Diffusive Shock Acceleration in Galactic Winds: Multimessenger prospects

Enrico Peretti

[Based on:
- *Peretti, Morlino, Blasi & Cristofari 2022;*
- *Peretti, Lamastra, Saturni, Ahlers, Blasi, Morlino & Cristofari 2022 in prep.]*

PASTO
Particle Acceleration in aSTrophysical Objects
2022

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 and evolution
- Acceleration and transport in wind bubbles
- Solution: radial distribution and spectra
- Multimessenger implications: SBGs & AGNi

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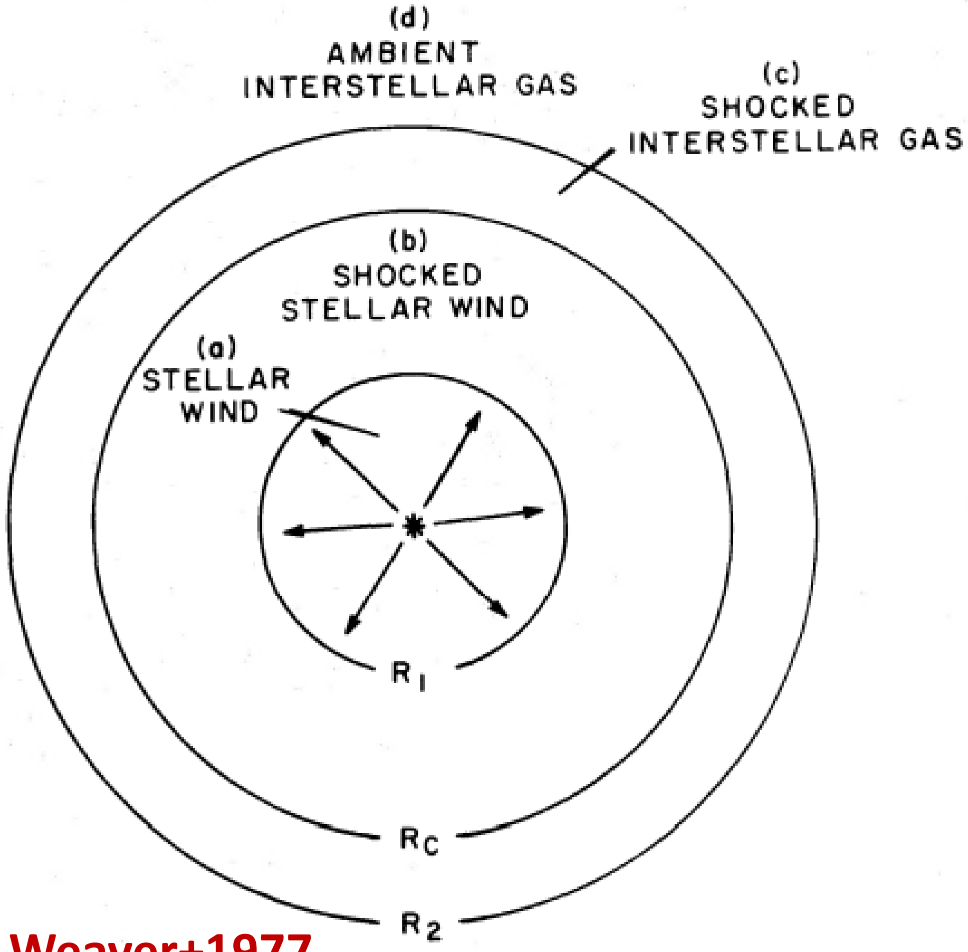
Wind Bubbles

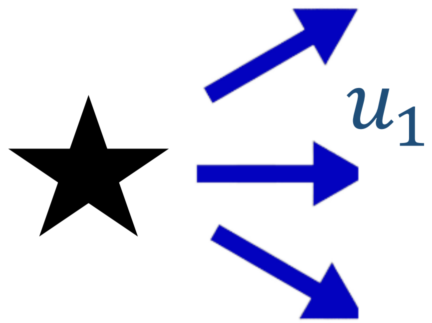


Weaver+1977

- 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

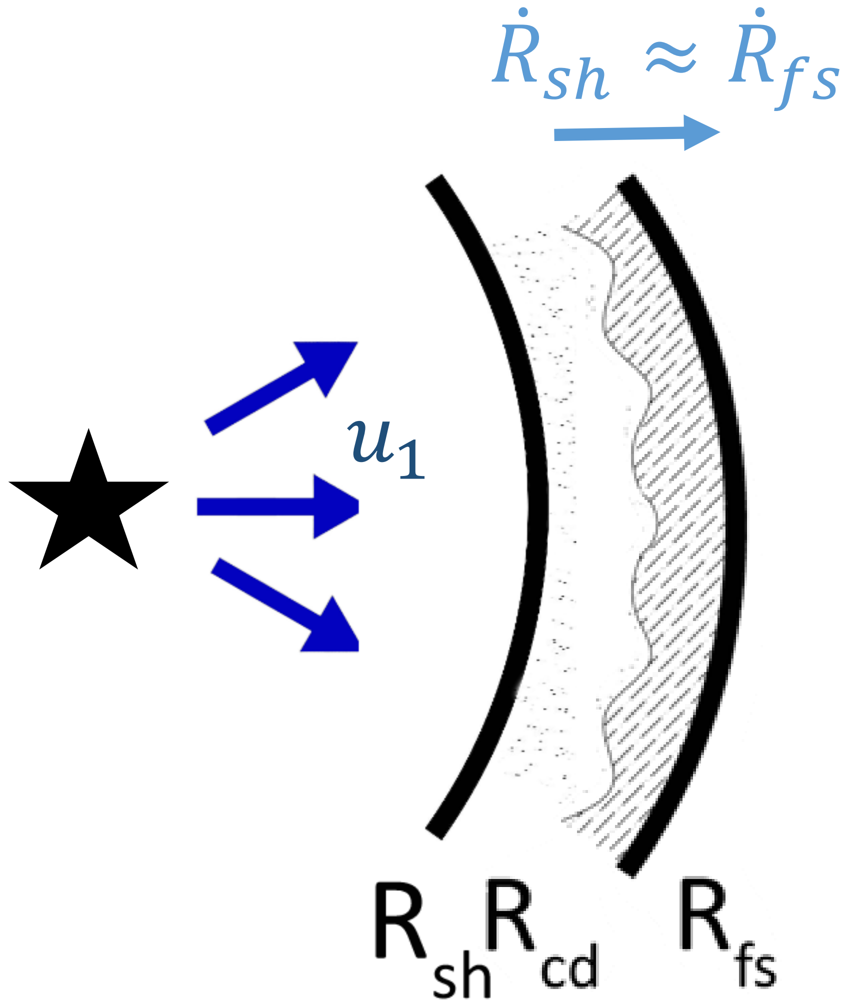
- Macroscopic parameters:
  1. Terminal wind speed: V_∞
  2. Mass loss rate: $\dot{M}$

Wind bubble: structure and evolution



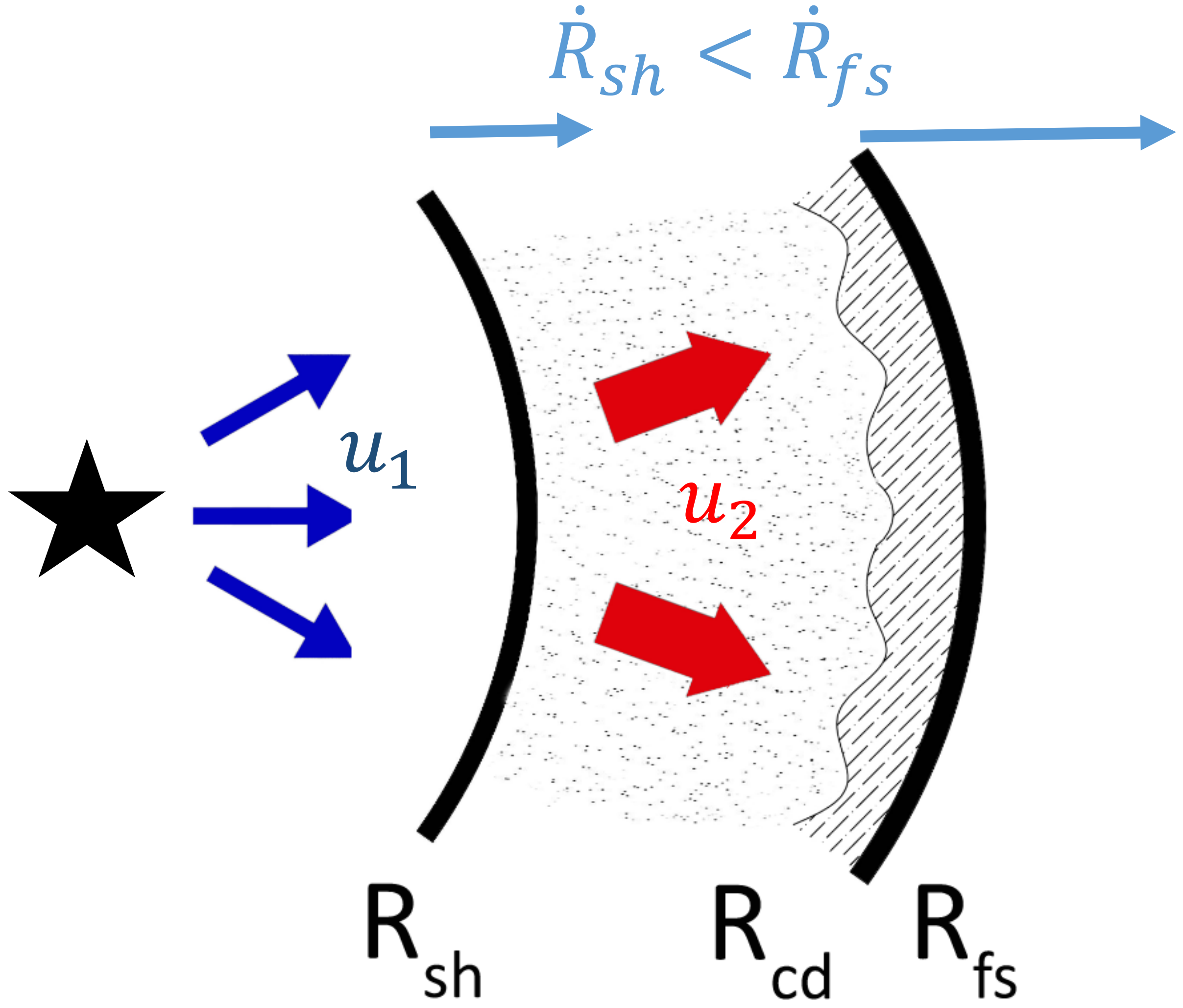
1. The outflow is launched - t_0

Wind bubble: structure and evolution



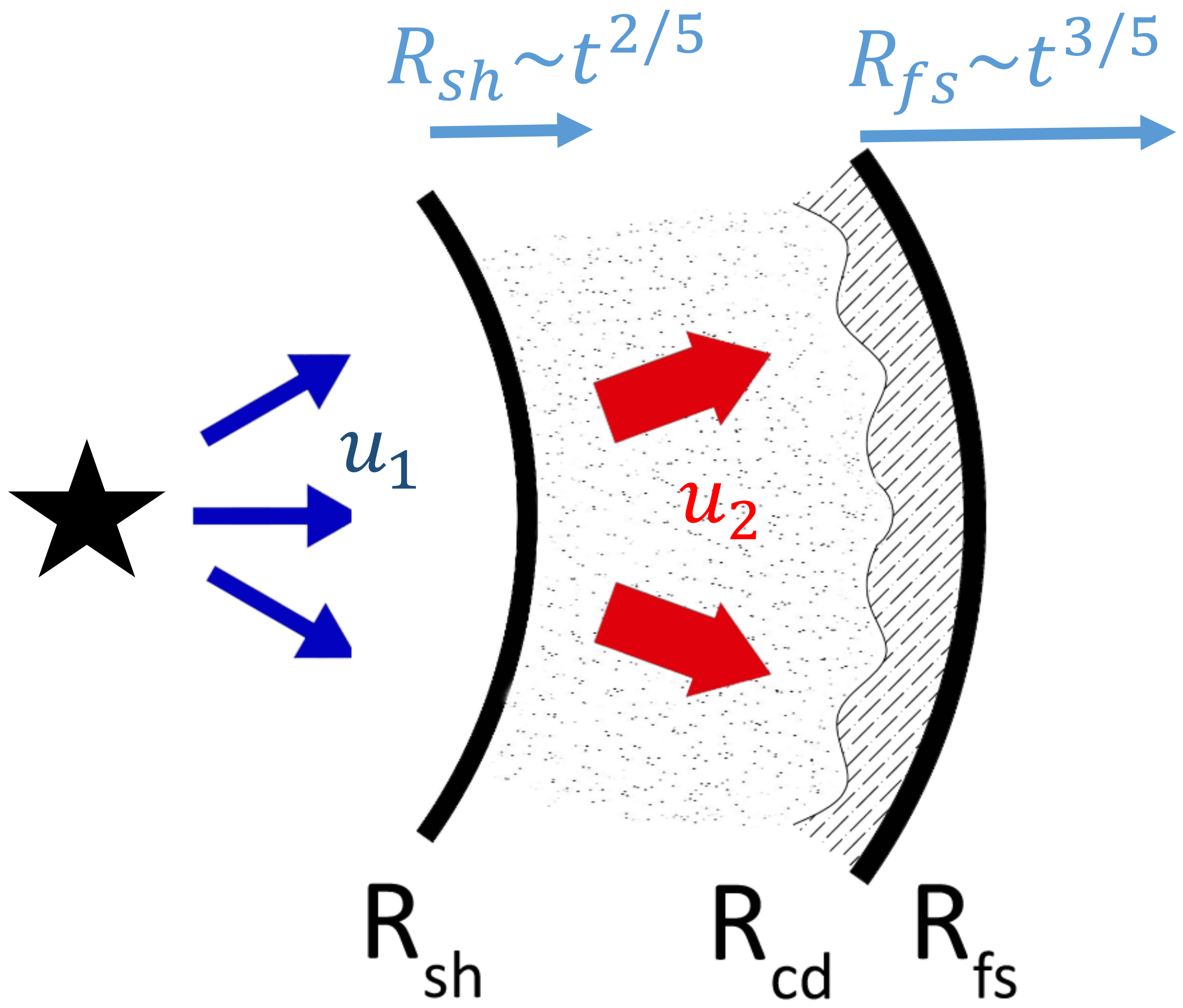
1. The outflow is launched - t_0
2. Free expansion phase - t_1

Wind bubble: structure and evolution



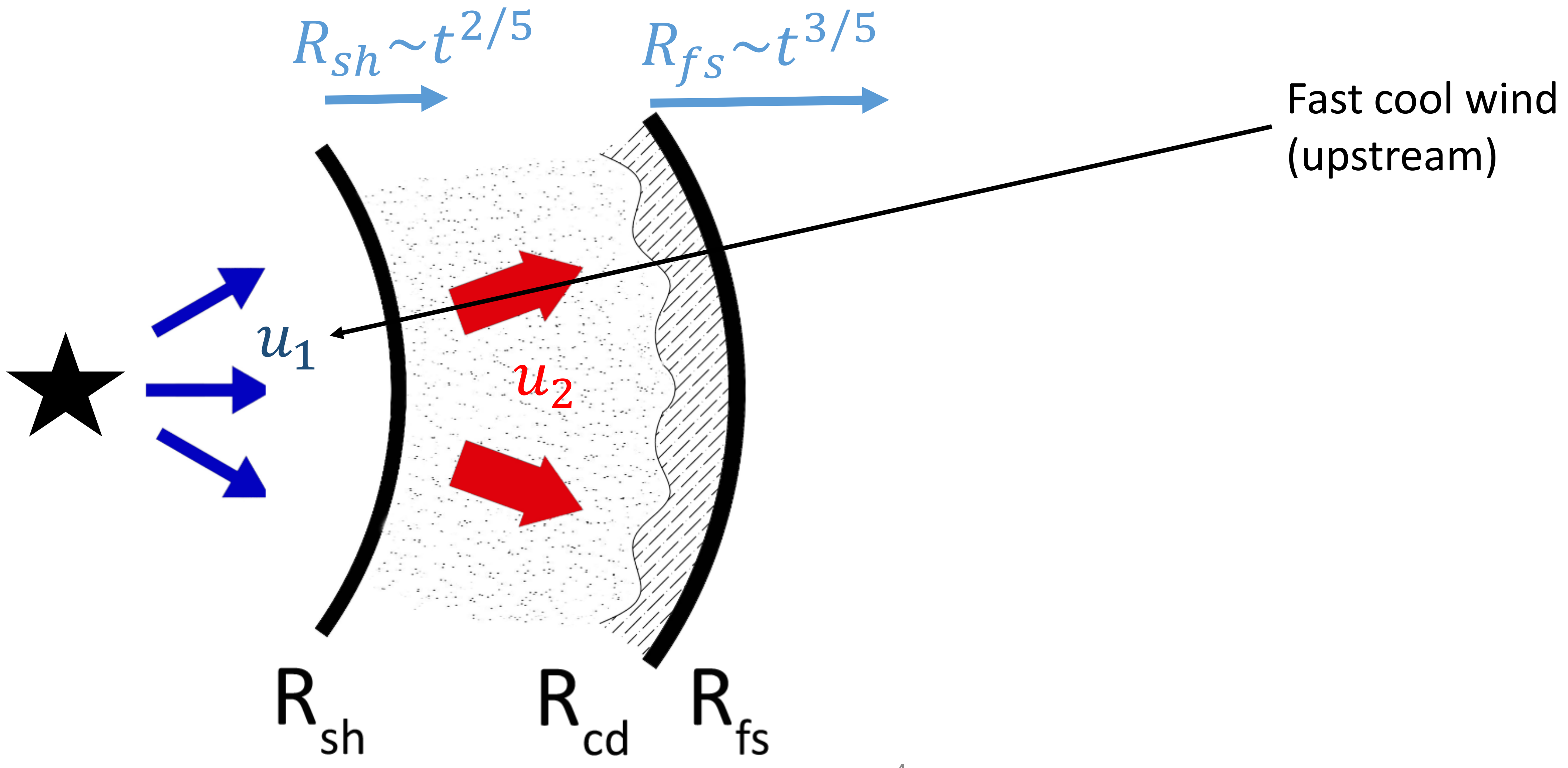
1. The outflow is launched - t_0
2. Free expansion phase - t_1
3. Deceleration phase - $t > t_1$

Wind bubble: structure and evolution

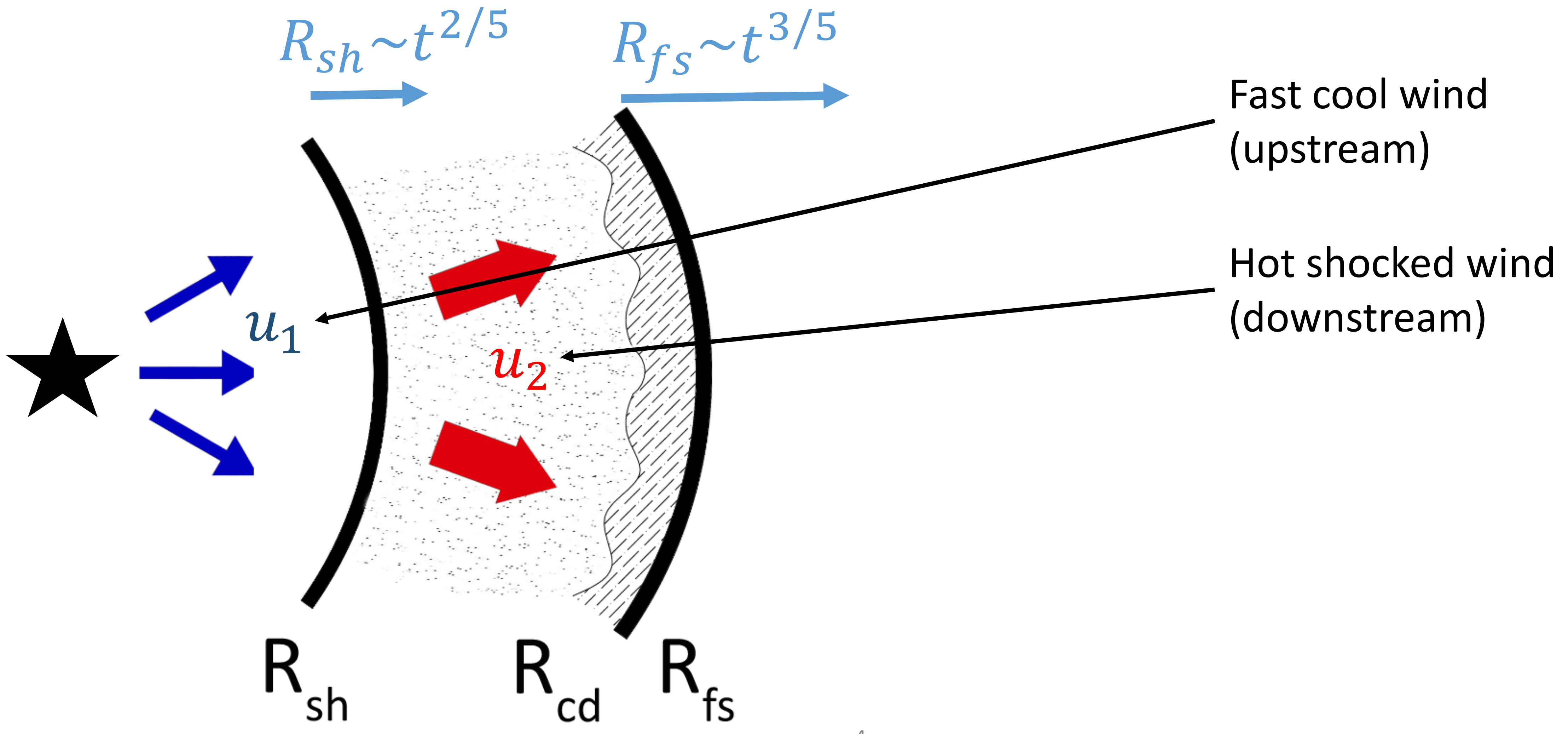


- R_{sh} → Wind shock (high Mach n.)
- R_{cd} → Contact discontinuity
- R_{fs} → Forward shock (Mach n.?)

Wind bubble: structure and evolution



Wind bubble: structure and evolution



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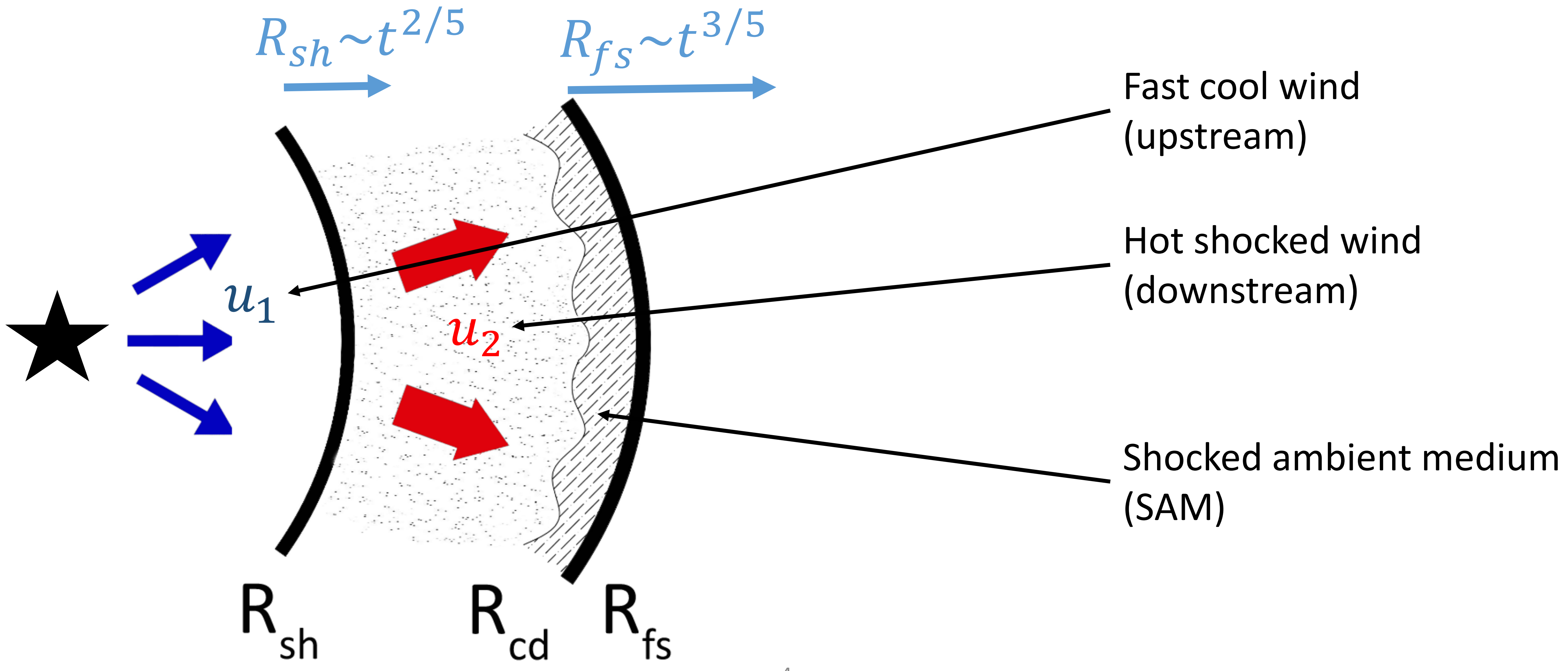

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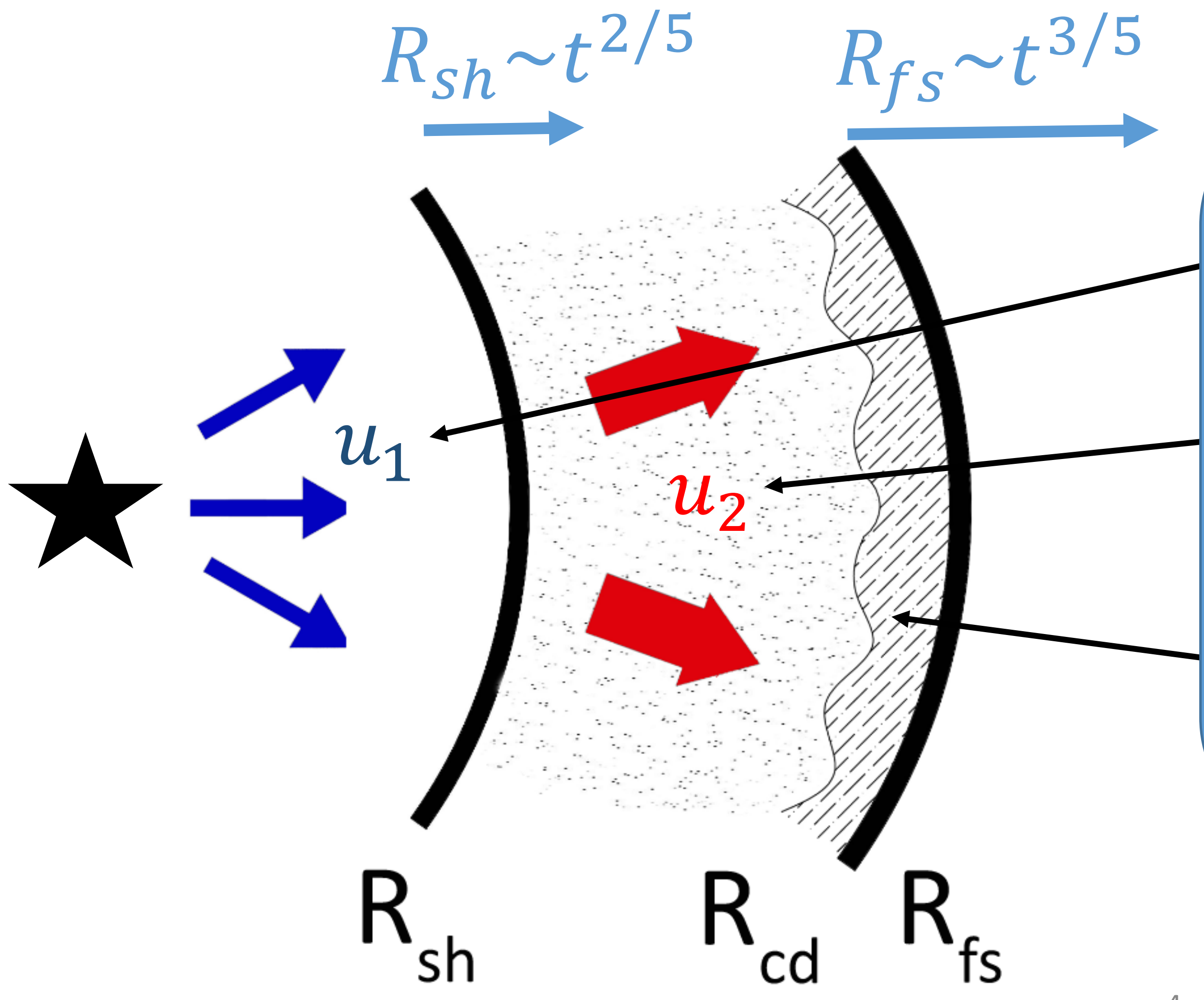
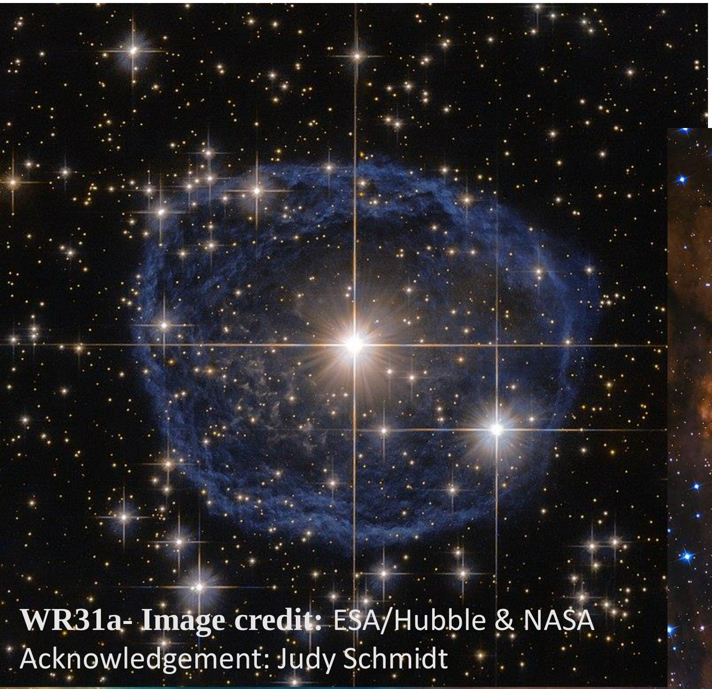


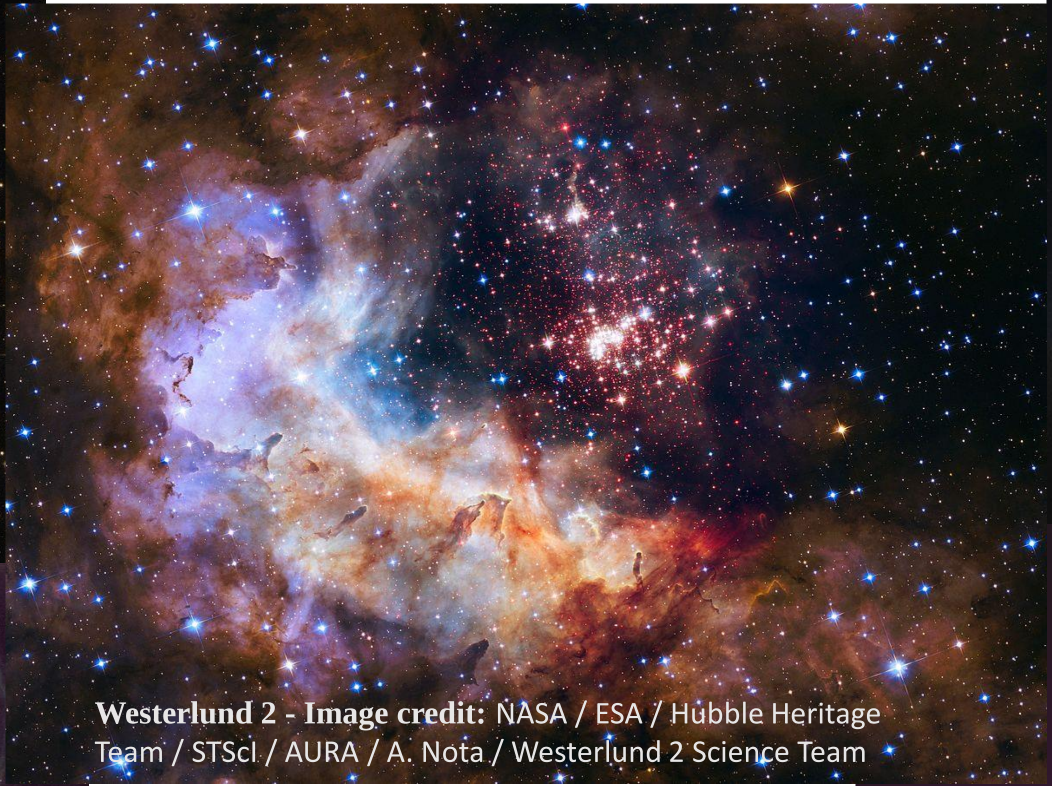
- $u_1 \gg \dot{R}_{sh}$
- The shocked wind is adiabatic
- The shocked wind region grows in t

Wind Bubbles: scales and power - 1

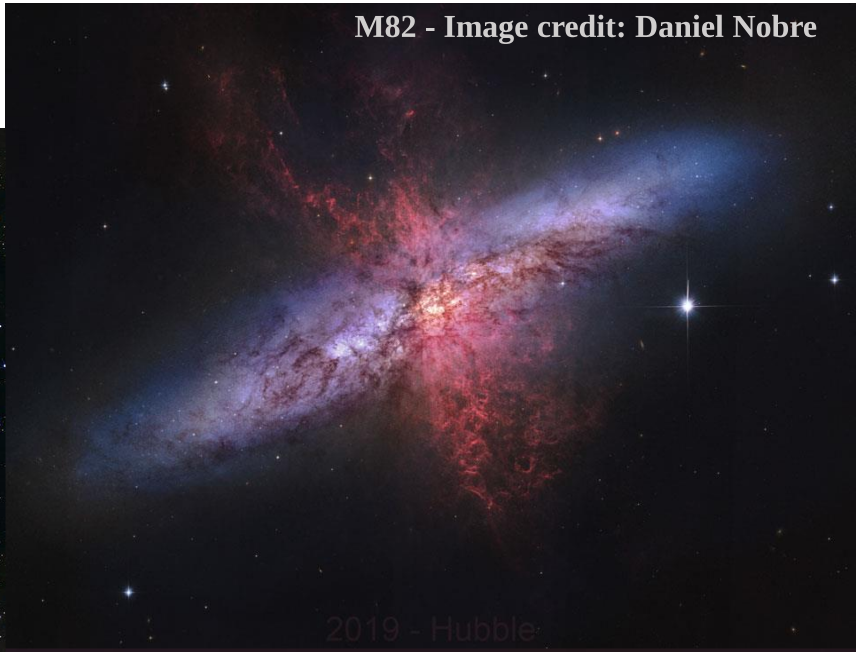


WR31a- Image credit: ESA/Hubble & NASA
Acknowledgement: Judy Schmidt

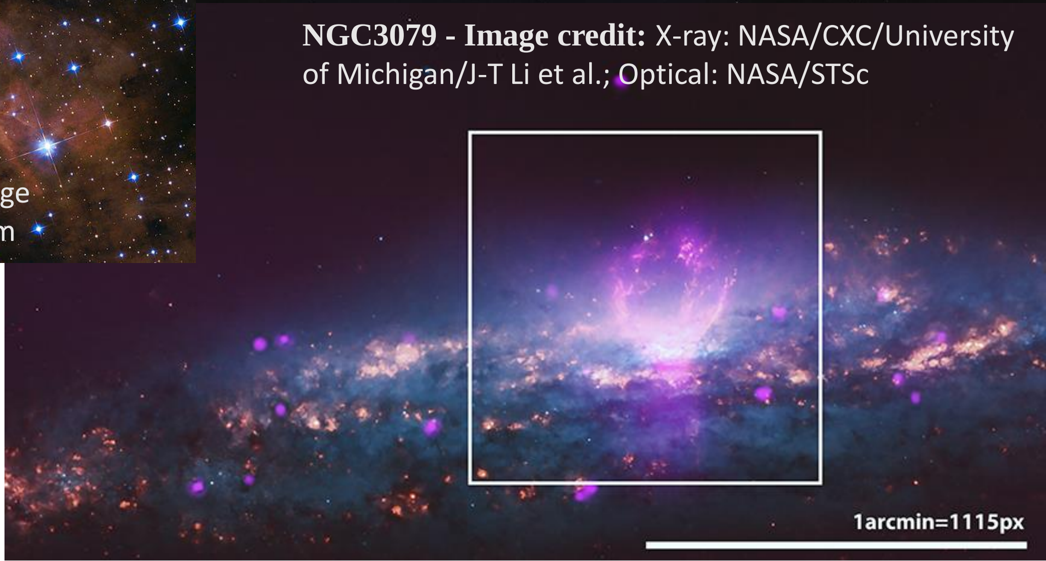
NGC7635- Image credit: NASA Goddard Space Flight Center from Greenbelt, MD, USA



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



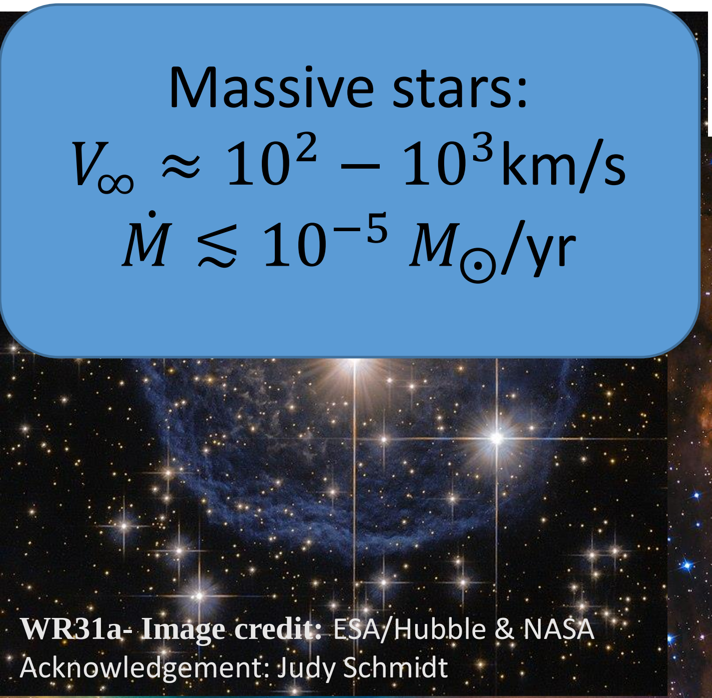
M82 - Image credit: Daniel Nobre



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

Wind Bubbles: scales and power - 1

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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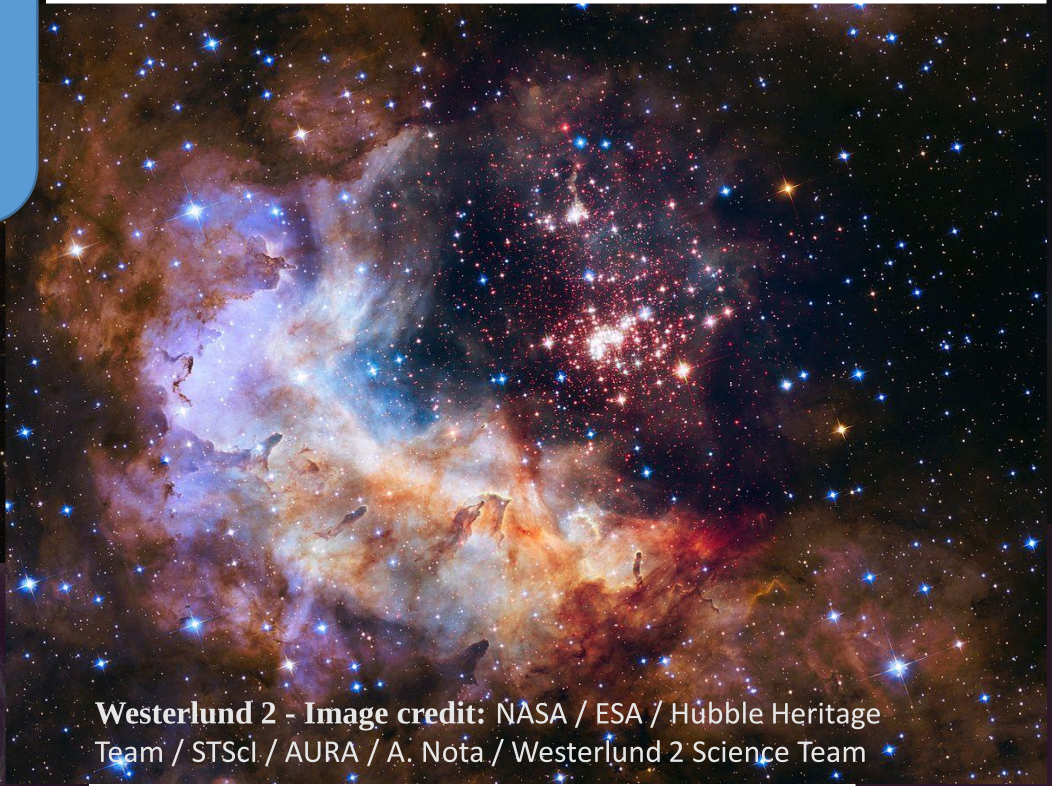

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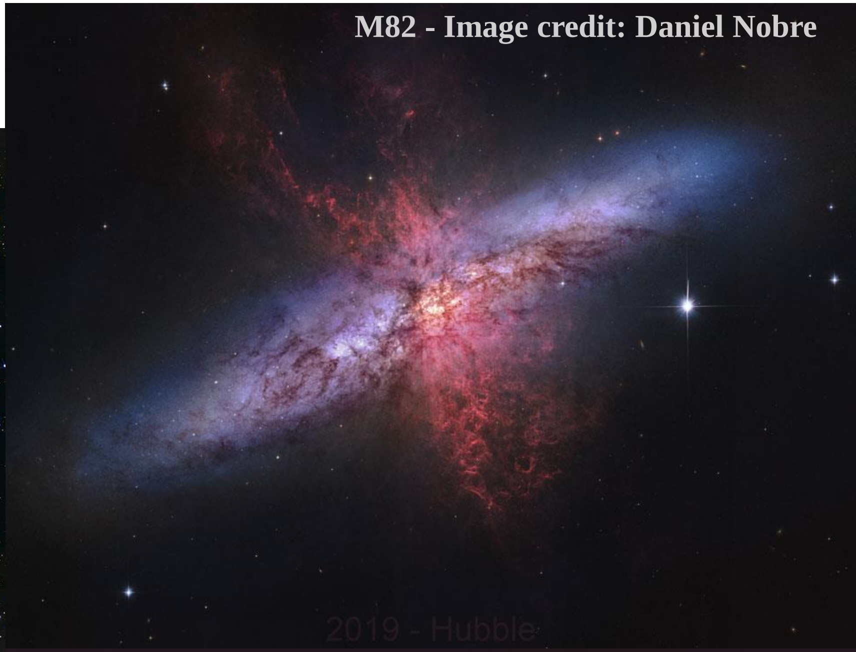

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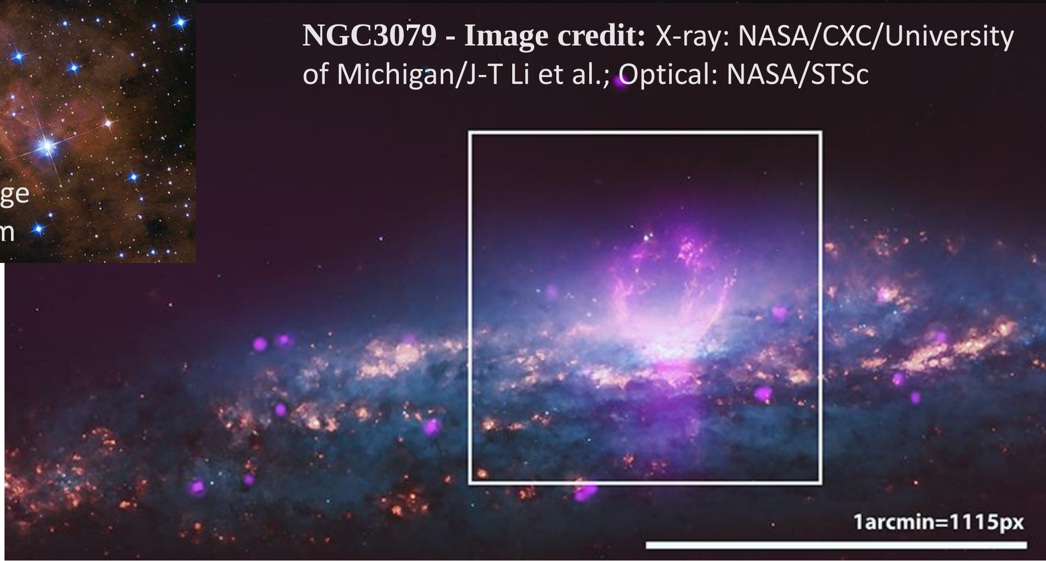

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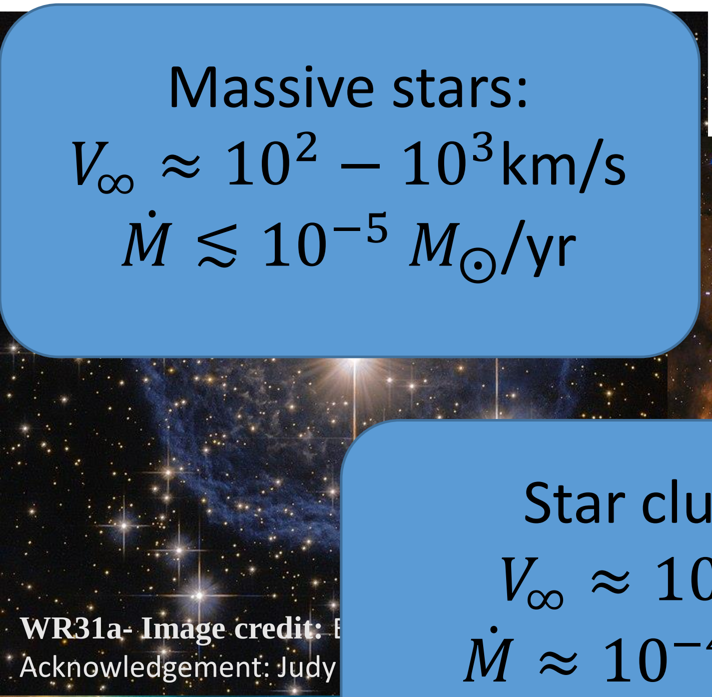

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Star clusters:
$V_\infty \approx 10^3$km/s
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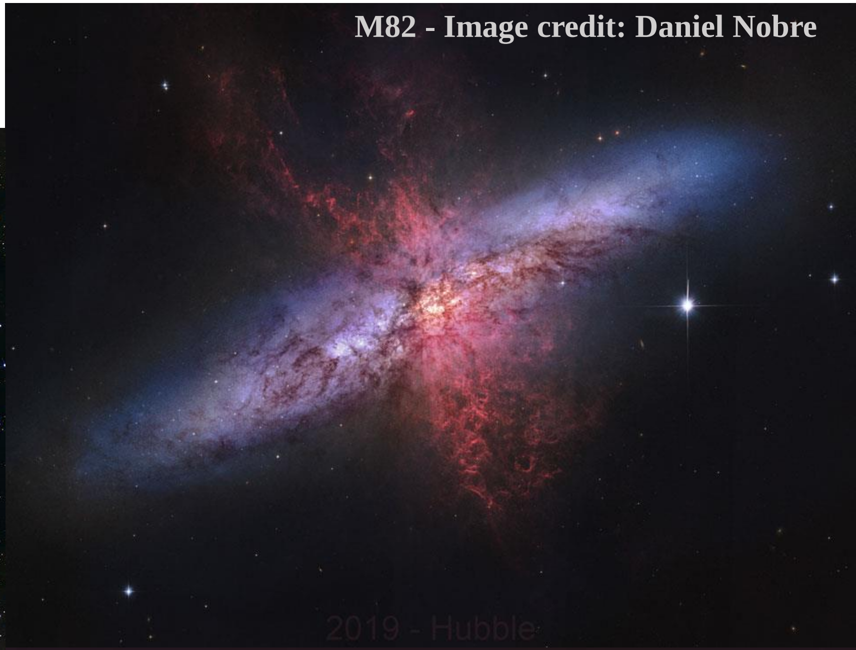

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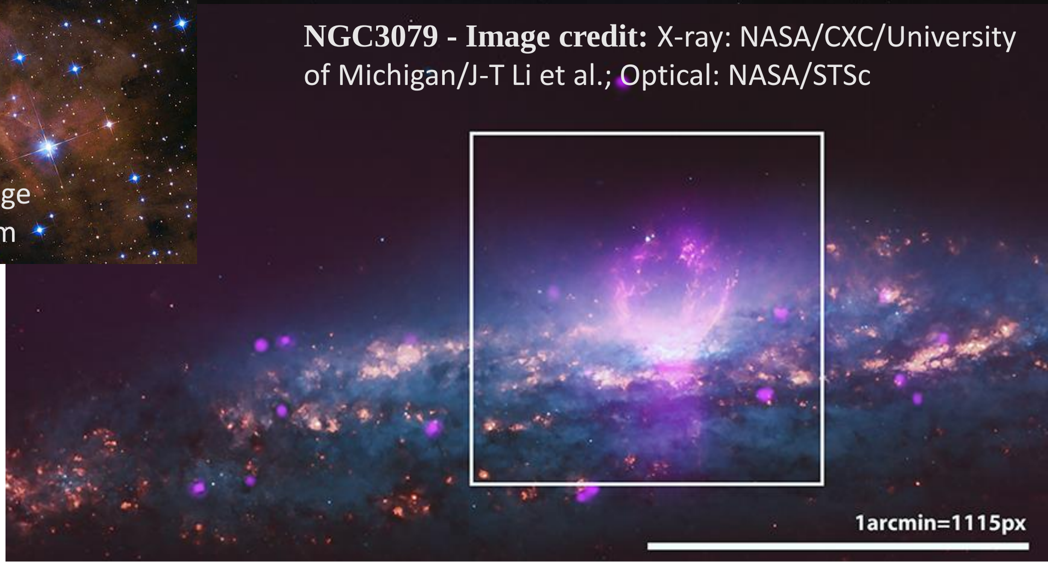

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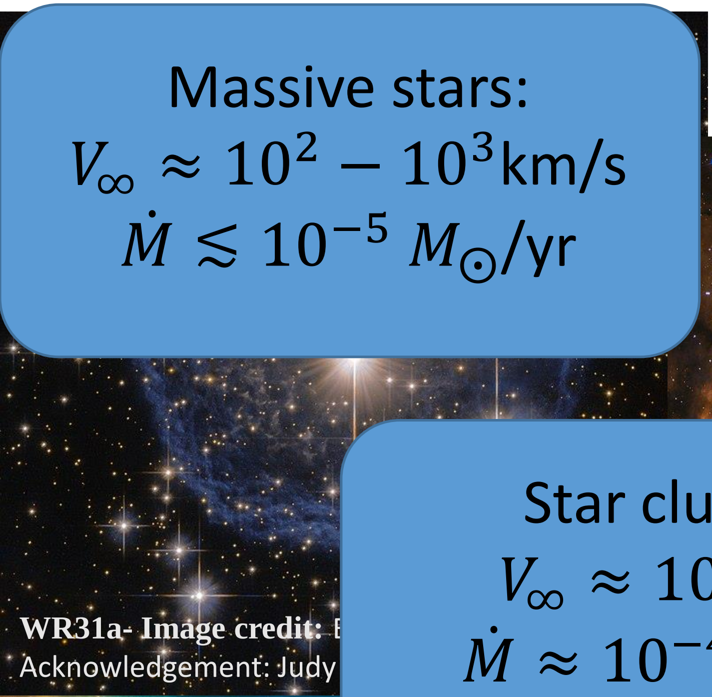

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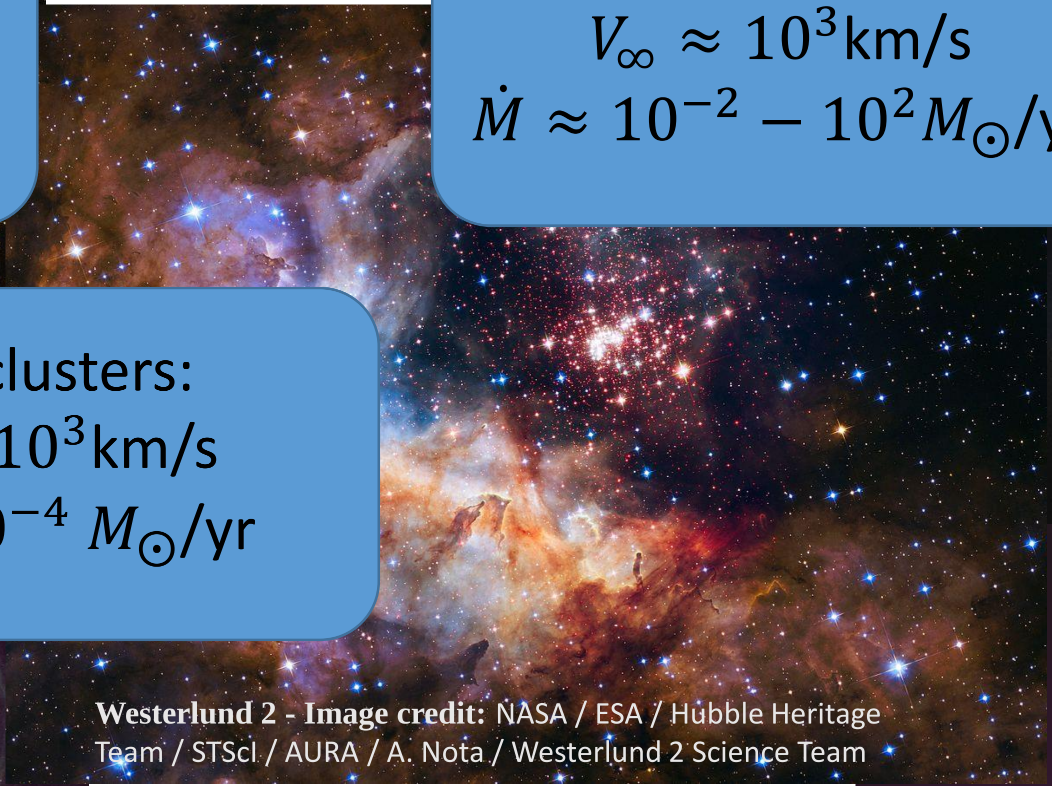

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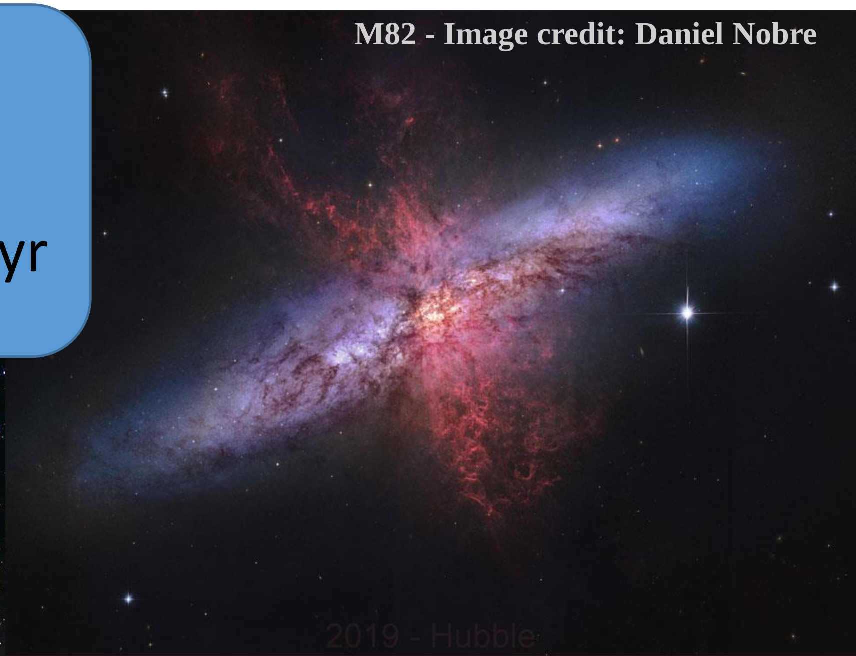

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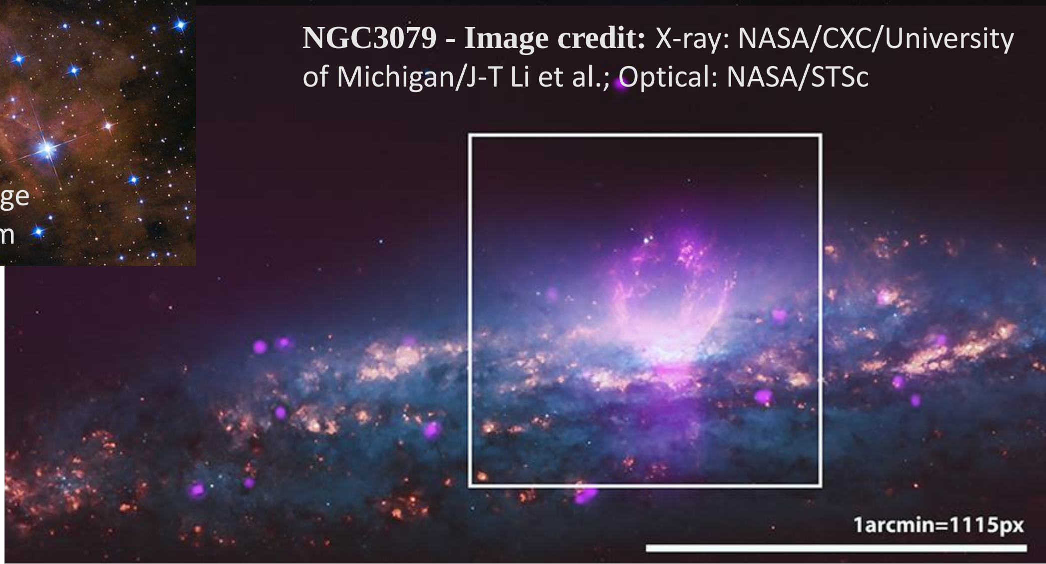

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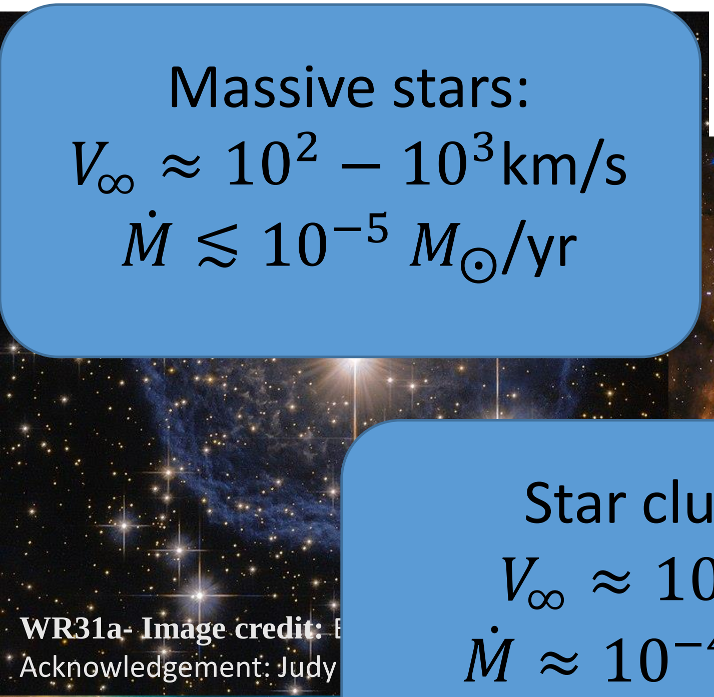

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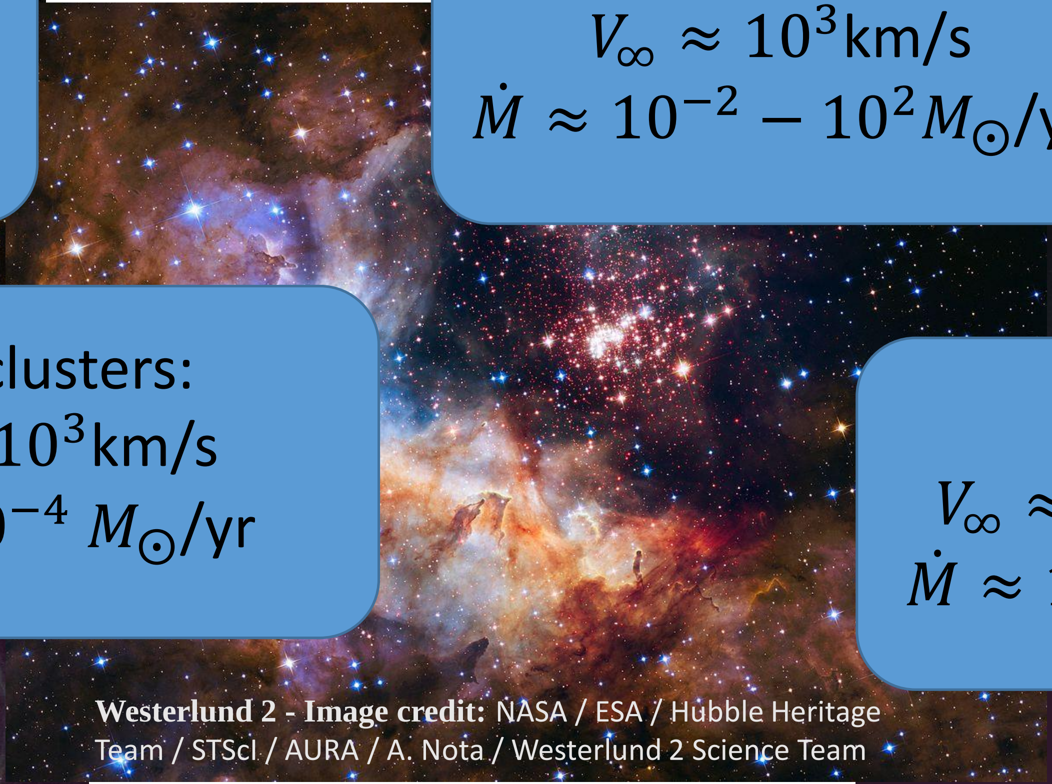

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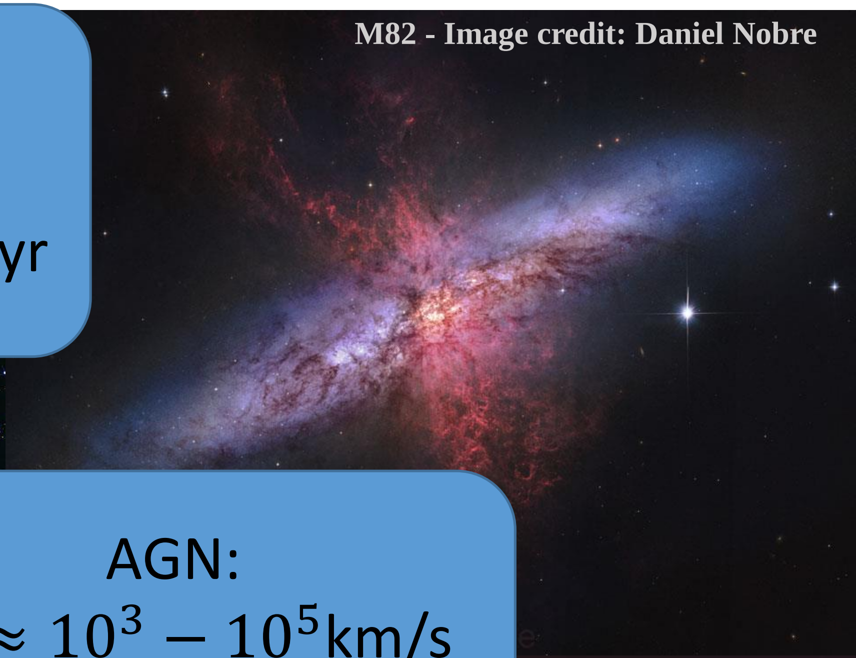

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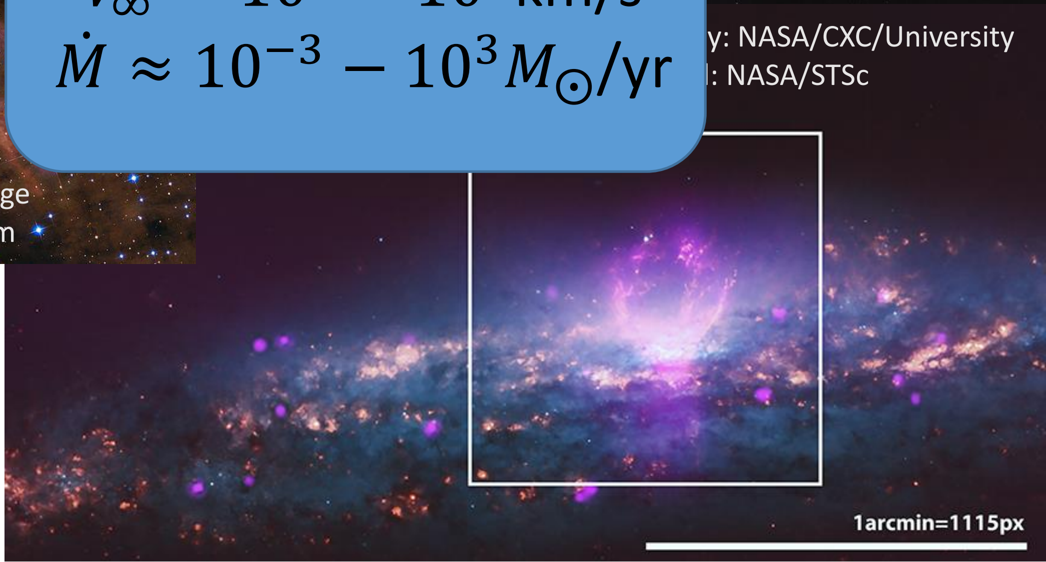
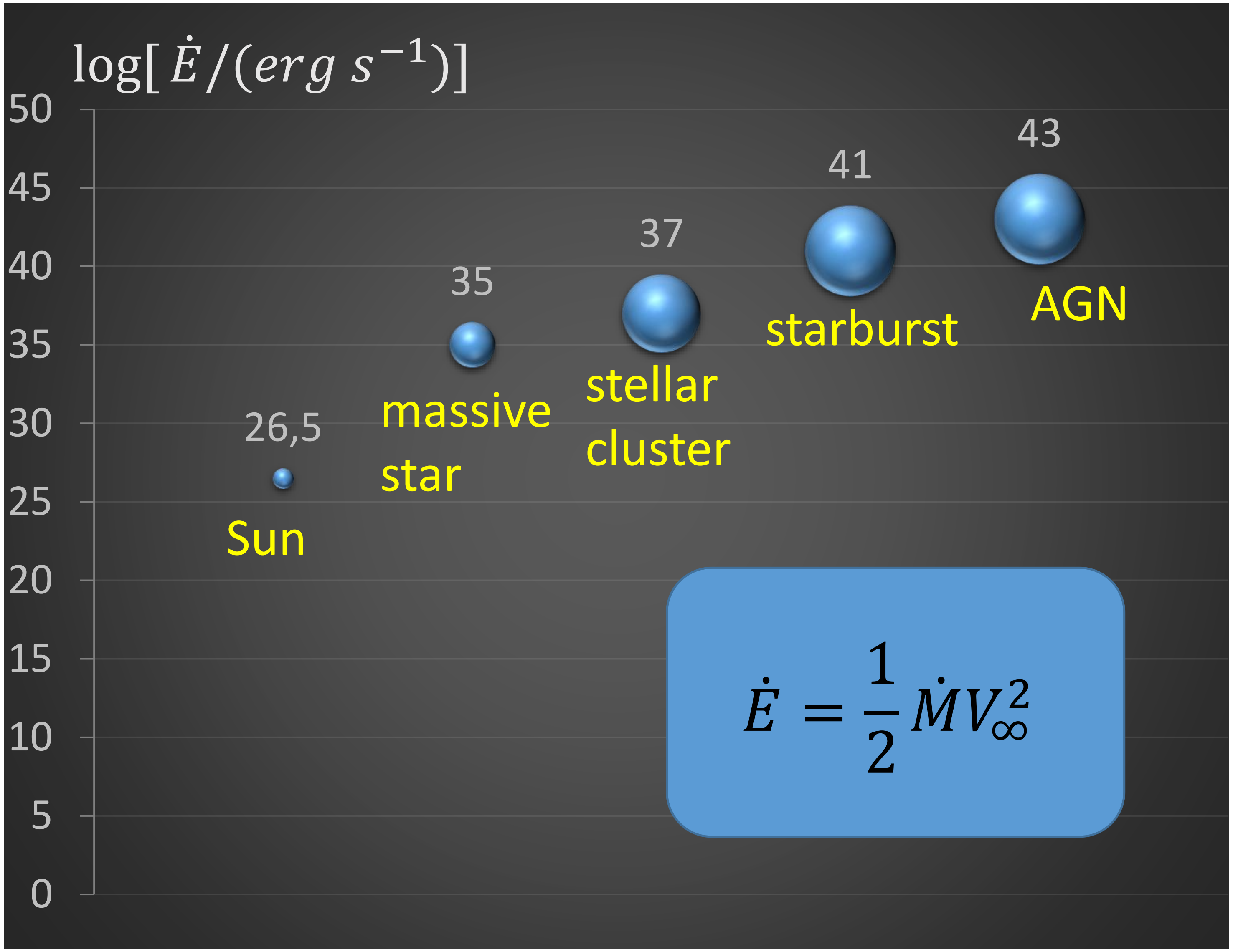


y: NASA/CXC/University
: NASA/STSc

Wind Bubbles: scales and power - 2

<u>Spatial size</u>:

- Star: 1 -10 pc
- Stellar cluster: 10 - 100 pc
- Starburst: 1 - 10 kpc
- AGN: pc (UFO) – 10 kpc (wind)



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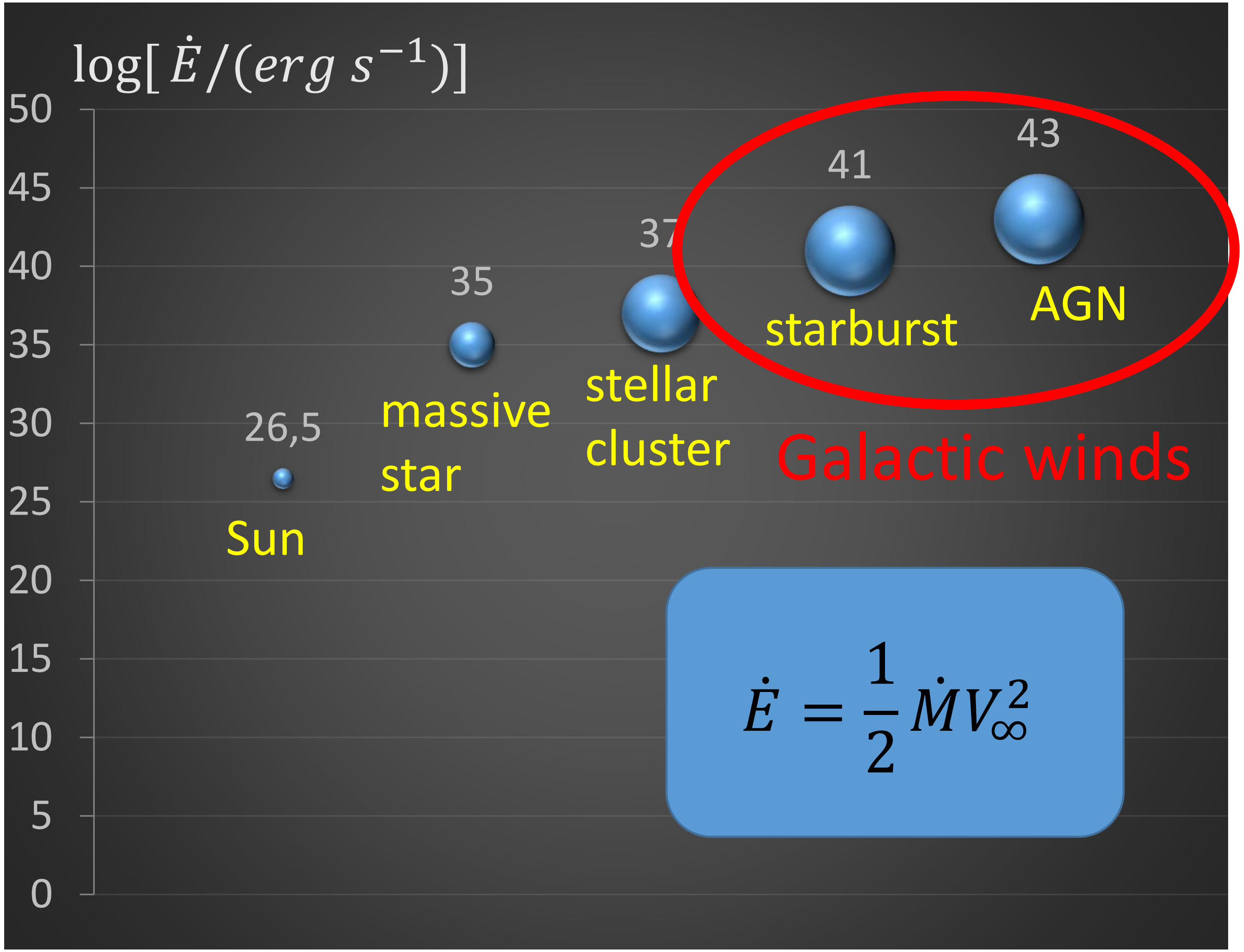

Maximum Energy: a first guess

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

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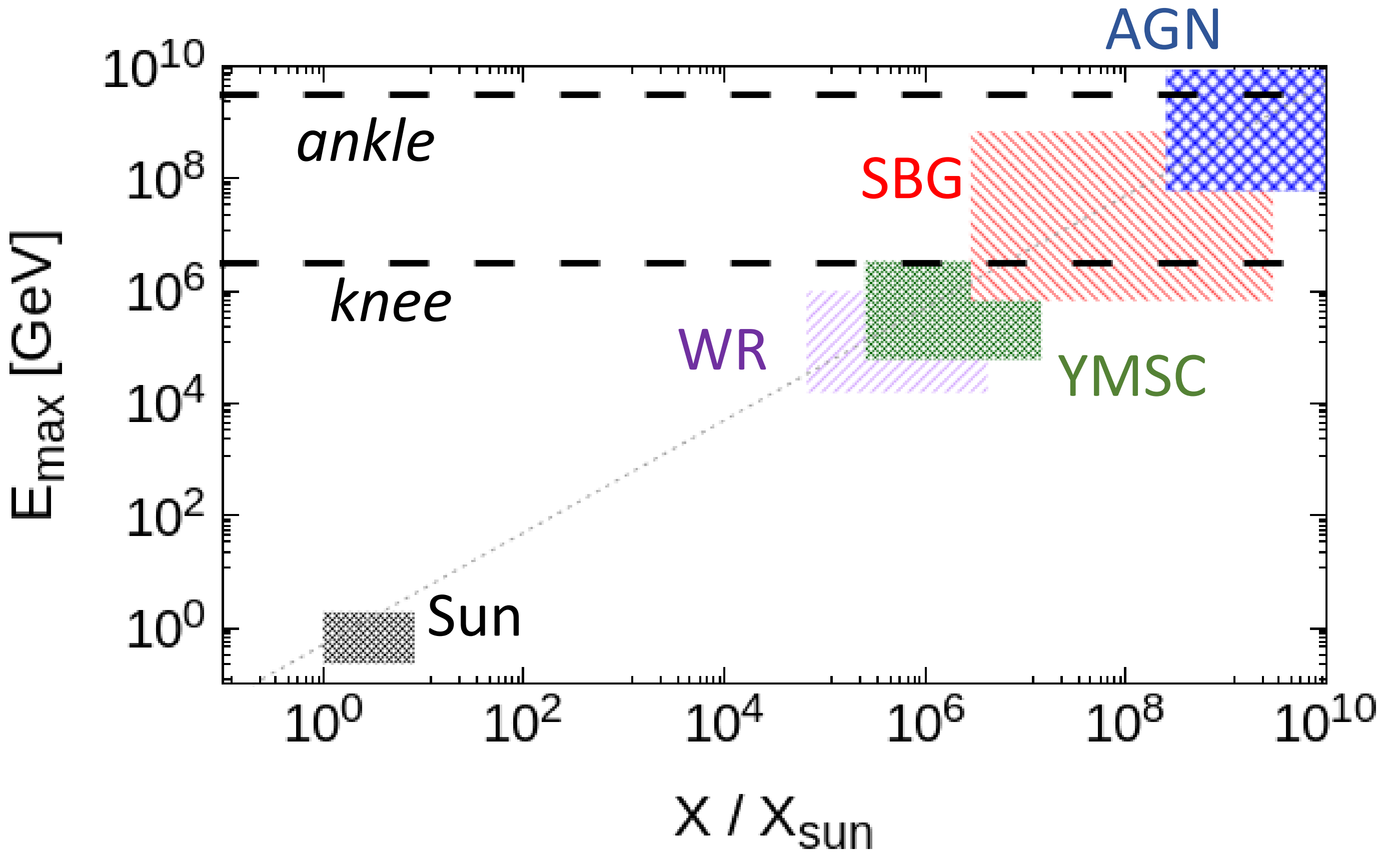
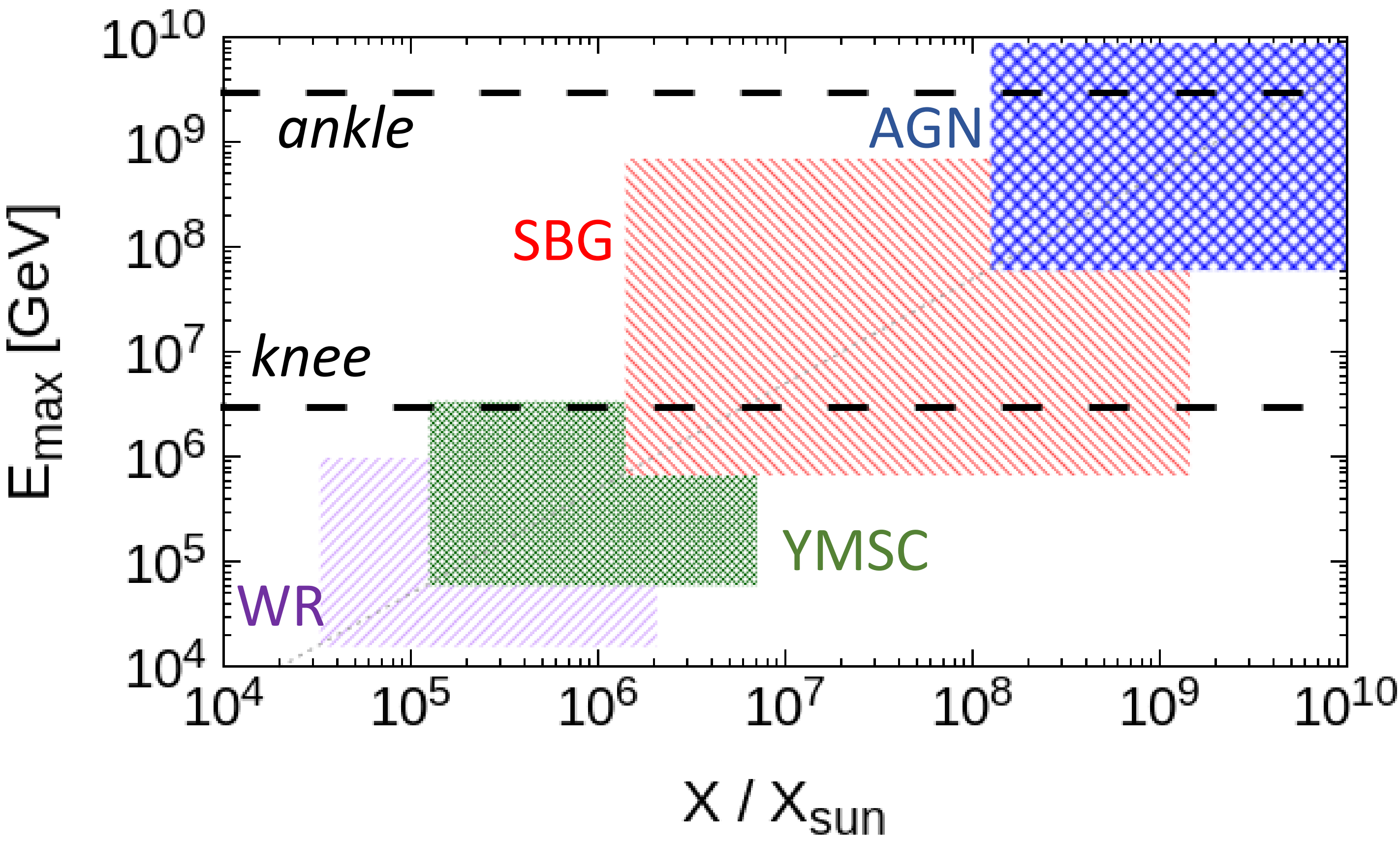
$$X = \dot{E}\dot{P}^{-1/2}$$



Why wind bubbles?

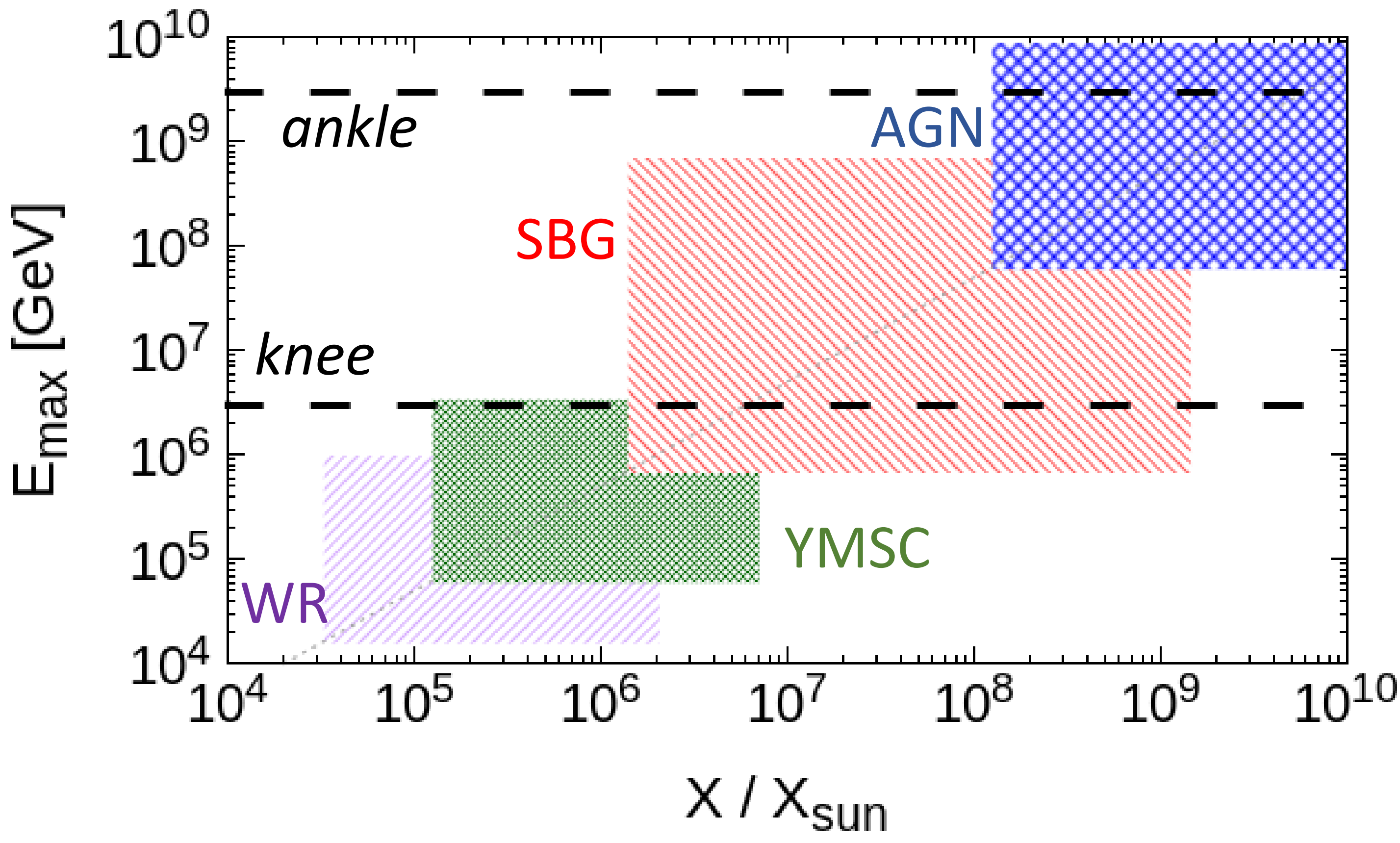
<u>Questions:</u>



Why wind bubbles?

Questions:

1. Can wind bubbles get to the highest energies both in our Galaxy and outside?

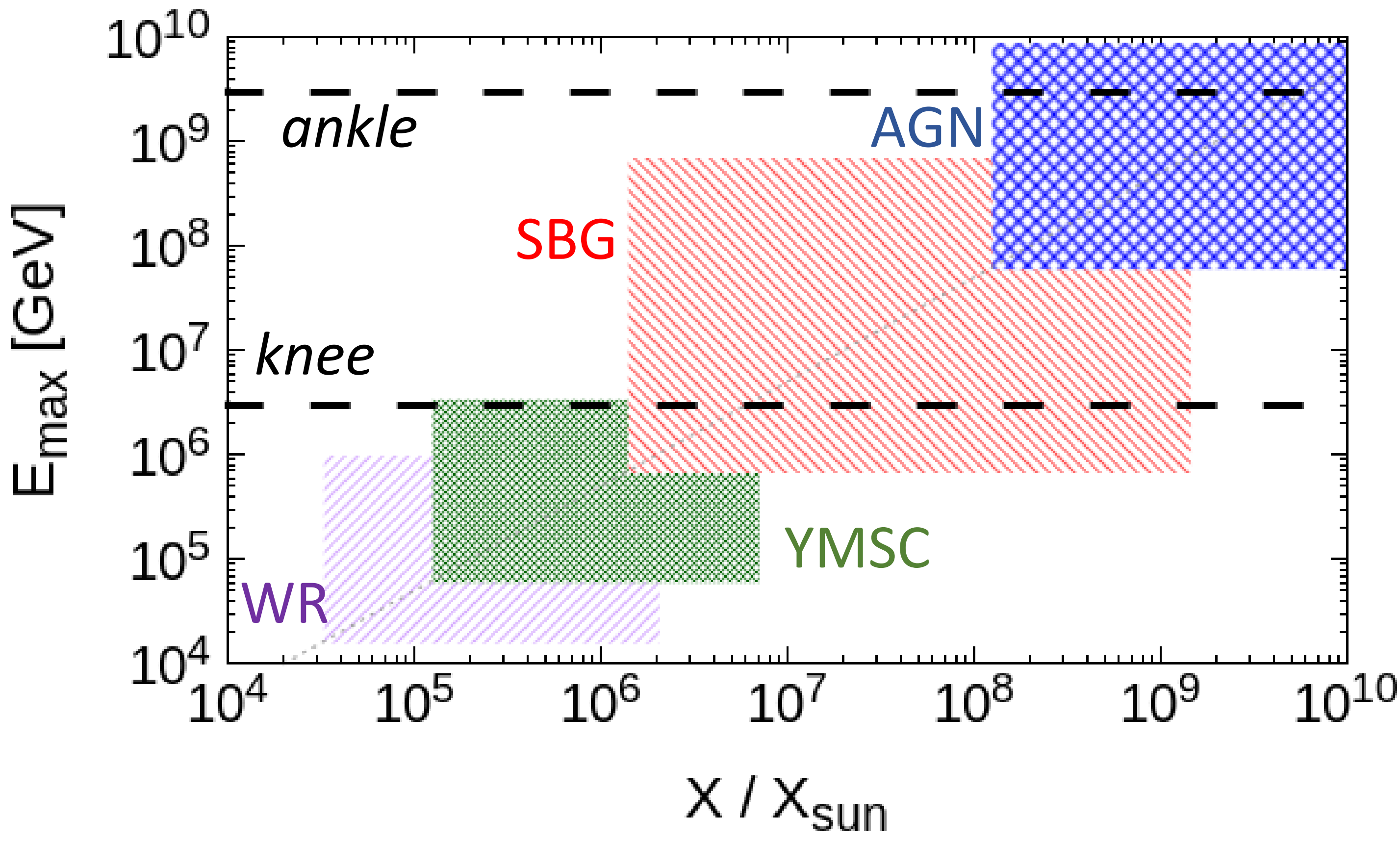


Why wind bubbles?

Questions:

1. Can wind bubbles get to the highest energies both in our Galaxy and outside?

2. What are the multimessenger implications?



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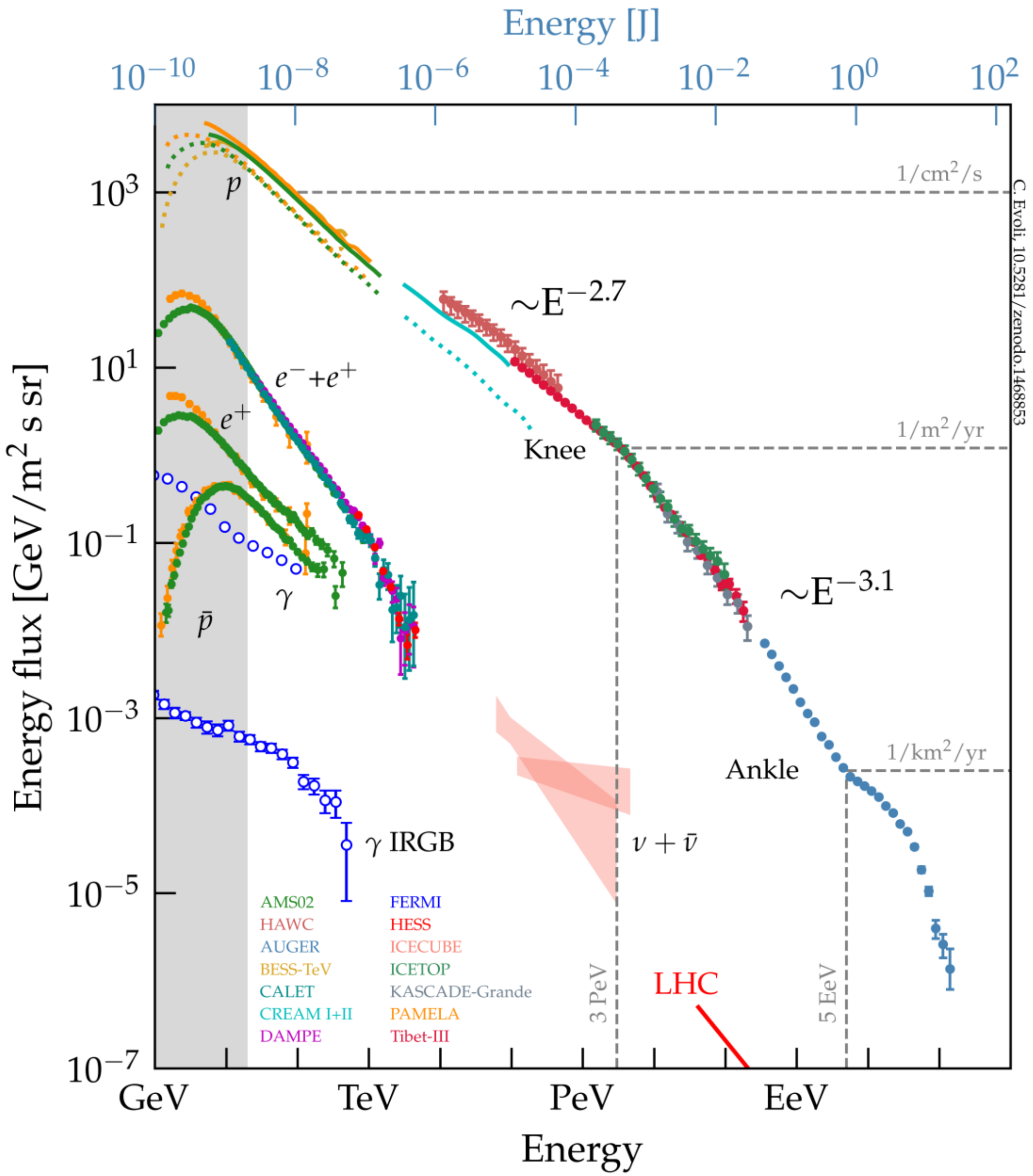

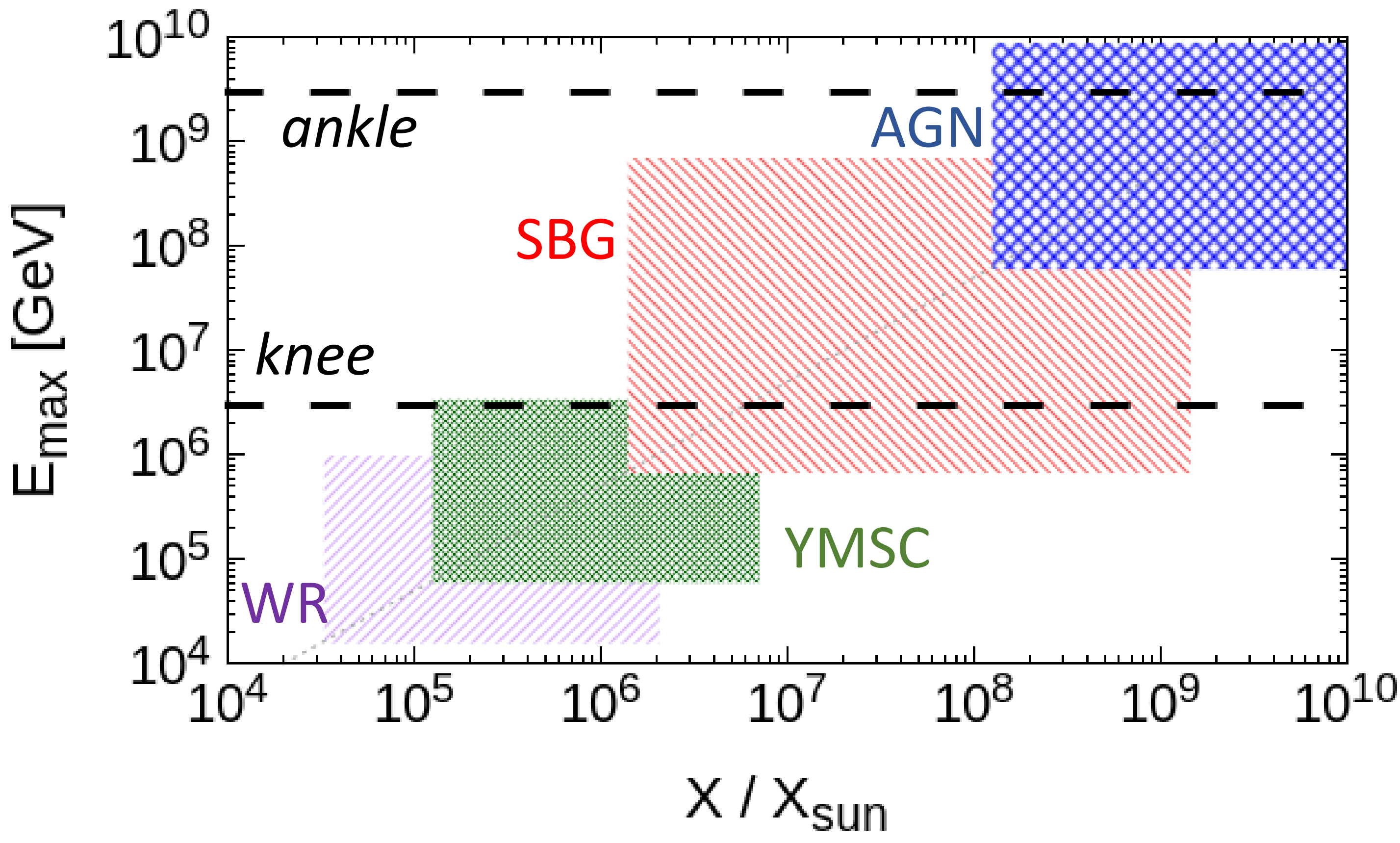

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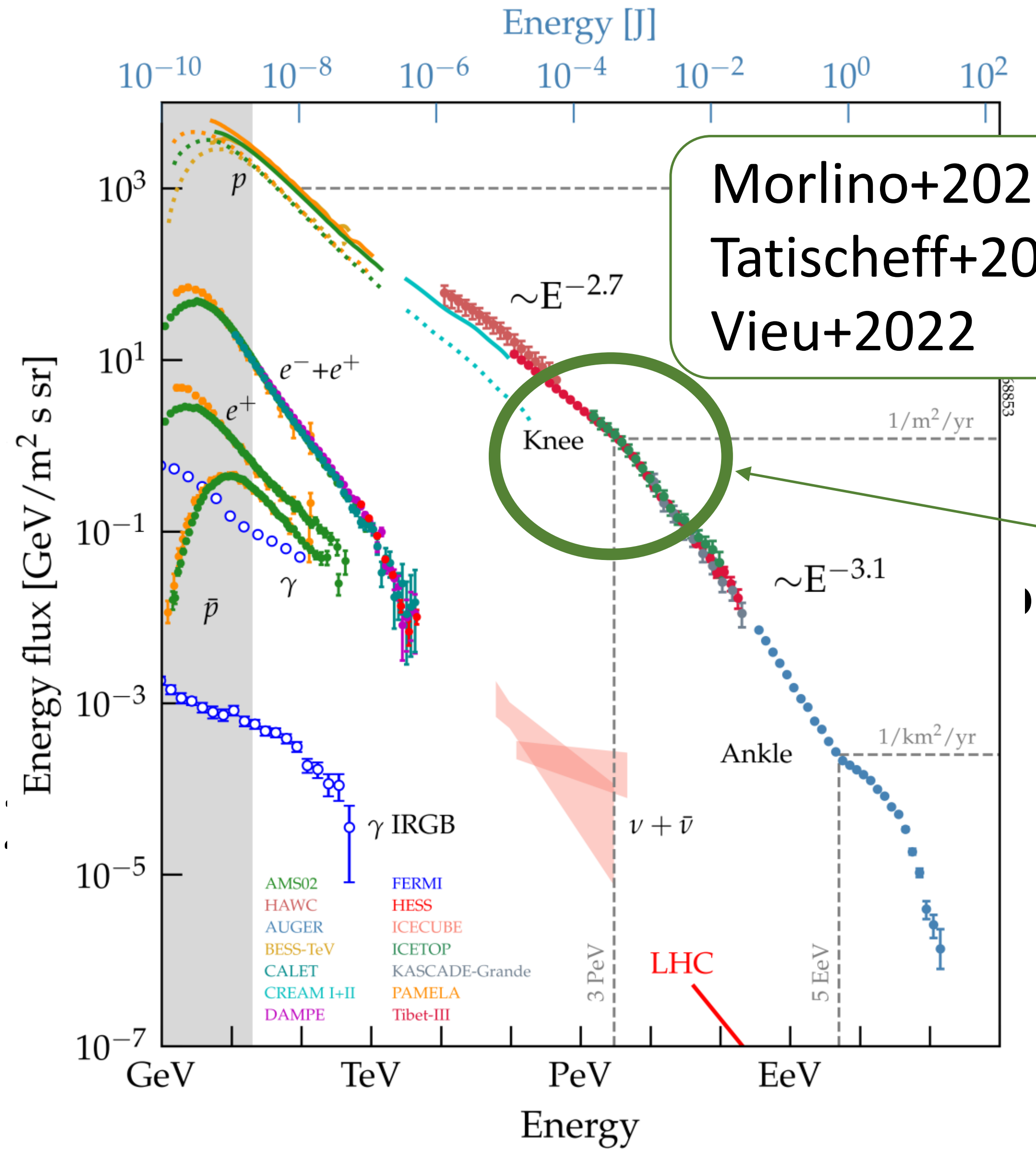
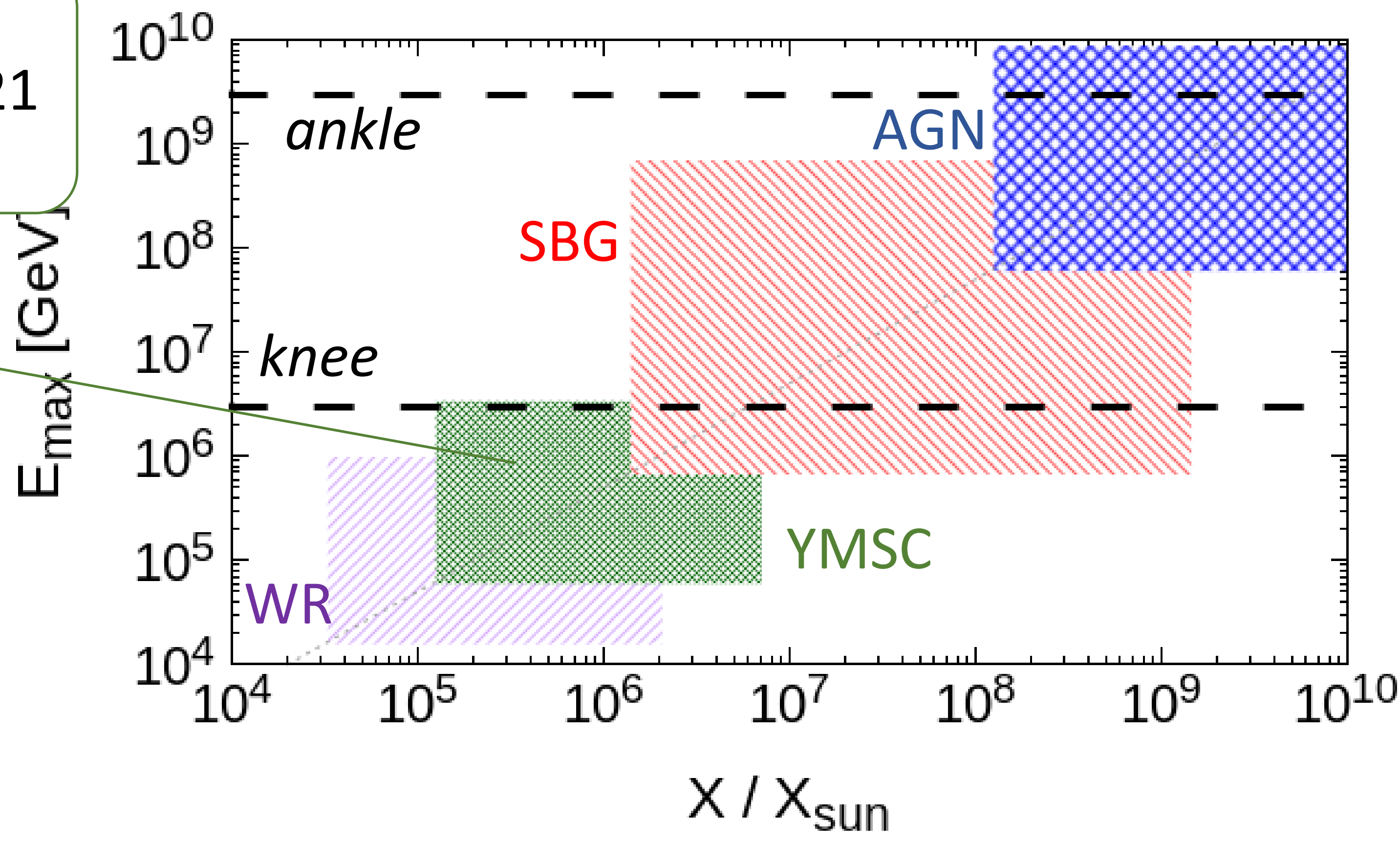


Morlino+2021
Tatischeff+2021
Vieu+2022



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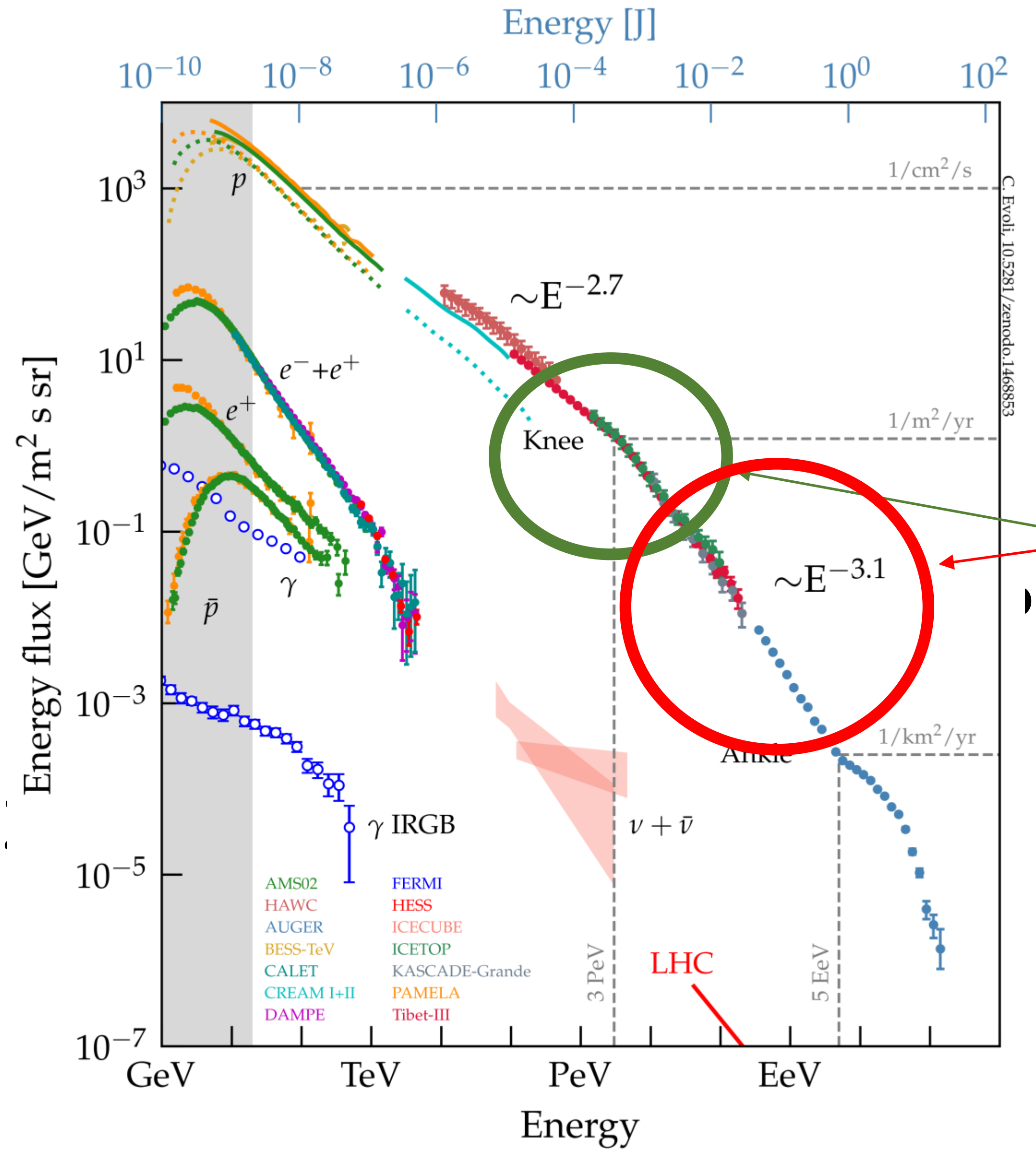

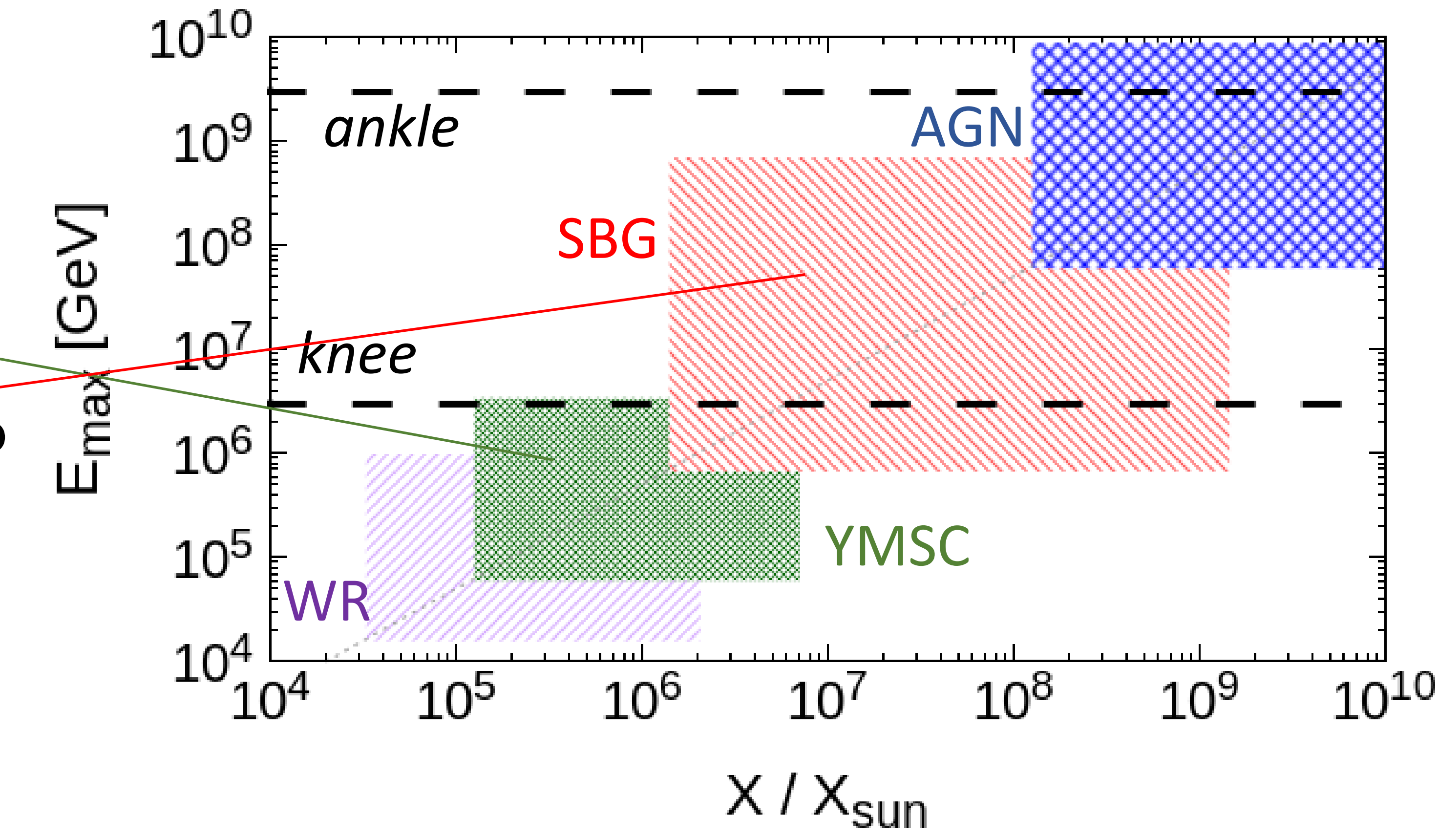

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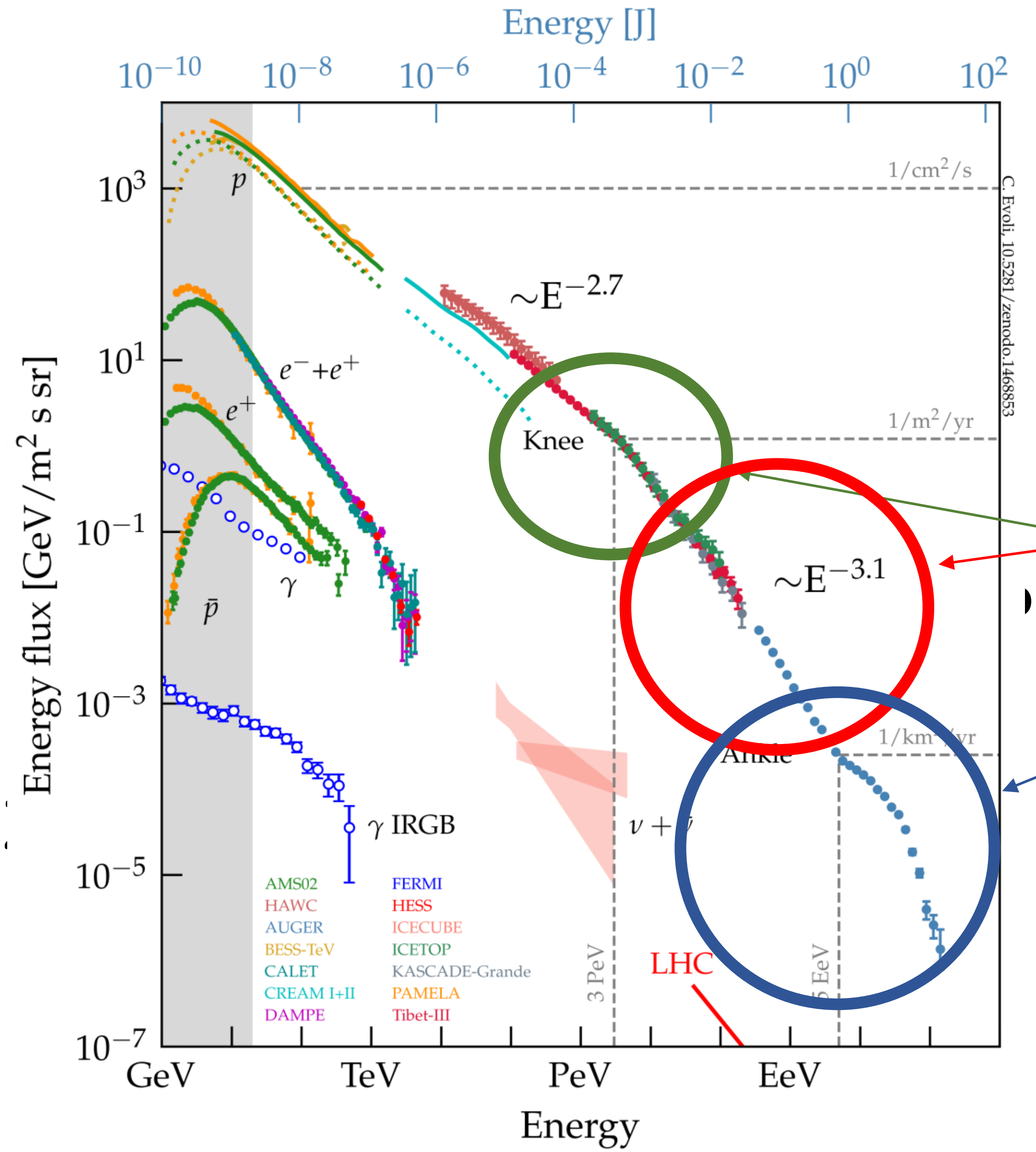

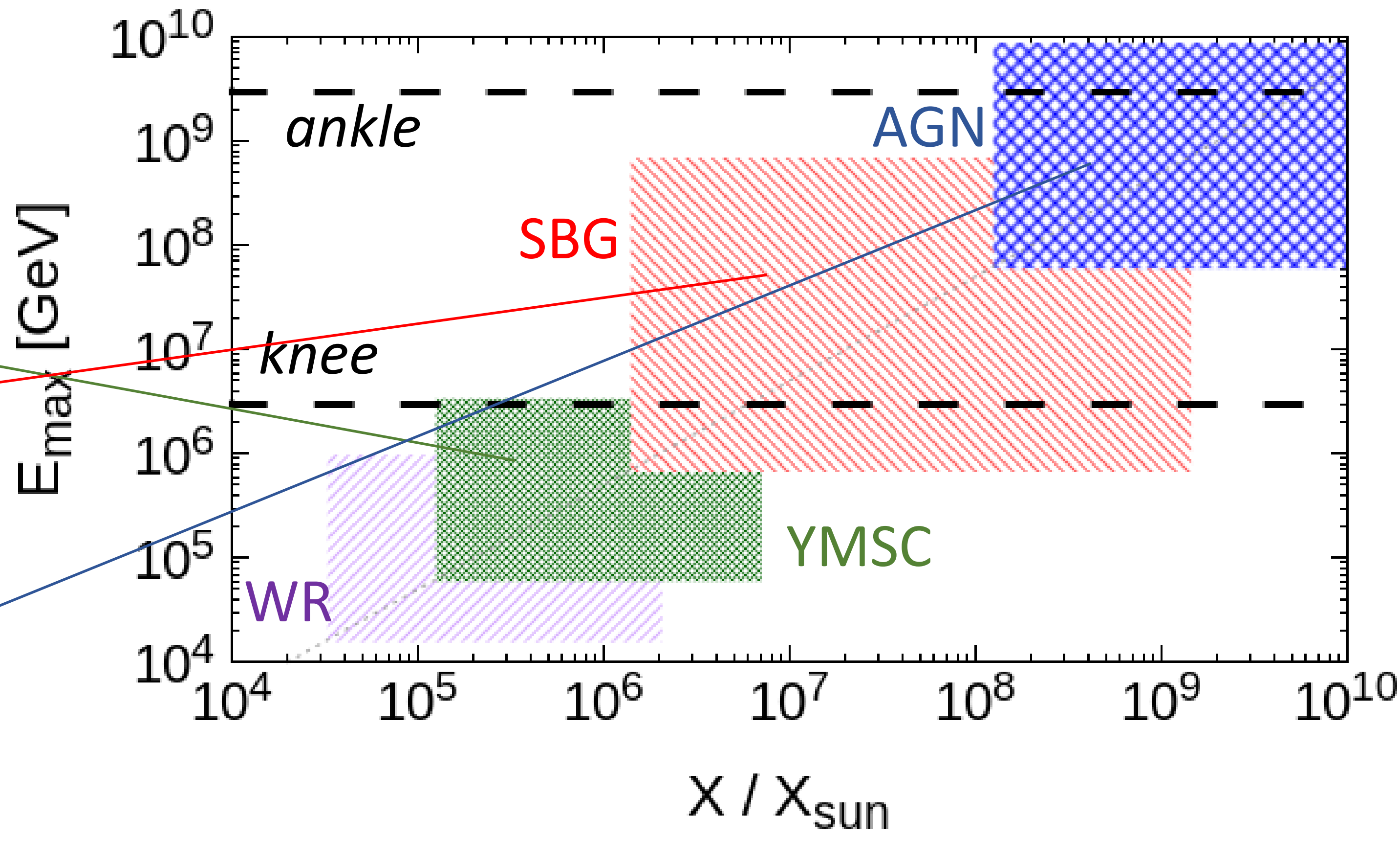

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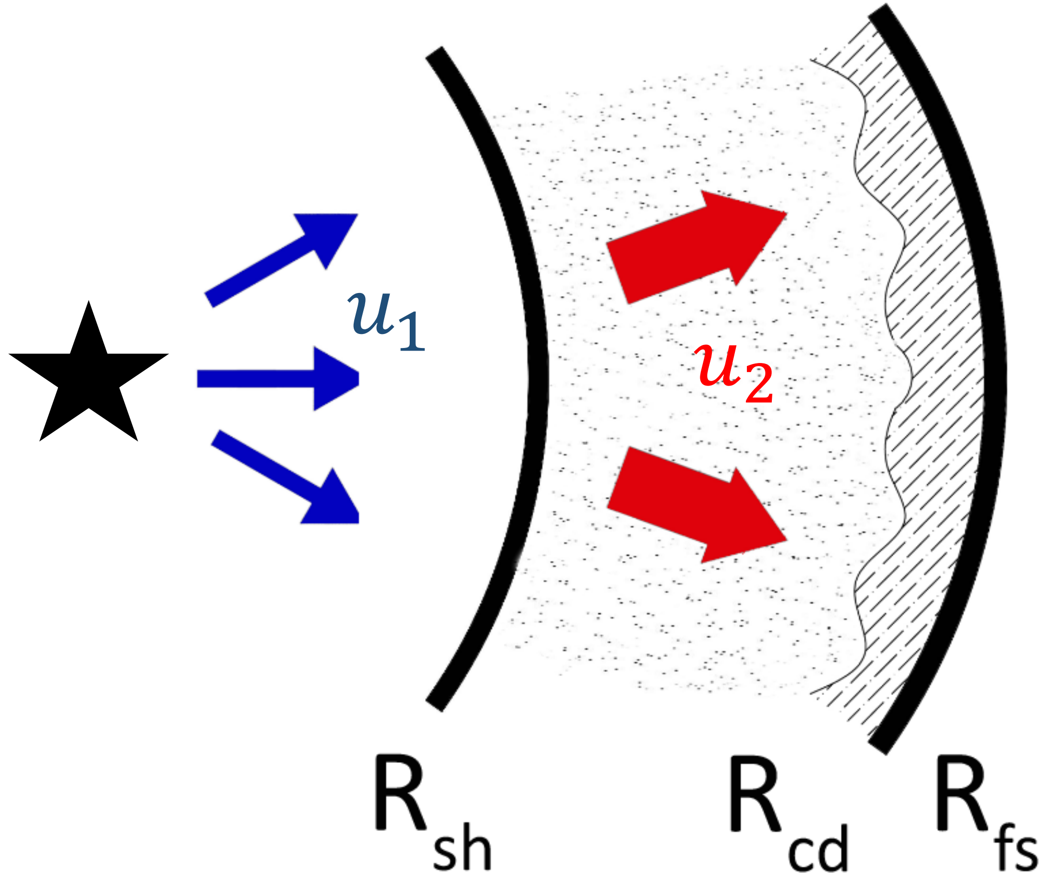
Building the model

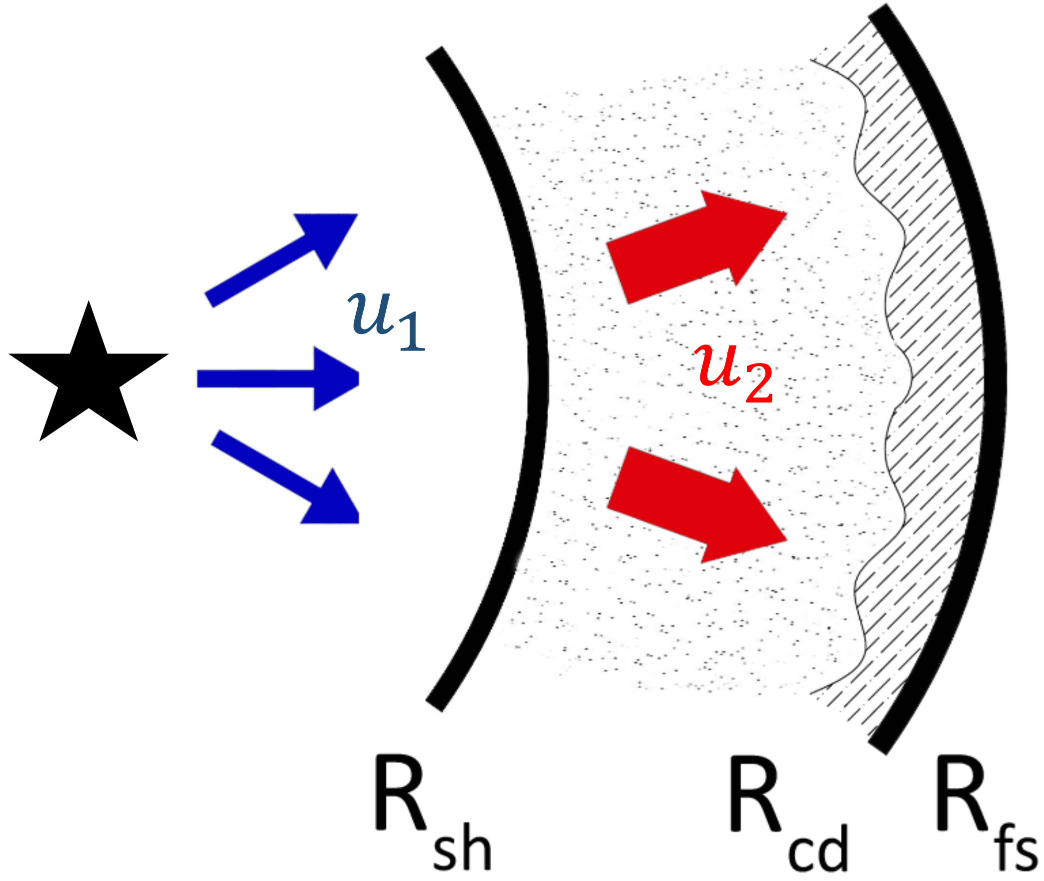
$$TIME\ VARIATION = ADVECTION + DIFFUSION + LOSSES + INJECTION$$



- Spherically symmetric

Building the model

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



- Spherically symmetric
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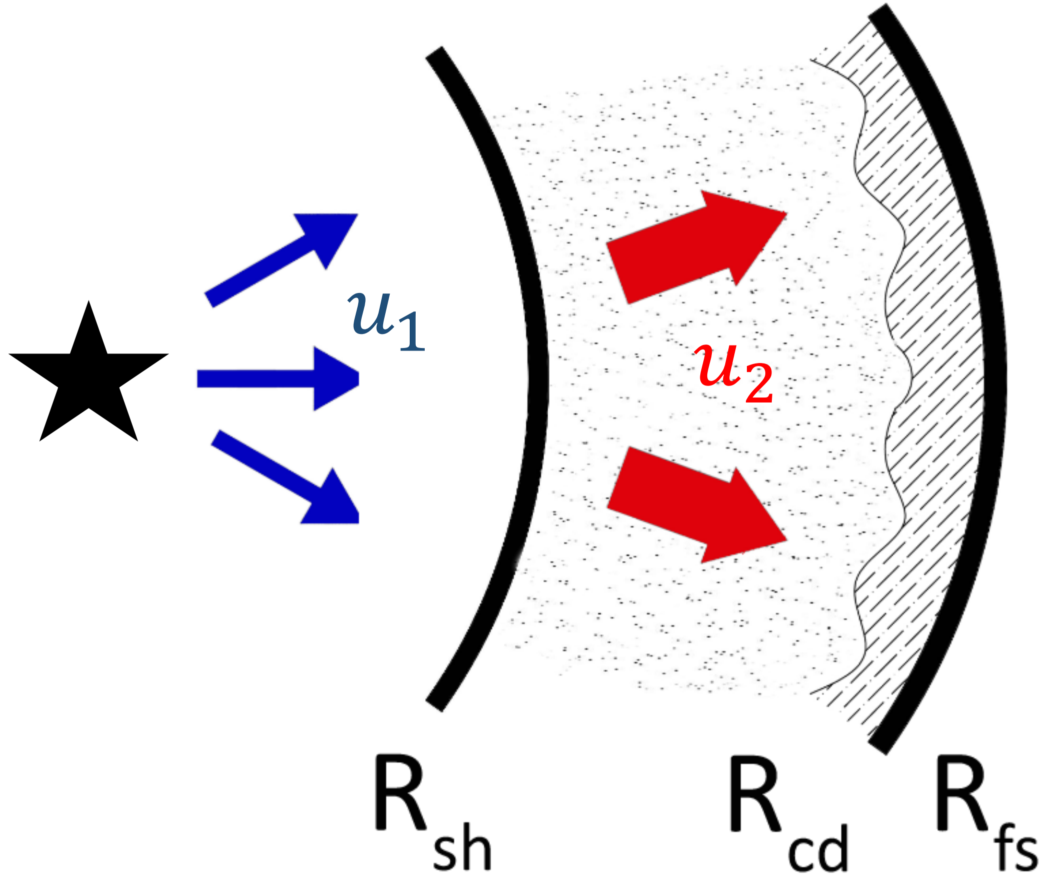
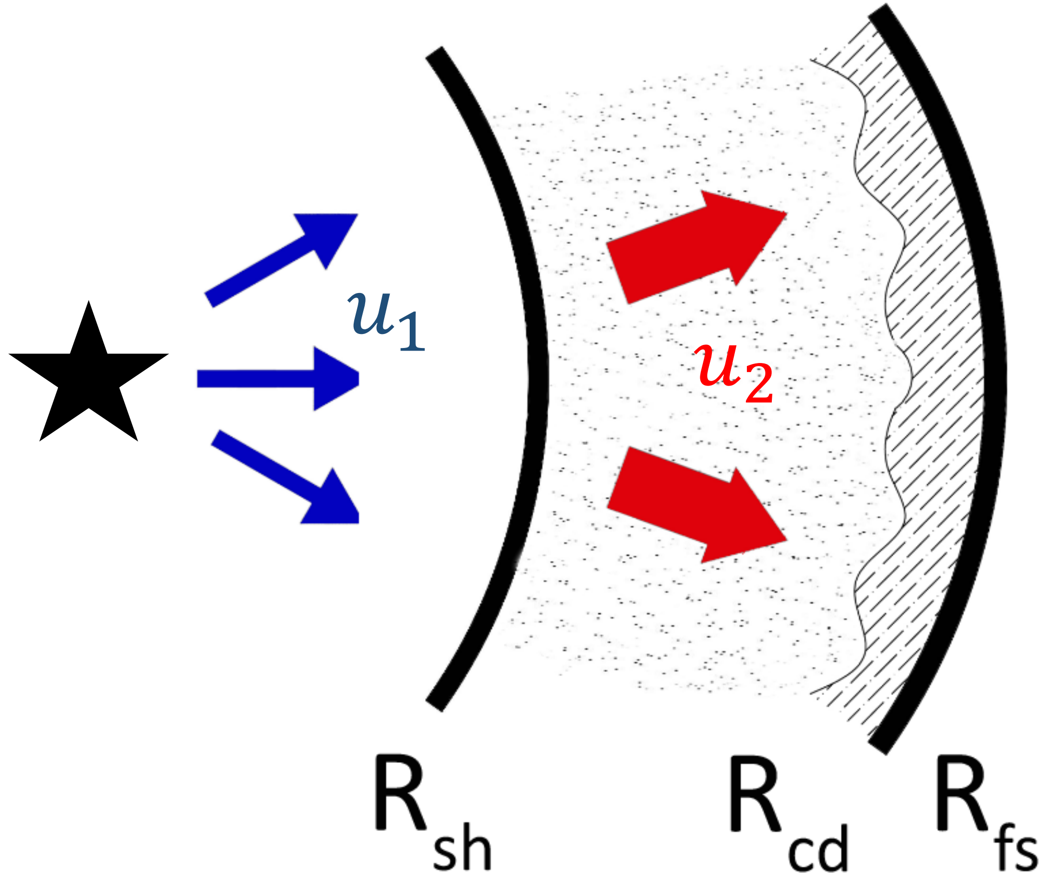


- Spherically symmetric
- Stationary
- $U_{B,1} = \epsilon_B P_{ram,1}$
- $D = \frac{1}{3} v r_L^{2-\delta} l_c^{\delta-1}$

Building the model

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

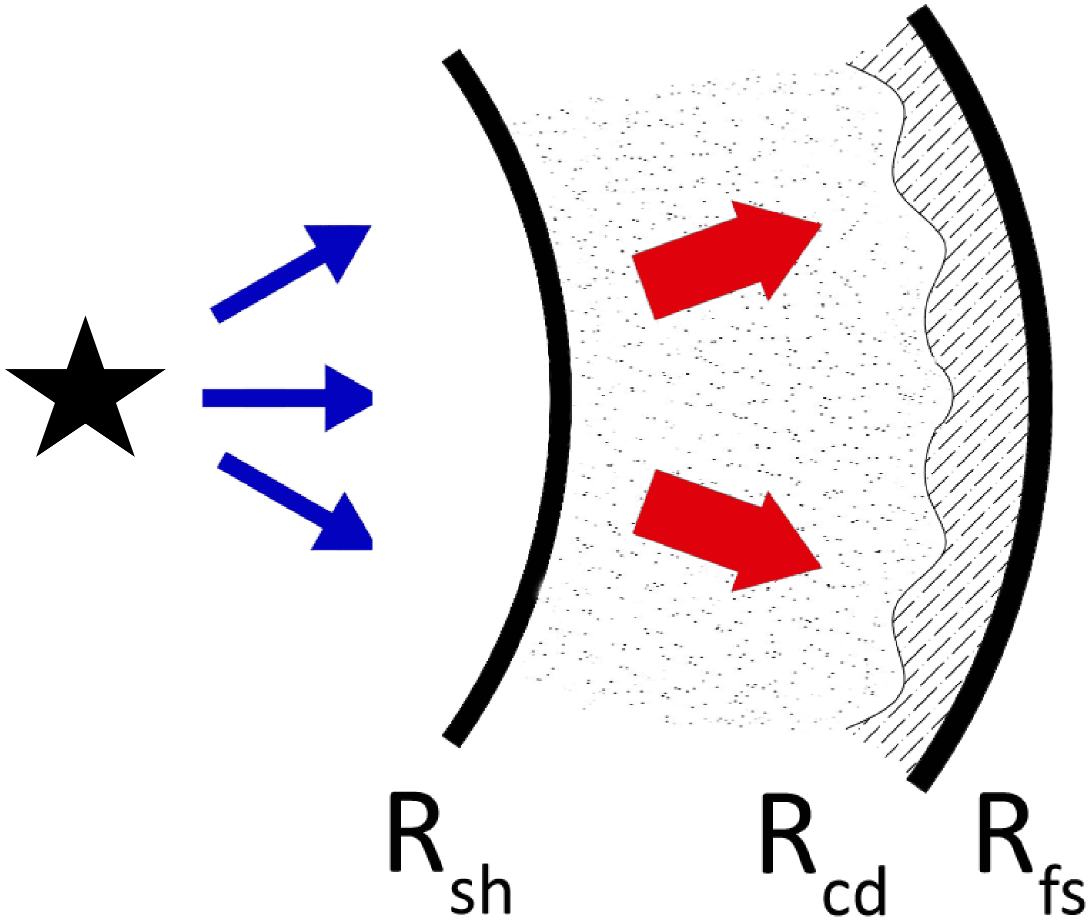


Boundary conditions:

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

Acceleration-transport model

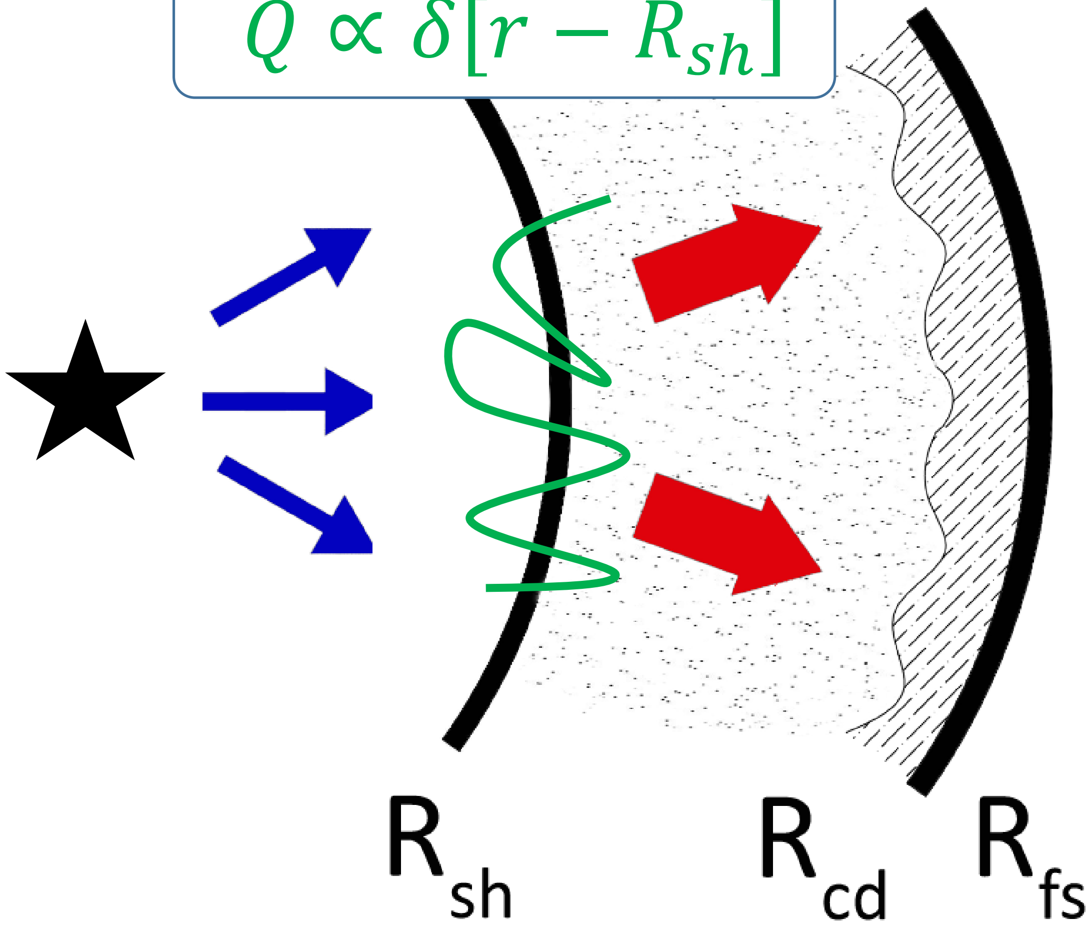
$$0 = -r^2 u(r)\partial_r f + \partial_r[r^2 D(r,p)\partial_r f] + \frac{p}{3}\partial_r[r^2 u(r)]\partial_p f - r^2 \Lambda(r,p) + r^2 Q(r,p)$$



Acceleration-transport model

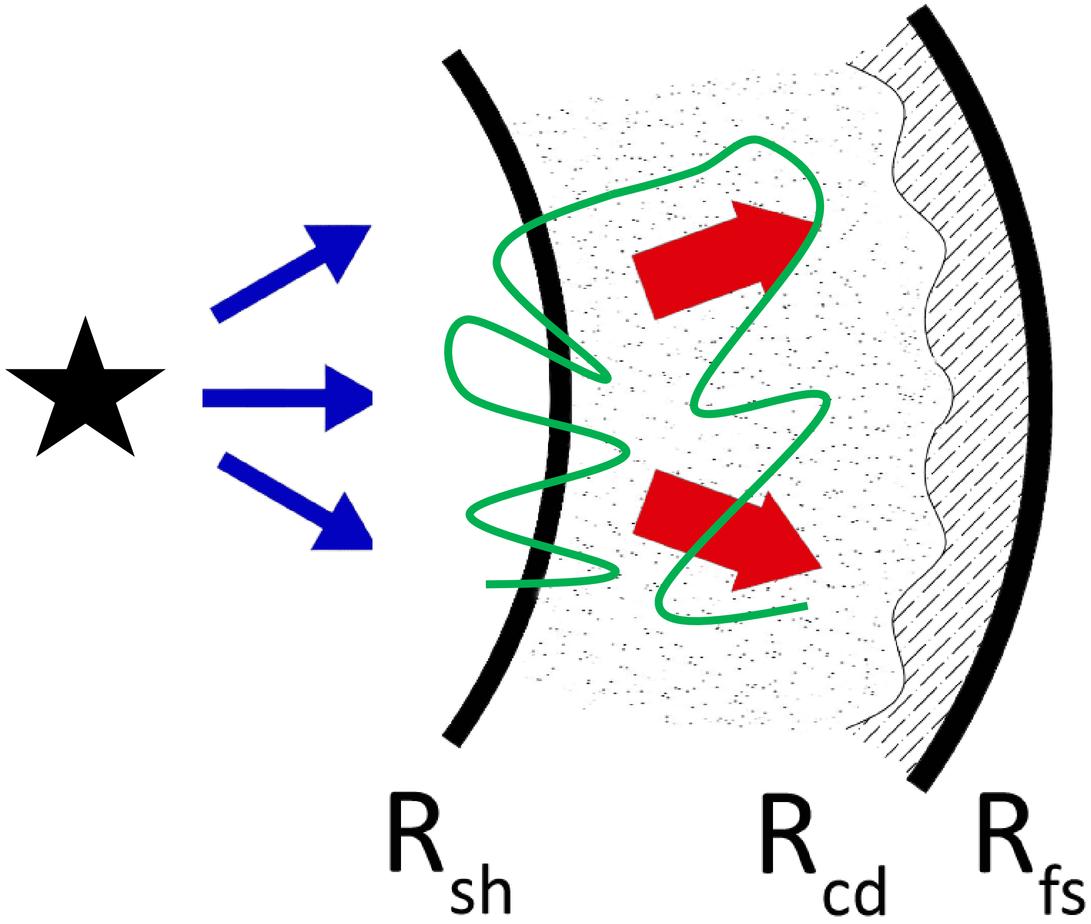
$$r^2 u(r)\partial_r f = \partial_r[r^2 D(r,p)\partial_r f] + \frac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p) - r^2\Lambda(r,p)$$

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



Acceleration-transport model

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



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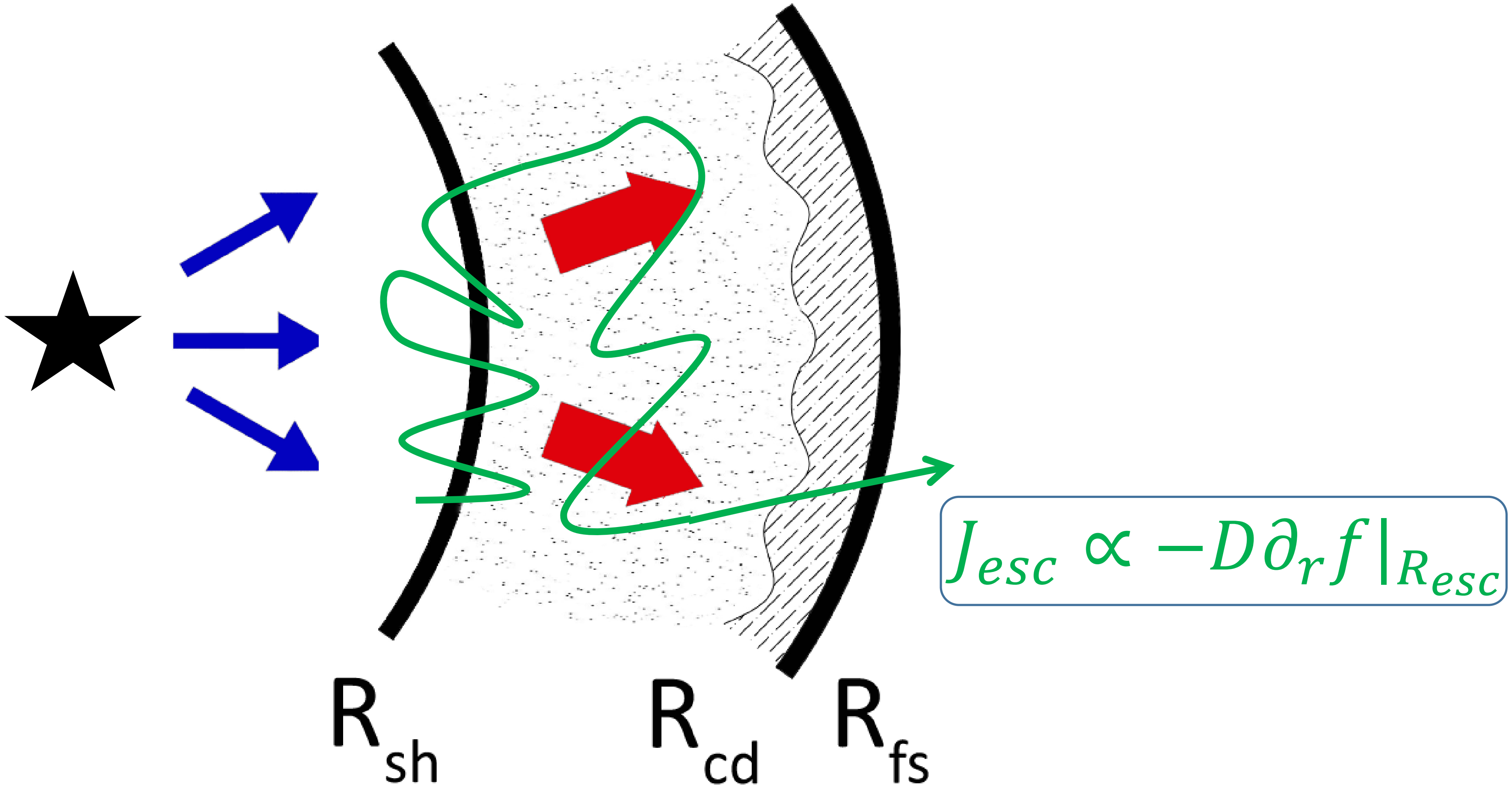
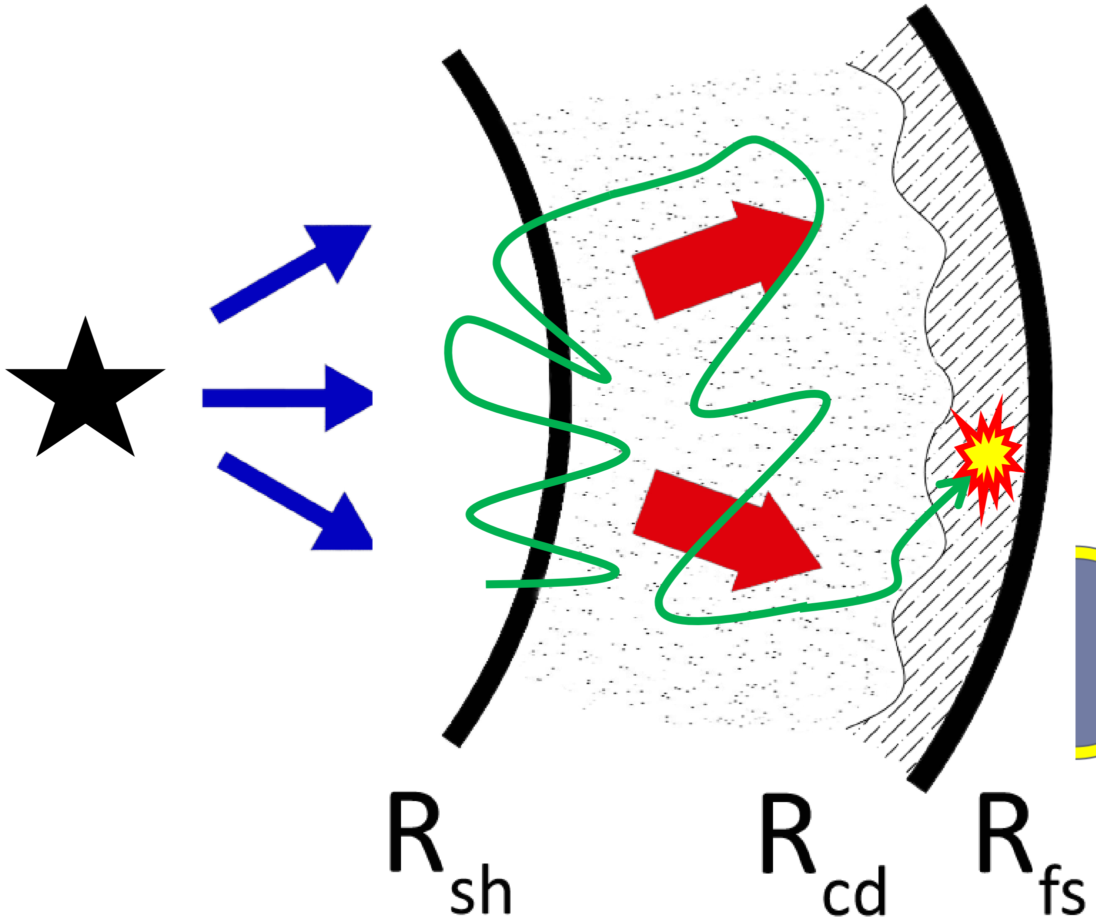
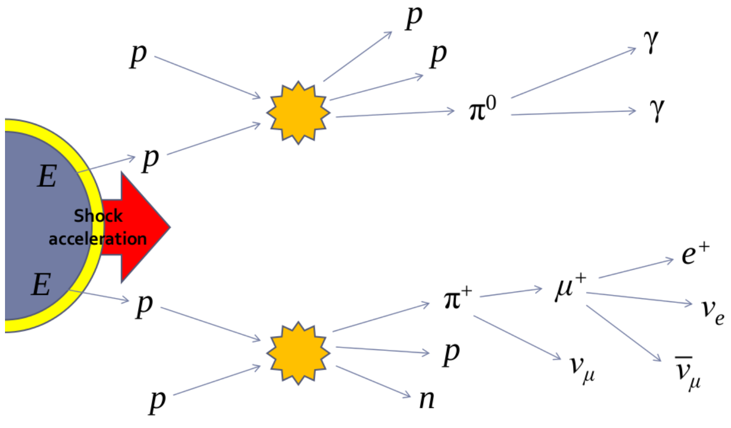


Acceleration-transport model

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

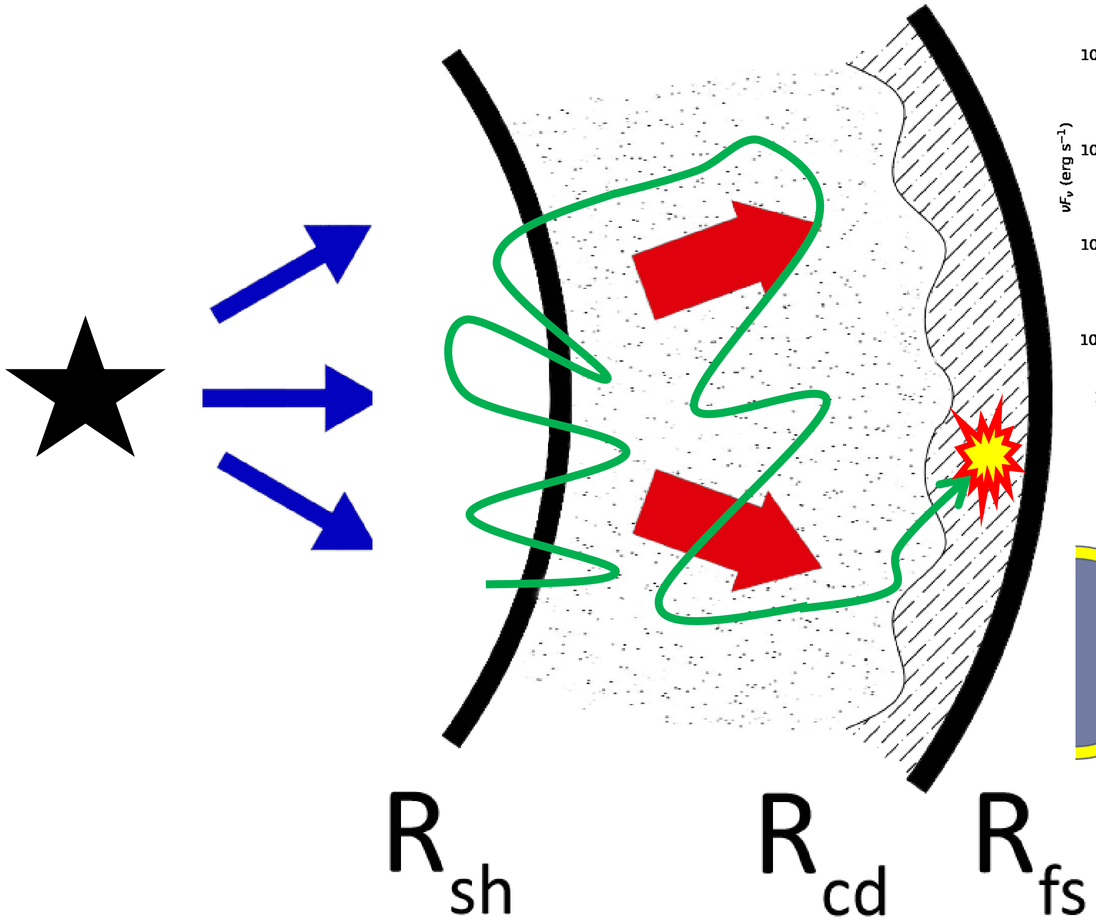


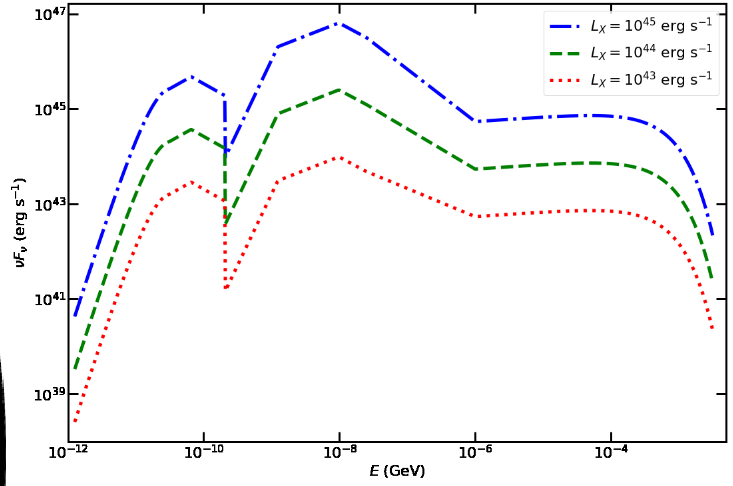


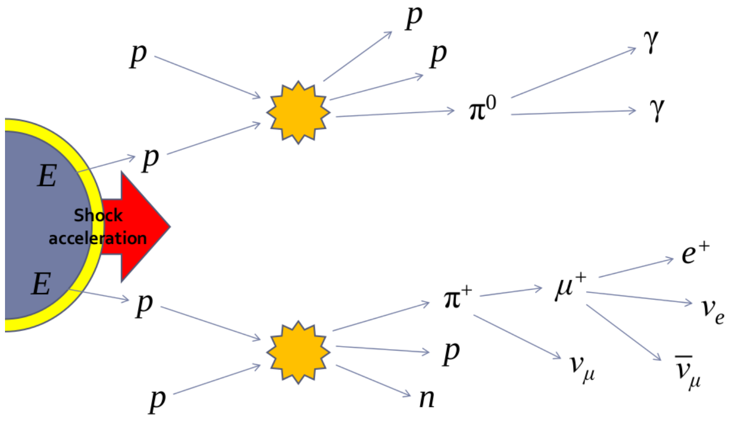
Website: http://www.astro.wisc.edu/~gvance/index.html

Acceleration-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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Outline

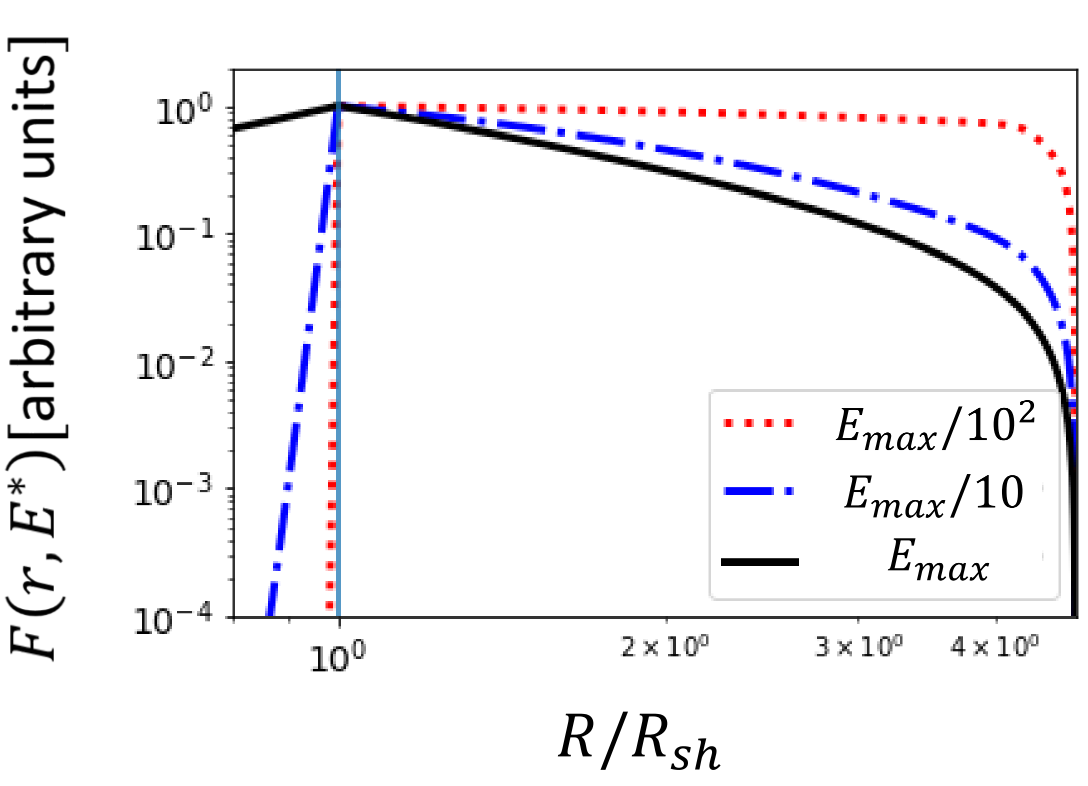
- Wind bubbles: structure and evolution
- Acceleration and transport in wind bubbles
- Solution: radial distribution and spectra
- Multimessenger implications: SBGs & AGNi

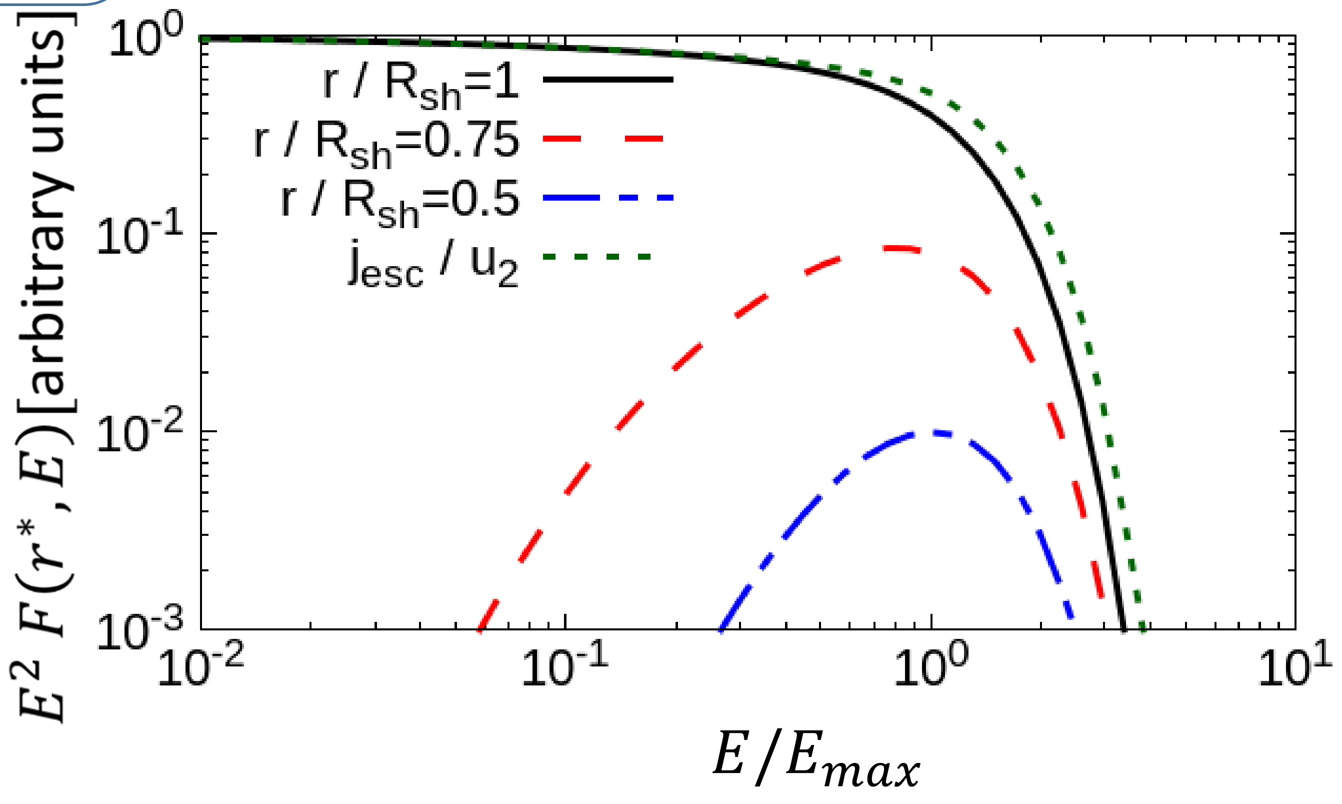
Solution: radial behavior and spectra

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

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

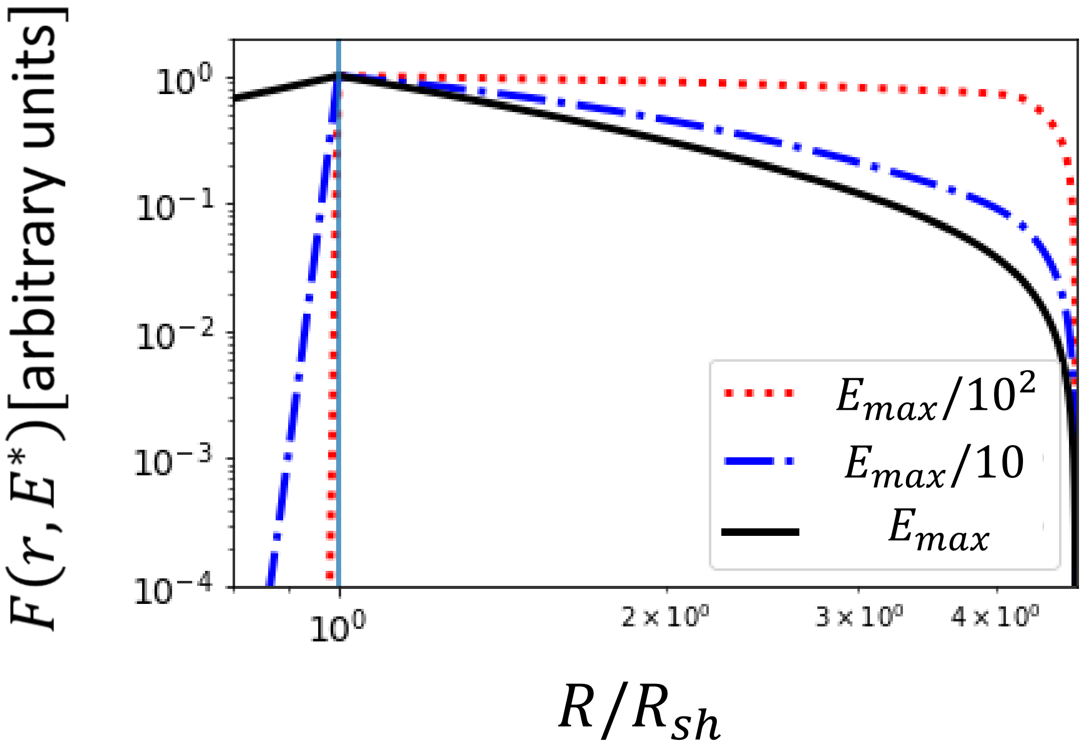
$$f_{sh}(p) \propto p^{-s} e^{-\Gamma_1(p)} e^{-\Gamma_2(p)}$$

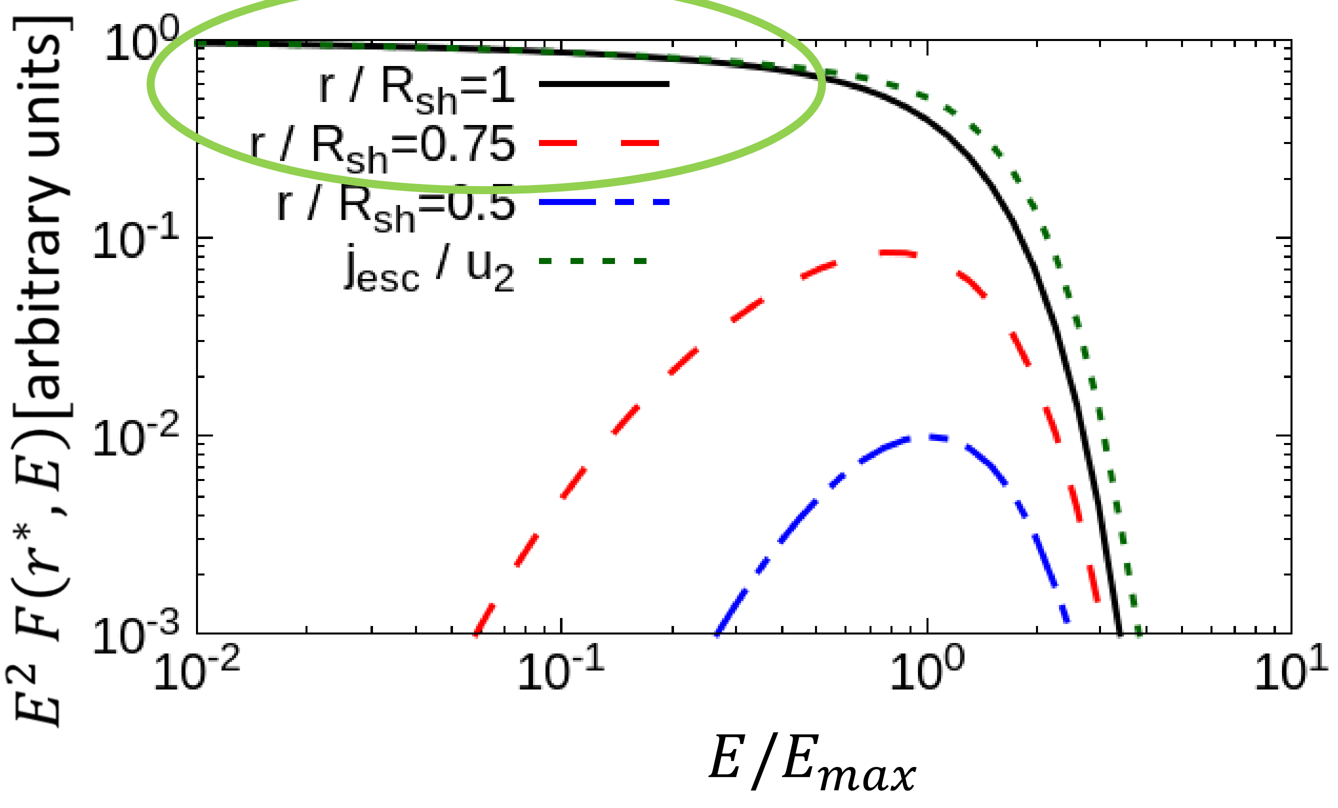




Solution: radial behavior and spectra

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

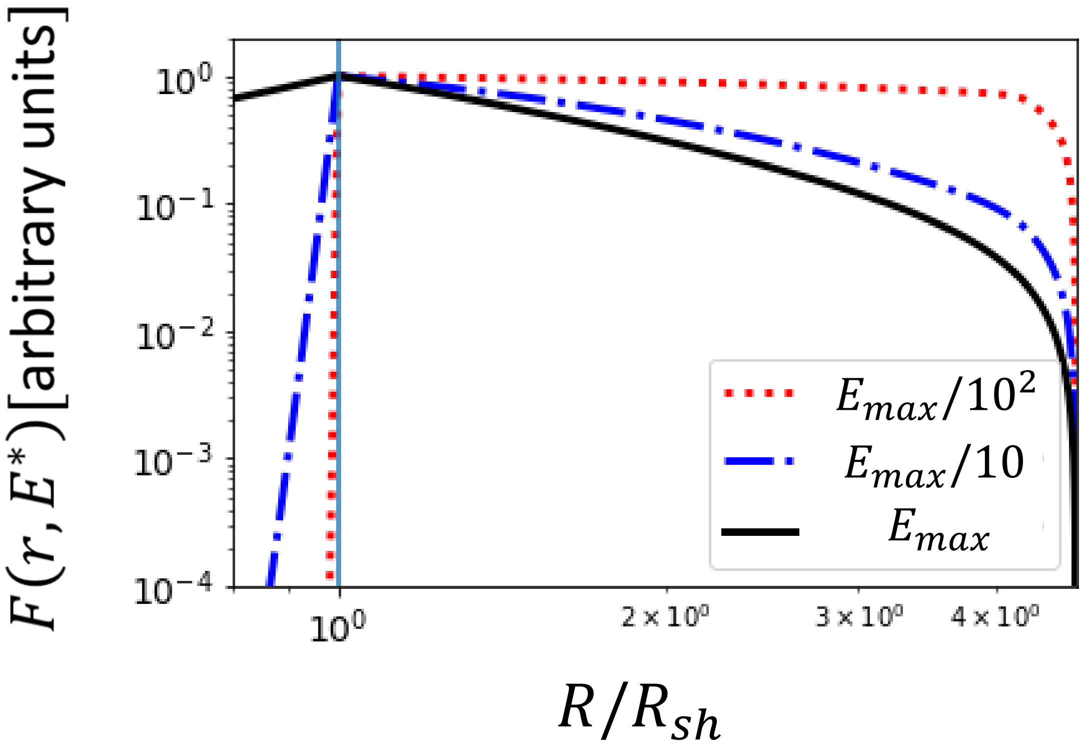


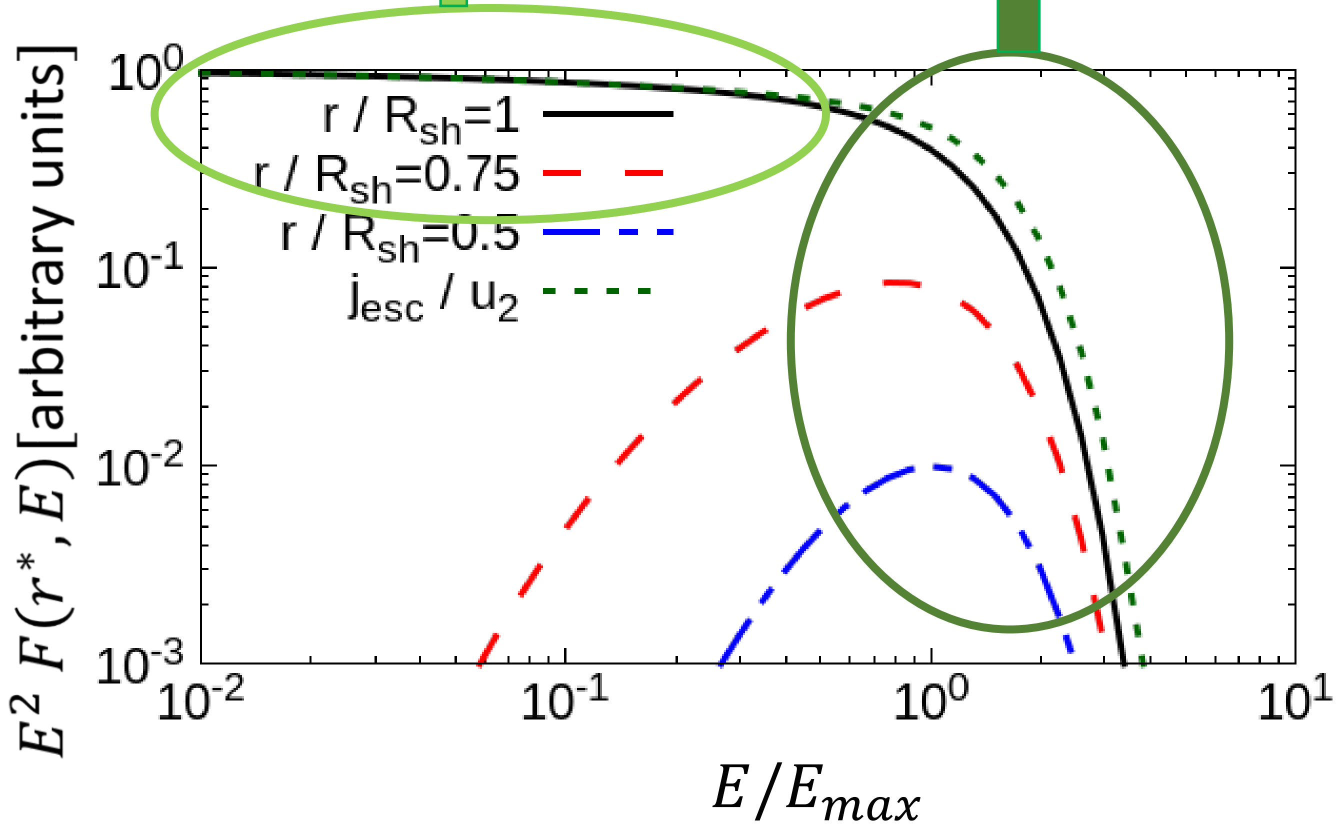


Solution: radial behavior and spectra

$F \sim e^{-\Gamma(E_{max})}$

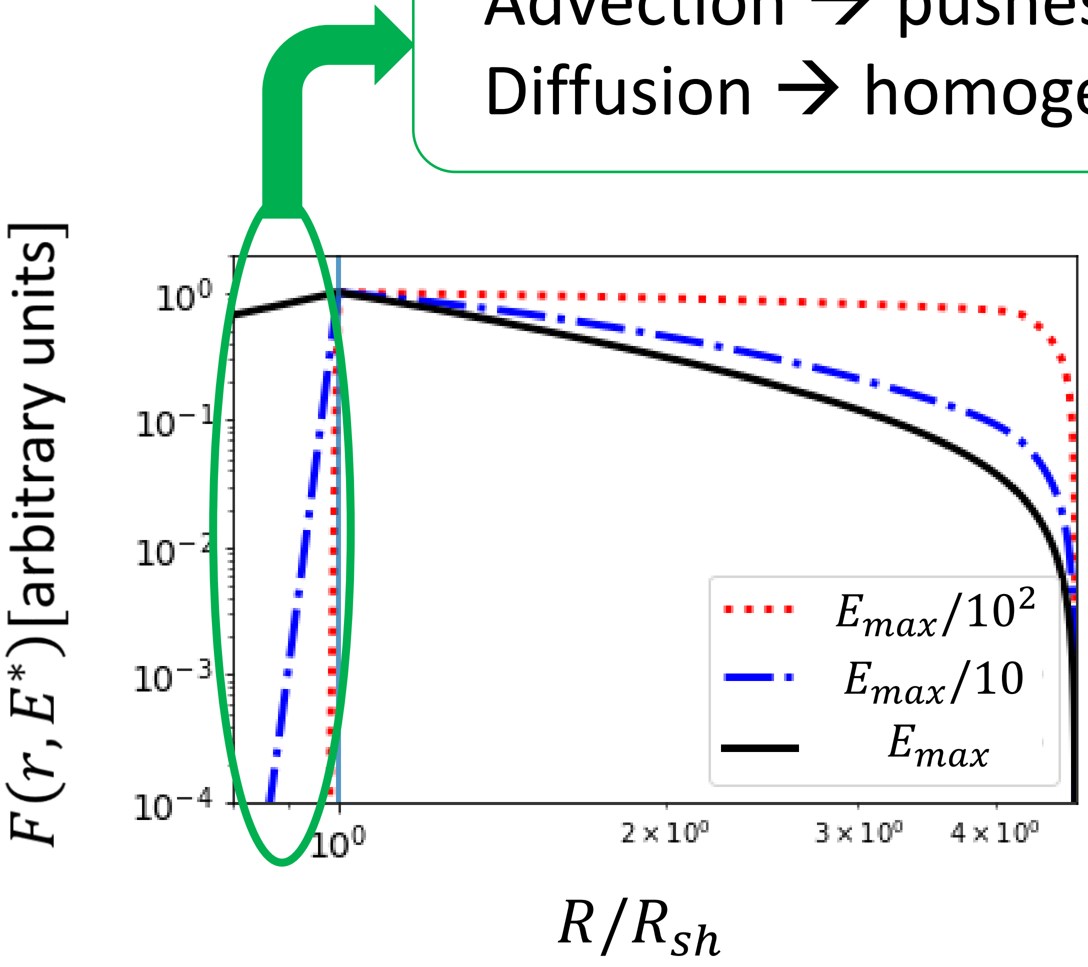
$F \sim E^{-2} \Leftrightarrow$ DSA

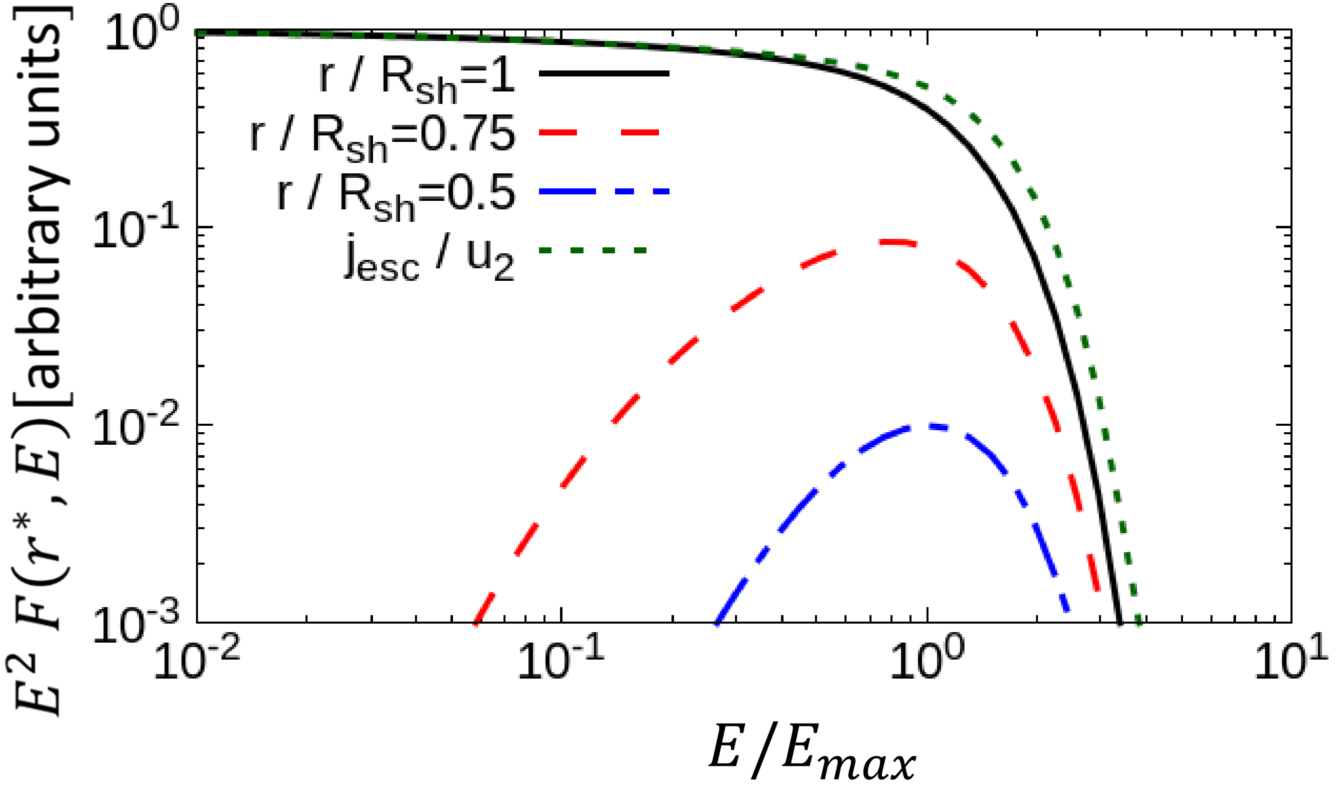




Solution: radial behavior and spectra

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





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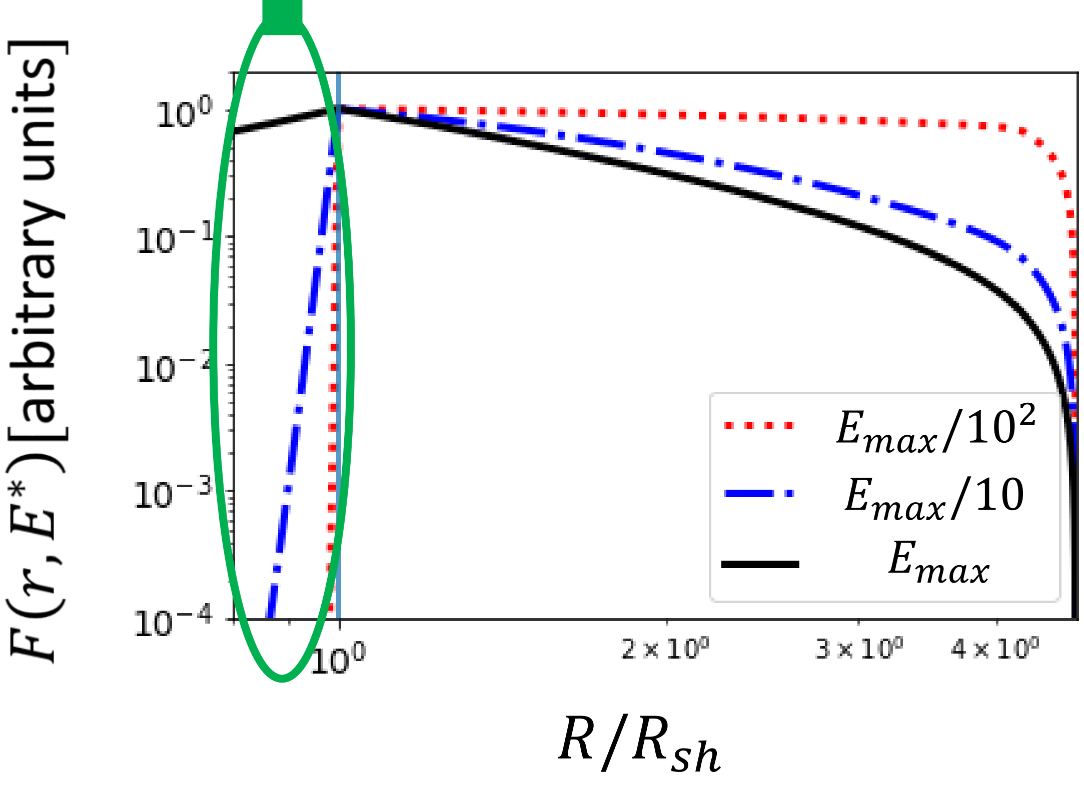
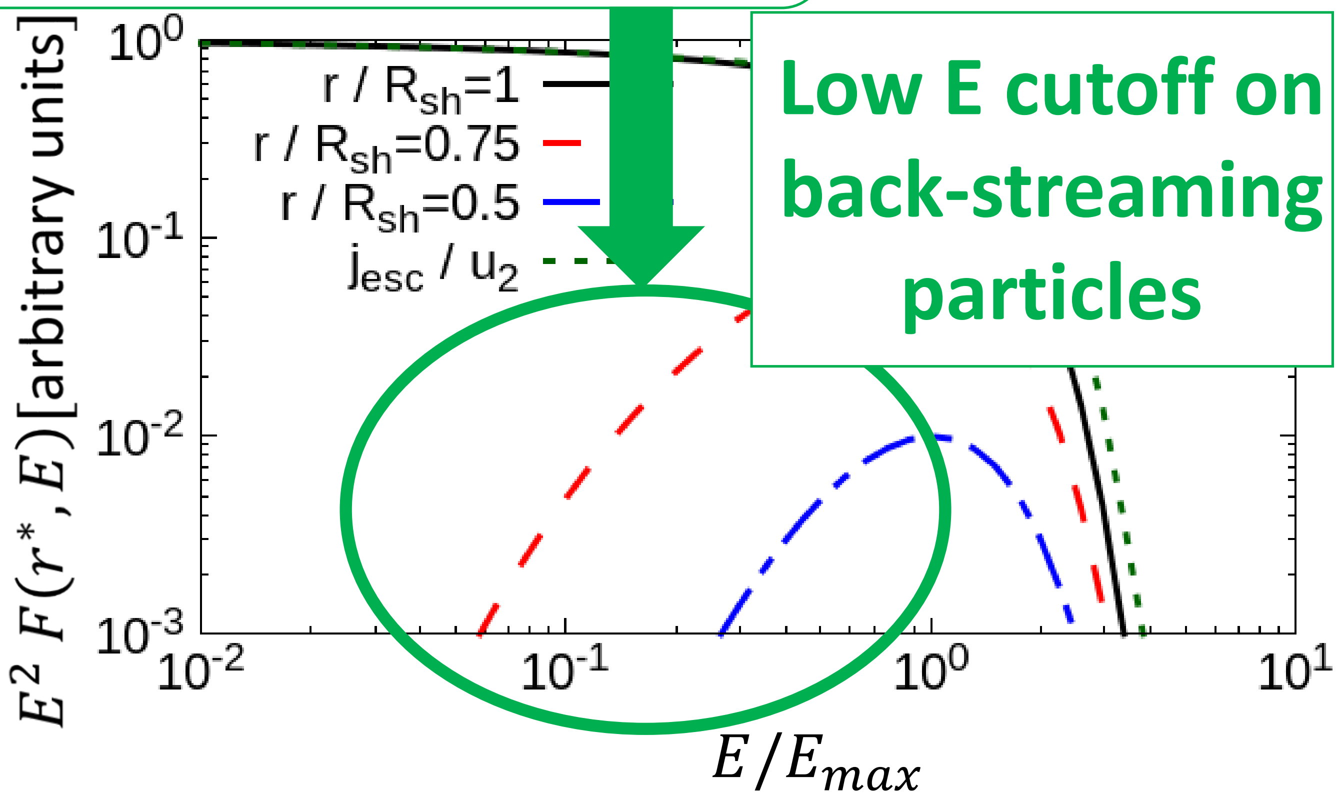
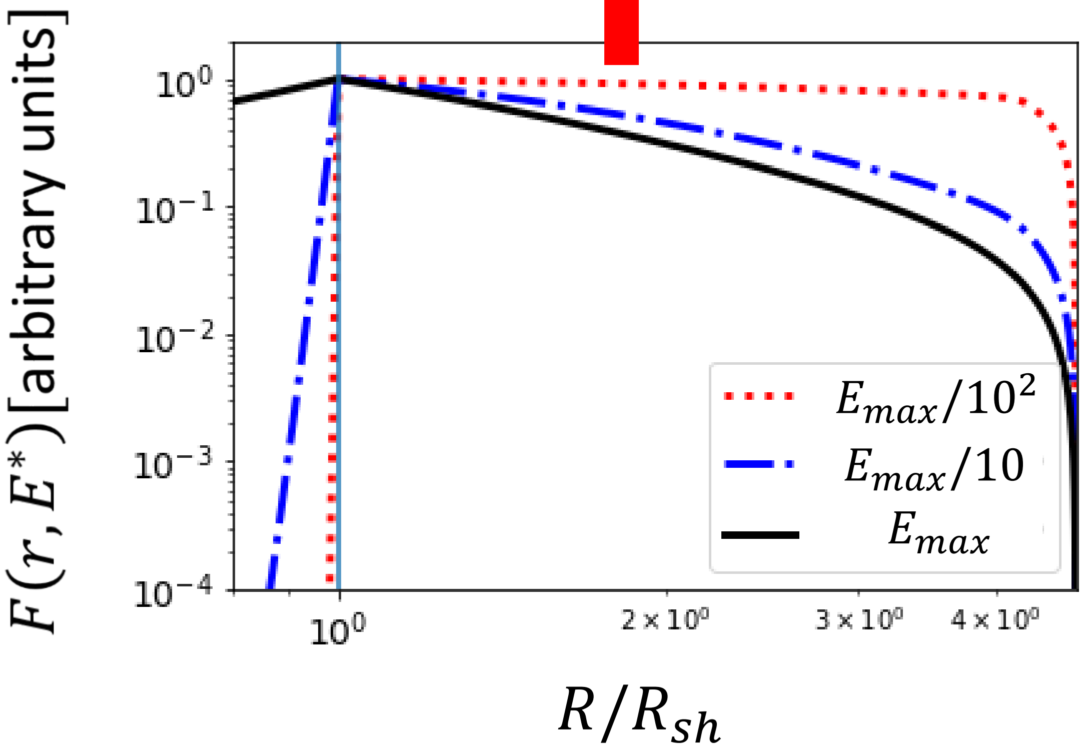
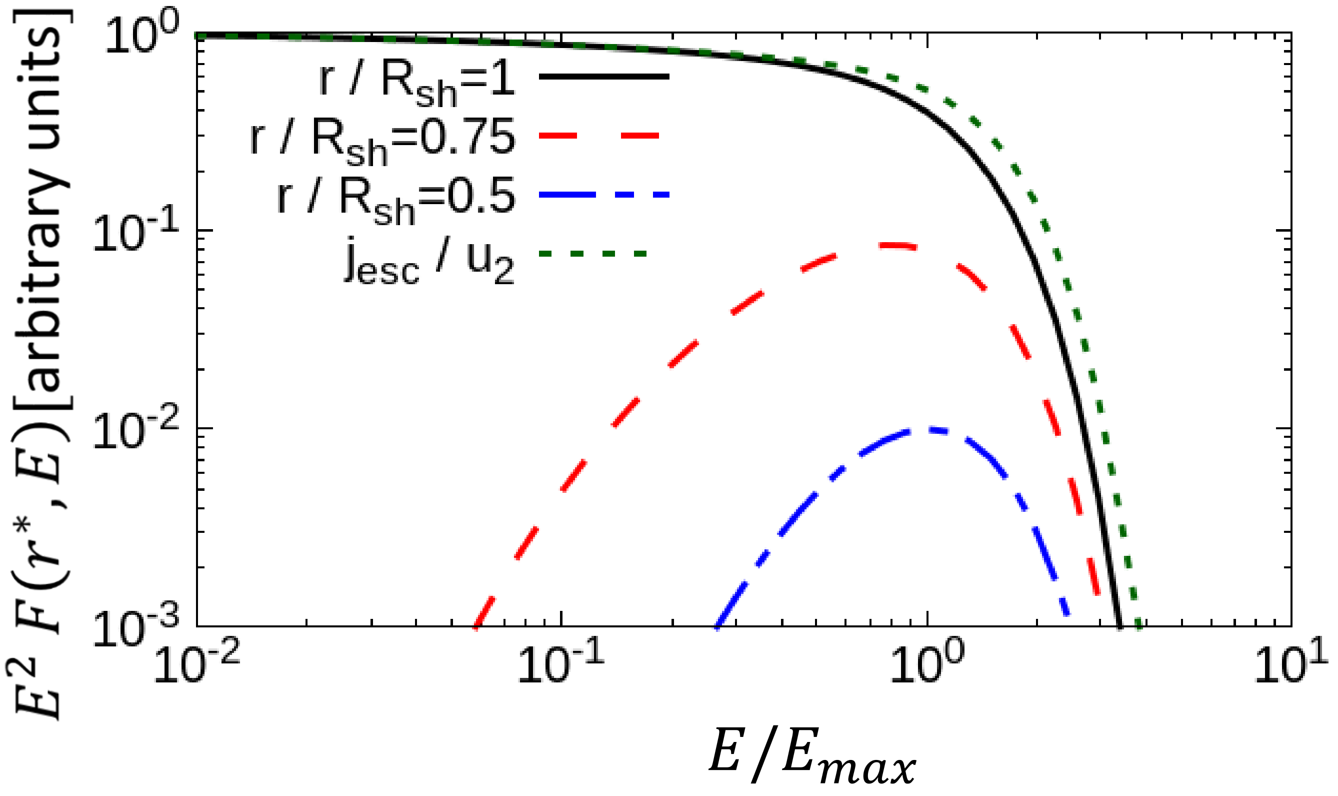




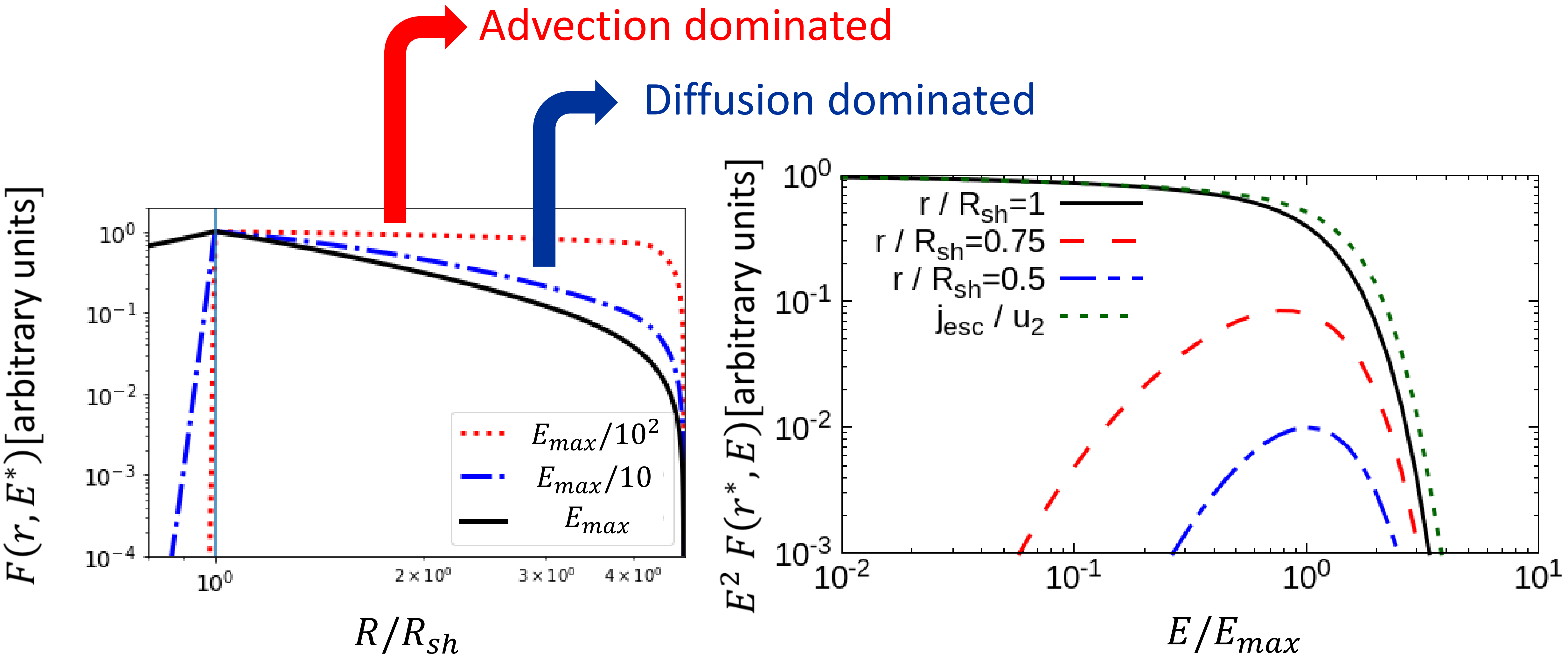
Solution: radial behavior and spectra

Advection dominated





Solution: radial behavior and spectra

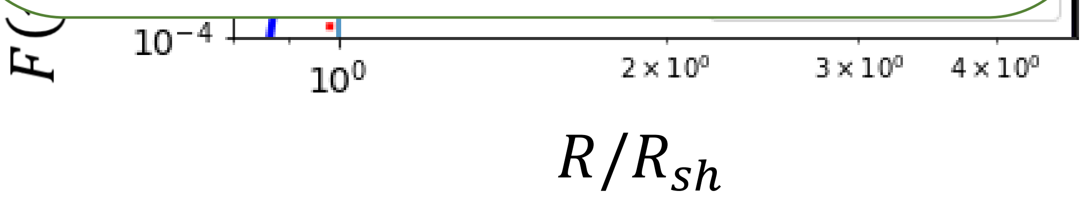


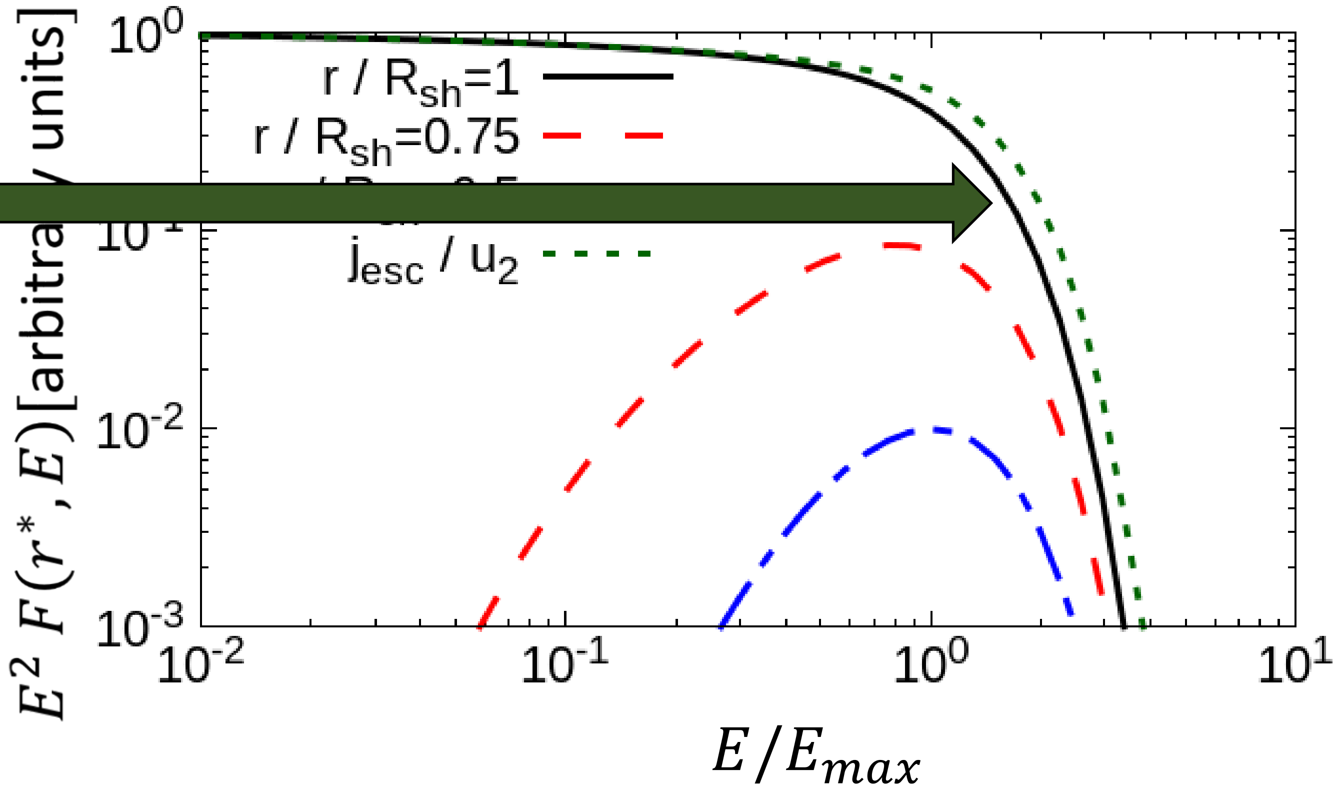
Solution: radial behavior and spectra

Advection dominated

Diffusion dominated

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





Outline

- Wind bubbles: structure and evolution
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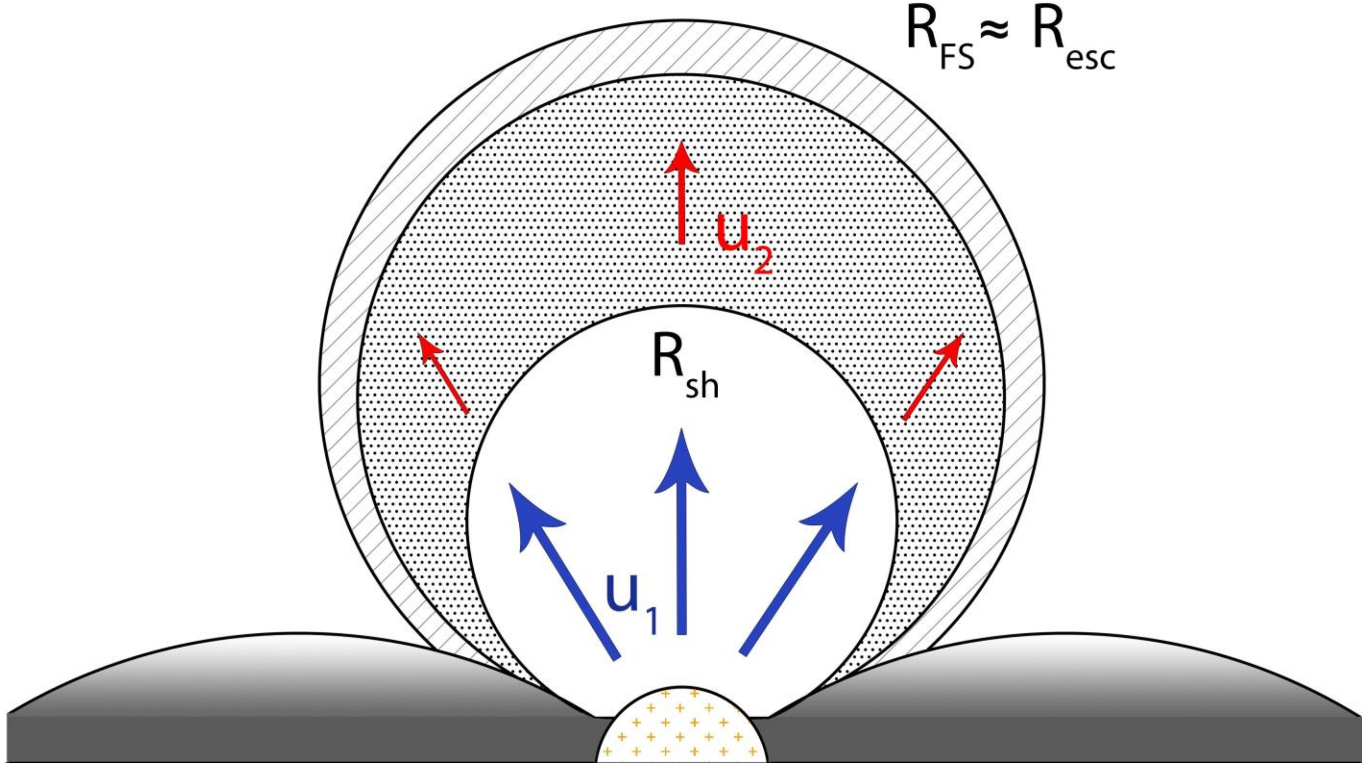
- Multimessenger implications: SBGs & AGNi

Starburst-driven wind bubbles

Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

Starburst-driven wind bubbles

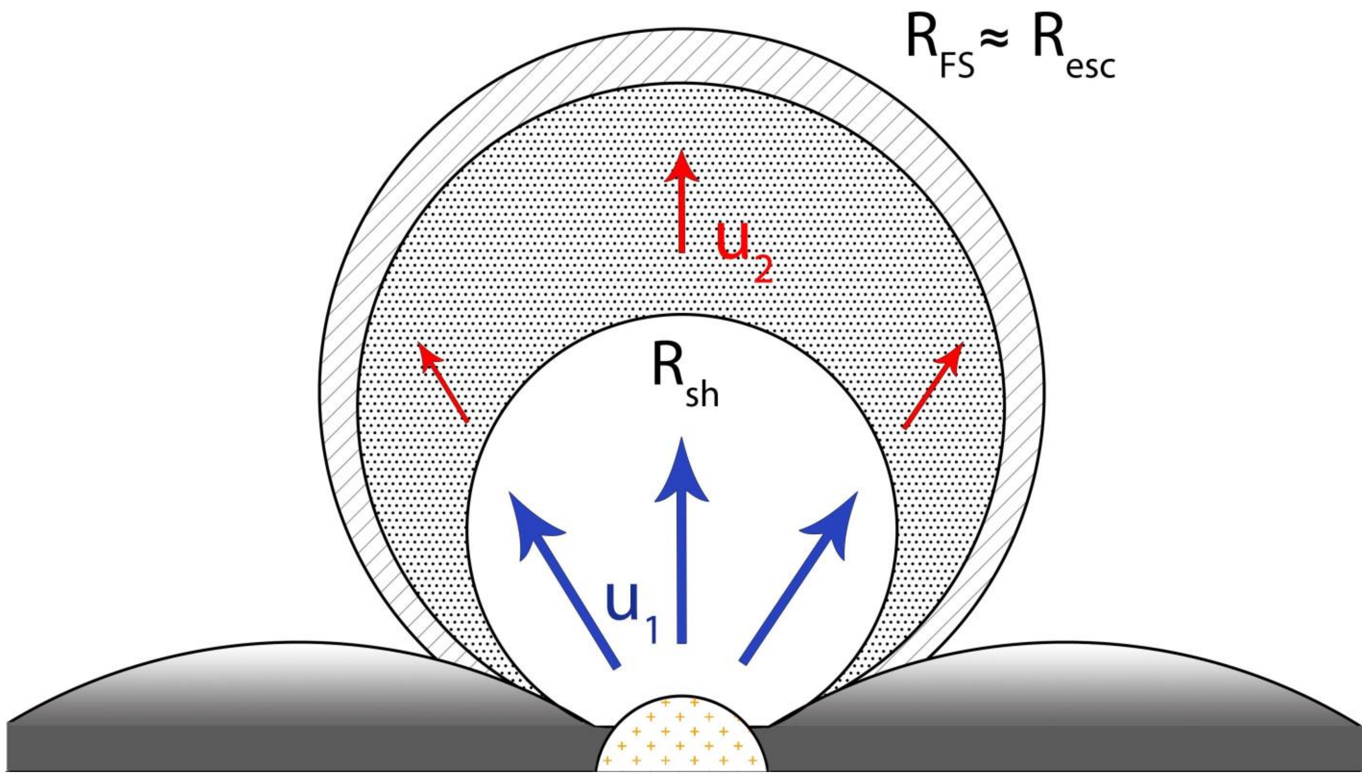
- $V_\infty \approx 10^3\ km/s$
- $\dot{M} \approx 10^{-2} - 10^2\ M_\odot/yr$
- $\dot{E} \approx 10^{39} - 10^{44}$ erg/s



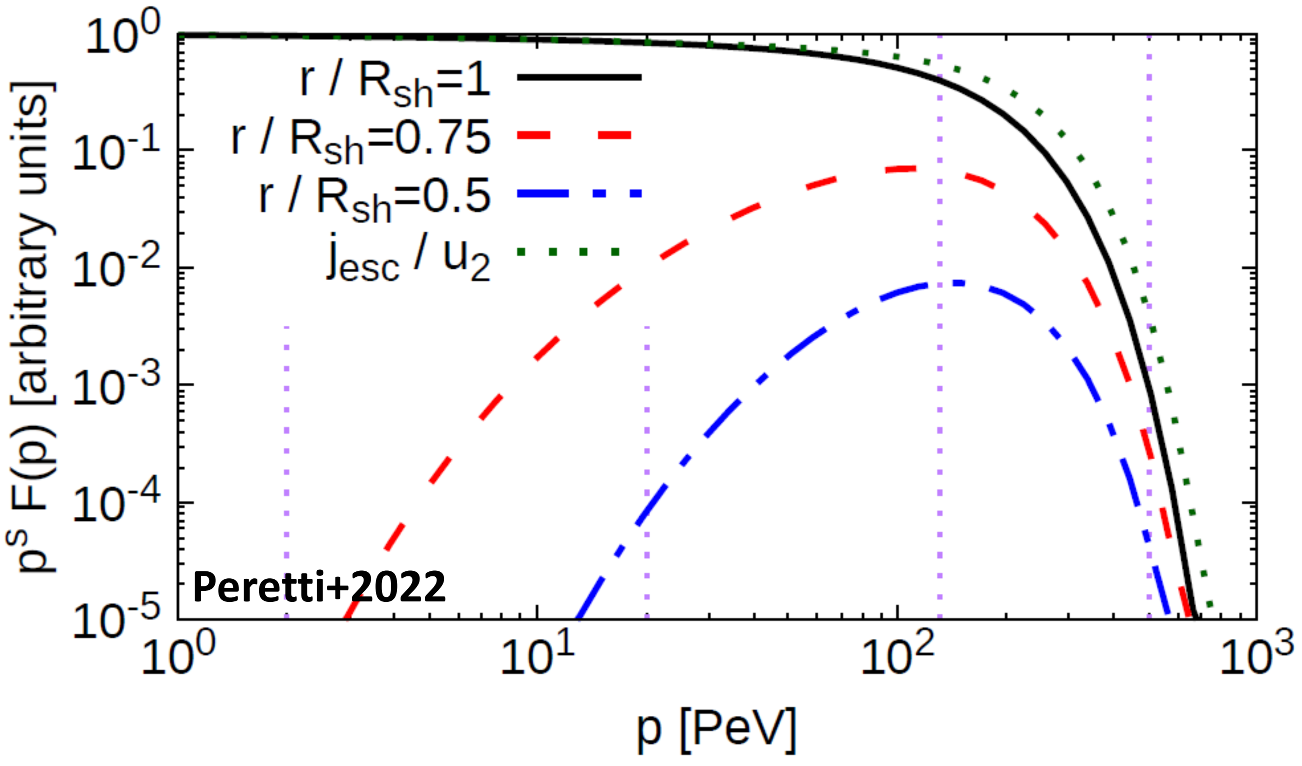
Starburst-driven wind bubbles

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

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



SBGs – Maximum Energy



Parameters

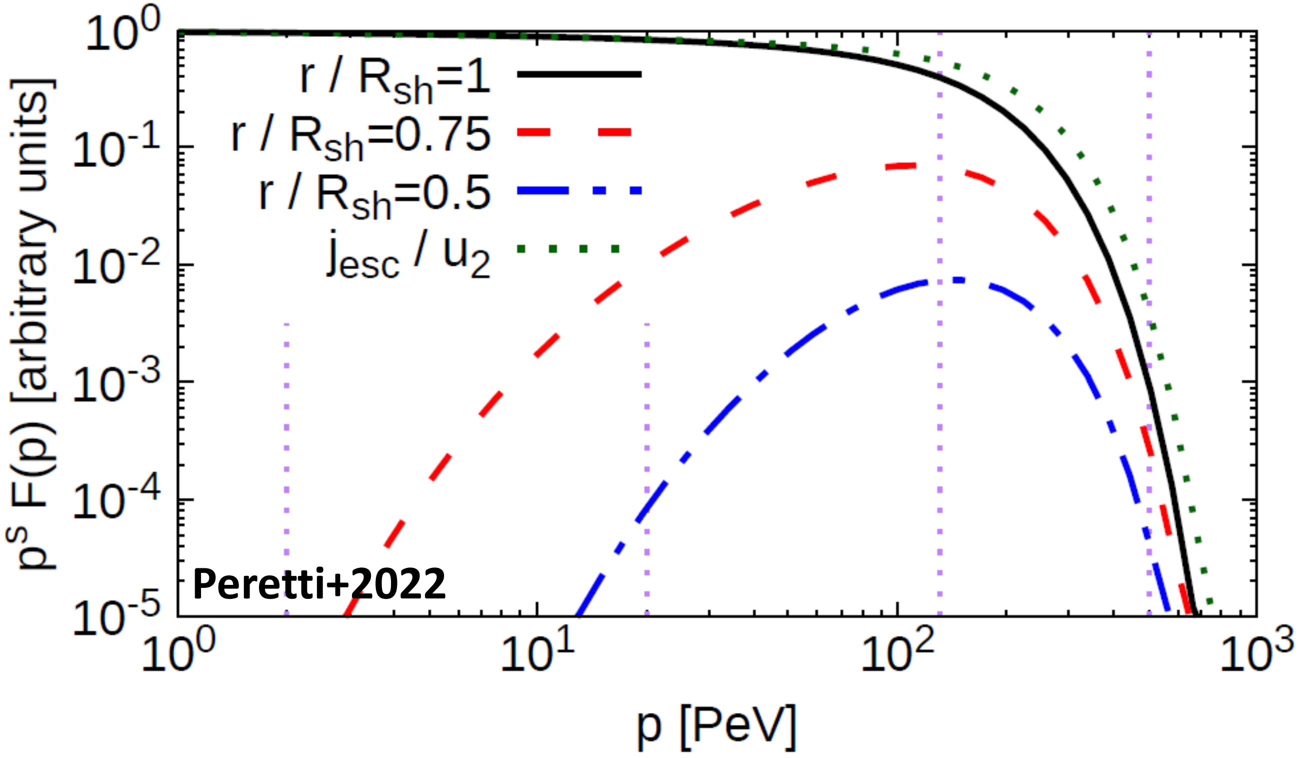
$$\dot{M} = 10\ M_{\odot}\ yr^{-1}$$

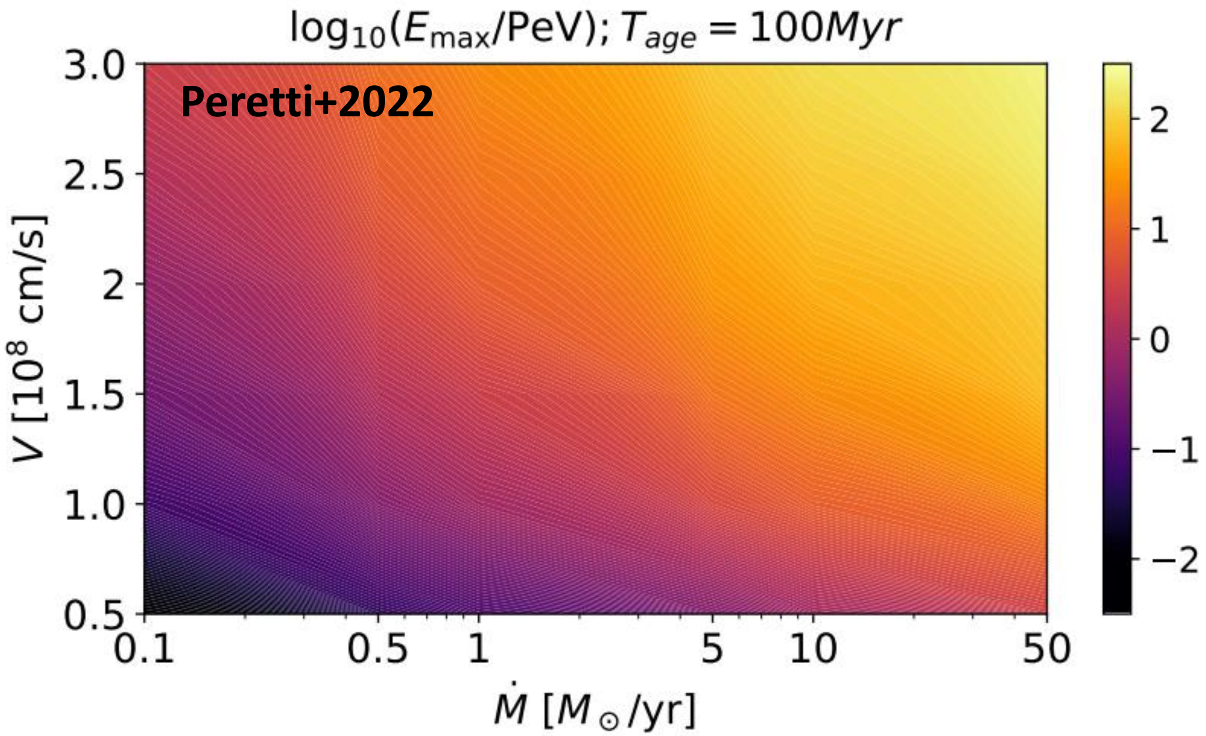
$$V_{\infty} = 3000\ km\ \ s^{-1}$$

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

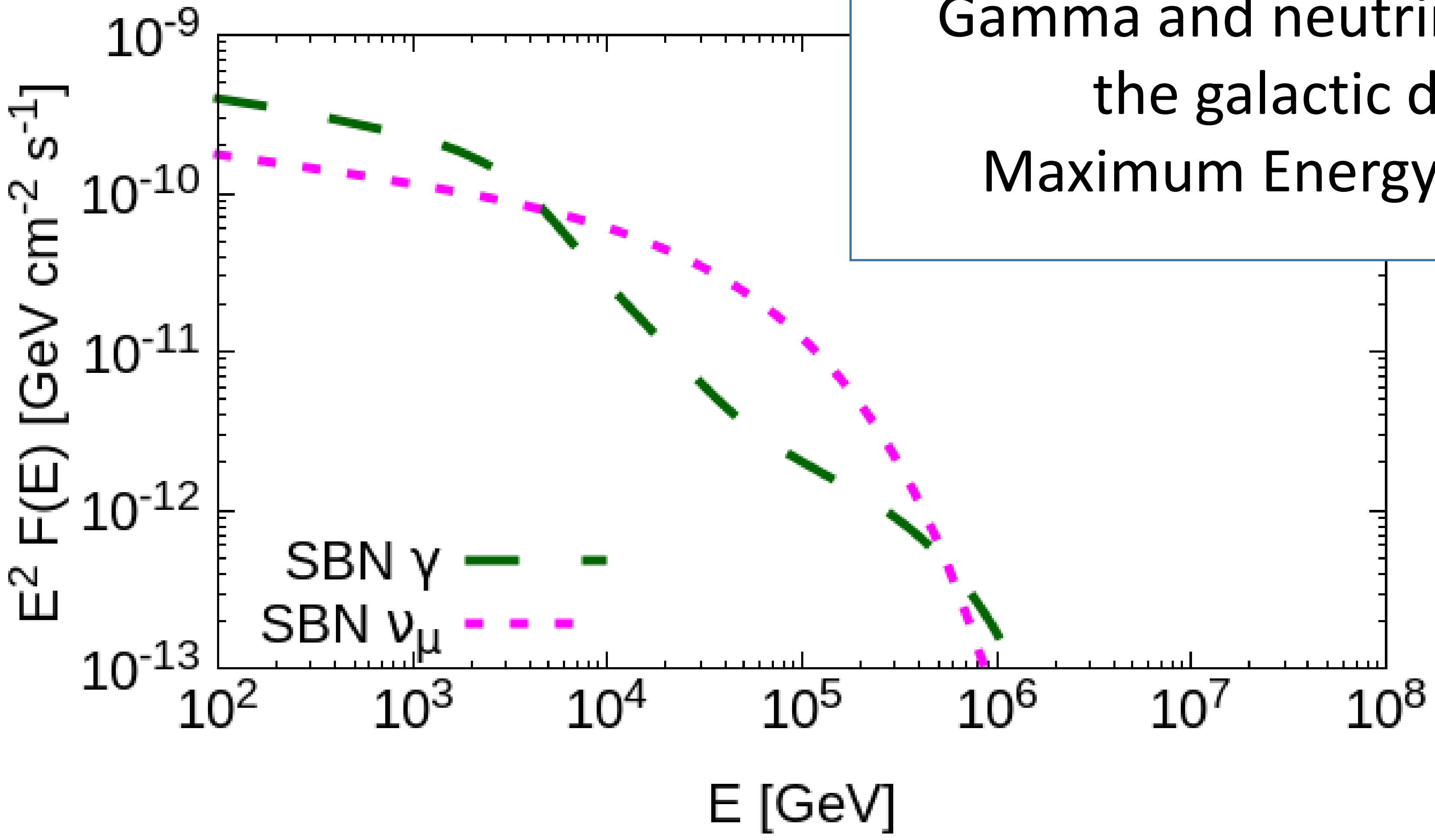
$$R_{FS} = 55\ kpc$$

SBGs – Maximum Energy





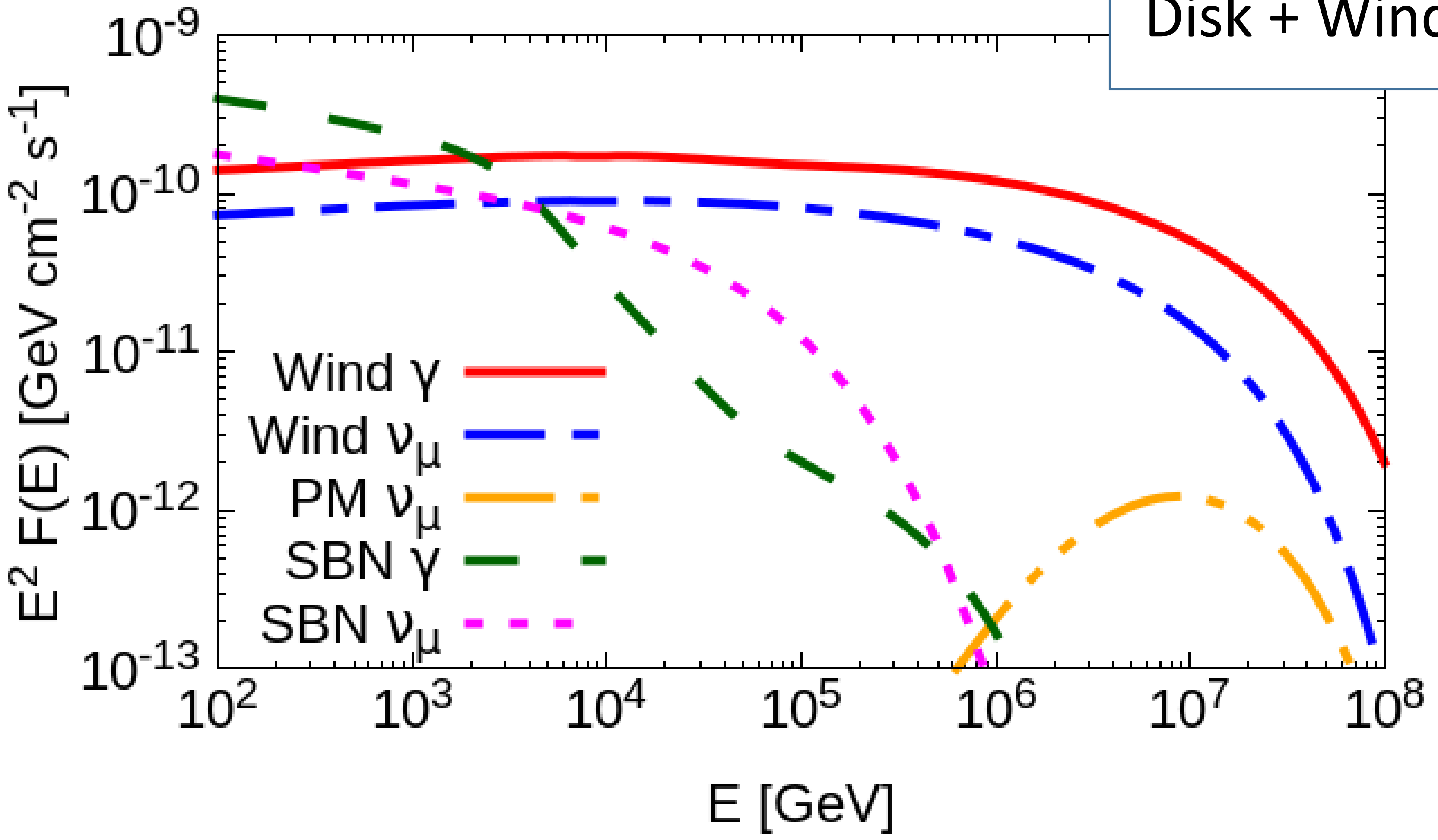
SBGs - High-Energy SED and Neutrinos



Gamma and neutrinos from the galactic disk
Maximum Energy: 1 PeV

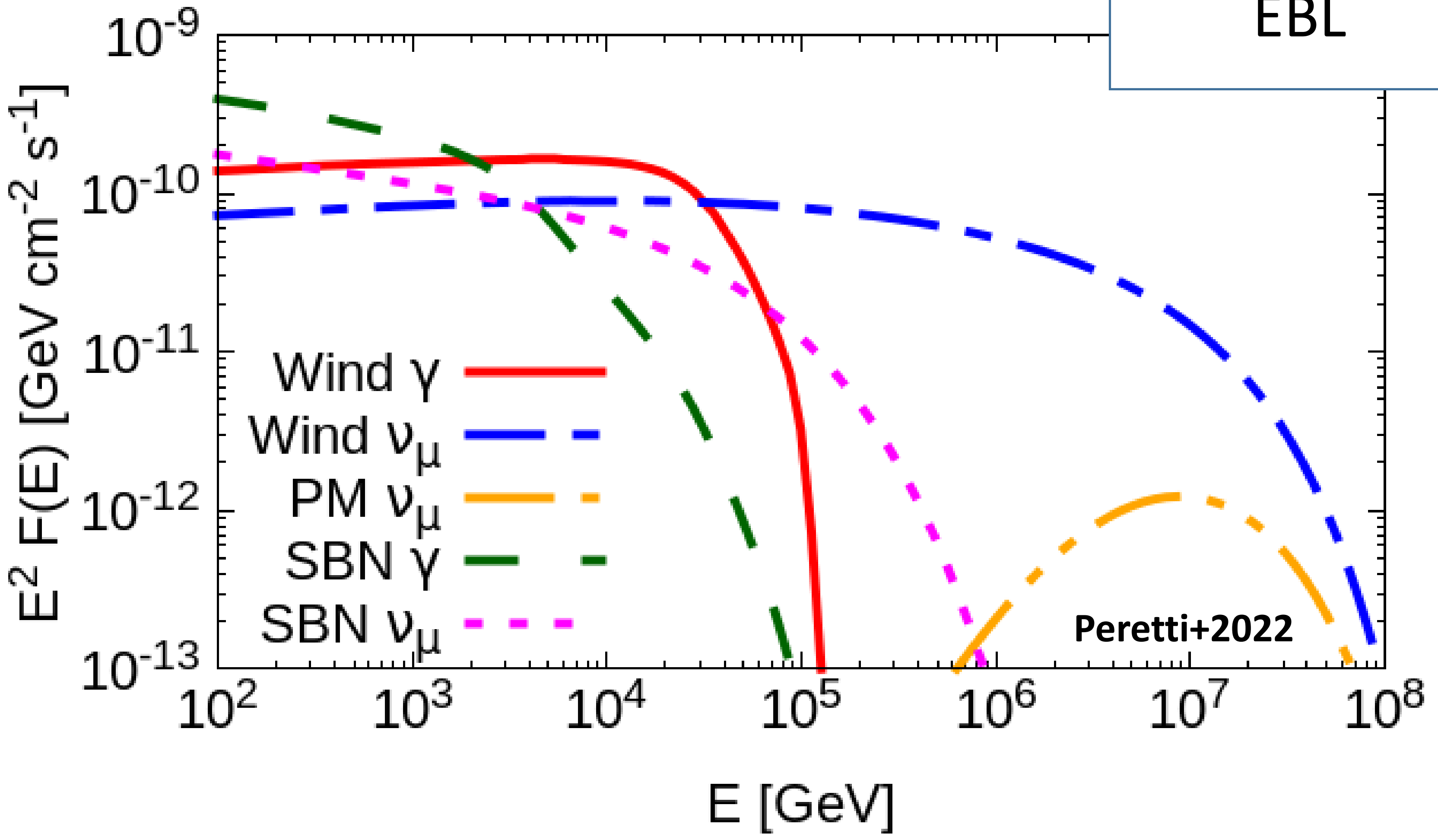
SBGs - High-Energy SED and Neutrinos

Disk + Wind

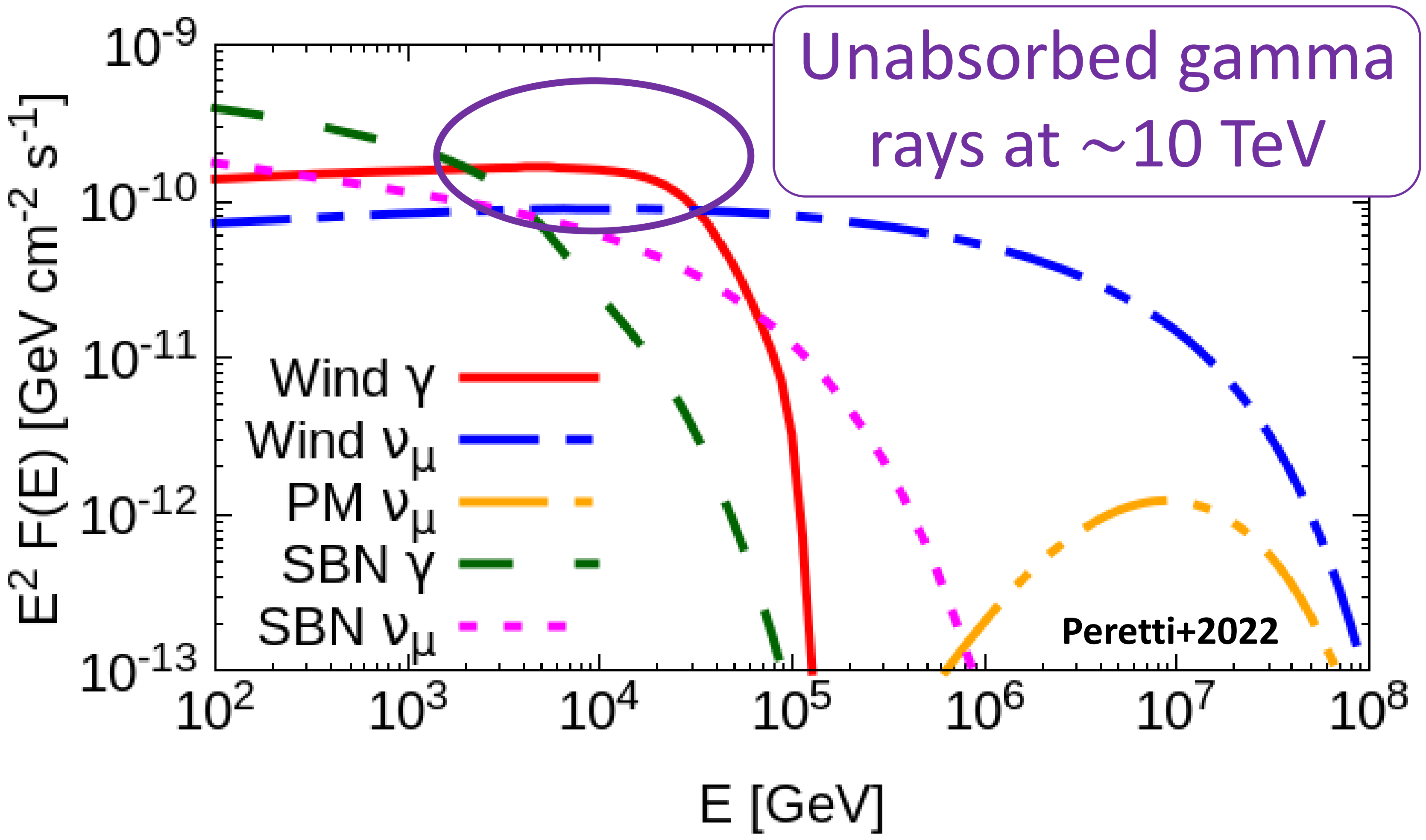


SBGs - High-Energy SED and Neutrinos

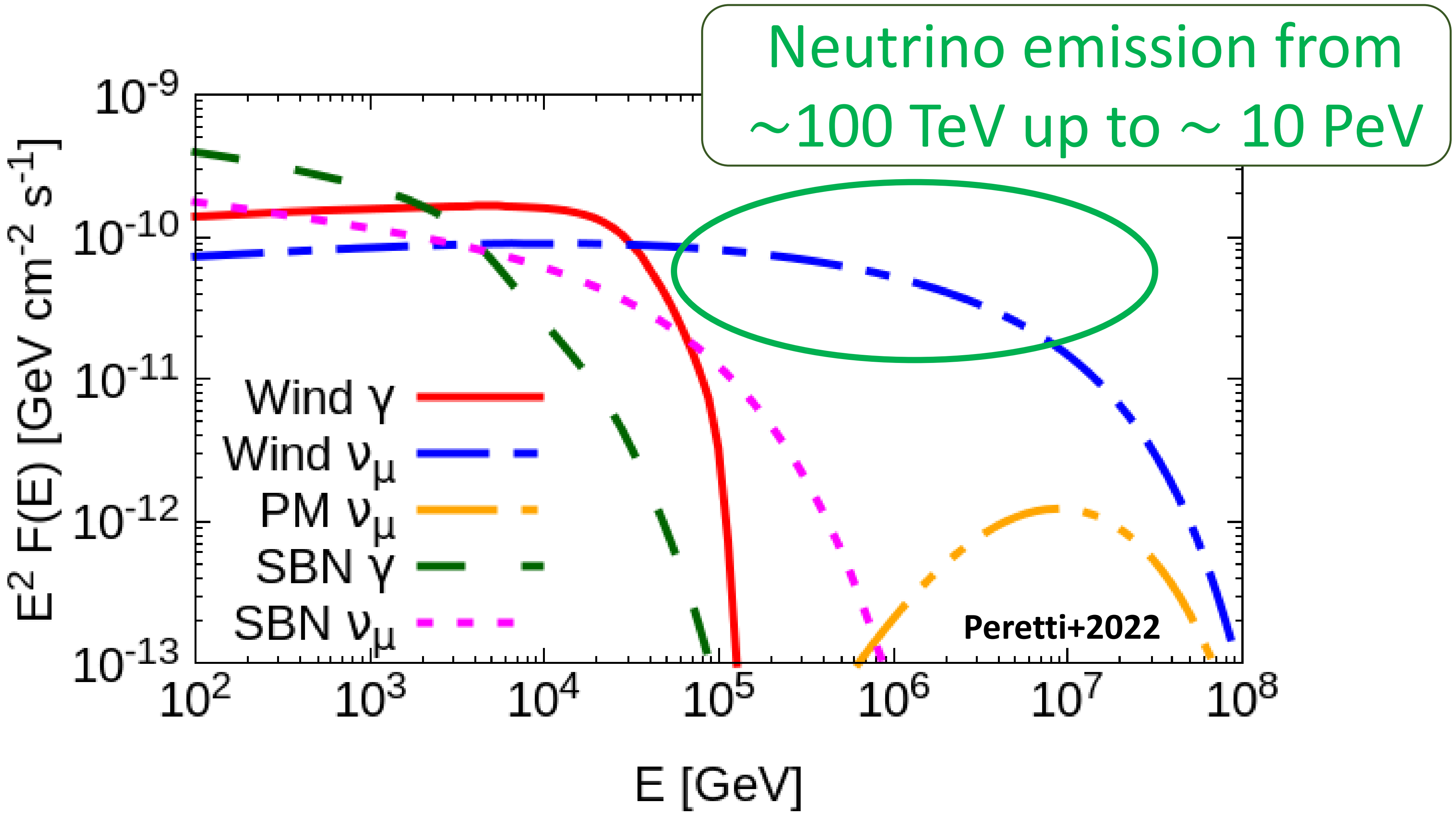
EBL



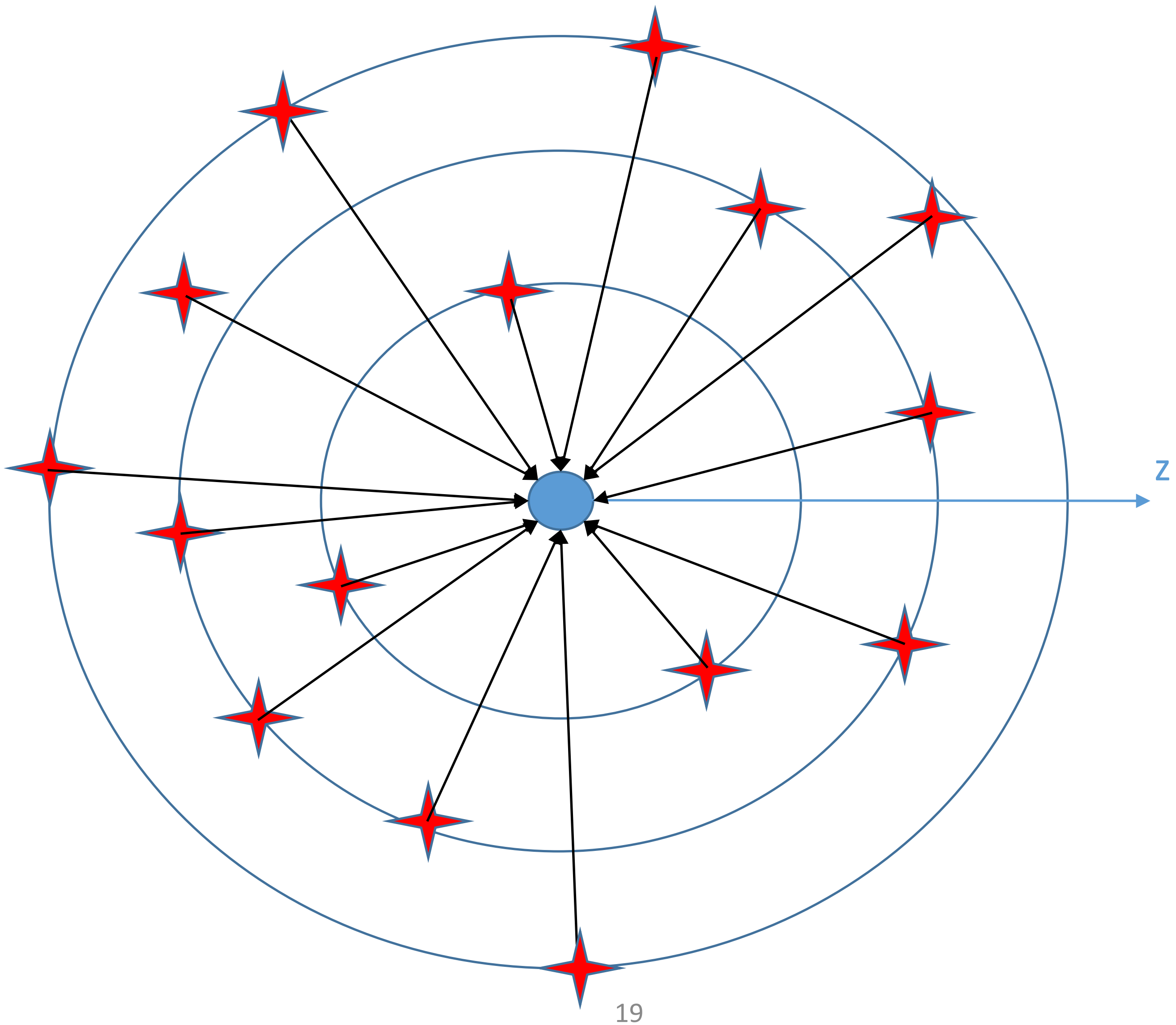
SBGs - High-Energy SED and Neutrinos



SBGs - High-Energy SED and Neutrinos



Counting starbursts



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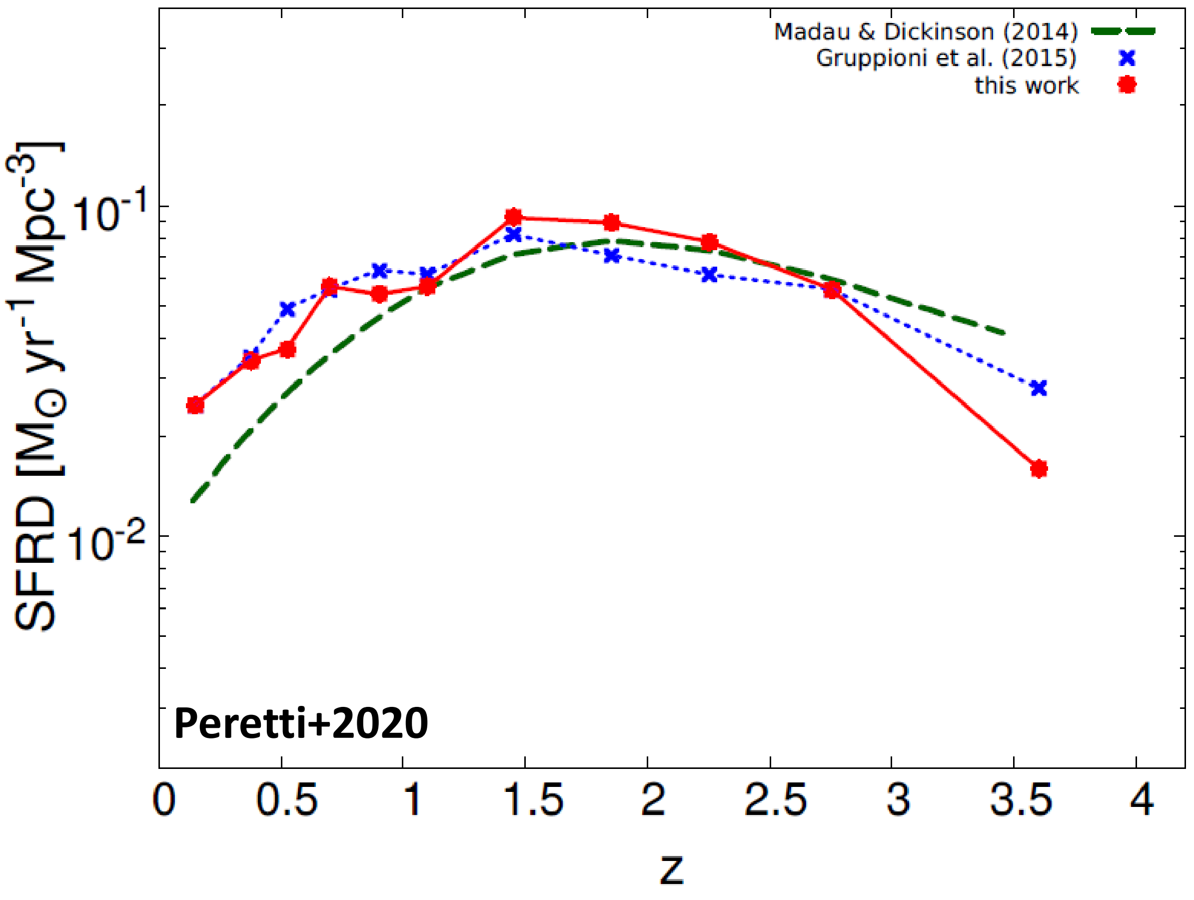

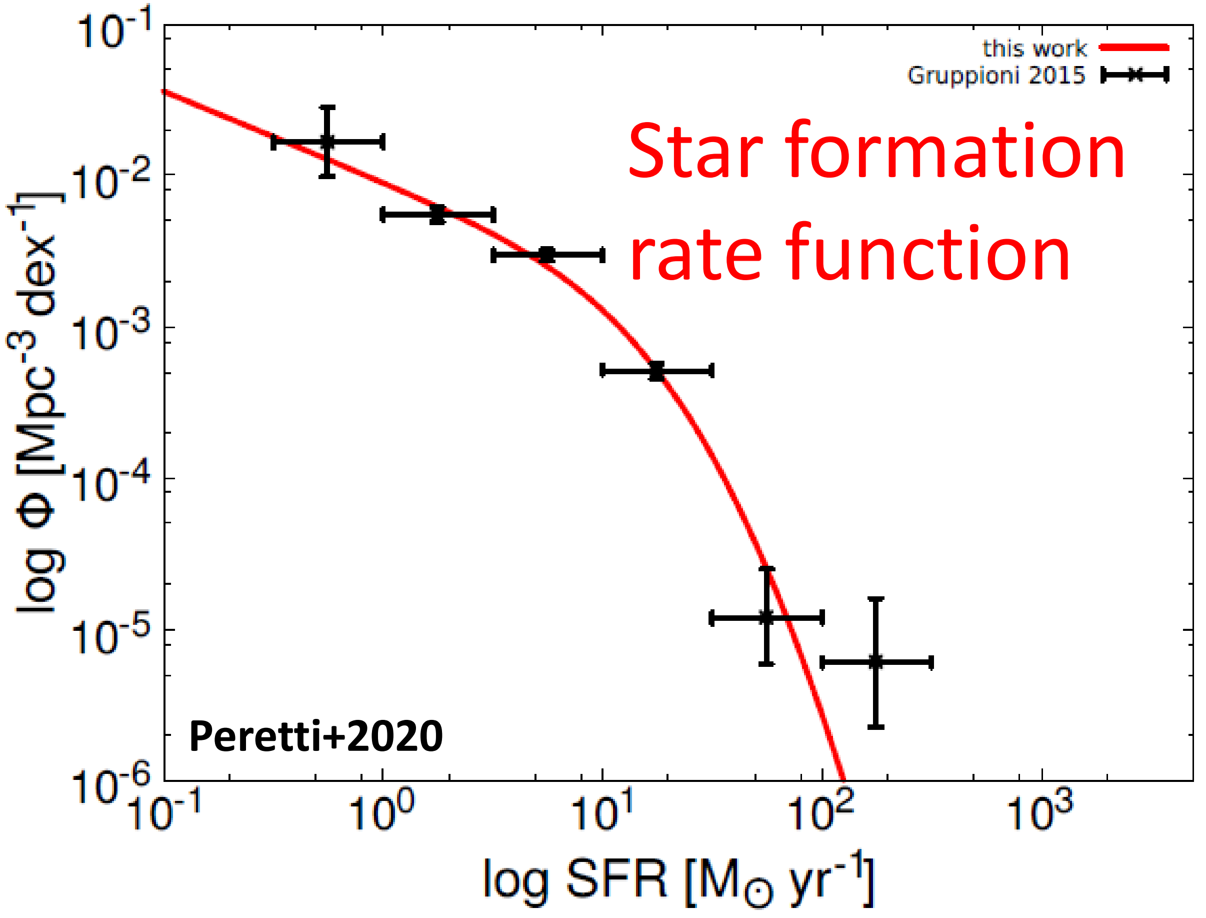

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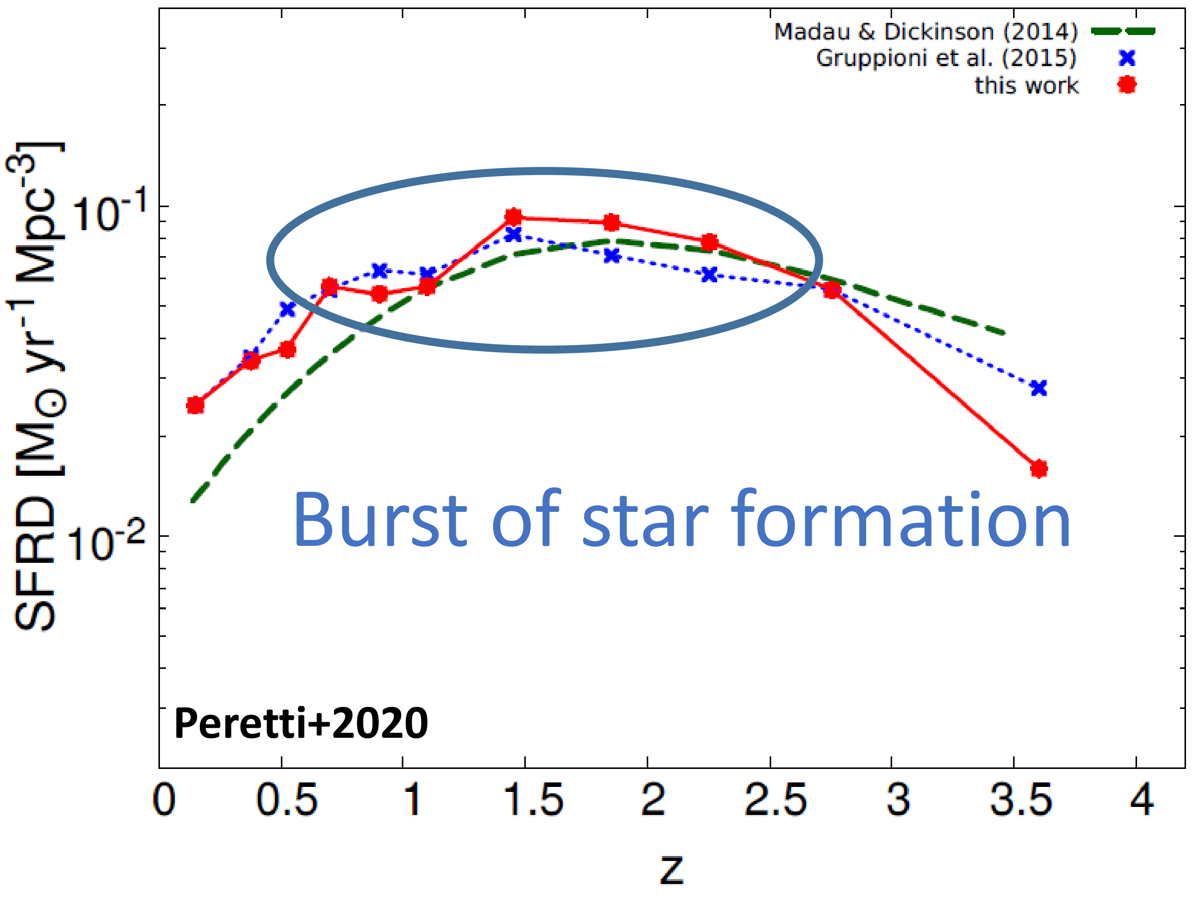
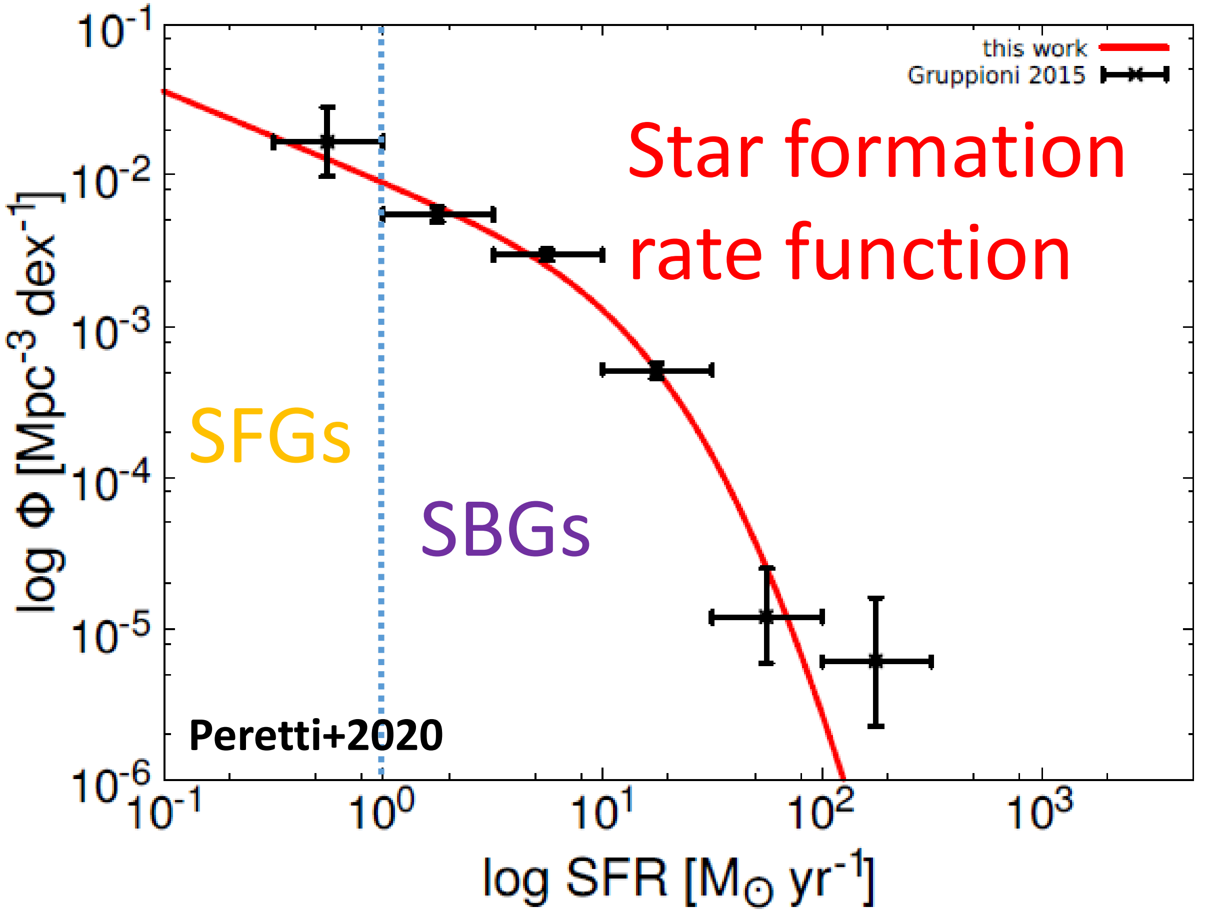
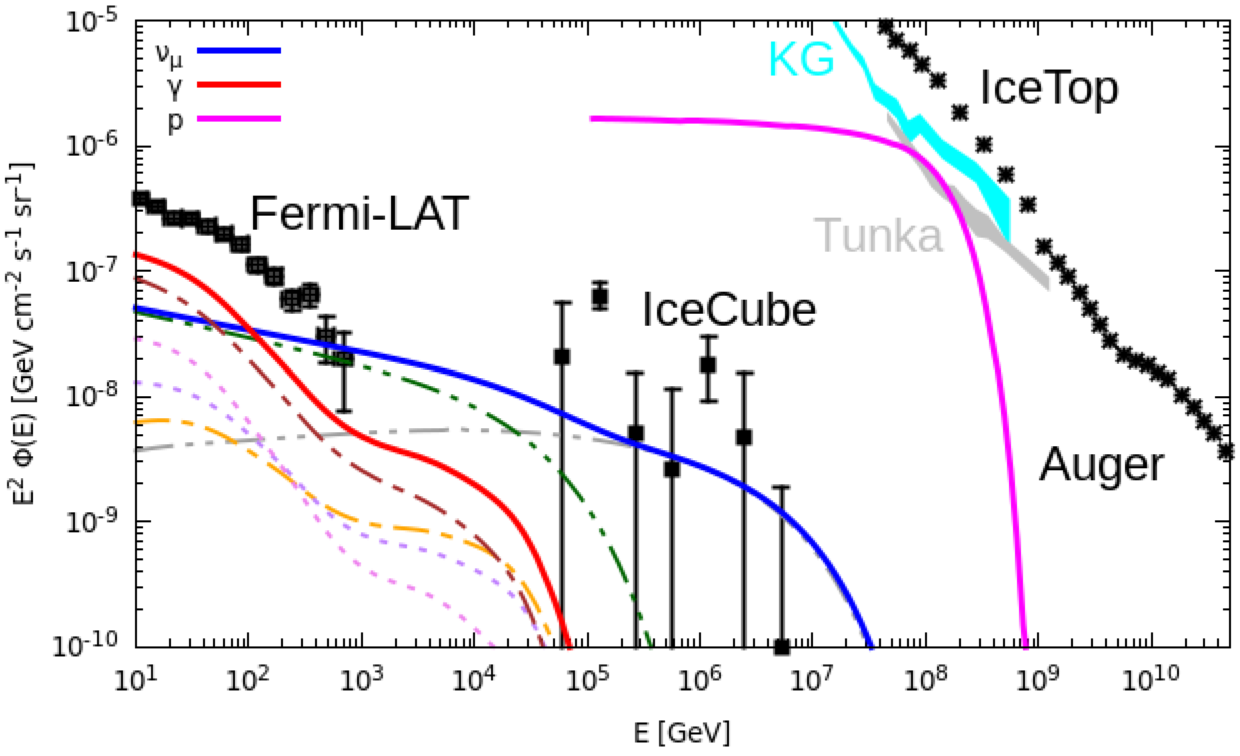


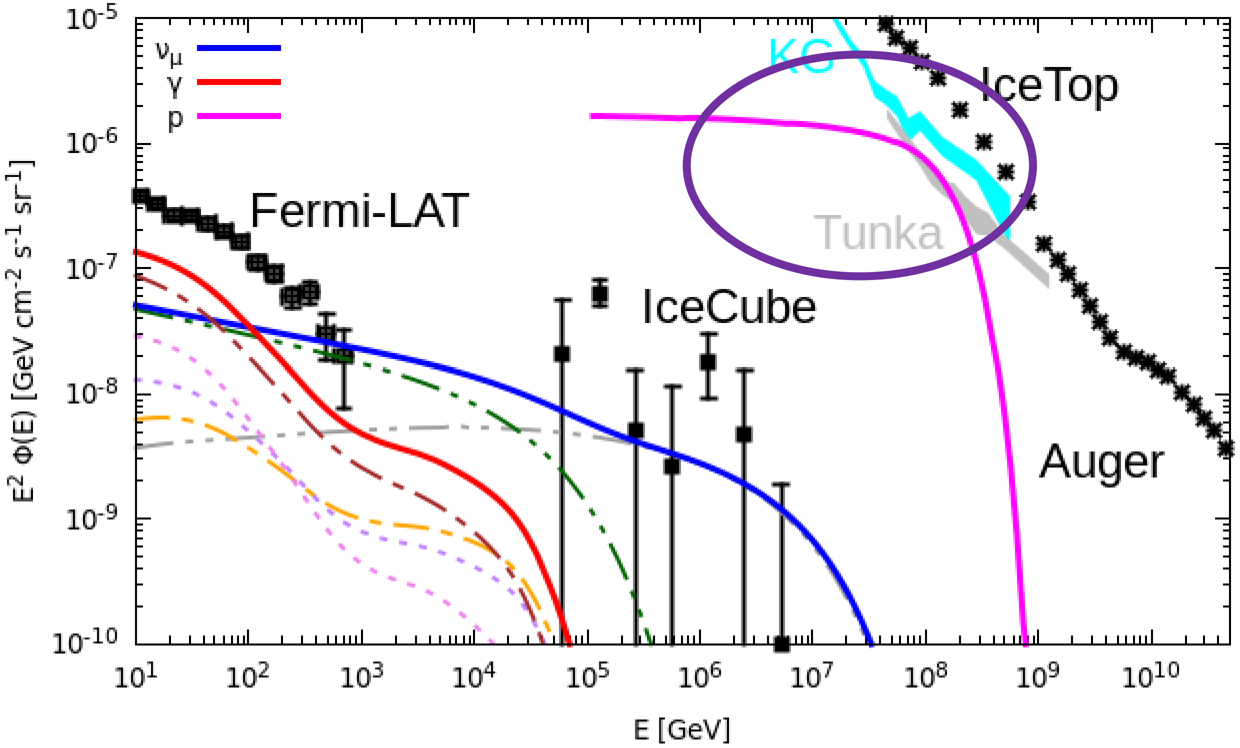


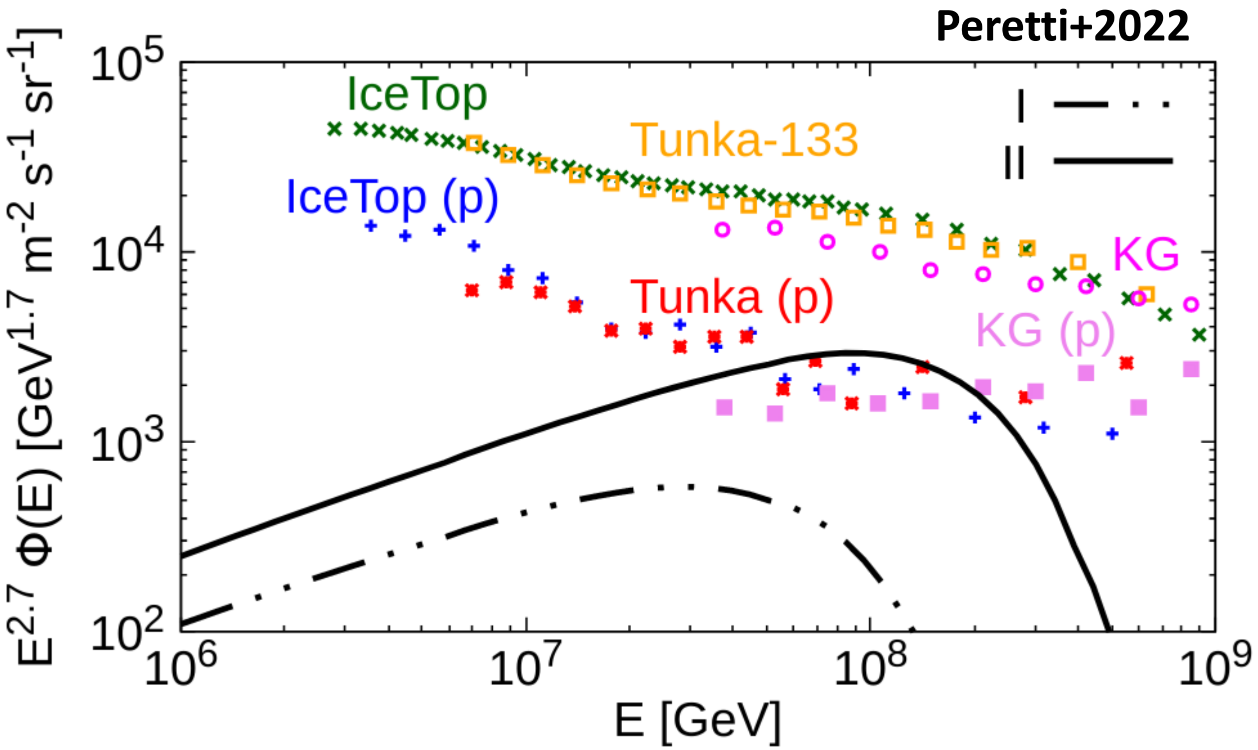
Cumulative radiation from SBGs



- 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





Take home message 1

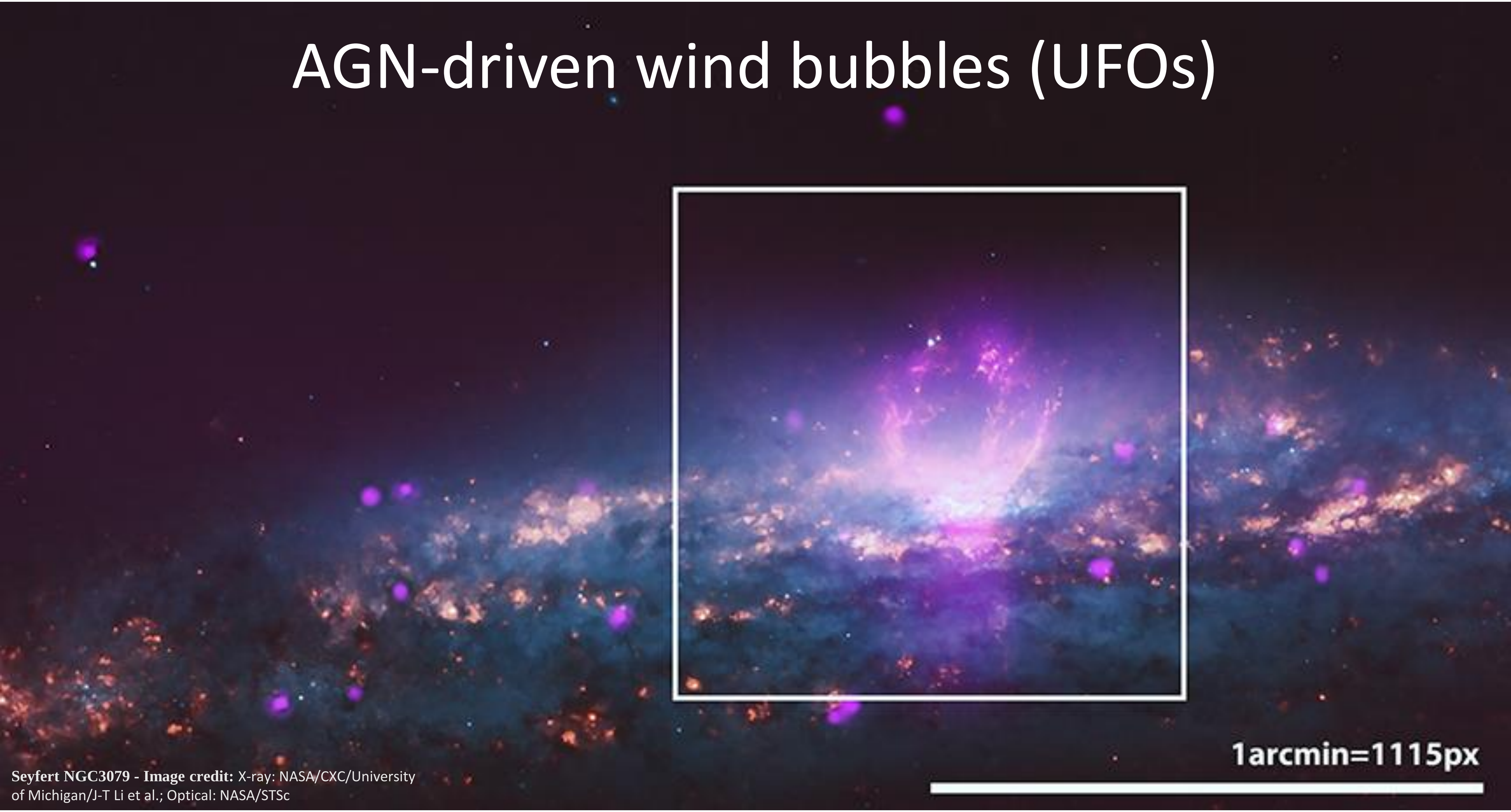
- Starburst-driven wind bubbles can be efficient particle accelerators up to 10^2 PeV

- 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)

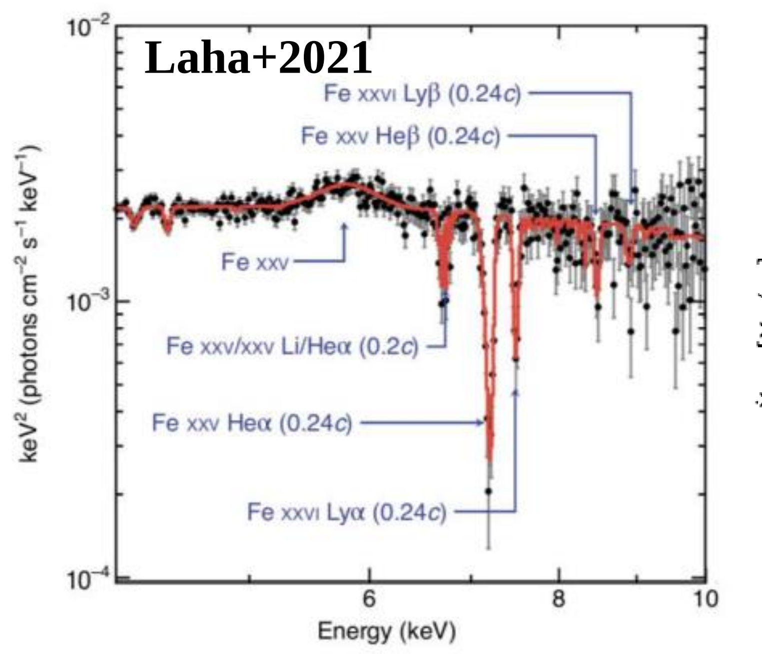


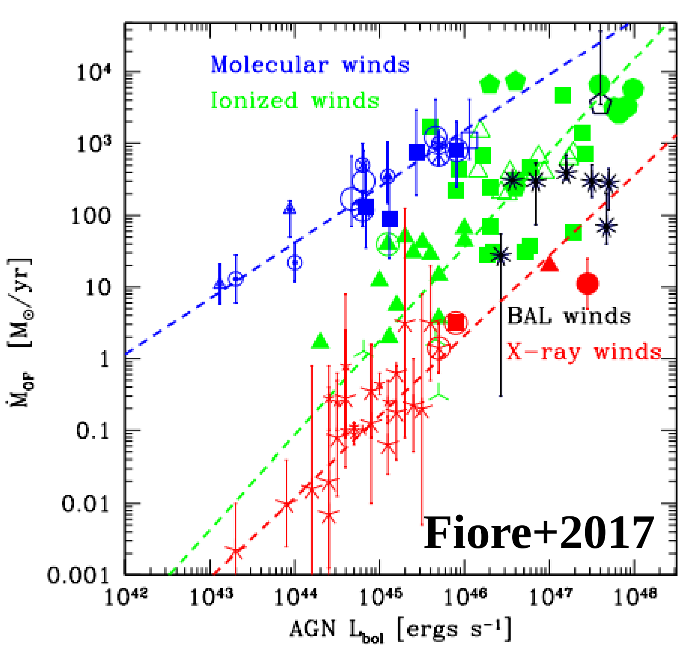
Seyfert NGC3079 - Image credit: X-ray: NASA/CXC/University of Michigan/J-T Li et al.; Optical: NASA/STSc

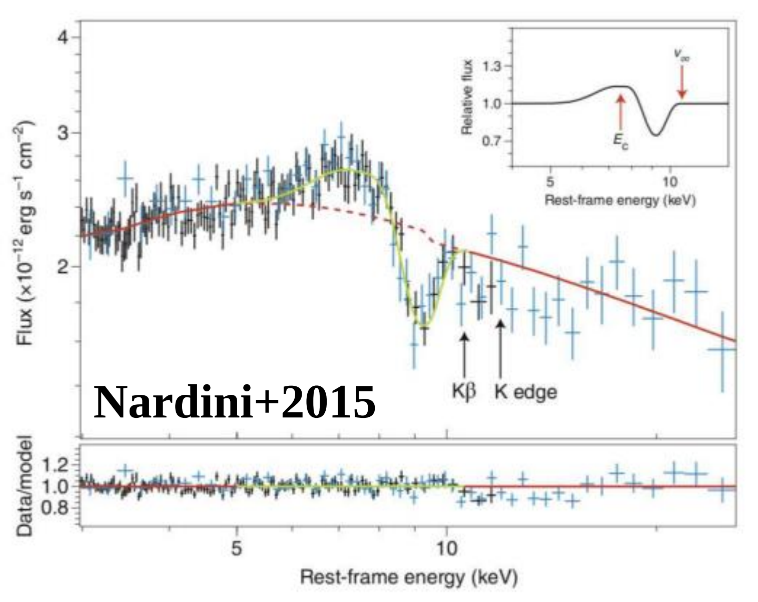
Seyfert NGC3079 - Image credit: X-ray: NASA/CXC/University of Michigan/J-T Li et al.; Optical: NASA/STSc

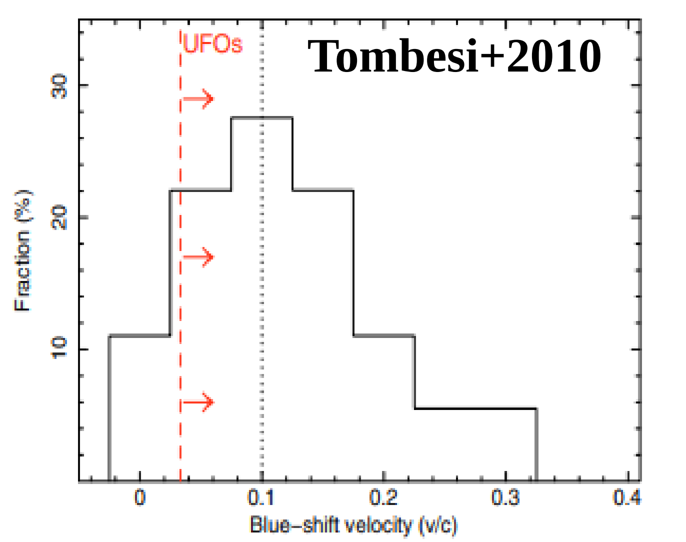
Ultra-Fast Outflows (UFOs)

- 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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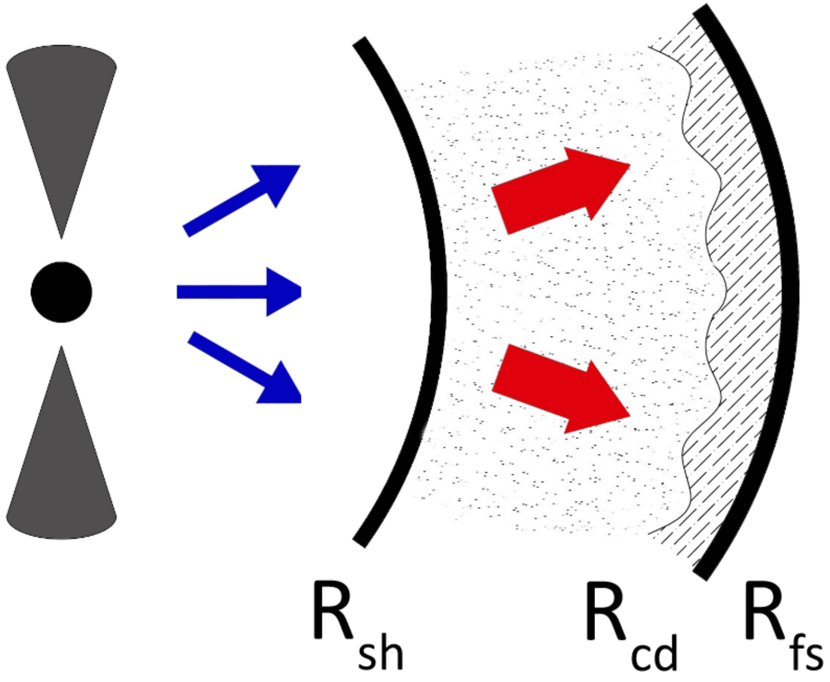
The UFO wind bubble

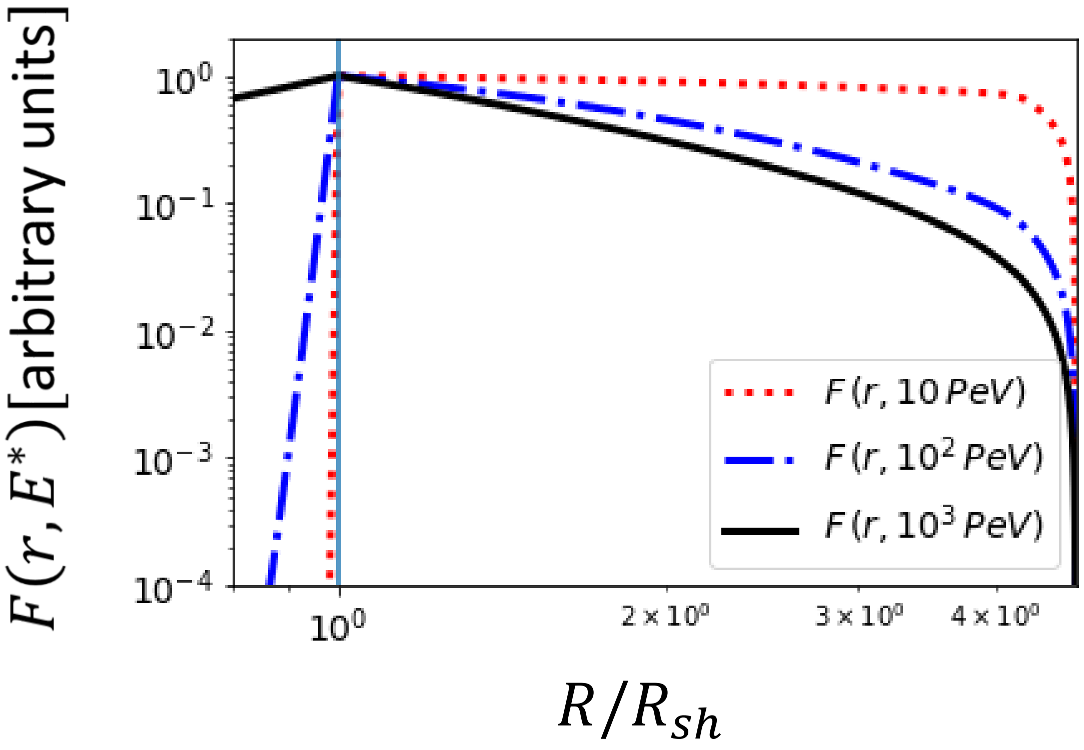
$$r^2 u(r)\partial_r f = \partial_r[r^2 D(r,p)\partial_r f] + \frac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p) - r^2\Lambda(r,p)$$

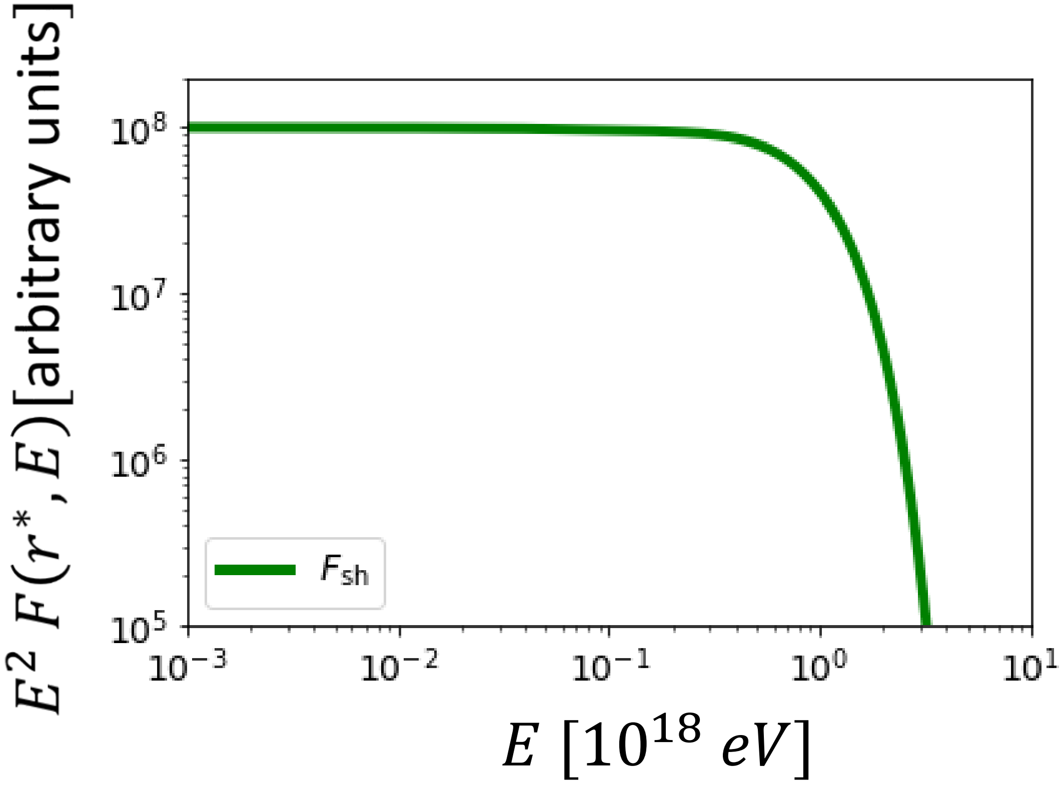


Parameters:

- $u_1 = 0.28\ c$
- $\dot{M} = 0.05\ M_\odot\ yr^{-1}$
- $l_c = 0.05\ pc$
- $T_{age} = 1000\ yr$

Solution: radial behavior and spectra





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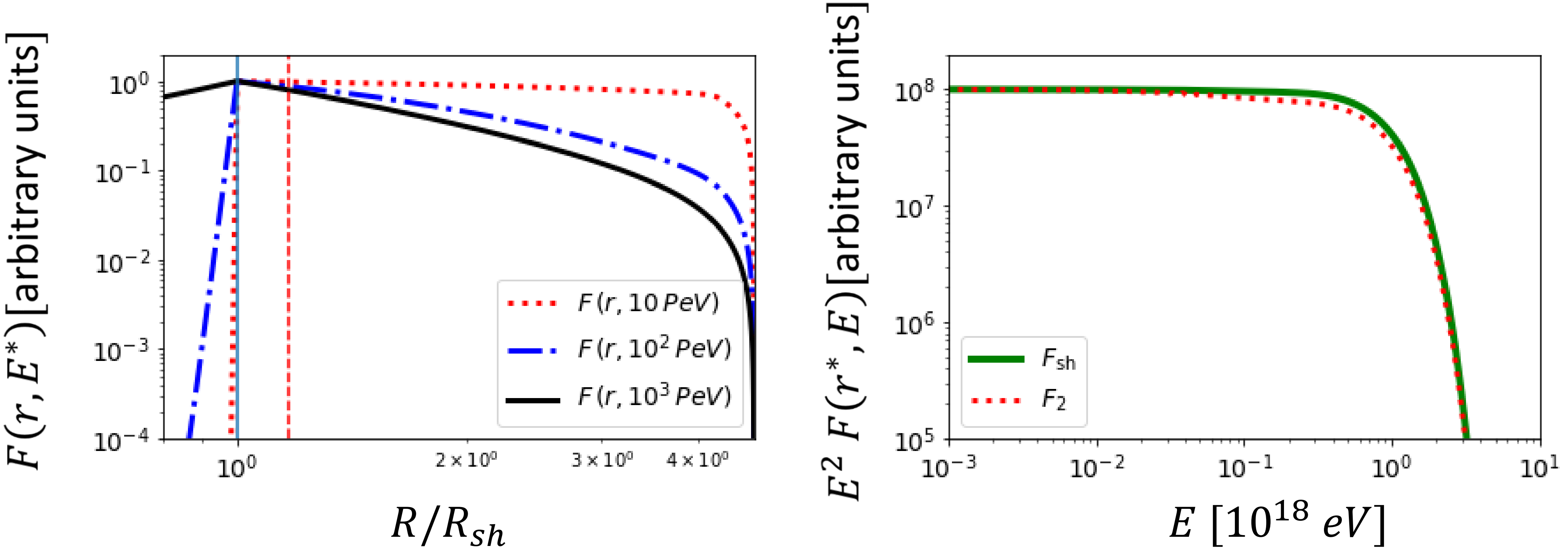

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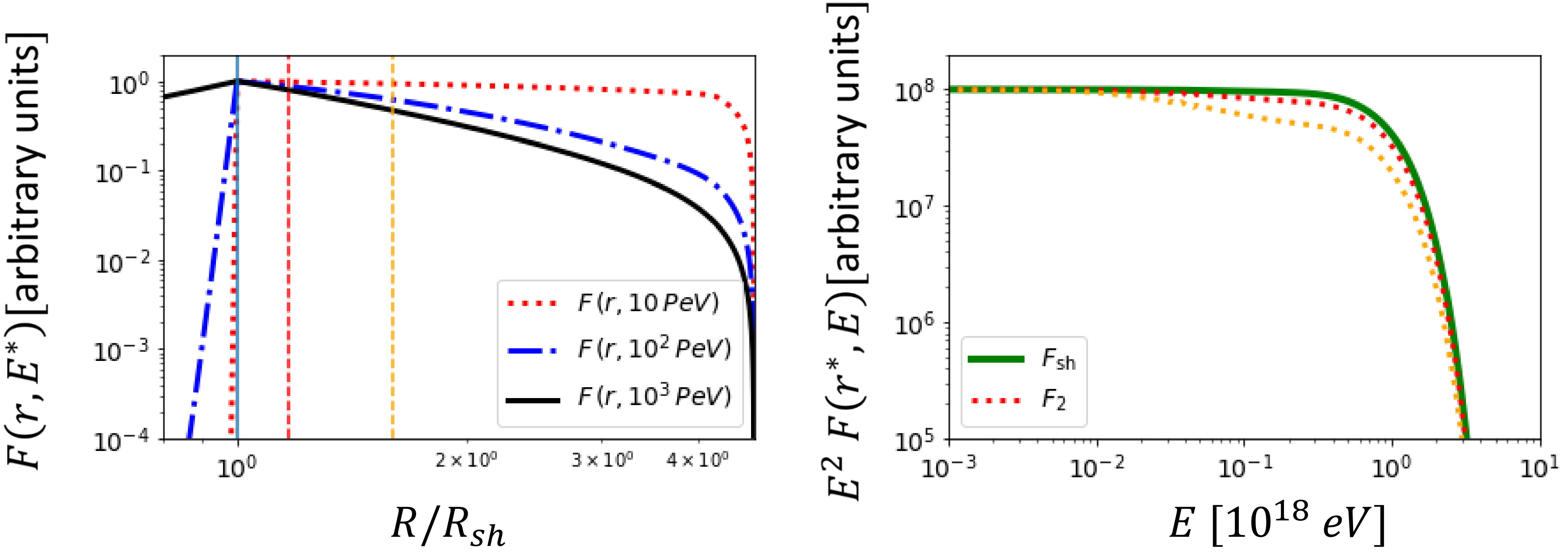

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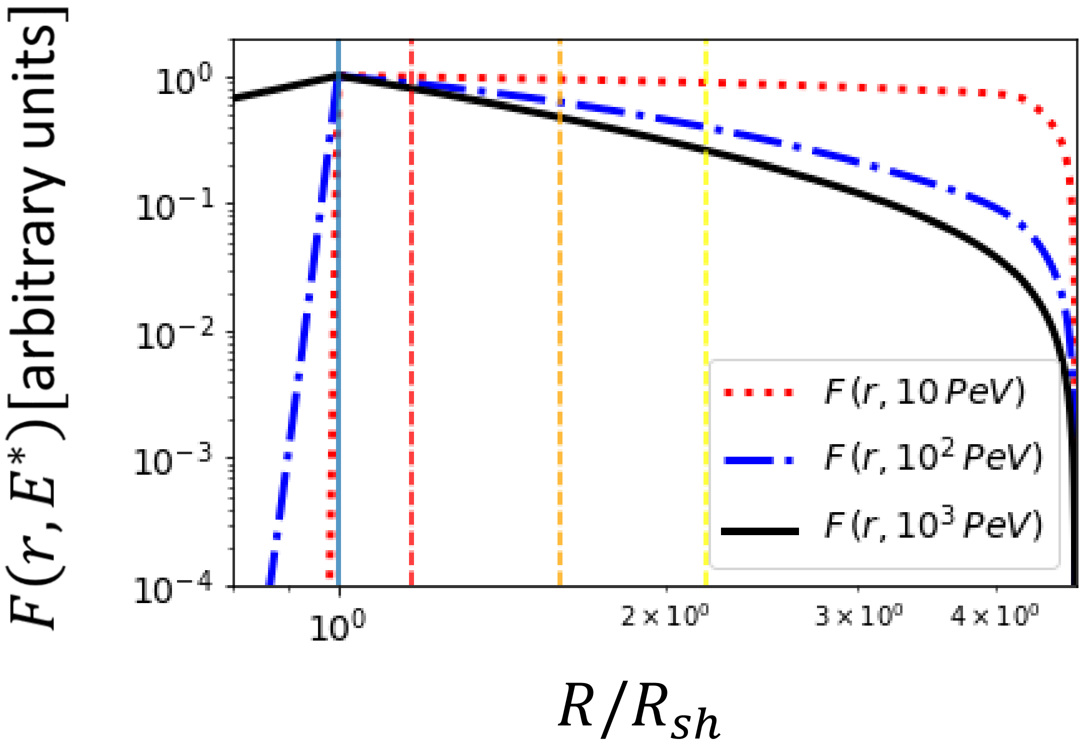

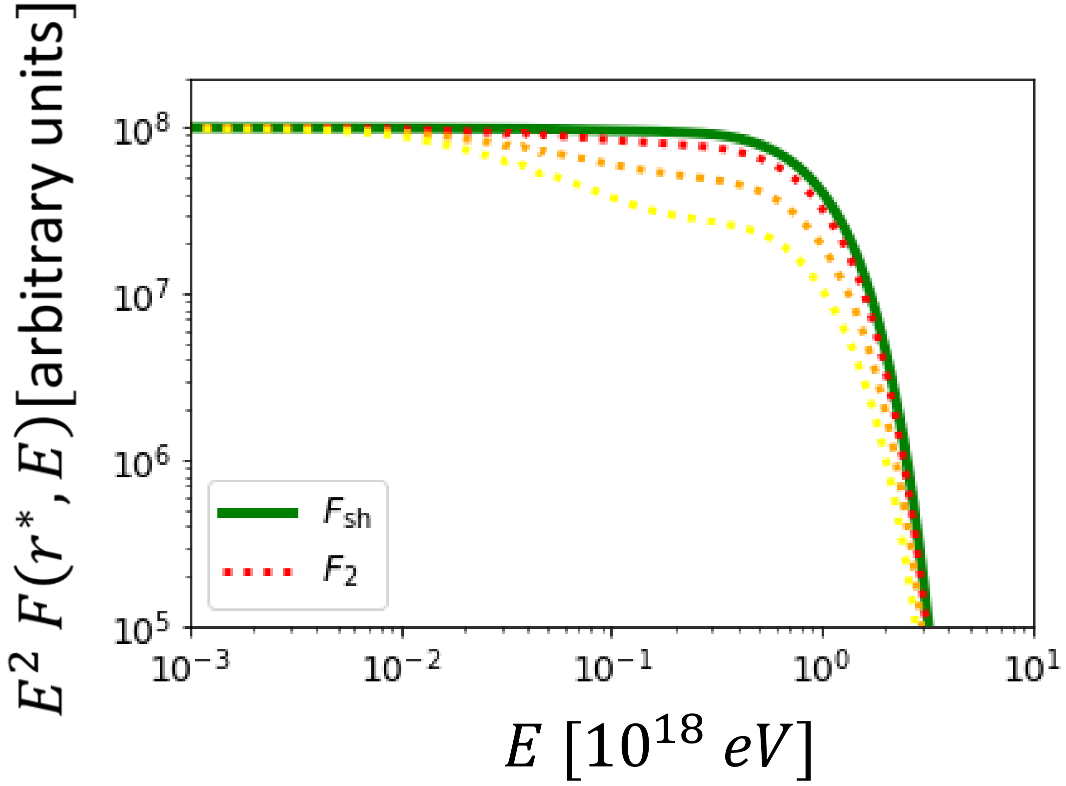

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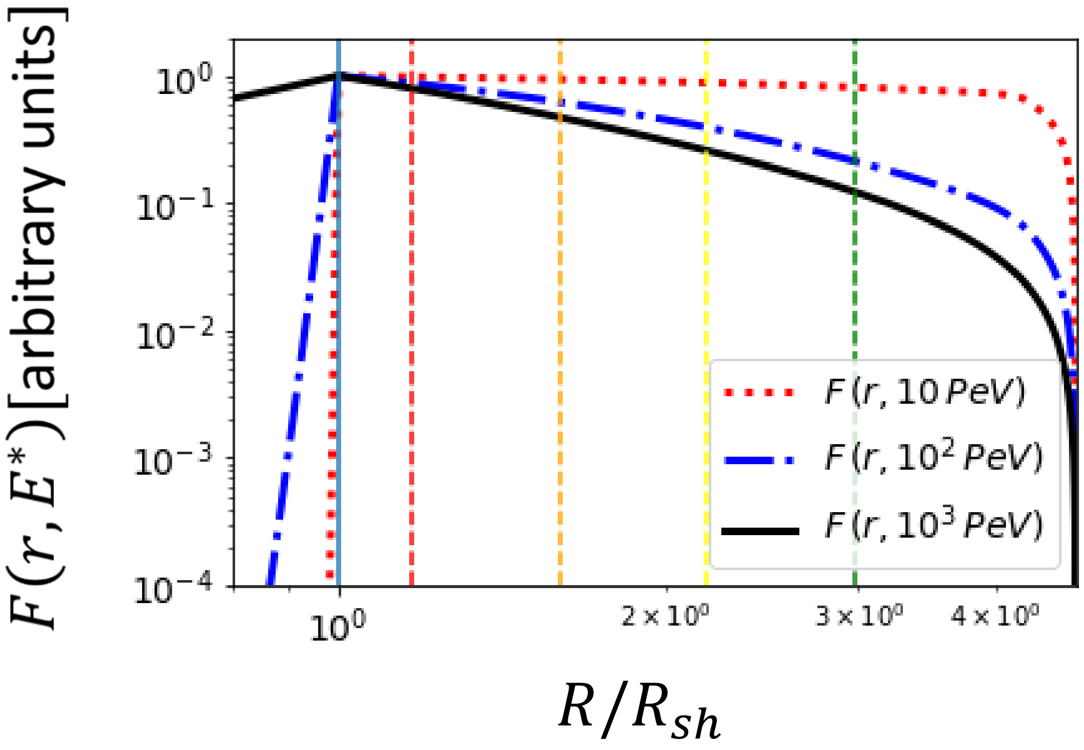

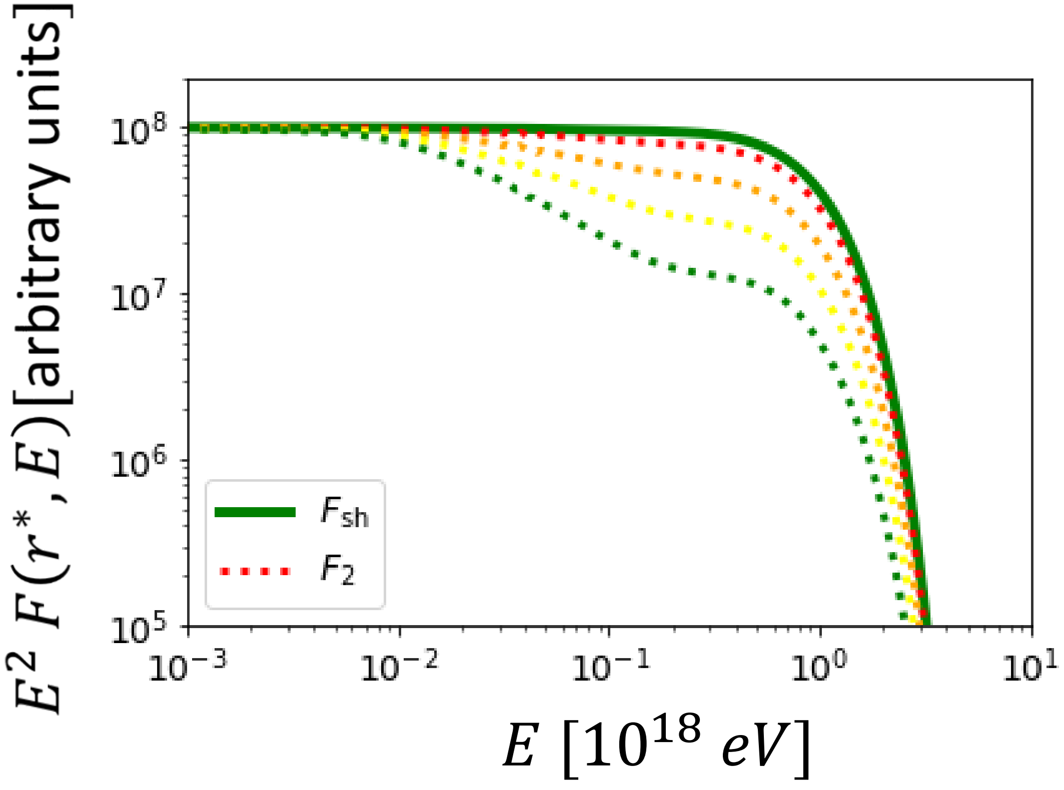

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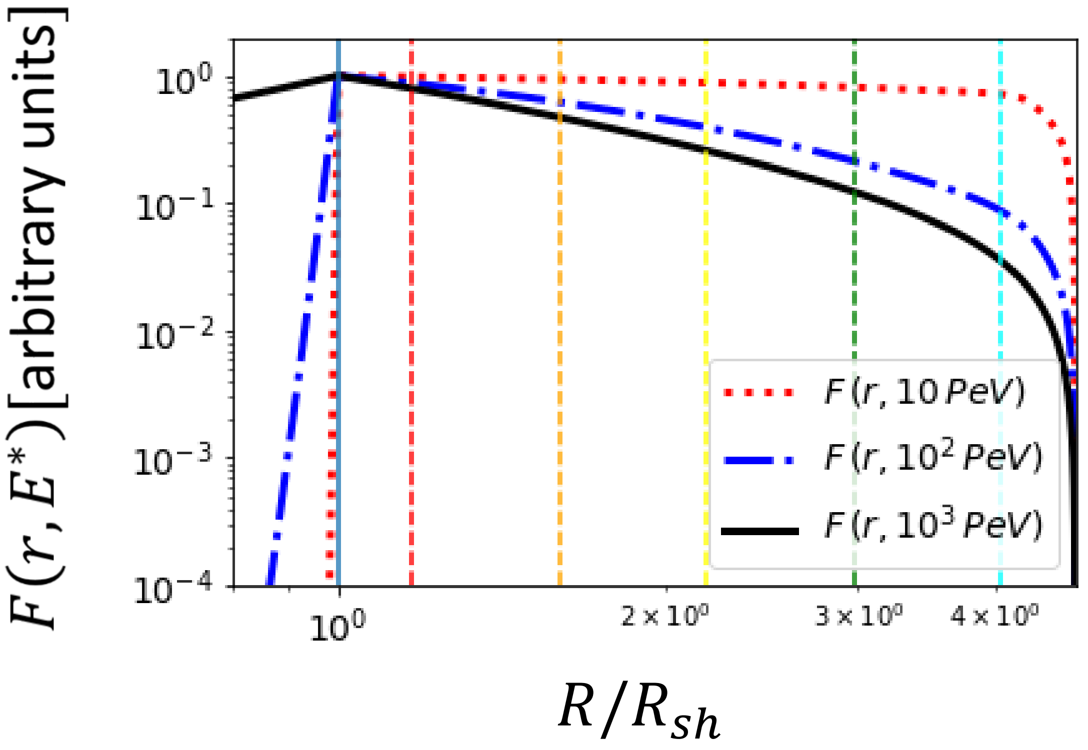

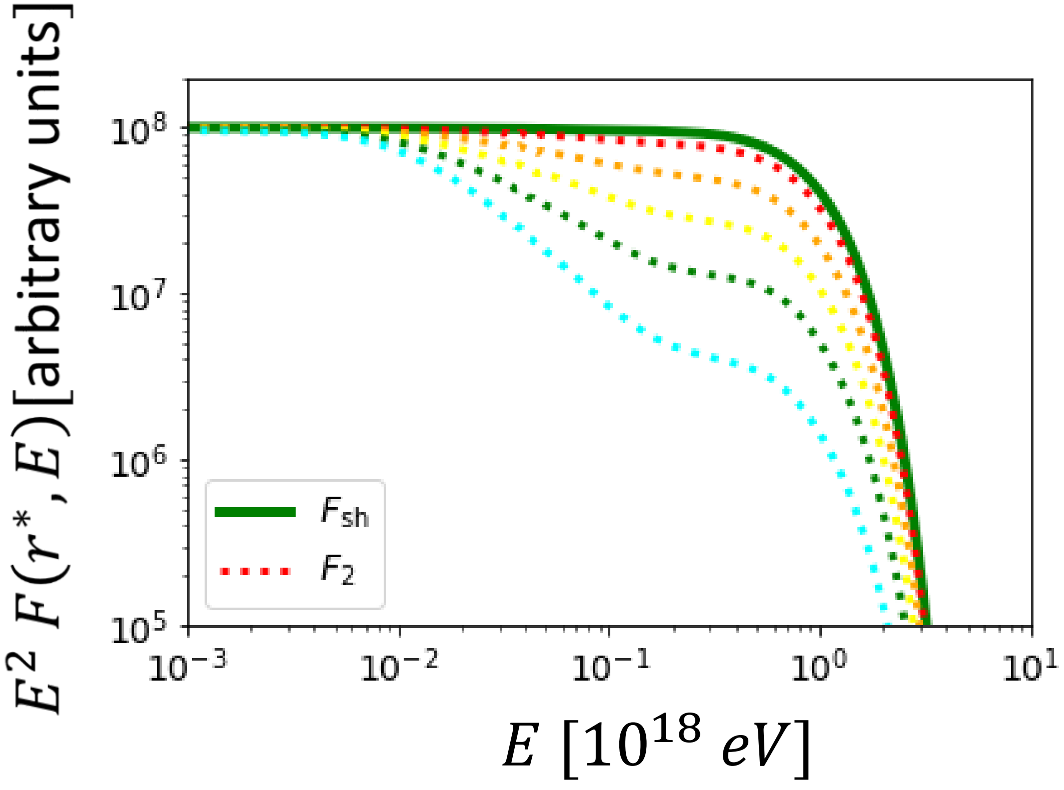

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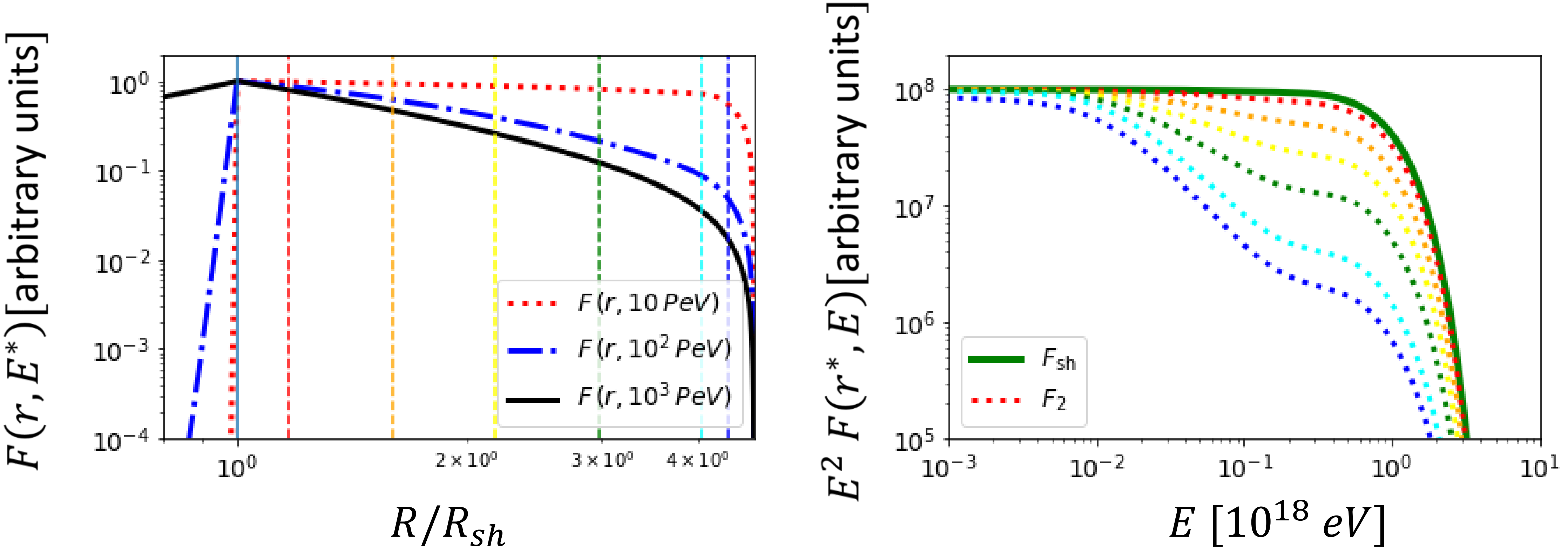

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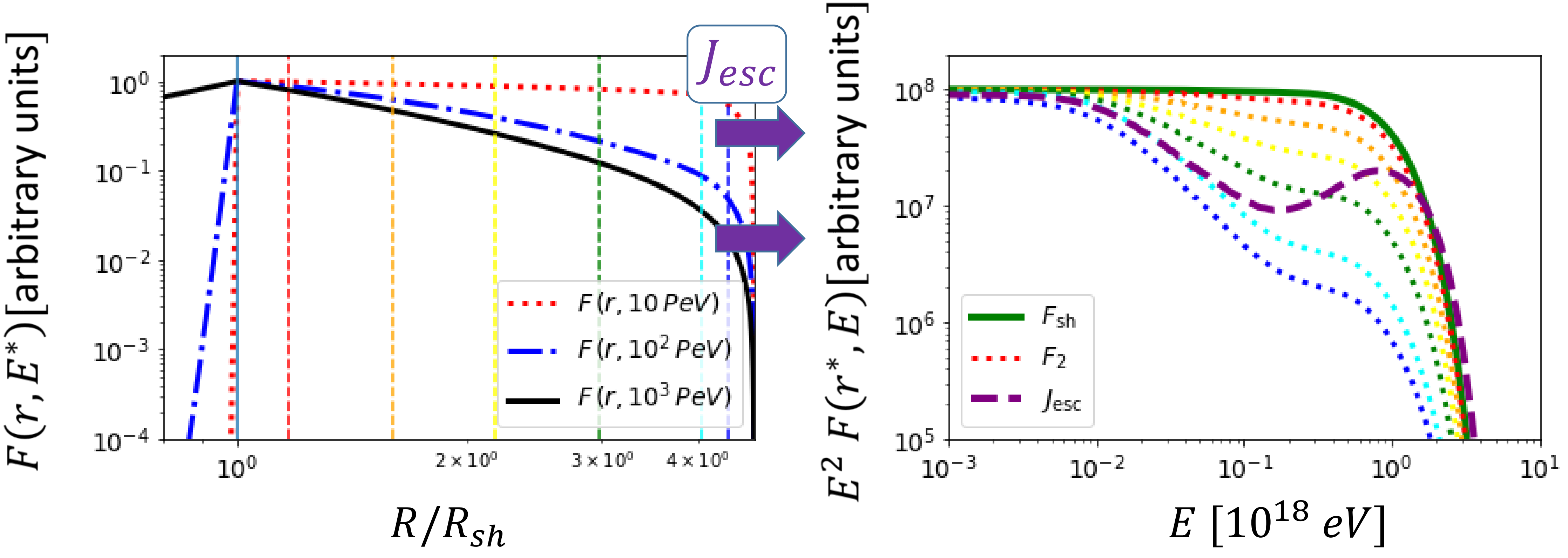
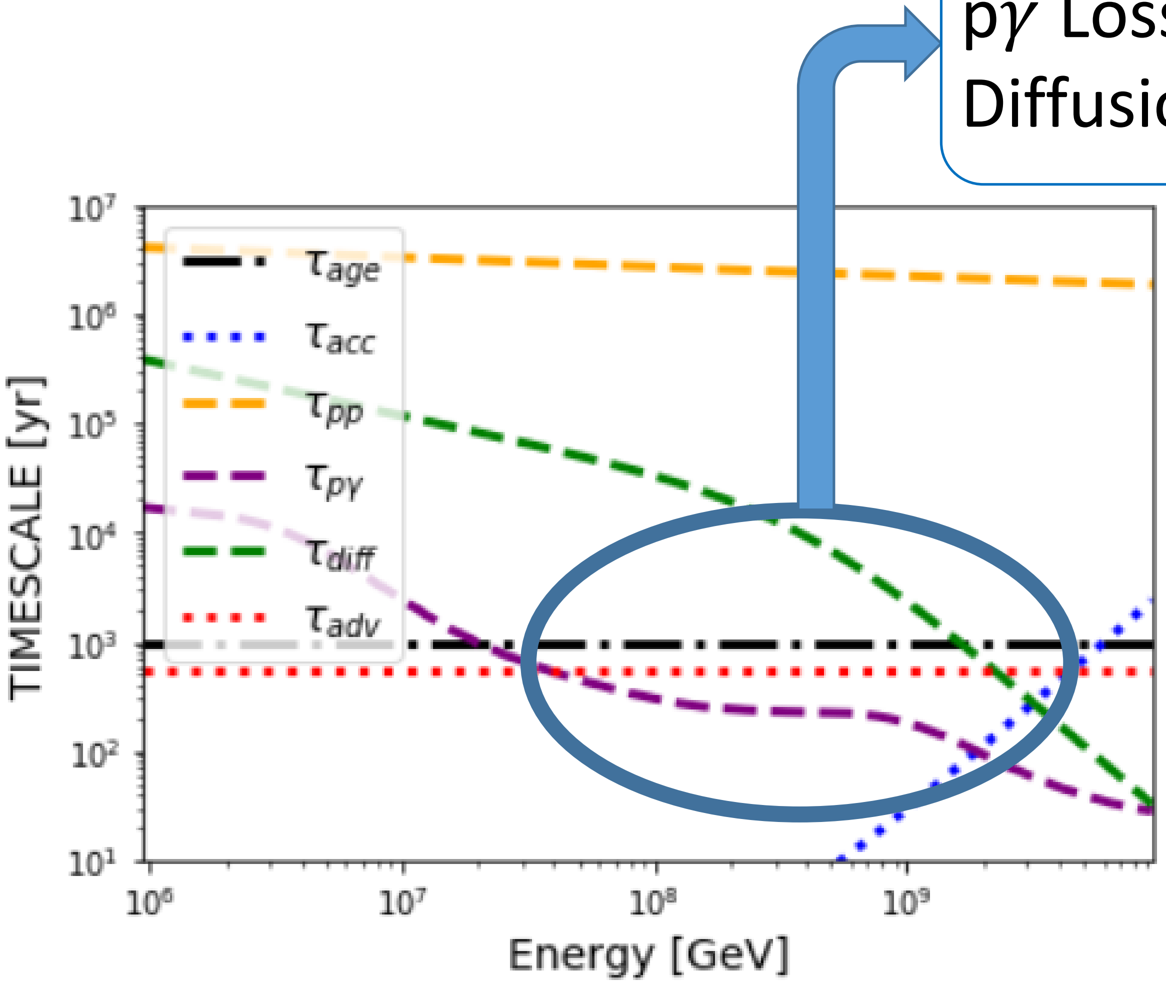
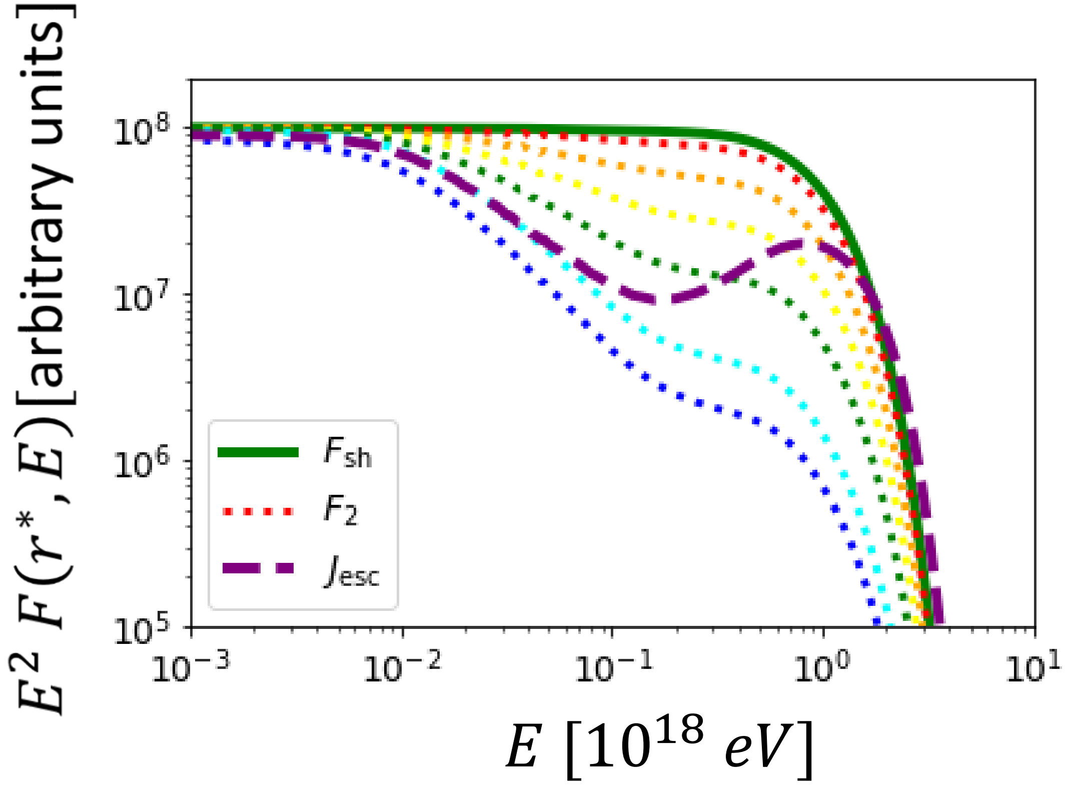


Solution: radial behavior and spectra

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





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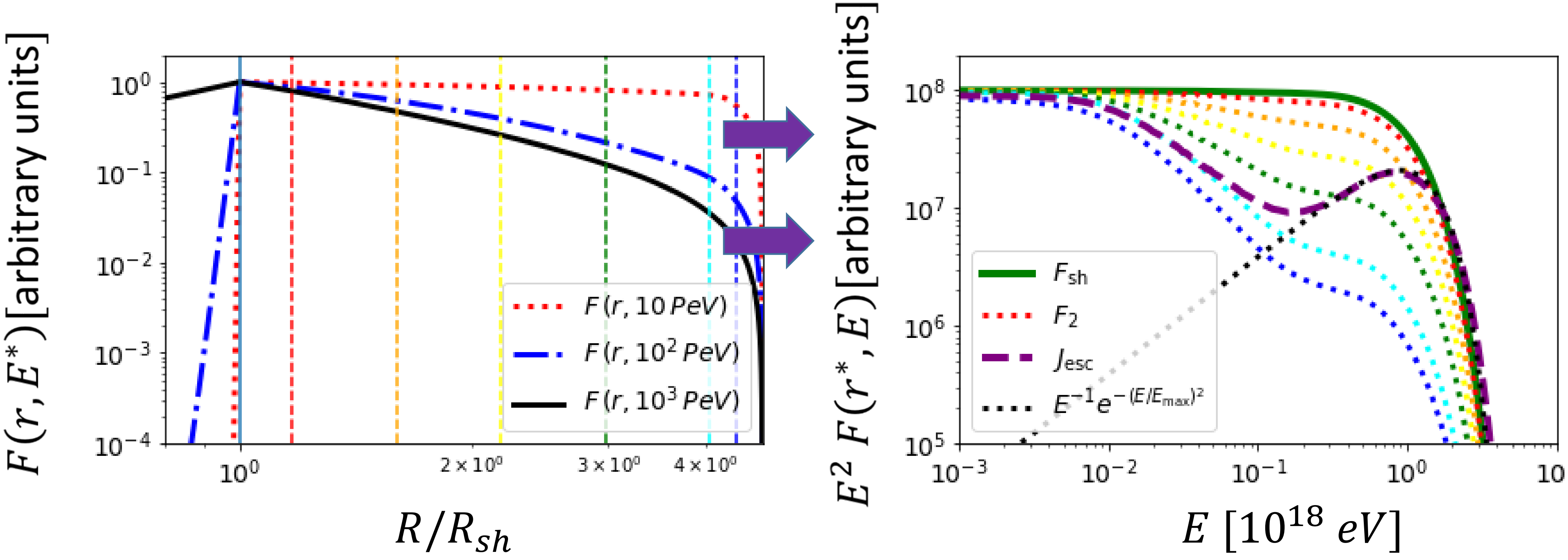

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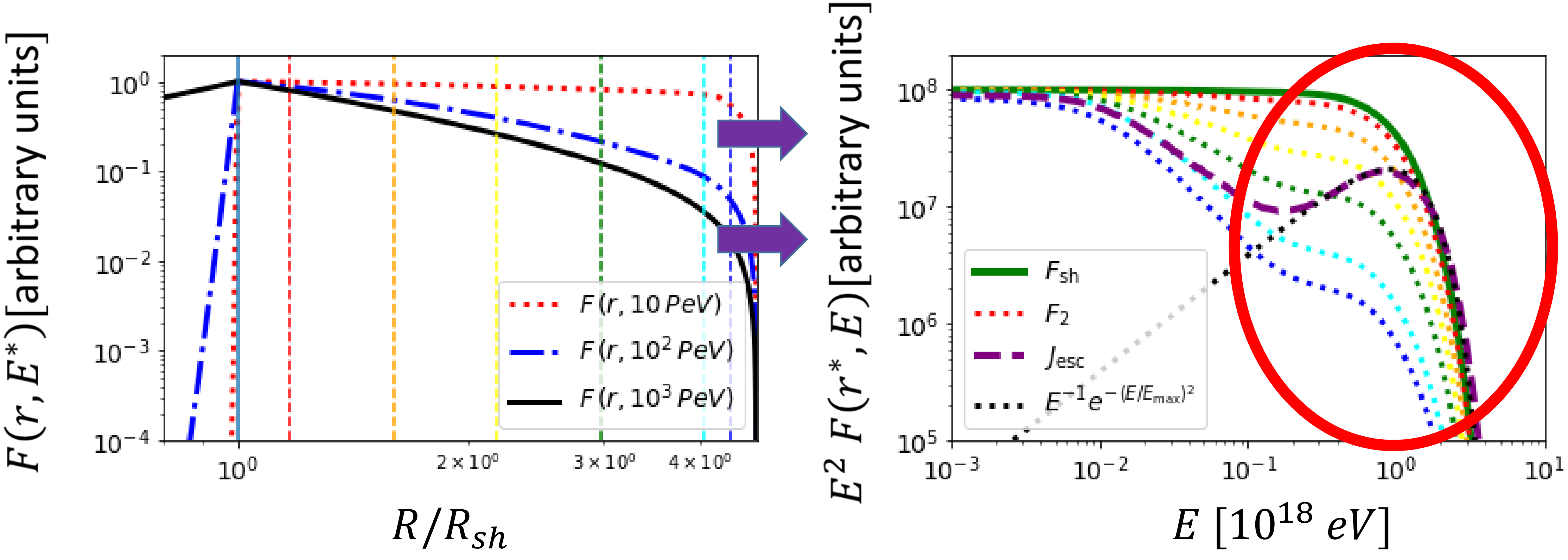
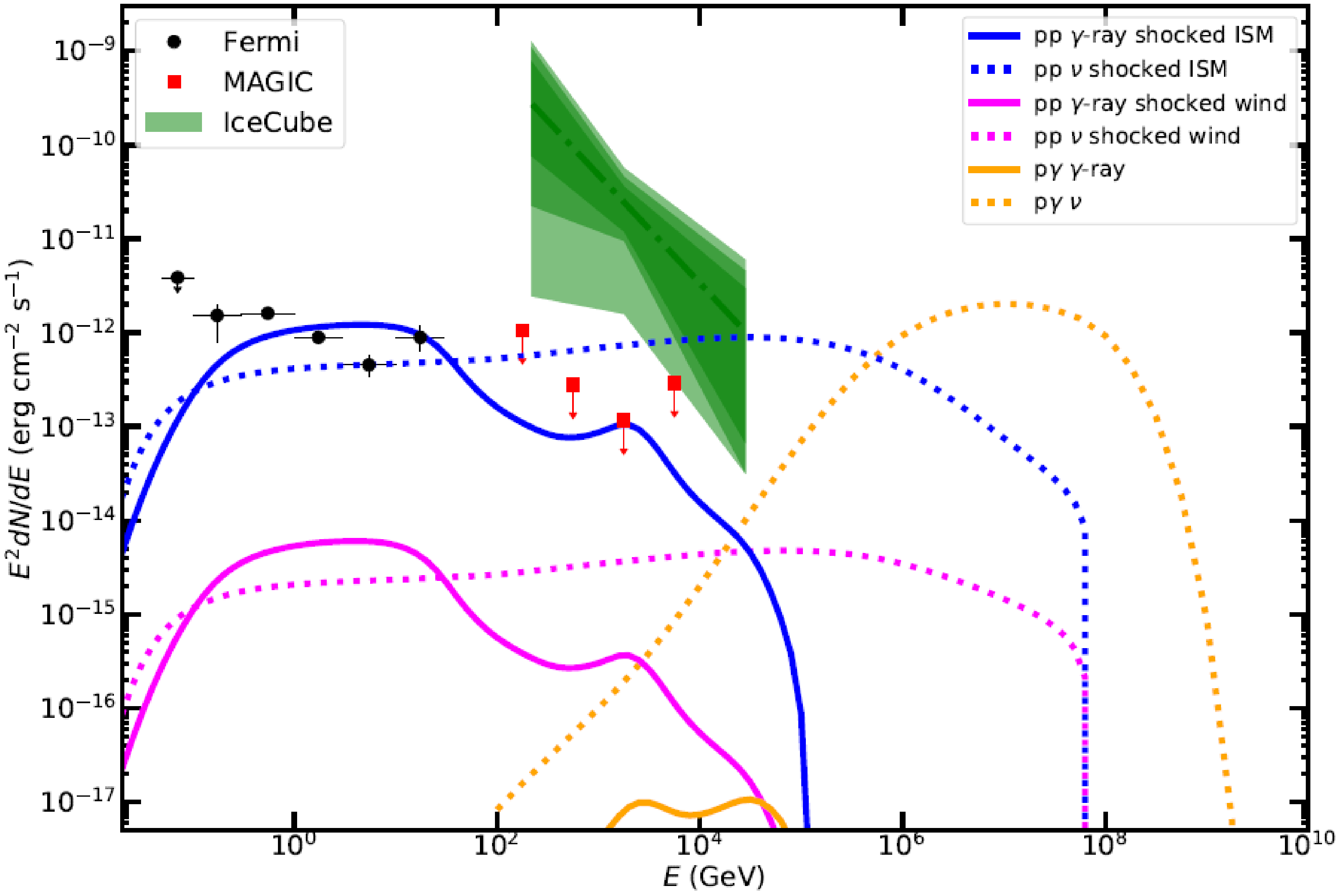
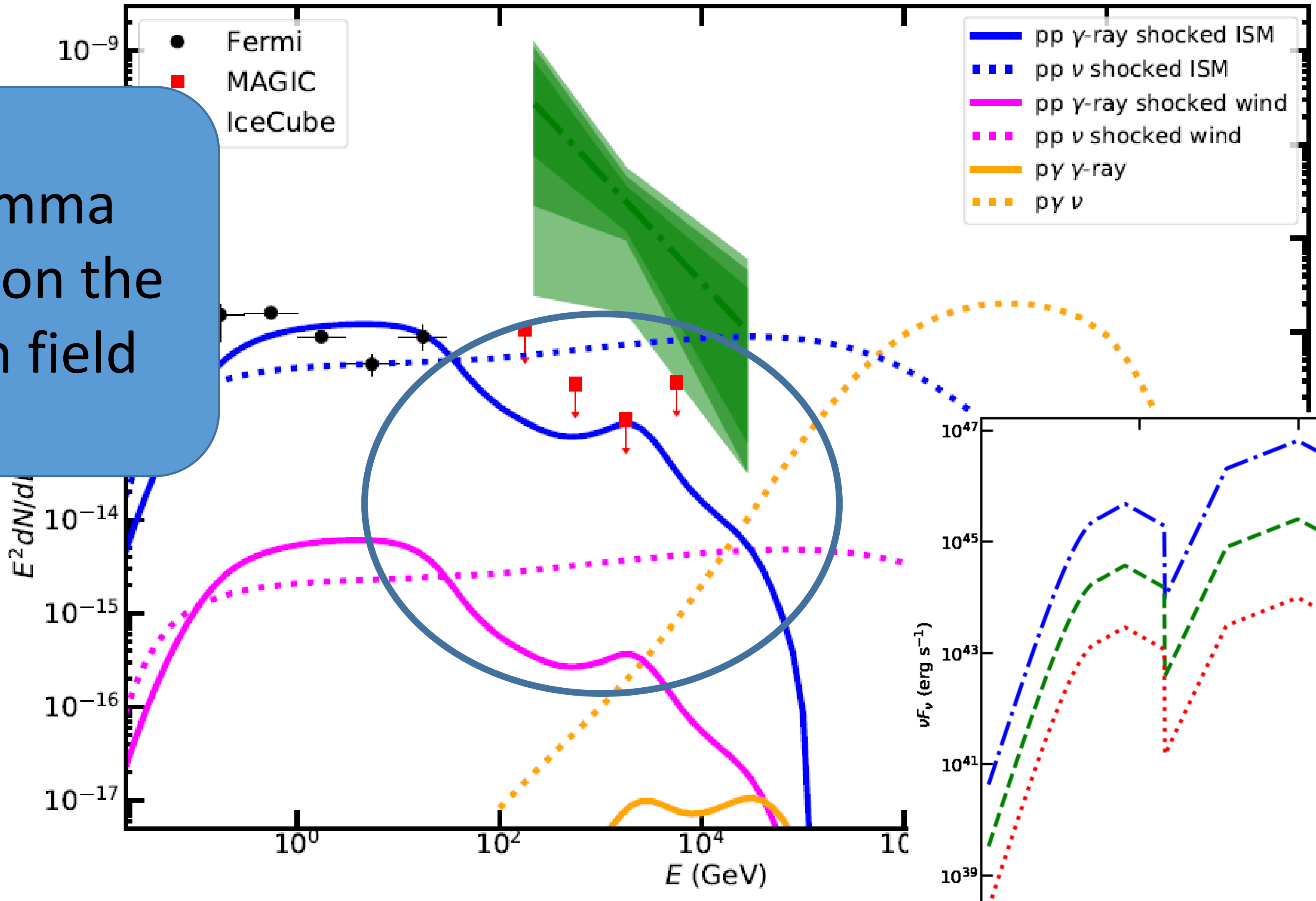


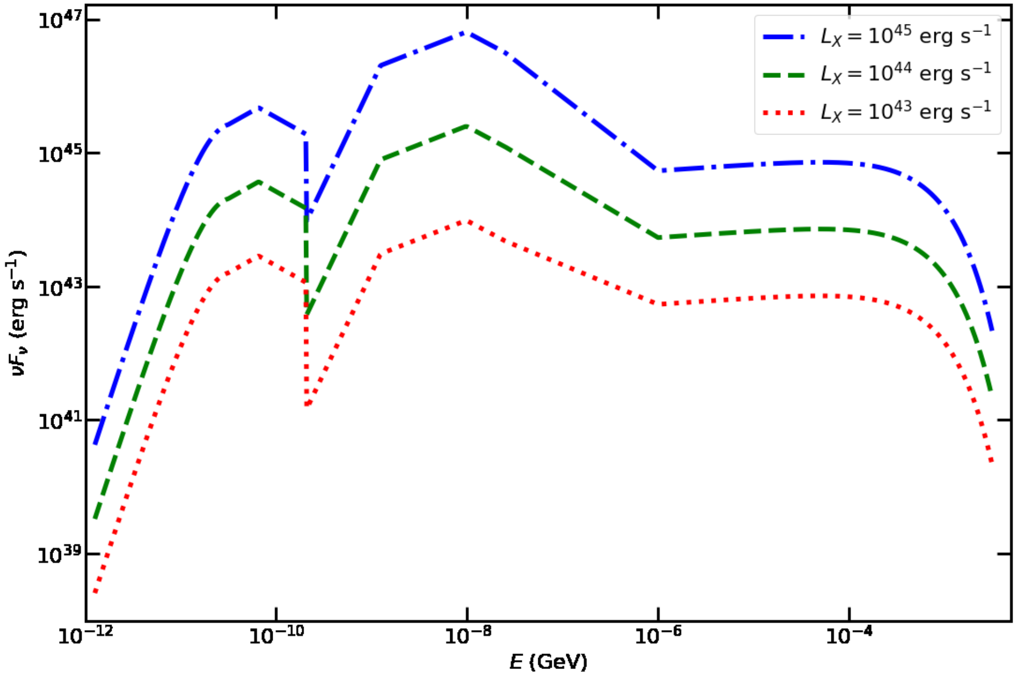
Multimessenger implications: NGC1068



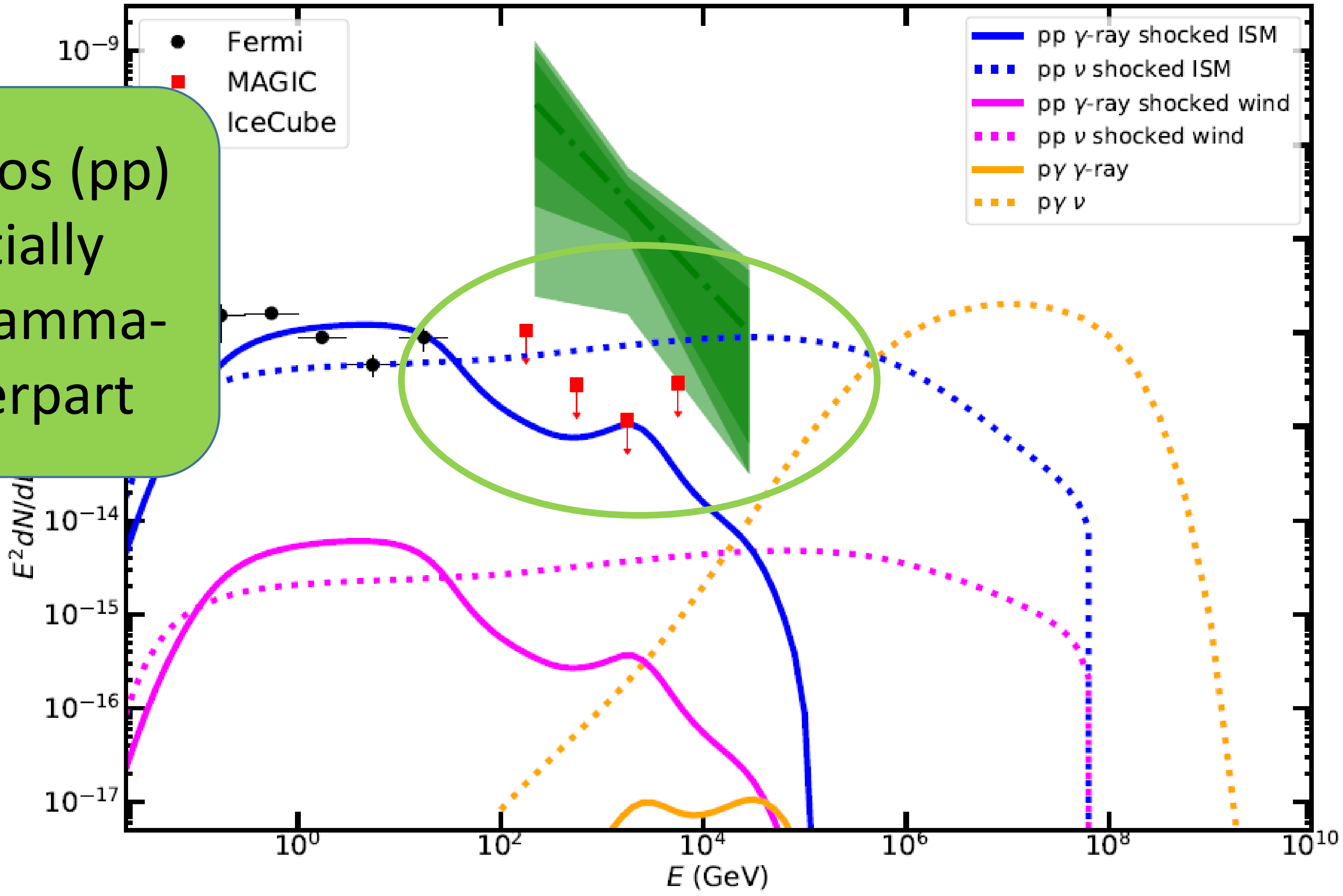
Multimessenger implications: NGC1068

Gamma-gamma absorption on the BKG photon field



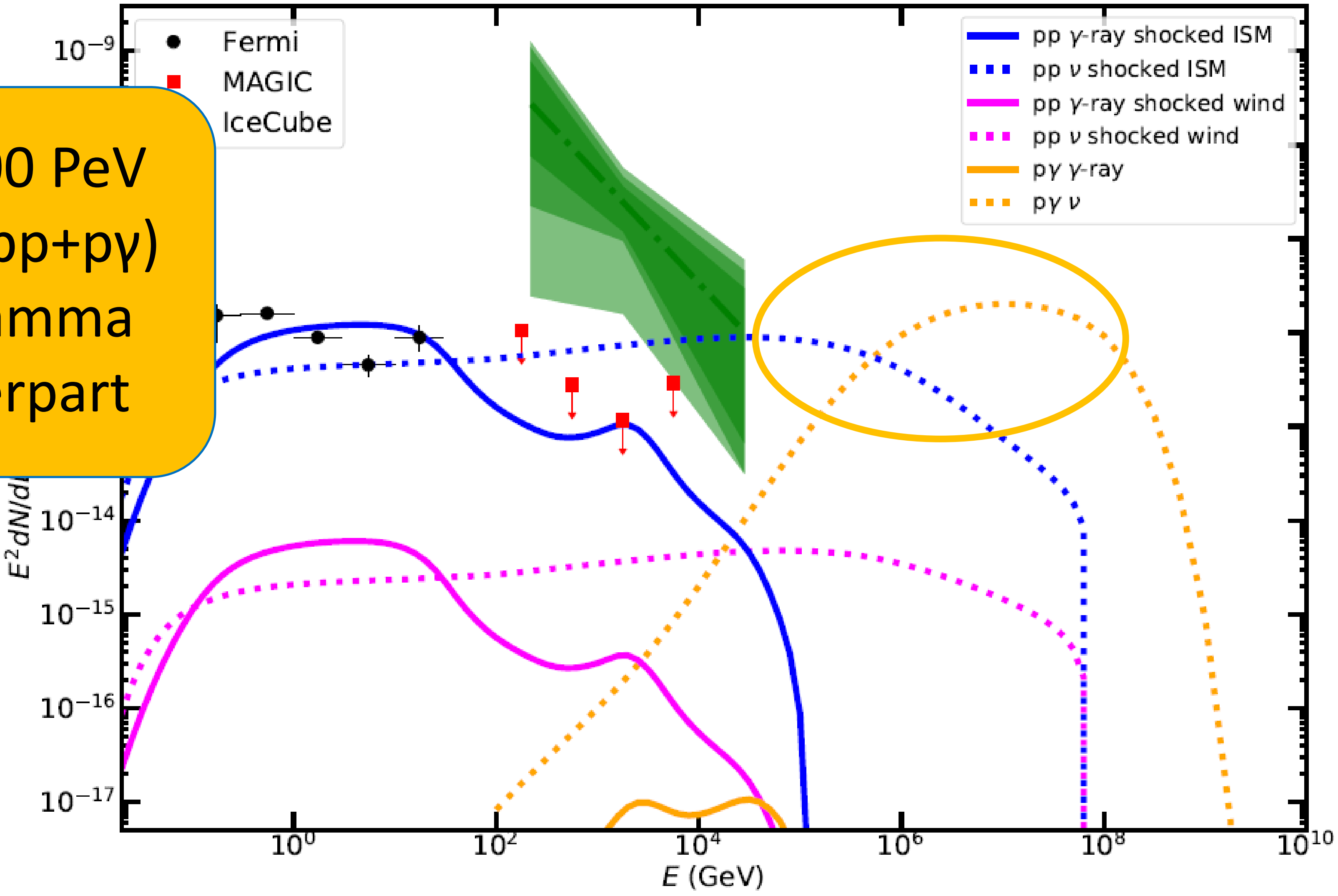


Multimessenger implications: NGC1068



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

Multimessenger implications: NGC1068



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

Take home messages 2

- 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

Thanks for your attention!