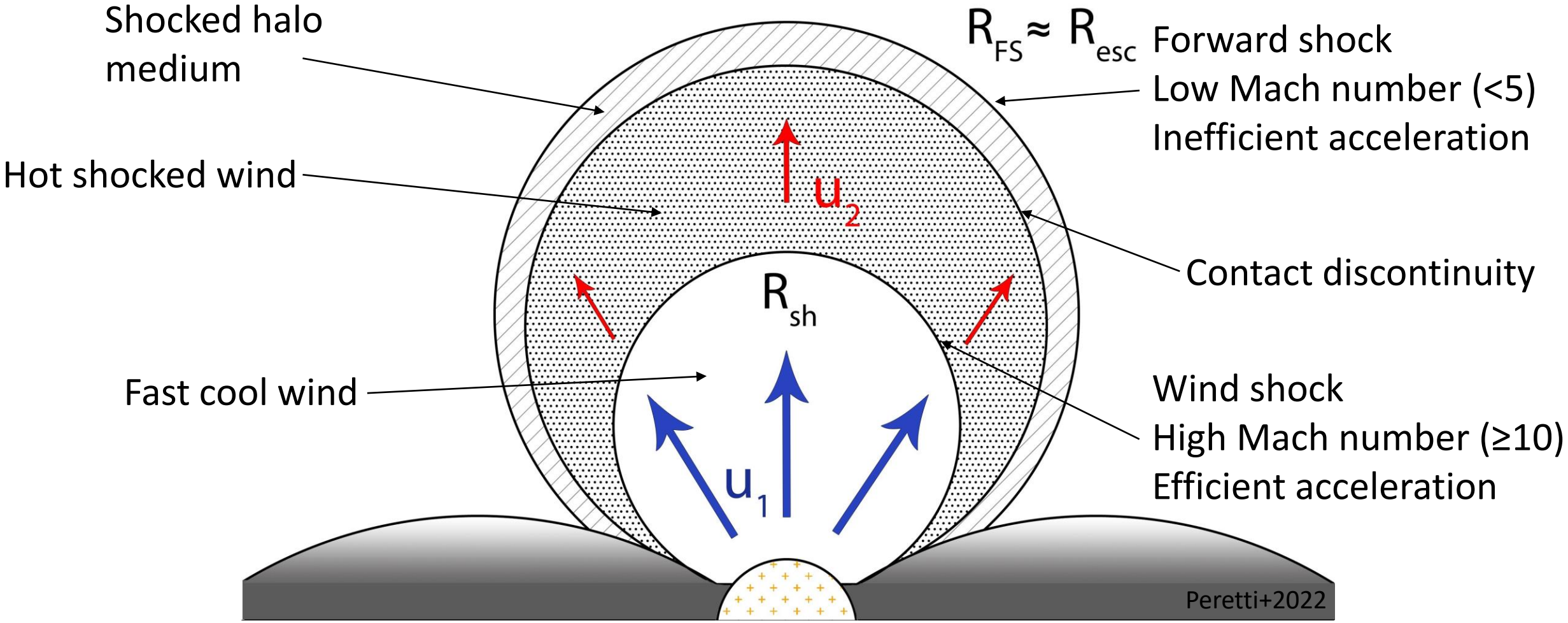
AGN:

$V_\infty \approx 10^2 - 10^5$km/s
$\dot{M} \approx 10^{-3} - 10^3 M_\odot$/yr
$R_{sh} \approx 10^{-1} pc - 10$ kpc

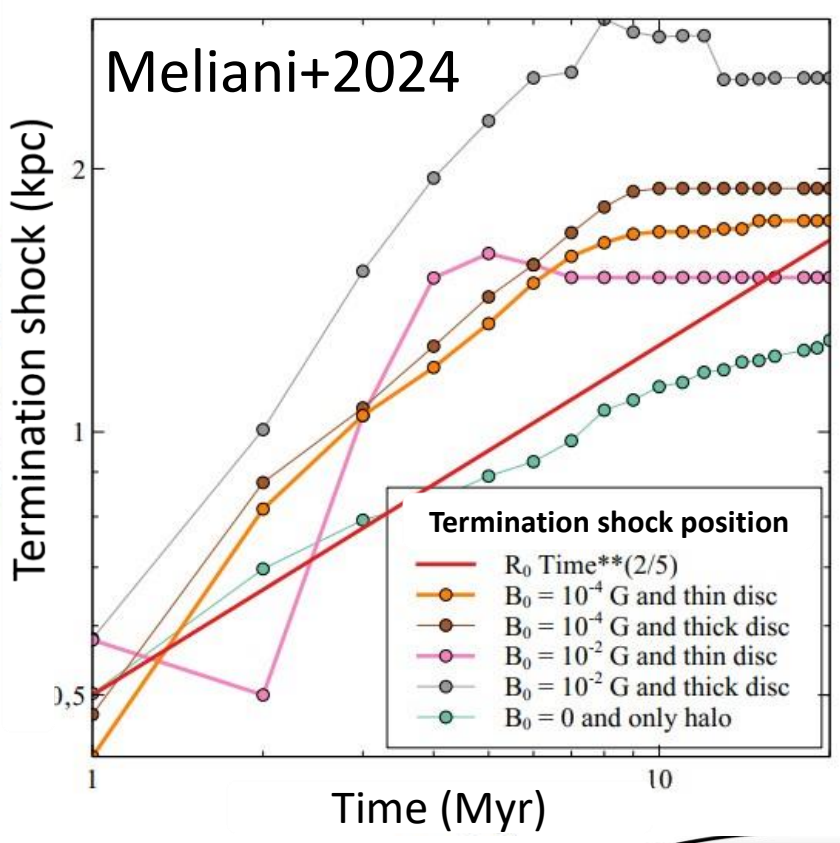
$L_{kin} \approx 10^{42} - 10^{45}\ erg\ /s$

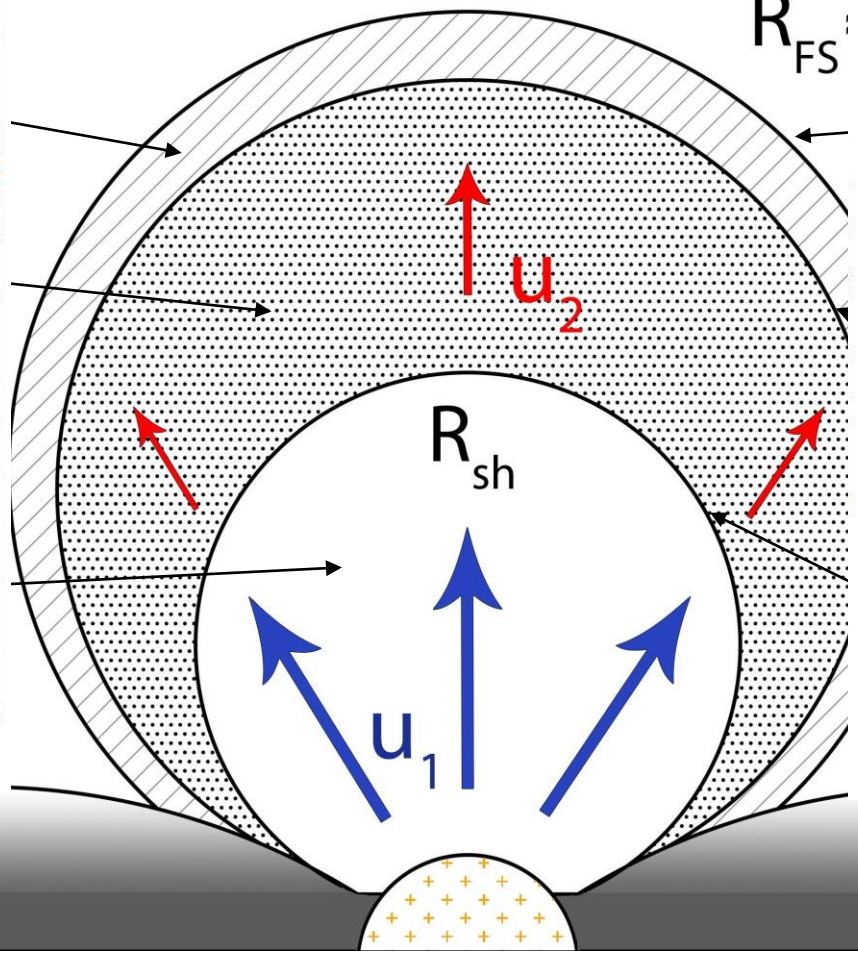


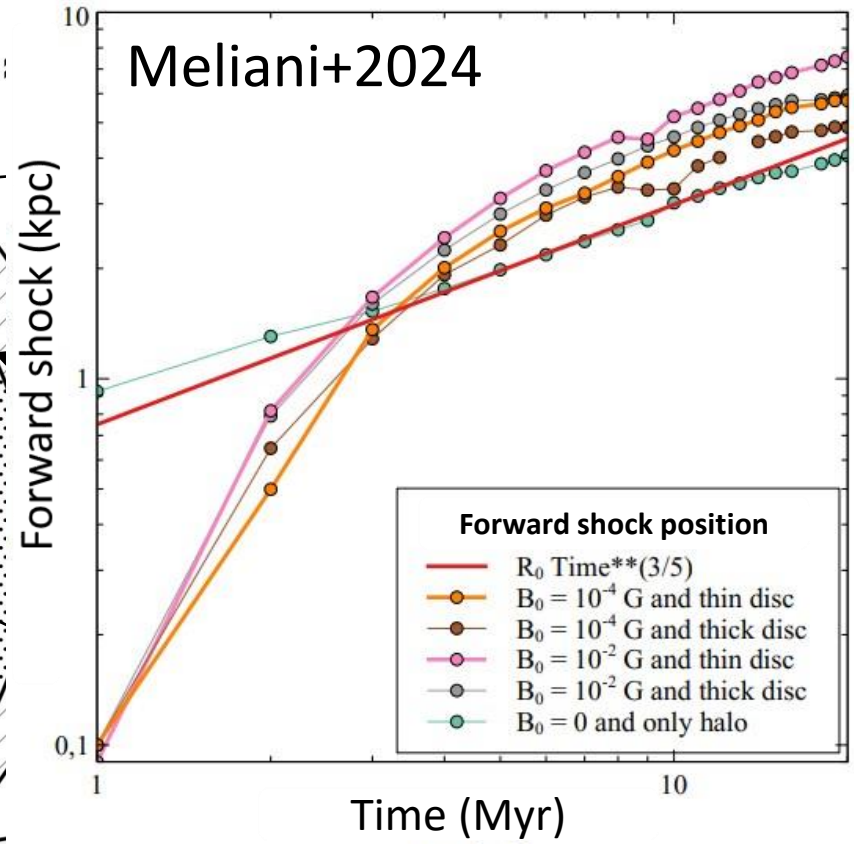
Wind bubble structure



Wind bubble structure

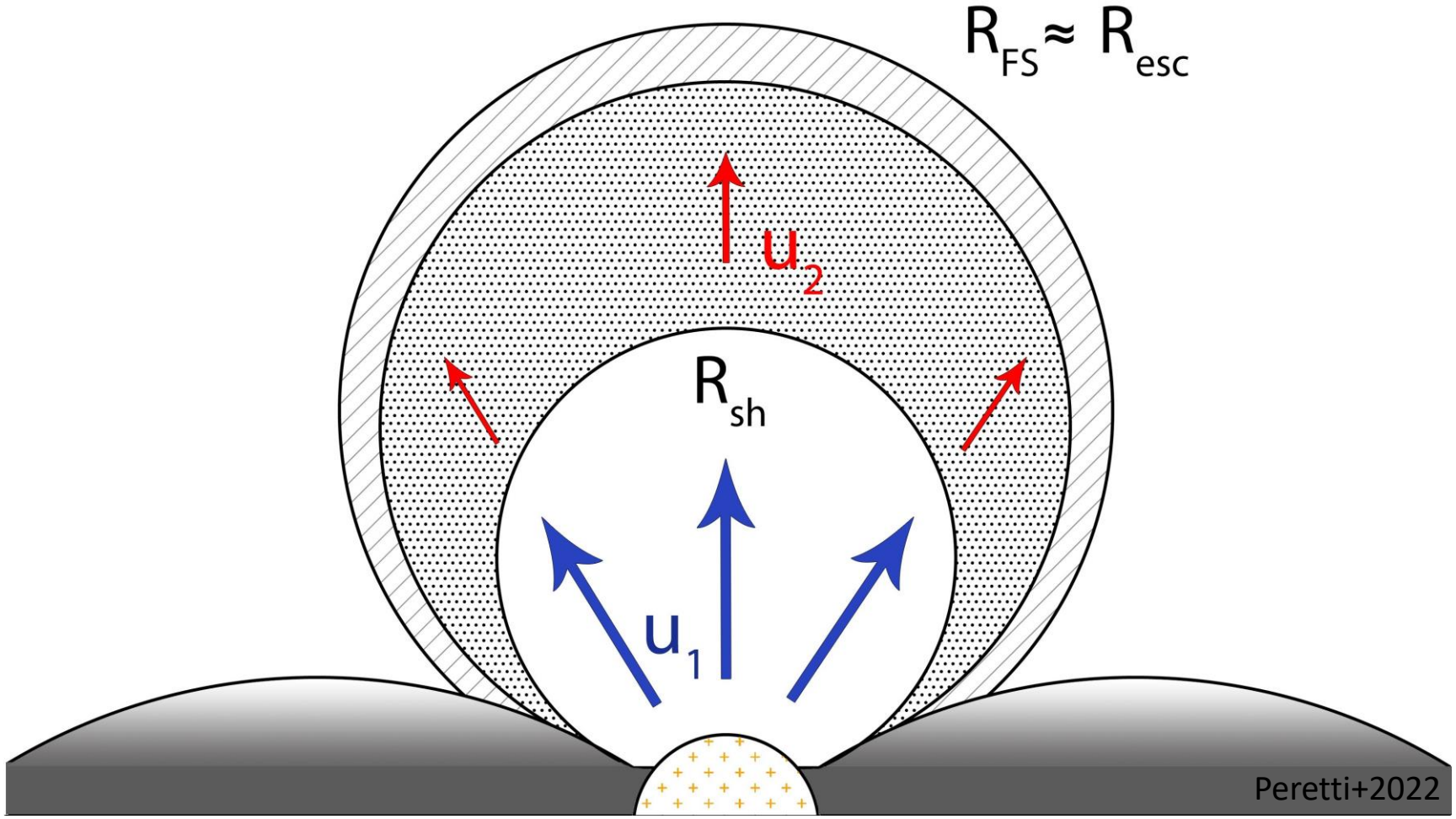






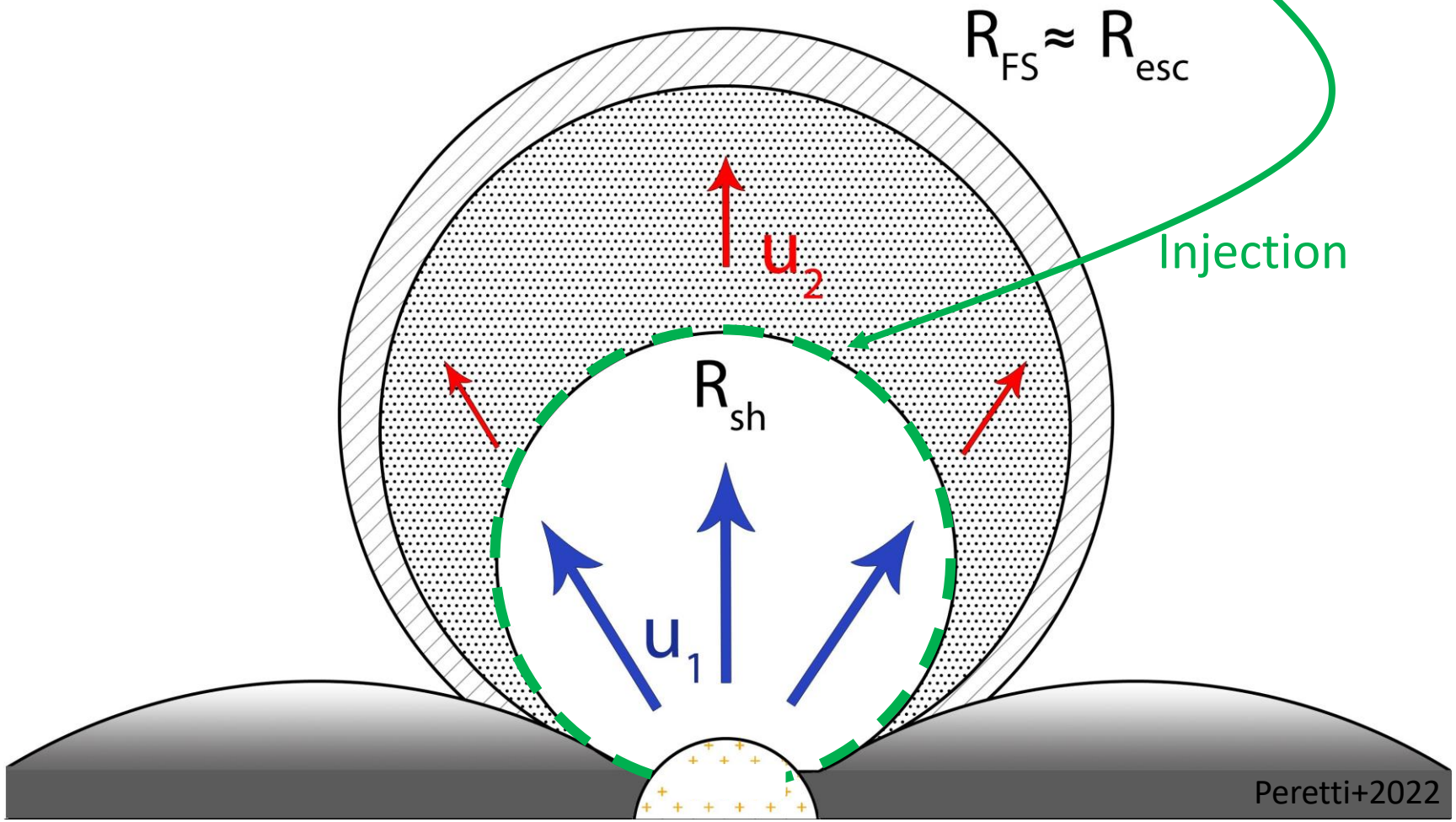
Transport model

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



Transport model

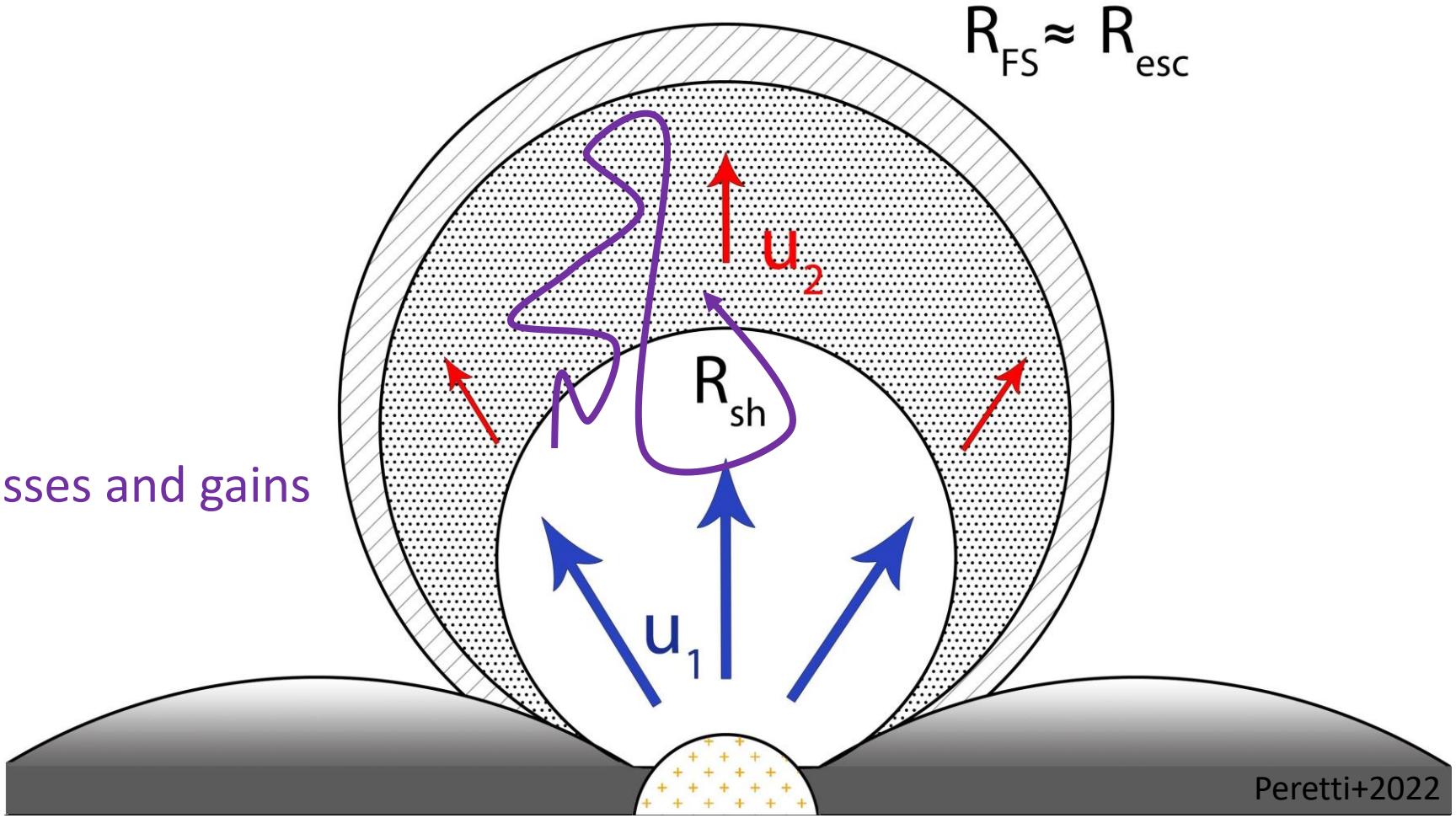
$$r^2 u(r)\partial_r f = \partial_r[r^2 D(r,p)\partial_r f] + \tfrac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p) - r^2\Lambda(r,p)$$



Transport model

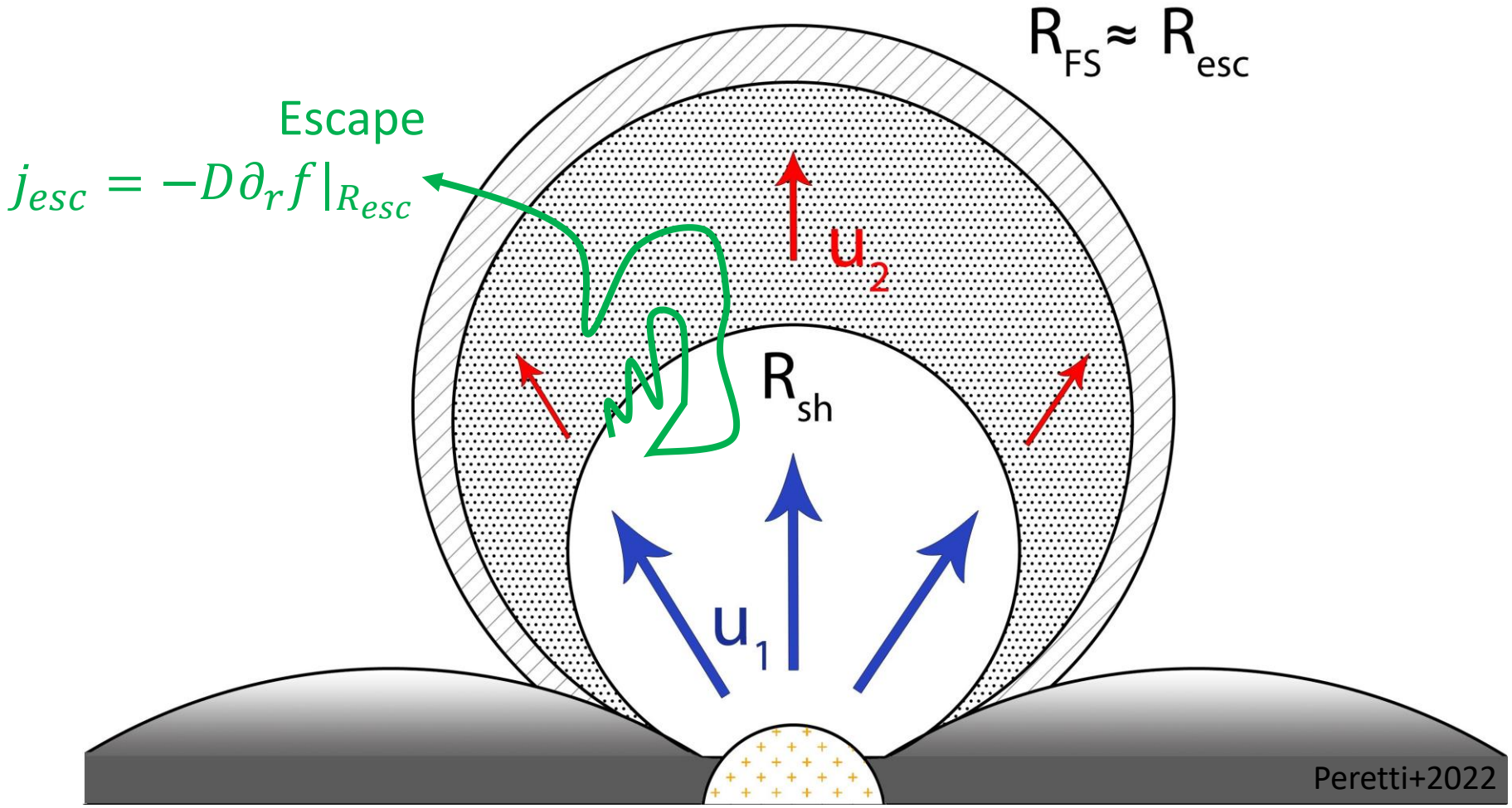
$$r^2 u(r)\partial_r f = \partial_r[r^2 D(r,p)\partial_r f] + \tfrac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p) - r^2 \Lambda(r,p)$$

- Advection
- Diffusion
- Adiabatic losses and gains



Transport model

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

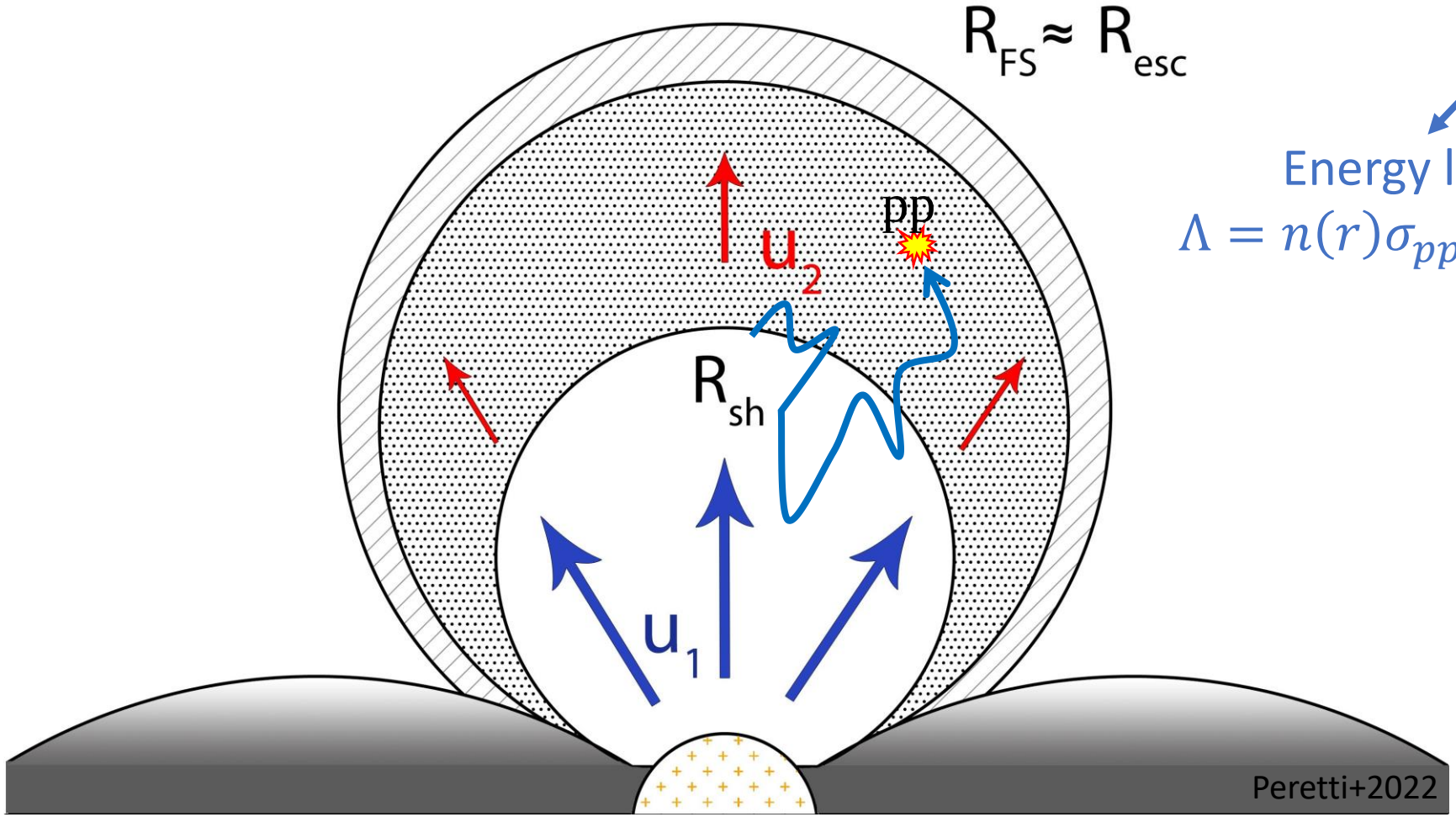


Transport model

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

Energy losses

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



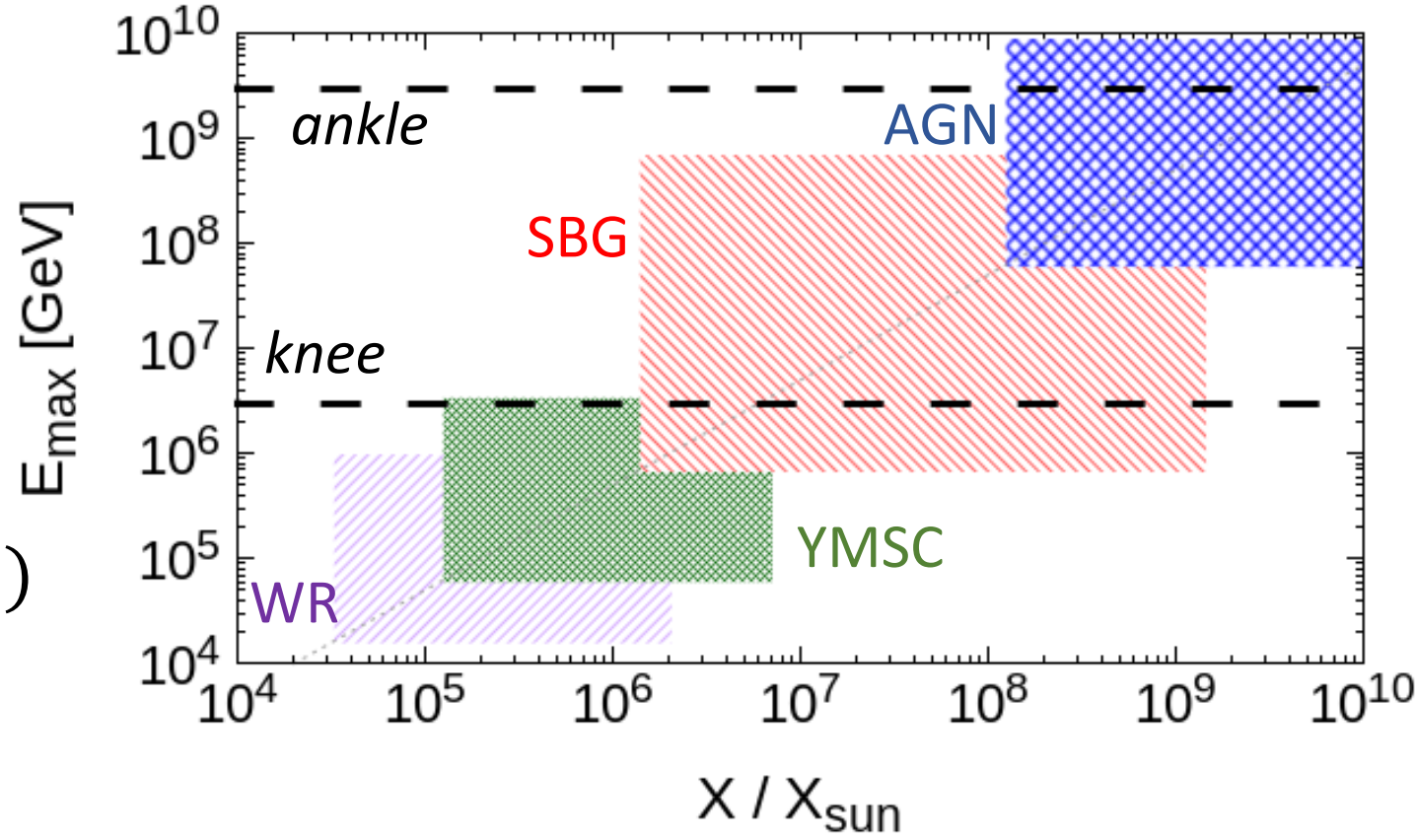
Maximum Energy

$$E_{max} \approx \xi\, q\, B\, \frac{u_1}{c} R_{sh}$$

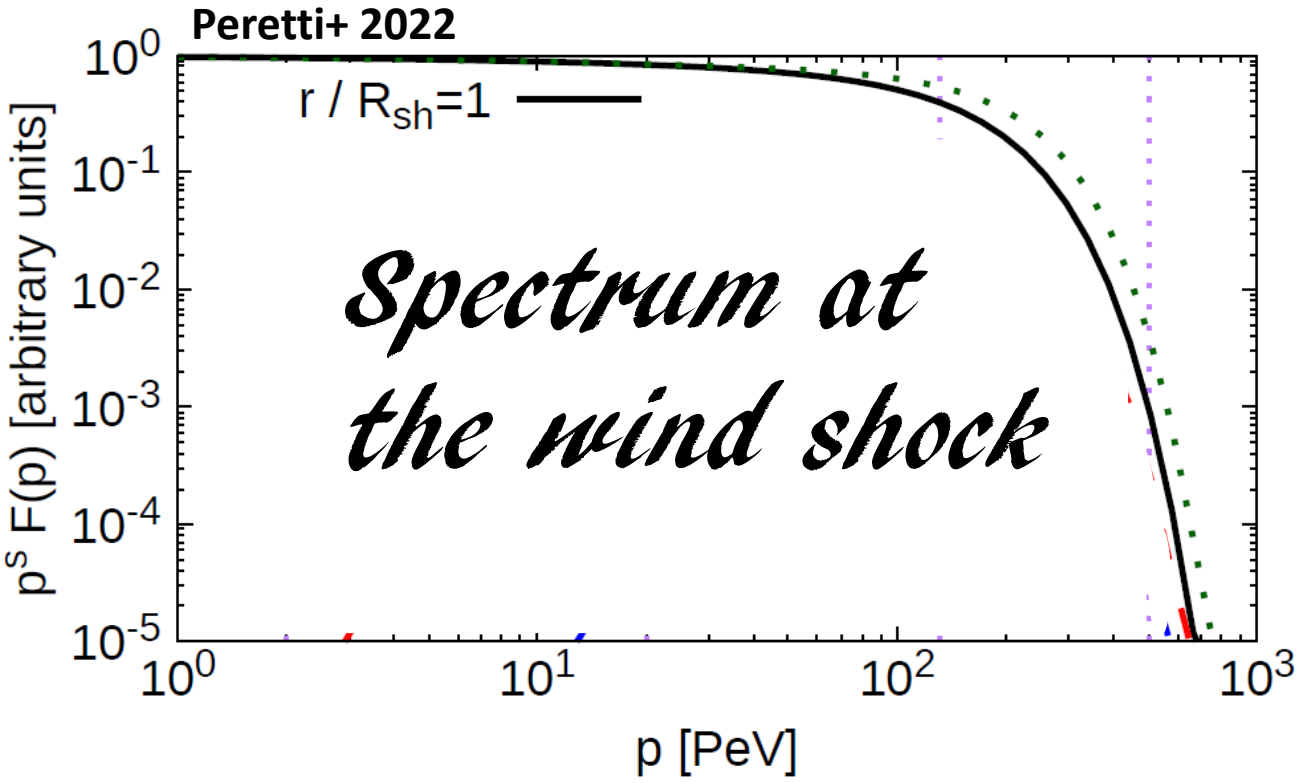
$$U_B = \epsilon_B P_{ram} = \epsilon_B \frac{\dot{M}}{4\pi R_{sh}^2} u_1$$

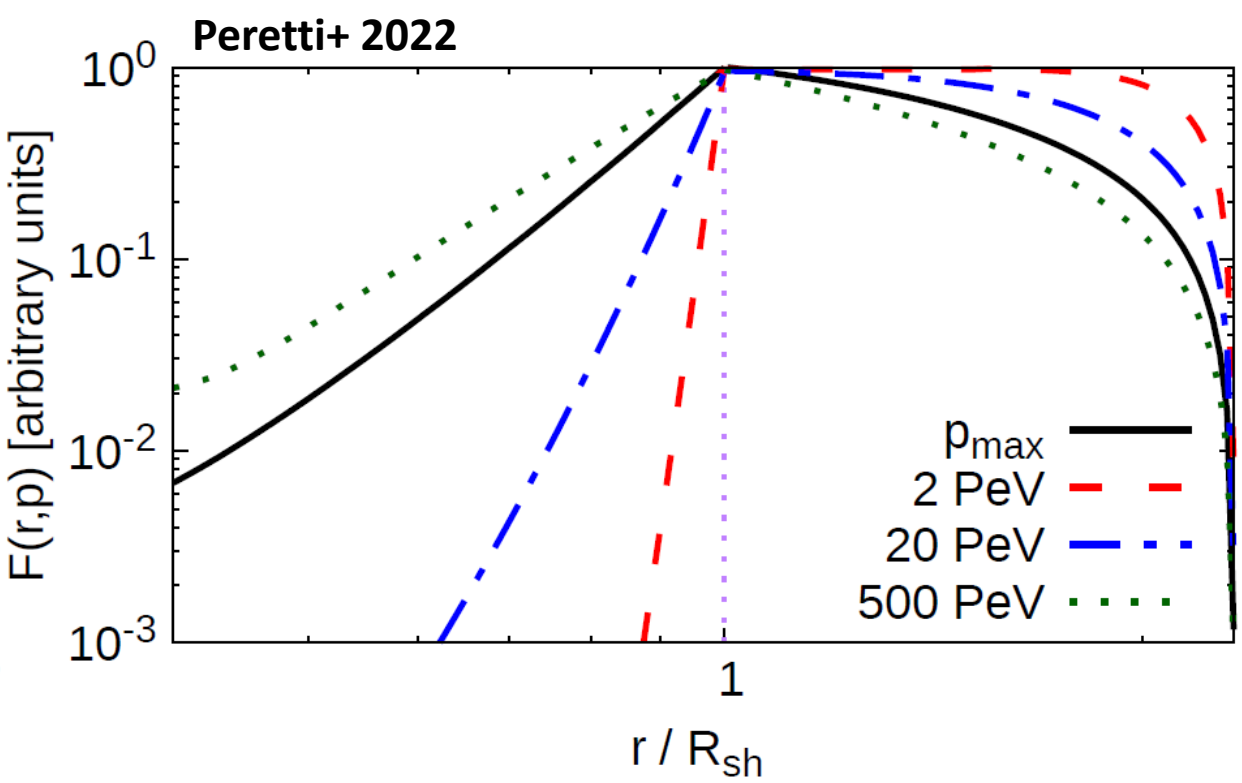
$$E_{max} = E_{max}\left(u_1, \dot{M}\right) = E_{max}(\dot{E}, \dot{P})$$

$$X = \dot{E}\dot{P}^{-1/2}$$

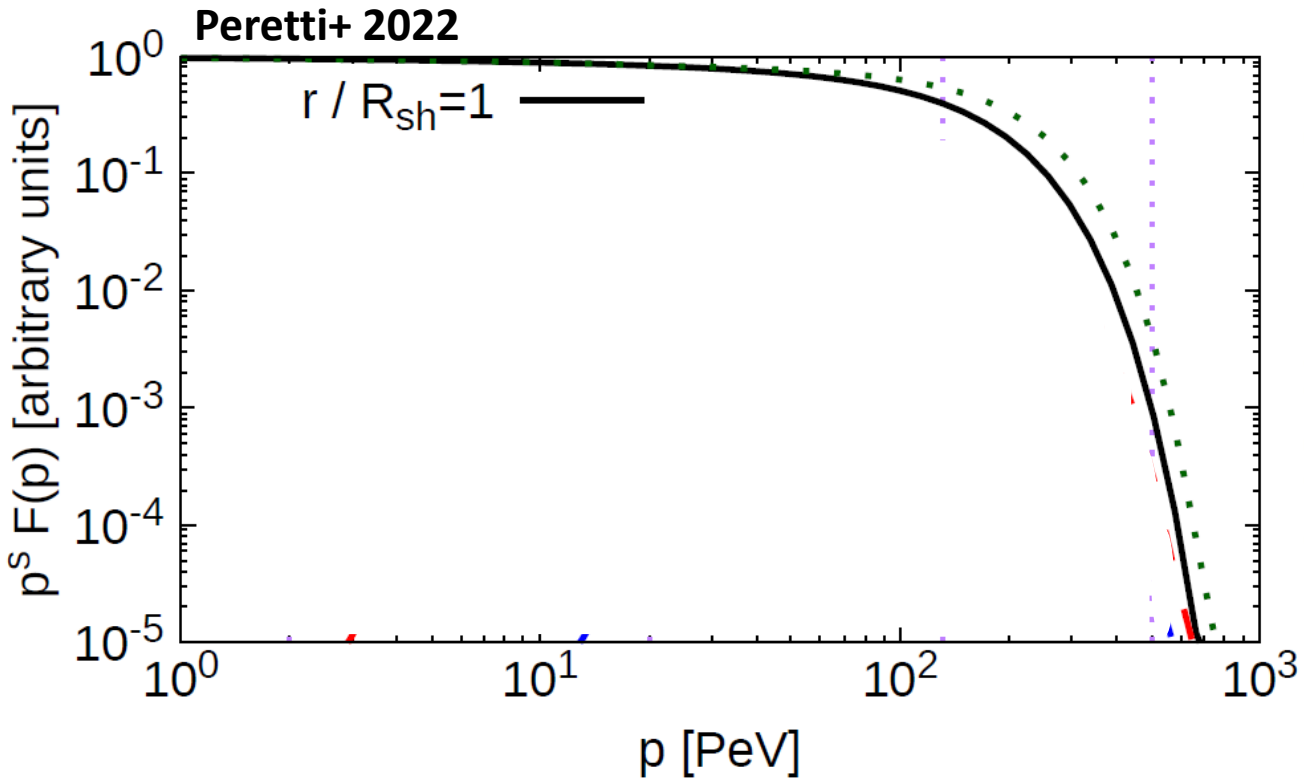


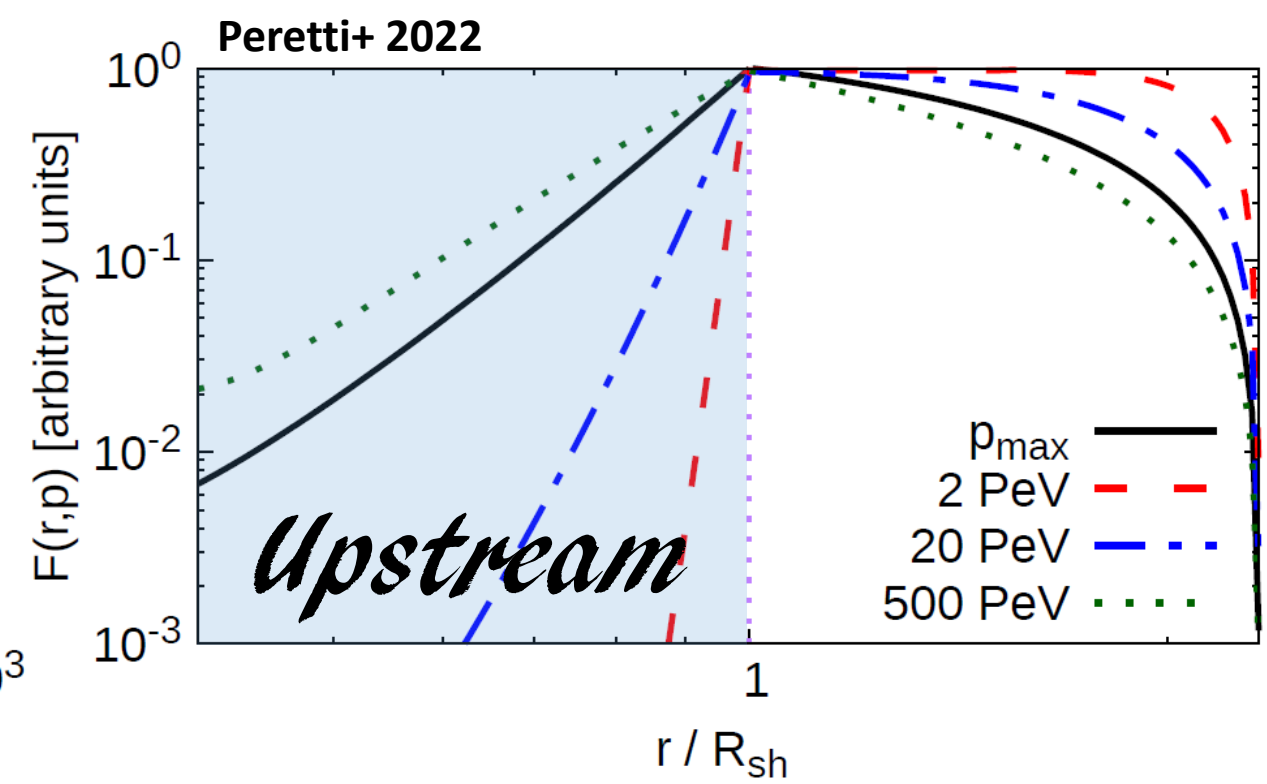
High-Energy particles in the system



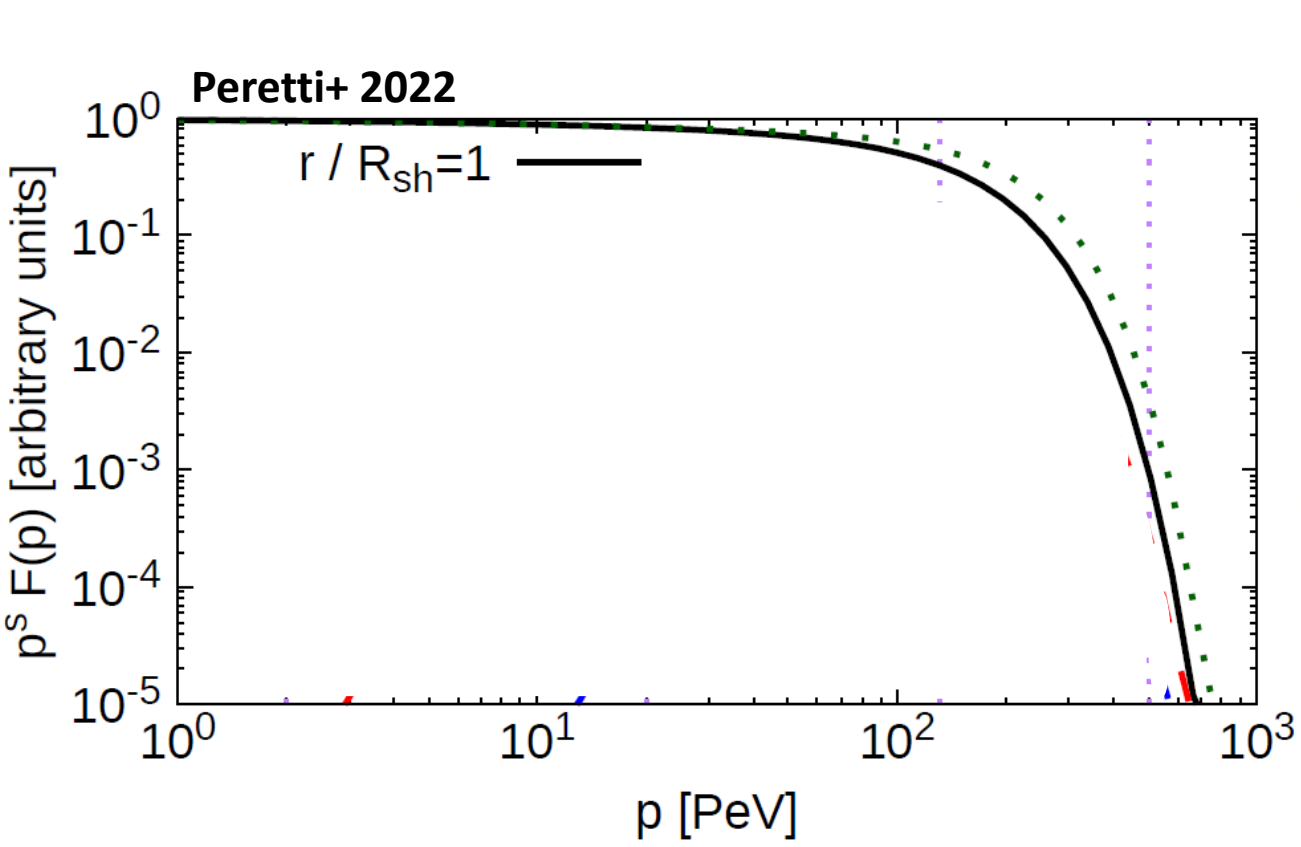


High-Energy particles in the system

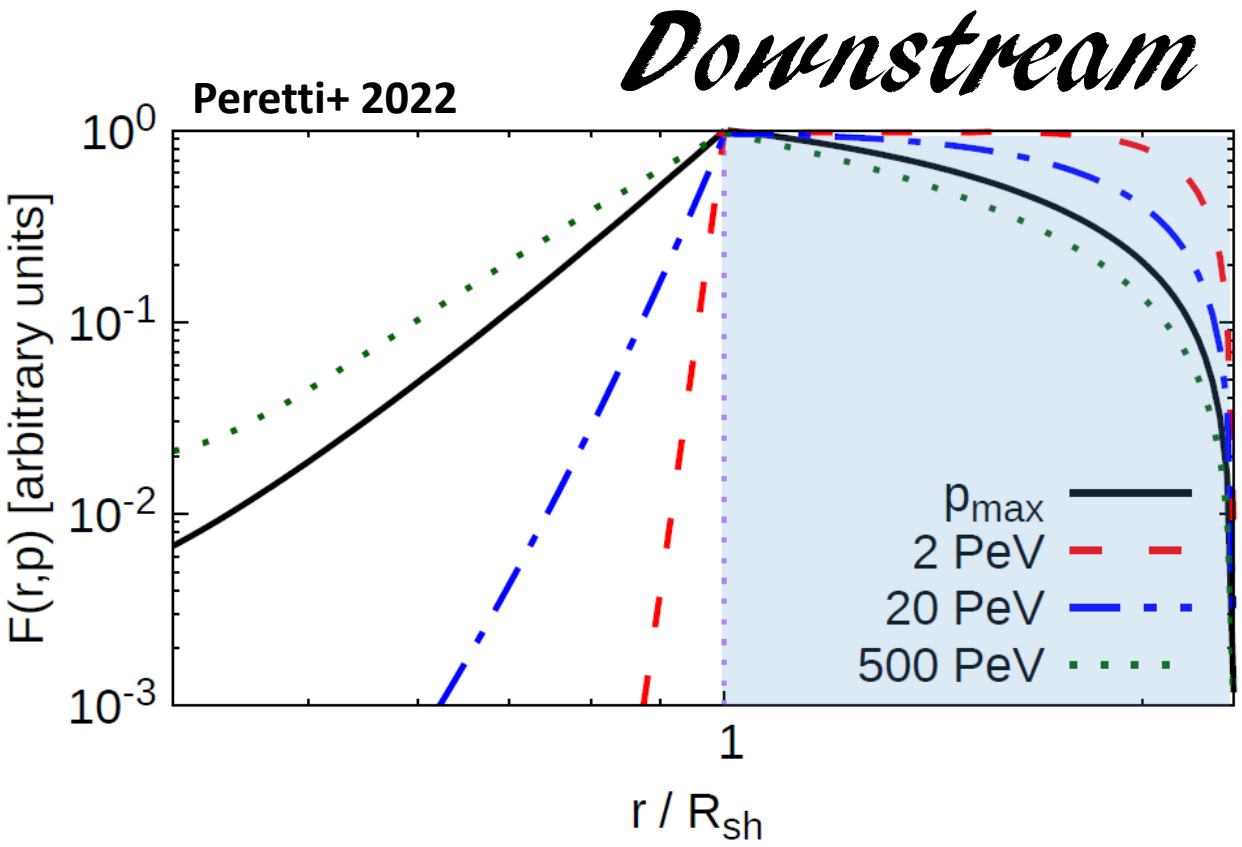




High-Energy particles in the system

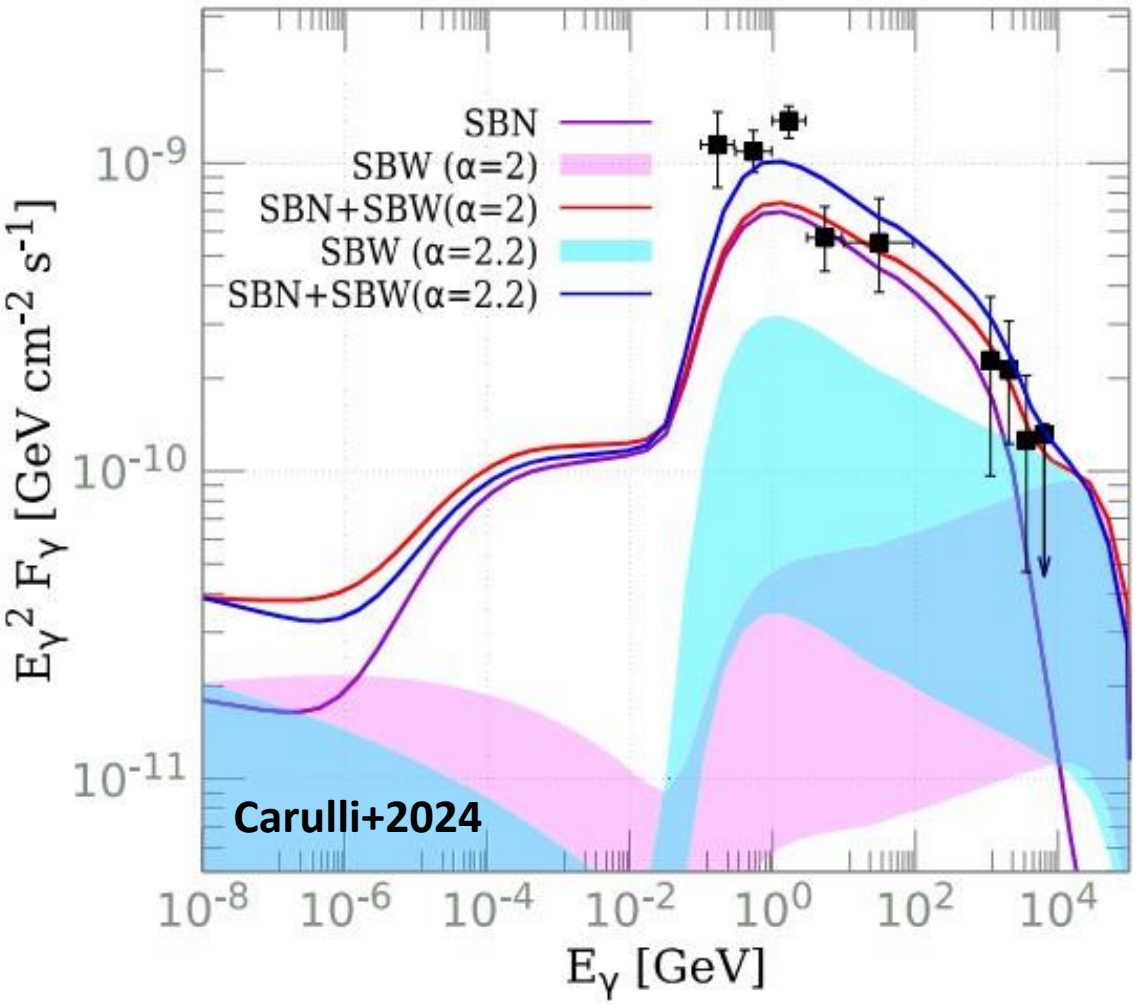


Downstream

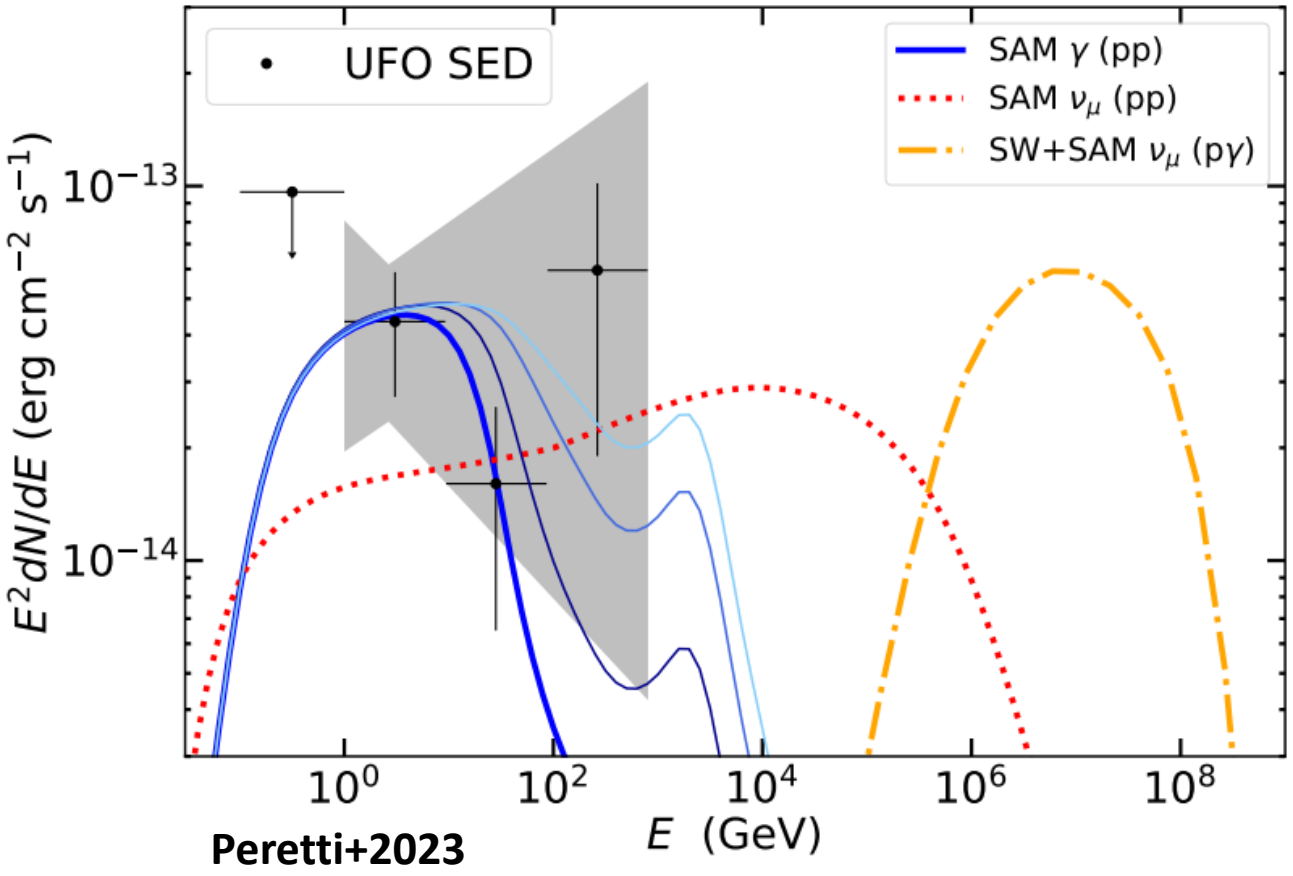


Multi-messenger radiation from winds

Starburst

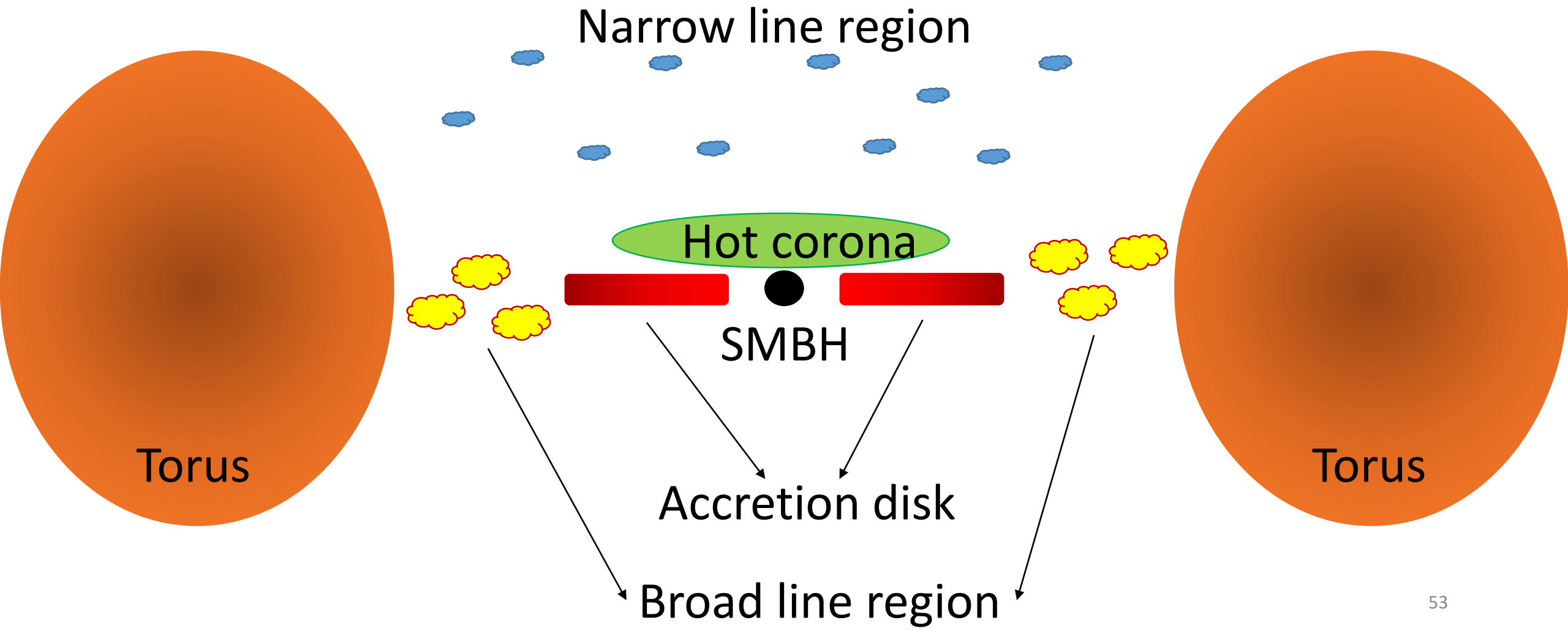


Ultra-fast Outflow



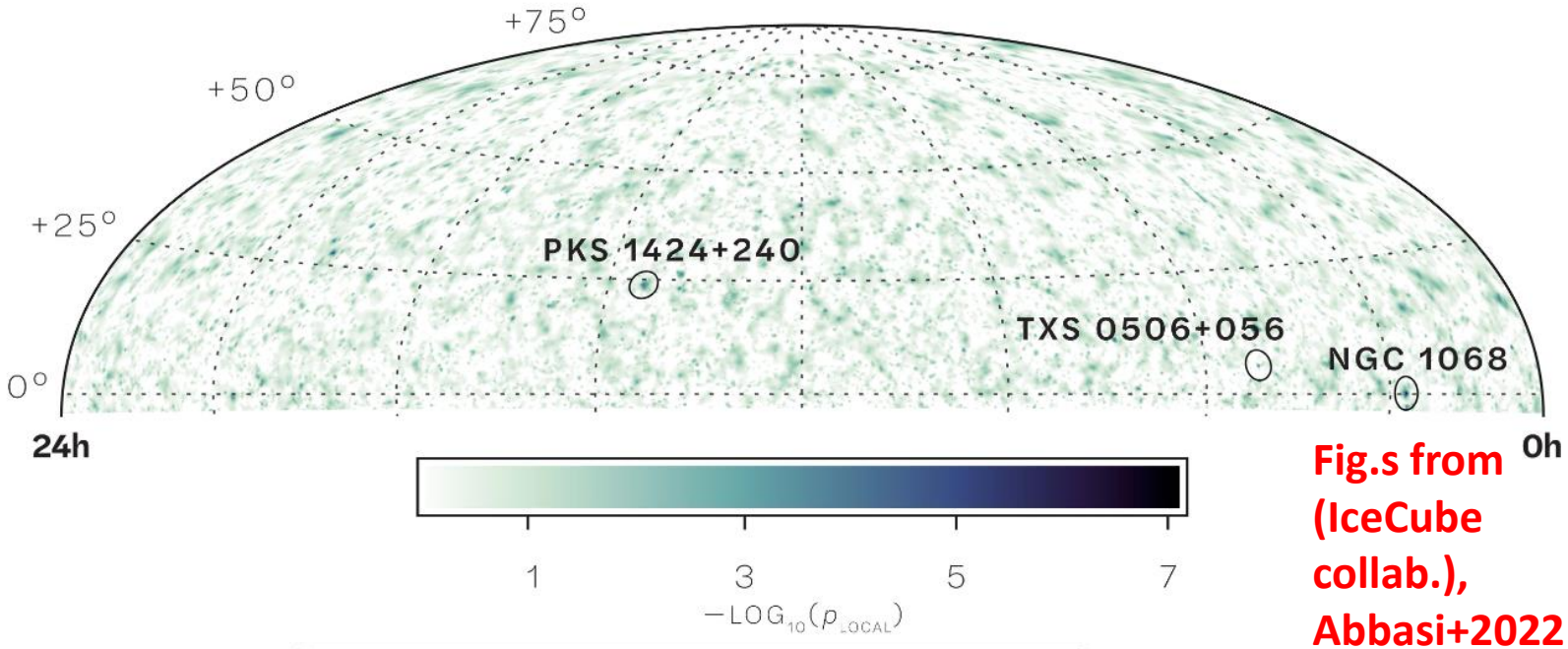
AGN Coronae

Active Galactic Nuclei



Credit: NASA, ESA & A. van der Hoeve

NGC 1068 is the brightest hotspot of IceCube



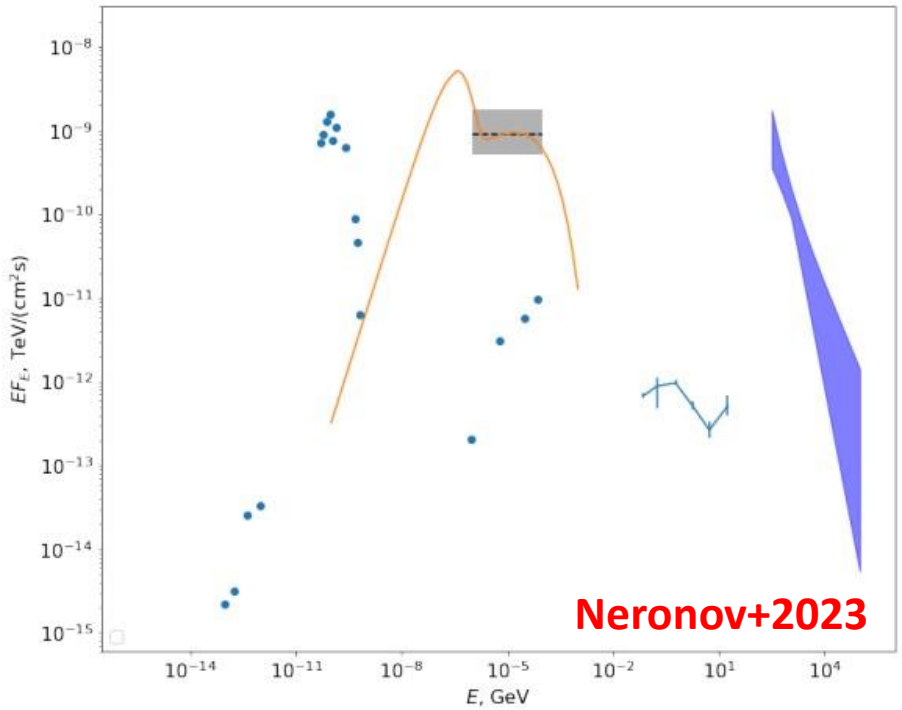
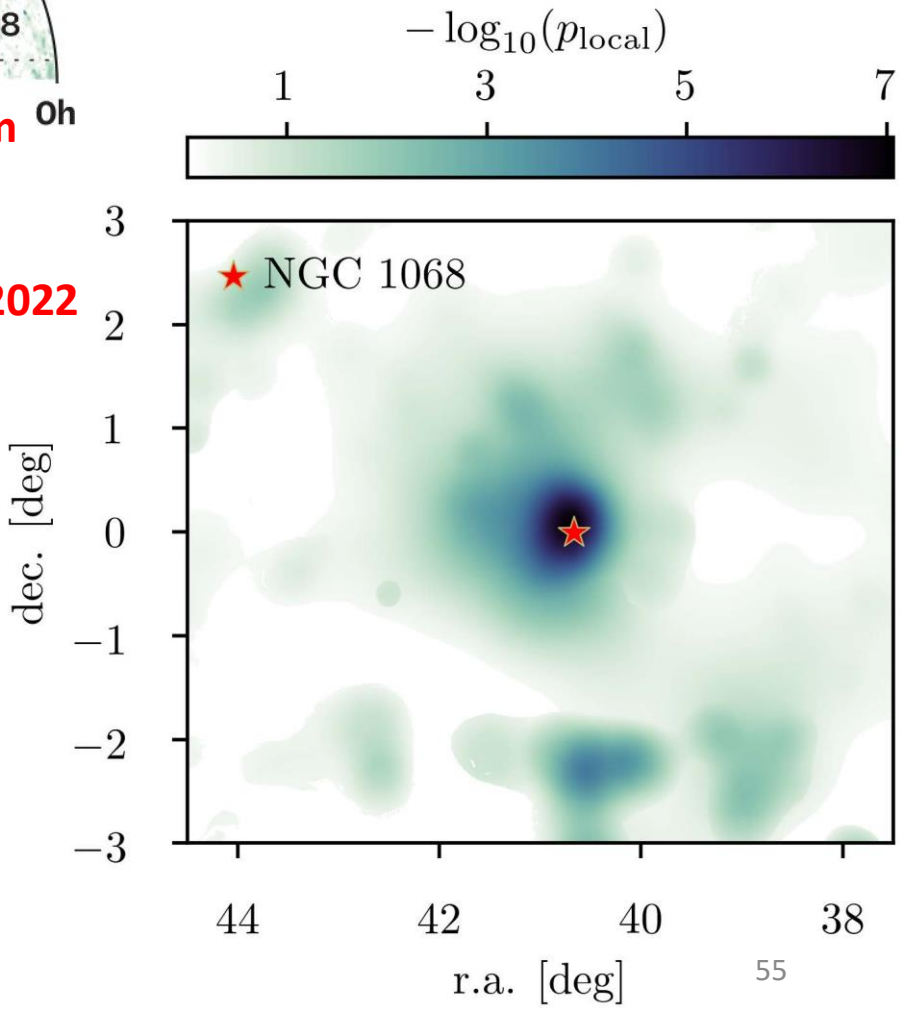


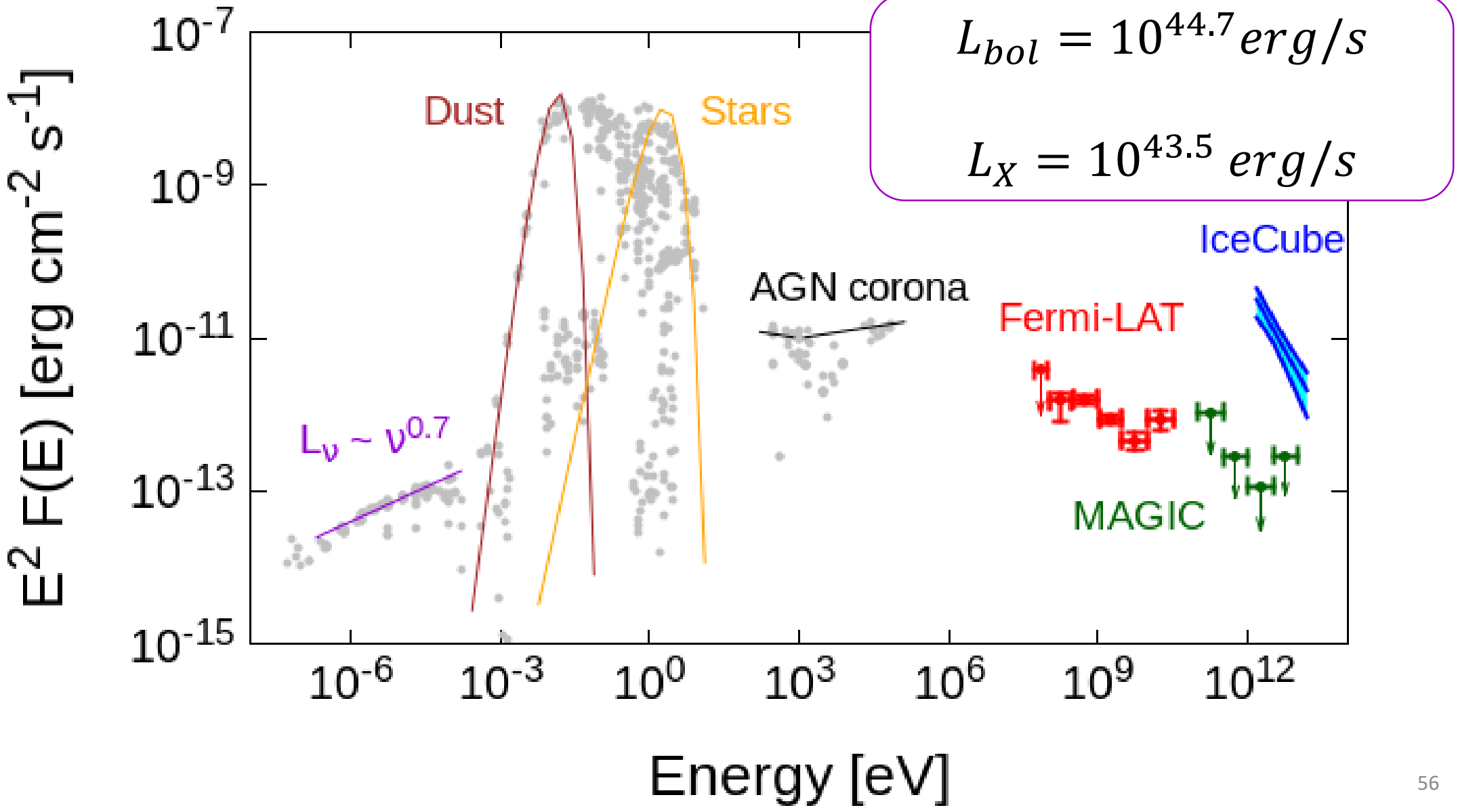
Fig.s from (IceCube collab.), Abbasi+2022



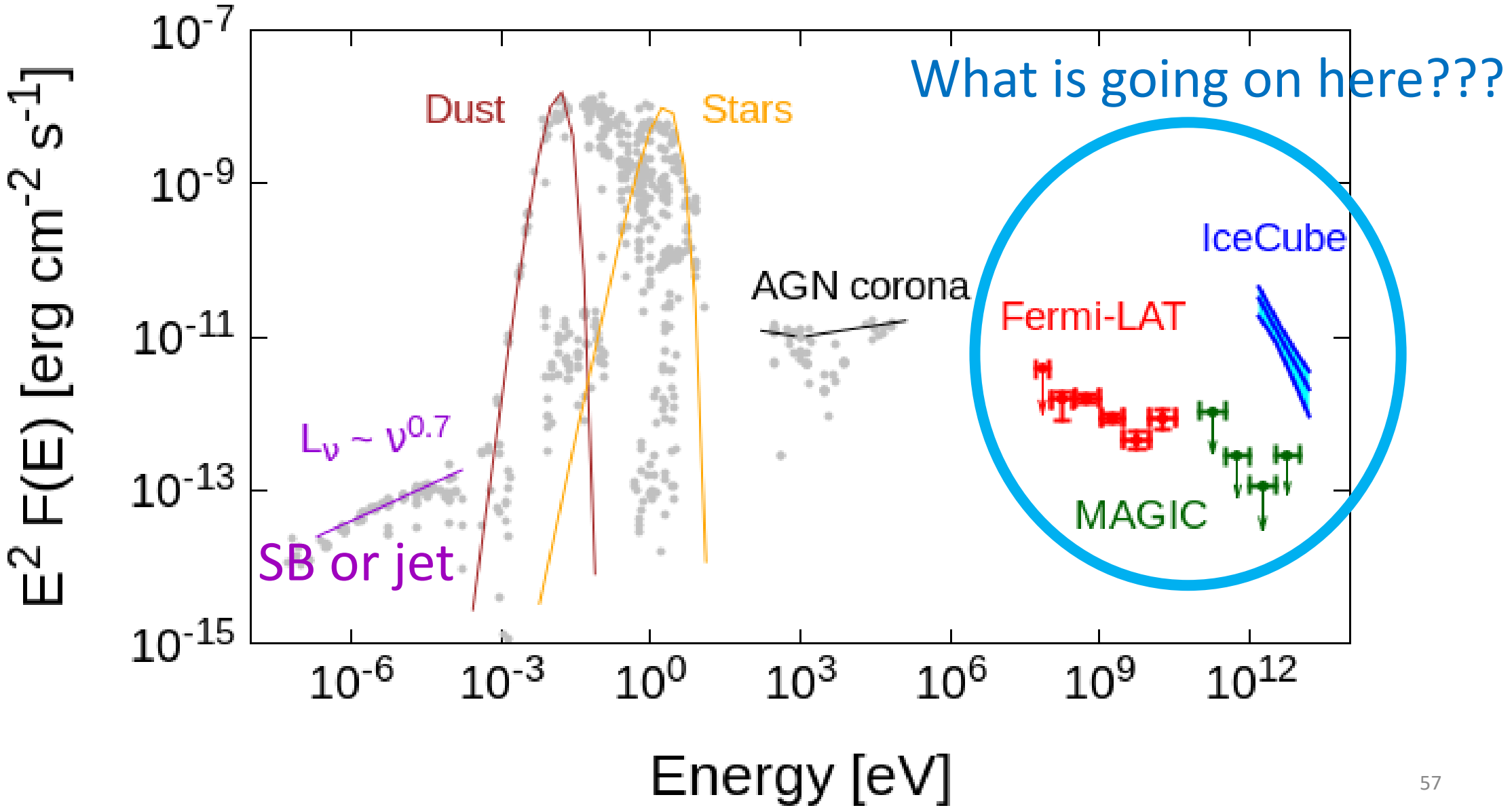
The problem of NGC 1068

$L_{bol} = 10^{44.7} erg/s$

$L_X = 10^{43.5}\ erg/s$



The problem of NGC 1068



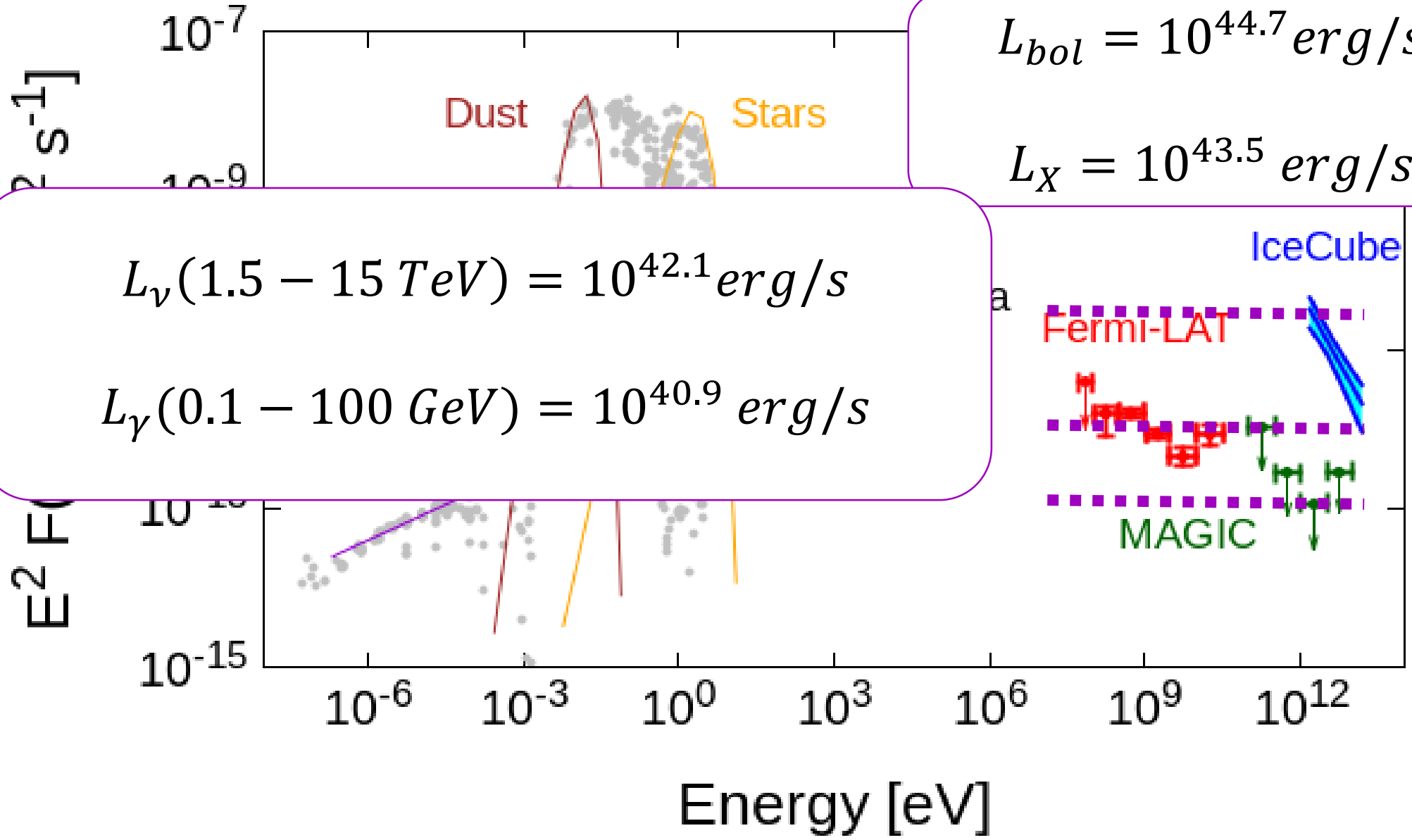
The problem of NGC 1068

$$L_{bol} = 10^{44.7} erg/s$$

$$L_X = 10^{43.5}\ erg/s$$

$$L_\nu(1.5 - 15\ TeV) = 10^{42.1} erg/s$$

$$L_\gamma(0.1 - 100\ GeV) = 10^{40.9}\ erg/s$$



Hidden sources

§9. Hidden sources

In the example of a massive black hole in a cocoon we encountered a model of a hidden source: an object which contains particles accelerated to high energies, but is not seen in high-energy electromagnetic radiation (X-ray and (or) gamma-ray radiation).

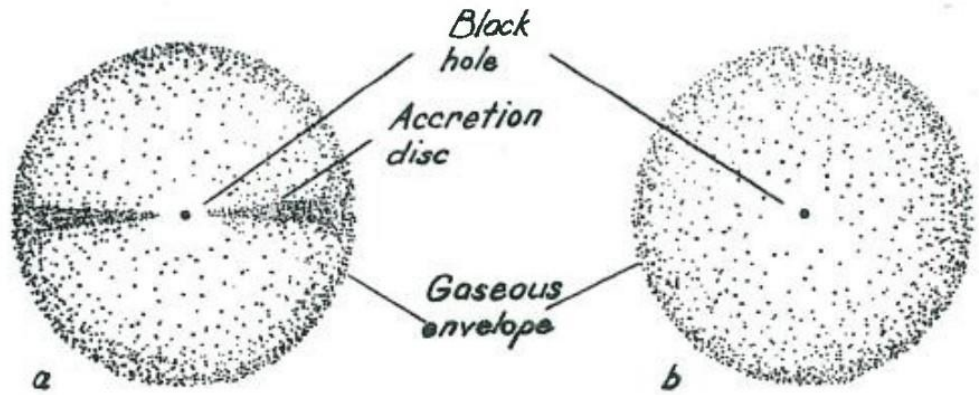


Fig. 8.3. Black hole in a cocoon: (a) disc accretion, (b) quasispherical accretion. The acceleratio takes place in the vacuum cavity.

Astrophysics of Cosmic rays, Berezinskii et al. 1990 (textbook)

Berezinsky & Ginzburg 1981

Silberberg & Shapiro 1979

NEUTRINOS AS A PROBE FOR THE NATURE OF

AND PROCESSES IN ACTIVE GALACTIC NUCLEI

R. Silberberg and M. M. Shapiro
Laboratory for Cosmic Ray Physics
Naval Research Laboratory
Washington, D. C. 20375, U.S.A.

Eichler 1979

HIGH-ENERGY NEUTRINO ASTRONOMY: A PROBE OF GALACTIC NUCLEI?

DAVID EICHLER
Enrico Fermi Institute, University of Chicago
Received 1978 April 24; accepted 1979 February 13

ABSTRACT

The powerful infrared emission from active galactic nuclei may be driven, directly or indirectly, by nonthermal processes, in which case the power of high-energy particle production may be as high as the IR luminosity. The nuclei of active galaxies contain, on various scales, enough matter to stop high-energy protons before they diffuse out of the nuclear region via pion-producing collisions. Thus, the luminosity of the nucleus in high-energy neutrinos ($E_\nu \gtrsim 10^{12}$ eV) (the primary decay product of charged pions) may in turn be comparable to the total power radiated by the nucleus.

If such a hypothesis is true, then many active galactic nuclei may be detectable as point sources in high-energy neutrinos with the neutrino "telescopes" that are being discussed. The overall cosmic neutrino background due to active galaxies may be orders of magnitude above the detection threshold.

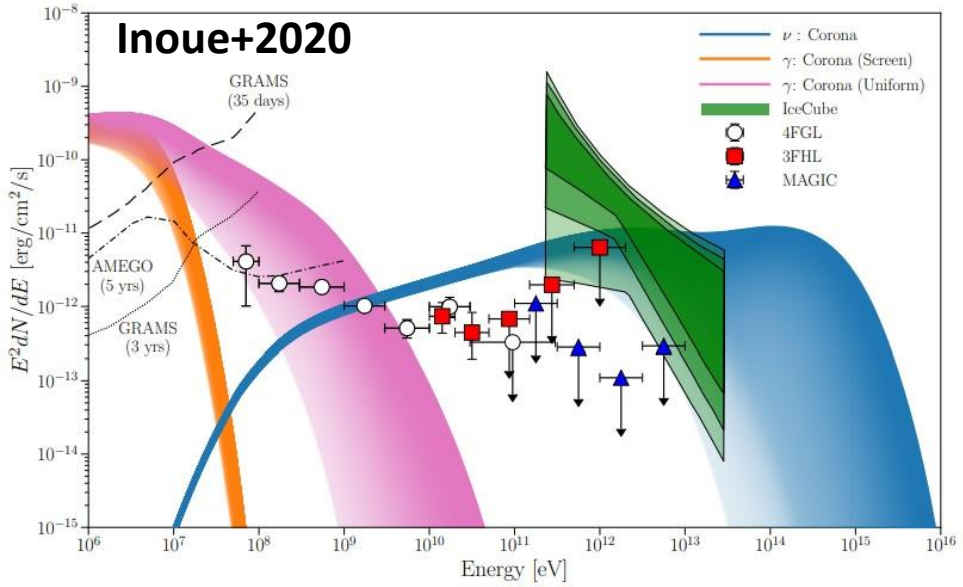
EXTRATERRESTRIAL NEUTRINO SOURCES AND HIGH ENERGY NEUTRINO ASTROPHYSICS

V.S.Berezinsky
Institute for Nuclear Research of the USSR Academy of Sciences

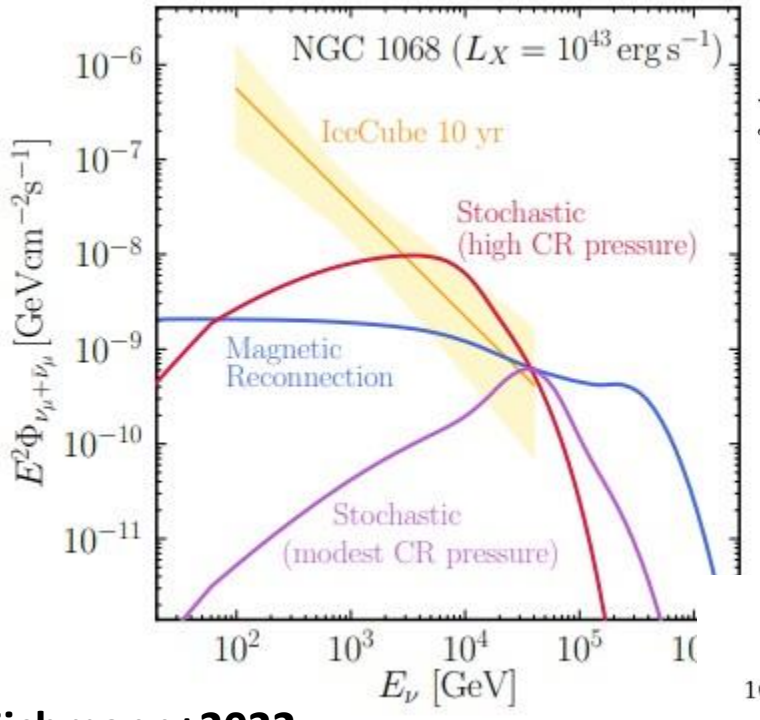
Berezinsky 1977

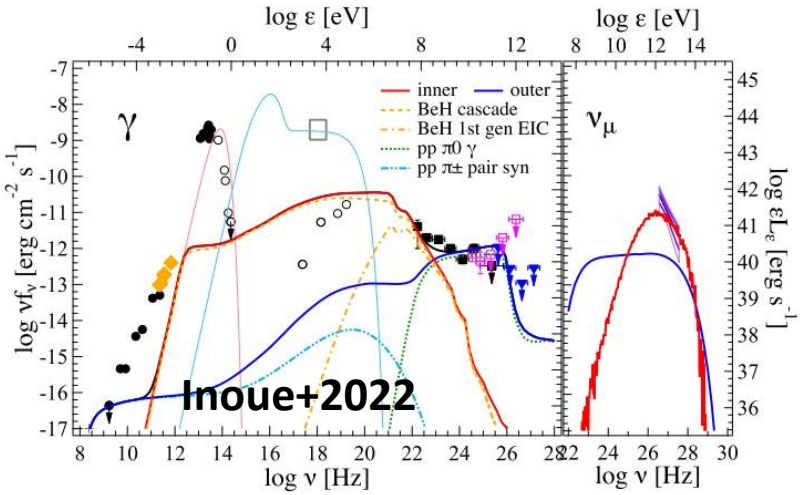
Recent models

Inoue+2020



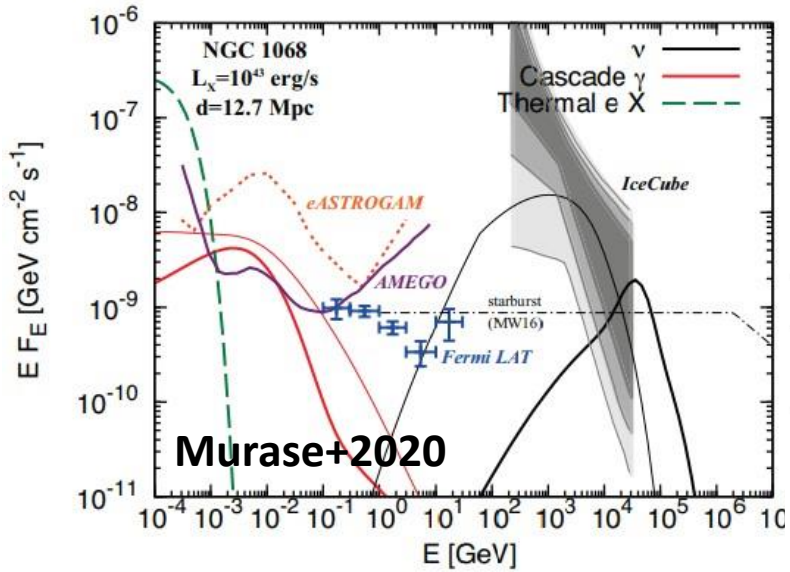
Kheirandish+2021



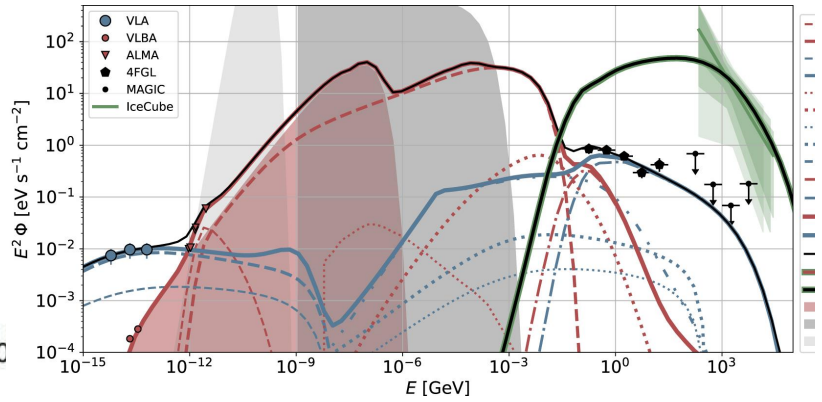


Inoue+2022

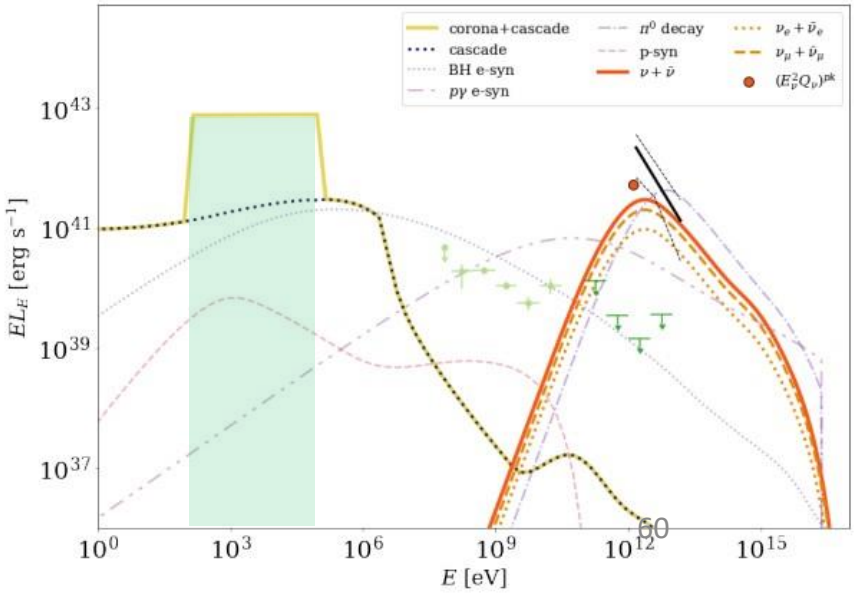
Murase+2020



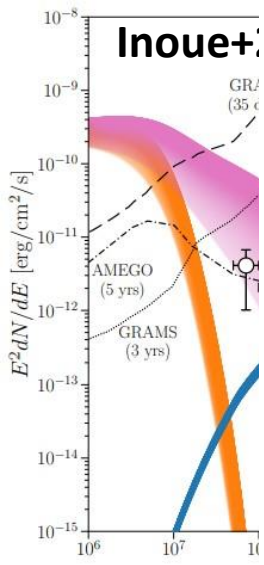
Eichmann+2022

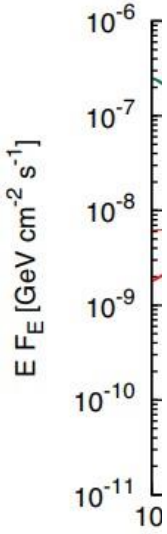


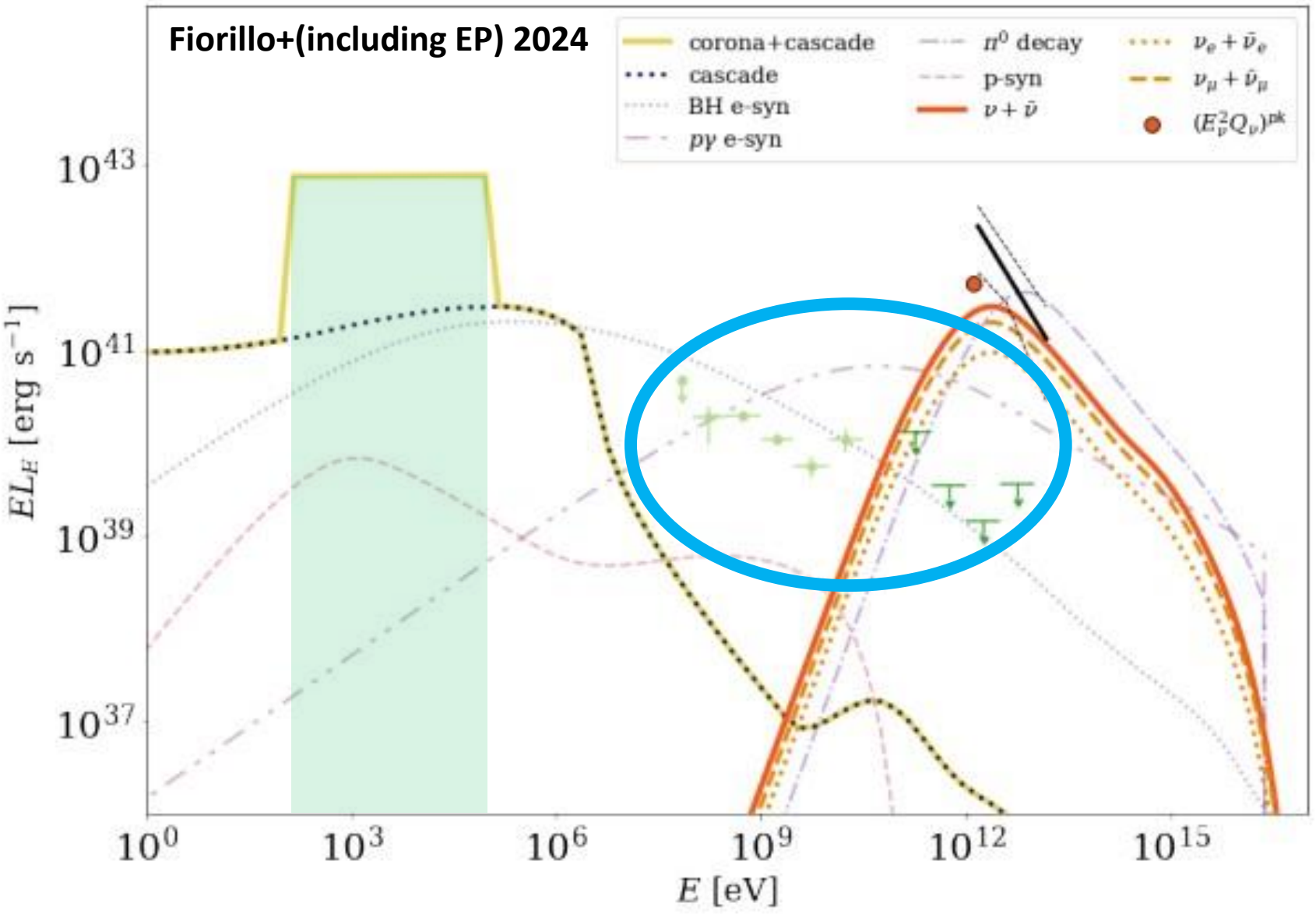
Fiorillo+(including EP) 2024

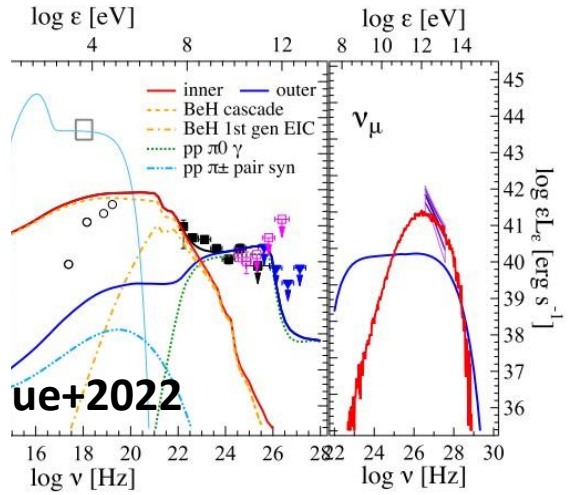


Recent models

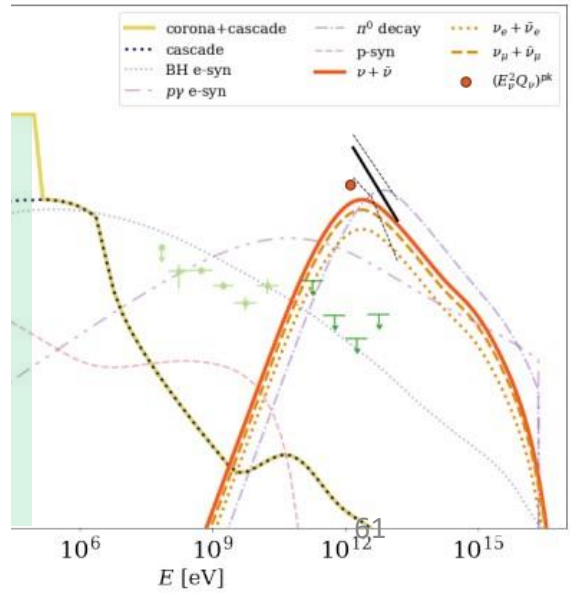






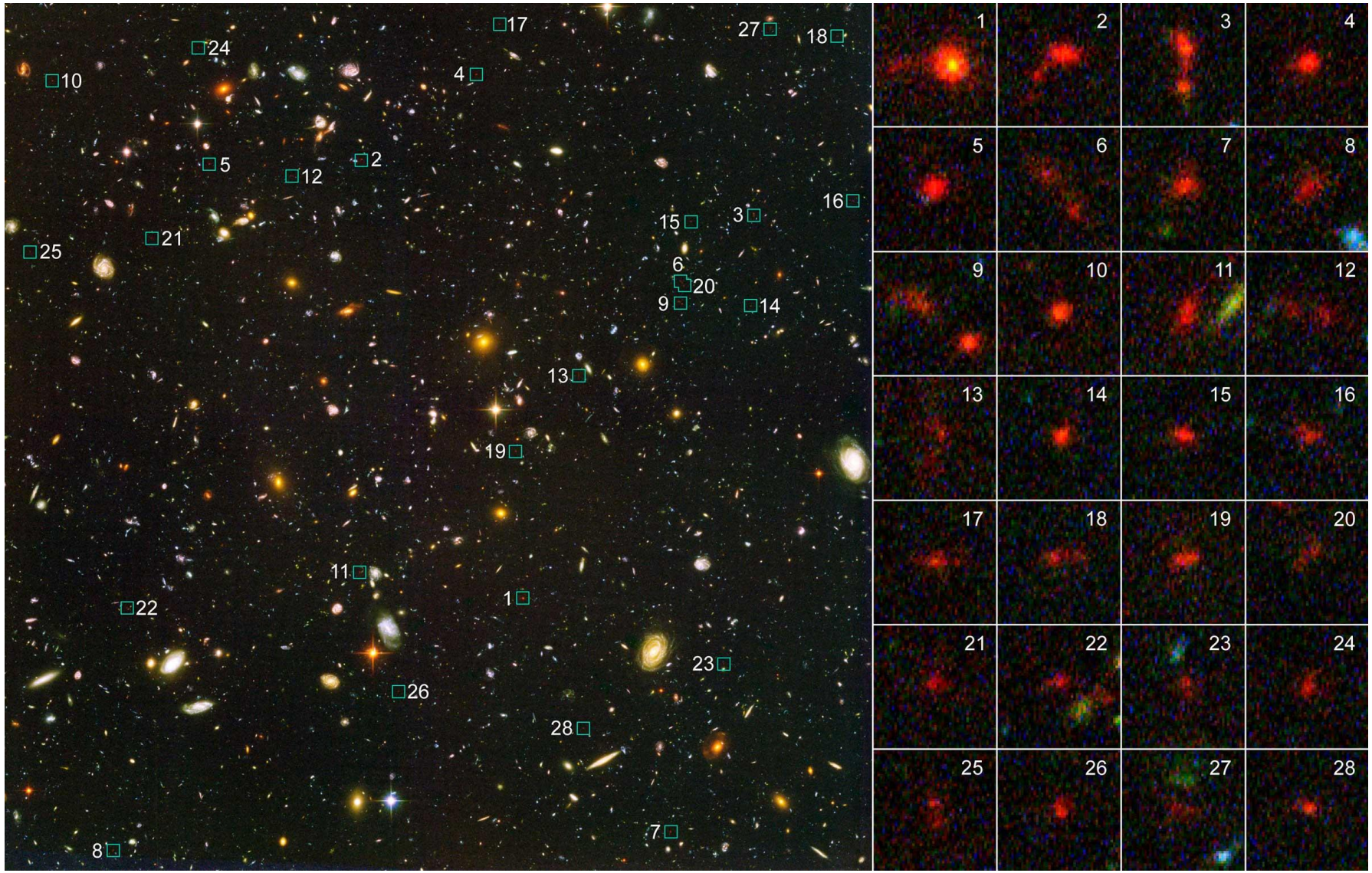


Fiorillo+(including EP) 2024

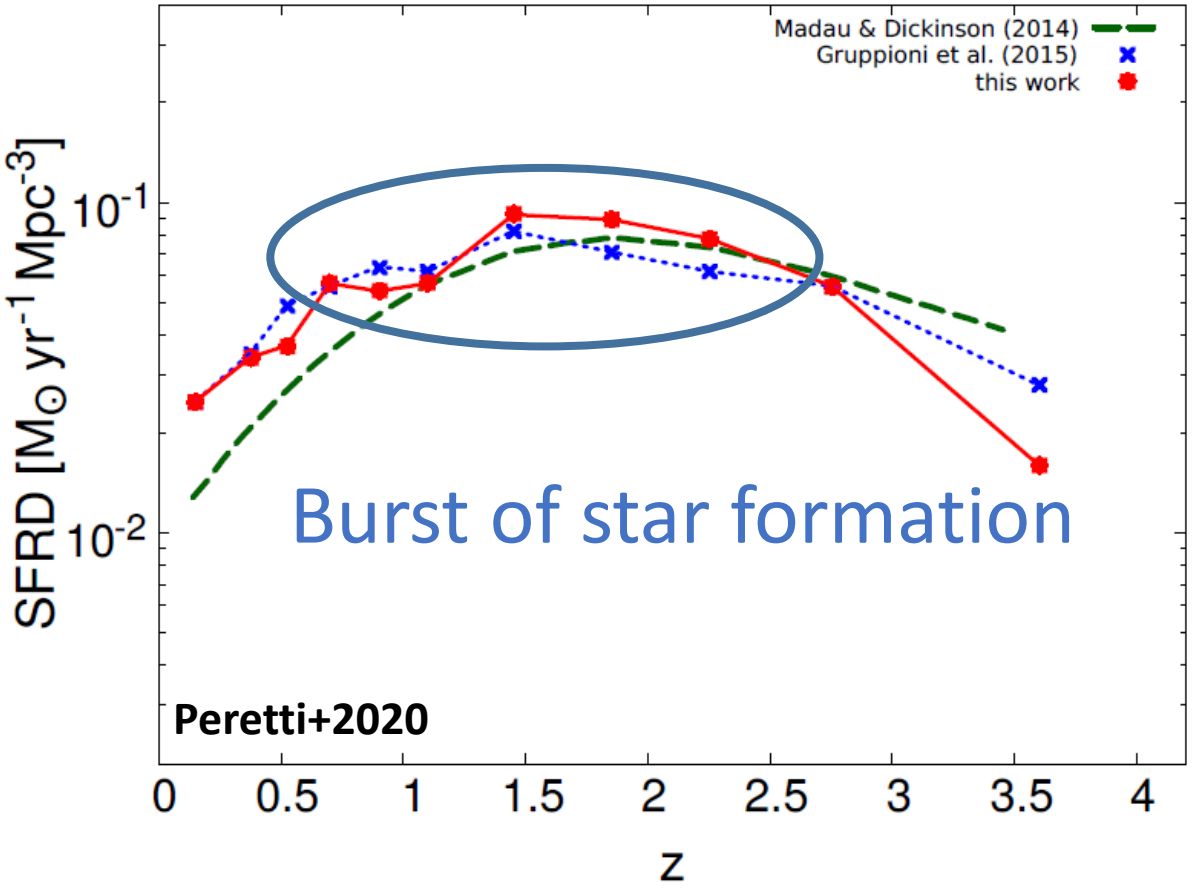


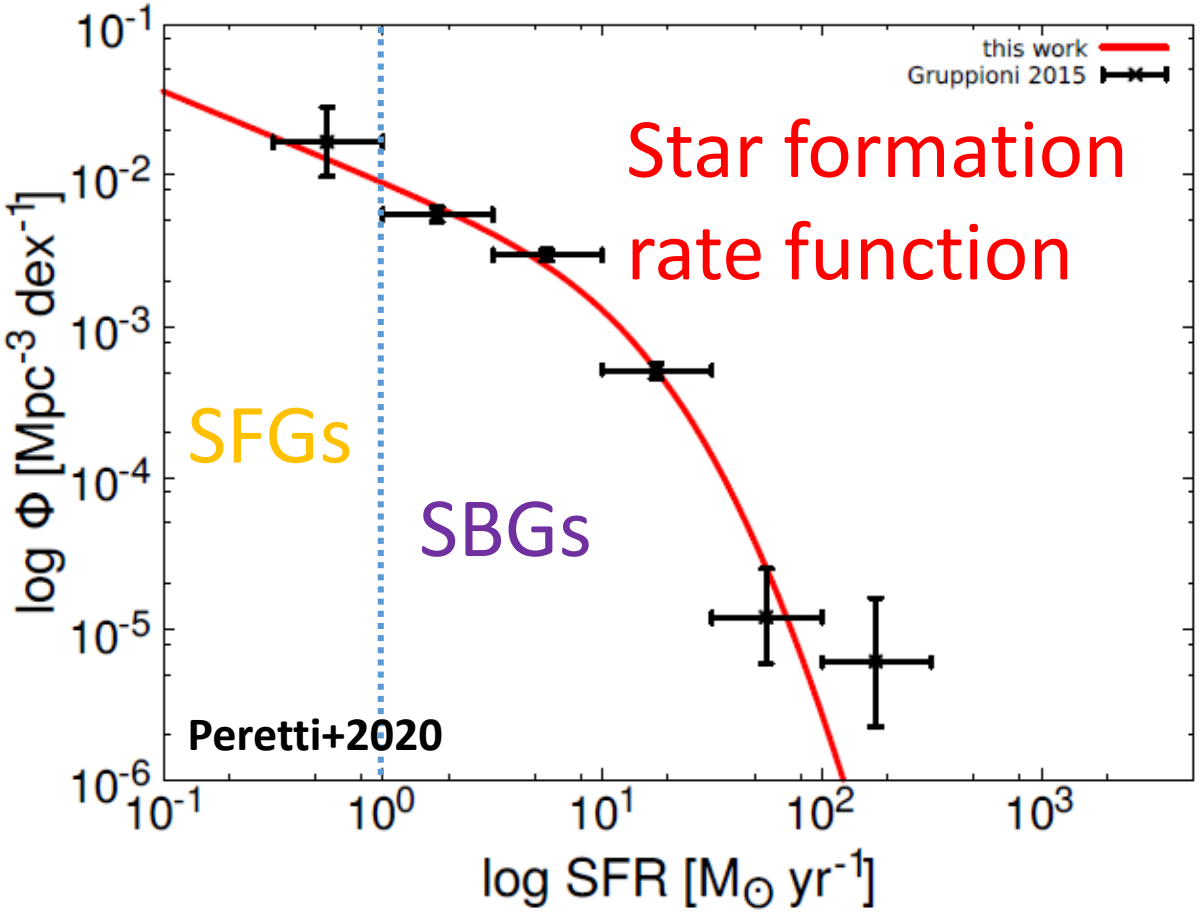
Multi-messenger diffuse flux

Diffuse emission from starbursts

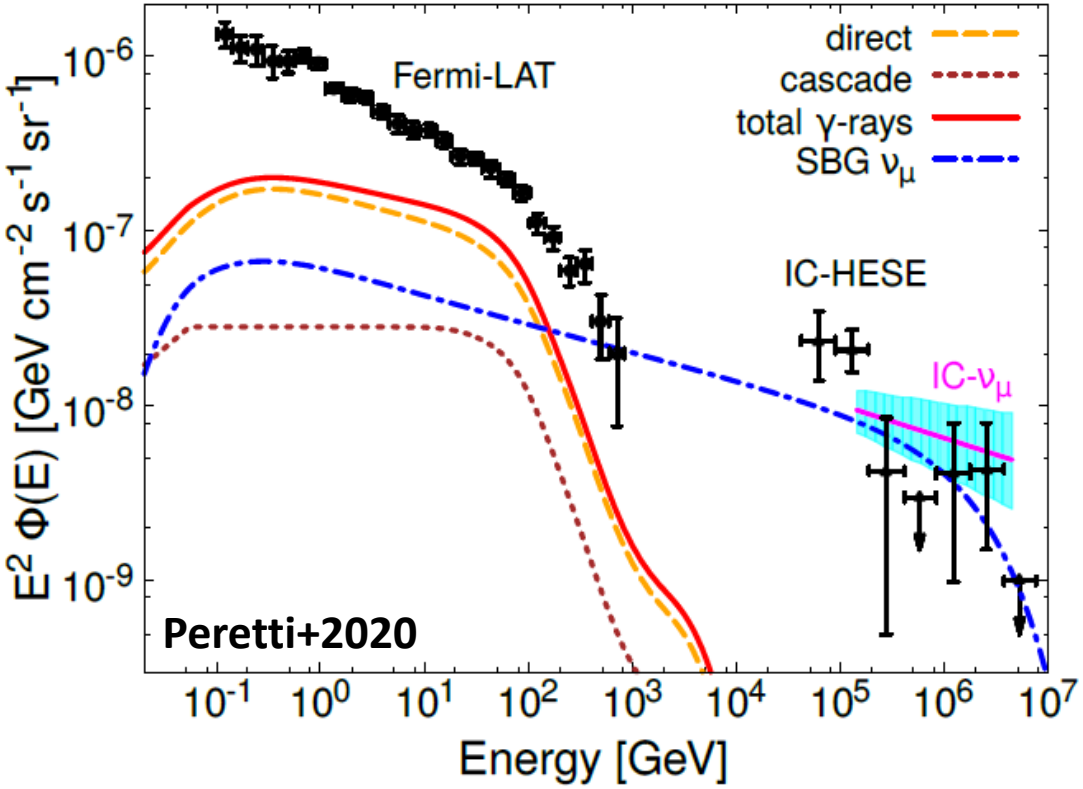


Starbursts as diffuse sources



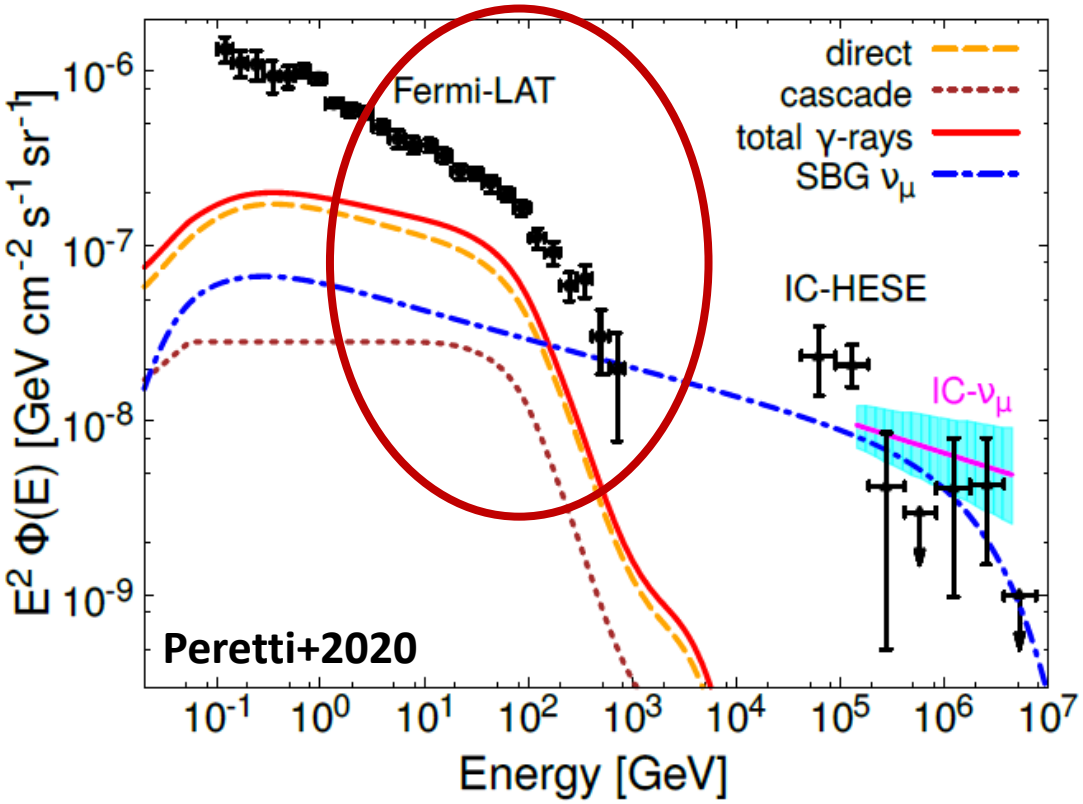


Diffuse emission from Starburst Galaxies



- SBNi only

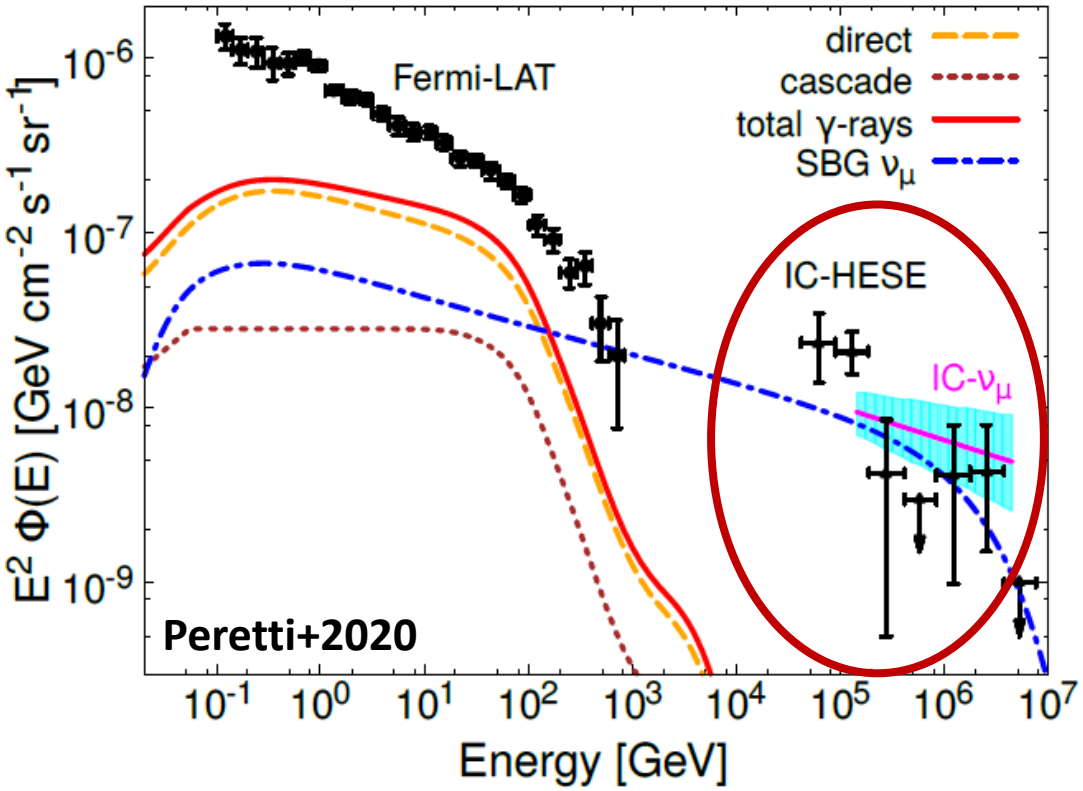
Diffuse emission from Starburst Galaxies



- SBNi only

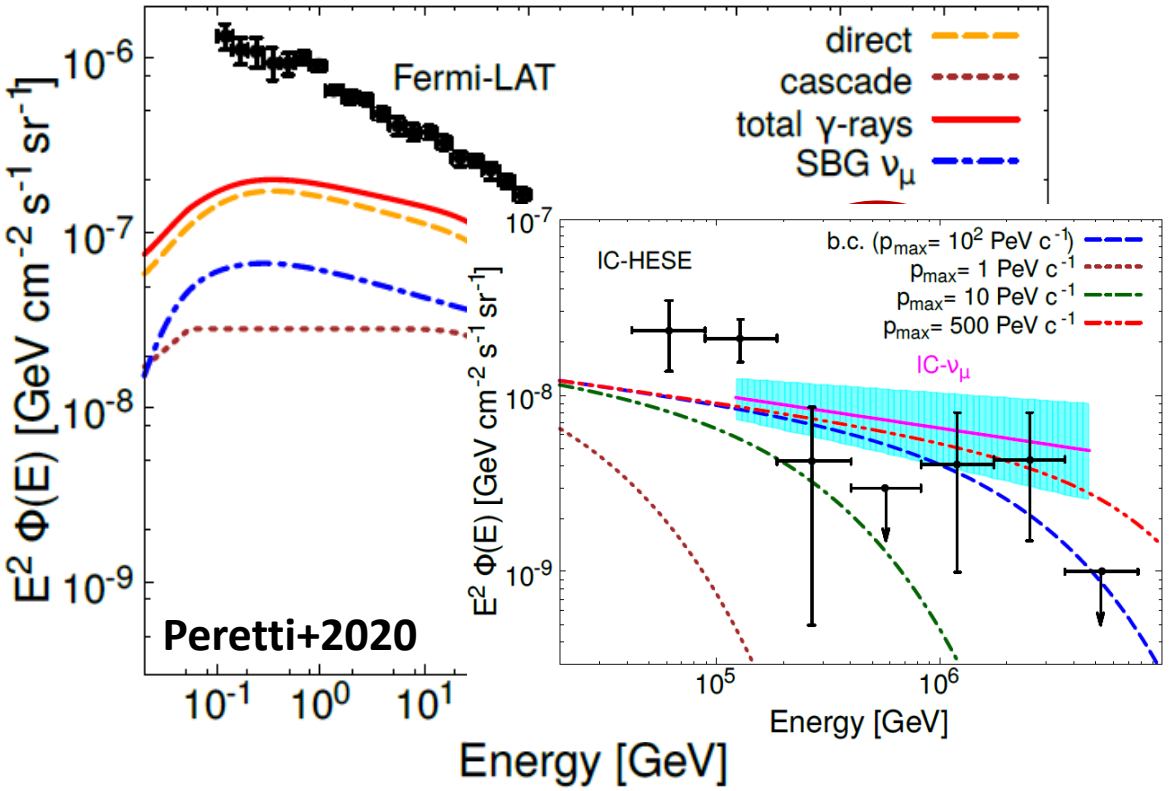
- Sizeable contribution to the diffuse flux observed by Fermi-LAT

Diffuse emission from Starburst Galaxies



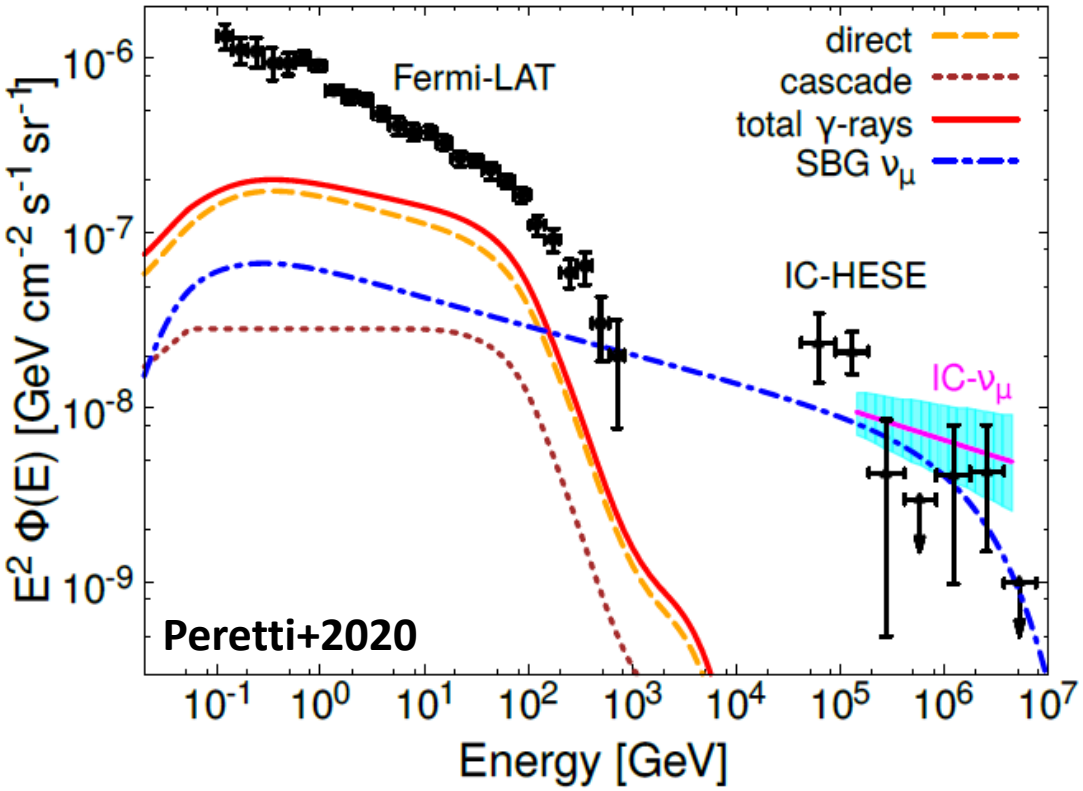
- SBNi only
- Sizeable contribution to the diffuse flux observed by Fermi-LAT
- Neutrino flux at the level of IceCube measurment

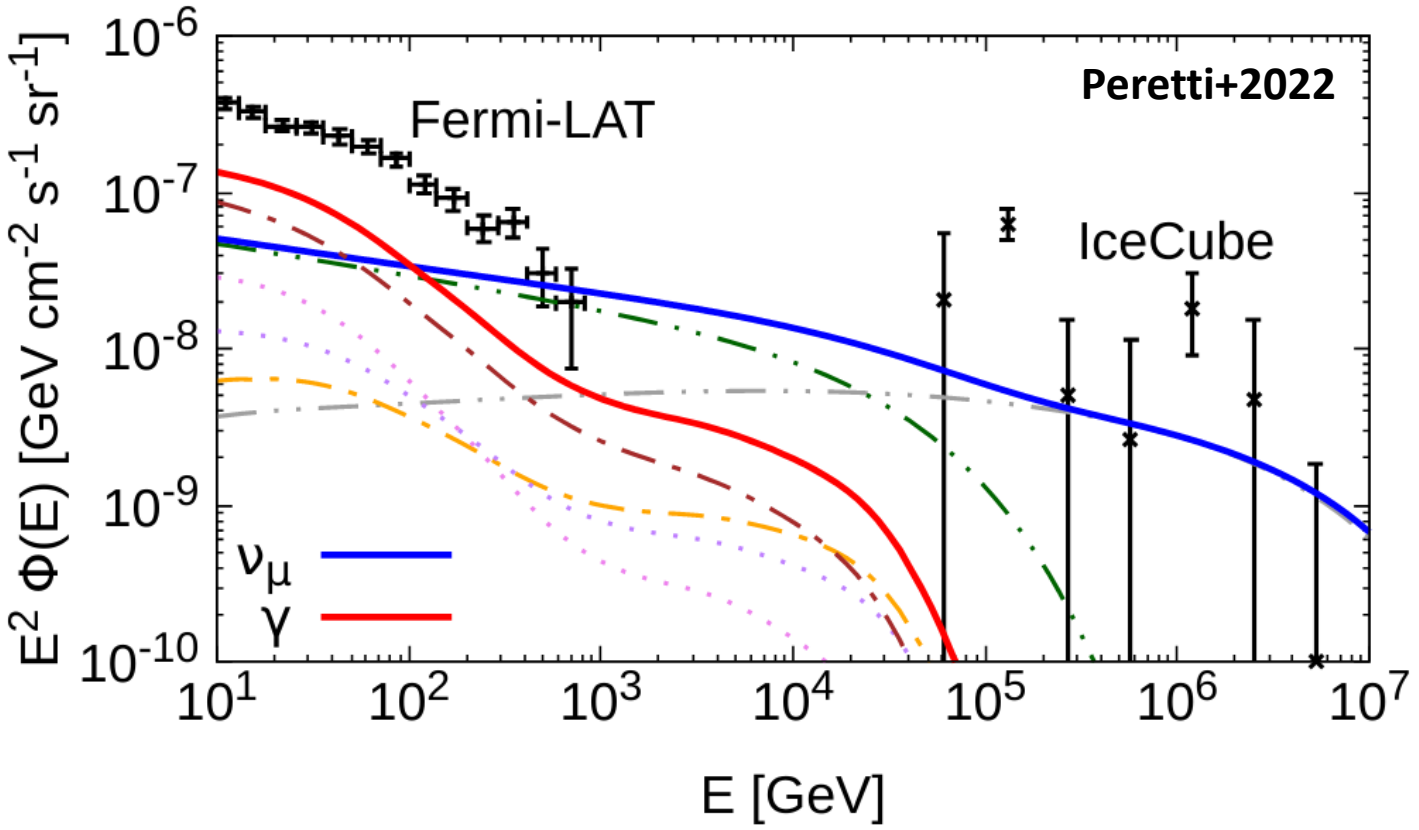
Diffuse emission from Starburst Galaxies



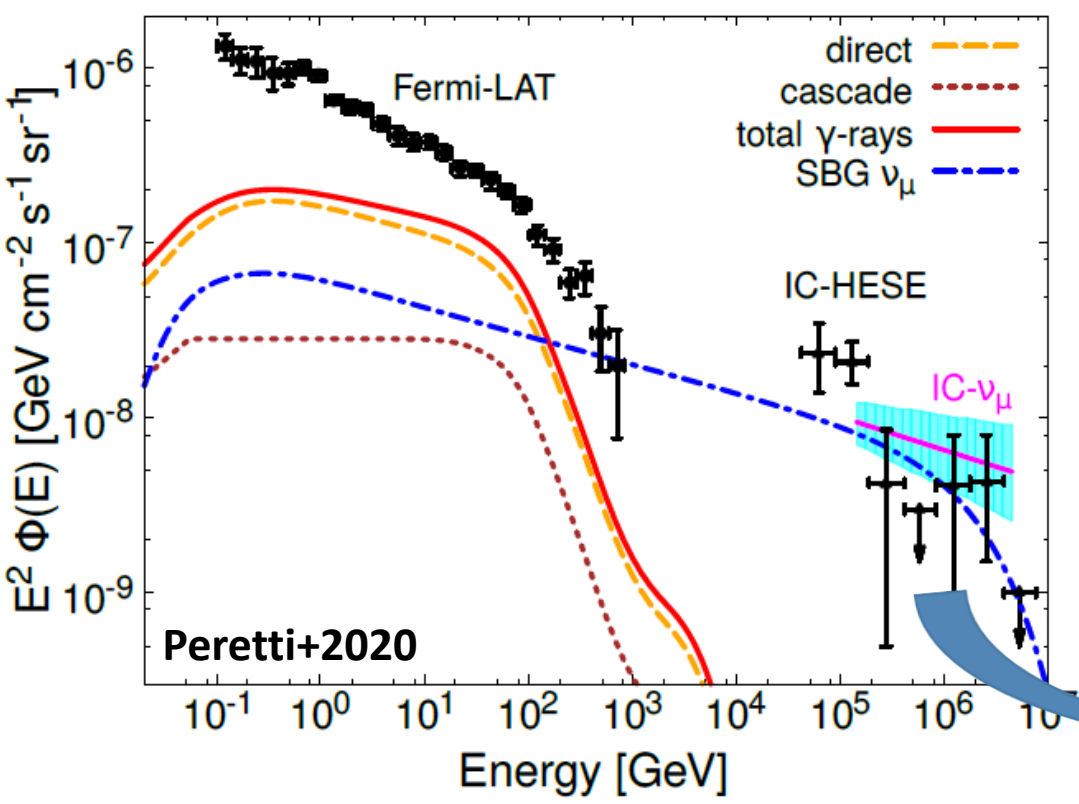
- SBNi only
- Sizeable contribution to the diffuse flux observed by Fermi-LAT
- Neutrino flux at the level of IceCube measurment

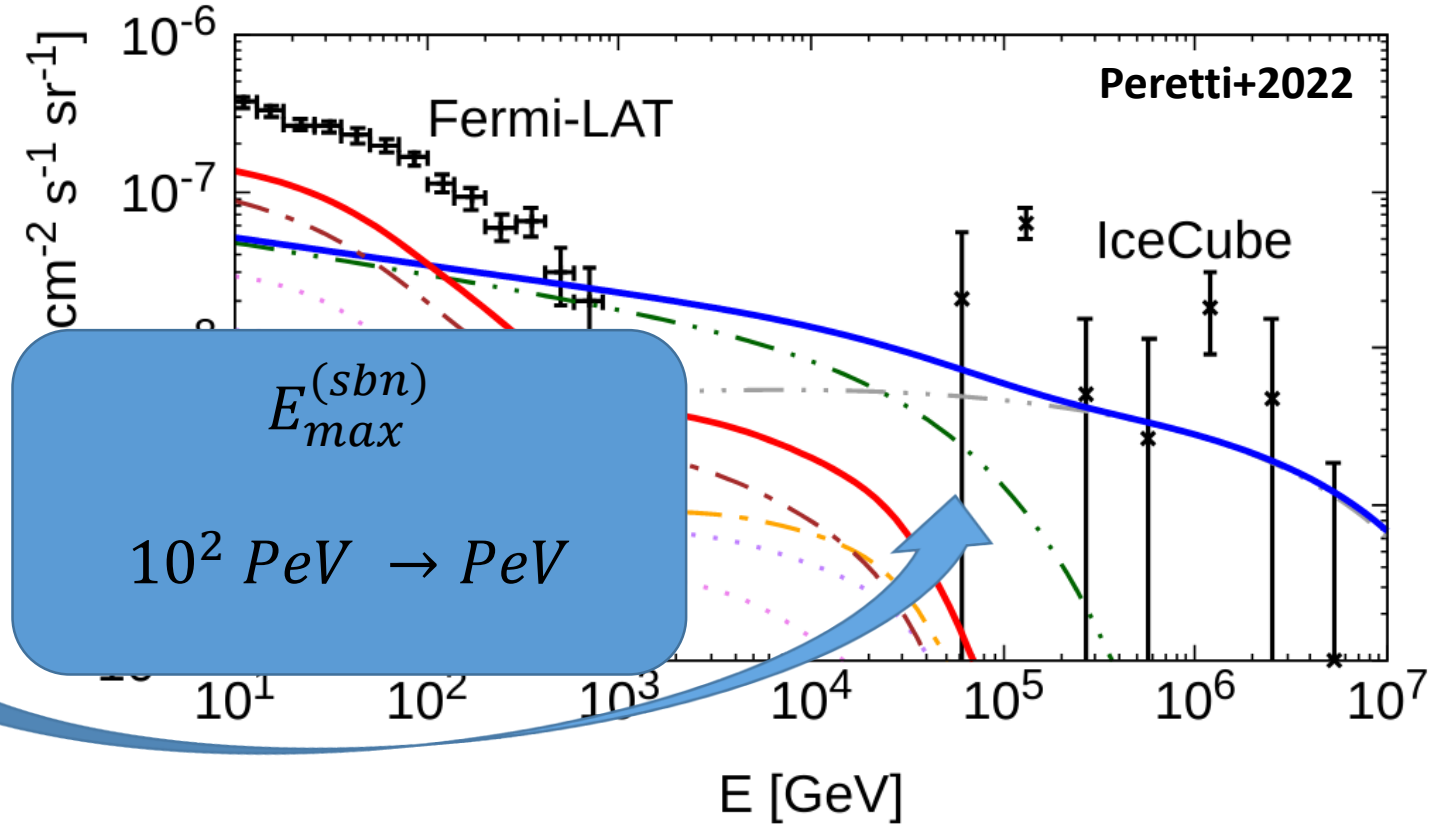
Diffuse emission from Starburst Winds





Diffuse emission from Starburst Winds

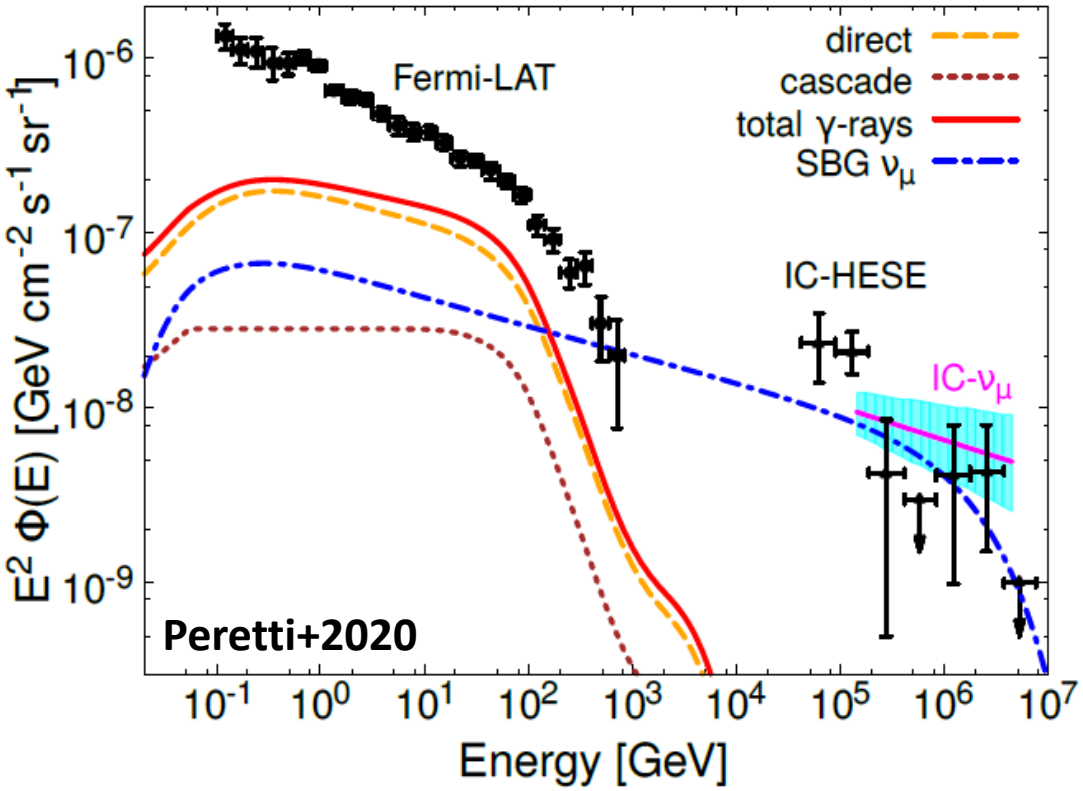


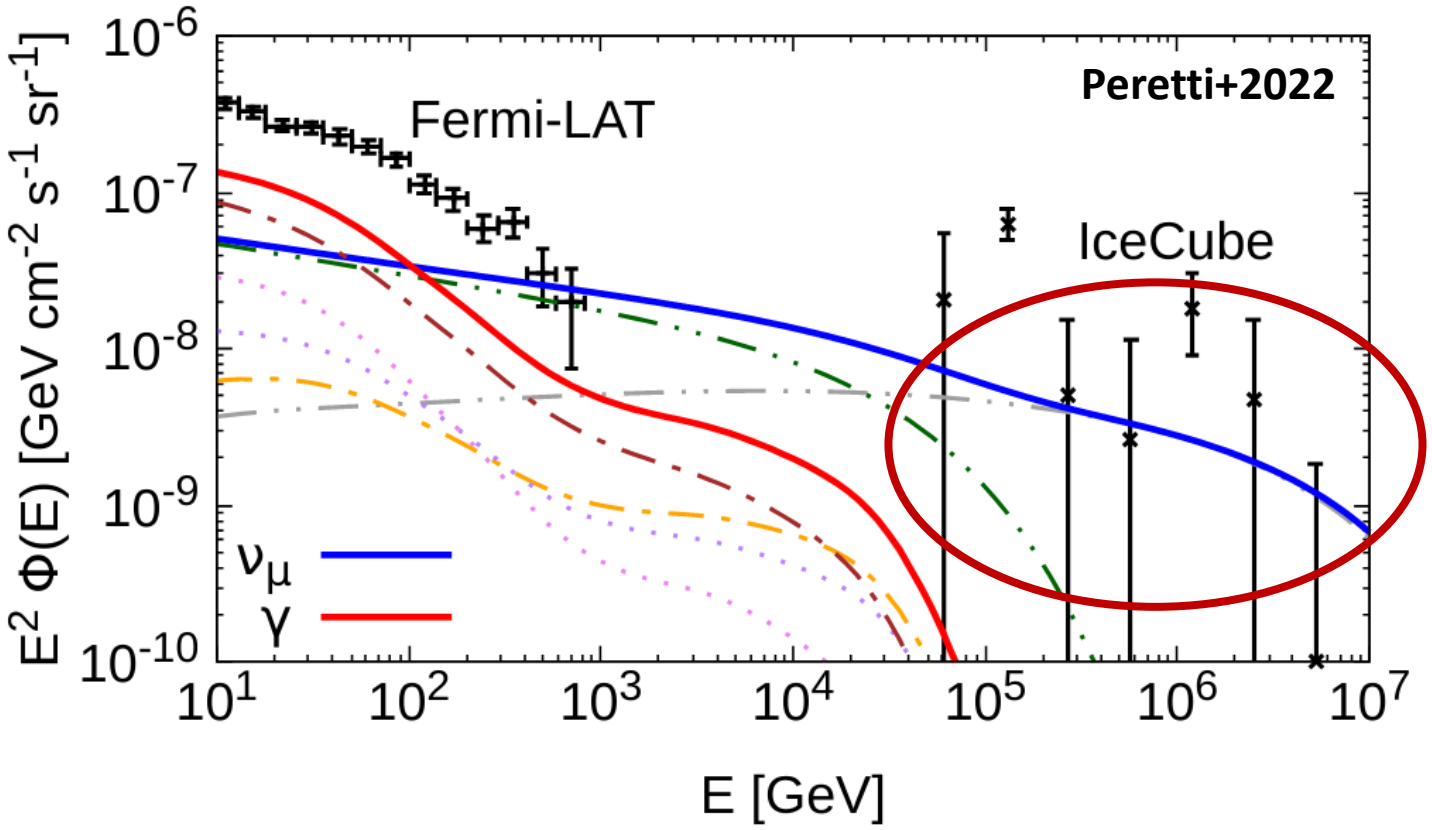


$$E_{max}^{(sbn)}$$

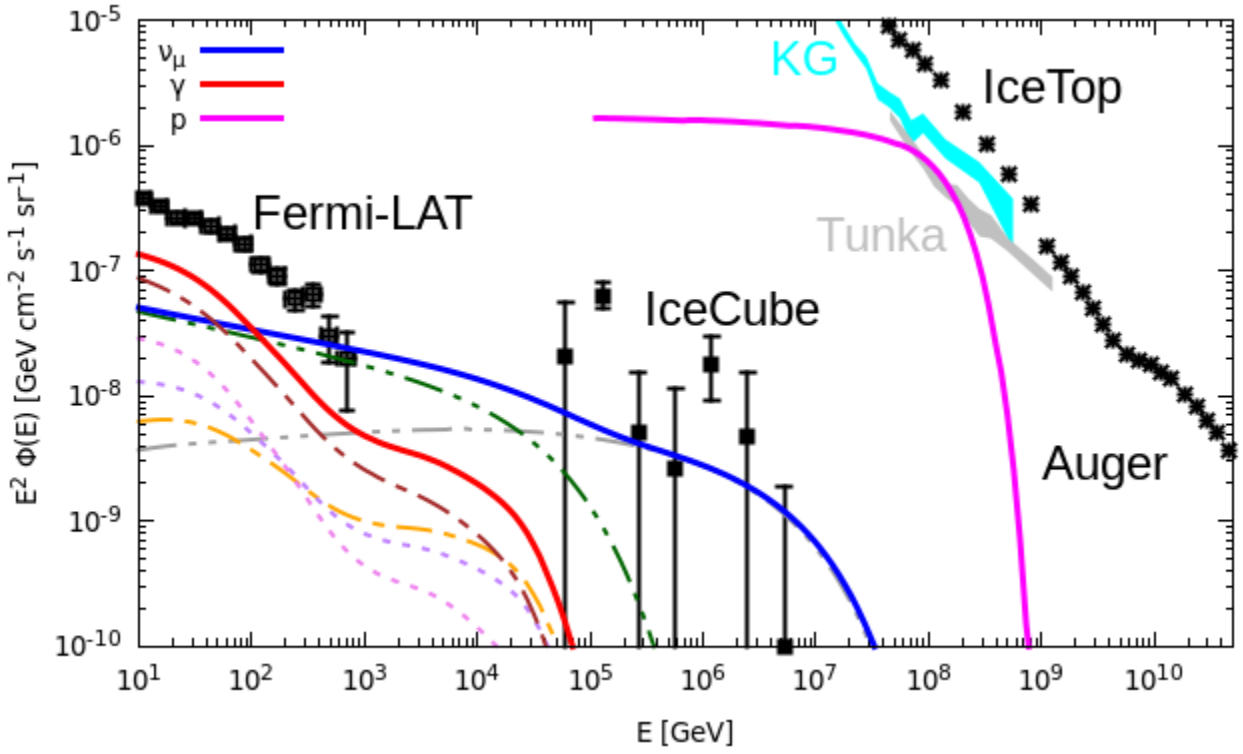
$$10^2\ PeV \rightarrow PeV$$

Diffuse emission from Starburst Winds

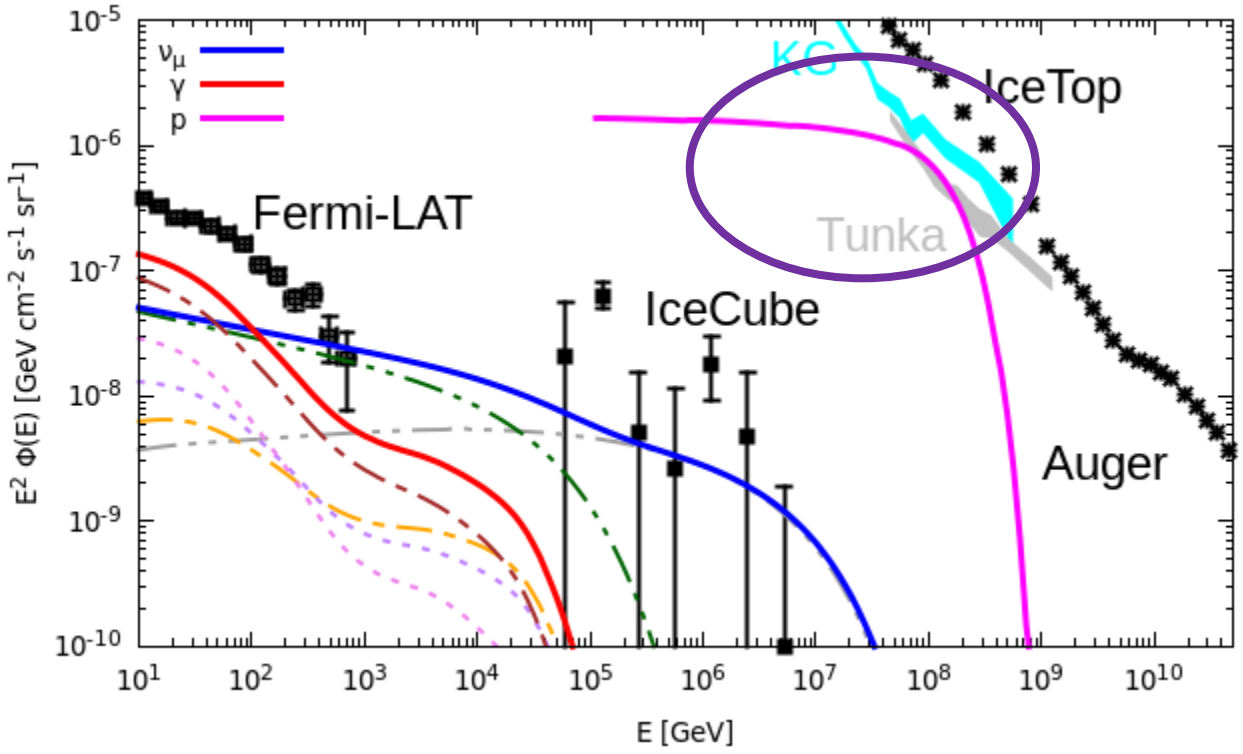


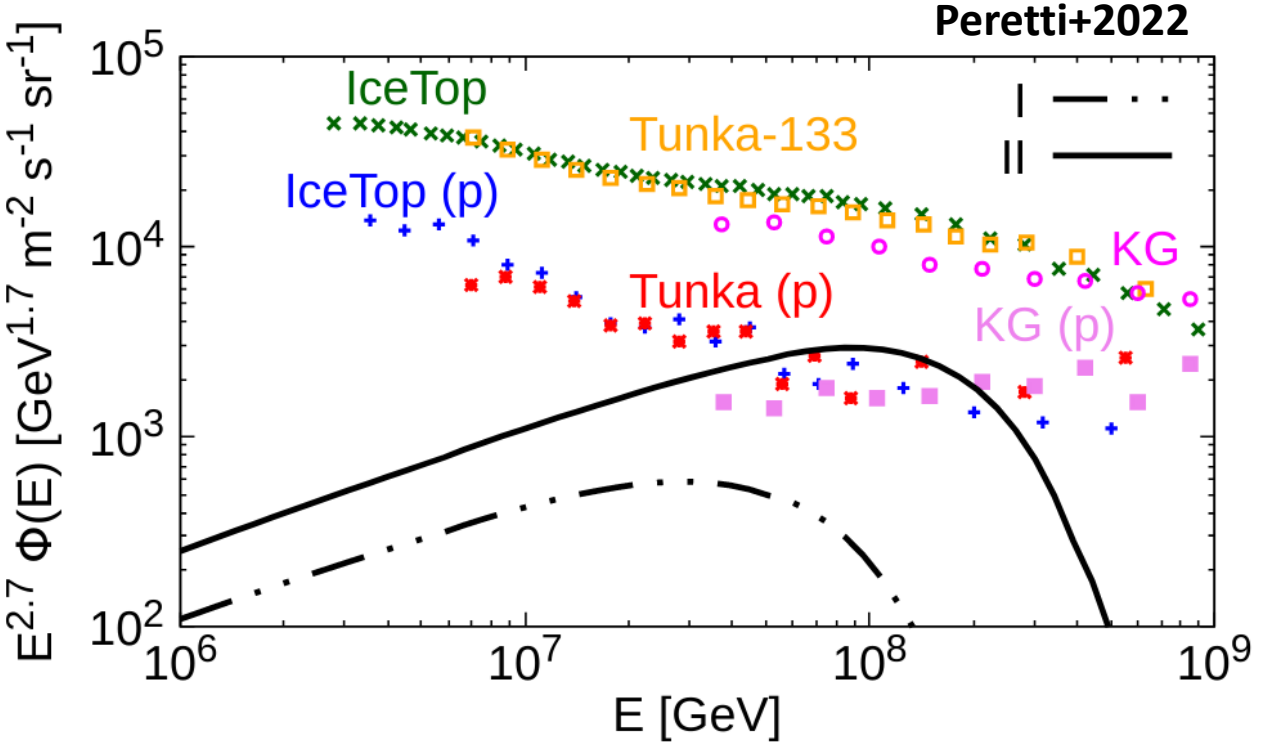


Multimessenger emission from Starburst Galaxies and their winds

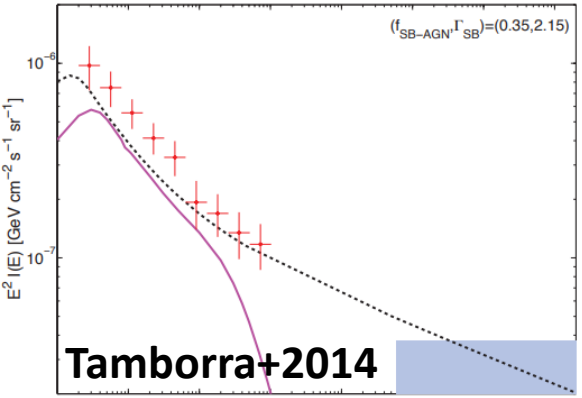


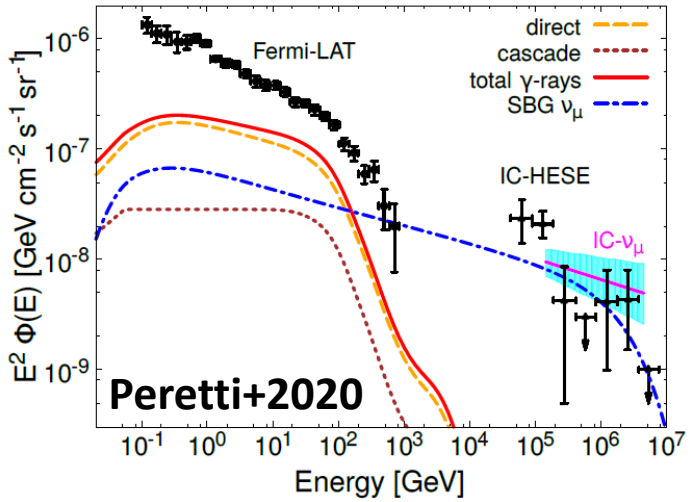
Multimessenger emission from Starburst Galaxies and their winds

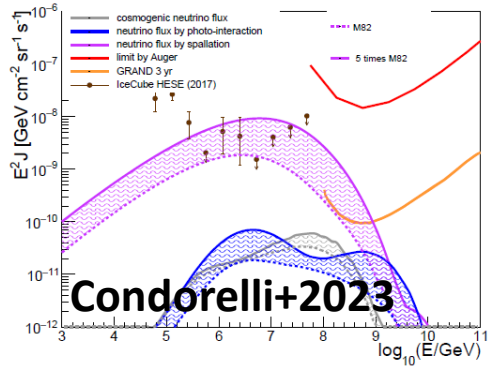


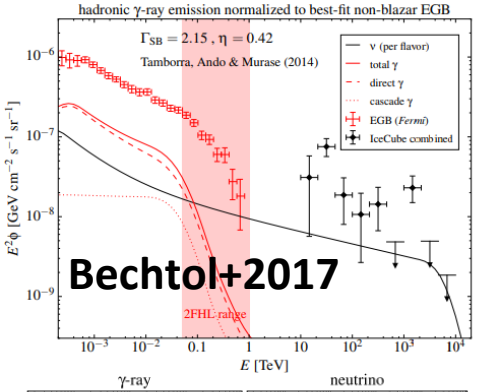


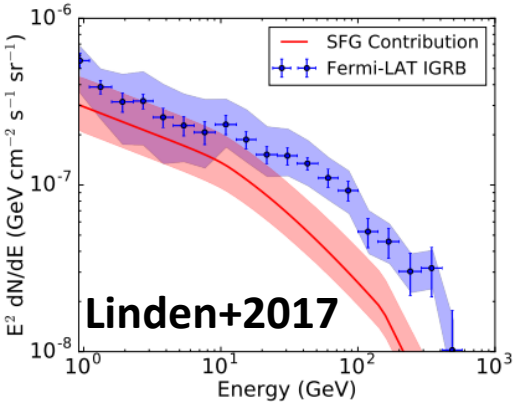
Starbursts in the last 10 years

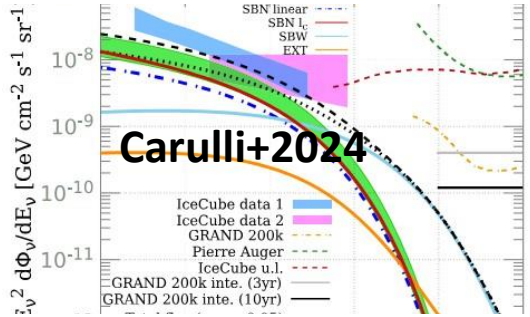


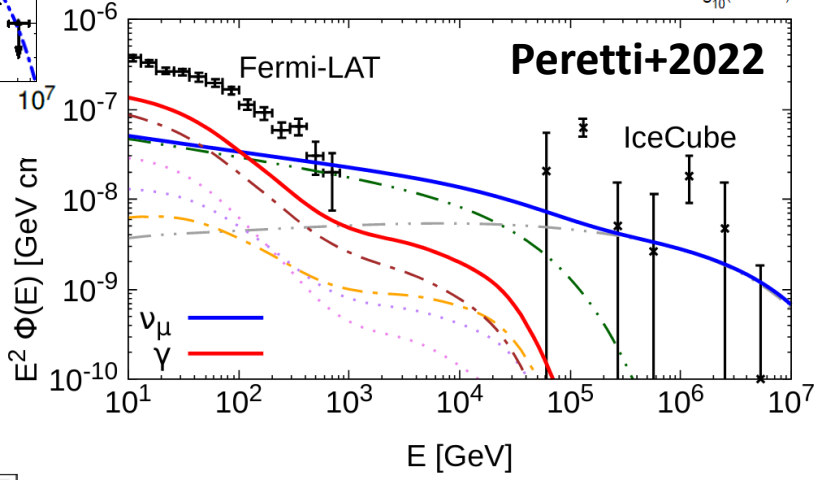


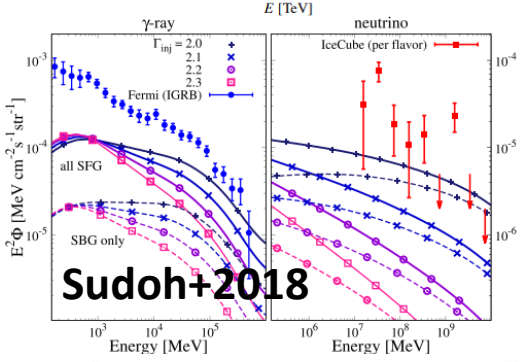


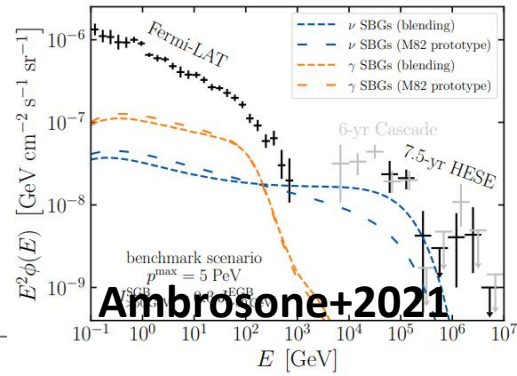


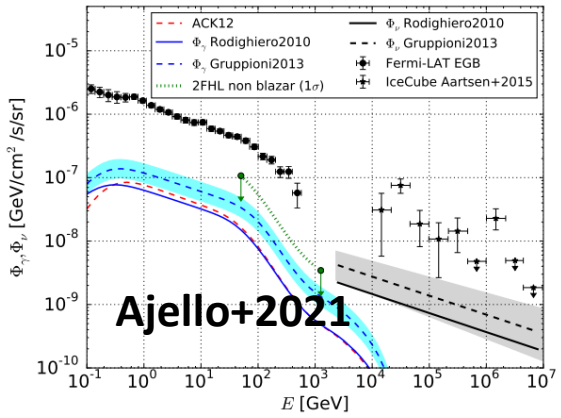


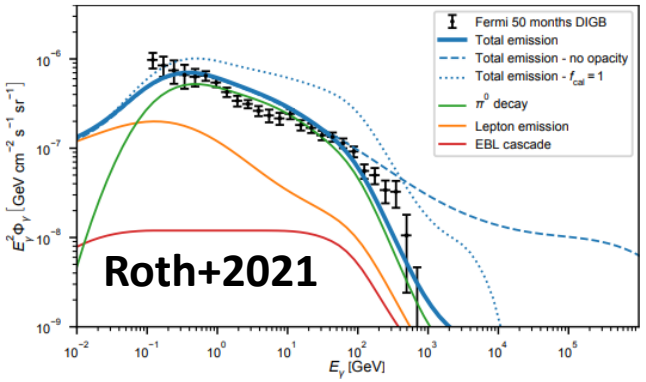


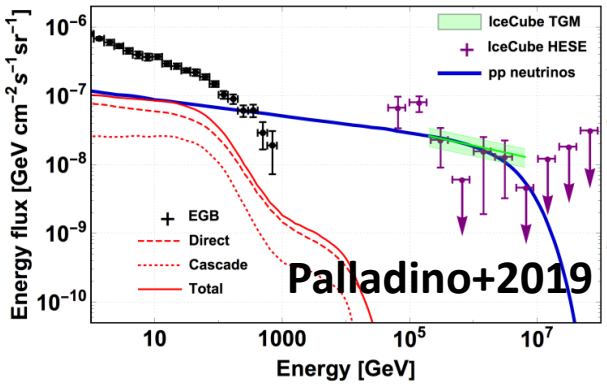


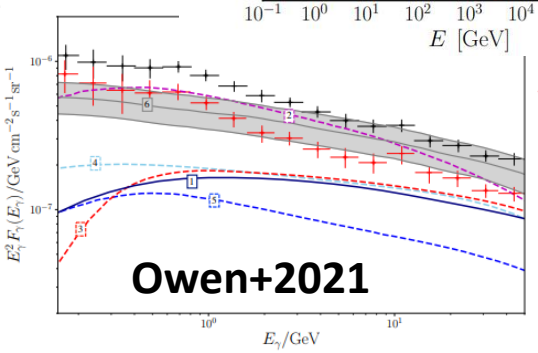






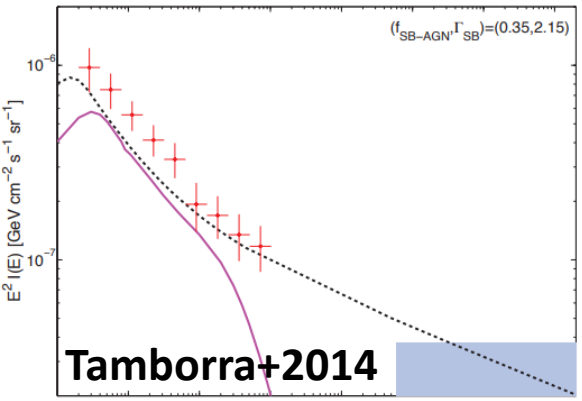


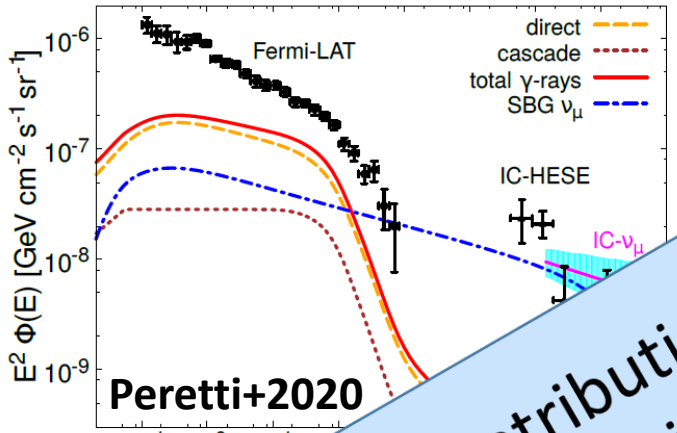


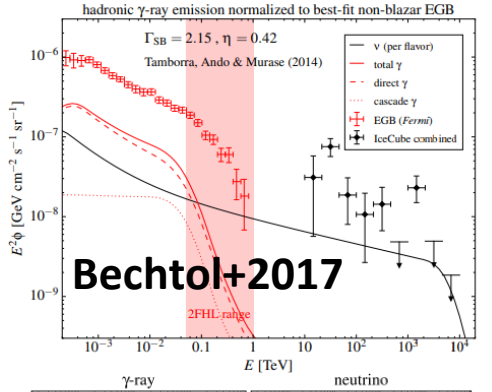


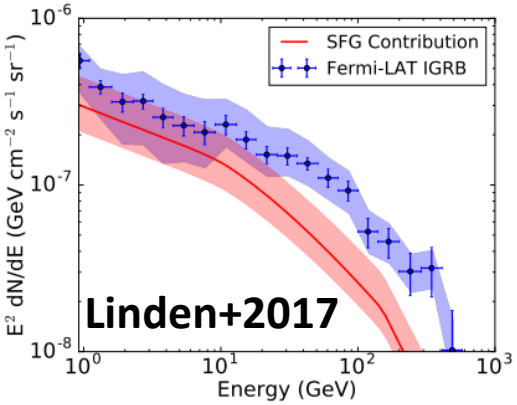
Starbursts in the last 10 years

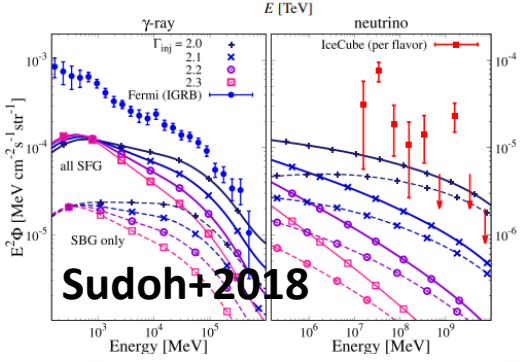
Starburst contribution to the diffuse γ-ray flux and HE neutrino flux beyond 100 TeV ranges from 1% up to 100%

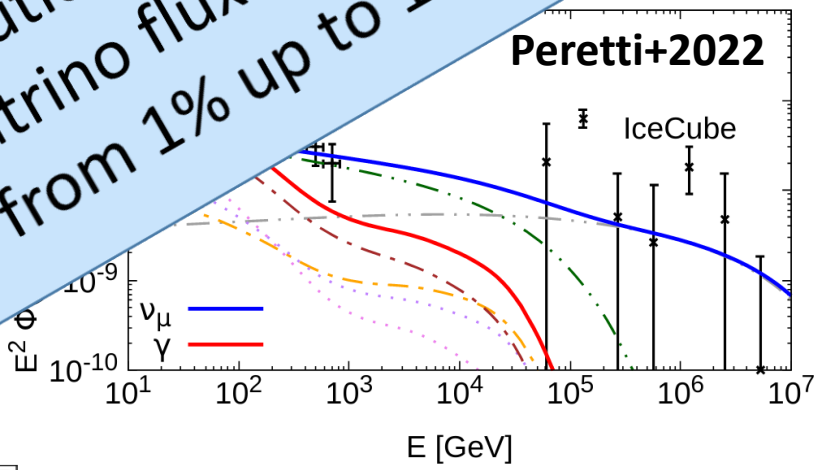


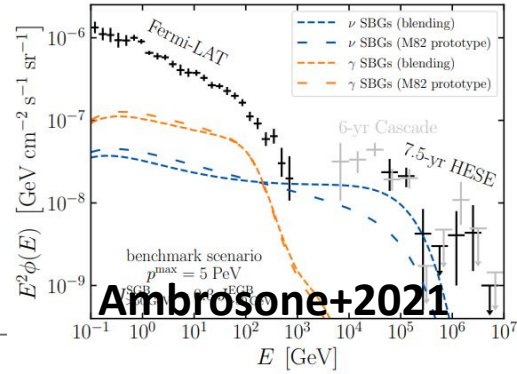


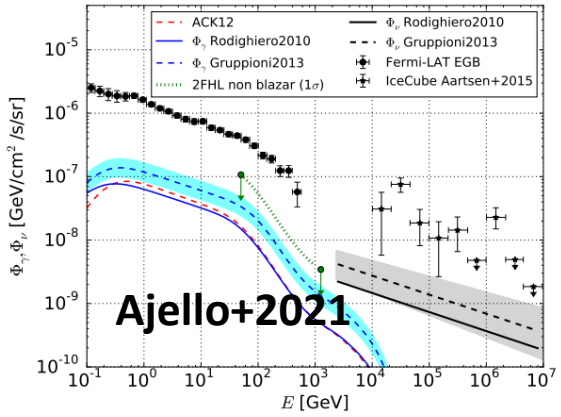


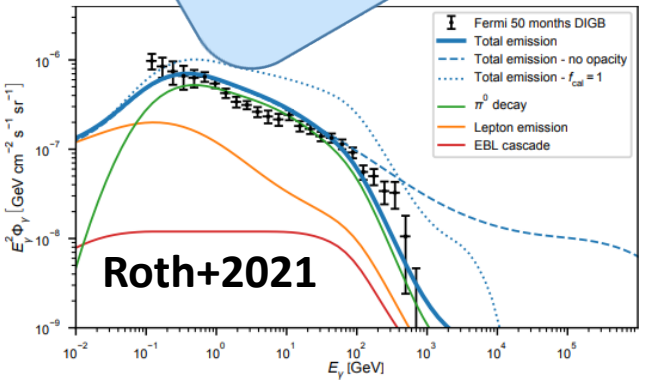


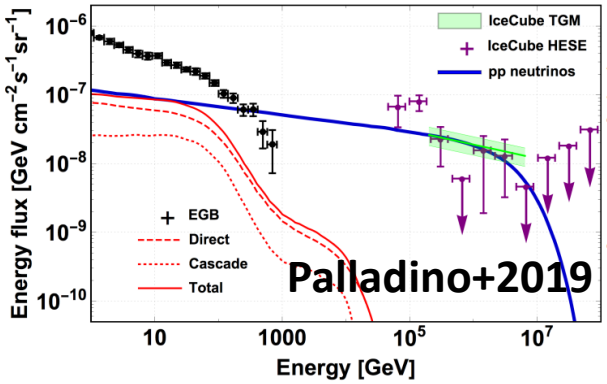


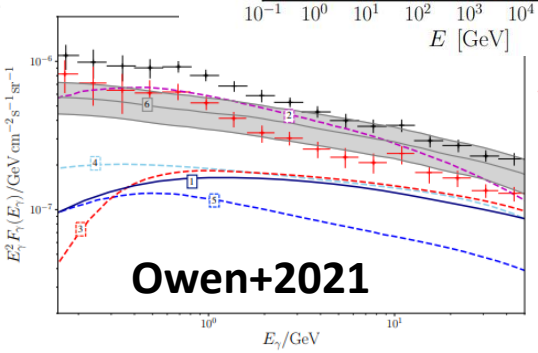




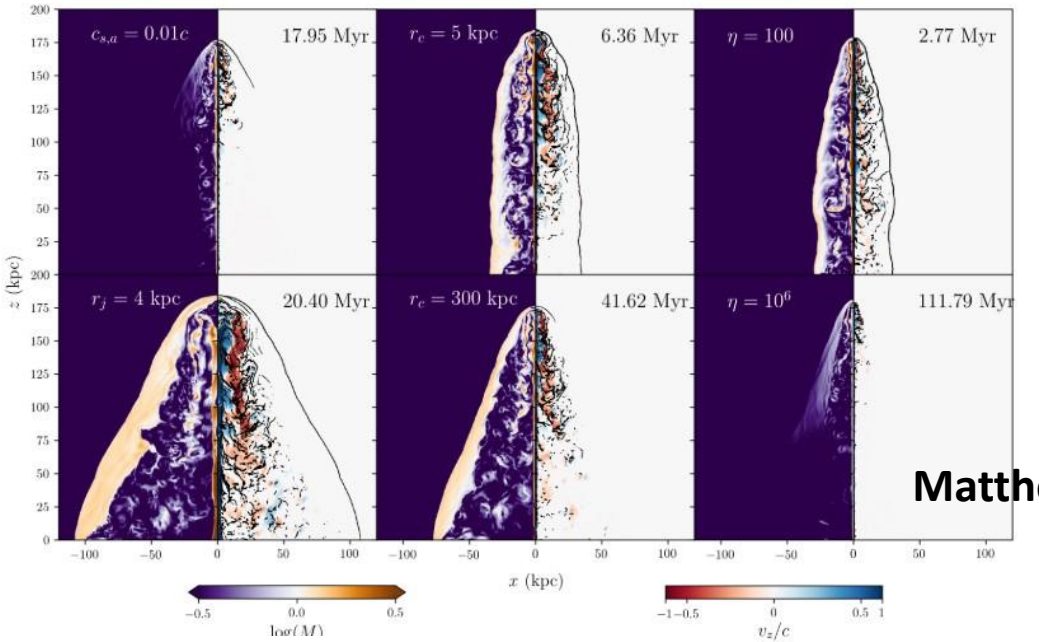




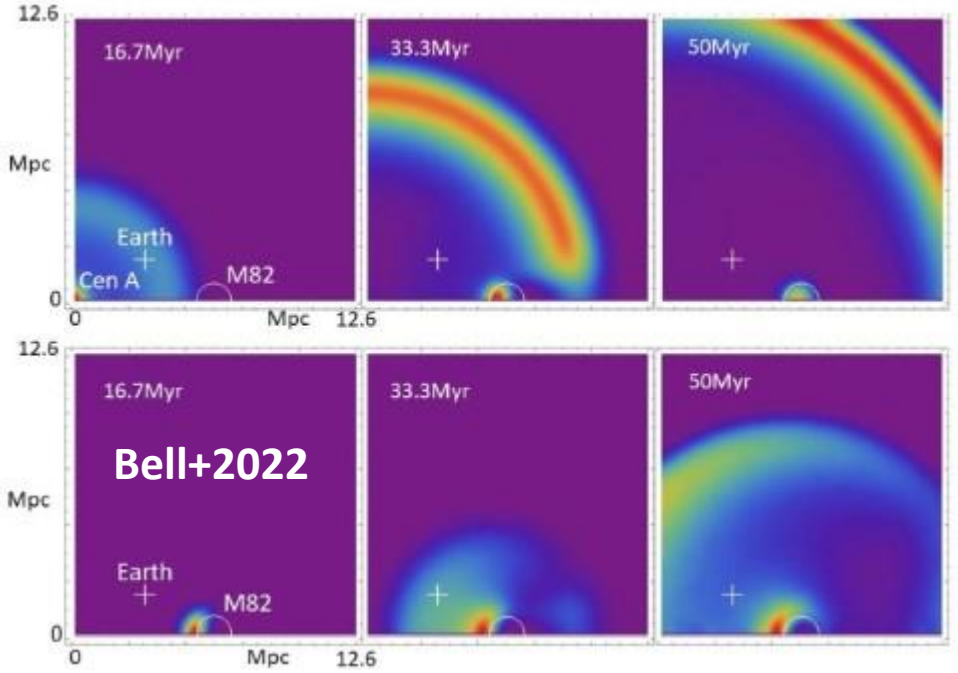




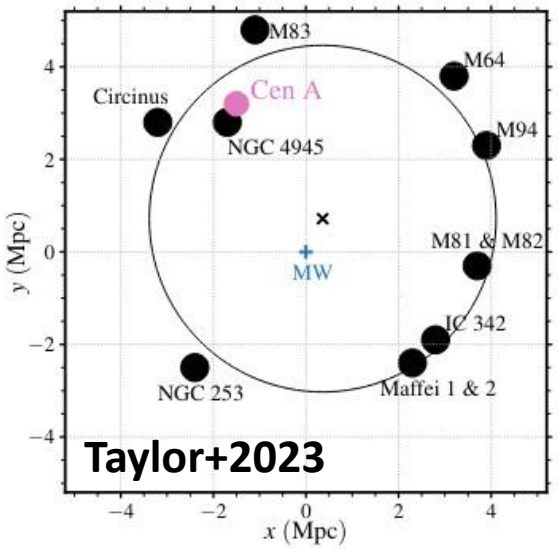
Alternative scenario: Echoes of Cen A activity



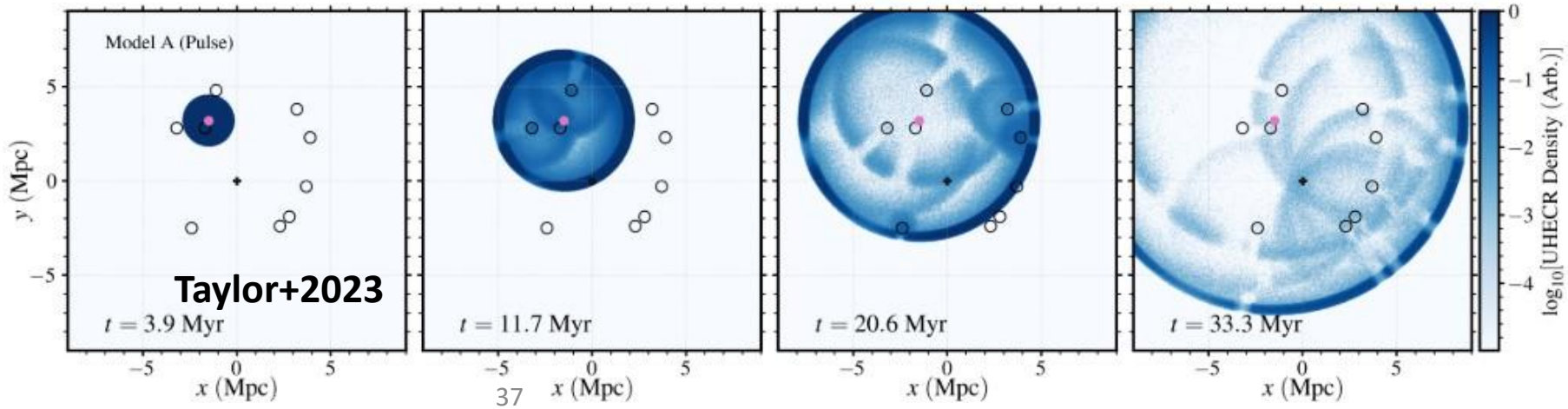
Matthews+2018



Bell+2022

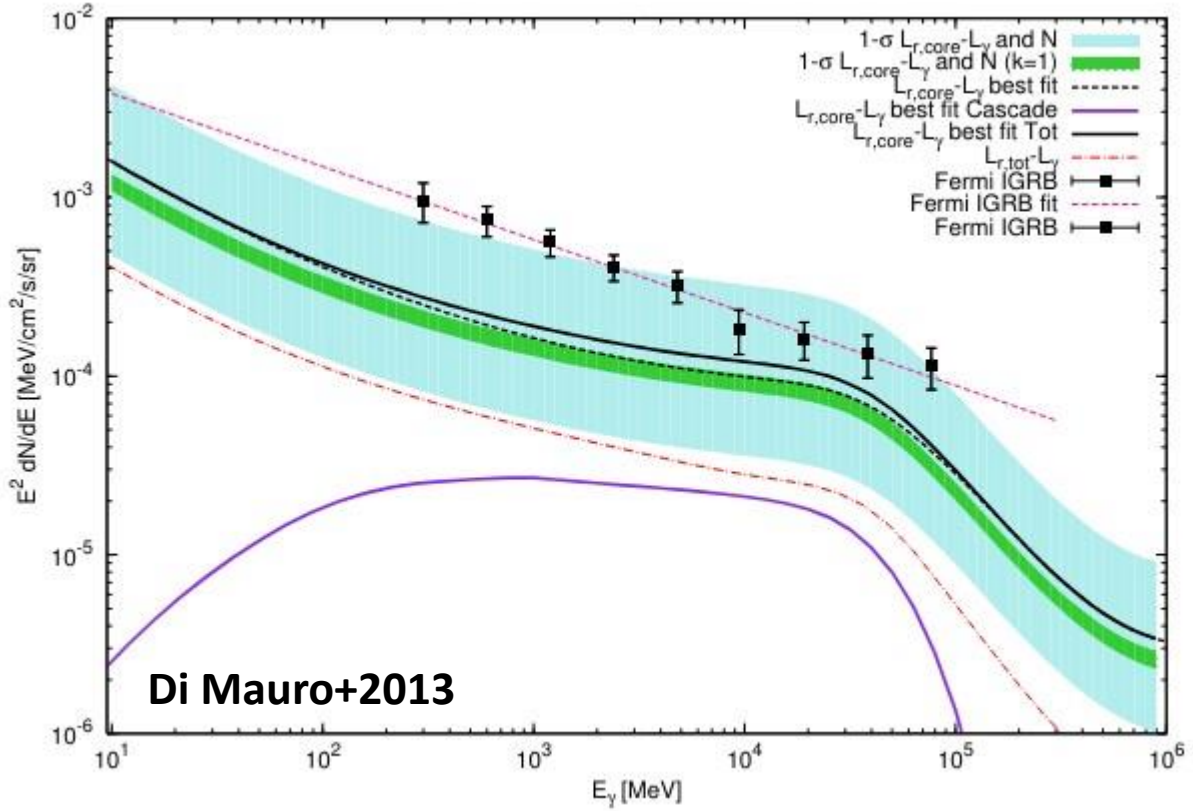


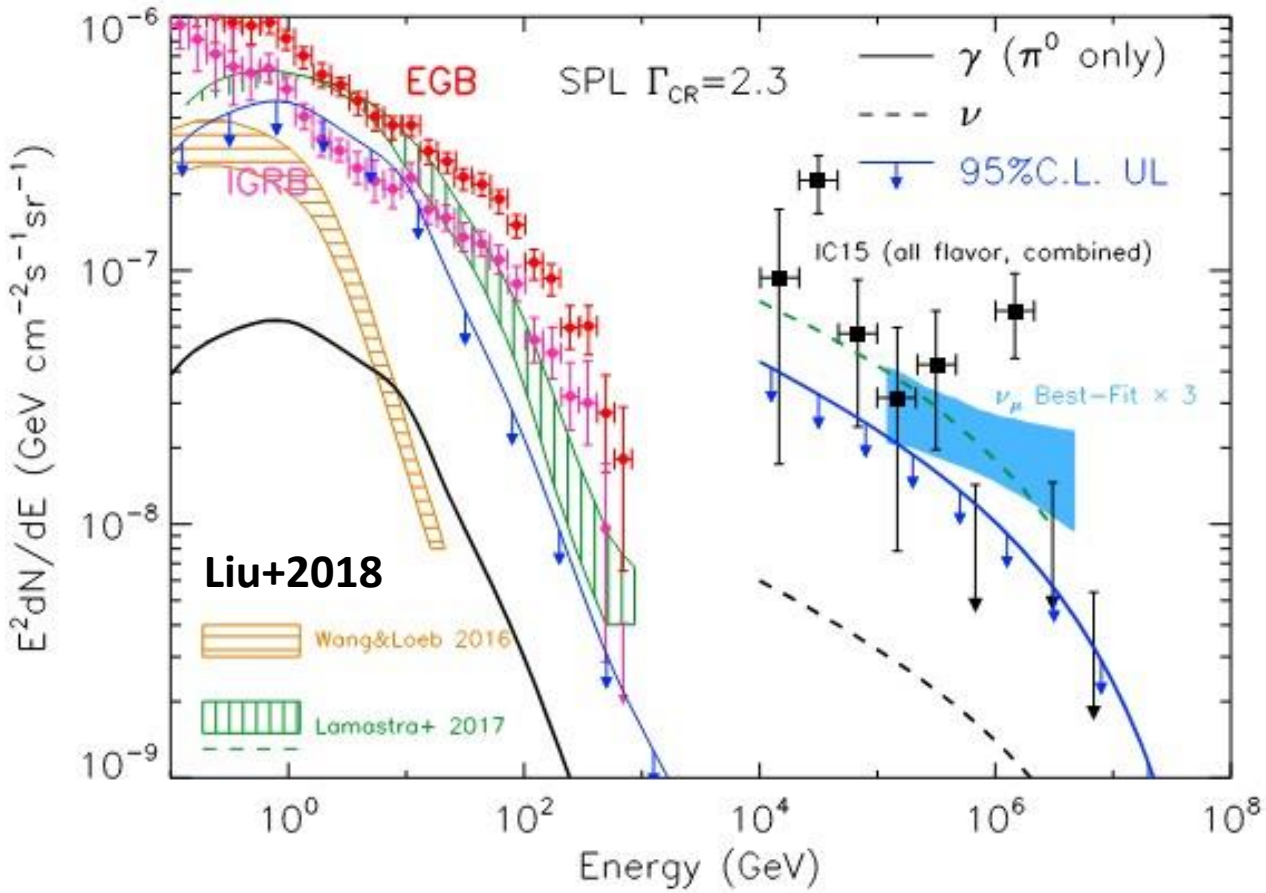
Taylor+2023



Taylor+2023

Diffuse emission from AGNi





Take home messages

1. Starburst galaxies (SBGs) and AGN are cosmic-ray factories

2. Starburst nuclei (SBNi) can approach calorimeteric conditions

3. Starburst and AGN winds can accelerate respectively up to 100 PV and EV

4. We expect γ-rays and neutrinos both from SBGs and AGN

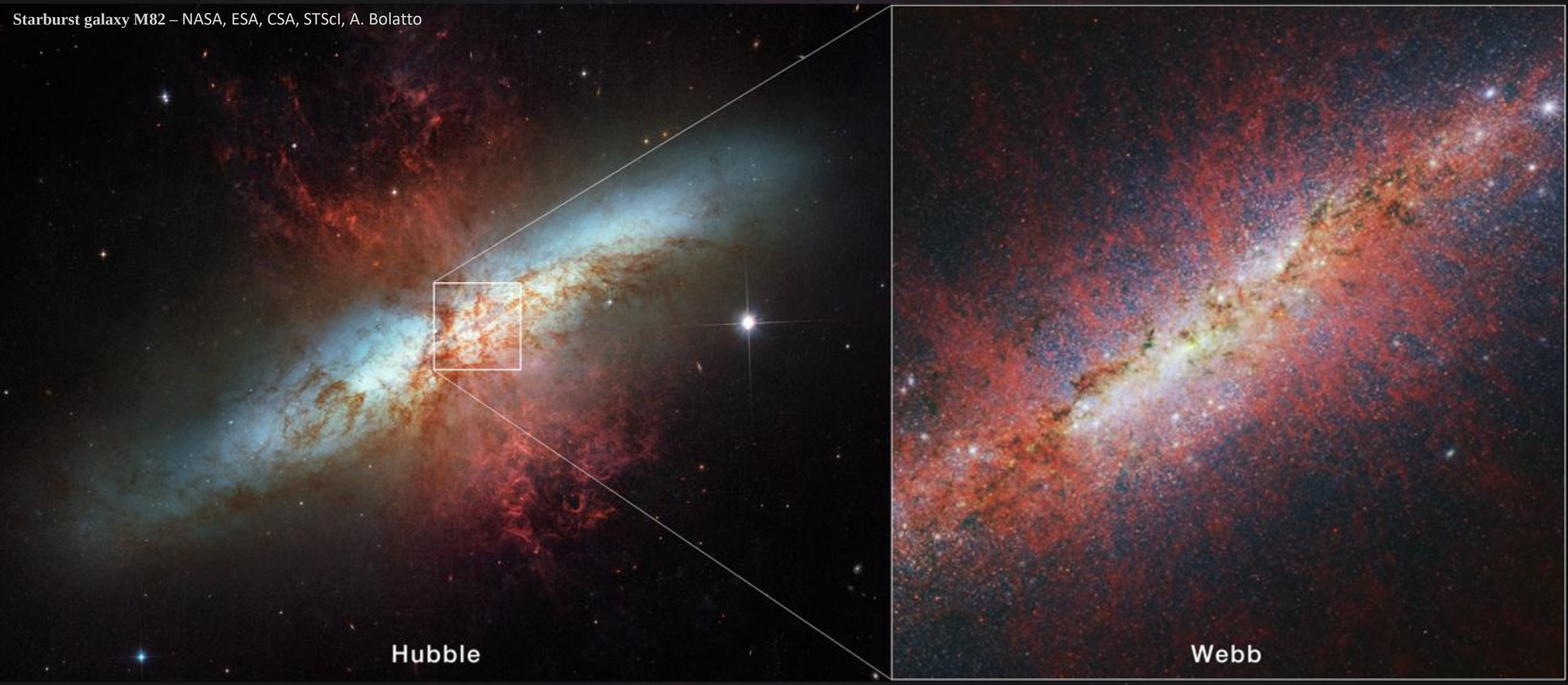
5. SFGs and AGN can dominate the multi-messenger diffuse flux

6. Which are the sources of UHECRs?

THANK YOU!

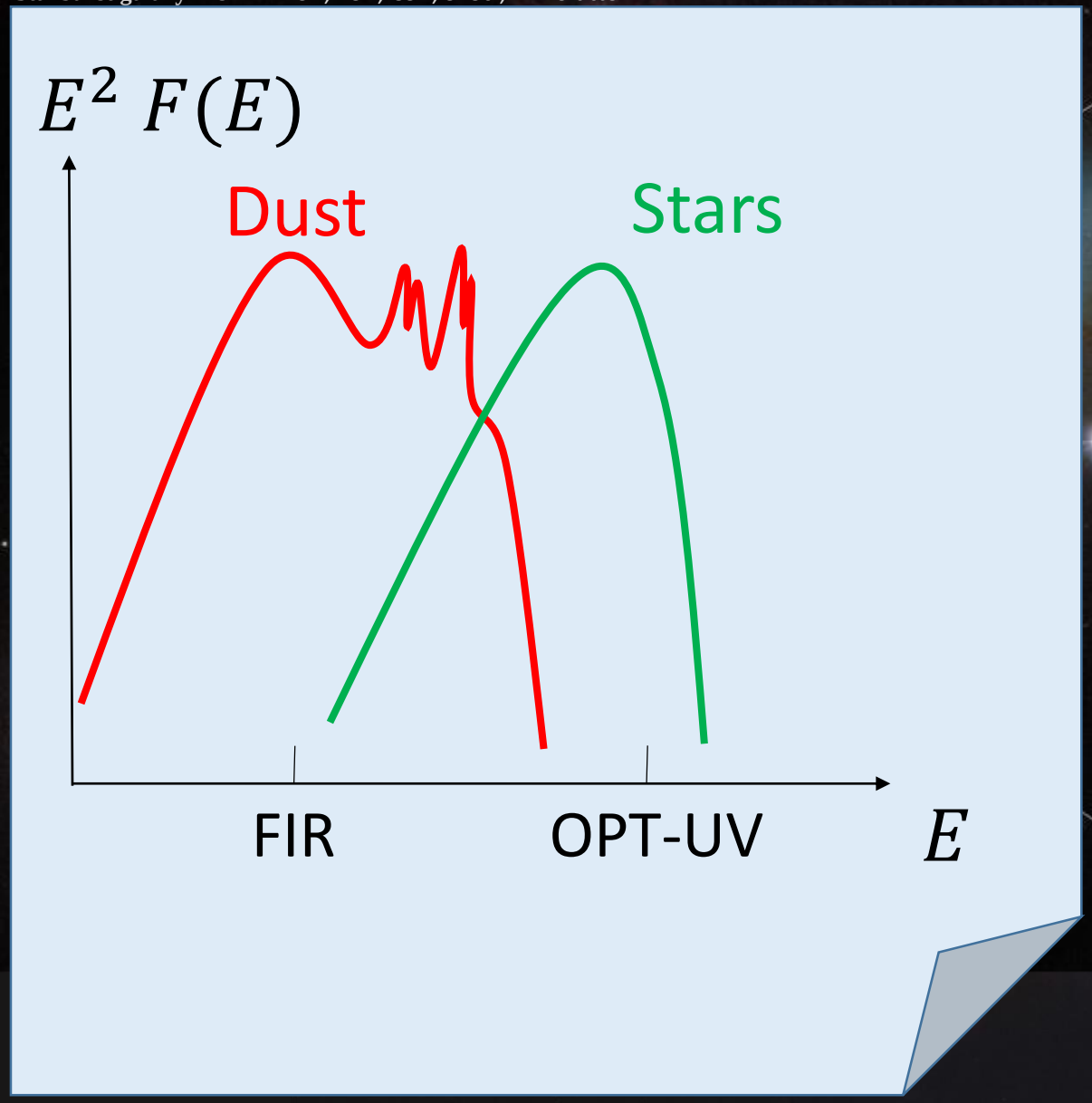
Back up

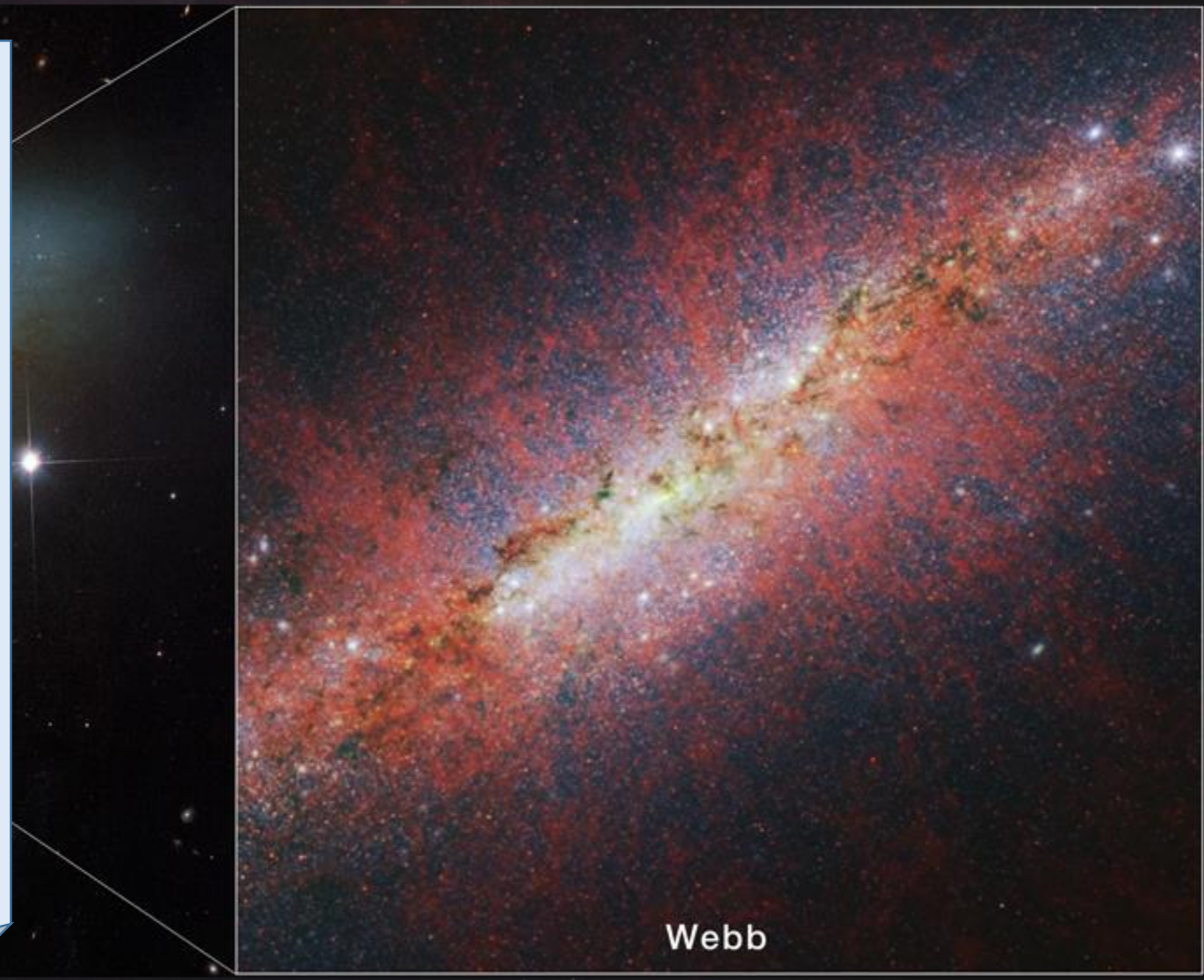
Starburst Galaxies



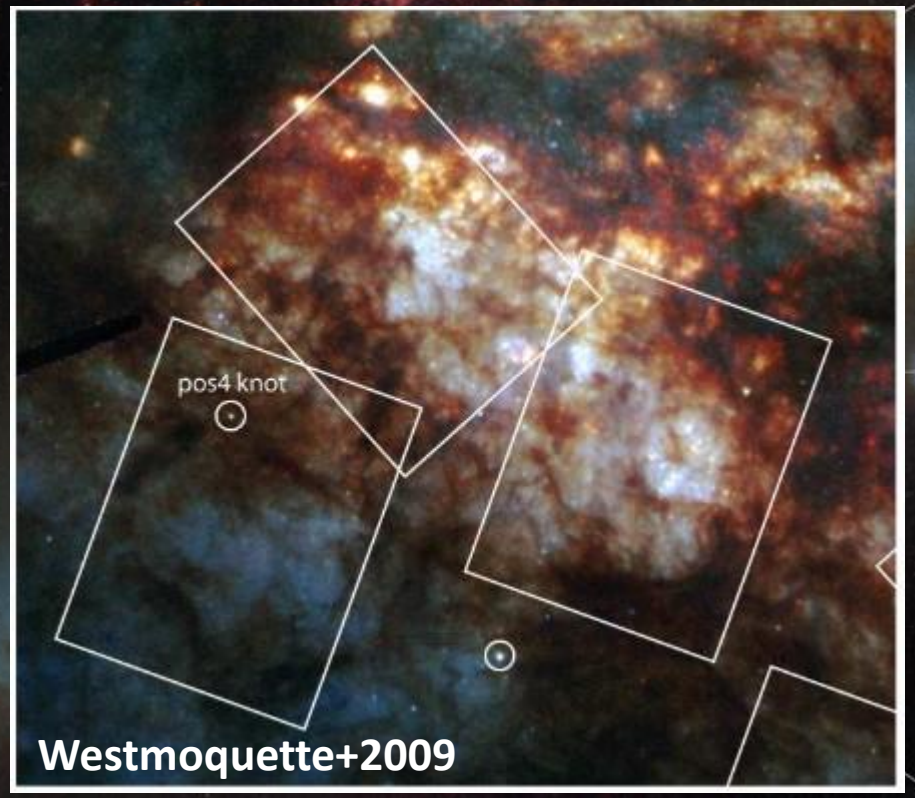
Starburst galaxy M82 – NASA, ESA, CSA, STScI, A. Bolatto

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



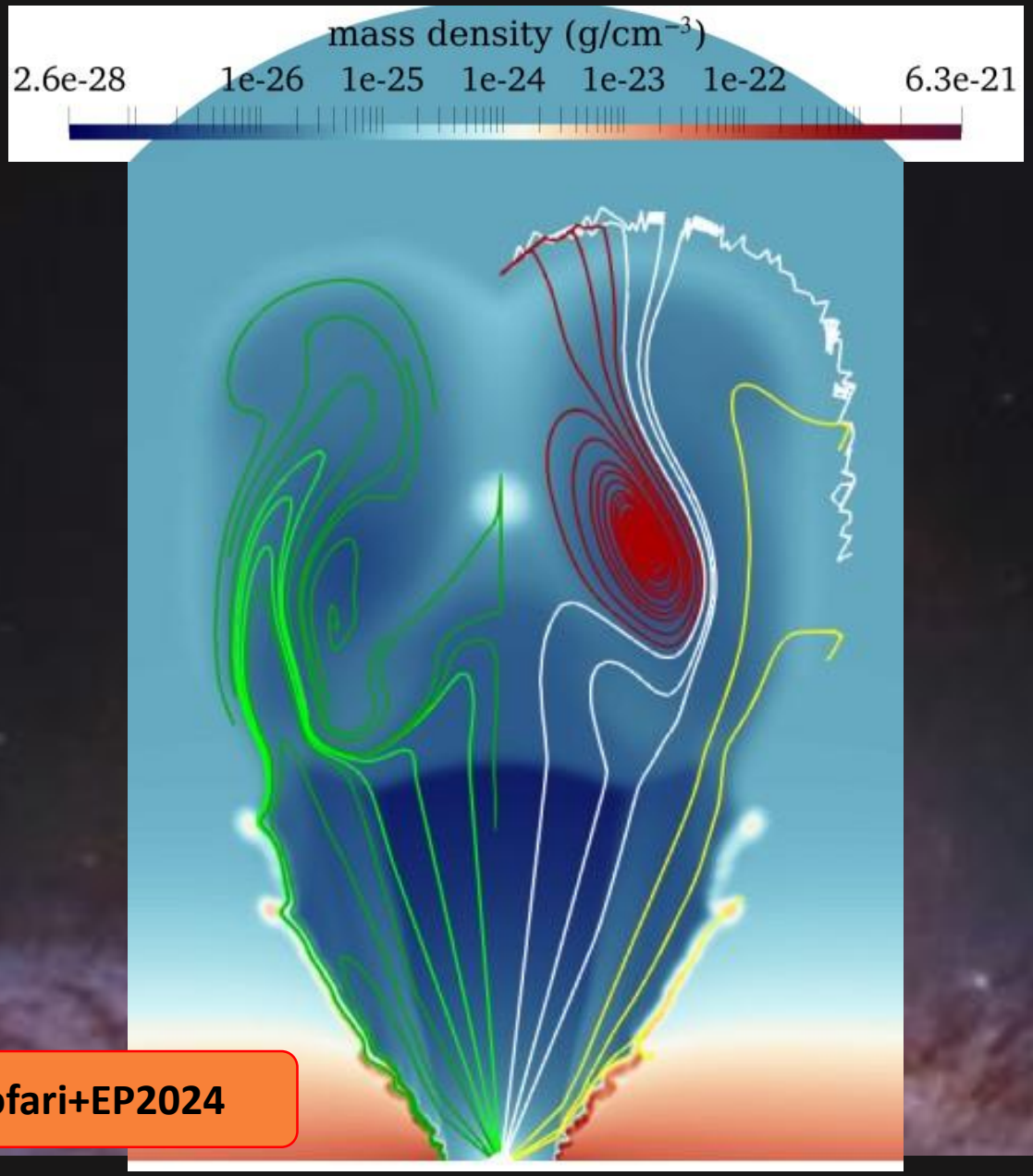


Starburst galaxy M82 – NASA, ESA, CSA, STScI, A. Bolatto



Hubble

Webb

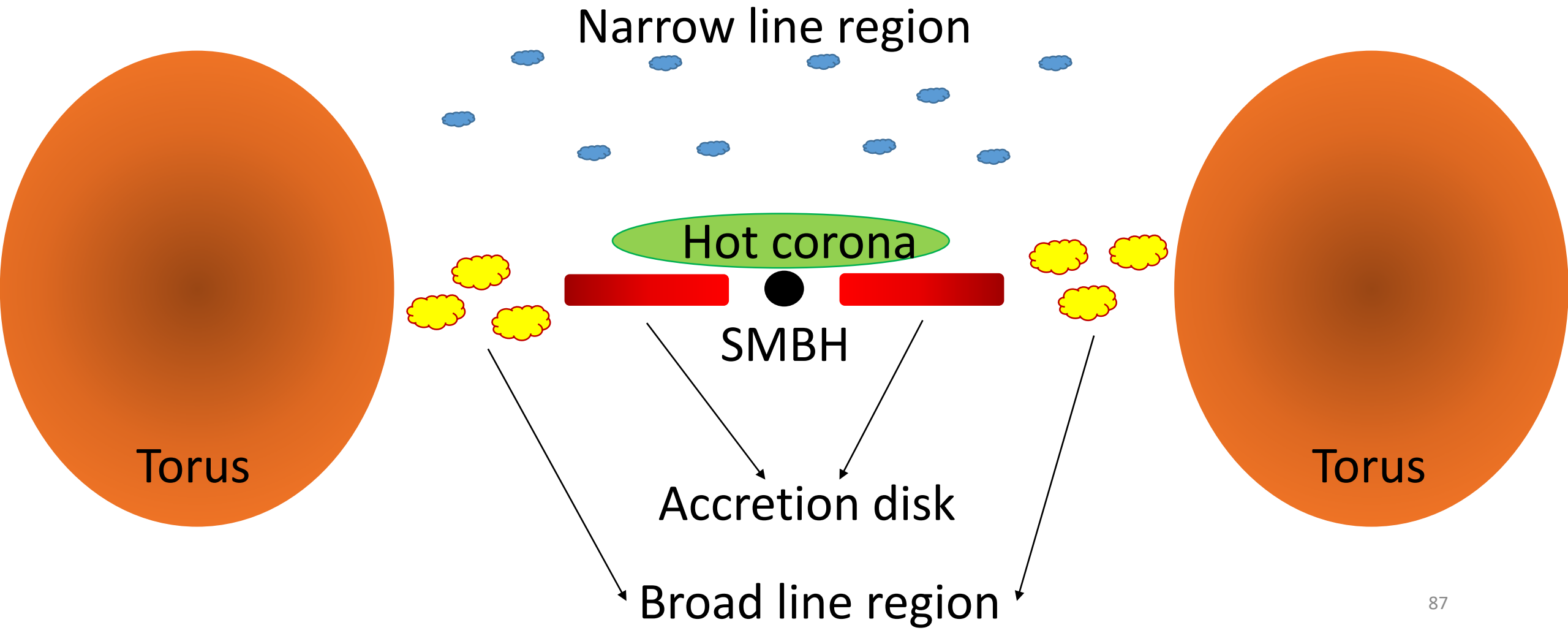


Meliani,Cristofari+EP2024

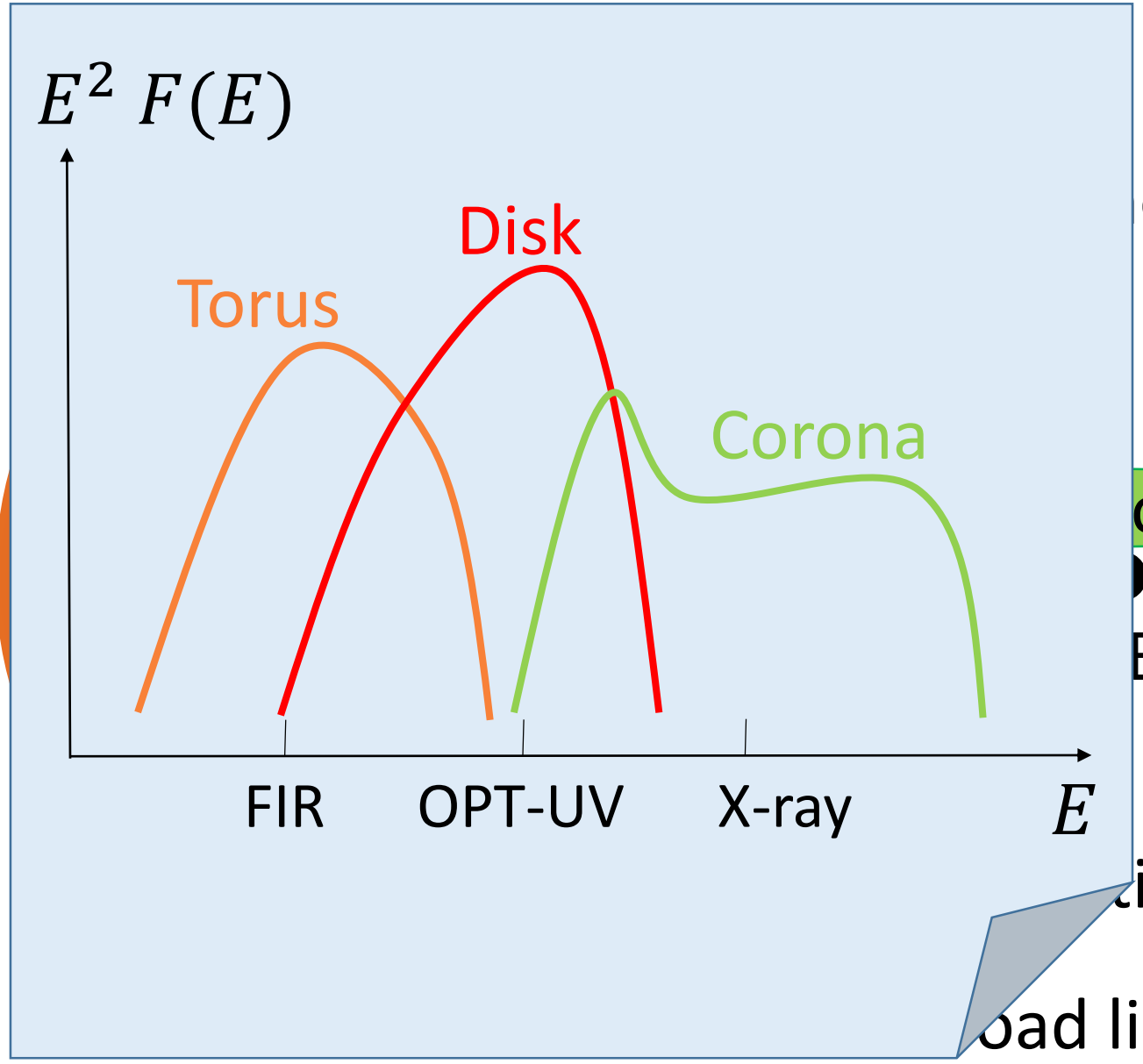
Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

Active Galactic Nuclei

Active Galactic Nuclei



Active Galactic Nuclei



e region

orona

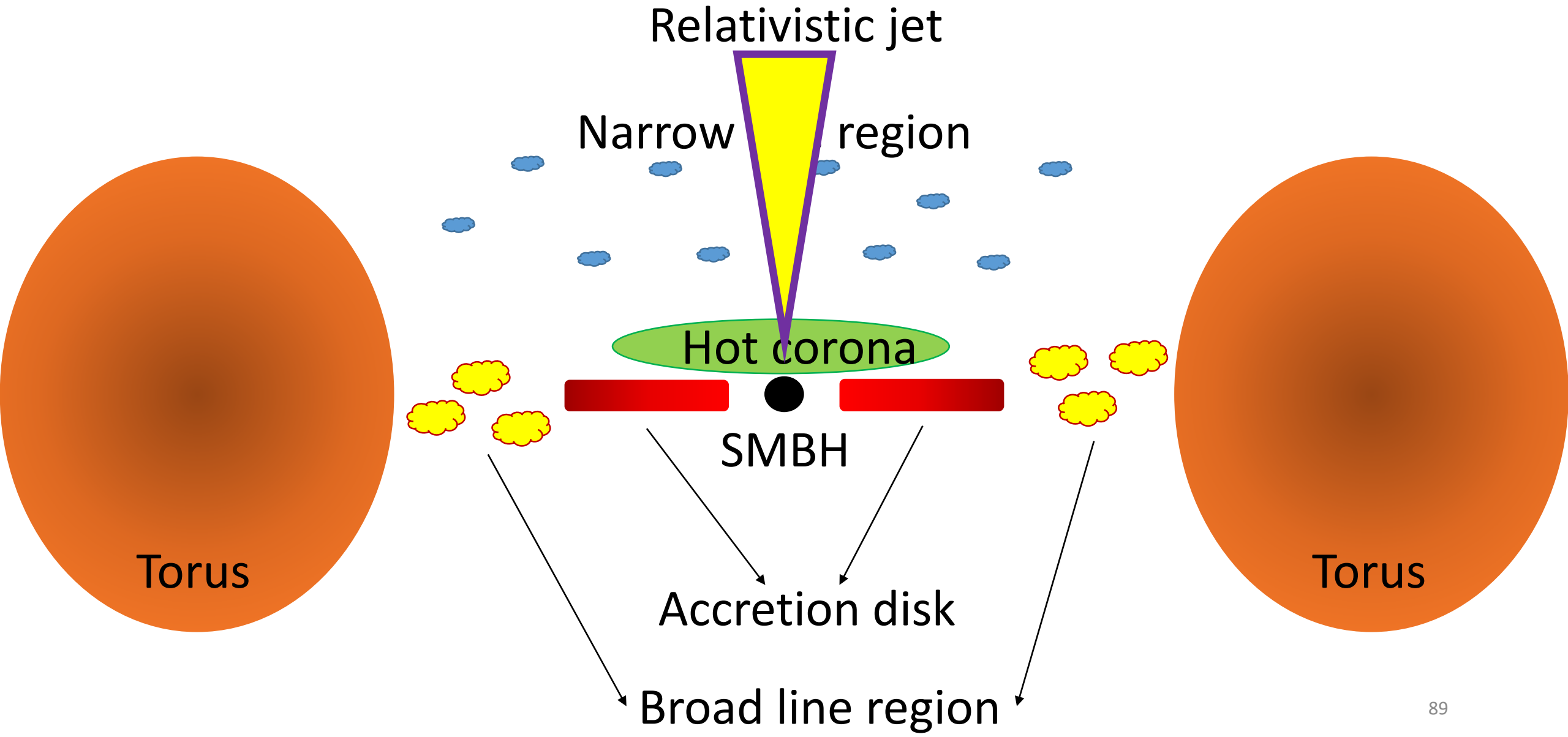
BH

ion disk

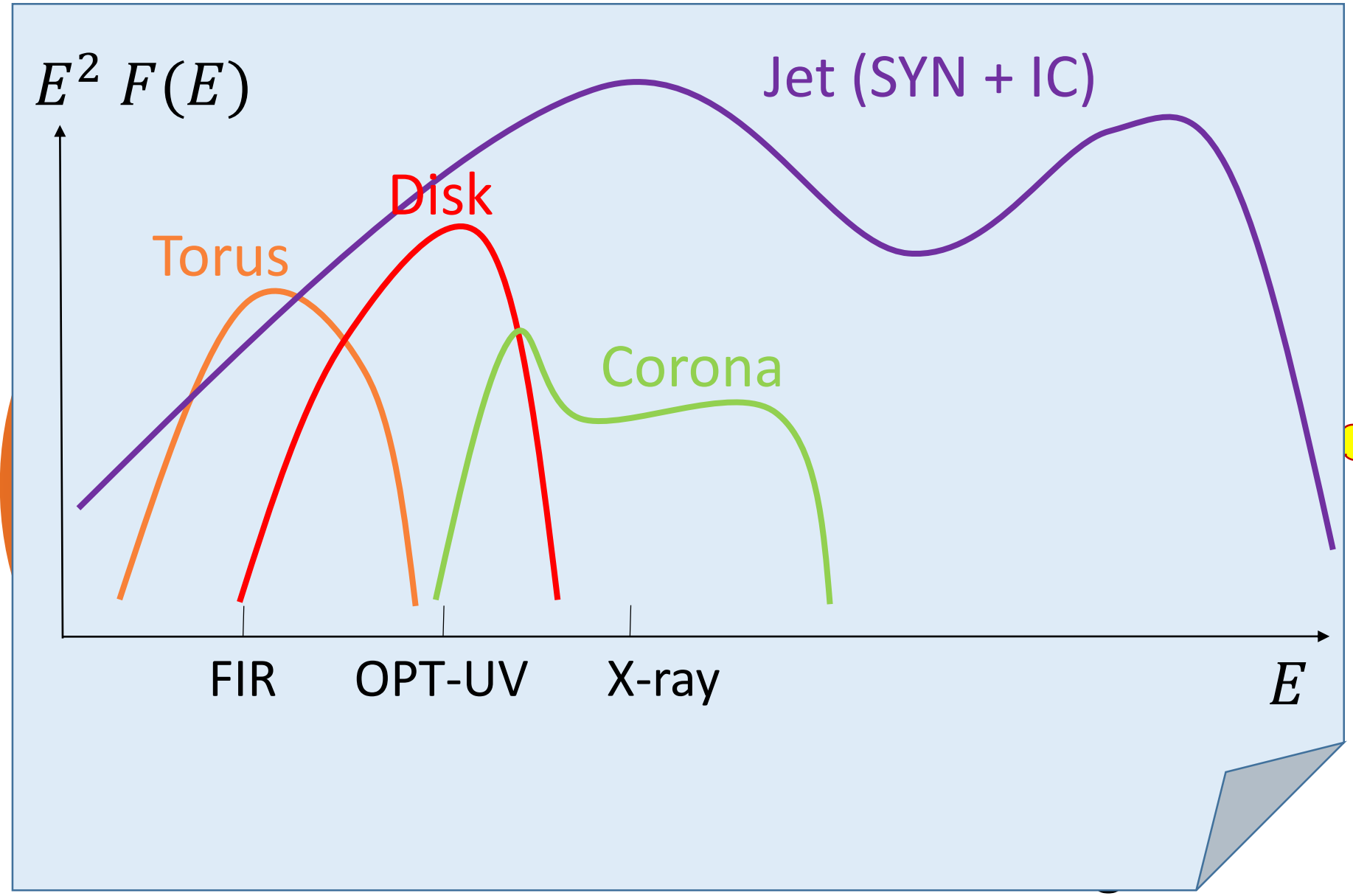
oad line region

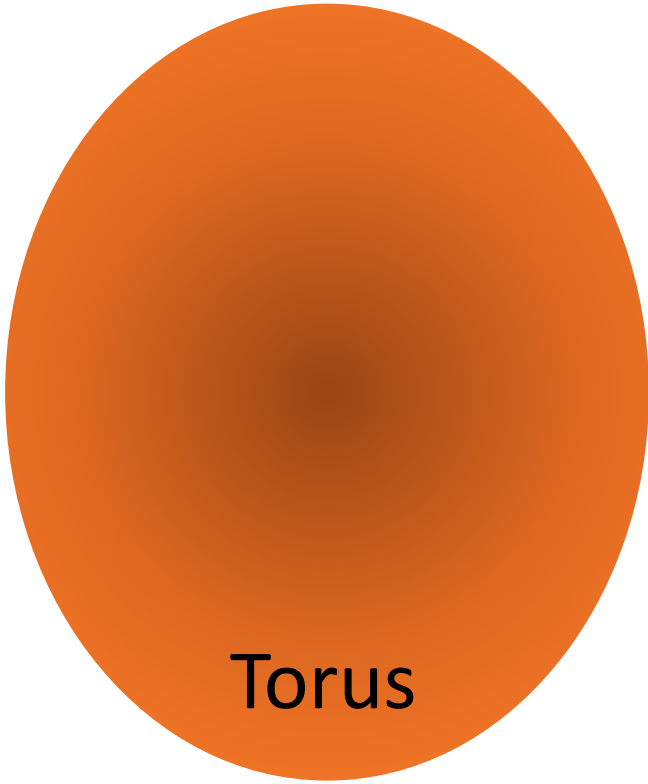
Torus

Active Galactic Nuclei

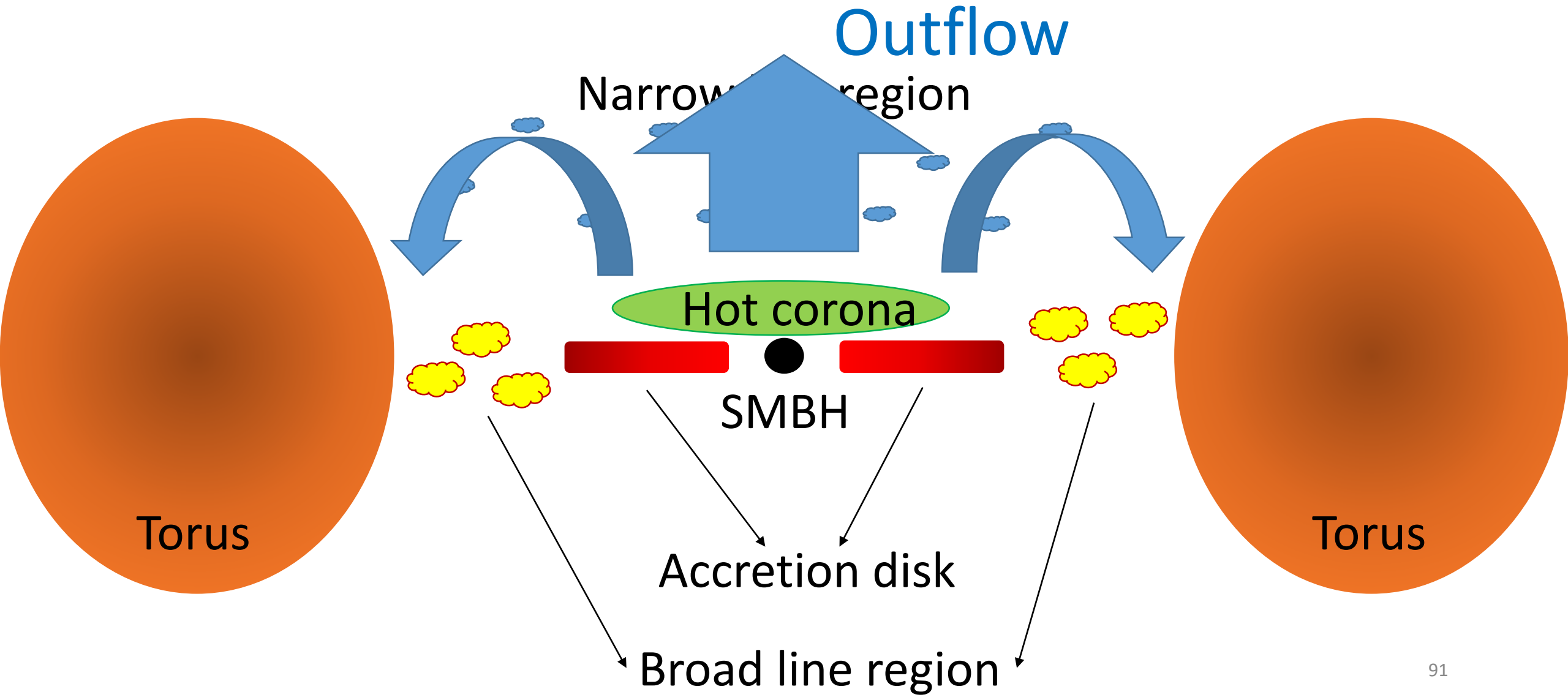


Active Galactic Nuclei

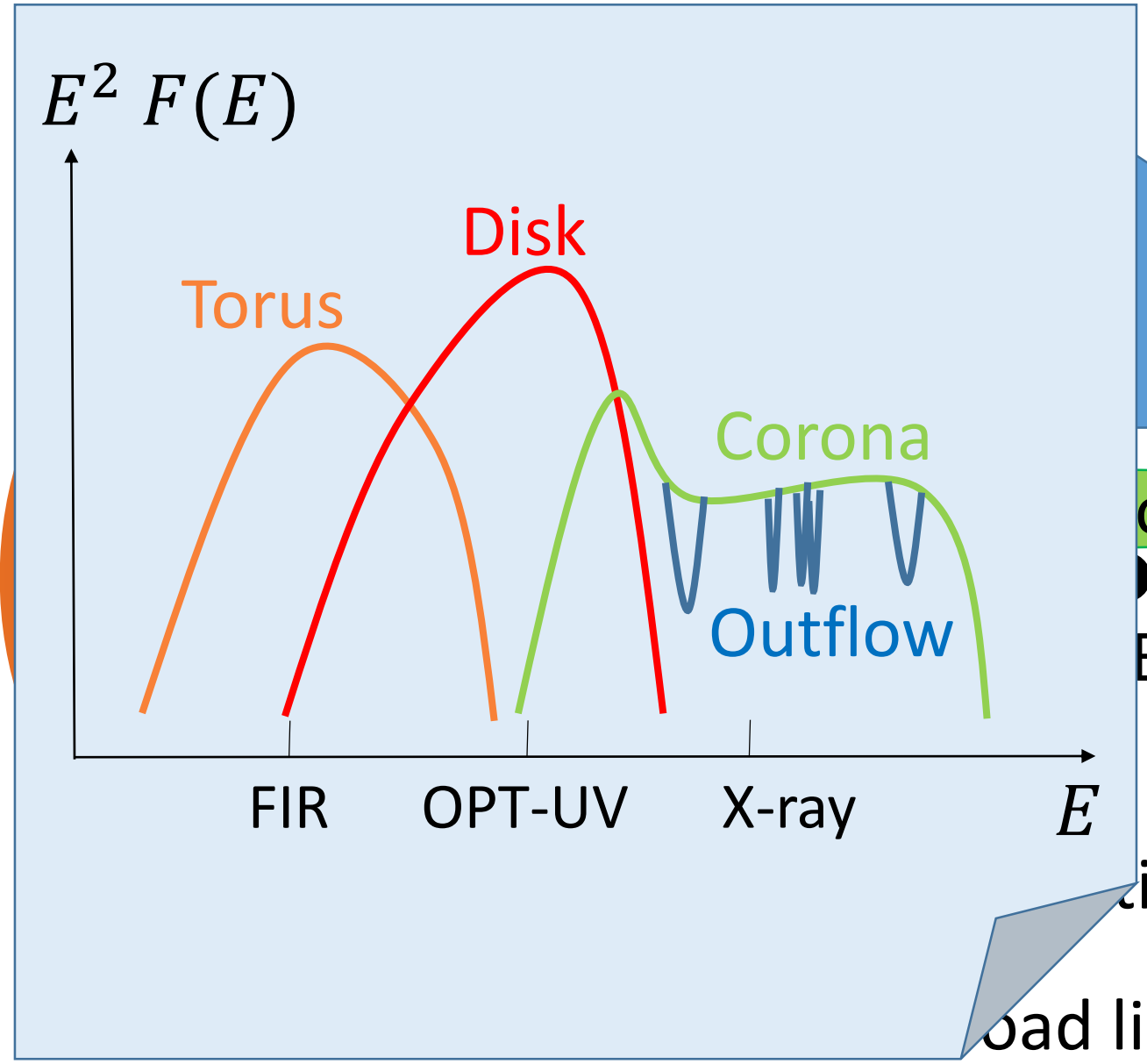




Active Galactic Nuclei



Active Galactic Nuclei



Outflow

region

orona

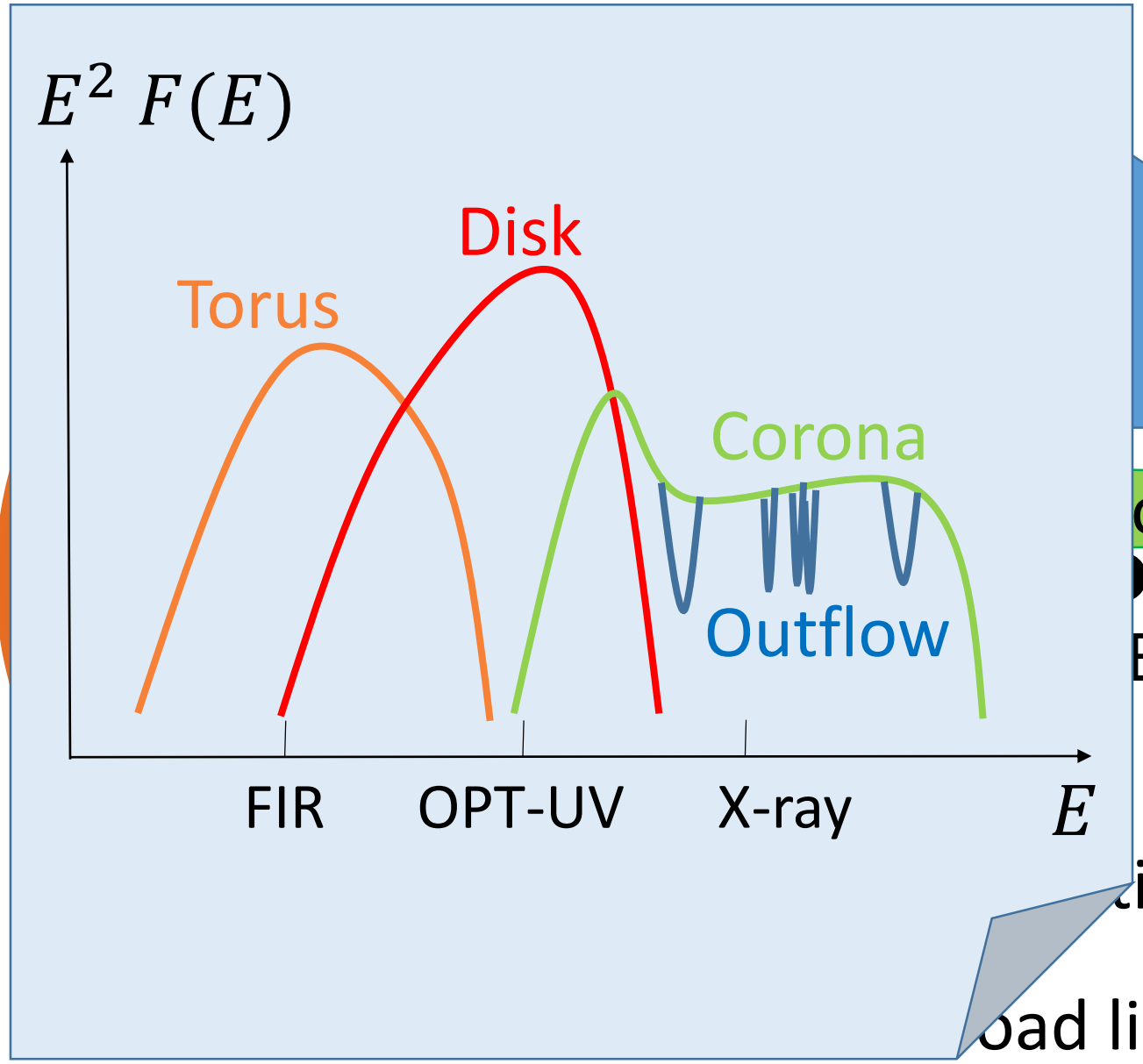
BH

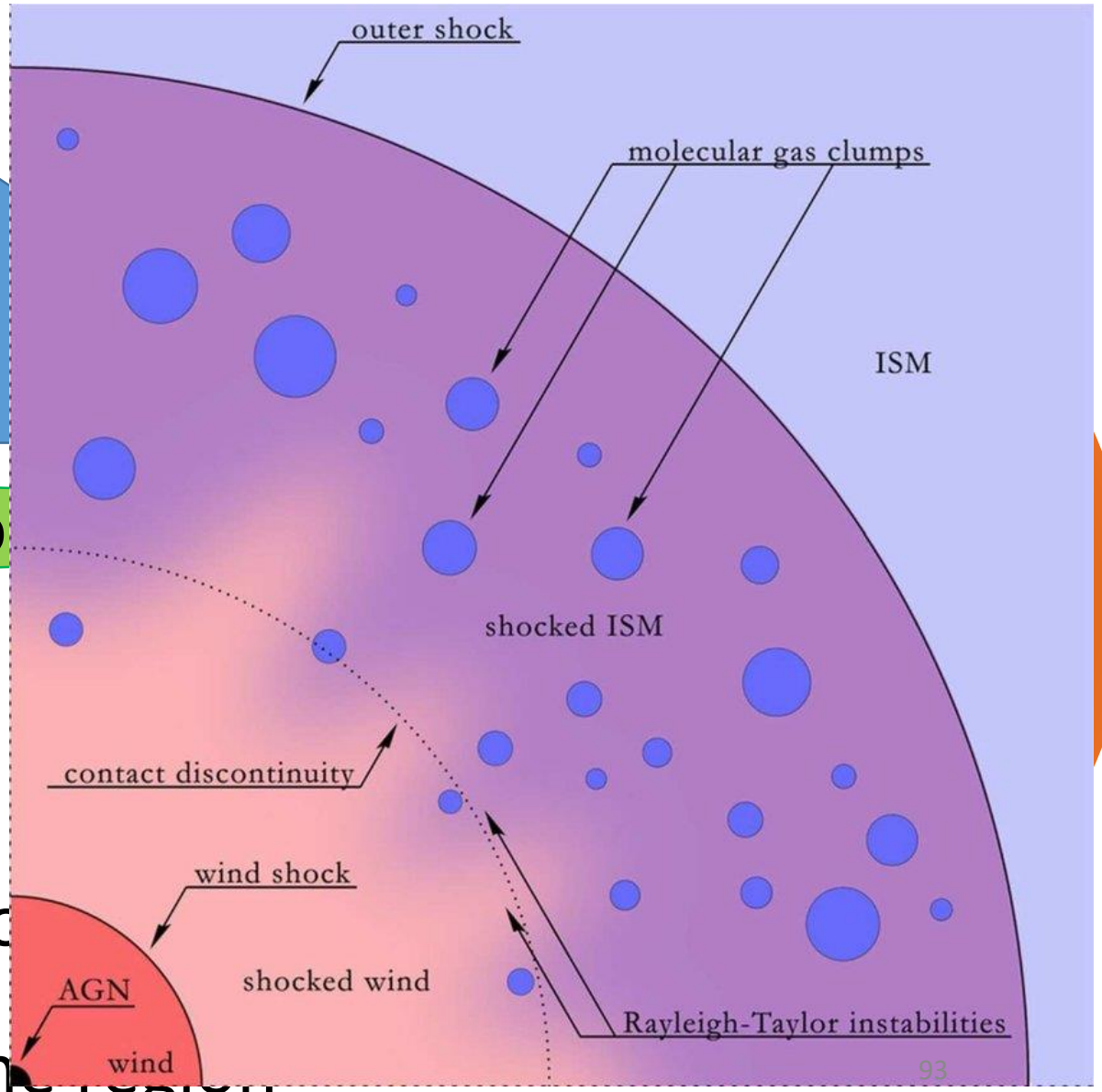
ion disk

oad line region

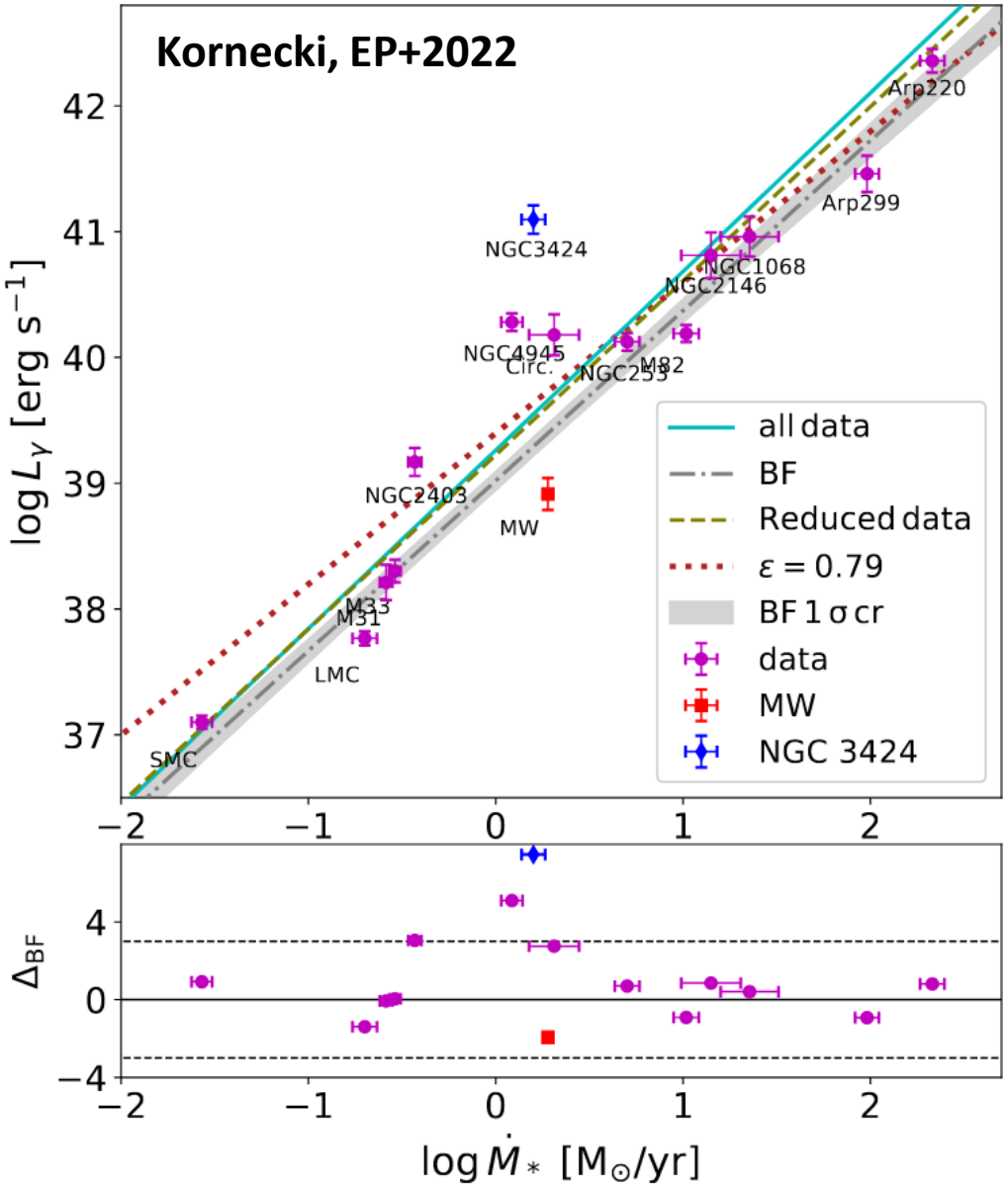
Torus

Active Galactic Nuclei



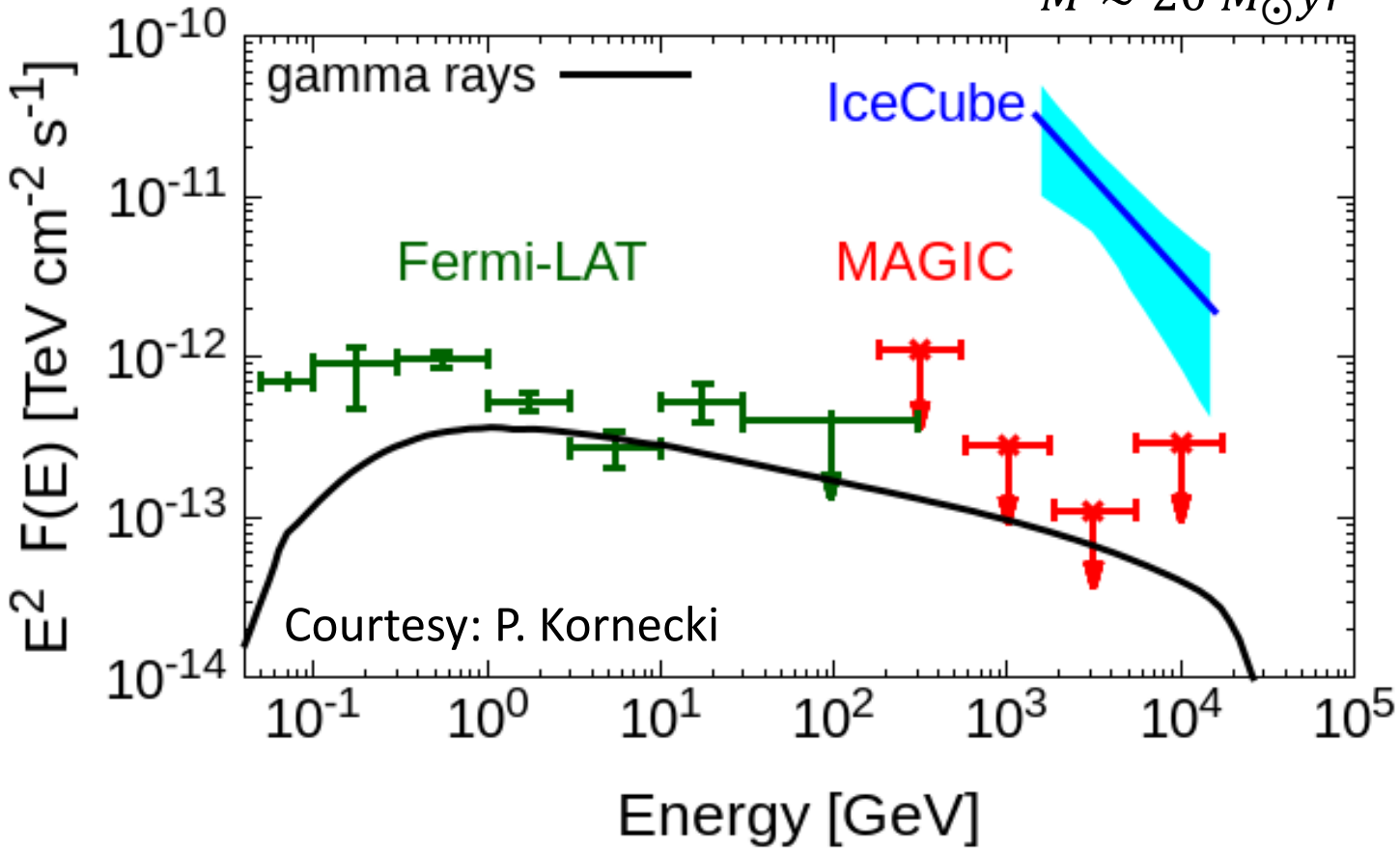


The starburst of NGC 1068

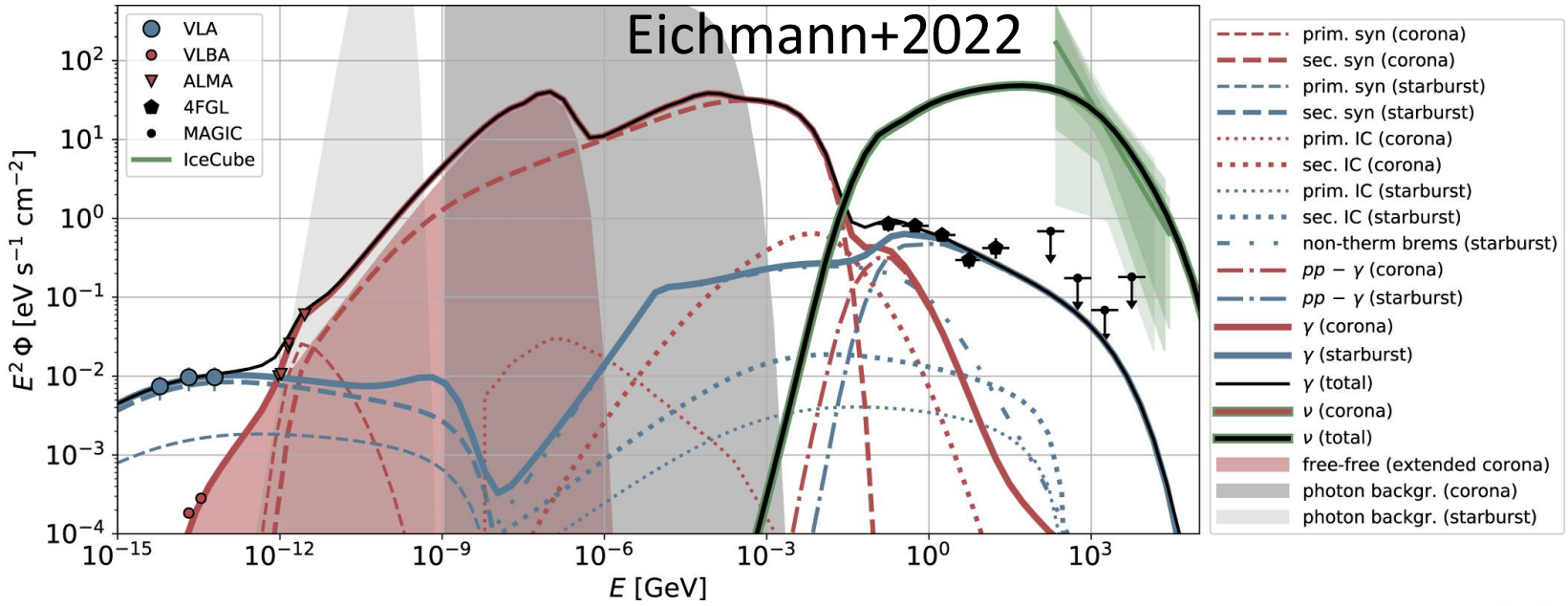


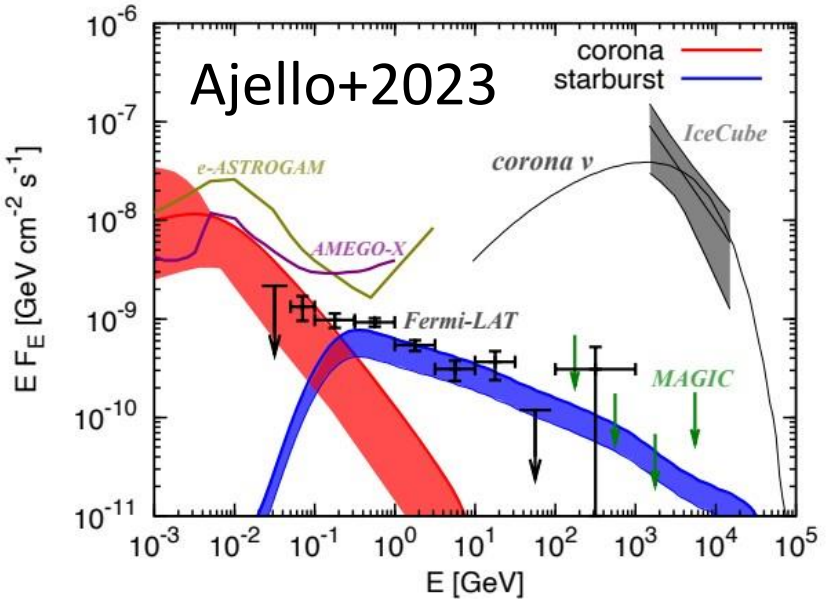
$D = 14.4\ Mpc$

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

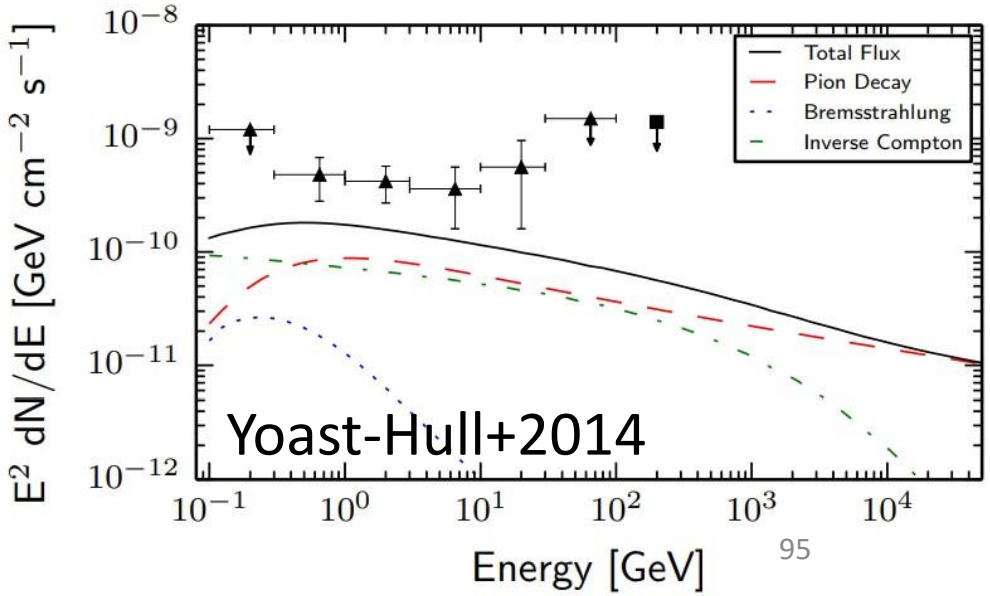


The starburst of NGC 1068





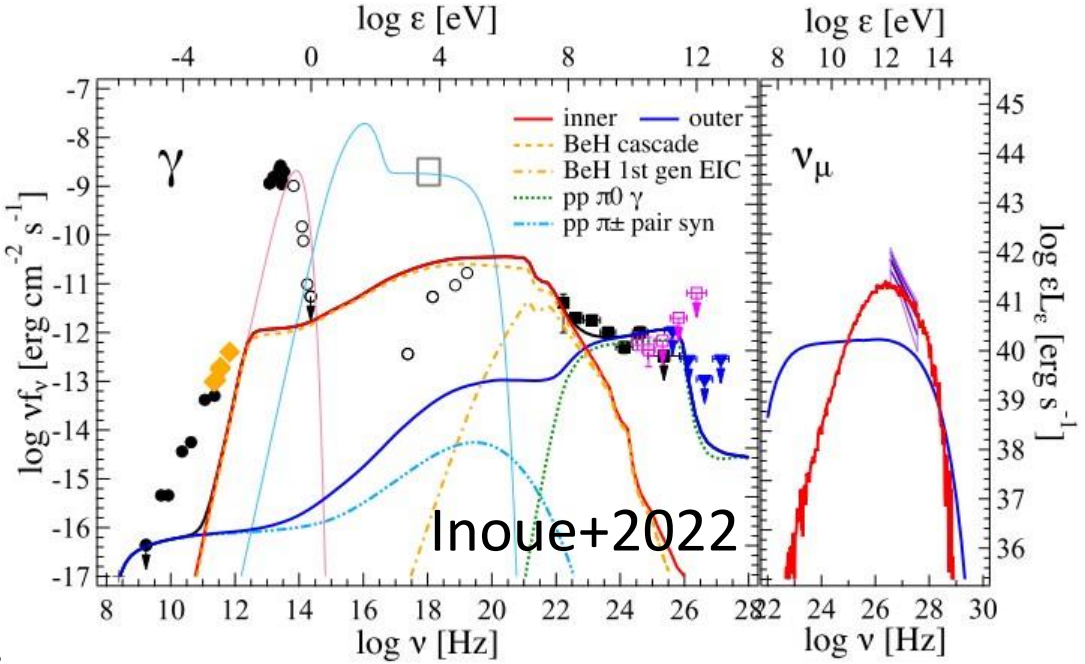
The starburst appears as the most plausible region for the production of gamma rays. However, it is not clear whether only the starburst is the only efficient gamma-ray emitter.

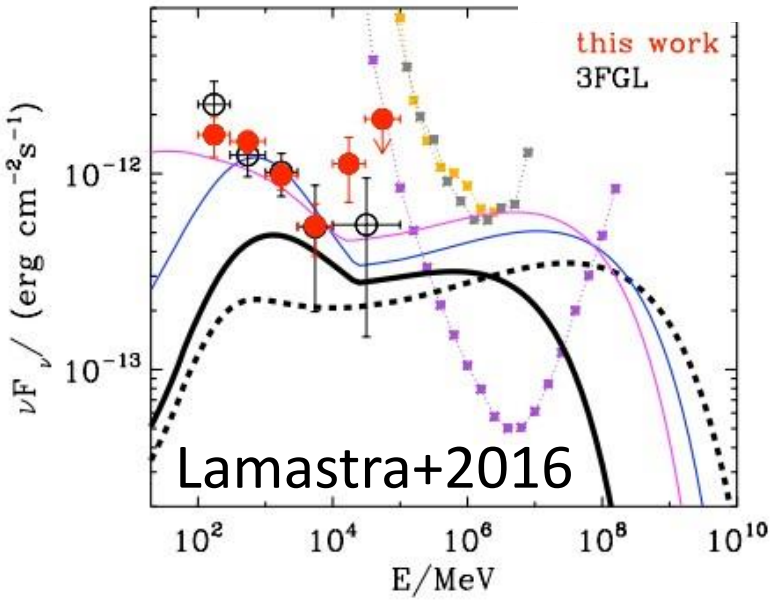


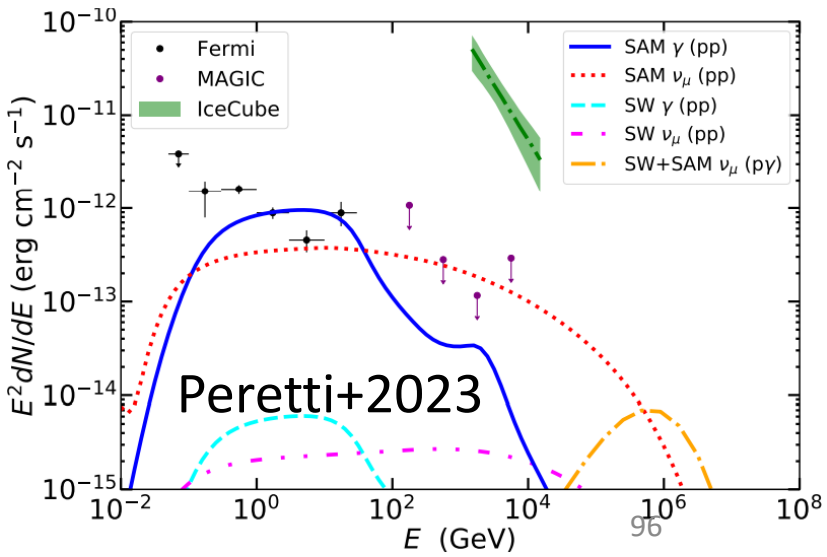
The AGN wind of NGC 1068

The AGN-driven wind could contribute to the gamma-ray luminosity of NGC 1068.

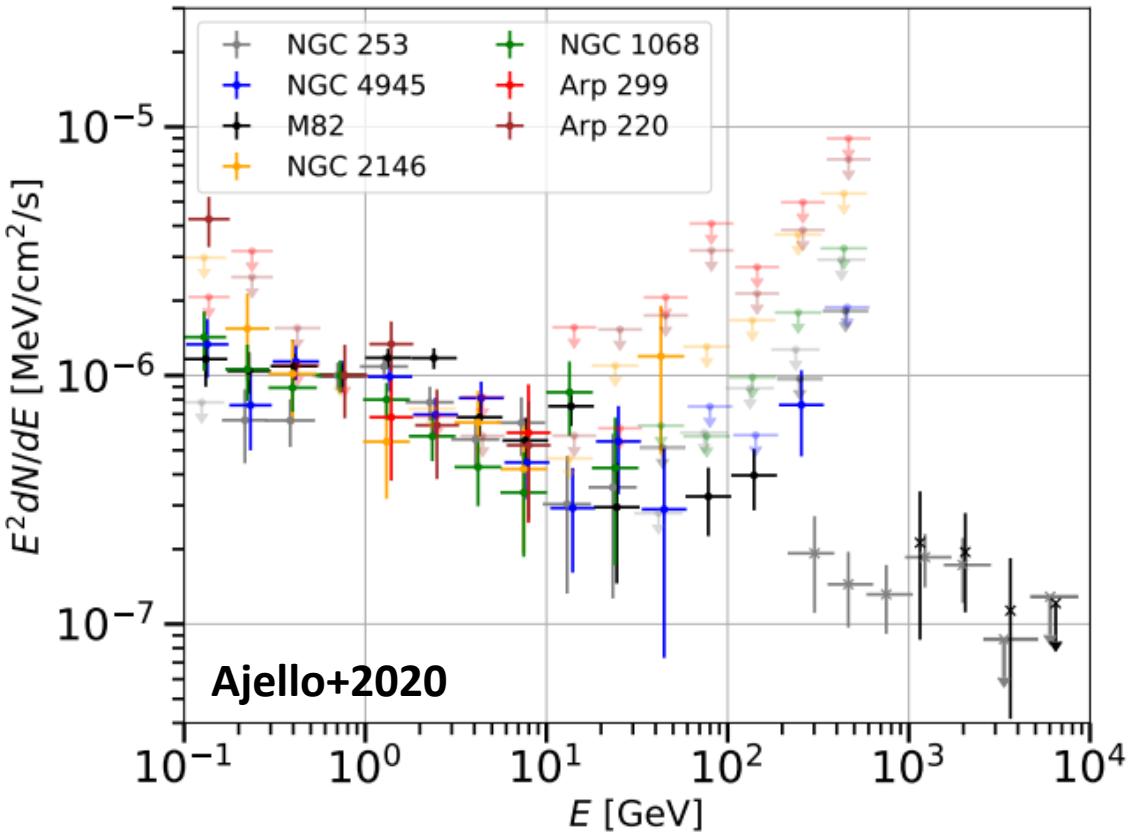
Diffusive shock acceleration in the molecular outflow as well as in inner wind - such as Ultra-Fast Outflows - can reach the required power.



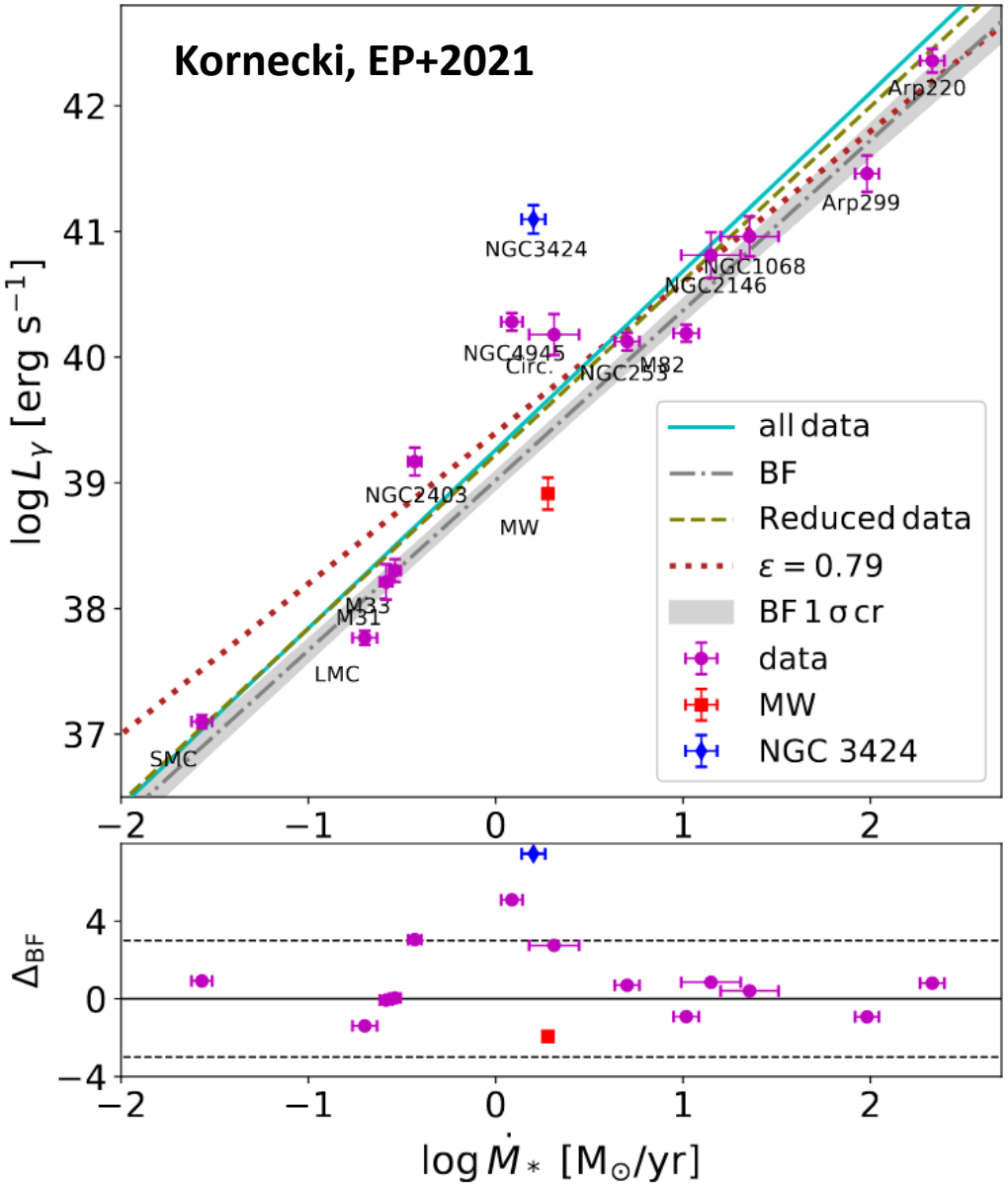


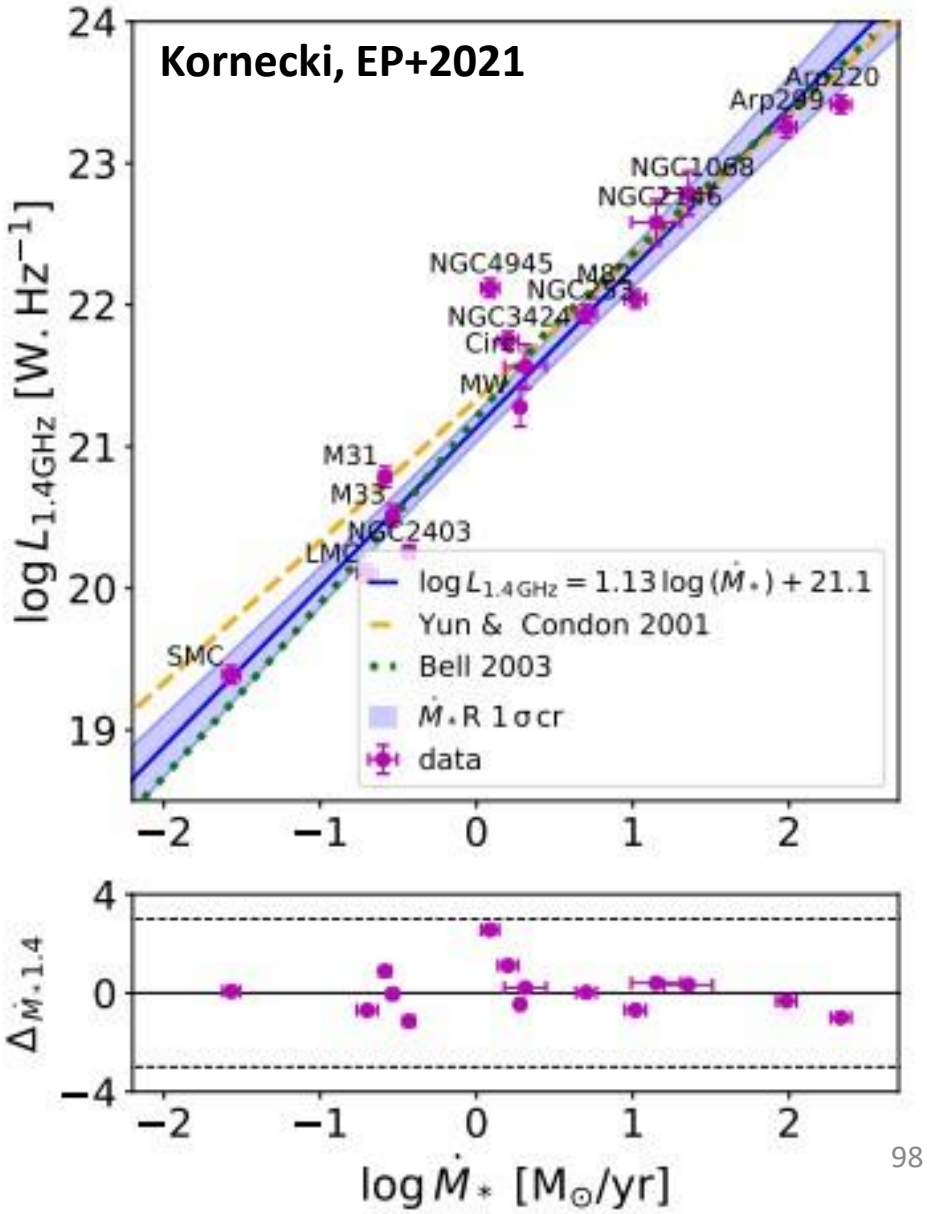


Observation of Star-forming Galaxies - Gamma

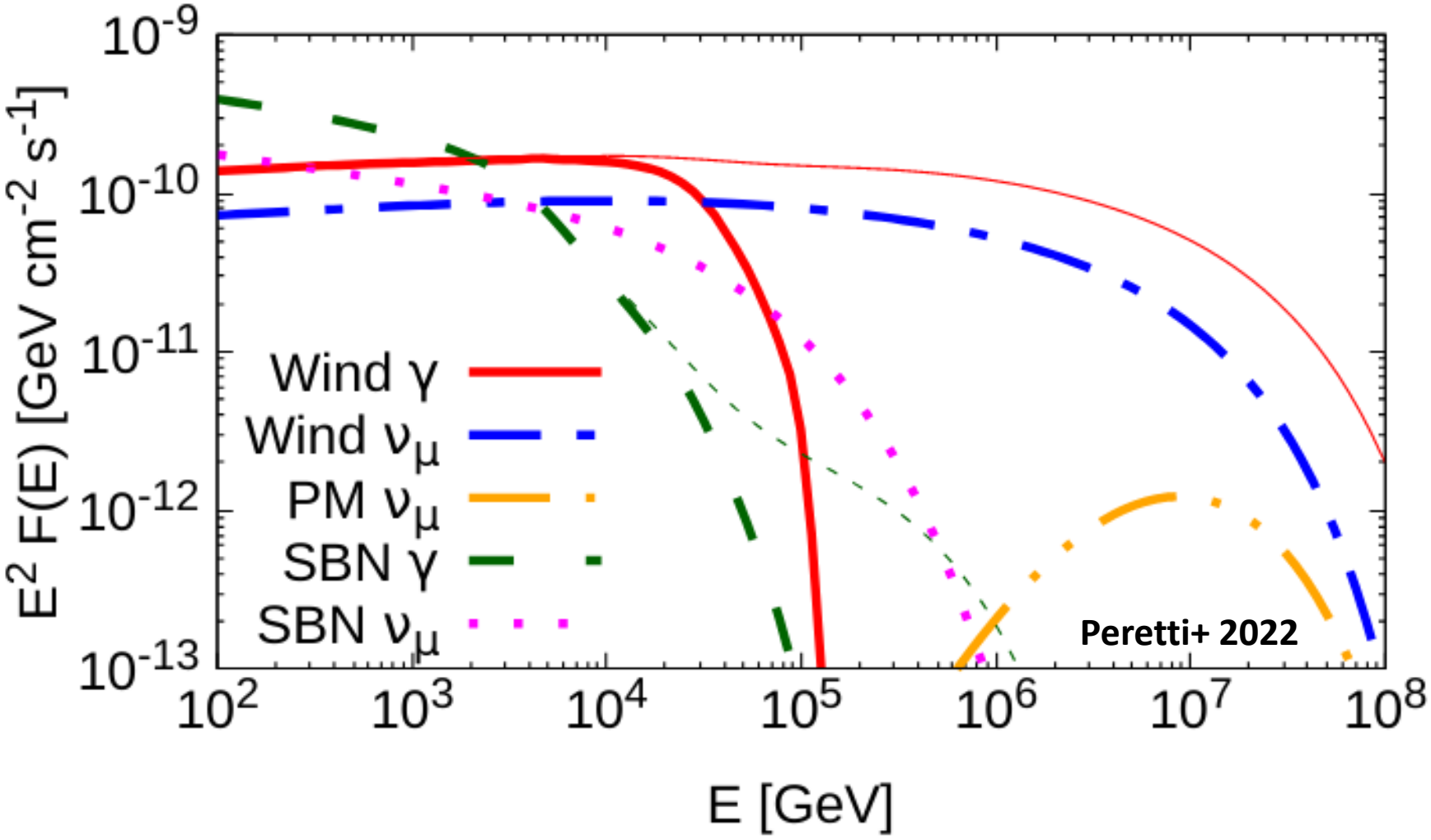


Observation of Star-forming Galaxies - Correlations

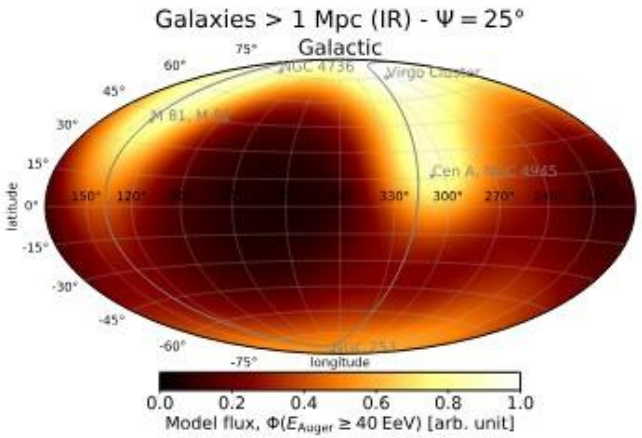


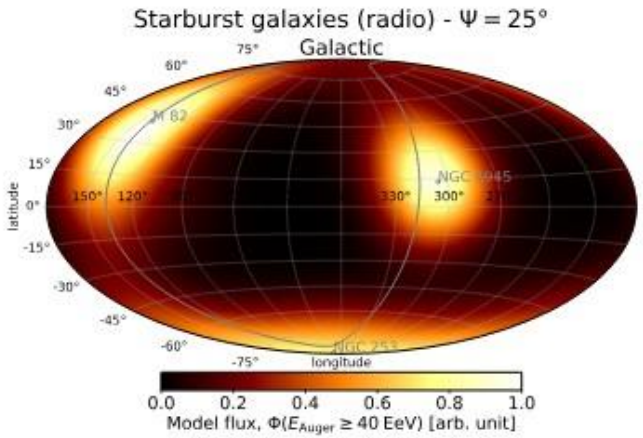


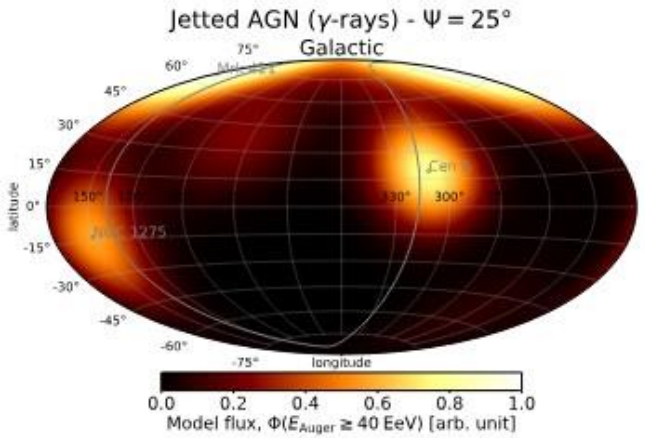
High-Energy SED and Neutrinos

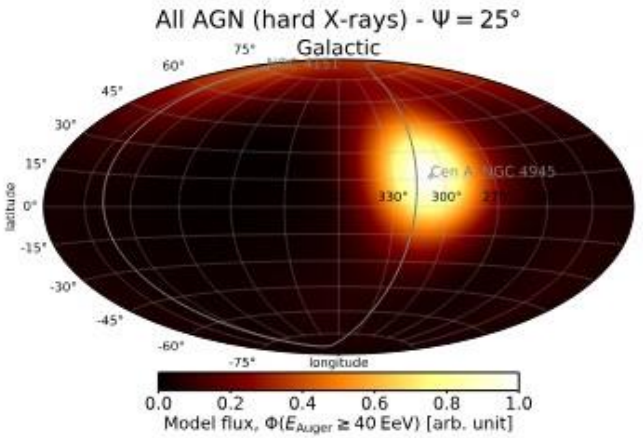


Starbursts and Ultra-High-Energy cosmic rays

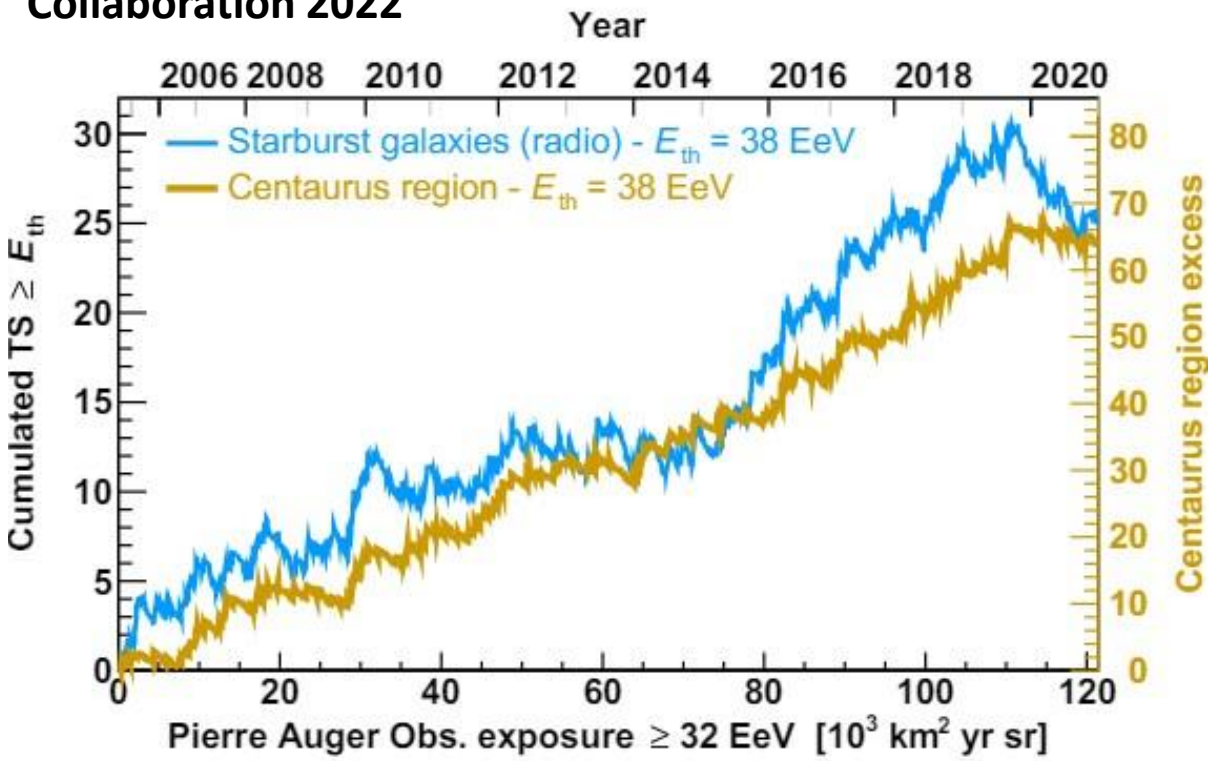








The Pierre Auger Collaboration 2022



Ultra-High-Energy cosmic rays in starbursts