Cosmic ray acceleration and multi-messenger radiation from wind bubbles

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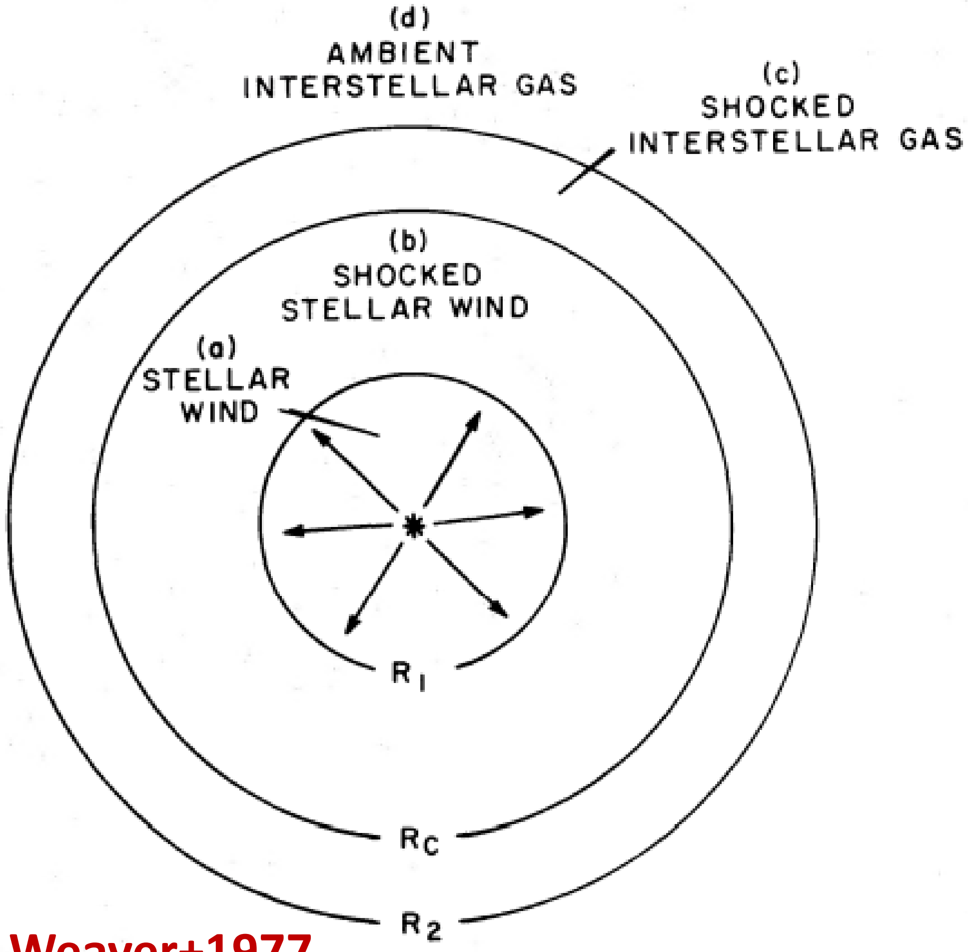
Cosmic Rays in the Multi-Messenger Era
5-7 December 2022, APC Laboratory (Paris)

VILLUM FONDEN
UNIVERSITY OF COPENHAGEN
Niels Bohr Institutet
The Niels Bohr International Academy
Co-financed by the Connecting Europe Facility of the European Union

Outline

- Wind bubbles: structure, evolution and state-of-art
- Diffusive shock acceleration at the wind termination shock
- Some applications: YMSCs, SBGs & AGNi

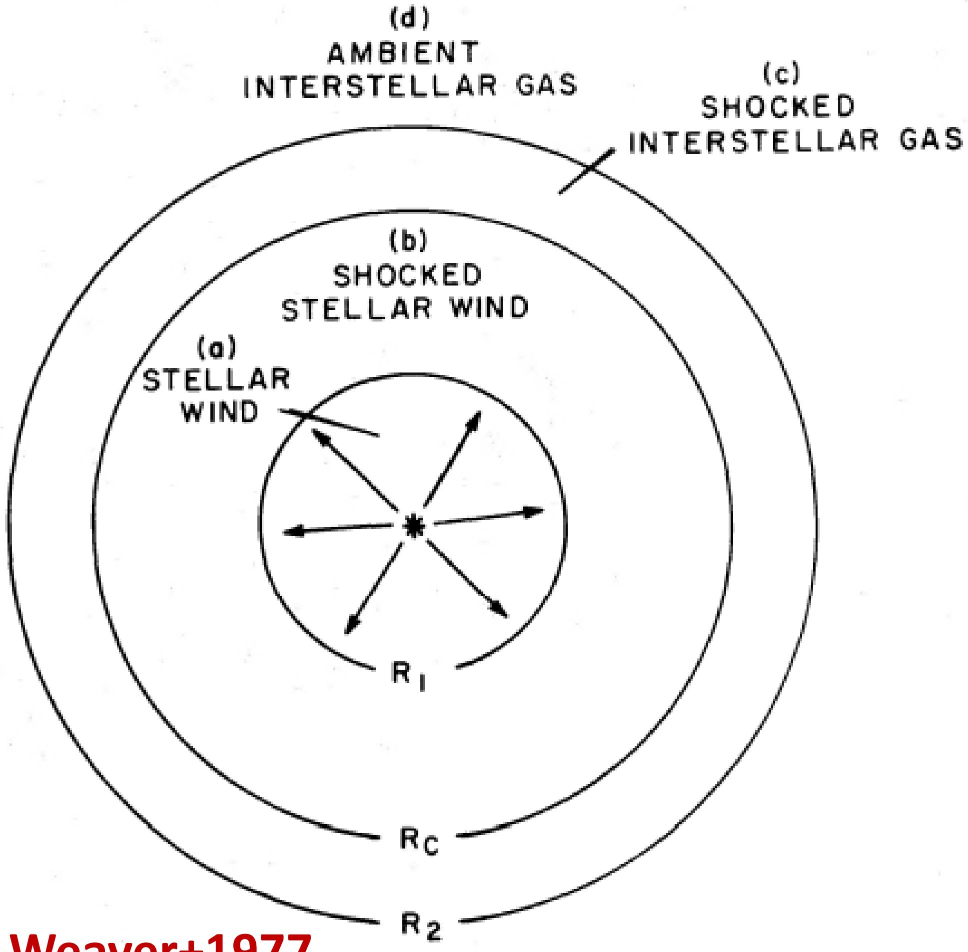
Wind Bubbles



Weaver+1977
Koo & McKee1992

- A wind bubble is a cavity in the interstellar medium resulting from the activity of a compact source blowing a steady flow with high velocity and large opening angle

Wind Bubbles



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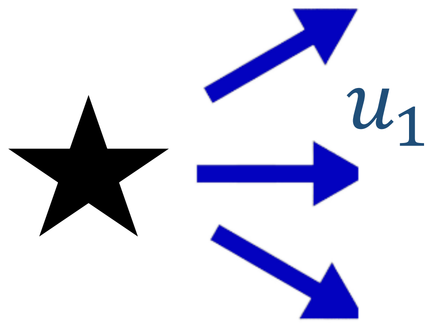
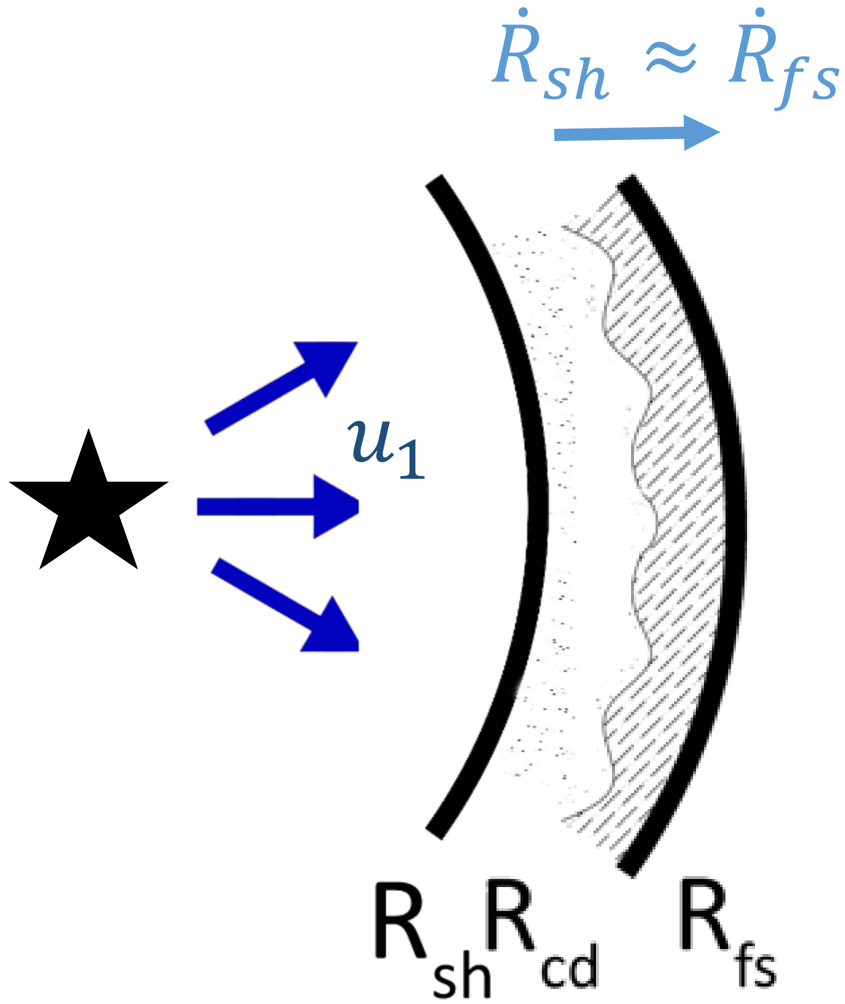
- Macroscopic parameters:
  1. Terminal wind speed: V_∞
  2. Mass loss rate: $\dot{M}$
  3. Age and surroundings: t_{age}, n_0

Wind bubble: structure and evolution



1. The outflow is launched - t_0

Wind bubble: structure and evolution



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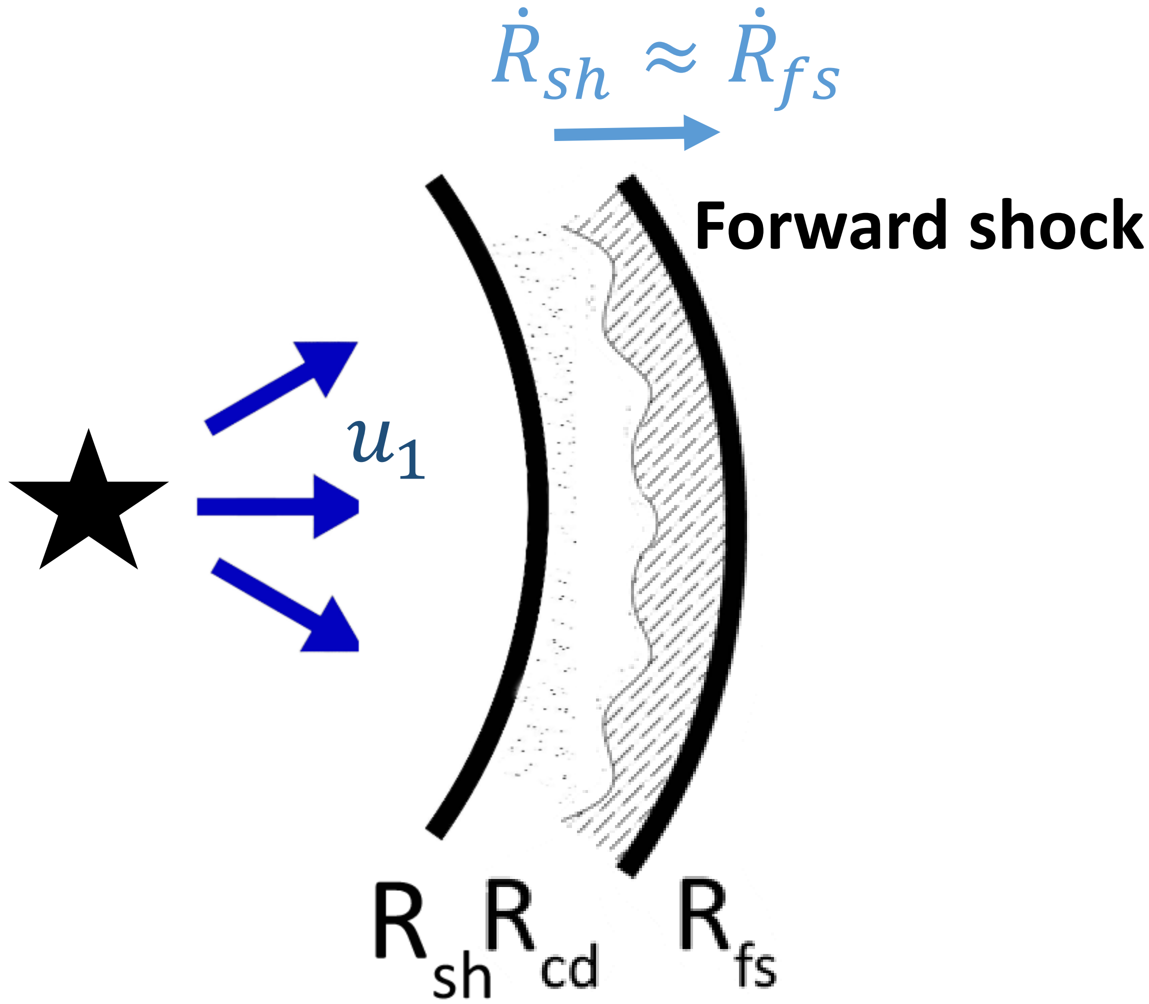

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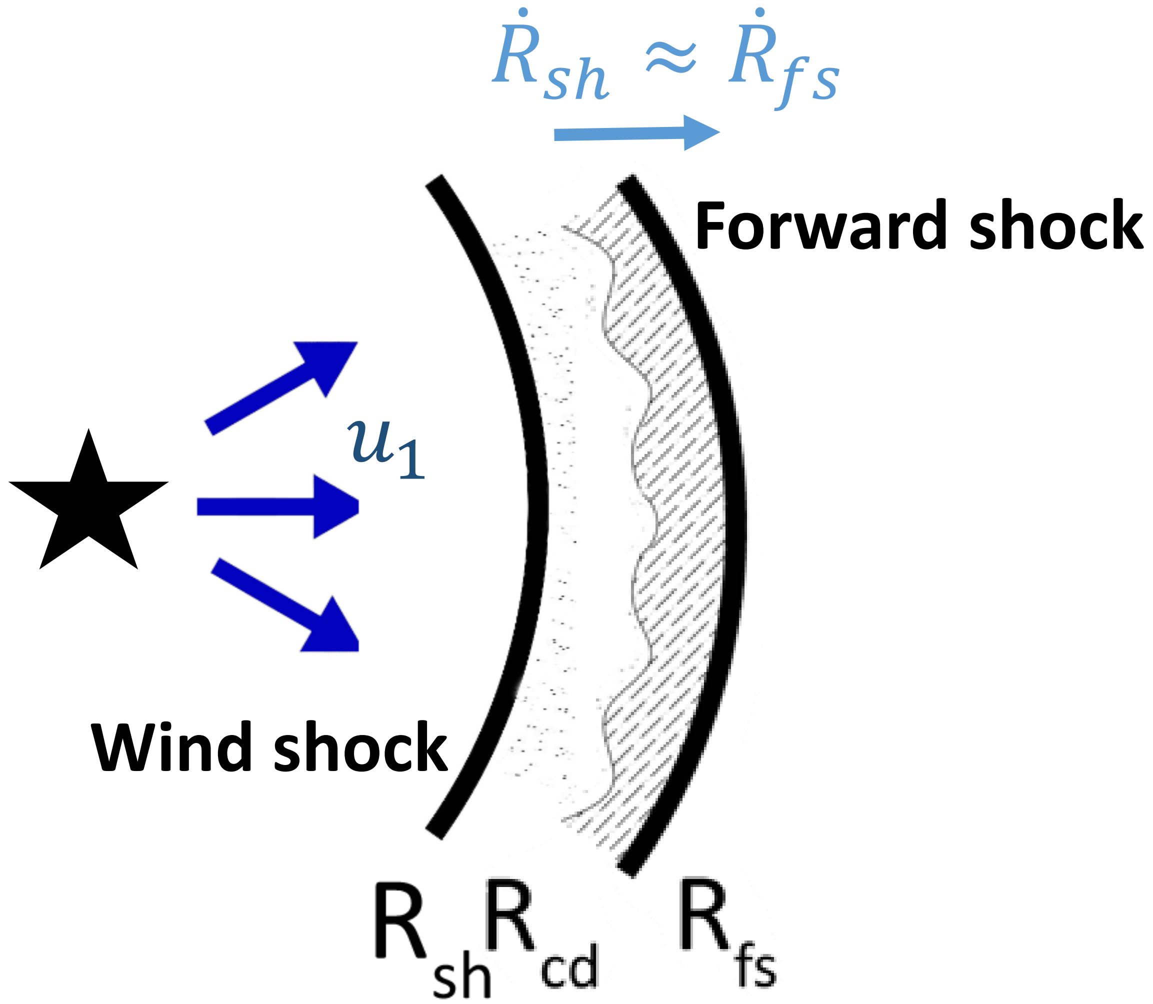

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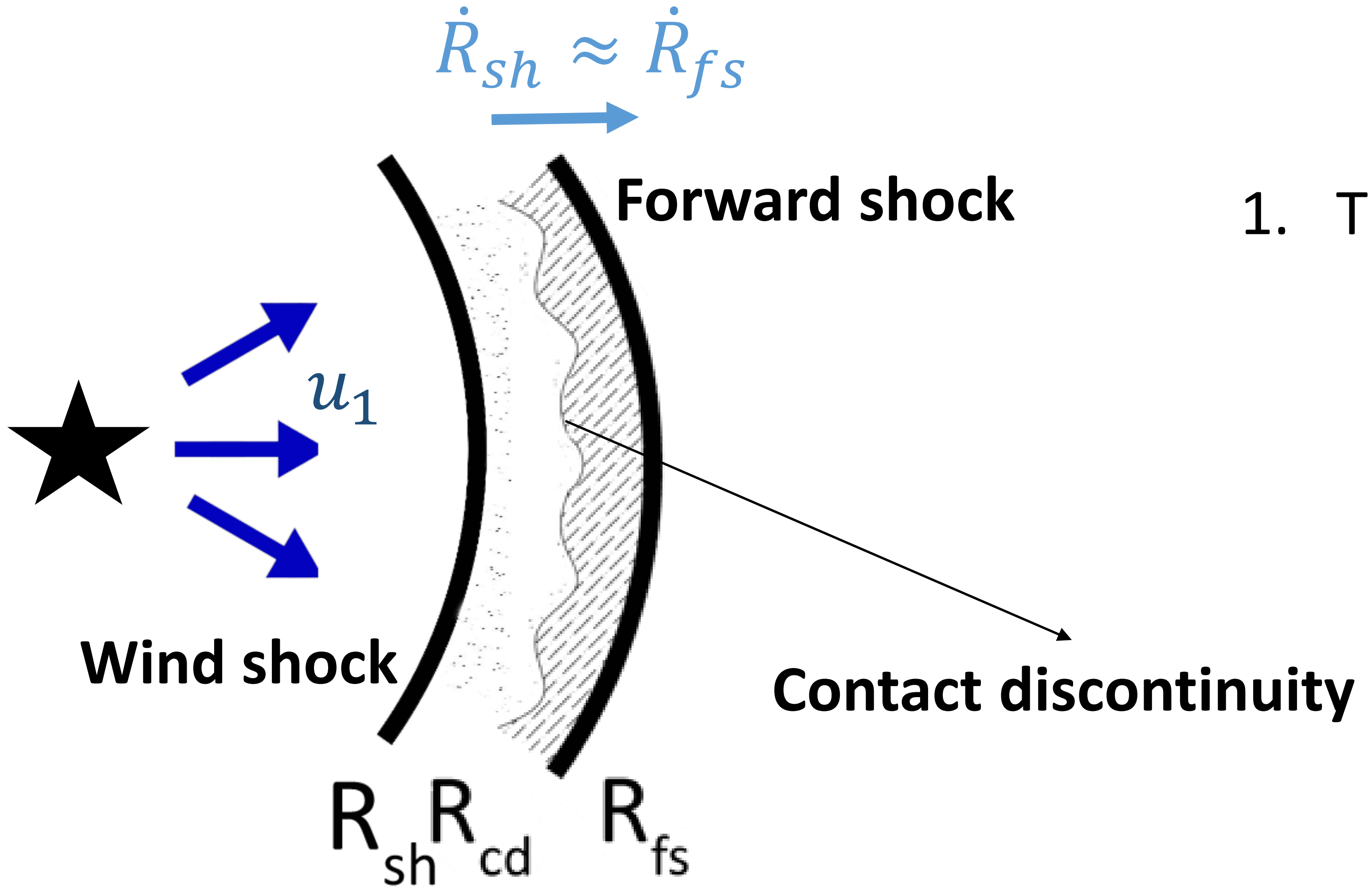

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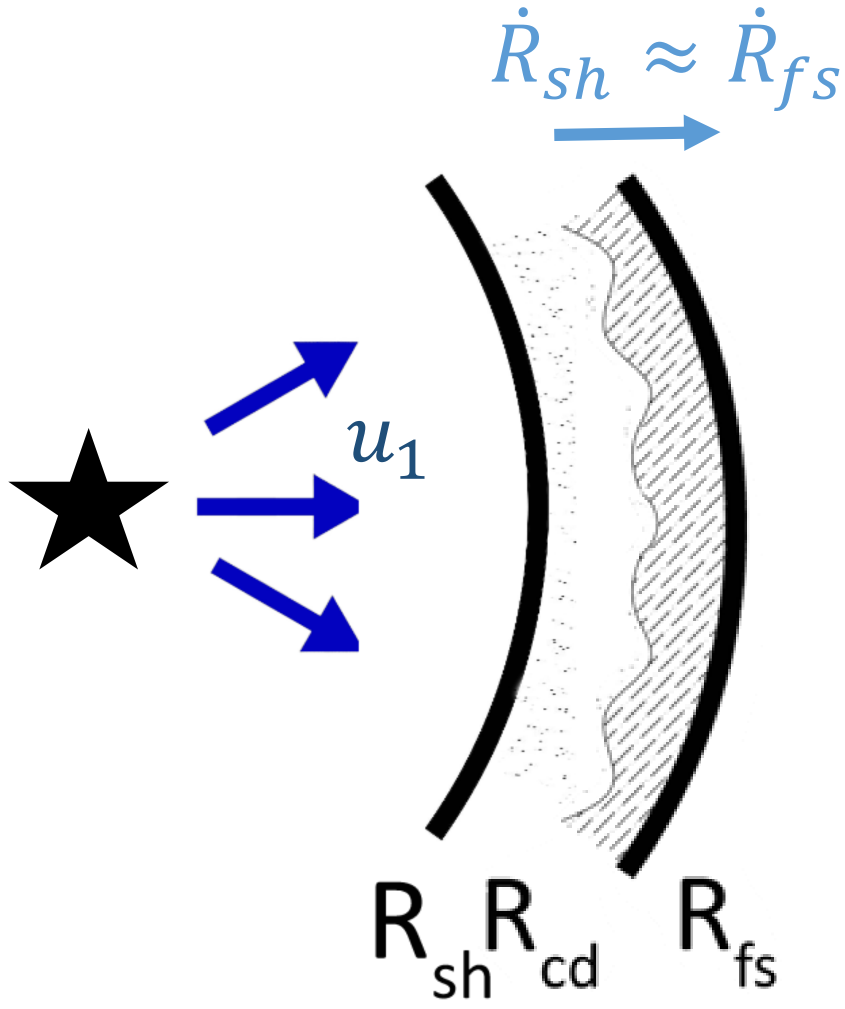
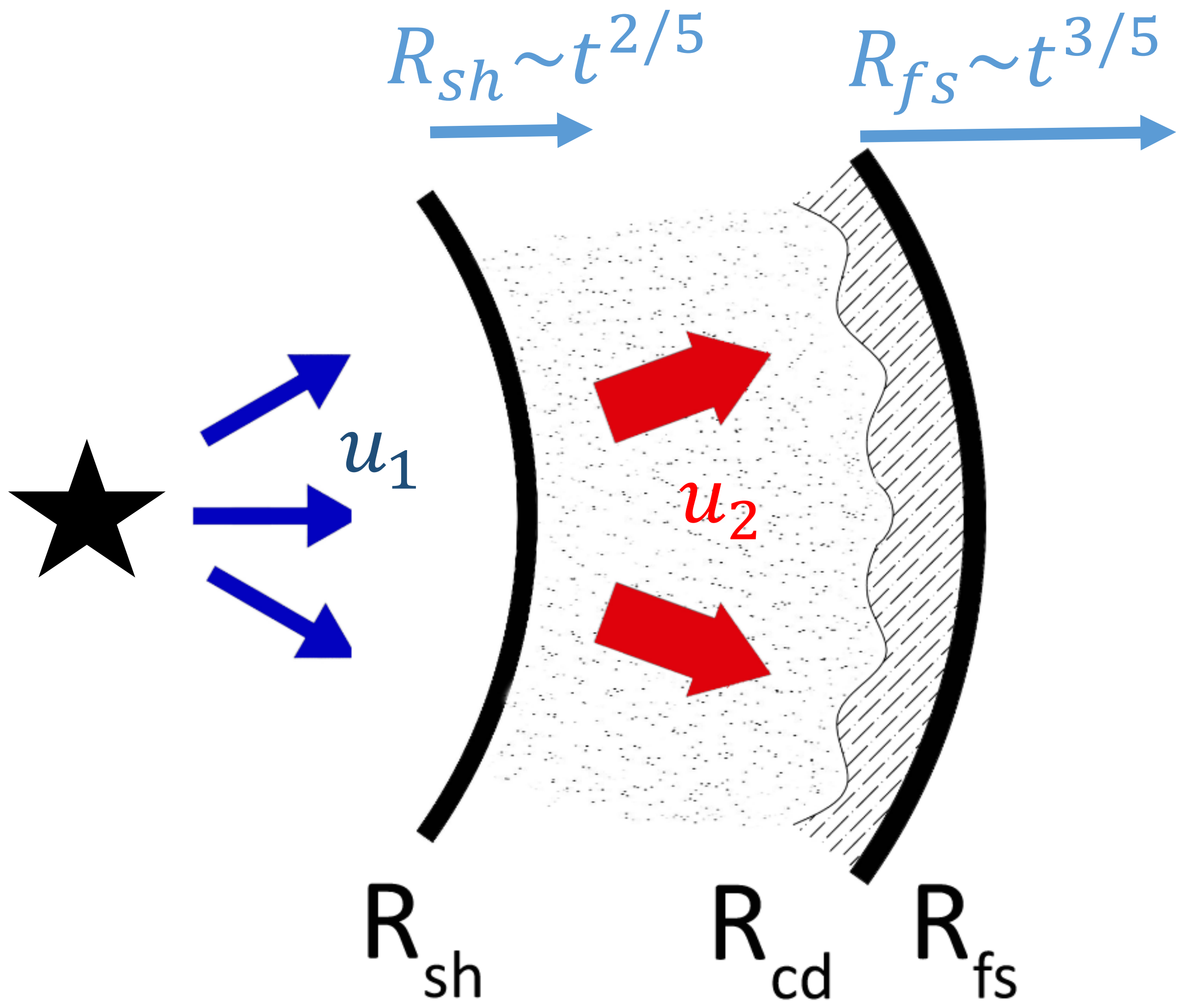


1. The outflow is launched - t_0
2. Free expansion phase - t_1

Wind bubble: structure and evolution



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

Recent developments in Galactic wind bubbles

Stellar wind bubbles and superbubbles have long been considered as promising site for the acceleration of Galactic cosmic rays

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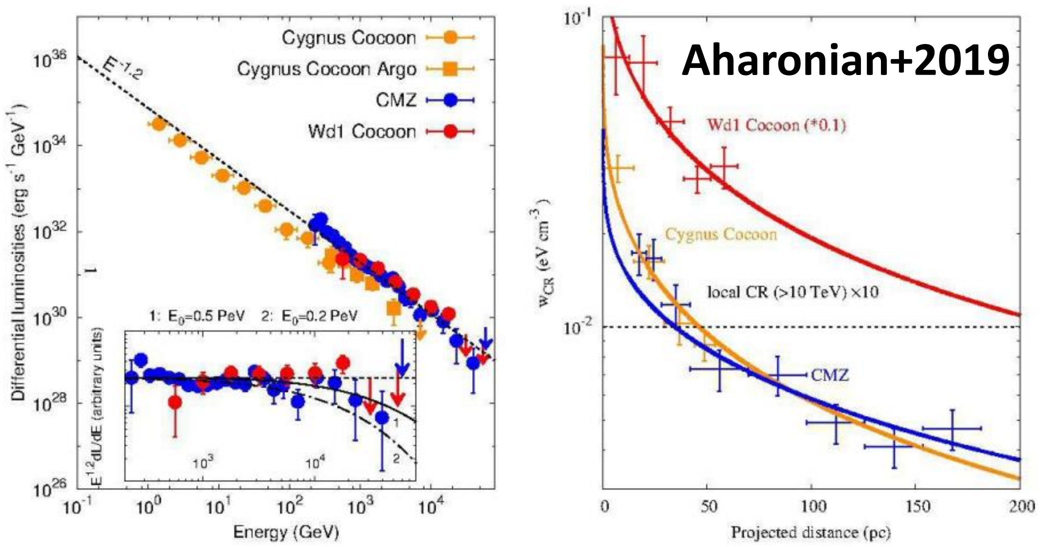
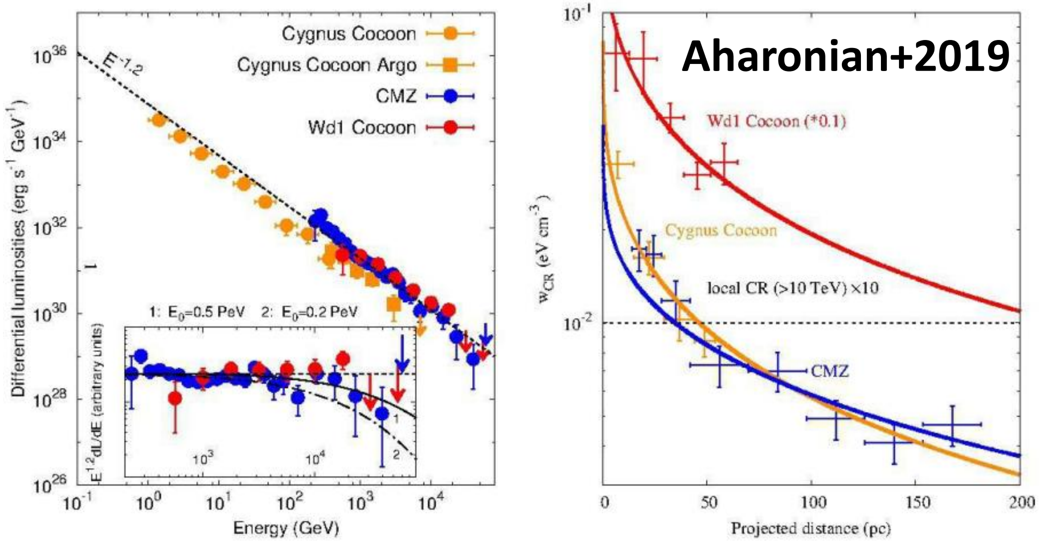
Cassé+1980-1982, Volk+1982, Cesarsky+1983, Webb+1985, Bykov+1992, Parizot+2004, Ferrand+2009, Zirakashvili+2017

Recent developments in Galactic wind bubbles



Recent gamma-ray observations brought the attention back to young stars

Recent developments in Galactic wind bubbles



Aharonian+2019

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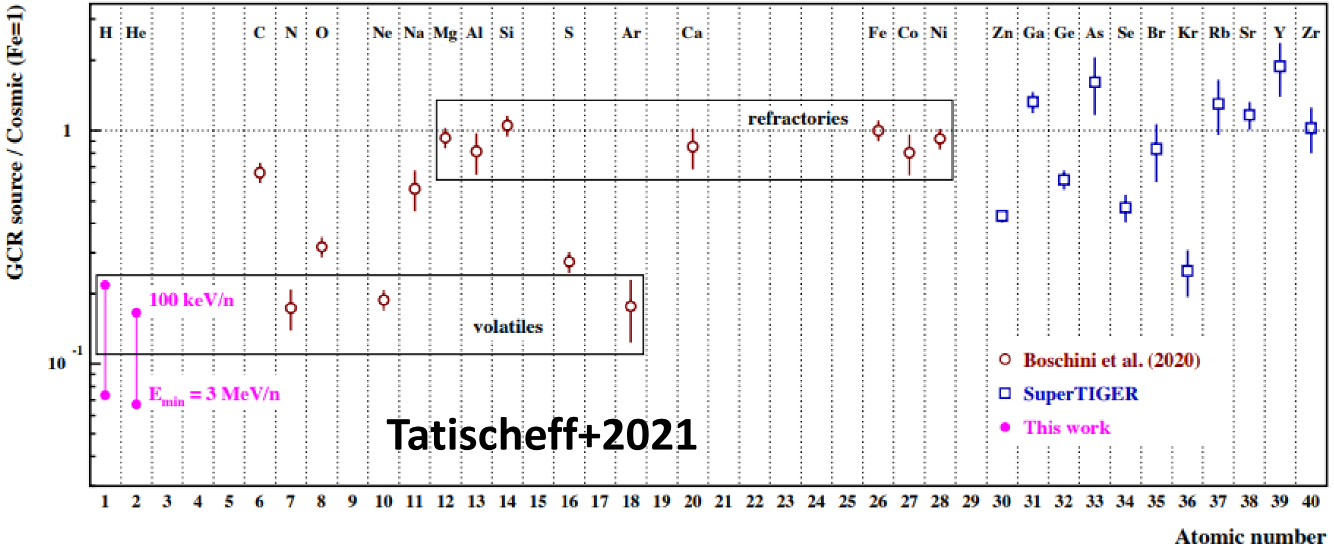
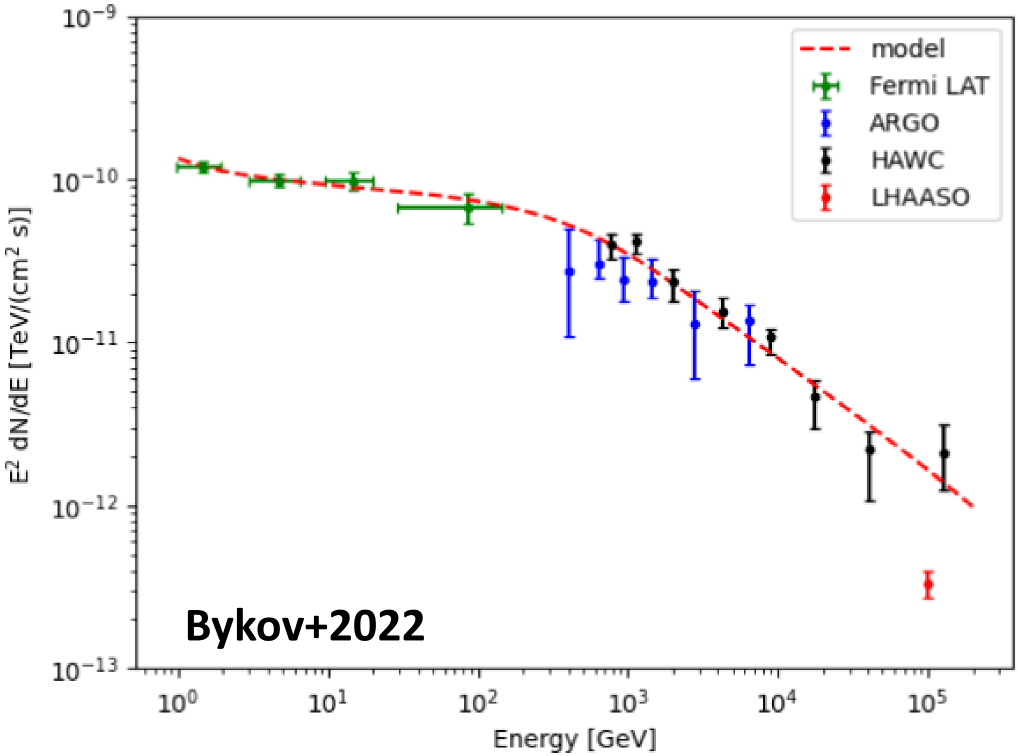


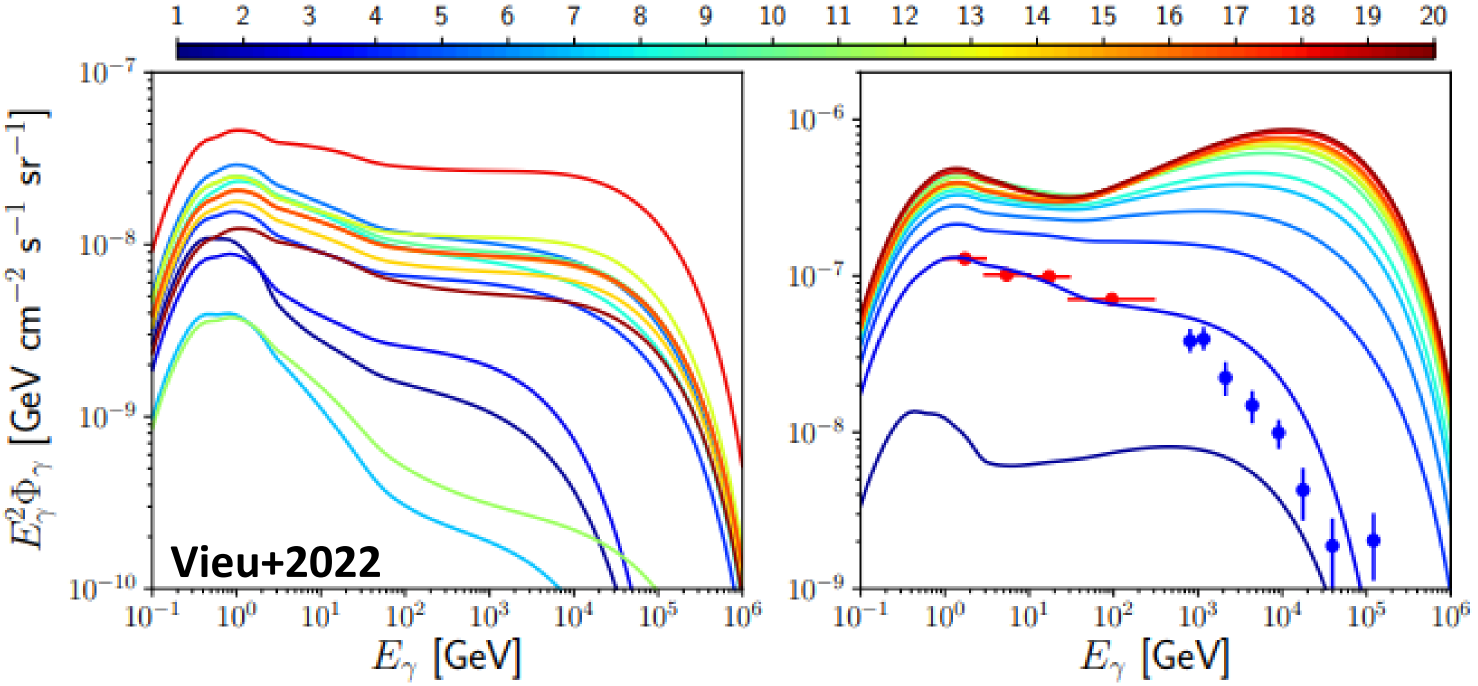
Tatischeff+2021

Detailed studies on the composition reveal a key role played by superbubbles

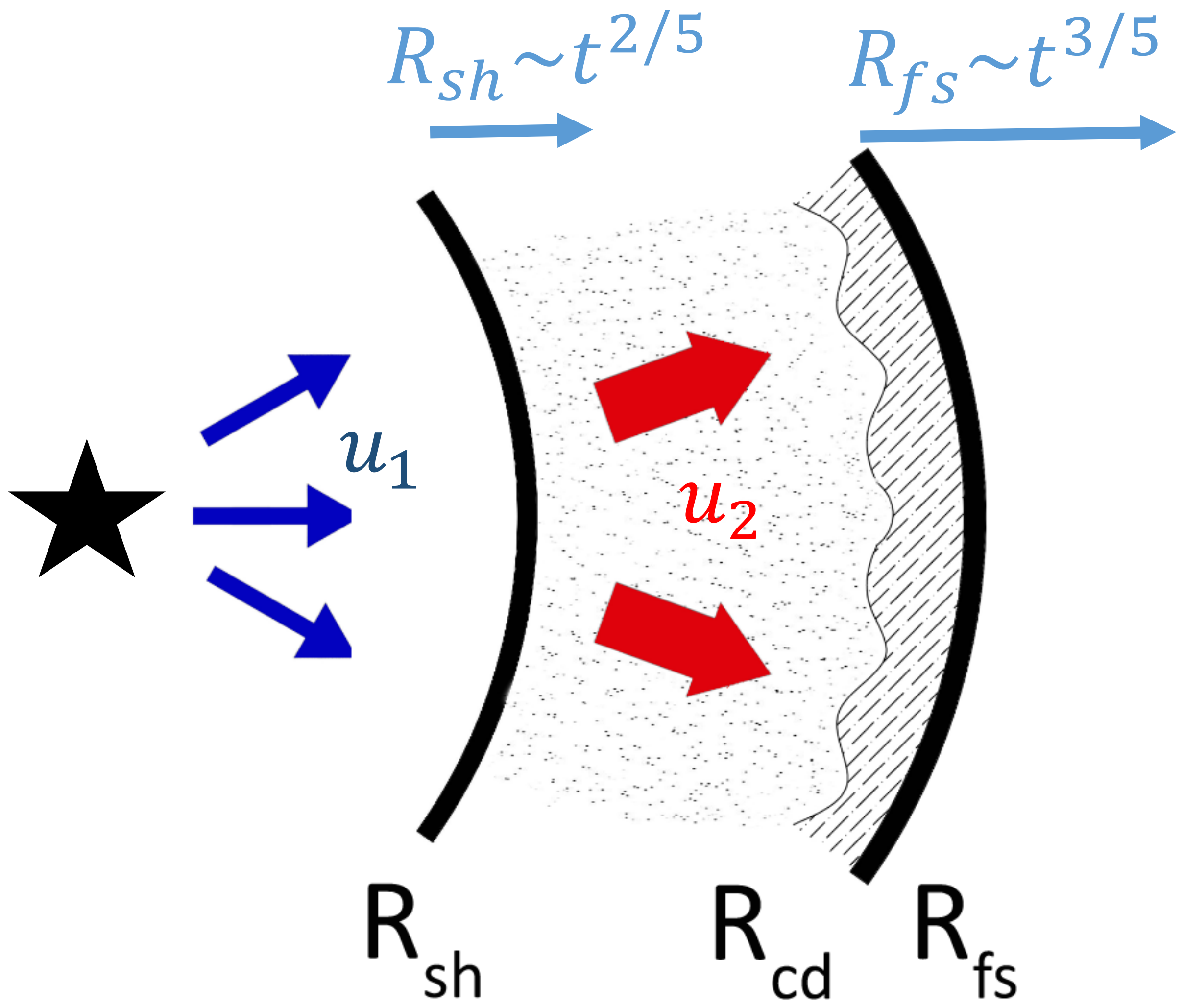
Recent developments in Galactic wind bubbles

Theoretical models were developed in order to explore the acceleration potential and gamma-ray flux from star clusters and superbubbles



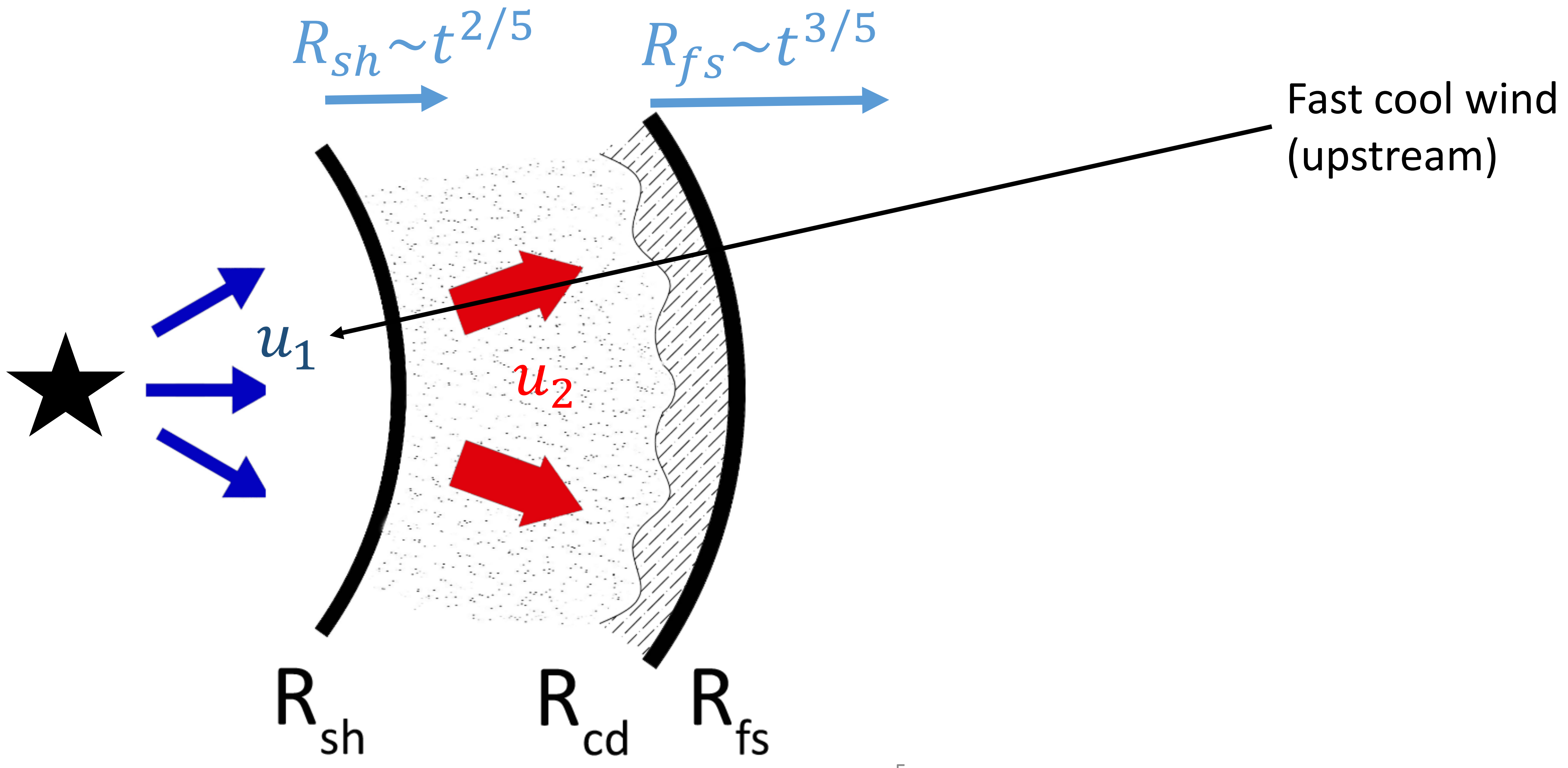


DSA at the wind termination shock



- $u_1 \gg \dot{R}_{sh}$ ➔ $\mathcal{M}_1 \gg 1$
- The shocked wind is adiabatic
- The shocked wind region grows in t

DSA at the wind termination shock



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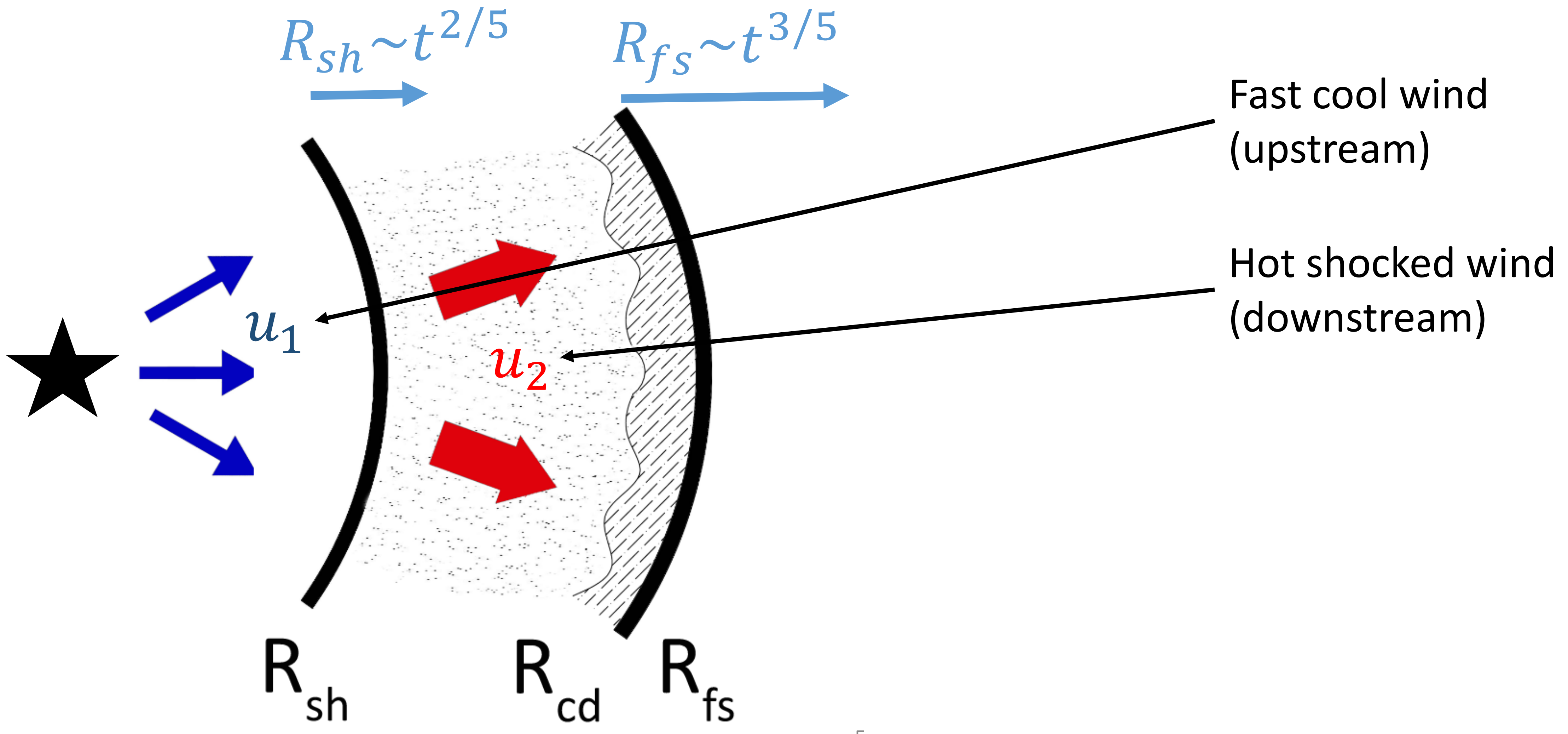

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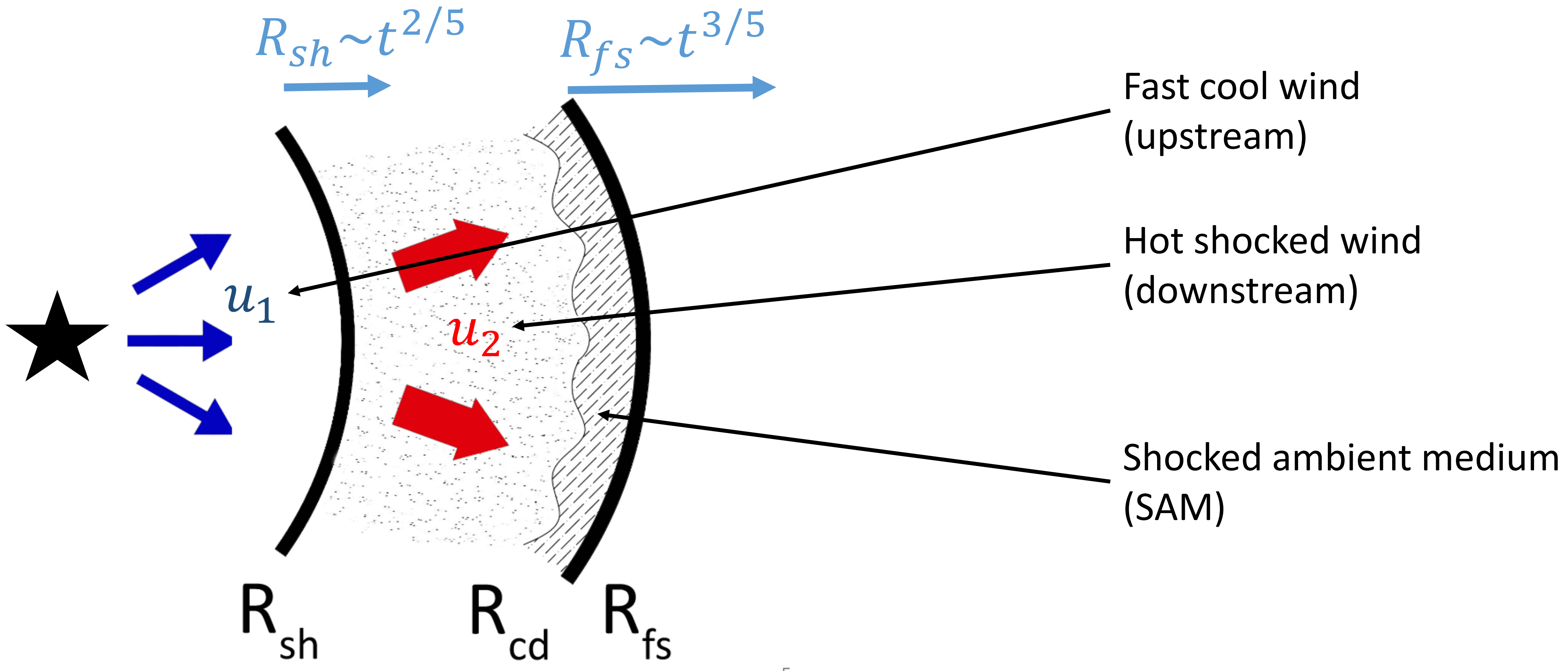

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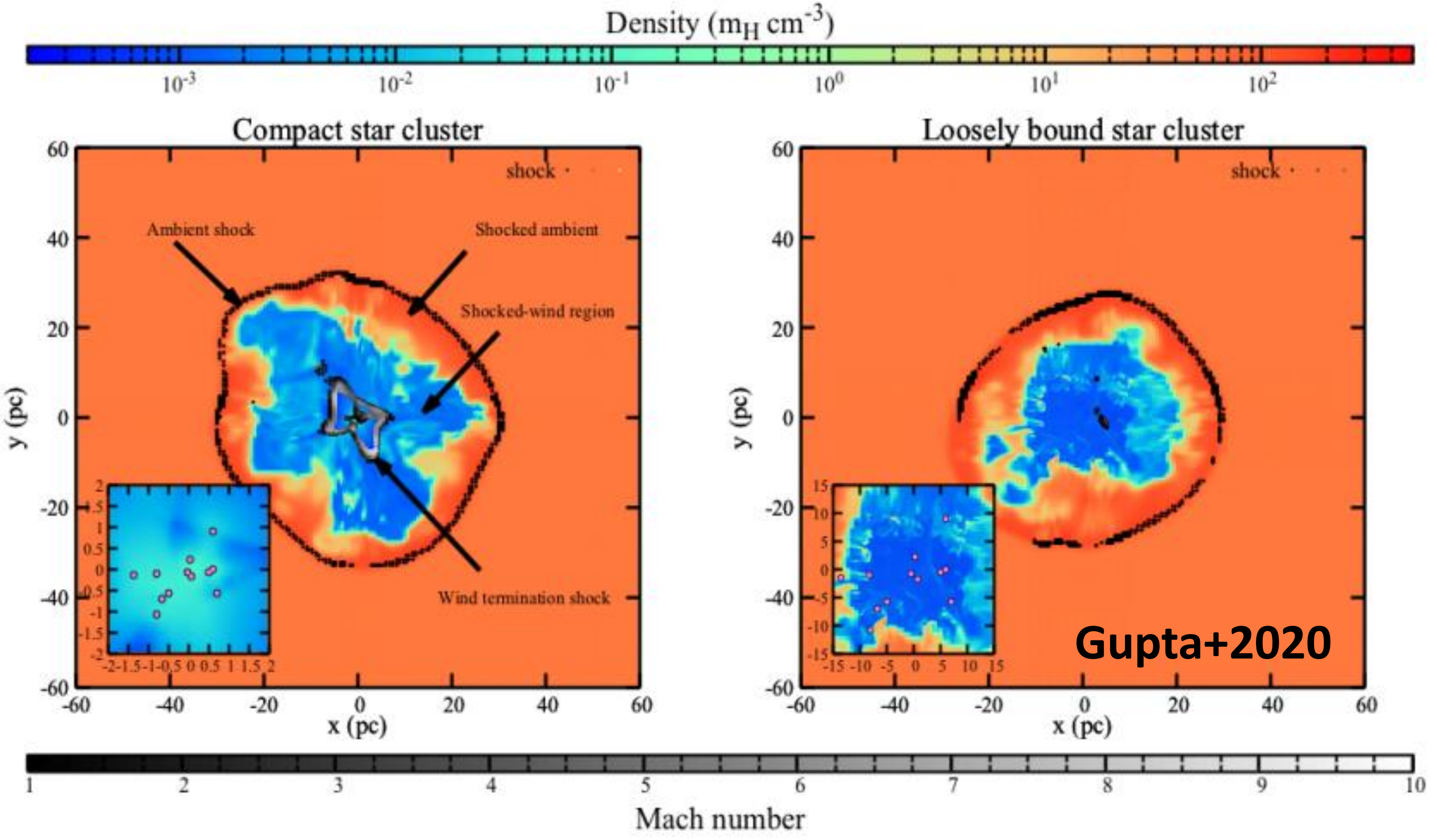
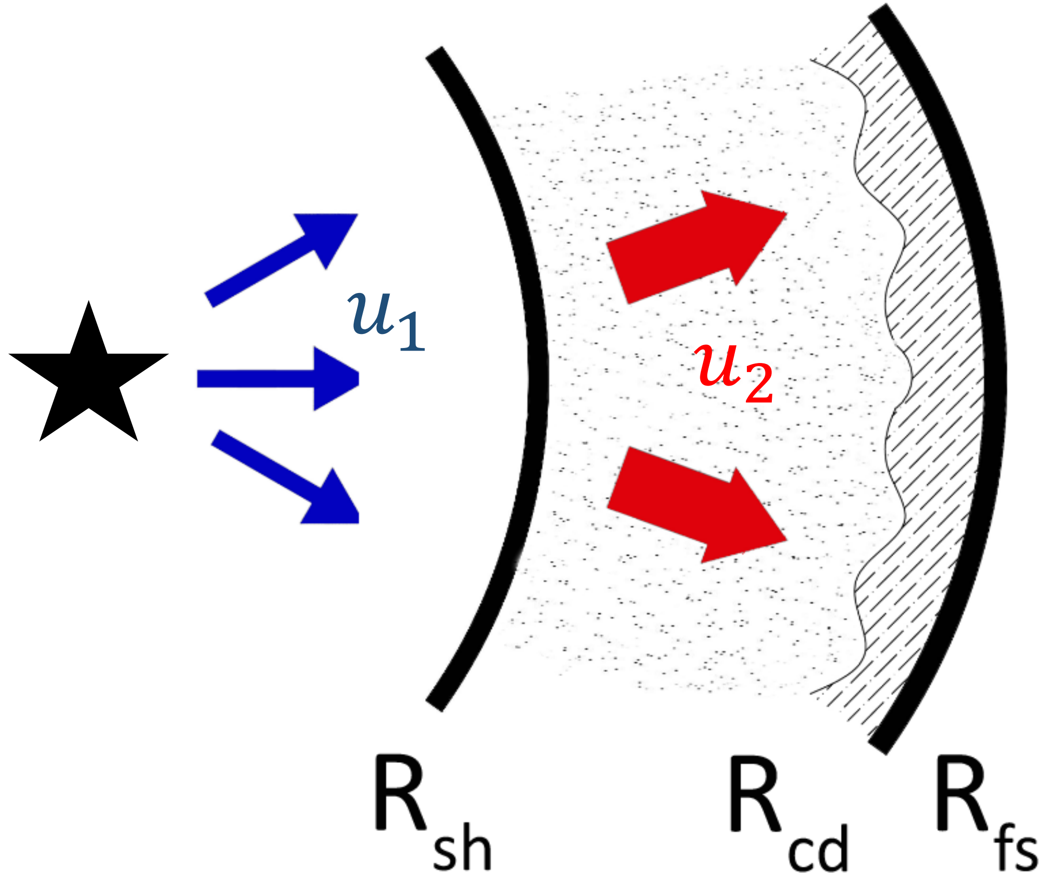


The central engine must be compact in order to develop an efficient wind termination shock

DSA at the wind termination shock

$$\color{red}{TIME\ VARIATION} = \color{orange}{ADVECTION} + \color{green}{DIFFUSION} + \color{purple}{LOSSES} + INJECTION$$

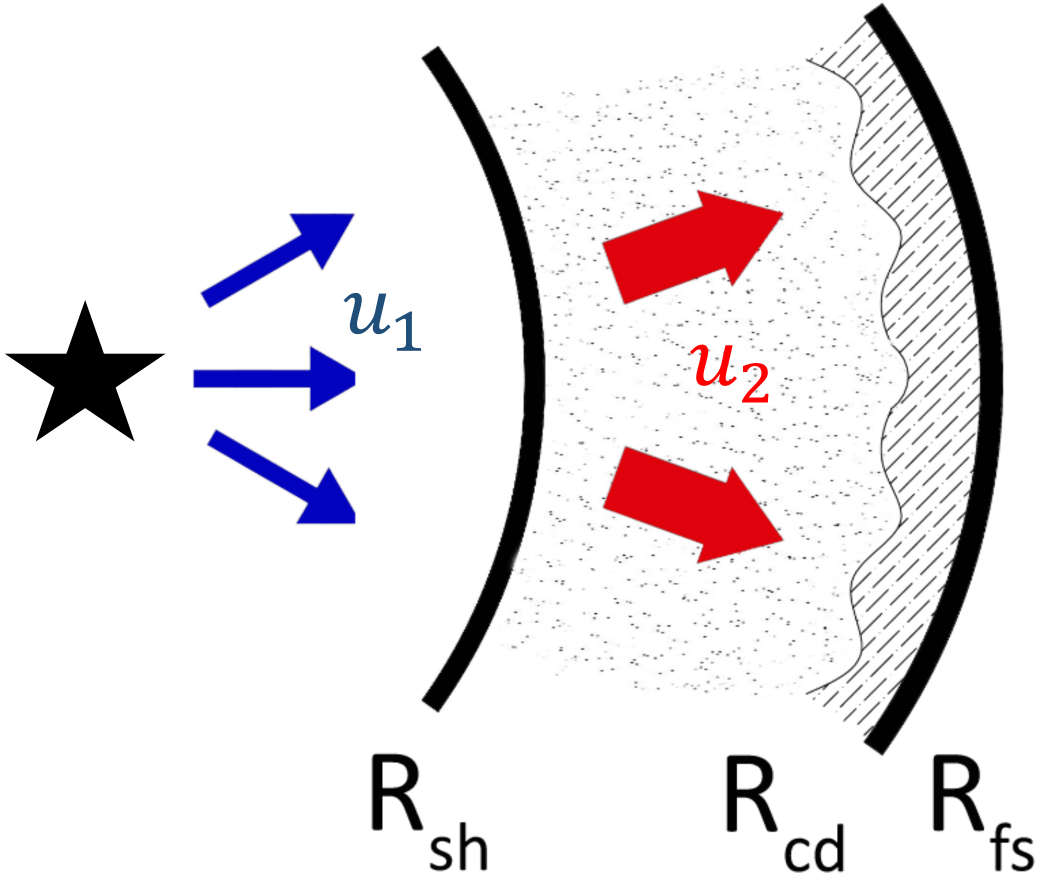


Based on:

- Morlino, Blasi, Peretti & Cristofari 2021
- Peretti, Morlino, Blasi & Cristofari 2022
- Peretti, Lamastra, Saturni, Ahlers, Morlino, Blasi & Cristofari in prep

DSA at the wind termination shock

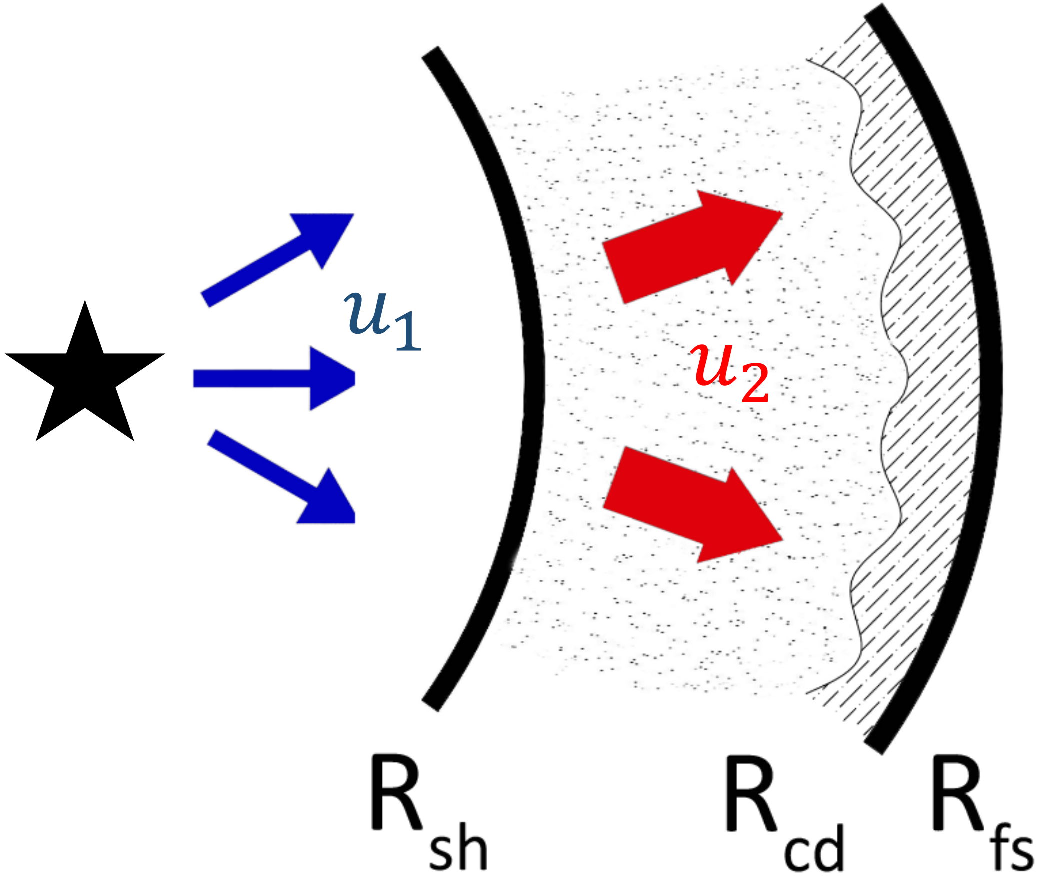
$$TIME\ VARIATION = ADVECTION + DIFFUSION + LOSSES + INJECTION$$



- Spherically symmetric

DSA at the wind termination shock

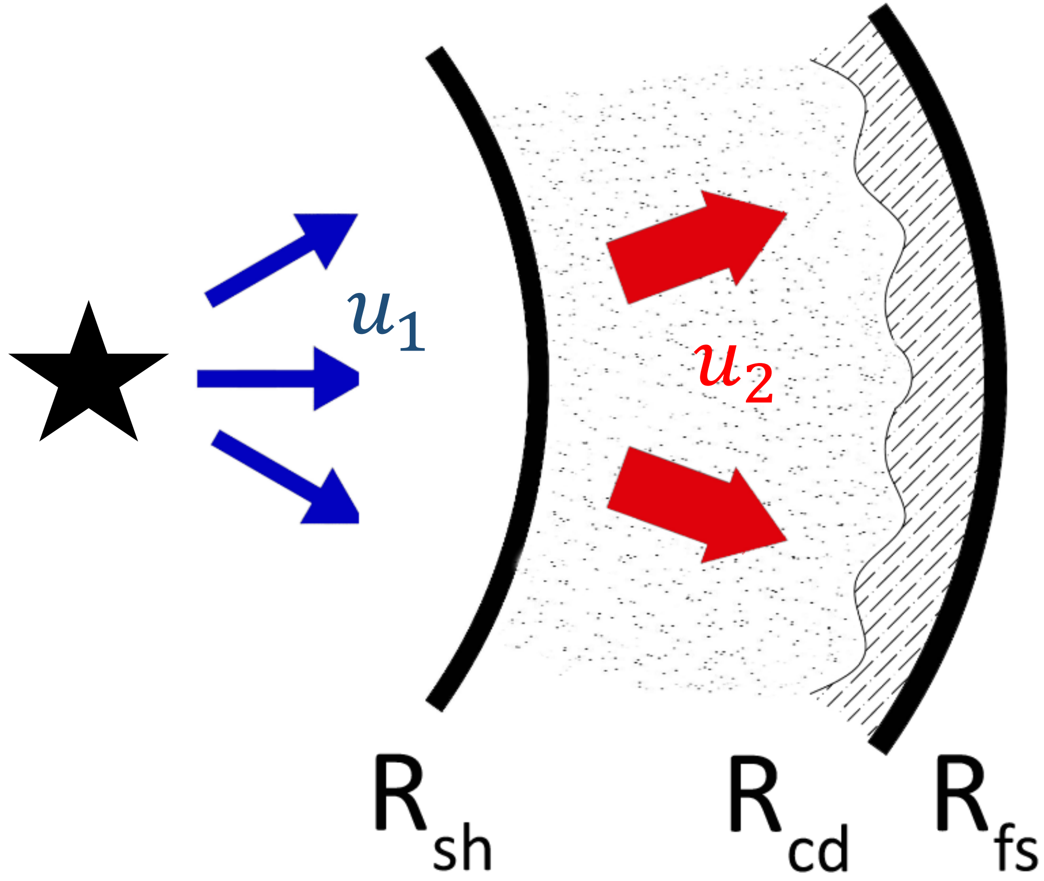
$$\text{TIME VARIATION} = \text{ADVECTION} + \text{DIFFUSION} + \text{LOSSES} + \text{INJECTION}$$



- Spherically symmetric
- Stationary

DSA at the wind termination shock

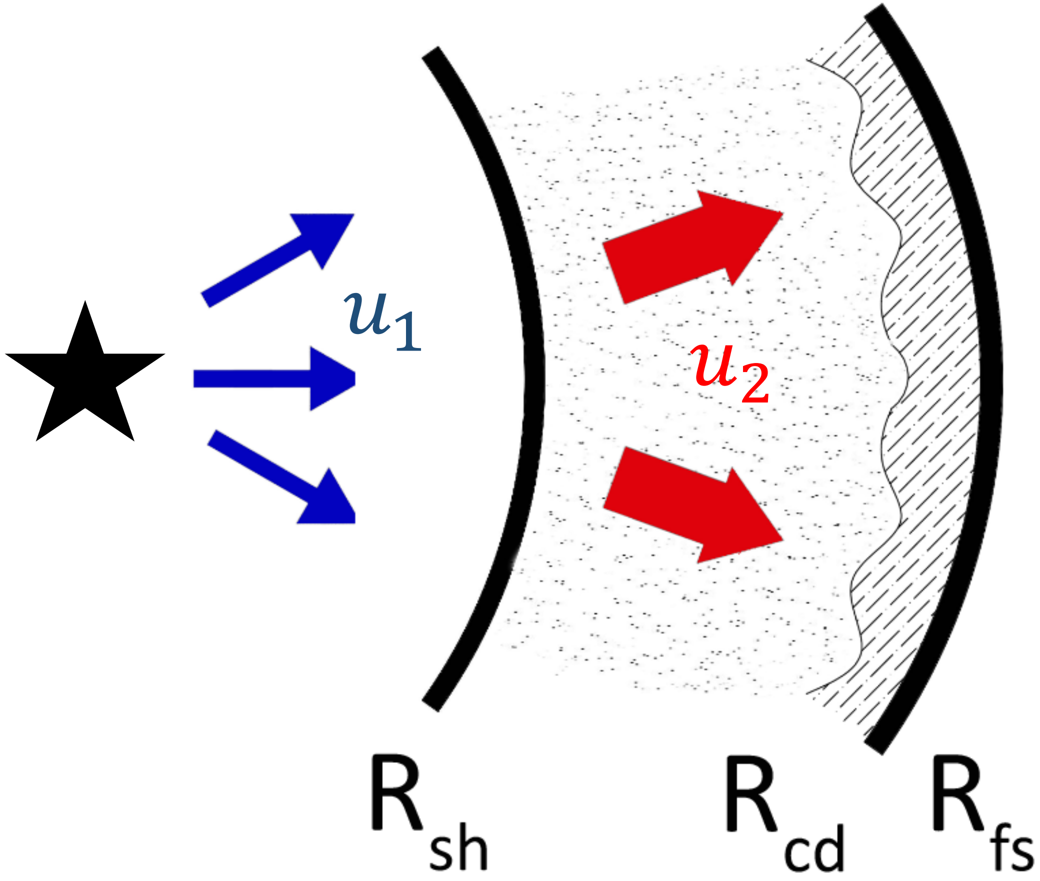
~~$TIME\ VARIATION$~~ $= ADVECTION + DIFFUSION + LOSSES + INJECTION$



- Spherically symmetric
- Stationary
- $U_{B,1} = \epsilon_B P_{ram,1}$
- $D = \frac{1}{3} v r_L^{2-\delta} l_c^{\delta-1}$

DSA at the wind termination shock

$$\cancel{TIME\ VARIATION} = ADVECTION + DIFFUSION + LOSSES + INJECTION$$

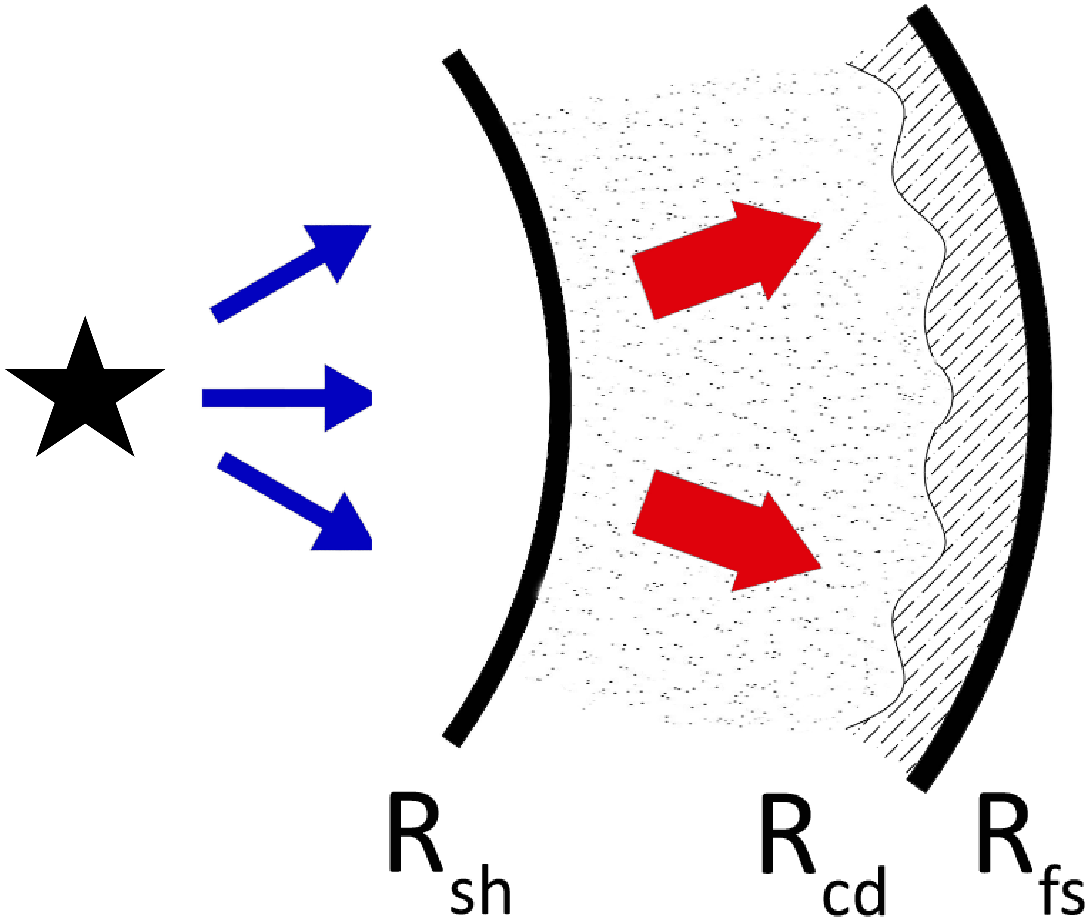


<u>Boundary conditions:</u>

- Free escape at R_{fs}
- Null net flux at $r = 0$

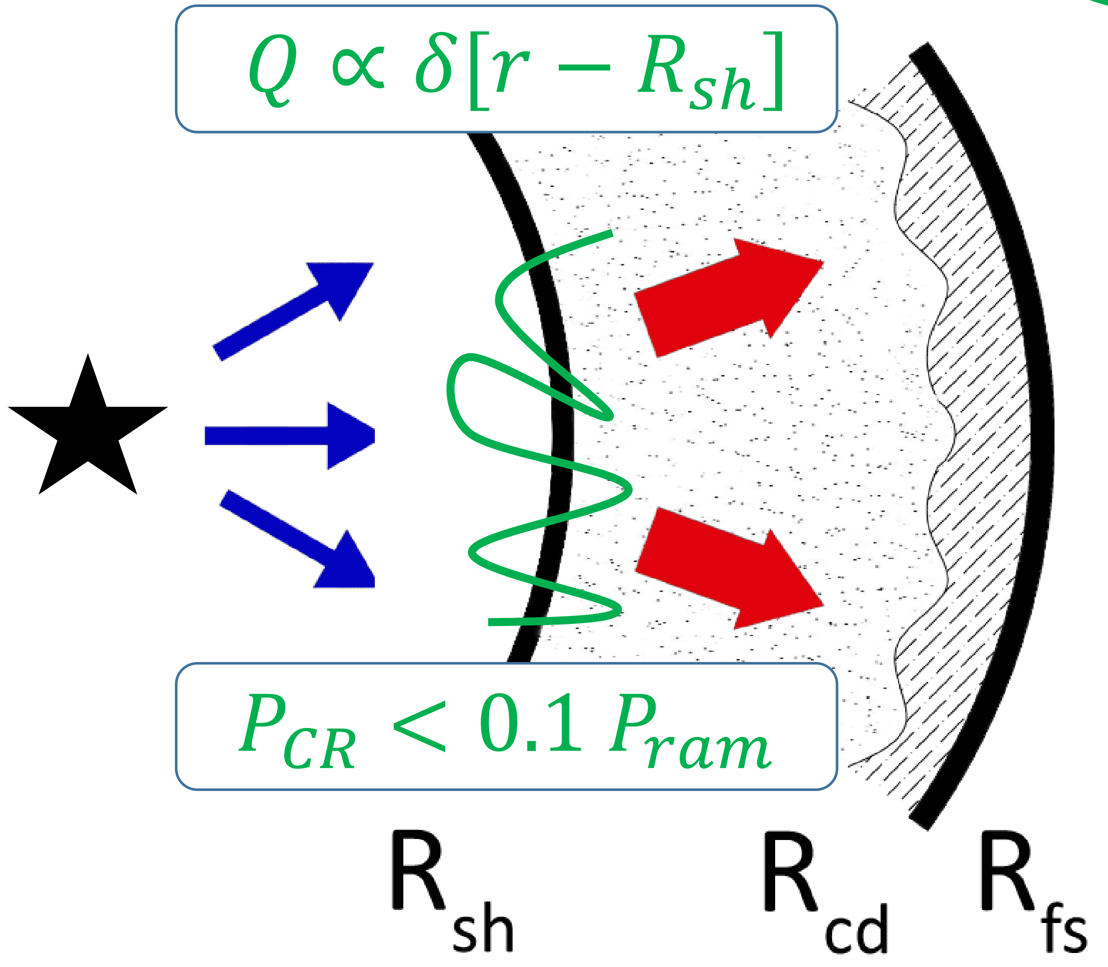
DSA at the wind termination shock

$$0 = -r^2 u(r)\partial_r f + \partial_r[r^2 D(r,p)\partial_r f] + \frac{p}{3}\partial_r[r^2 u(r)]\partial_p f - r^2\Lambda(r,p) + r^2 Q(r,p)$$



DSA at the wind termination shock

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



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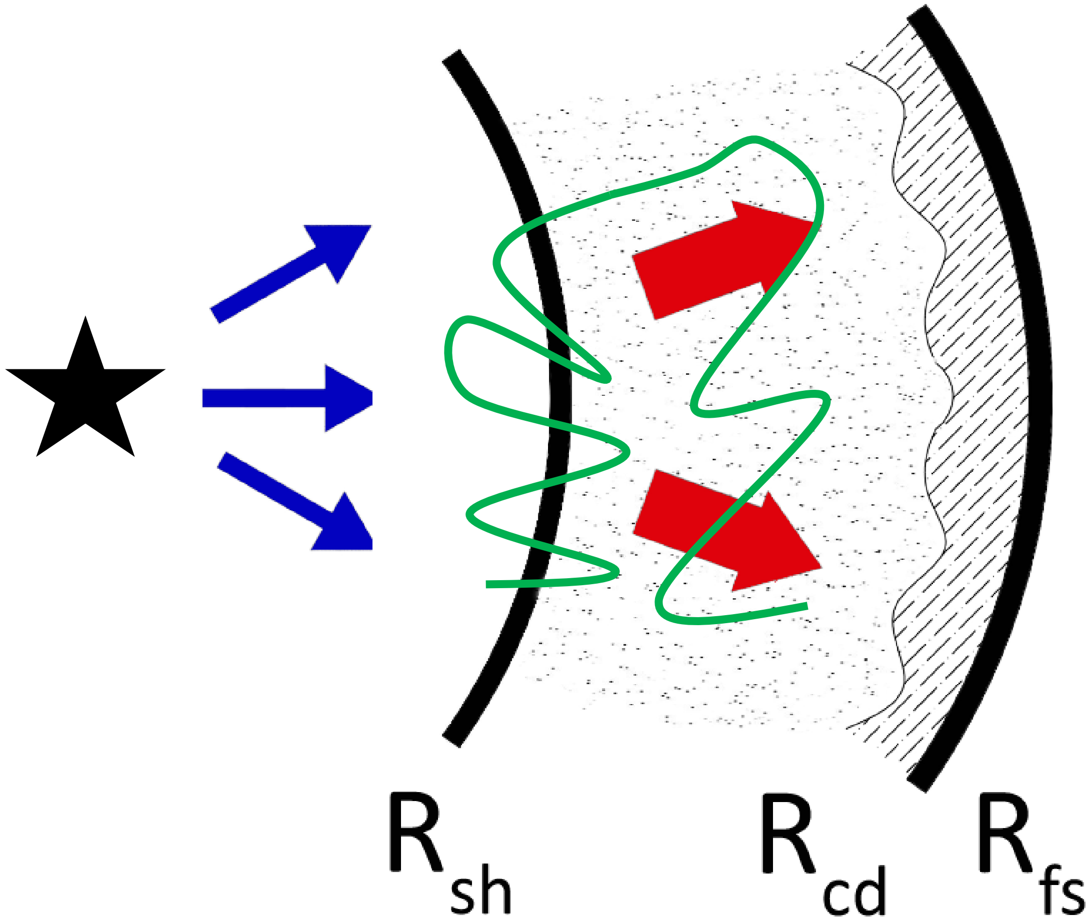

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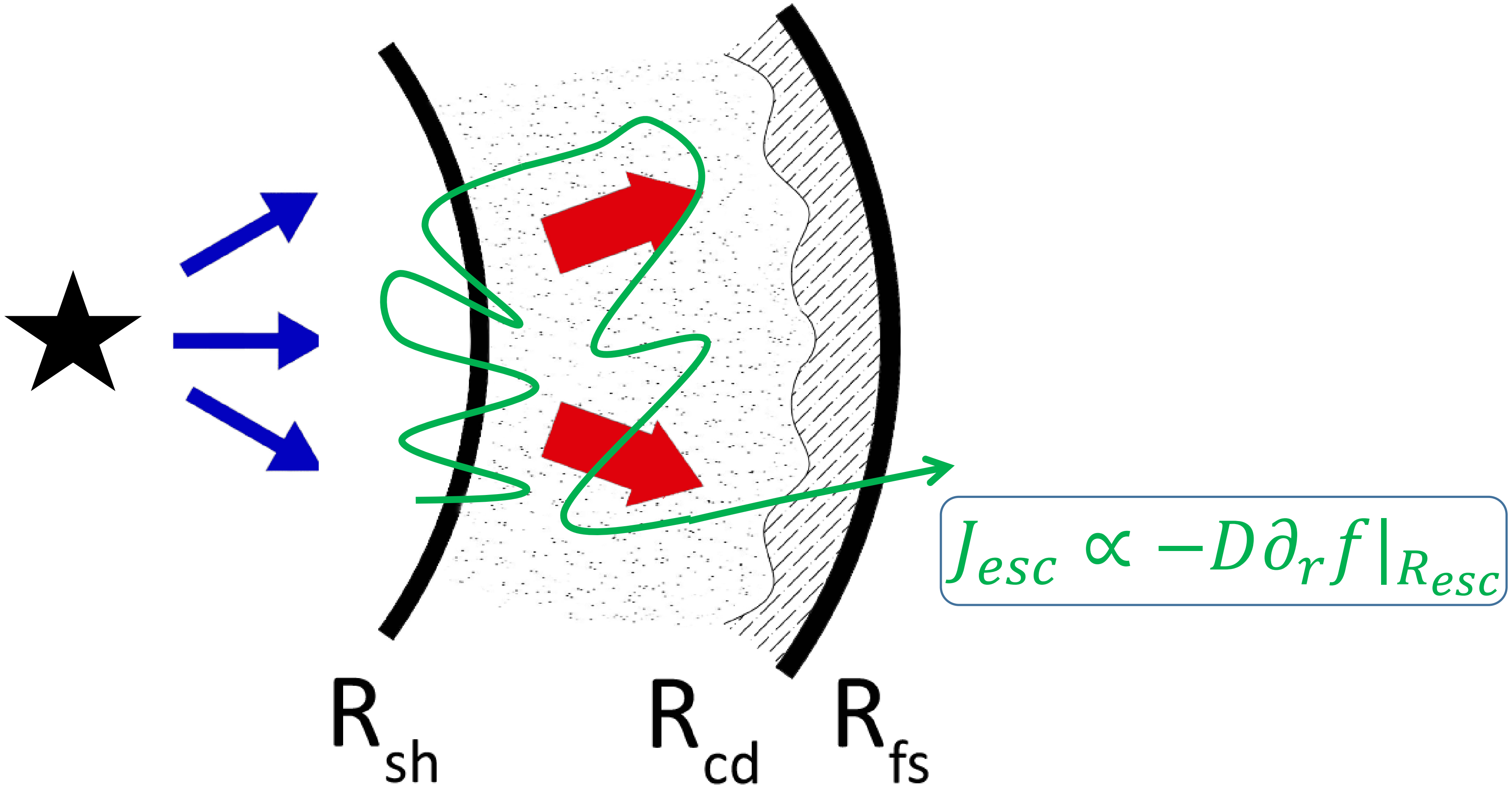

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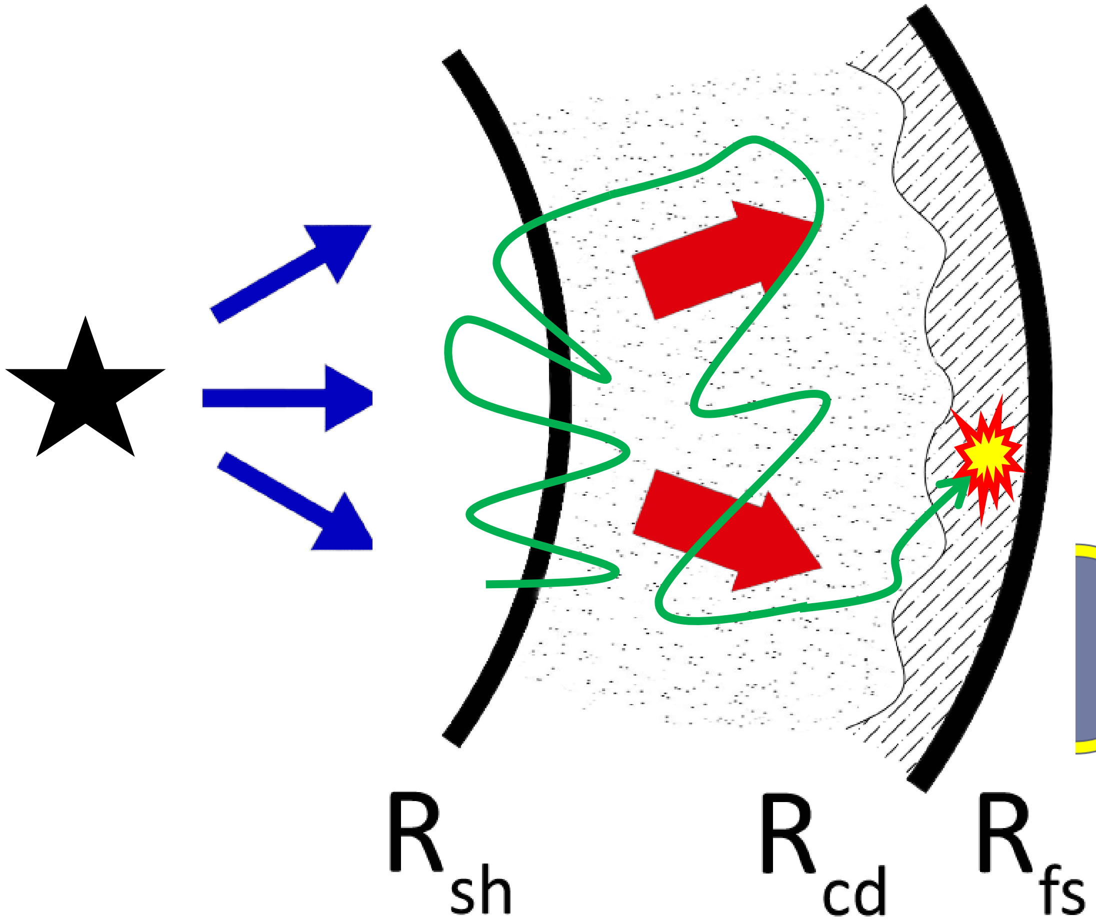

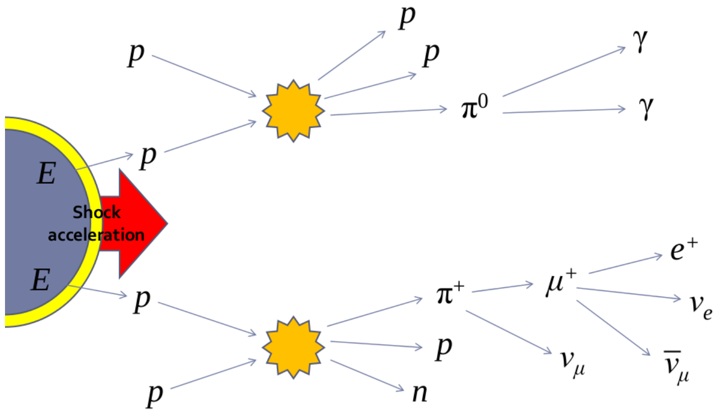

Website: http://www.astro.wisc.edu/~gvance/index.html

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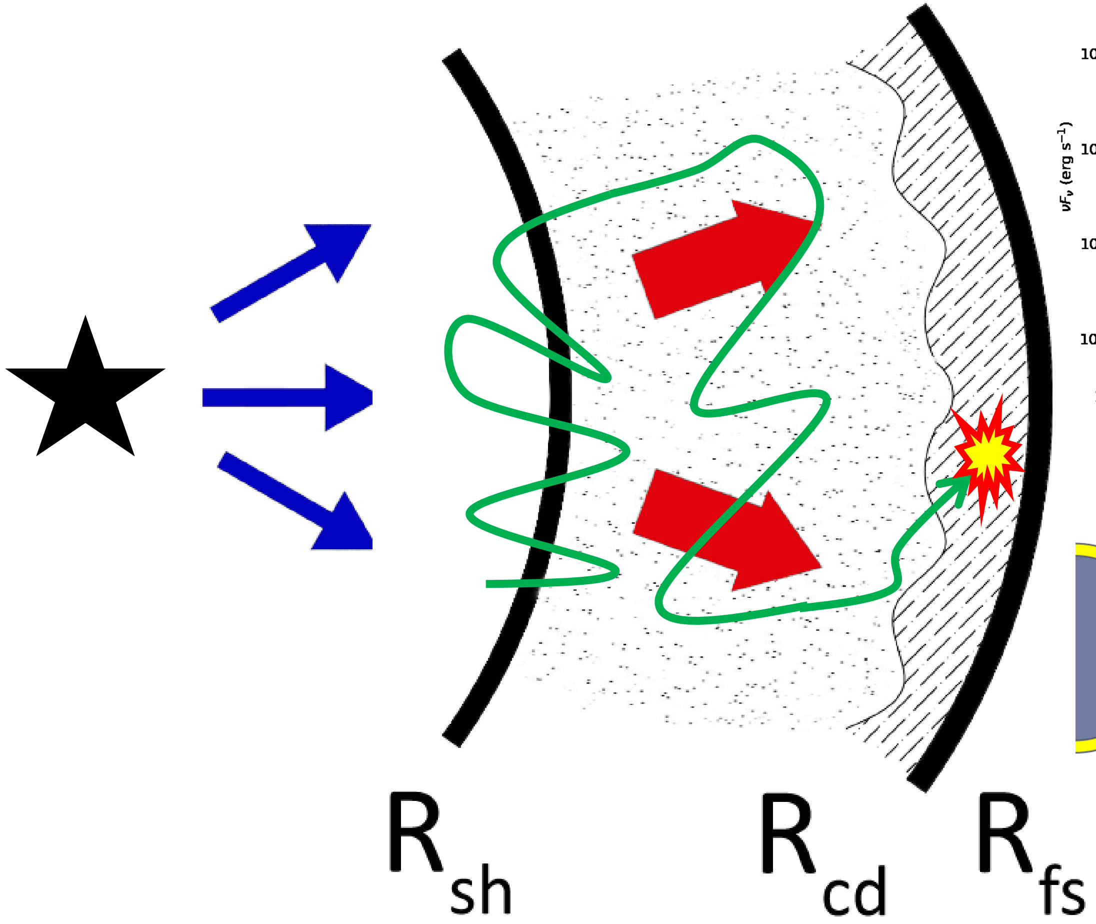

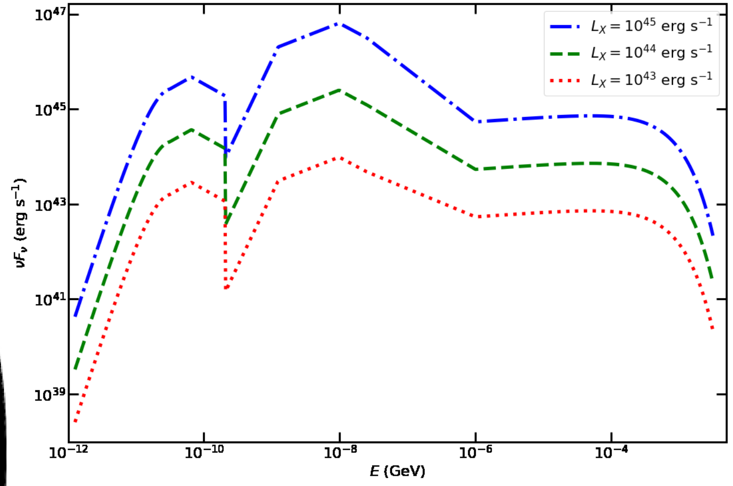

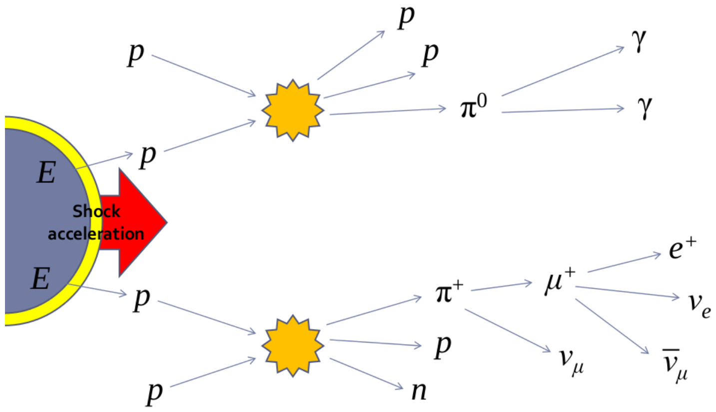

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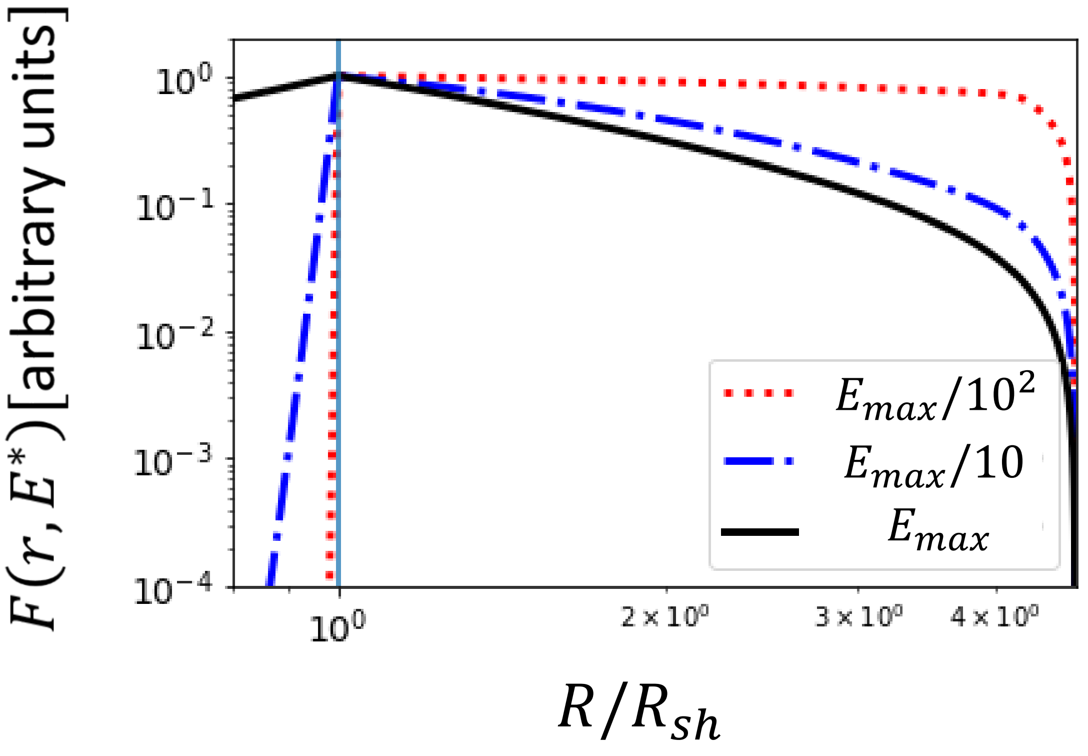
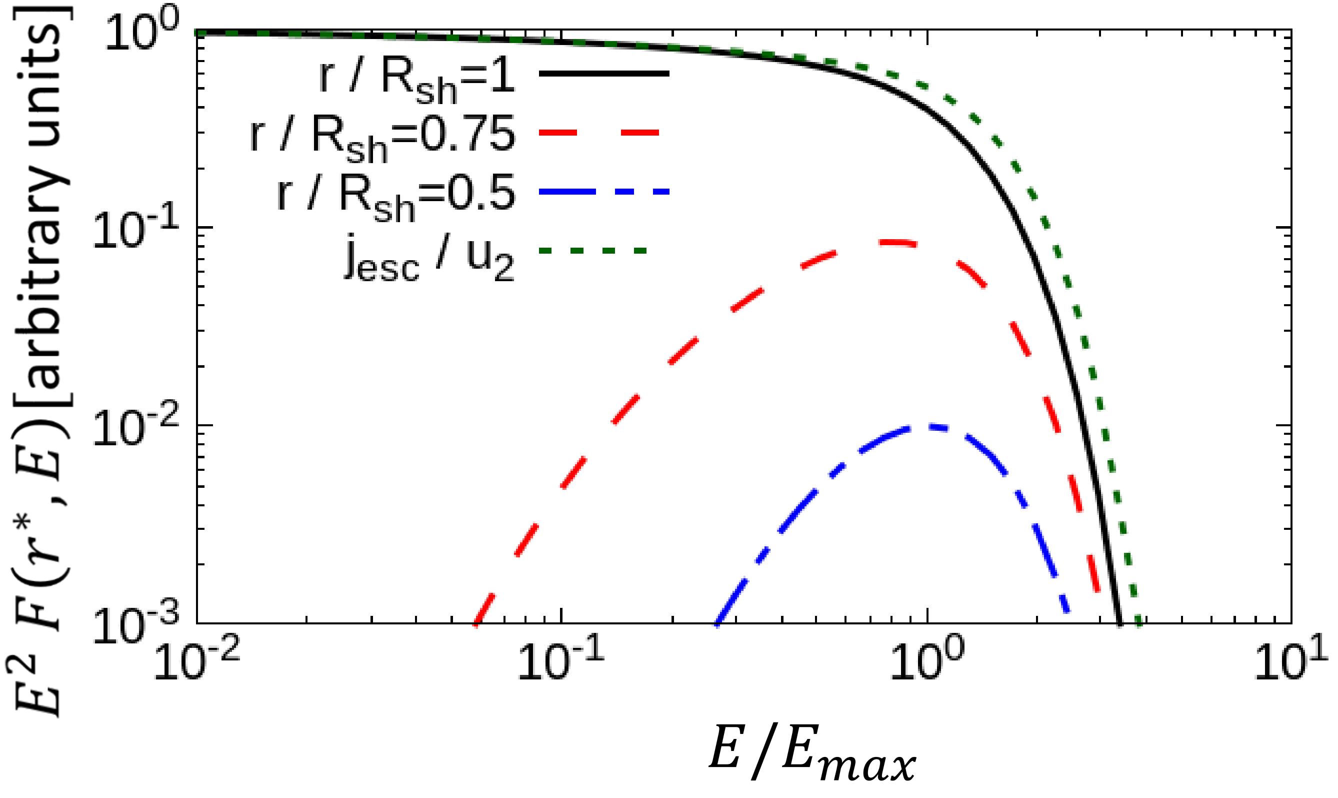
Solution: radial behavior and spectra

$$f_u(r,p) = f_{sh}(p)\, e^{-\int_r^{R_{sh}} \left(\frac{u_{eff,1}}{D_1}\right) dr'}$$
$$f_d(r,p) = f_{sh}(p) X(r,p)\, e^{\int_{R_{sh}}^{r} \left(\frac{u_{eff,2}}{D_2}\right) dr'}$$

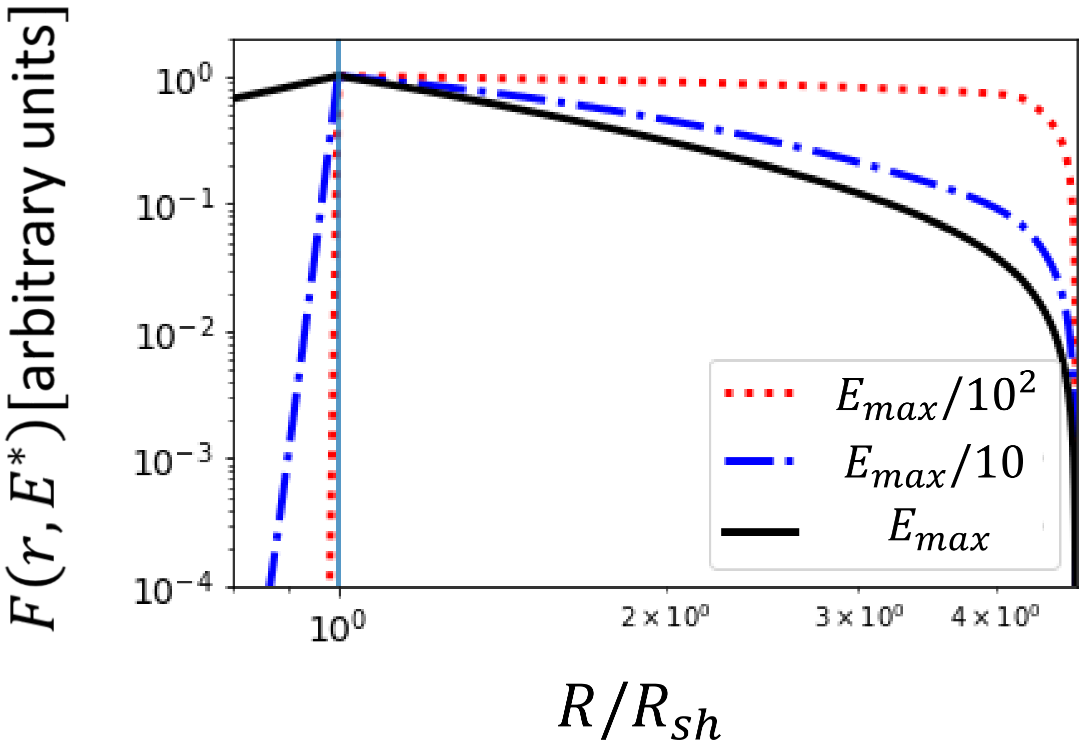
$$f_{sh}(p) \propto p^{-s} e^{-\Gamma_1(p)} e^{-\Gamma_2(p)}$$

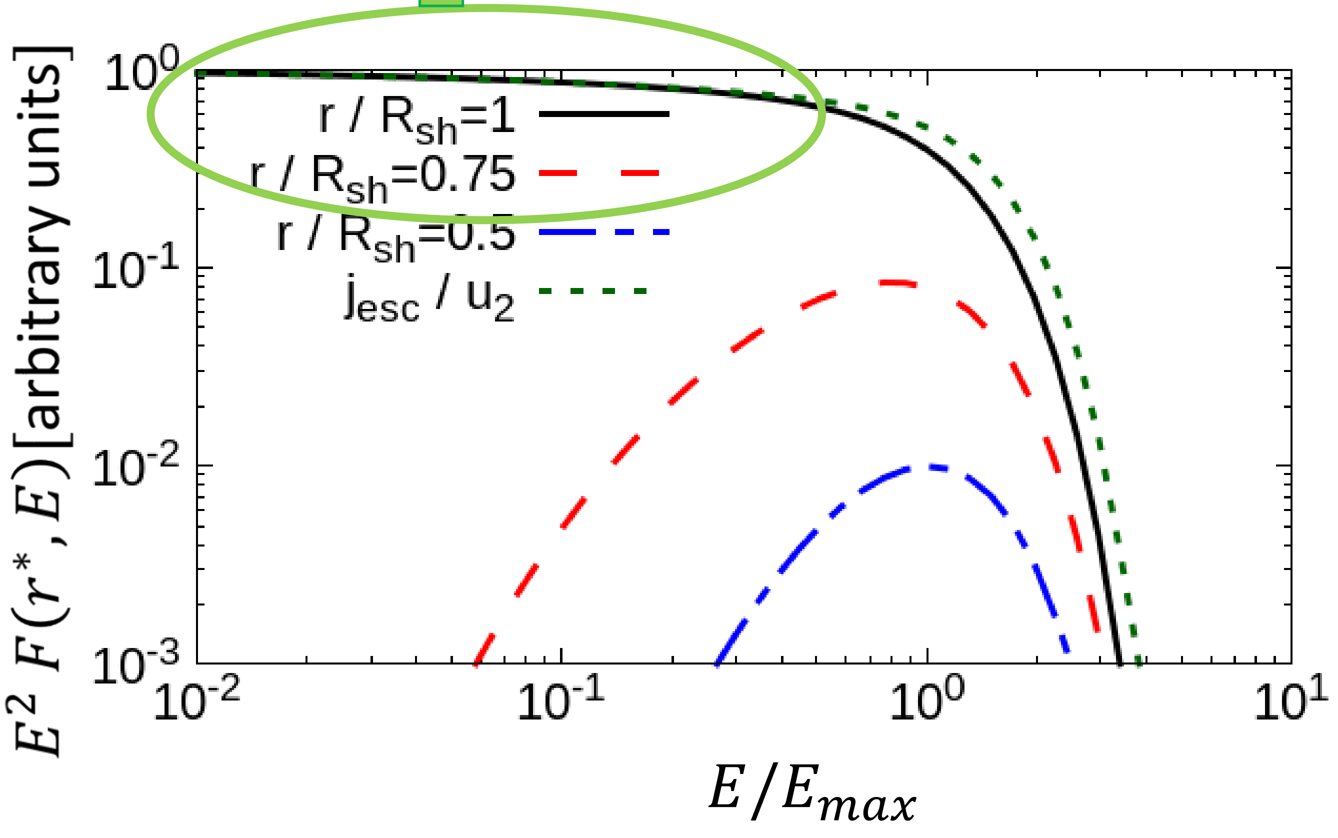




Solution: radial behavior and spectra

$F \sim E^{-2} \Leftrightarrow$ DSA





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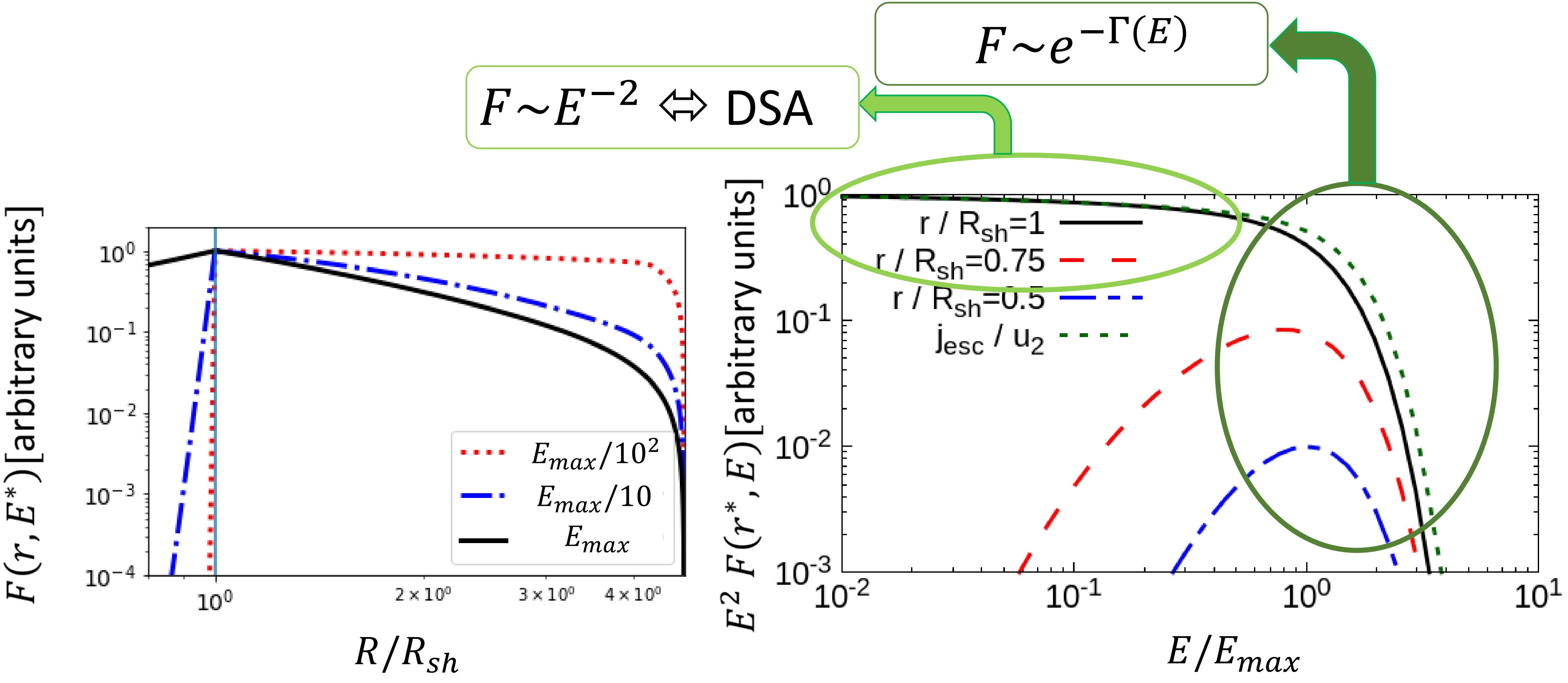
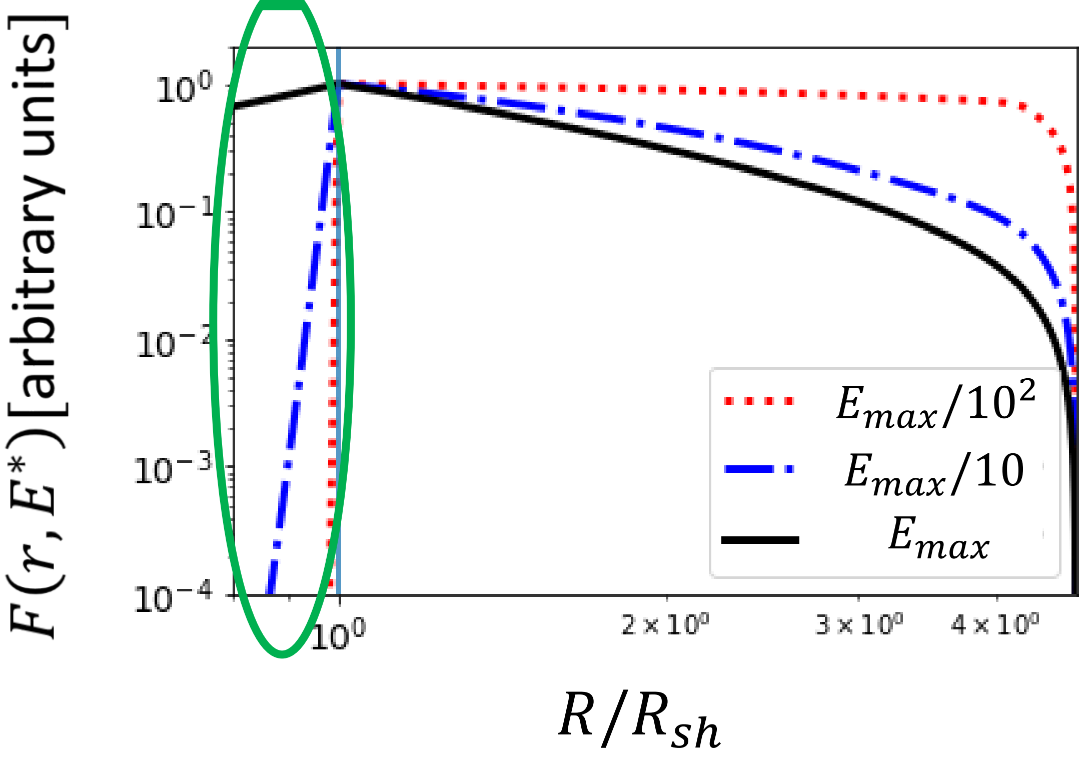
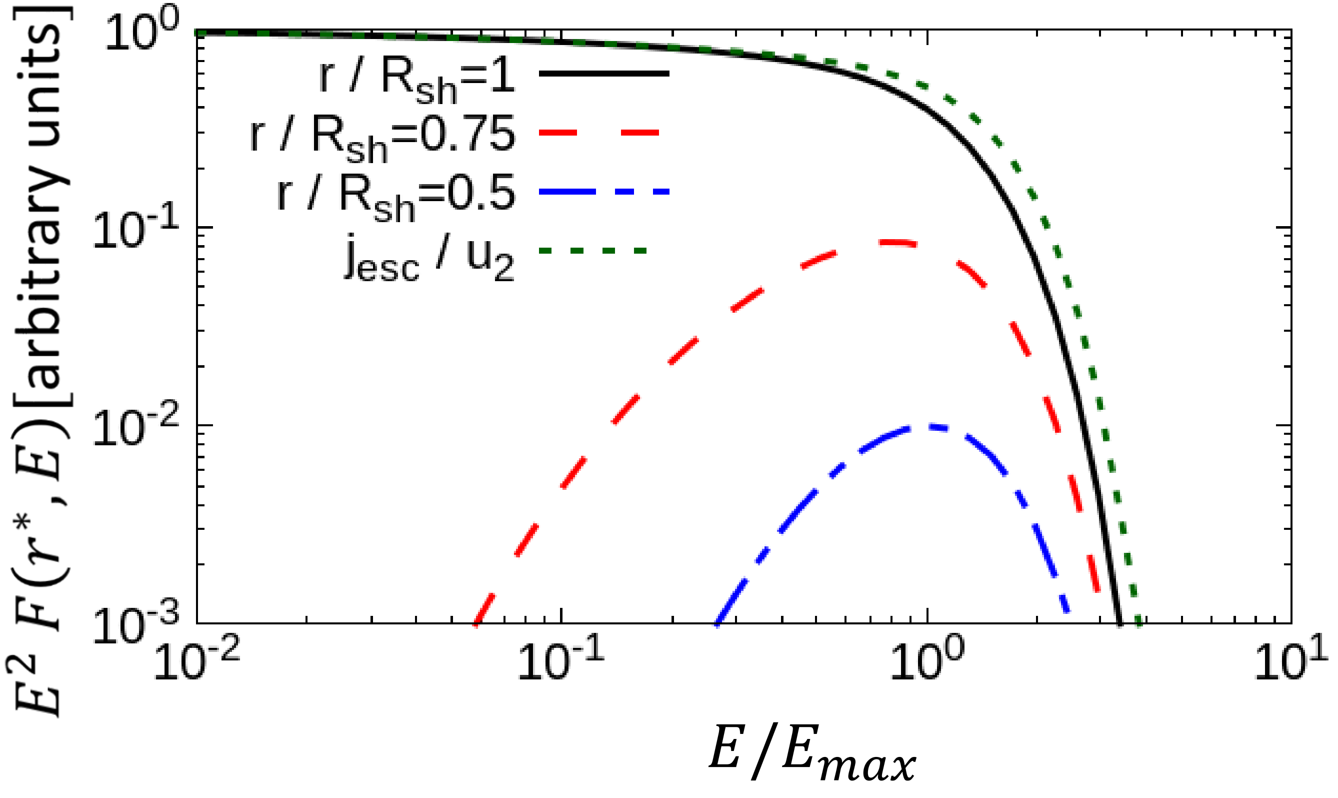


Solution: radial behavior and spectra

Advection → pushes particle towards R_{sh}
Diffusion → homogenizes particles





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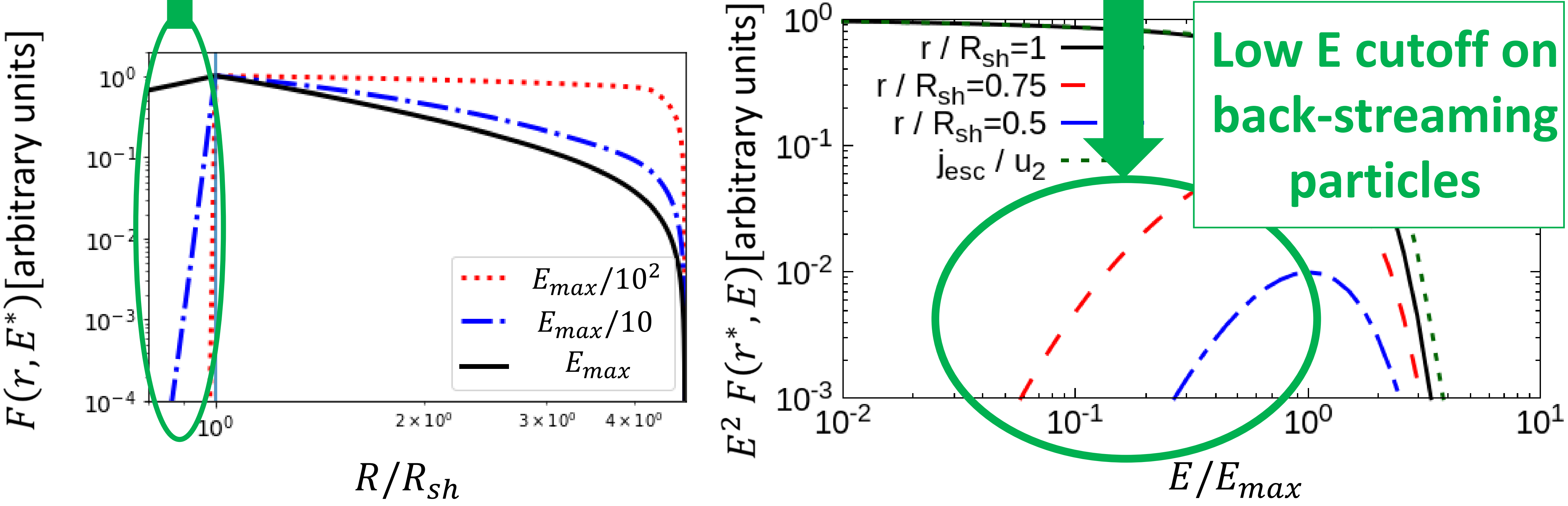
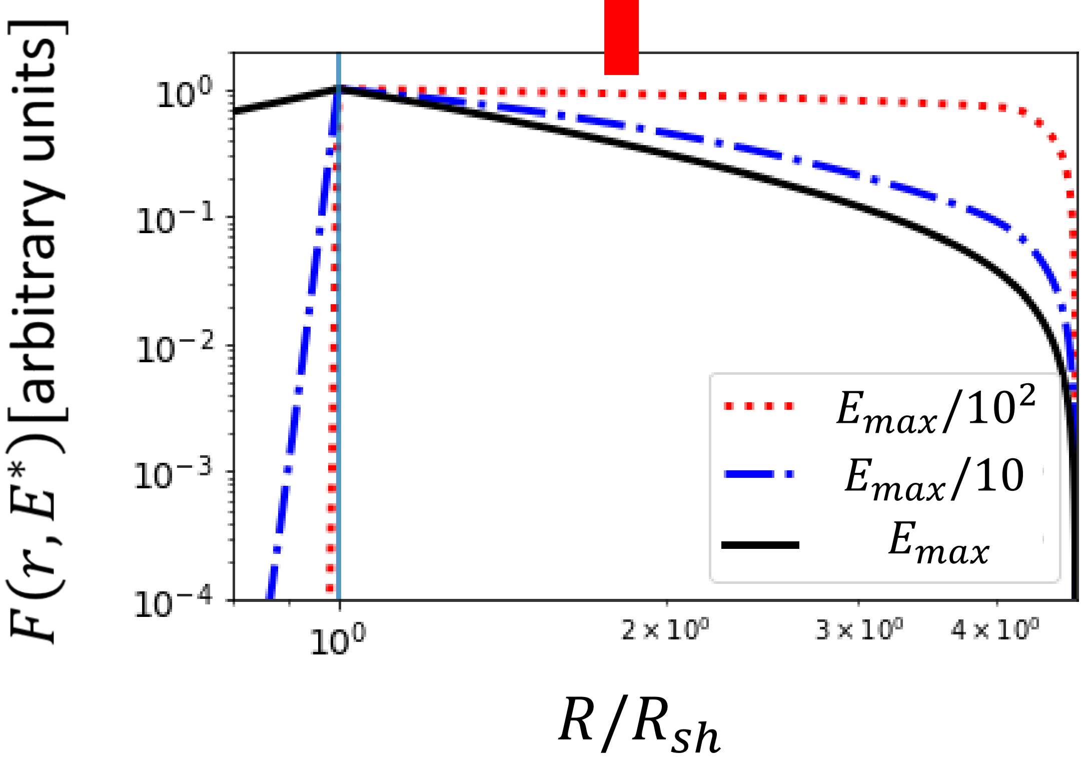
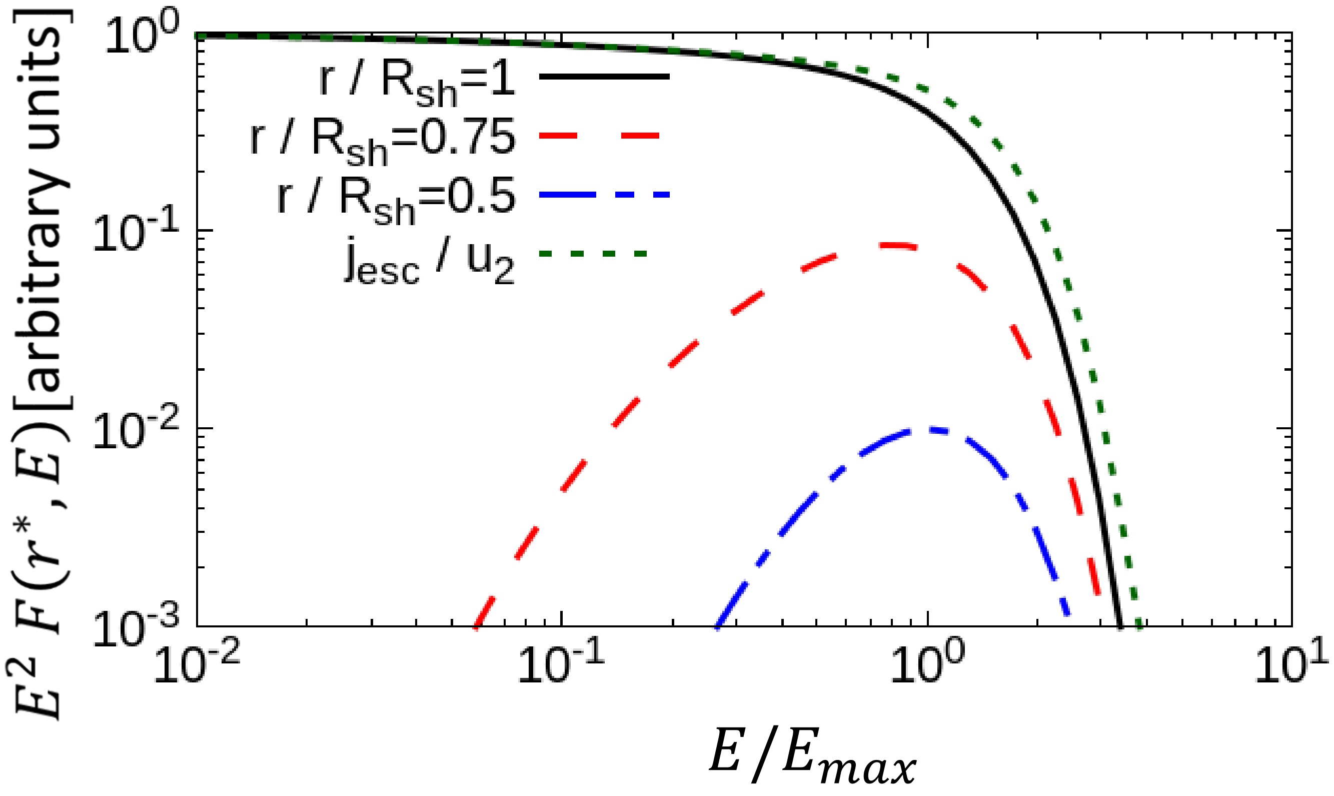


Solution: radial behavior and spectra

Advection dominated





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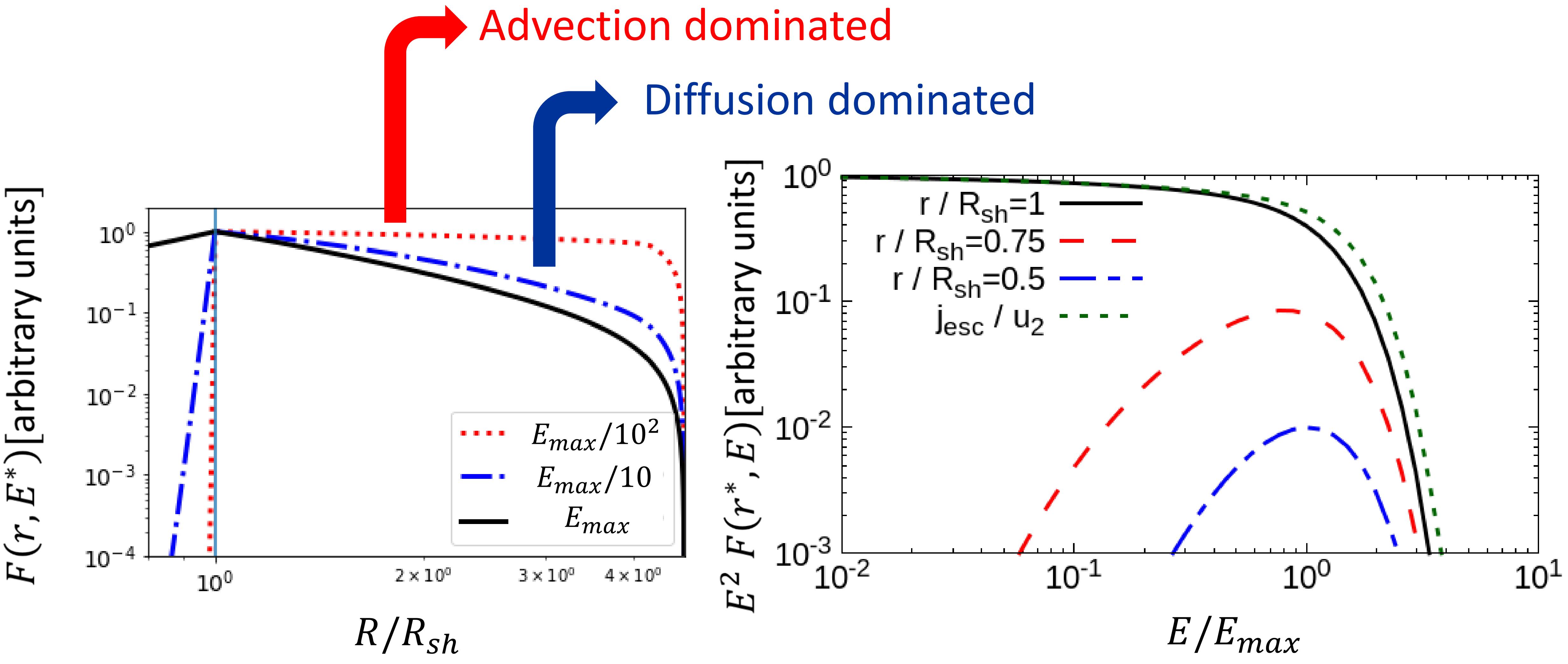
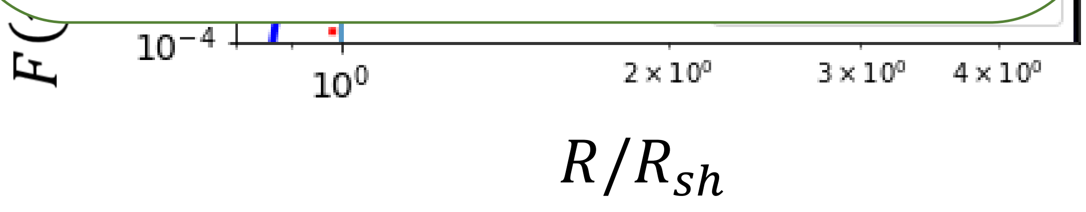


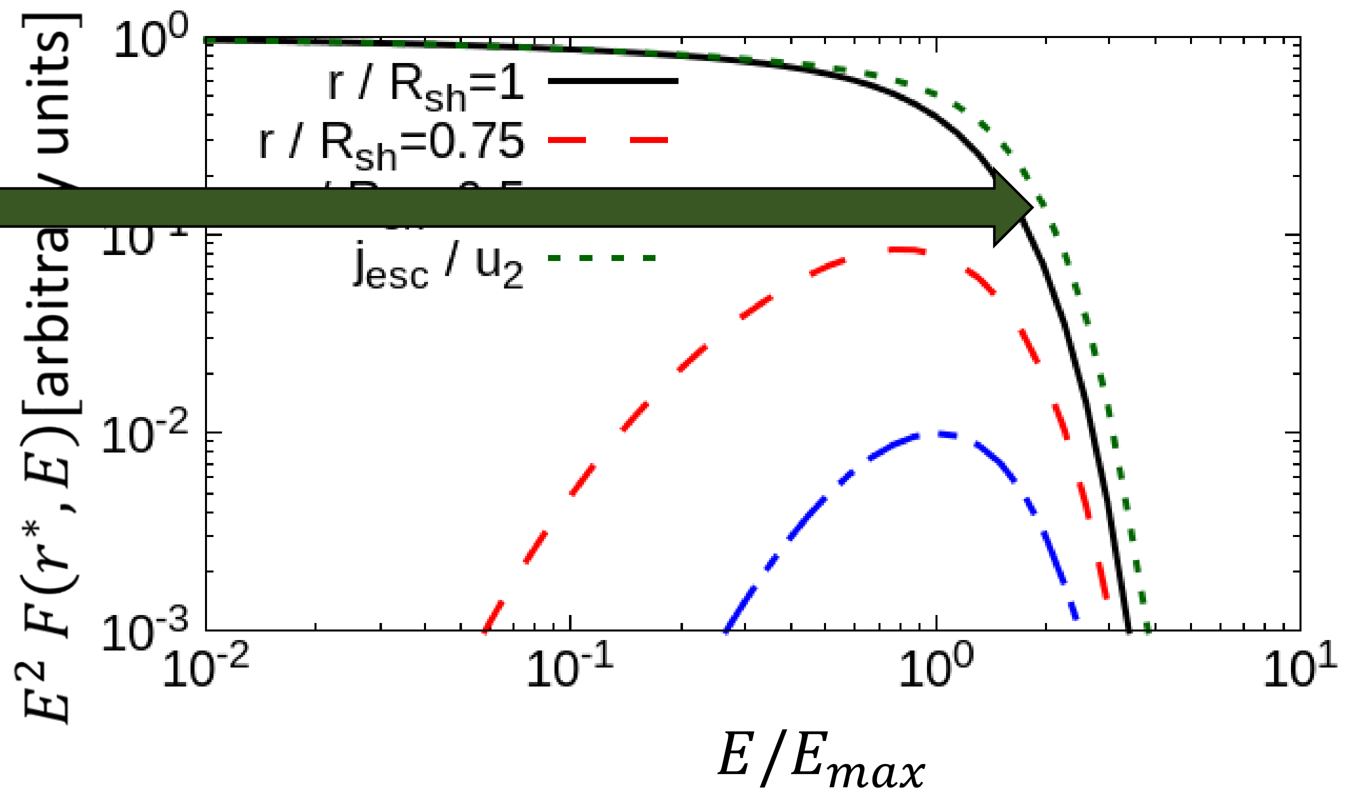
Solution: radial behavior and spectra

Advection dominated

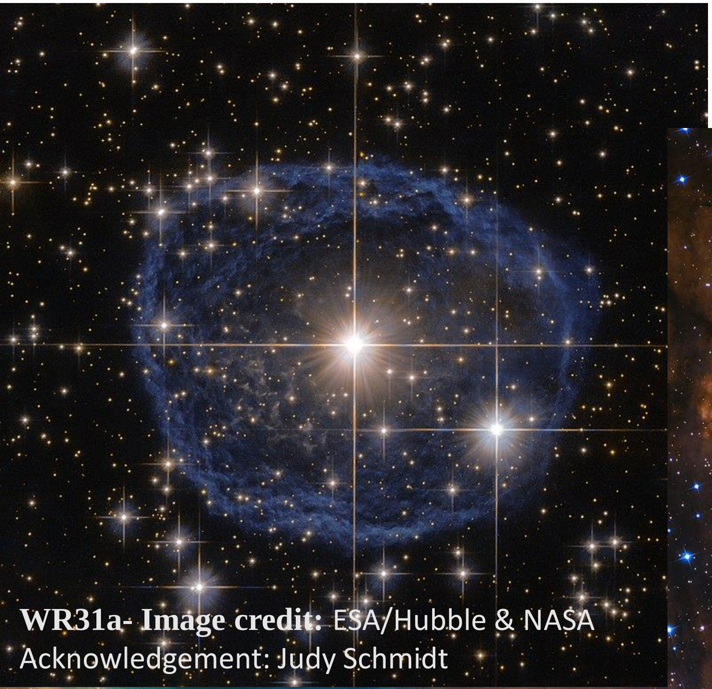
Diffusion dominated

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

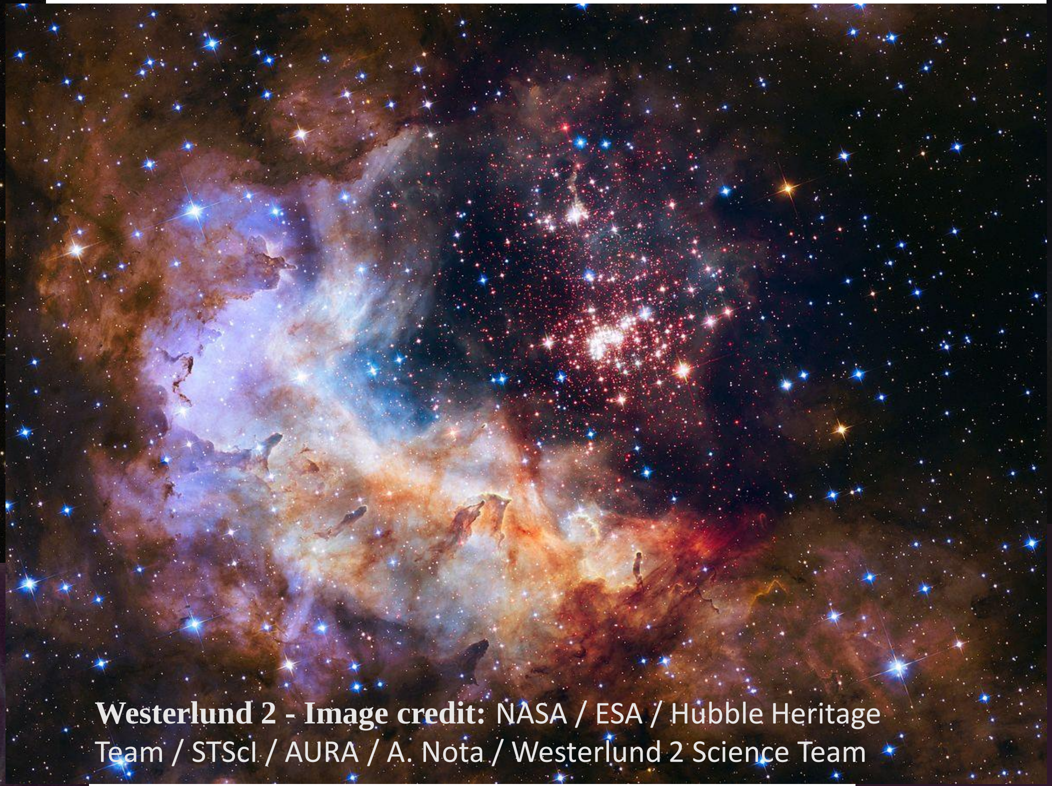




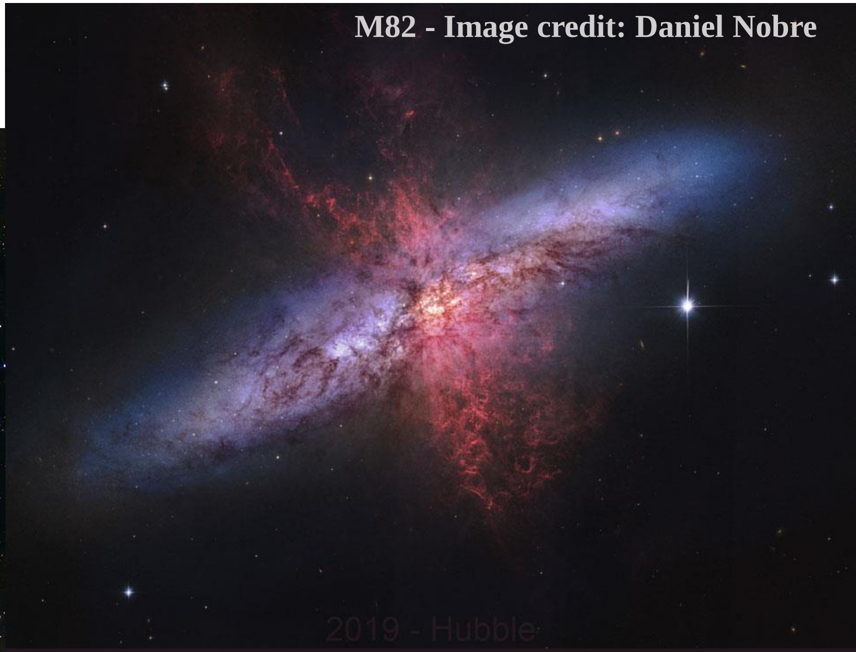
Wind Bubbles: scales and power



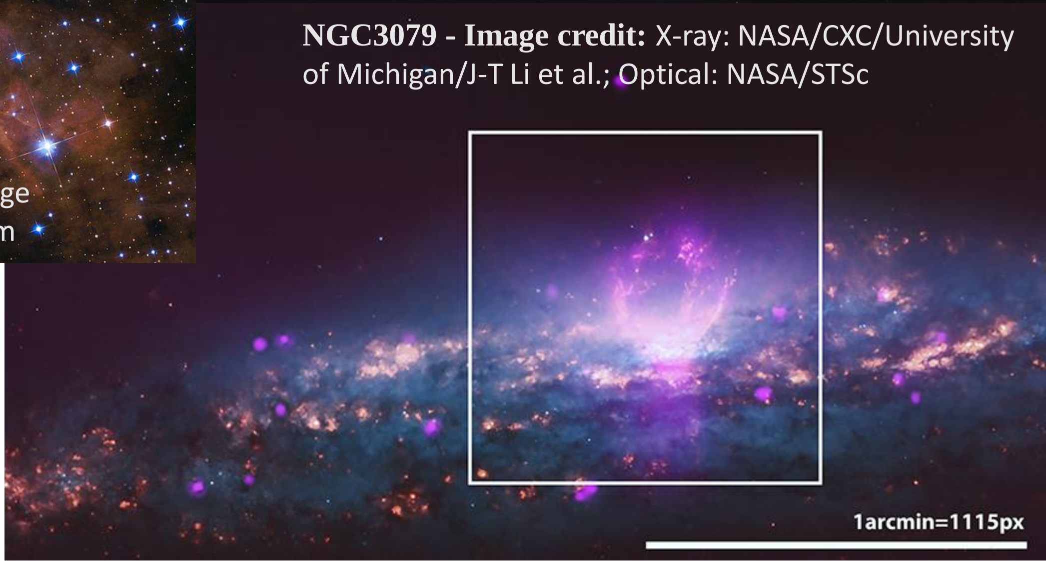
WR31a- Image credit: ESA/Hubble & NASA
Acknowledgement: Judy Schmidt



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



M82 - Image credit: Daniel Nobre



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

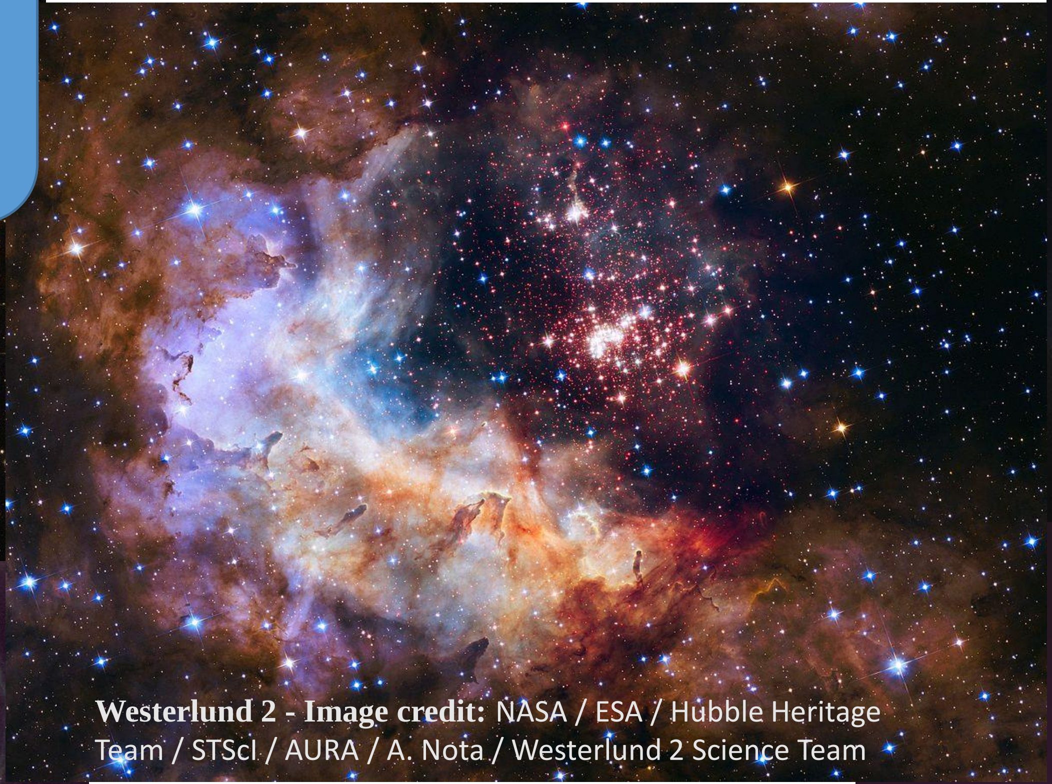
NGC7635- Image credit: NASA Goddard Space Flight Center from Greenbelt, MD, USA

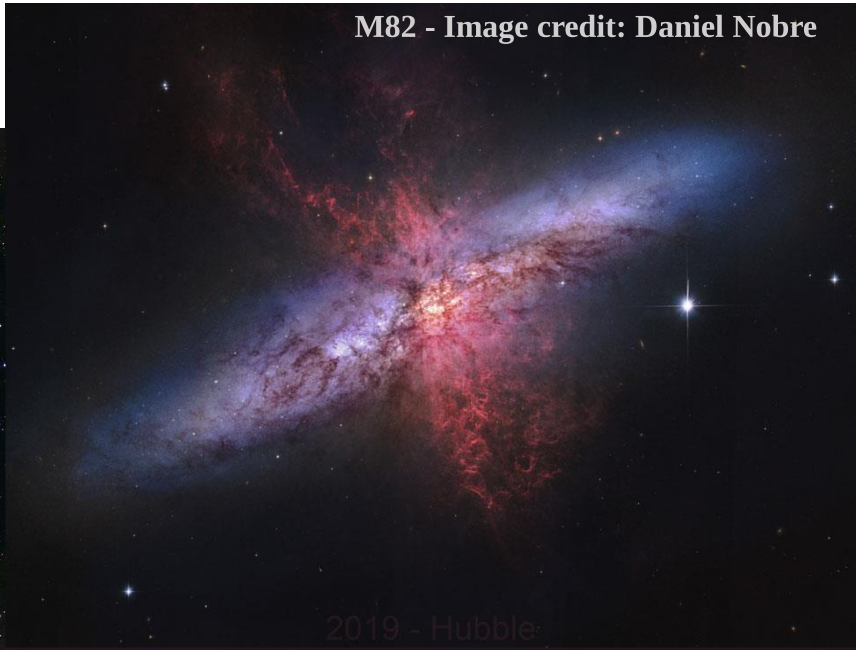
Wind Bubbles: scales and power

Massive stars:
$V_{\infty} \approx 10^2 - 10^3 \text{km/s}$
$\dot{M} \lesssim 10^{-5}\ M_{\odot}/\text{yr}$

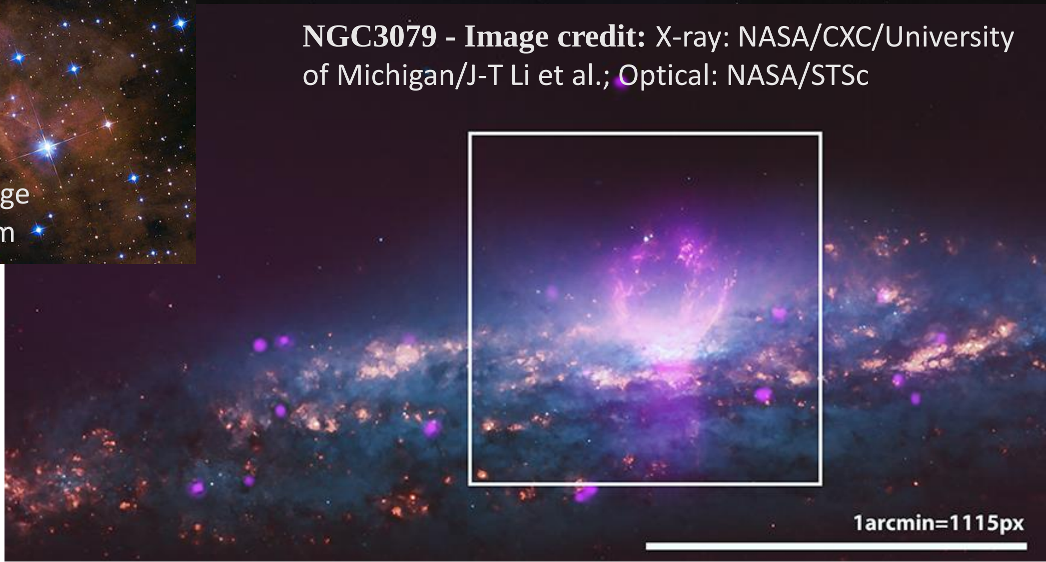

WR31a- Image credit: ESA/Hubble & NASA Acknowledgement: Judy Schmidt


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


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



M82 - Image credit: Daniel Nobre



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

Wind Bubbles: scales and power

Massive stars:

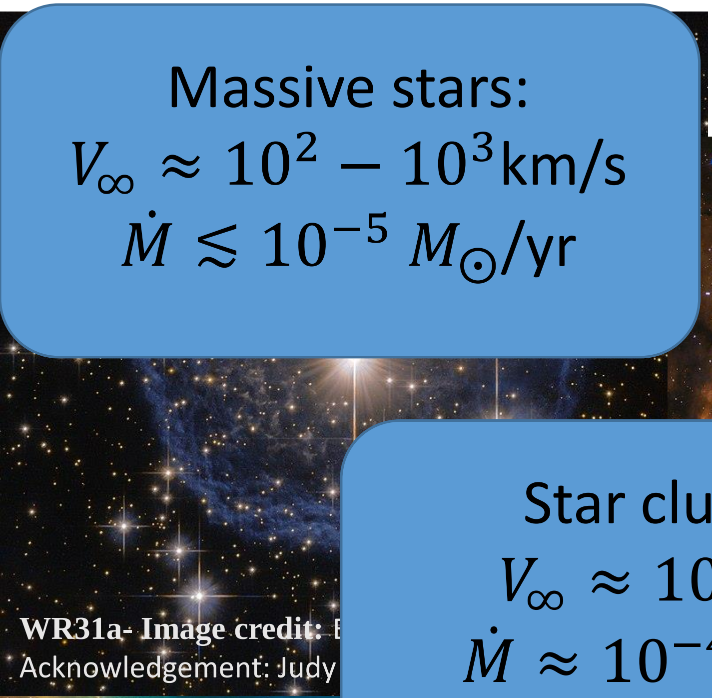
$V_\infty \approx 10^2 - 10^3 \text{km/s}$

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

Star clusters:

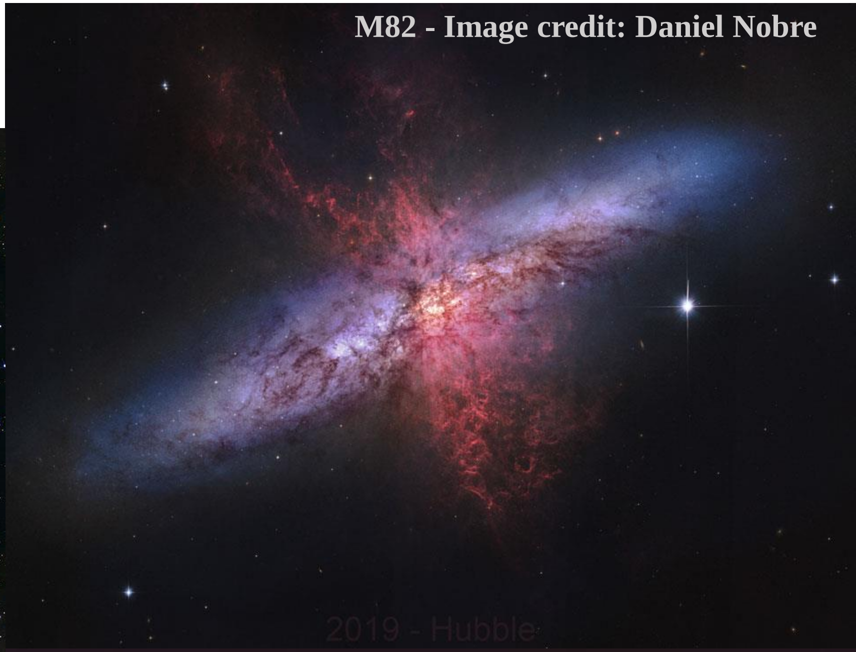
$V_\infty \approx 10^3 \text{km/s}$

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

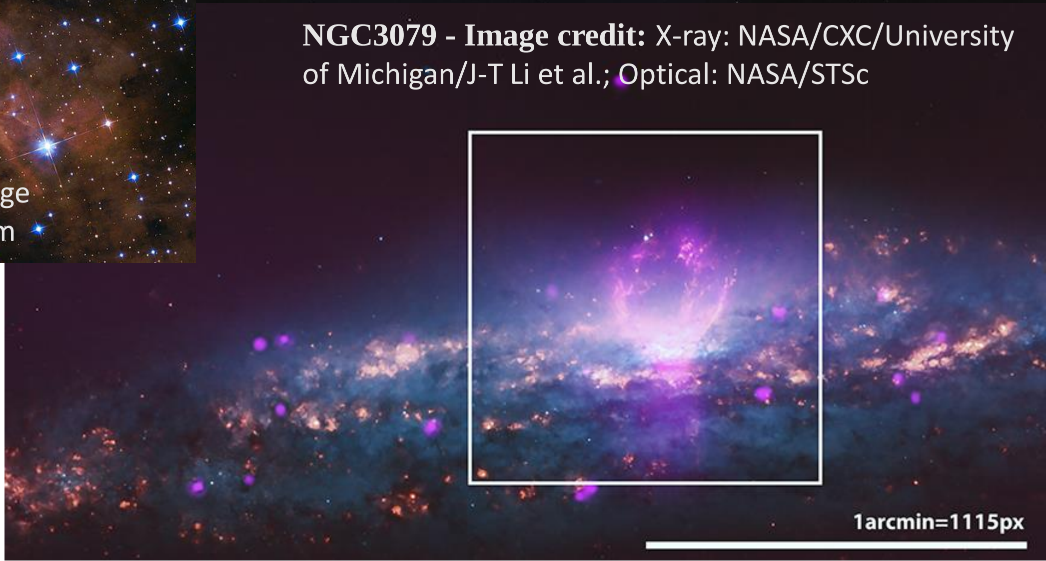


WR31a- Image credit: E... Acknowledgement: Judy...

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



M82 - Image credit: Daniel Nobre



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

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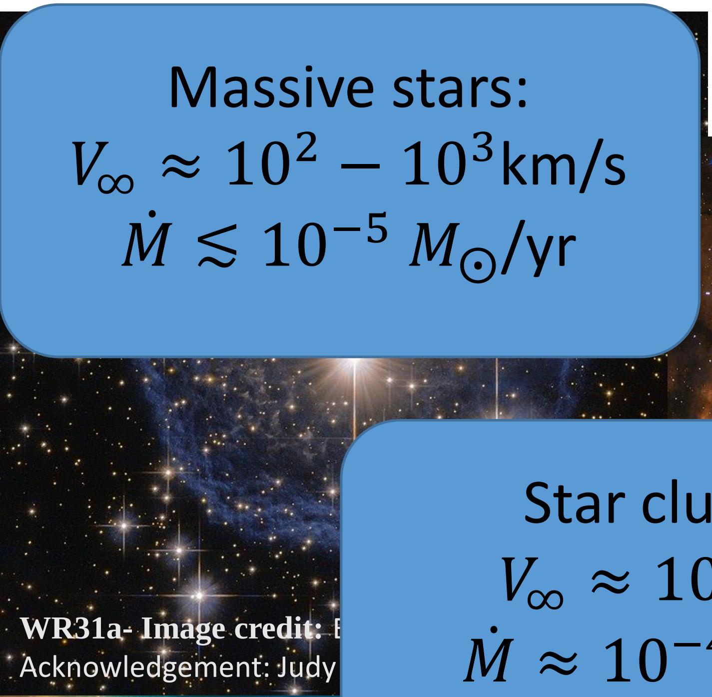

WR31a- Image credit: E
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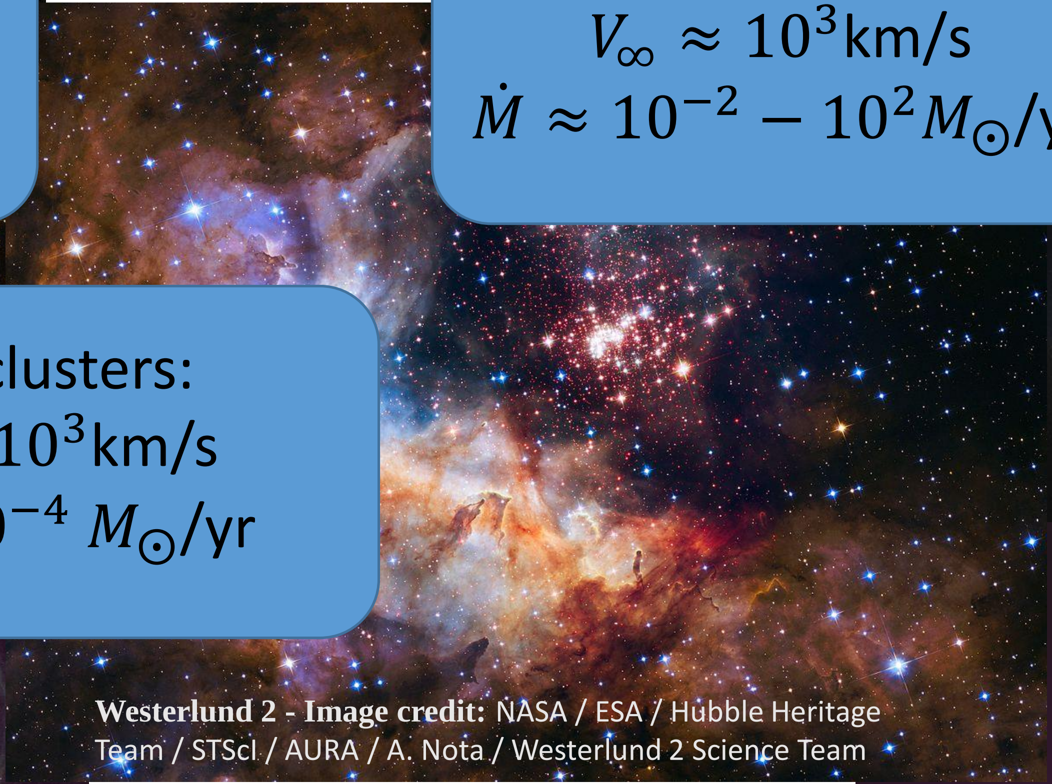
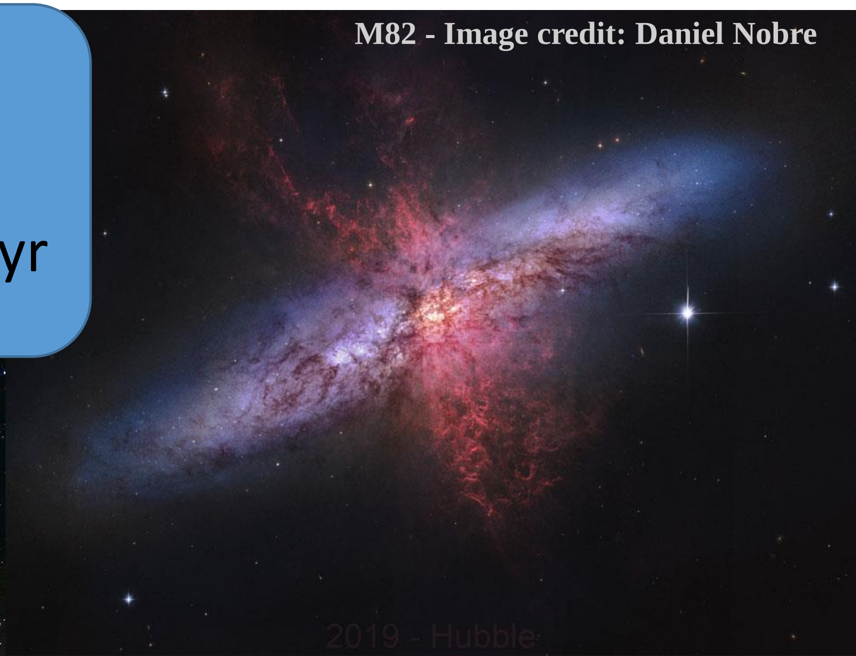
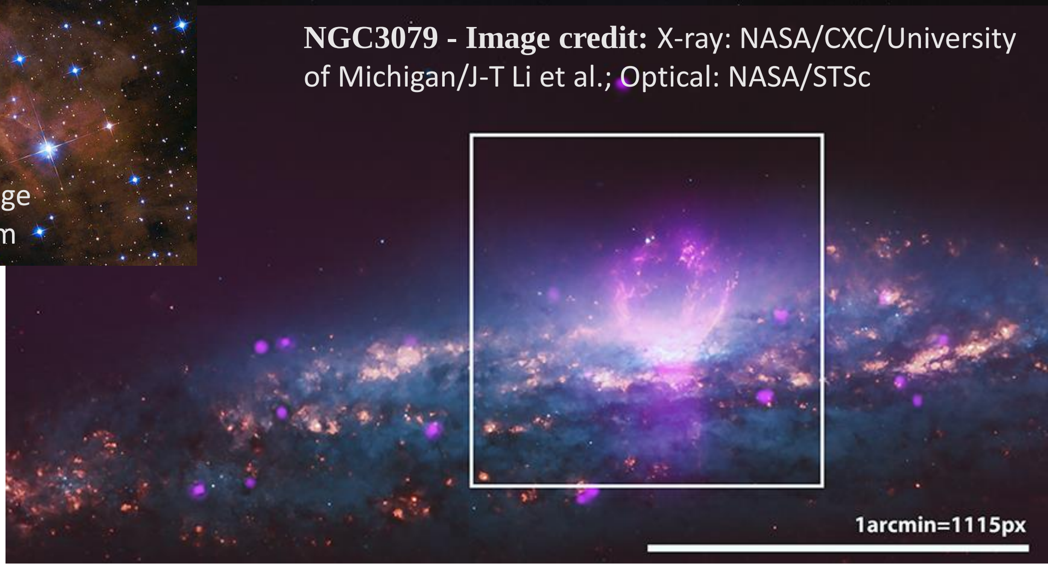


Westerlund 2 - Image credit: NASA / ESA / Hubble Heritage Team / STScI / AURA / A. Nota / Westerlund 2 Science Team



M82 - Image credit: Daniel Nobre

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



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AGN:
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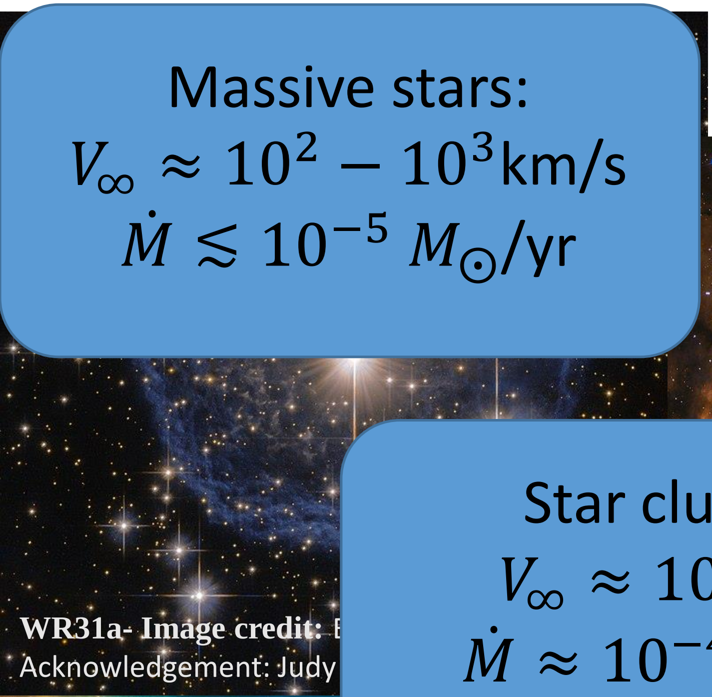
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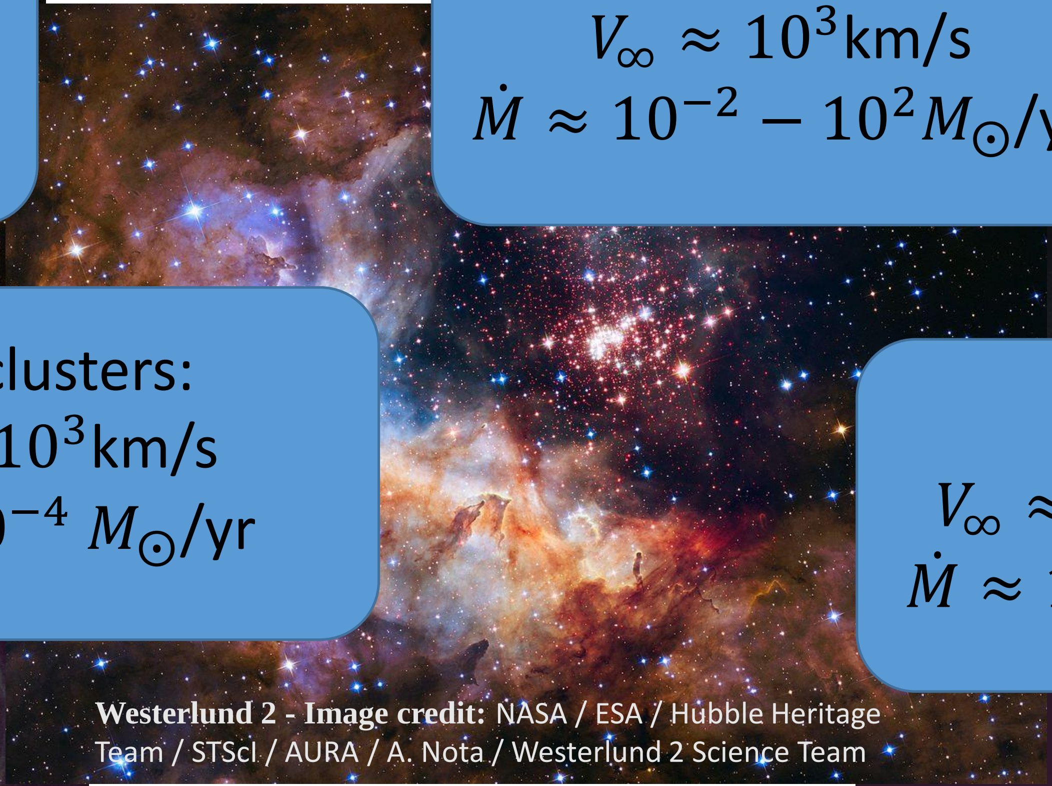
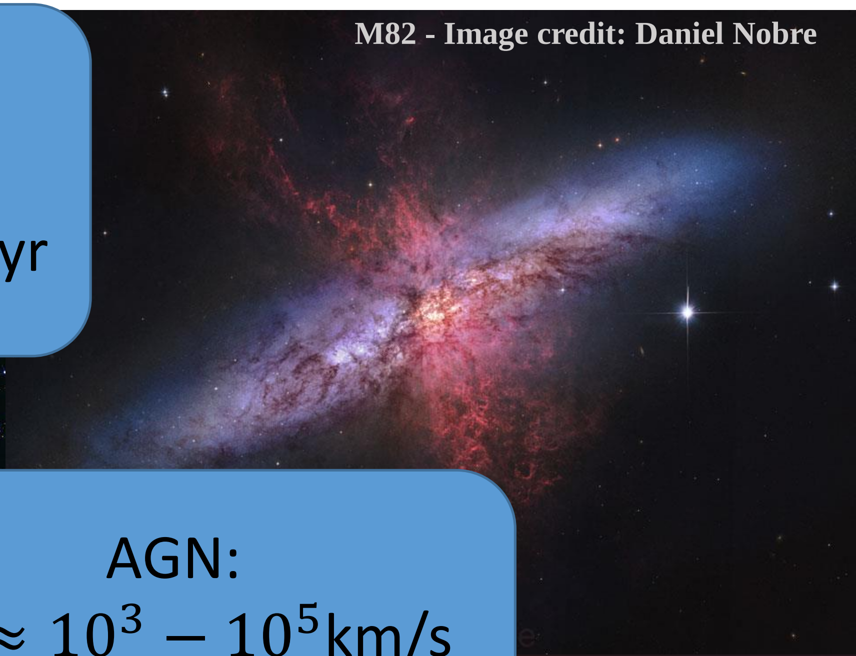

Westerlund 2 - Image credit: NASA / ESA / Hubble Heritage Team / STScI / AURA / A. Nota / Westerlund 2 Science Team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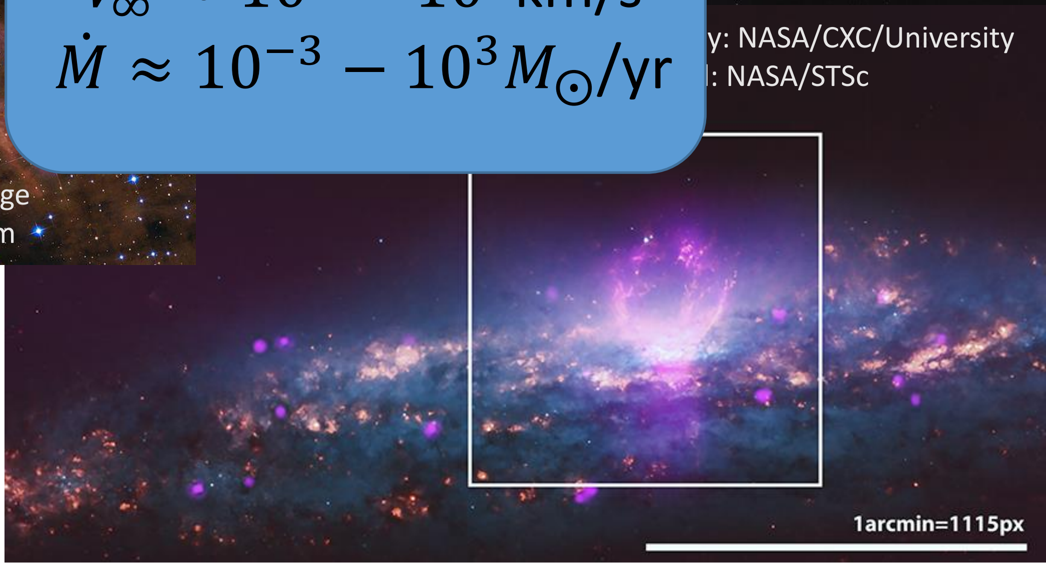


y: NASA/CXC/University
: NASA/STSc


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

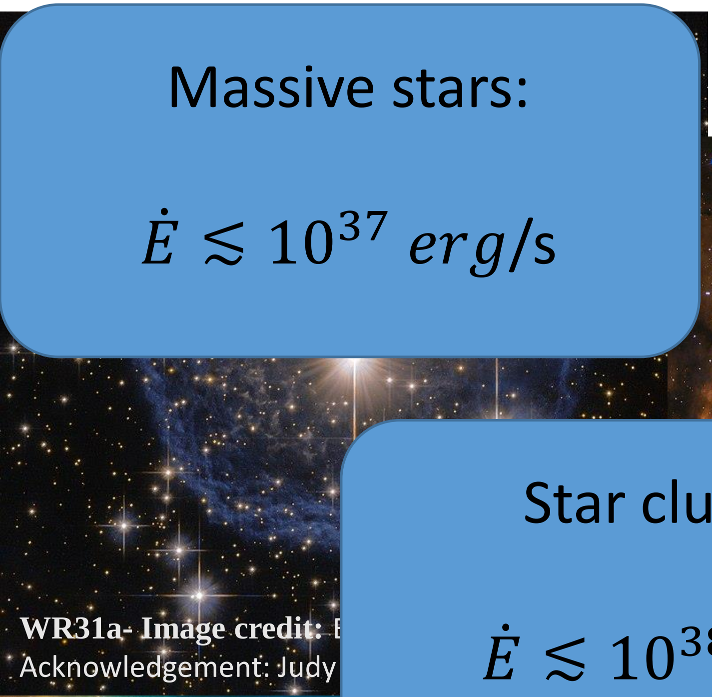
Wind Bubbles: scales and power

Massive stars:

$$\dot{E} \lesssim 10^{37}\ erg/s$$

Starbursts:

$$\dot{E} \lesssim 10^{42}\ erg/s$$

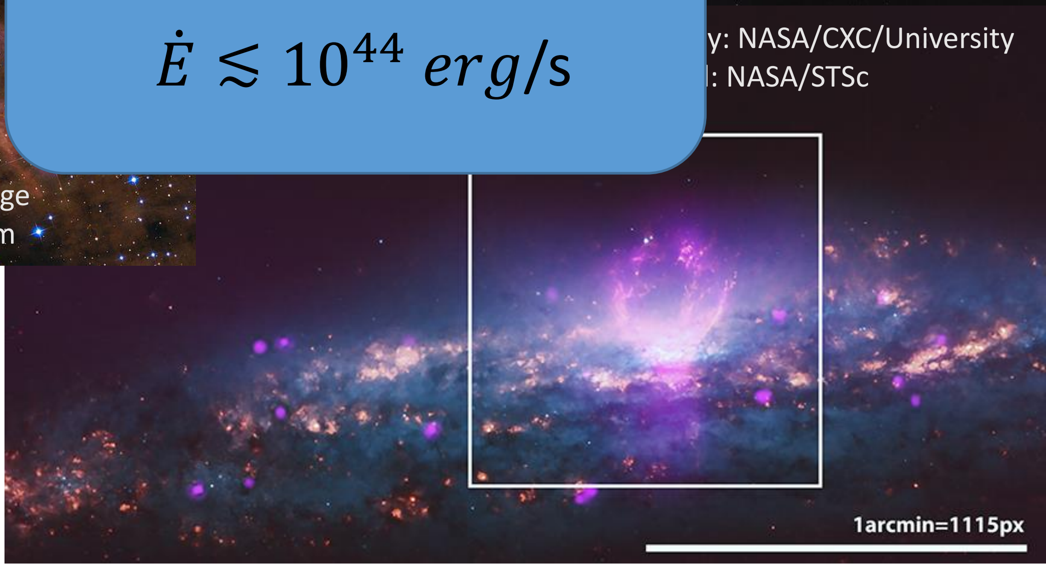


Star clusters:

$$\dot{E} \lesssim 10^{38}\ erg/s$$

AGN:

$$\dot{E} \lesssim 10^{44}\ erg/s$$



Maximum Energy: a first guess

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

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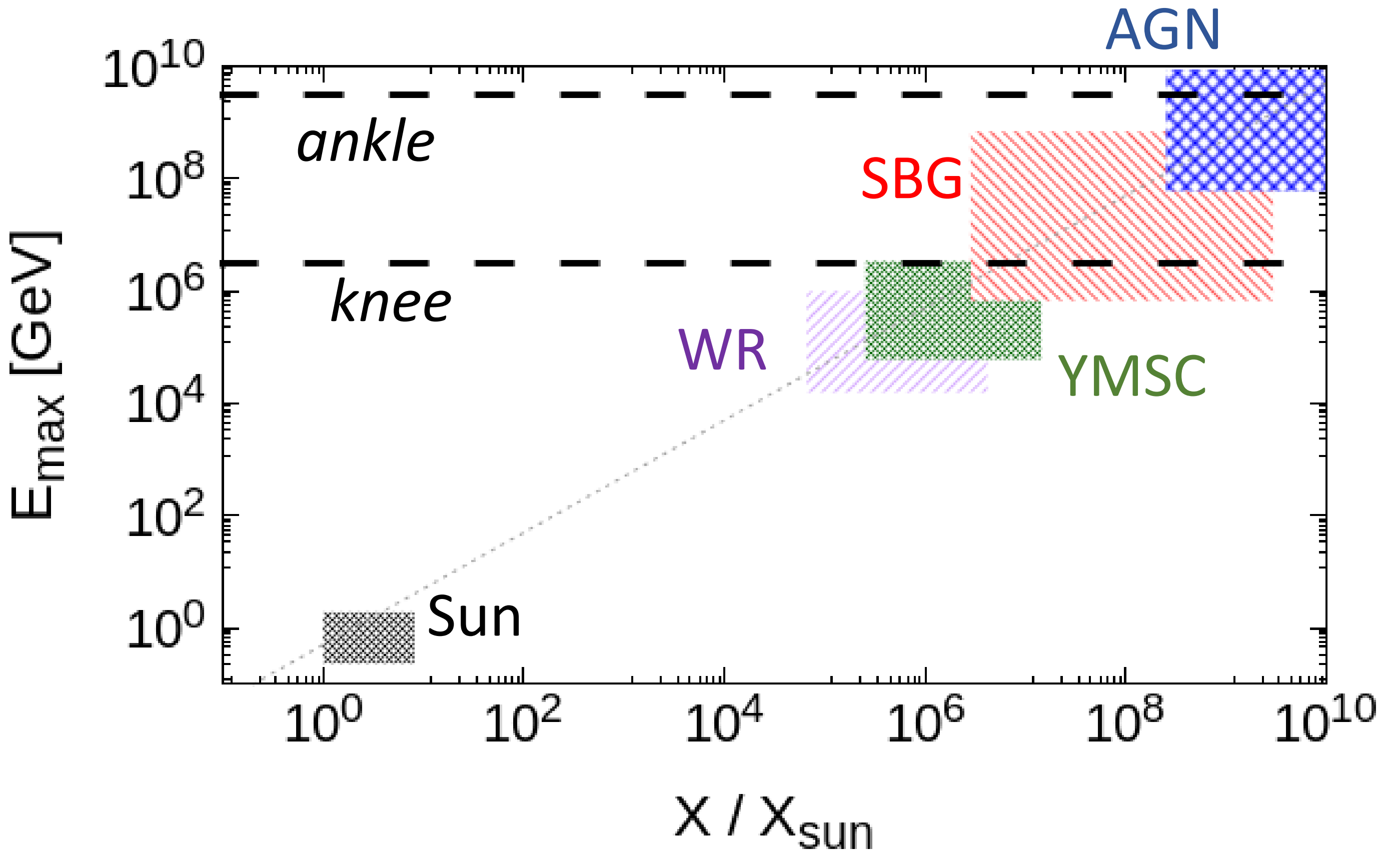
$$X = \dot{E}\dot{P}^{-1/2}$$



Key questions

1. Can wind bubbles get to the highest energies both in Galactic and Extragalactic context?

2. Can wind bubbles be efficient gamma-ray and HE neutrino sources?

Multimessenger role of wind bubbles

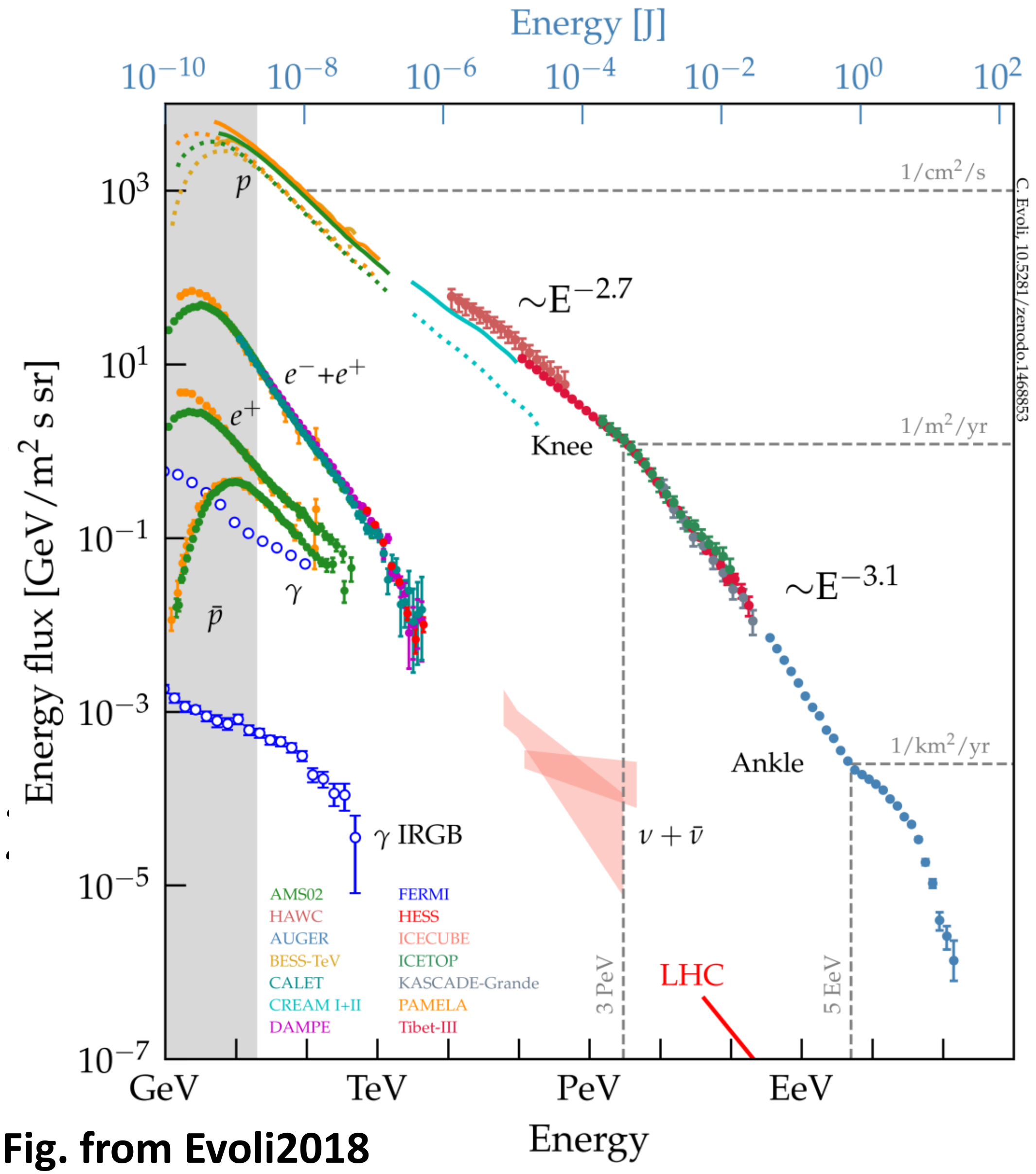
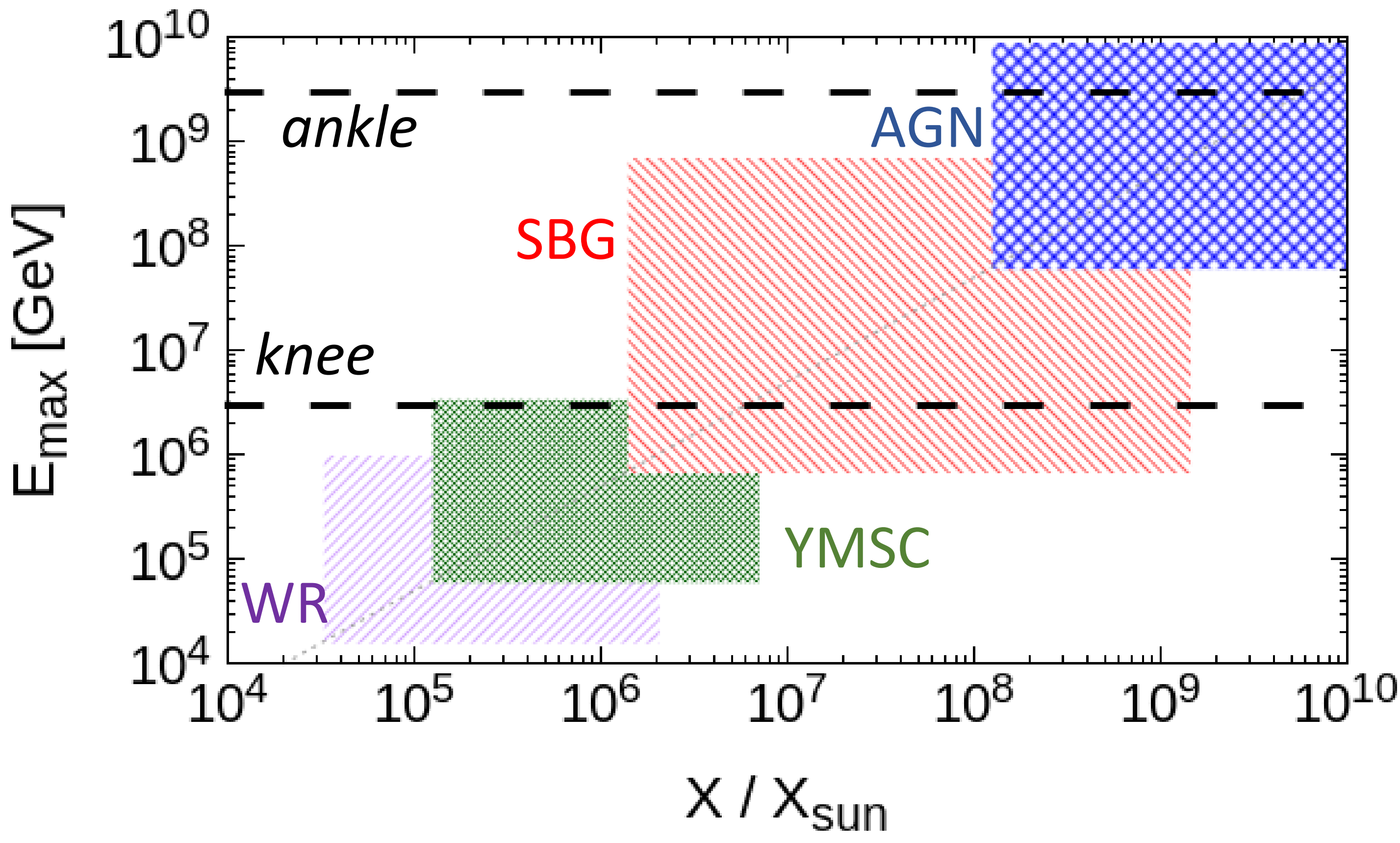
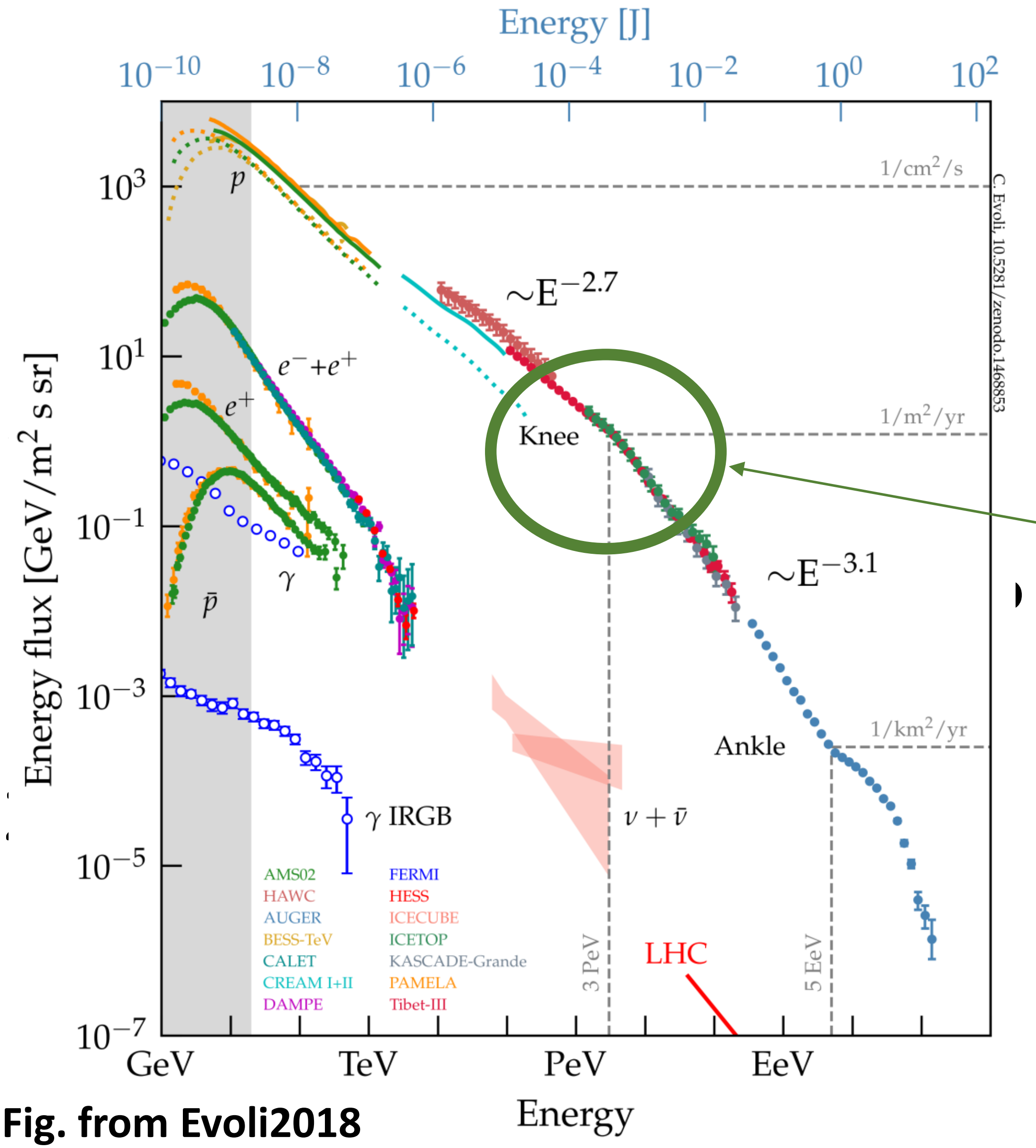


Fig. from Evoli2018



Multimessenger role of wind bubbles



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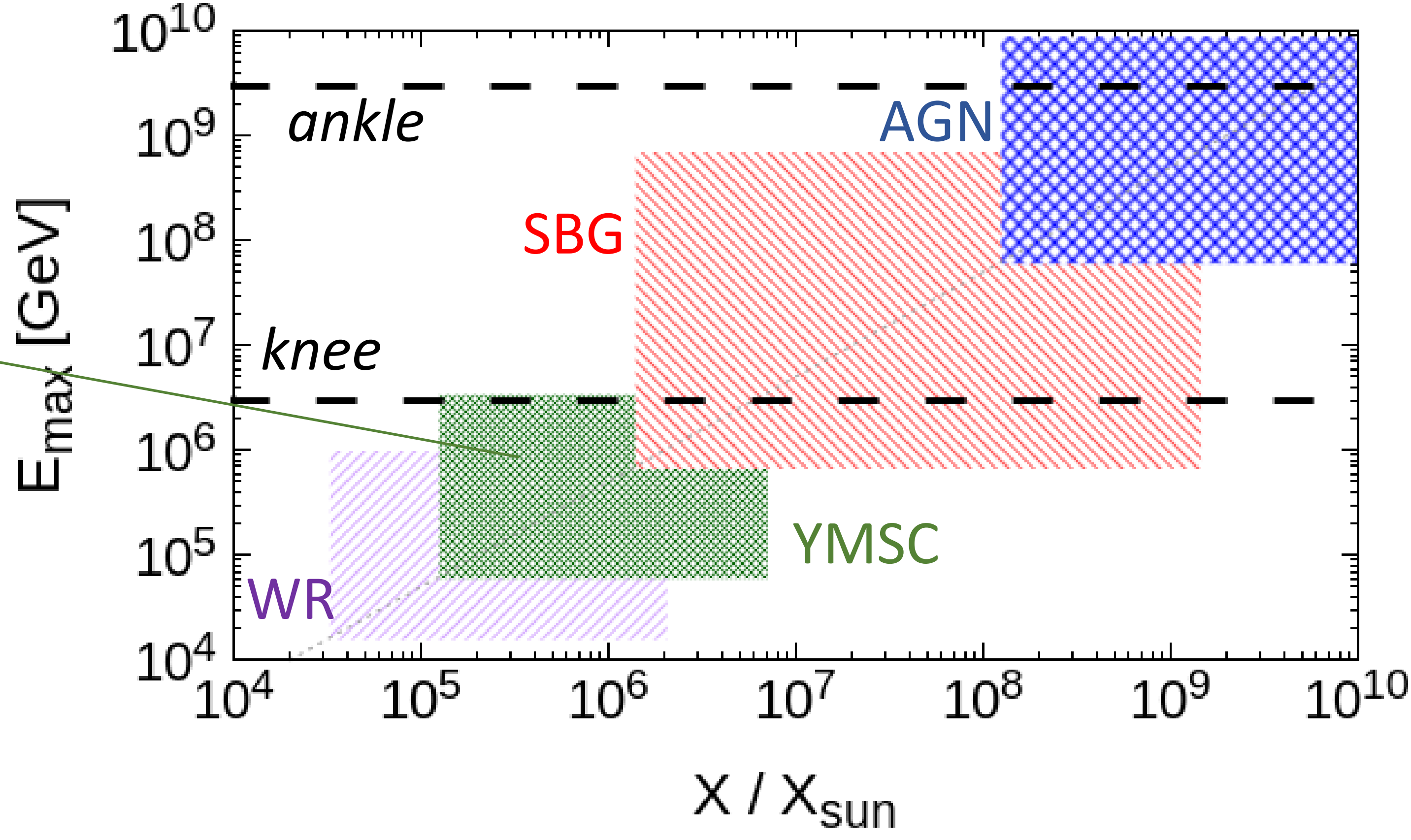

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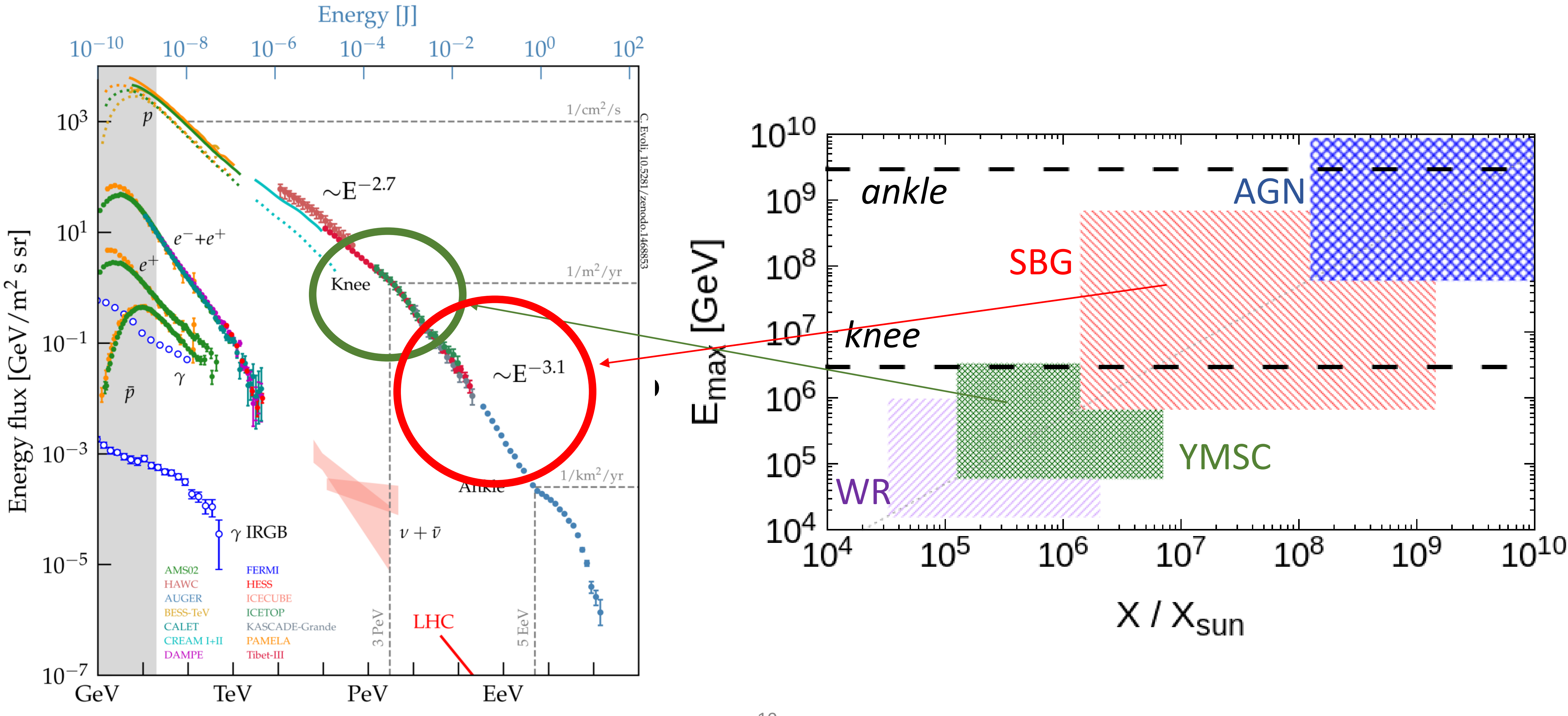

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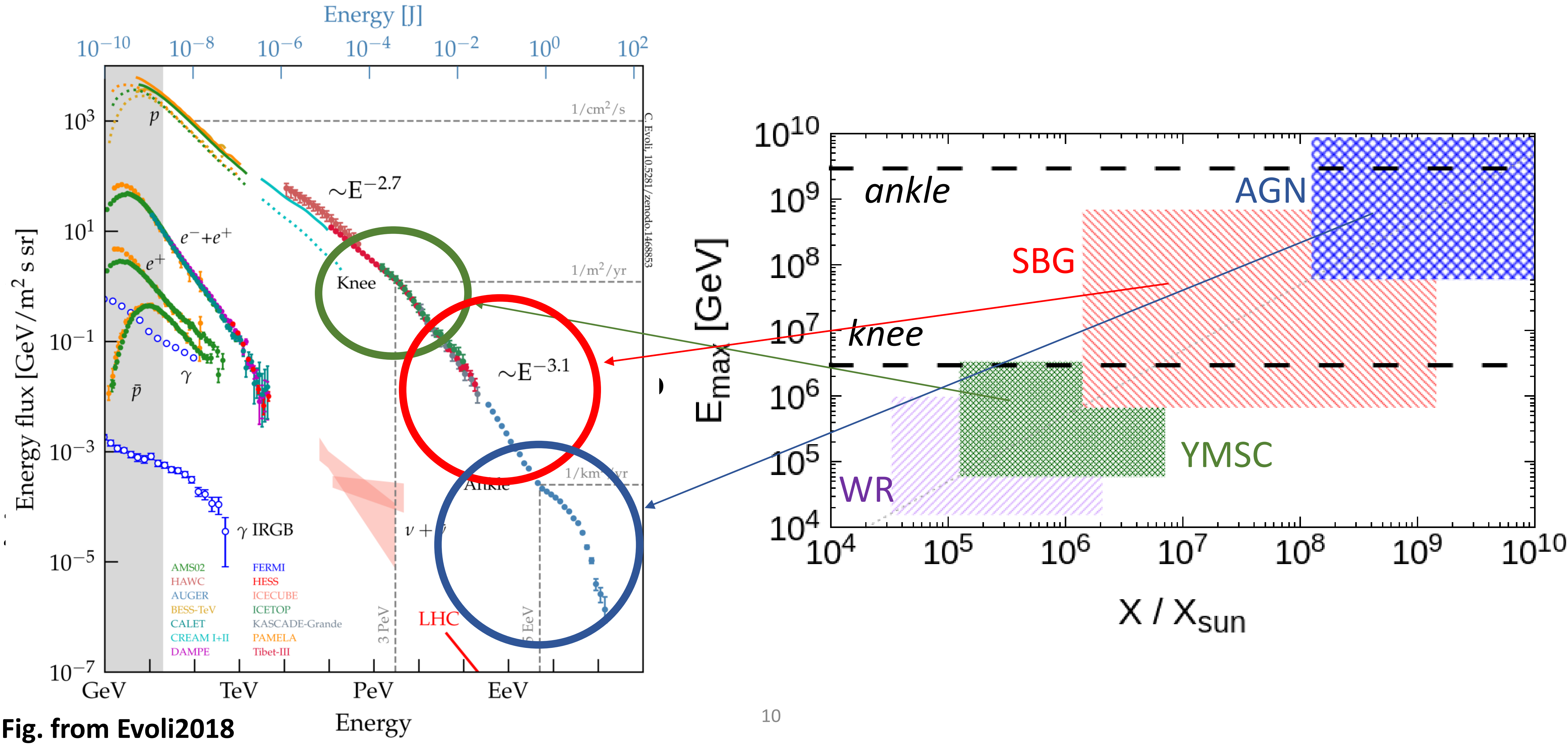

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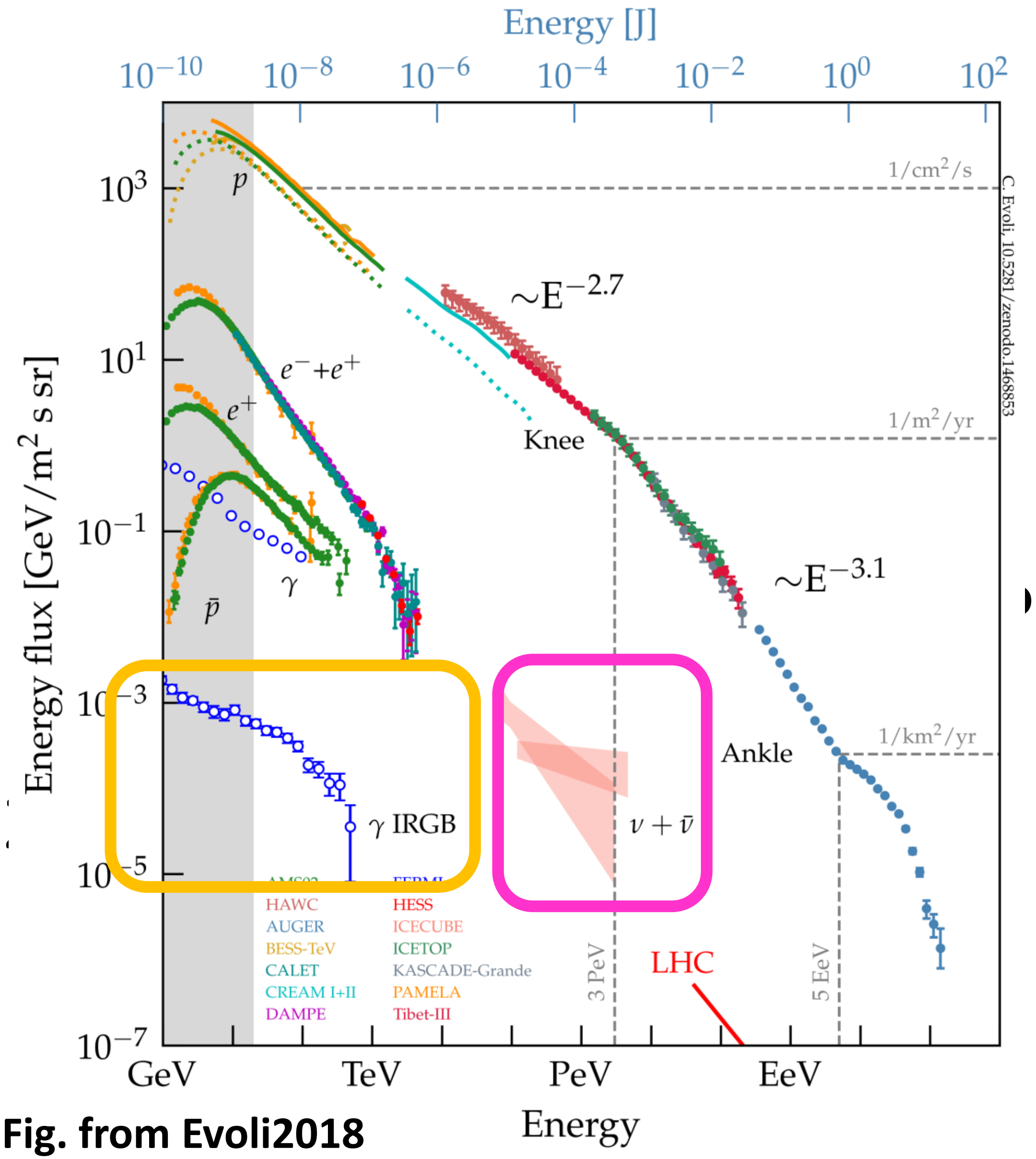

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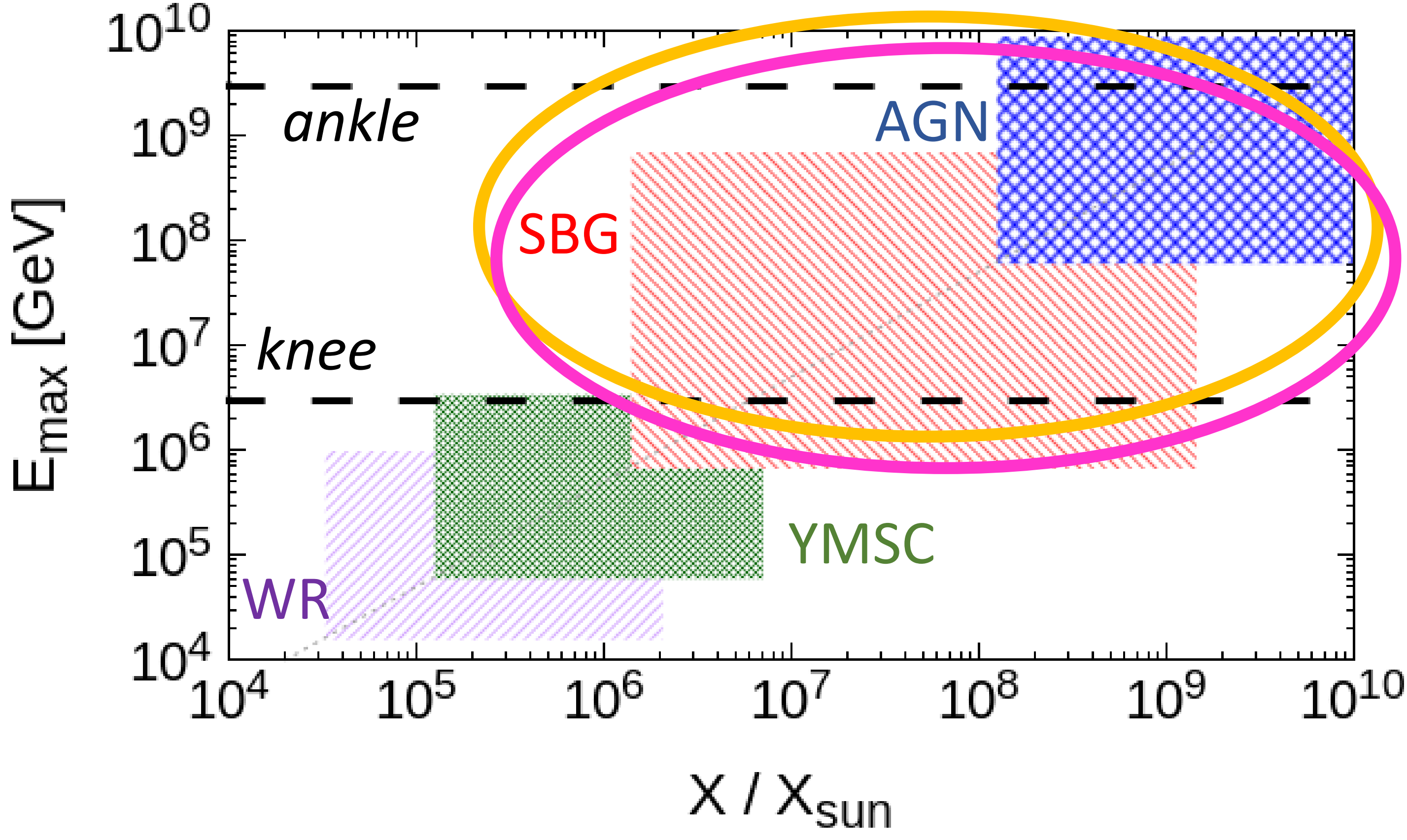
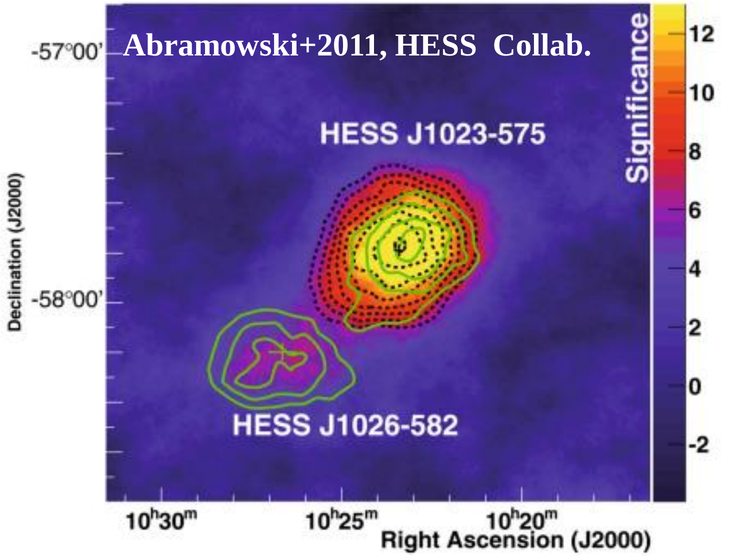
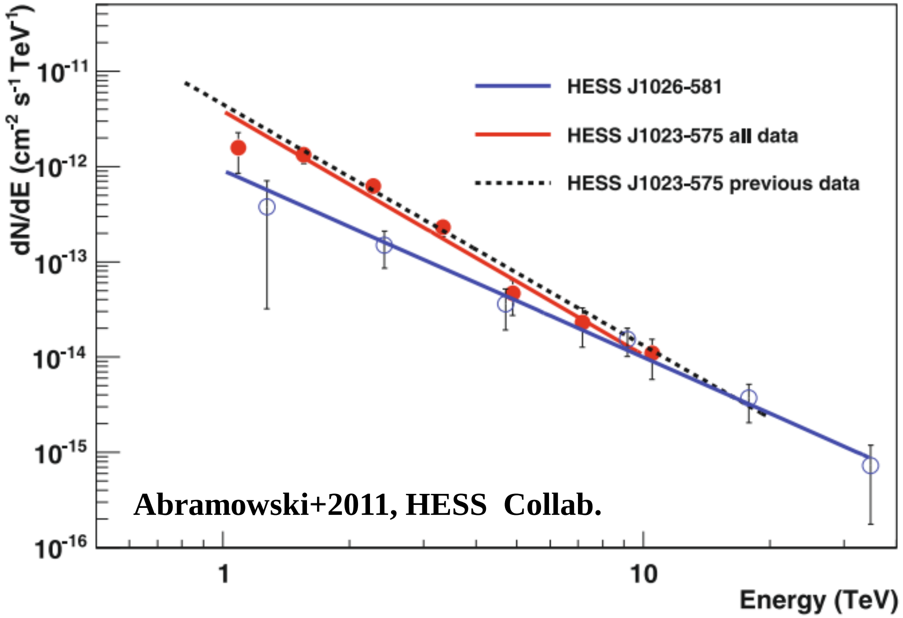


Young Massive Stellar Cluster





Cassé+1980-1982, Volk+1982, Cesarsky+1983, Webb+1985, Bykov+1992, Parizot+2004, Ferrand+2009, Zirakashvili+2017, Aharonian+2019, Gupta+2020, Morlino+2021, Vieu+2022

Young Massive Star Cluster - 2

Typical properties

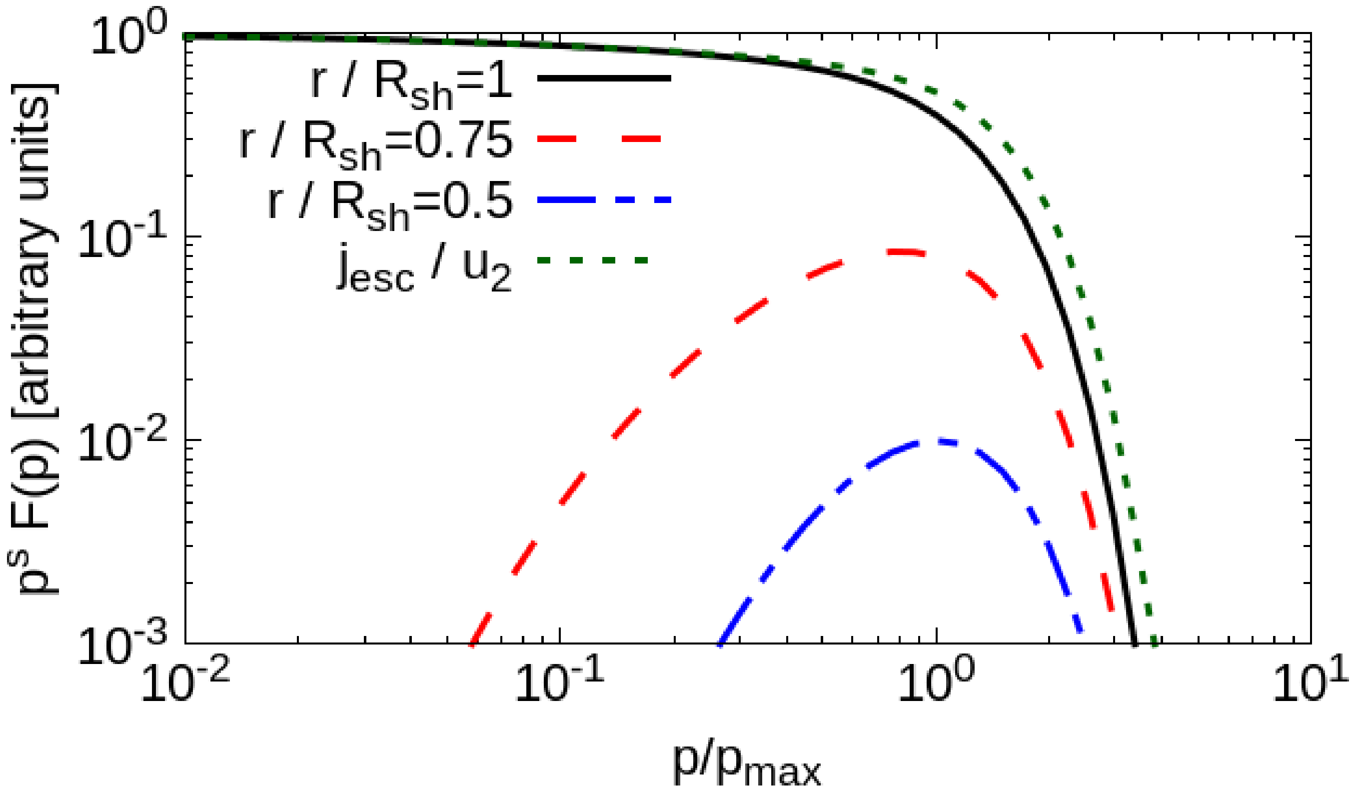
$\dot{M} \approx 10^{-4}\, M_{\odot}\, yr^{-1}$

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

$t_{age} \approx 1 - 5\, Myr$

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

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



Young massive star clusters - 3

Target density

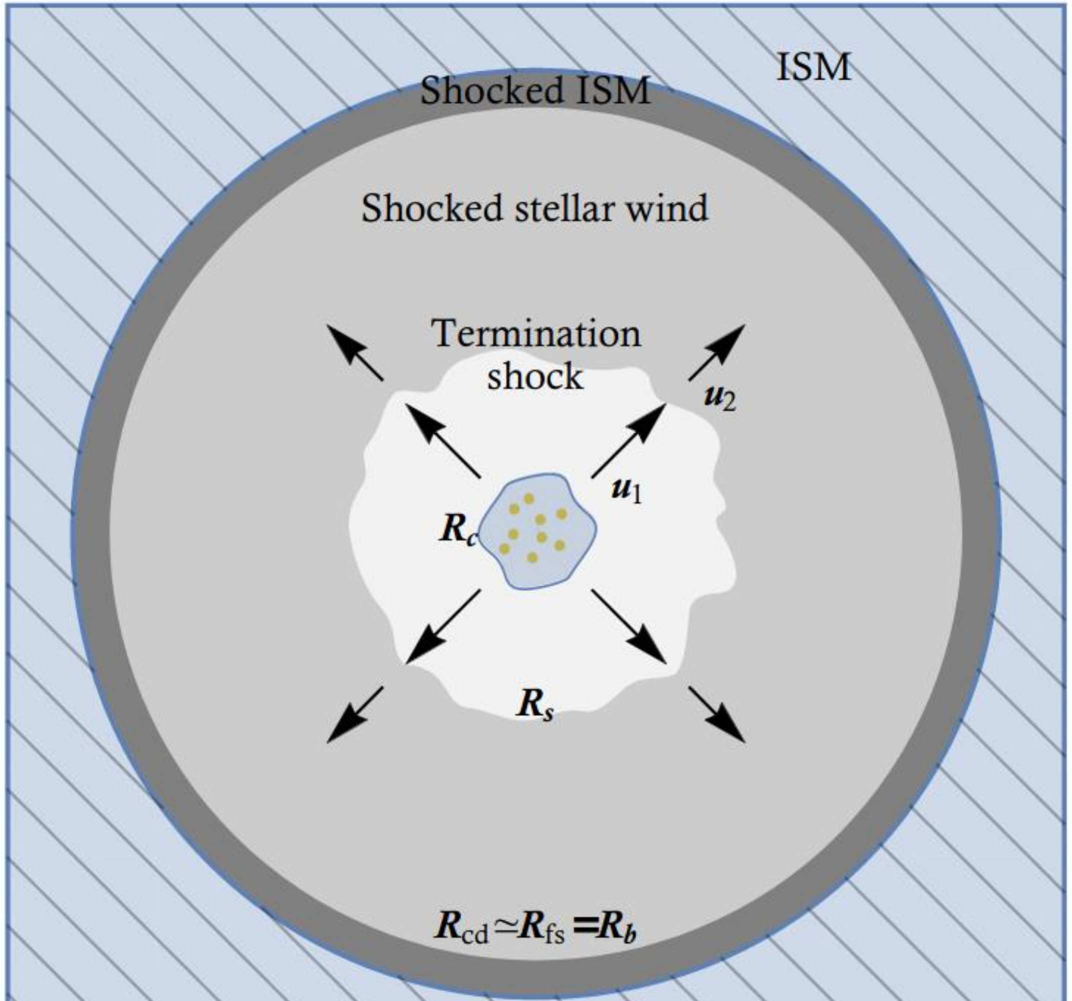
Shocked stellar wind ($R_{sh} - R_{cd}$):

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

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

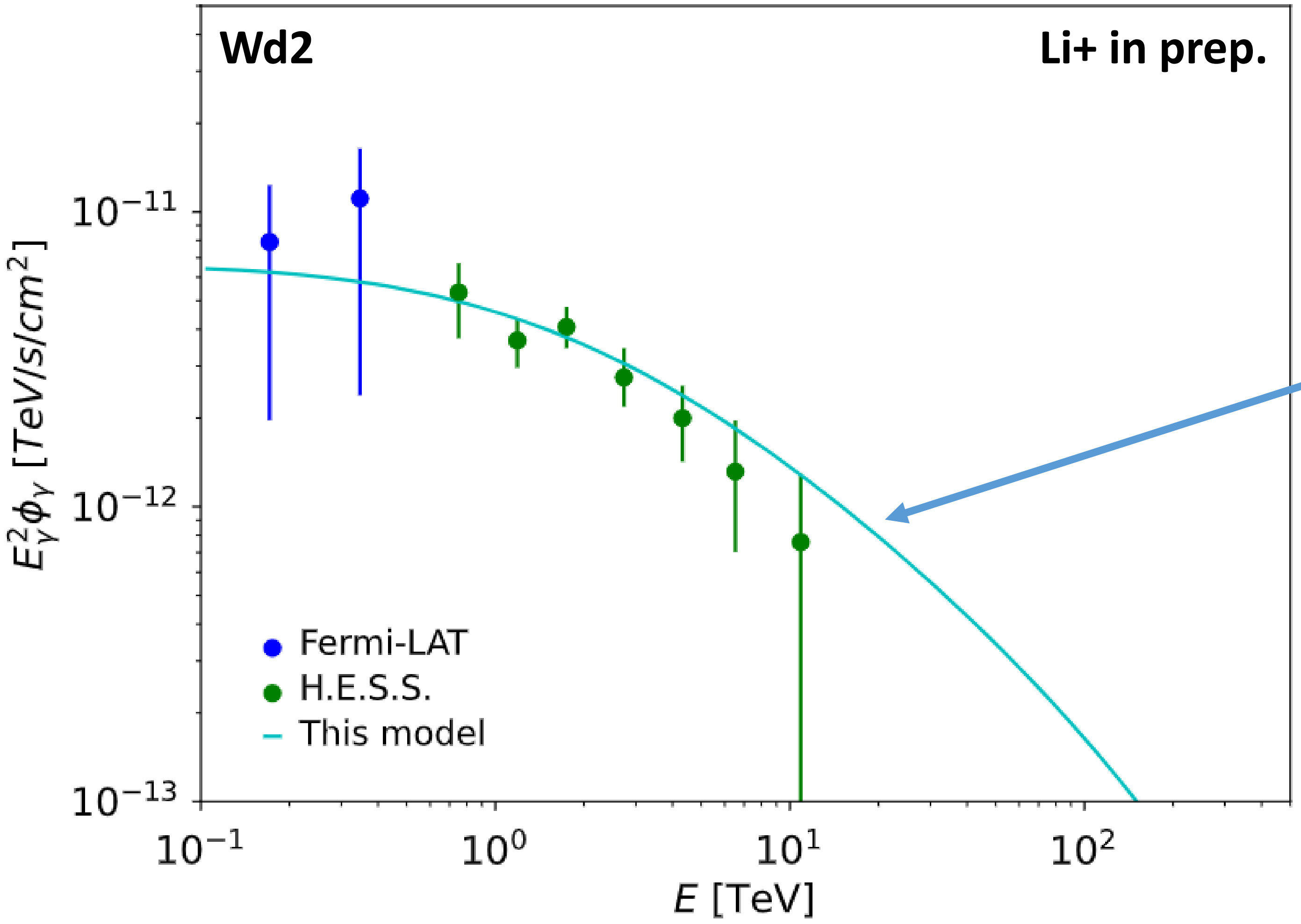
$$n_{SAM} = \rho n_0 \approx 1 - 10^2\ cm^{-3}$$

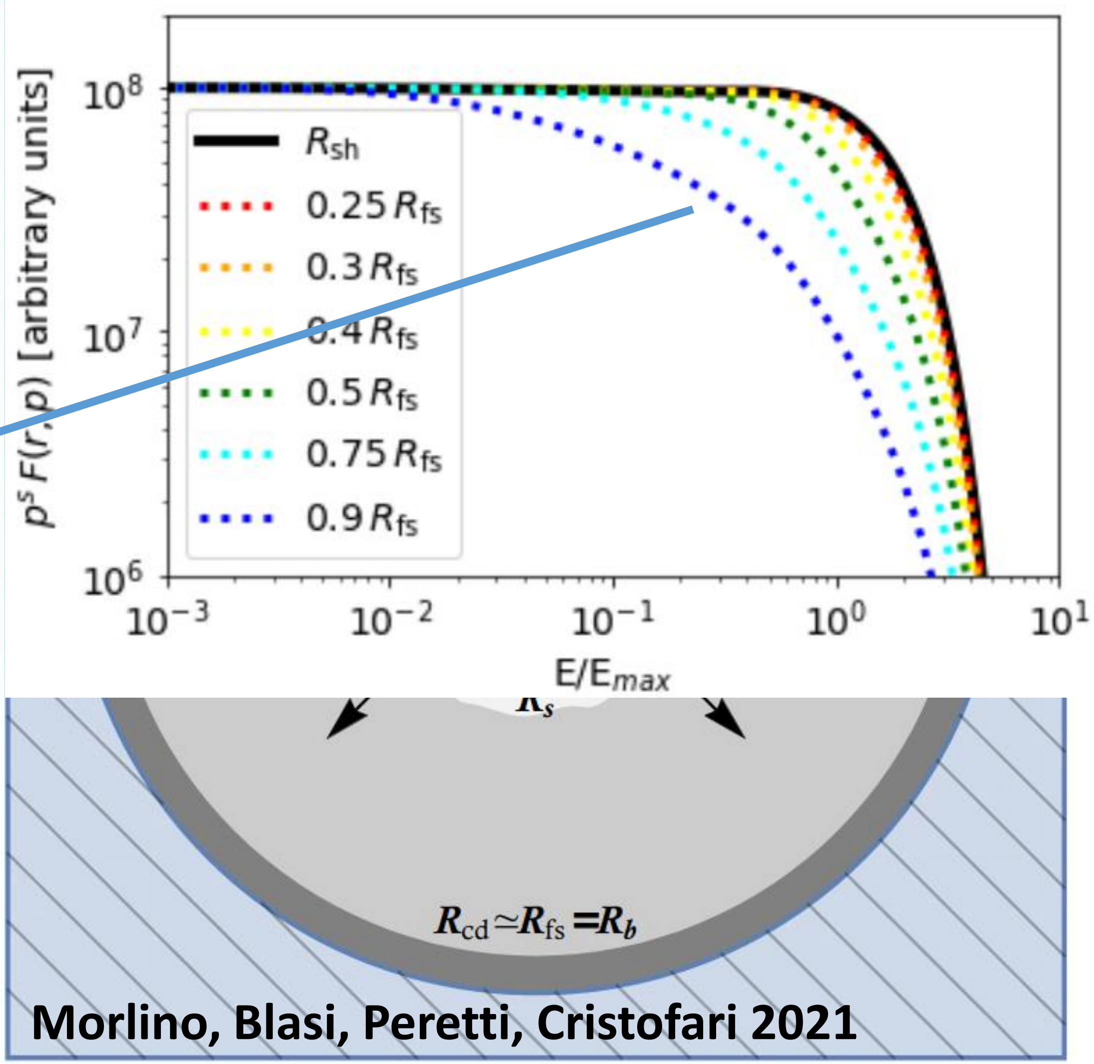
$$V_{SAM}/V_{sw} \approx 0.38$$



Morlino, Blasi, Peretti, Cristofari 2021

Hadronic emission from star clusters





Morlino, Blasi, Peretti, Cristofari 2021

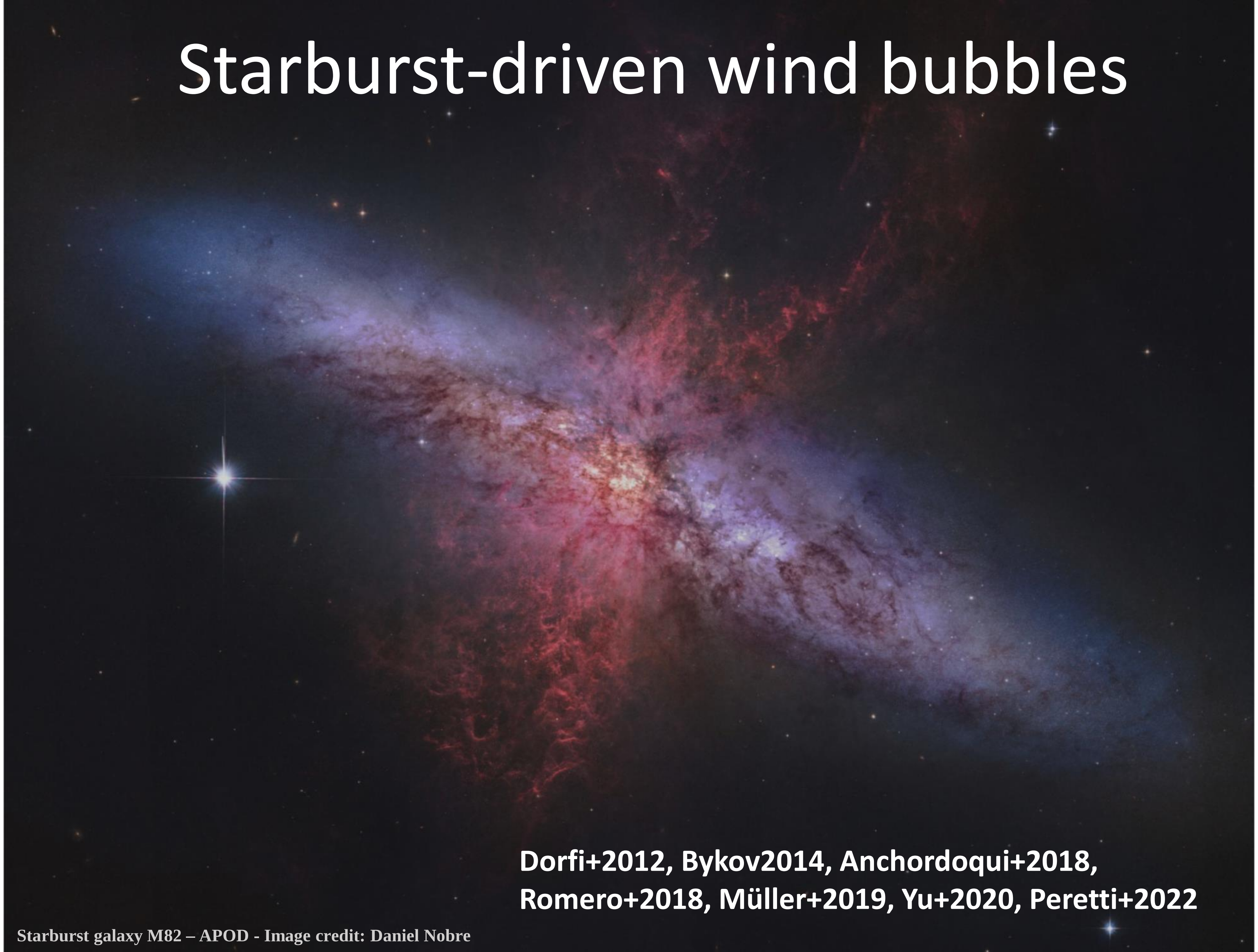
Take home message - 1

- Diffusive shock acceleration can take place efficiently at wind shocks of YMSCs

- Maximum energies up to PeV can be reached

- YMSCs could be relevant sources of gamma rays and high-energy neutrinos in the Galaxy

Starburst-driven wind bubbles

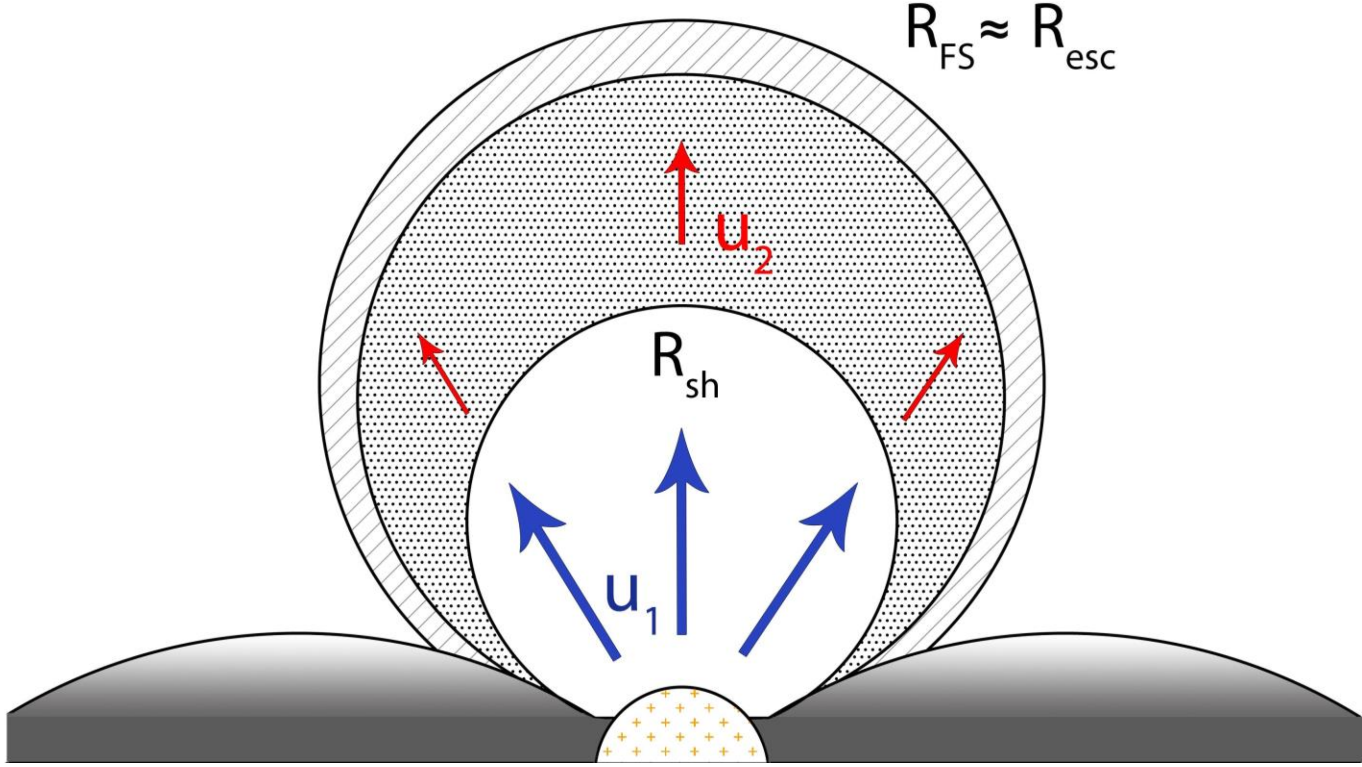


Dorfi+2012, Bykov2014, Anchordoqui+2018,
Romero+2018, Müller+2019, Yu+2020, Peretti+2022

Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

Starburst-driven wind bubbles

- $V_\infty \approx 10^3\ km/s$
- $\dot{M} \approx 10^{-2} - 10^2\ M_\odot/yr$
- $\dot{E} \approx 10^{39} - 10^{42}$ erg/s



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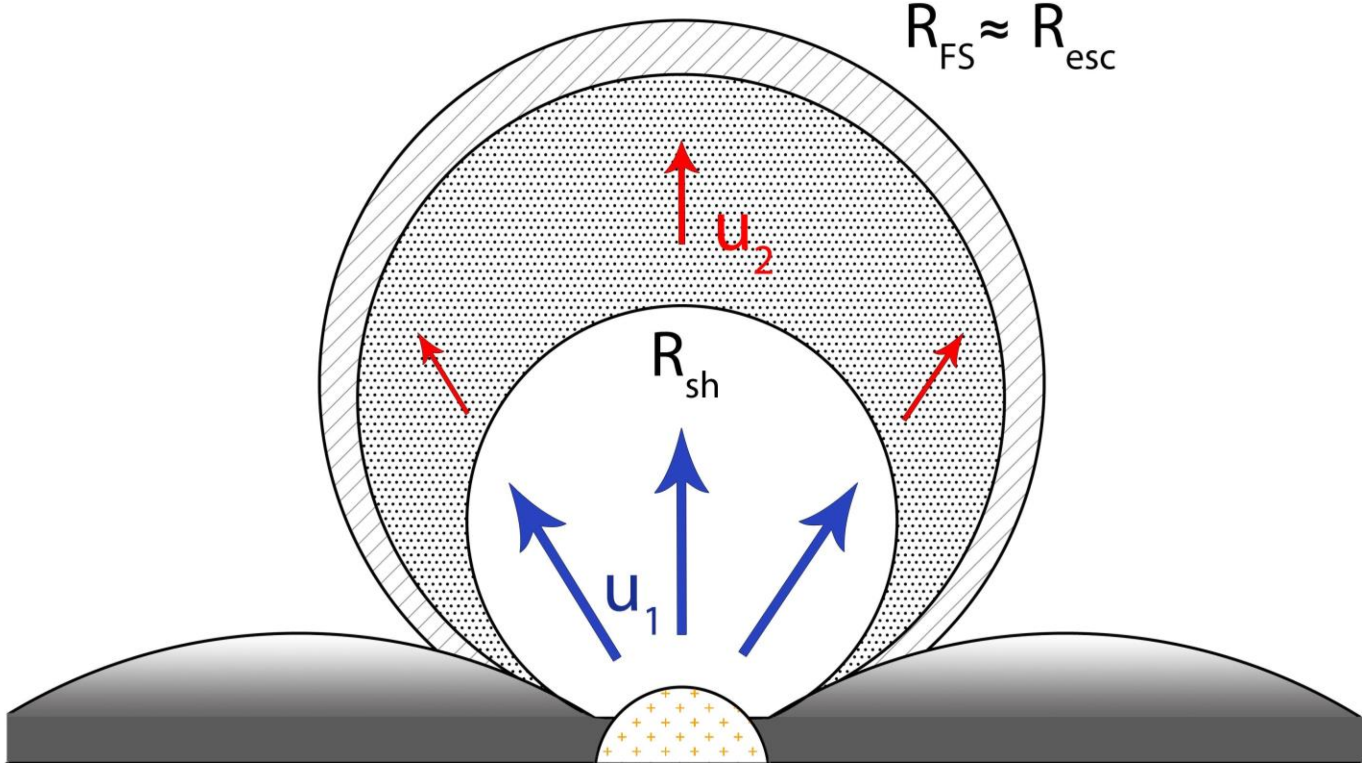
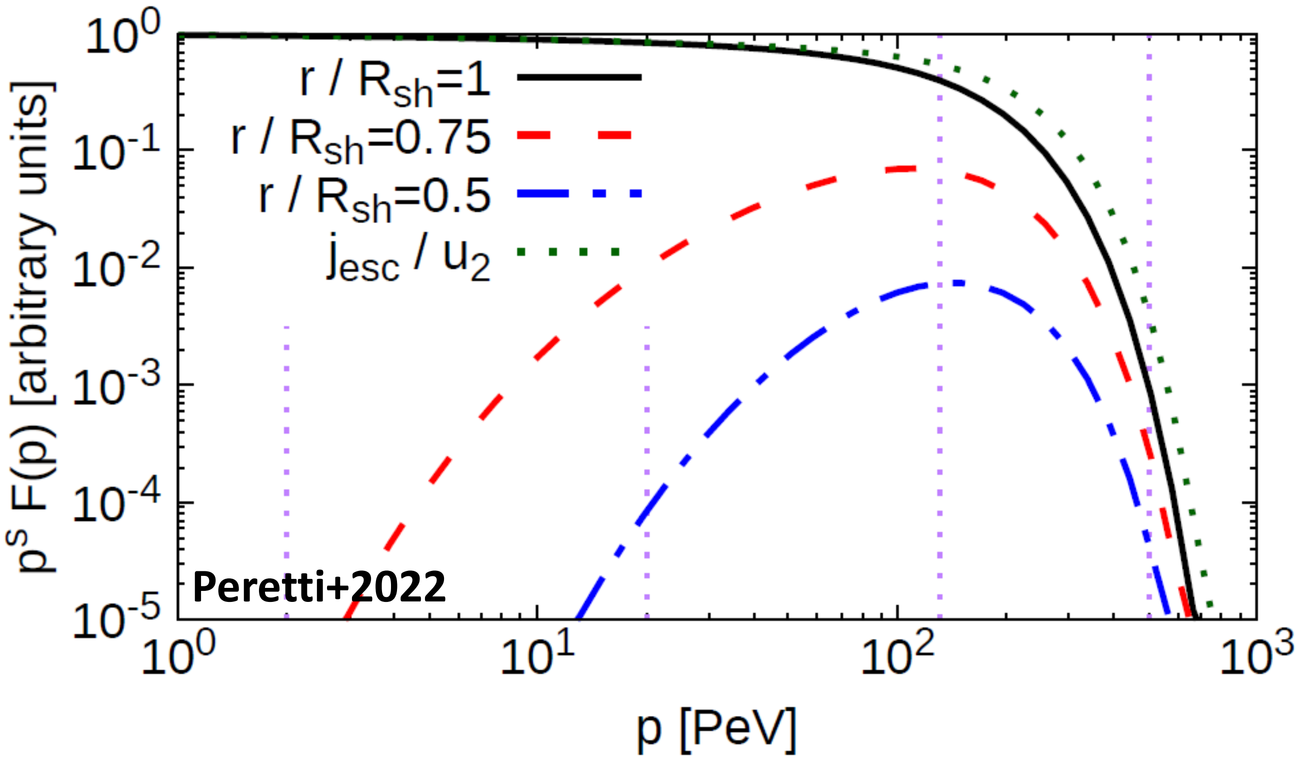
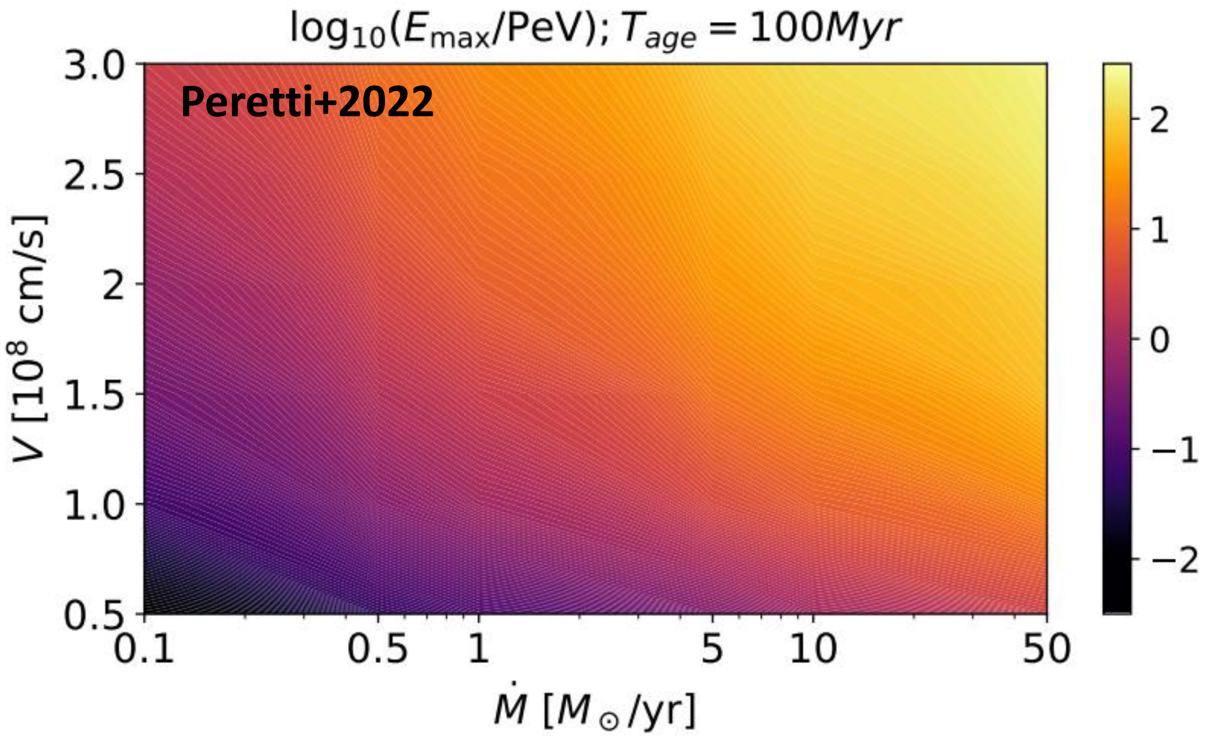
$$E_{max} \lesssim 10^2\ PeV$$

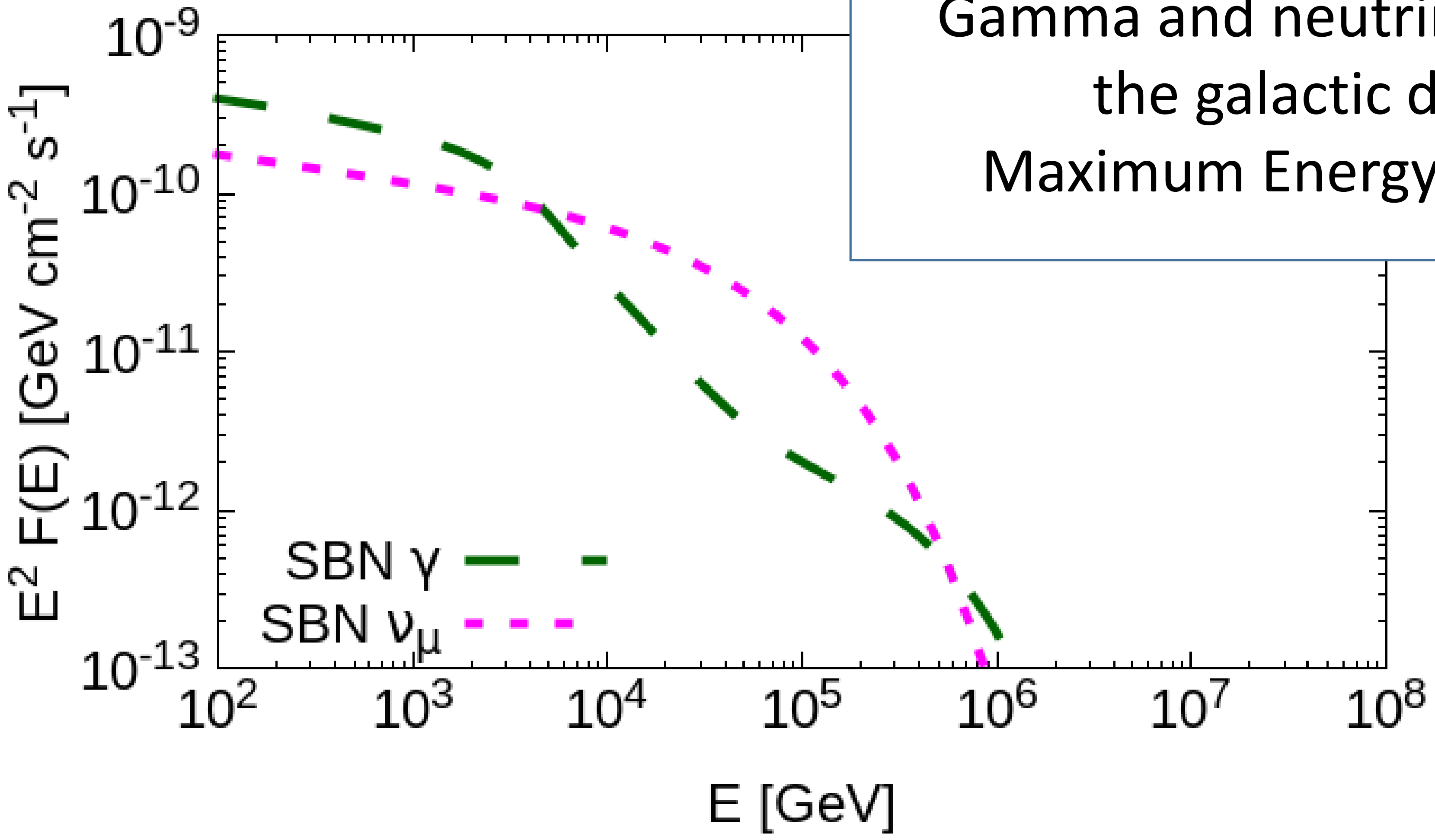


SBGs – Maximum Energy





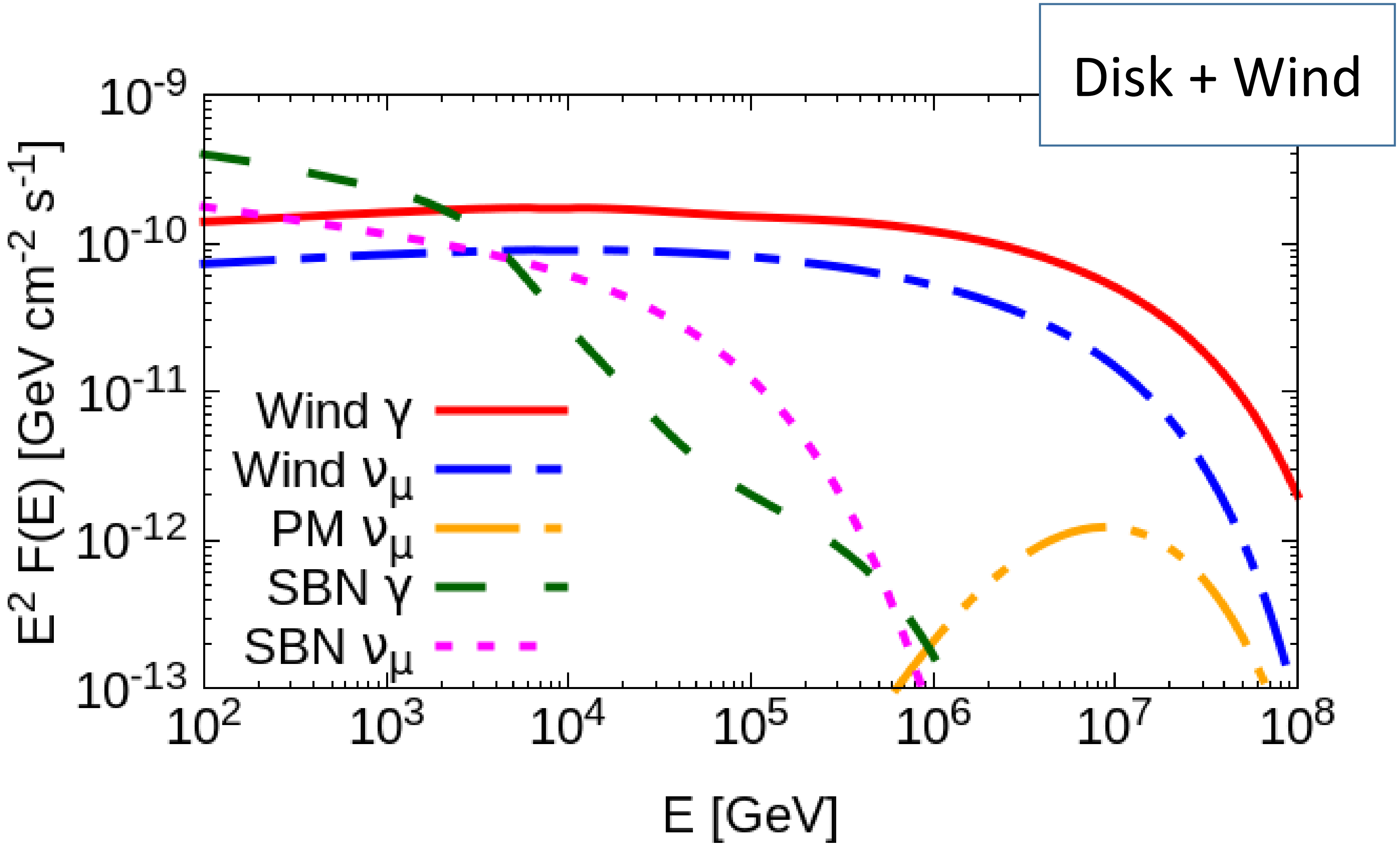
SBGs - High-Energy SED and Neutrinos



Gamma and neutrinos from the galactic disk

Maximum Energy: 1 PeV

SBGs - High-Energy SED and Neutrinos



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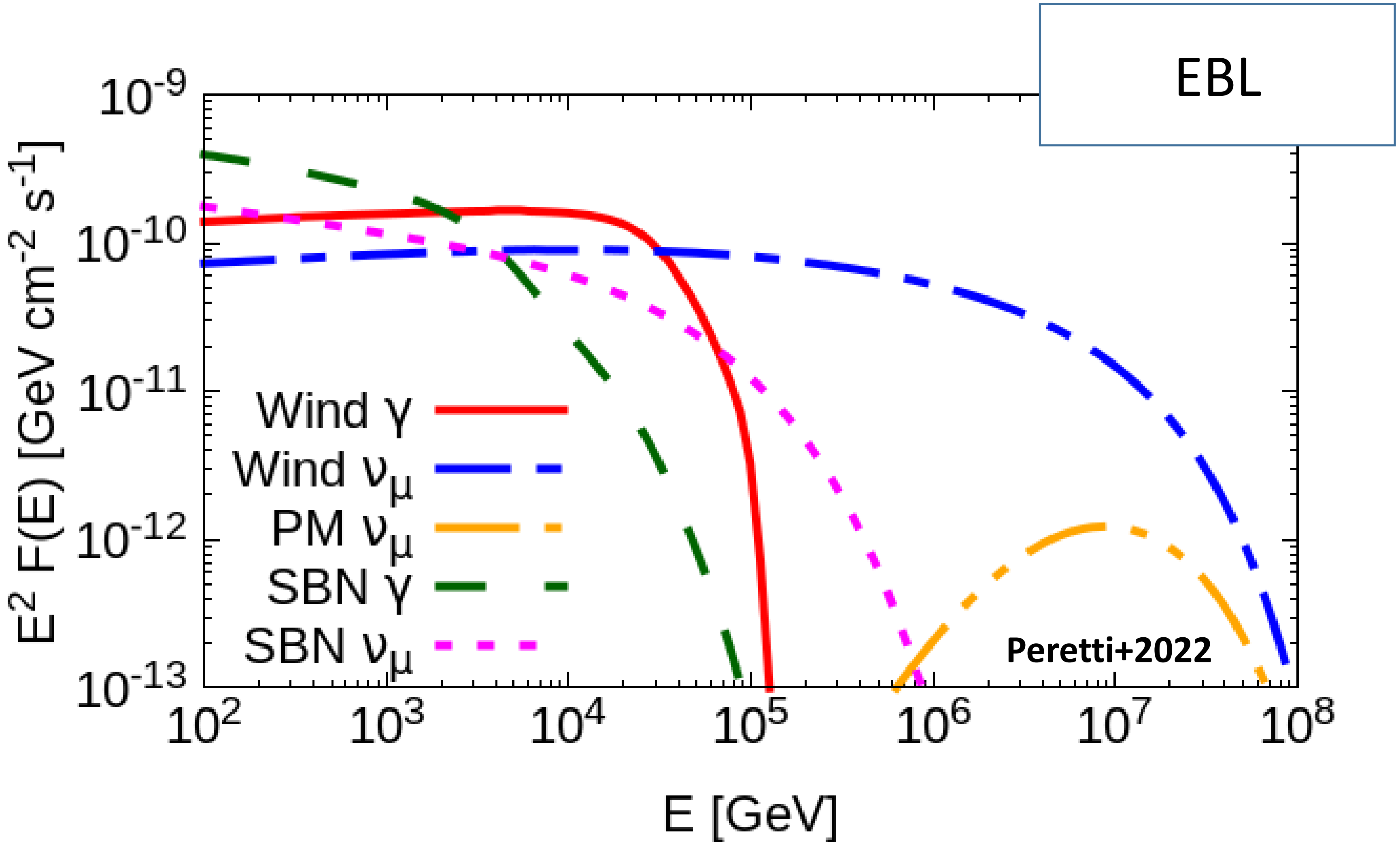

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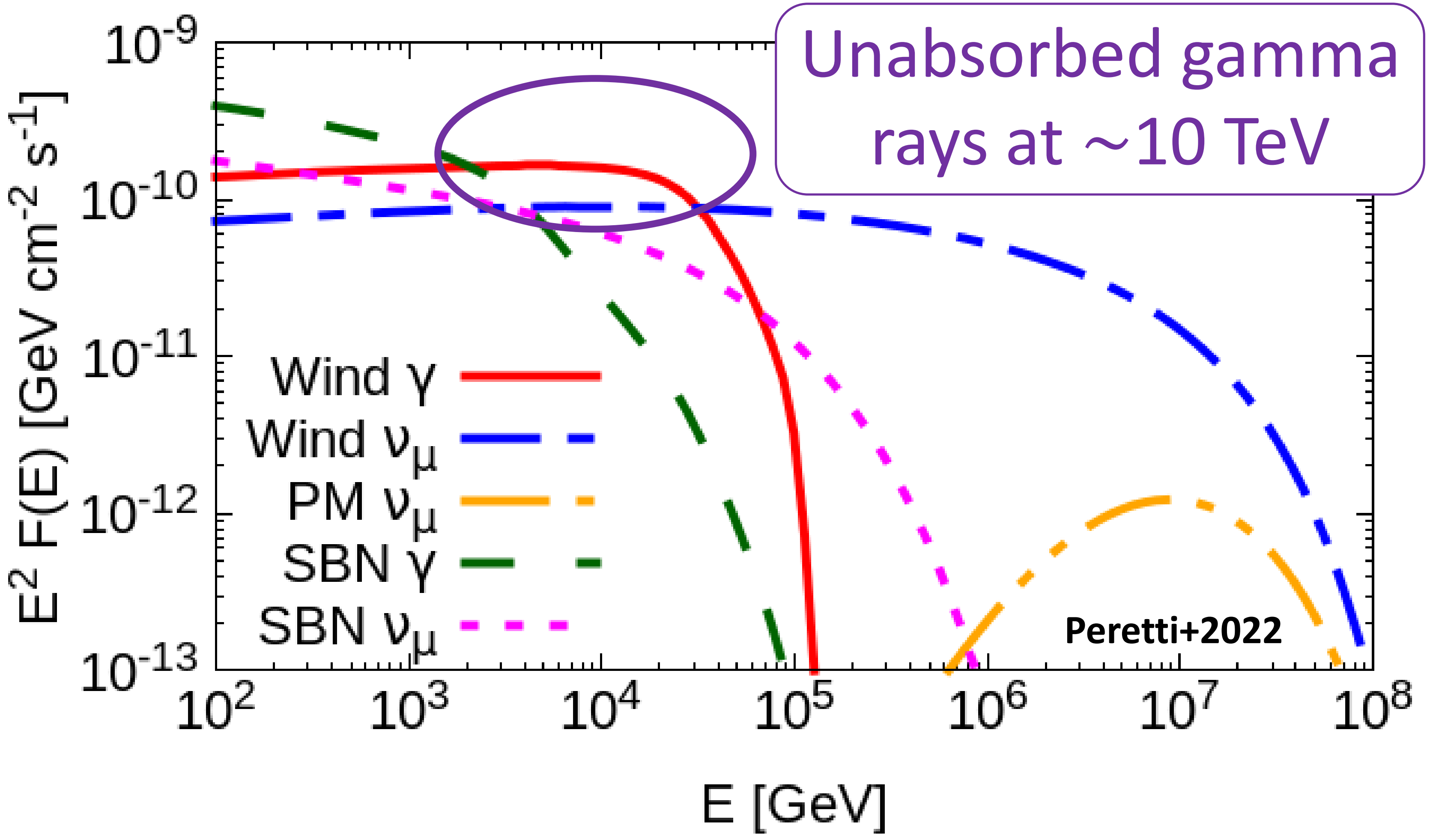

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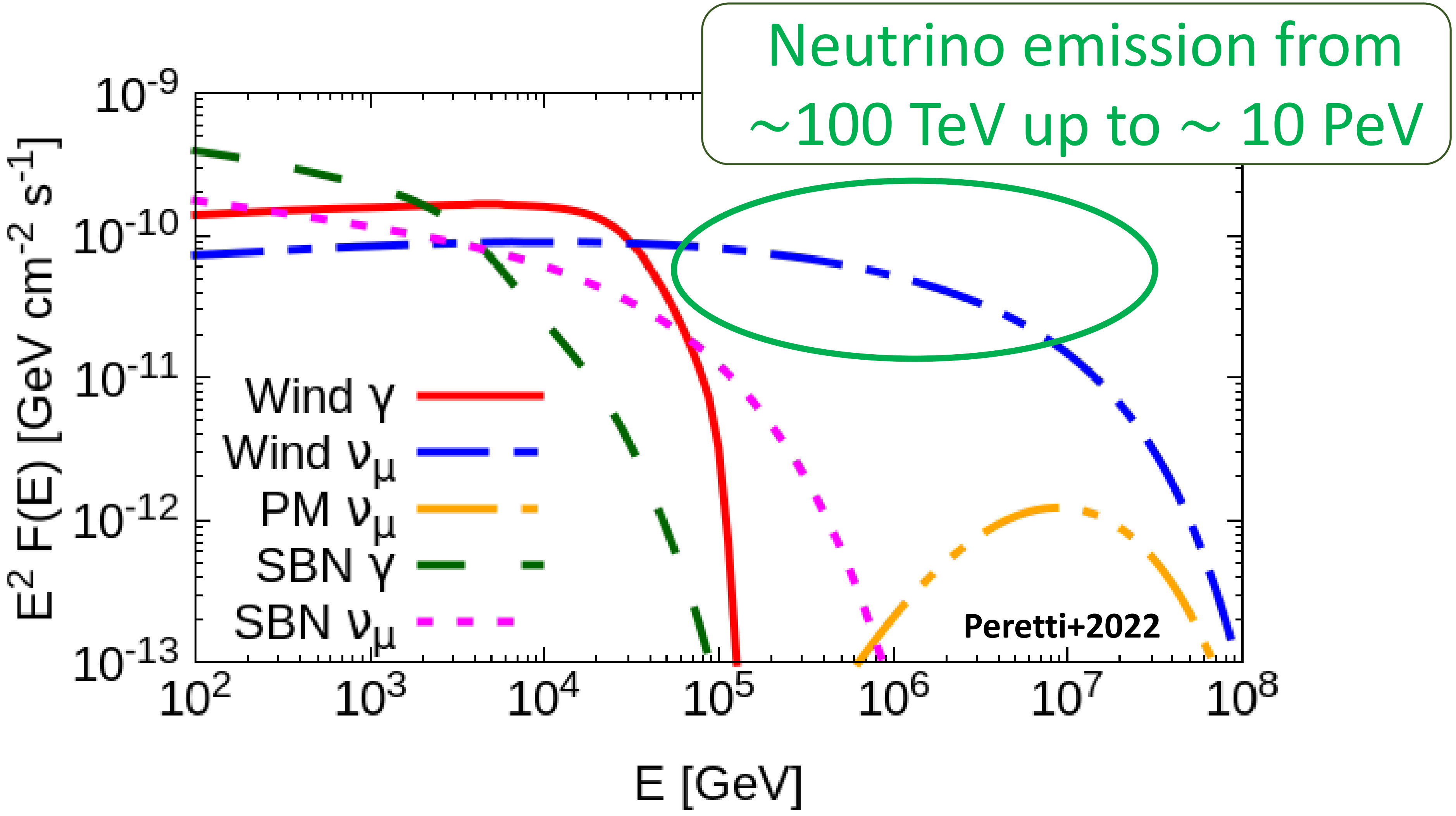
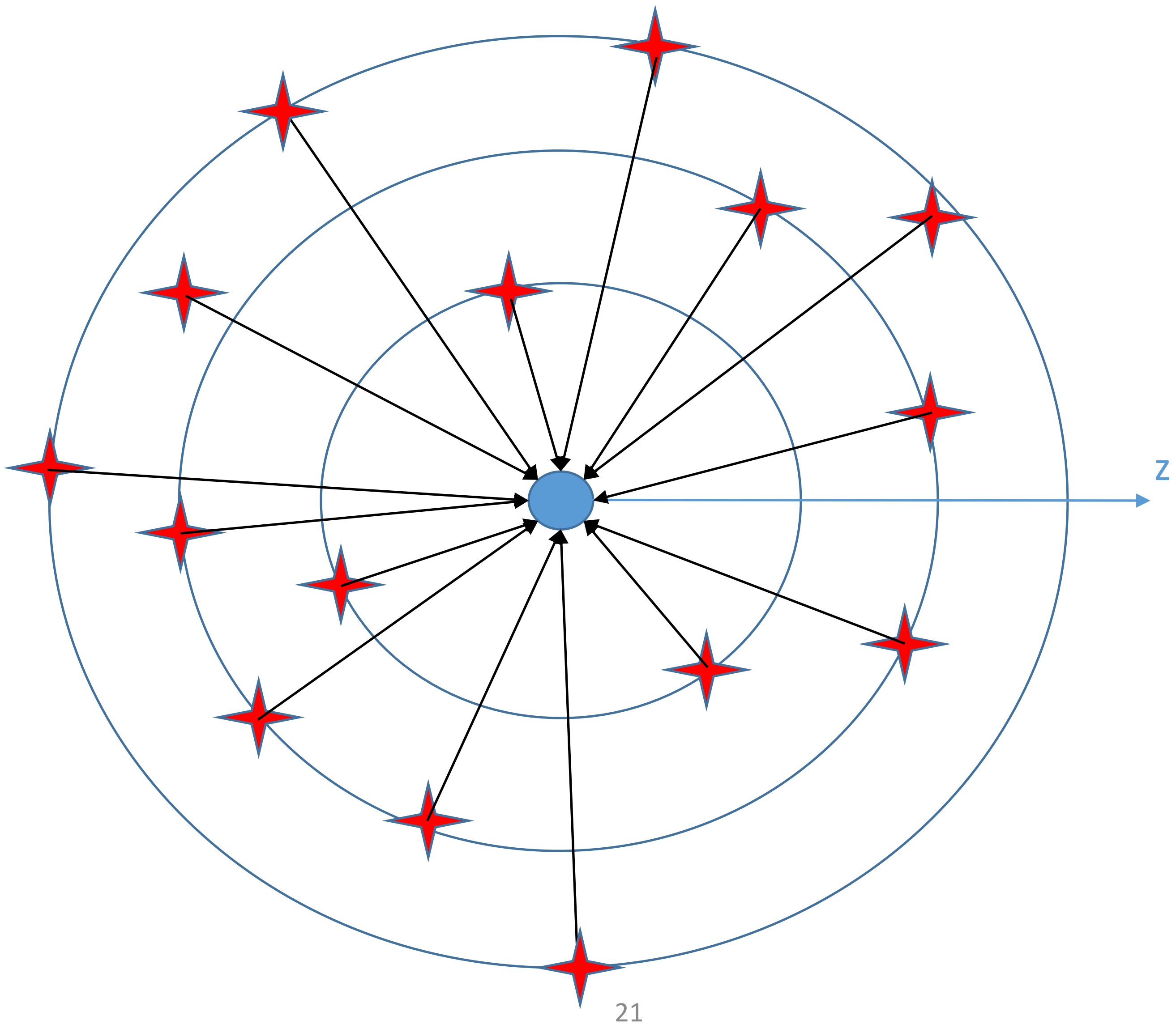


Counting starbursts



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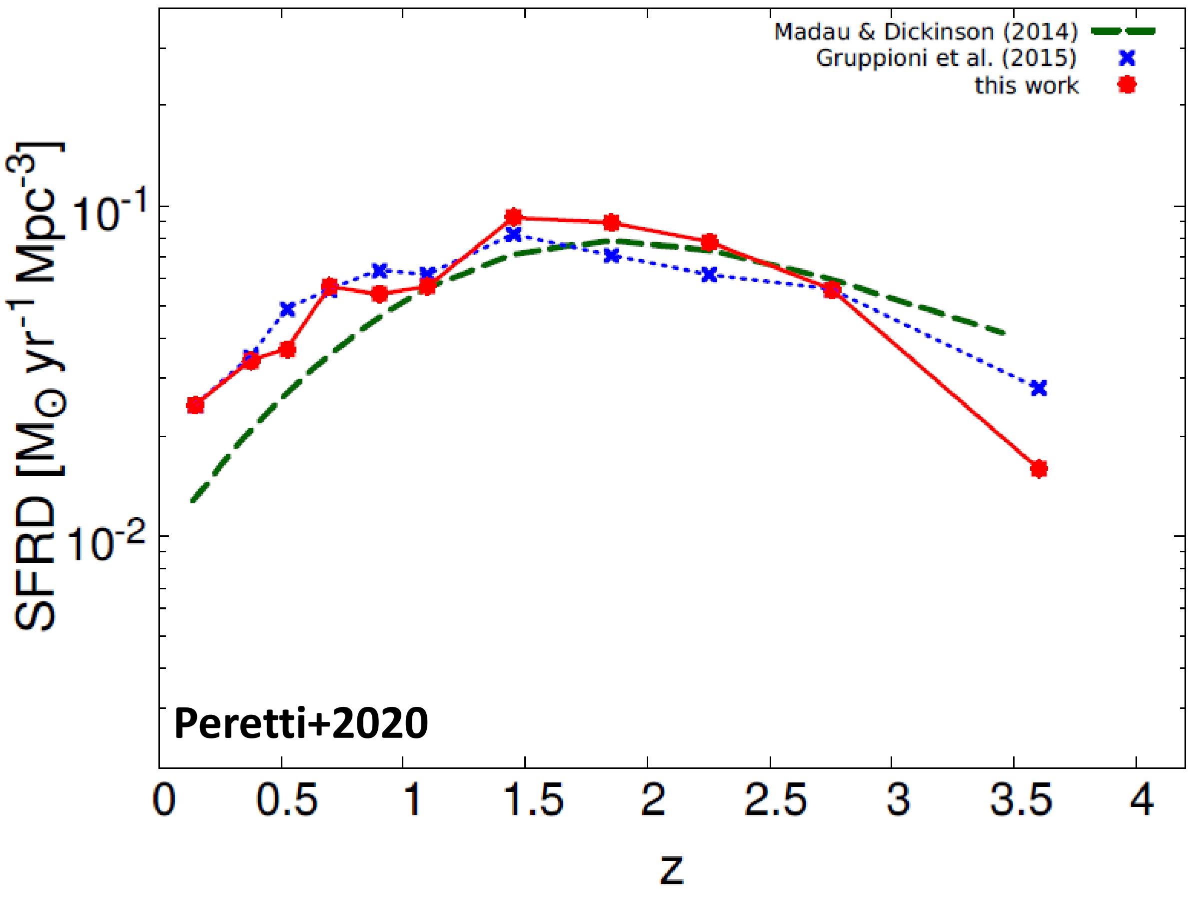

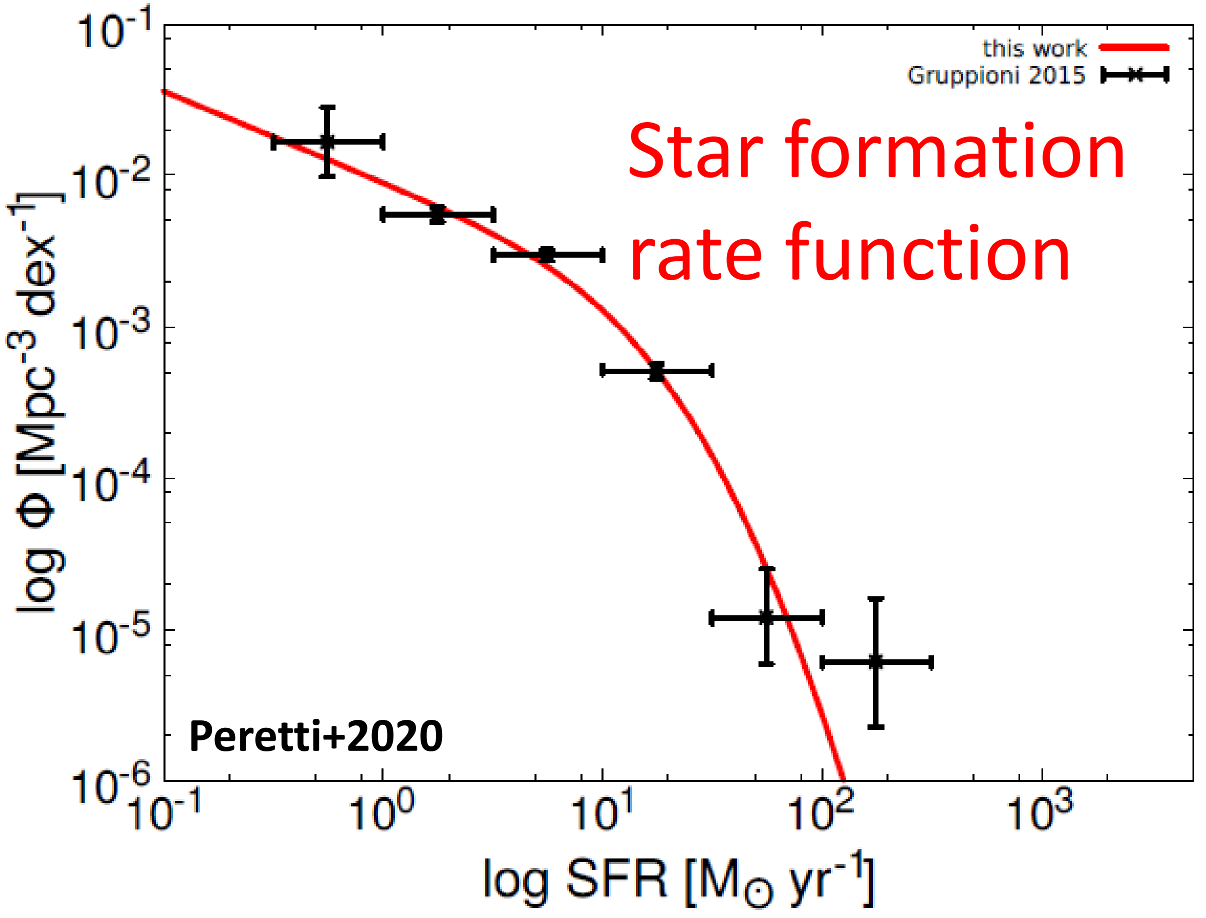

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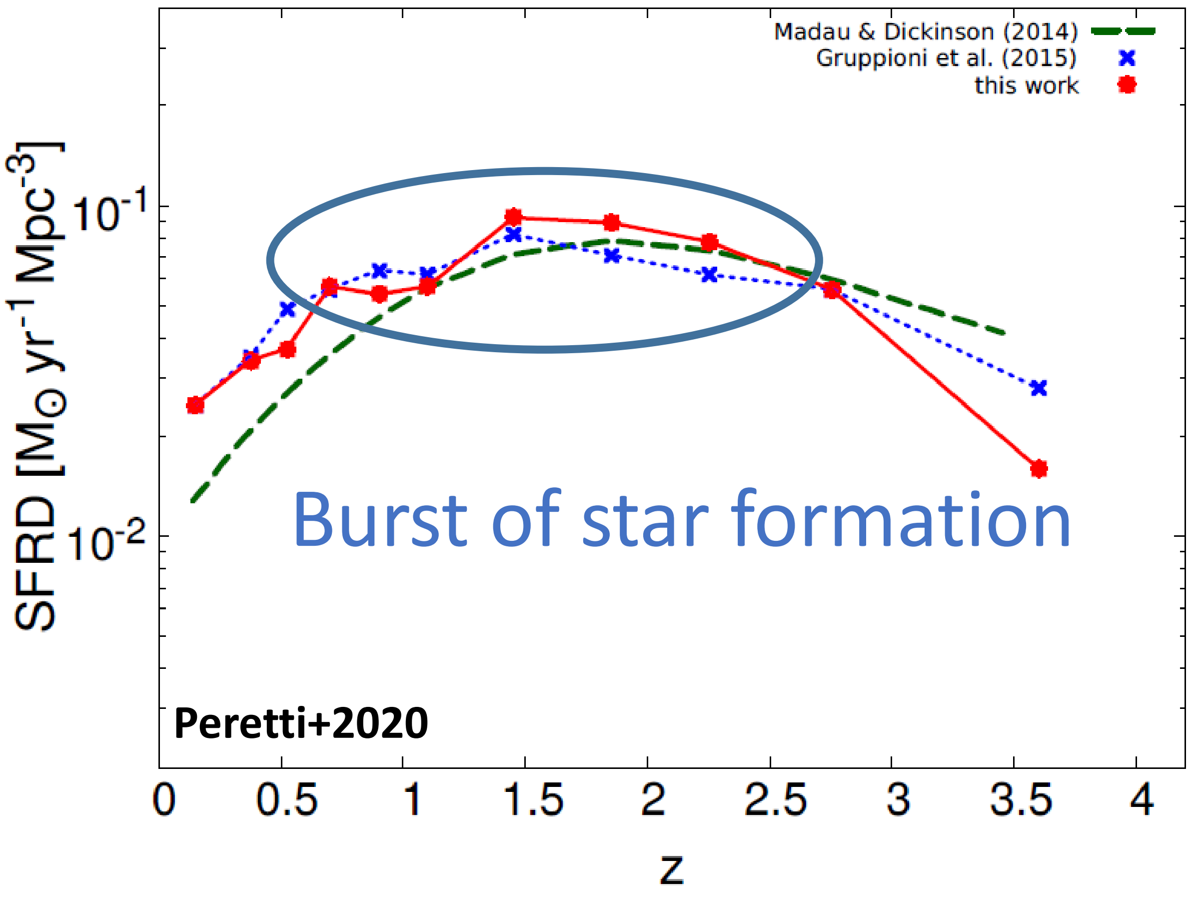
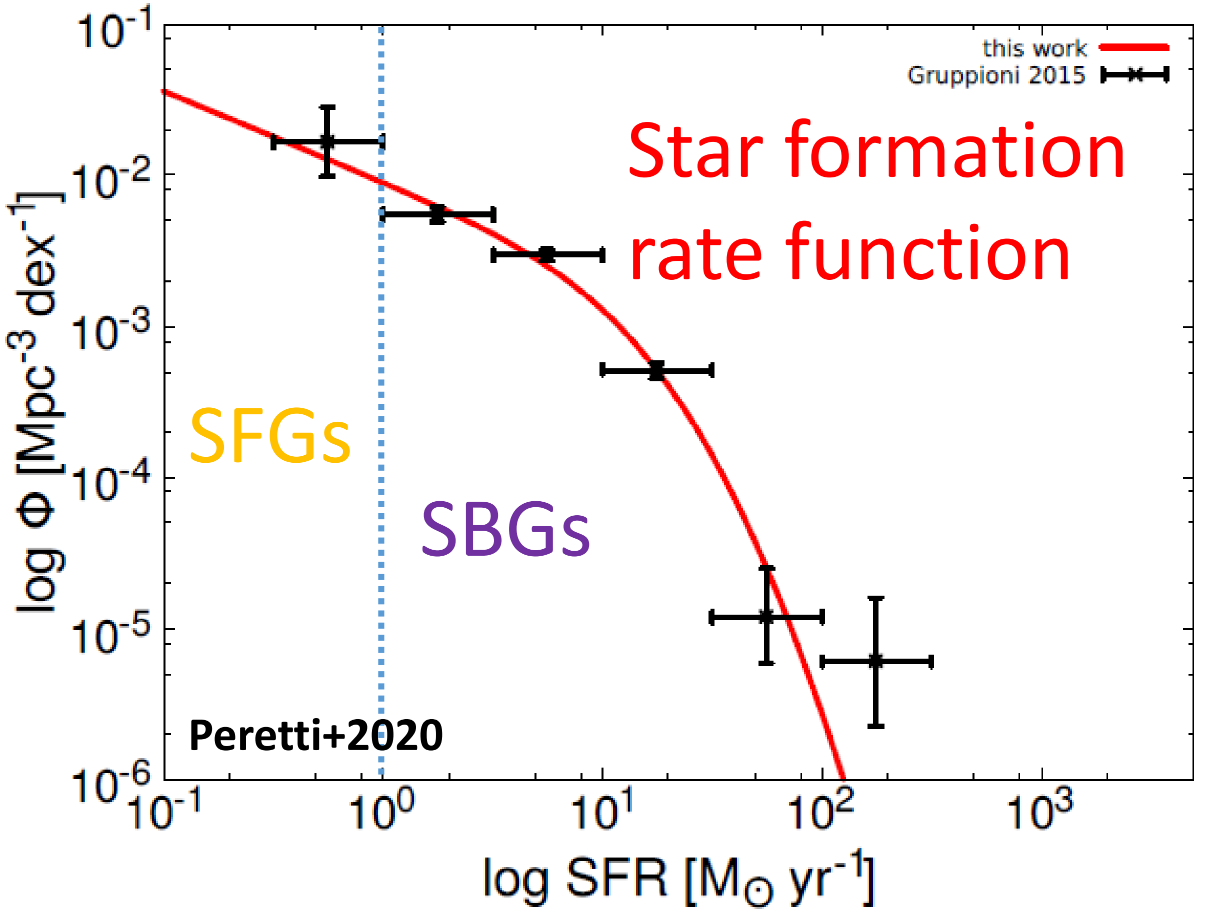
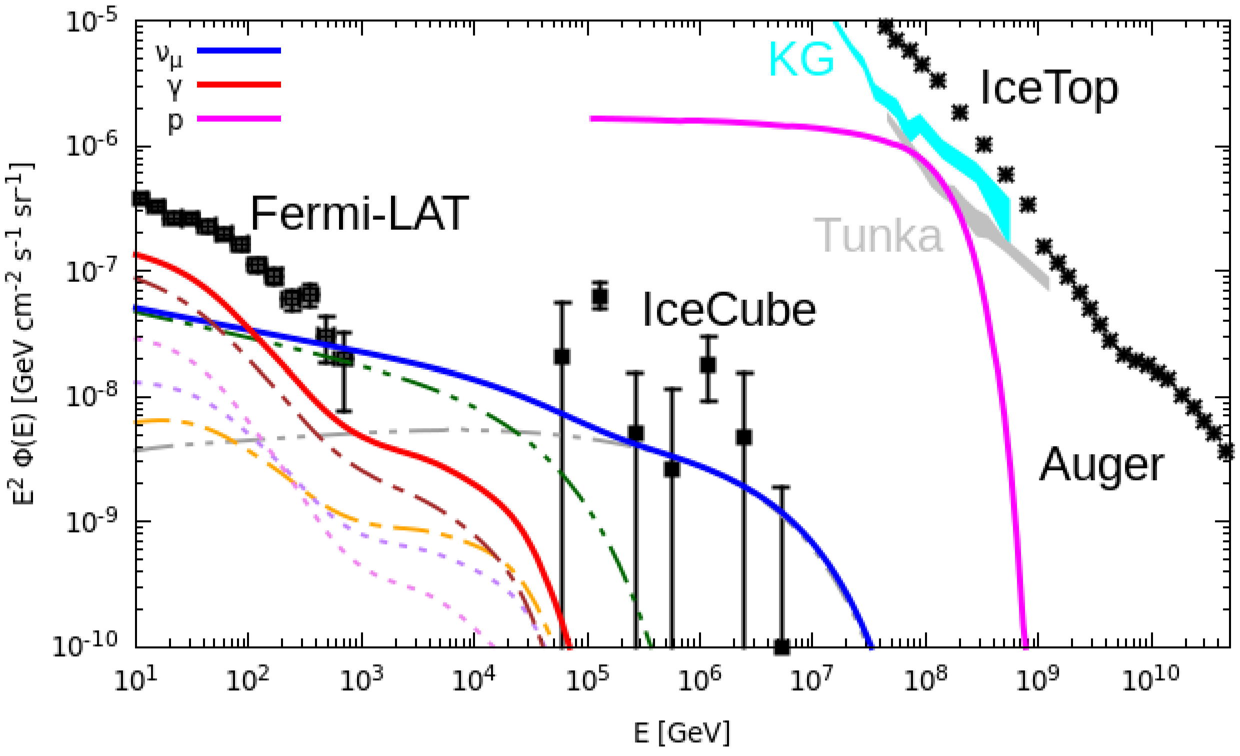


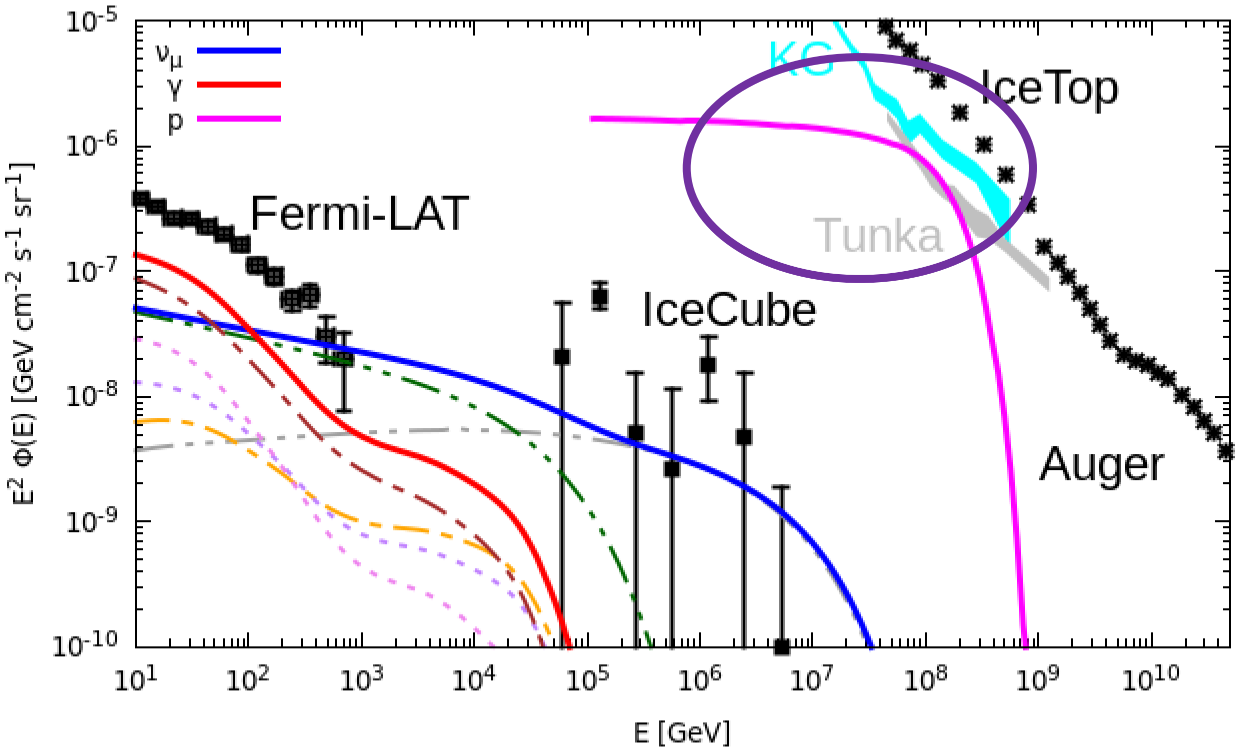


Cumulative radiation from SBGs

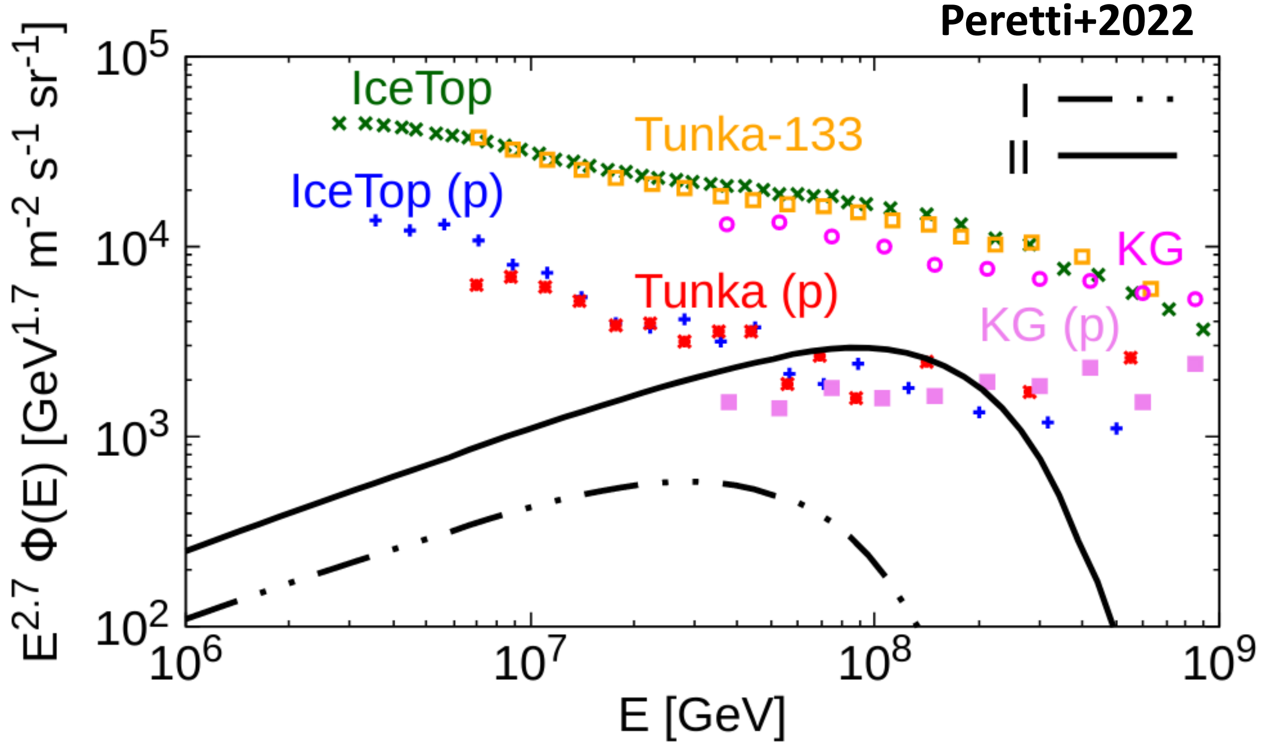


- Sizeable contribution to the gamma-ray flux (room for AGNi and SFGs)
- Relevant contribution to the neutrino flux from 100 TeV to 10 PeV

Cumulative radiation from SBGs



Peretti+2022



Take home message - 2

- Starburst-driven wind bubbles can be efficient particle accelerators up to 10^2 PeV

- Inelastic pp collisions take place in the shocked wind region where gamma-ray and neutrino are copiously produced

- Observational signatures might come from VHE gamma rays

- Possible relevant role to the multimessenger diffuse flux (p,γ,ν)

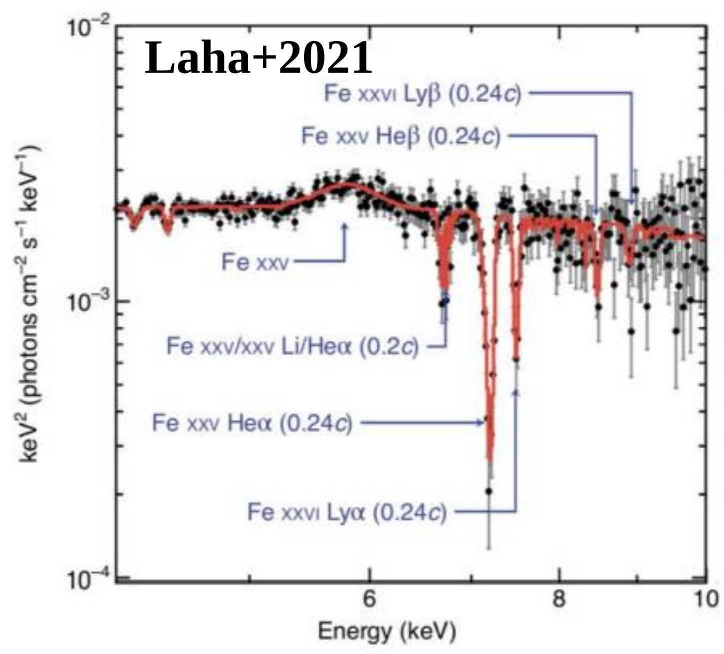
AGN-driven wind bubbles (UFOs)

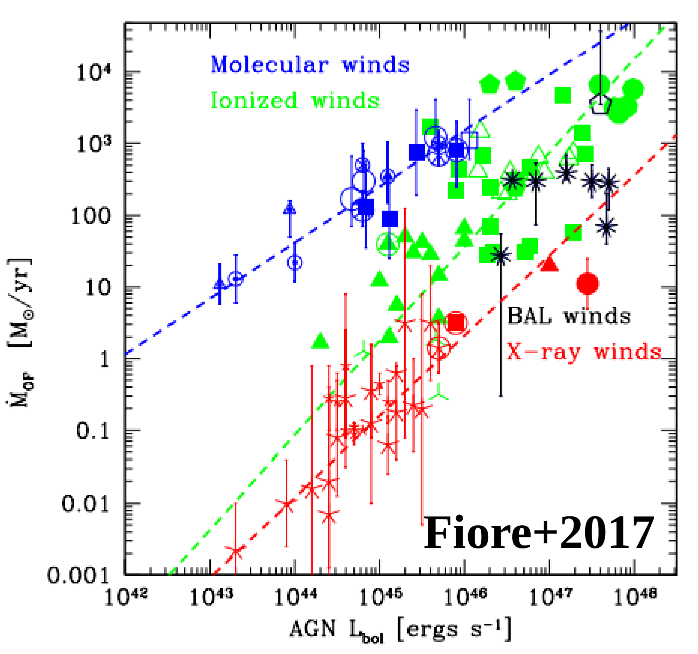
Seyfert NGC3079 - Image credit: X-ray: NASA/CXC/University of Michigan/J-T Li et al.; Optical: NASA/STSc

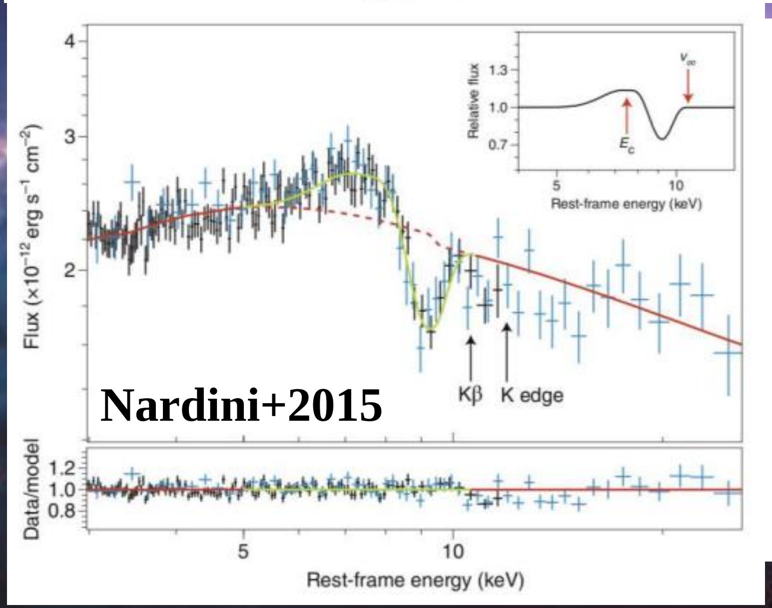
Seyfert NGC3079 - Image credit: X-ray: NASA/CXC/University of Michigan/J-T Li et al.; Optical: NASA/STSc

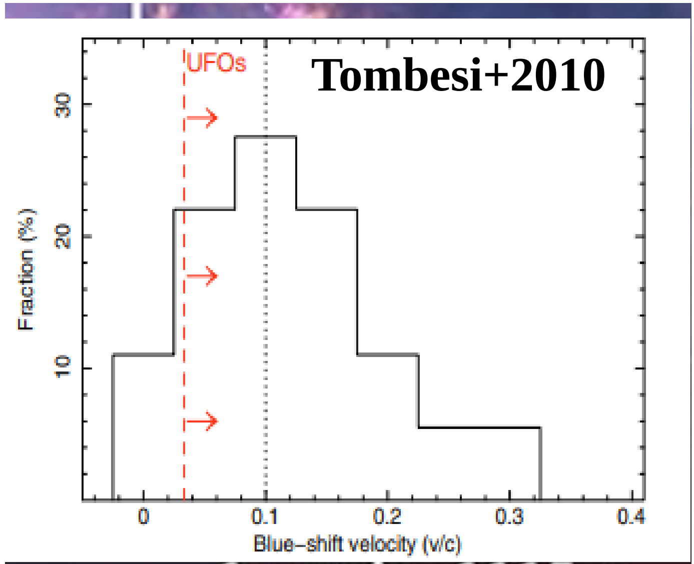
Ultra-Fast Outflows (UFOs)

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









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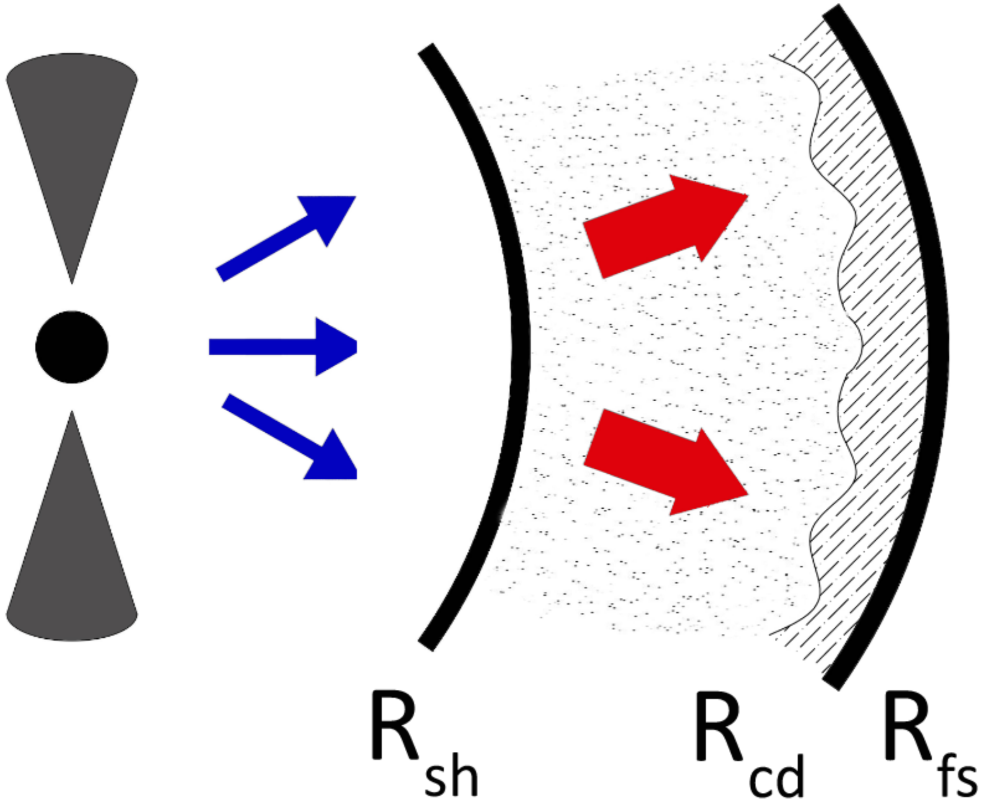
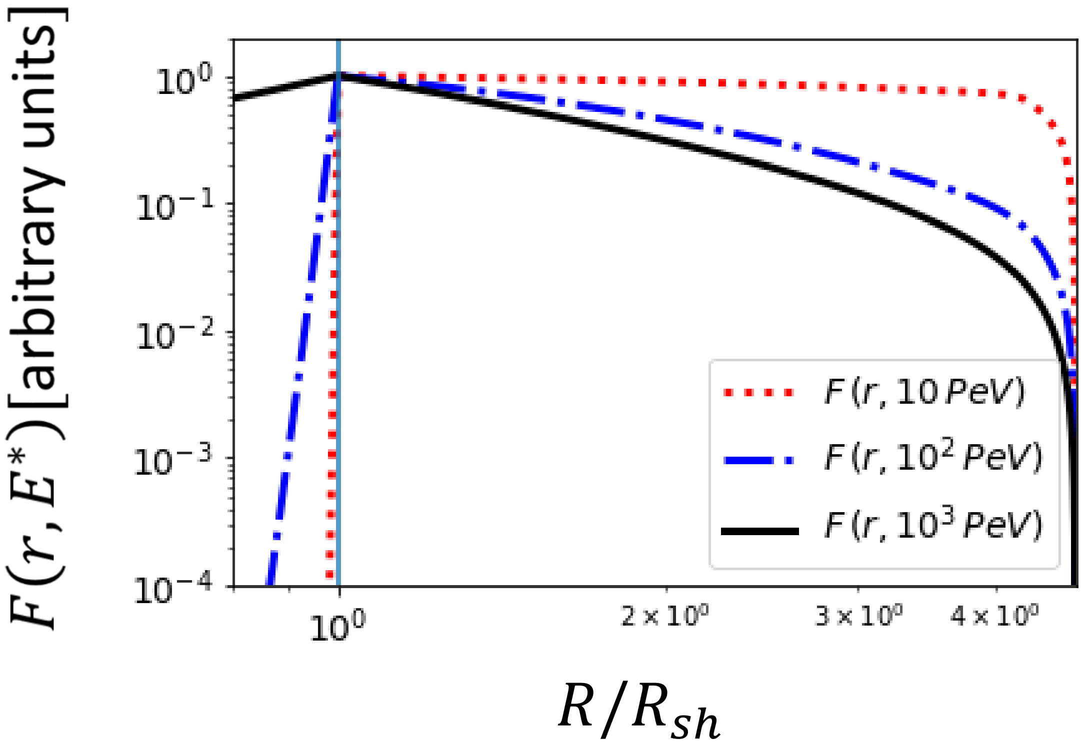
The UFO wind bubble

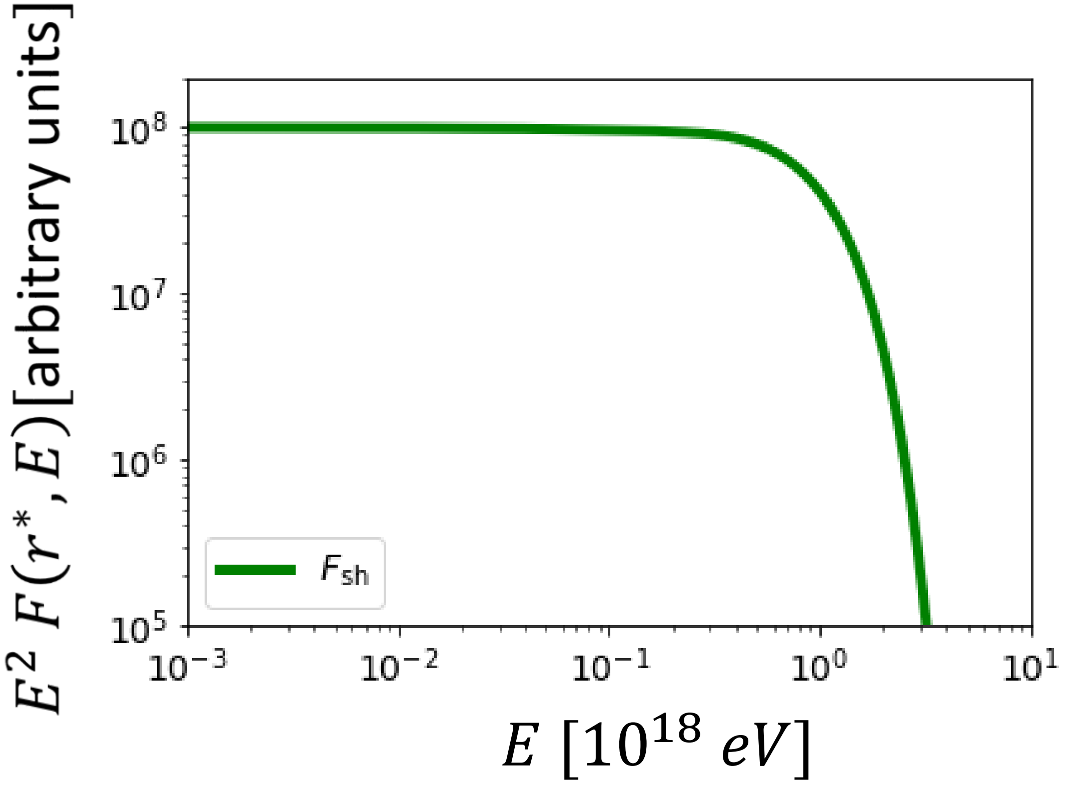


Parameters:

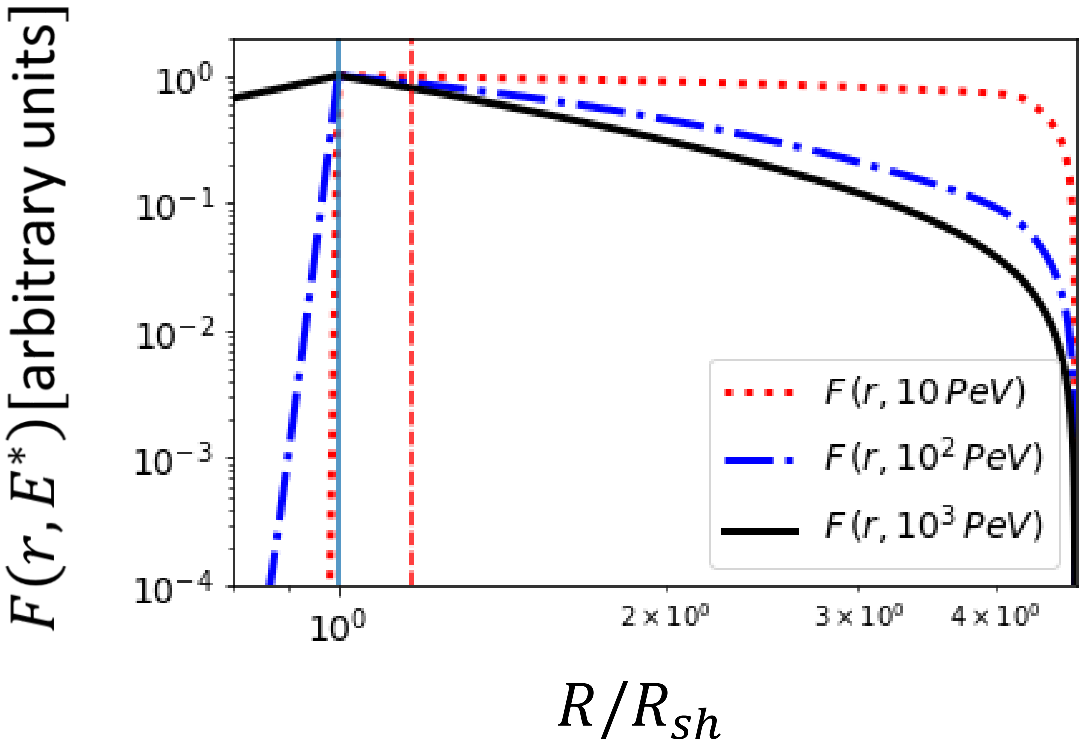
- $u_1 = 0.2\ c$
- $\dot{M} = 0.1\ M_{\odot}\ yr^{-1}$
- $l_c = 0.05\ pc$
- $t_{age} = 1000\ yr$

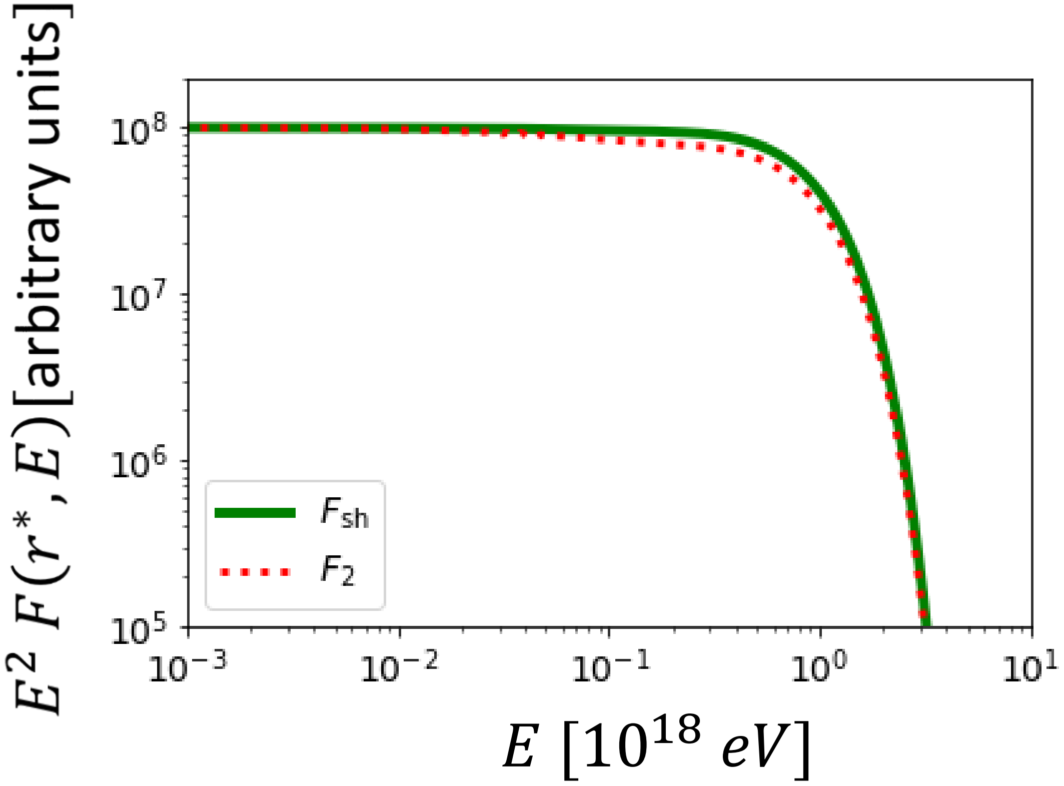
Solution: radial behavior and spectra



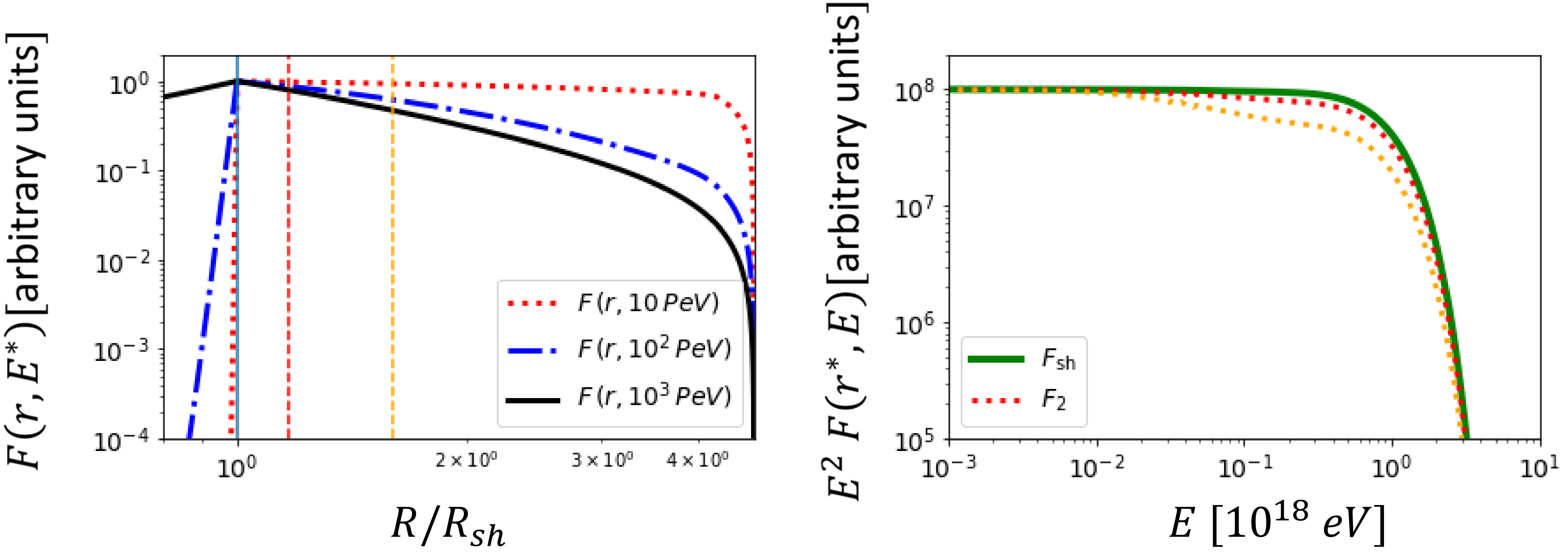


Solution: radial behavior and spectra

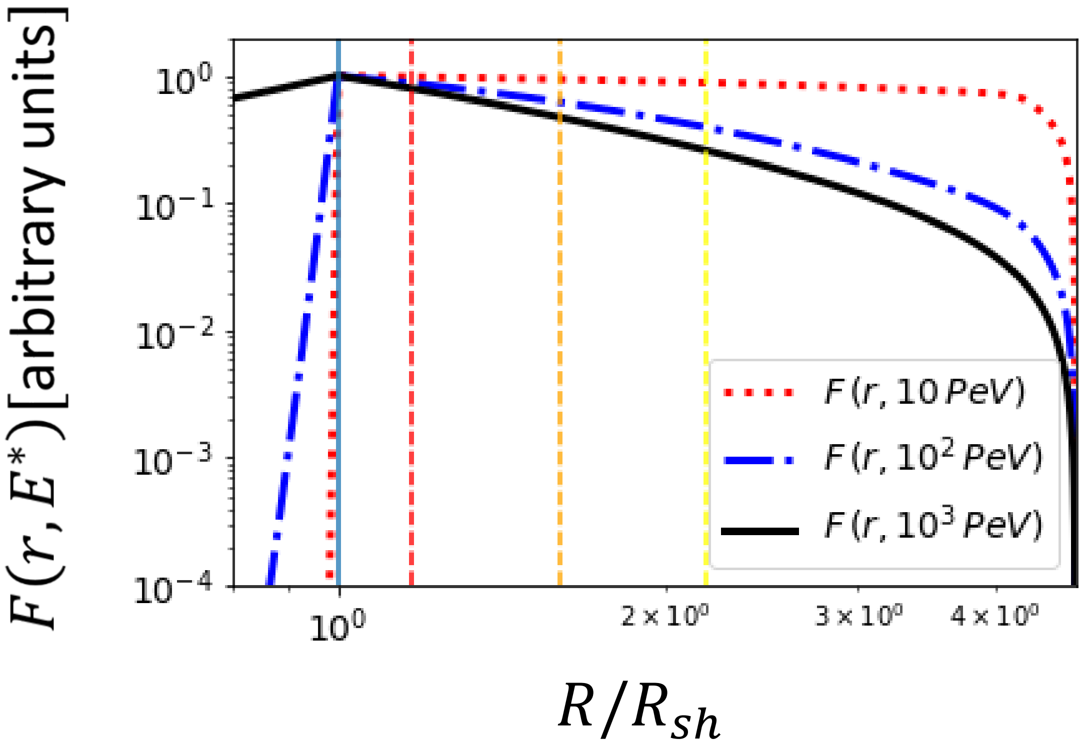


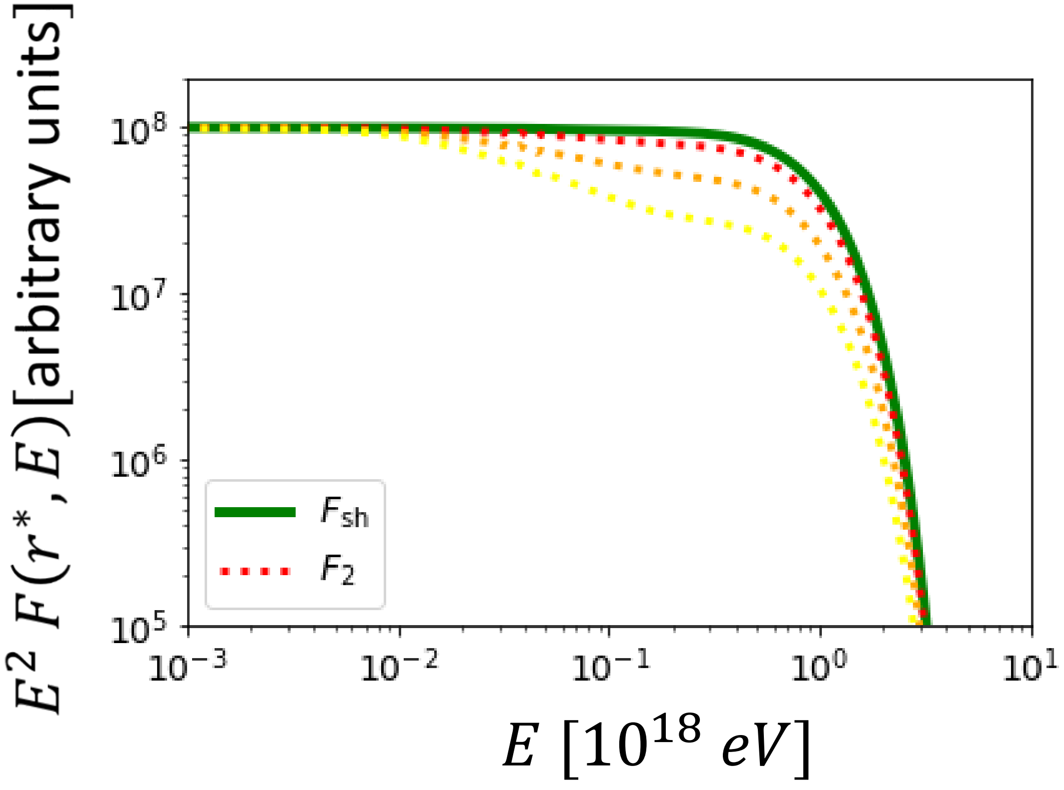


Solution: radial behavior and spectra

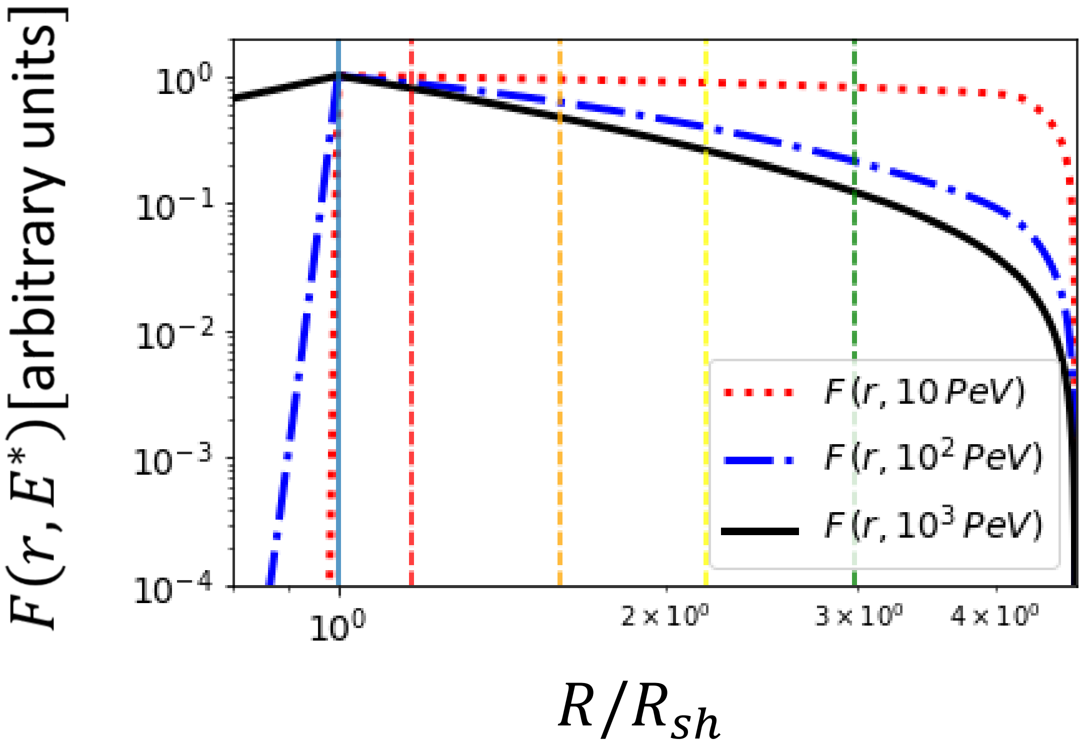


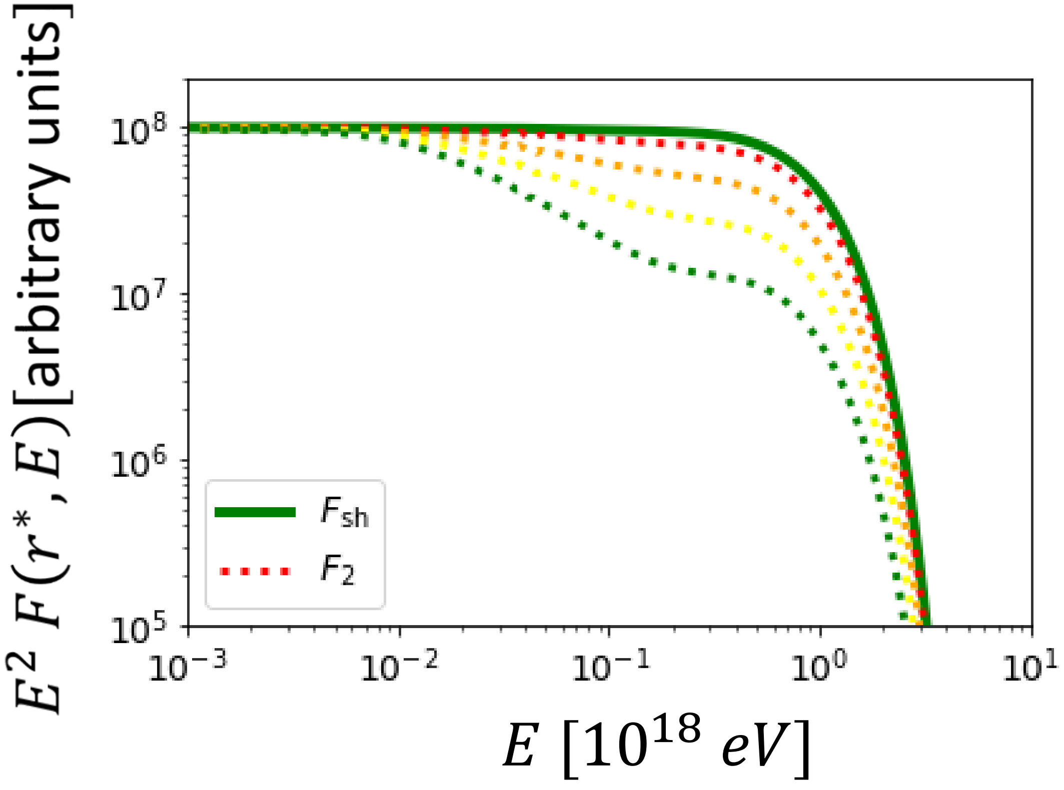
Solution: radial behavior and spectra



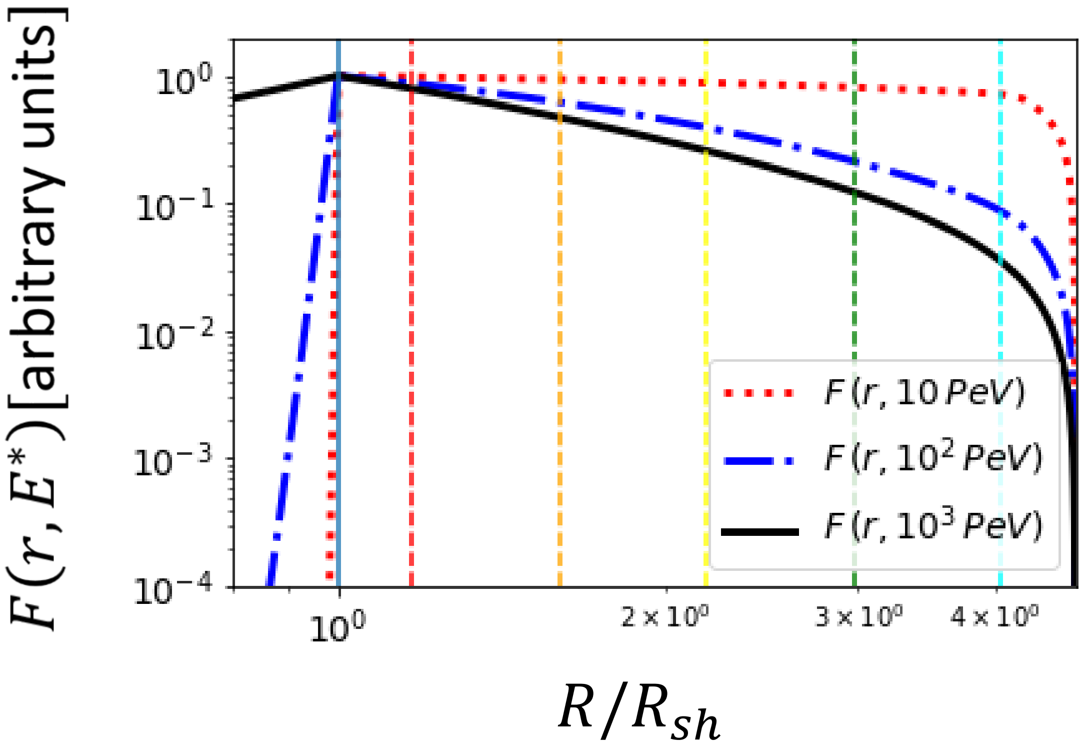


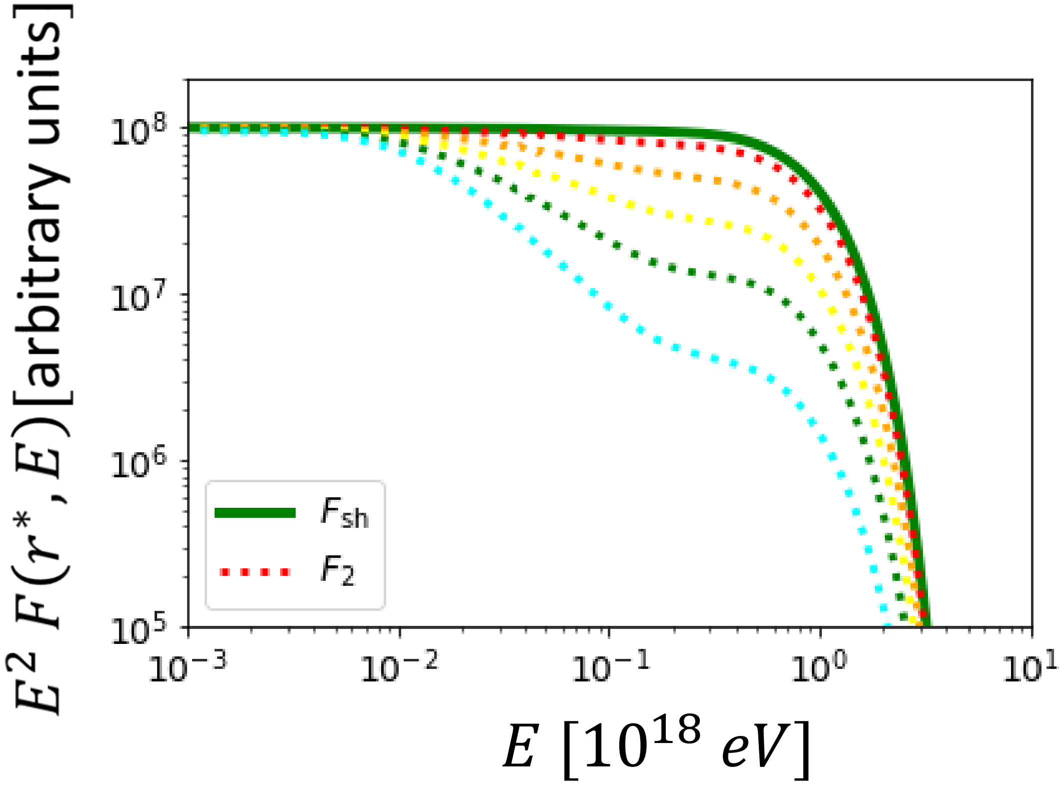
Solution: radial behavior and spectra



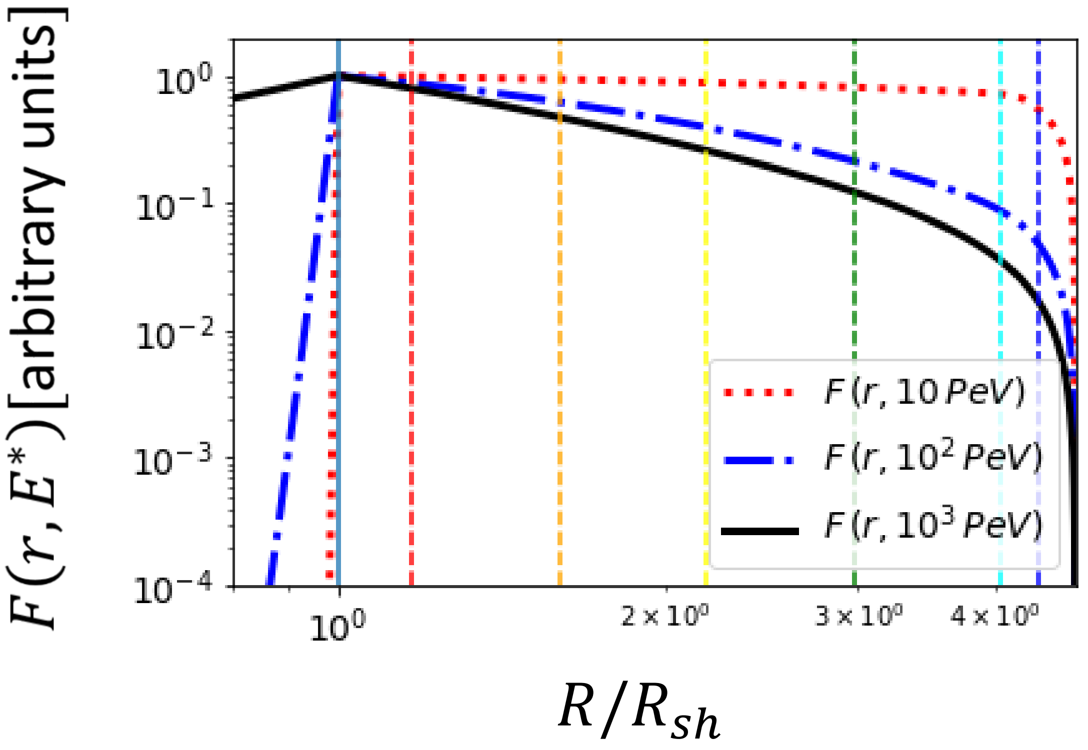


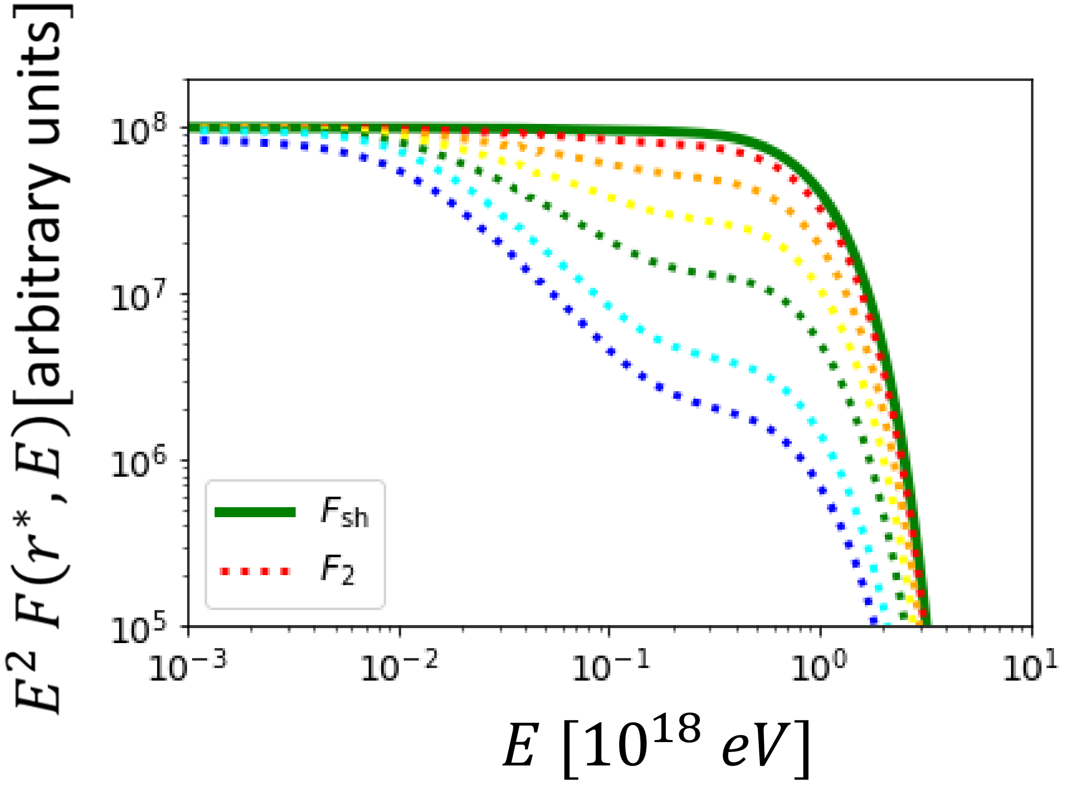
Solution: radial behavior and spectra



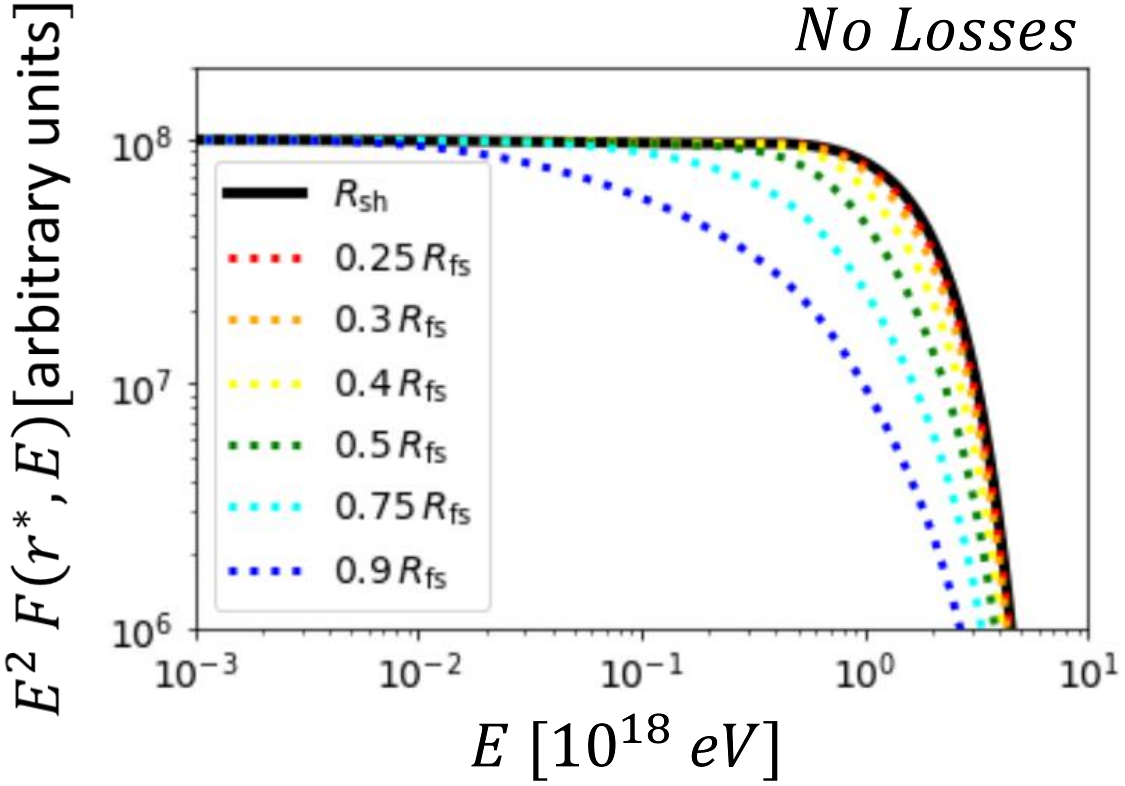


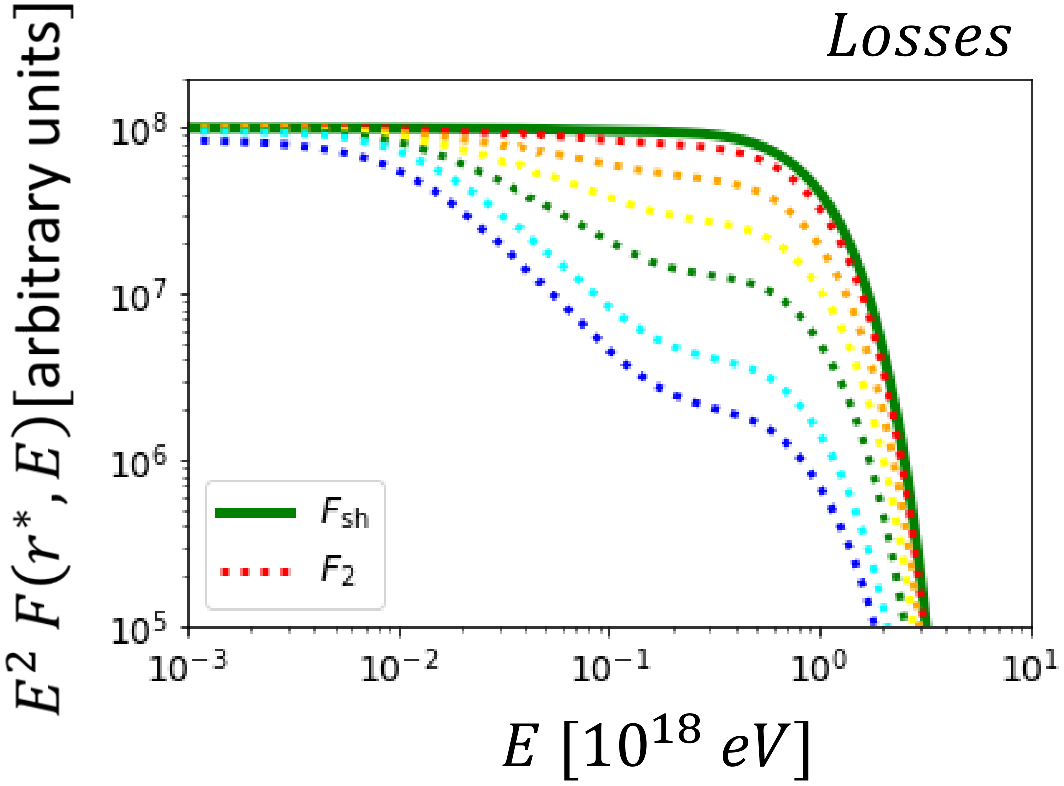
Solution: radial behavior and spectra



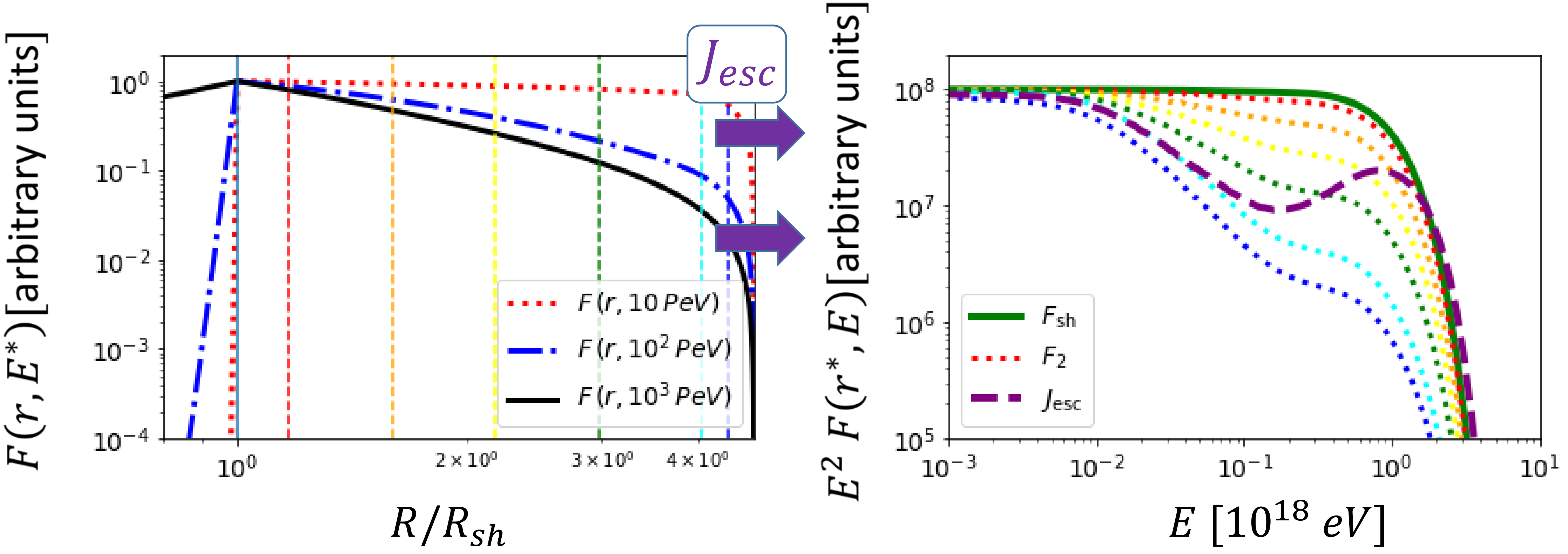


Solution: radial behavior and spectra



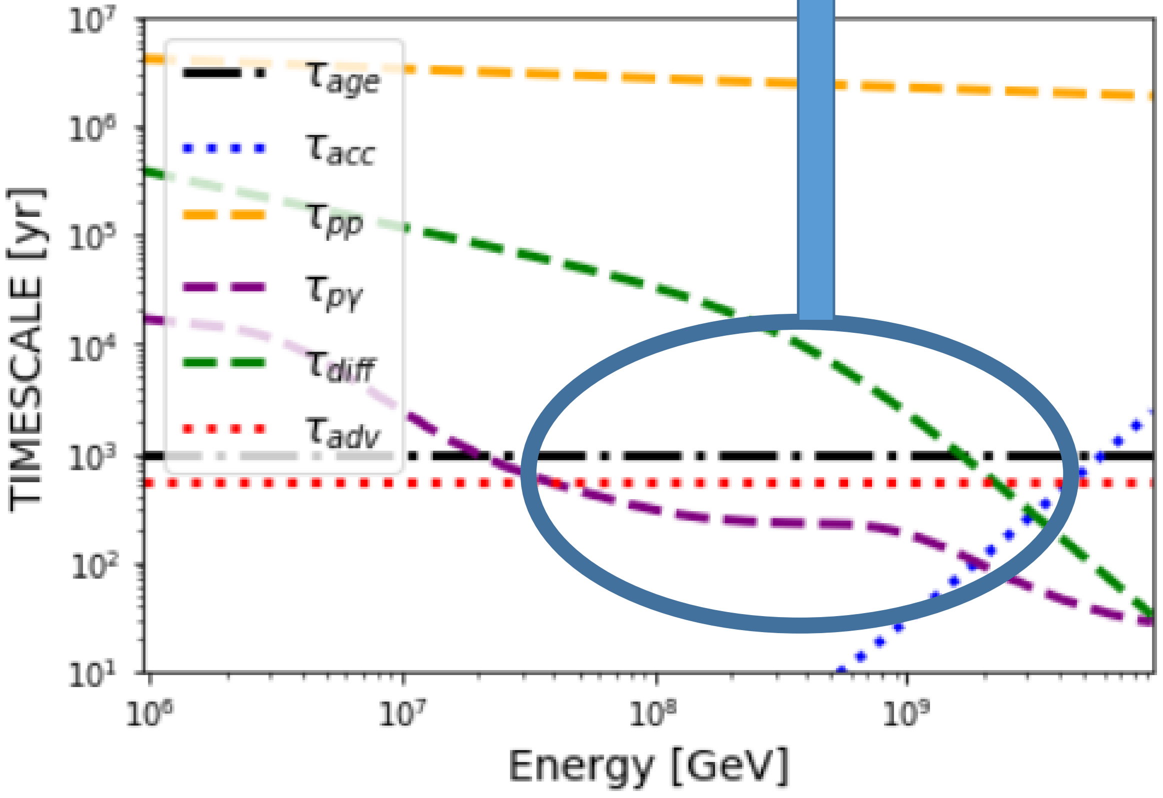


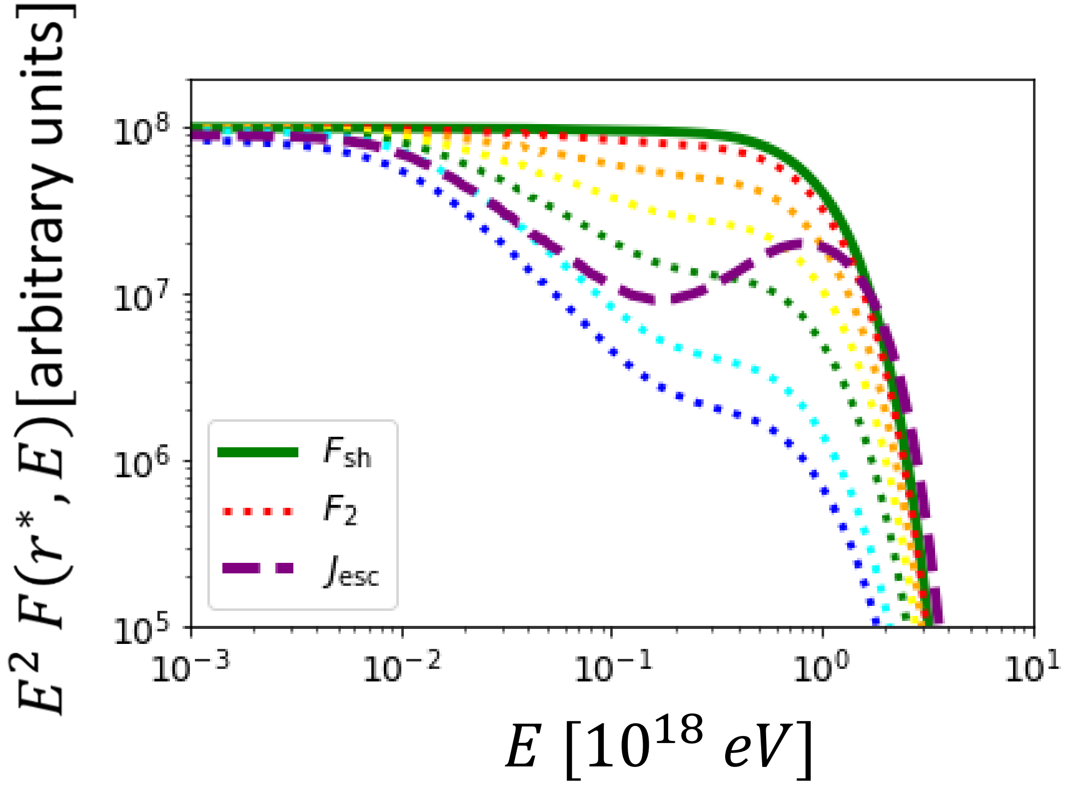
Solution: radial behavior and spectra



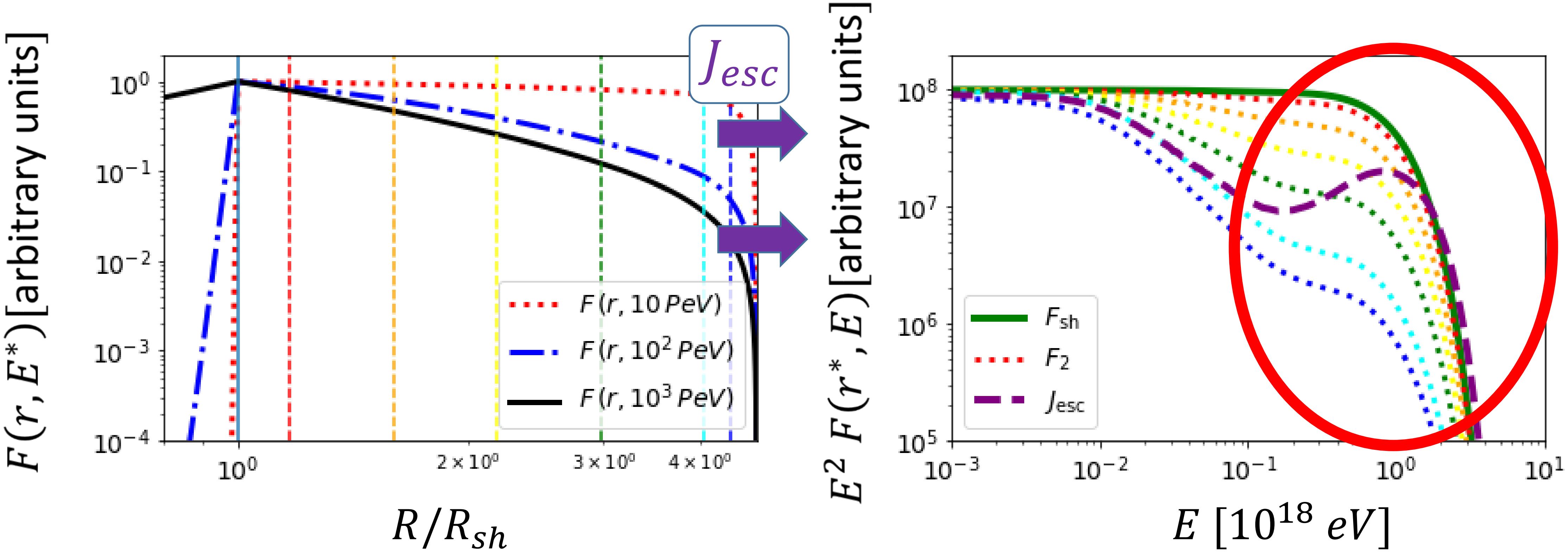
Solution: radial behavior and spectra

pγ Losses → less efficient while r increases
Diffusion → strong energy dependence

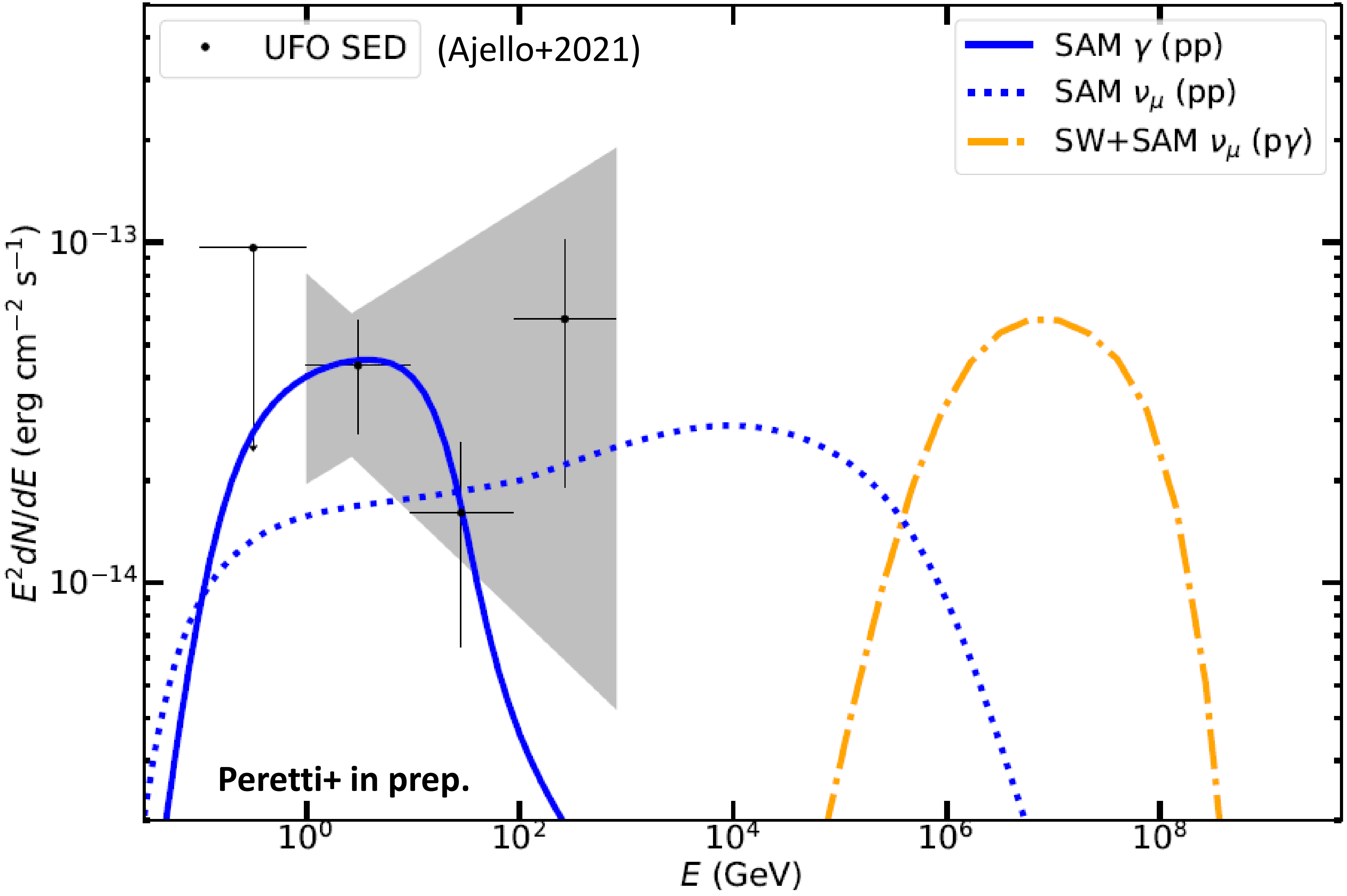




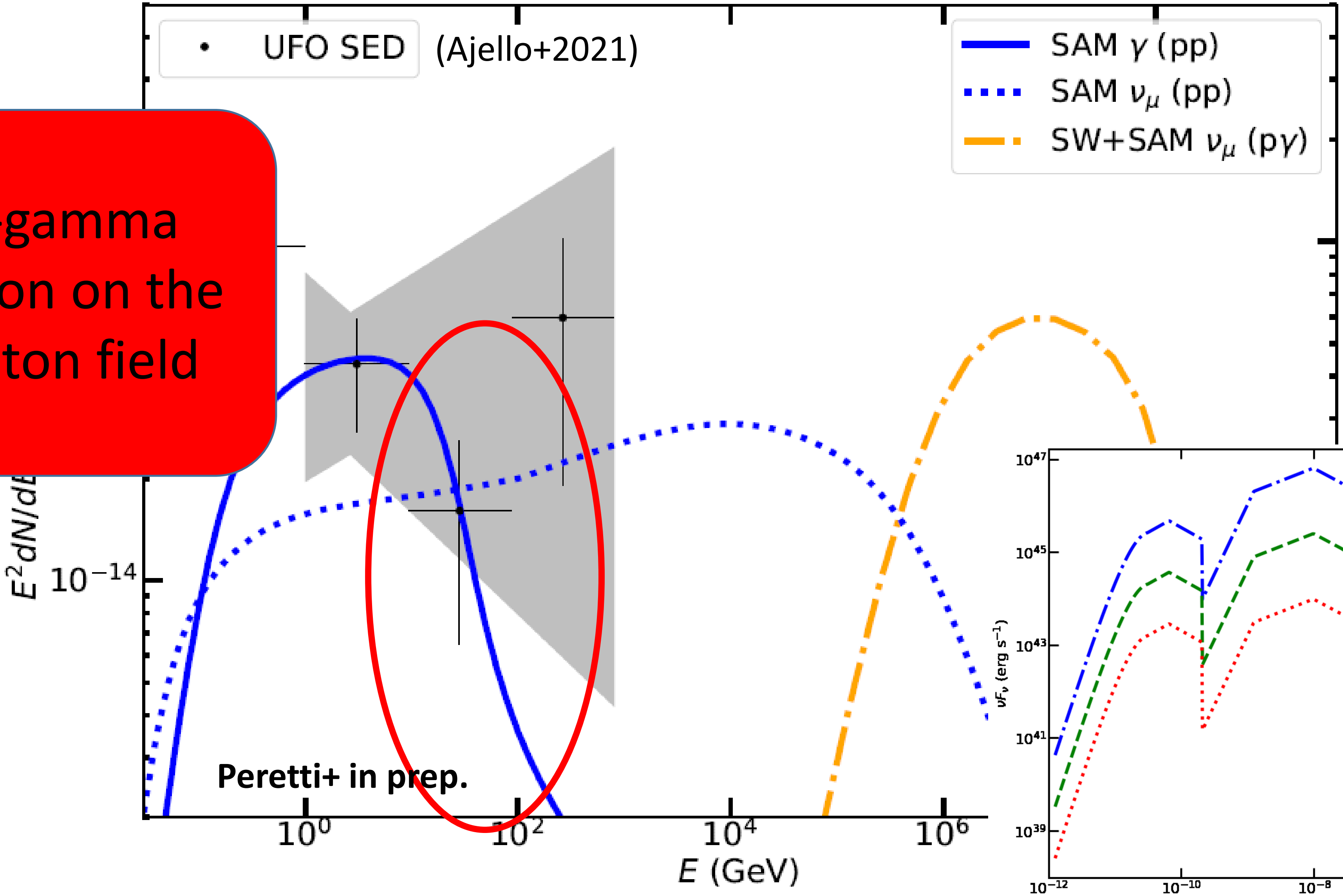
Solution: radial behavior and spectra



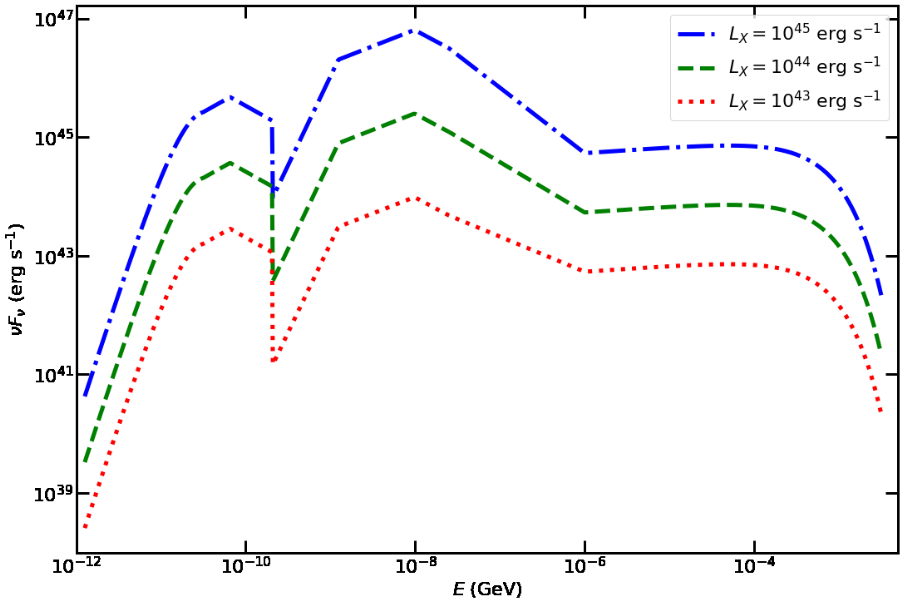
Prototype UFO



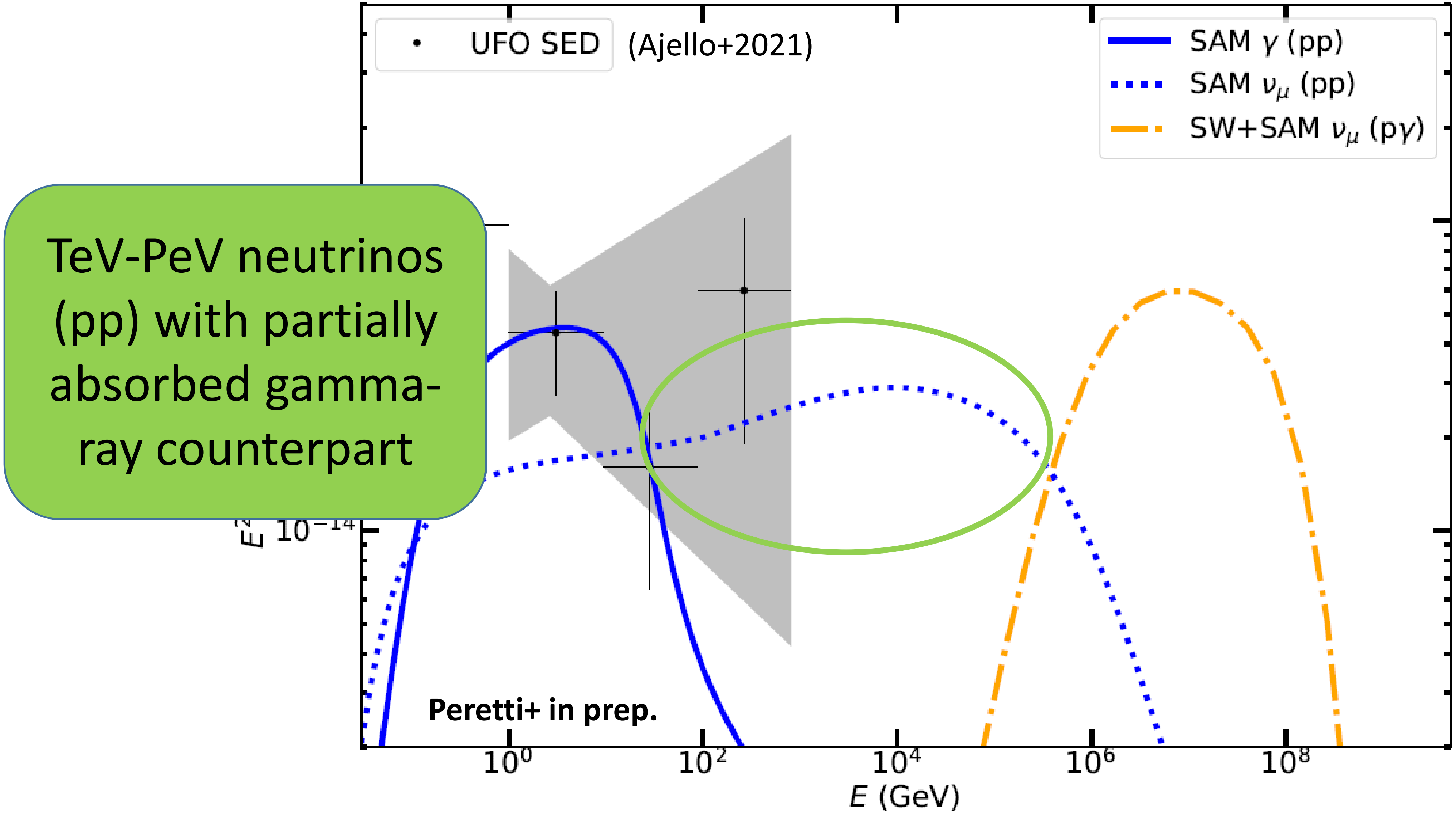
Prototype UFO



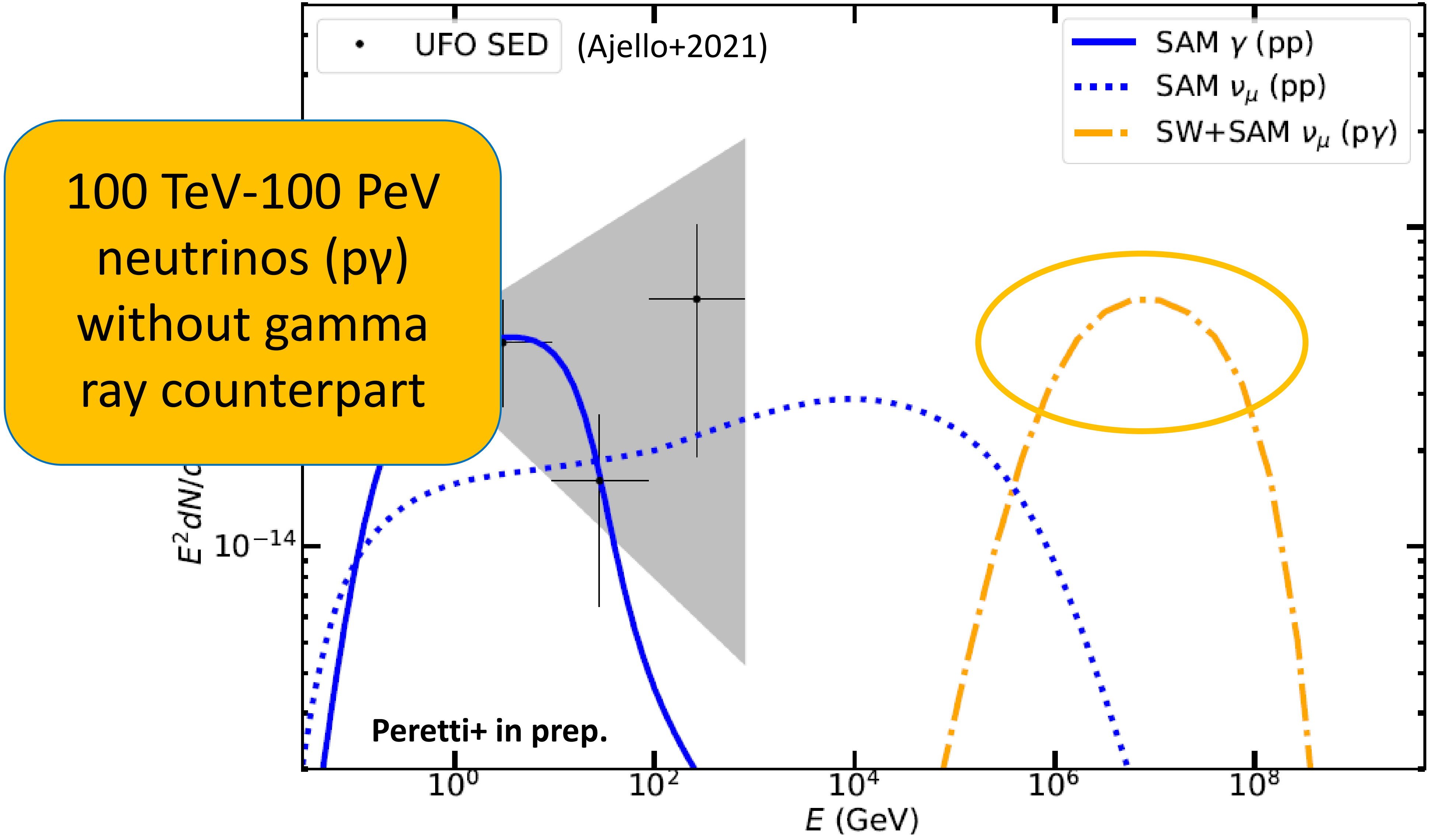
Gamma-gamma absorption on the BKG photon field



Prototype UFO



Prototype UFO



Take home message - 3

- Diffusive shock acceleration can take place efficiently at wind shocks of UFOs

- Maximum energies up to EeV can be reached

- UHECRs injected in the host galaxy can feature a hard spectral slope

- UFOs can be bright neutrino sources while being opaque to gamma rays

Key questions

1. Can wind bubbles get to the highest energies both in Galactic and Extragalactic context?

2. Can wind bubbles be efficient gamma-ray and HE neutrino sources?

Key questions

1. Can wind bubbles get to… both in Galactic a… …t?

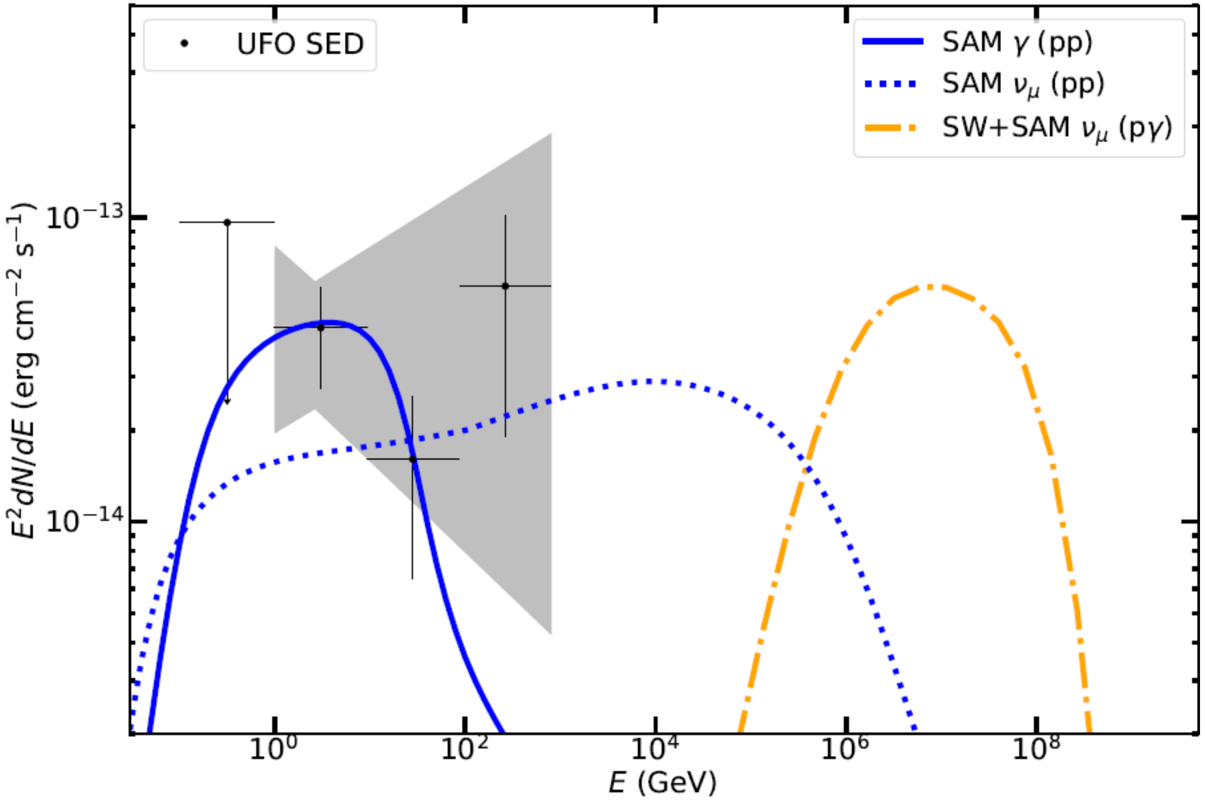
2. Ca… …ient gamma-ray …rces?

They can but some work must be done to find that out

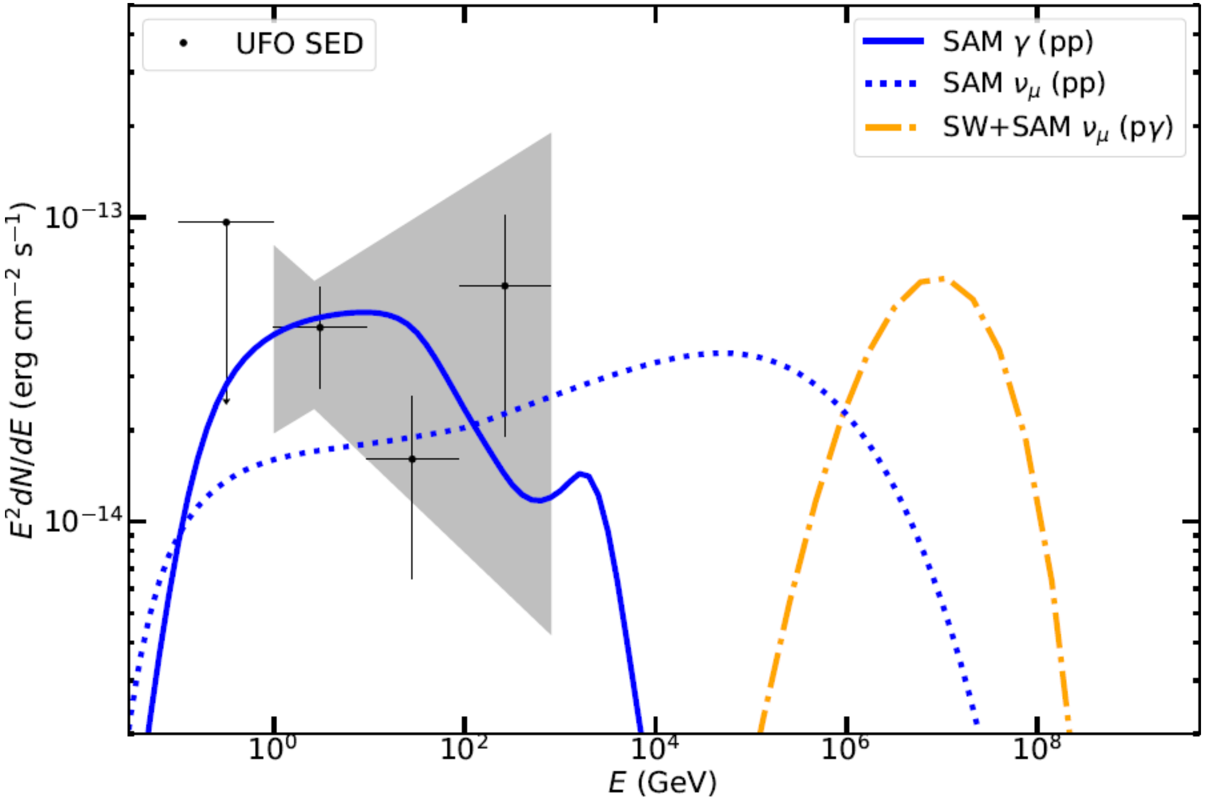
Thanks for your attention!

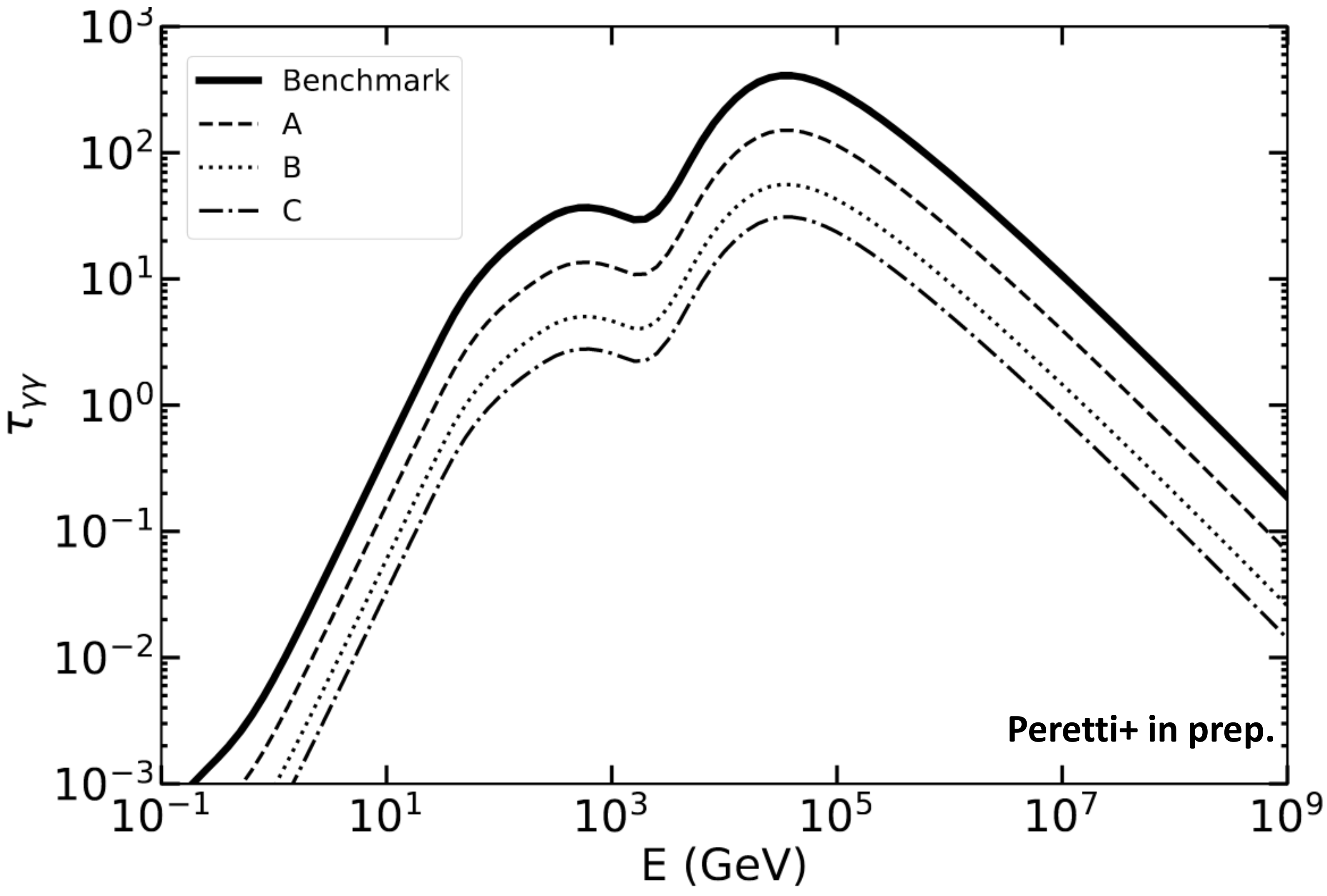
Back up

Peretti+ in prep.



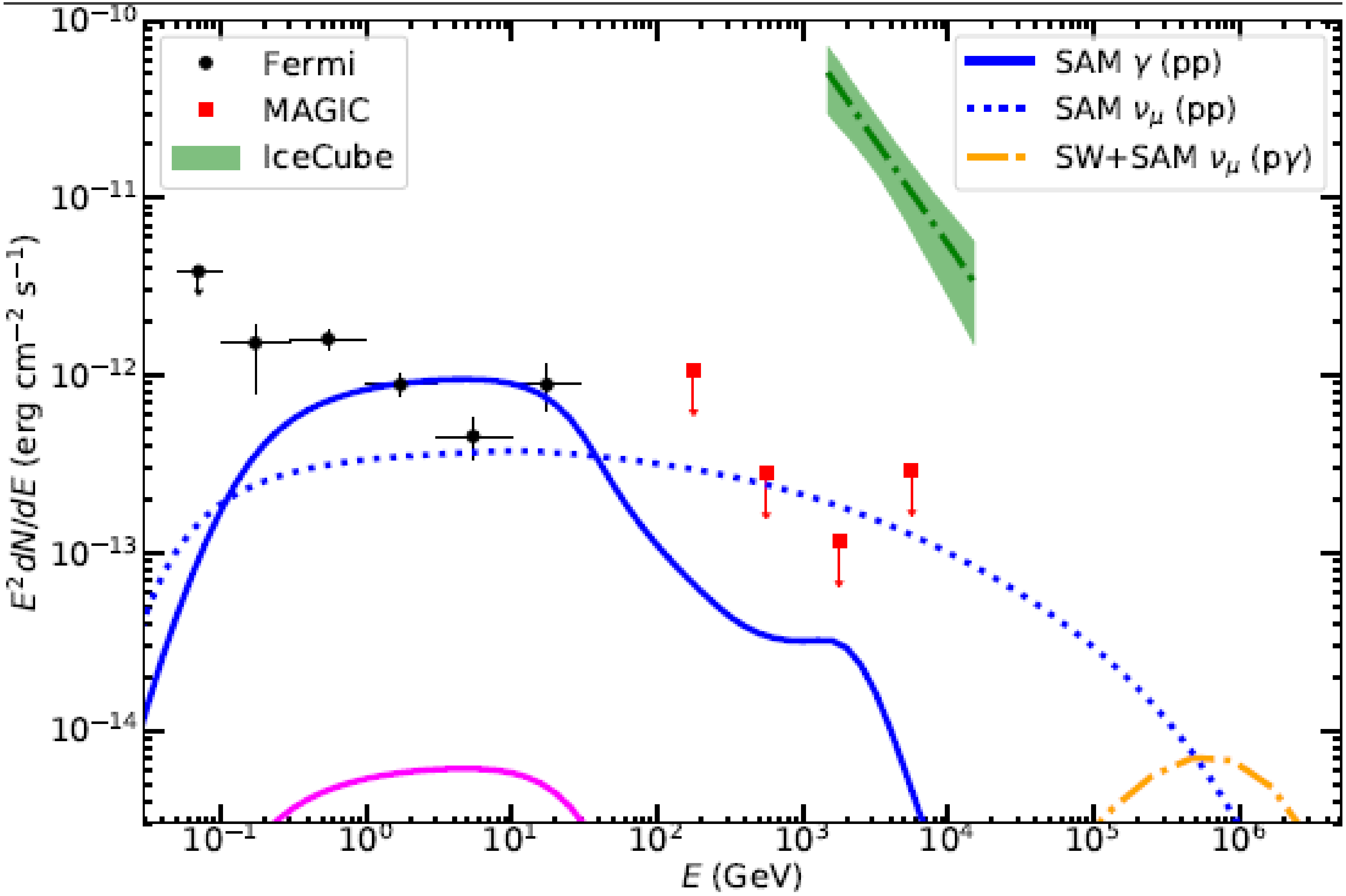
Peretti+ in prep.



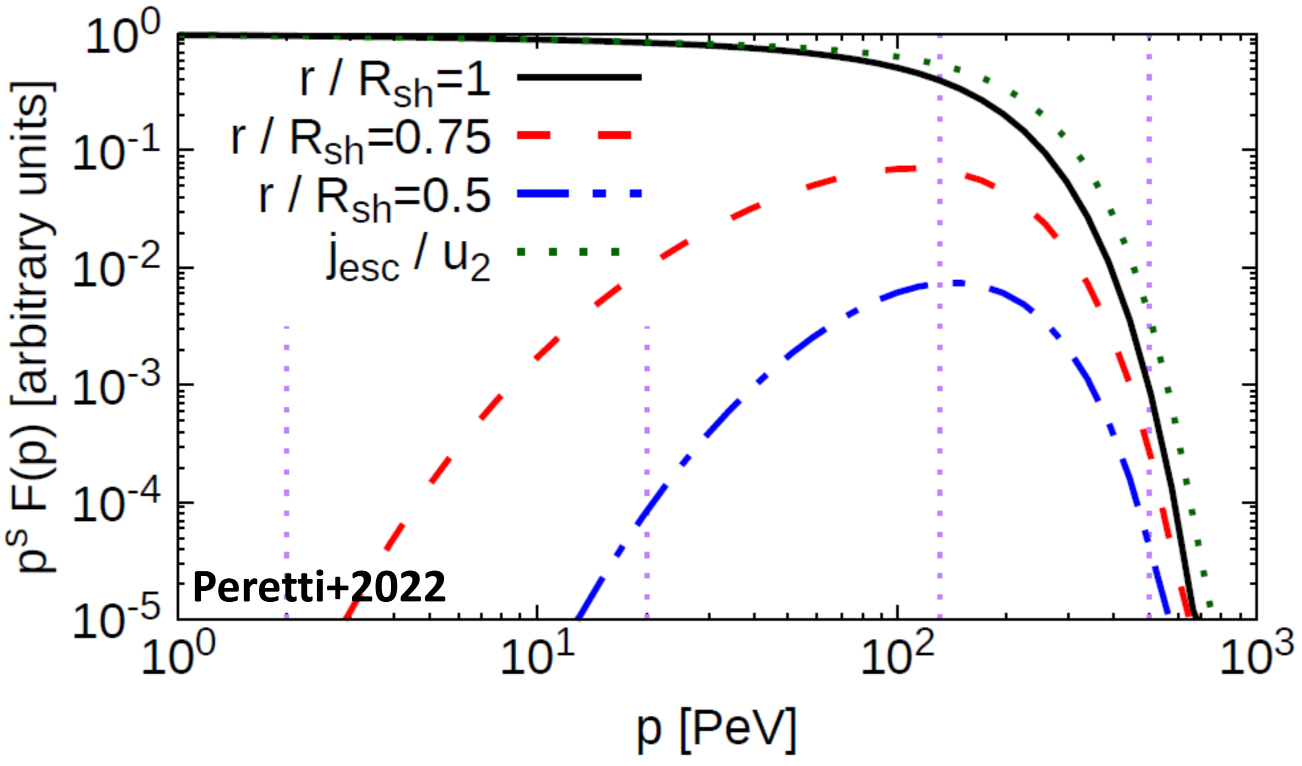


Benchmark
A
B
C
Peretti+ in prep.
$\tau_{\gamma\gamma}$
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-1}
10^{1}
10^{3}
10^{5}
10^{7}
10^{9}
E (GeV)

Peretti+ in prep.



SBGs – Maximum Energy



Parameters

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

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

$t_{age} = 10 - 100\ Myr$

$R_{FS} = 55\ kpc$