Particle acceleration and multi-messenger radiation from astrophysical outflows

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April 19 2023, NTNU Trondheim

VILLUM FONDEN

UNIVERSITY OF COPENHAGEN

Niels Bohr Institutet

The Niels Bohr International Academy

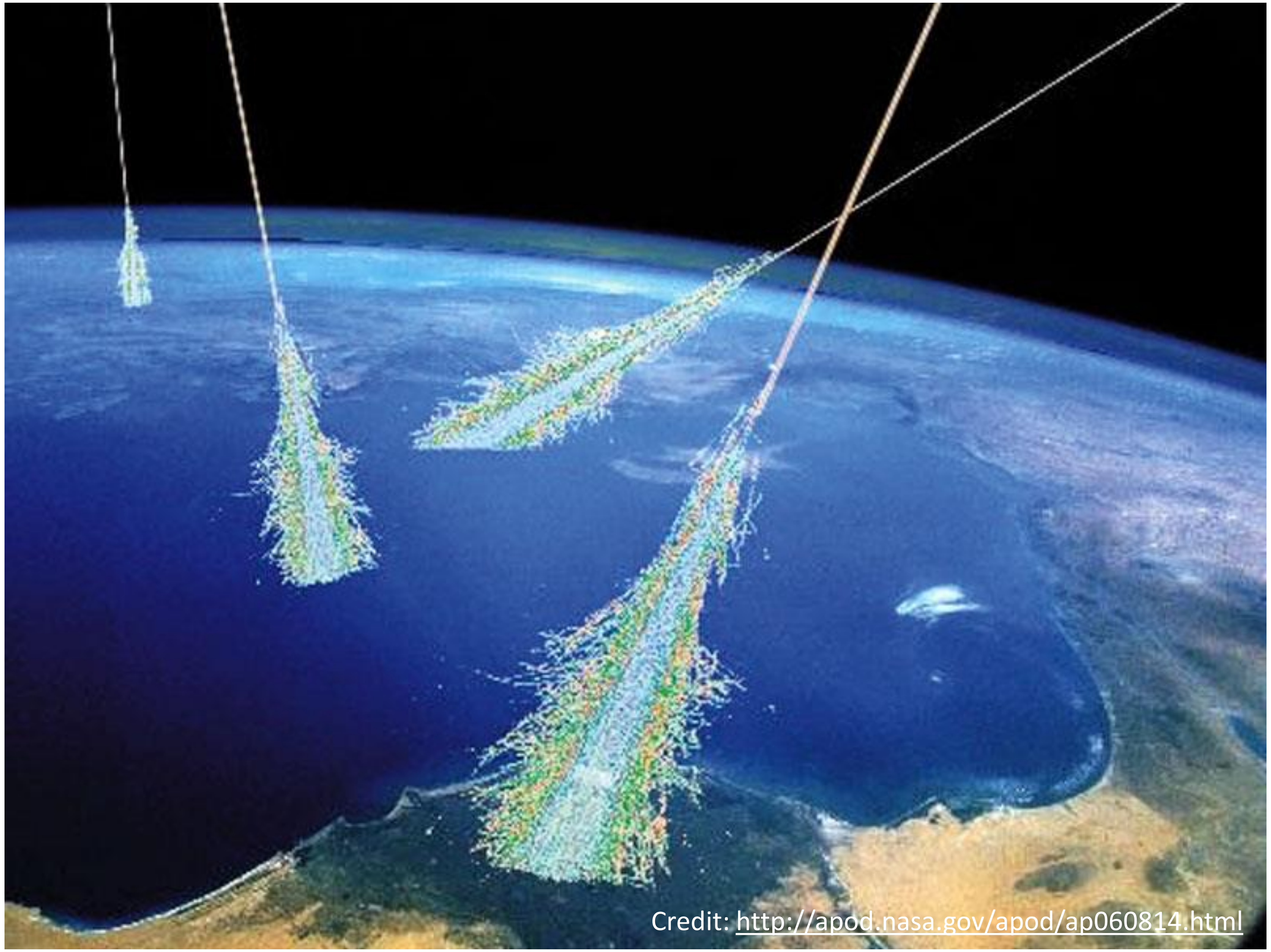
Co-financed by the Connecting Europe Facility of the European Union

Introduction on cosmic rays

Cosmic Rays

- Cosmic rays: Relativistic particles of cosmic origin hitting the top of the atmosphere with a rate of

$$\sim 1\, cm^{-2} s^{-1}$$



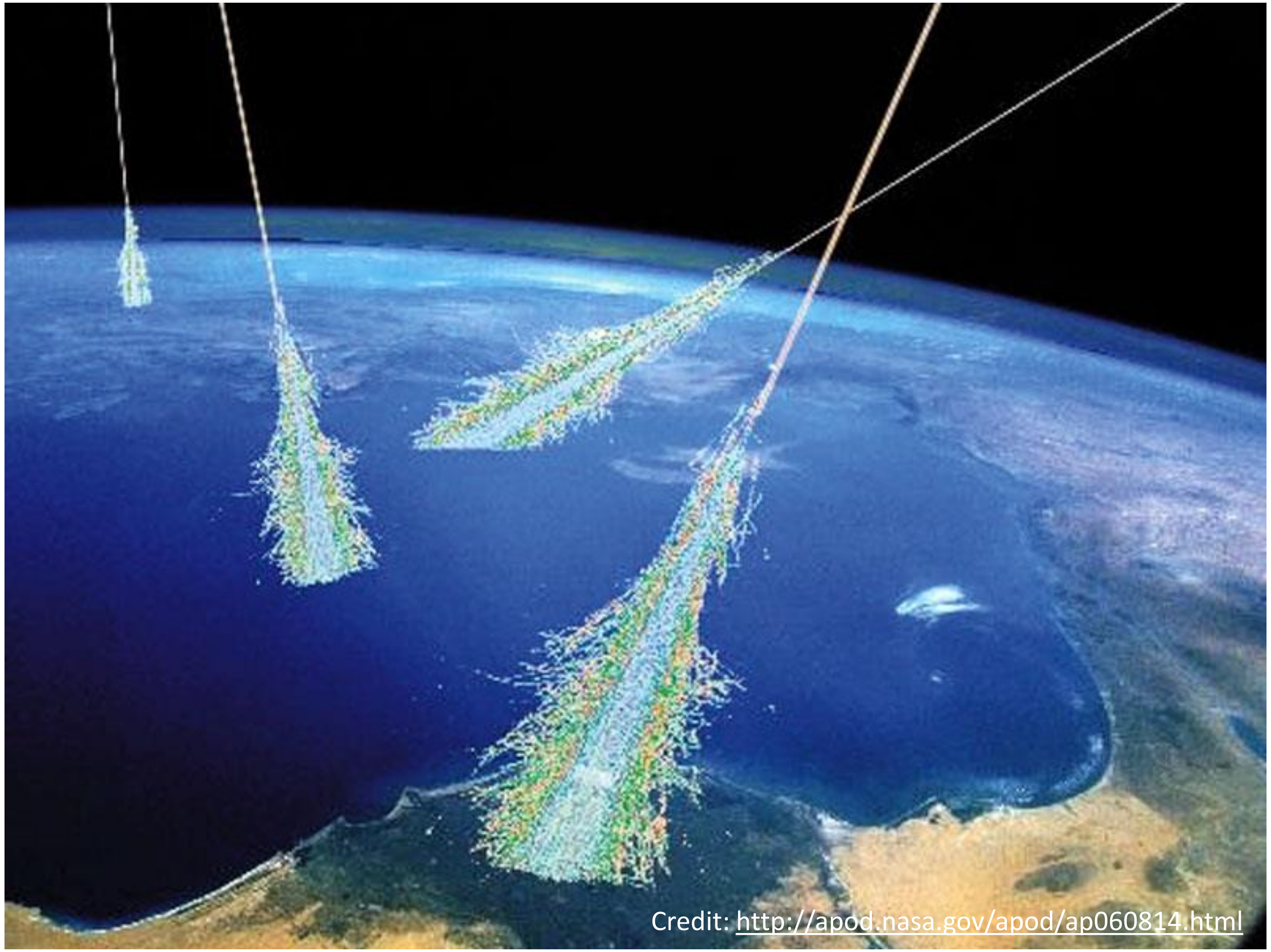
Credit: http://apod.nasa.gov/apod/ap060814.html

Cosmic Rays

- Cosmic rays: Relativistic particles of cosmic origin hitting the top of the atmosphere with a rate of

$$\sim 1\, cm^{-2} s^{-1}$$

- Composition: Protons (90%), Helium nuclei (9%), leptons and heavy nuclei (1%)



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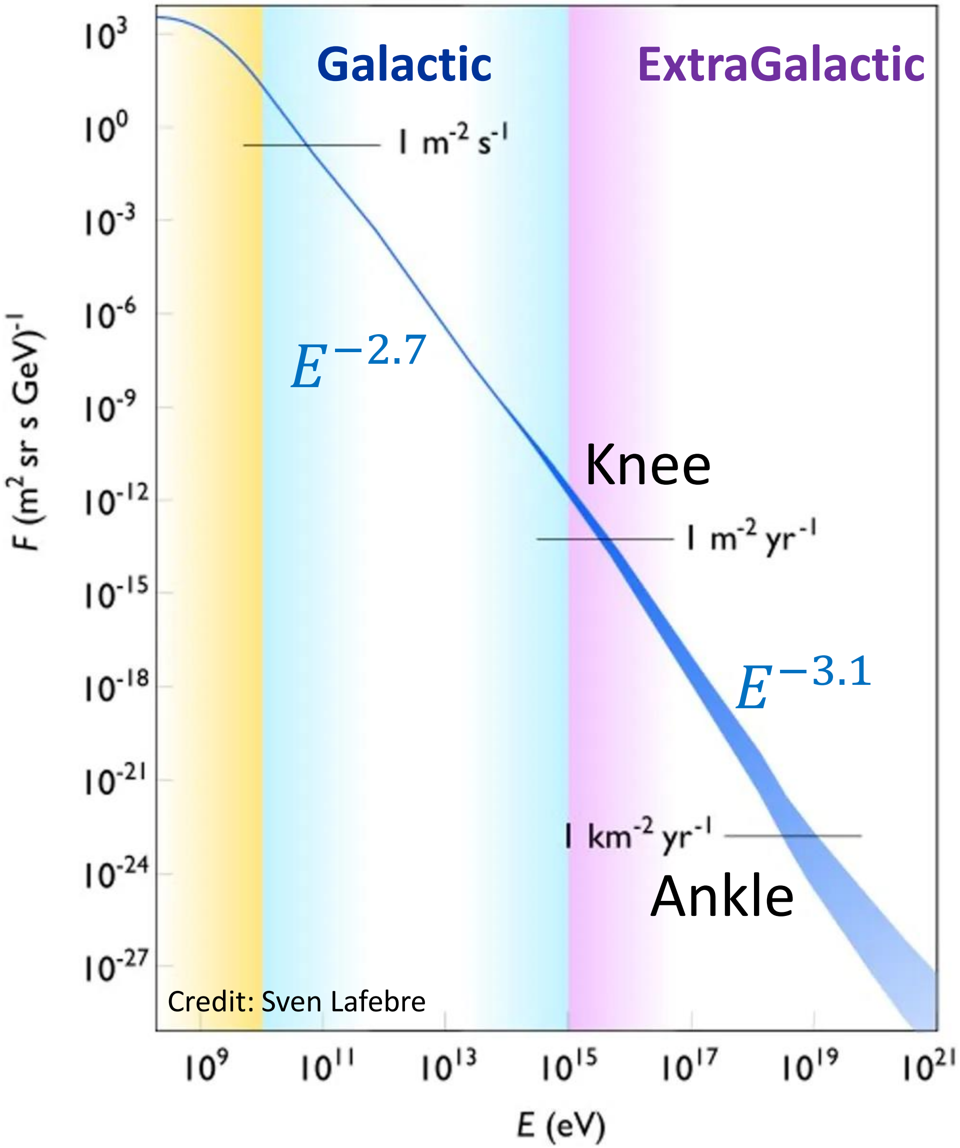
The cosmic-ray spectrum



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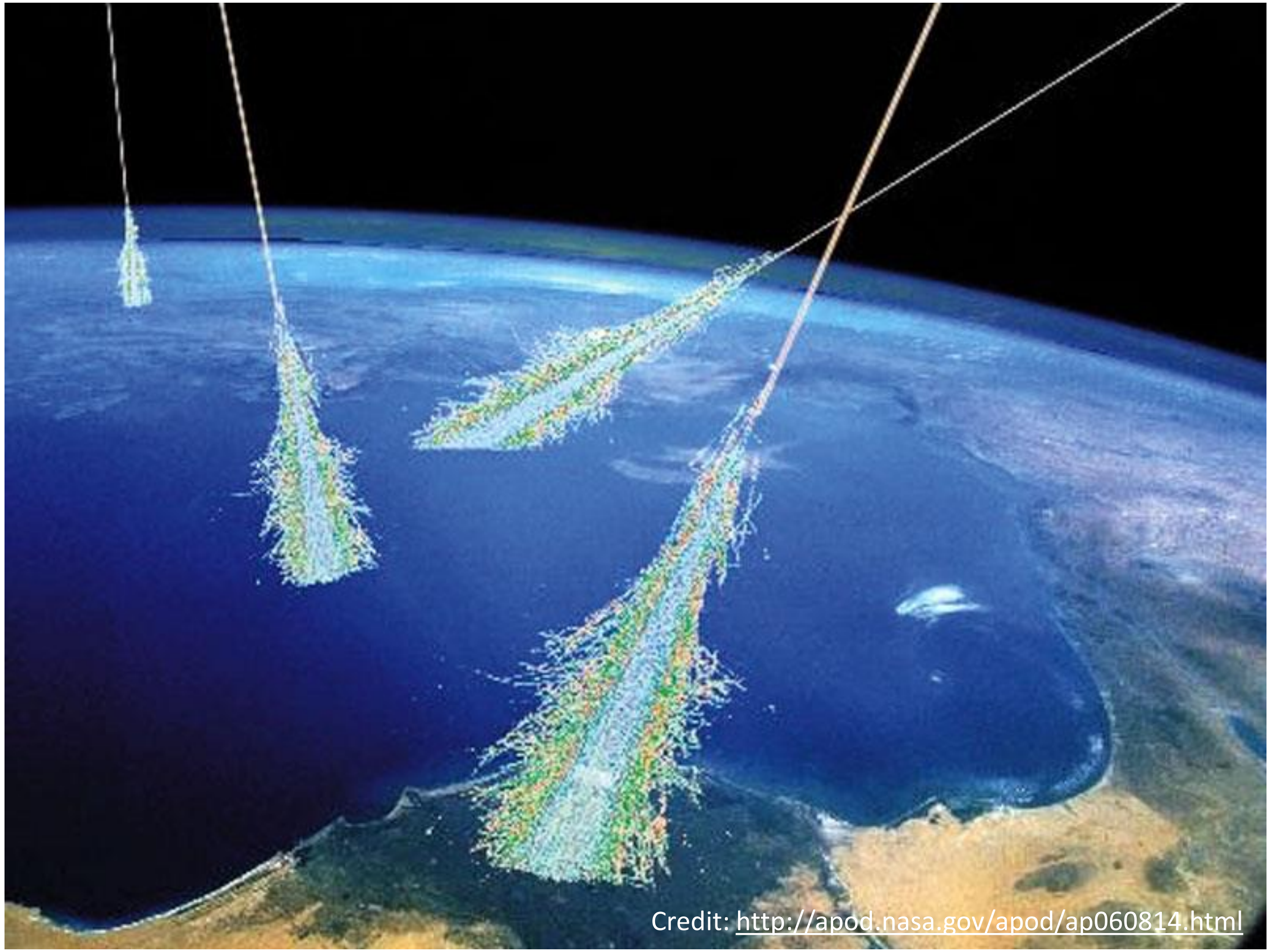

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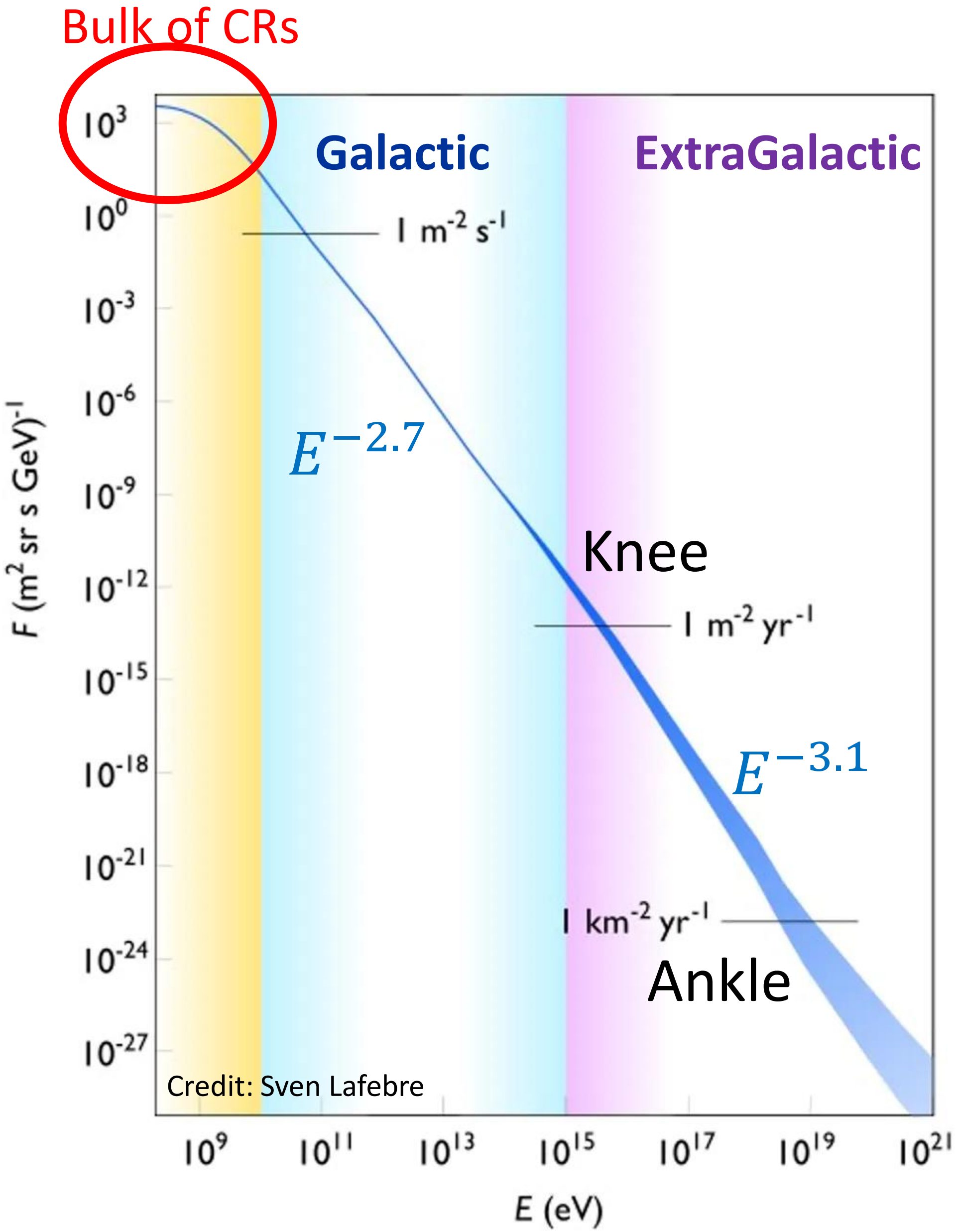

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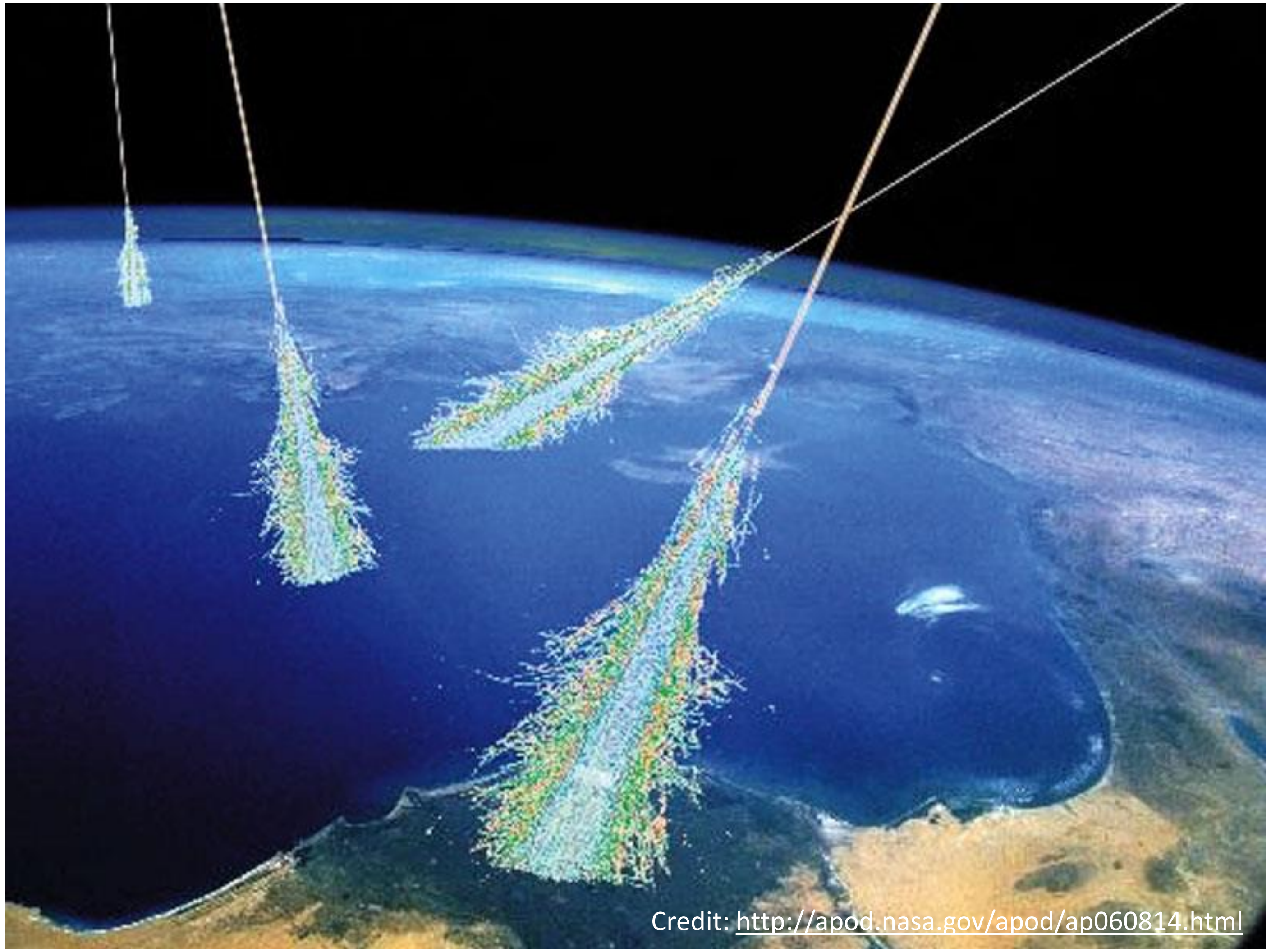

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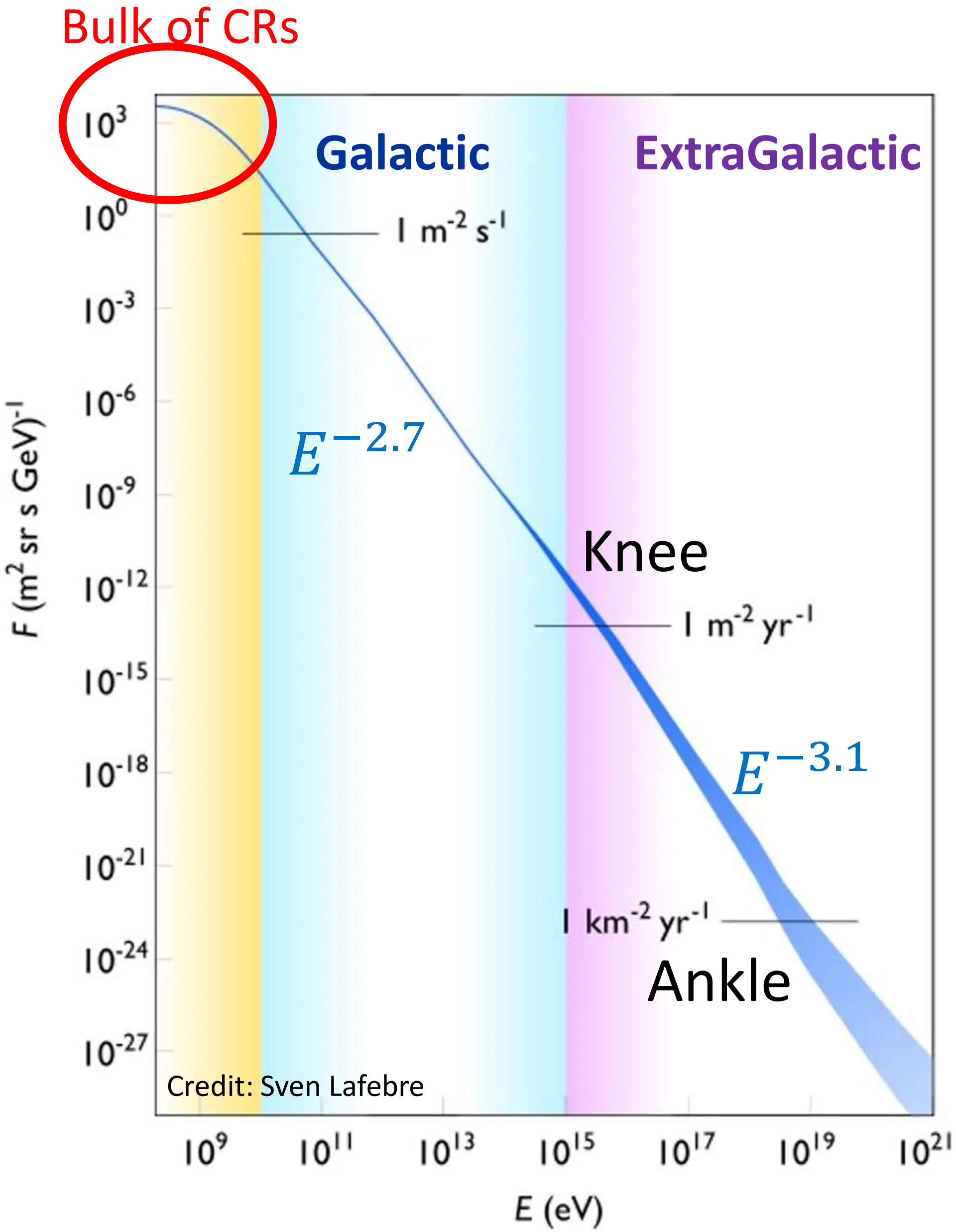

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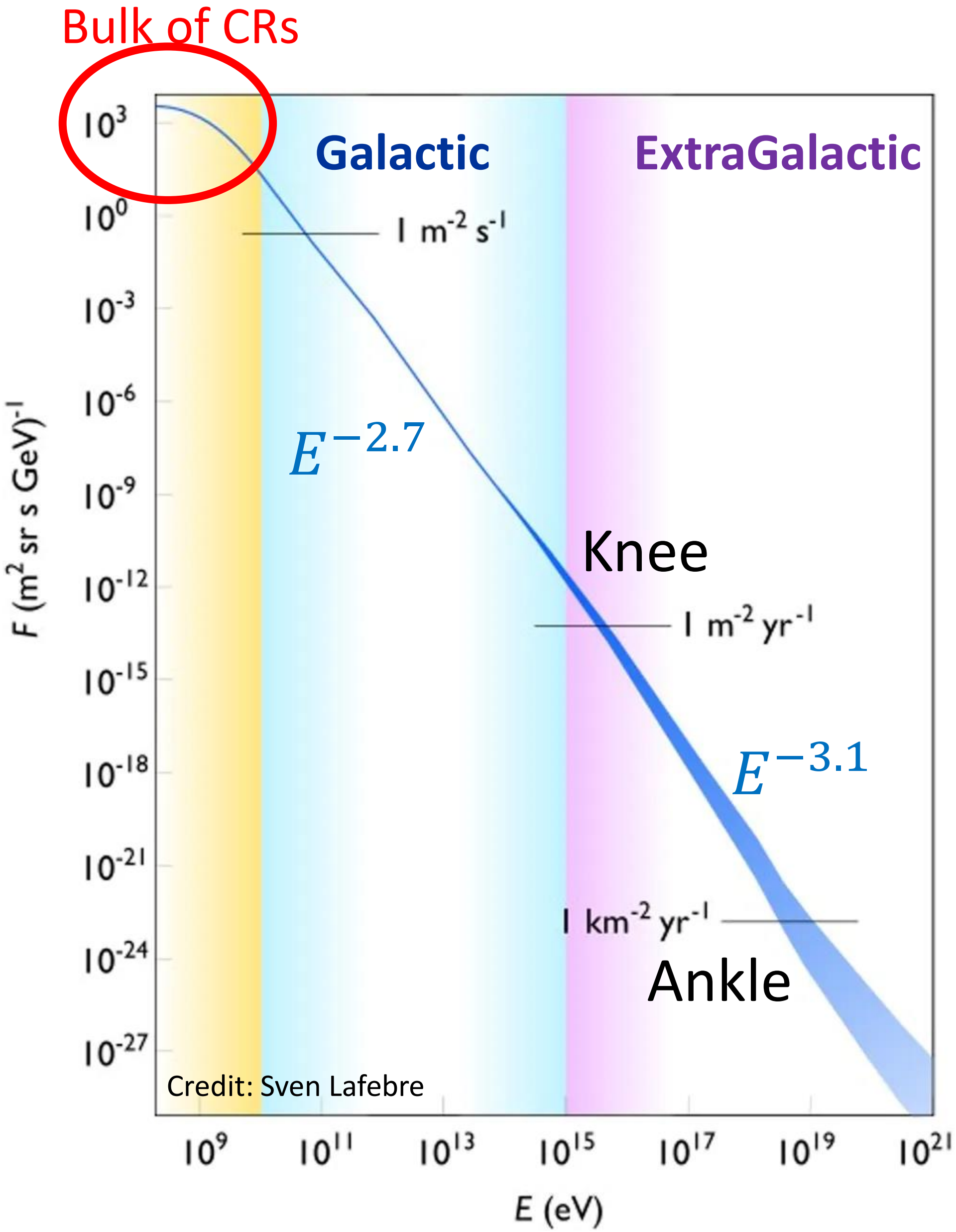
- Cosmic-ray energy density

- Magnetic field and Th. pressure

- Photon field energy density (SL+CMB)

The cosmic-ray spectrum



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- Cosmic-ray energy density

$$U_{CR} \approx 1\ eV\ cm^{-3}$$

- Magnetic field and Th. pressure

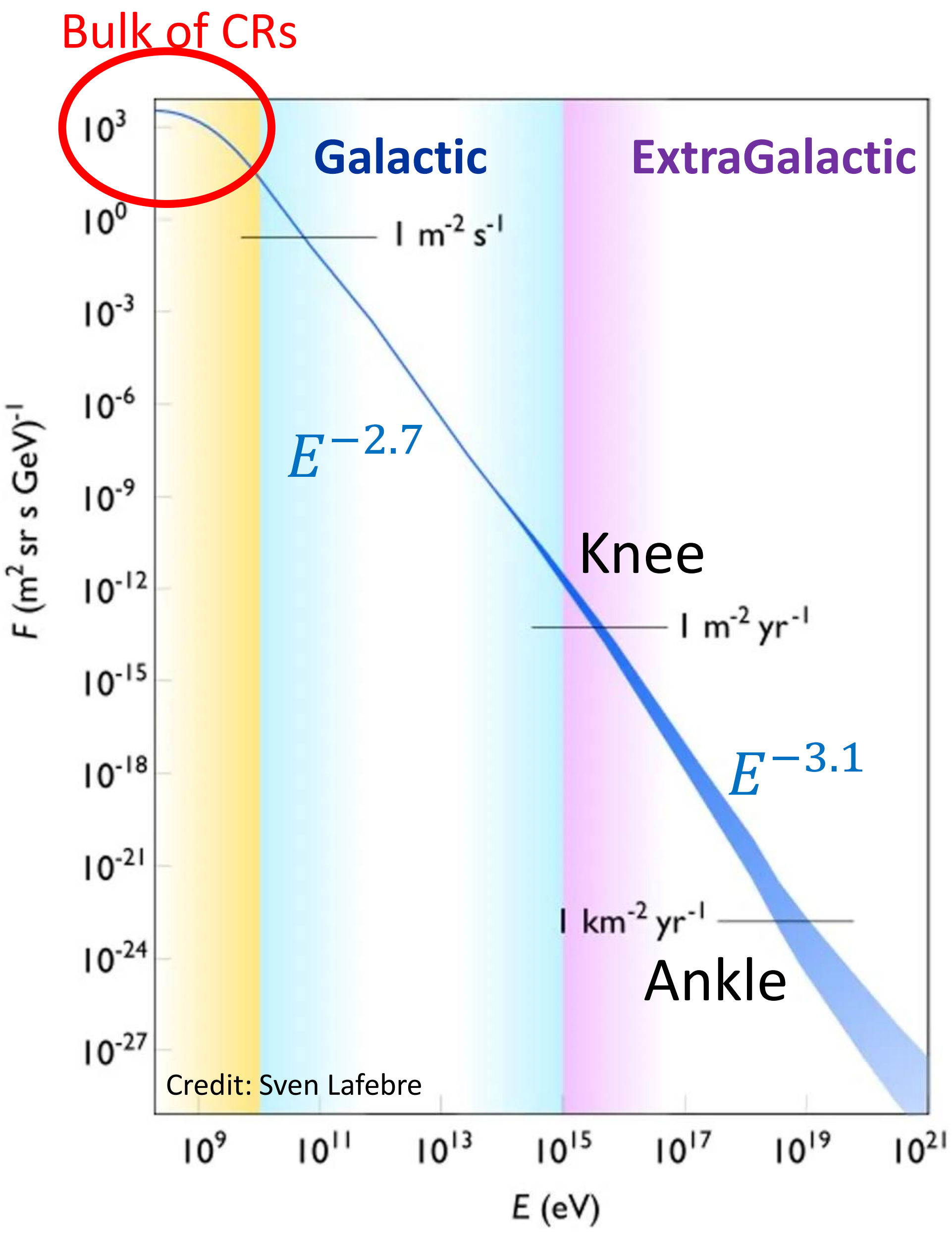
$$U_B = {B^2}/{8\pi} \approx 1\ eV\ cm^{-3}$$

$$P_{ISM} = nk_BT \approx 1\ eV\ cm^{-3}$$

- Photon field energy density (SL+CMB)

$$U_{RAD} \approx 1\ eV\ cm^{-3}$$

The cosmic-ray spectrum



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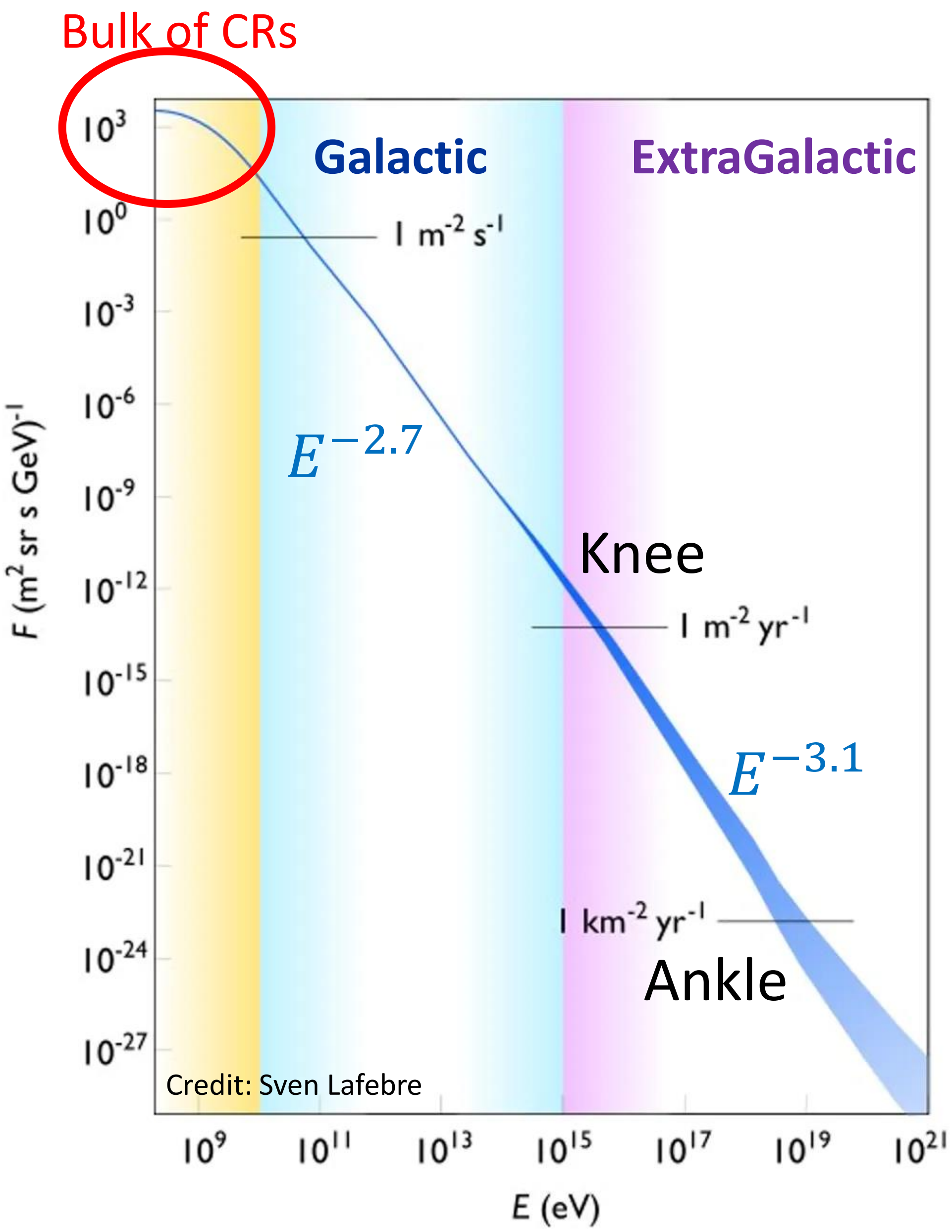
CRs dynamically relevant in the ISM!

The cosmic-ray spectrum



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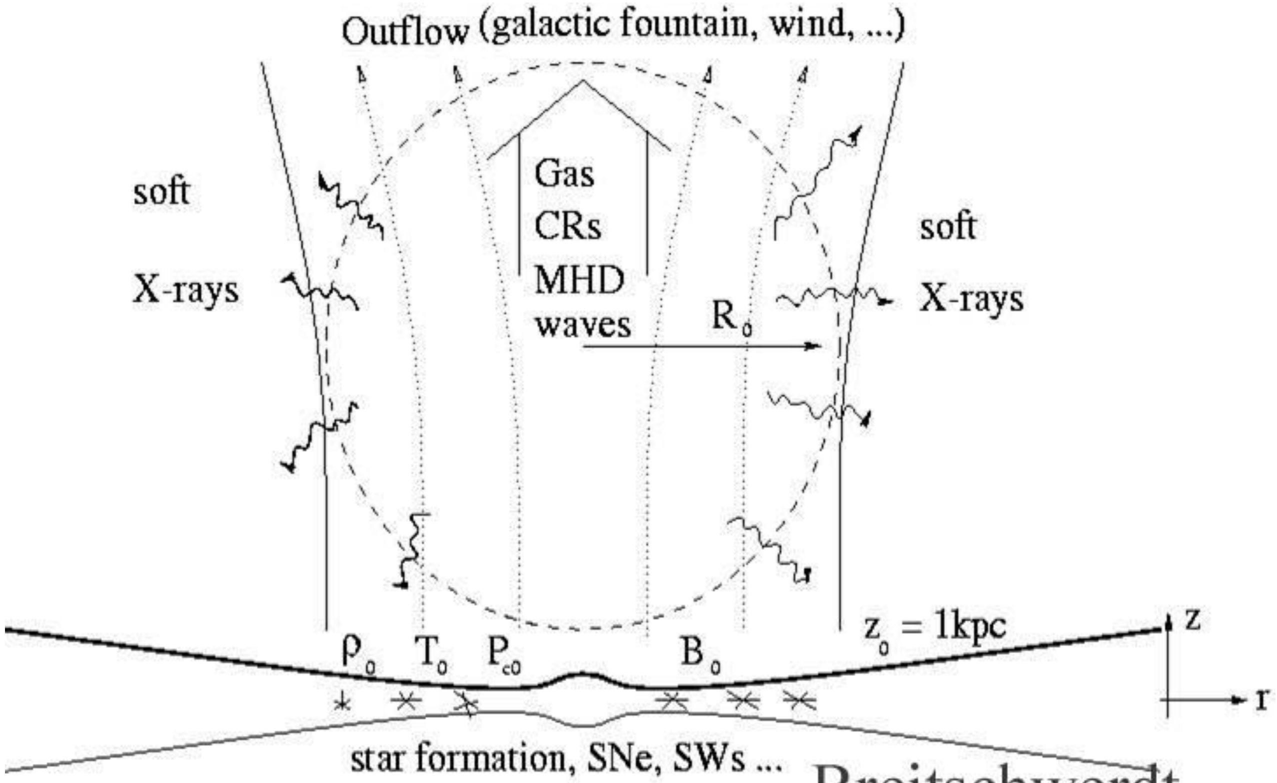
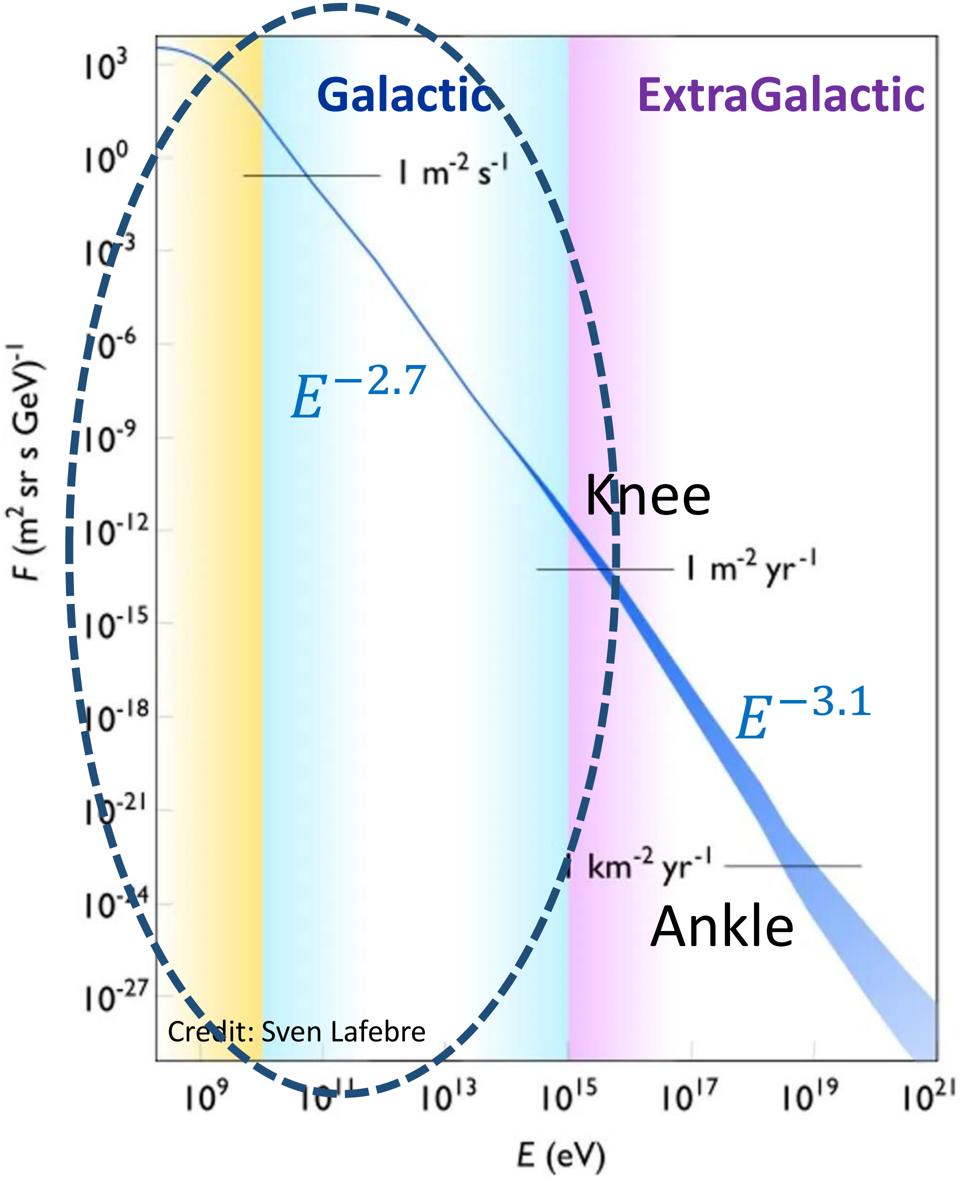


Breitschwerdt
(2002)

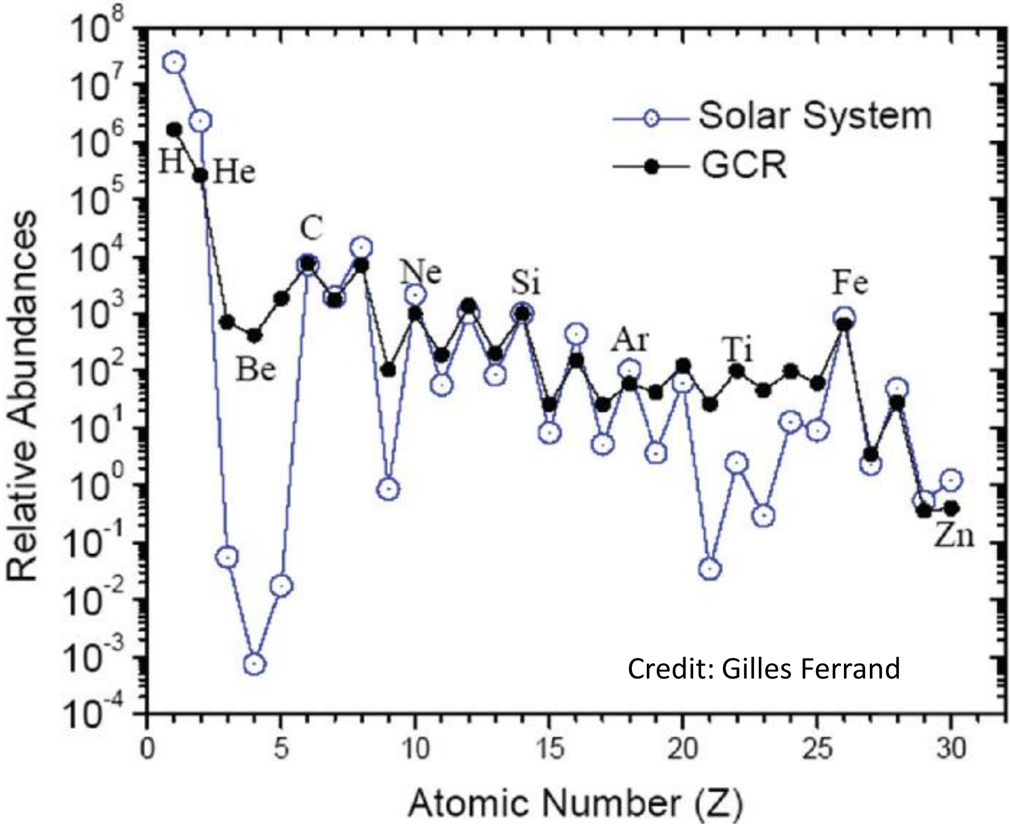
Galactic cosmic rays



Credit: Sven Lafebre

- Abundances of Li, Be, B help constraining the residence time of CRs in the Galaxy

$$\tau_{esc}(GeV)\sim 10^2 Myr$$



Credit: Gilles Ferrand

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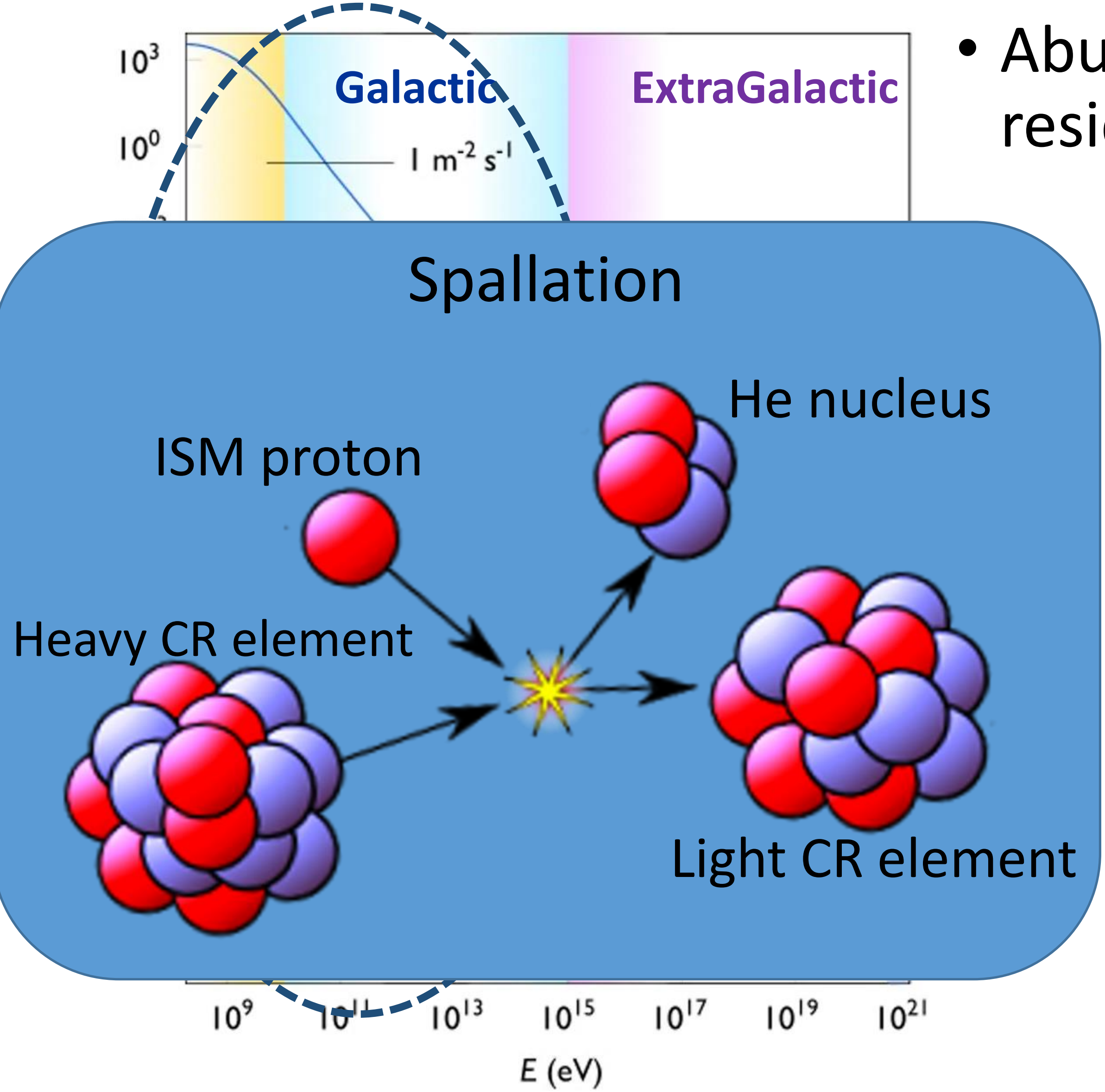

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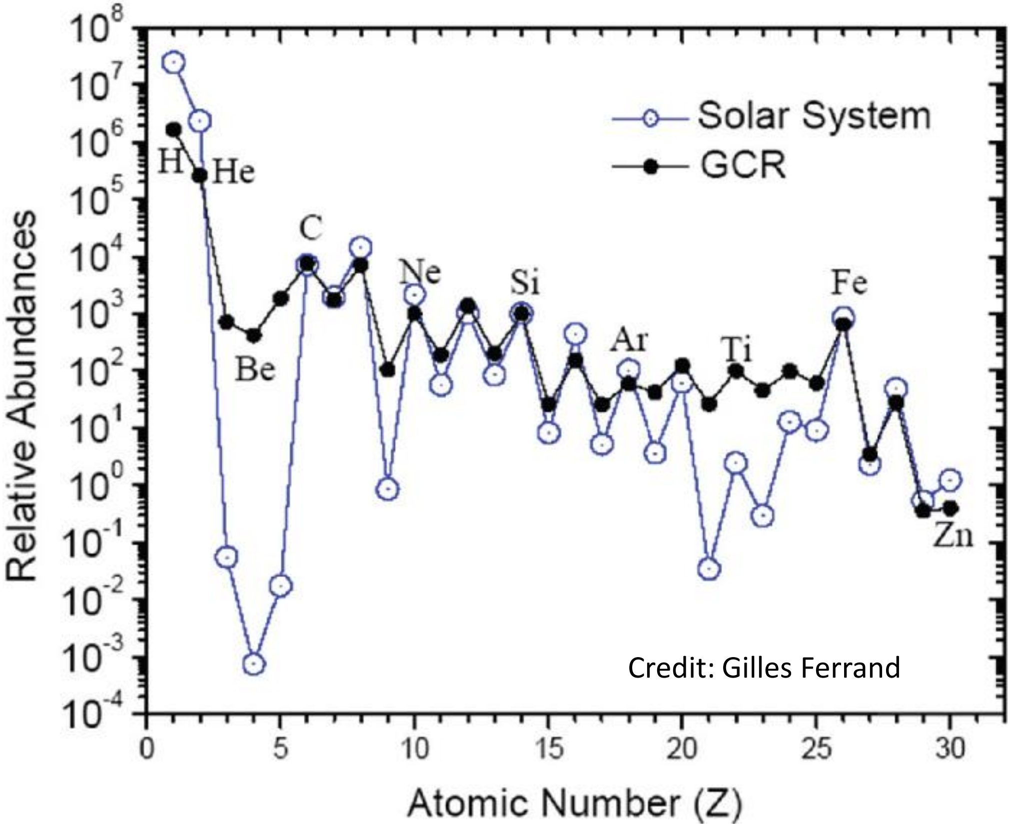

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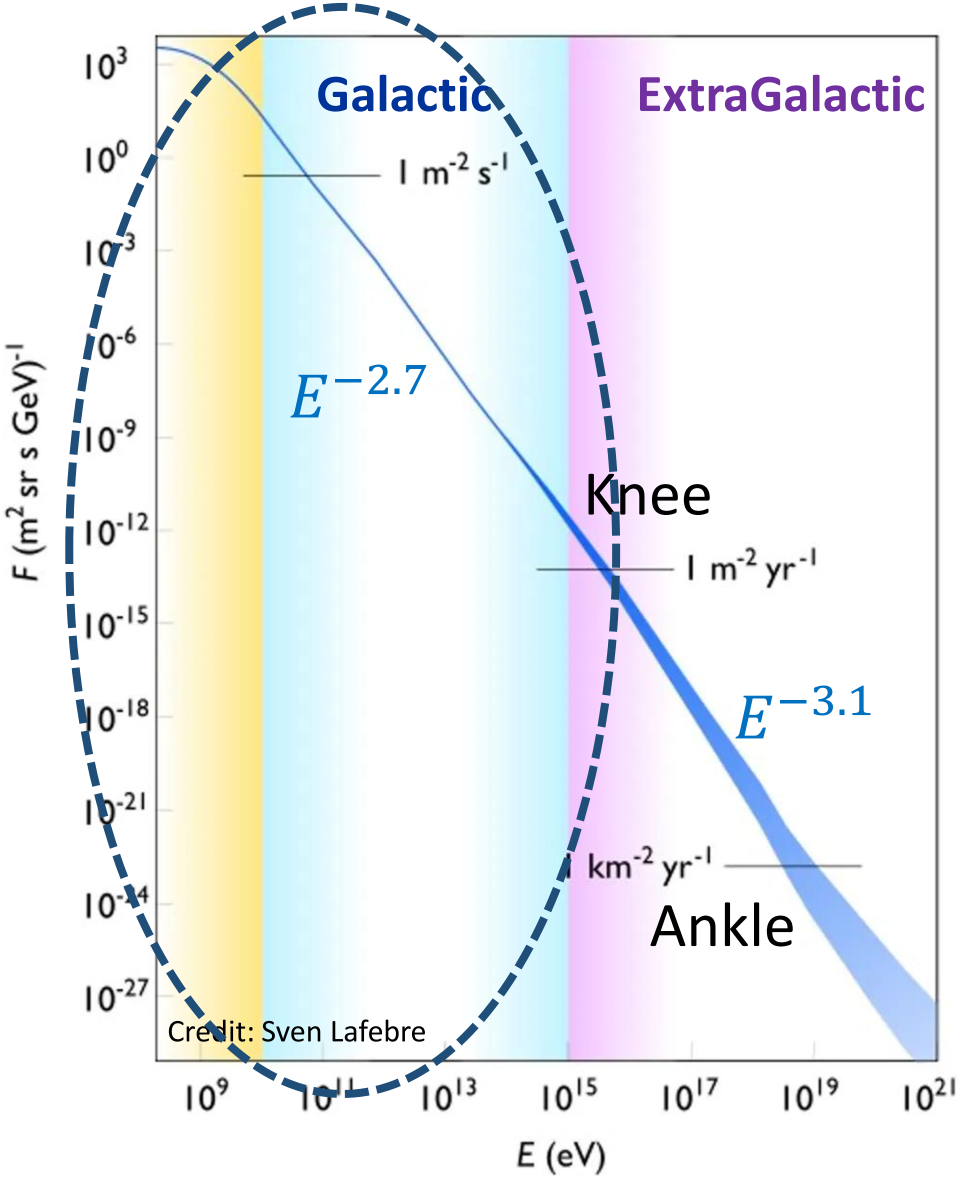

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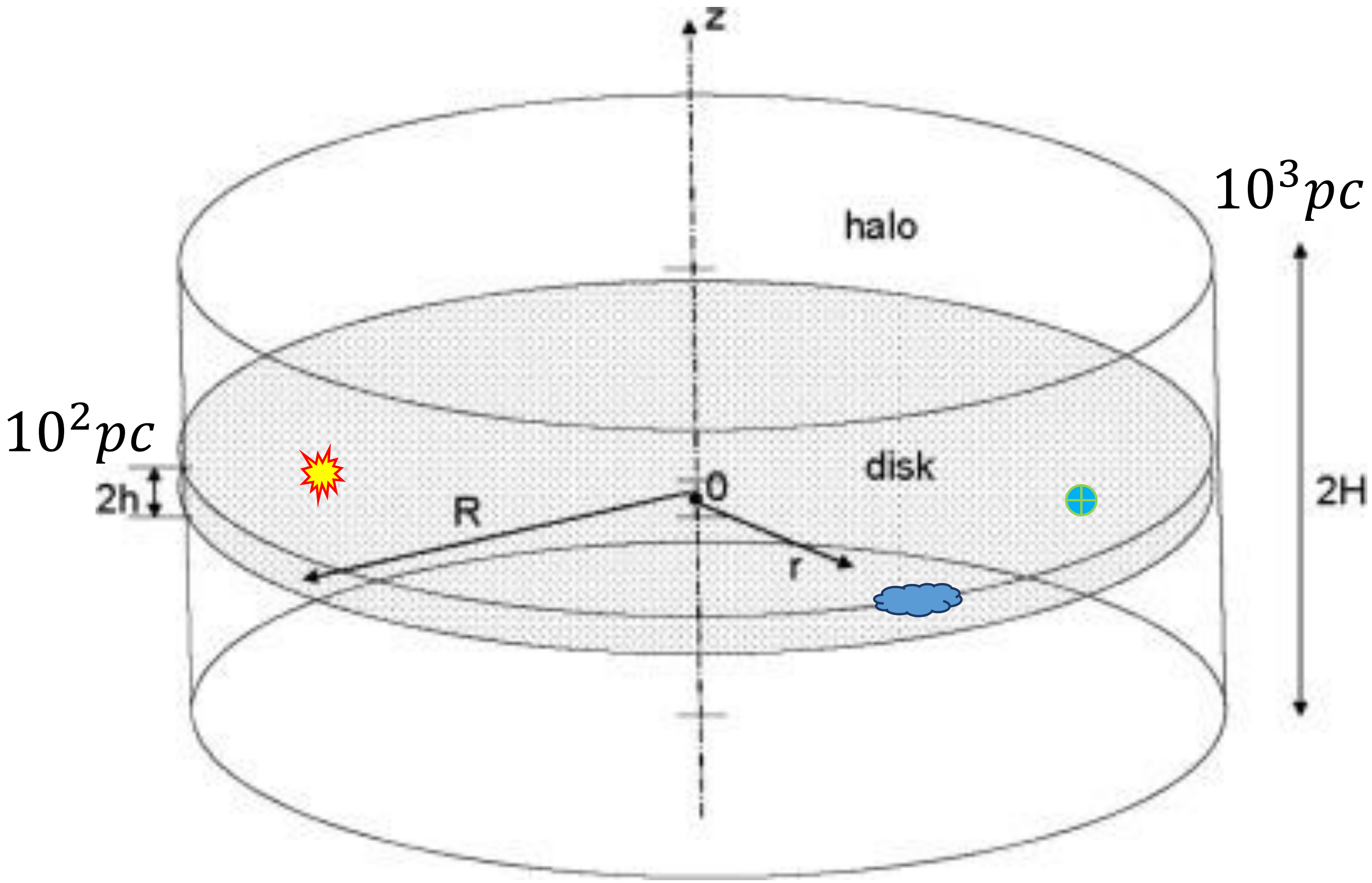

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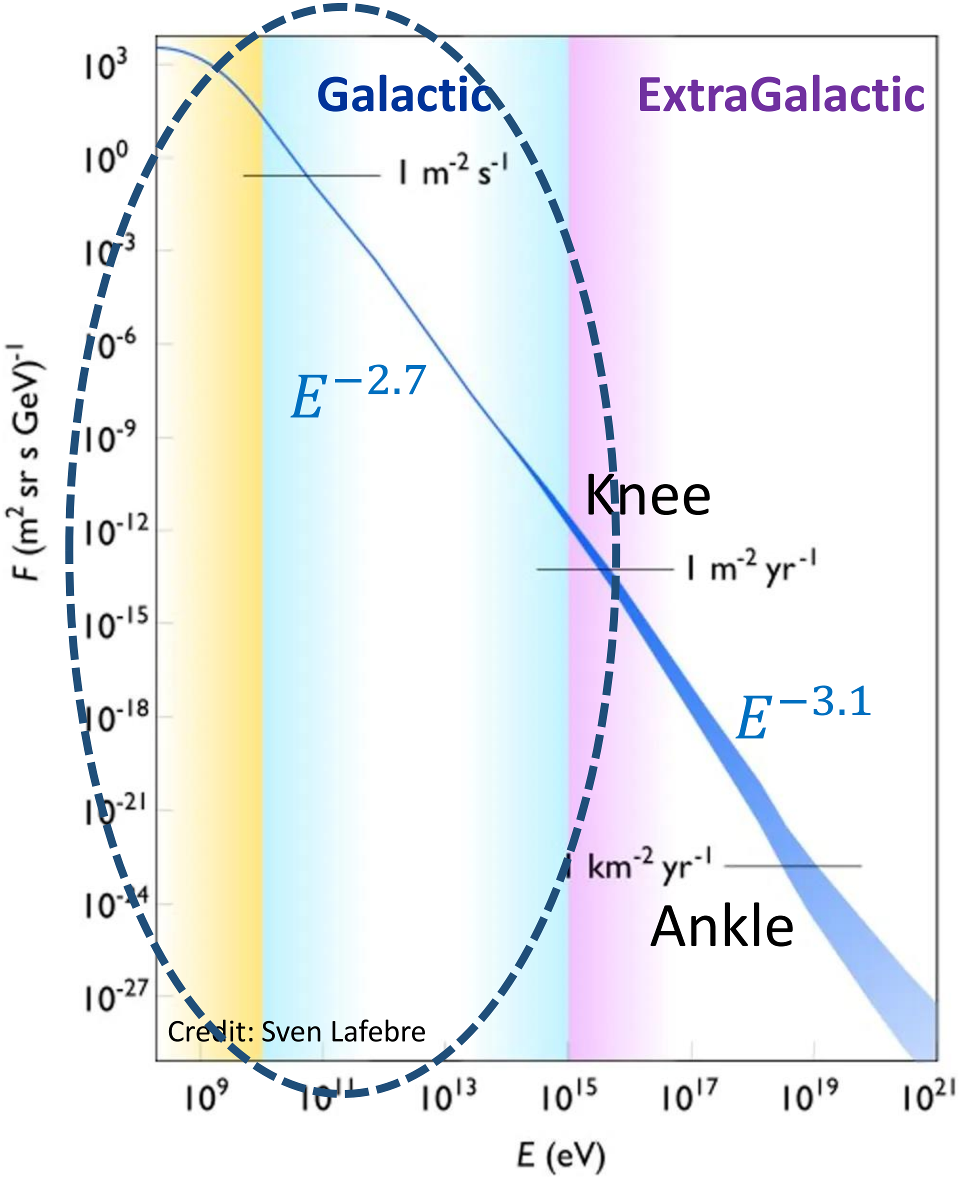

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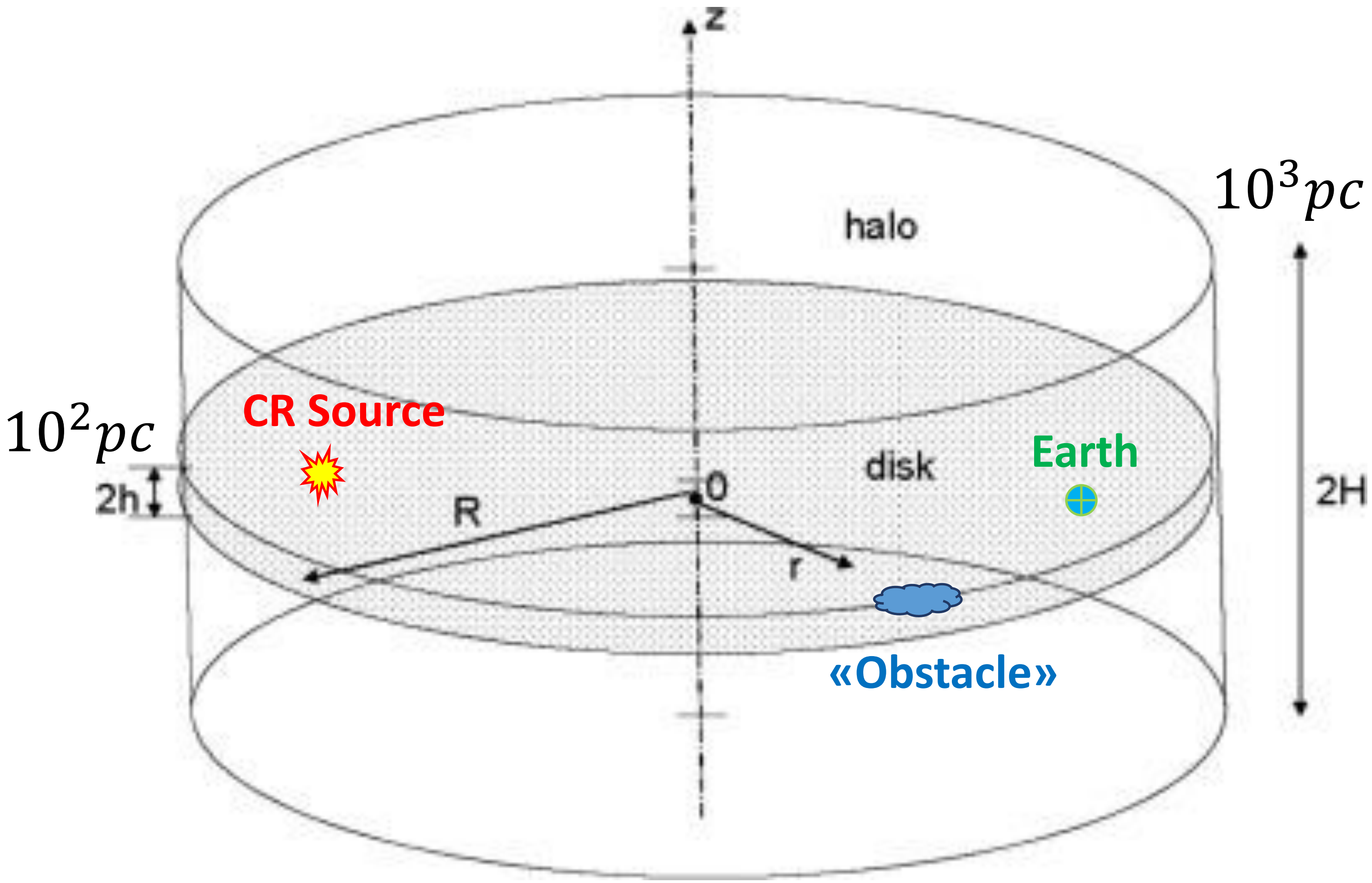

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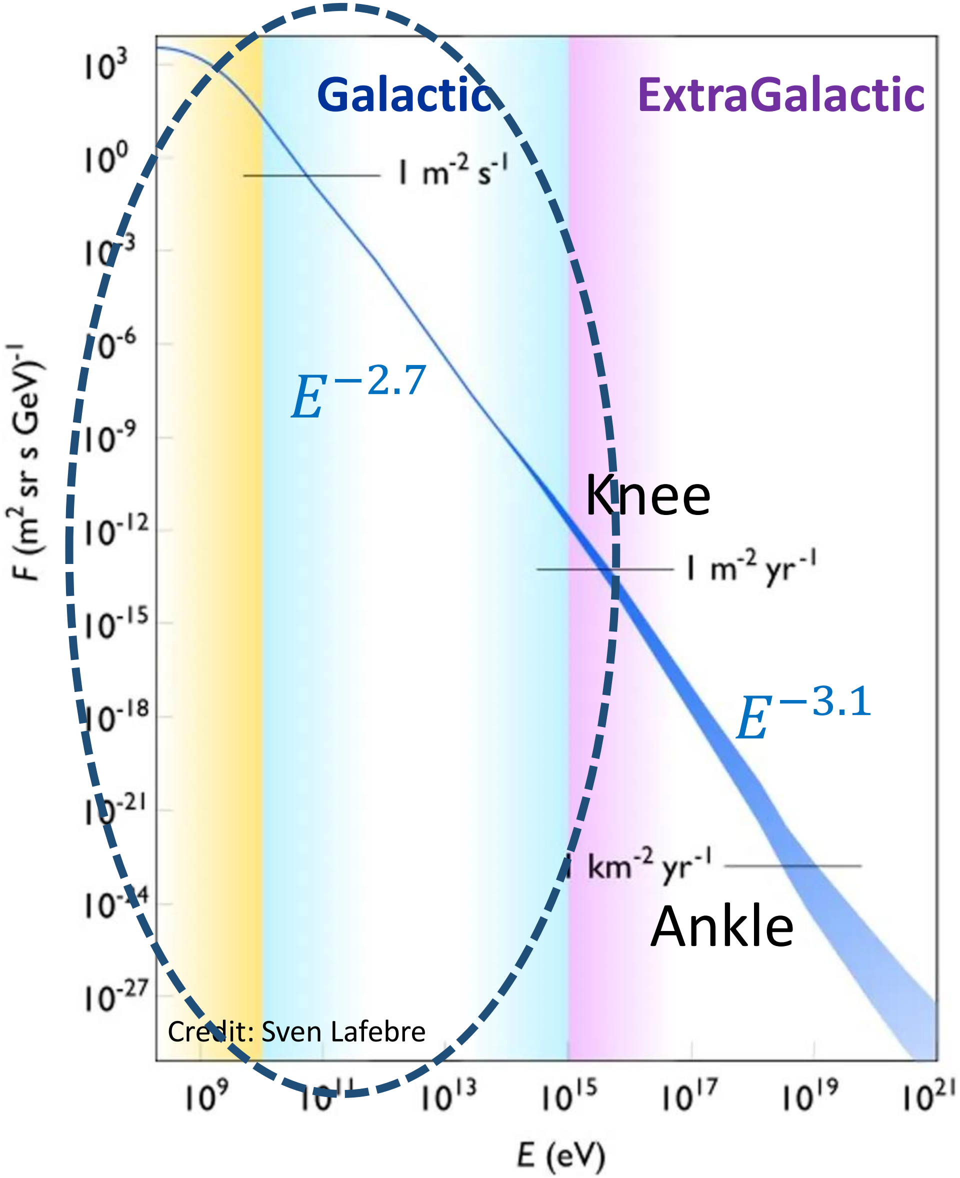

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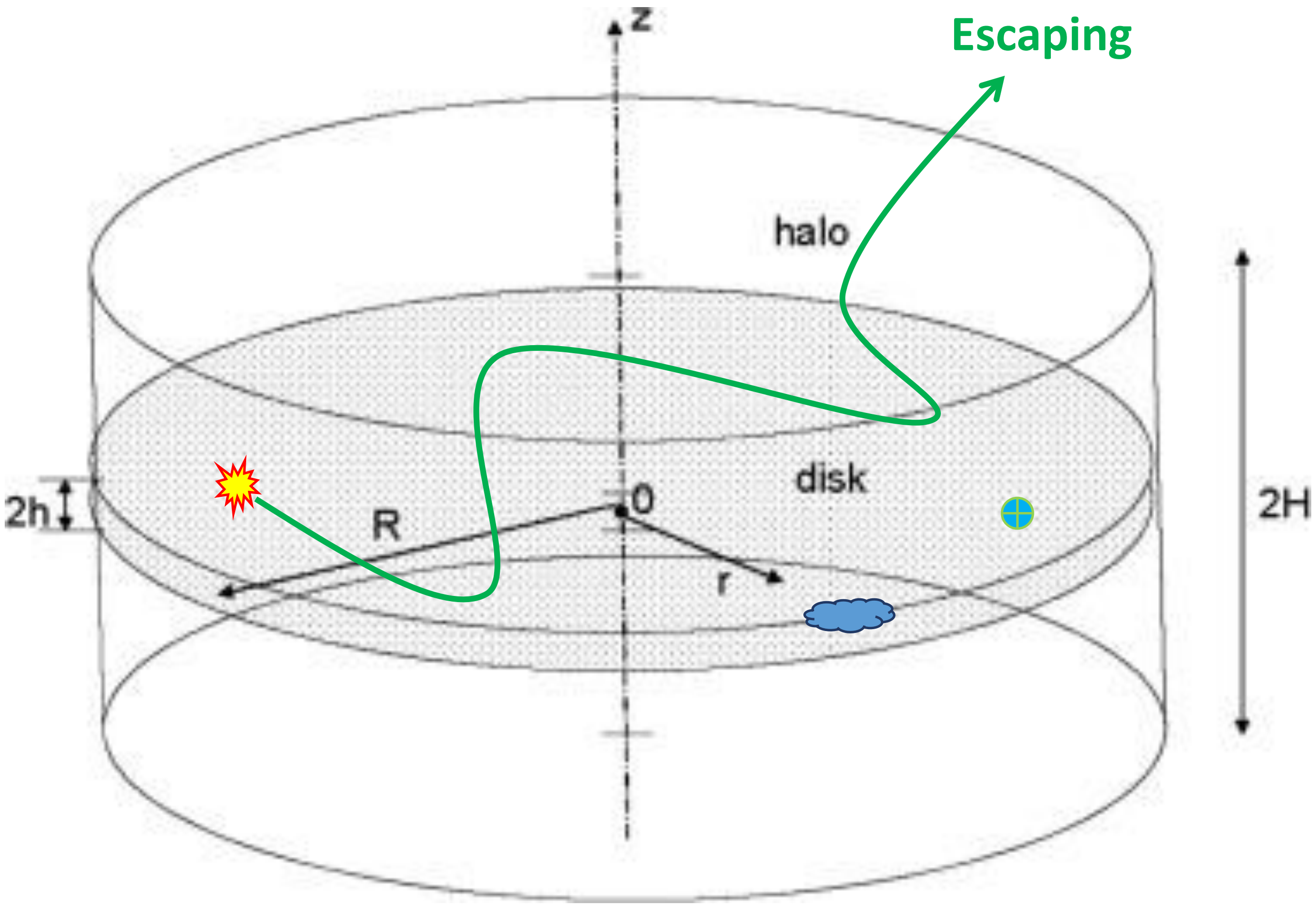

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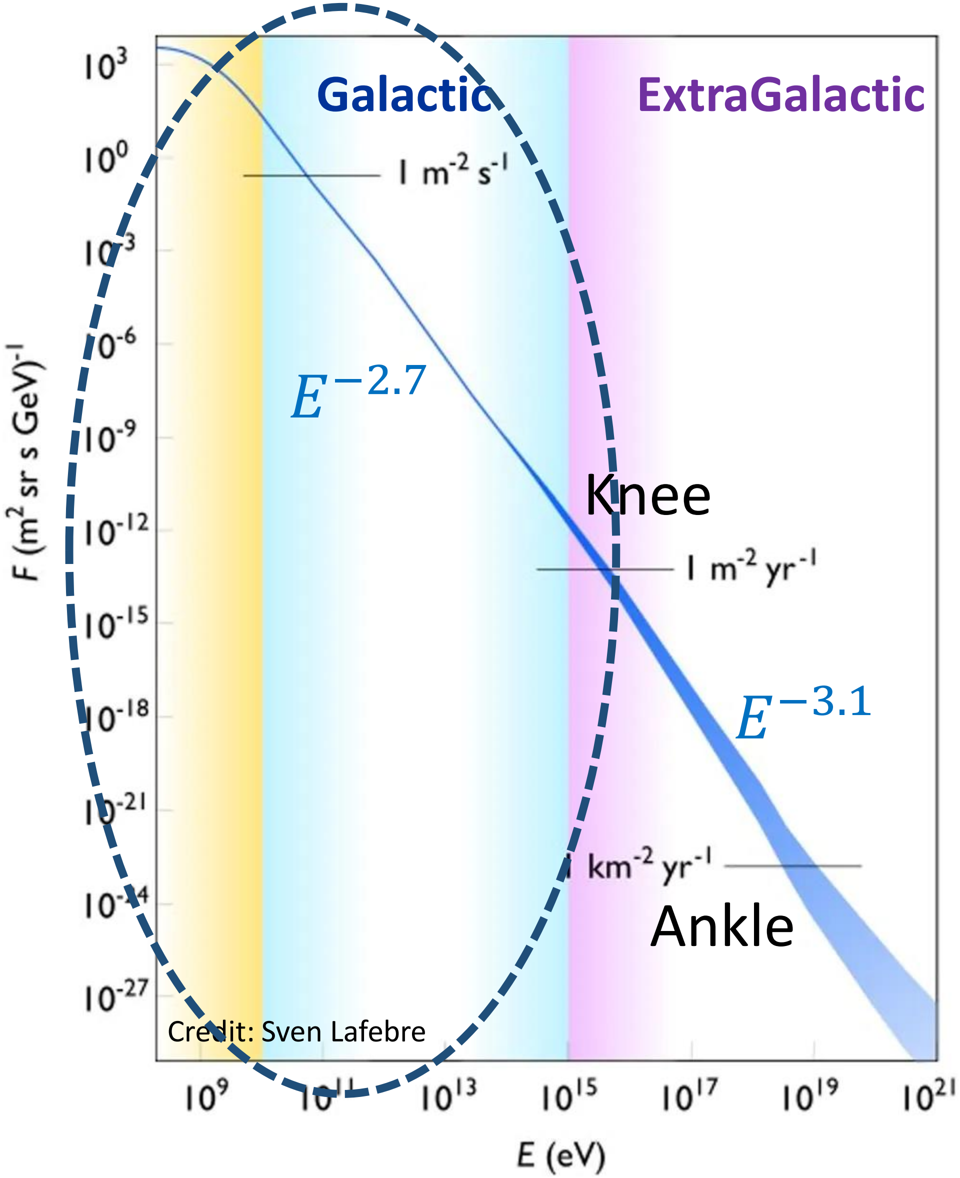

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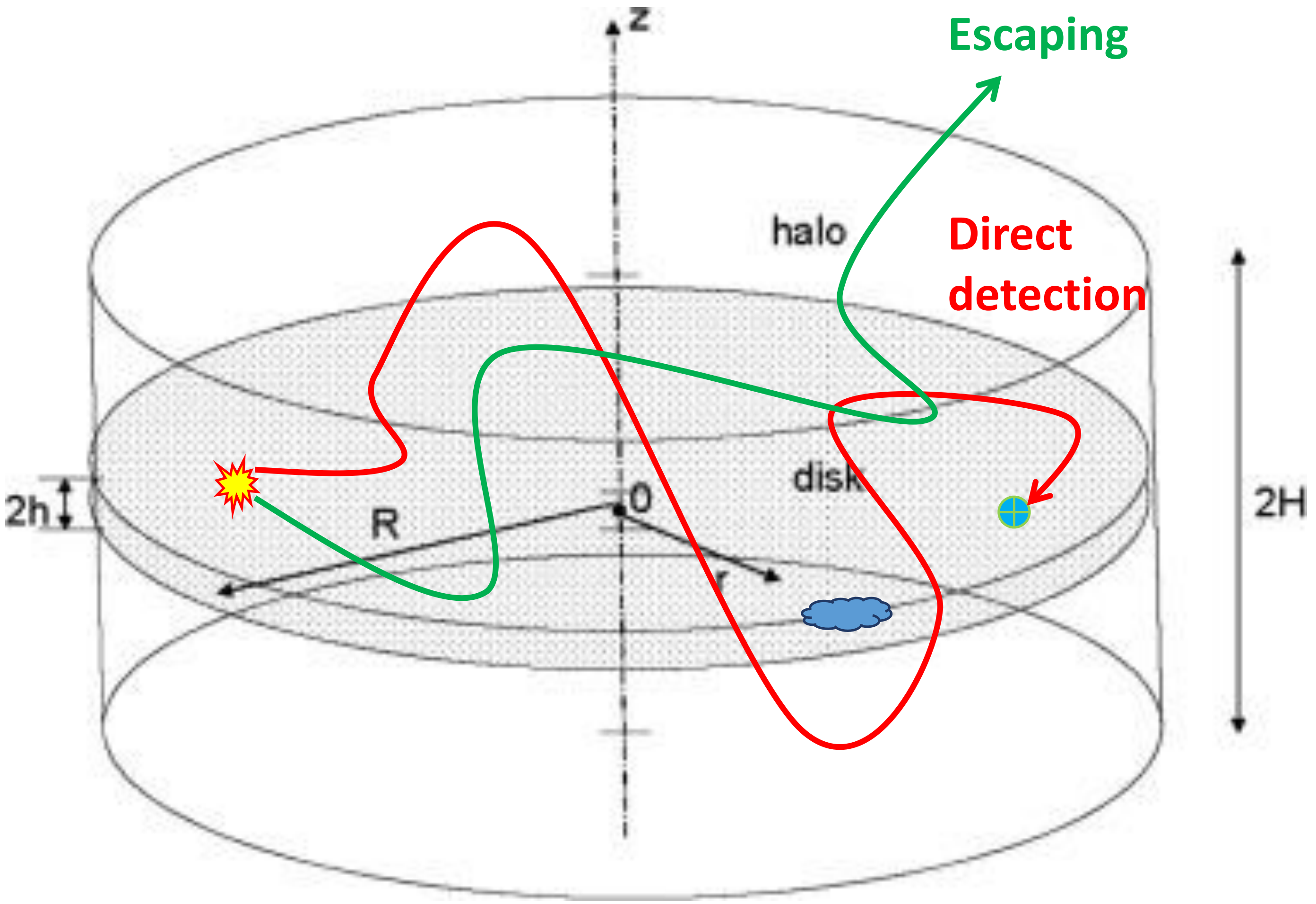

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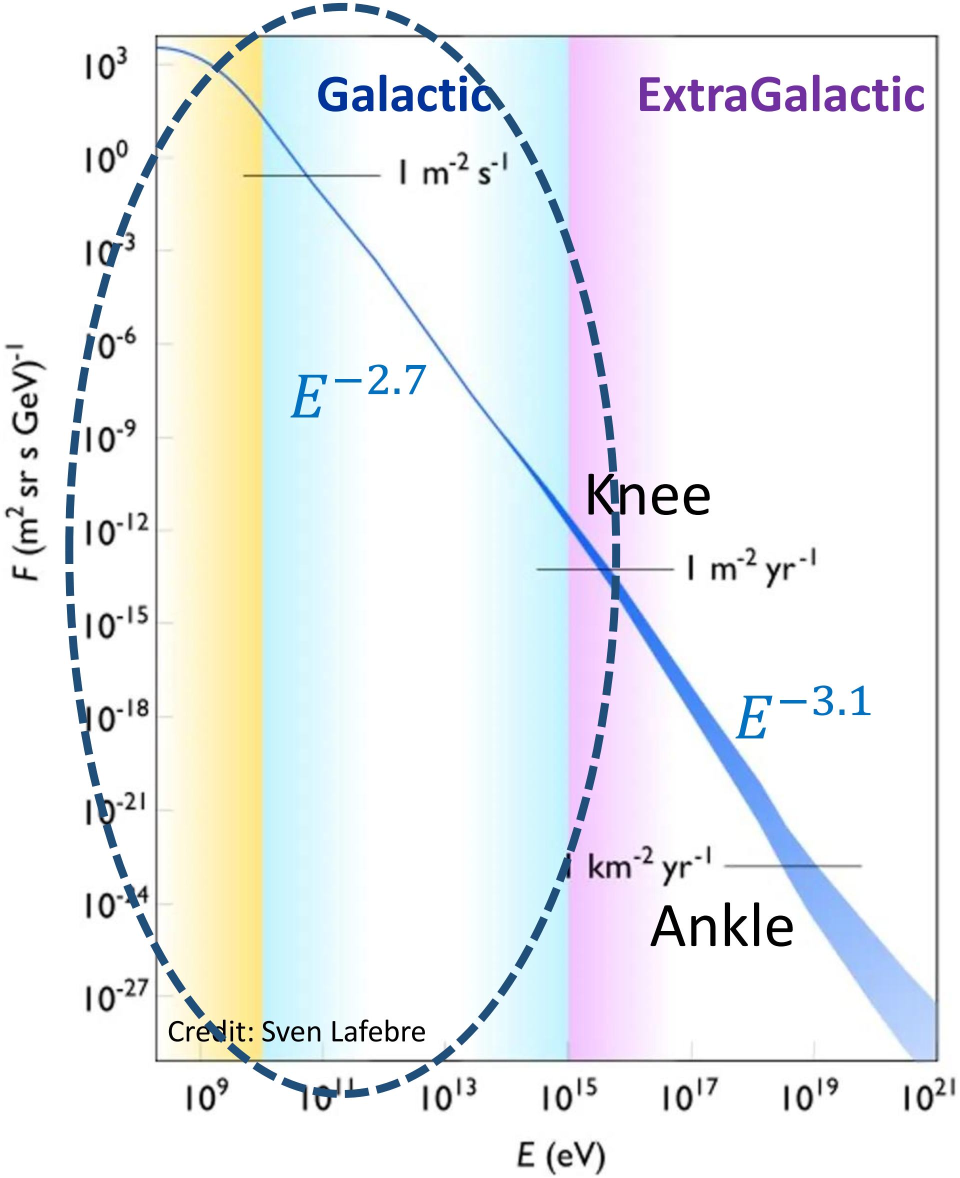

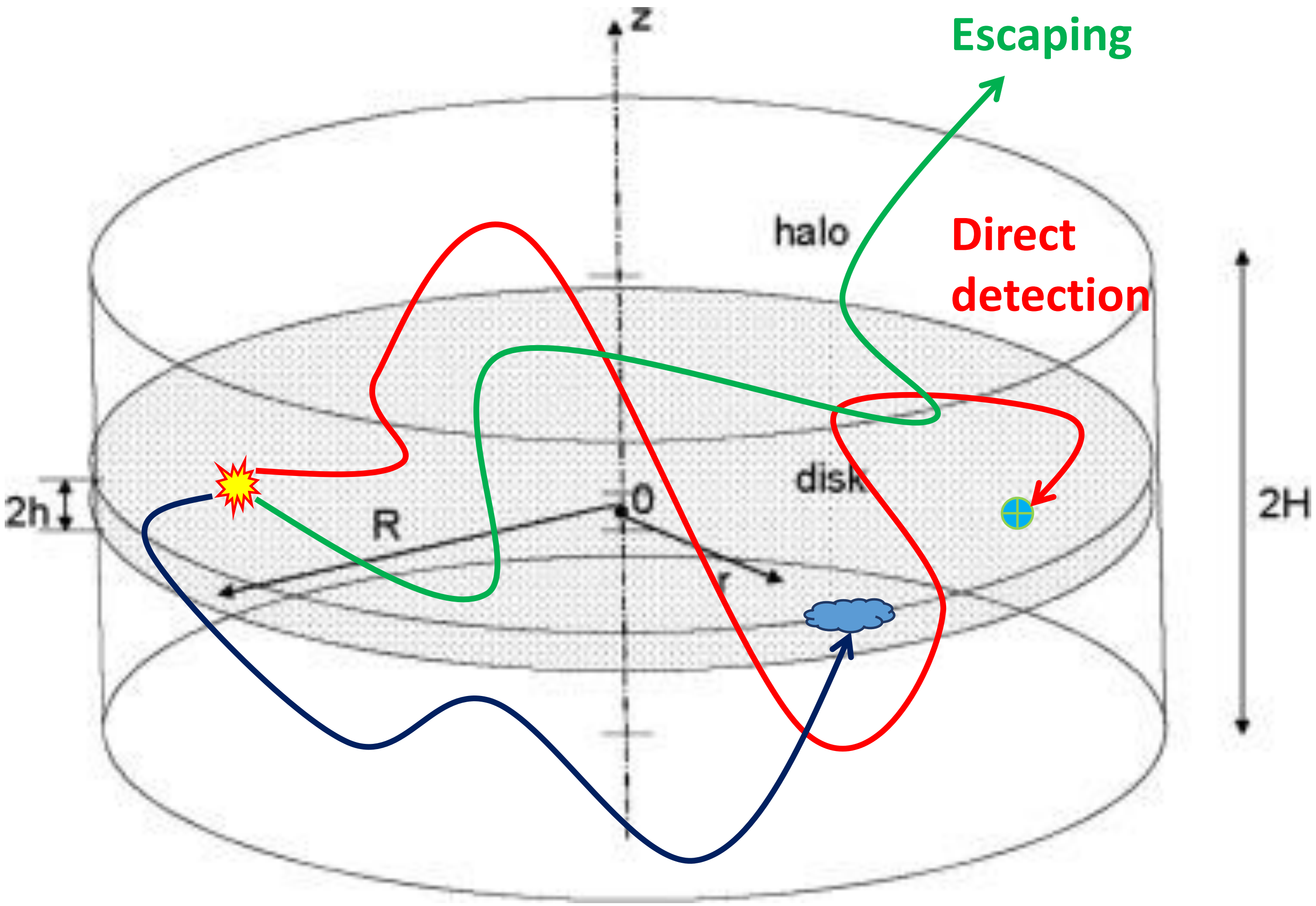

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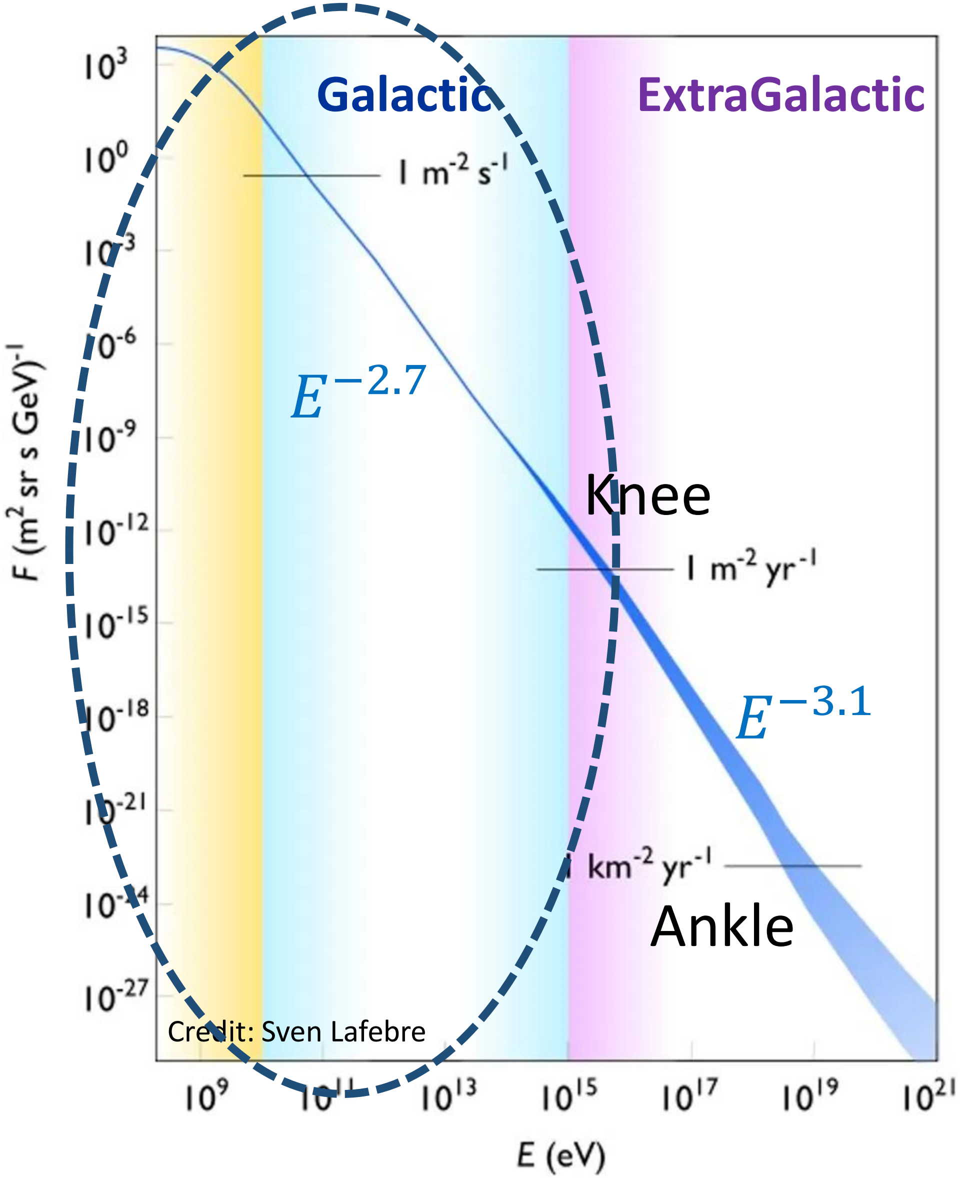

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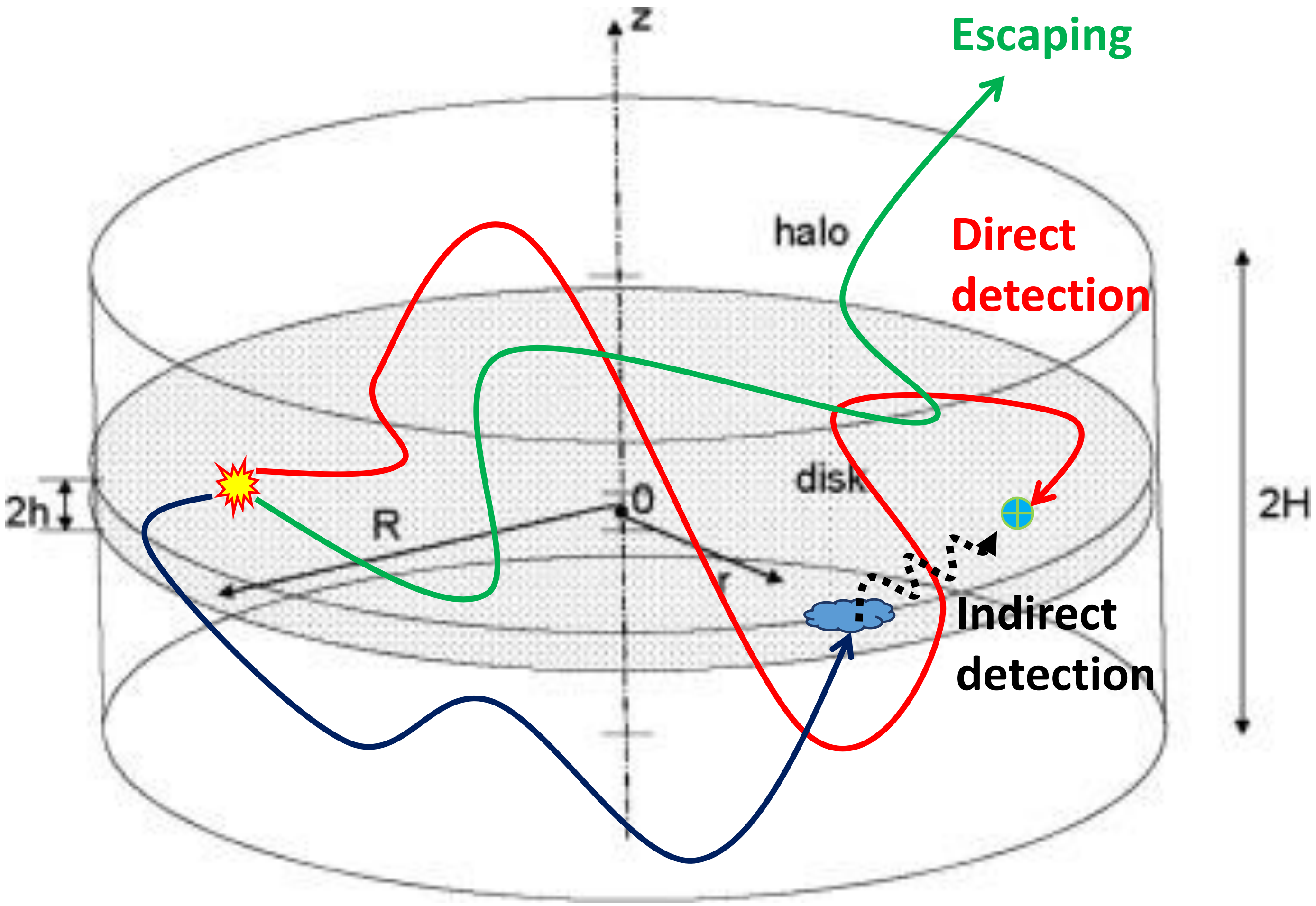
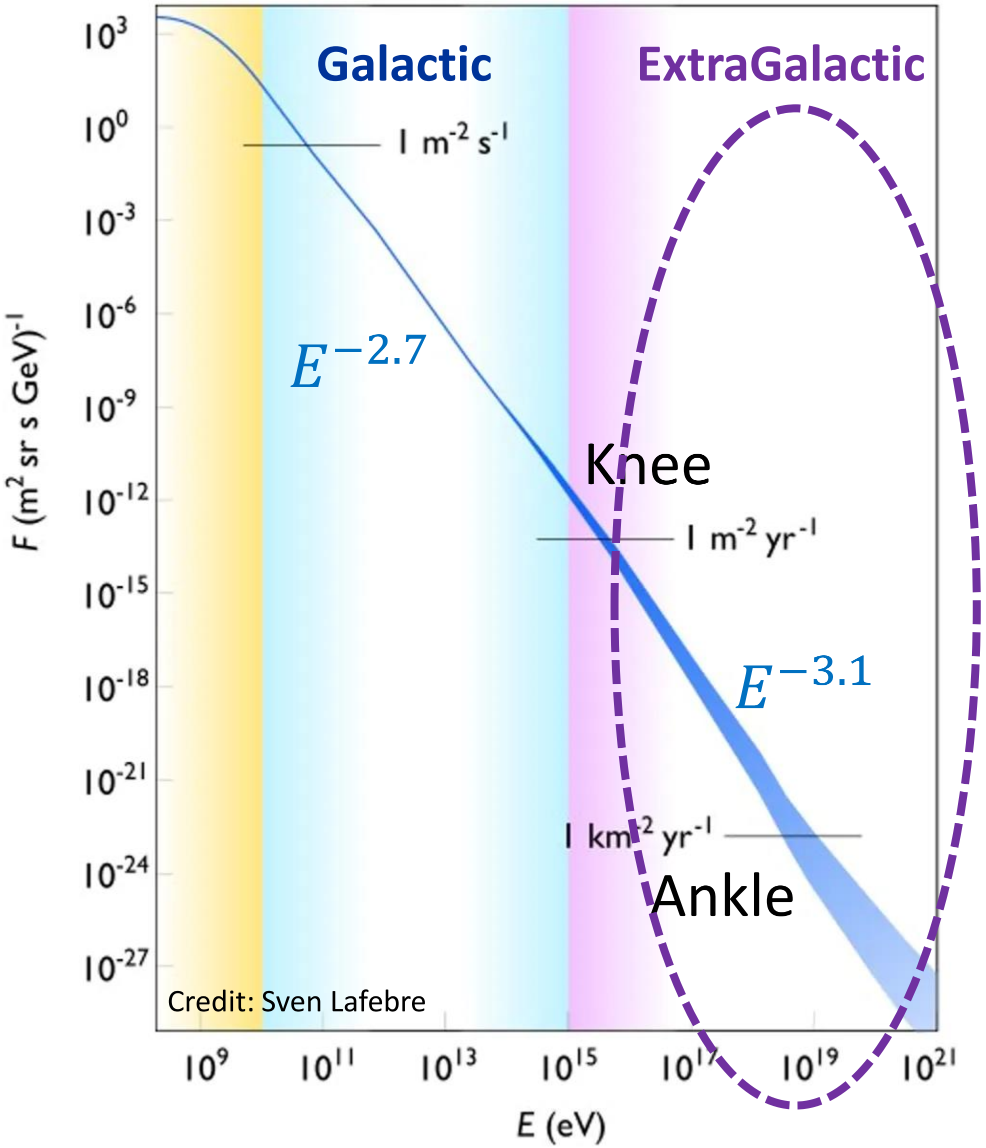


Extragalactic cosmic rays



- Lack of strong anisotropies in the sky
- The Galaxy cannot confine the highest energy particles with $B \approx 1\ \mu G$

$$E_{max} < q\ B\ R \approx 3q \cdot 10^{18}\ eV$$

- Only a few possible candidates as Galactic PeV-atrons (SLSN? YMSC? GC?)
- No indication of multi-PeV Galactic accelerators

Study and model cosmic rays

Cosmic-ray acceleration

- Stochastic acceleration (II order Fermi mechanism)
- Diffusive shock acceleration (I order Fermi mechanism)
- Plasma phenomena (magnetic reconnection, turbulence)

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Diffusive Shock Acceleration

Veil Nebula– Credit: HST
Spacetelescope.org/news/heic1520/

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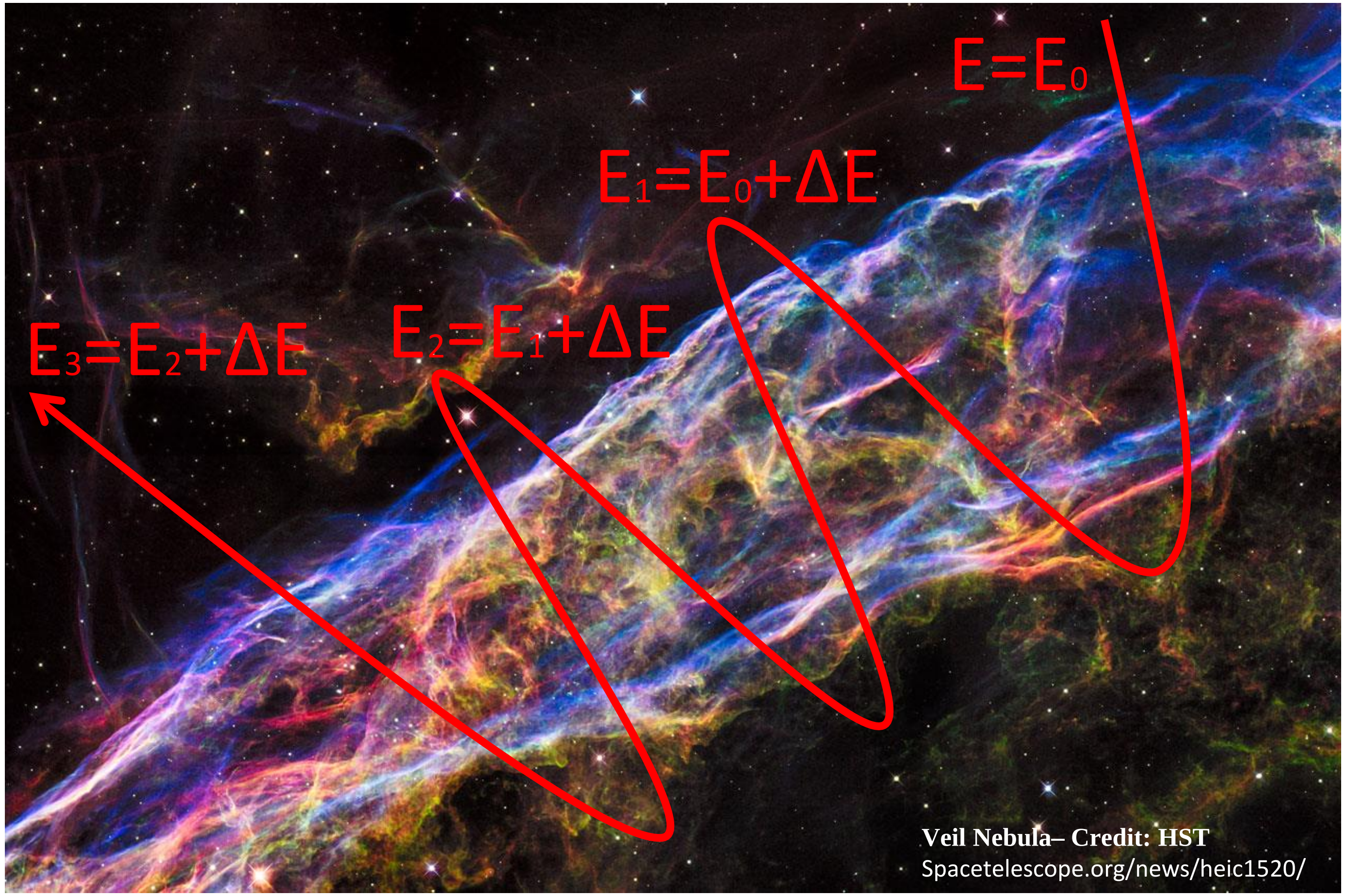

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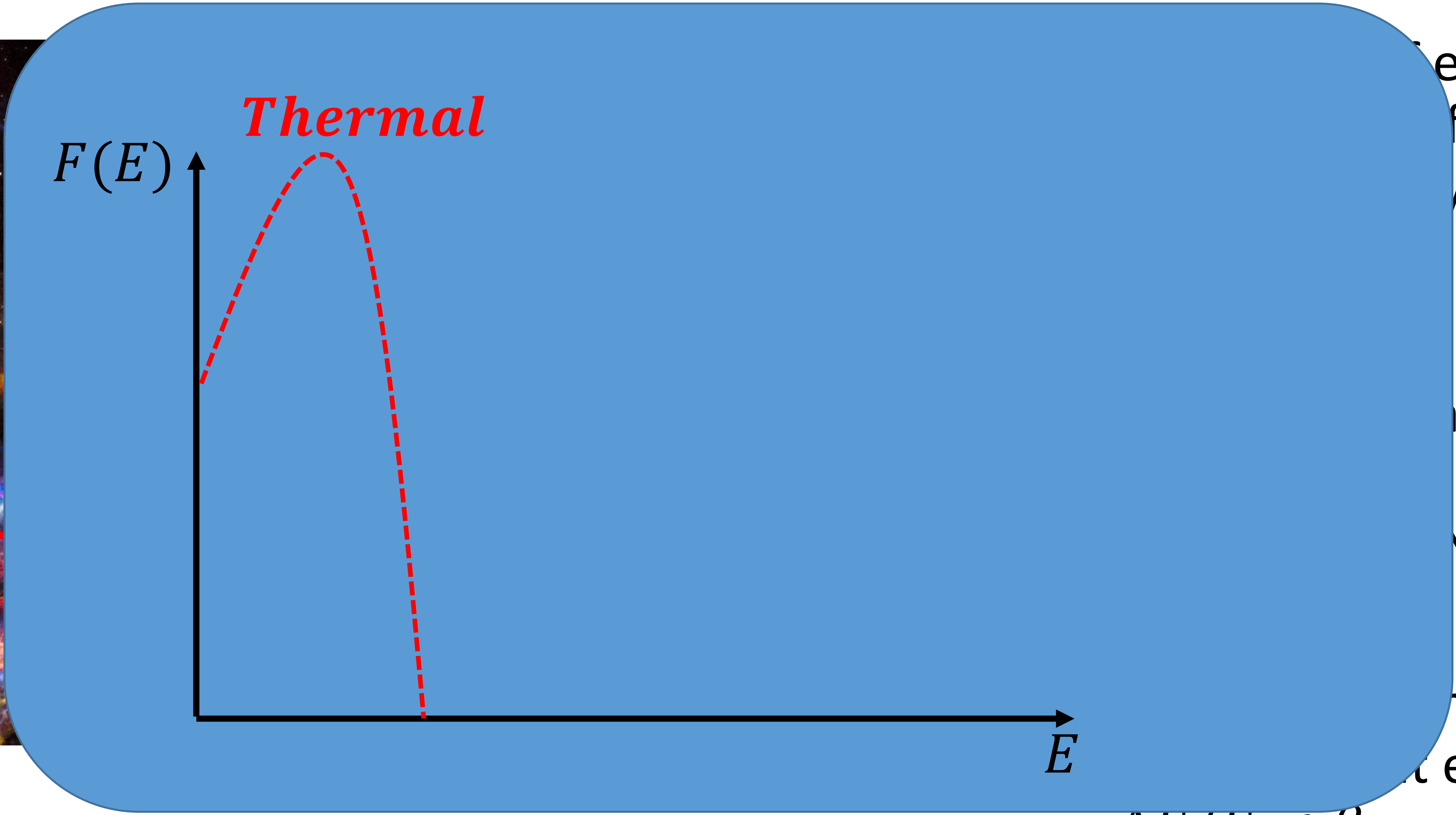
- One of the most simple and efficient first order Fermi mechanism we know in Nature
- Particles diffuse across shock waves gaining energy at each cycle $\Delta E/E \propto \beta_{sh}$

Diffusive Shock Acceleration



explosions
flows →
ysical

nd

Nature

hock
each cycle
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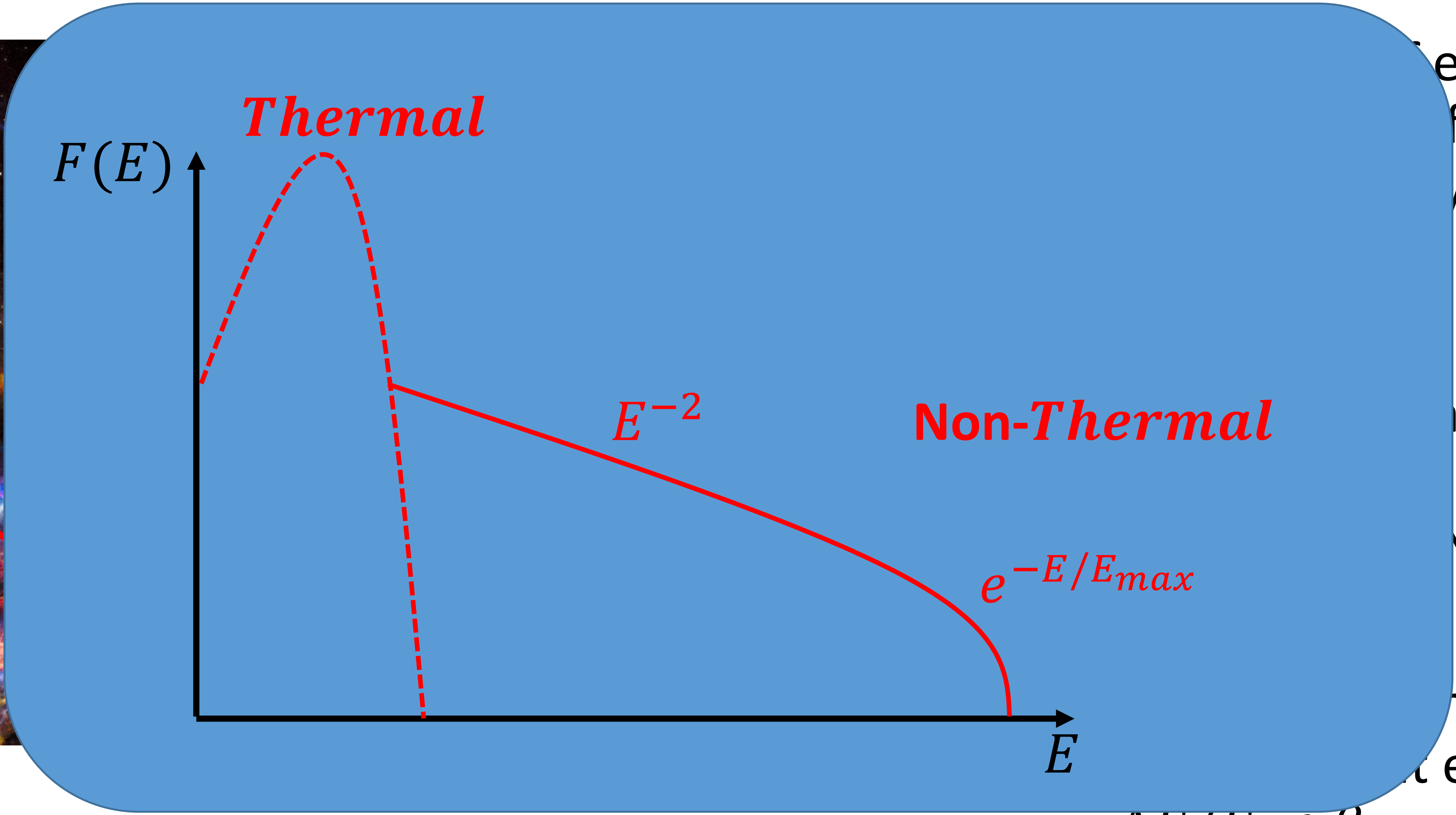

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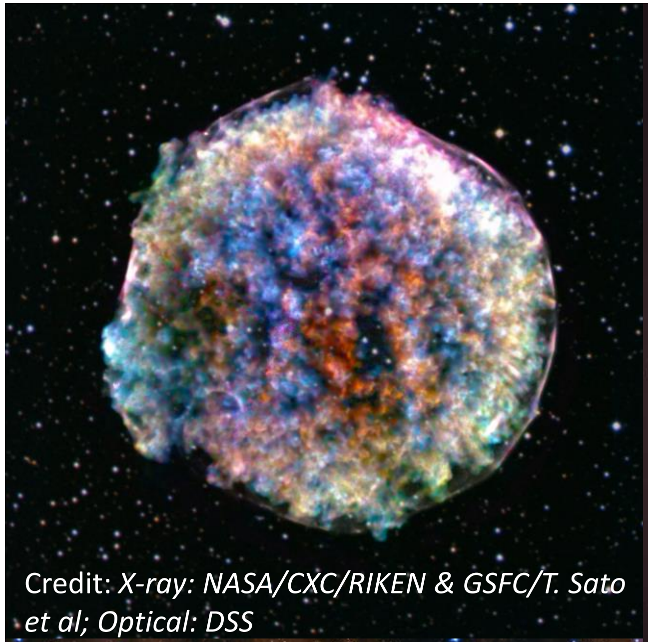
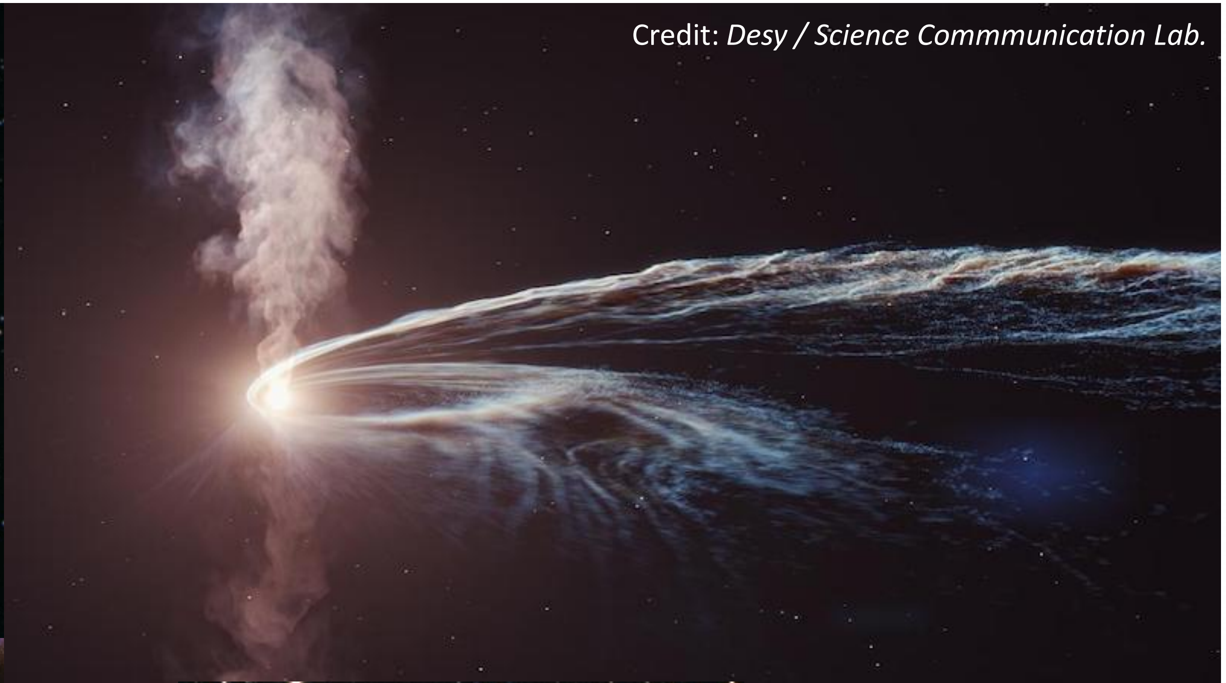
Physics of cosmic rays: Injection at sources



Credit: *X-ray: NASA/CXC/RIKEN & GSFC/T. Sato et al; Optical: DSS*



Credit: *Desy / Science Commmunication Lab.*

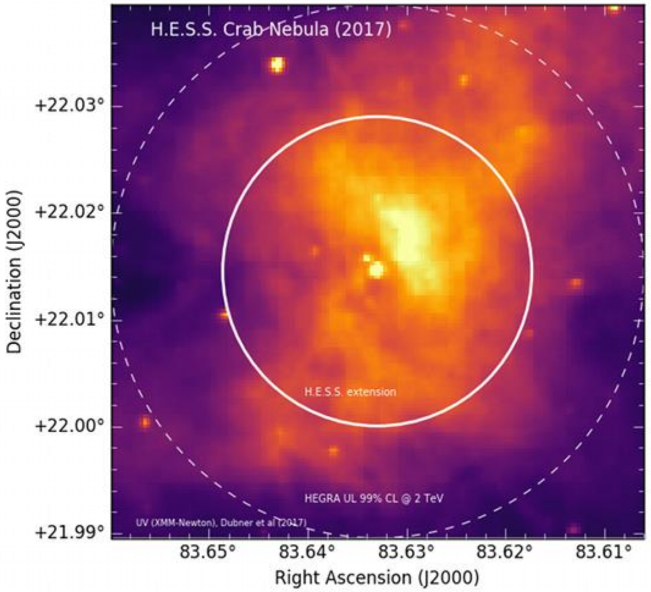
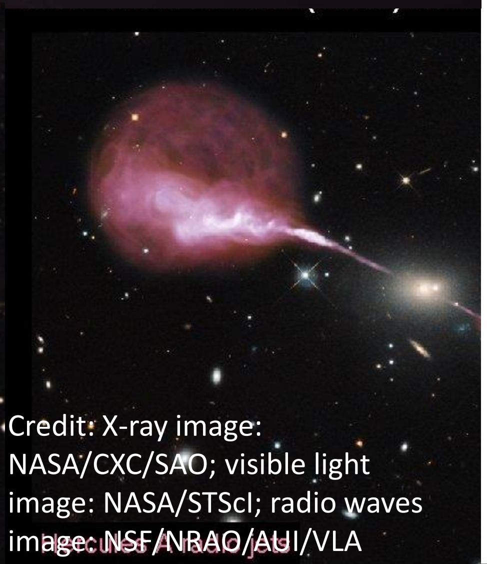
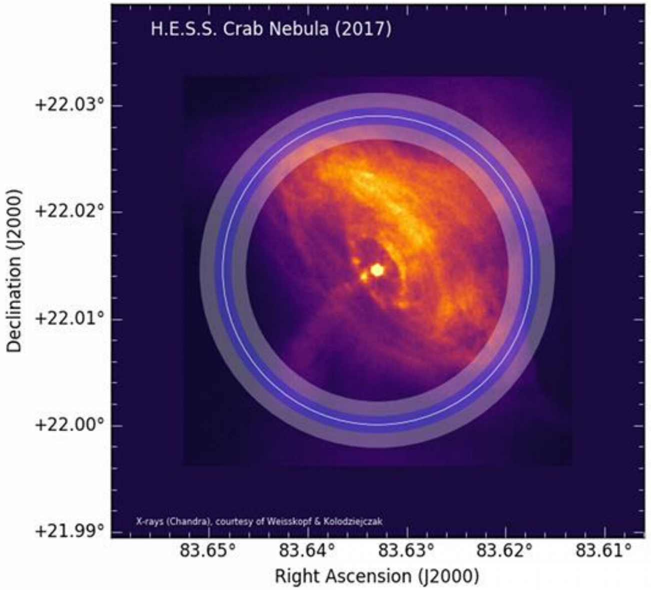


Image Credit & Copyright: NASA, ESA, the Hubble Heritage Team (STScI / AURA), A. Nota (ESA/STScI), and the Westerlund 2 Science Team

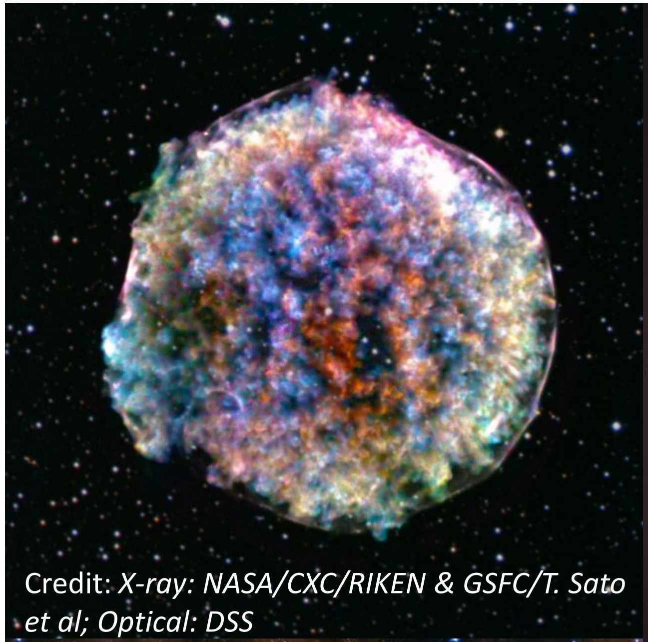
Credit: X-ray: NASA/CXC/Univ. of Wisconsin-Madison/S. Heinz et al; Optical: DSS; Radio: CSIRO/ATNF/ATCA



Credit: X-ray image: NASA/CXC/SAO; visible light image: NASA/STScI; radio waves image: NSF/NRAO/AUI/VLA



Physics of cosmic rays: Injection at sources



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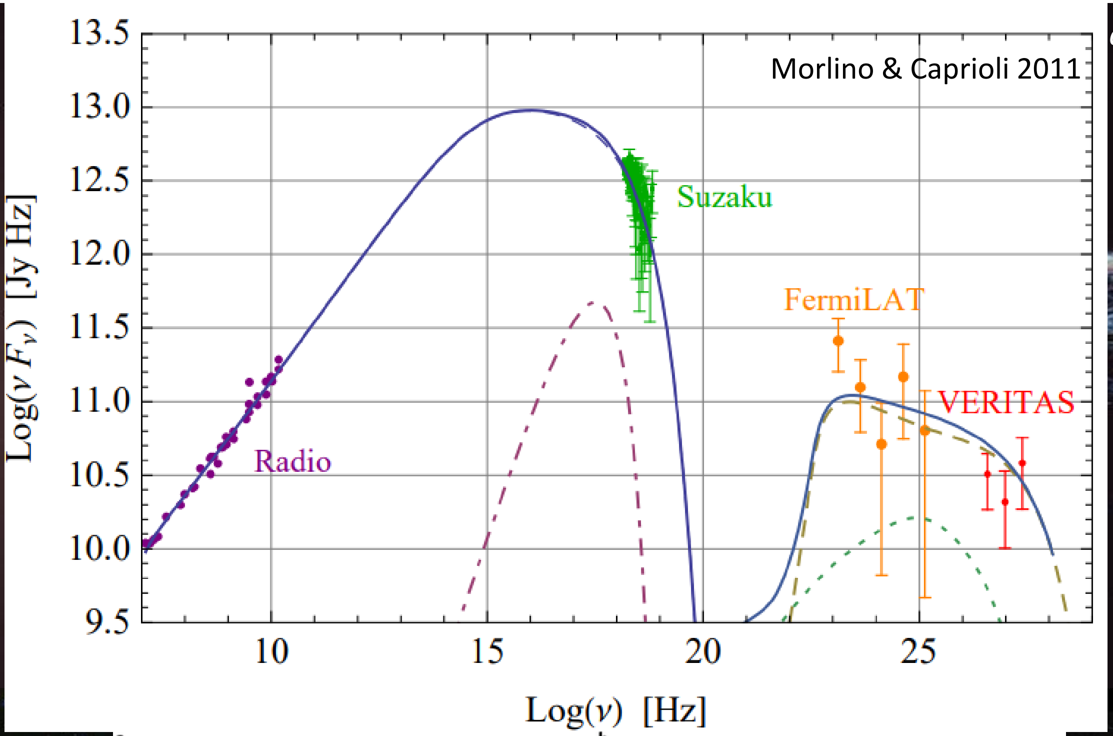

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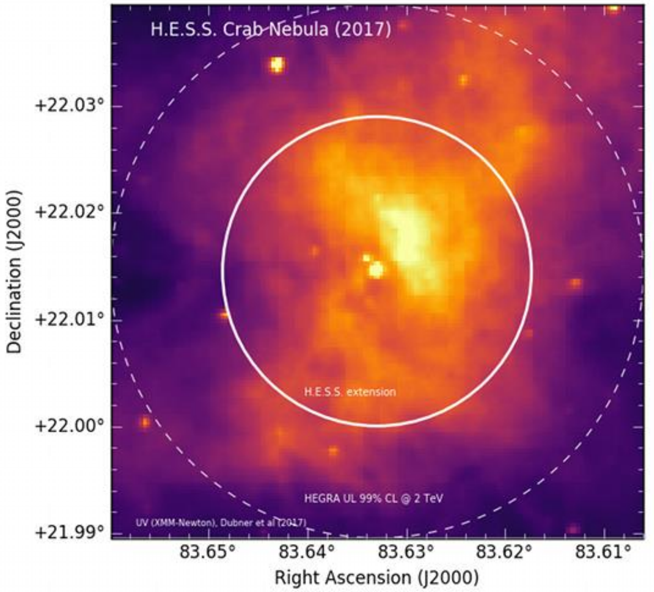

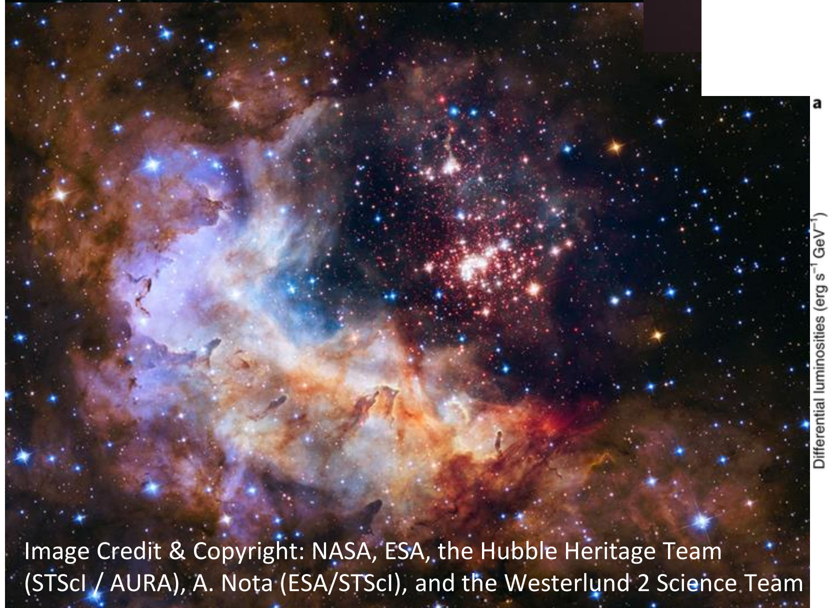

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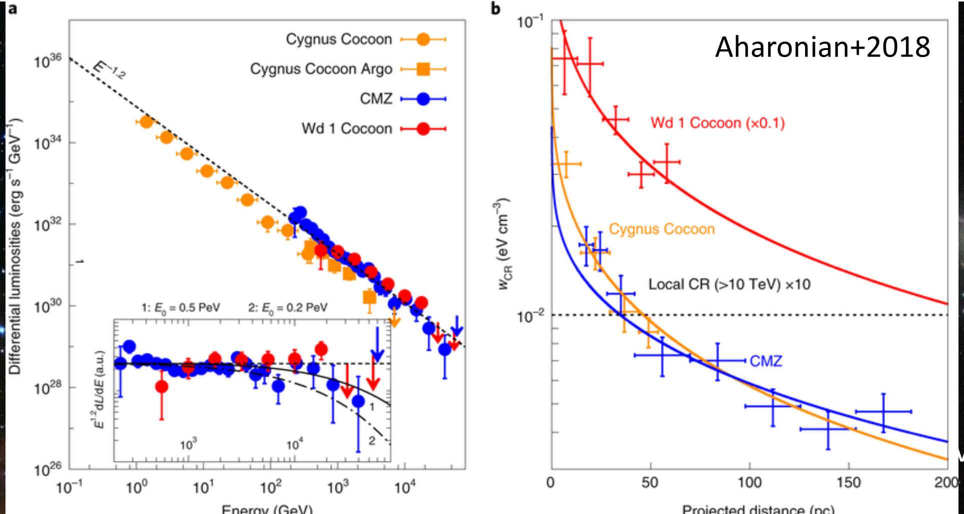

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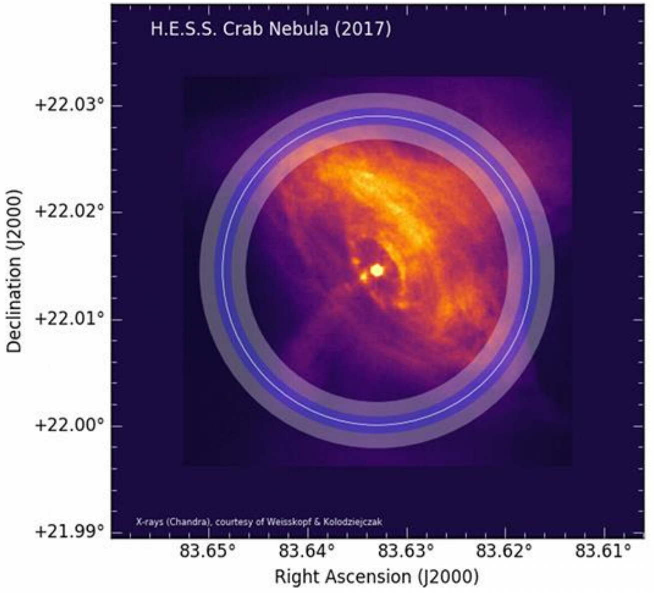
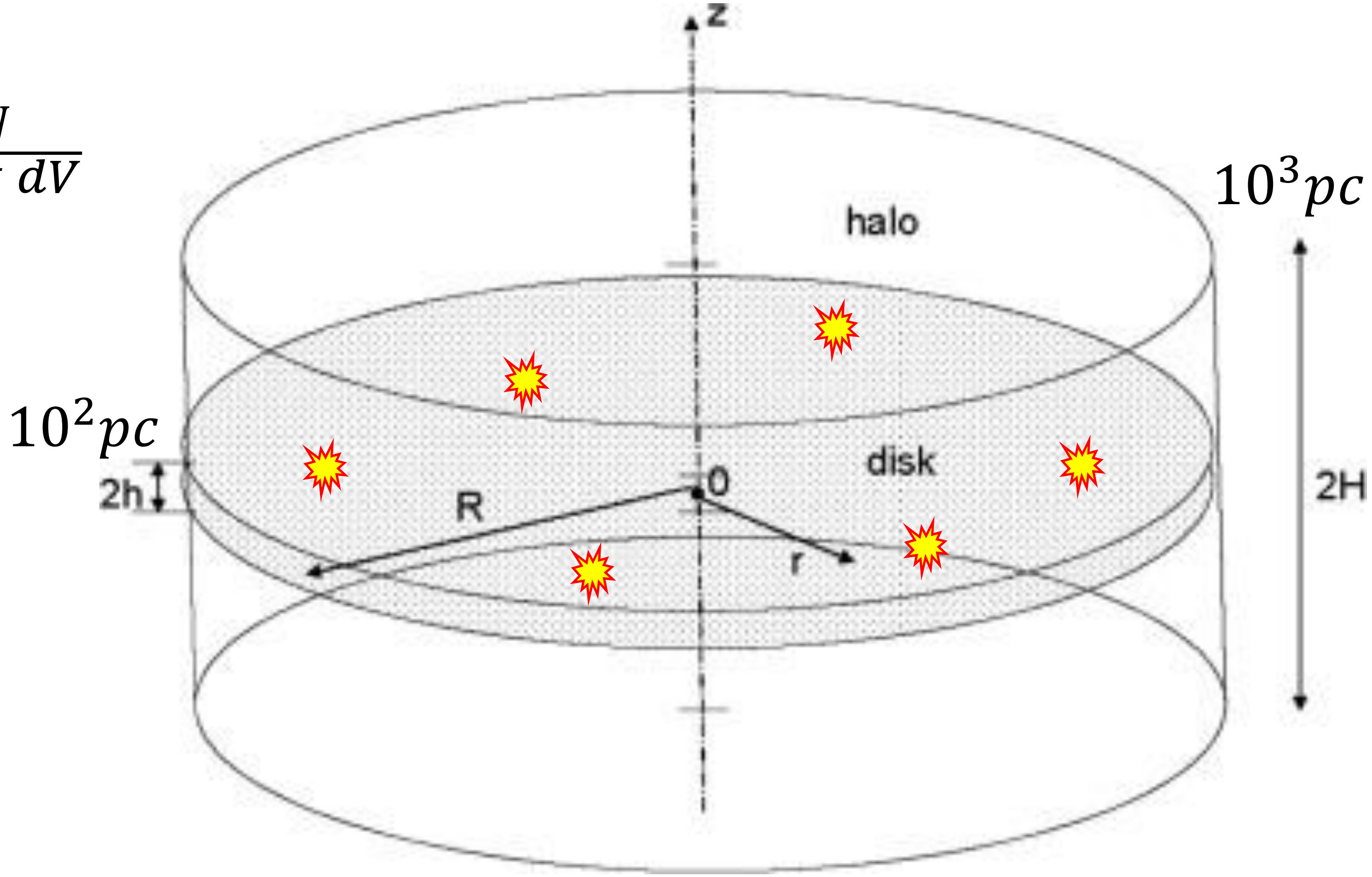
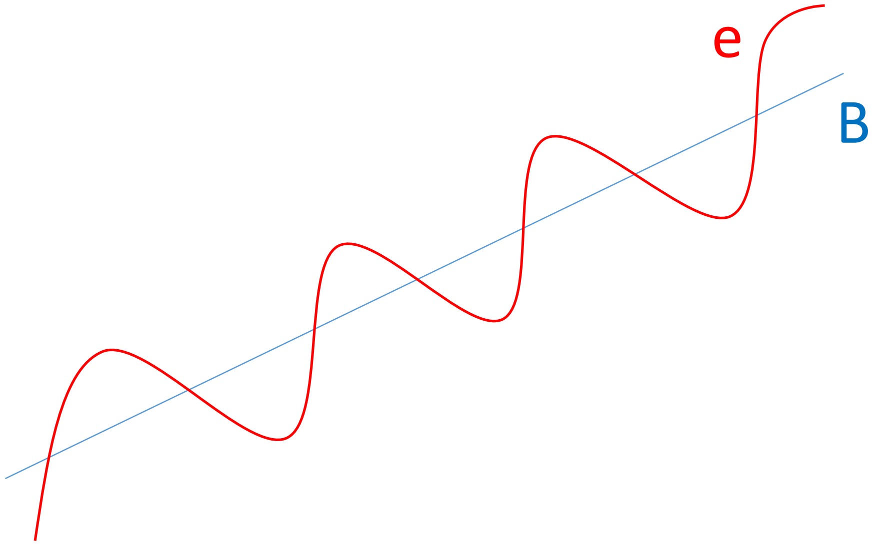


Physics of cosmic rays: Injection at sources

$$Q(E) = \frac{dN}{dE\ dt\ dV}$$



Physics of cosmic rays: Diffusion - 1



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

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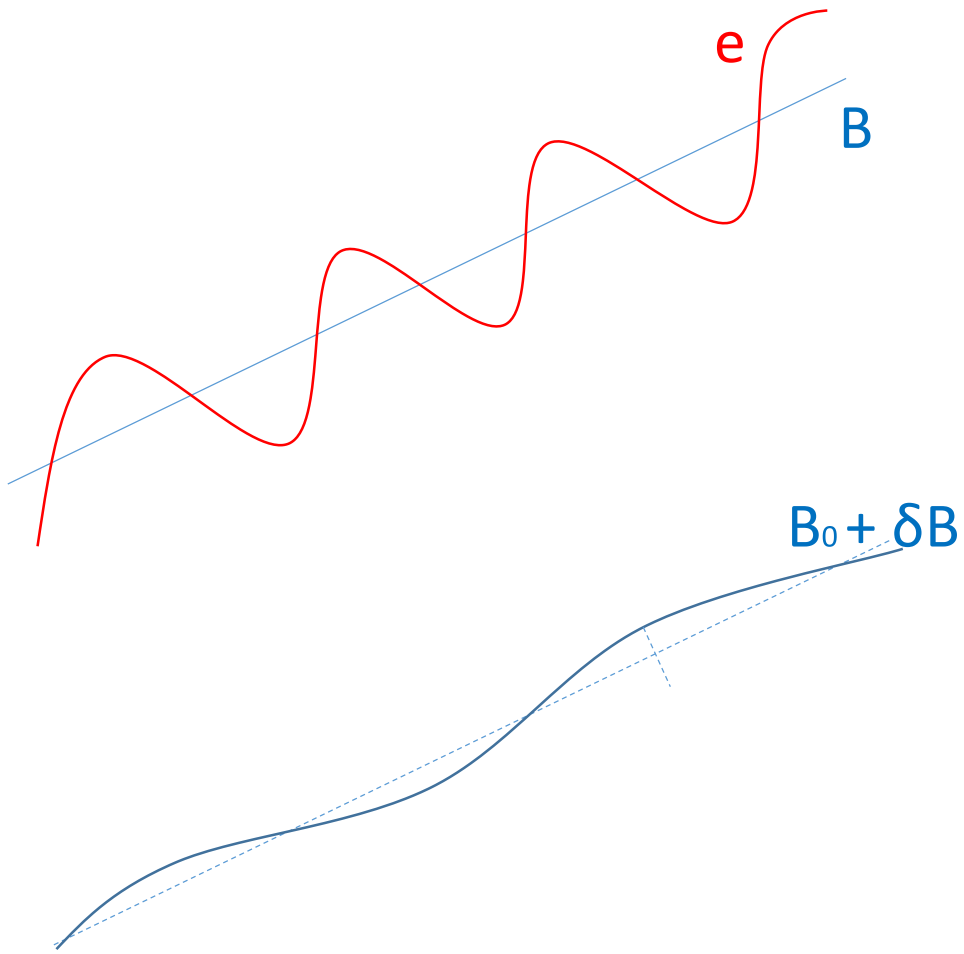

- The ISM is a turbulent plasma
- The magnetic field is also turbulent (δB)

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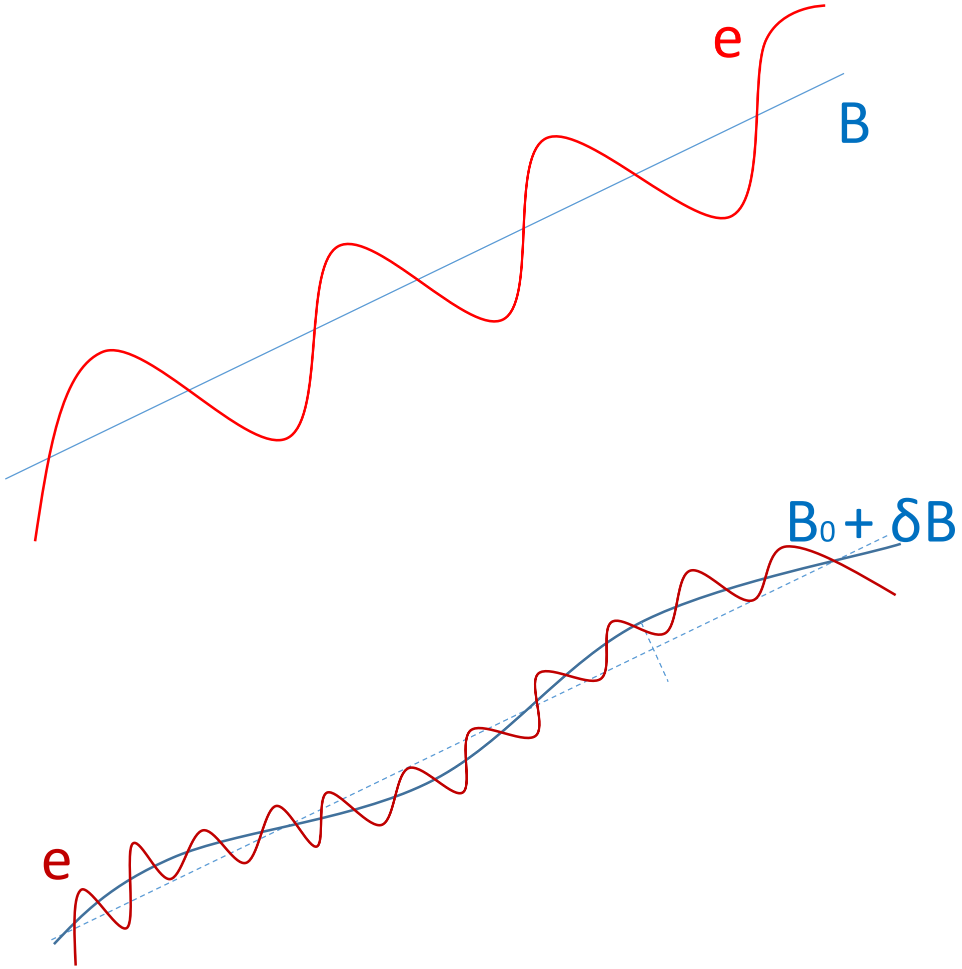

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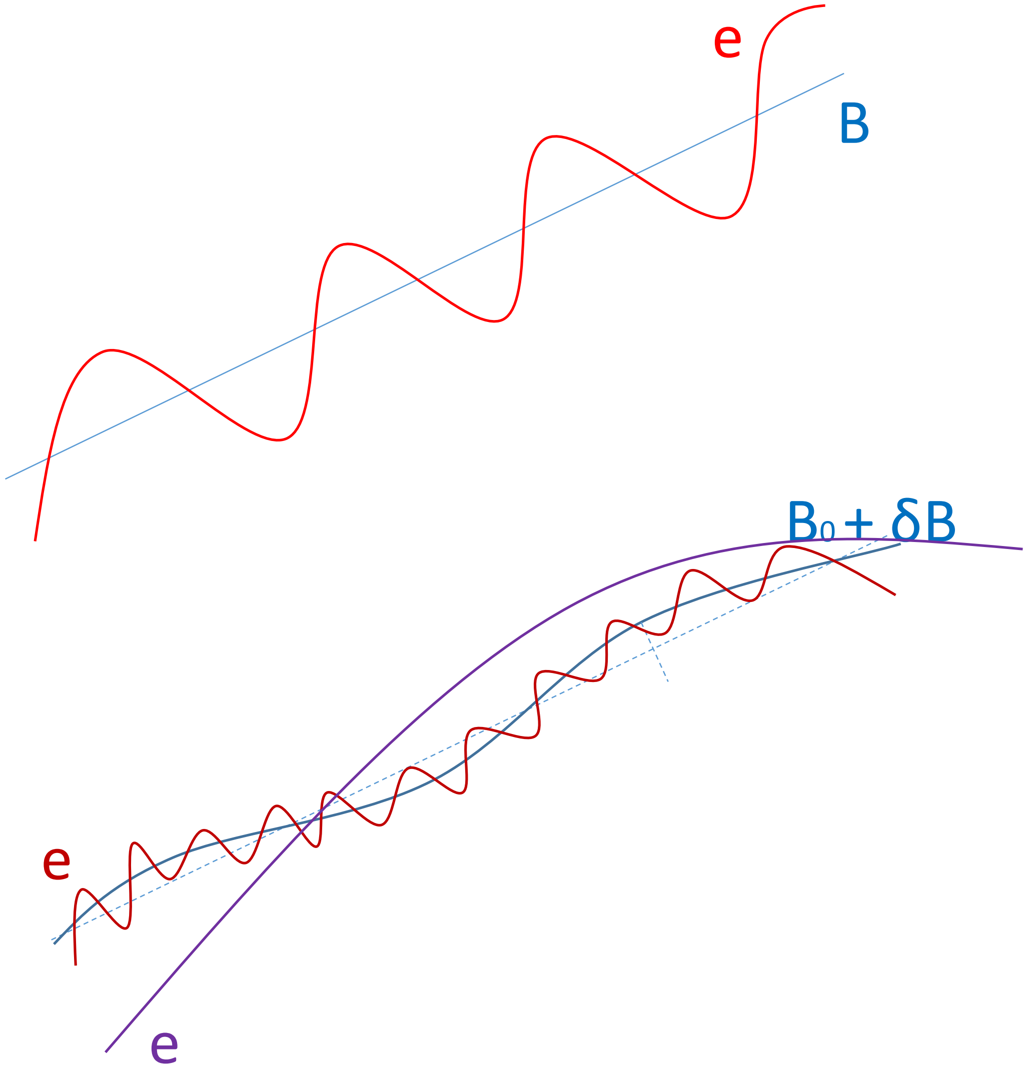

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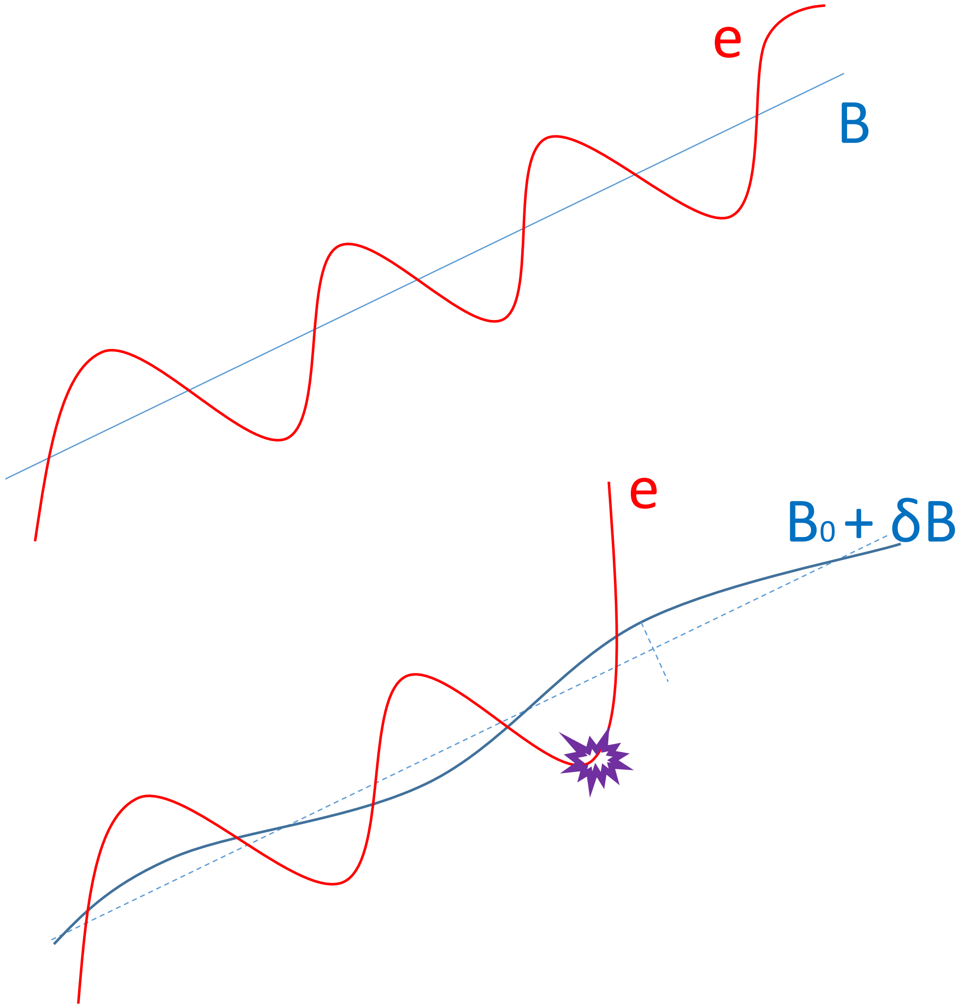

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- Particles pitch angle evolves in time when in presence of magnetic field disturbances

Helical motion→ Spatial diffusion

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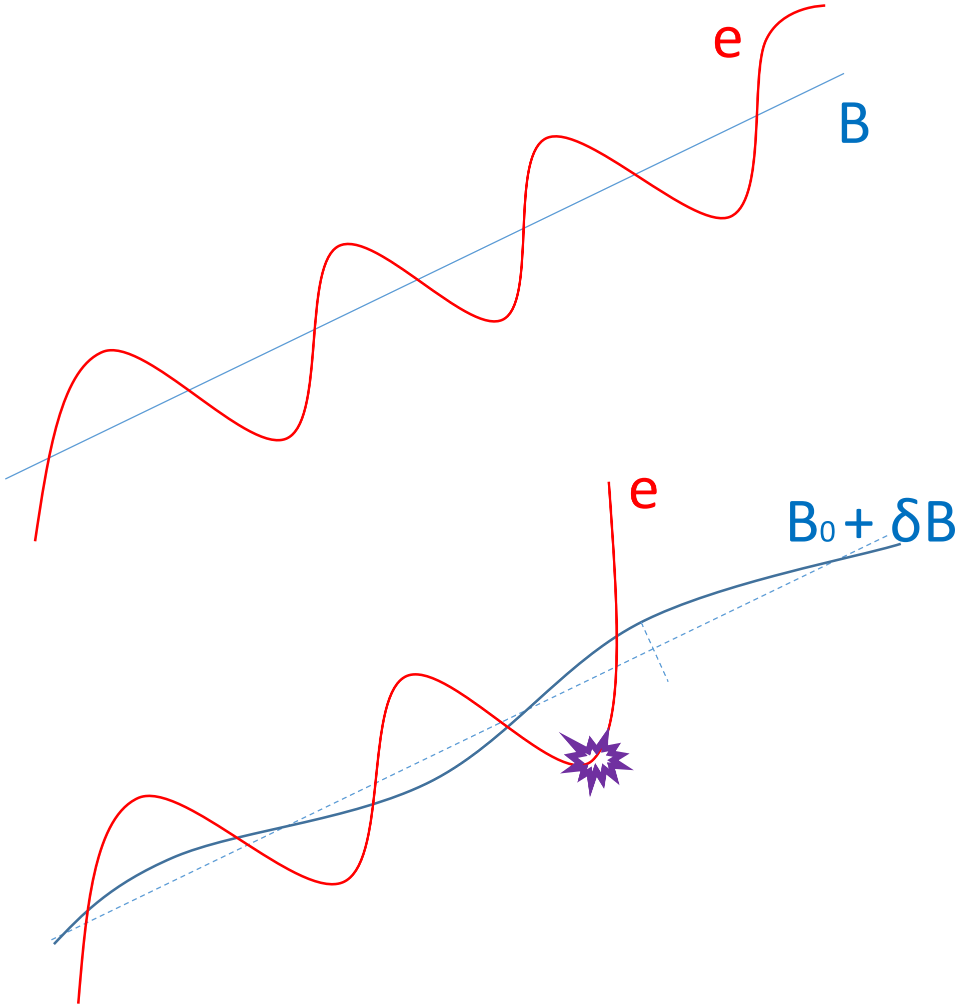

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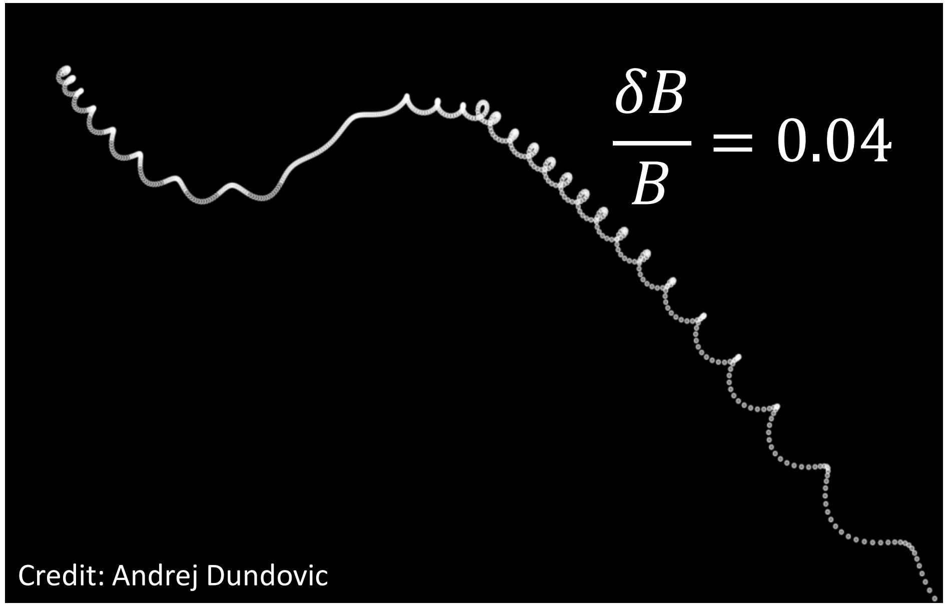
Helical motion→ Spatial diffusion

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

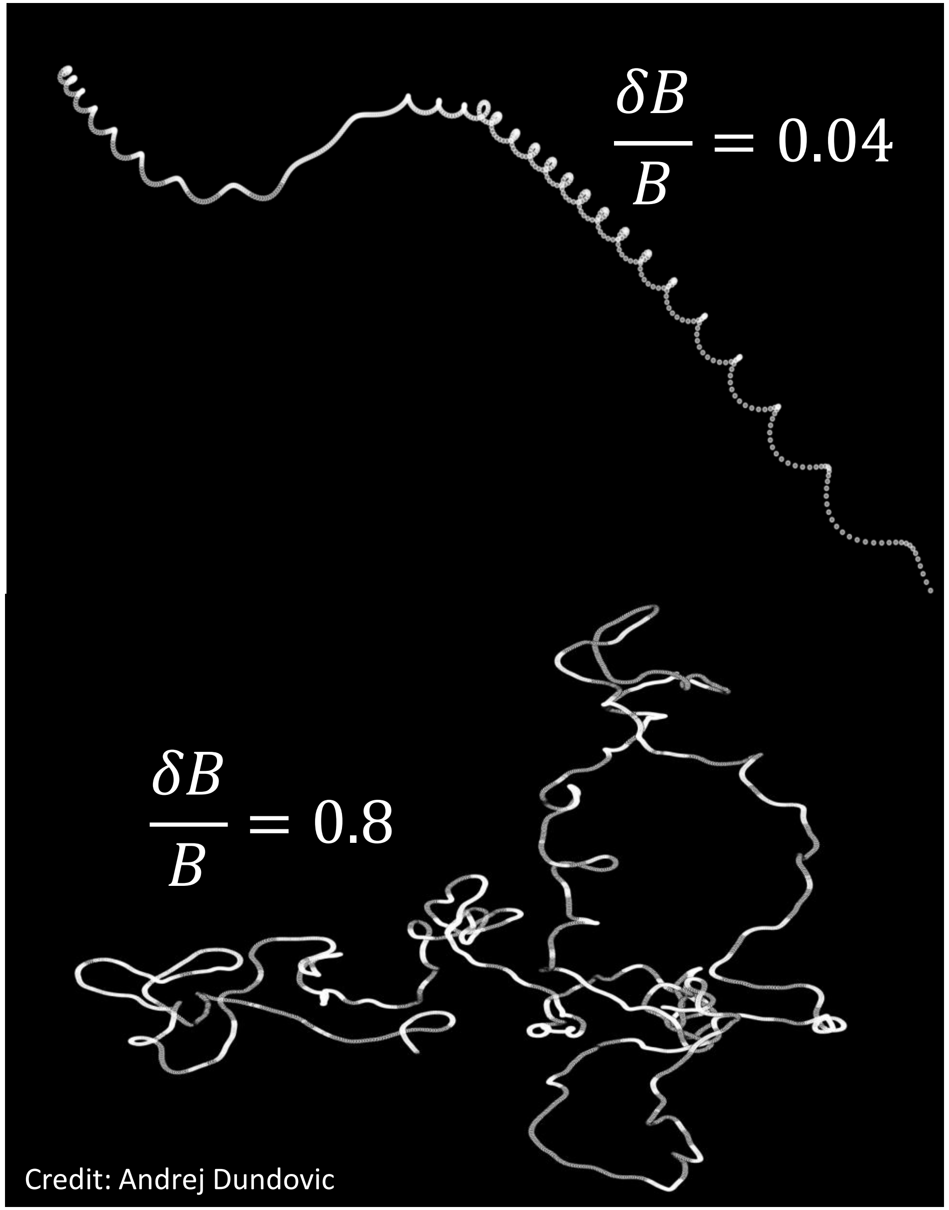
Physics of cosmic rays: Diffusion - 2



Credit: Andrej Dundovic

- Low turbulence environment allows to observe standard helical motions

Physics of cosmic rays: Diffusion - 2

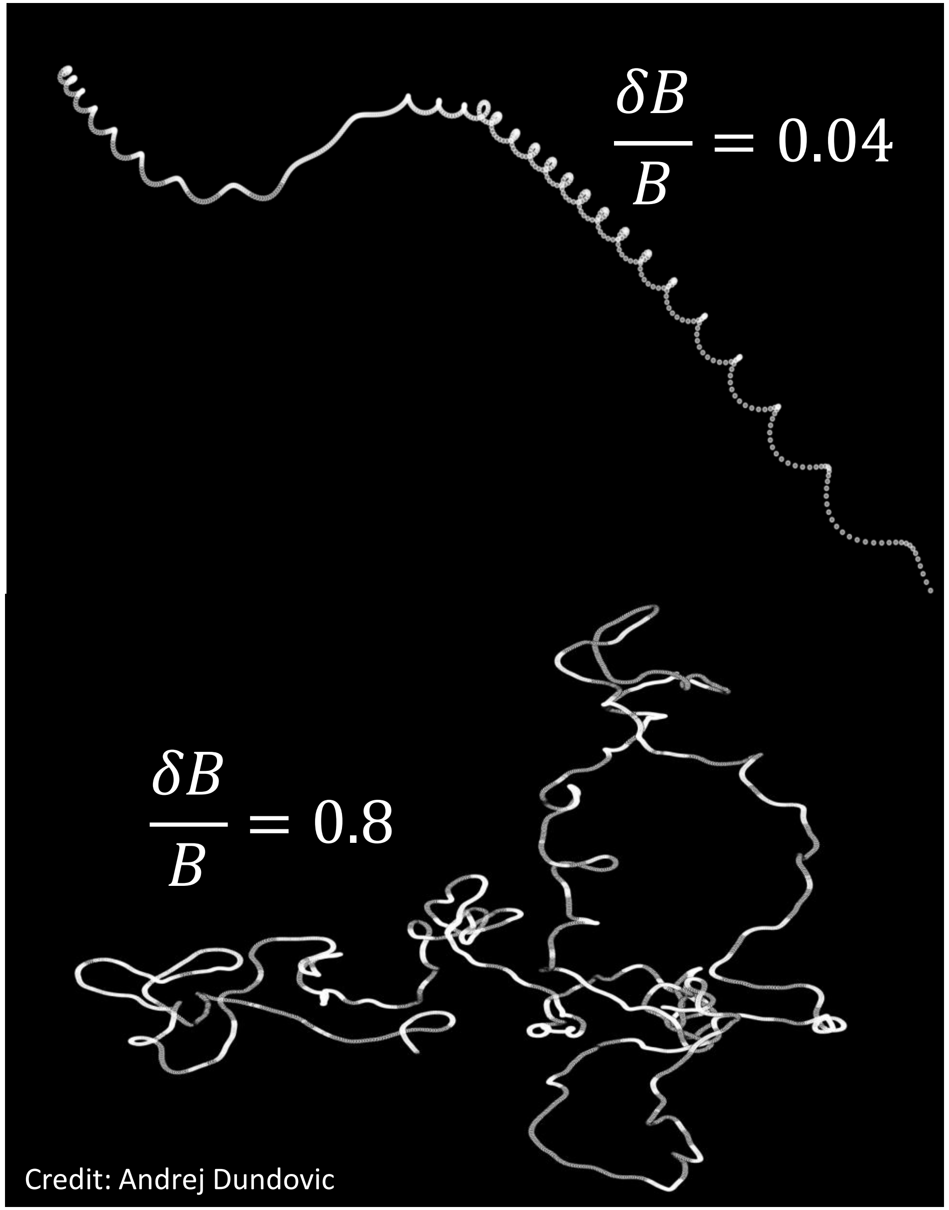


Credit: Andrej Dundovic

- Low turbulence environment allows to observe standard helical motions
- When the turbulence is strong the motion of particles from helicoidal becomes diffusive

Jokipii1966, Blandford+1987, Blasi2013, Snodin+2016, Subedi+2017, Dundovic+2020, Kuhlen+2022

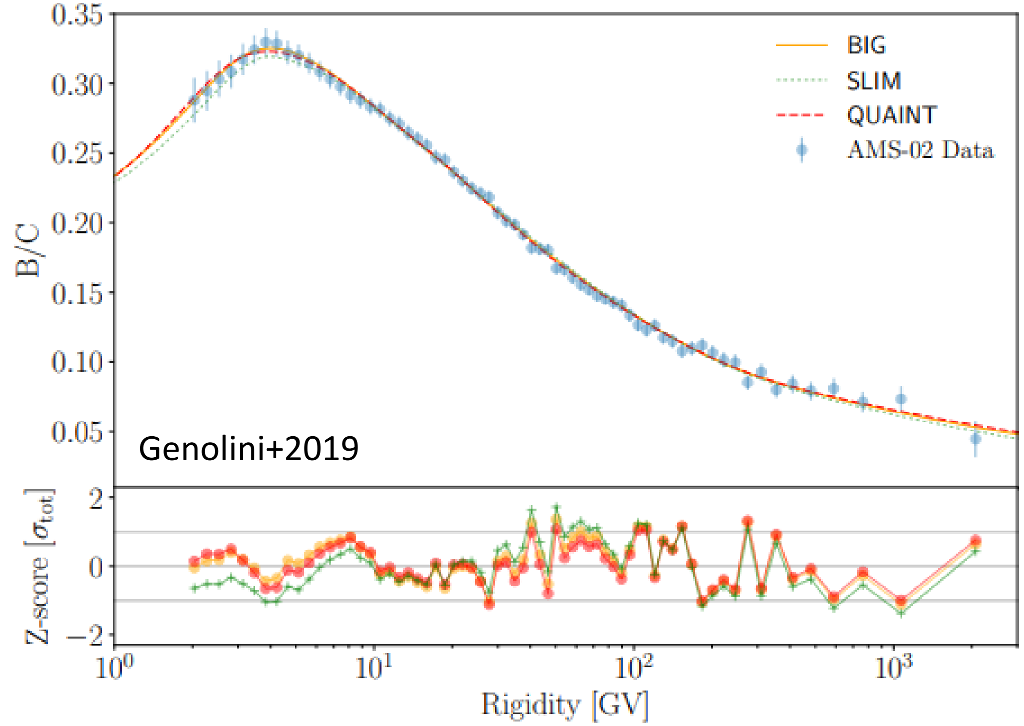
Physics of cosmic rays: Diffusion - 2



Credit: Andrej Dundovic

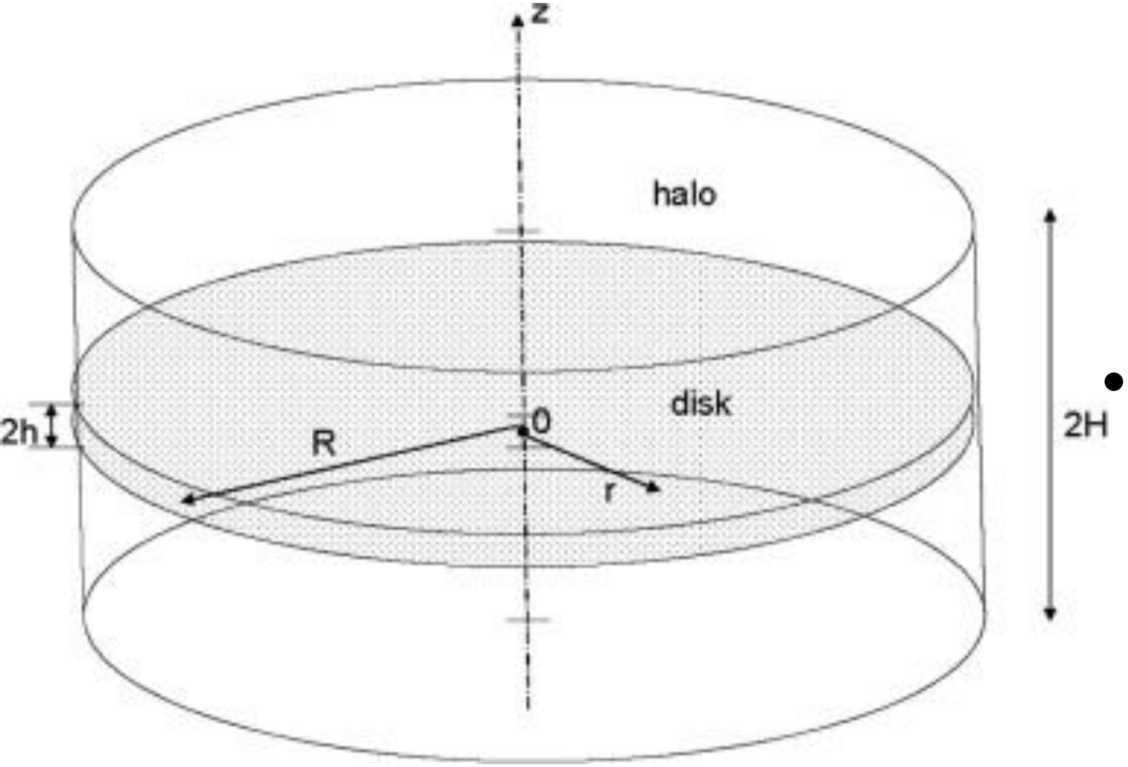
- Galactic diffusion coefficient

$$D(GeV) \approx 0.1 \frac{kpc^2}{Myr}$$



Genolini+2019

Physics of cosmic rays: Diffusion - 2



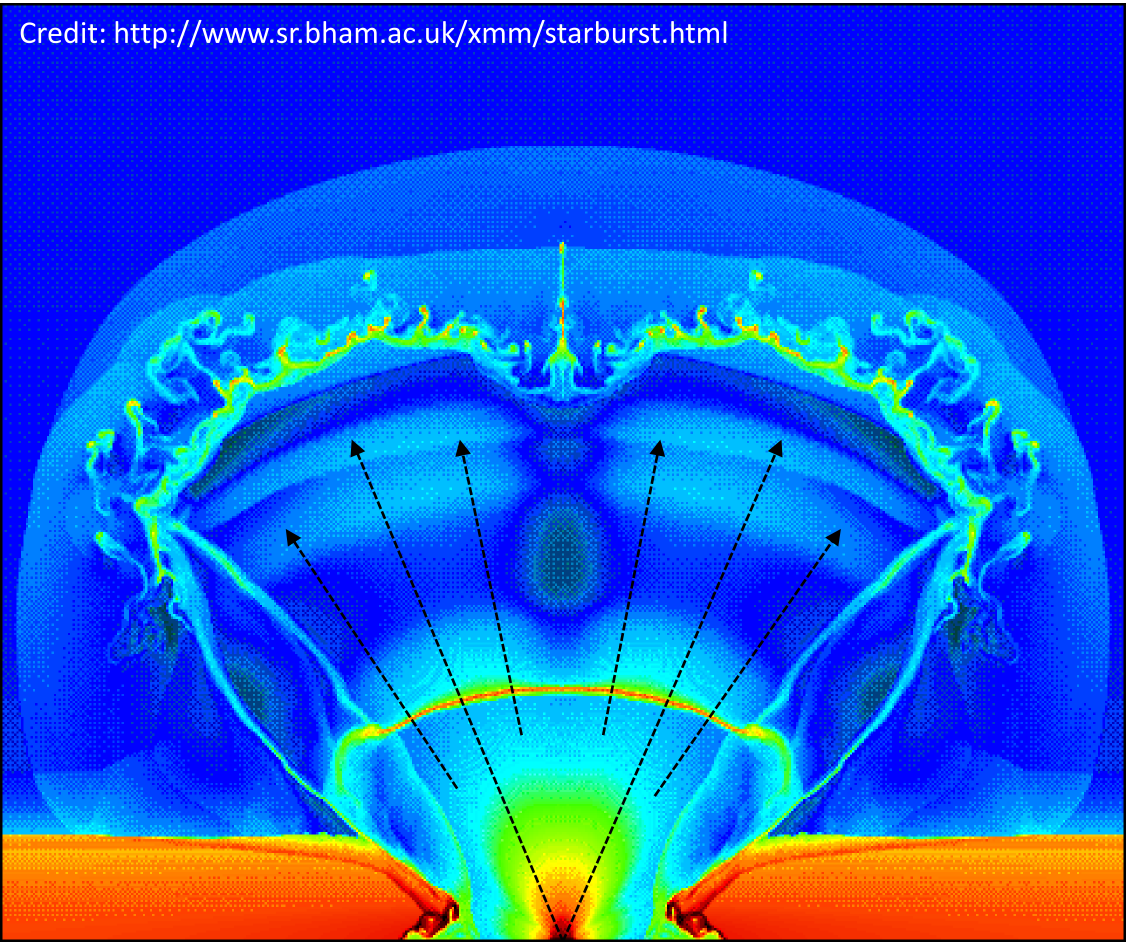
- Galactic diffusion coefficient

$$D(GeV) \approx 0.1\,\frac{kpc^2}{Myr}$$

- Escape timescale from a Gal. box of heigth H

$$\tau_{diff}(E) \approx \frac{H^2}{D(E)} \rightarrow 10^2\ Myr\ H^2_{3kpc} E^{-\delta}_{GeV}$$

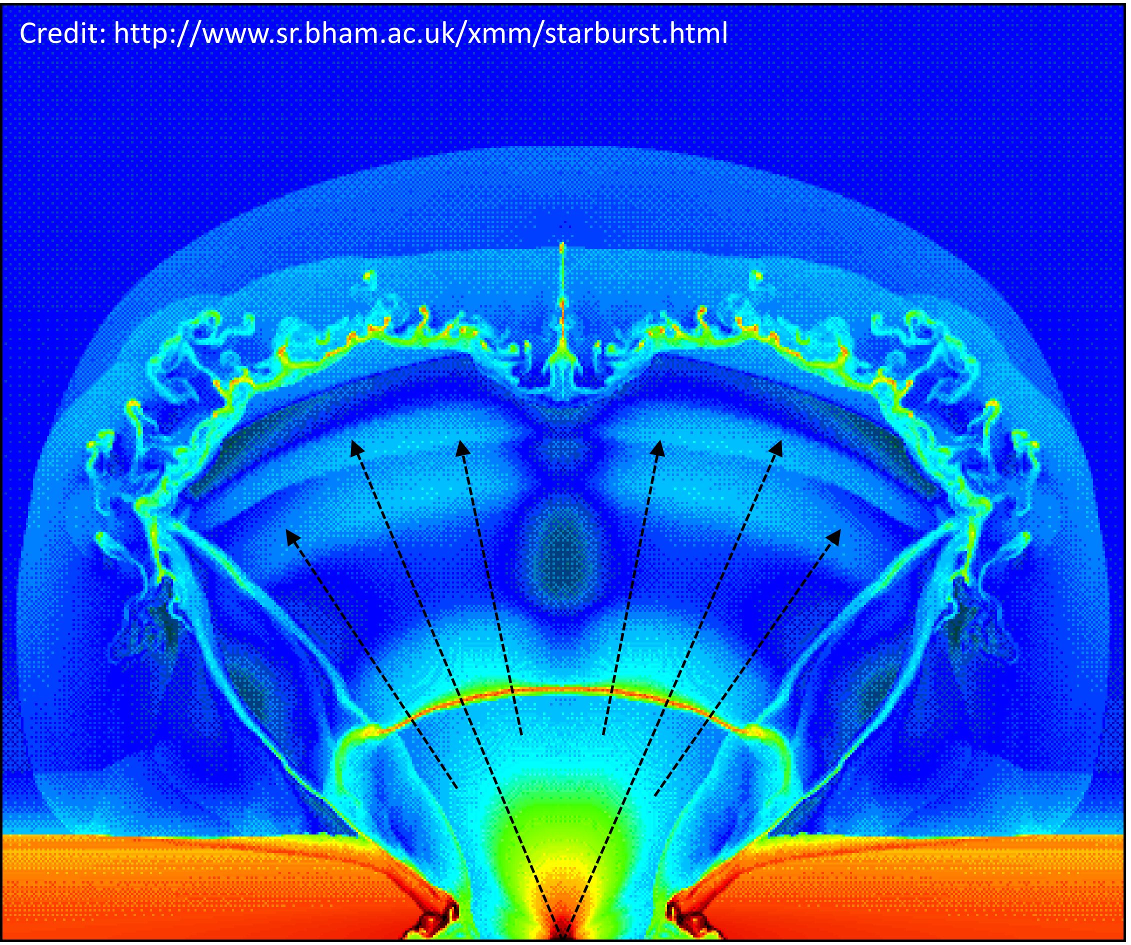
Physics of cosmic rays: Advection and Adbiabatic losses



Credit: http://www.sr.bham.ac.uk/xmm/starburst.html

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

Physics of cosmic rays: Advection and Adbiabatic losses

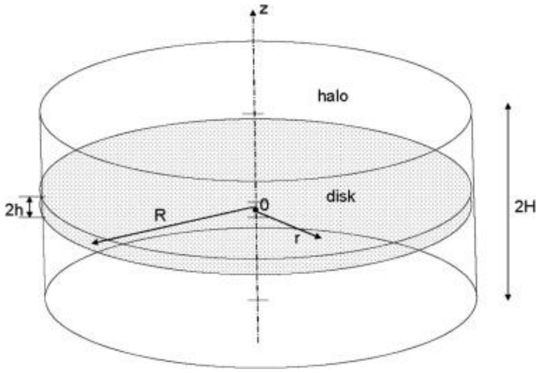


Credit: http://www.sr.bham.ac.uk/xmm/starburst.html

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

- CRs in a box of size H can be advected in flow of velovity v and escape

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



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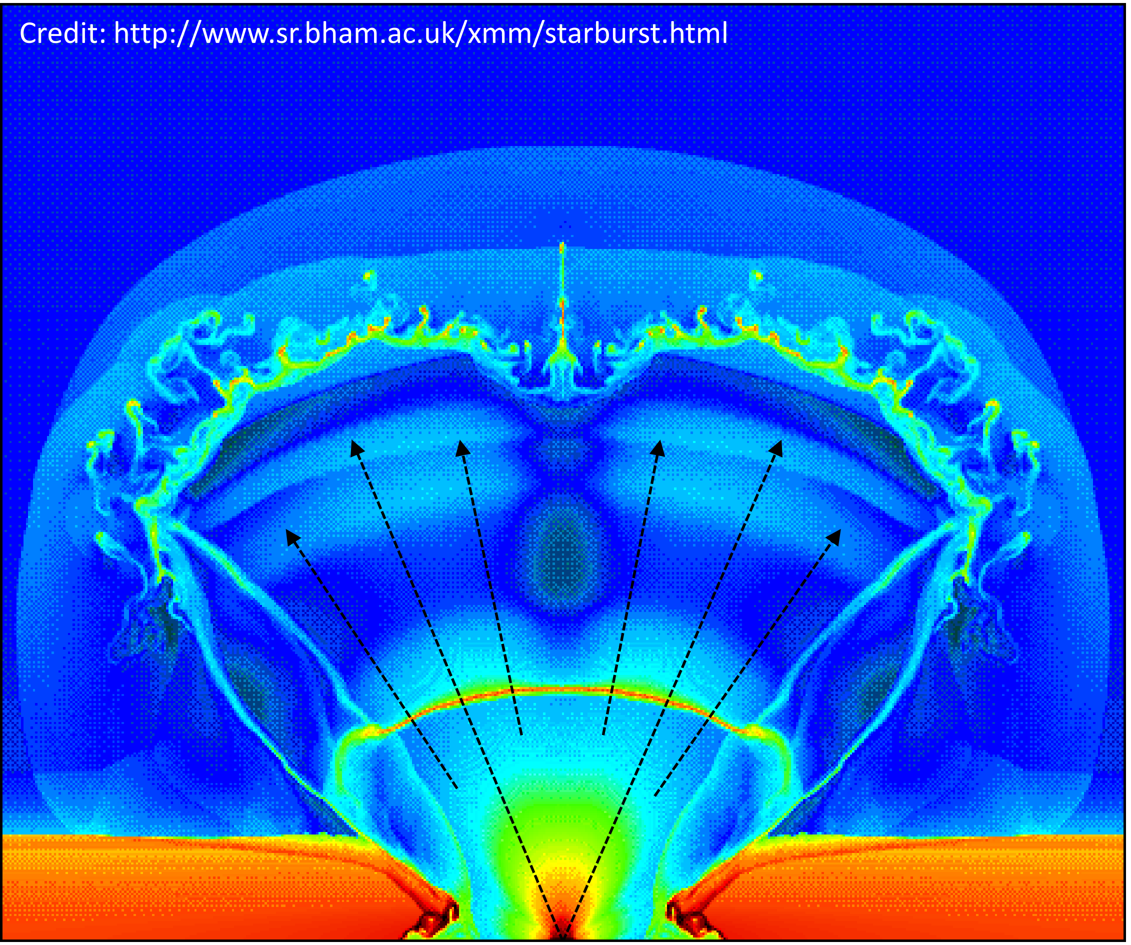

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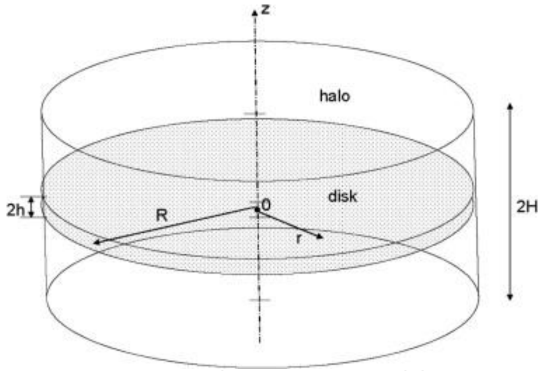

- CRs can lose or gain energy adiabatically

Physics of cosmic rays: E losses & radiative processes

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

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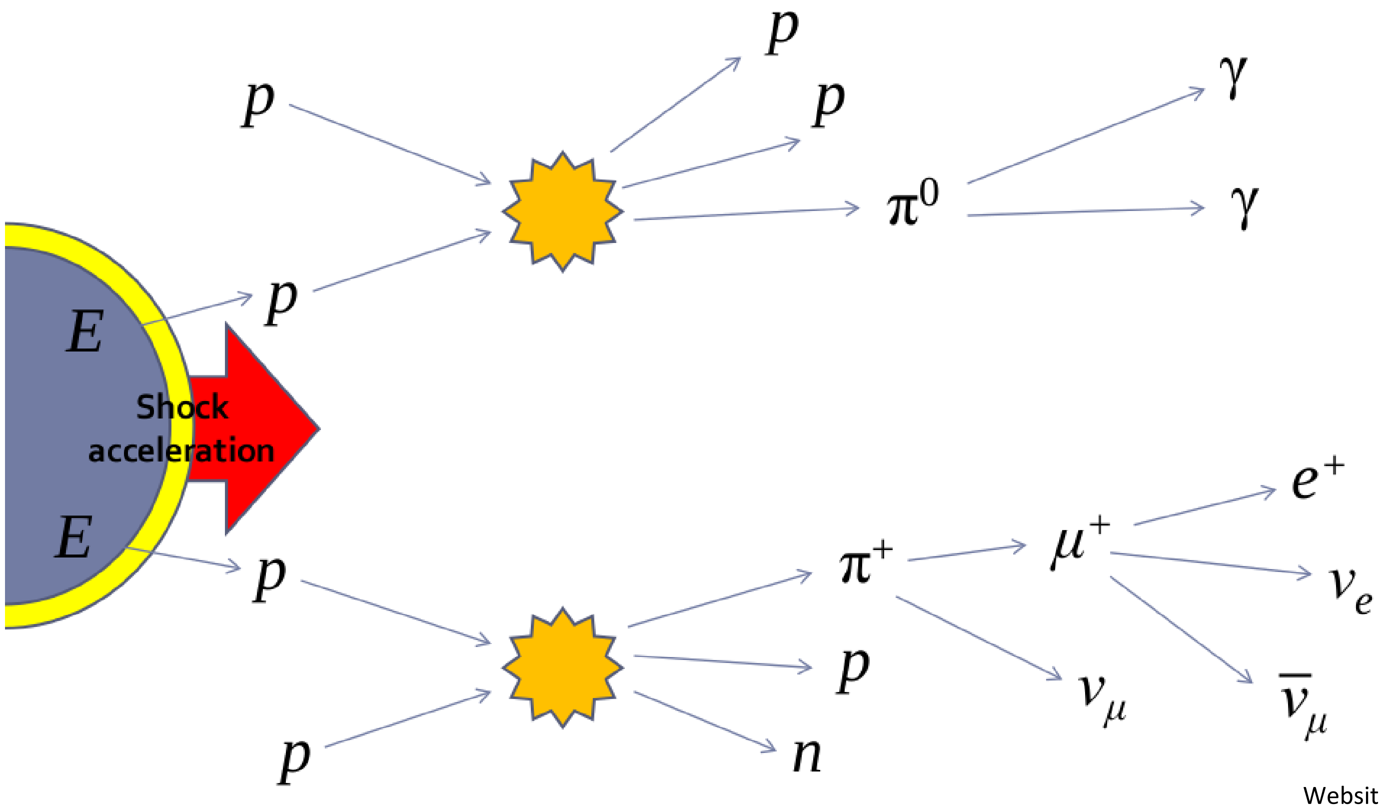

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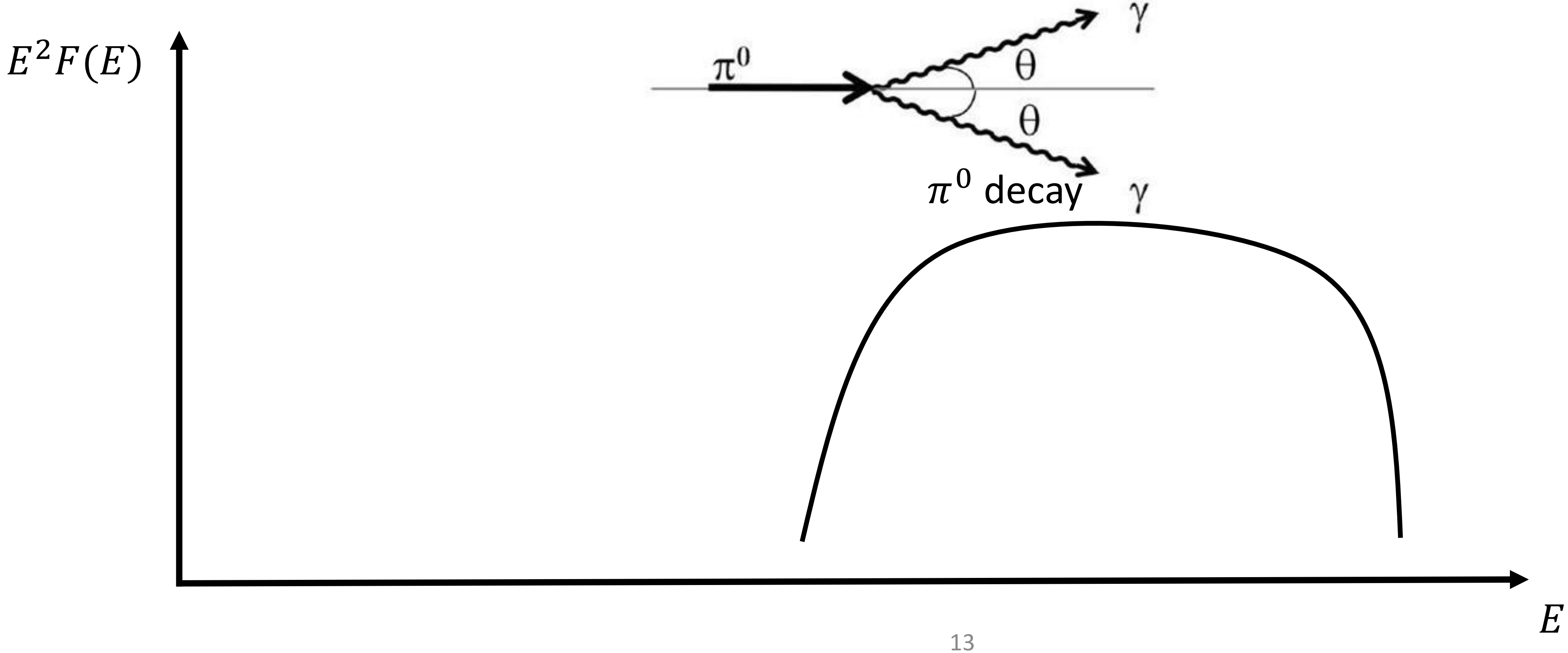

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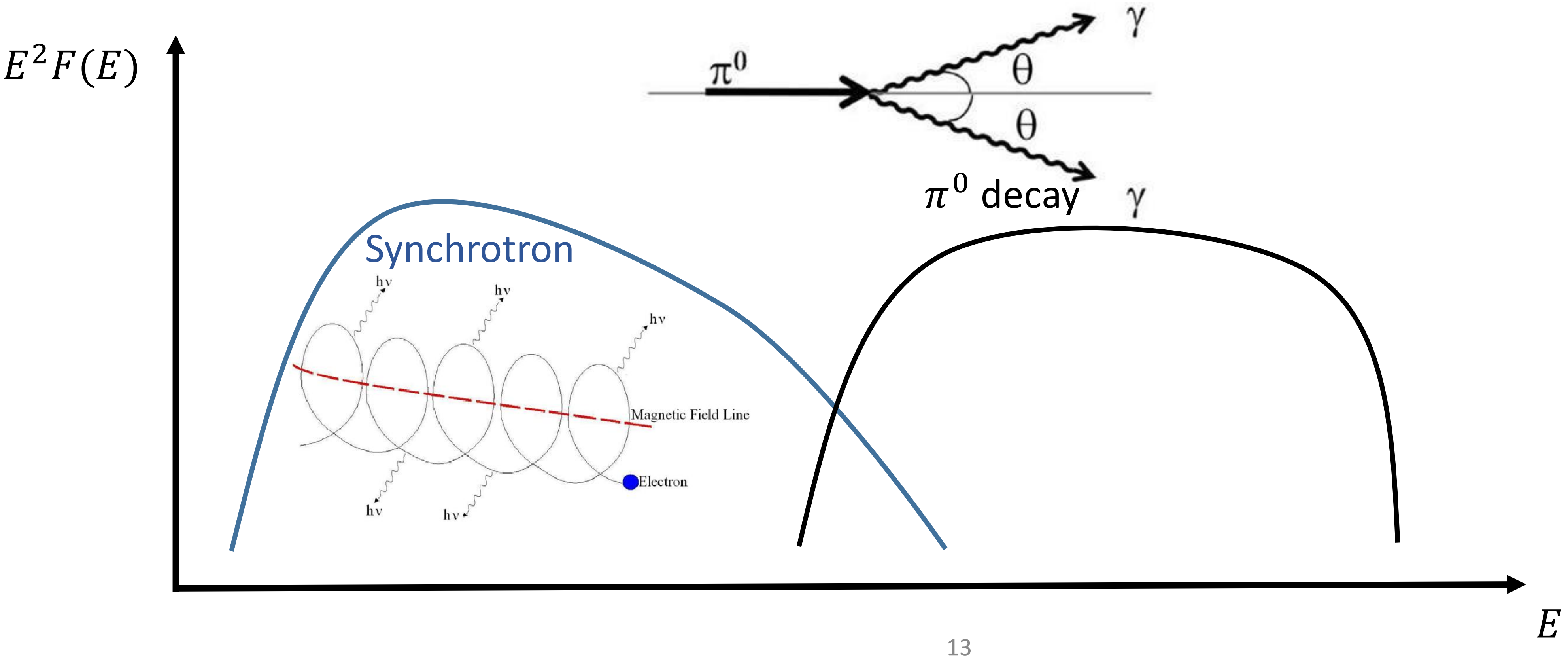

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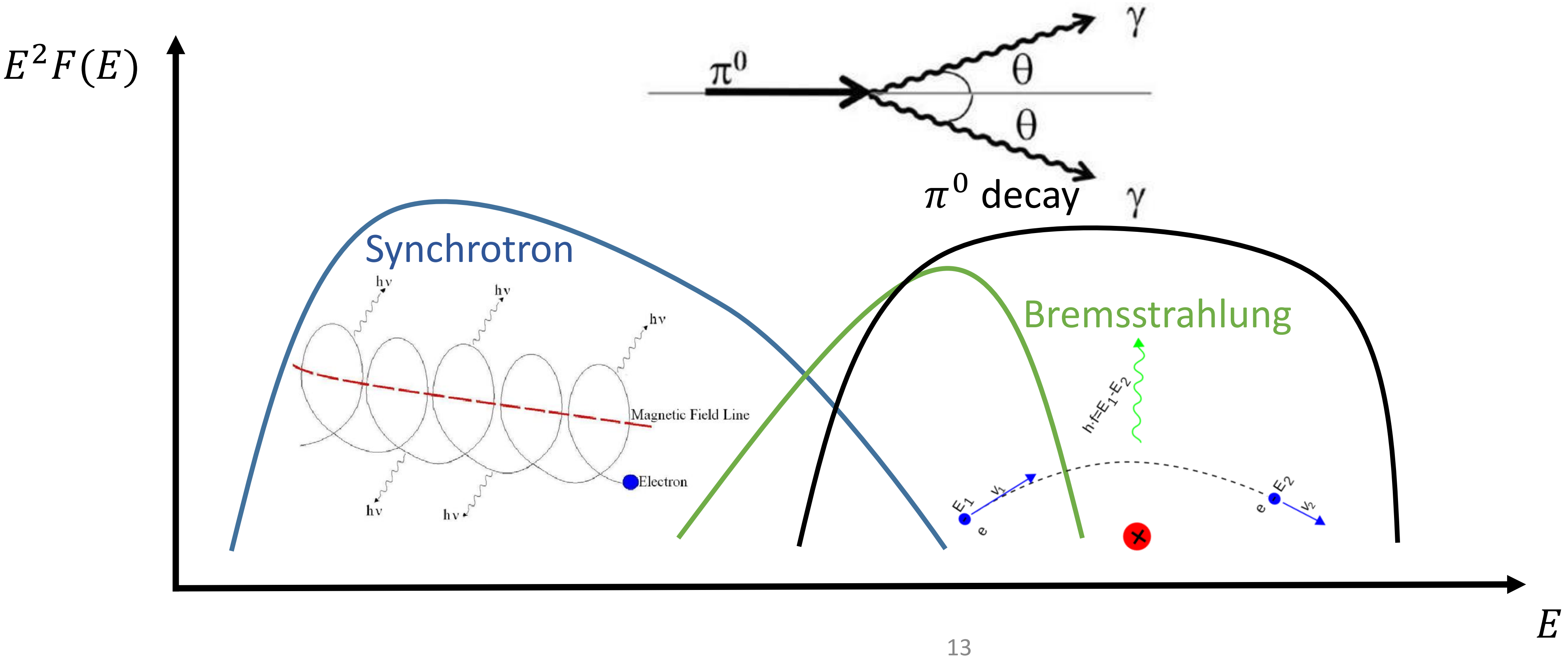

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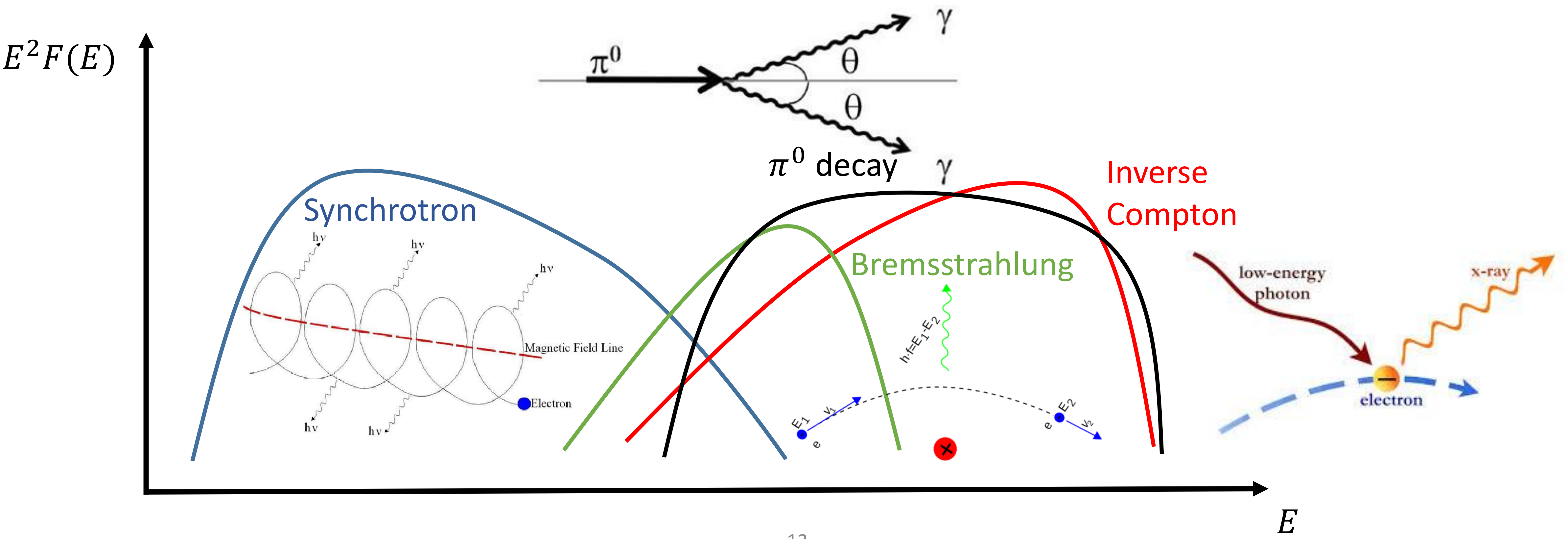

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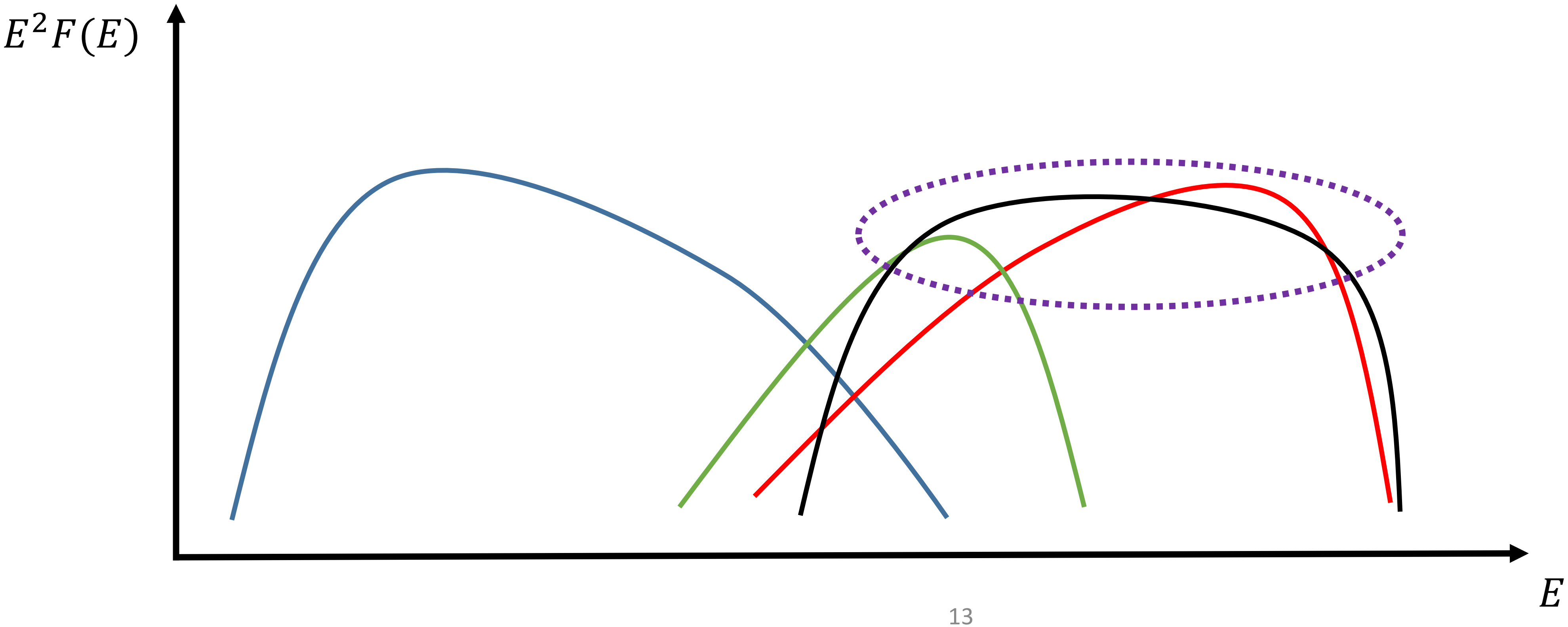

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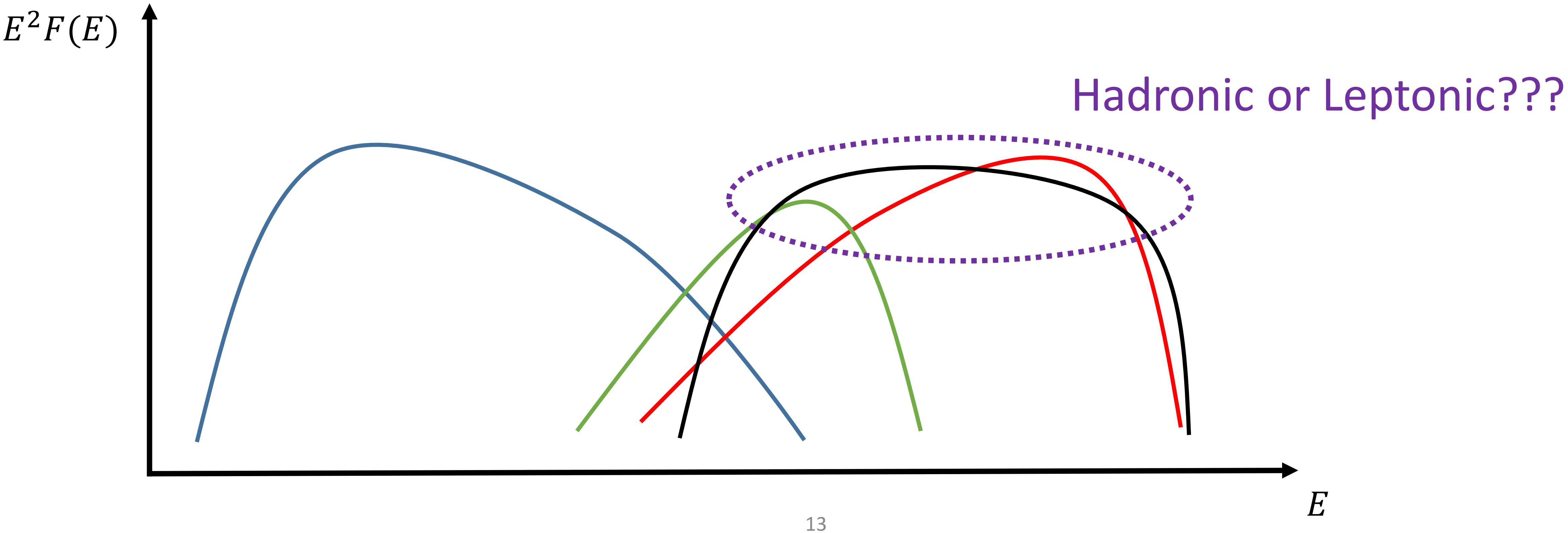

Physics of cosmic rays: E losses & radiative processes

- Ions (p): Ionization, Coulomb interaction, spallation (pp), Aγ (pγ)
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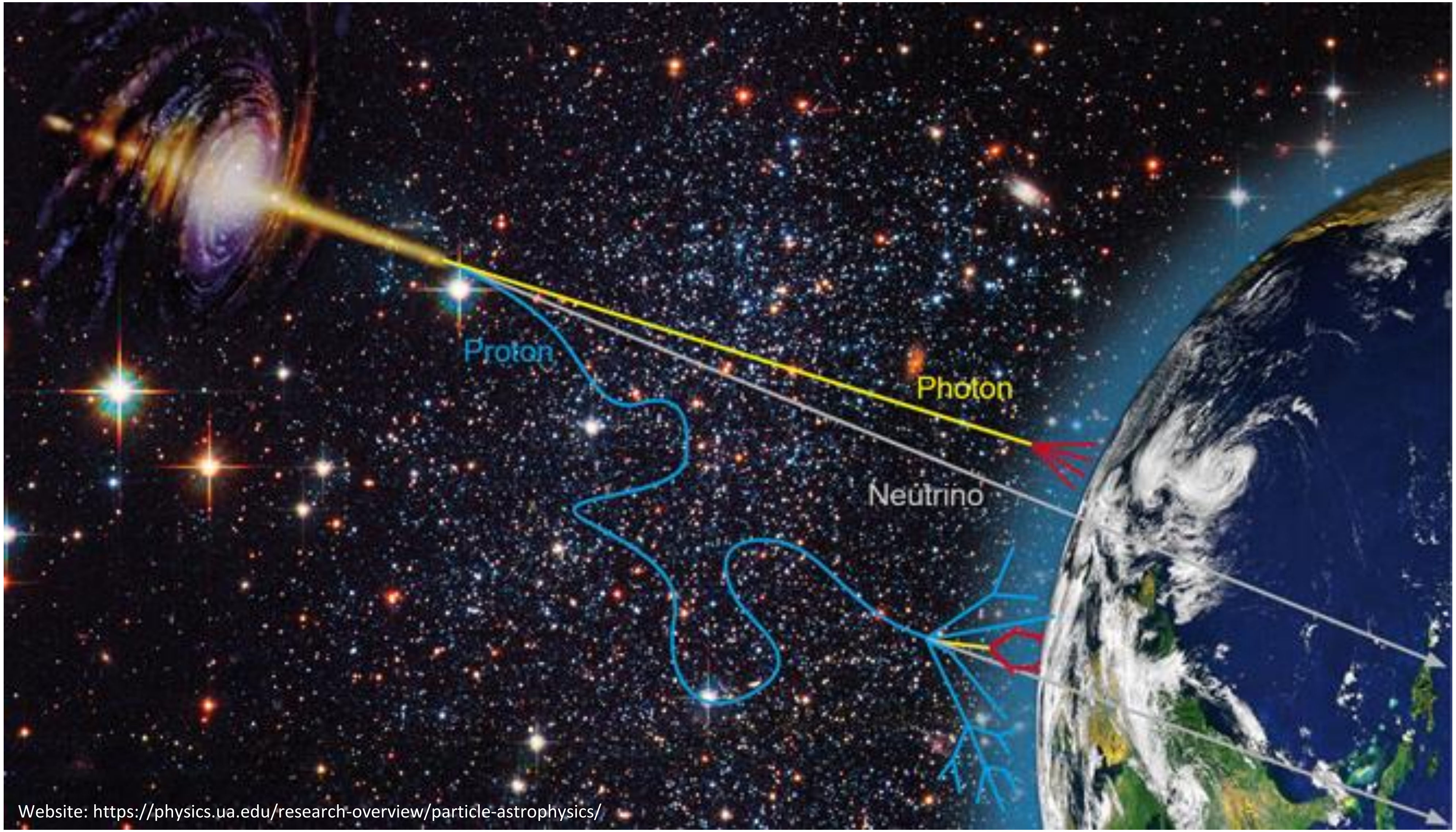
- E loss mechanism can be often associated to a typical rate/timescale which allows to model properly CR transport and possibly answer on the origin of an observed non-thermal spectrum

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

Multimessenger (particle) astrophysics



Website: https://physics.ua.edu/research-overview/particle-astrophysics/

Multimessenger picture of the Cosmos

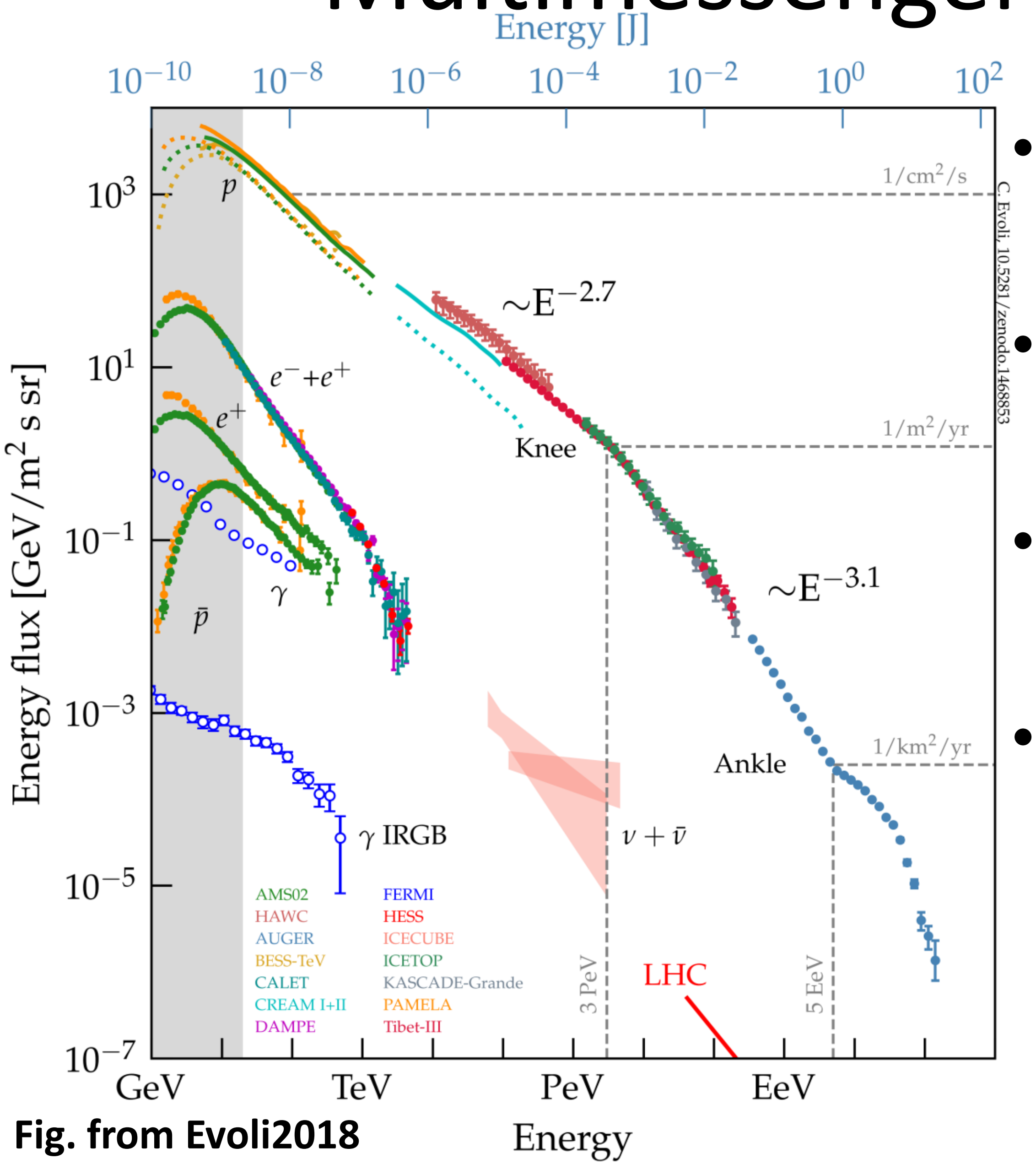


Fig. from Evoli2018

- Electrons and positrons and antimatter
- Total gamma-ray flux (sources+Gal. plane)
- Diffuse gamma-ray flux (IRGB)
- IceCube Neutrino flux

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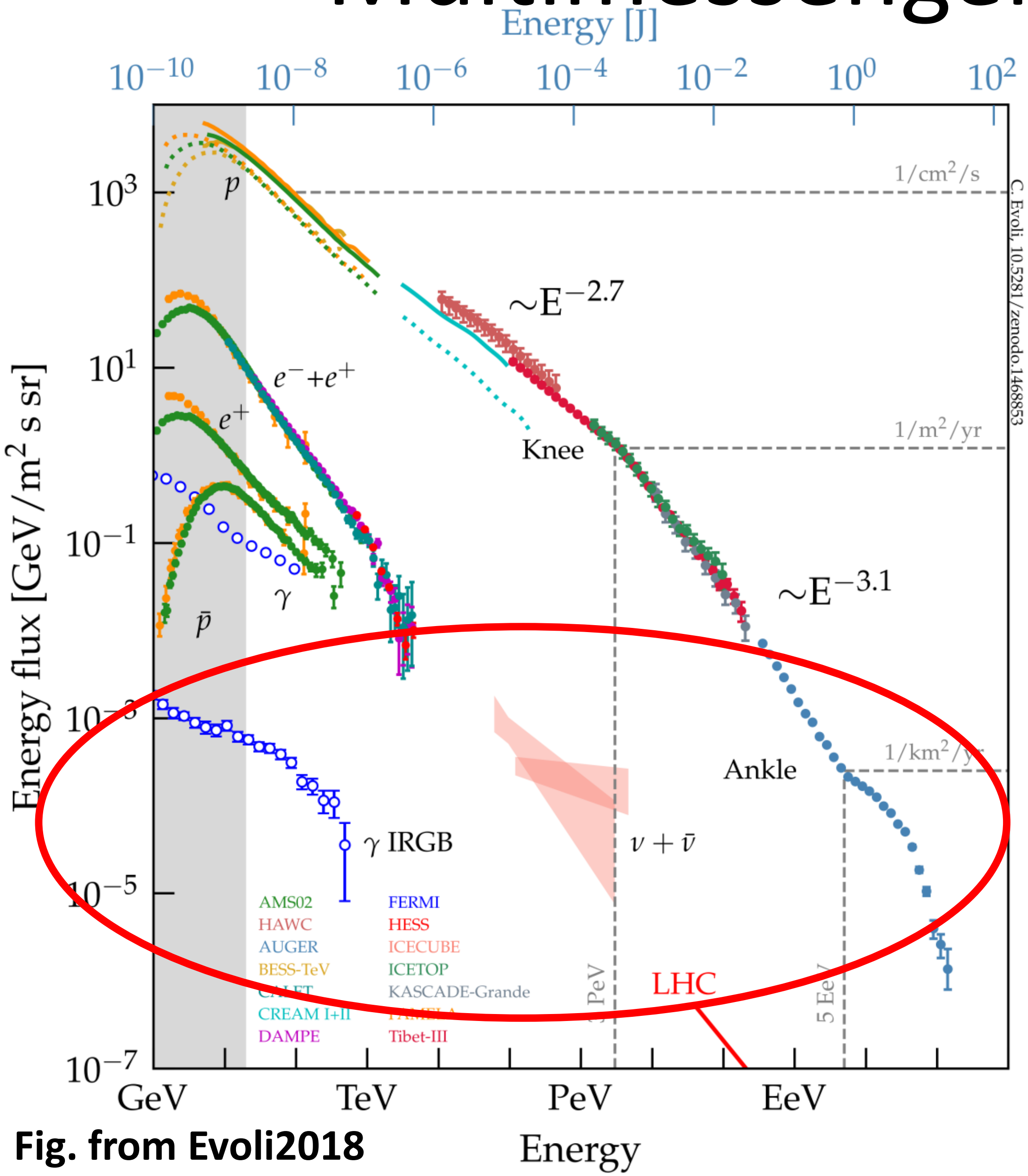

Fig. from Evoli2018

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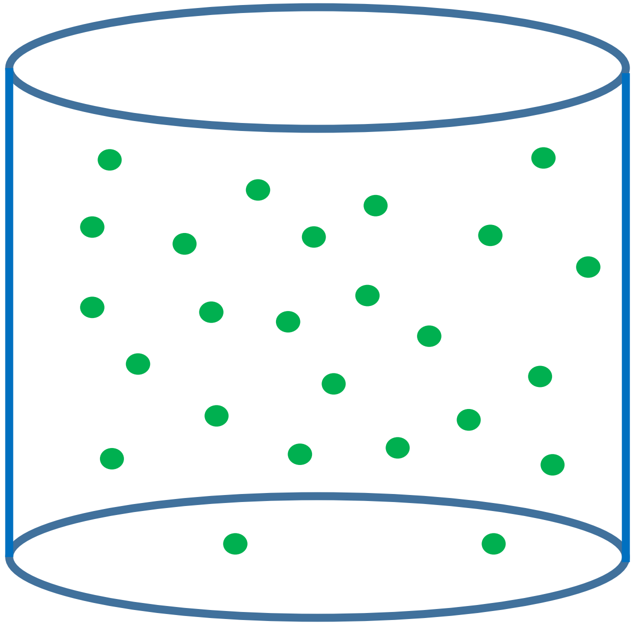
No identified sources of IRGB, UHECRs and IceCube neutrinos but similar energy flux!

Physics of cosmic rays: Transport equation



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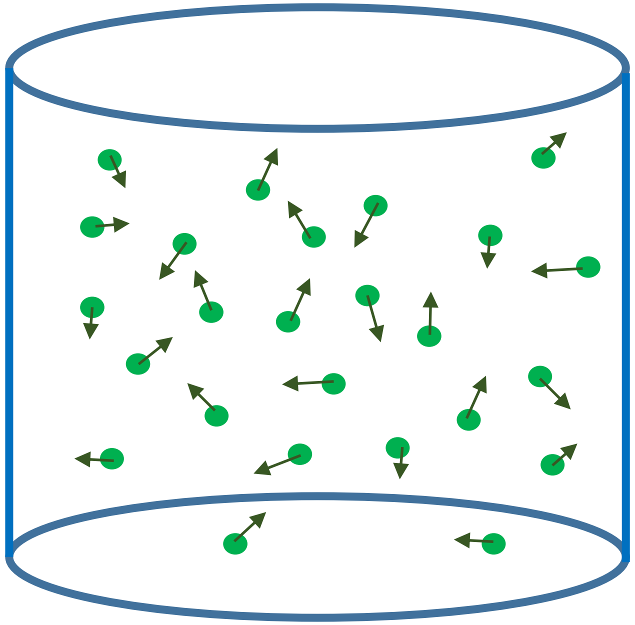

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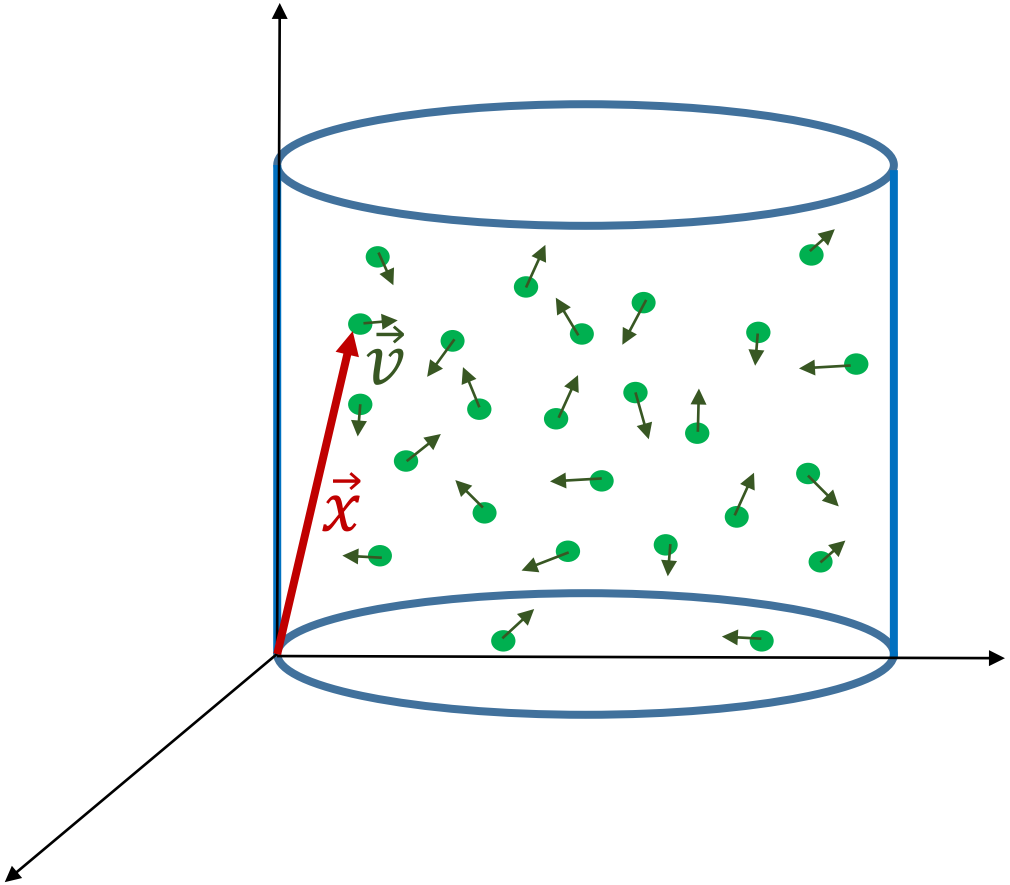

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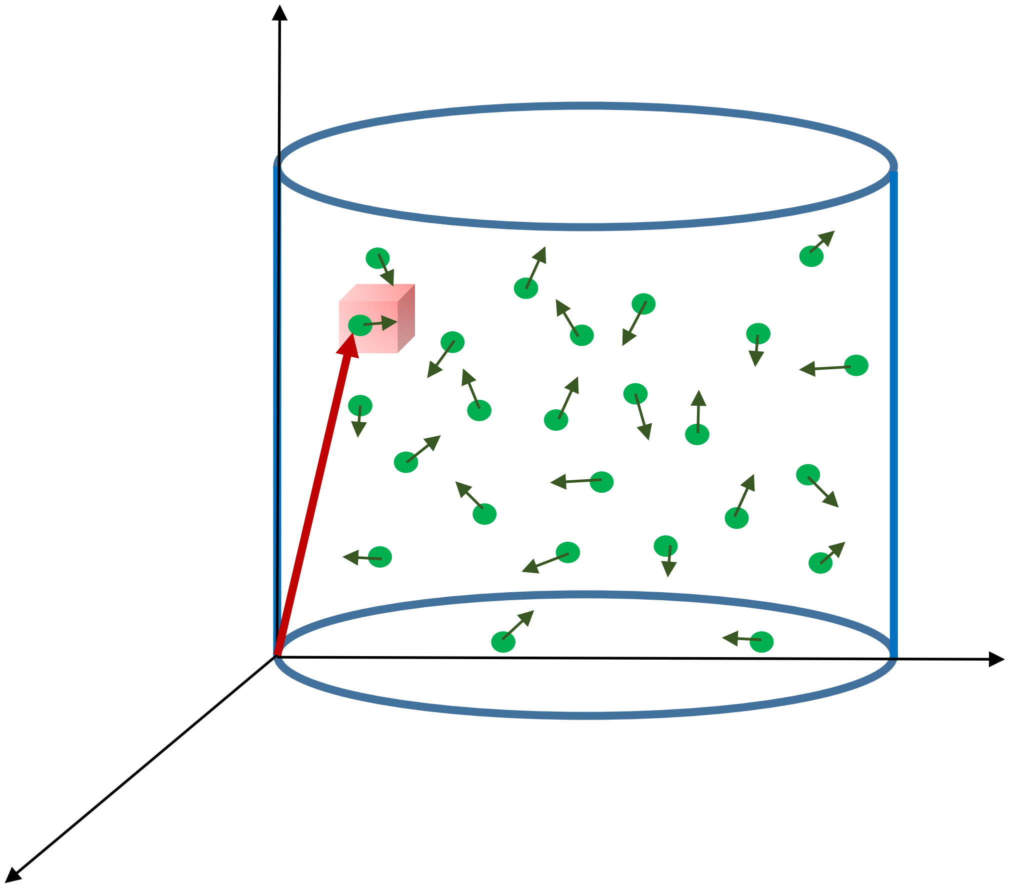
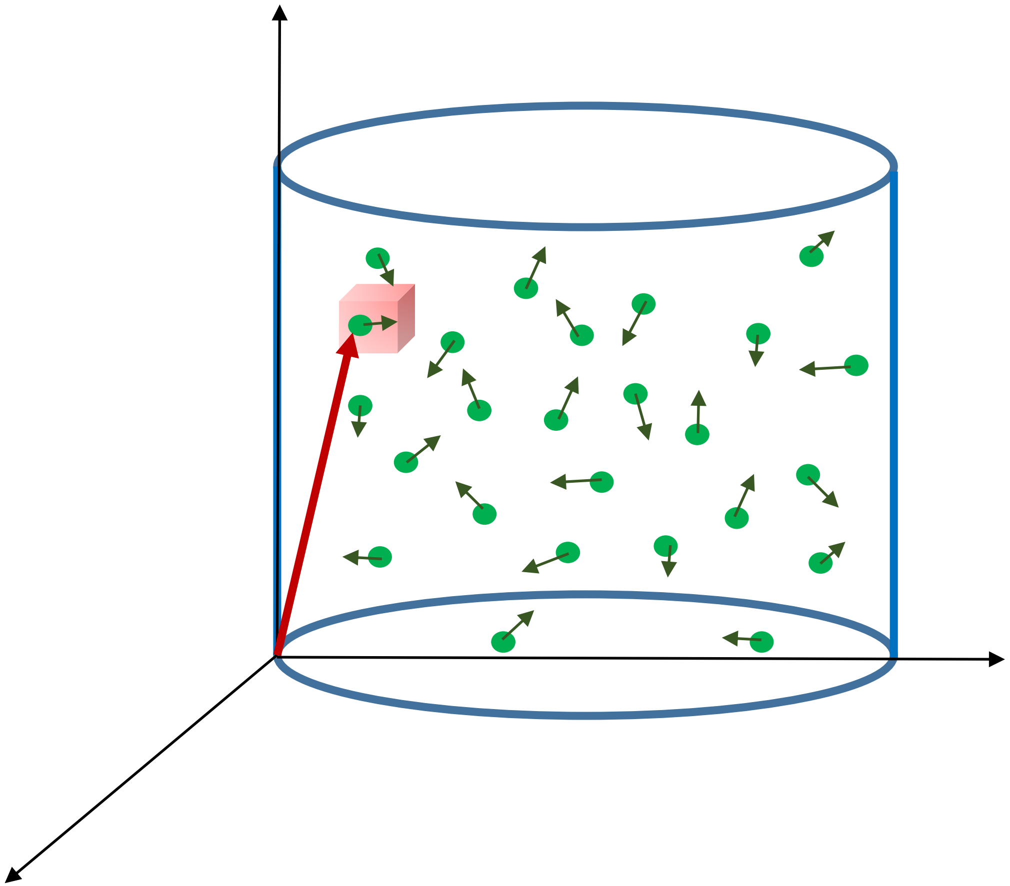


Physics of cosmic rays: Transport equation

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



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

Physics of cosmic rays: Transport equation

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- When the transport is stationary, homogeneous and isotropic:

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

Any question?

Outline

- Diverging flows: structure and evolution
- Acceleration and transport model in diverging flows
- Multimessenger implications: YMSCs, SBGs & AGNi

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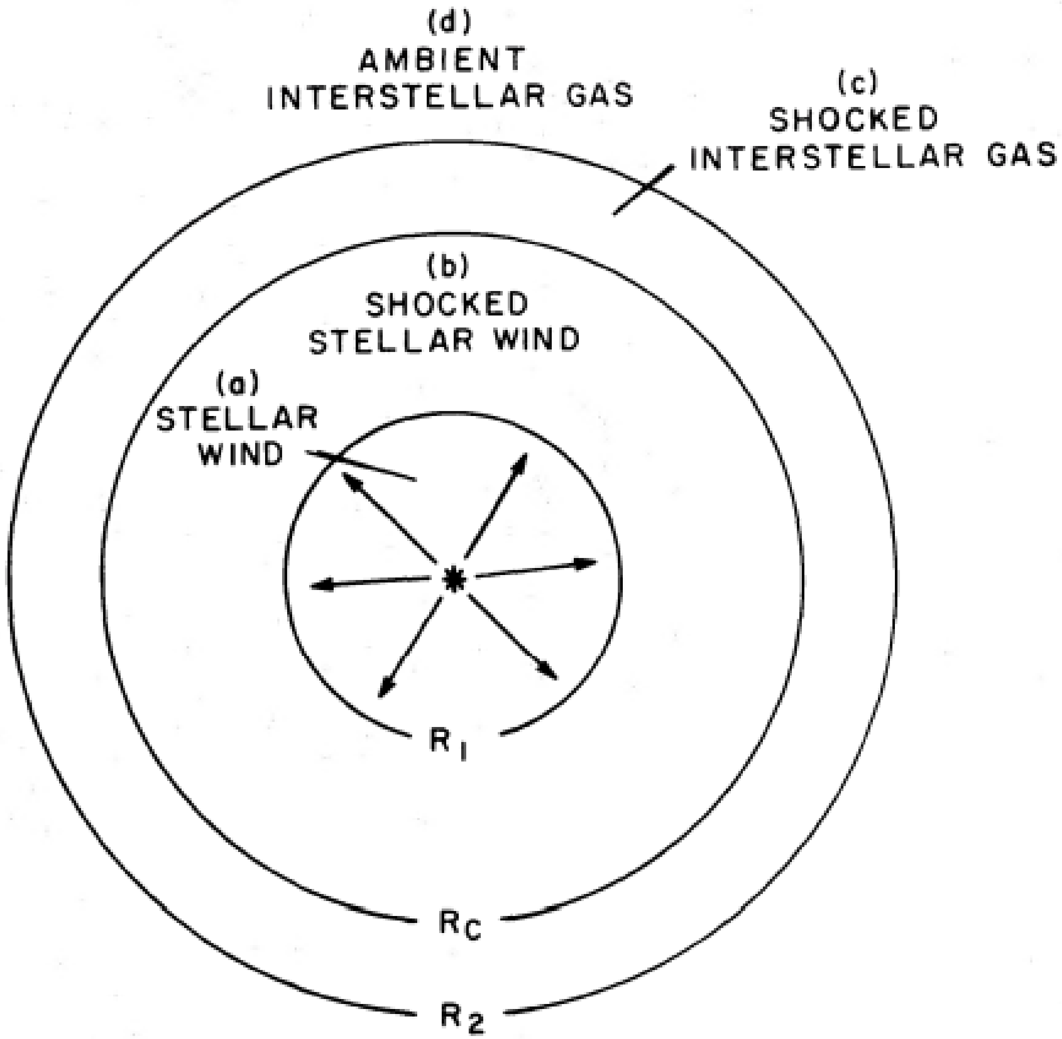
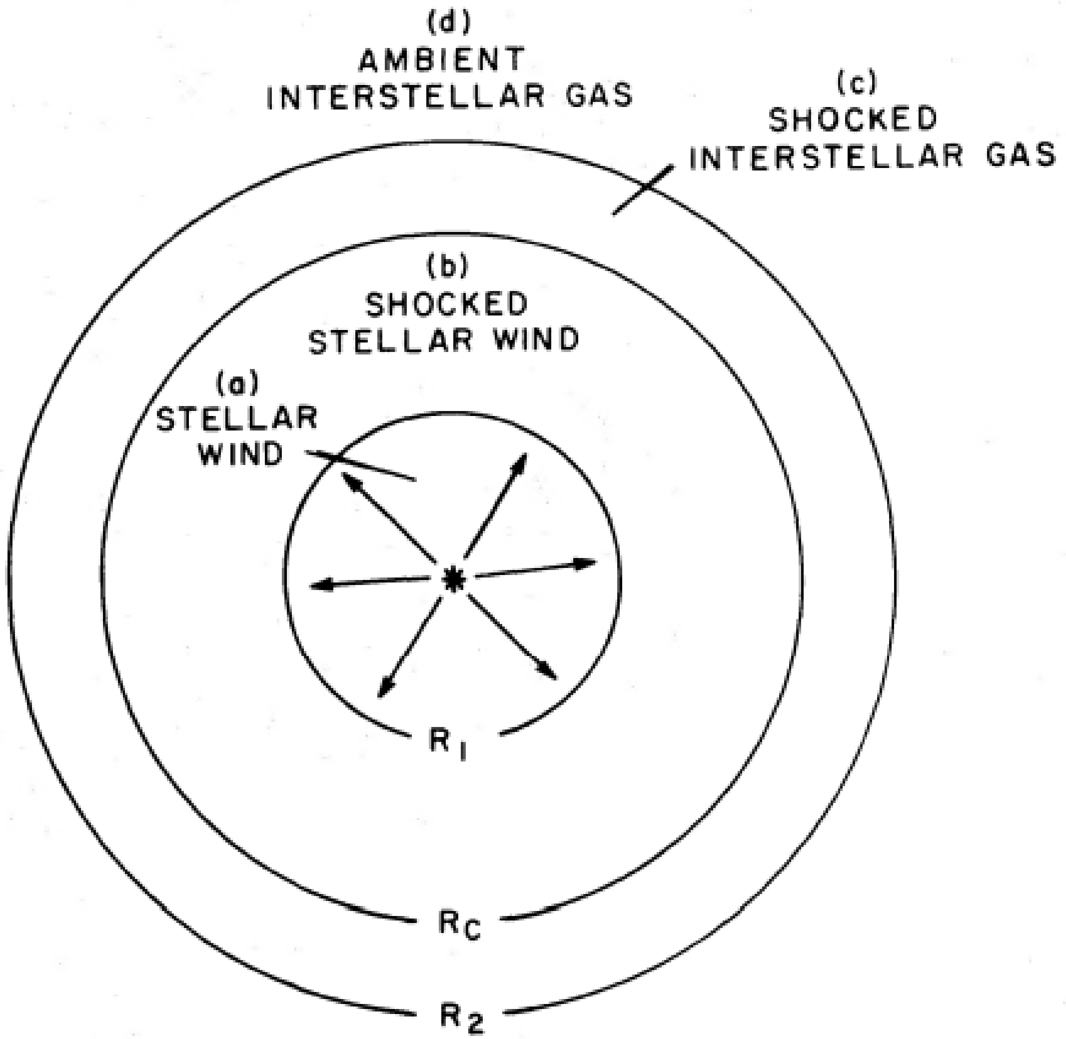
Diverging flows (wind bubbles)



Weaver+1977

- **Cavity in the ISM** excavated by the activity of a source blowing a **steady wind** with high velocity and large opening angle

Diverging flows (wind bubbles)

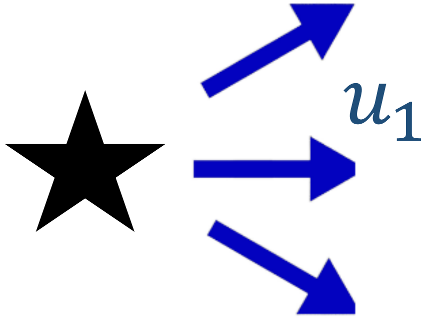


Weaver+1977

- **Cavity in the ISM** excavated by the activity of a source blowing a **steady wind** with high velocity and large opening angle

- Main macroscopic parameters:
  1. Terminal wind speed: V_∞
  2. Mass loss rate: $\dot{M}$
  3. External medium: n_{ISM}
  4. Age of the system: t_{age}

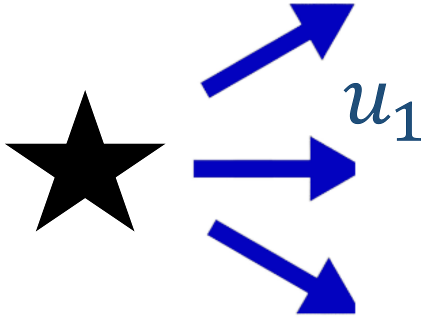
Structure and Evolution



1. The outflow is launched - t_0

Structure and Evolution

$$u_1 \gg c_s$$



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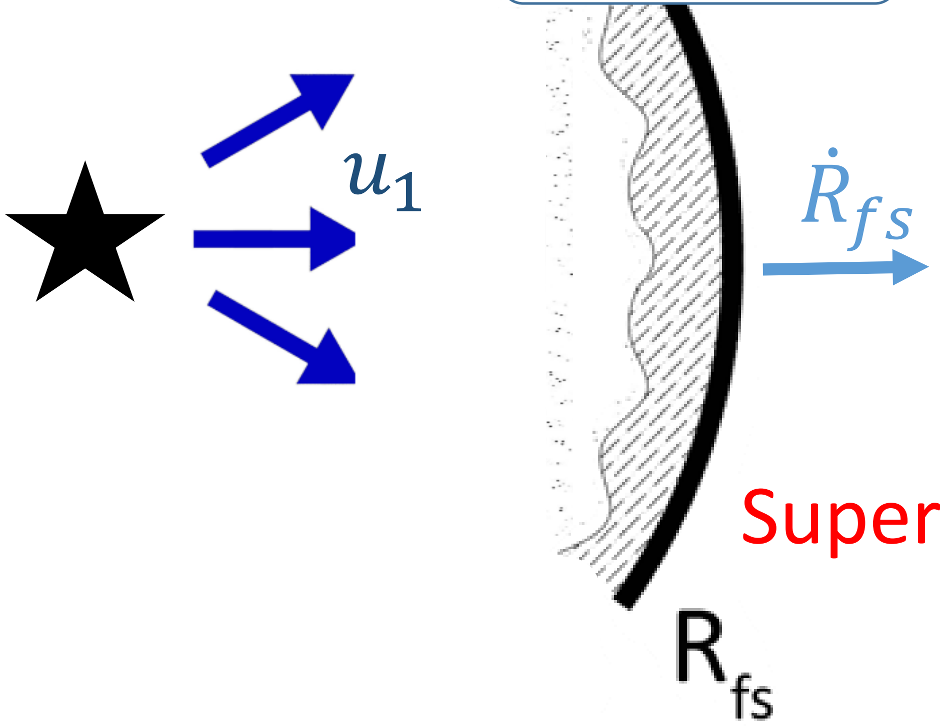
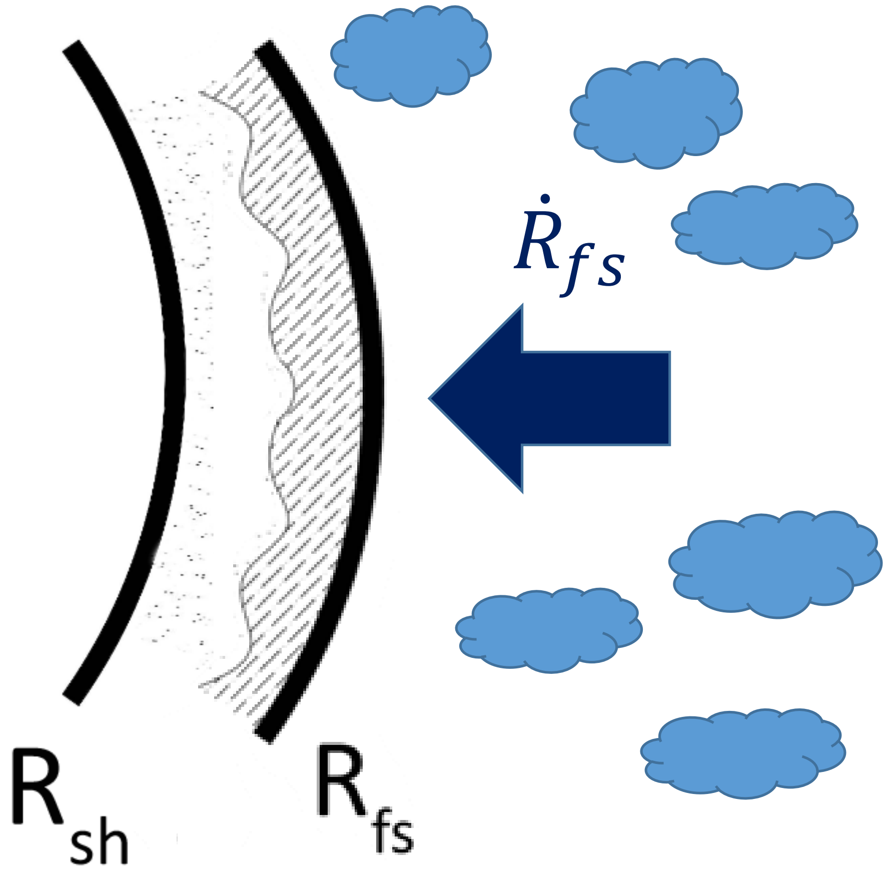


1. The outflow is launched - t_0

Supersonic → forward shock

Structure and Evolution

Collision with ISM → wind shock



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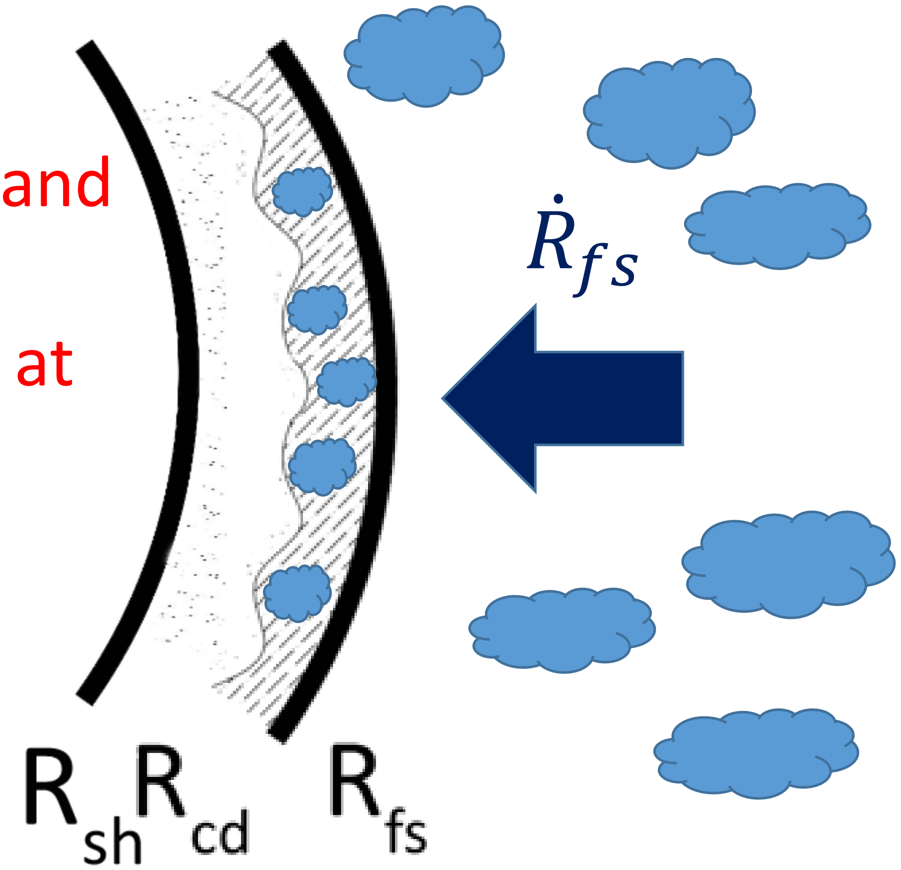
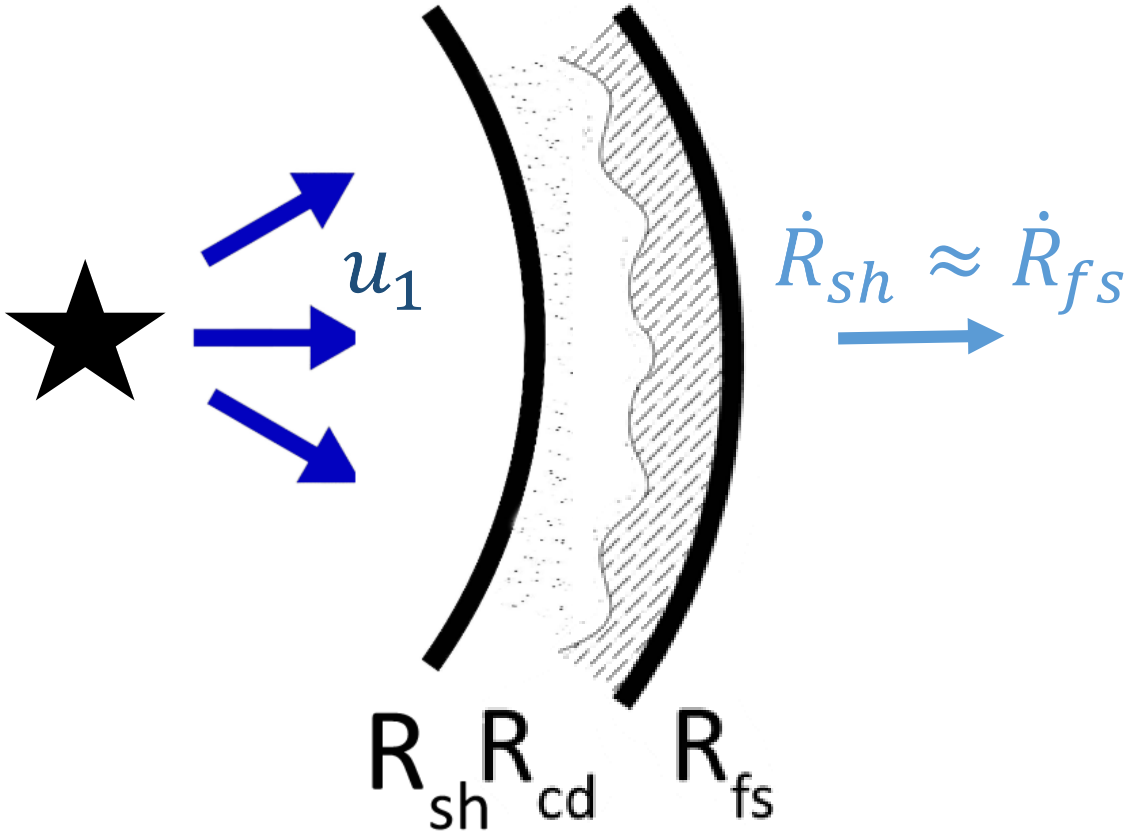


Compressed and shocked ISM accumulated at the contact discontinuity

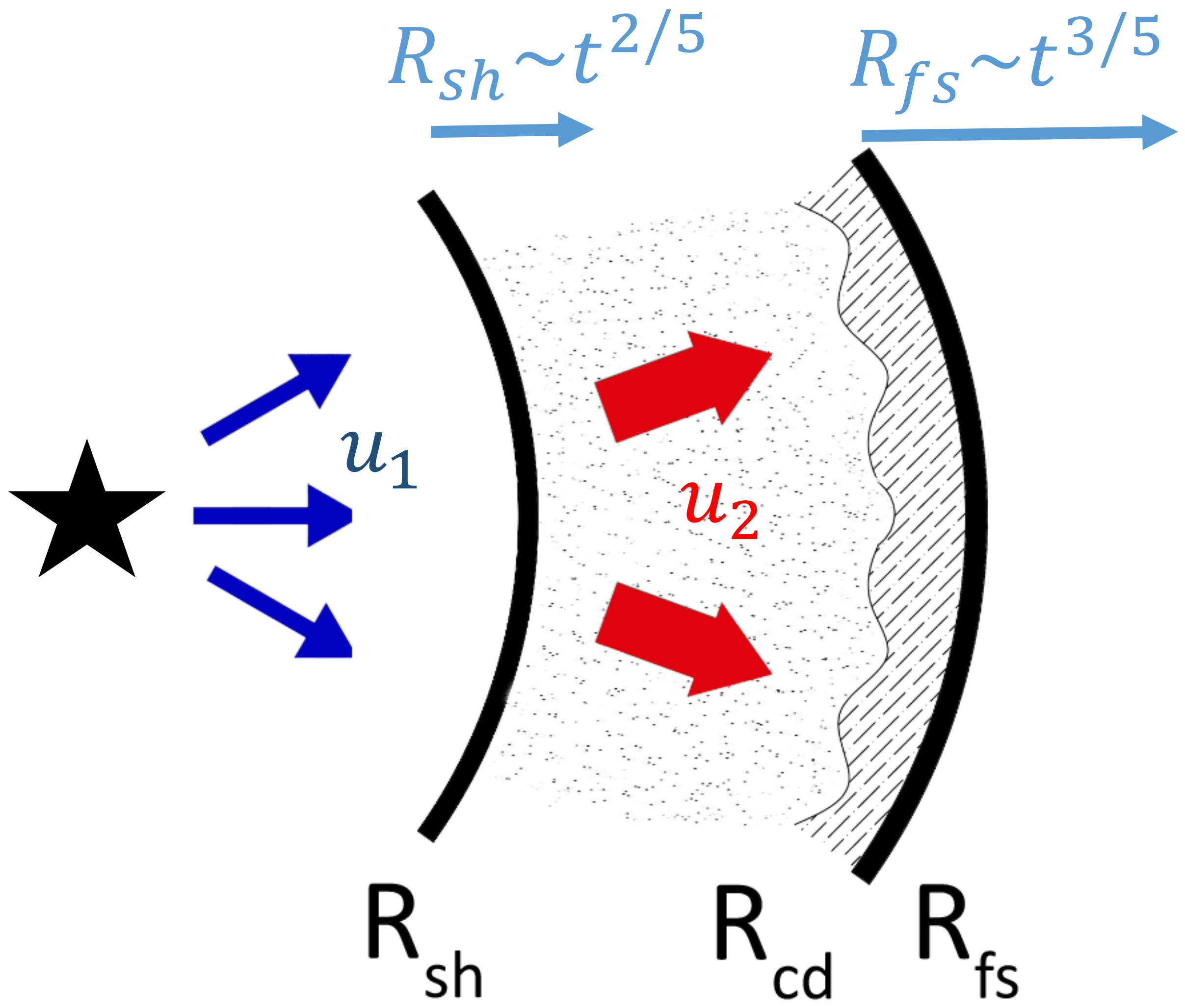
1. The outflow is launched - t_0

Structure and Evolution



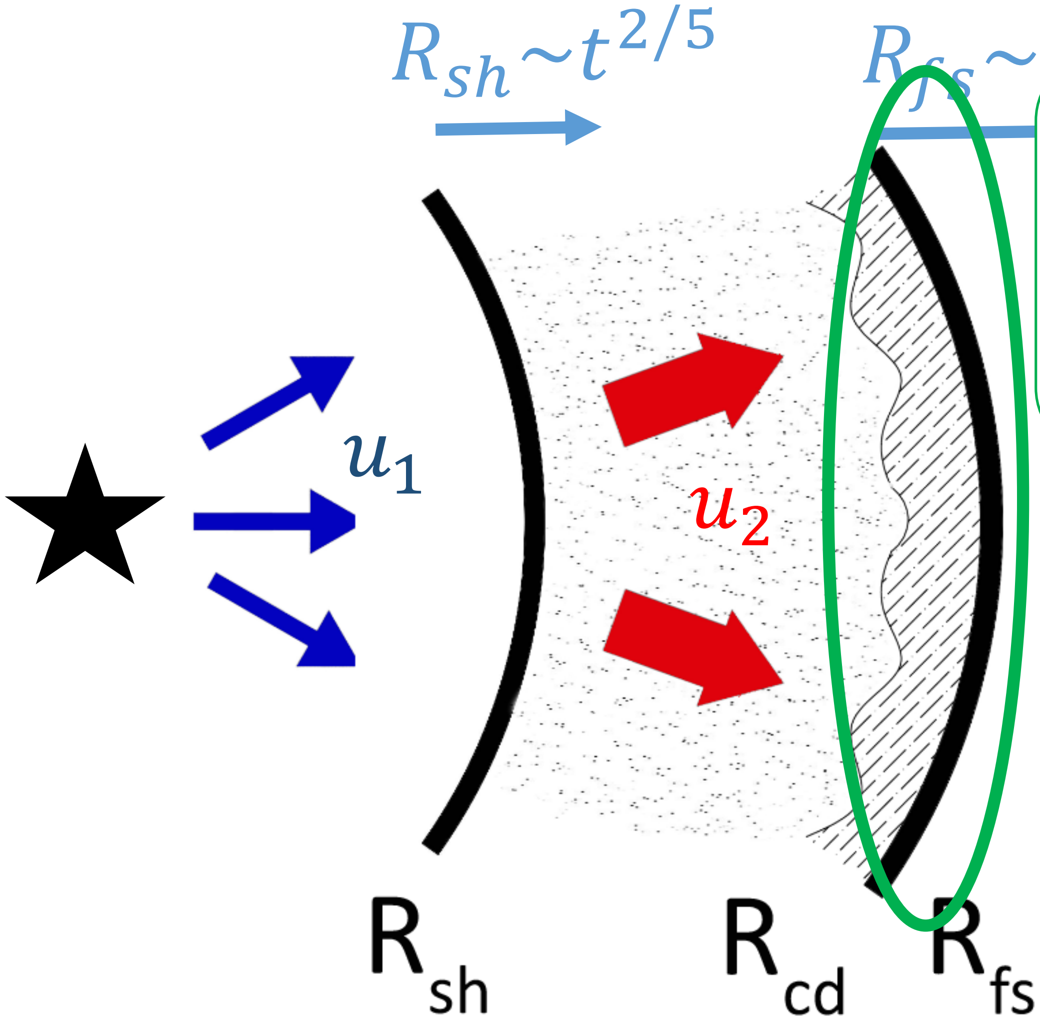
1. The outflow is launched - t_0
2. Free expansion phase - t_1

Structure and Evolution



1. The outflow is launched - t_0
2. Free expansion phase - t_1
3. Deceleration phase - $t > t_1$

Characterizing the accelerator



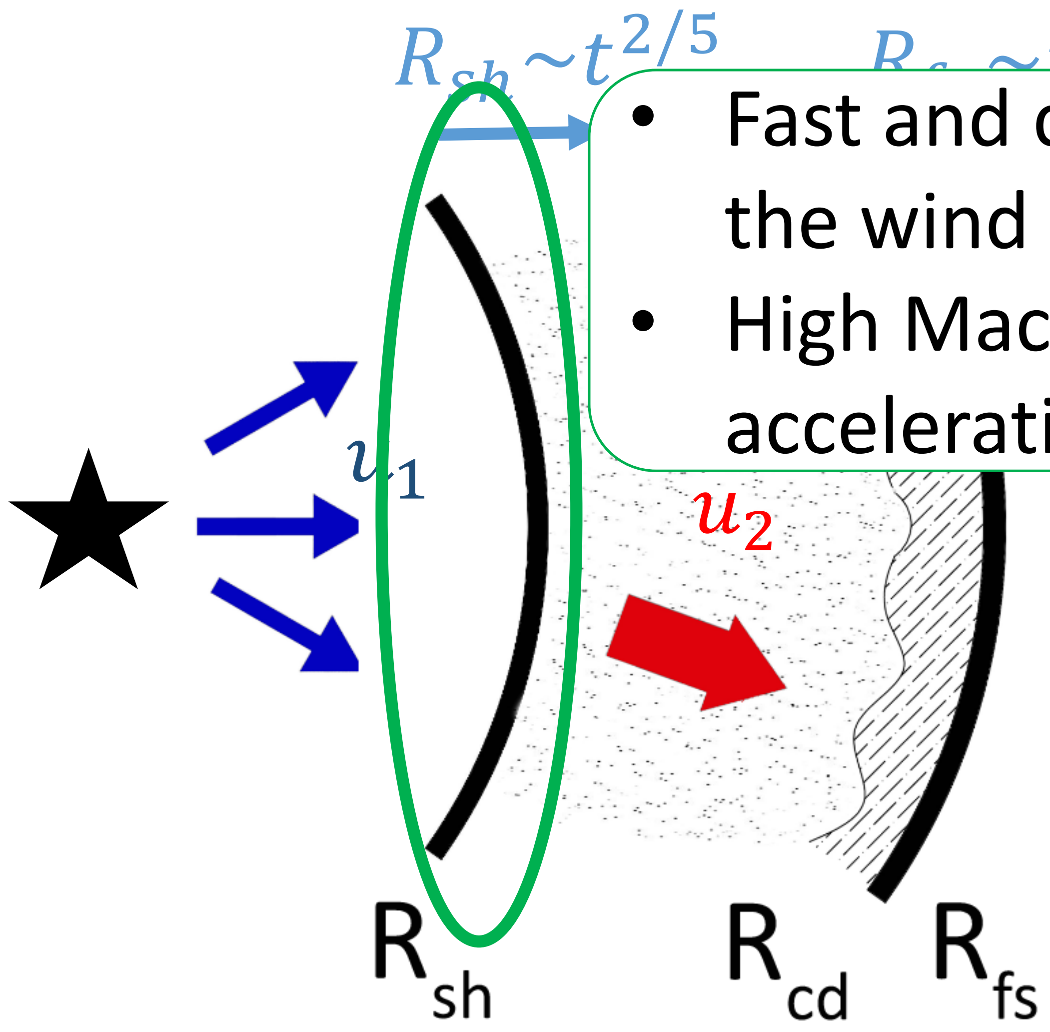
- Rapid fall of acceleration efficiency in time
- Mach number dependent on the external medium

hed - t_0

2. Free expansion phase - t_1

3. Deceleration phase - $t > t_1$

Characterizing the accelerator



- Fast and cool plasma at the wind shock
- High Mach number and acceleration efficiency

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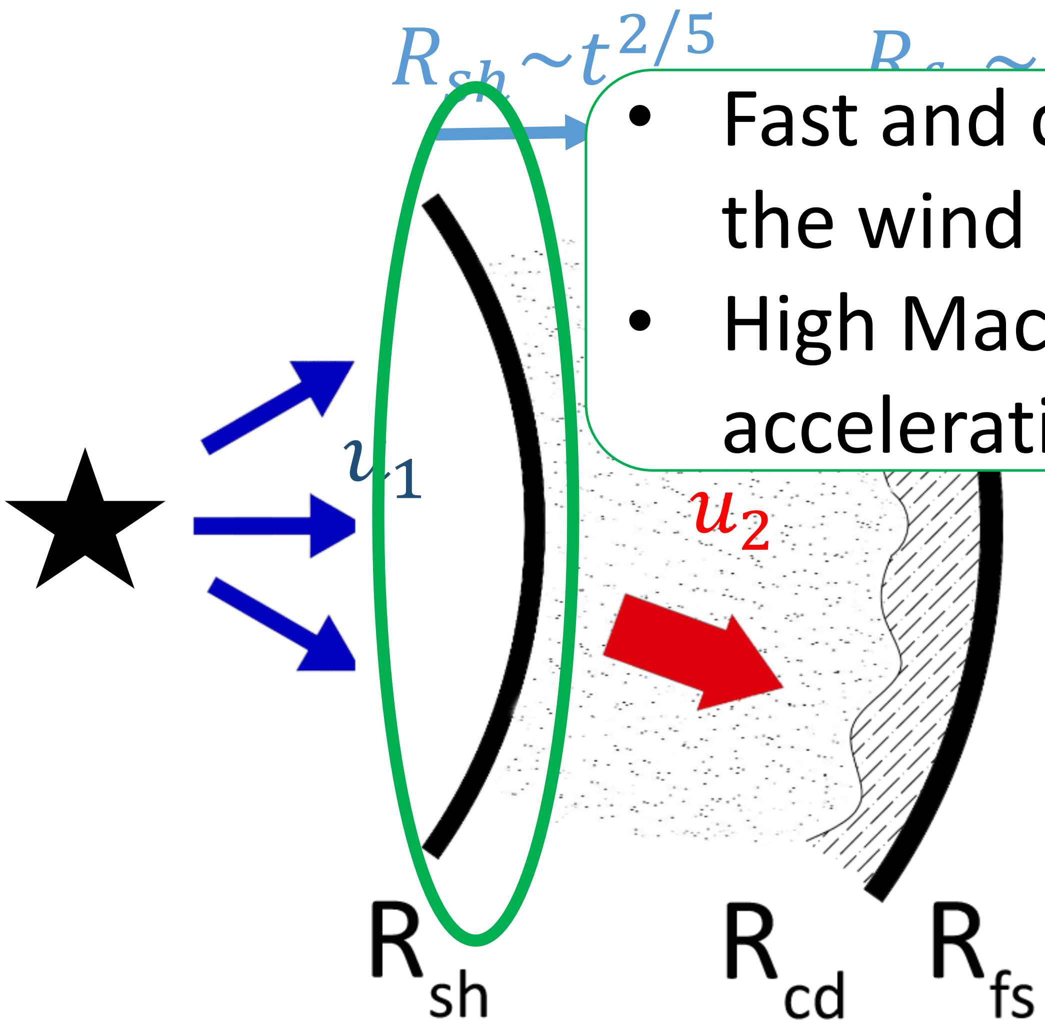

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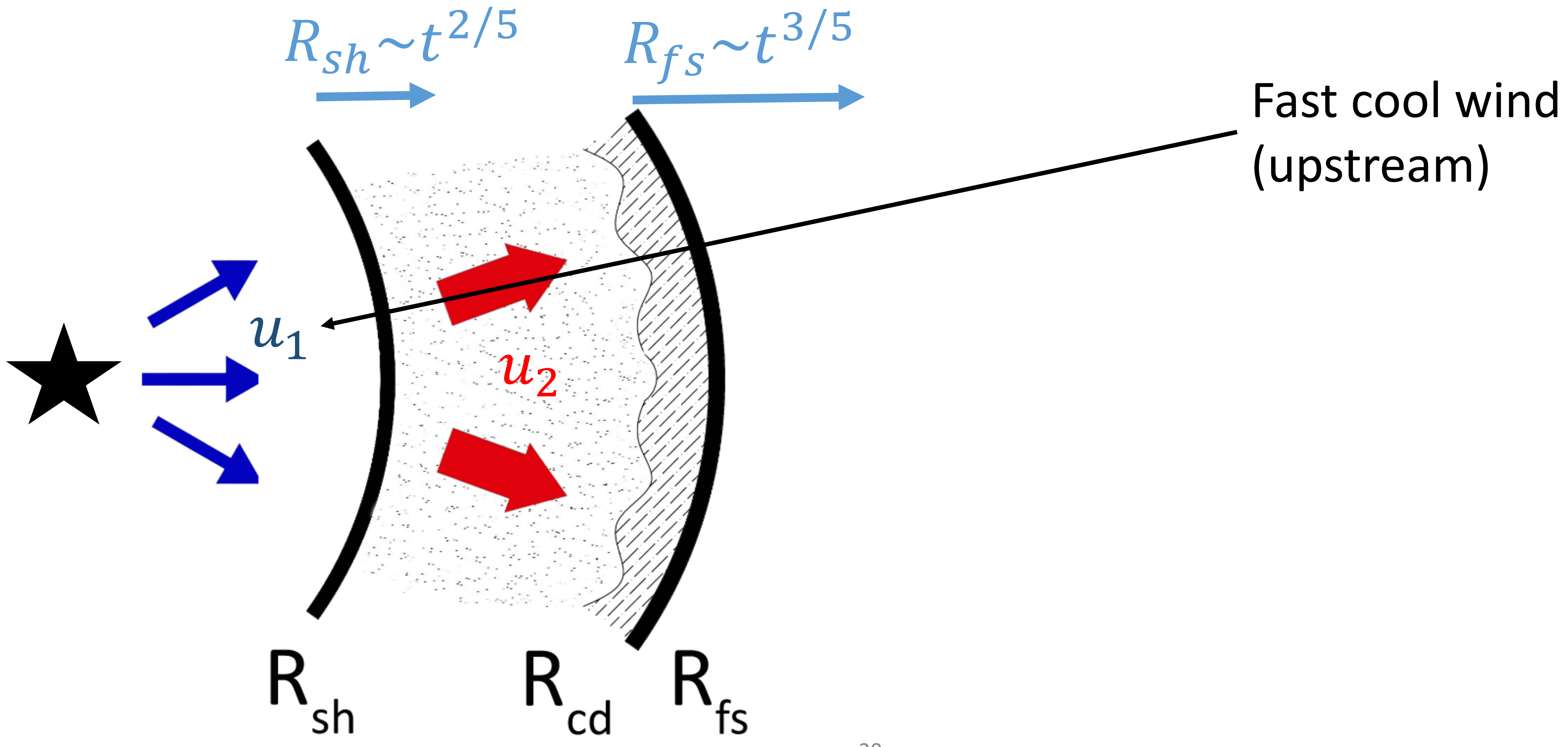

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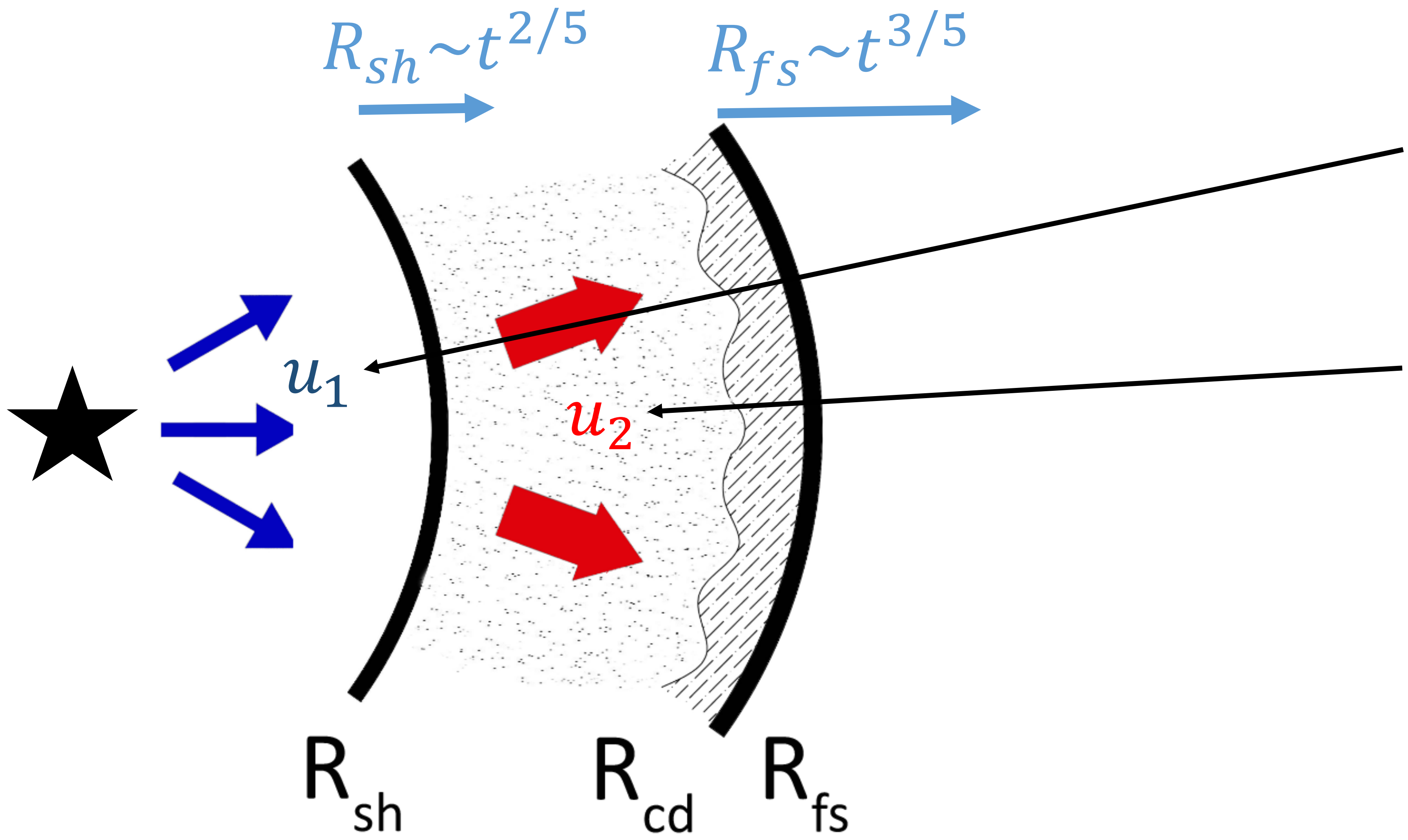
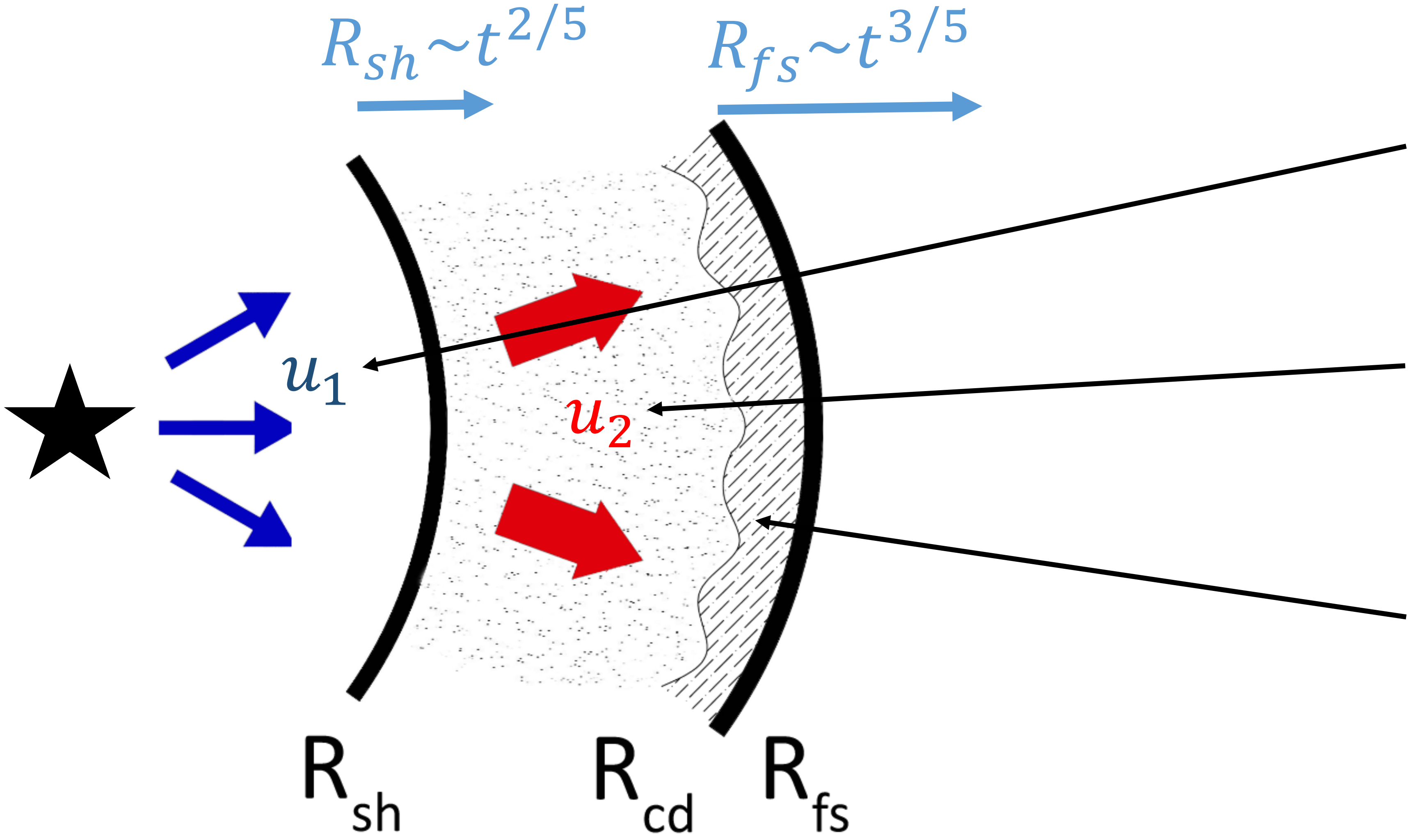


Fast cool wind
(upstream)

Hot shocked wind
(downstream)

Characterizing the accelerator

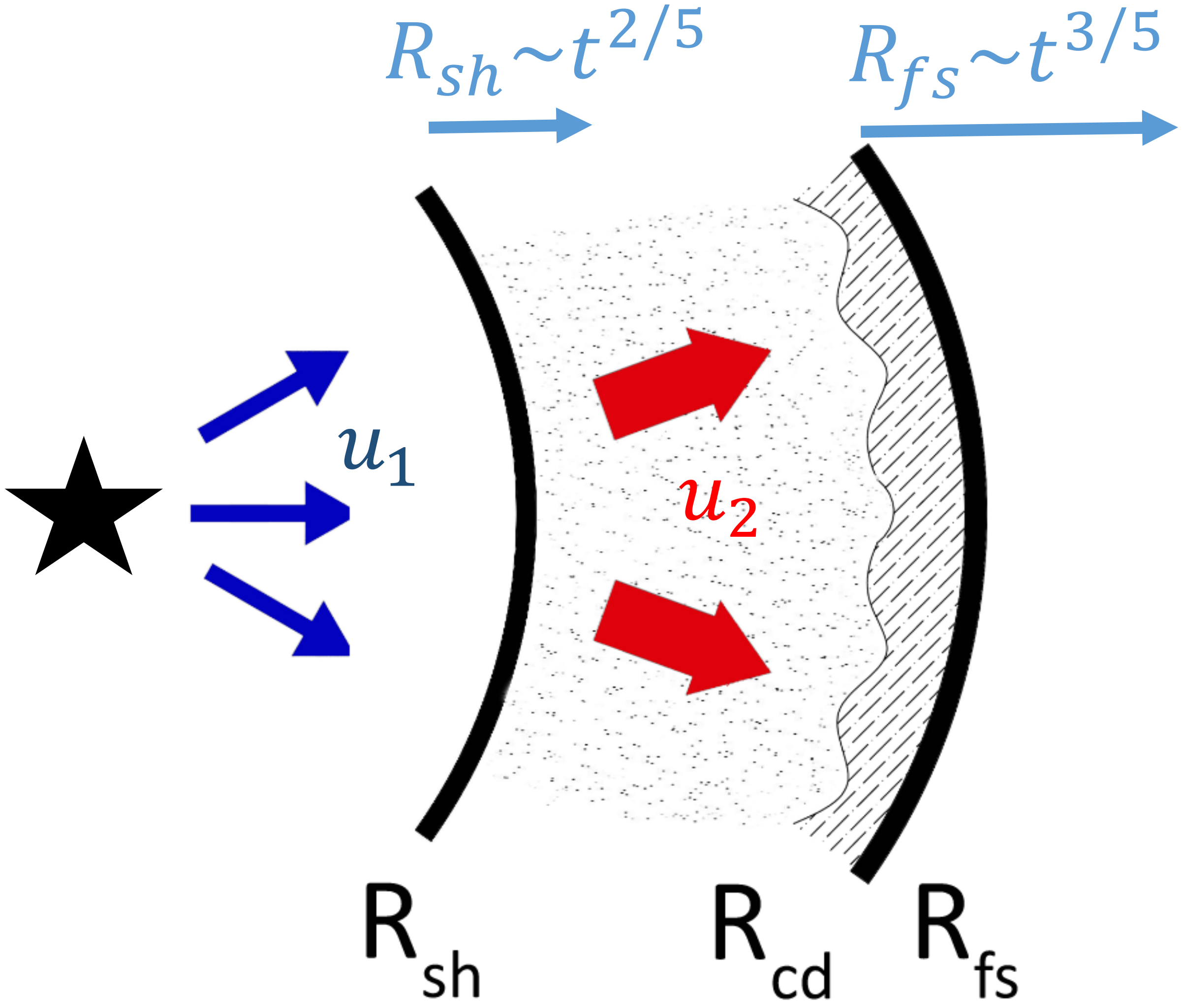


Fast cool wind
(upstream)

Hot shocked wind
(downstream)

Shocked ambient
medium (SAM)

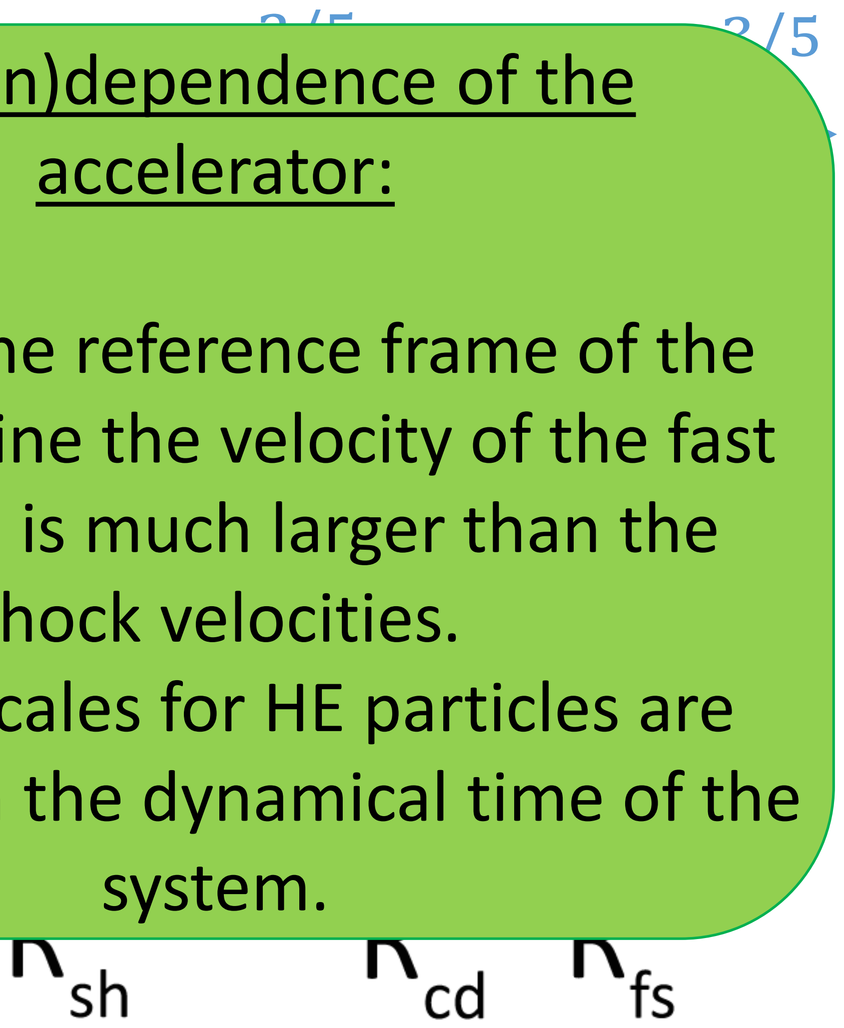
Characterizing the accelerator



<u>Geometry of the accelerator:</u>

Diverging flows such as wind bubbles formed by ultra-fast outflow feature a strong qualitative difference from standard cosmic accelerators such as supernova remnants.
Here the escape takes is only possible through the downstream region.

Characterizing the accelerator



Time (in)dependence of the accelerator:

Sitting in the reference frame of the central engine the velocity of the fast cool wind is much larger than the shock velocities.

The timescales for HE particles are shorter than the dynamical time of the system.

Geometry of the accelerator:

Diverging flows such as wind bubbles formed by ultra-fast outflow feature a strong qualitative difference from standard cosmic accelerators such as supernova remnants.

Here the escape takes is only possible through the downstream region.

Characterizing the accelerator

Time (in)dependence of the accelerator:

Stationary diffusive shock acceleration is a good approximation.

Geometry of the accelerator:

We can get very high maximum energies «for free».

R_{sh} R_{cd} R_{fs}

Outline

- Diverging flows: structure and evolution
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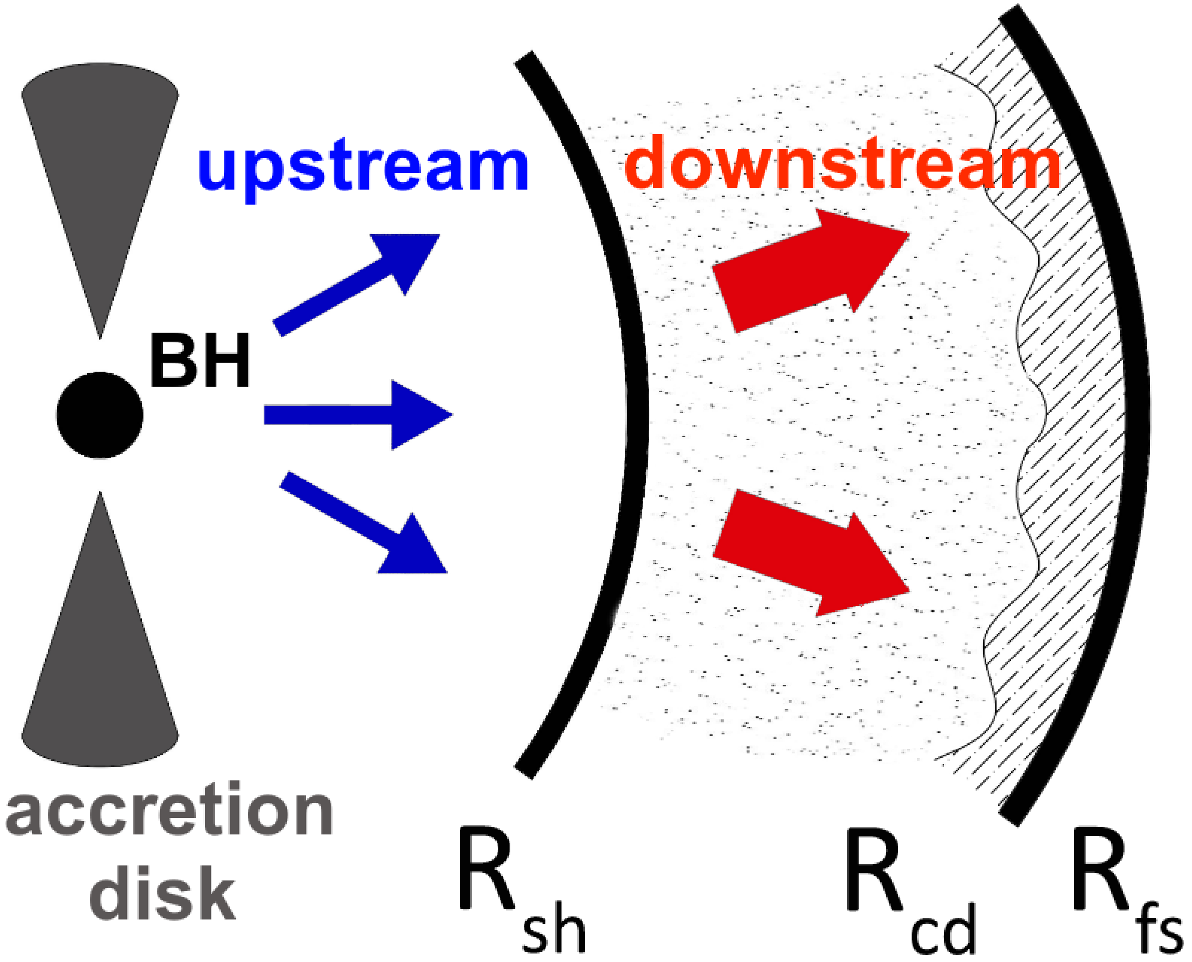
Acceleration and transport model

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



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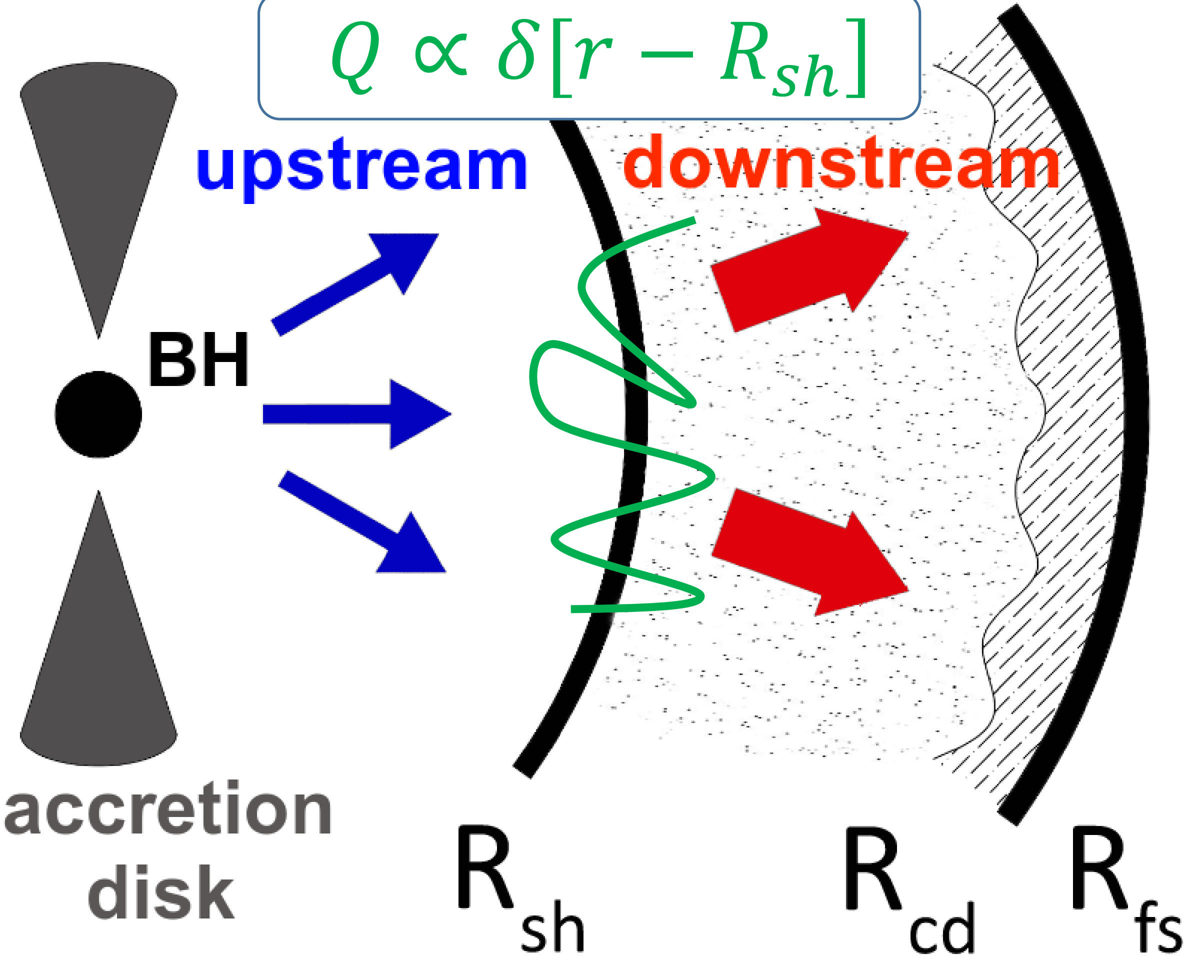
$$Q \propto \delta[r - R_{sh}]$$



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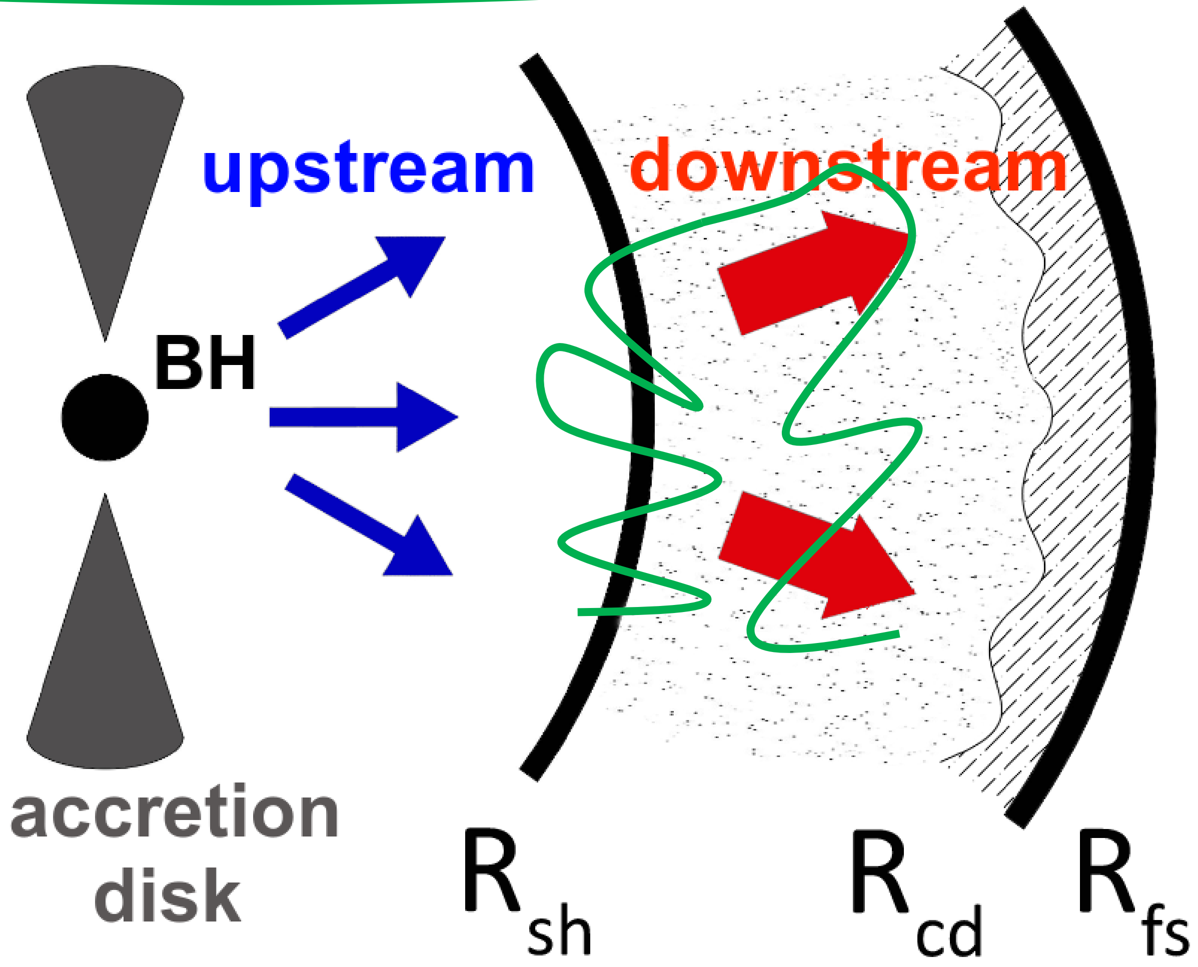

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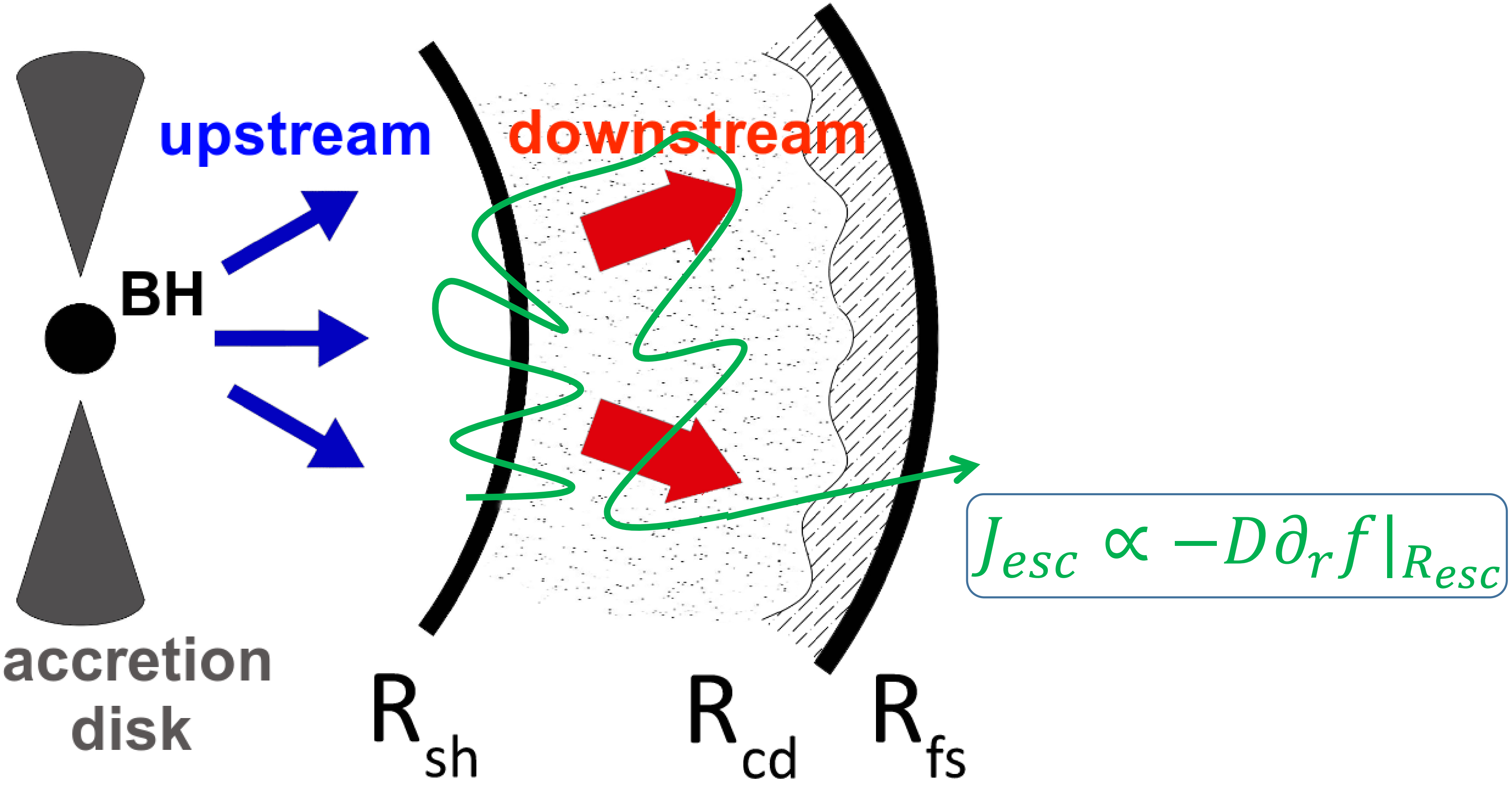

$J_{esc} \propto -D\partial_r f|_{R_{esc}}$

Acceleration and transport model

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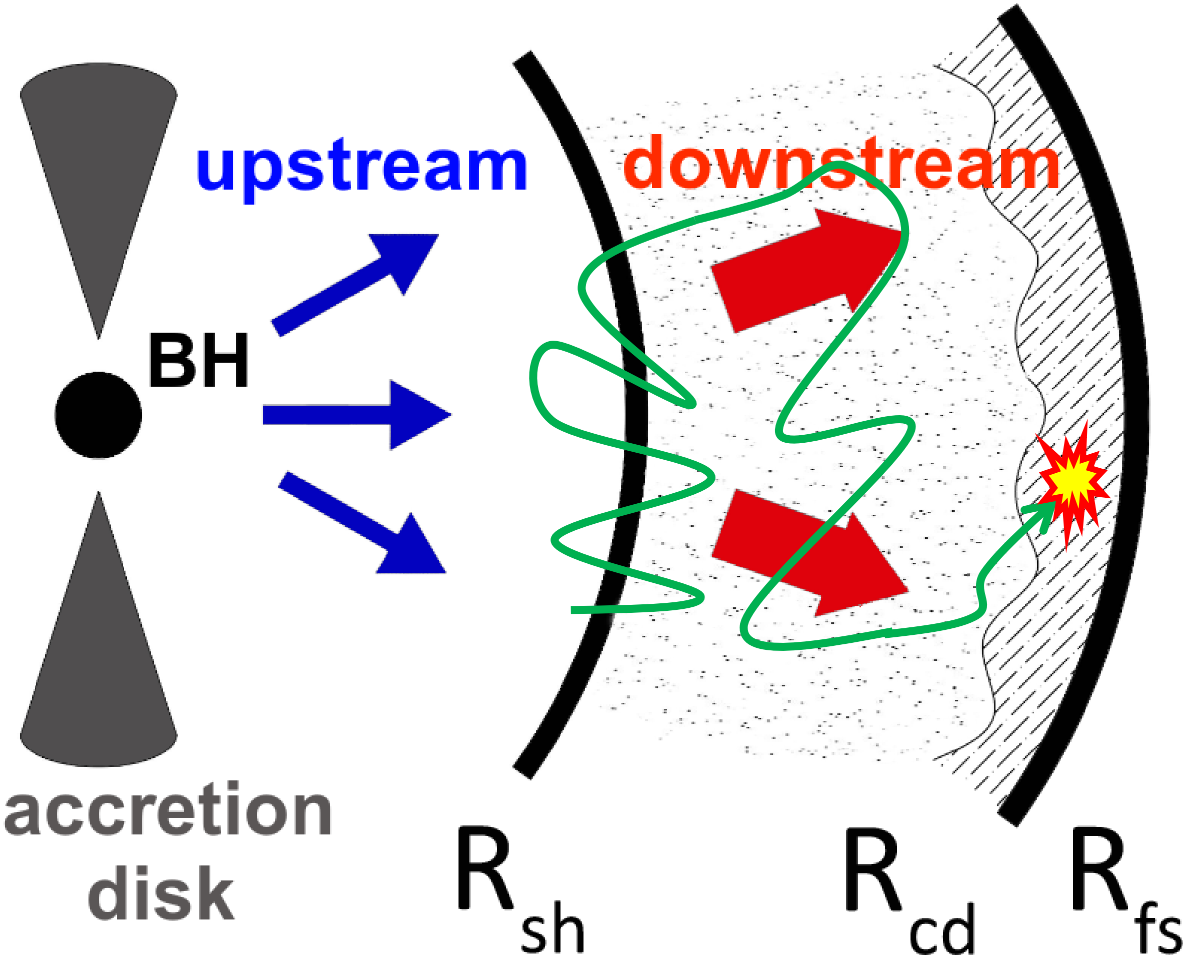

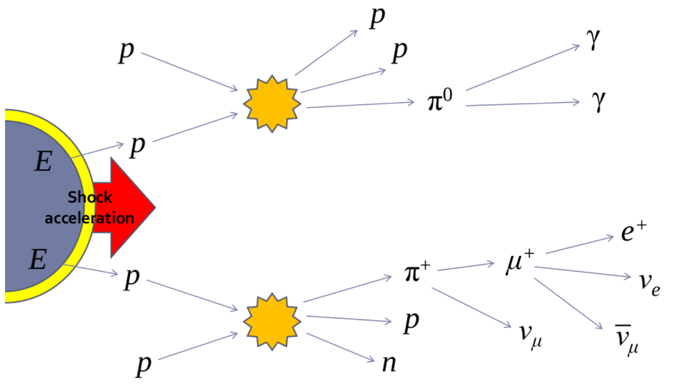

Website: http://www.astro.wisc.edu/~gvance/index.html

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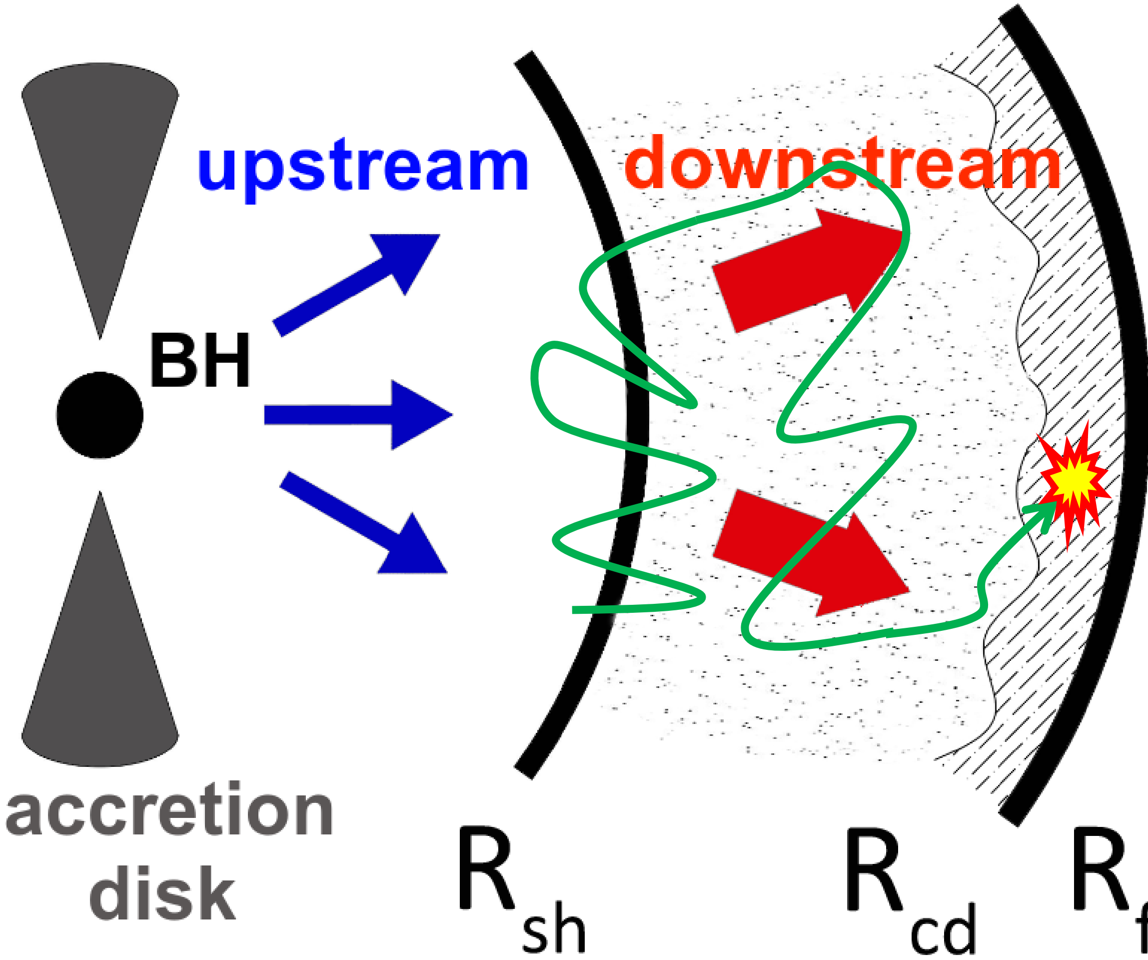
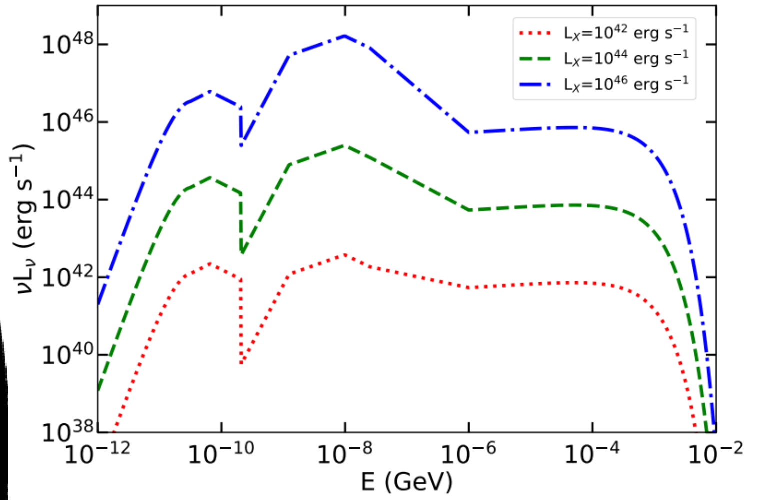
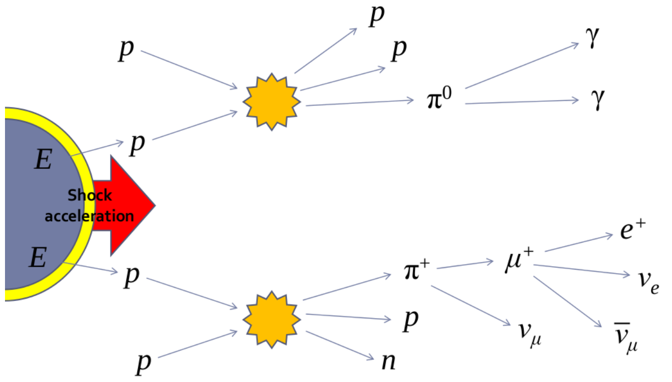
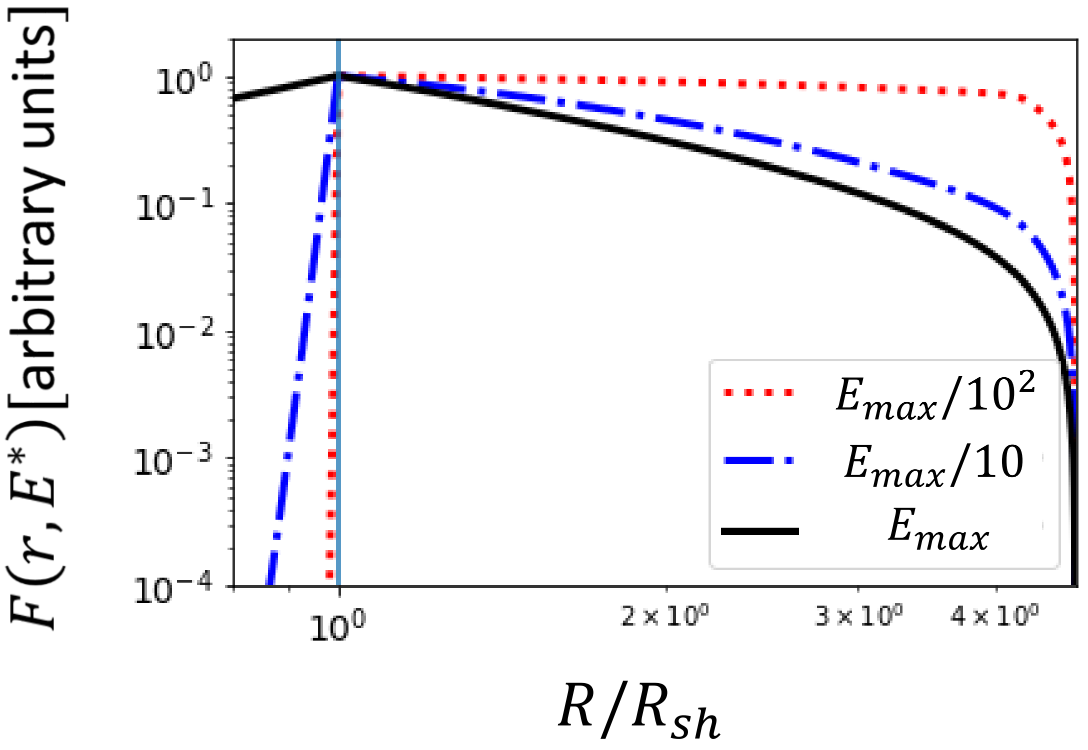


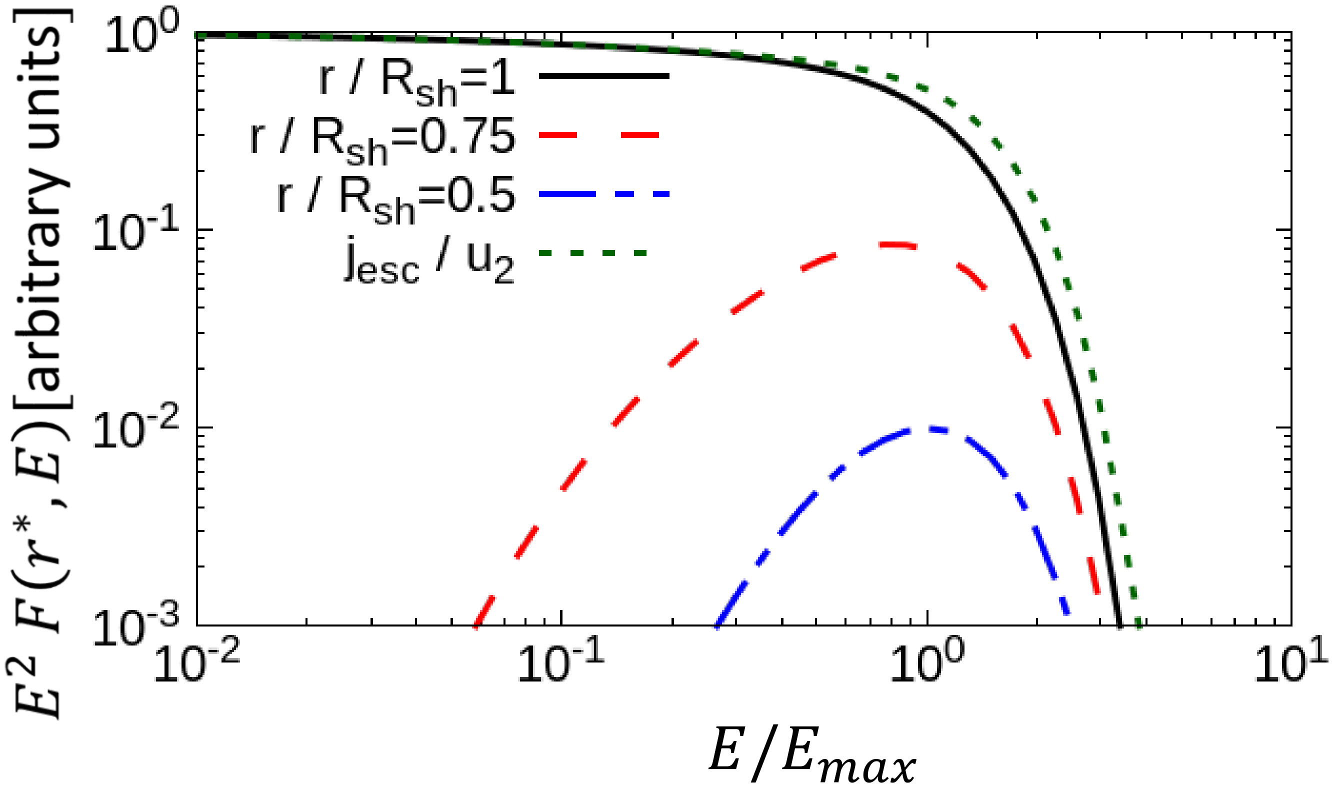




Website: http://www.astro.wisc.edu/~gvance/index.html

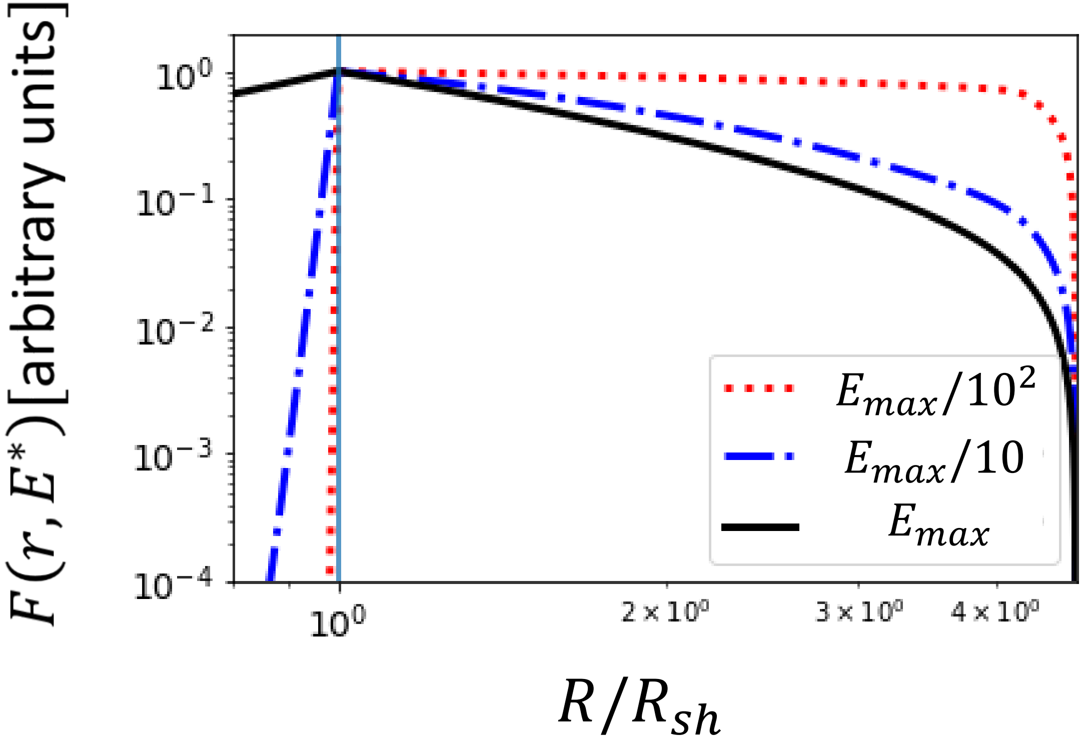
Solution: radial behavior and spectra

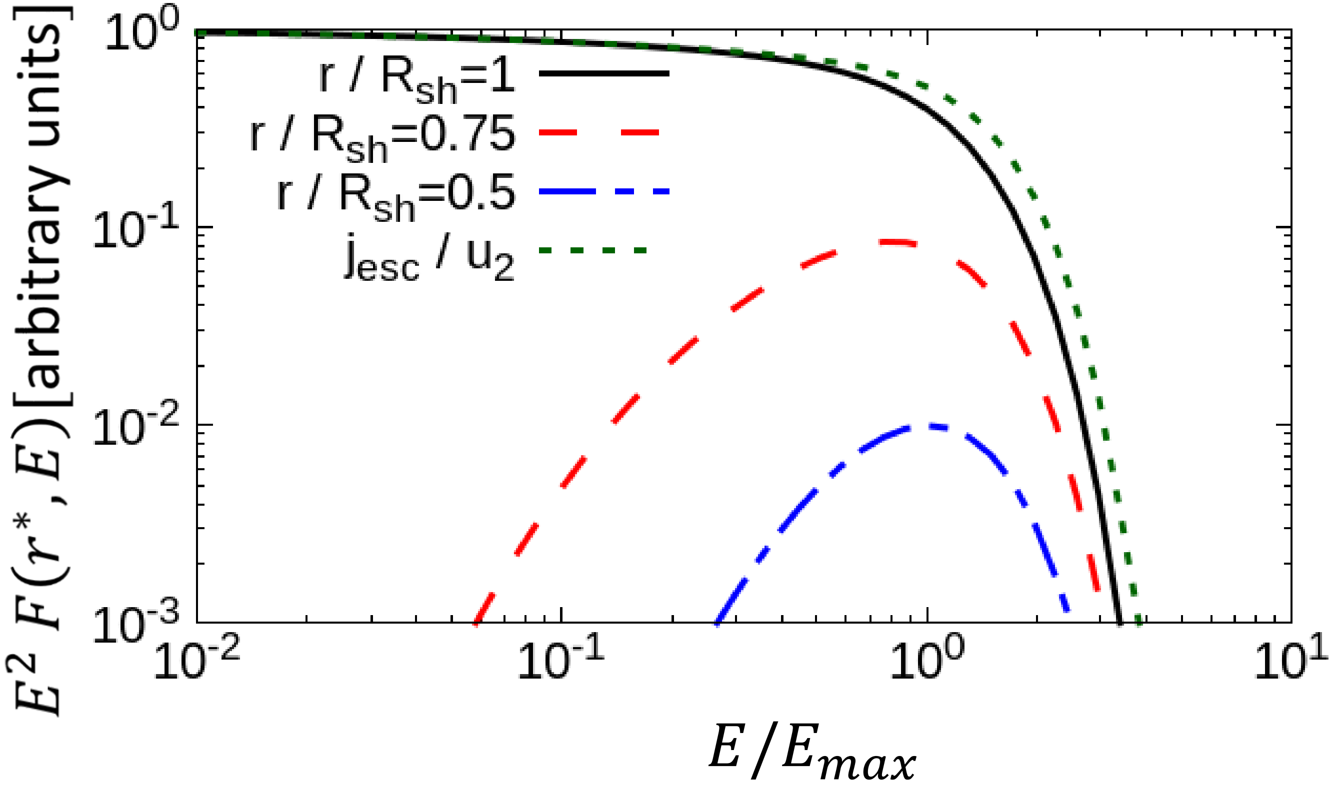




Solution: radial behavior and spectra

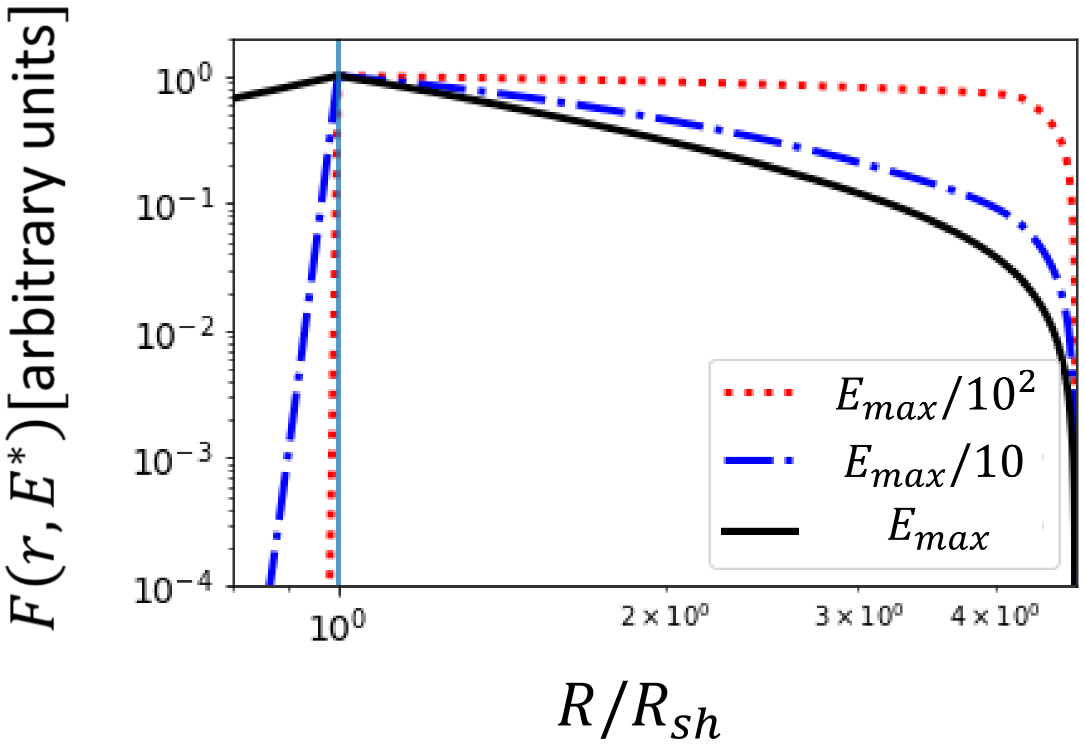
Radial distribution of particles
Please ask if you are interested

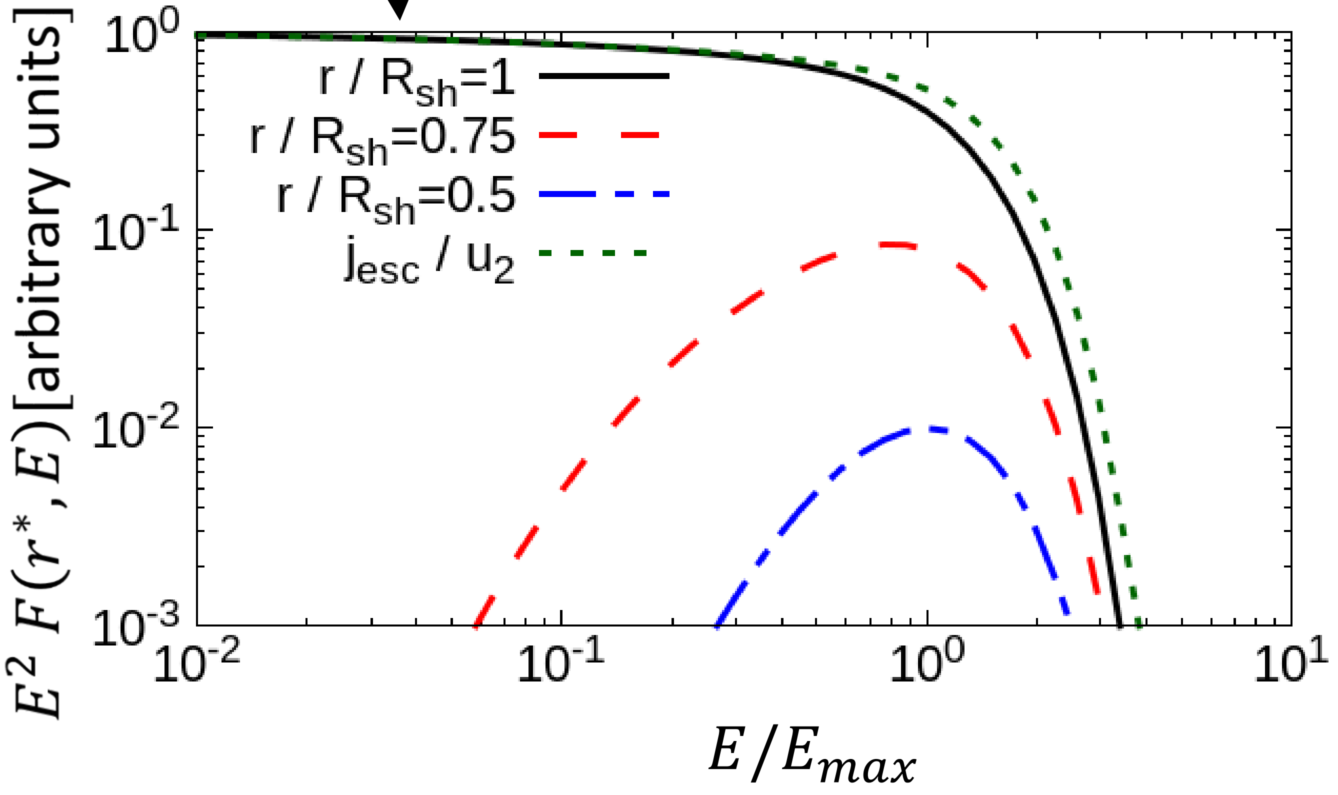




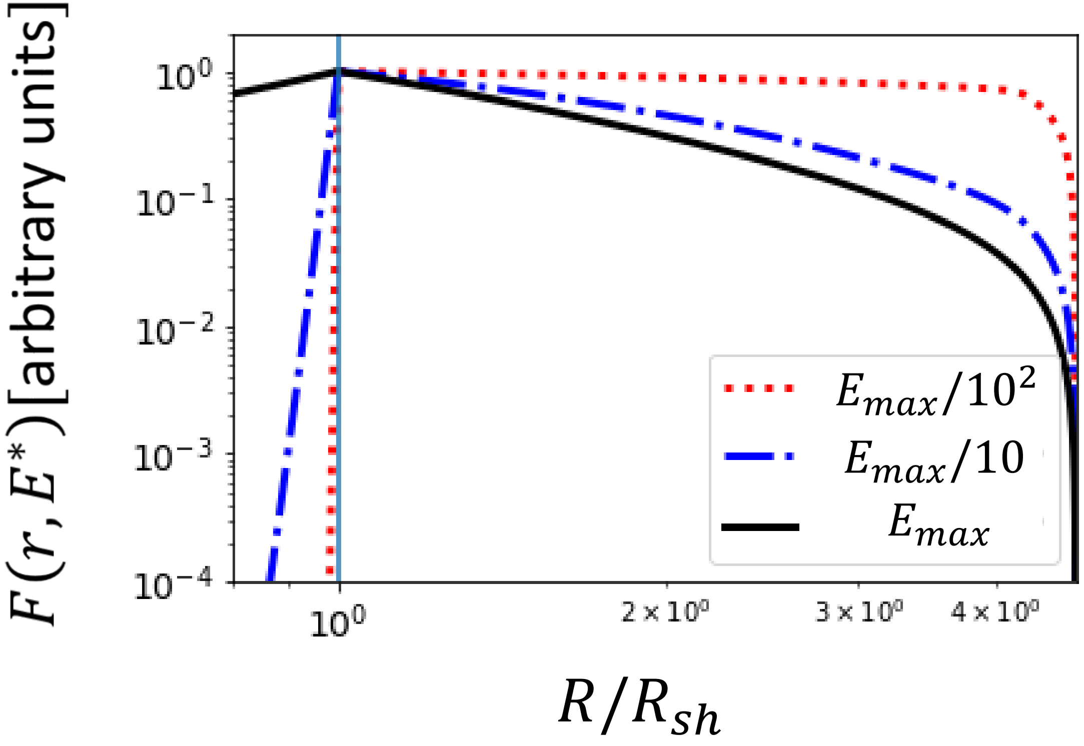
Solution: radial behavior and spectra

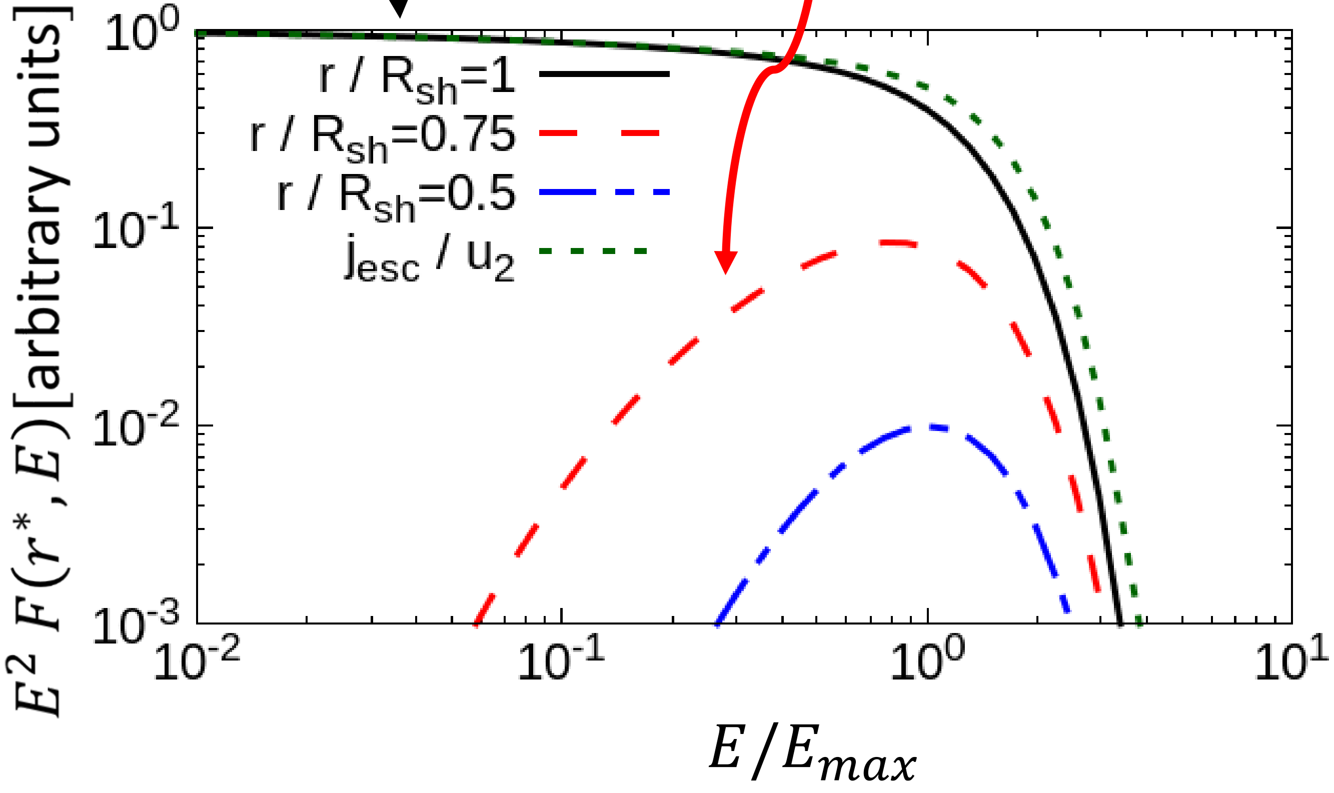
Solution at the shock





Solution: radial behavior and spectra



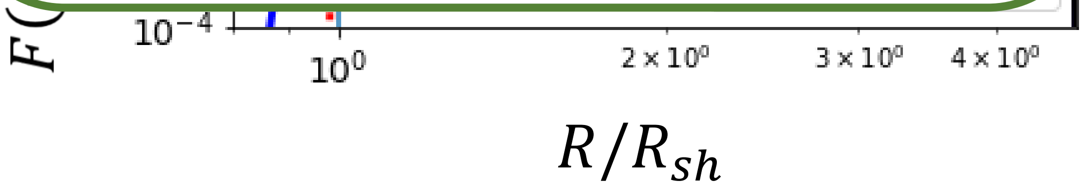


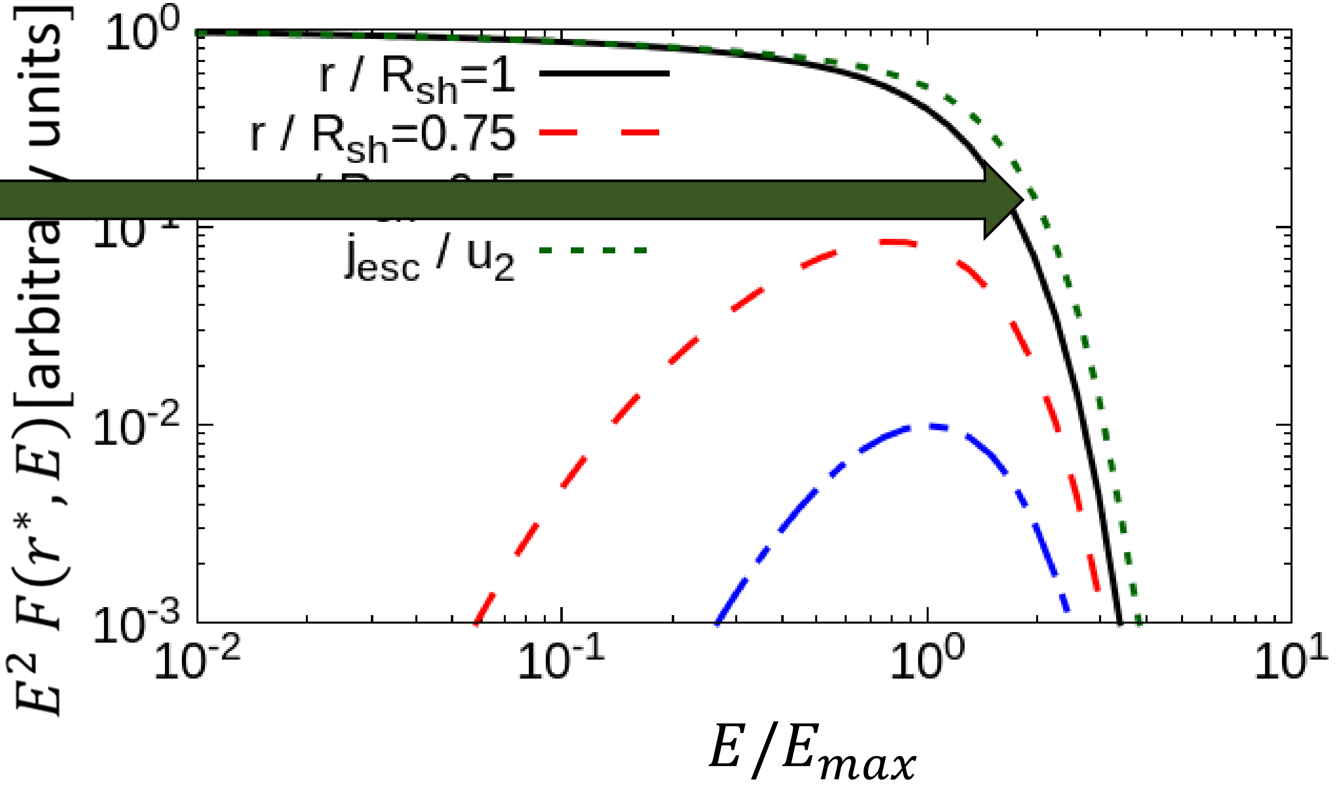
Solution at the shock

Upstream spectrum

Solution: radial behavior and spectra

Negligible energy losses result in no relevant difference between the spectrum at the shock and the escaping flux

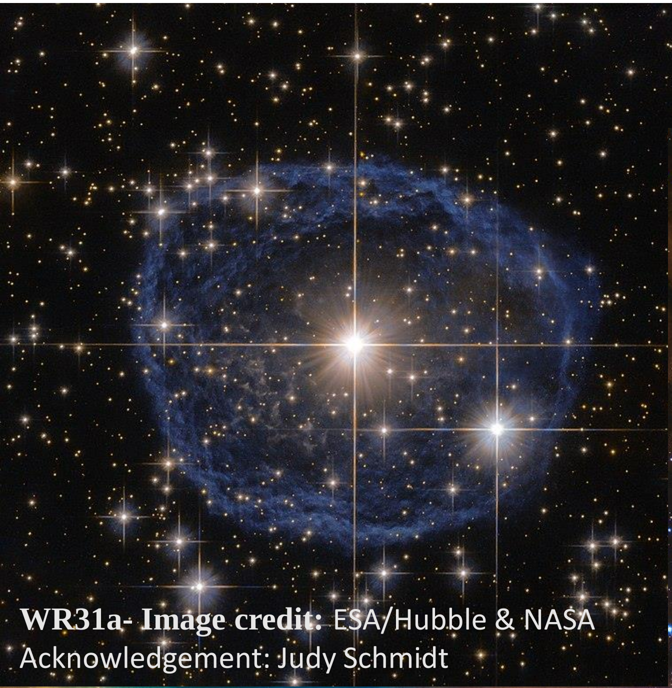




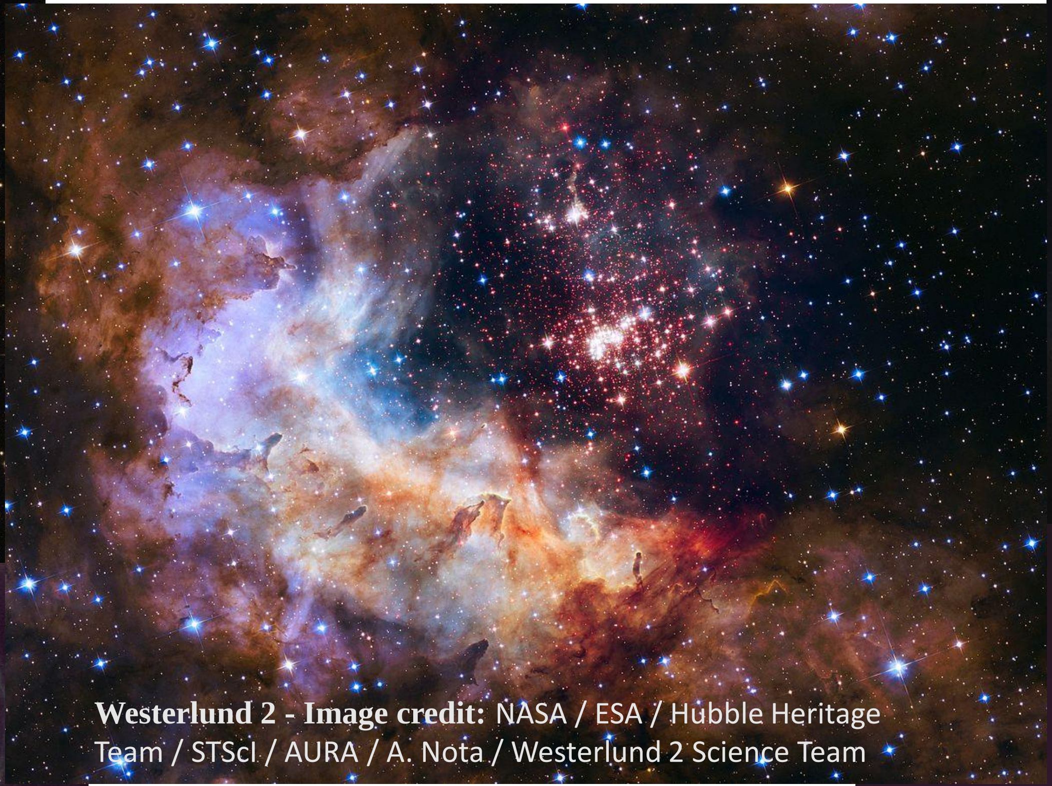
Outline

- Diverging flows: structure and evolution
- Acceleration and transport model in diverging flows
- Multimessenger implications: YMSCs, SBGs & AGNi

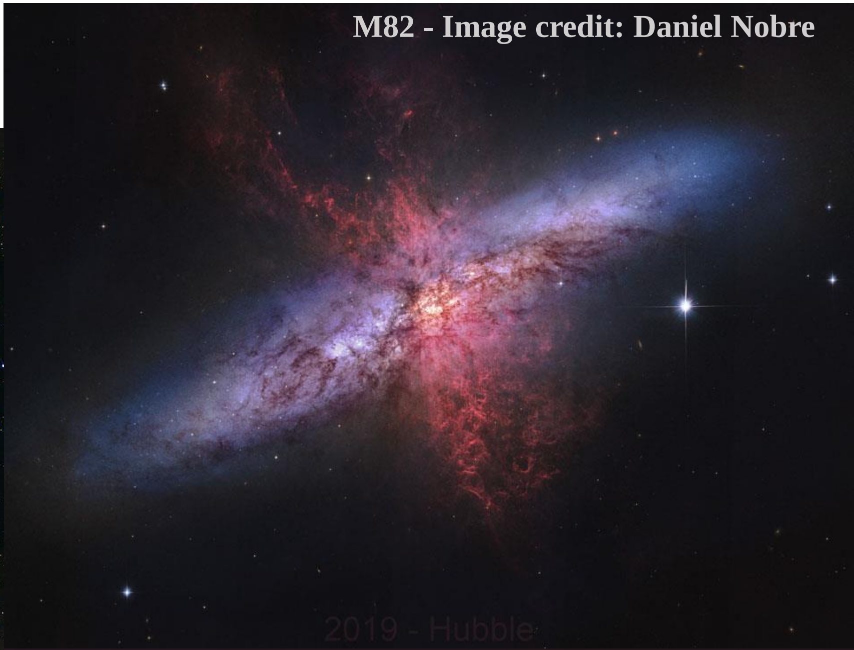
Scale and power



WR31a- Image credit: ESA/Hubble & NASA Acknowledgement: Judy Schmidt

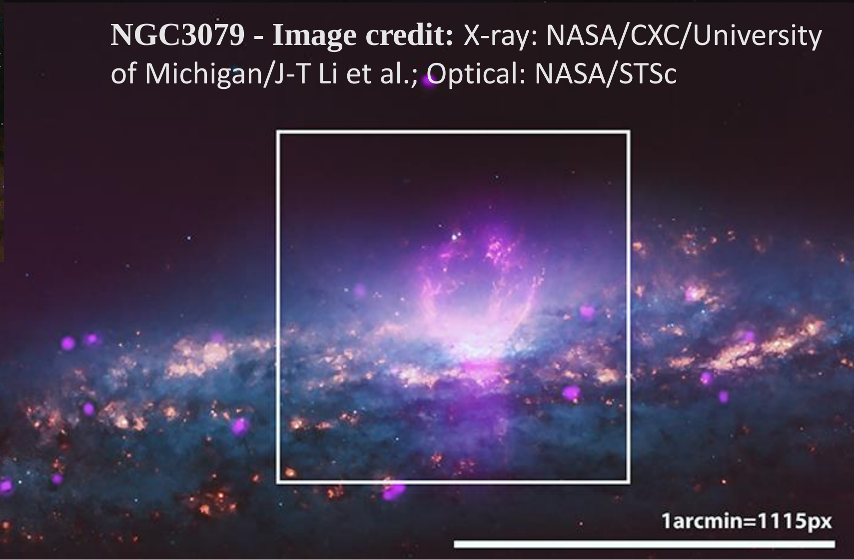


Westerlund 2 - Image credit: NASA / ESA / Hubble Heritage Team / STScI / AURA / A. Nota / Westerlund 2 Science Team



M82 - Image credit: Daniel Nobre

NGC7635- Image credit: NASA Goddard Space Flight Center from Greenbelt, MD, USA



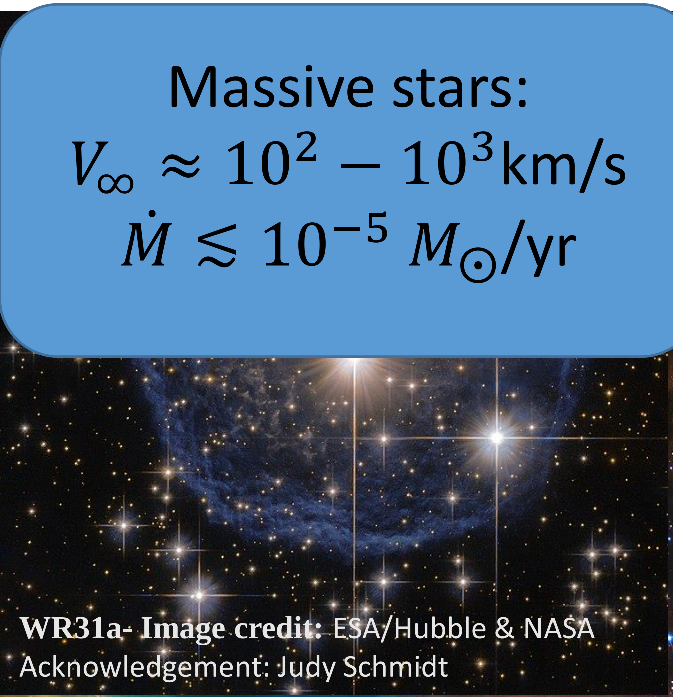
NGC3079 - Image credit: X-ray: NASA/CXC/University of Michigan/J-T Li et al.; Optical: NASA/STSc

Scale and power

Massive stars:

$V_\infty \approx 10^2 - 10^3\text{km/s}$

$\dot{M} \lesssim 10^{-5}\ M_\odot/\text{yr}$



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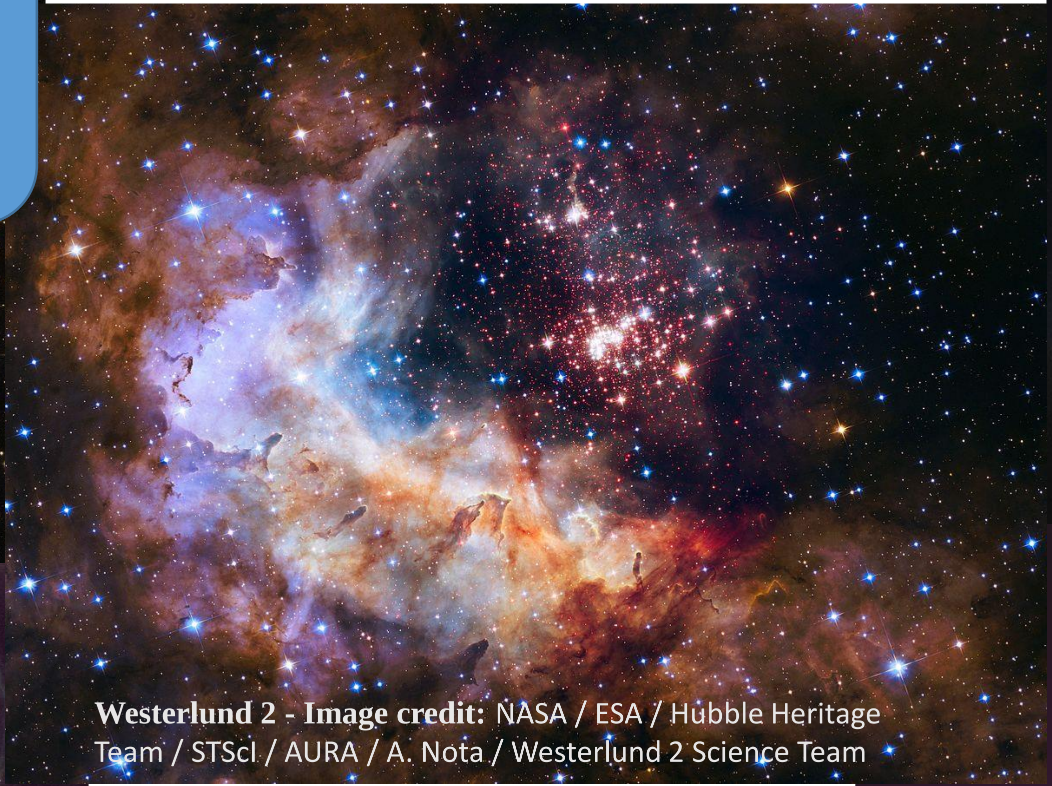

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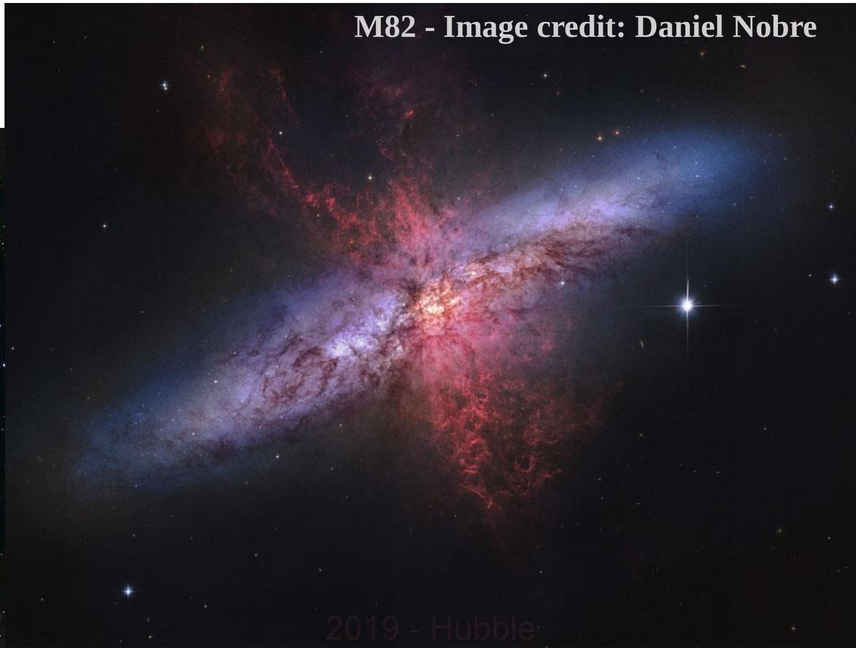

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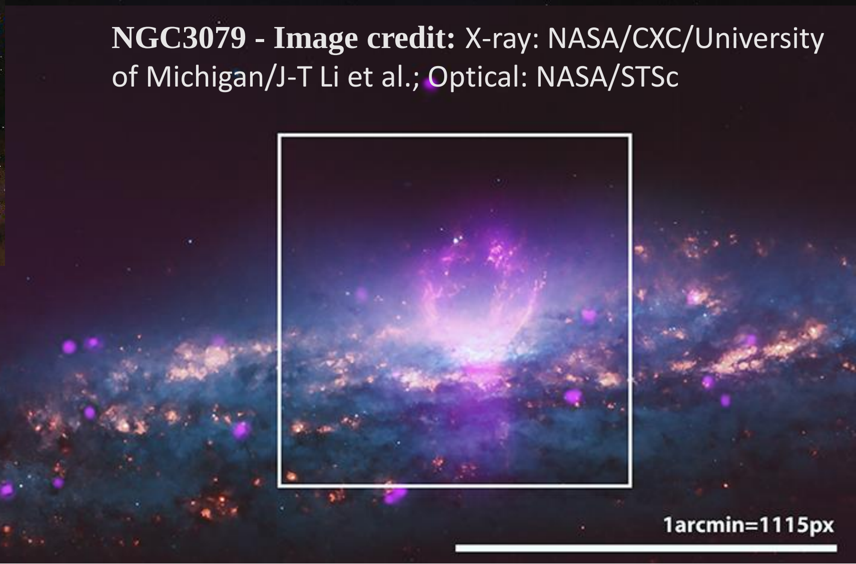

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Star clusters:

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Acknowledgement: Judy

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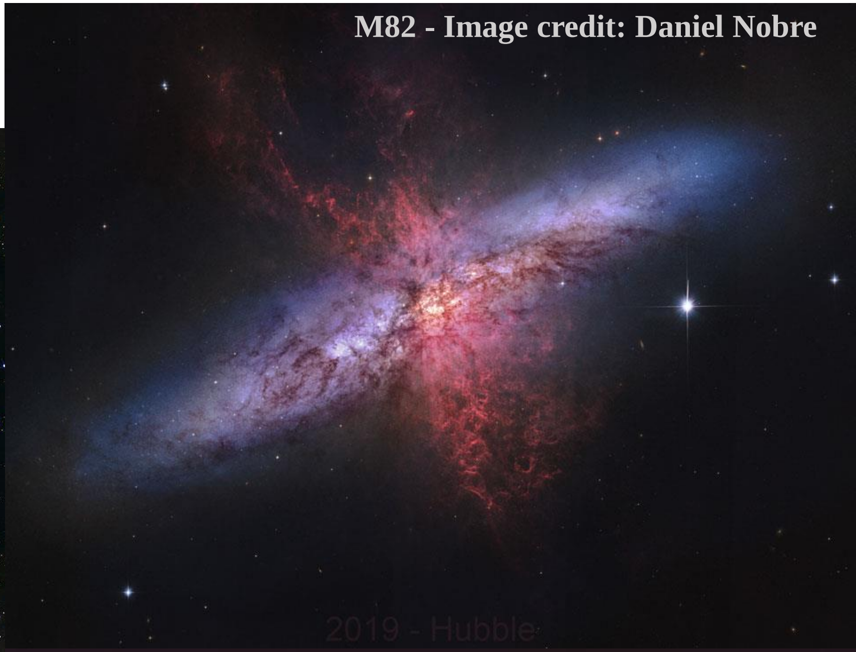

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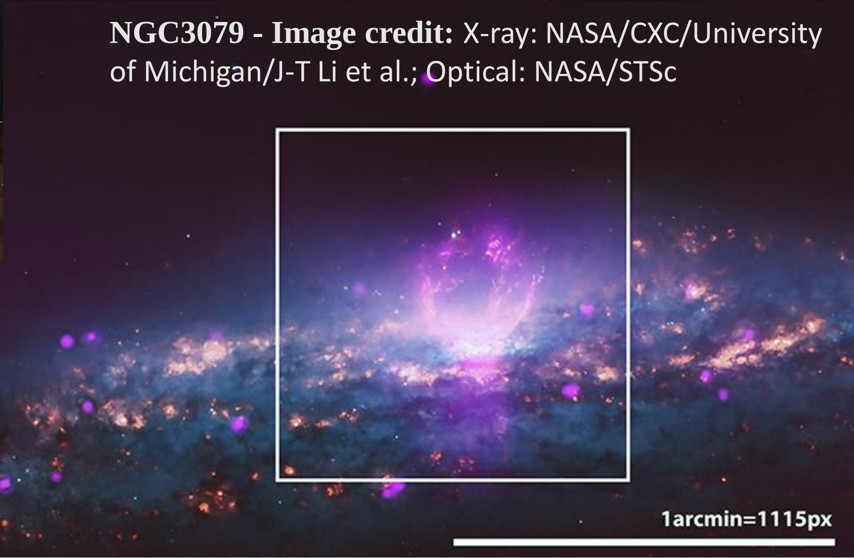

NGC3079 - Image credit: X-ray: NASA/CXC/University of Michigan/J-T Li et al.; Optical: NASA/STSc

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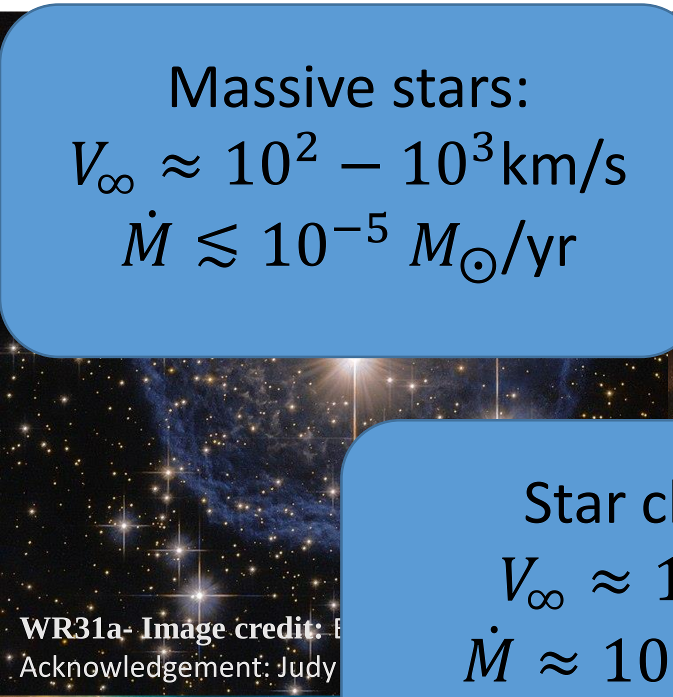

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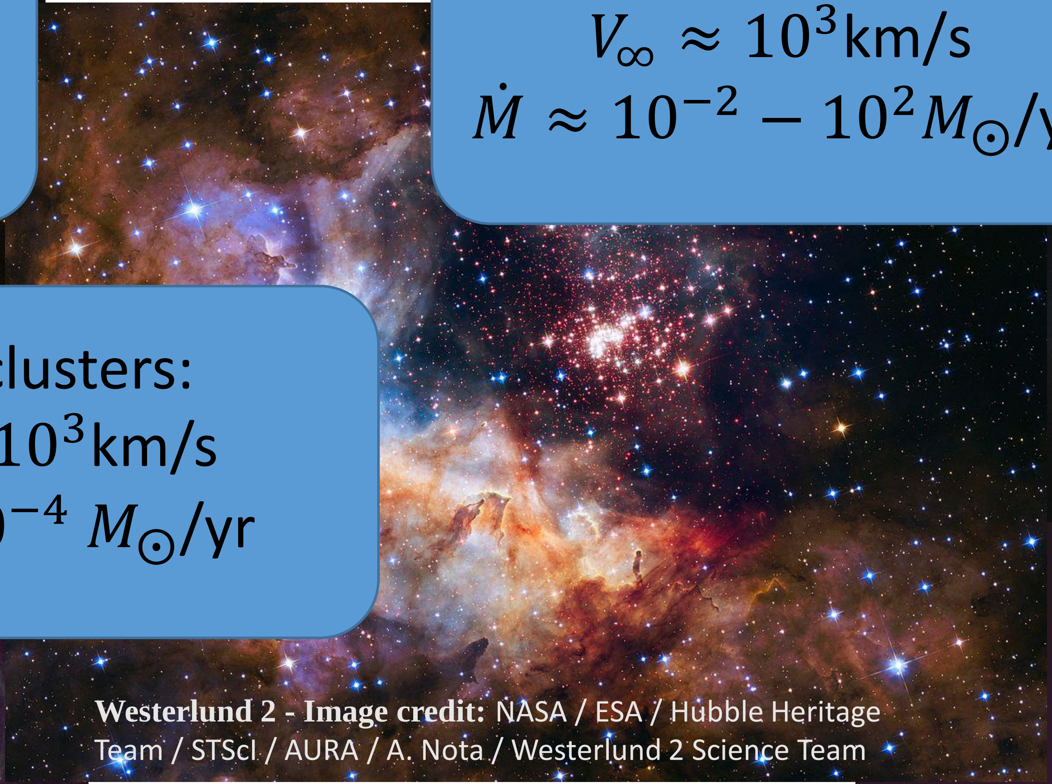

Westerlund 2 - Image credit: NASA / ESA / Hubble Heritage Team / STScI / AURA / A. Nota / Westerlund 2 Science Team

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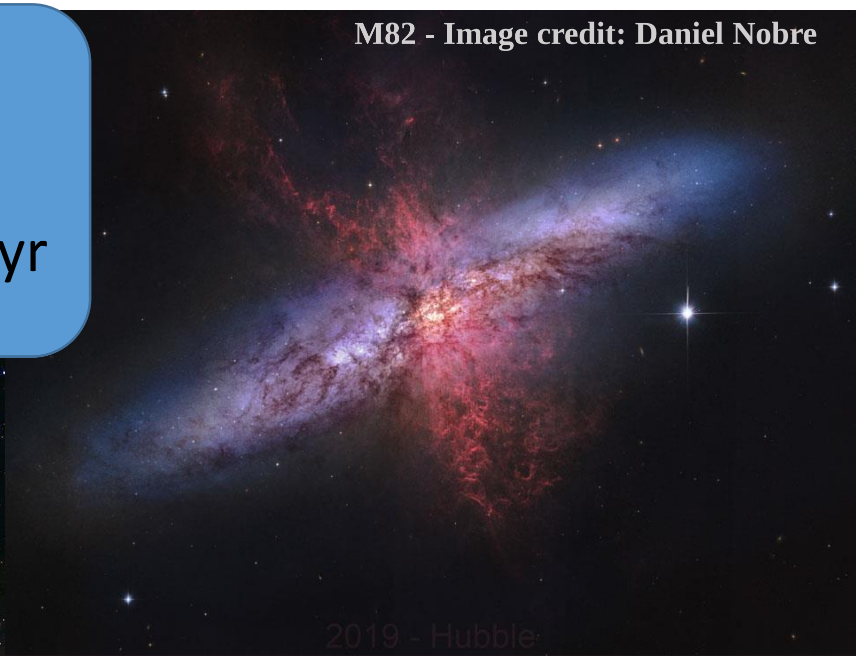
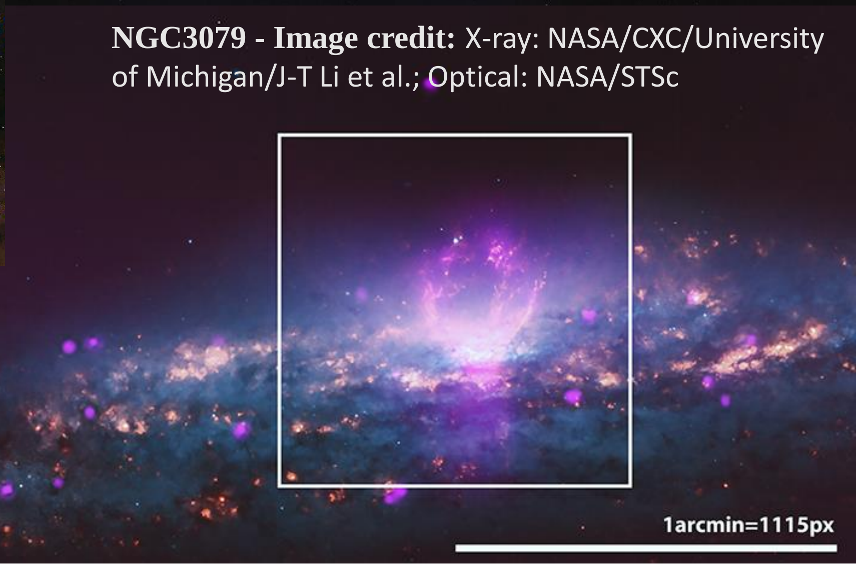


M82 - Image credit: Daniel Nobre

Starbursts:
$V_\infty \approx 10^3 \text{km/s}$
$\dot{M} \approx 10^{-2} - 10^2 M_\odot/\text{yr}$

NGC7635- Image credit: NASA Goddard Space Flight Center from Greenbelt, MD, USA



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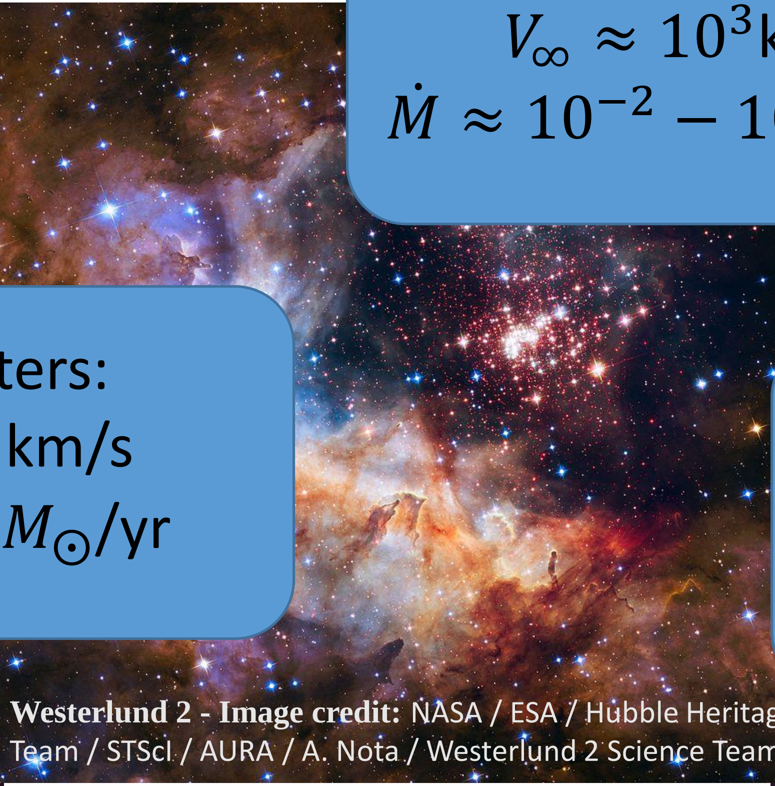

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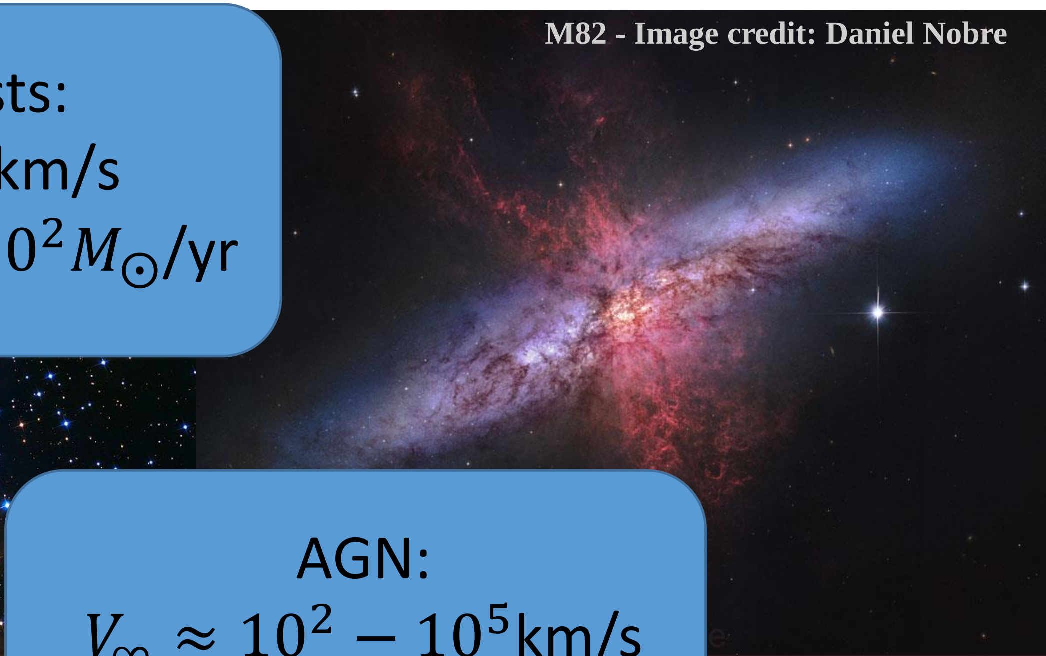

M82 - Image credit: Daniel Nobre

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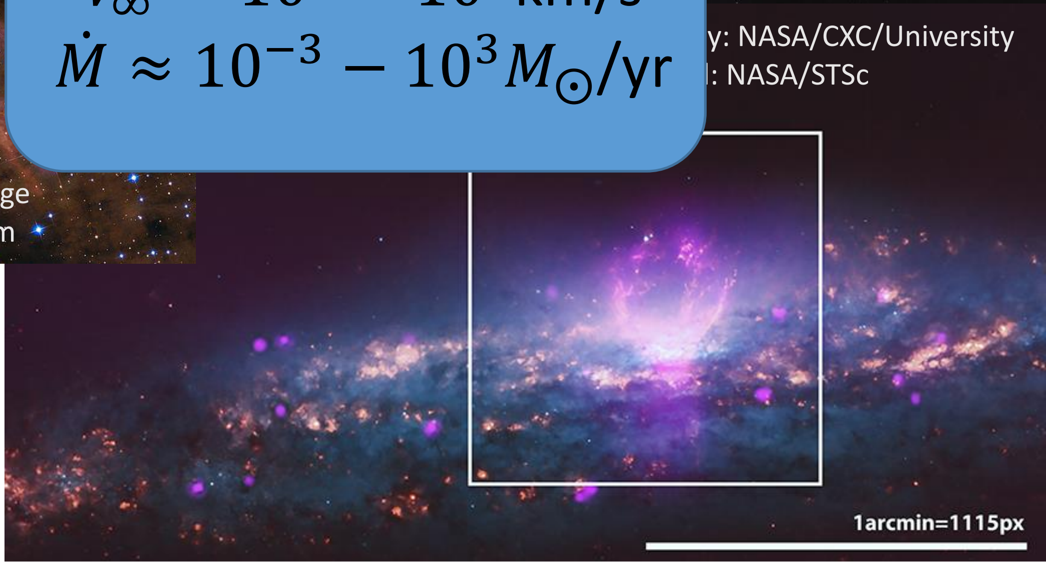

y: NASA/CXC/University
l: NASA/STSc

Maximum Energy: a first guess

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

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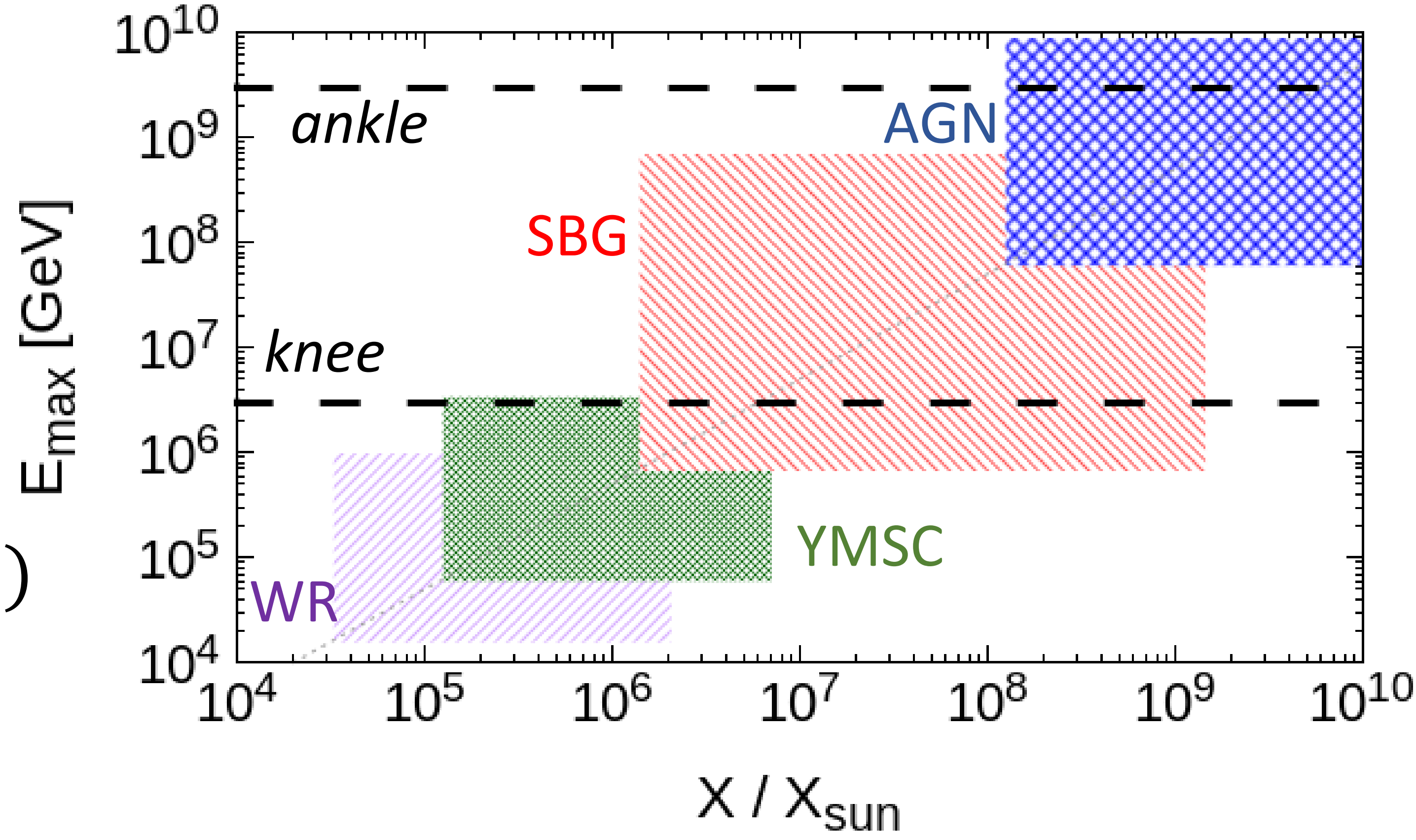
$$X = \dot{E}\dot{P}^{-1/2}$$



Diverging flows as cosmic-ray sources

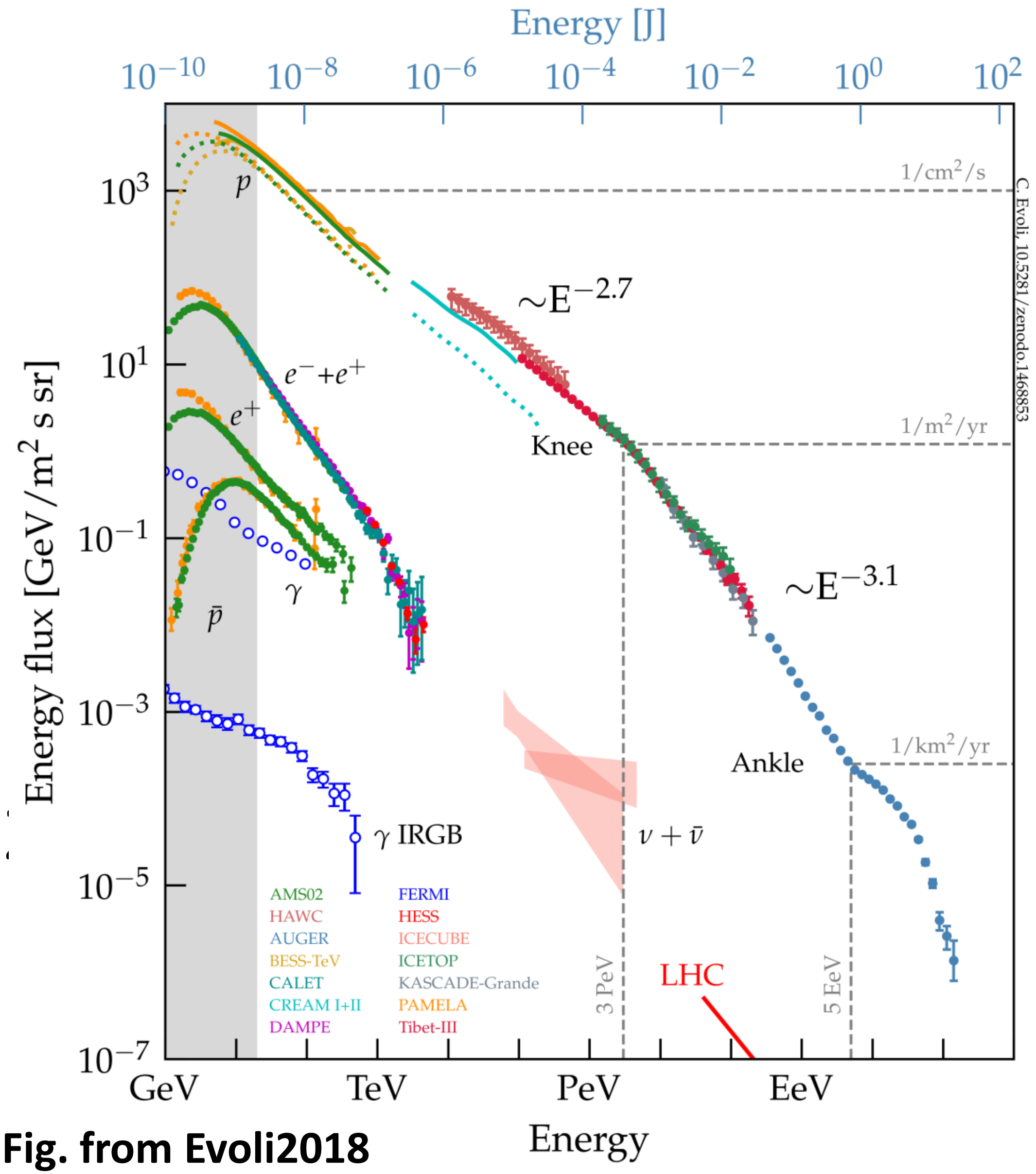
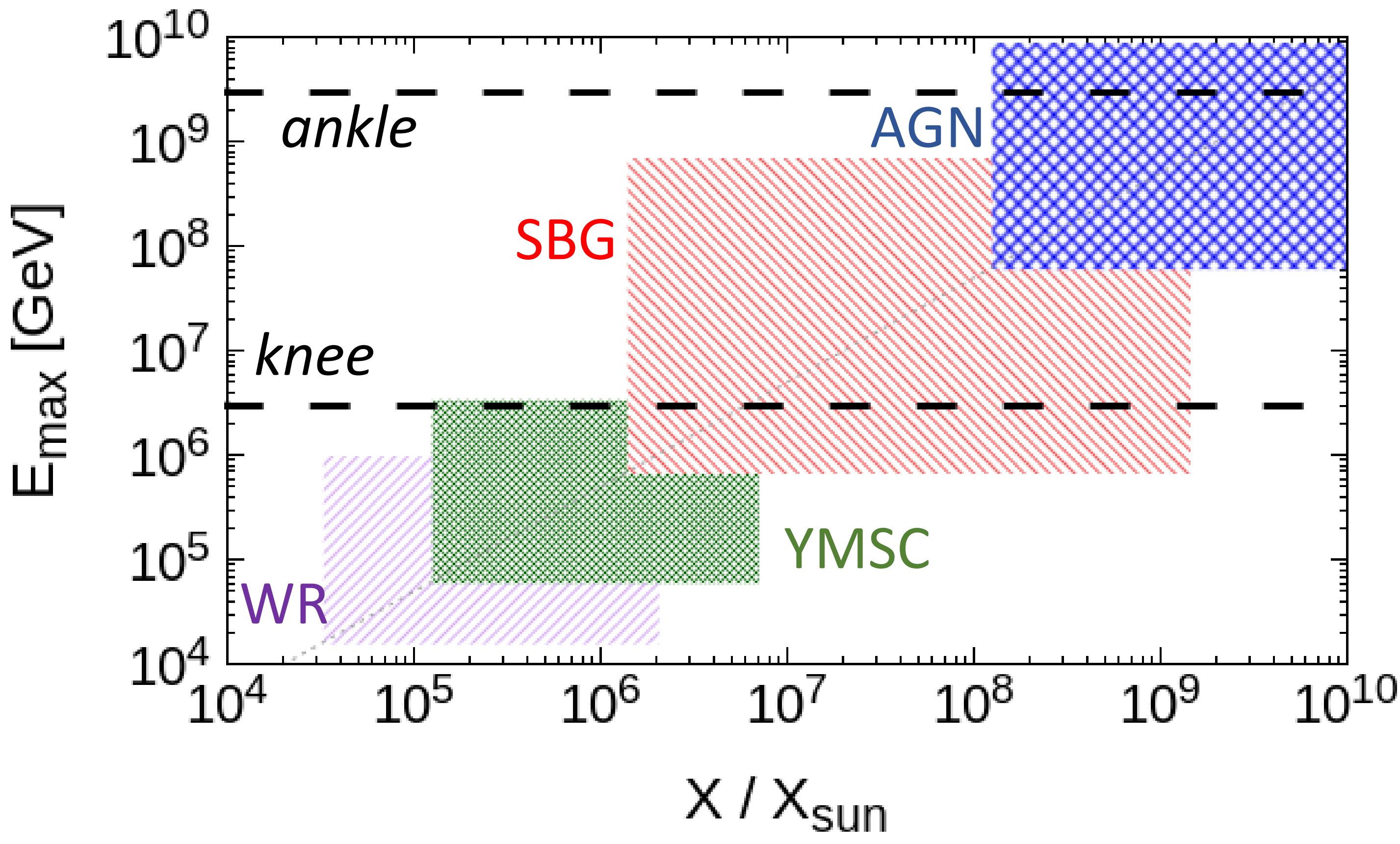


Fig. from Evoli2018



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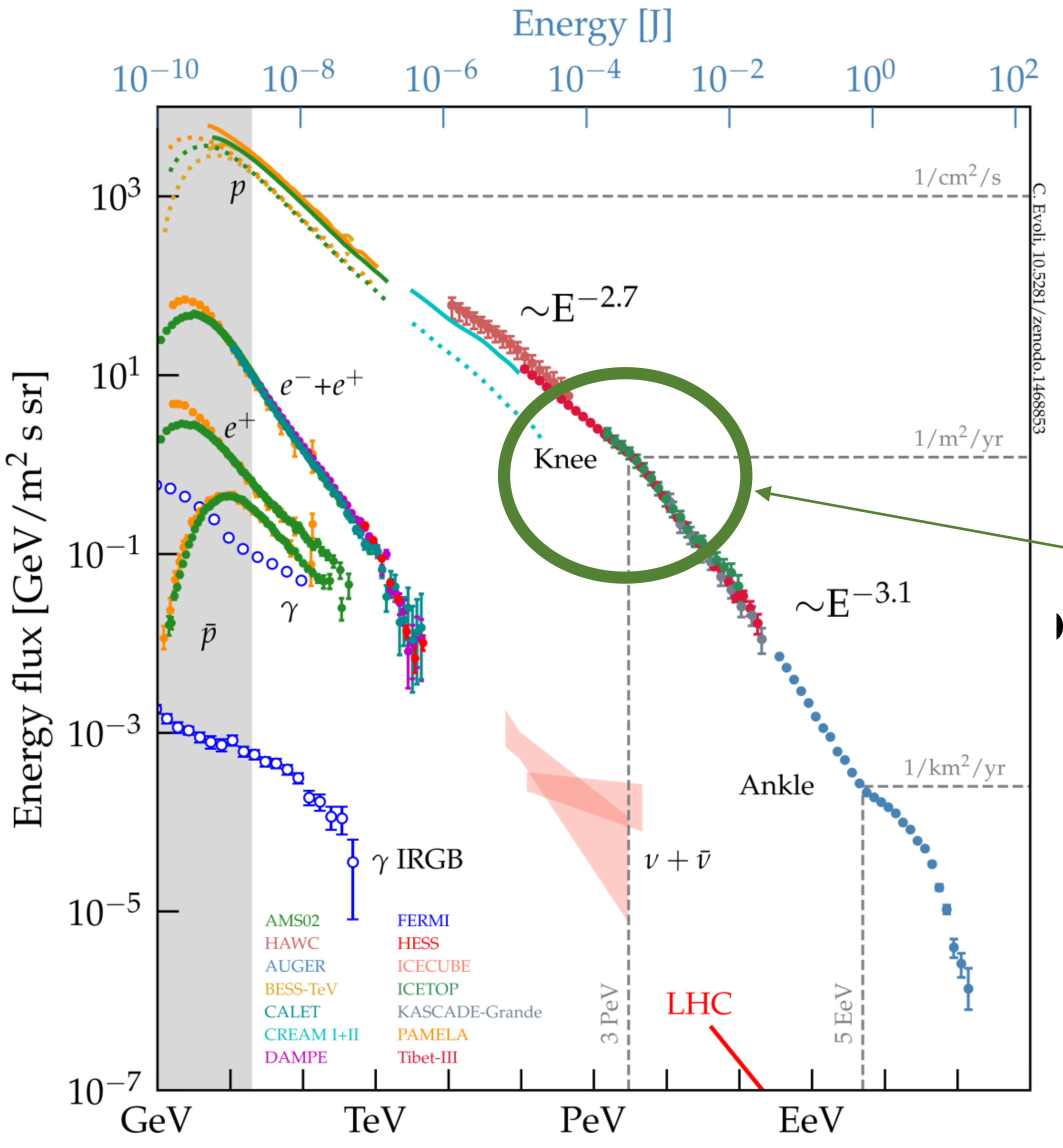

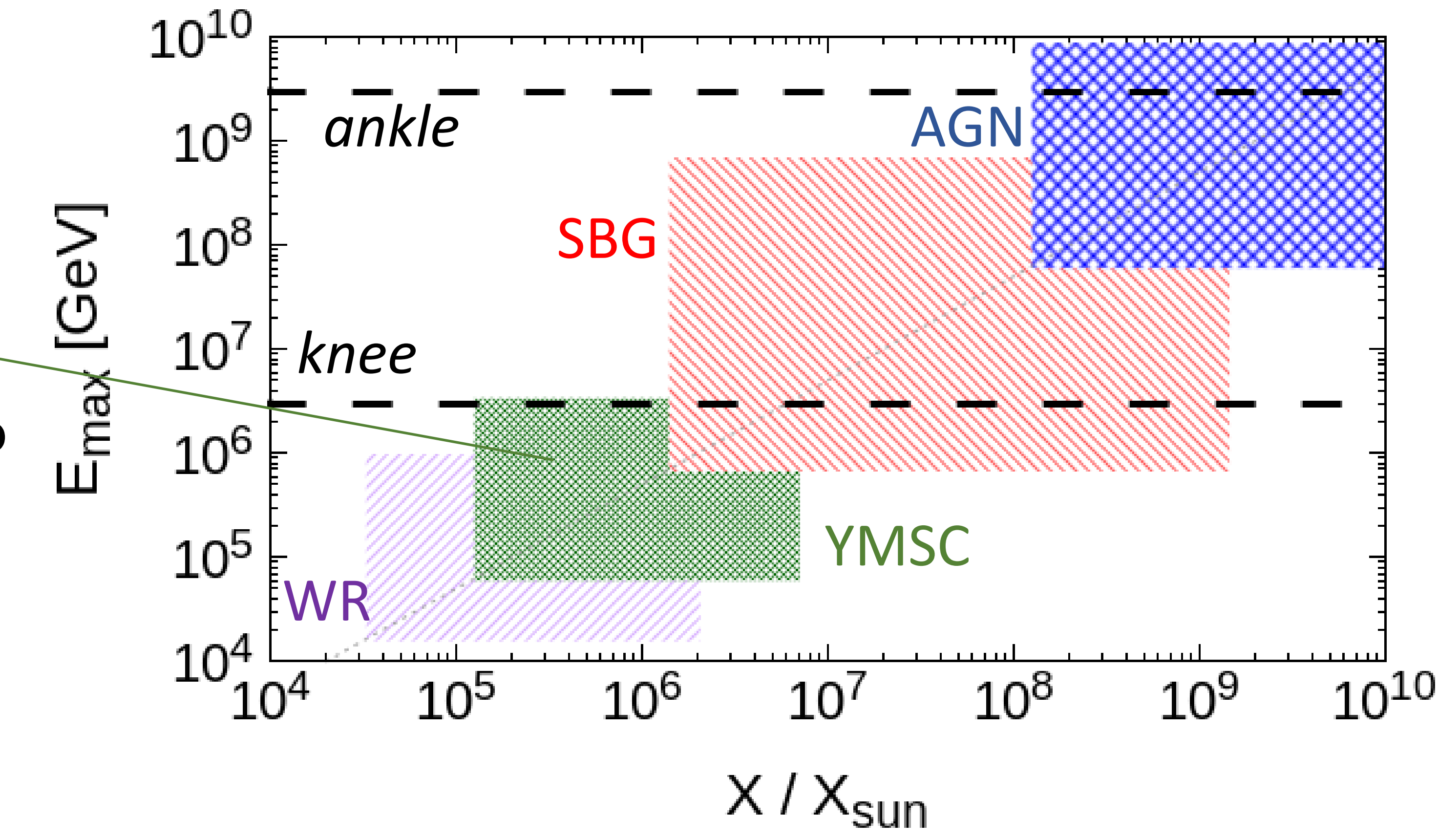

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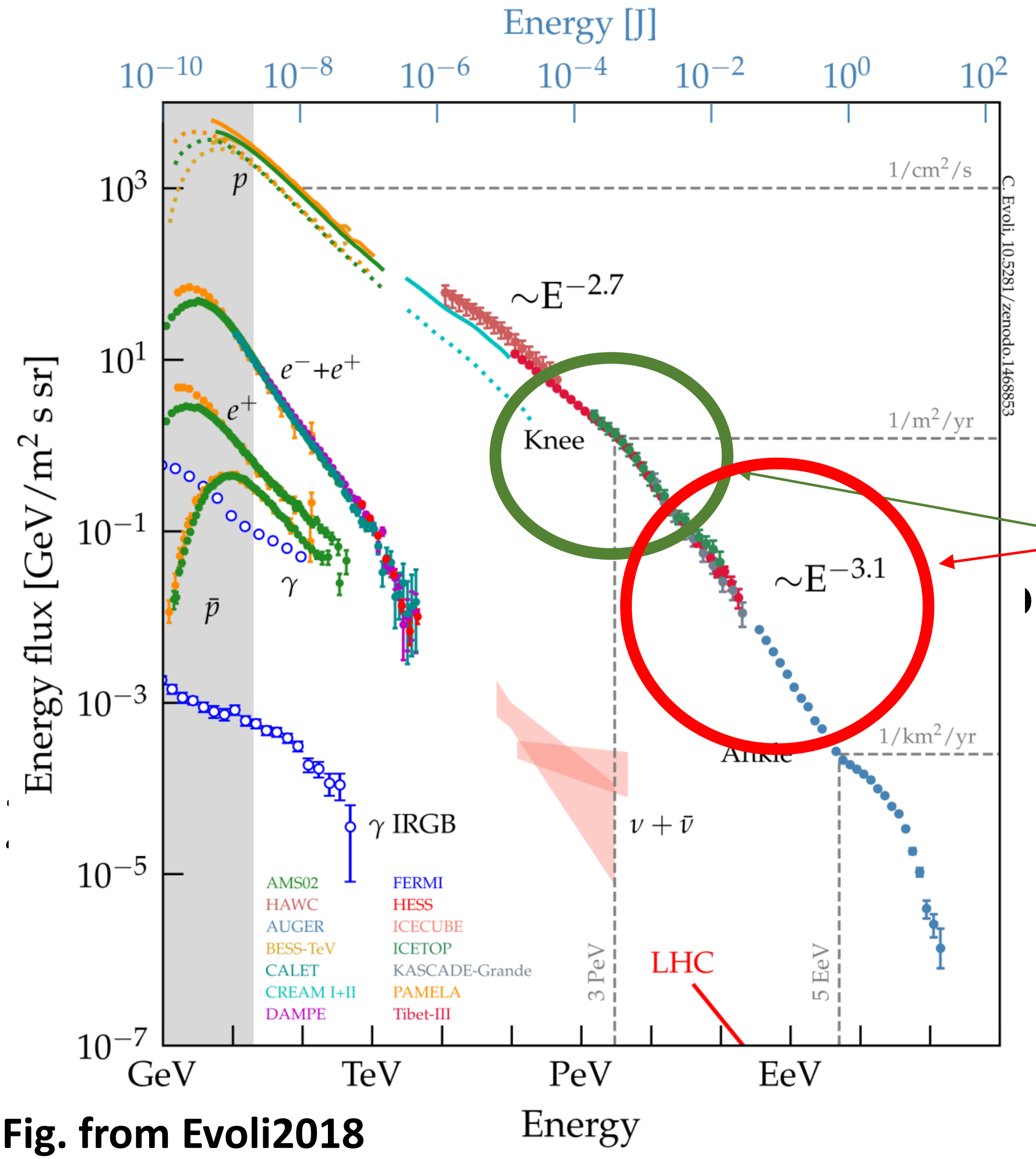
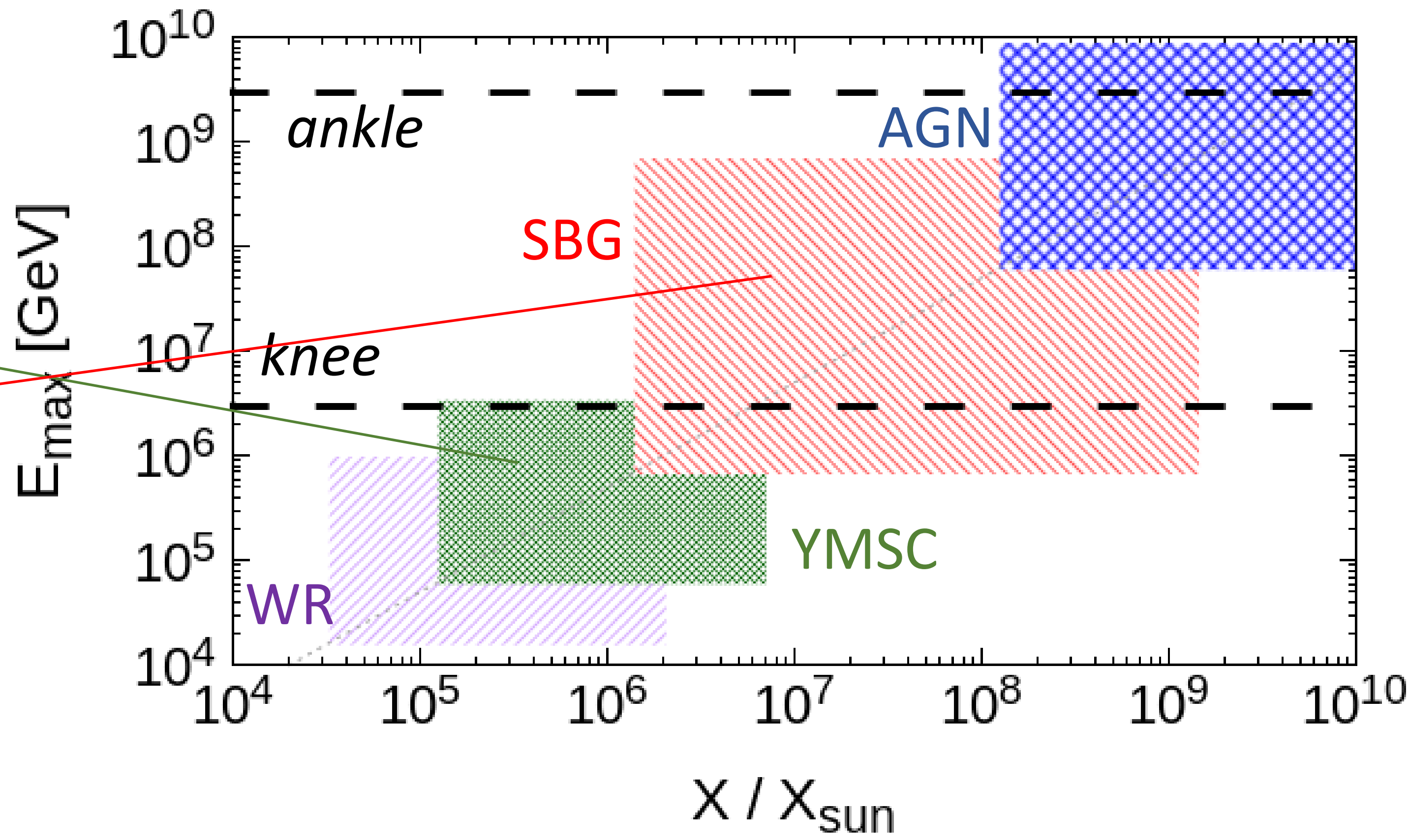


Fig. from Evoli2018



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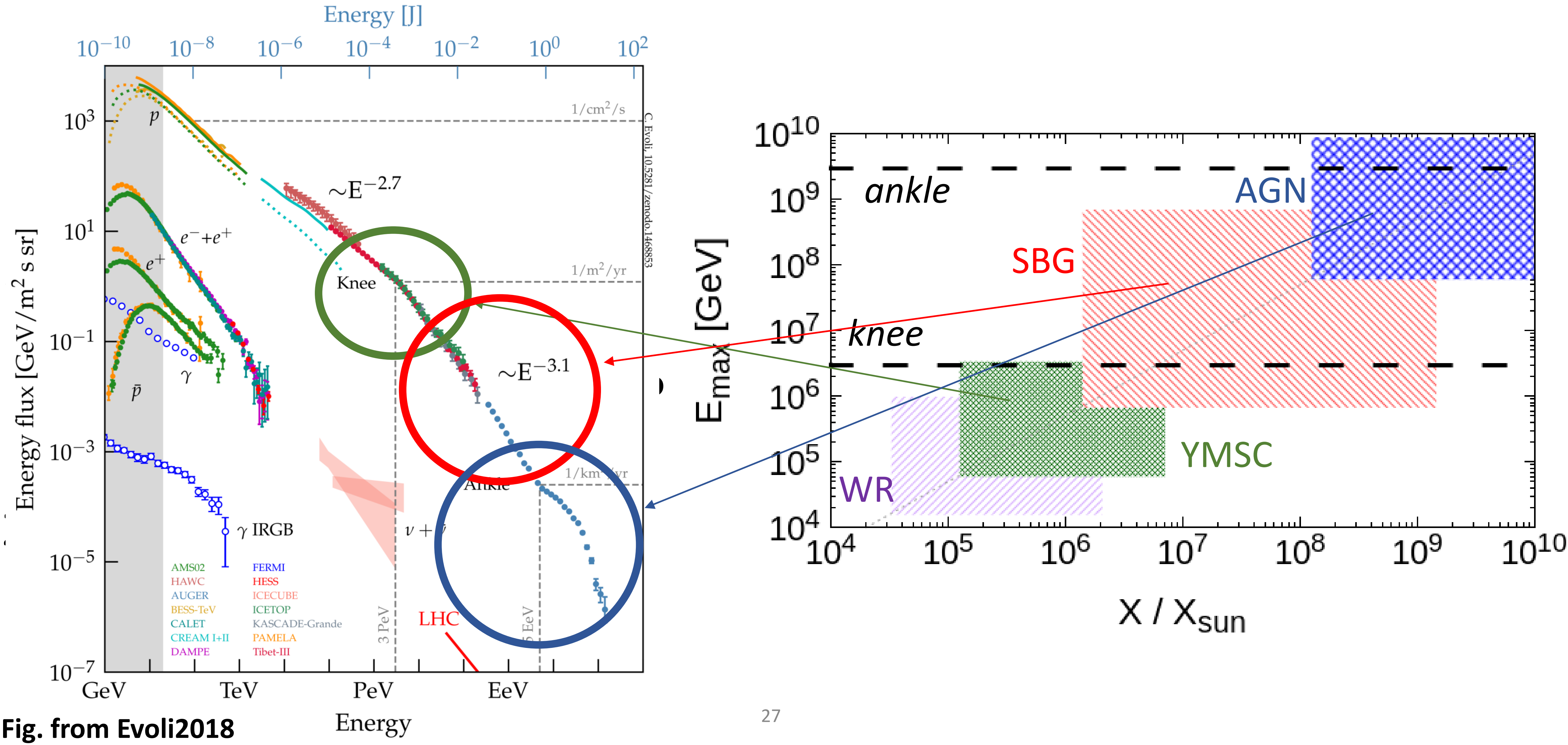
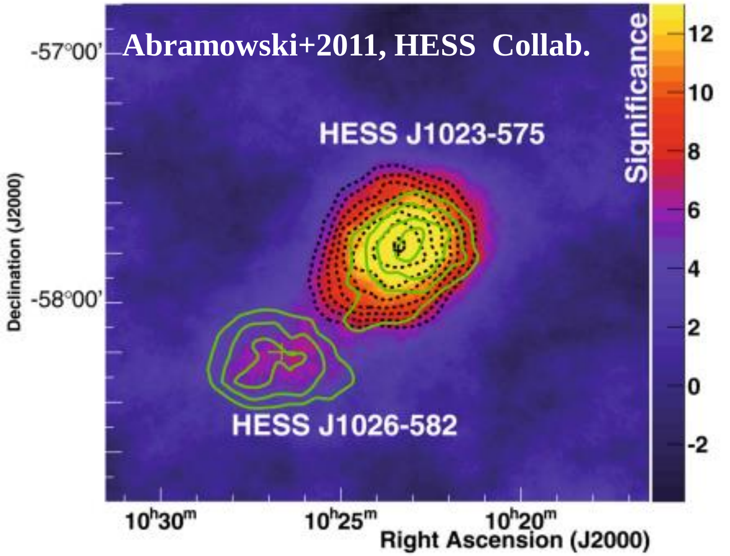
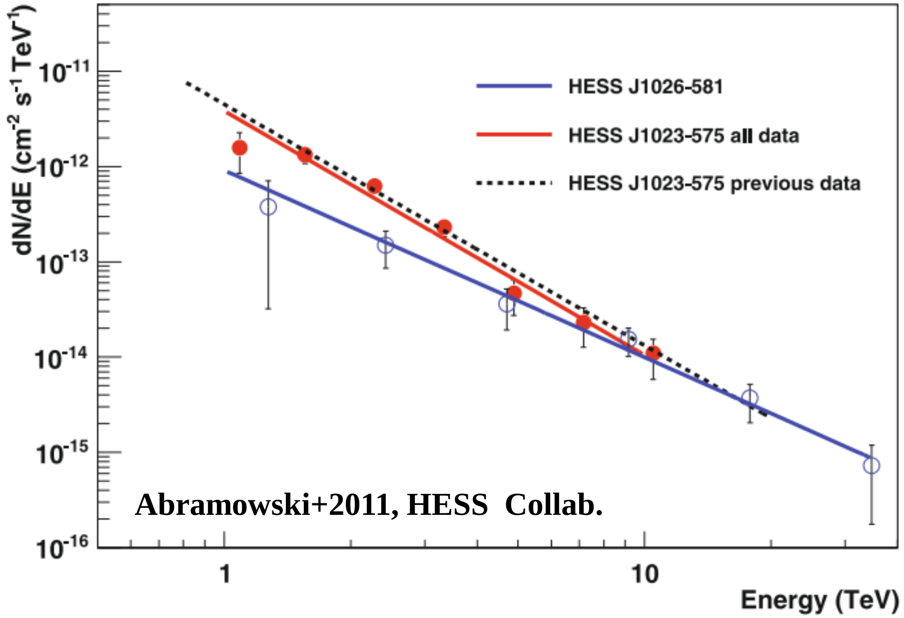


Fig. from Evoli2018

Young Massive Stellar Cluster

Westerlund 2 - Image credit: NASA / ESA / Hubble Heritage Team / STScI / AURA / A. Nota / Westerlund 2 Science Team





Cassé+1980-1982, Volk+1982, Cesarsky+1983, Webb+1985, Zirakashvili+2017, Aharonian+2019, Morlino+2021, Vieu+2022

Young Massive Star Cluster

Typical properties

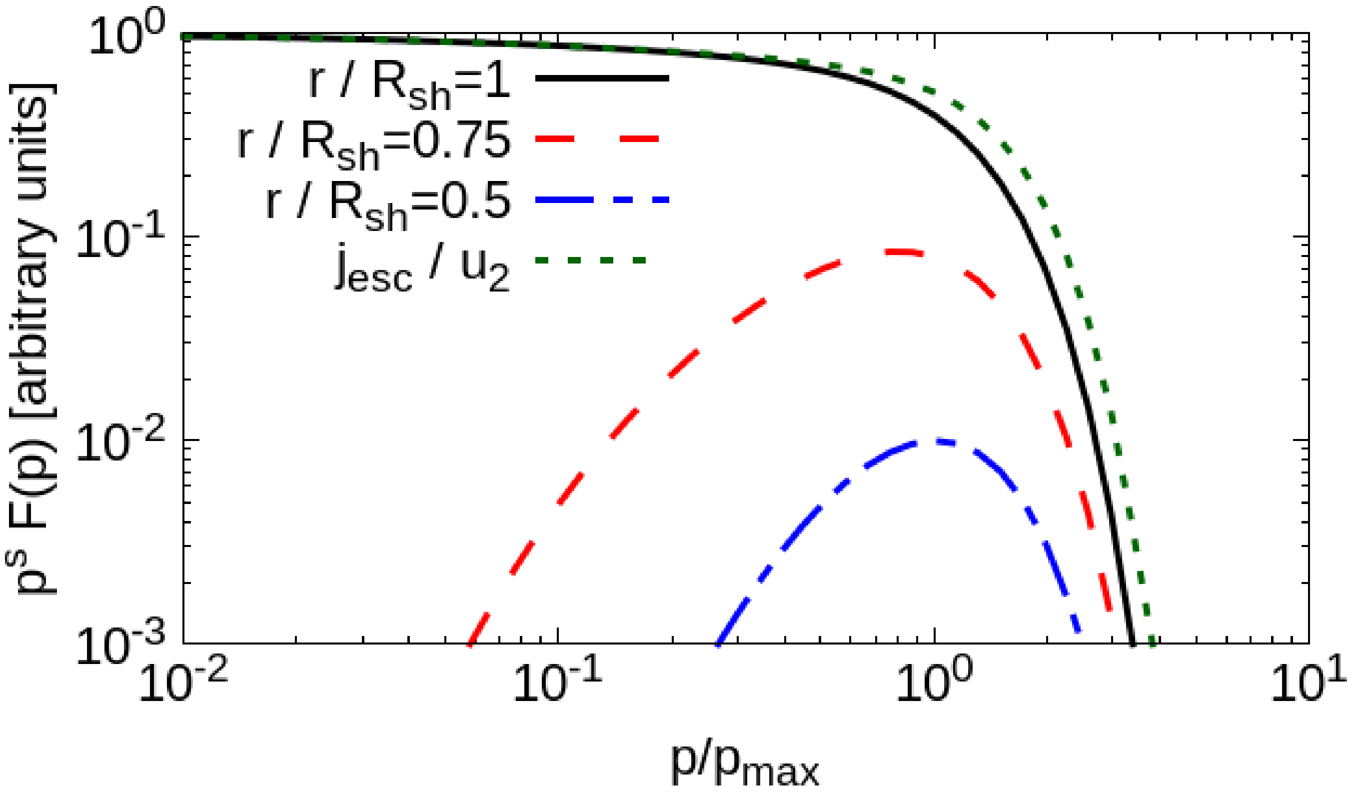
$$\dot{M} \approx 10^{-4}\ M_{\odot}\ yr^{-1}$$

$$V_{\infty} \approx u_1 \approx 10^3\ km\ \ s^{-1}$$

$$R_{sh} \approx 10\ pc$$

$$R_{fs} \approx 50\ pc$$

$$E_{max} \lesssim 3\ PeV$$



Young massive star clusters

Target density

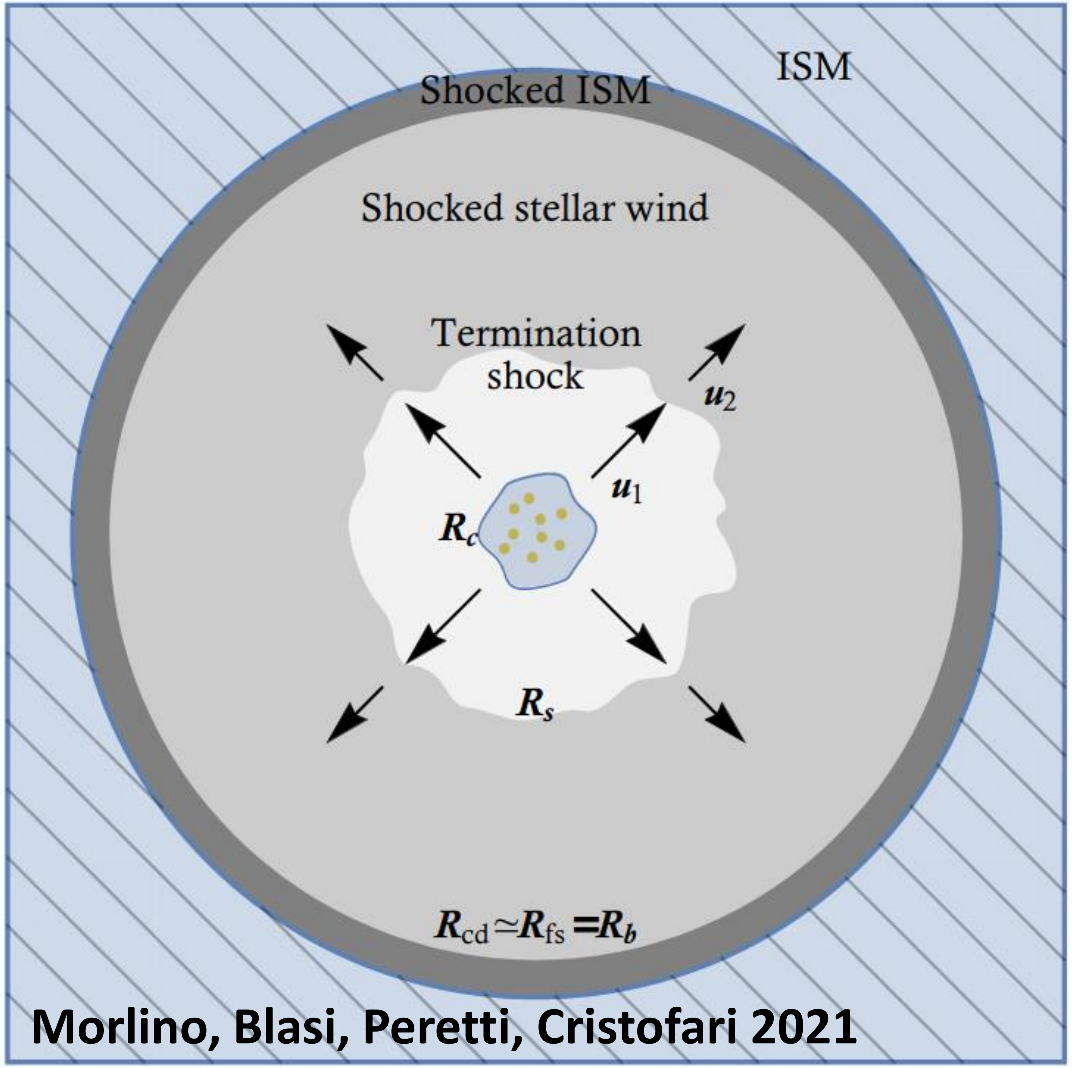
Shocked stellar wind ($R_{sh} - R_{cd}$):

$$n_{sw} = \rho \frac{\dot{M}}{4\pi R_{sh}^2 u_1 m_p} \approx 10^{-2} - 10^{-3}\ cm^{-3}$$

Shocked ambient medium ($R_{cd} - R_{fs}$):

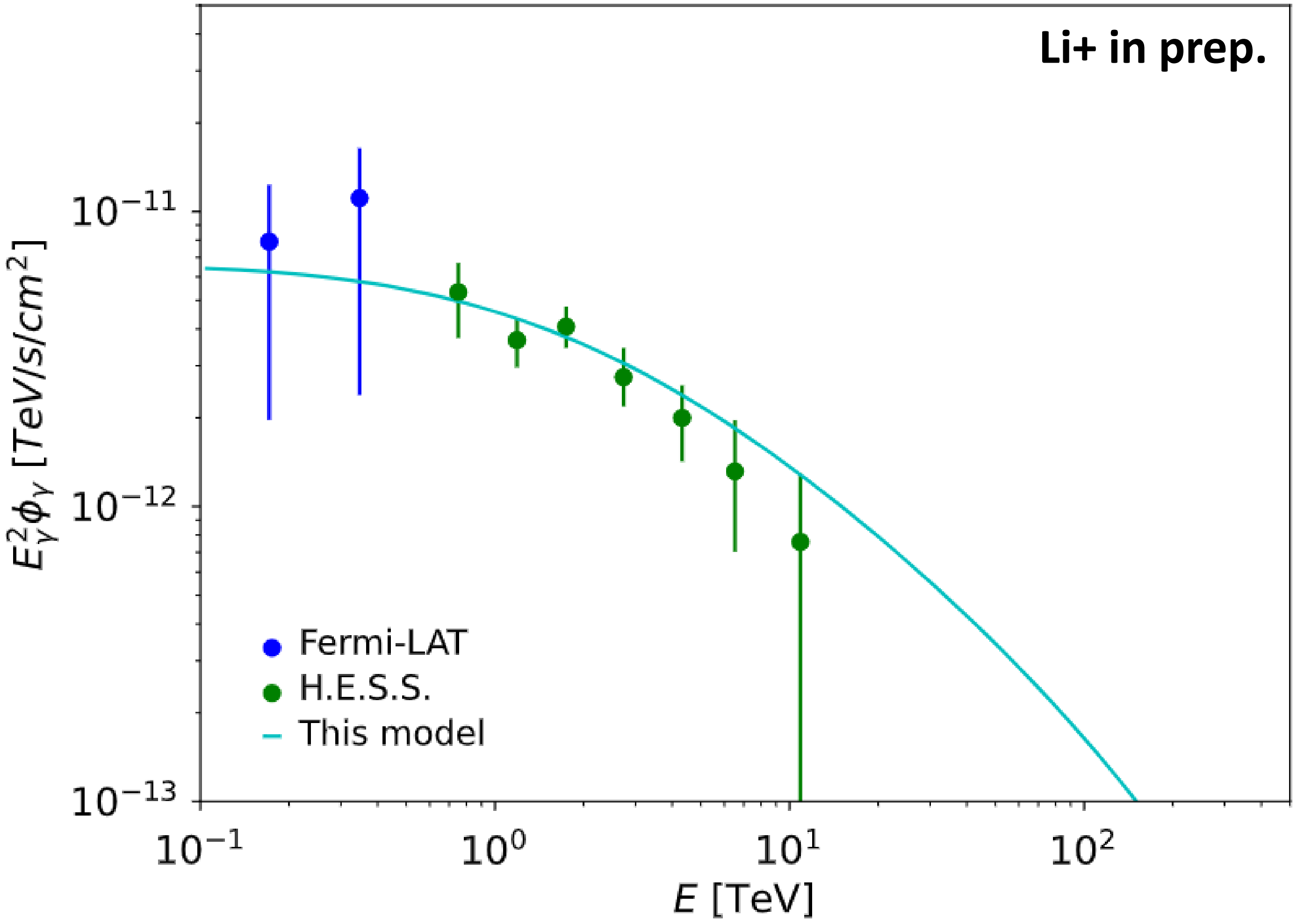
$$n_{SAM} = \rho n_0 \approx 1 - 10^2\ cm^{-3}$$

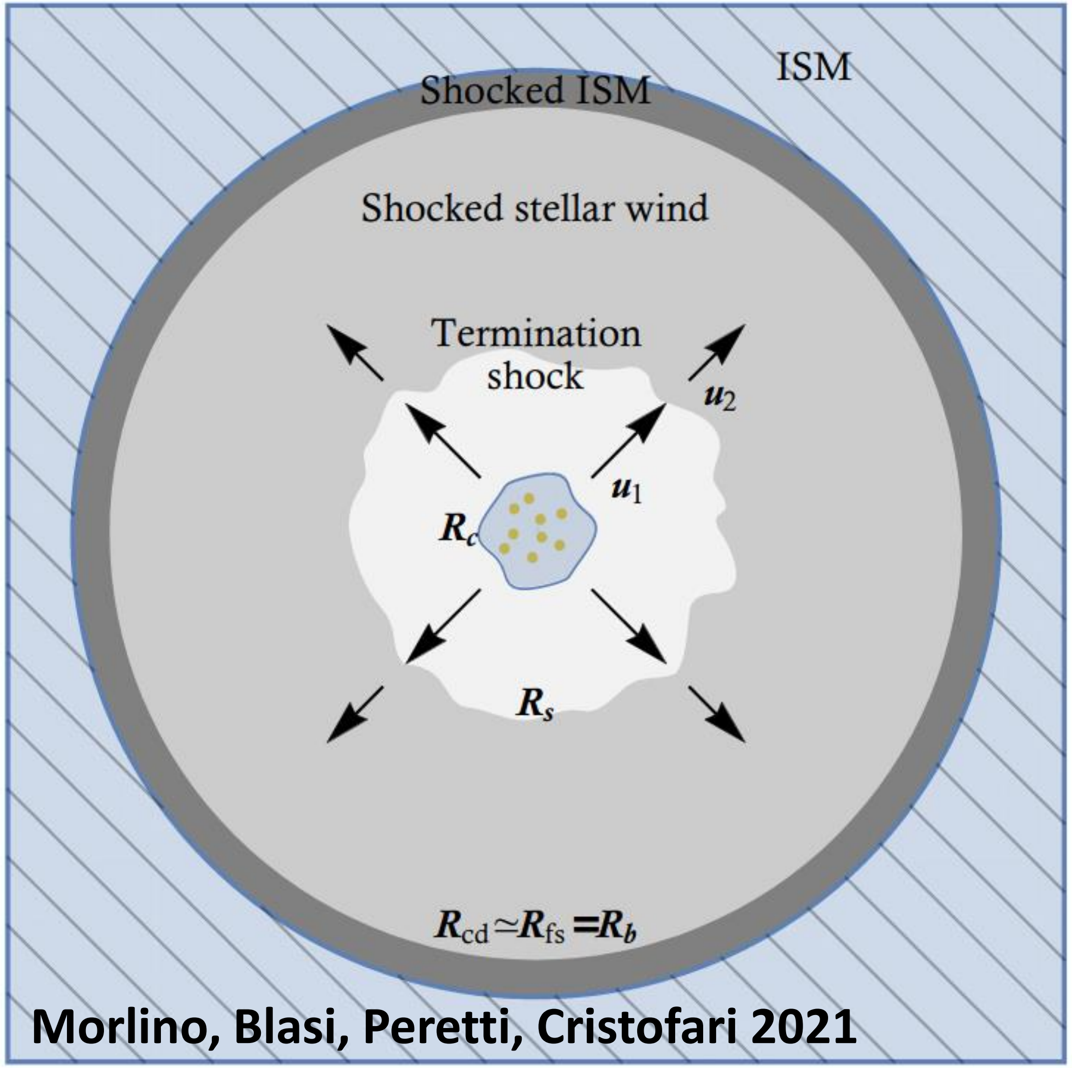
$$V_{SAM}/V_{sw} \approx 0.38$$



Morlino, Blasi, Peretti, Cristofari 2021

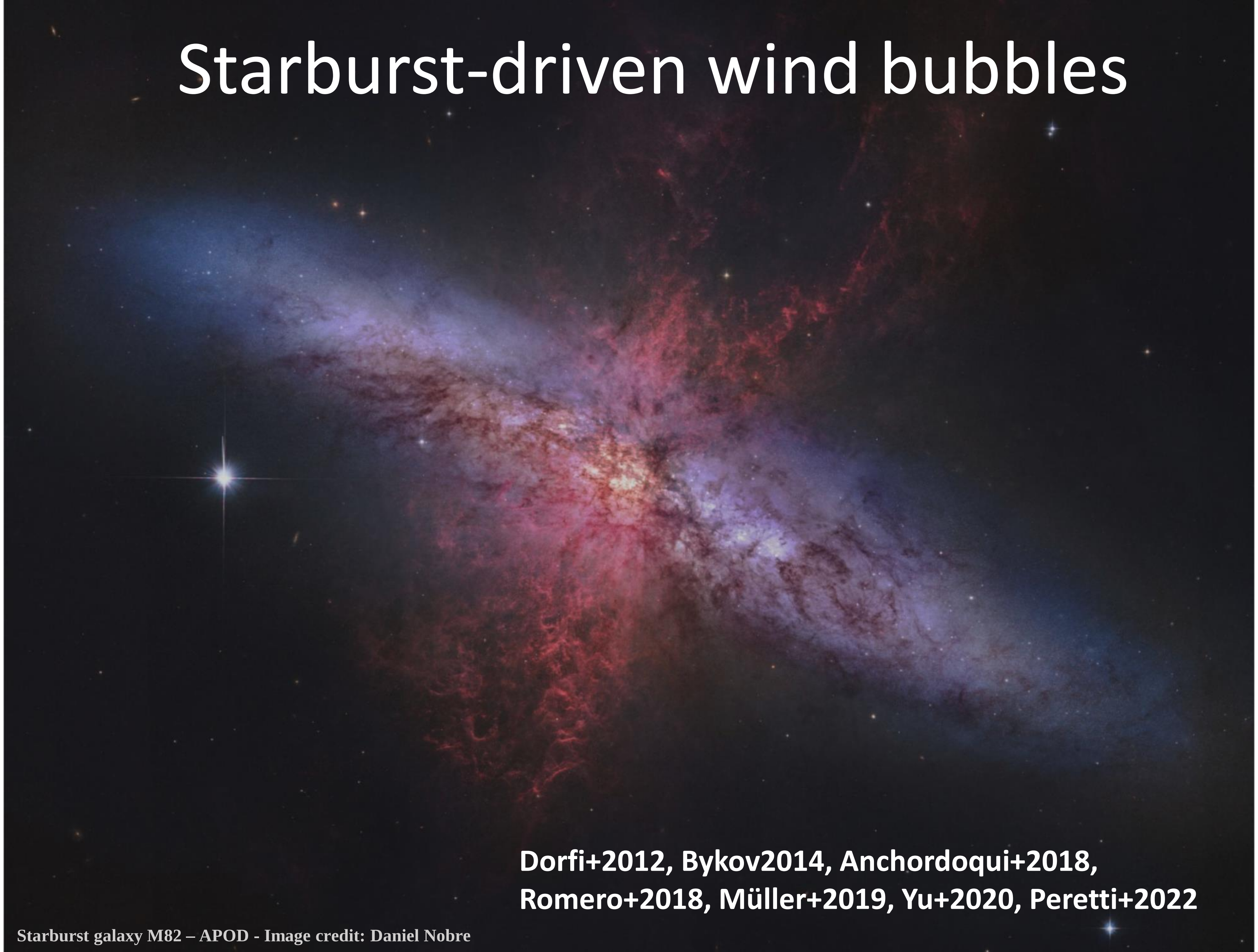
Hadronic emission from star clusters





Morlino, Blasi, Peretti, Cristofari 2021

Starburst-driven wind bubbles



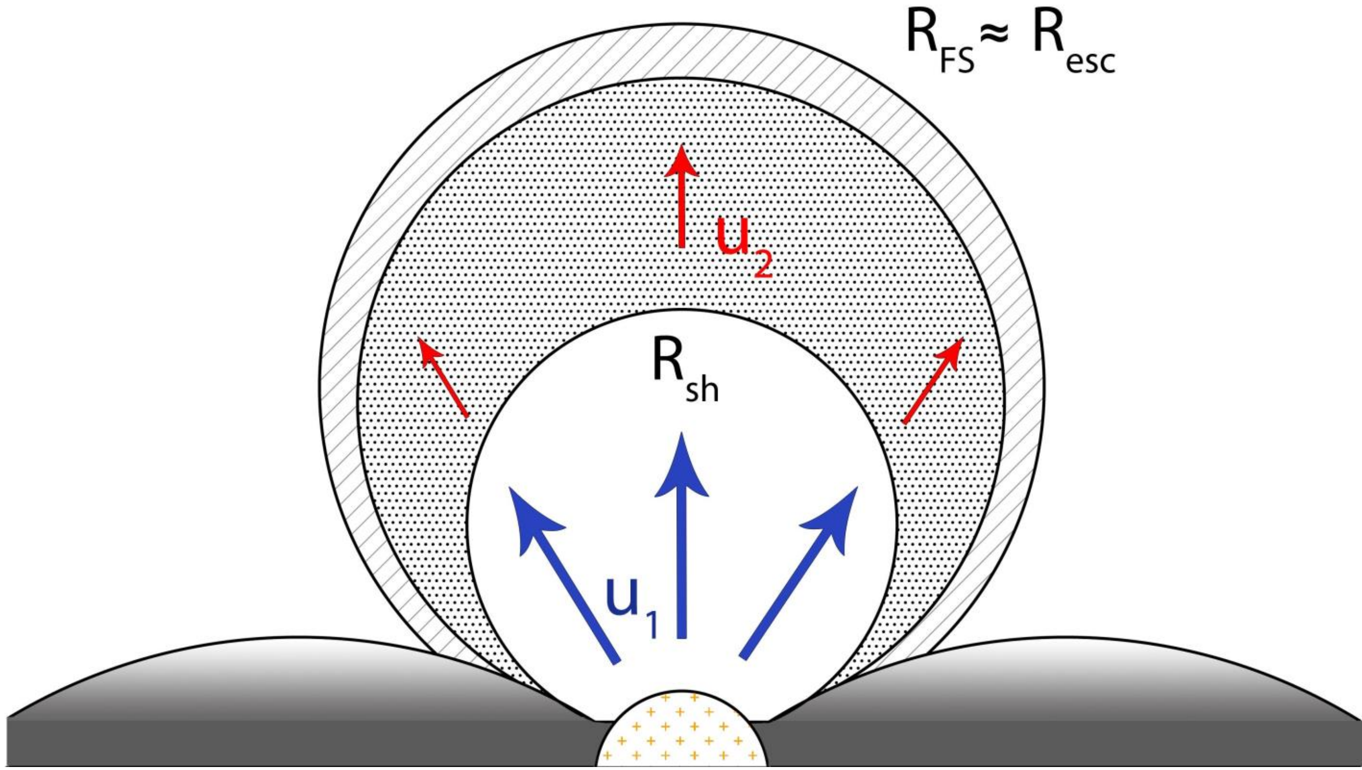
Dorfi+2012, Bykov2014, Anchordoqui+2018, Romero+2018, Müller+2019, Yu+2020, Peretti+2022

Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

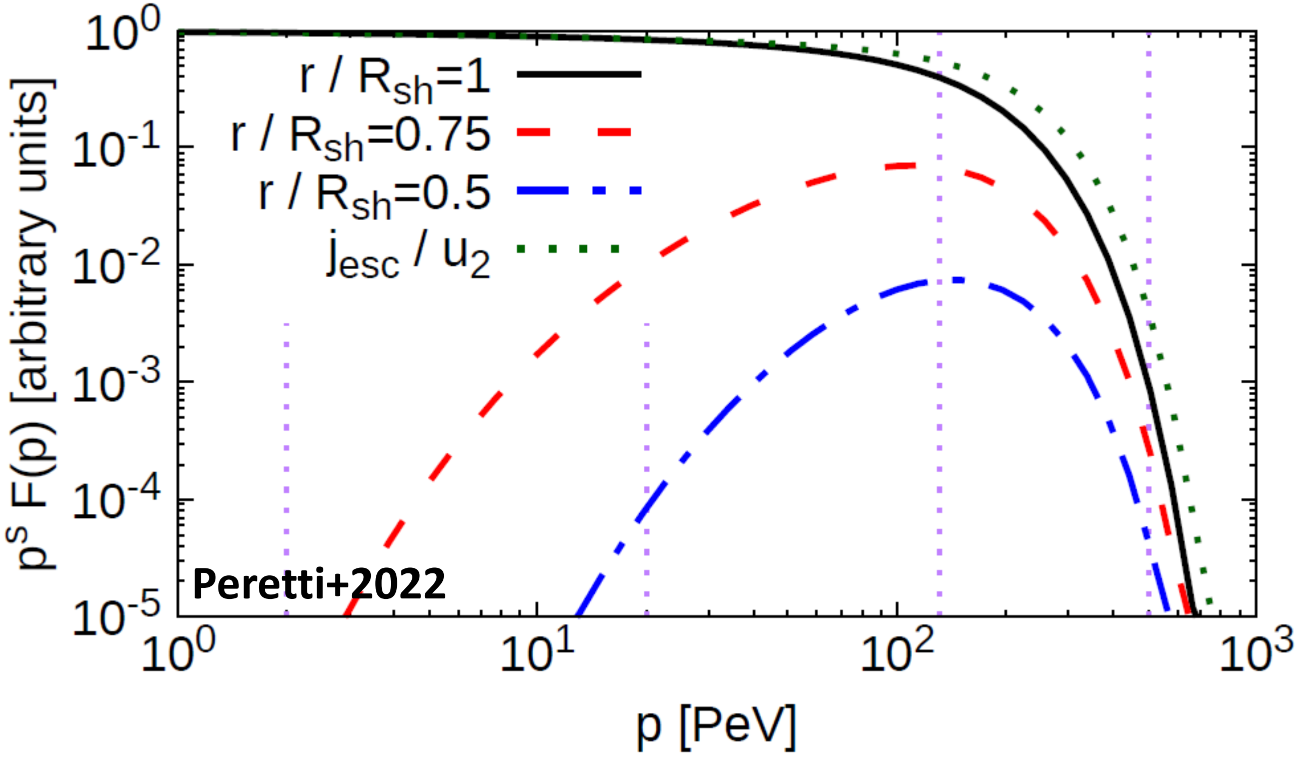
Starburst-driven wind bubbles

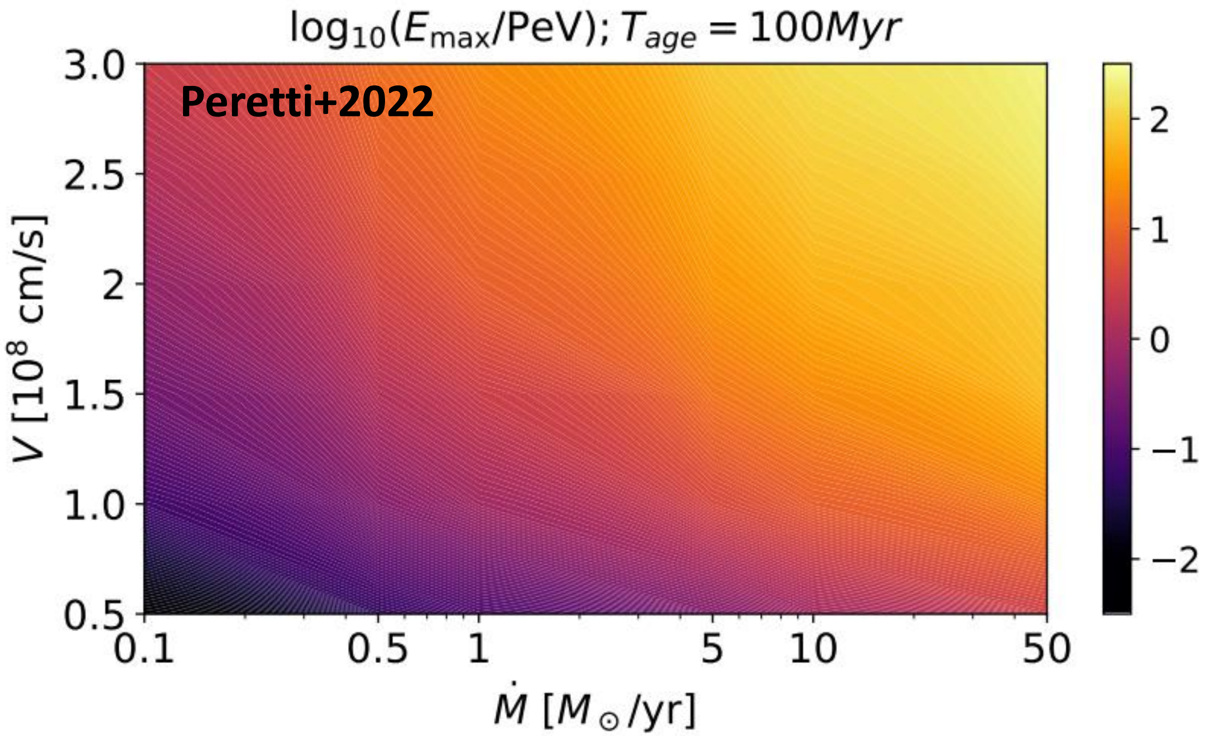
- $V_\infty \approx 10^3\ km/s$
- $\dot{M} \approx 10^{-2} - 10^2\ M_\odot/yr$
- $\dot{E} \approx 10^{39} - 10^{44}$ erg/s

$$\boxed{E_{max} \lesssim 10^2\ PeV}$$

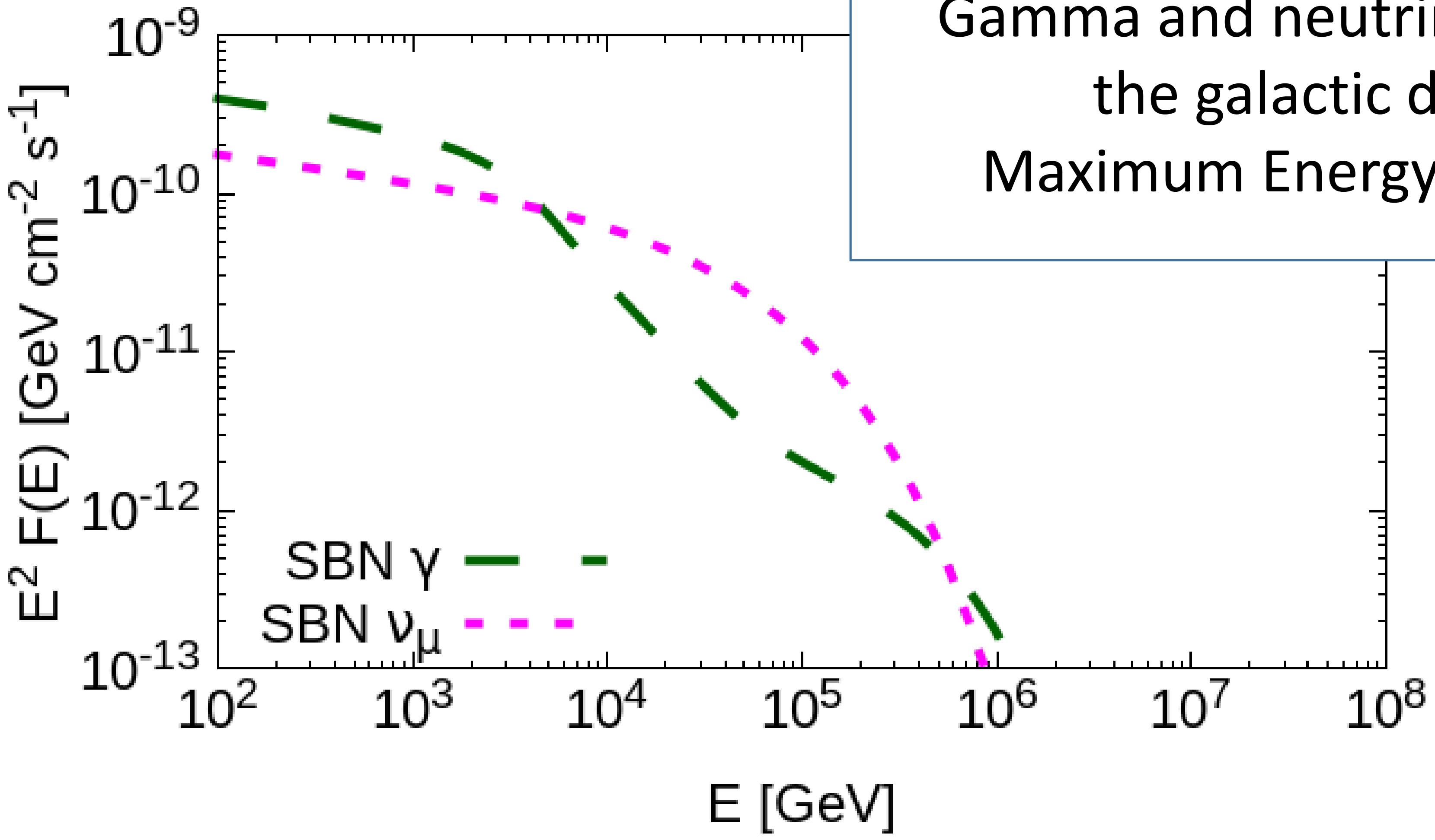


SBGs – Maximum Energy


Peretti+2022


Peretti+2022

SBGs - High-Energy SED and Neutrinos

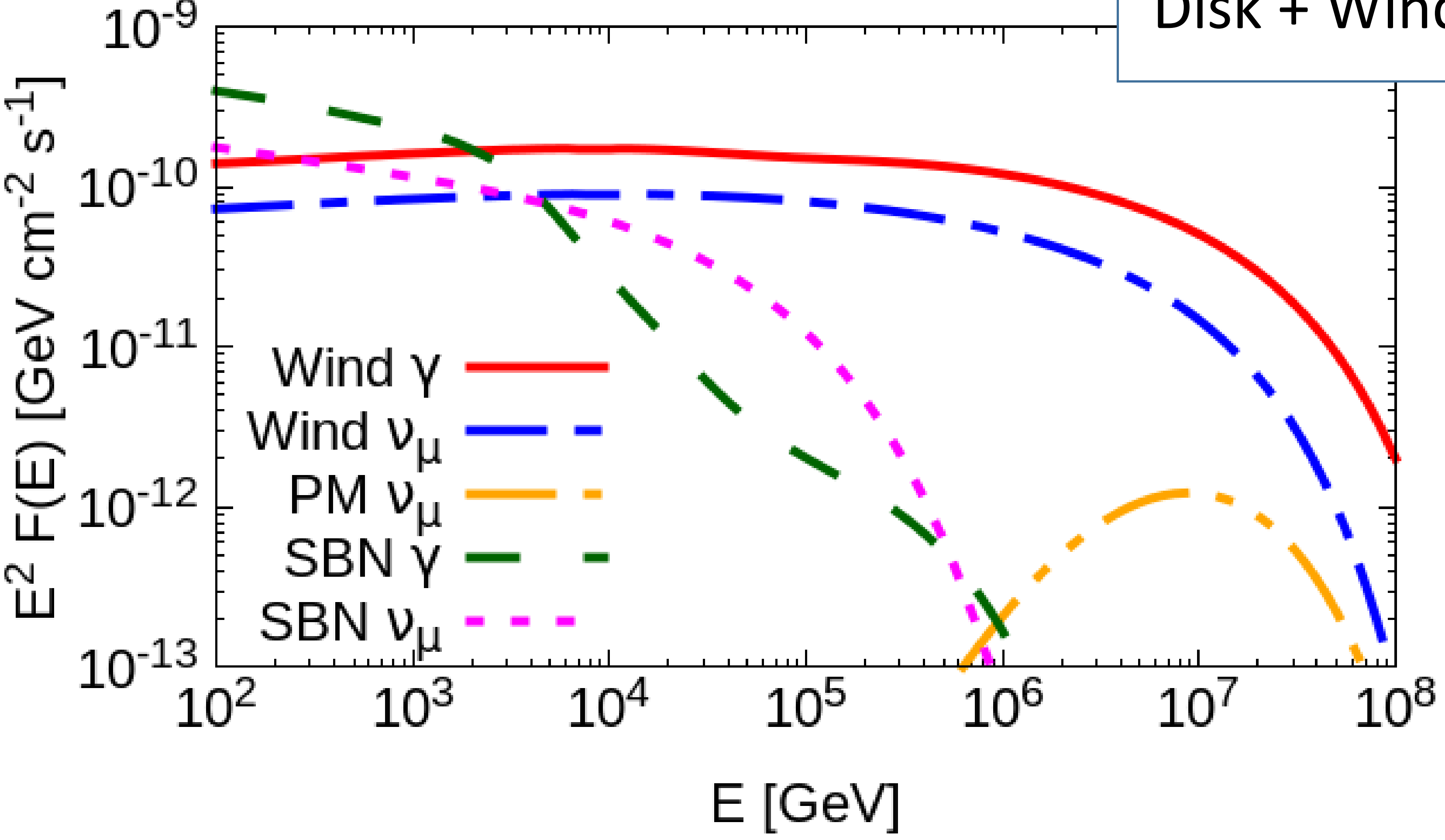


Gamma and neutrinos from the galactic disk

Maximum Energy: 1 PeV

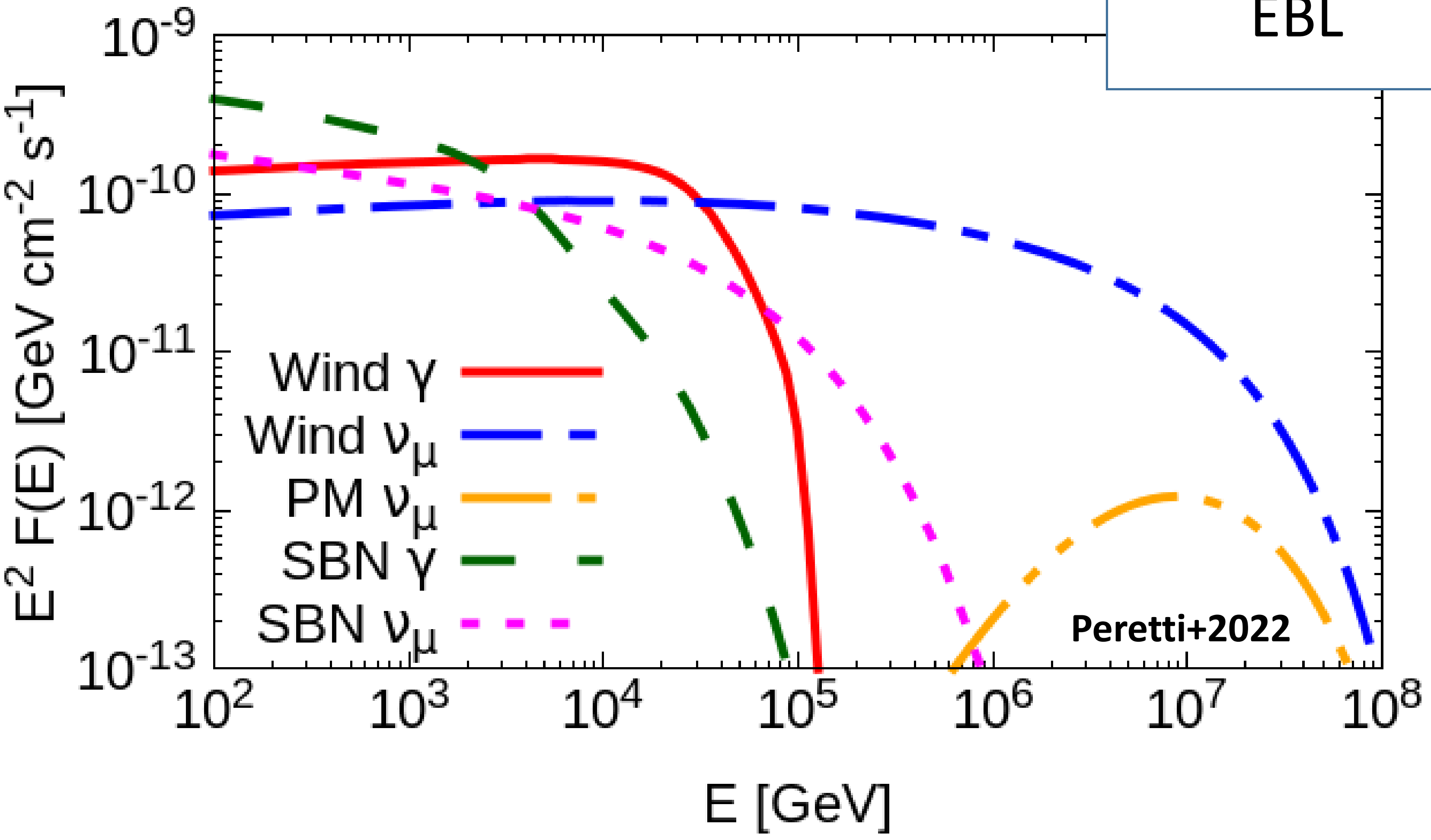
SBGs - High-Energy SED and Neutrinos

Disk + Wind



SBGs - High-Energy SED and Neutrinos

EBL



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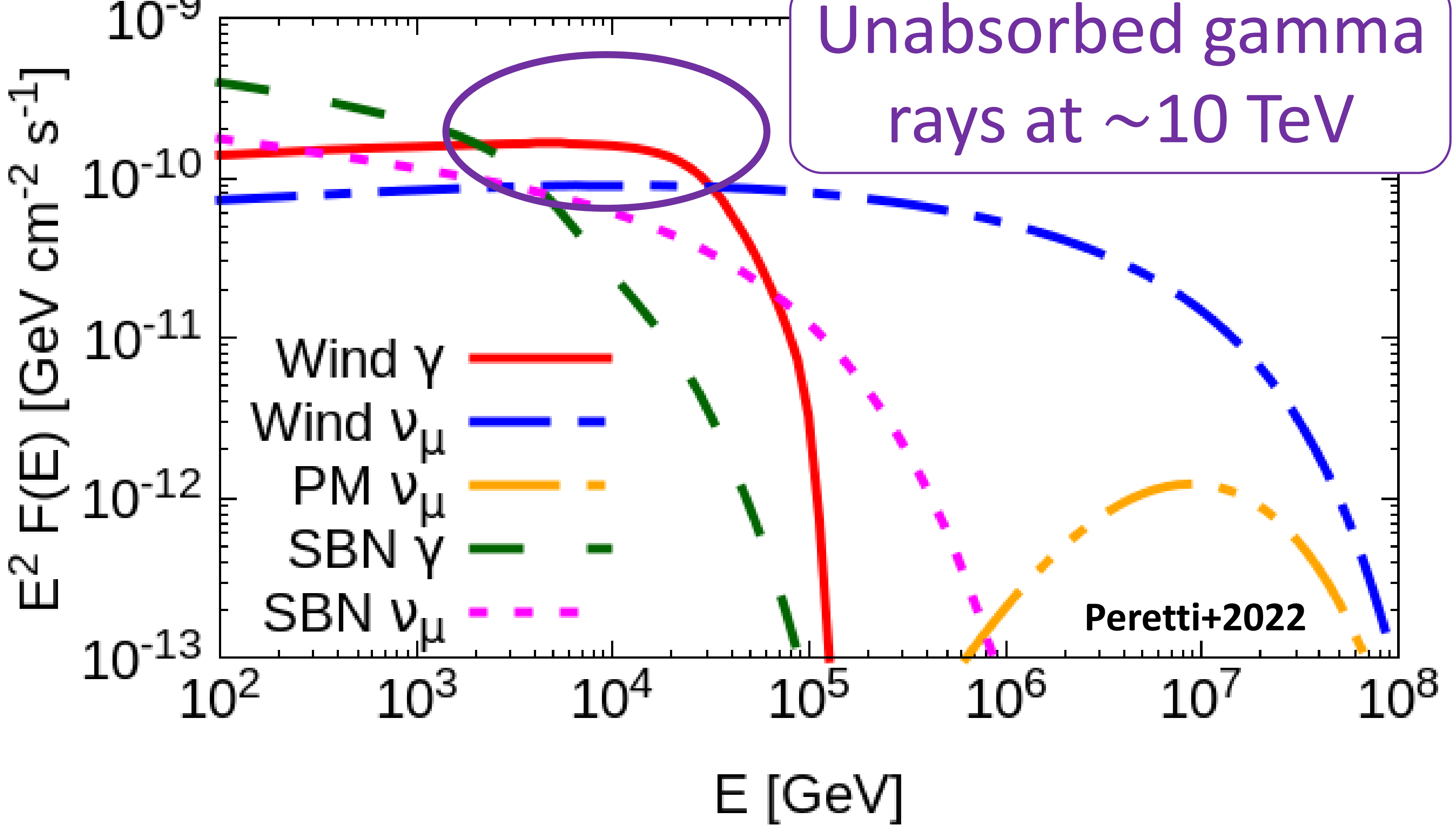
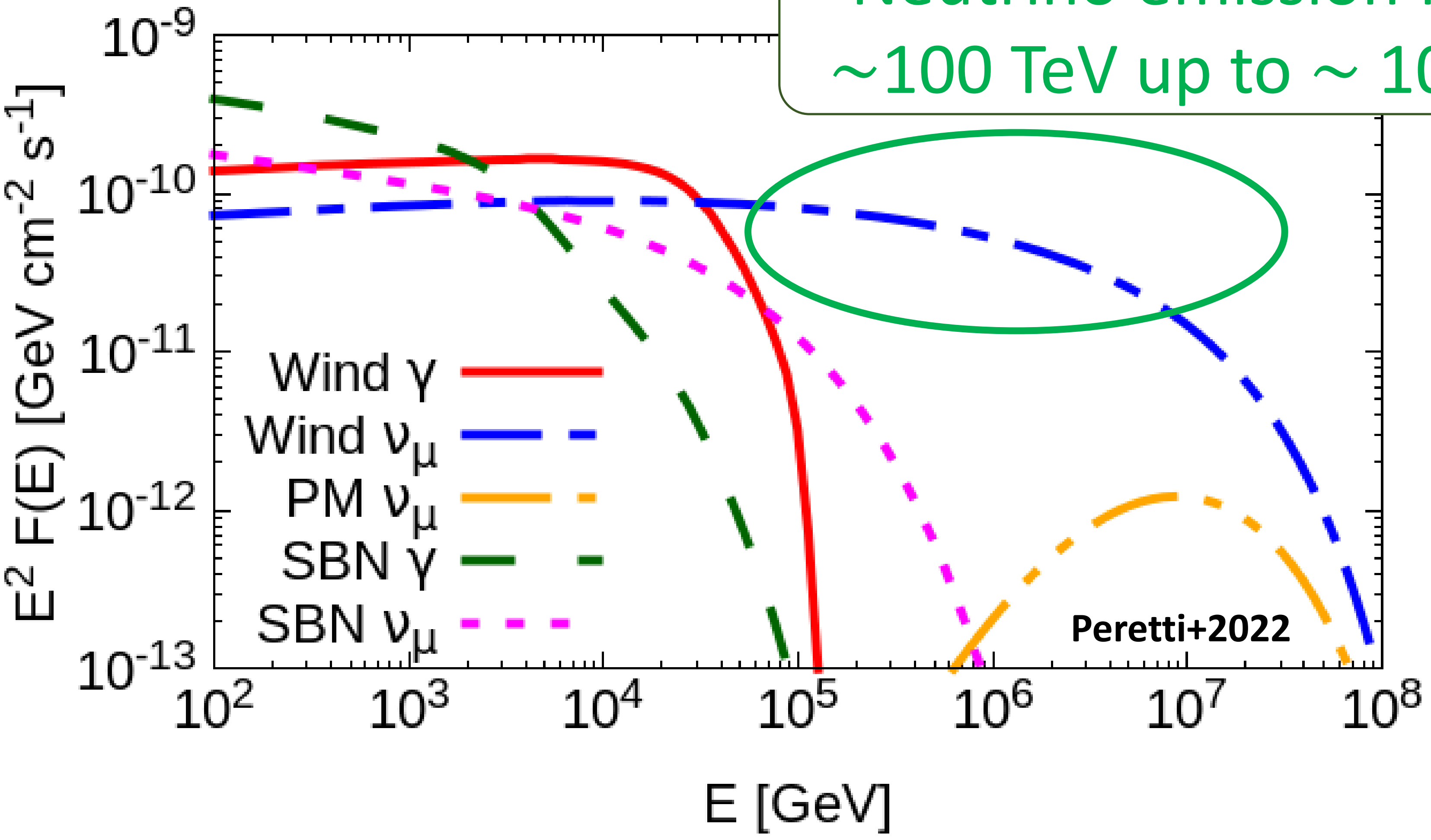


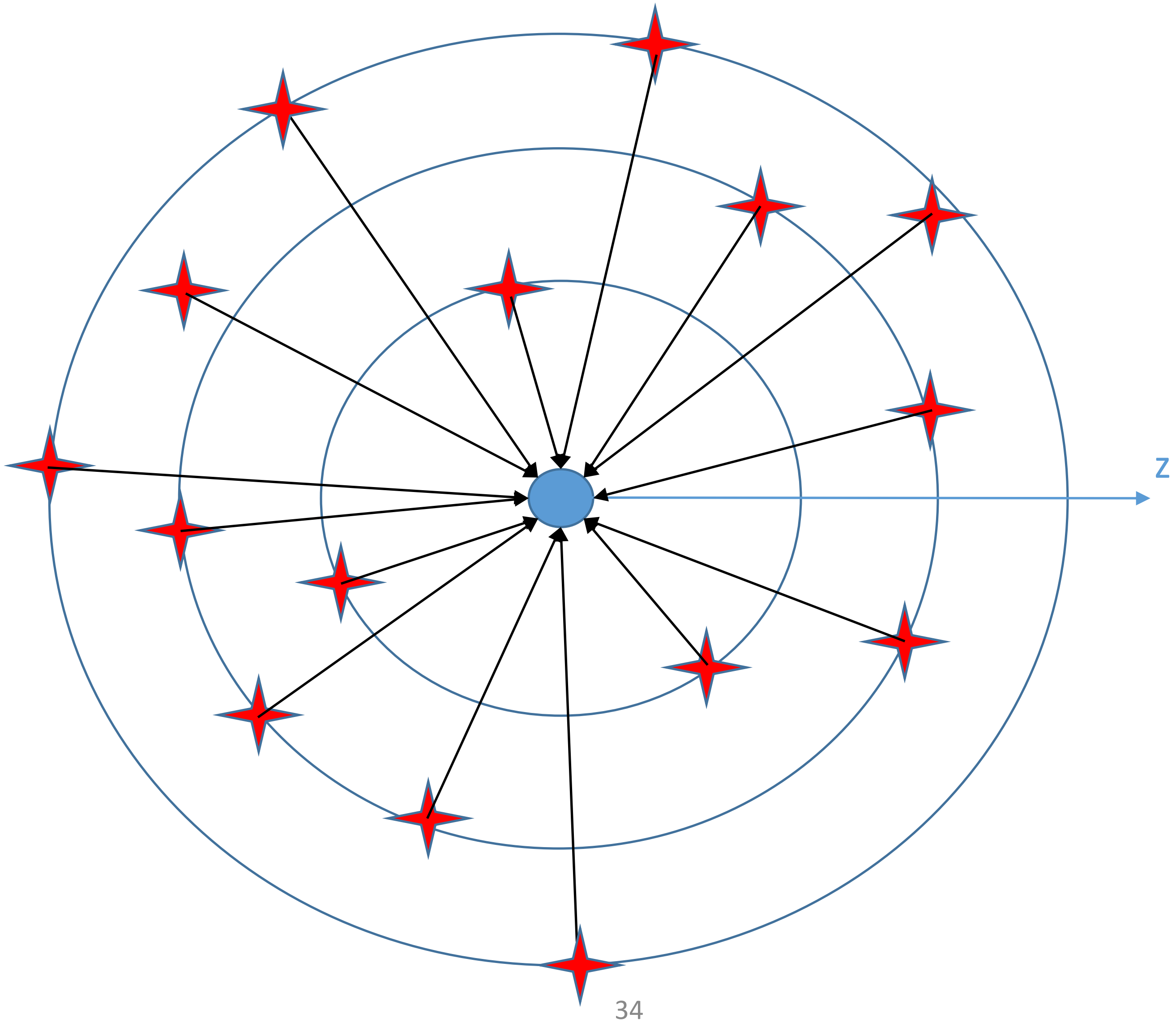
Unabsorbed gamma rays at ~10 TeV

SBGs - High-Energy SED and Neutrinos

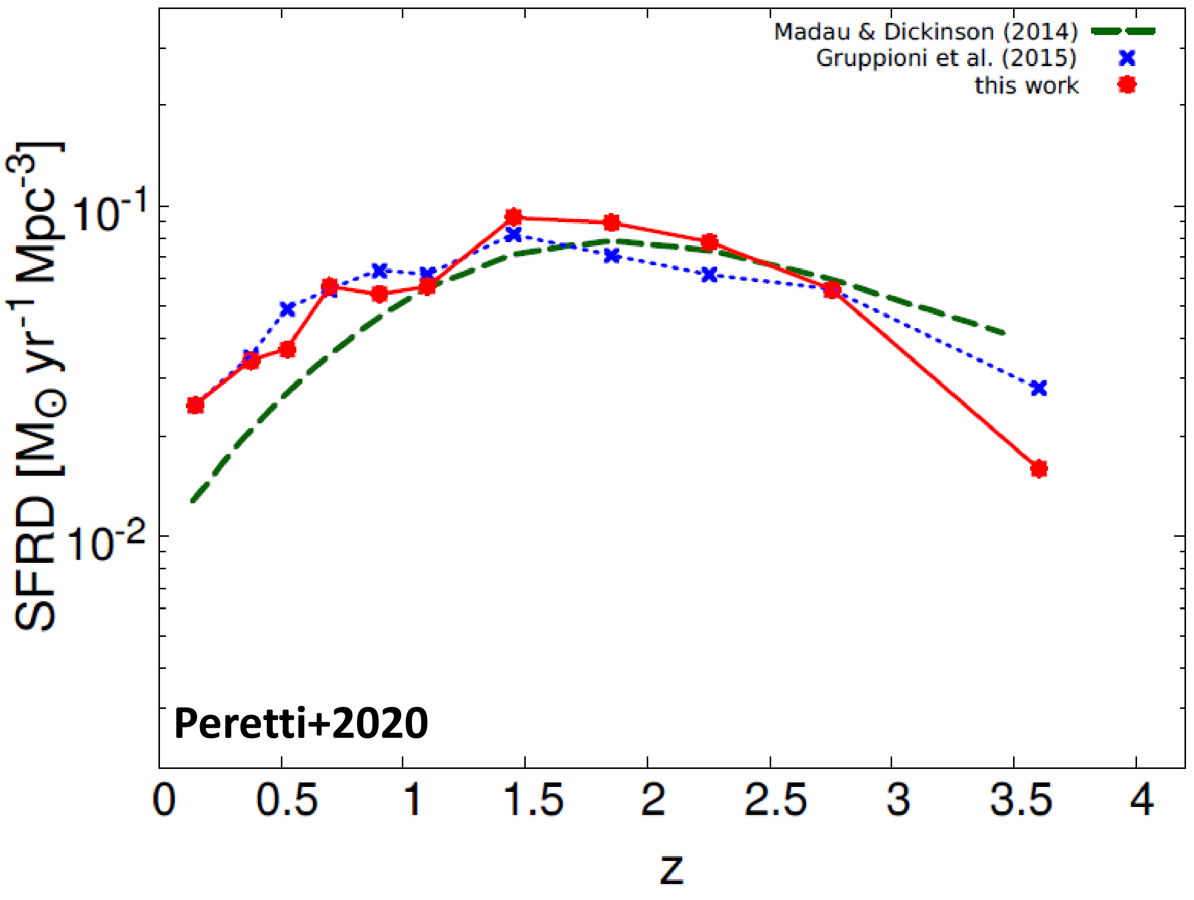
Neutrino emission from ~100 TeV up to ~ 10 PeV

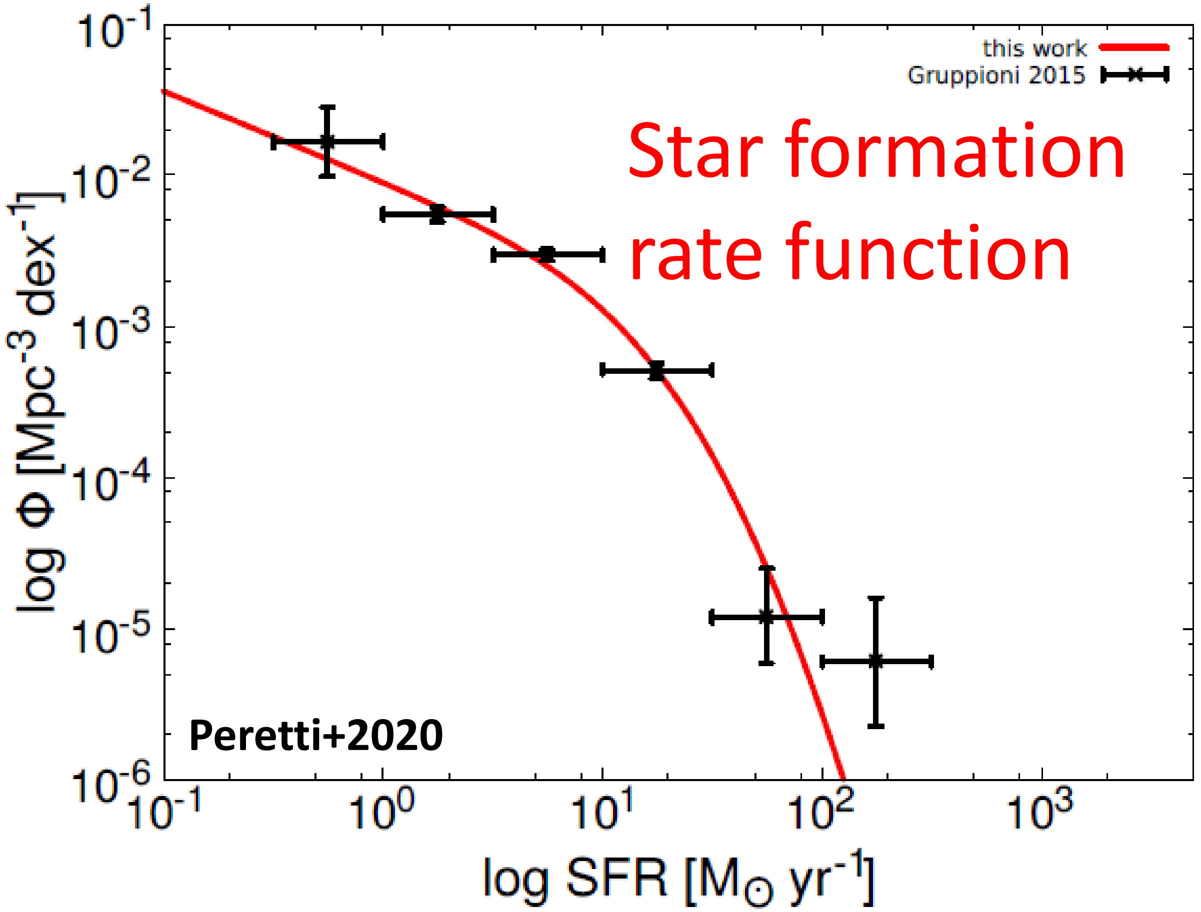


Counting starbursts

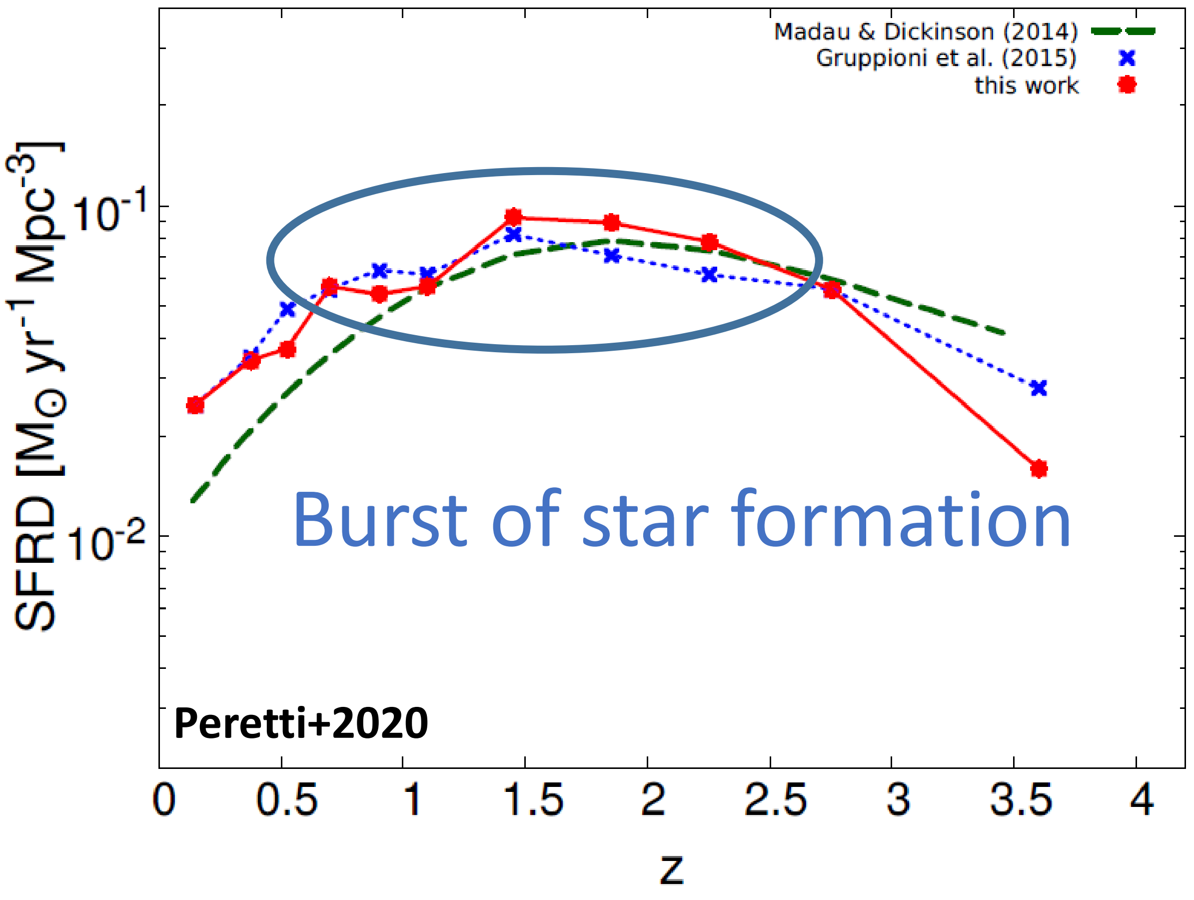


Counting starbursts



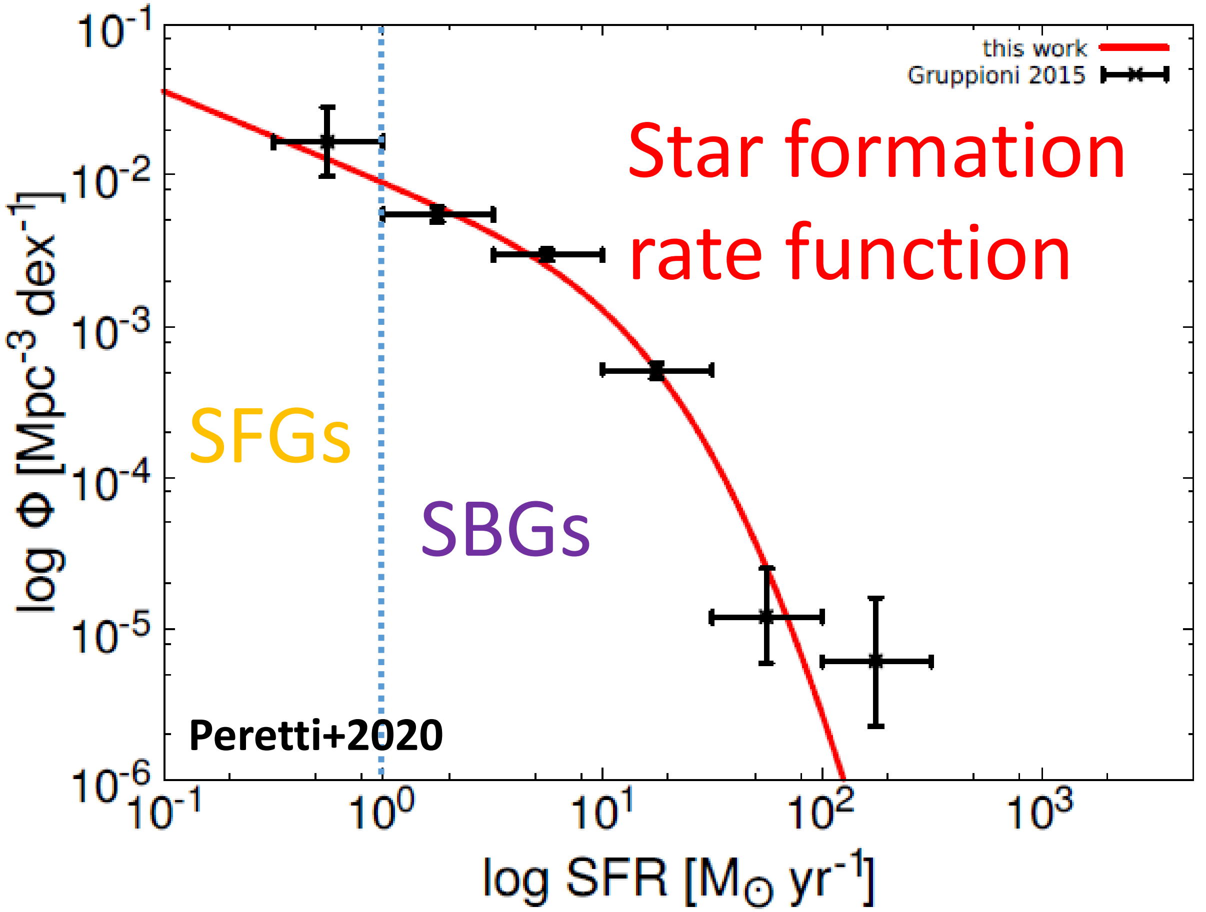


Counting starbursts



Burst of star formation

Peretti+2020



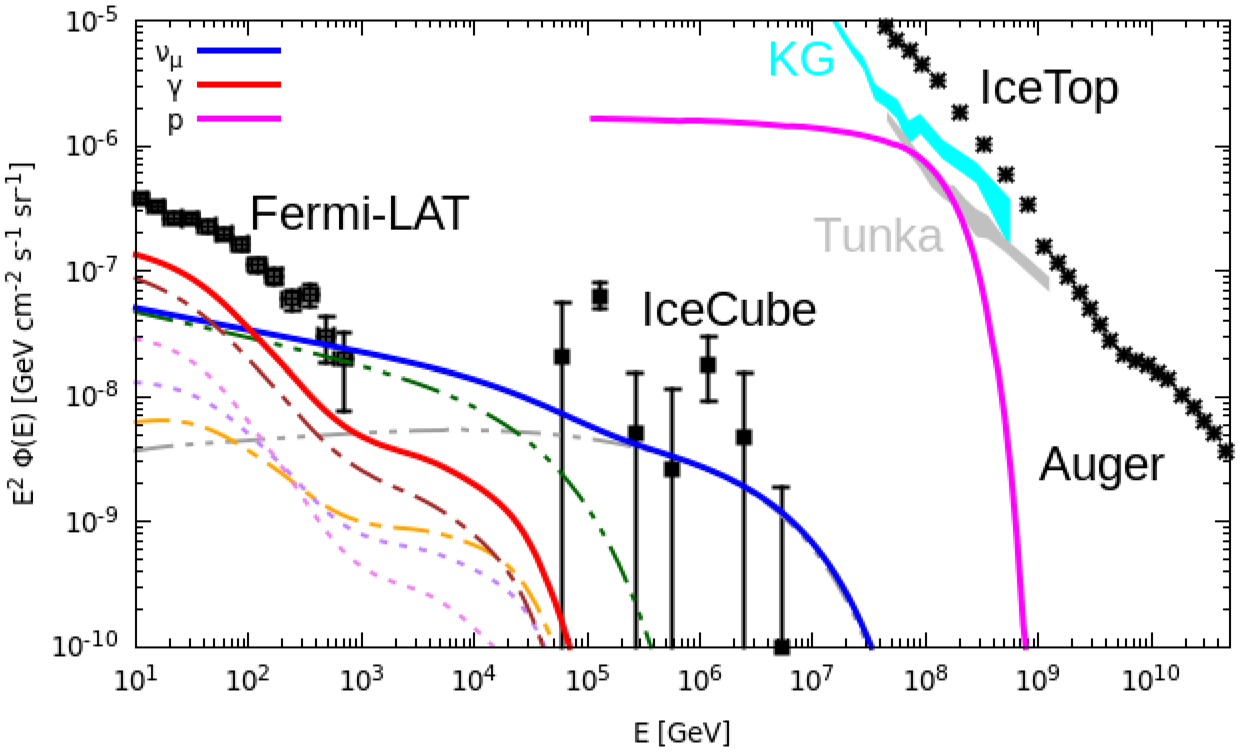
Star formation rate function

SFGs

SBGs

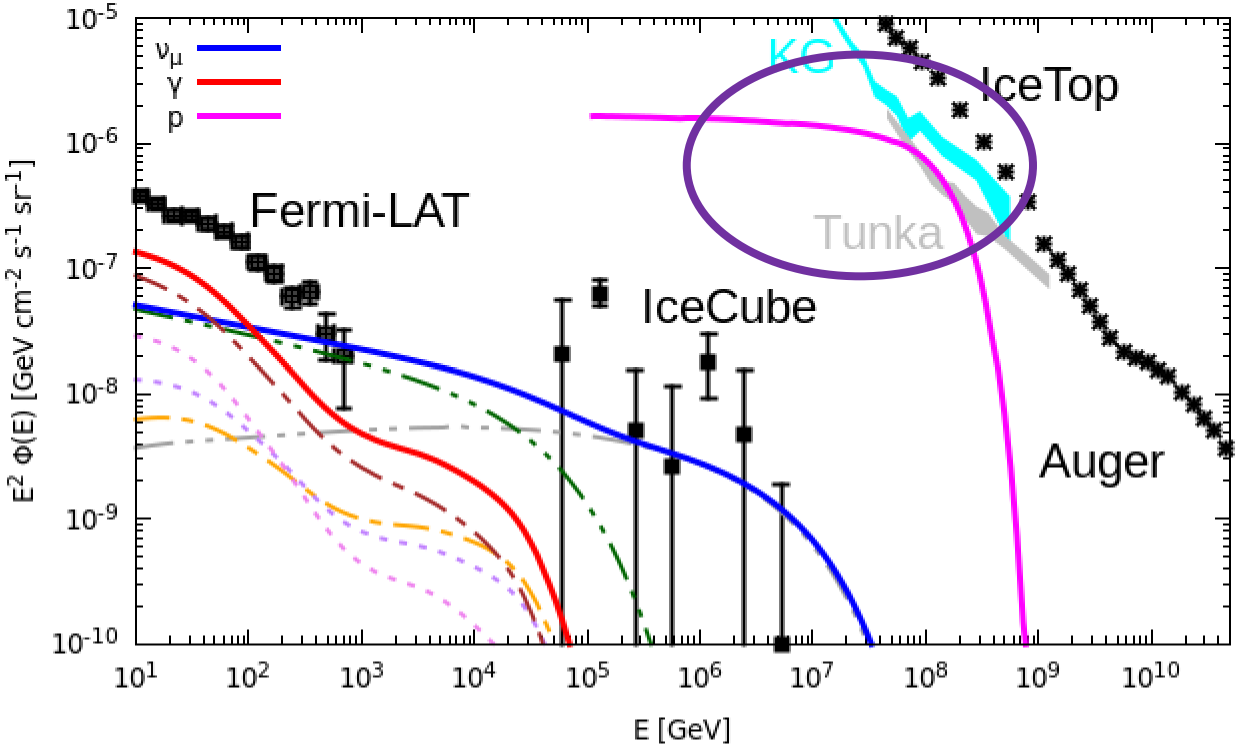
Peretti+2020

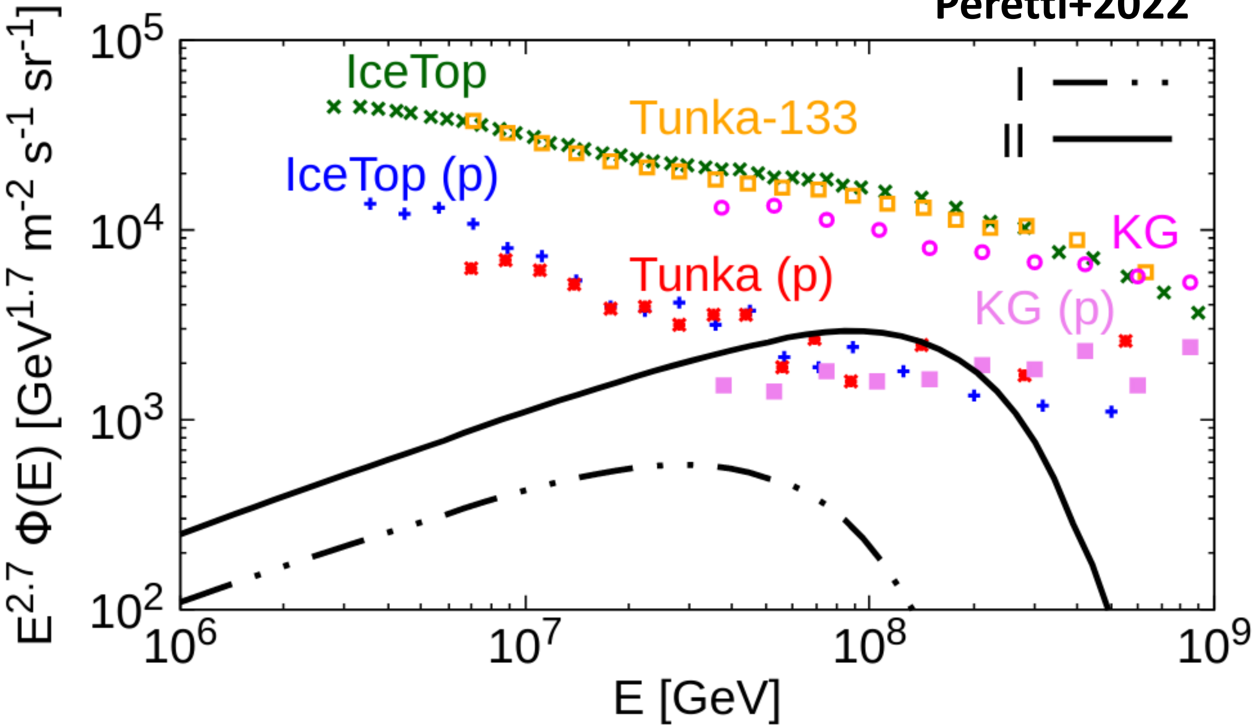
Cumulative radiation from SBGs



- Sizeable contribution to the gamma-ray flux (room for AGNi and SFGs)
- Relevant contribution to the neutrino flux from 100 TeV to 10 PeV

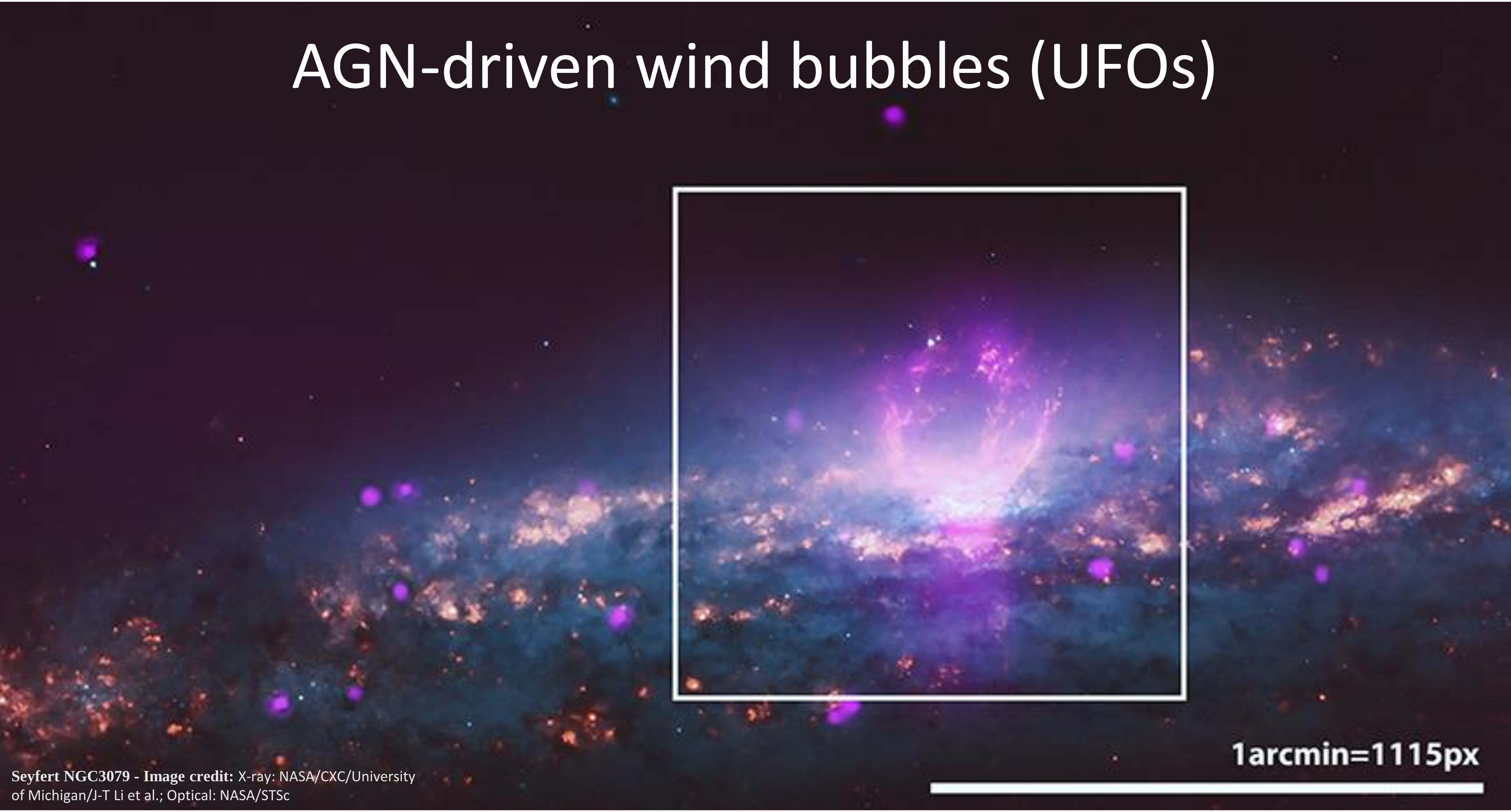
Cumulative radiation from SBGs





Peretti+2022

AGN-driven wind bubbles (UFOs)

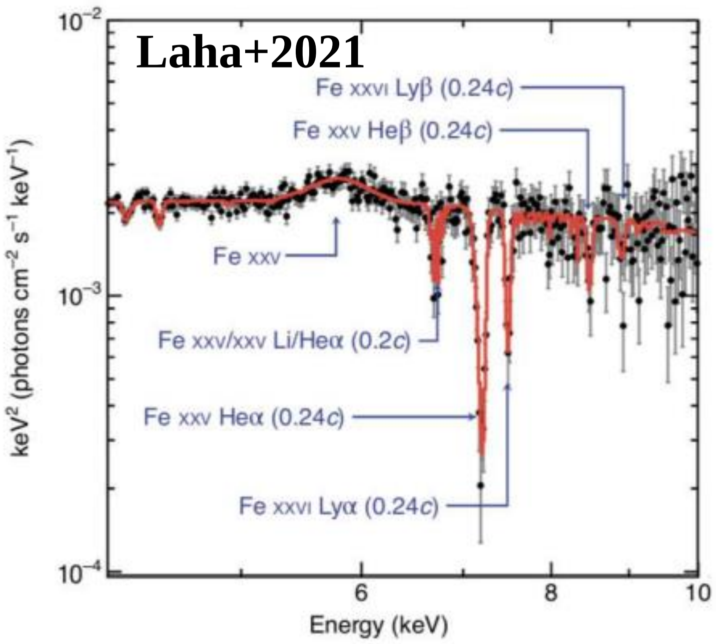


Seyfert NGC3079 - Image credit: X-ray: NASA/CXC/University of Michigan/J-T Li et al.; Optical: NASA/STSc

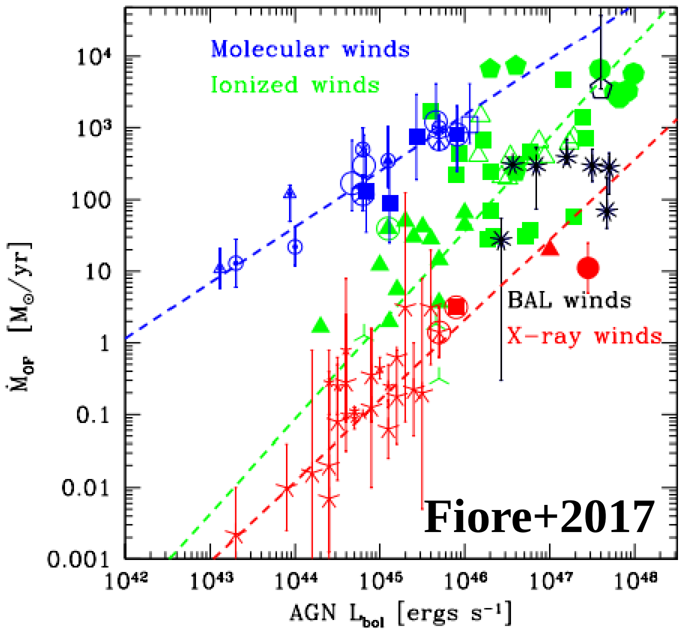
Seyfert NGC3079 - Image credit: X-ray: NASA/CXC/University of Michigan/J-T Li et al.; Optical: NASA/STSc

Ultra-Fast Outflows (UFOs)

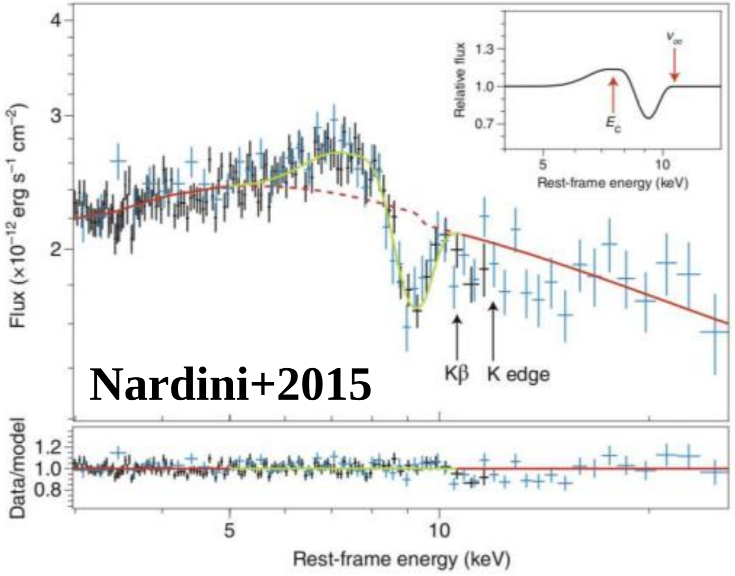
- Dist. scale = $10^{-4} - 10$ pc
- $v \approx 0.03\,c\; - 0.3\,c$
- $\Omega \gtrsim 3\pi$ sr
- $\dot{M} \approx 10^{-3} - 10\, M_{\odot} yr^{-1}$



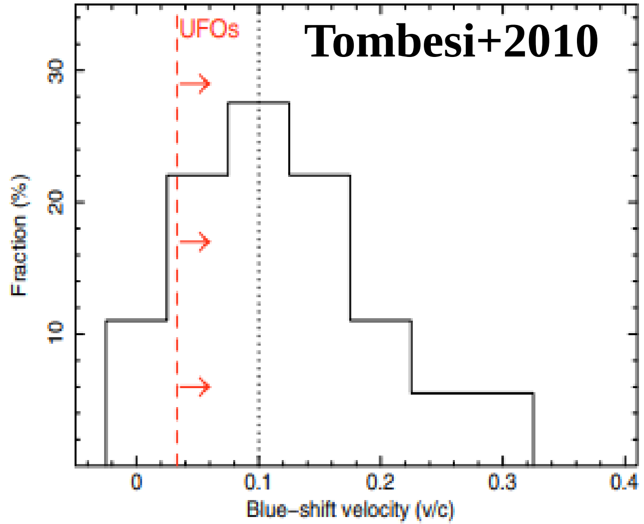
Laha+2021



Fiore+2017



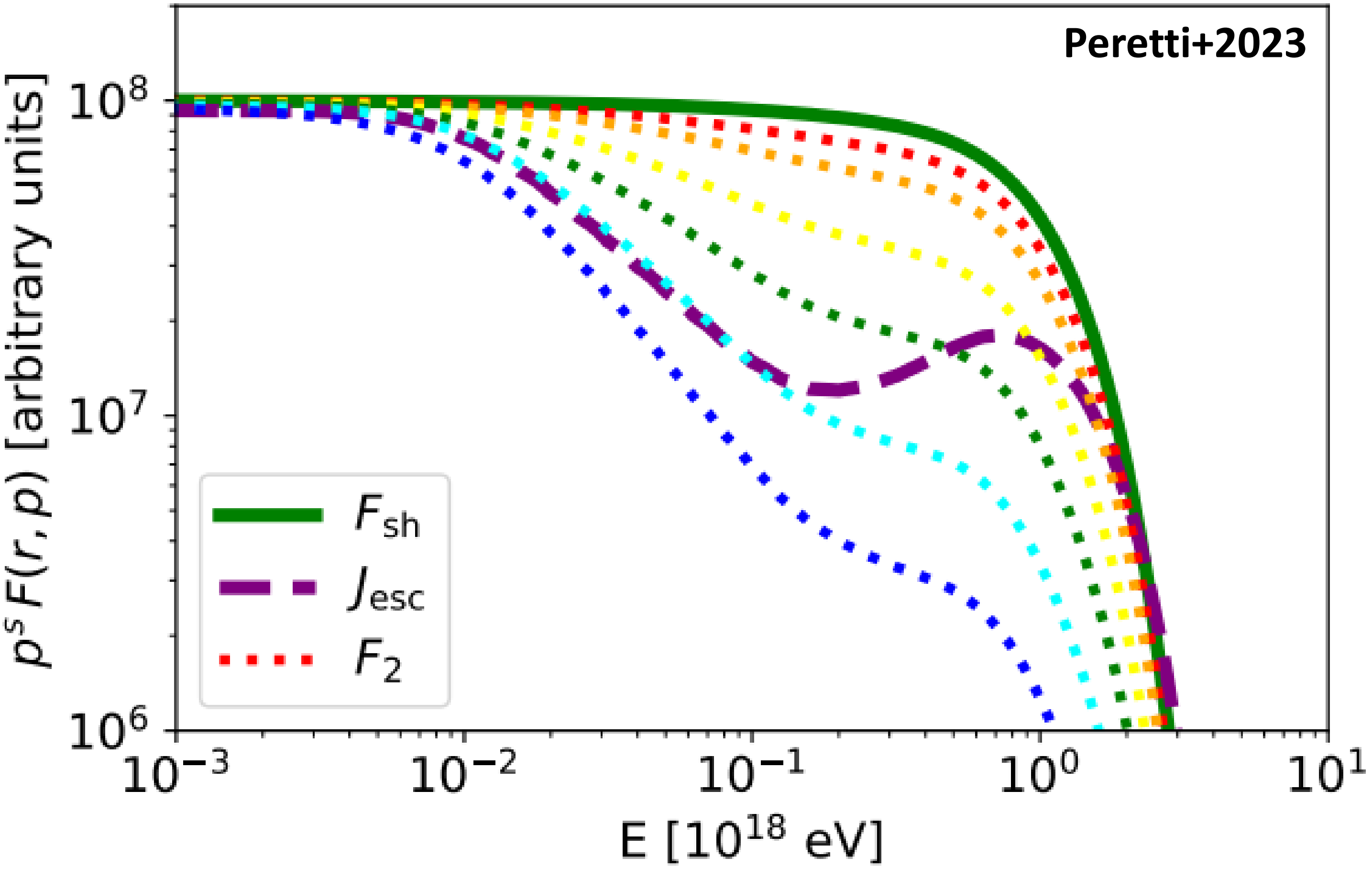
Nardini+2015



Tombesi+2010

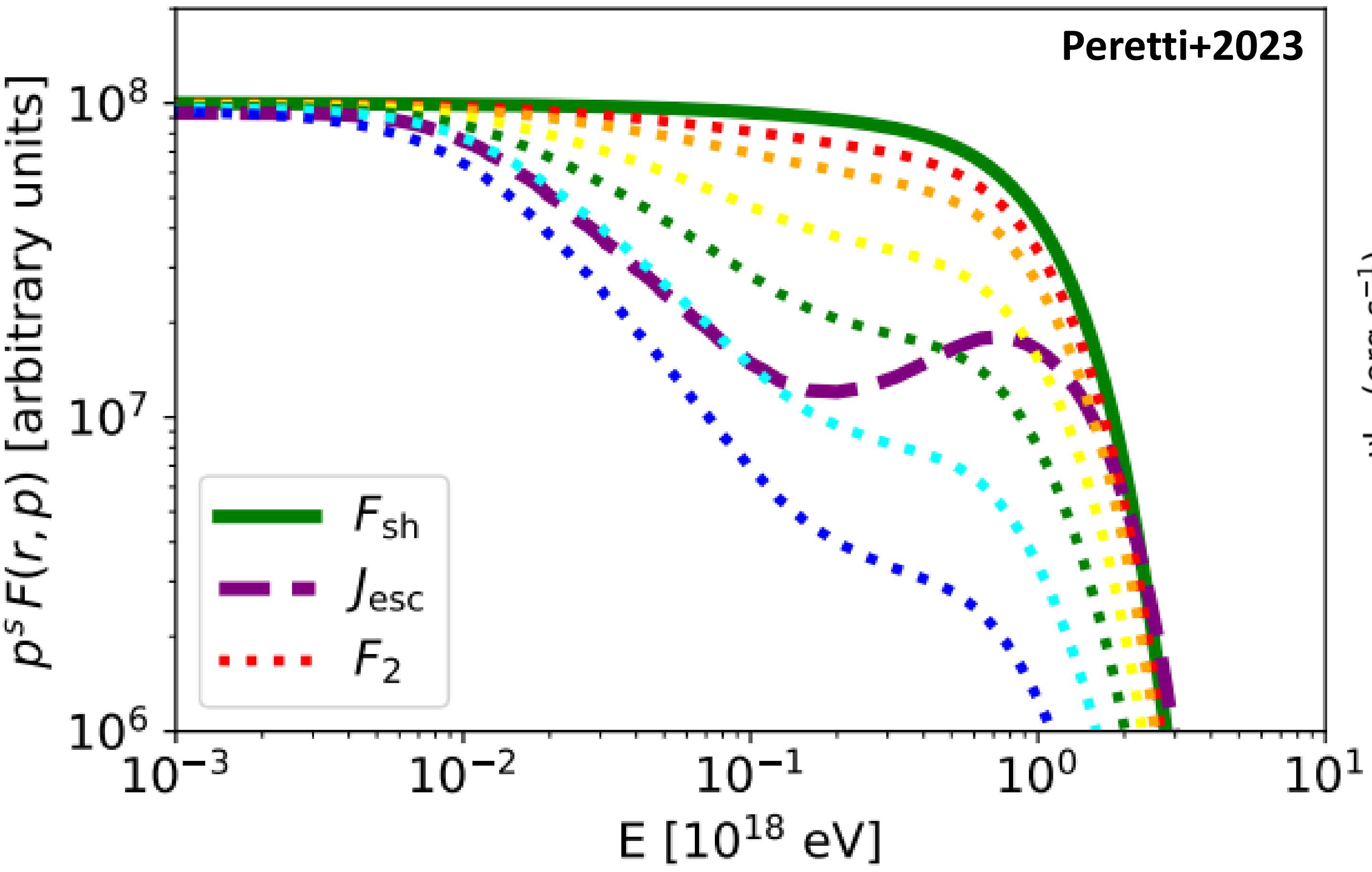
1arcmin=1115px

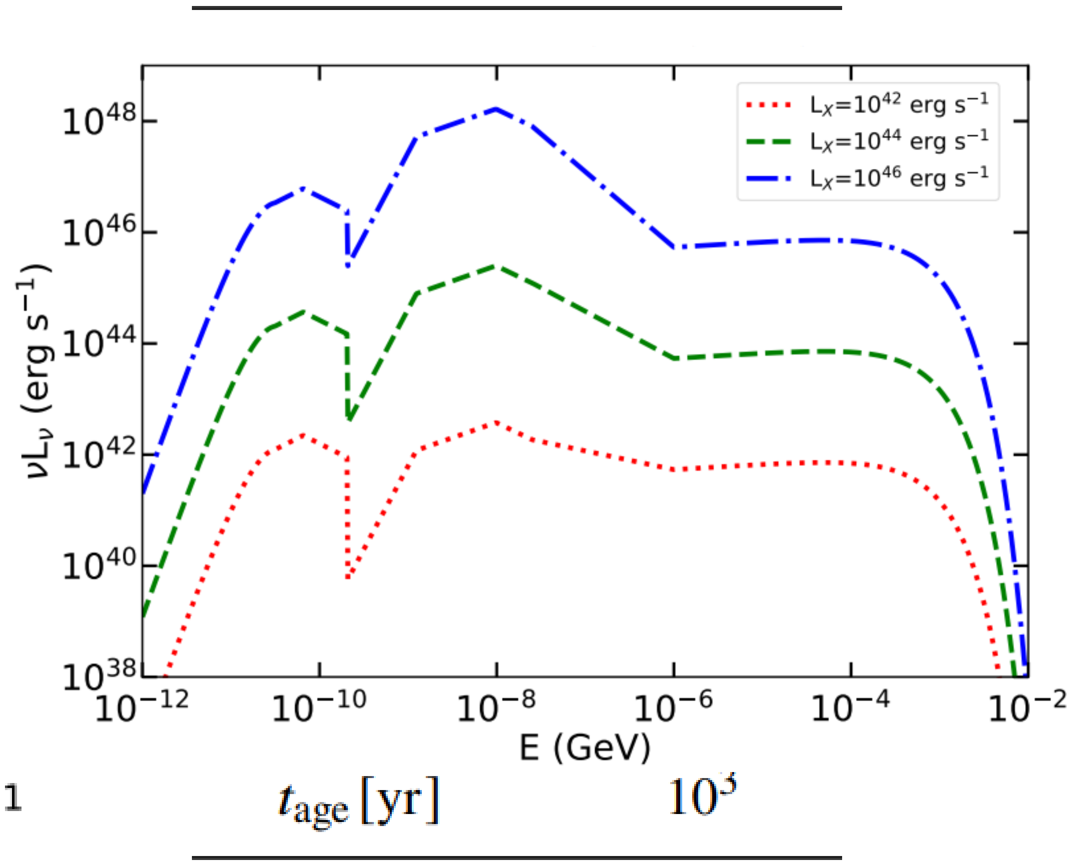
The prototype UFO



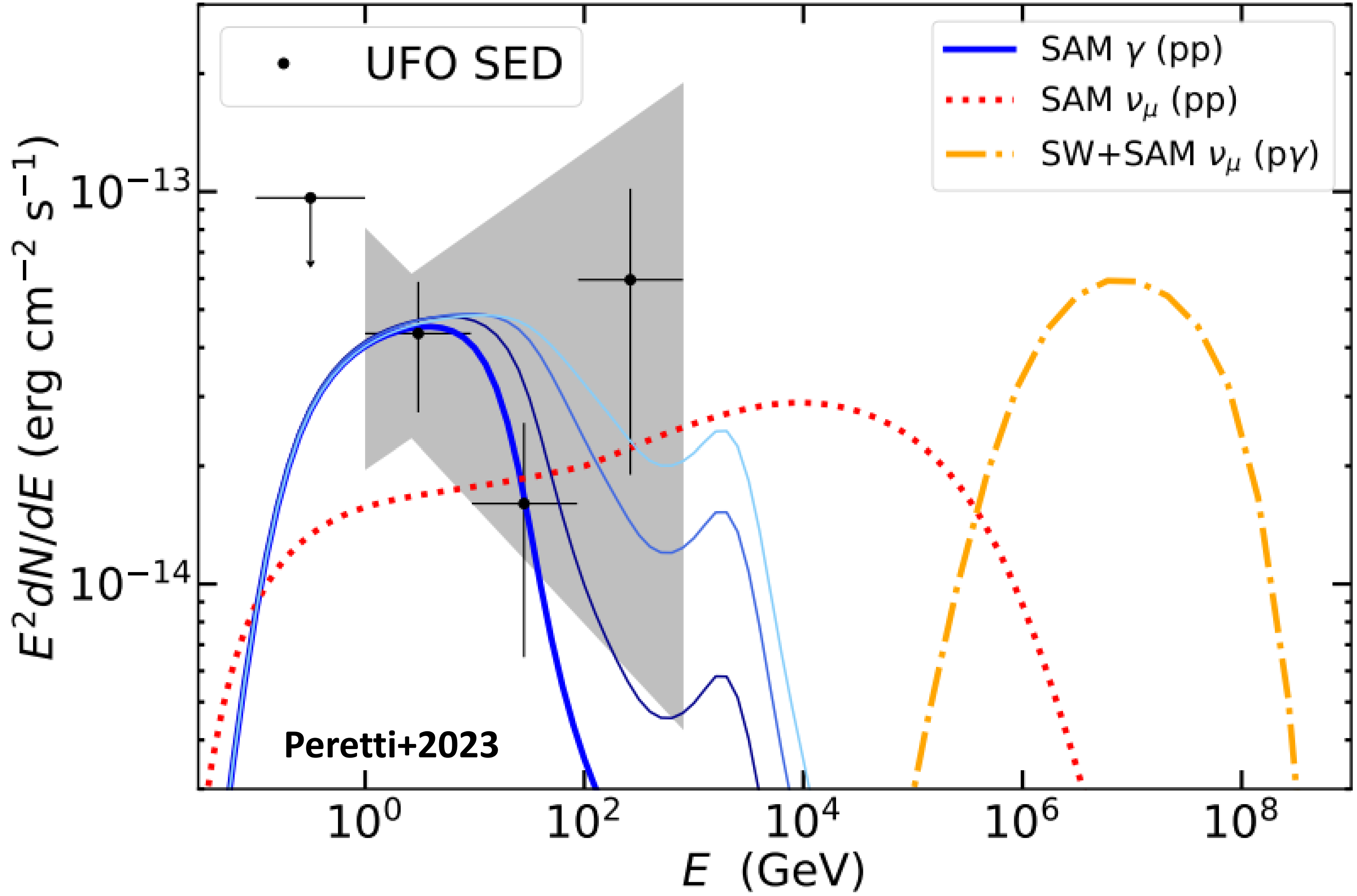
Parameter	benchmark
u_1/c	0.2
$\dot{M}$ [$M_\odot$ yr^{-1}]	10^{-1}
$\xi_{\rm CR}$	0.05
$\epsilon_{\rm B}$	0.05
l_c [pc]	10^{-2}
δ	3/2
L_X [erg s^{-1}]	10^{44}
$n_{\rm ISM}$ [cm^{-3}]	10^4
$t_{\rm age}$ [yr]	10^3

The prototype UFO



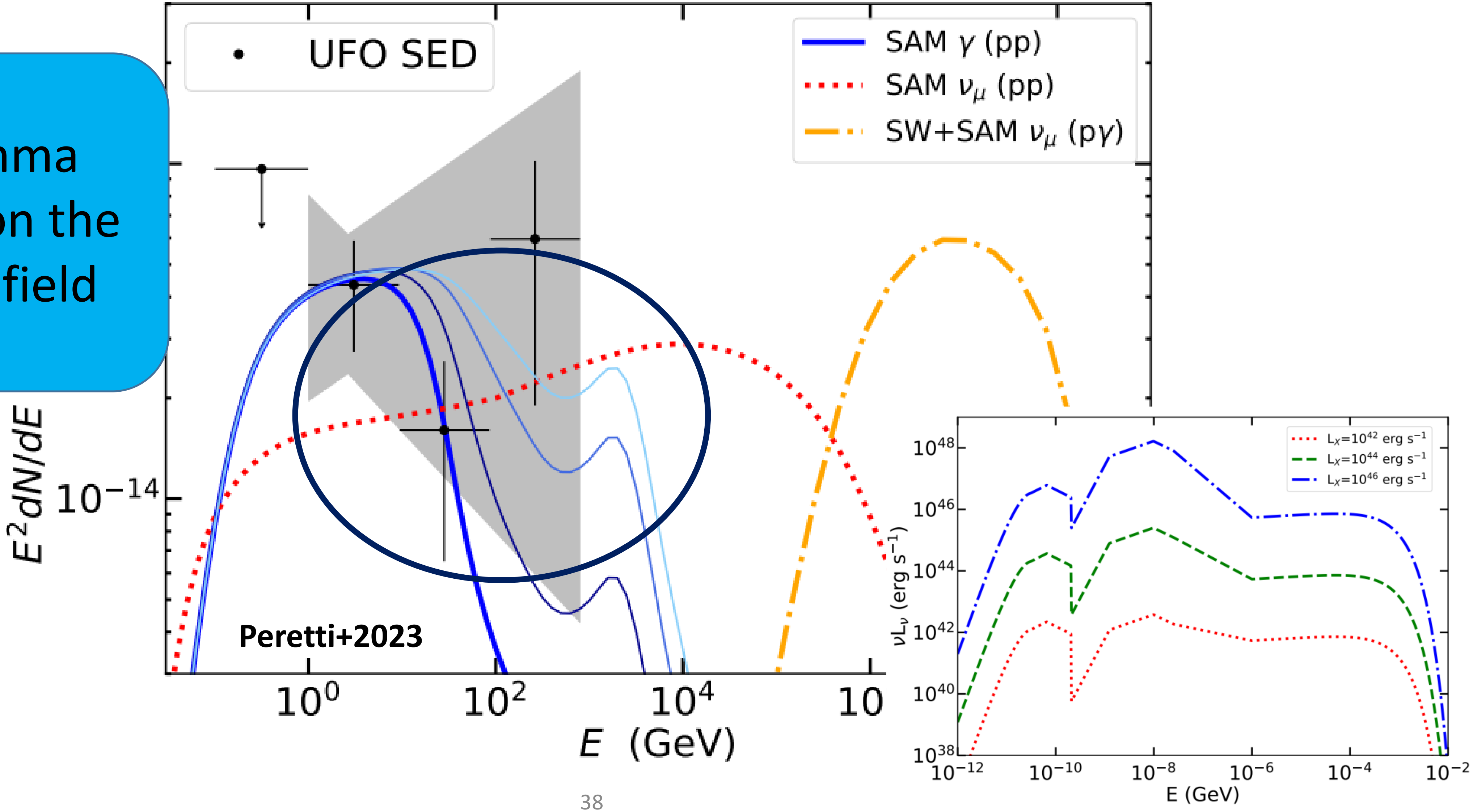


UFO model applied to Fermi-LAT results



UFO model applied to Fermi-LAT results

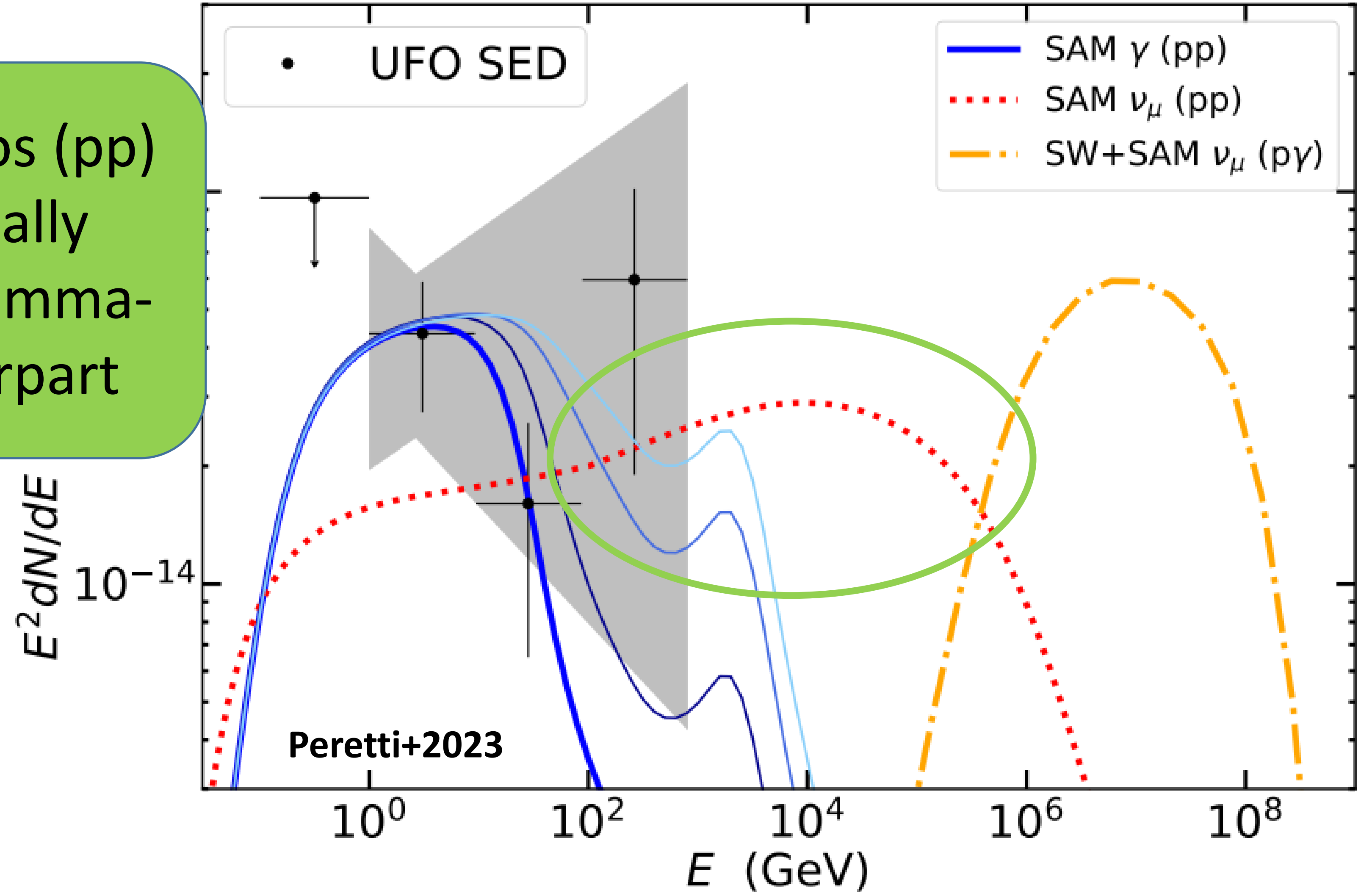
Gamma-gamma absorption on the BKG photon field



Peretti+2023

UFO model applied to Fermi-LAT results

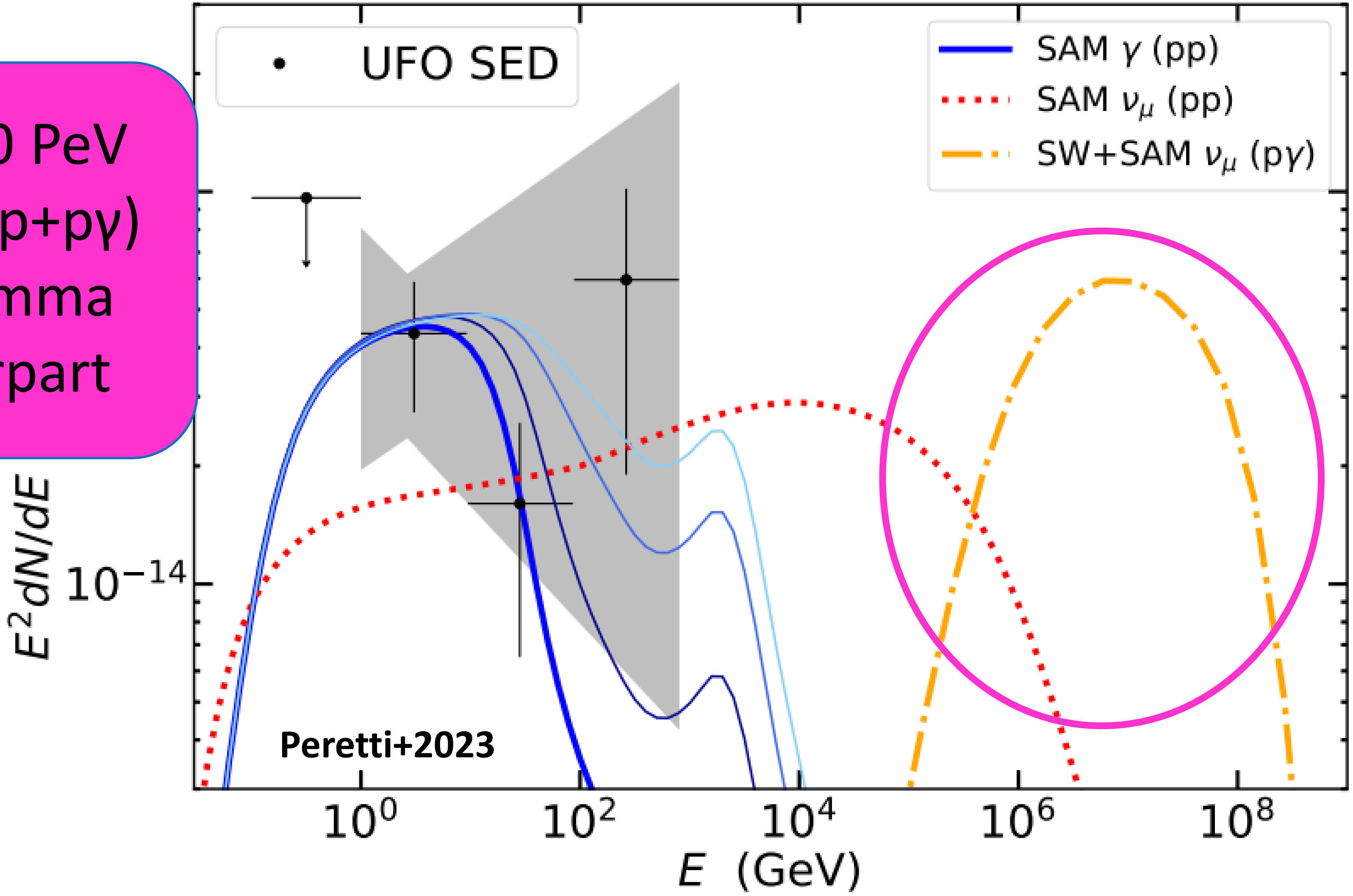
TeV neutrinos (pp) with partially absorbed gamma-ray counterpart



Peretti+2023

UFO model applied to Fermi-LAT results

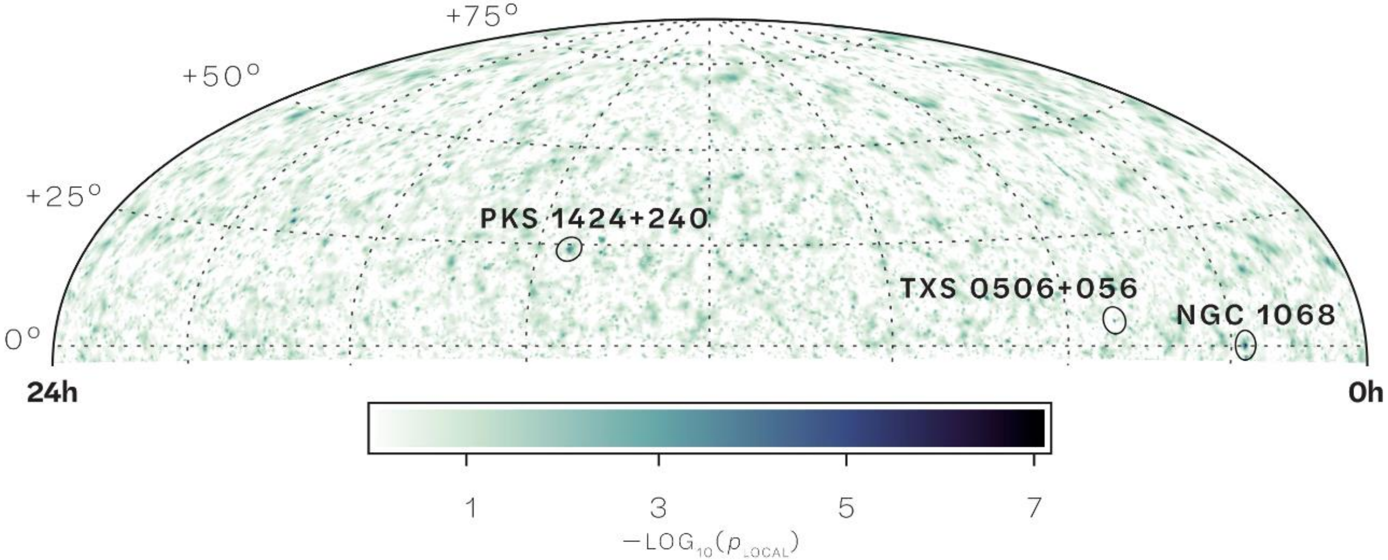
100 TeV-100 PeV neutrinos (pp+pγ) without gamma ray counterpart



Model application to NGC 1068

Credit: NASA, ESA & A. van der Hoeve

Model application to NGC 1068



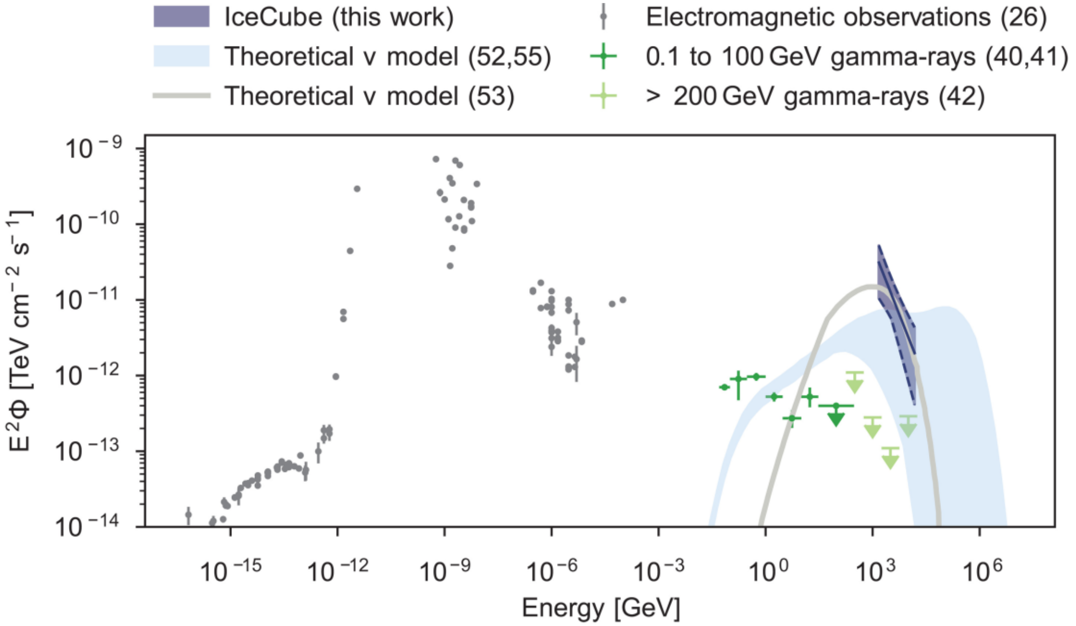
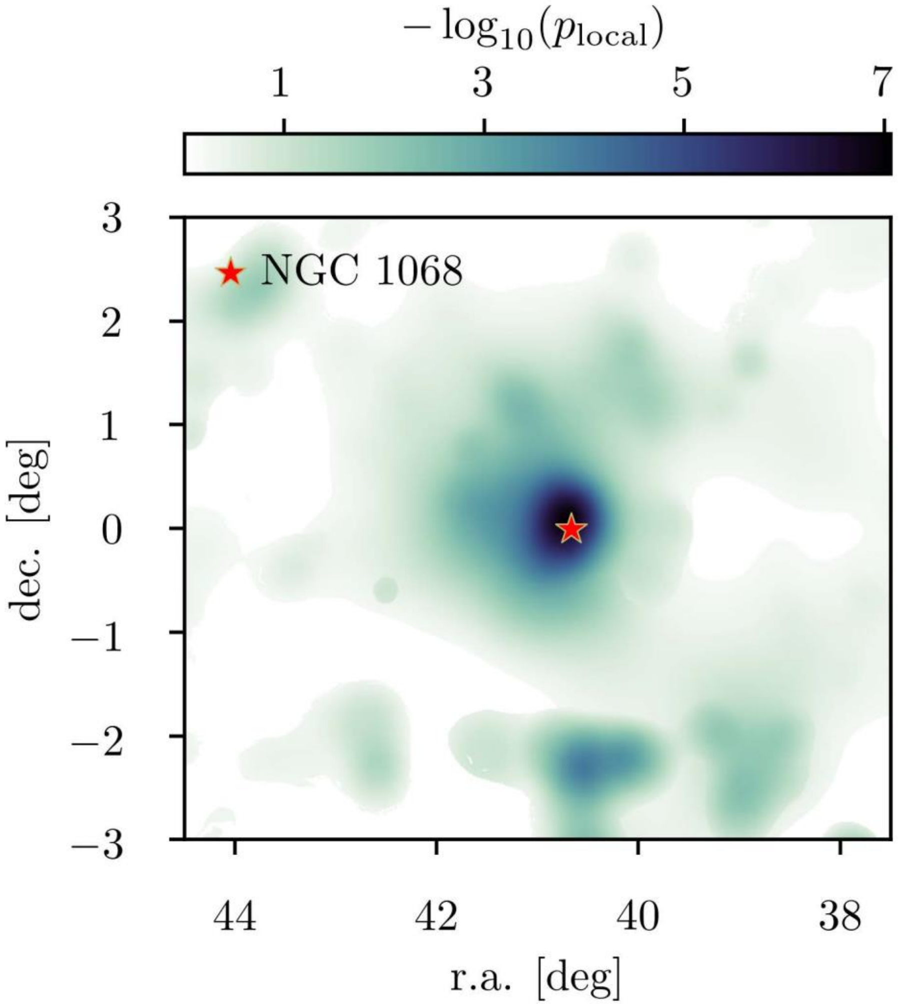
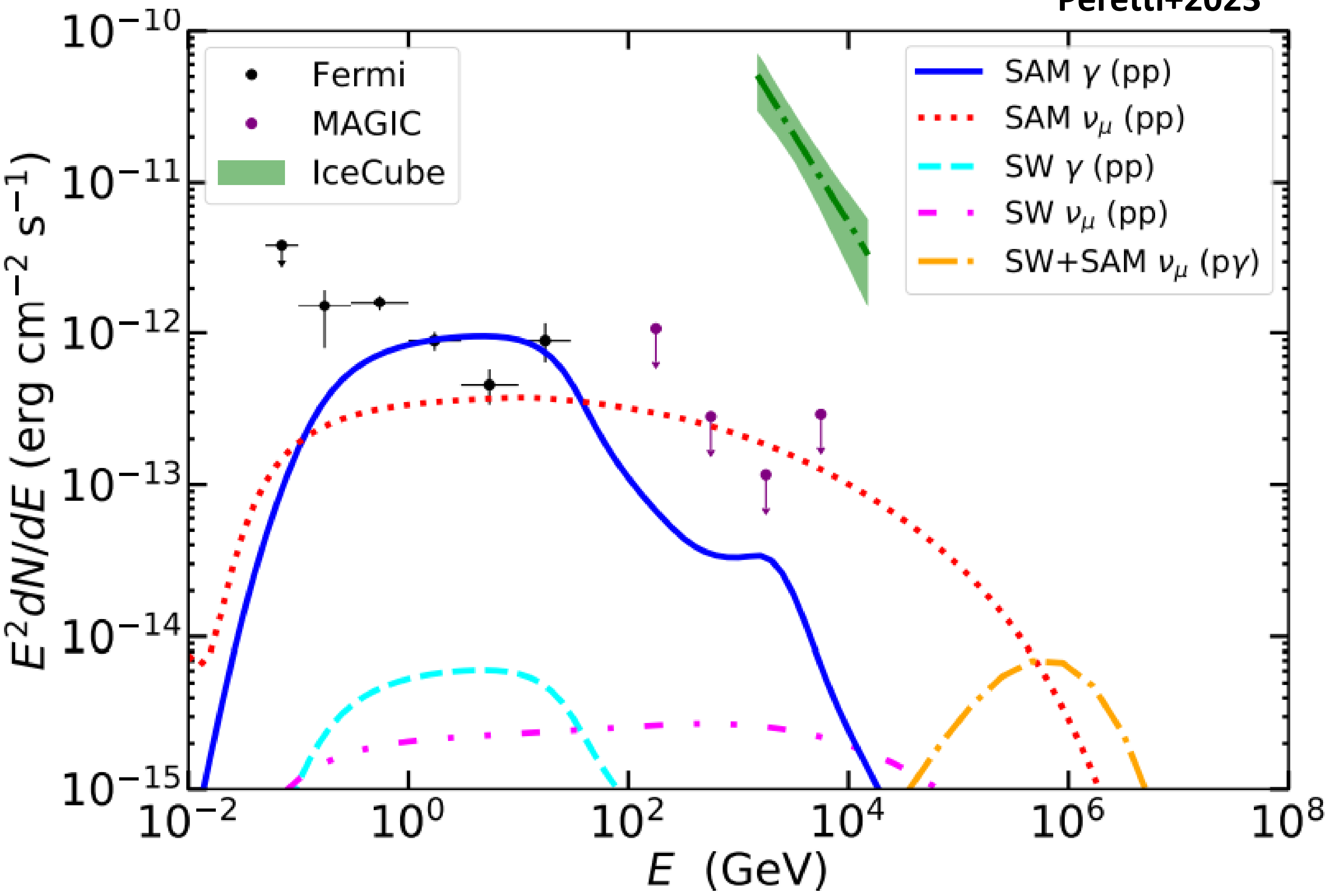


Fig.s from (IceCube collab.), Abbasi+2022



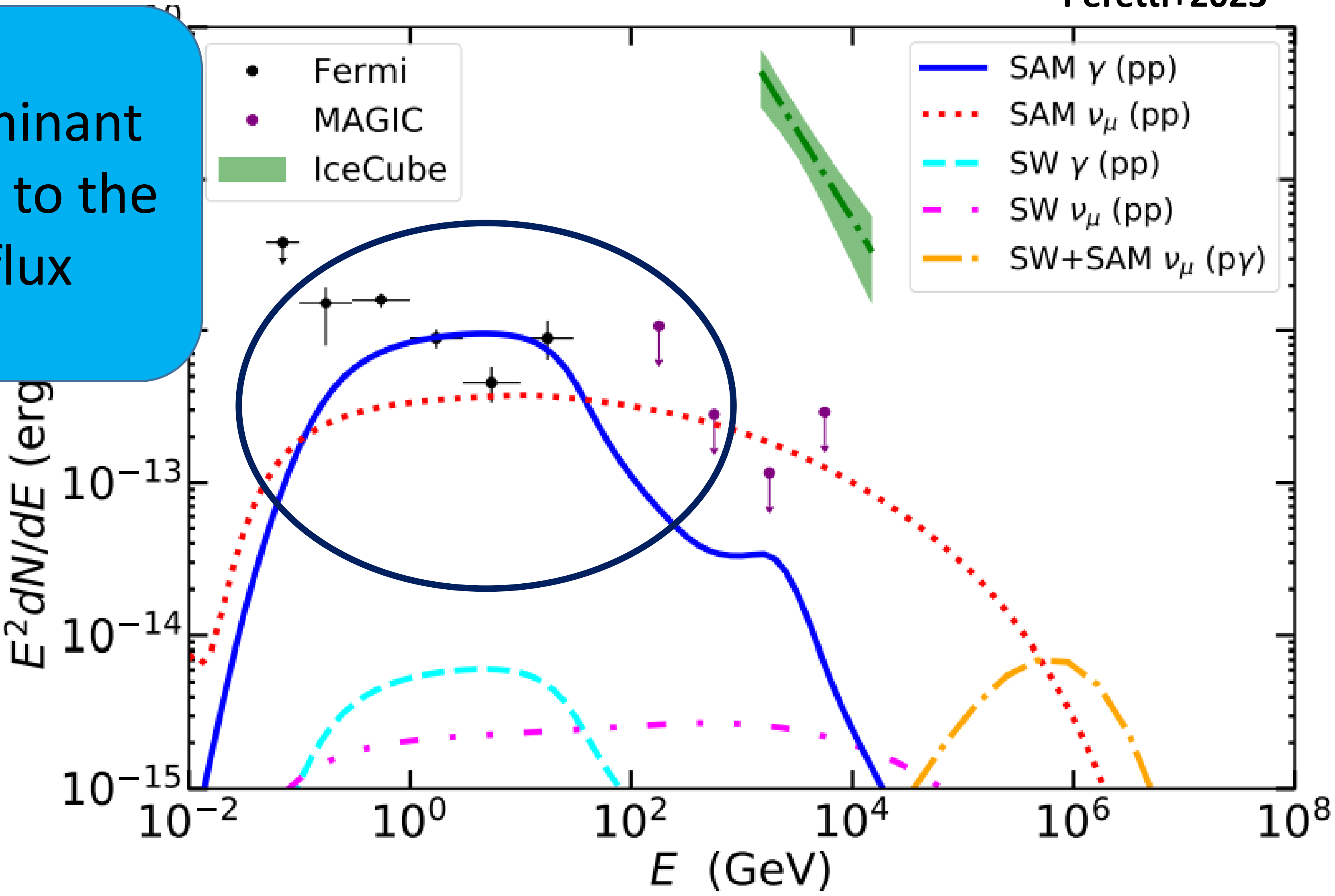
Application to NGC 1068

Peretti+2023



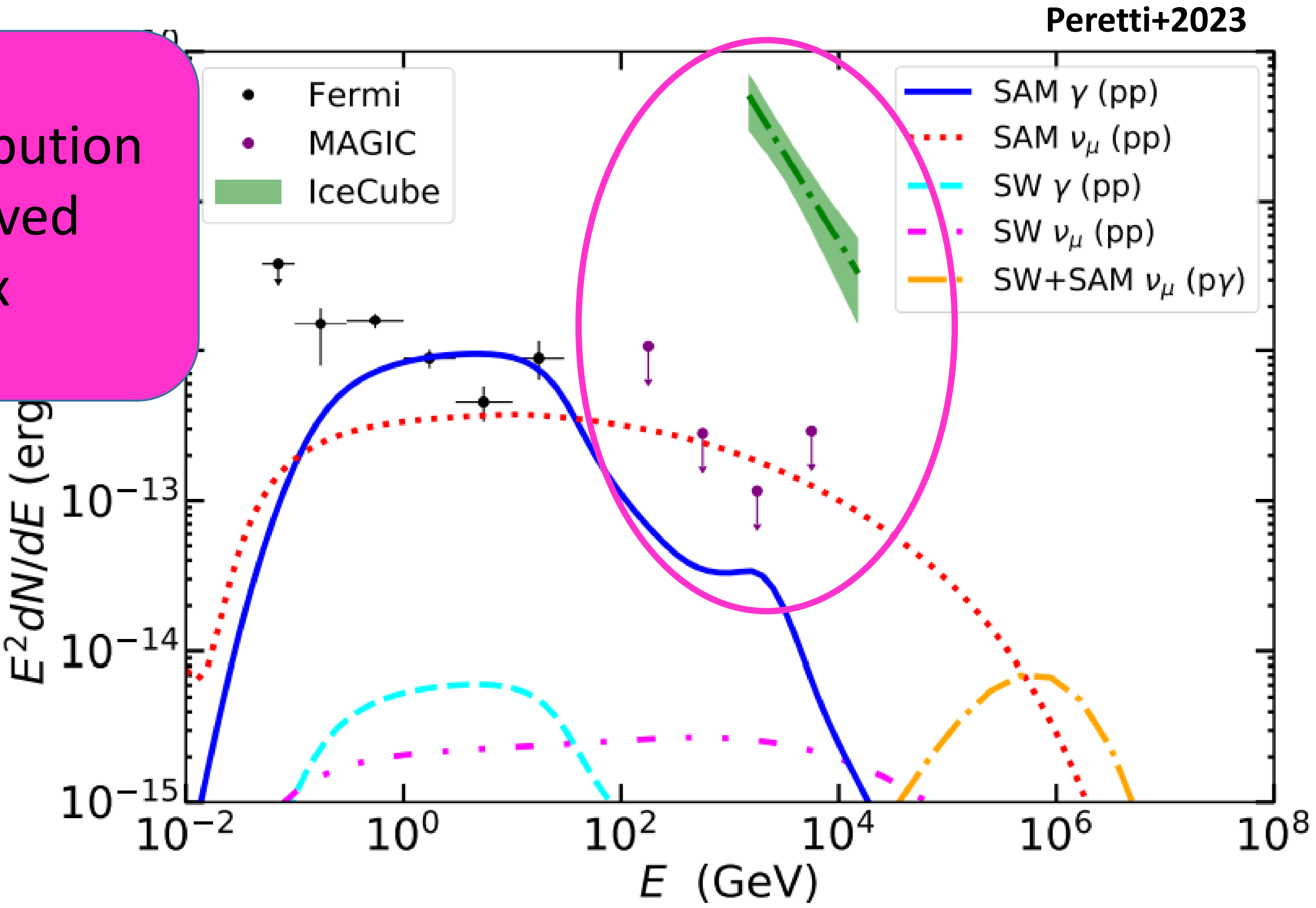
Application to NGC 1068

Possible dominant contribution to the gamma-ray flux



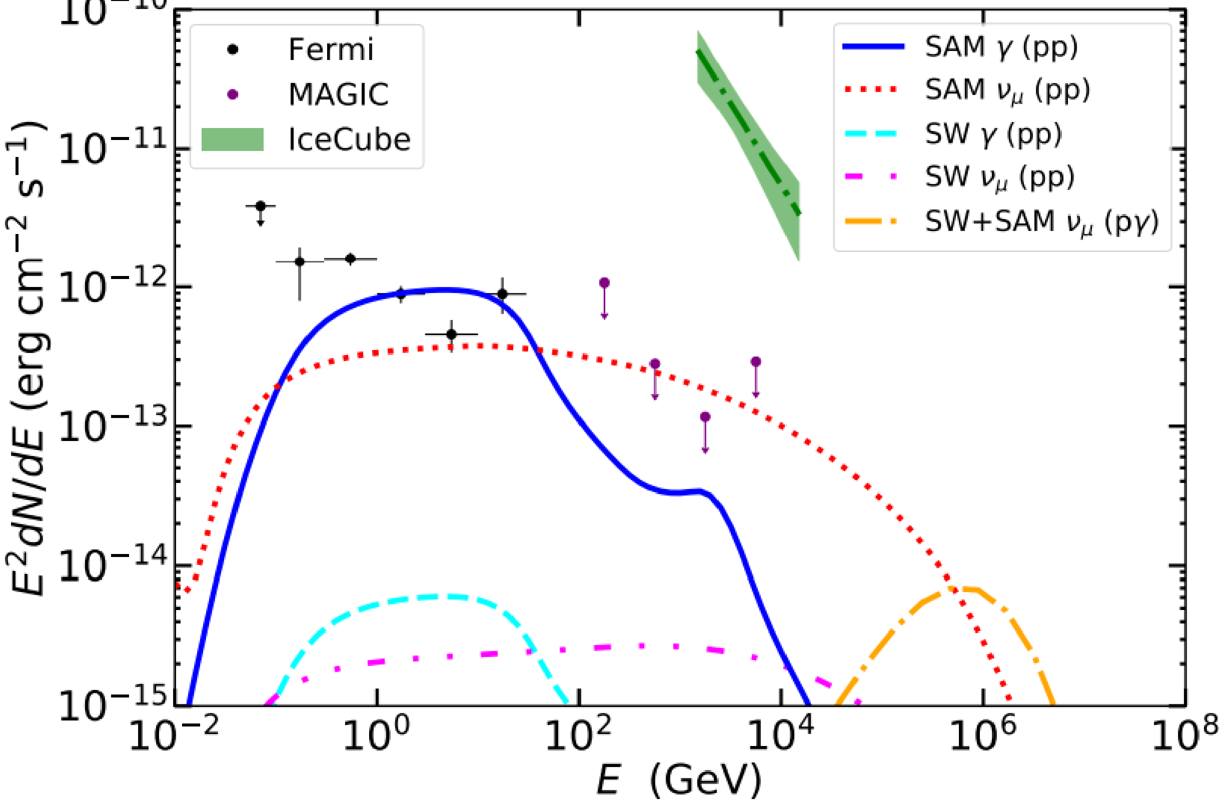
Peretti+2023

Application to NGC 1068

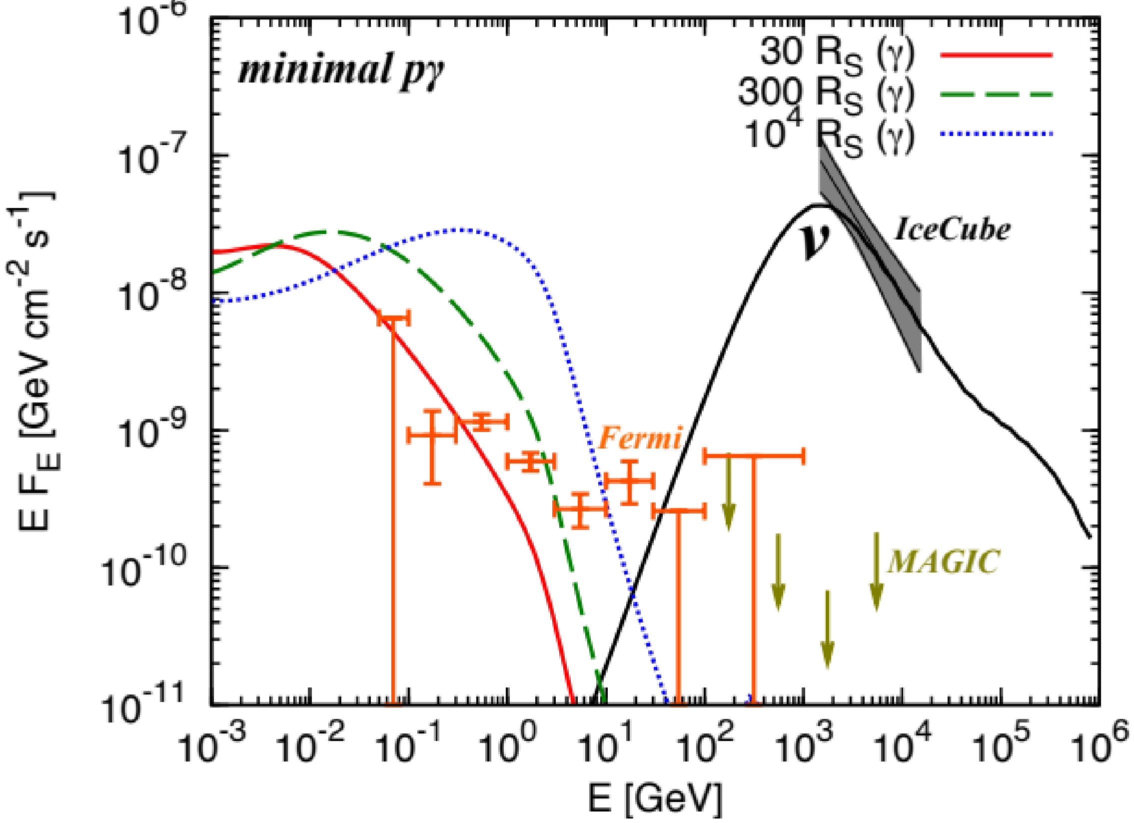


<10% contribution to the observed neutrino flux

Multi-zone perspective for NGC 1068



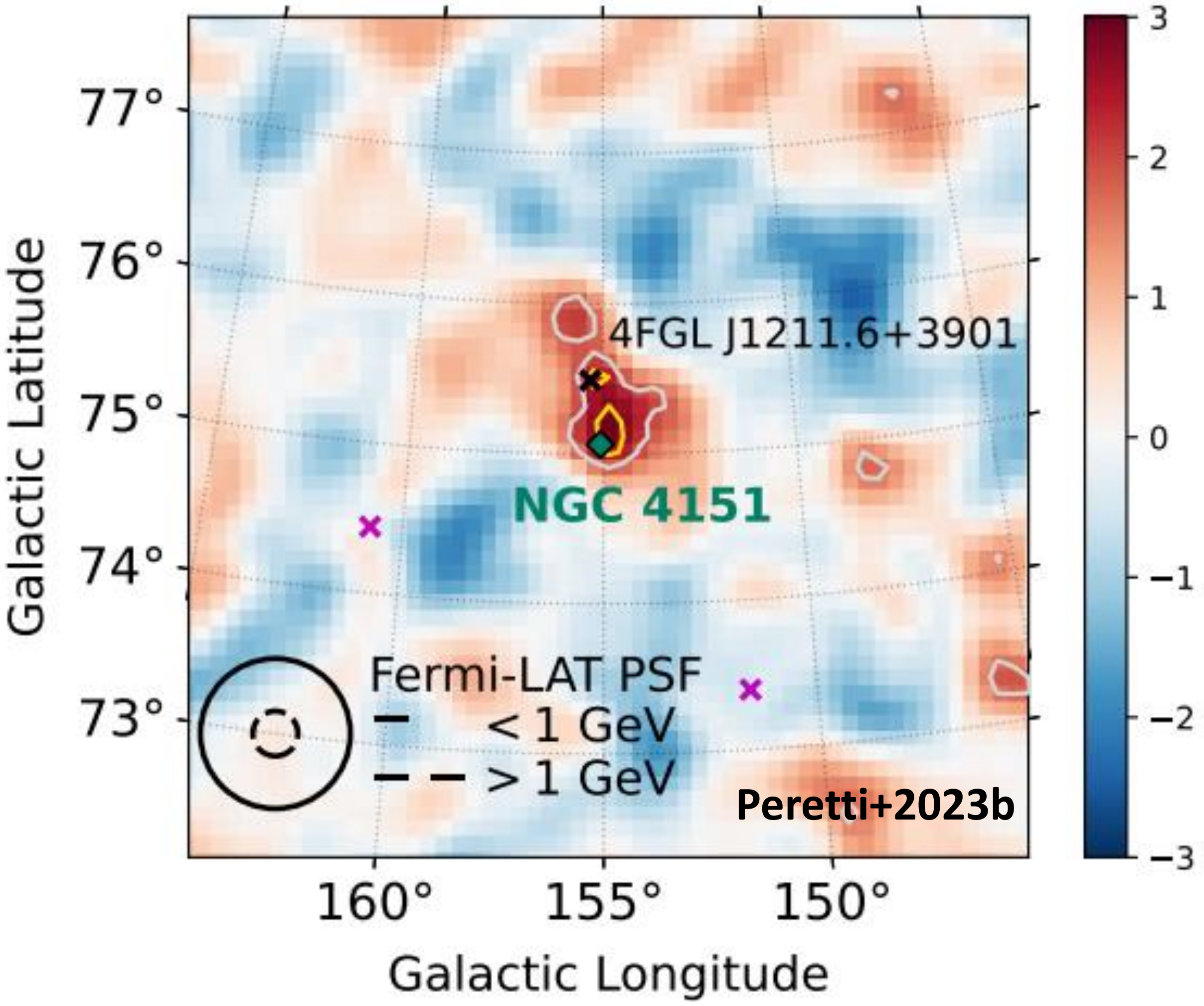
Peretti+2023

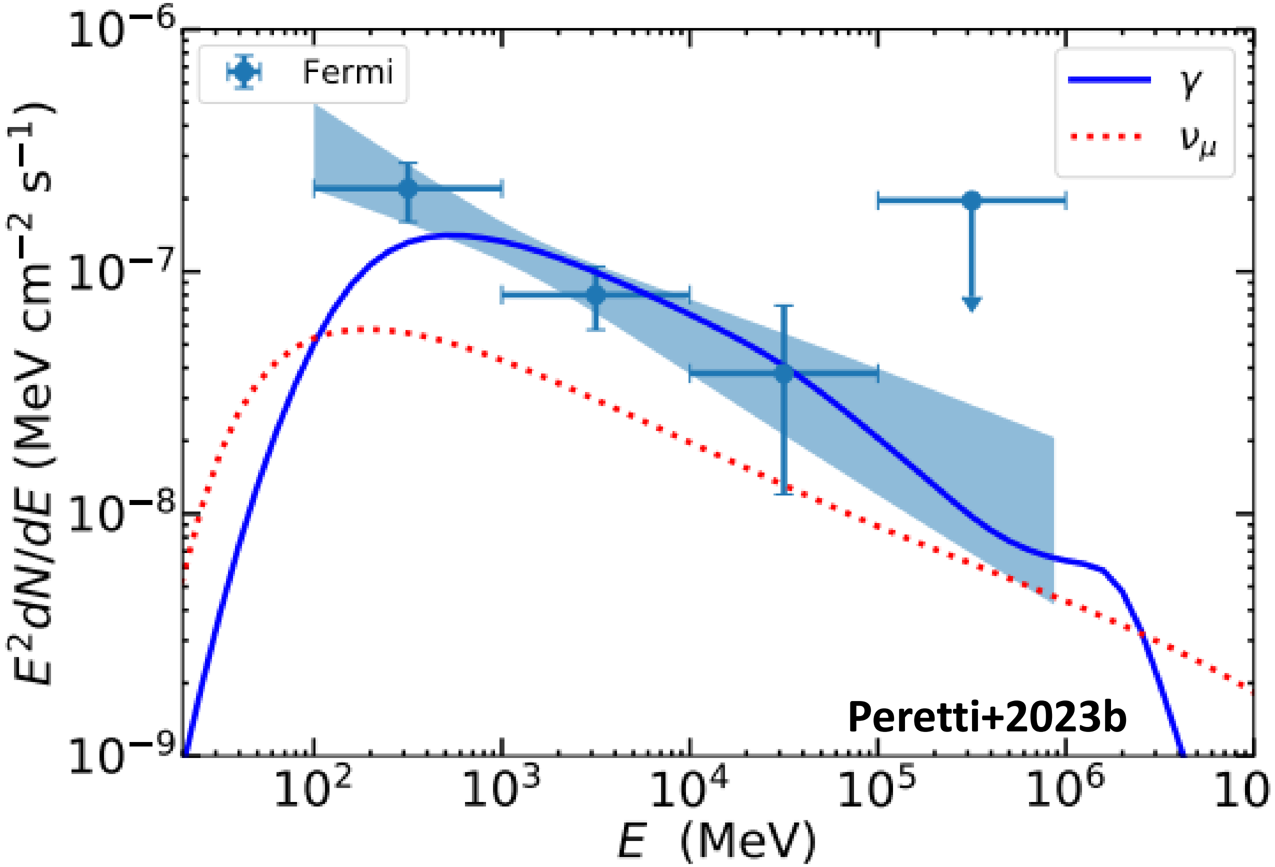


Corona model **Murase 2022**

- For similar 2 zone model studies see also: **Inoue S. et al. 2022** (failed wind/corona + successful wind/torus) and **Eichmann et al. 2022** (corona + starburst ring);
- For possible gamma-ray emission models see: **Lenain 2010** (jet and starburst), **Yoast-Hull+2014** (starburst) and **Lamastra+2016** (AGN wind forward shock model);
- For corona models see: **Murase+2020** and **Inoue Y.+2020**

NGC 4151: THE VERY FIRST UFO DETECTED IN GAMMA RAYS



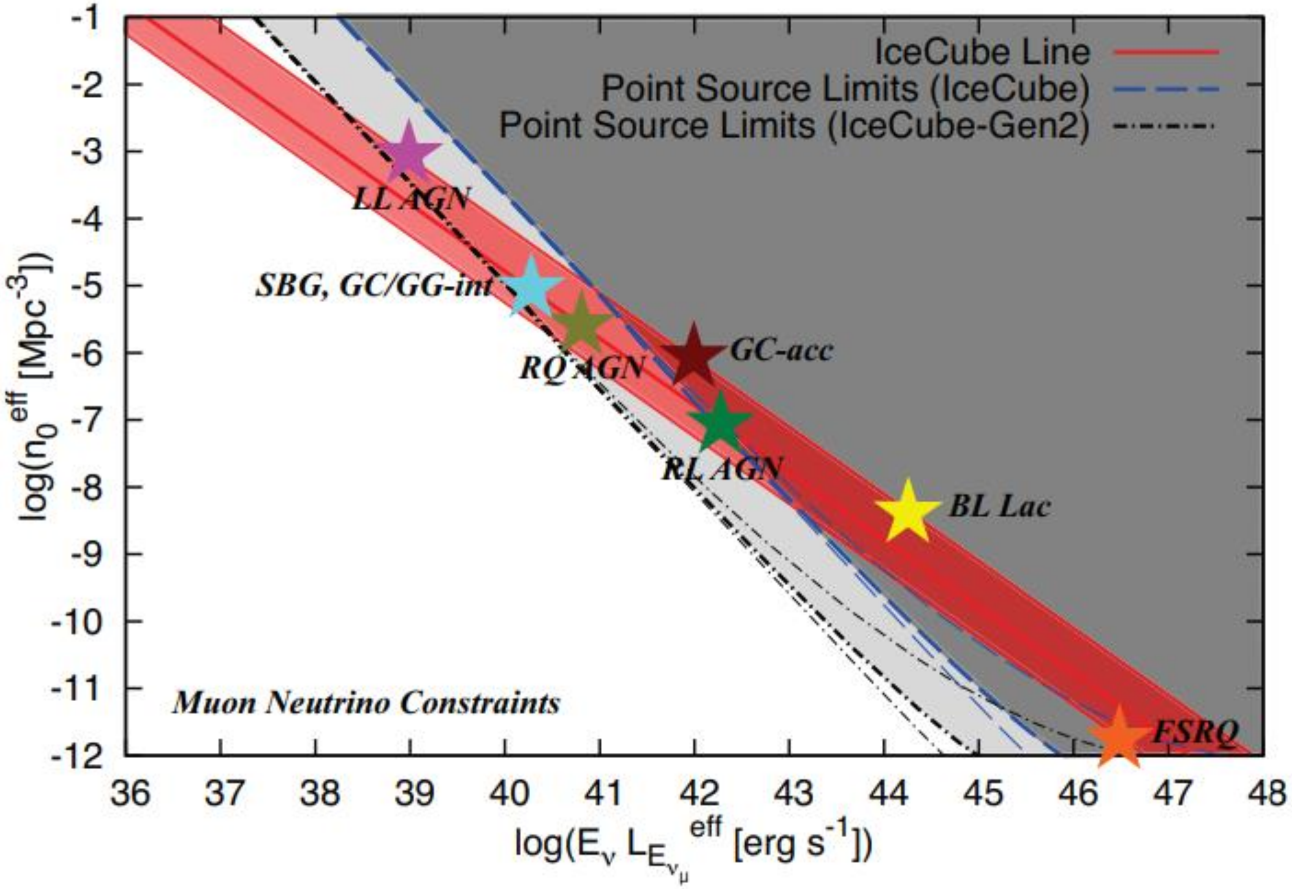


Multimessenger outlook

$$L_{CR} = \eta_{CR}\dot{E}_{kin}$$

$$L_{\nu} = \eta_{\nu}L_{CR} = \eta_{\nu}\eta_{CR}\dot{E}_{kin}$$

Murase+ 2016



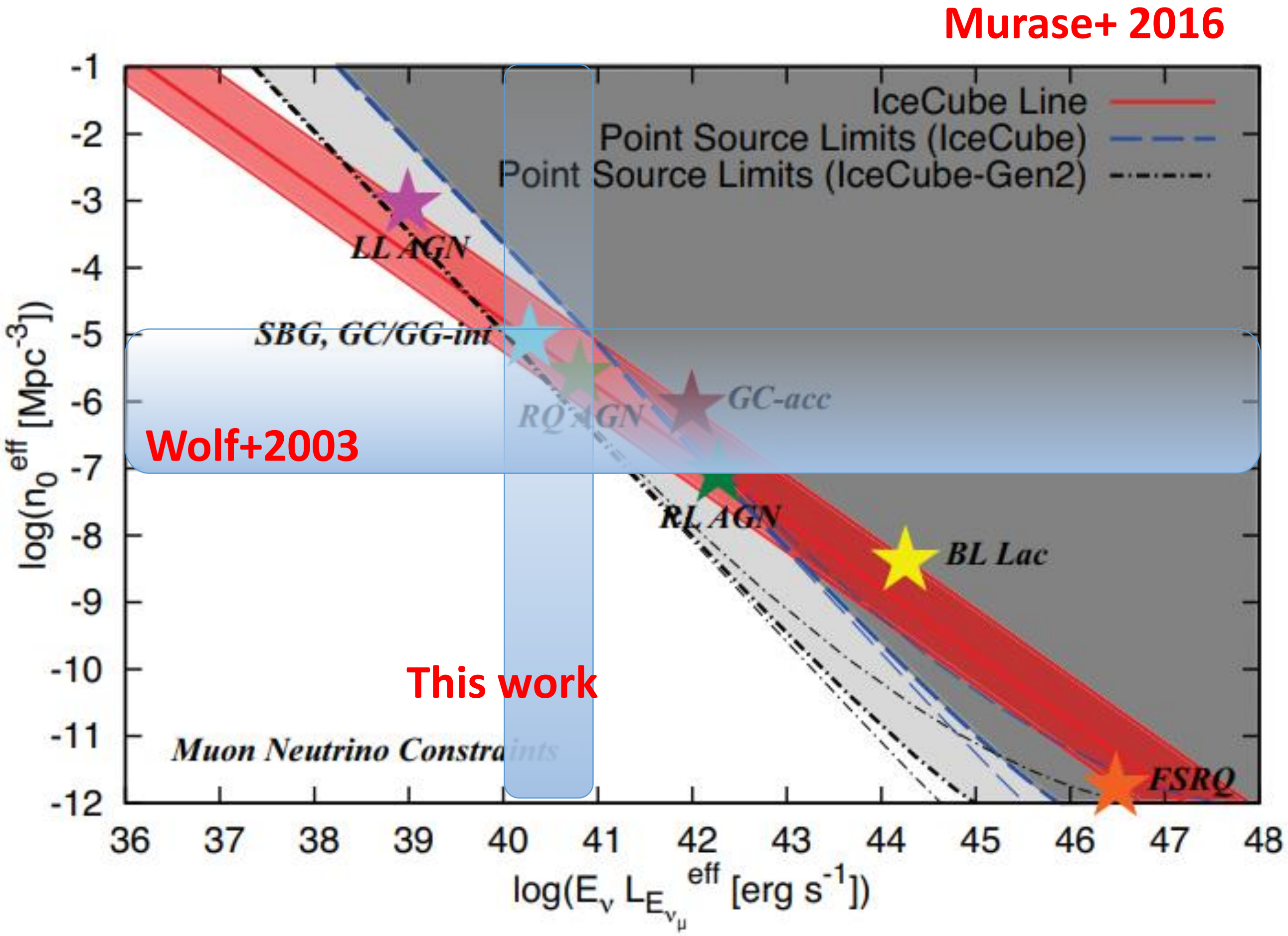
Multimessenger outlook

$$L_{CR} = \eta_{CR}\dot{E}_{kin}$$

$$L_{\nu} = \eta_{\nu}L_{CR} = \eta_{\nu}\eta_{CR}\dot{E}_{kin}$$

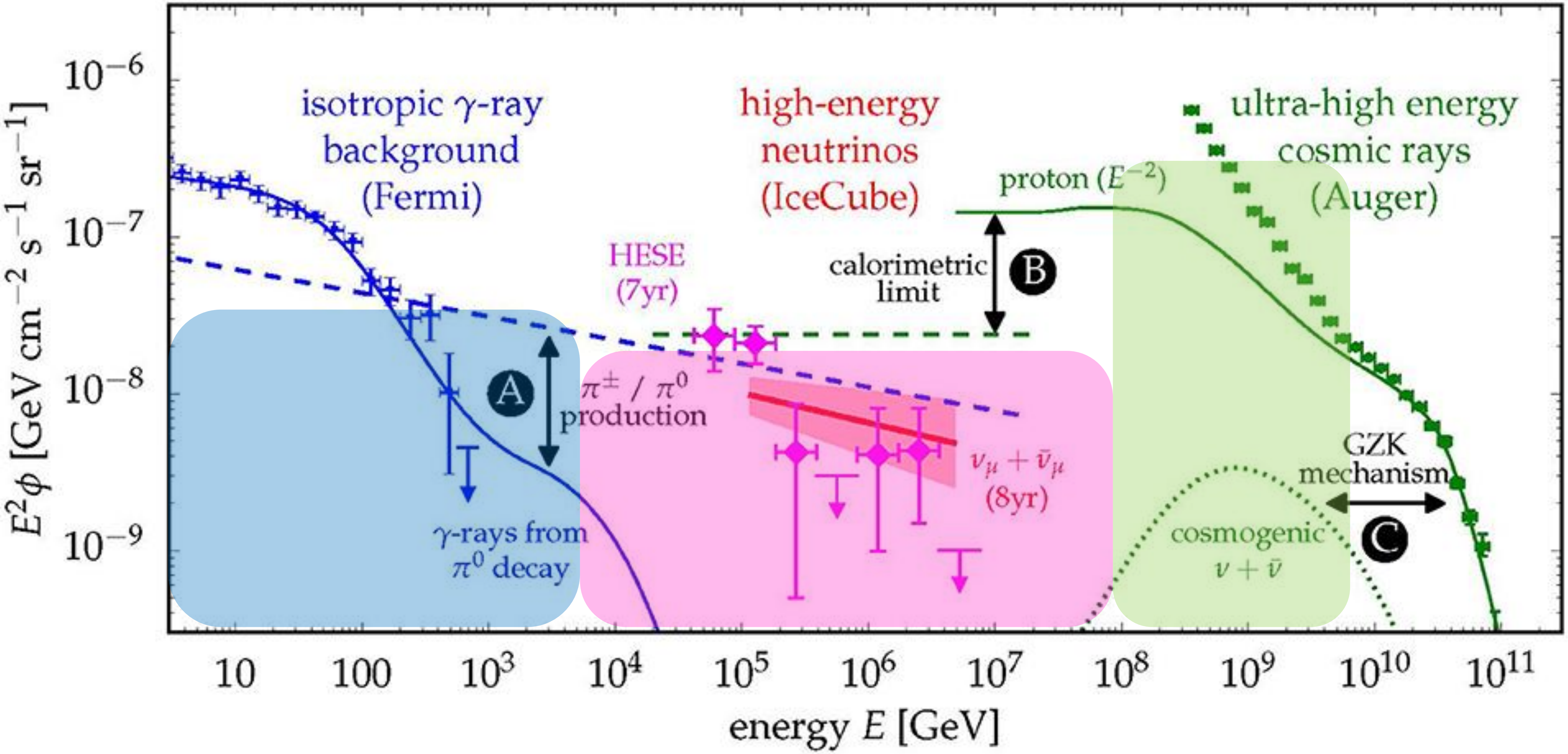
$$\dot{E}_{kin} = \ 10^{44}\ erg/s$$

$$\eta_{\nu} = \eta_{CR} = 0.1$$



Multimessenger outlook - 2

Ahlers+2018



Summary

- DSA can be very efficient at wind termination shocks of diverging flows
- Young massive stellar clusters are interesting Galactic PeV-atron candidates
- Starburst winds can accelerate particles up to 10^2 PeV and their collective contribution could populate the cosmic-ray spectrum between Knee and Ankle
- Ultra-fast outflows can accelerate particles up to EeV and their multi-messenger radiation could sizeably contribute to Fermi-LAT and IceCube diffuse flux

Thanks for your attention!

BACK UP

Acceleration and transport model

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

Technical details

Acceleration slope: s = 4

Wind profile: $u(r) = \ u_1\, \theta[R_{sh} - r] + \ u_2\, \left({}^{R_{sh}}/{}_{r}\right)^2 \theta[r - R_{sh}]$

Matter density: $\rho(r) = \ \dot{M}/4\pi r^2 u(r)$

Magnetic field: $U_B(r) = \ \epsilon_B\, P_{ram}\theta[R_{sh} - r] + 11\, U_B(R_{sh})\theta[r - R_{sh}]$

Diffusion coefficient: $D(r,p) \approx \frac{c\sqrt{r_L l_c}}{3} + \frac{c l_c}{3}(\frac{r_L}{l_c})^2$

Injection: $Q(r,p) = \ \frac{\eta_{CR}(\xi_{CR}) n_1 u_1}{4\pi p^2}\delta\left[p - p_{inj}\right]\delta[r - R_{sh}]$

Normalization: $P_{CR,sh} = \xi_{CR} P_{ram,sh}$

Boundary conditions → inner: $u(r)f - D\partial_r f|_{r=0} = 0$; outer: $f\left(R_{fs}\right) = 0$

Wind Bubble dynamics – Forward shock

$$M(R) = \int_0^R dr\, 4\pi r^2 \rho_0(r)$$

$$\frac{d}{dt}\left[M(R)\dot{R}\right] = 4\pi R^2 P$$

$$\frac{d}{dt}\left[\frac{4}{3}\pi R^3 \frac{P}{\gamma_g - 1}\right] = L_w + 4\pi R^2 \dot{R} P - L_c$$

$$R(t) = At^{-\alpha} \rightarrow \alpha = 3/5$$

Wind Bubble dynamics – Wind shock

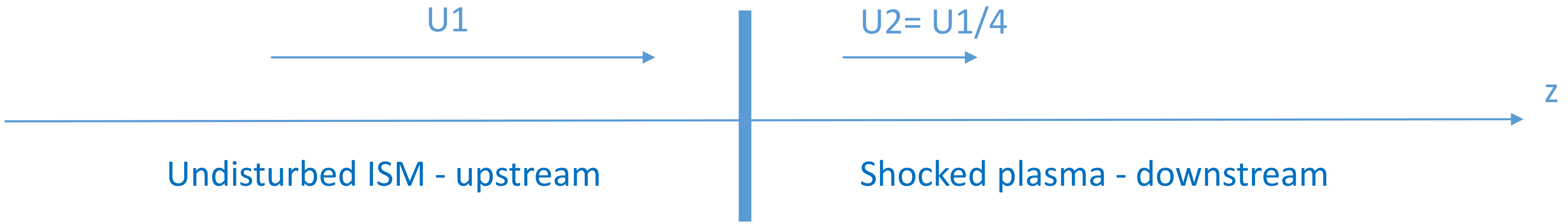
$$P_{ram,sh} = P_0$$

$$\frac{\dot{M} u_1}{4\pi R_{sh}^2} = \frac{7}{25} A^2 \rho_0 t^{-4/5}$$

$$R_{sh}(t) \propto t^{2/5}$$

Transport approach to DSA

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial z} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] + \frac{1}{3}\frac{\partial v}{\partial z}p\frac{\partial f}{\partial p} + Q - \frac{f}{\tau_{loss}}$$



U1

U2= U1/4

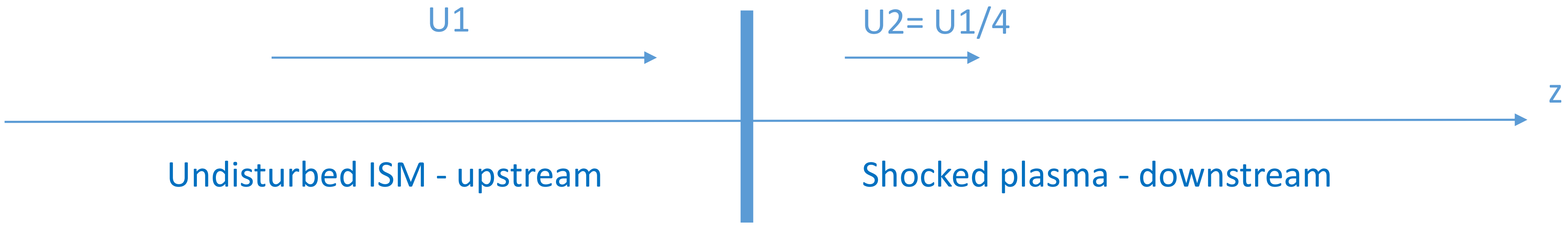
z

Undisturbed ISM - upstream

Shocked plasma - downstream

Transport approach to DSA

$$\overset{\text{STATIONARY}}{\cancel{\frac{\partial f}{\partial t}}} + v\frac{\partial f}{\partial z} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] + \frac{1}{3}\frac{\partial v}{\partial z}p\frac{\partial f}{\partial p} + Q - \overset{\text{NEGLIGIBLE}}{\cancel{\frac{f}{\tau_{loss}}}}$$



U1

U2= U1/4

z

Undisturbed ISM - upstream

Shocked plasma - downstream

Transport approach to DSA

STATIONARY

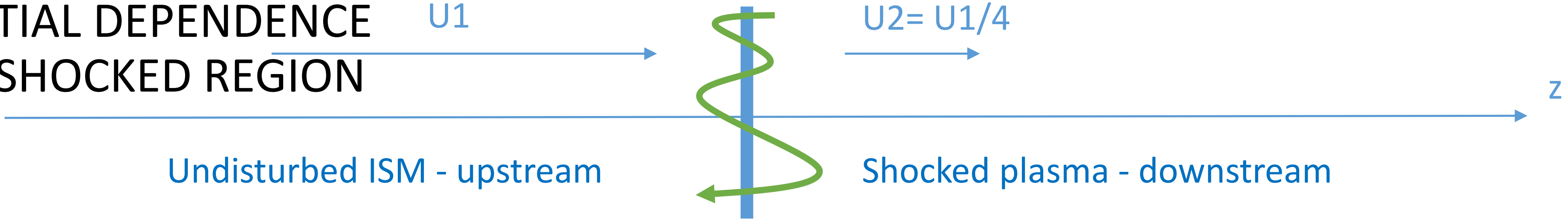
NEGLIGIBLE

$$\cancel{\frac{\partial f}{\partial t}} + v\frac{\partial f}{\partial z} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] + \frac{1}{3}\frac{\partial v}{\partial z}p\frac{\partial f}{\partial p} + Q - \cancel{\frac{f}{\tau_{loss}}}$$

BOUNDARY CONDITIONS:

- NO CRs FAR IN THE ISM
- NO SPATIAL DEPENDENCE IN THE SHOCKED REGION

INJECTION LOCALIZED AT THE SHOCK



Undisturbed ISM - upstream

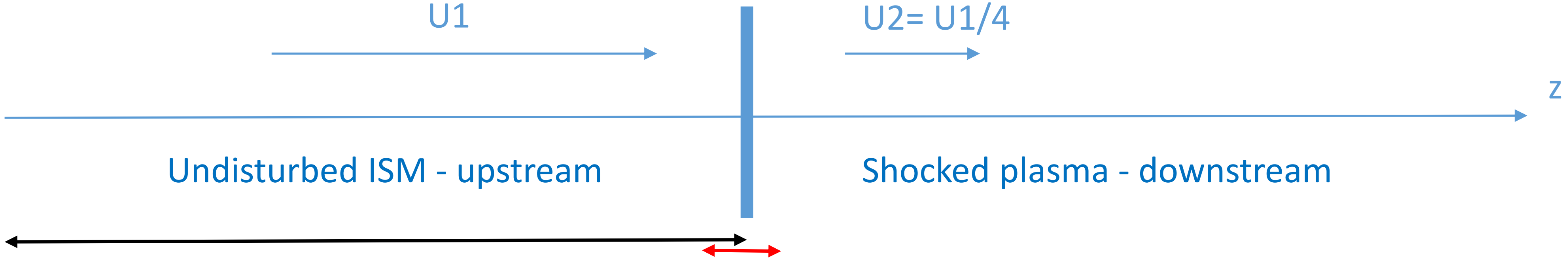
Shocked plasma - downstream

Transport approach to DSA

STATIONARY

NEGLIGIBLE

$$\cancel{\frac{\partial f}{\partial t}} + v\frac{\partial f}{\partial z} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] + \frac{1}{3}\frac{\partial v}{\partial z}p\frac{\partial f}{\partial p} + Q - \cancel{\frac{f}{\tau_{loss}}}$$



$$\int_{-\infty}^{0^-} dz\, T.E.$$

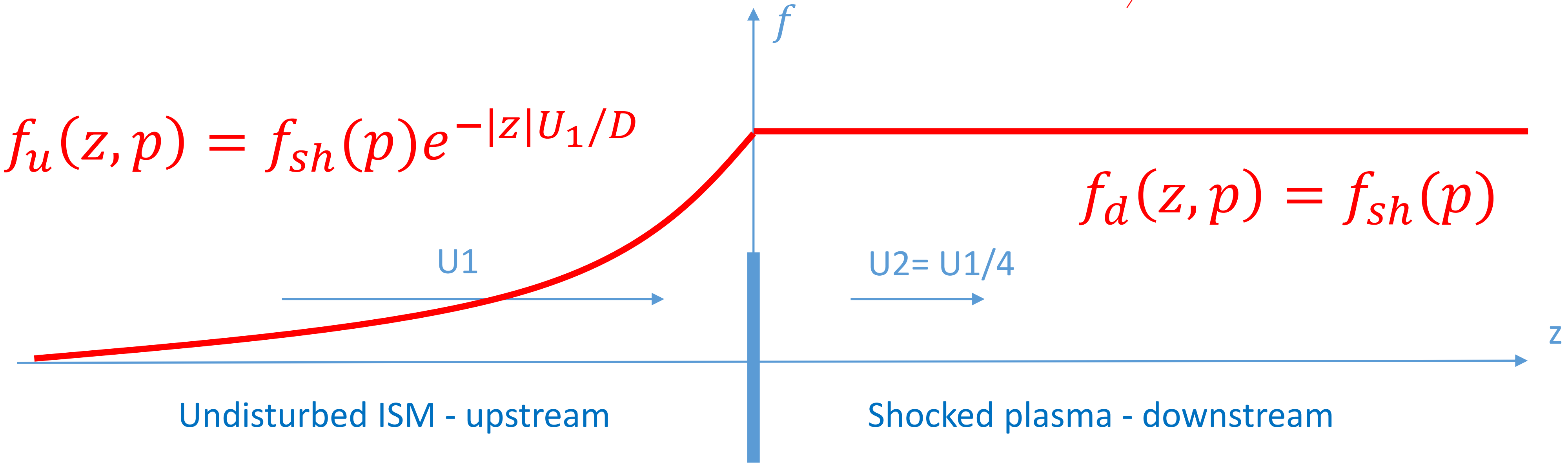
$$\int_{0^-}^{0^+} dz\, T.E.$$

Transport approach to DSA

STATIONARY

NEGLIGIBLE

$$\cancel{\frac{\partial f}{\partial t}} + v\frac{\partial f}{\partial z} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] + \frac{1}{3}\frac{\partial v}{\partial z}p\frac{\partial f}{\partial p} + Q - \cancel{\frac{f}{\tau_{loss}}}$$



$$f_u(z,p) = f_{sh}(p)e^{-|z|U_1/D}$$

$$f_d(z,p) = f_{sh}(p)$$

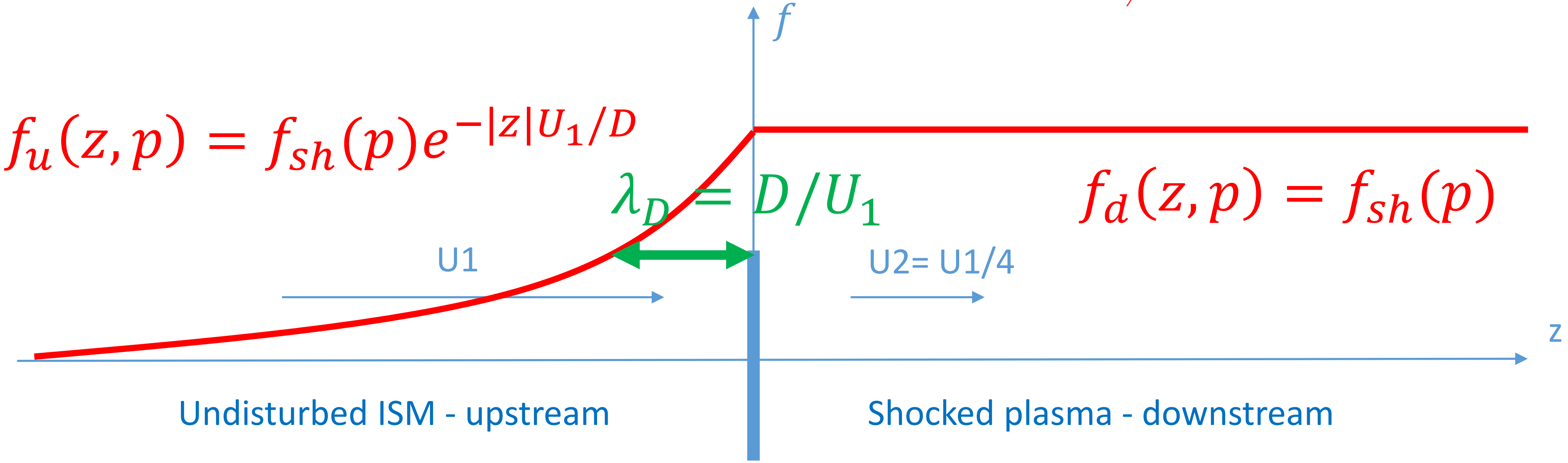
Undisturbed ISM - upstream

Shocked plasma - downstream

Transport approach to DSA

STATIONARY NEGLIGIBLE

$$\cancel{\frac{\partial f}{\partial t}} + v\frac{\partial f}{\partial z} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] + \frac{1}{3}\frac{\partial v}{\partial z}p\frac{\partial f}{\partial p} + Q - \cancel{\frac{f}{\tau_{loss}}}$$



$$f_u(z,p) = f_{sh}(p)e^{-|z|U_1/D}$$

$$\lambda_D = D/U_1$$

$$f_d(z,p) = f_{sh}(p)$$

Undisturbed ISM - upstream

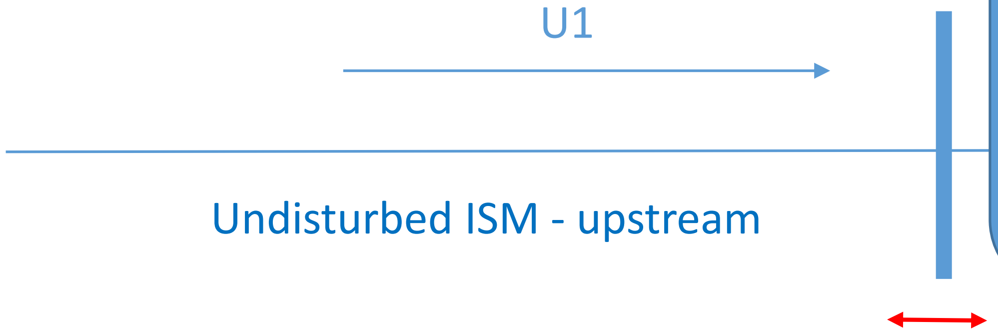
Shocked plasma - downstream

Transport approach to DSA

STATIONARY

NEGLIGIBLE

$$\cancel{\frac{\partial f}{\partial t}} + v\frac{\partial f}{\partial z} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] + \frac{1}{3}\frac{\partial v}{\partial z}p\frac{\partial f}{\partial p} + Q - \cancel{\frac{f}{\tau_{loss}}}$$



$$\int_{0^-}^{0^+} dz\, T.E.$$

$$s = \frac{3U_1}{U_1 - U_2} \rightarrow strong\ shock \ \rightarrow 4$$

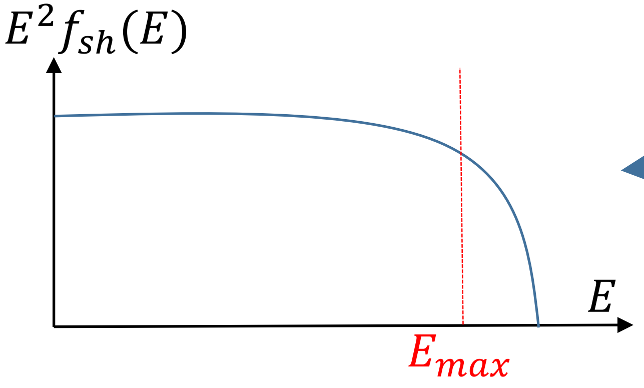
$$f_{sh}(p) \propto \left(\frac{p}{p_{inj}}\right)^{-s} \rightarrow f_{sh}(E \approx pc) \sim E^{2-s}$$

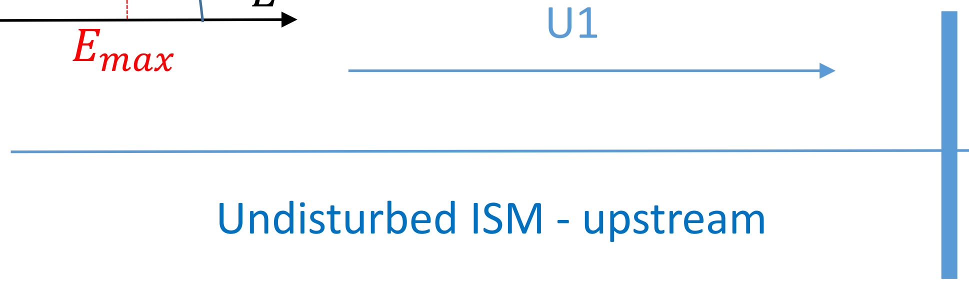
Transport approach to DSA

STATIONARY

NEGLIGIBLE

$$\cancel{\frac{\partial f}{\partial t}} + v\frac{\partial f}{\partial z} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] + \frac{1}{3}\frac{\partial v}{\partial z}p\frac{\partial f}{\partial p} + Q - \cancel{\frac{f}{\tau_{loss}}}$$





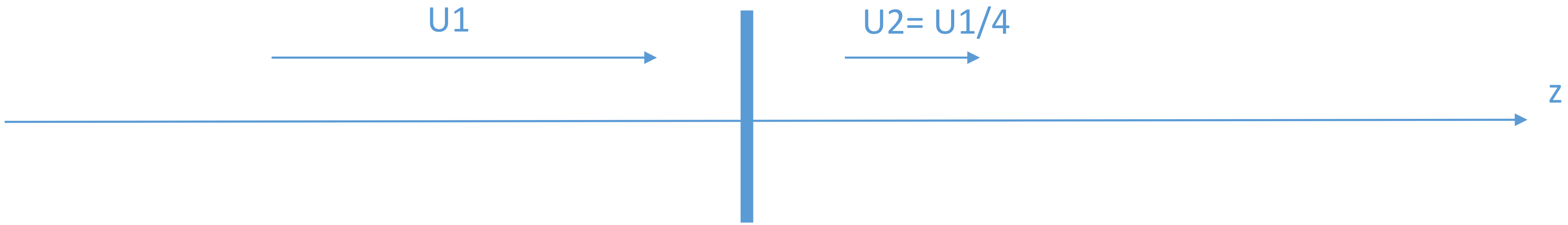
Undisturbed ISM - upstream

$$s = \frac{3U_1}{U_1 - U_2} \rightarrow strong\ shock\ \rightarrow 4$$

$$f_{sh}(p) \propto \left(\frac{p}{p_{inj}}\right)^{-s} \rightarrow f_{sh}(E \approx pc) \sim E^{2-s}$$

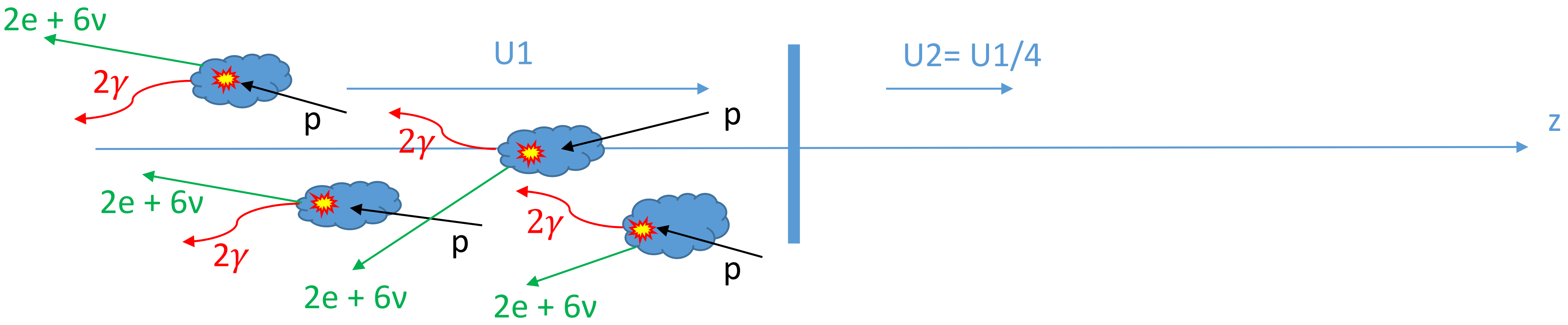
Observing DSA sites

$$\cancel{\frac{\partial f}{\partial t}} + v\frac{\partial f}{\partial z} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] + \frac{1}{3}\frac{\partial v}{\partial z}p\frac{\partial f}{\partial p} + Q \enclose{circle}{- \frac{f}{\tau_{loss}}}$$

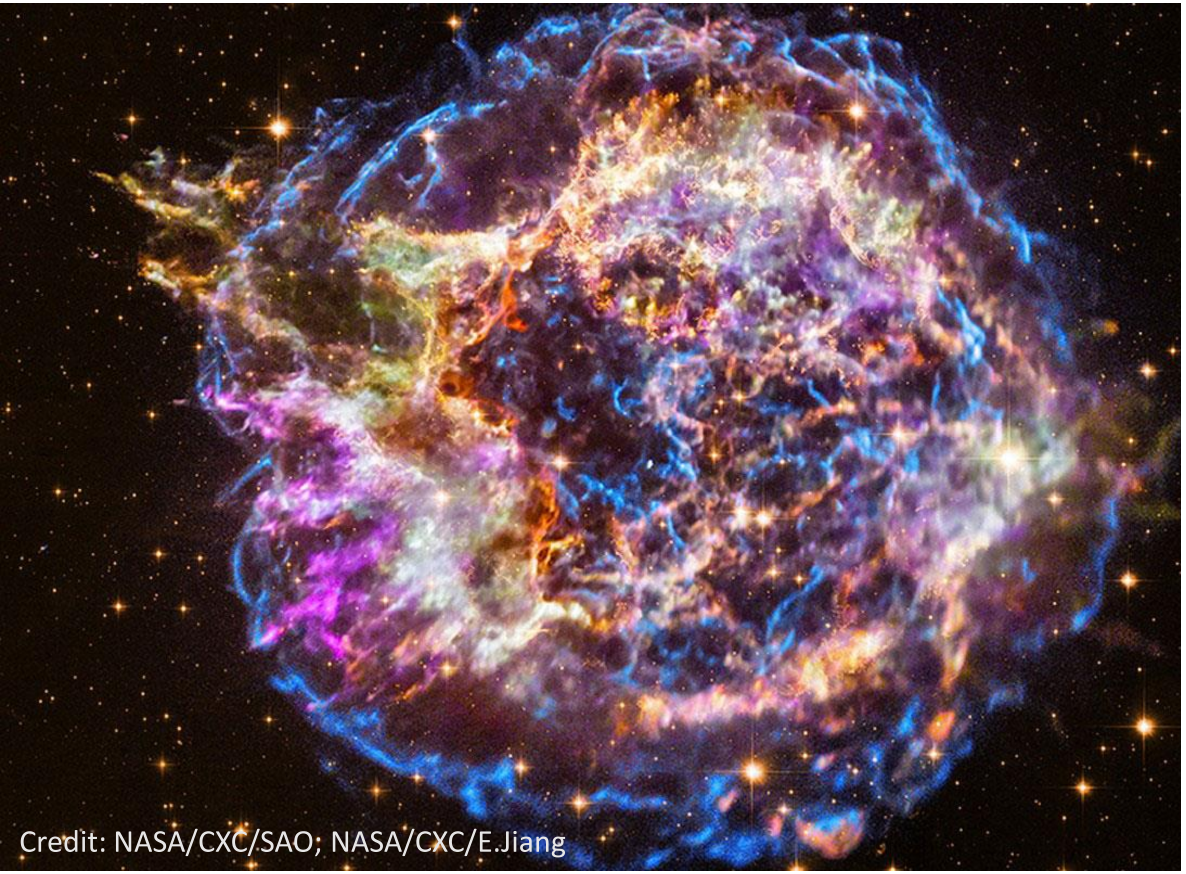


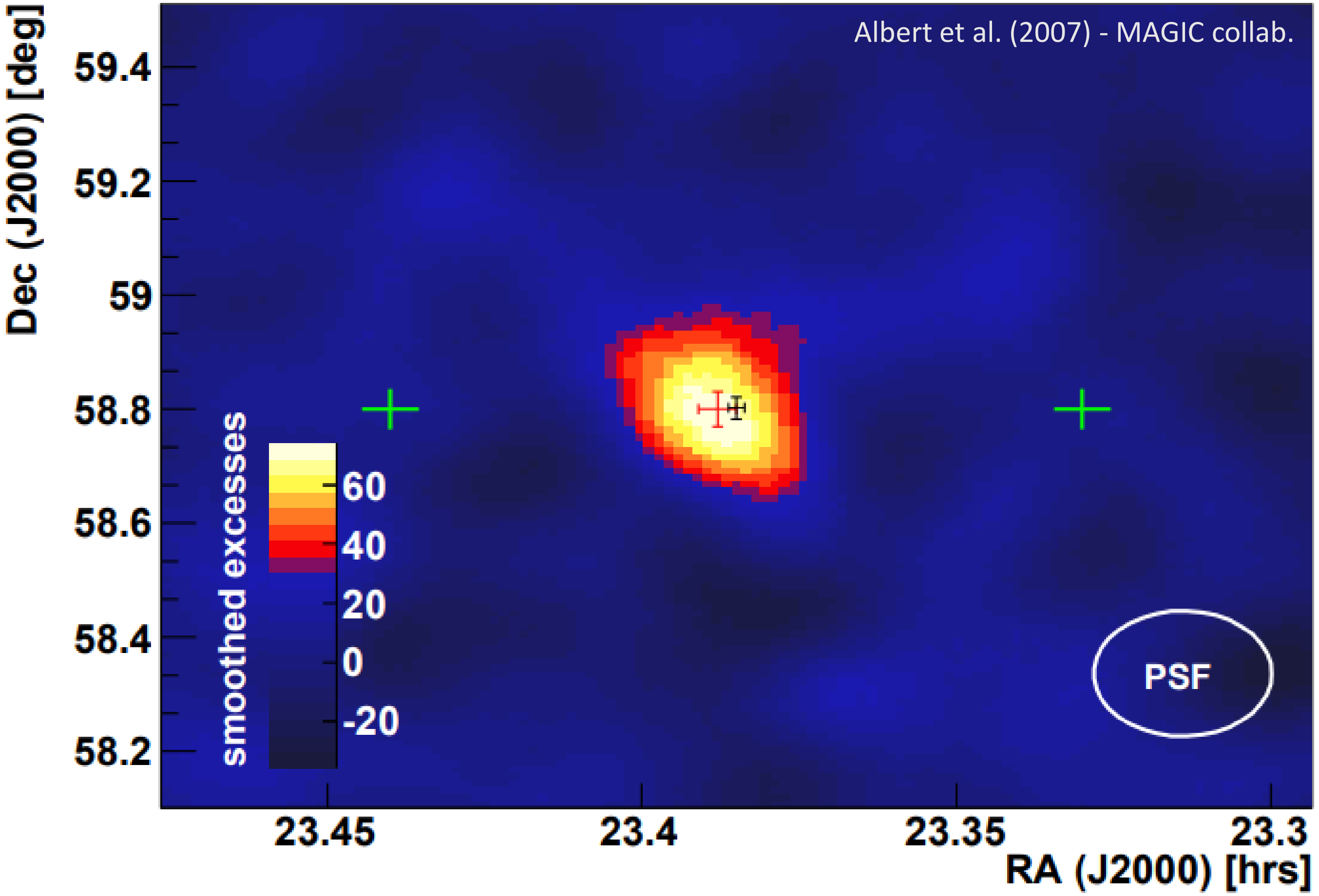
Observing DSA sites

$$\cancel{\frac{\partial f}{\partial t}} + v\frac{\partial f}{\partial z} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] + \frac{1}{3}\frac{\partial v}{\partial z}p\frac{\partial f}{\partial p} + Q - \frac{f}{\tau_{loss}}$$



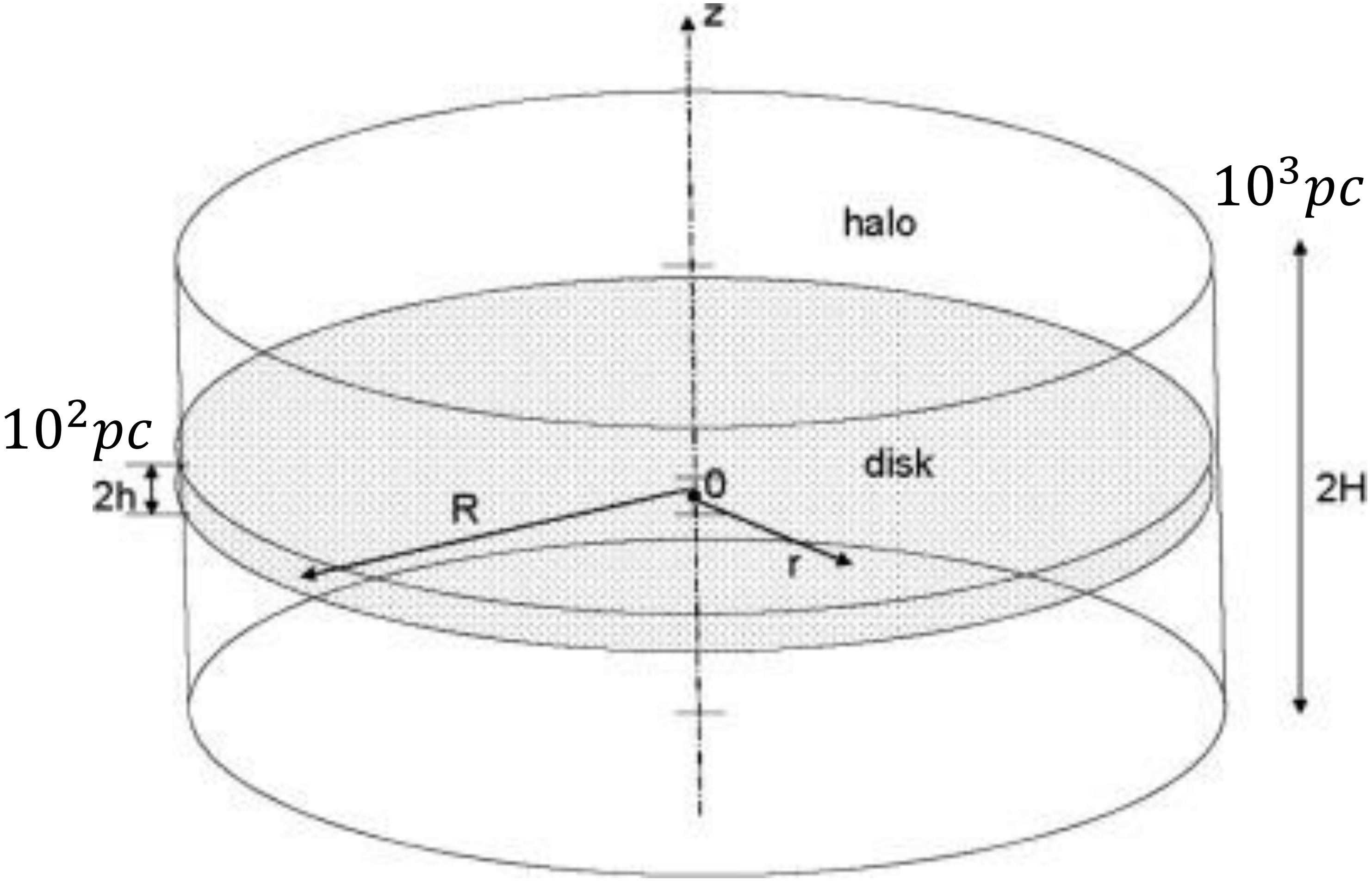
The supernova remnant paradigm


Credit: NASA/CXC/SAO; NASA/CXC/E.Jiang


Albert et al. (2007) - MAGIC collab.

Blandford+1978, Bell2005, Amato+2009, Morlino+2011, Cristofari+2013, Nava+2016, Celli+2018, Phan+2020, Pais+2020, Recchia+2021, Jacobs+2021

The supernova remnant paradigm



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Shortcoming?

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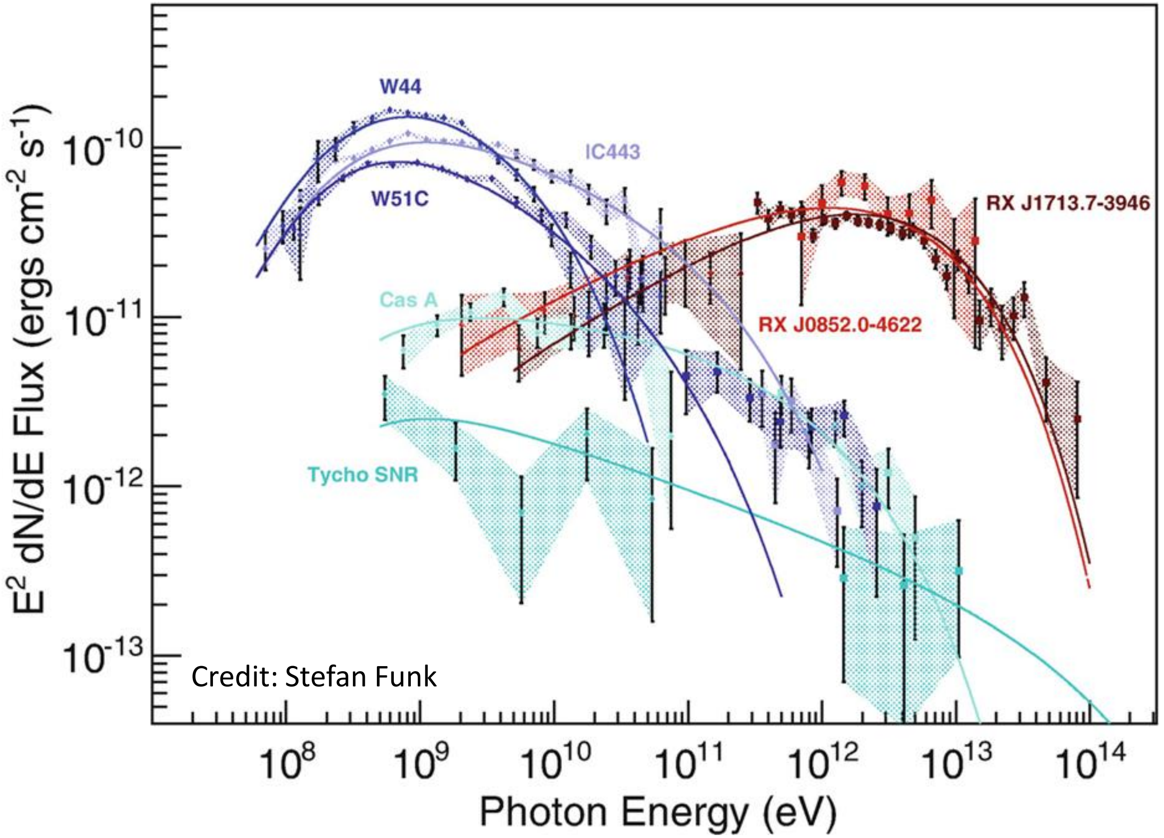
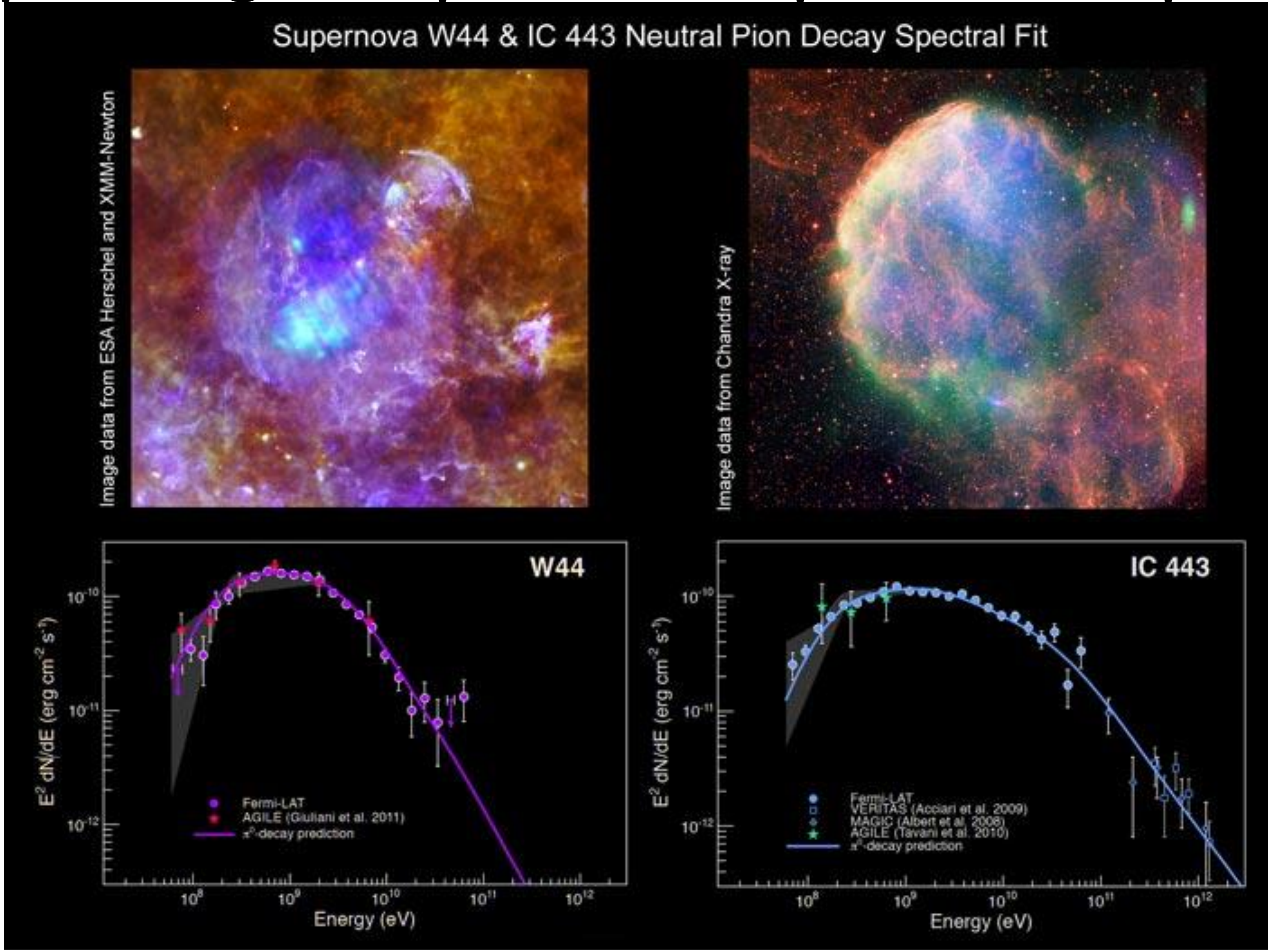
The supernova remnant paradigm

- SNRs can potentially explain the bulk of Galactic CRs
- SNRs can hardly produce the Galactic CRs up to the Knee (a few PeV)



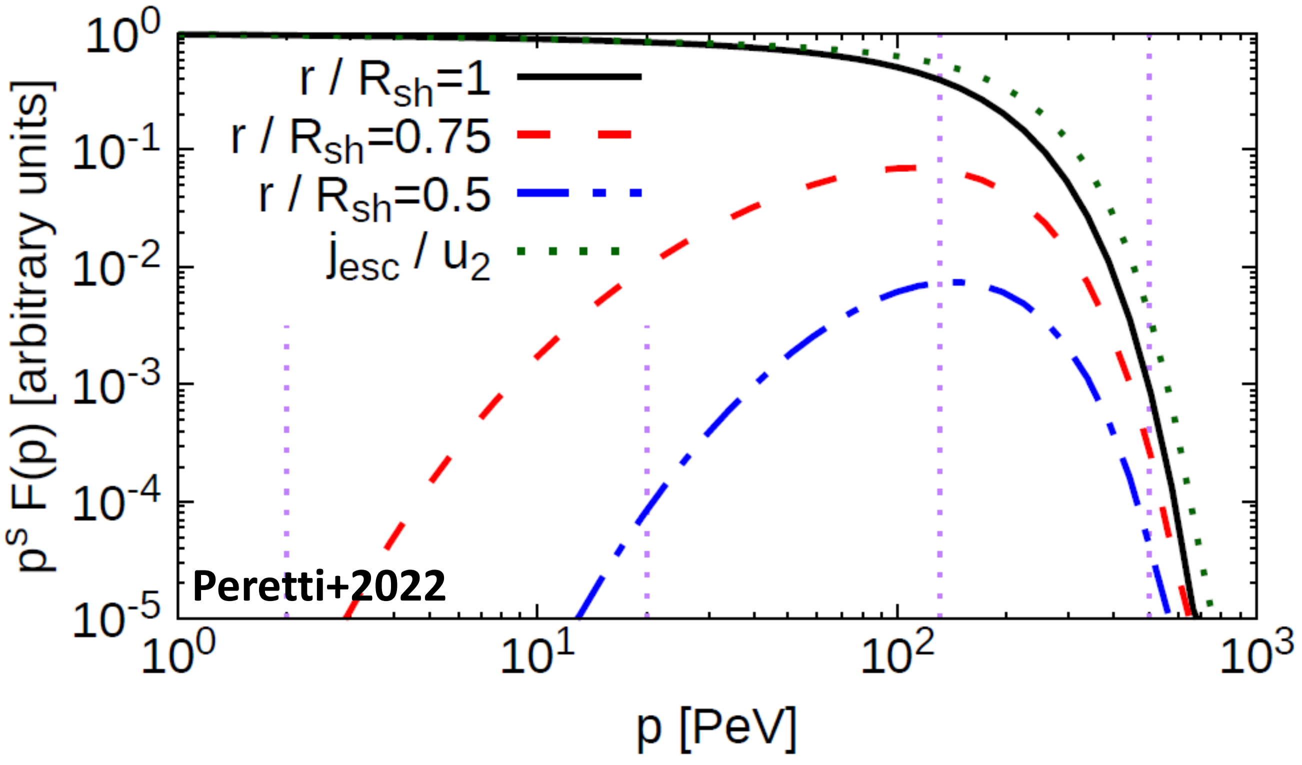
Credit: Stefan Funk

Spotting the pion bump in SNR spectra



Credit: NASA / DOE / Fermi-LAT Collaboration, Chandra X-ray Observatory, ESA; Herschel / XMM-Newton

SBGs – Maximum Energy



Parameters

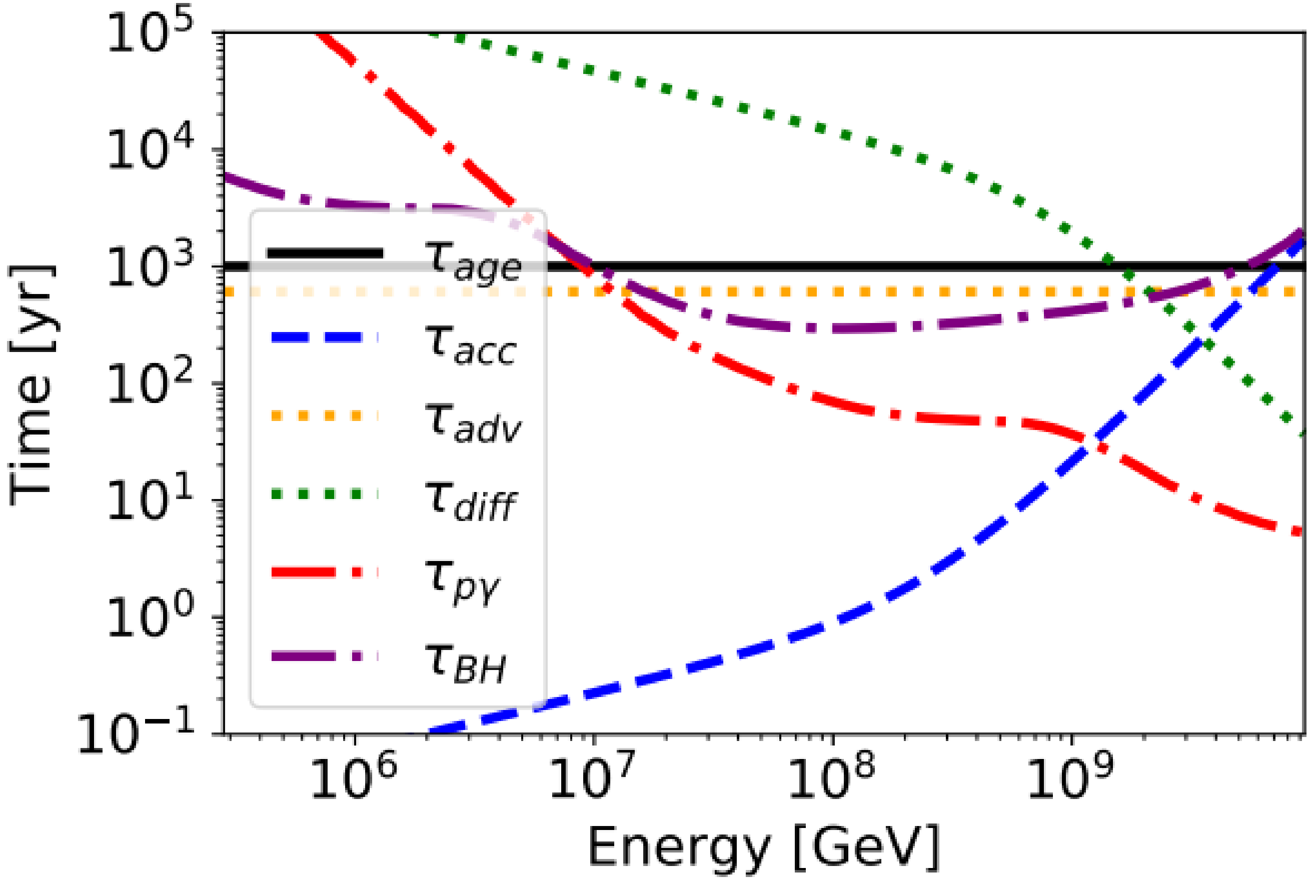
$$\dot{M} = 10\, M_{\odot}\, yr^{-1}$$

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

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

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

The prototype UFO



Parameter	benchmark
u_1/c	0.2
$\dot{M}$ [$\mathrm{M}_\odot$ yr^{-1}]	10^{-1}
ξ_{CR}	0.05
ϵ_{B}	0.05
l_c [pc]	10^{-2}
δ	3/2
L_X [erg s^{-1}]	10^{44}
n_{ISM} [cm^{-3}]	10^4
t_{age} [yr]	10^3