Diffusive shock acceleration in galactic wind bubbles

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Outline

- Wind bubbles: structure and evolution
- Model for particle acceleration in wind bubbles
- Solution: radial distribution and spectra
- Ultra Fast Outflows

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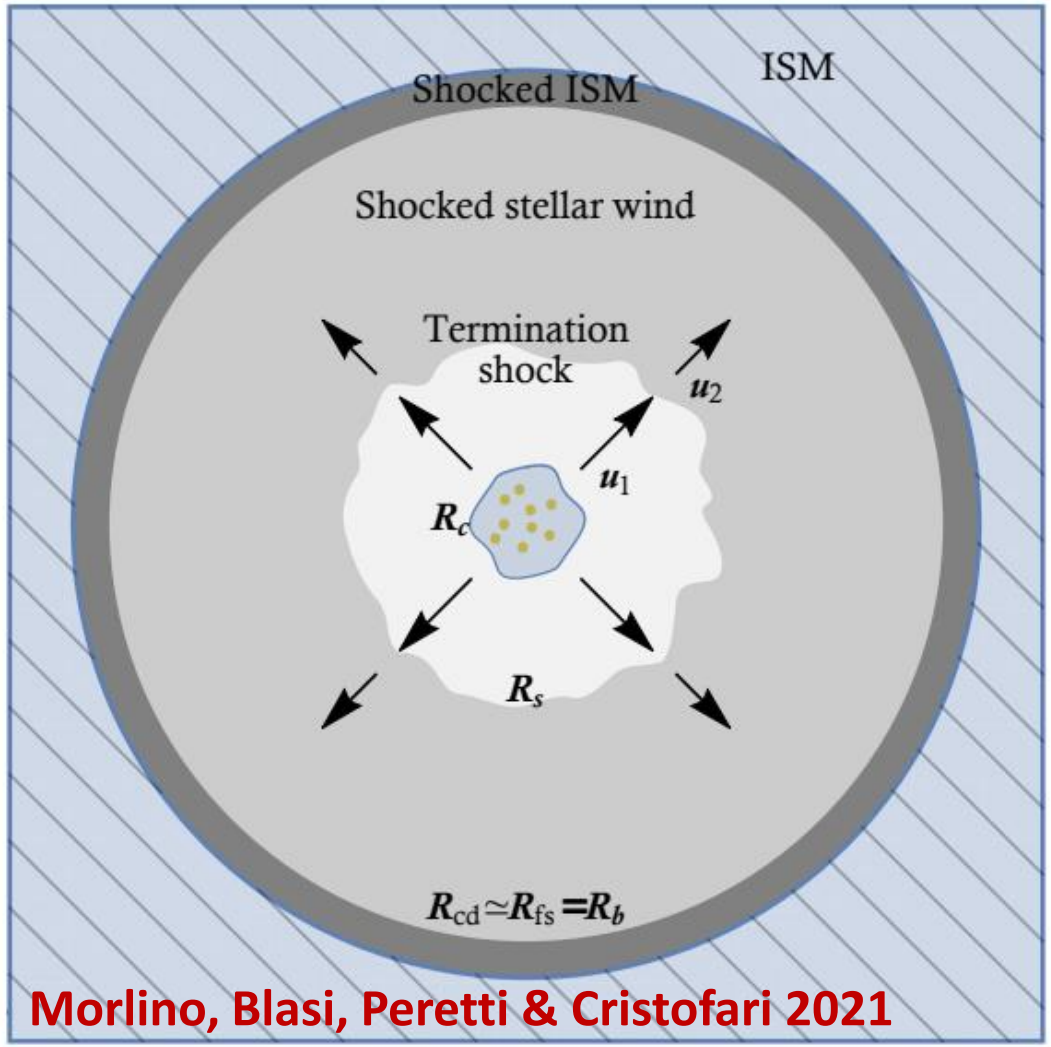
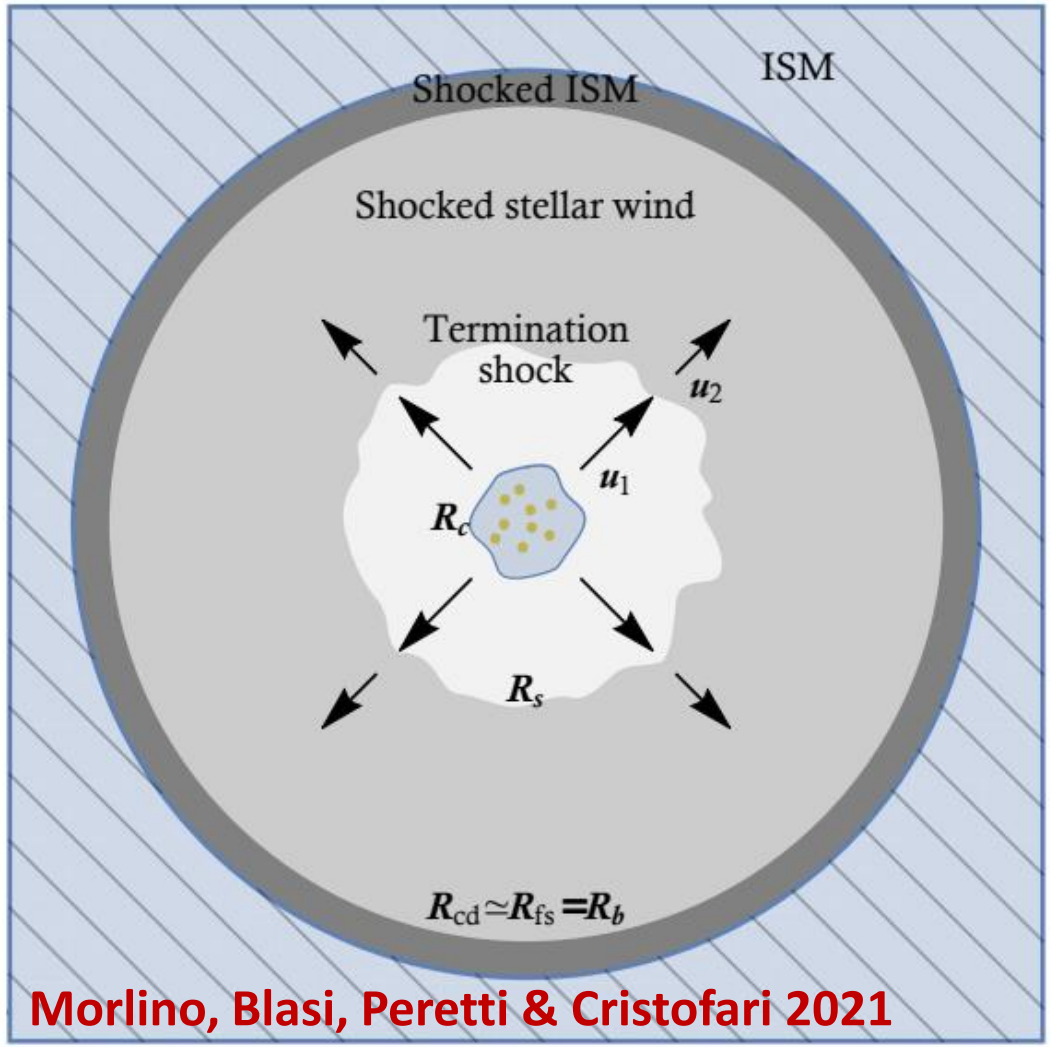
Wind Bubbles



Morlino, Blasi, Peretti & Cristofari 2021

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

Wind Bubbles

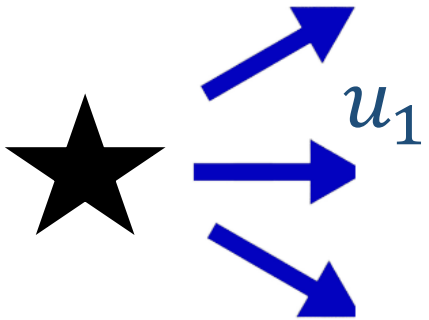


Morlino, Blasi, Peretti & Cristofari 2021

- **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: $\dot{M}$

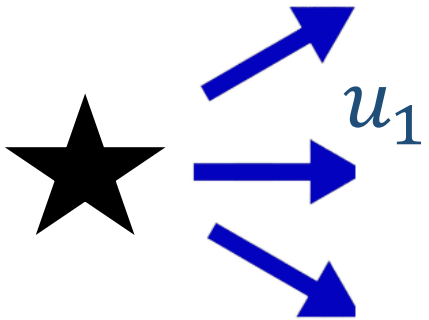
Wind bubble: structure and evolution



1. The outflow is launched - t_0

Wind bubble: structure and evolution

$u_1 \gg c_s$



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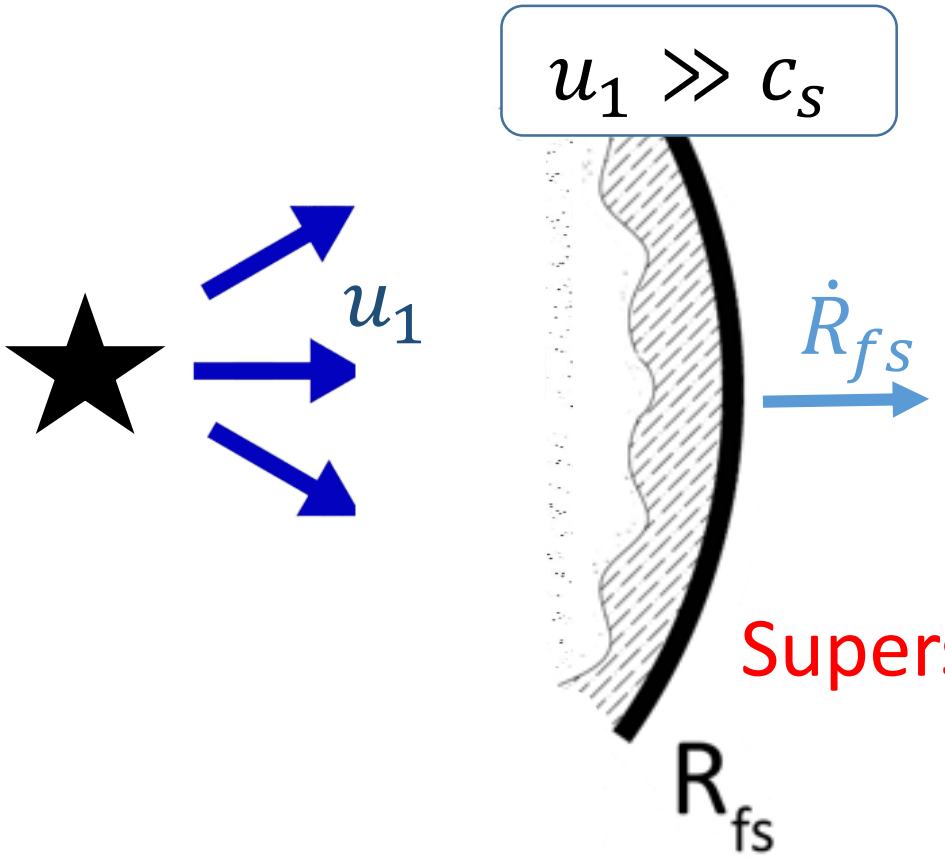

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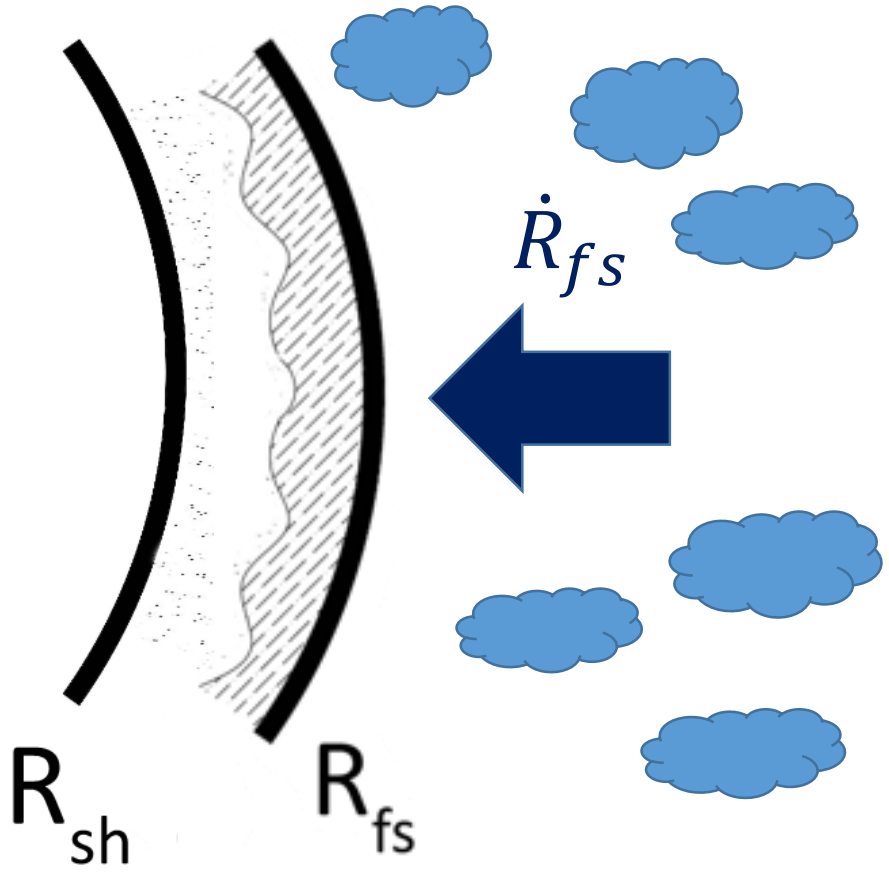
Supersonic → forward shock

Wind bubble: structure and evolution

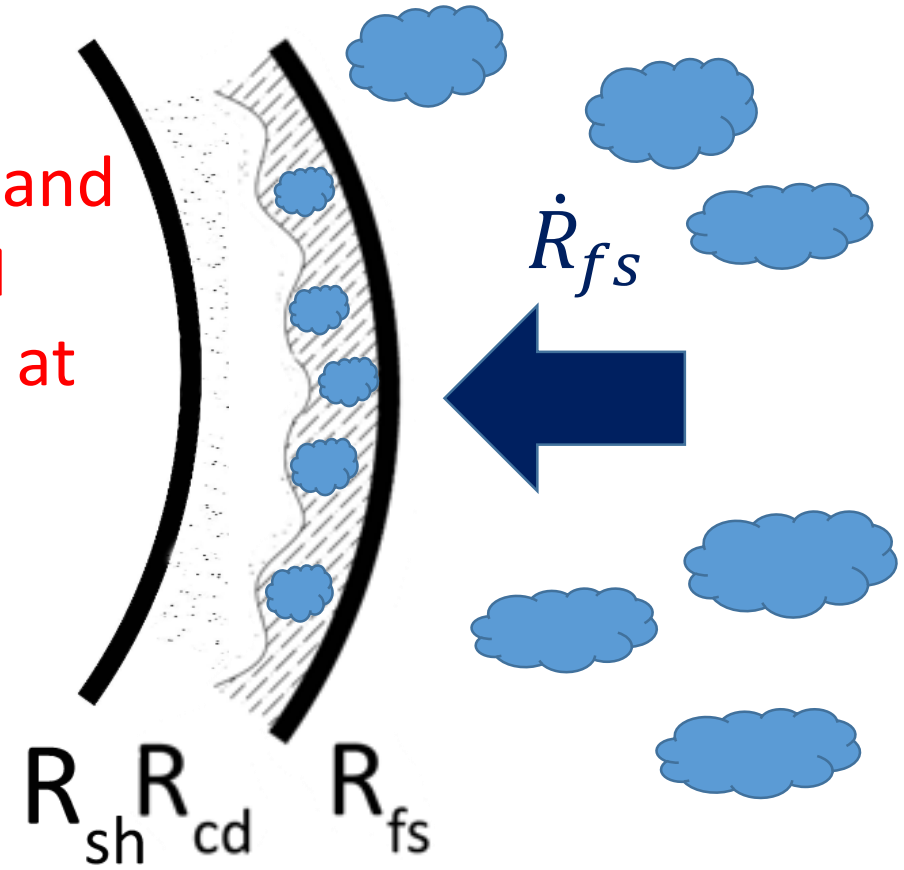
Collision with ISM → wind shock



1. The outflow is launched - t_0

Wind bubble: structure and evolution

Compressed and shocked ISM accumulated at the contact discontinuity



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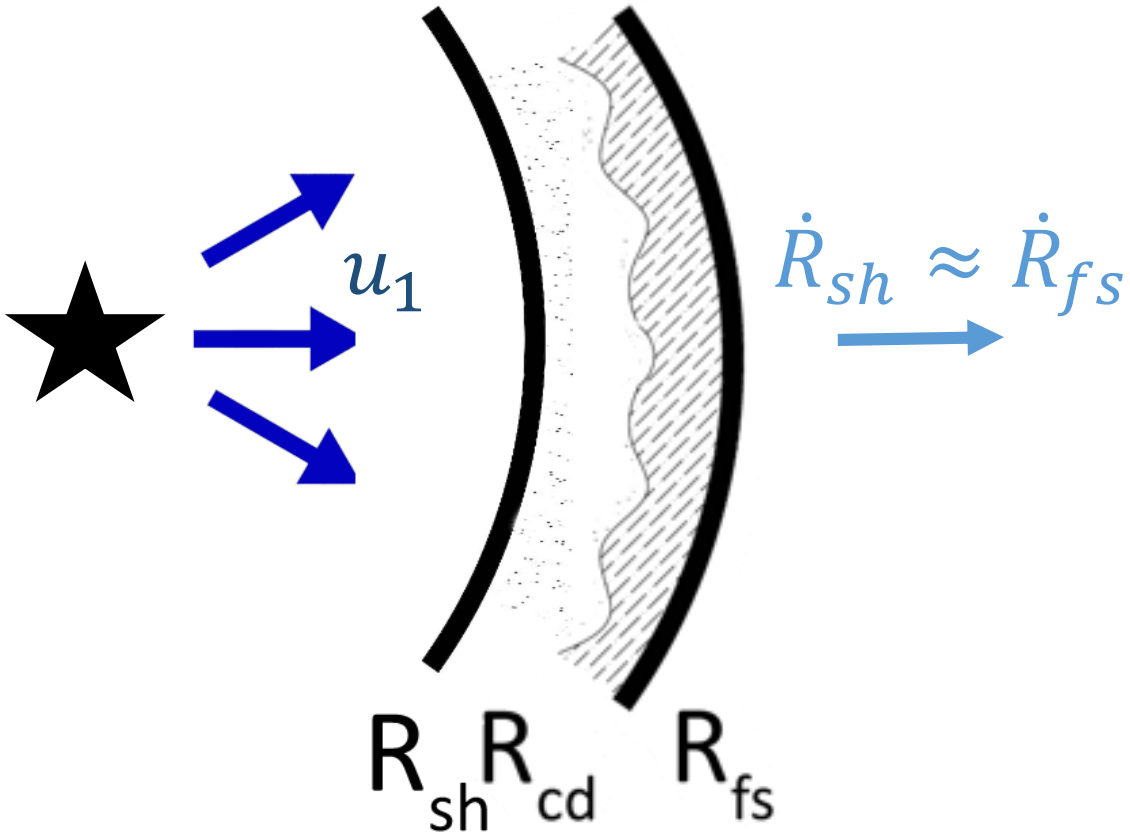
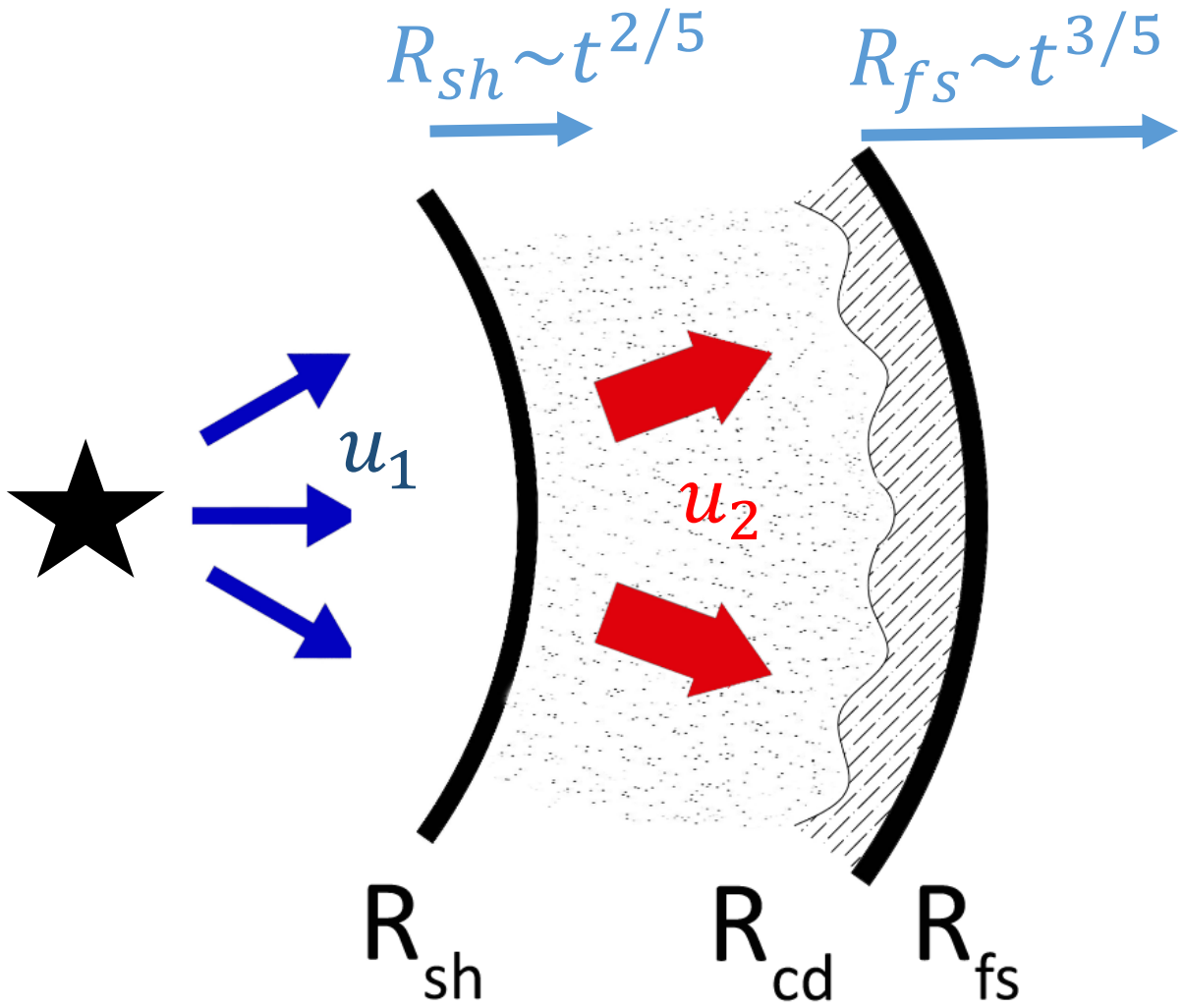
Wind bubble: structure and evolution



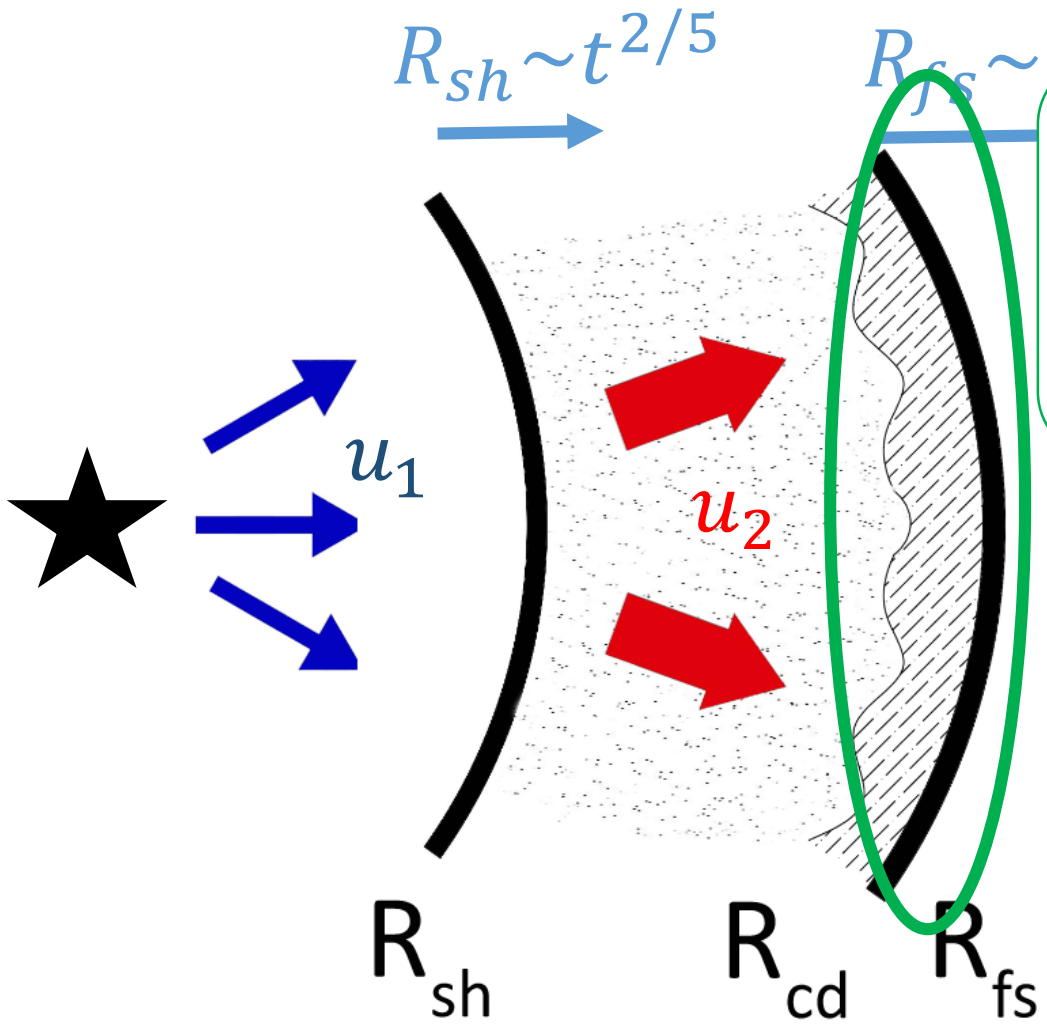
1. The outflow is launched - t_0
2. Free expansion phase - t_1

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



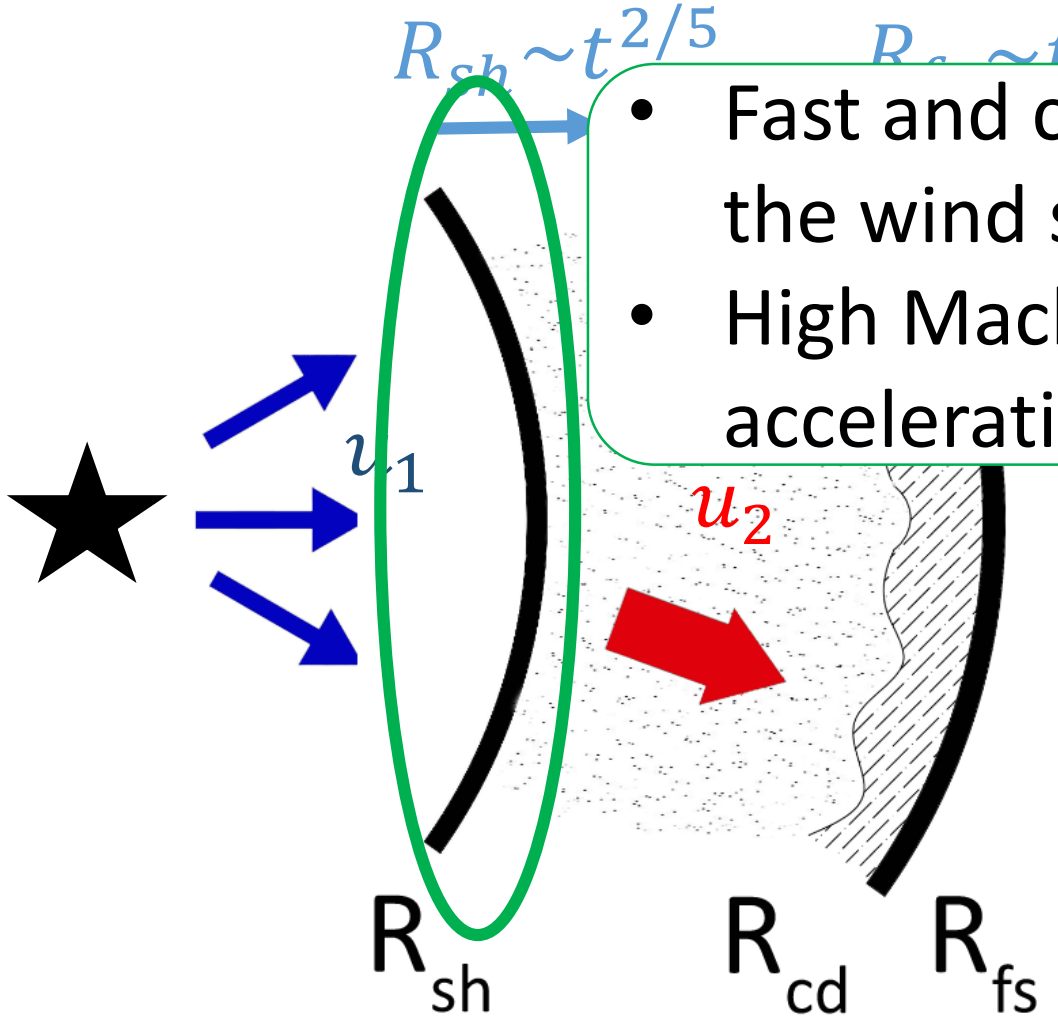
- Rapid fall of acceleration efficiency in time
- Mach number dependent on the external medium

hed - t_0

2. Free expansion phase - t_1

3. Deceleration phase - $t > t_1$

Wind bubble: structure and evolution



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

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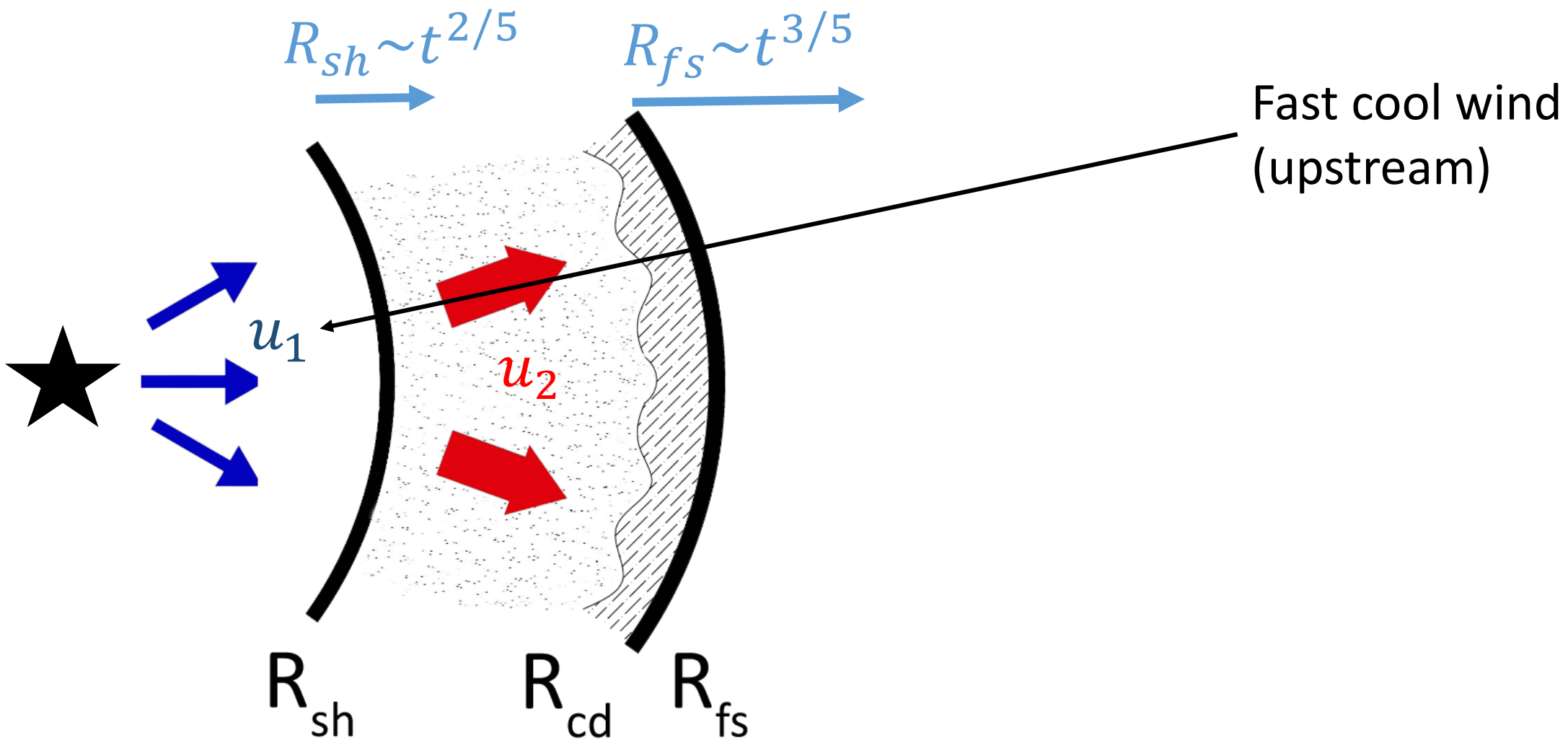
2. Free expansion phase - t_1

3. Deceleration phase - $t > t_1$

Wind bubble: structure and evolution



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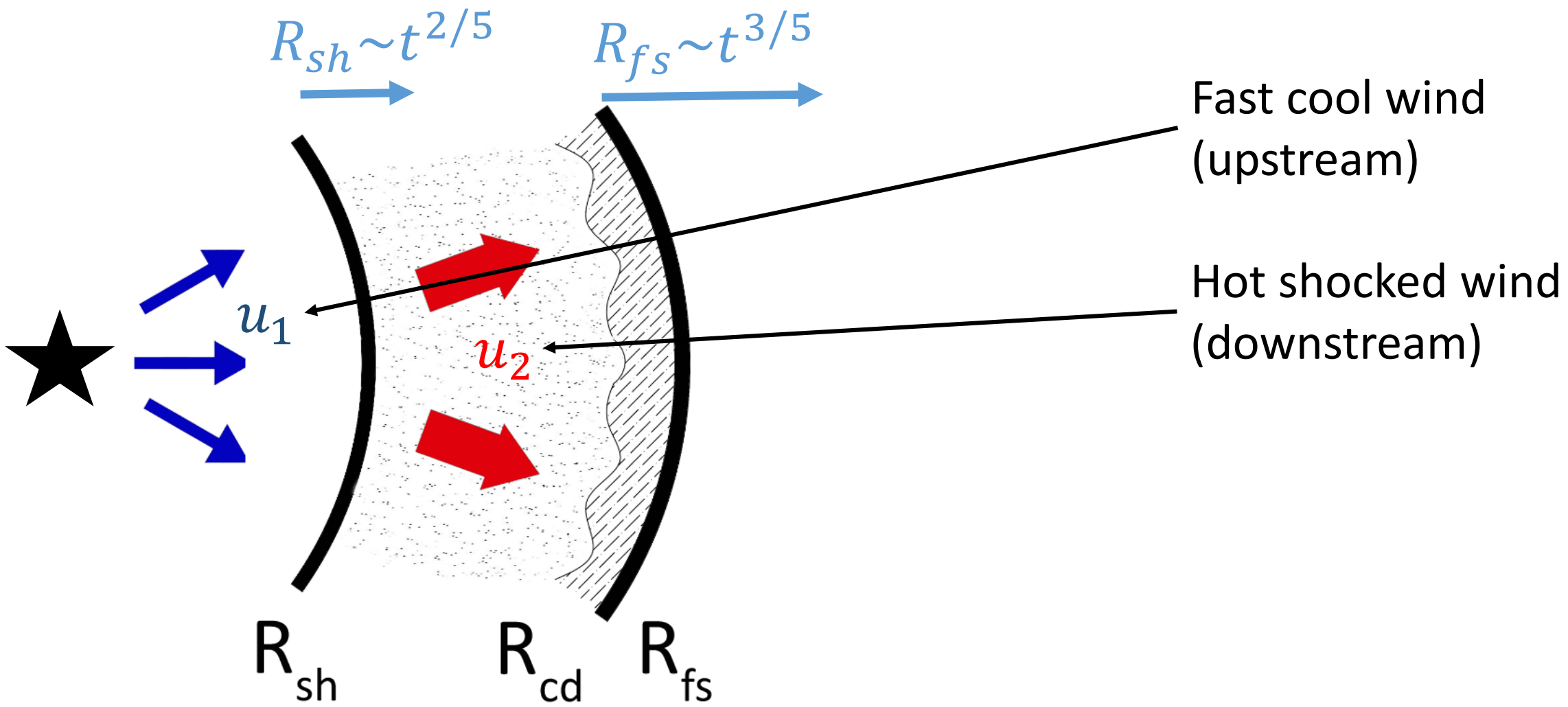

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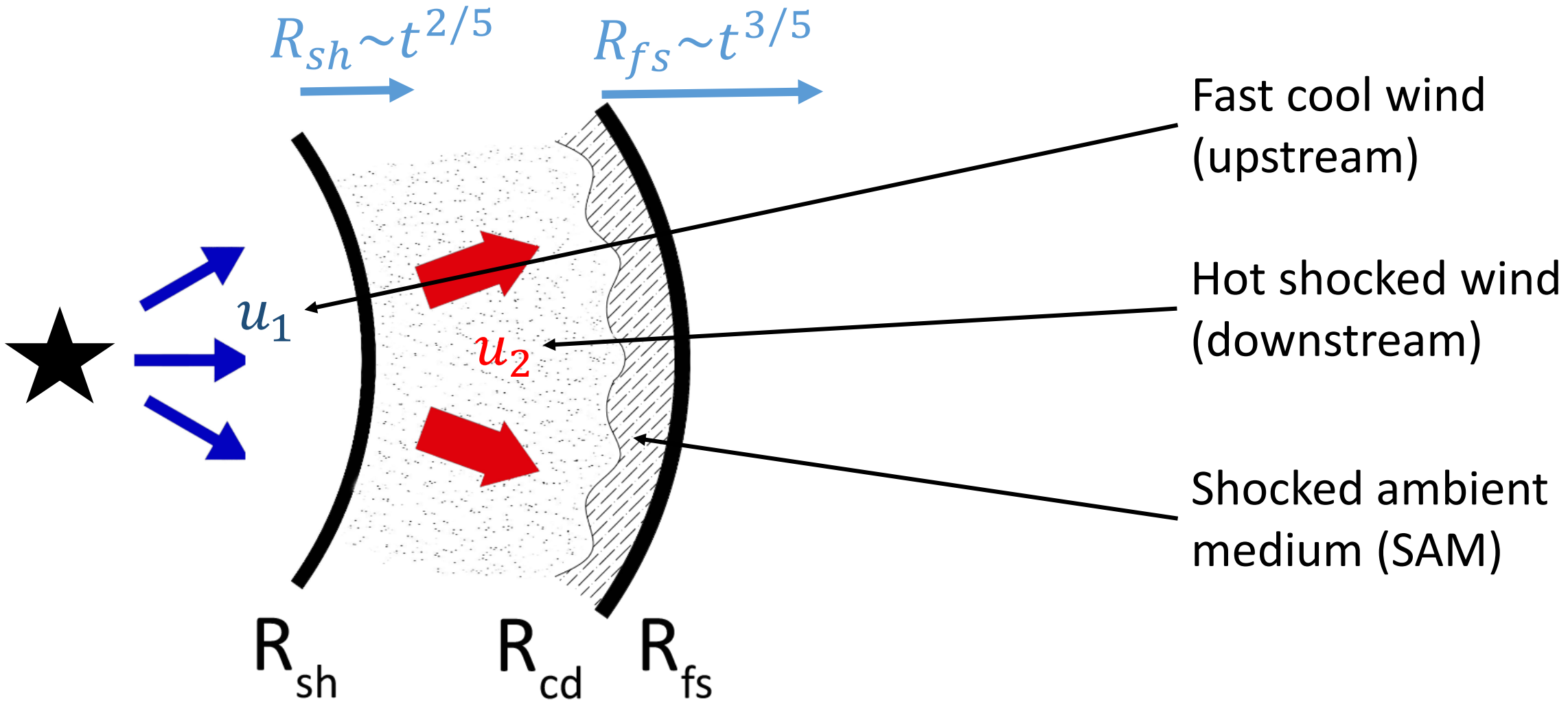
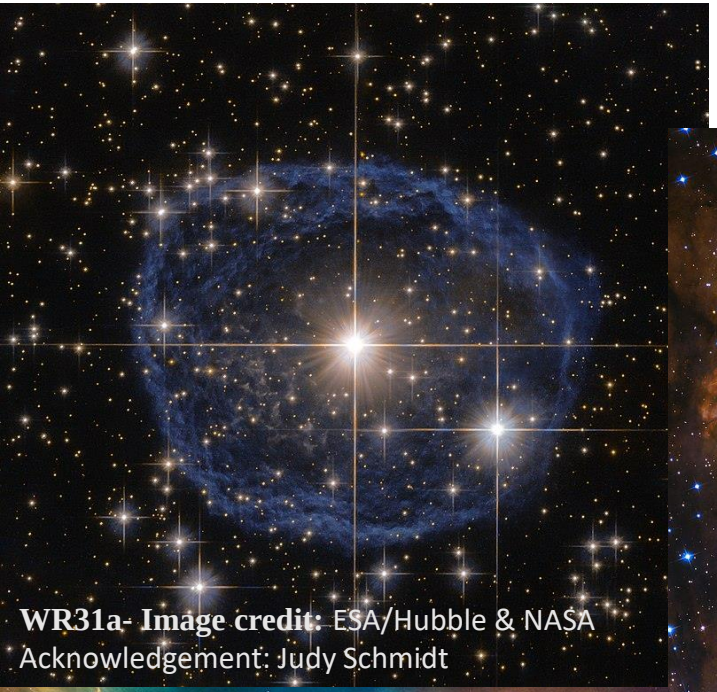
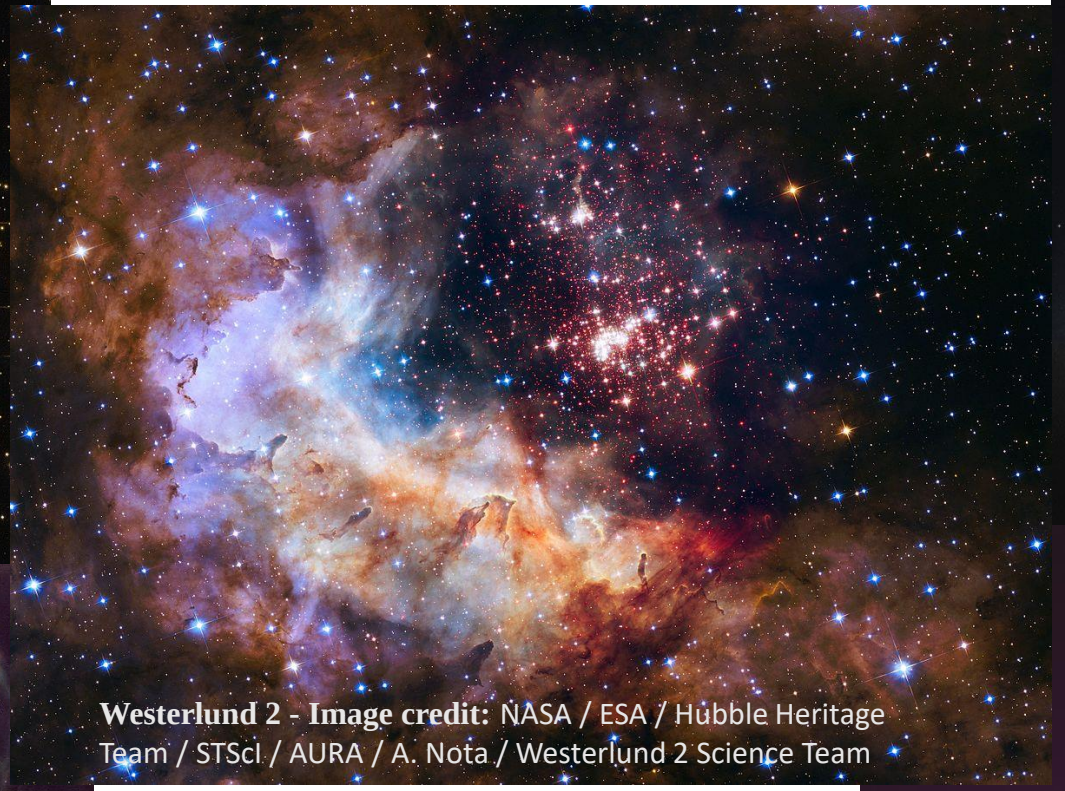


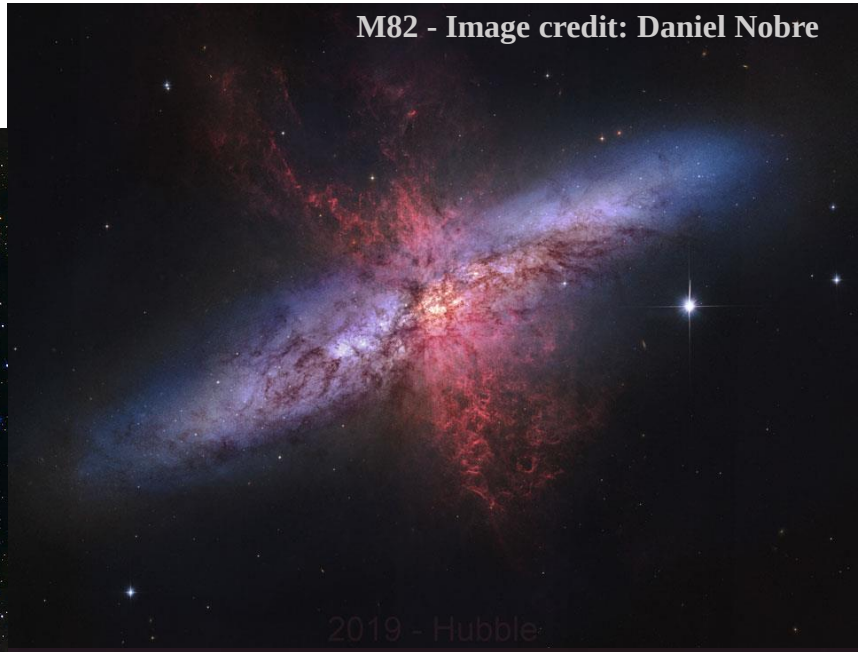
Wind Bubbles: scales and power



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

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

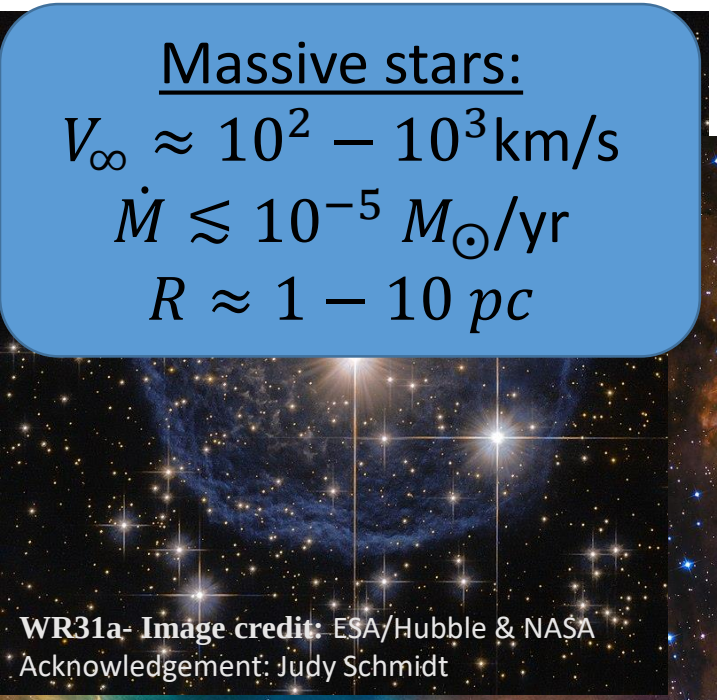
Wind Bubbles: scales and power

Massive stars:

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

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

$R \approx 1 - 10\ pc$



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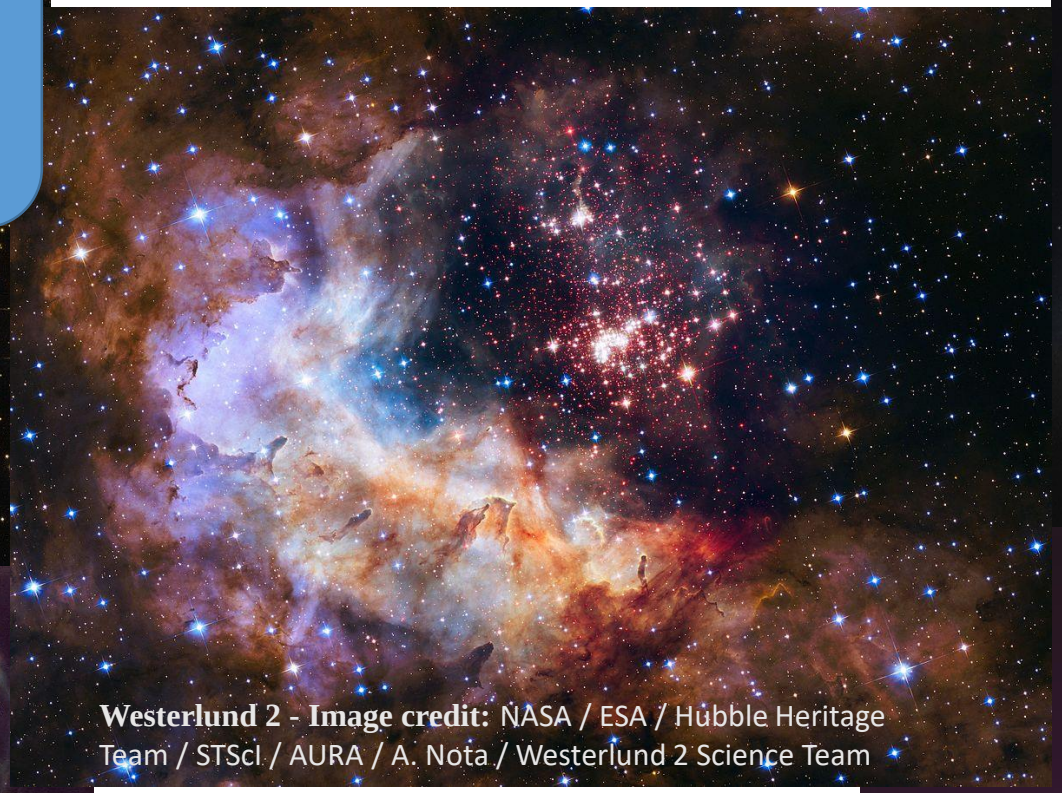

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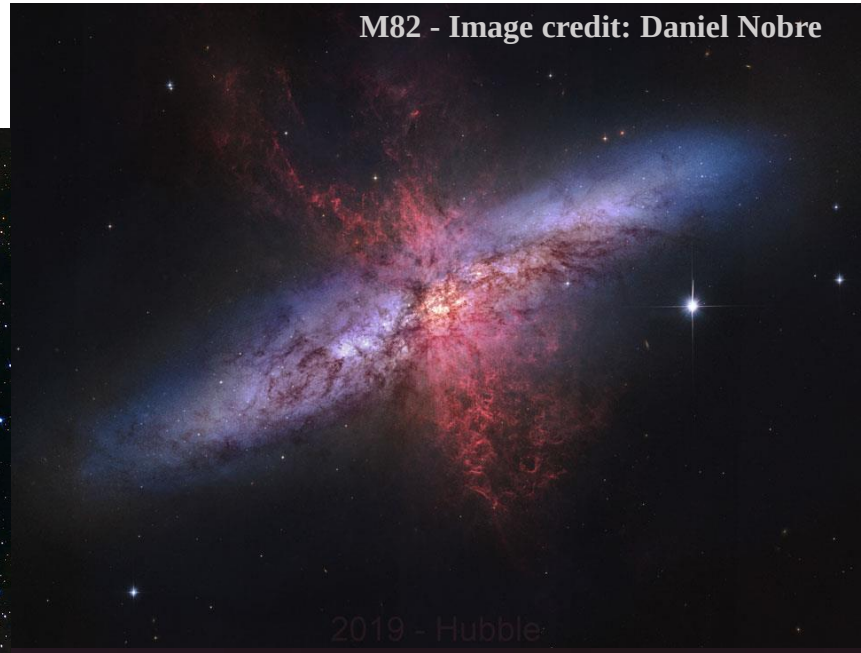

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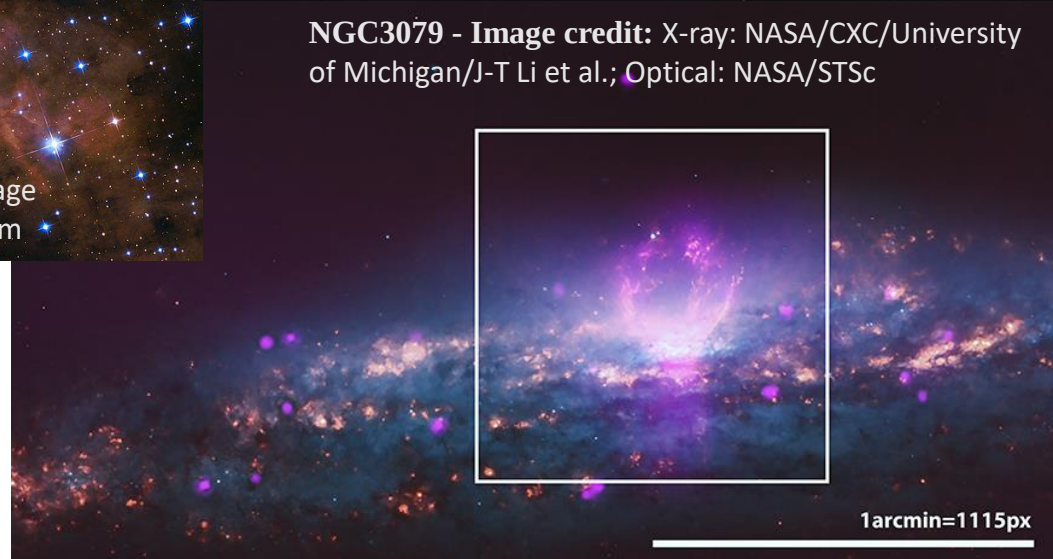

NGC3079 - Image credit: X-ray: NASA/CXC/University of Michigan/J-T Li et al.; Optical: NASA/STSc

Wind Bubbles: scales and power

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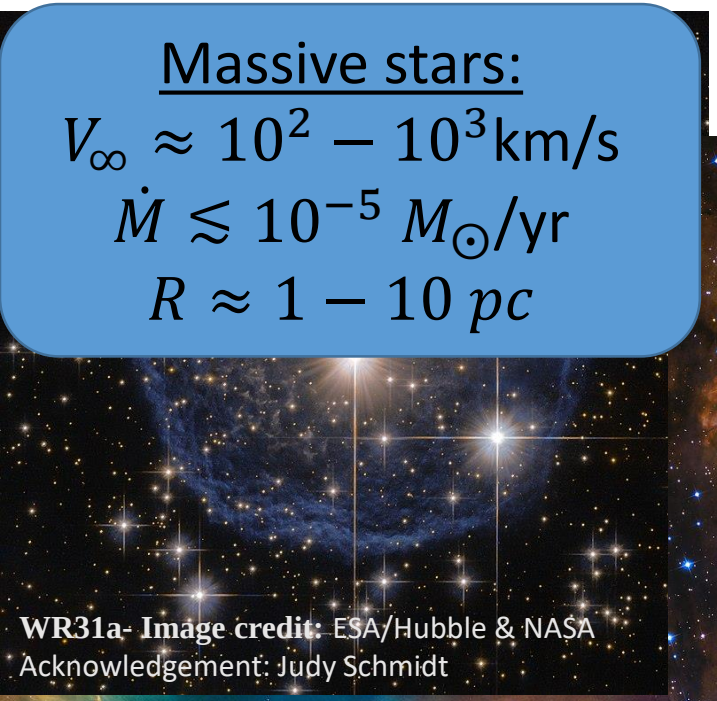

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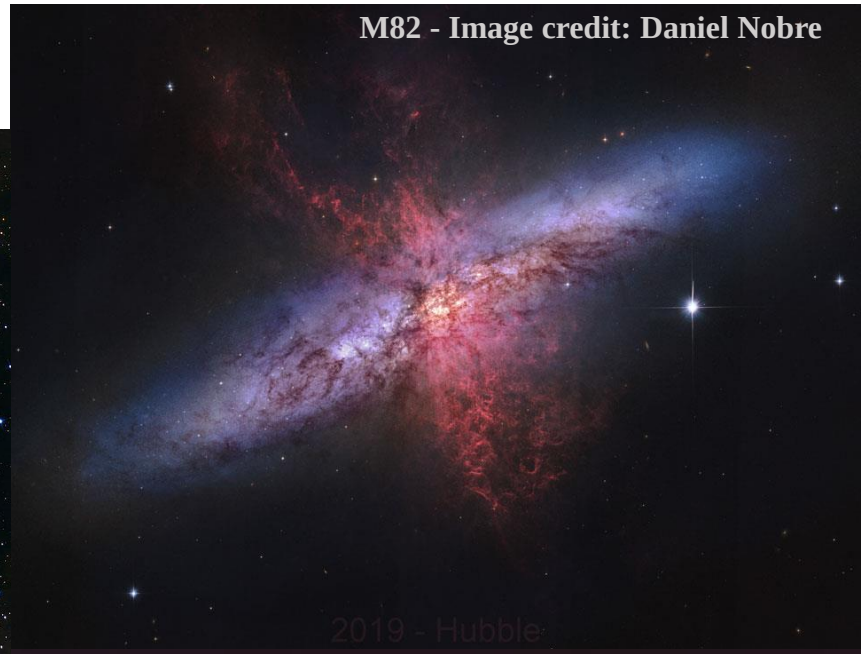

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Star clusters:

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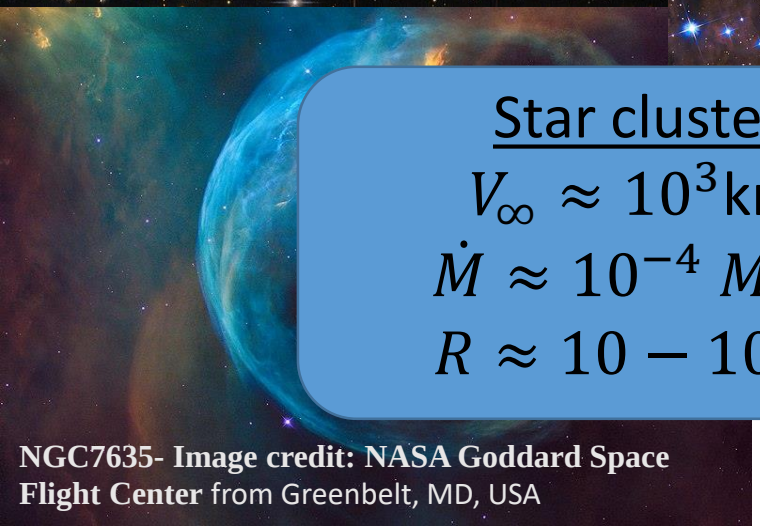

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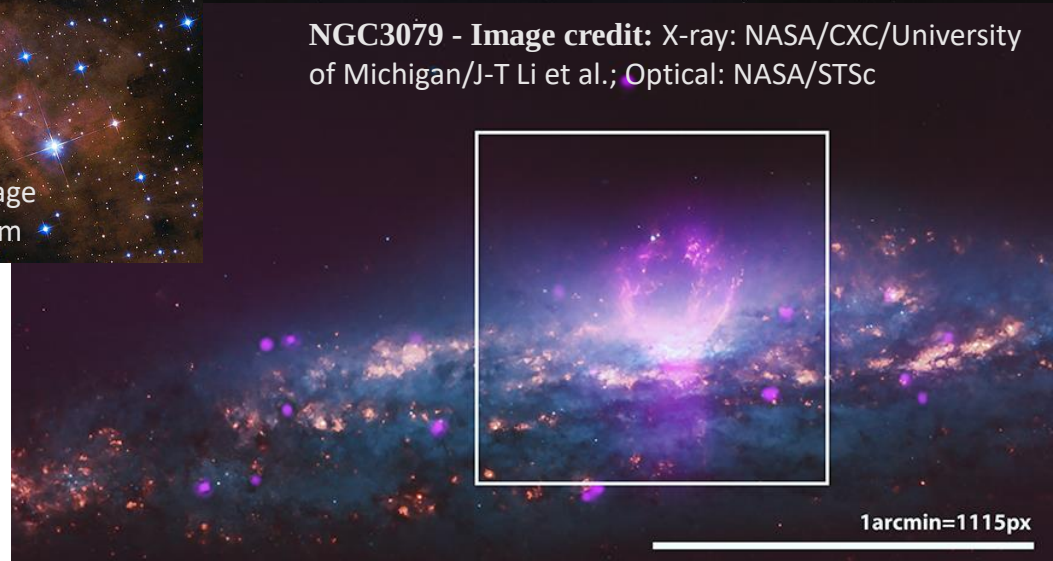

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Starbursts:

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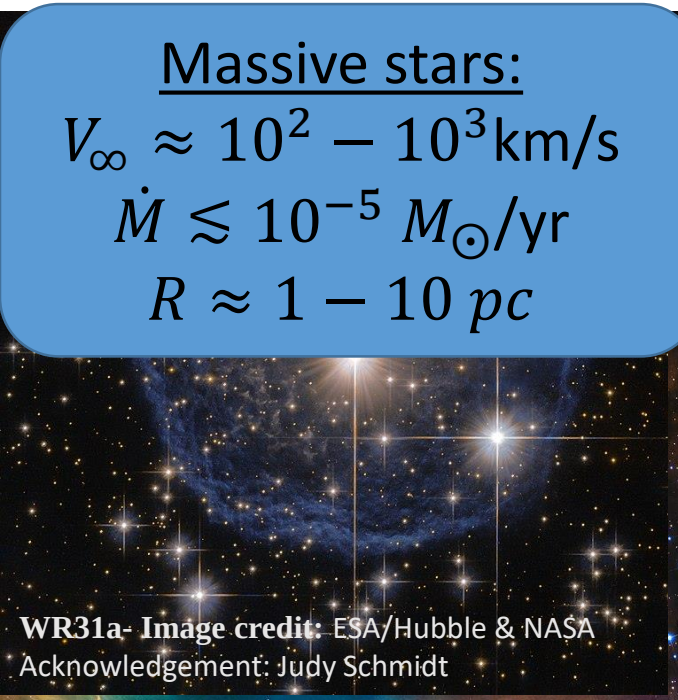

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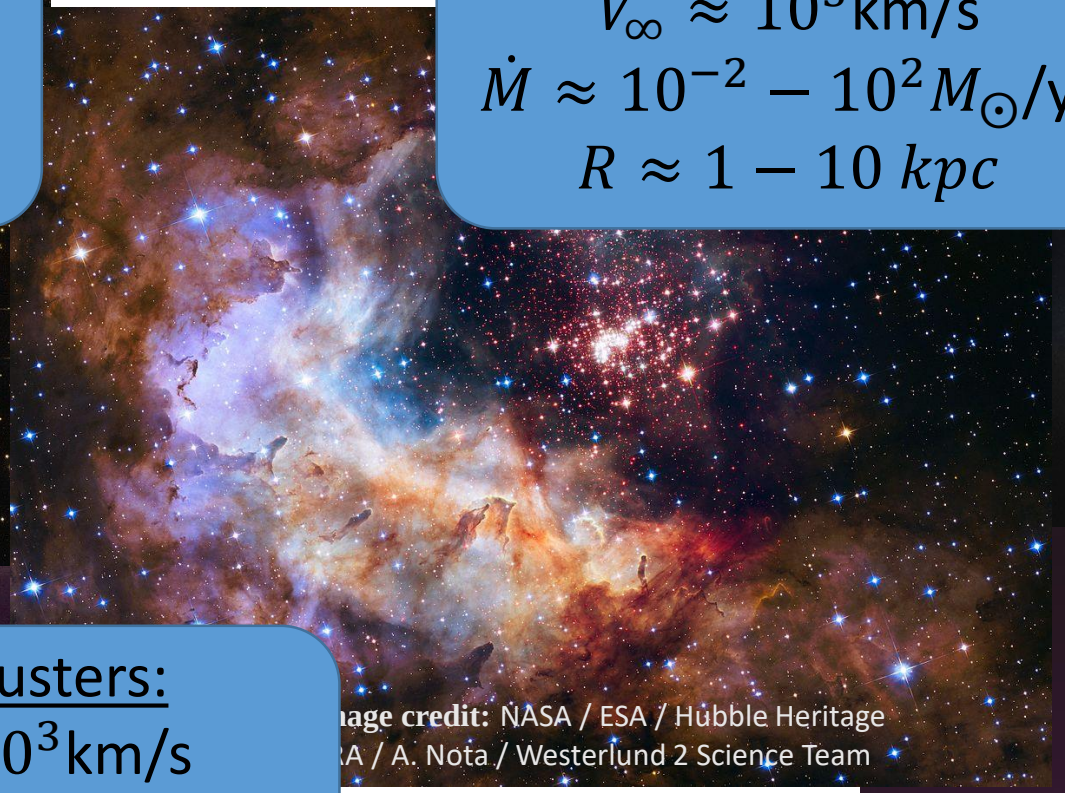

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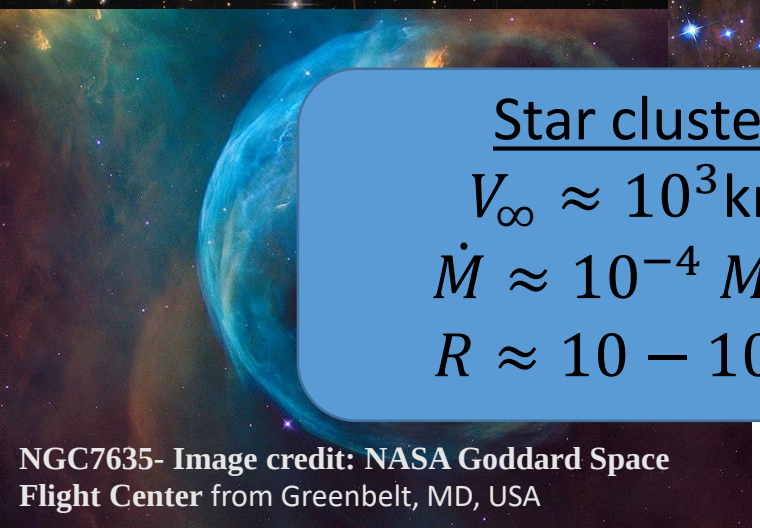

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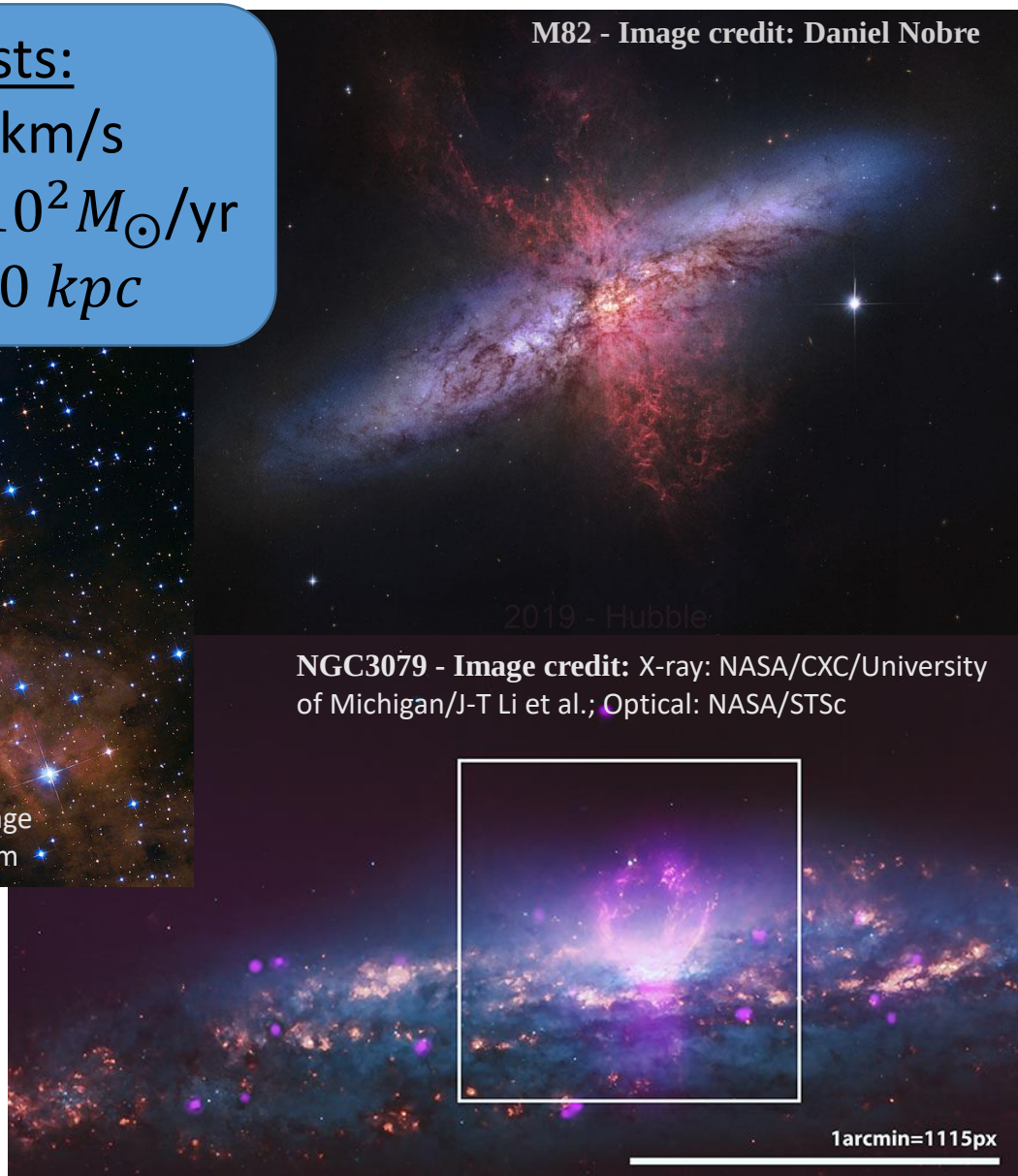

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2019 - Hubble

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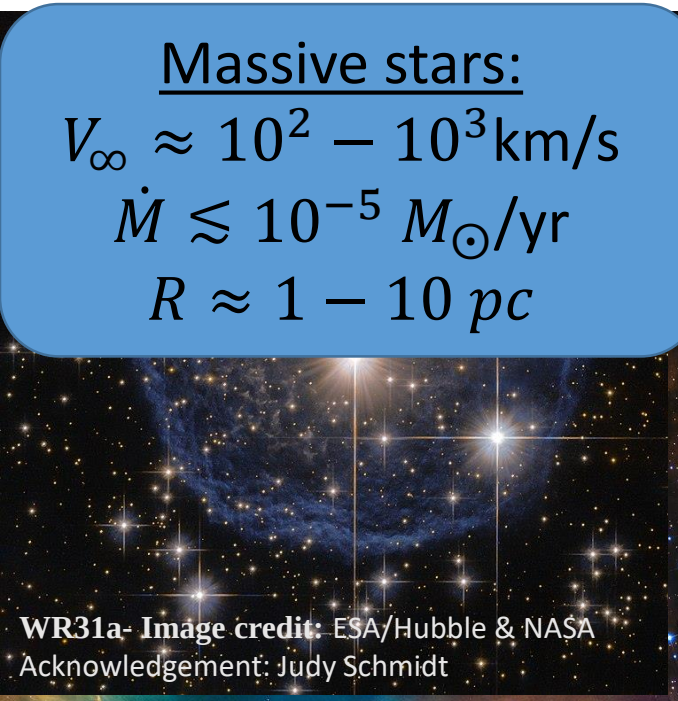

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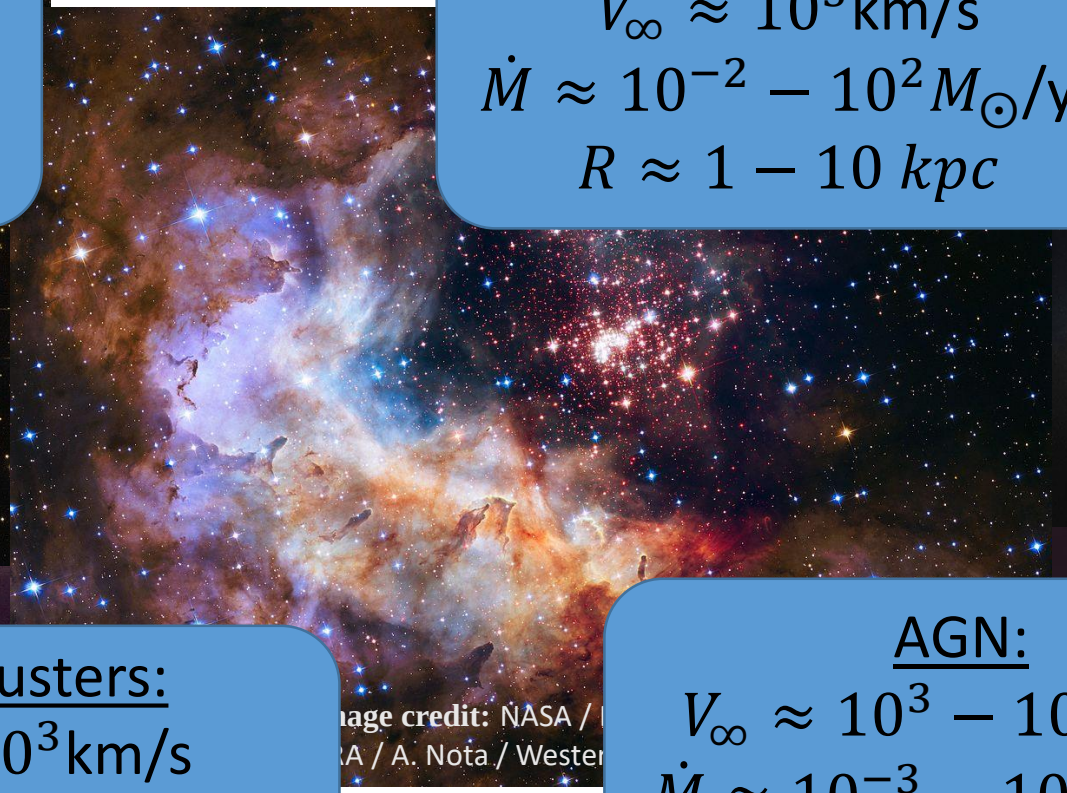

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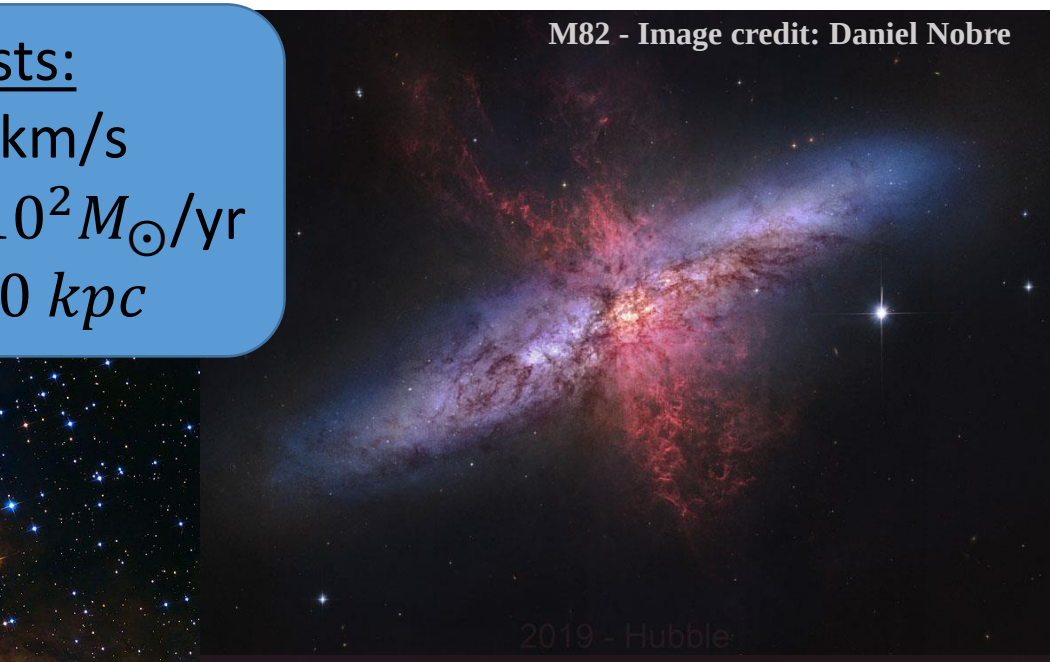

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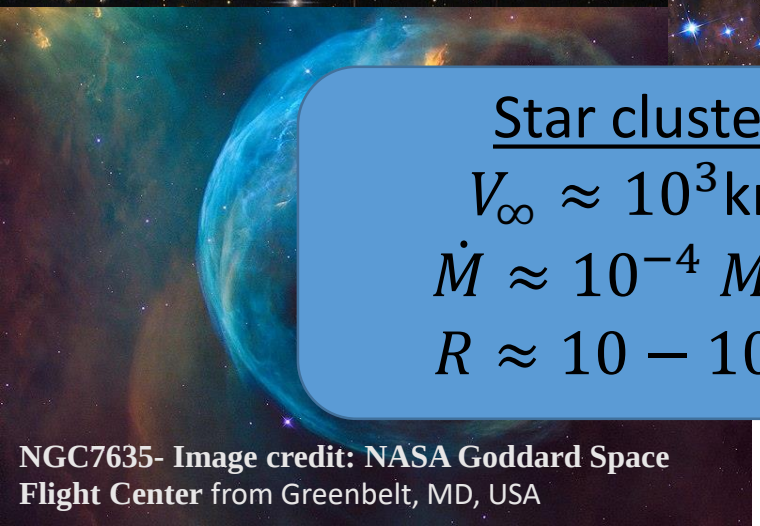

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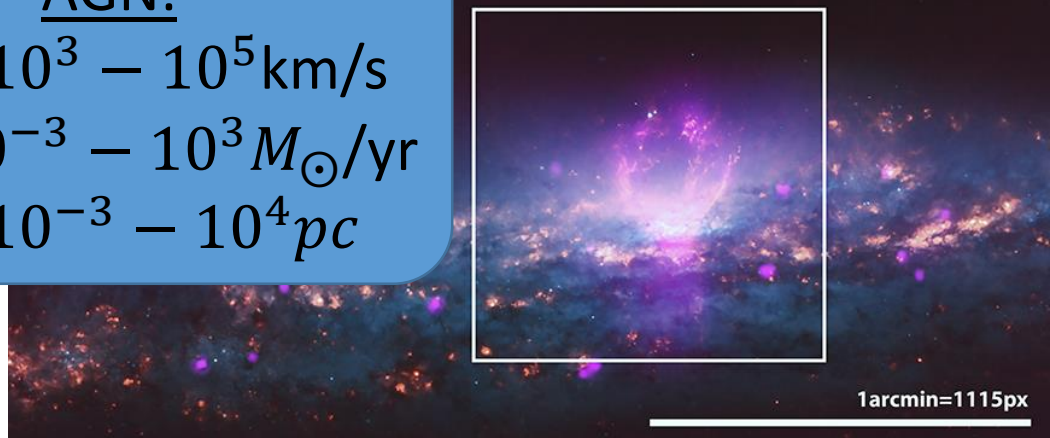

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Maximum Energy: a first guess

$$E_{max} \approx \xi \; q \; B \; \frac{u_1}{c} R_{sh}\left(u_1, \dot{M}\right)$$

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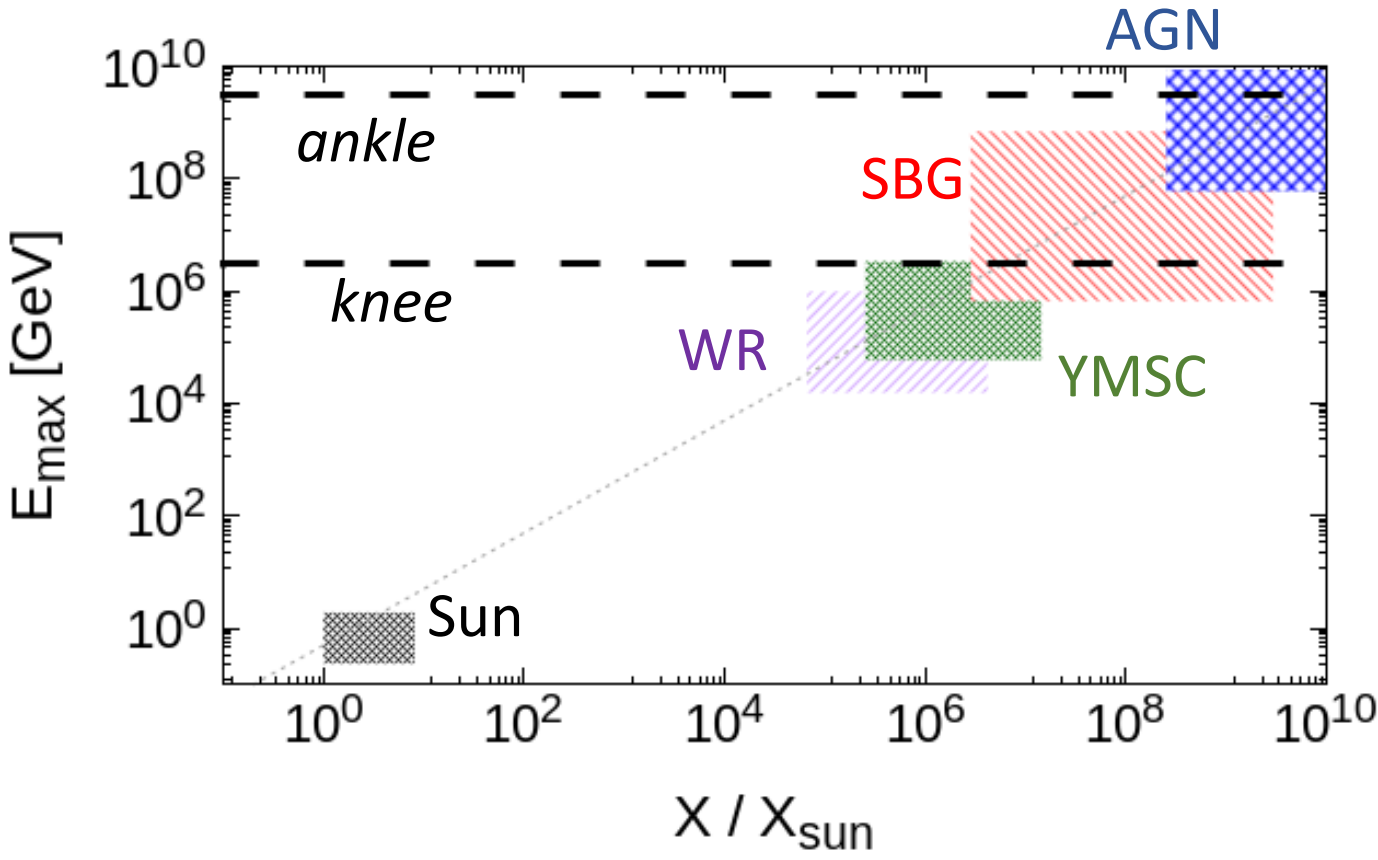
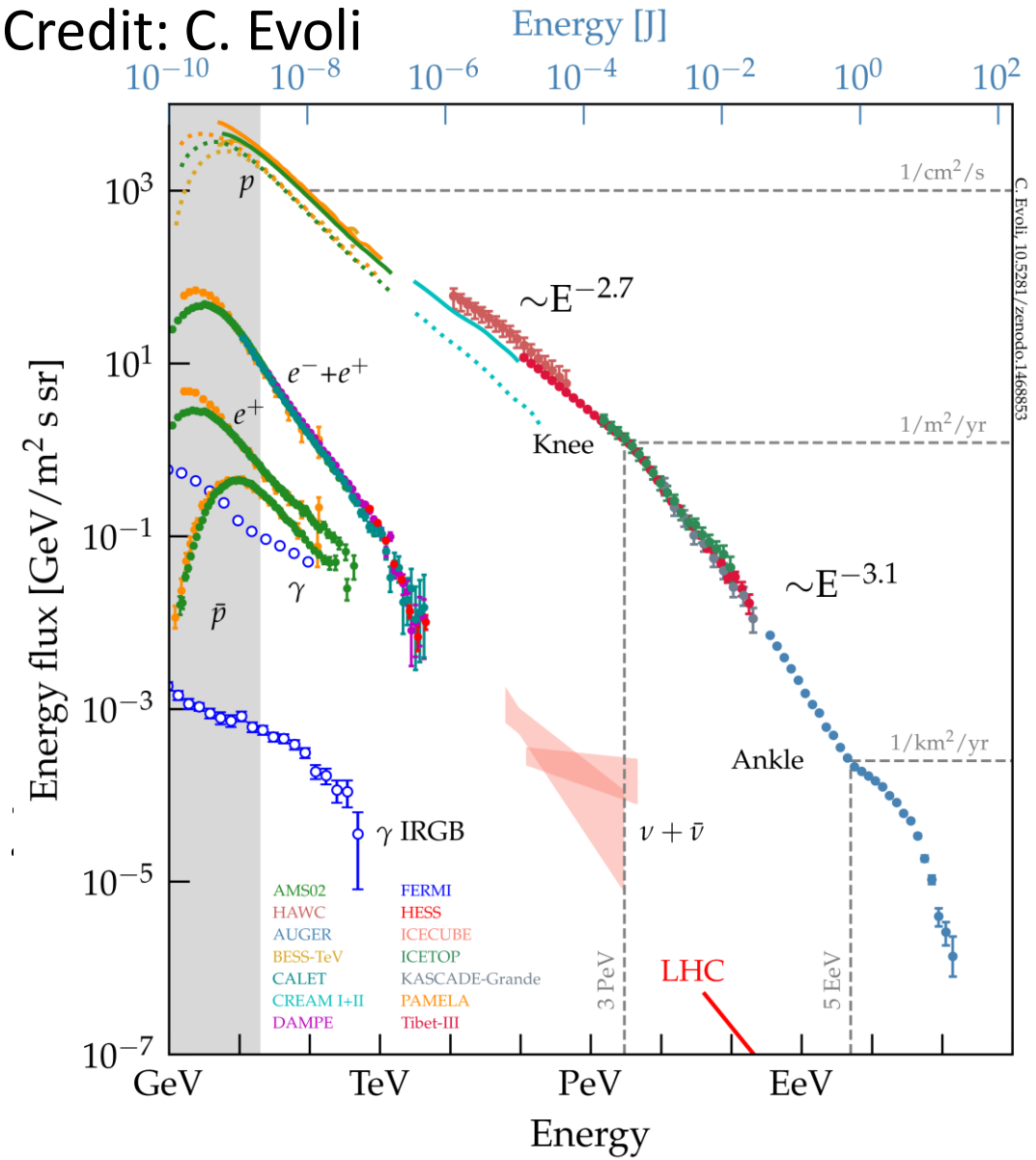
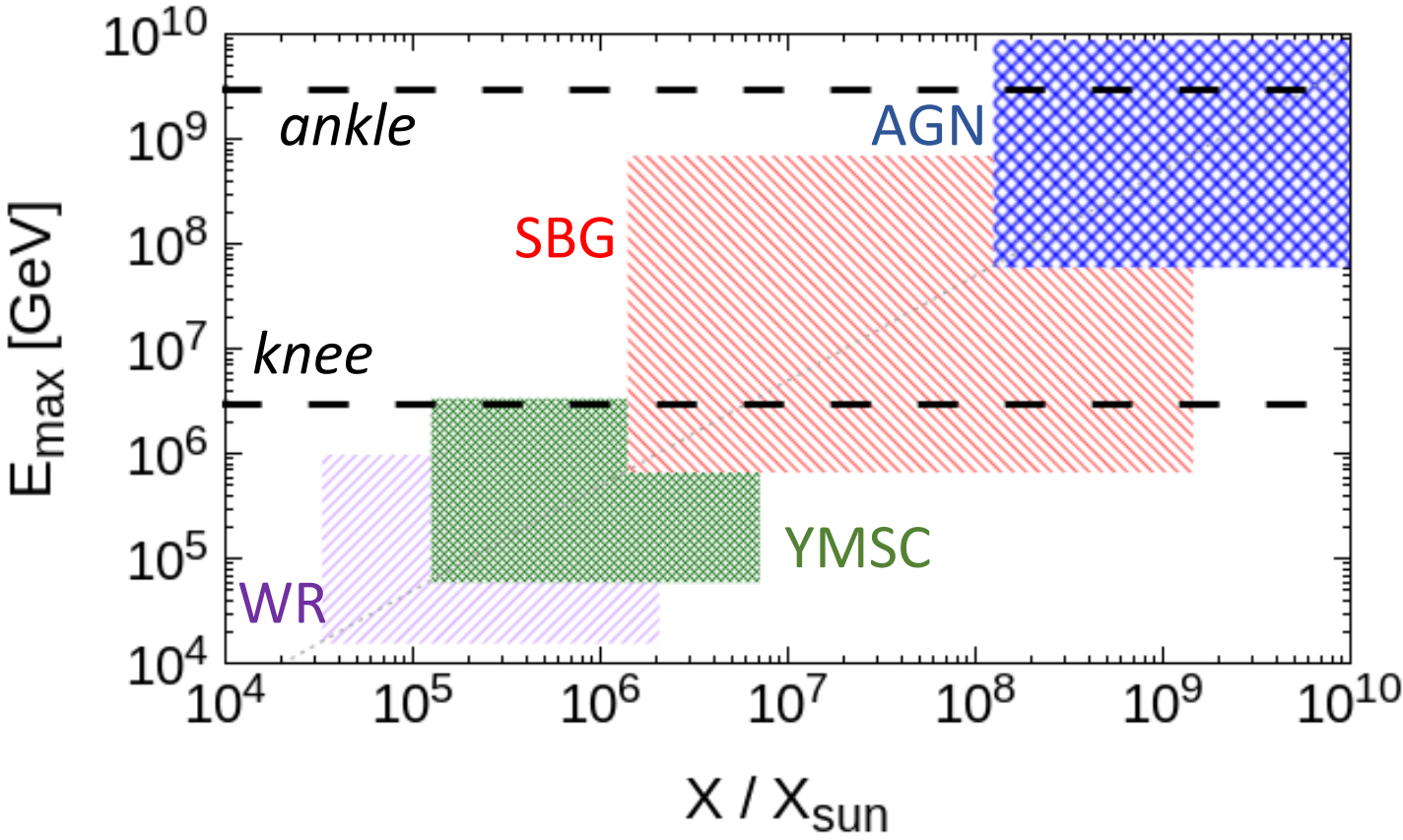
$$X \propto q\, \varepsilon_B^{1/2}\, \dot{M}^{1/2} u_1^{3/2}$$



Why wind bubbles?

Credit: C. Evoli





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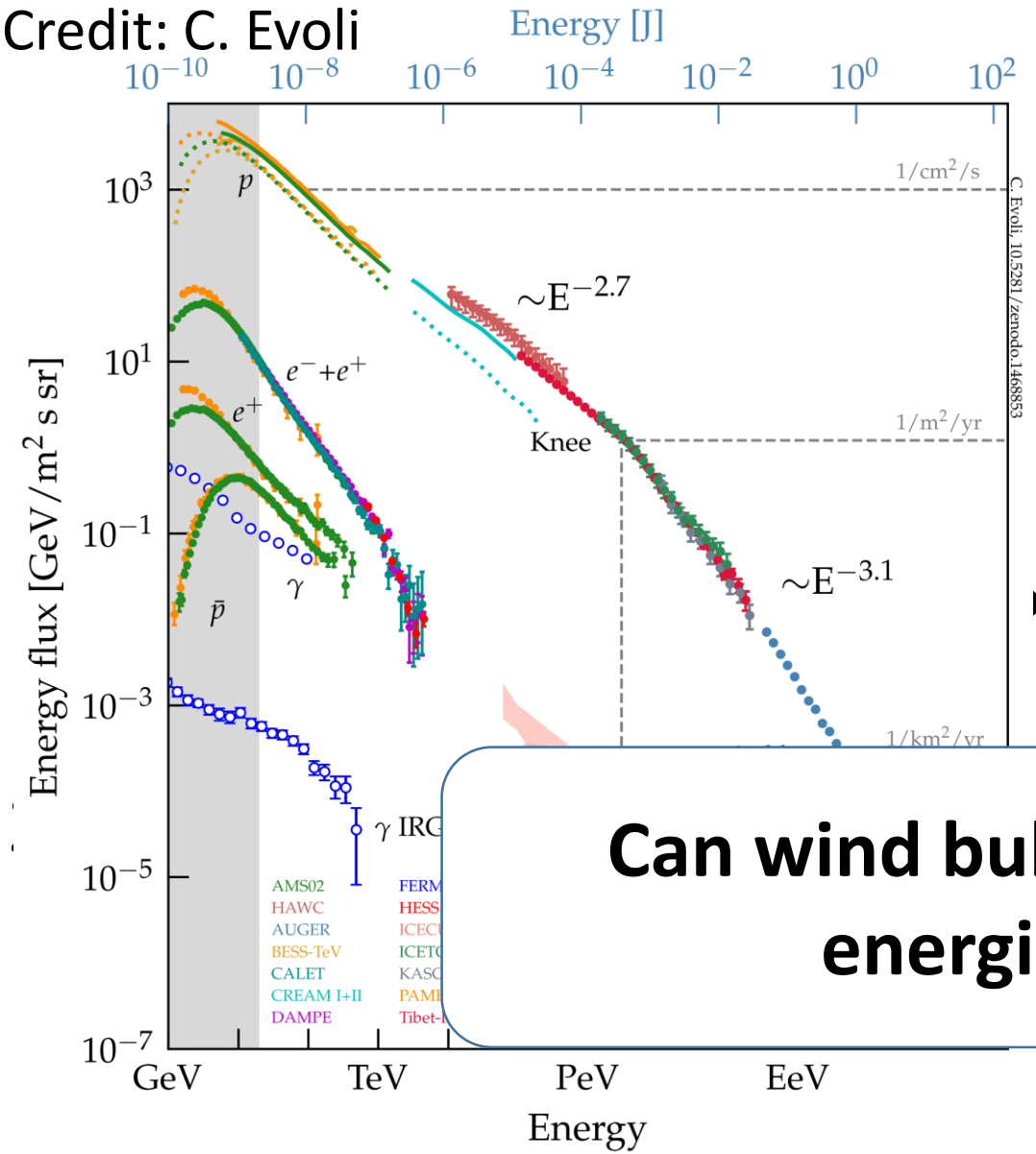

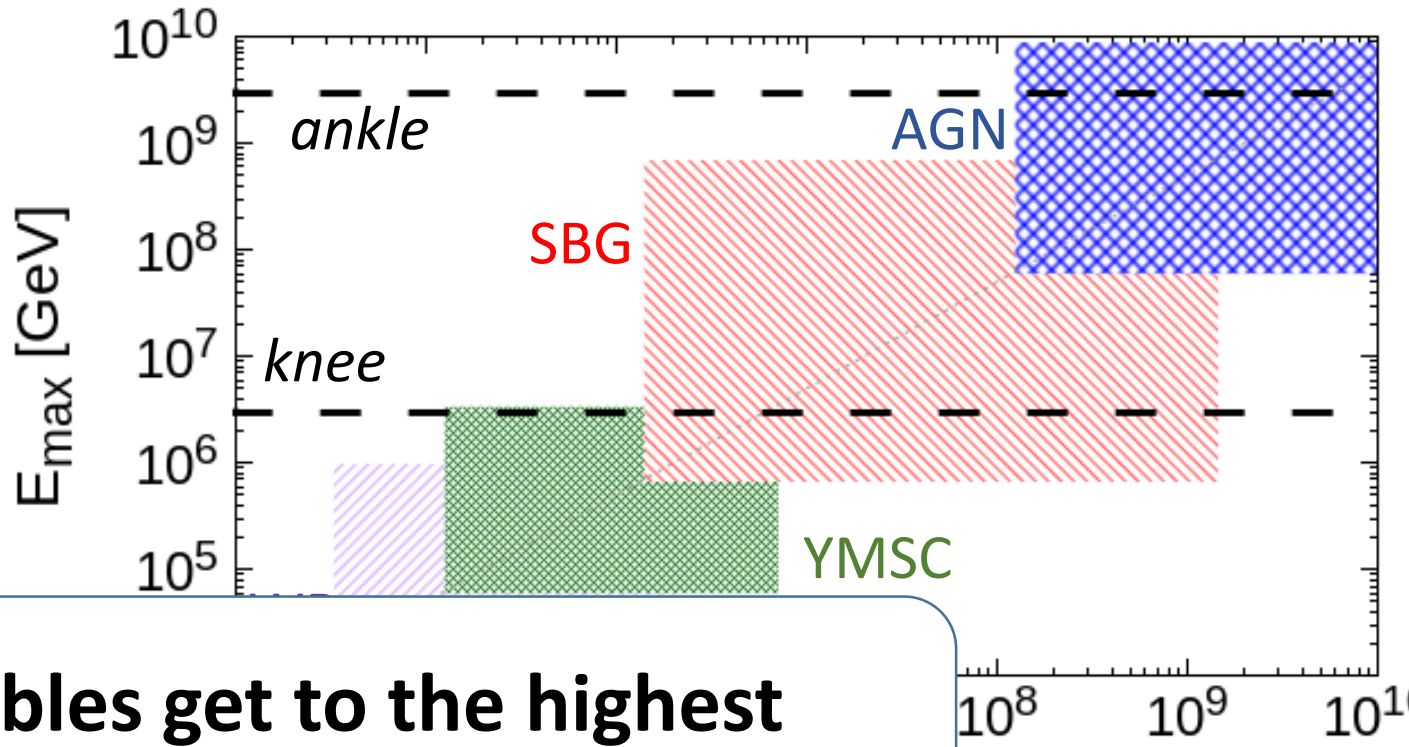

Can wind bubbles get to the highest energies in our Galaxy?

Why wind bub

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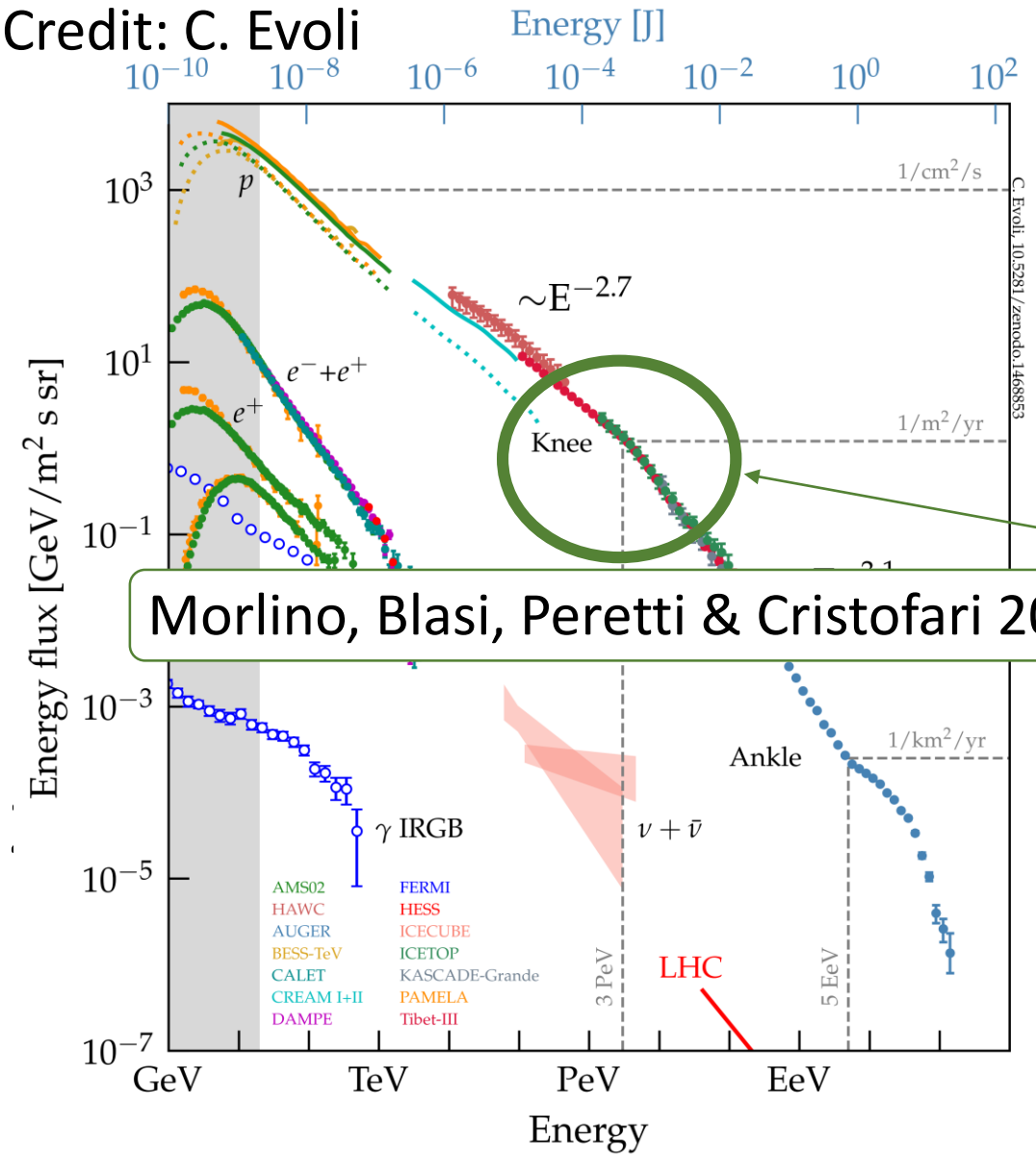
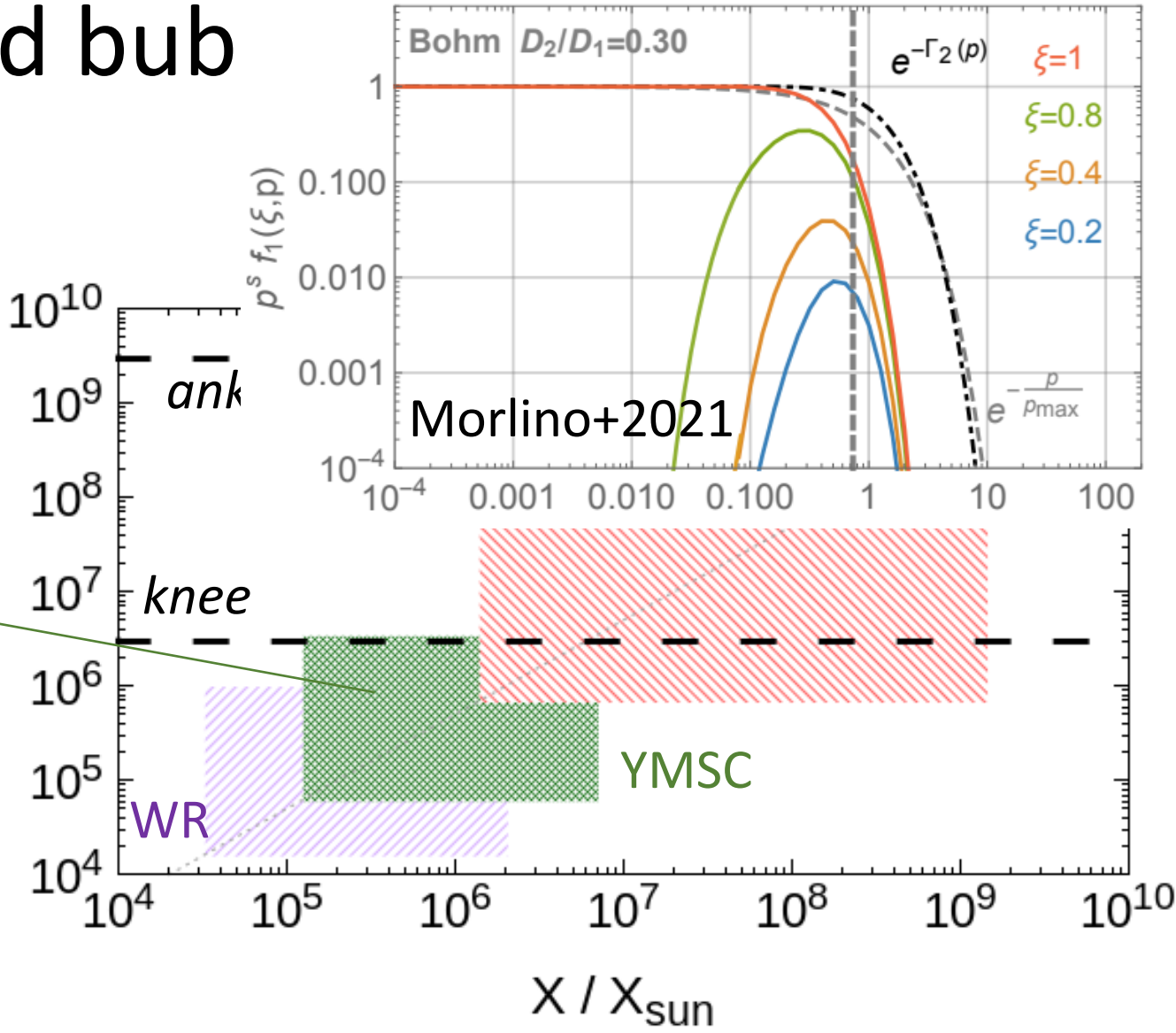


Morlino, Blasi, Peretti & Cristofari 2021



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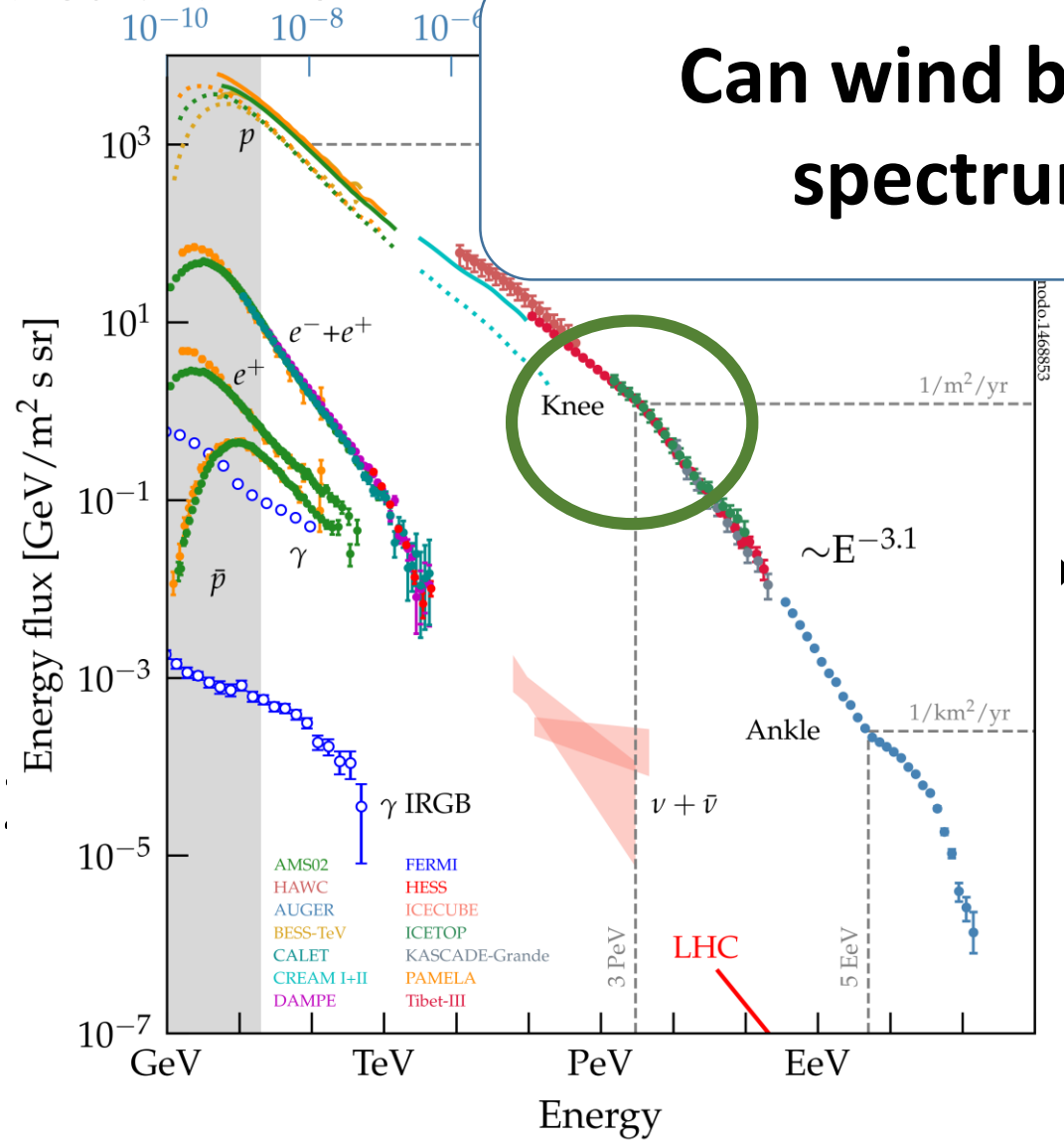
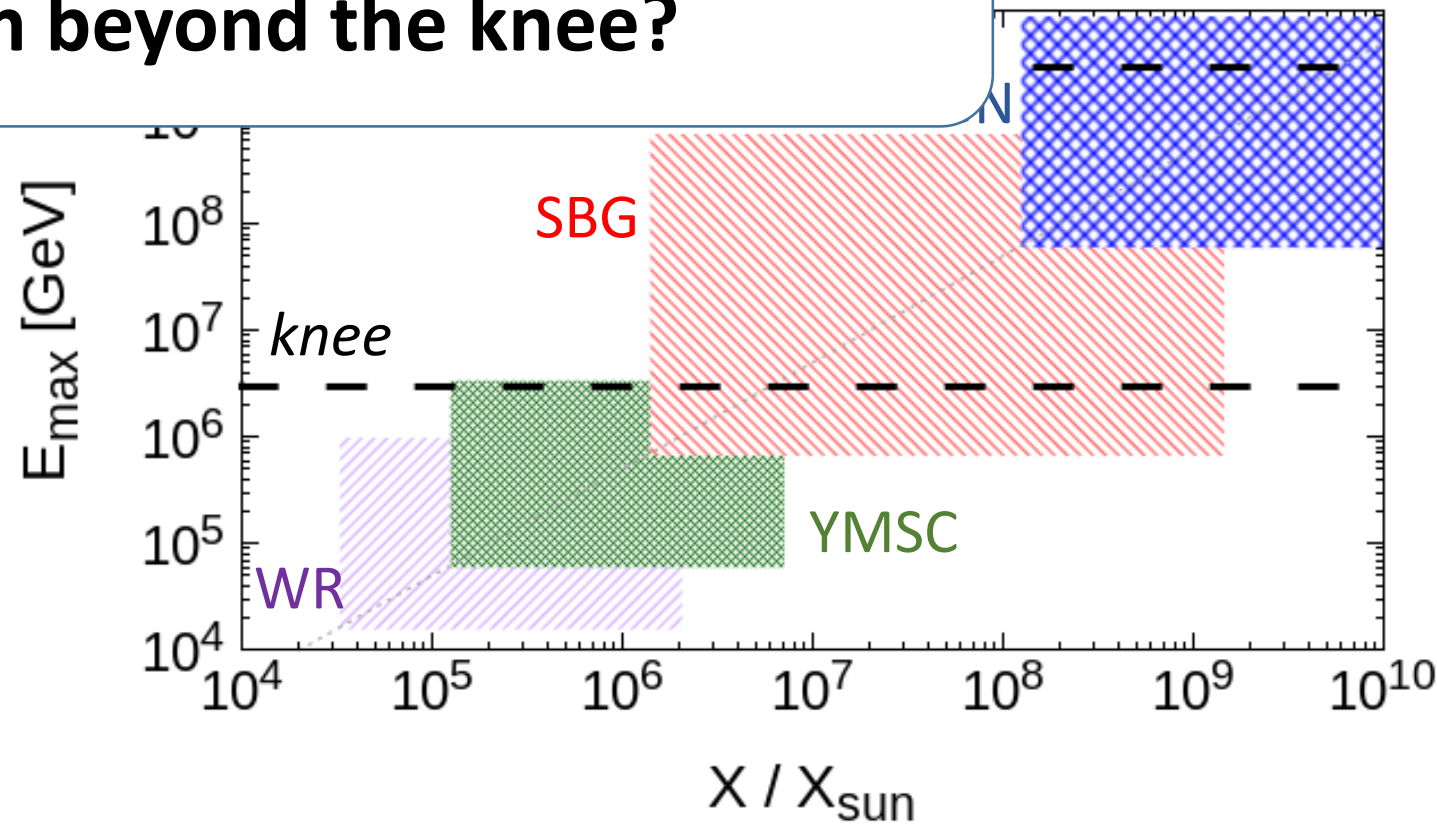
Can wind bubbles populate the CR spectrum beyond the knee?





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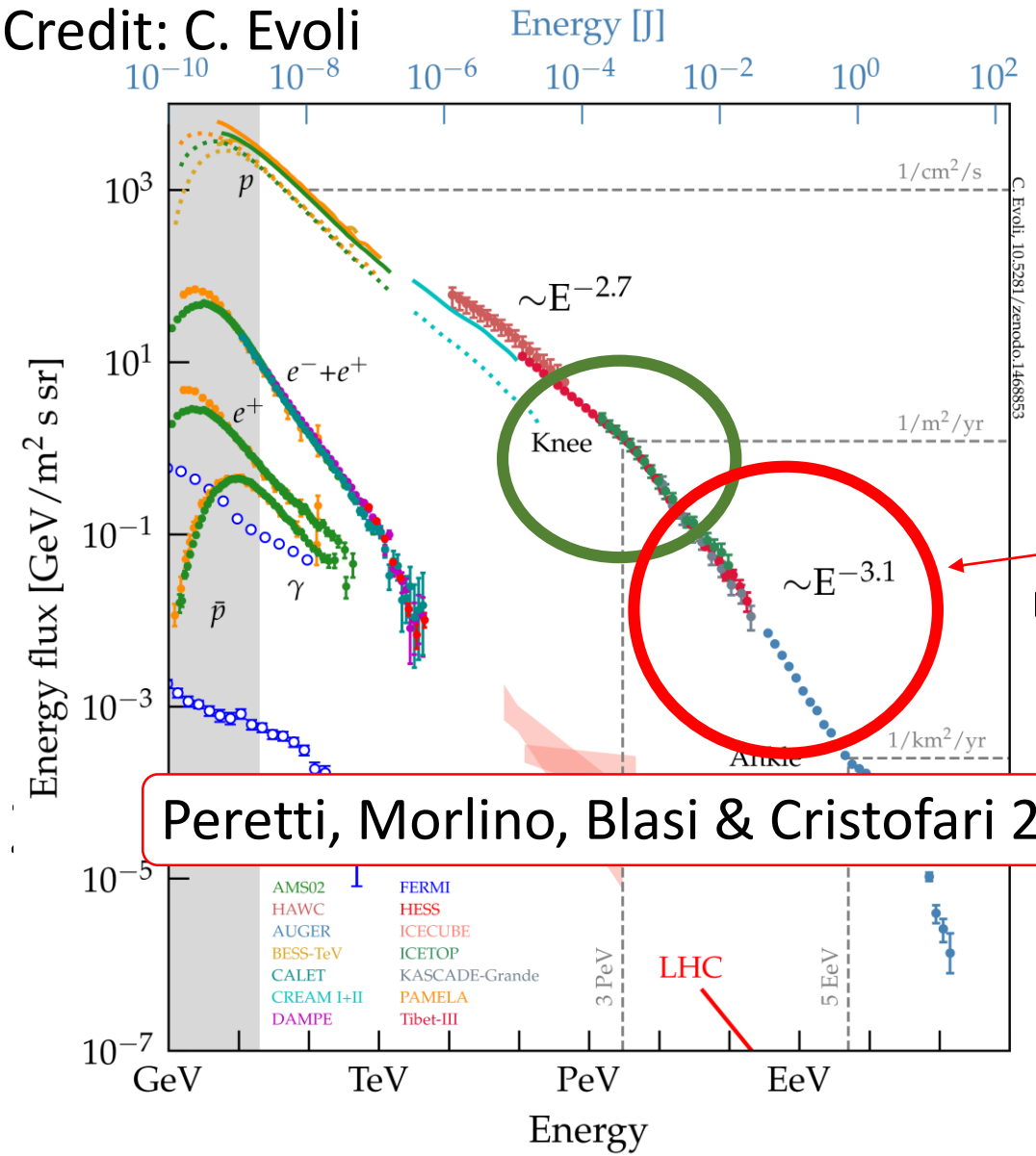
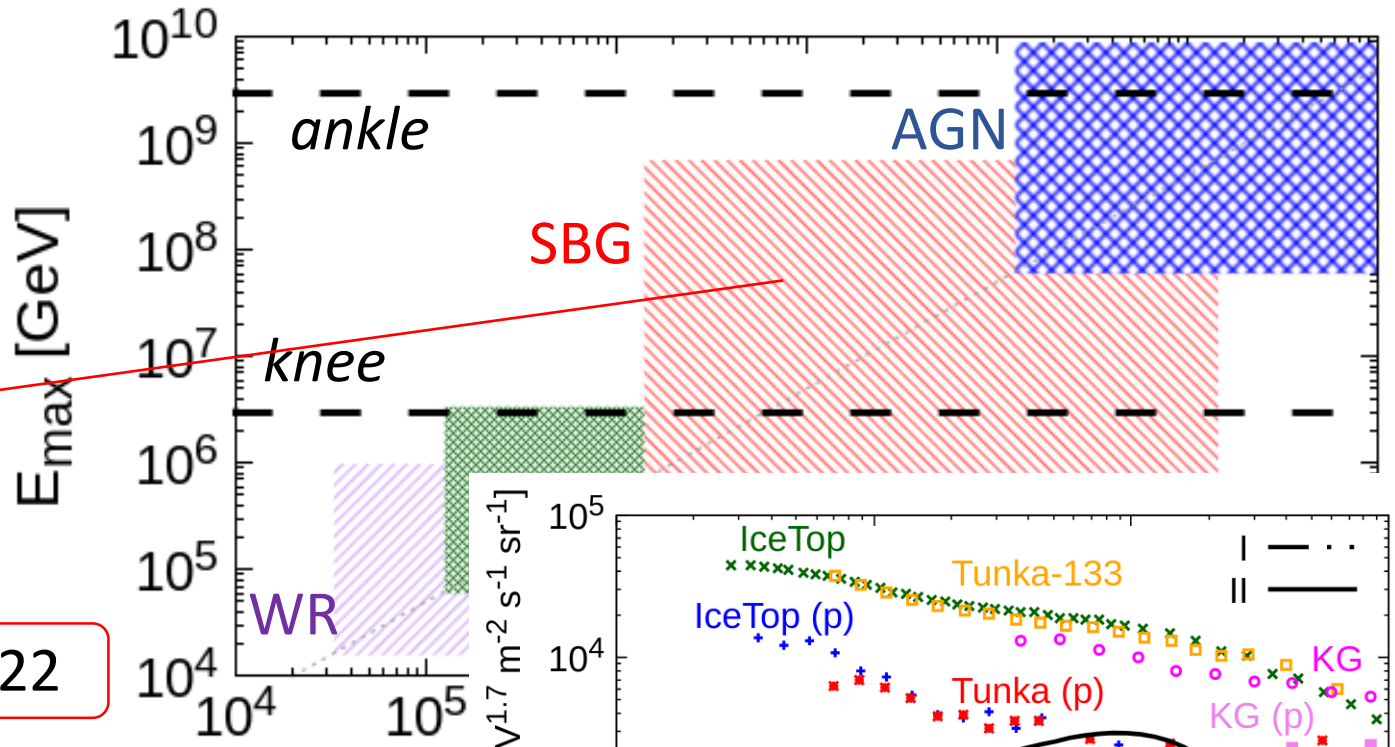
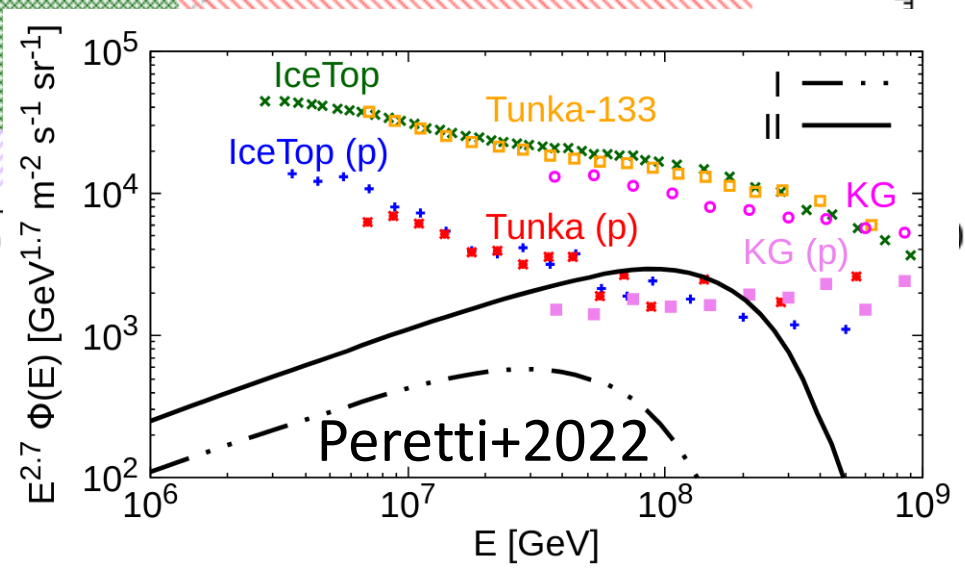


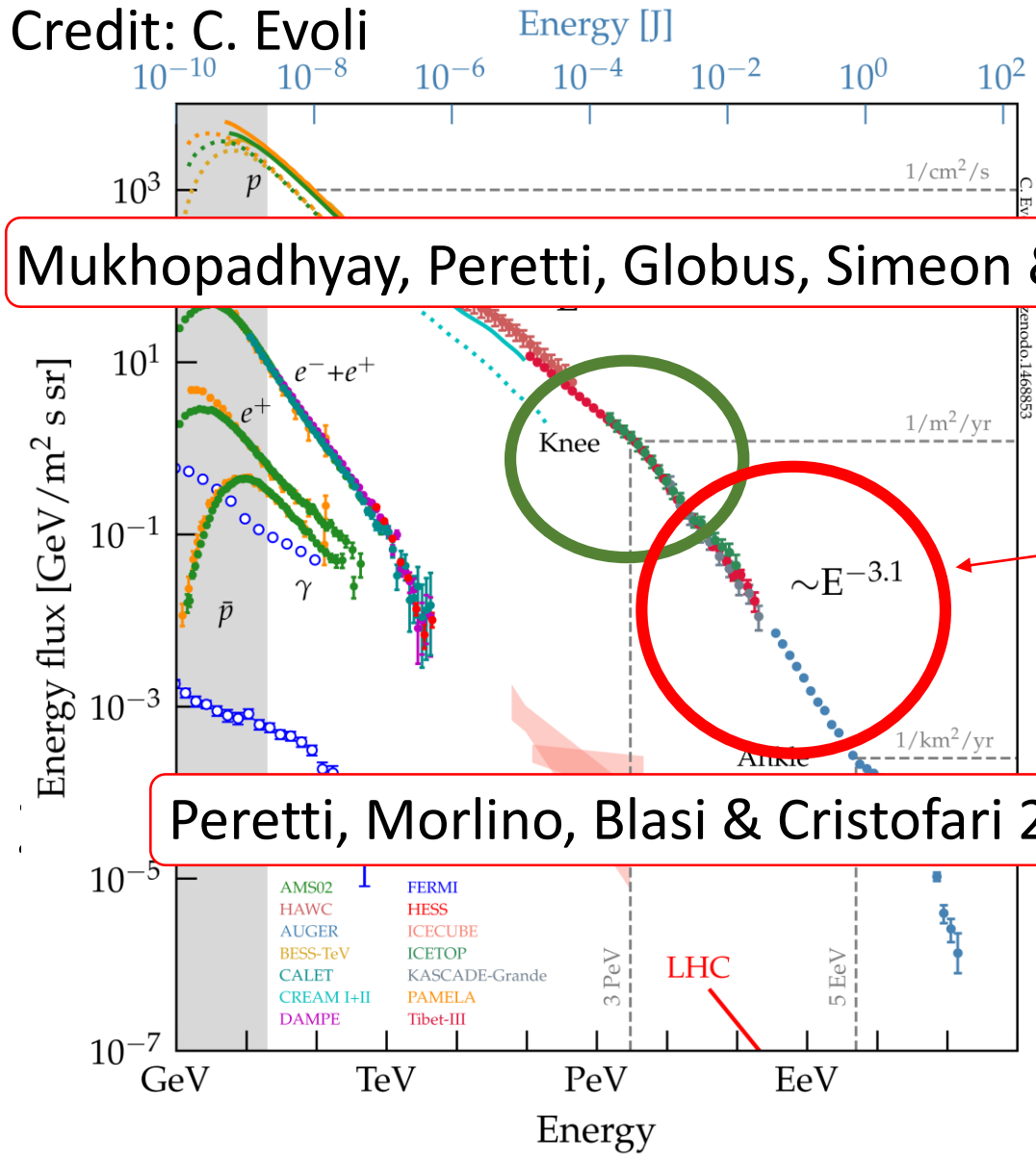
Peretti, Morlino, Blasi & Cristofari 2022





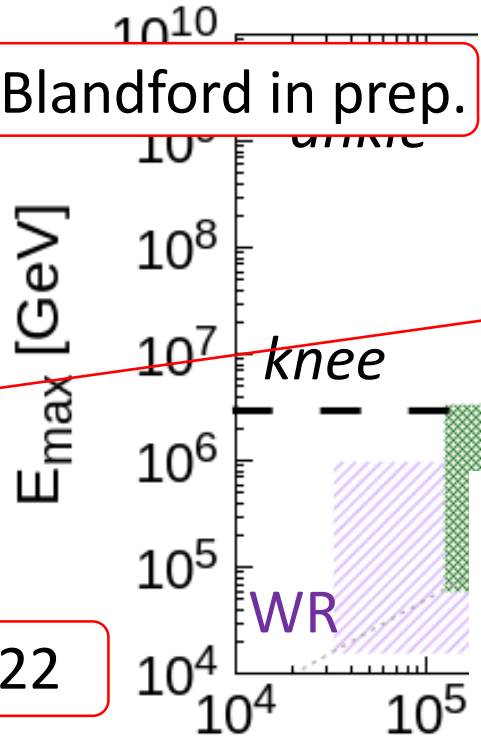
Why wind bubble

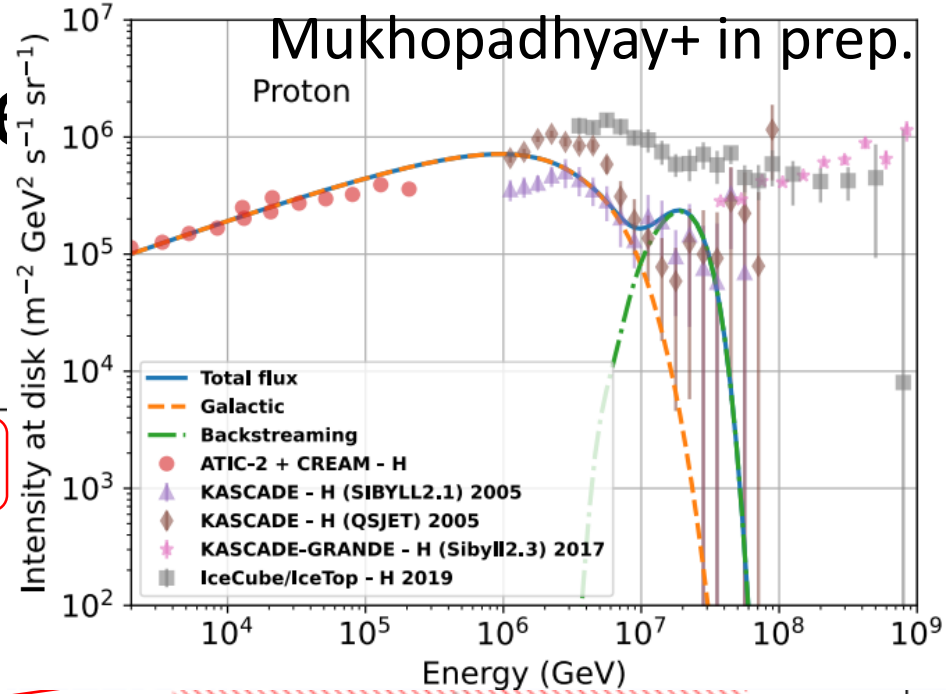
Credit: C. Evoli

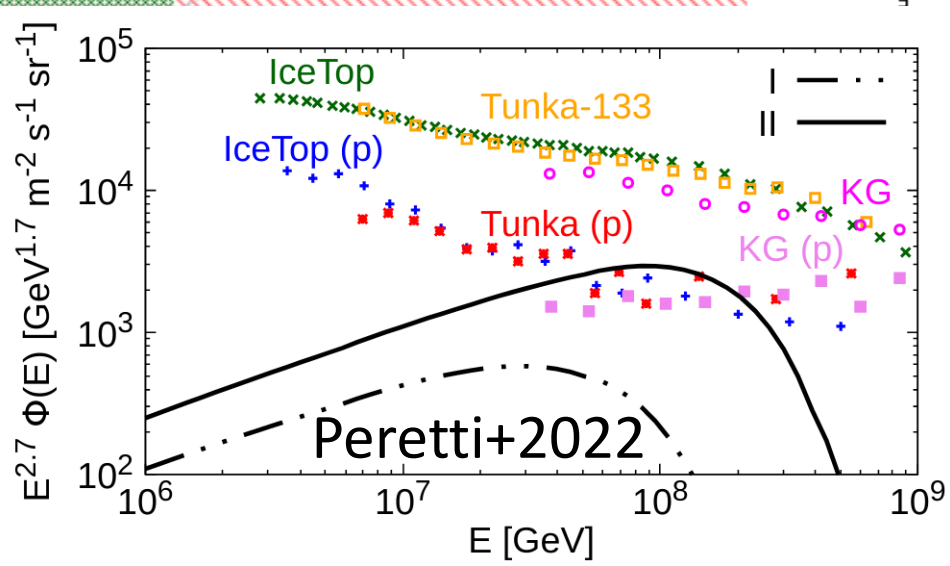


Mukhopadhyay, Peretti, Globus, Simeon & Blandford in prep.

Peretti, Morlino, Blasi & Cristofari 2022

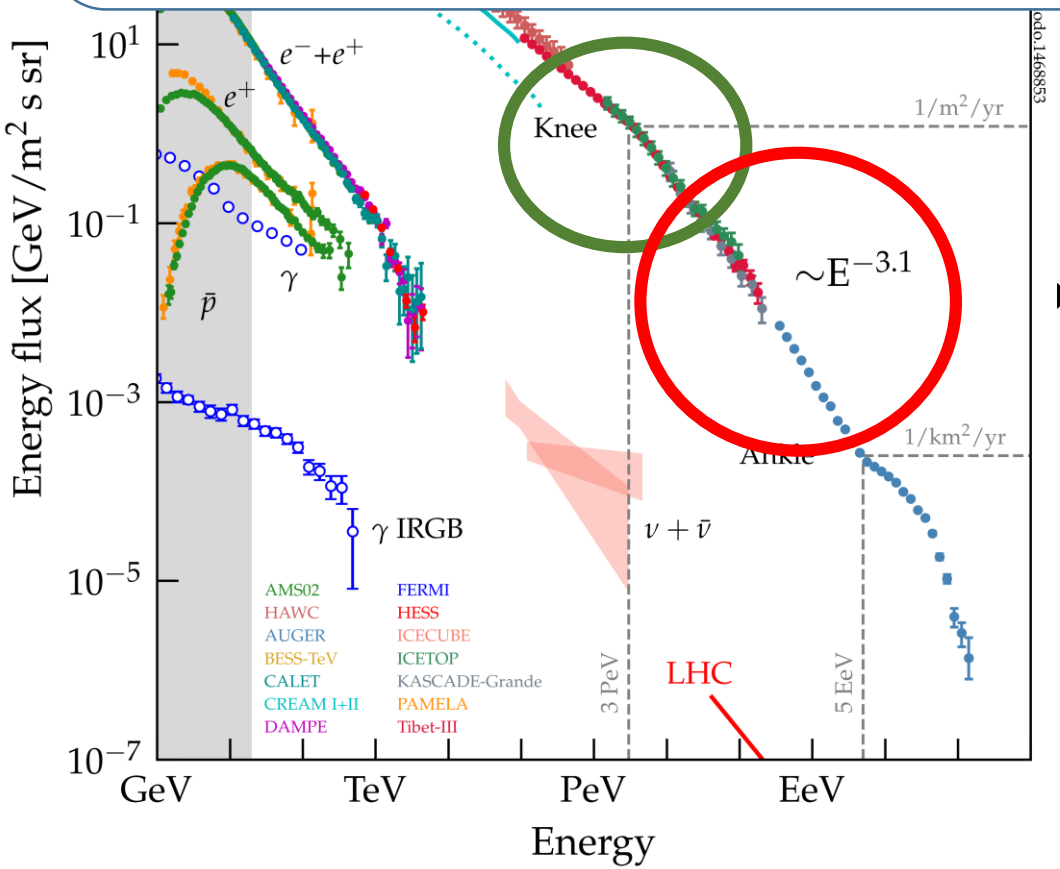


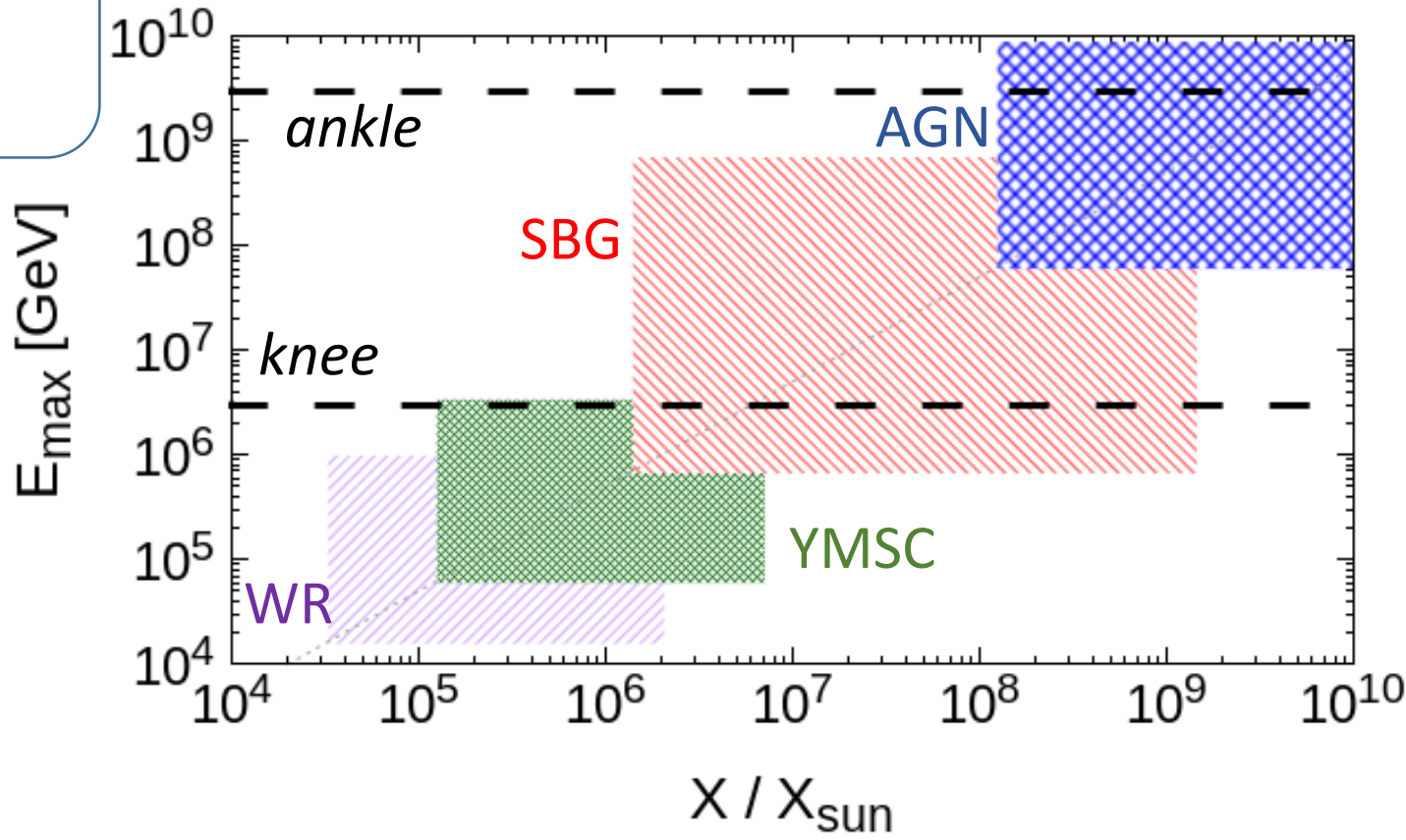




Why wind bubbles?

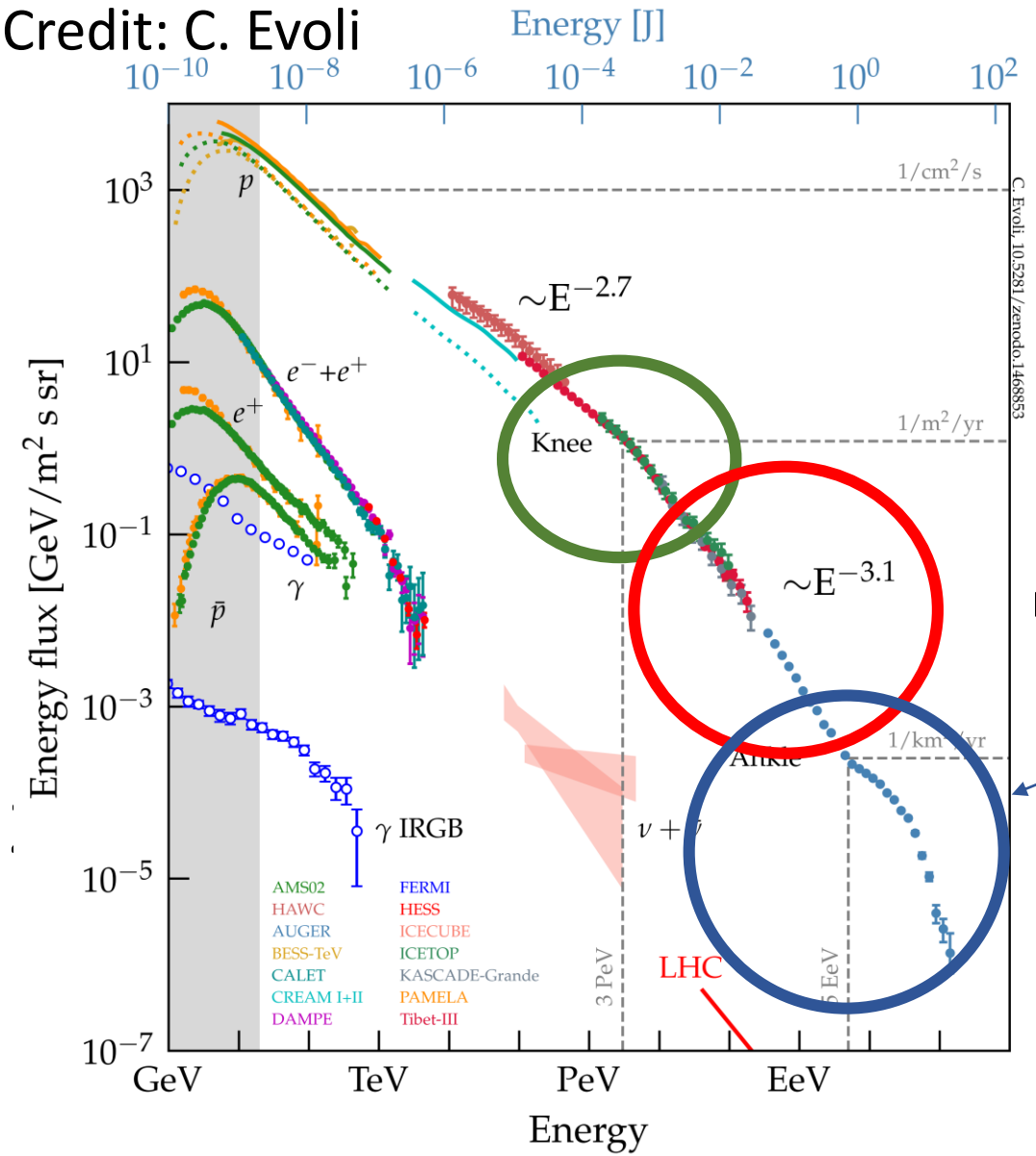
Can wind bubbles make it up to the UHEs?

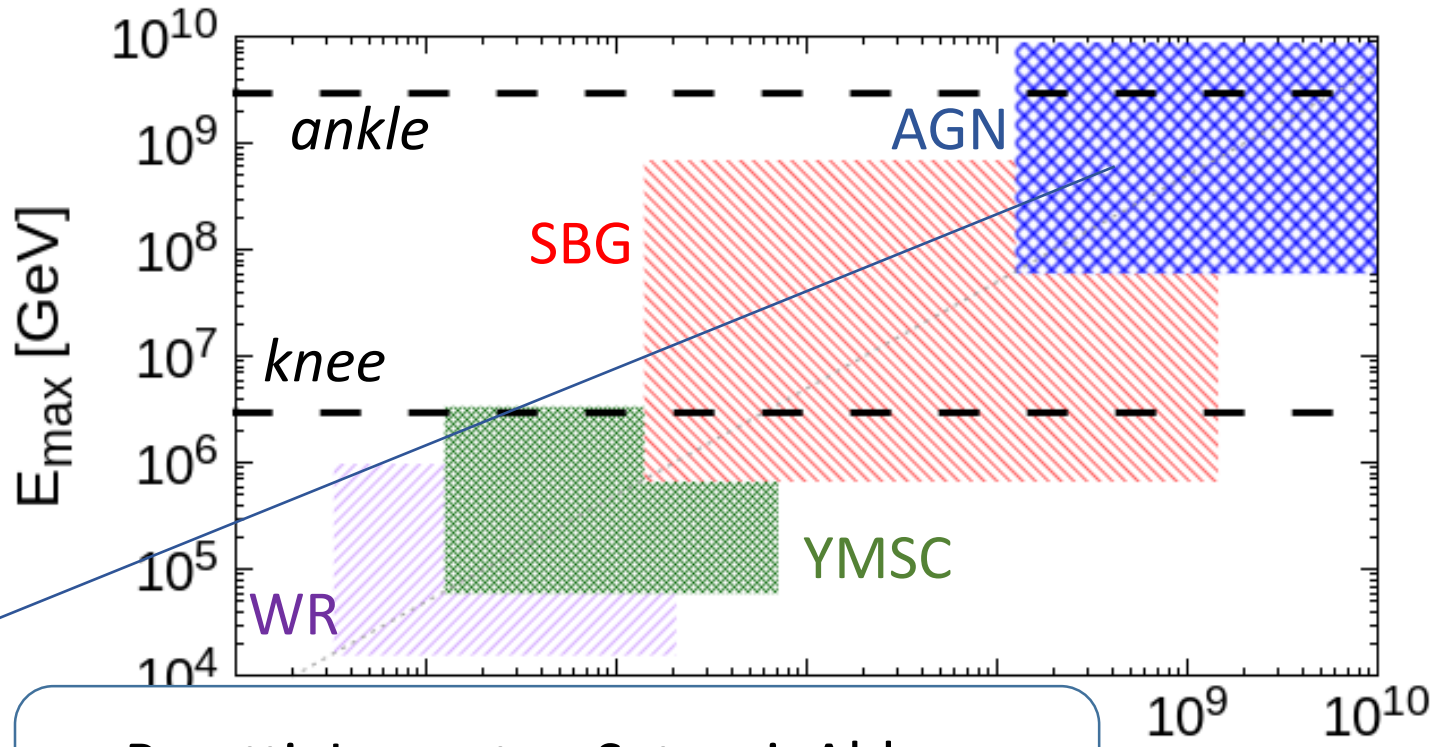




Why wind bubbles?

Credit: C. Evoli





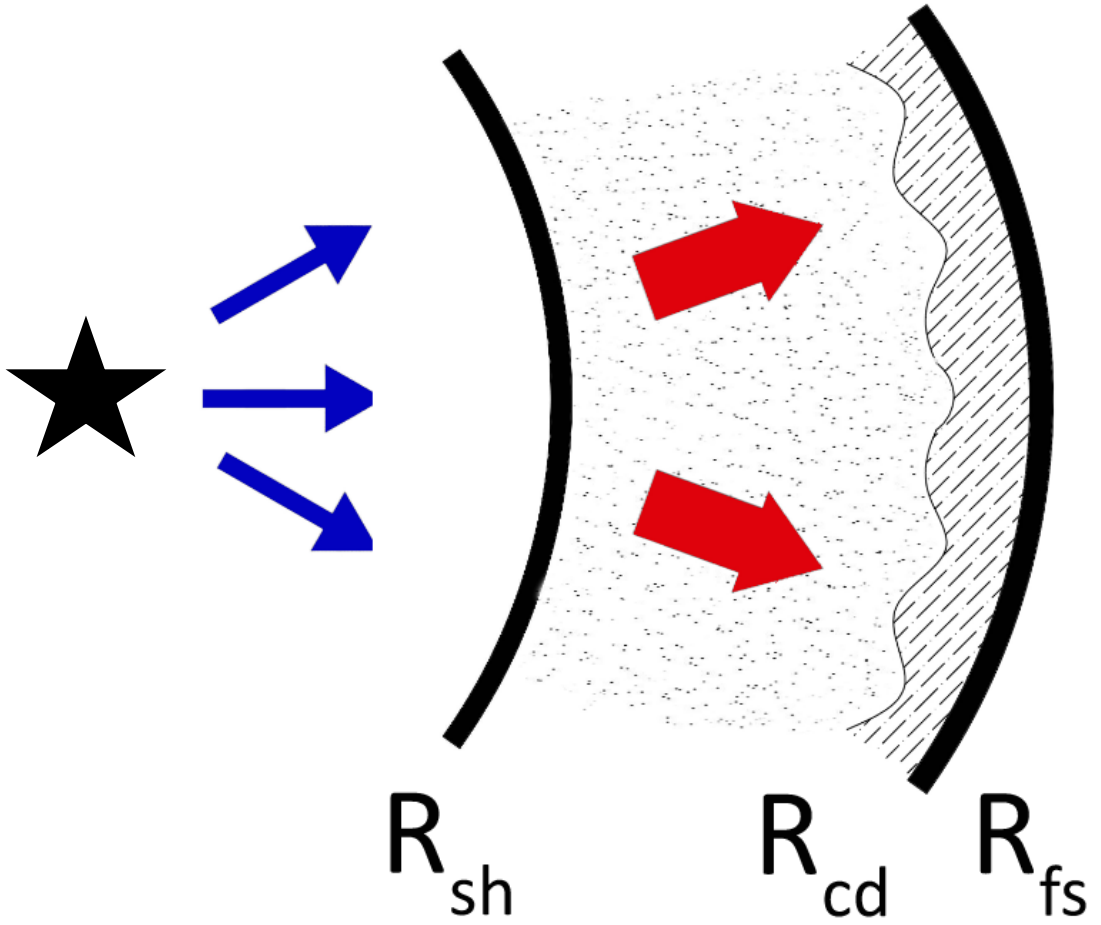
Peretti, Lamastra, Saturni, Ahlers, Morlino, Blasi, Cristofari in prep.

Outline

- Wind bubbles: structure and evolution
- Model for particle acceleration in wind bubbles
- Solution: radial distribution and spectra
- Ultra Fast Outflows

Acceleration and transport model

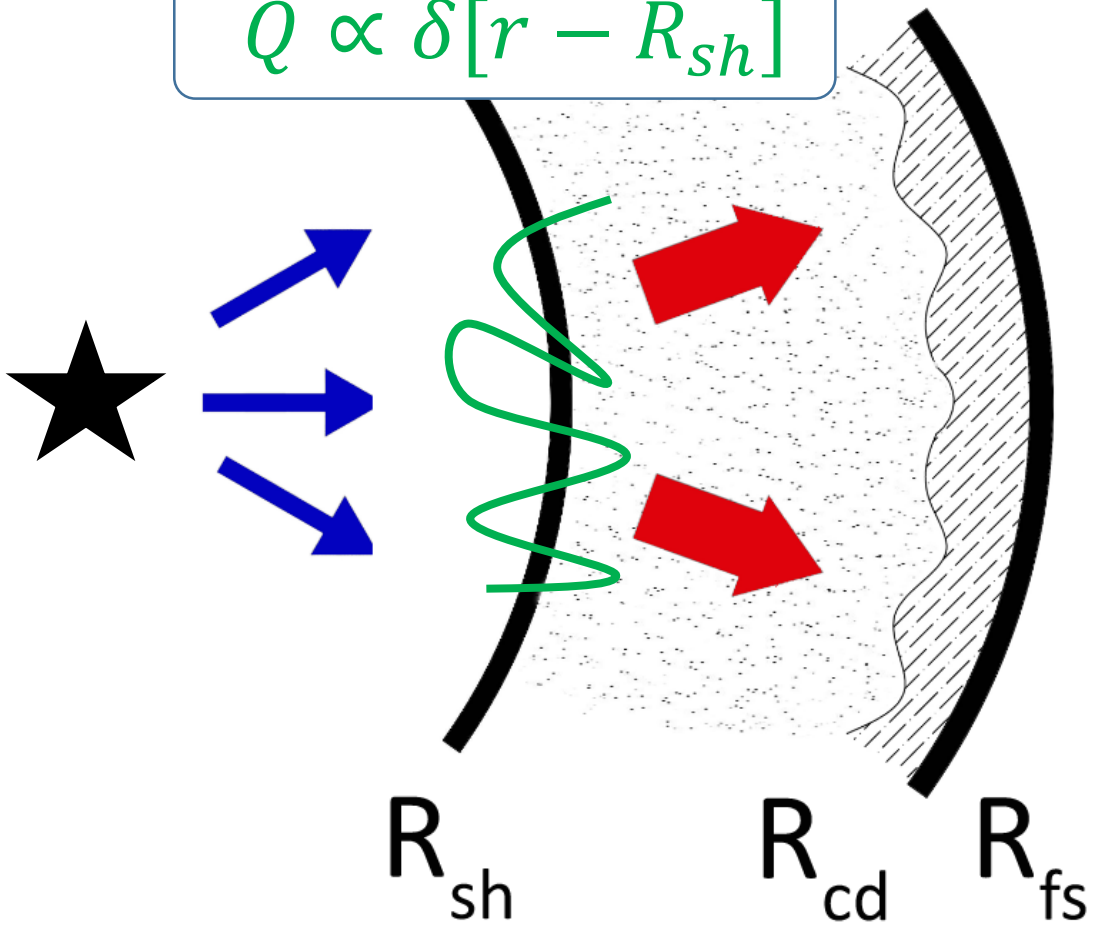
$$0 = -r^2 u(r)\partial_r f + \partial_r[r^2 D(r,p)\partial_r f] + \frac{p}{3}\partial_r[r^2 u(r)]\partial_p f - r^2\Lambda(r,p) + r^2 Q(r,p)$$



Acceleration and transport model

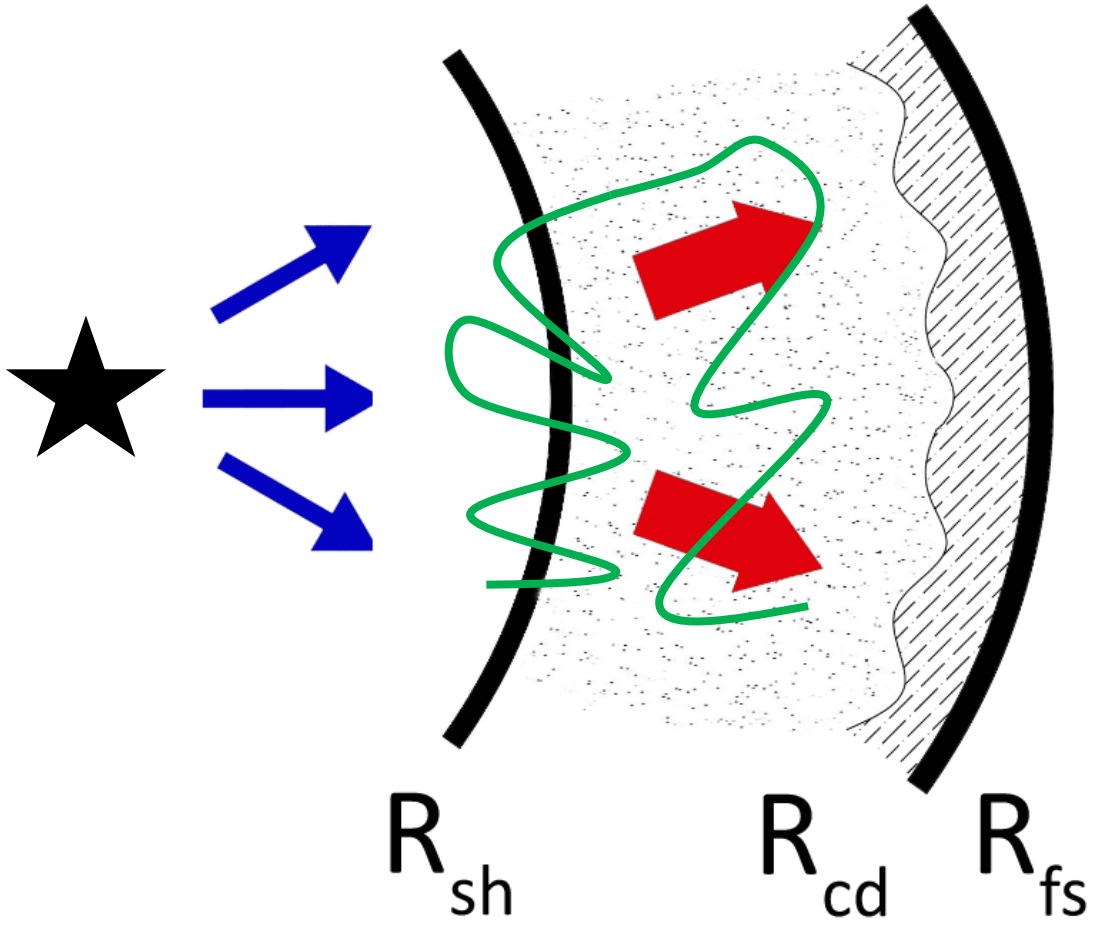
$$r^2 u(r)\partial_r f = \partial_r[r^2 D(r,p)\partial_r f] + \tfrac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p) - r^2 \Lambda(r,p)$$

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



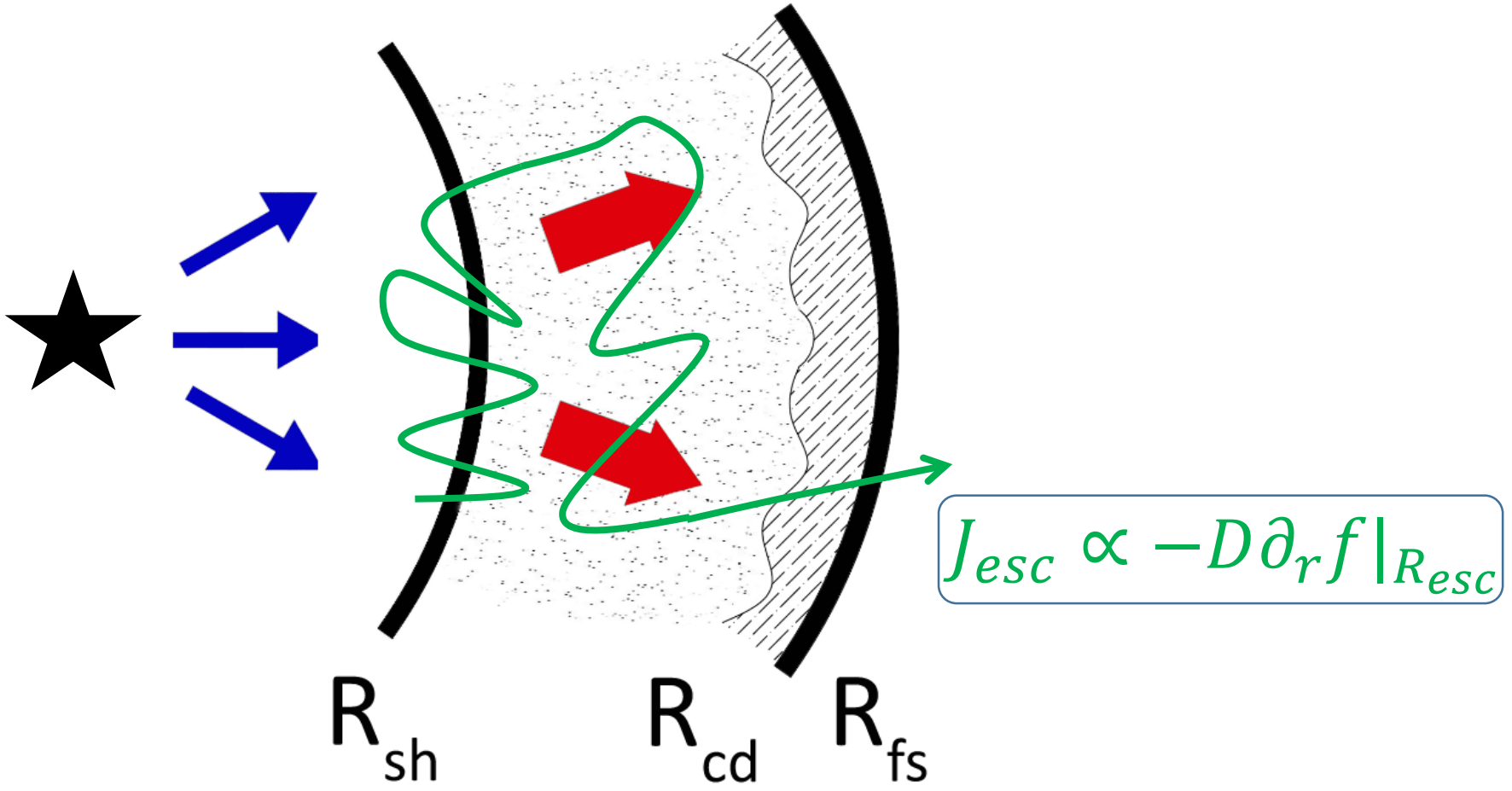
Acceleration and transport model

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



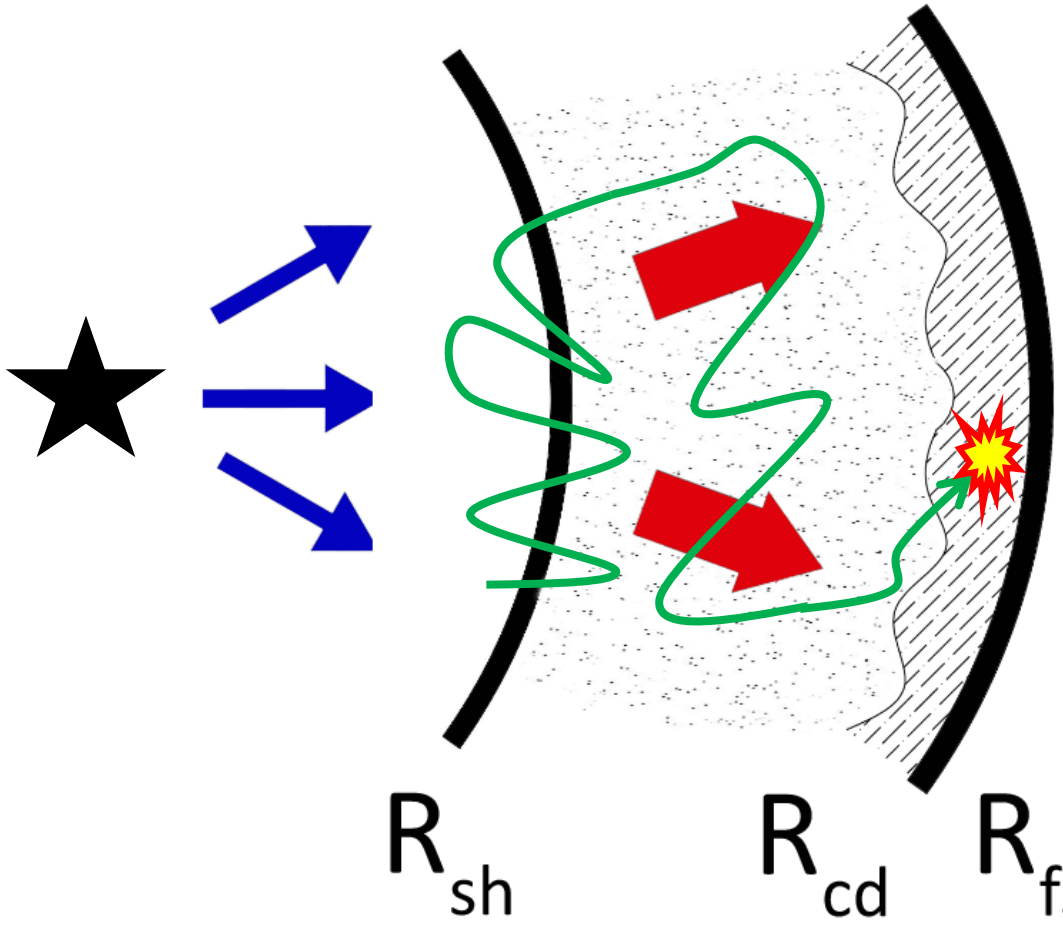
Acceleration and transport model

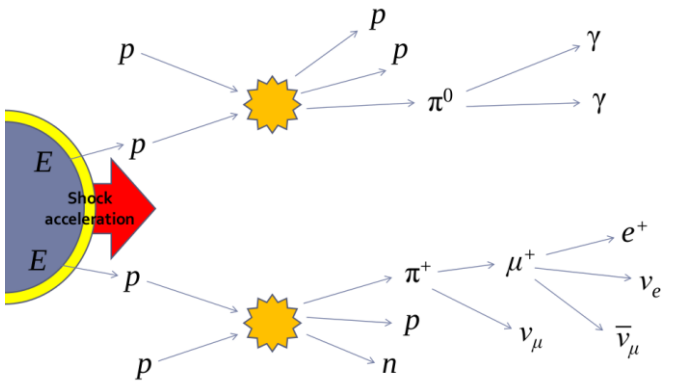
$$r^2 u(r)\partial_r f = \partial_r[r^2 D(r,p)\partial_r f] + \tfrac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p) - r^2 \Lambda(r,p)$$



Acceleration and transport model

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

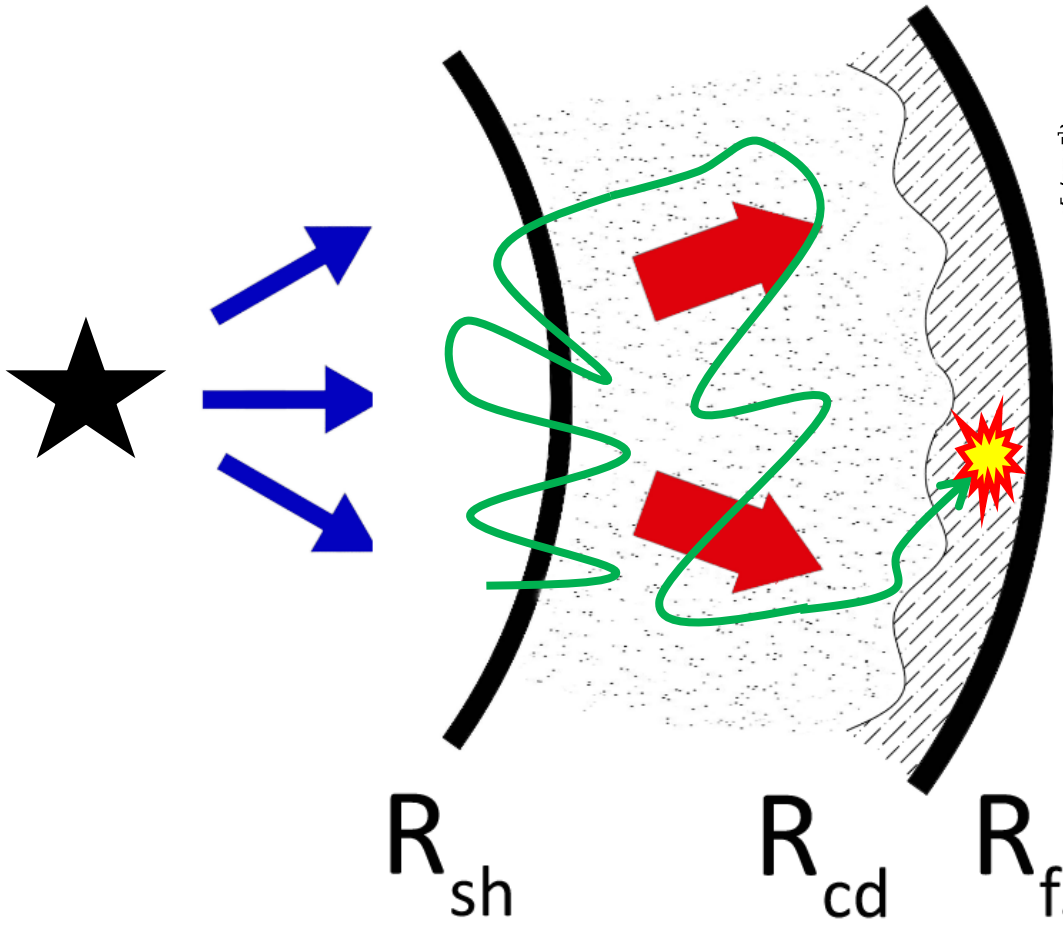


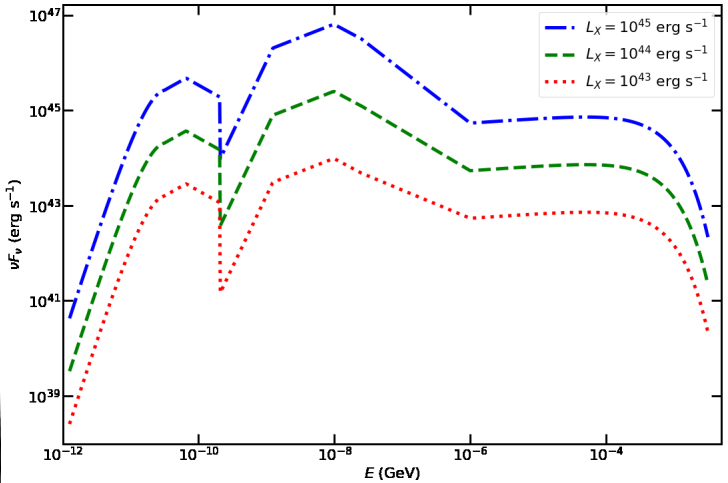


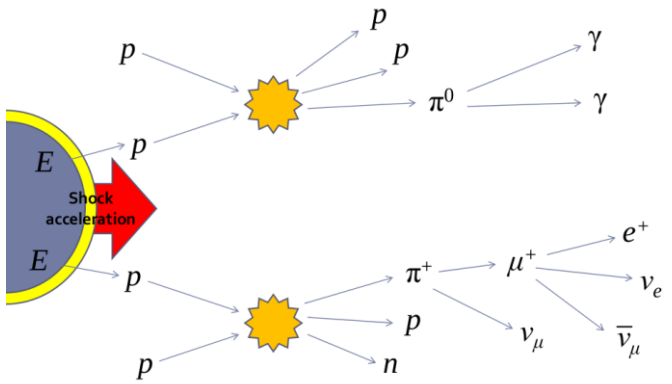
Website: http://www.astro.wisc.edu/~gvance/index.html

Acceleration and transport model

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





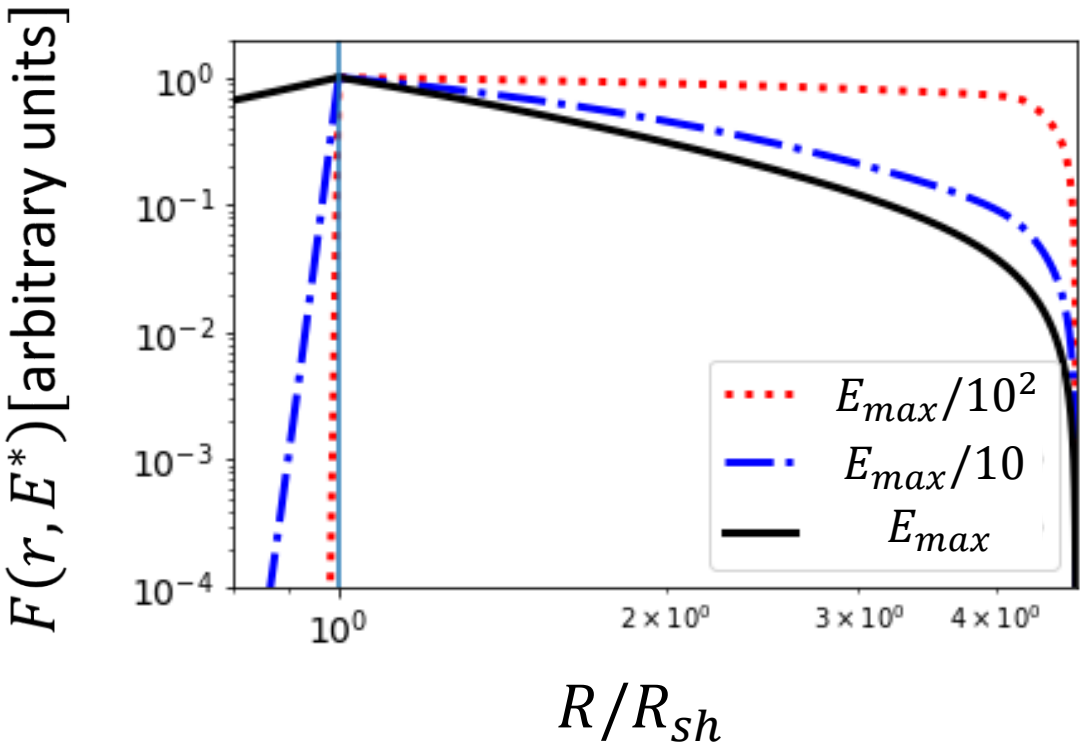


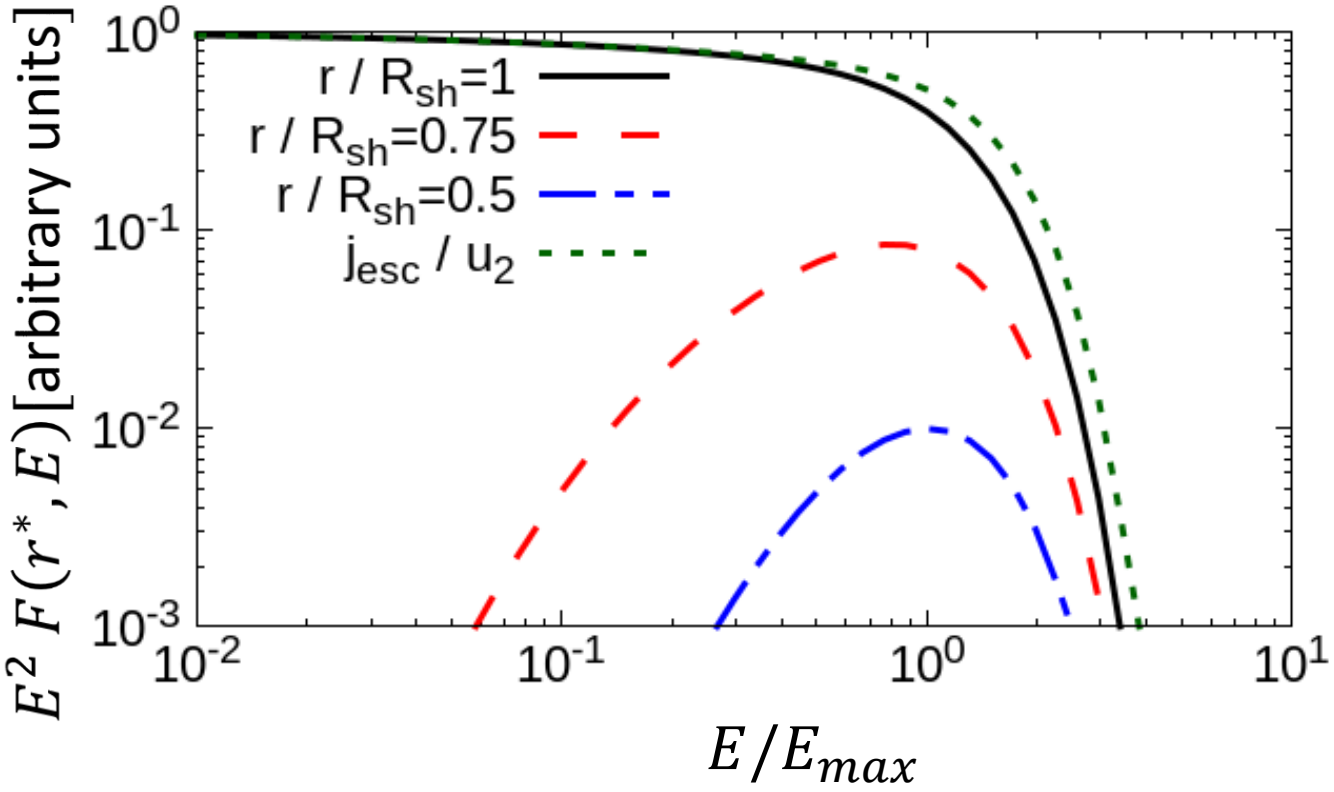
Website: http://www.astro.wisc.edu/~gvance/index.html

Outline

- Wind bubbles: structure and evolution
- Model for particle acceleration in wind bubbles
- Solution: radial distribution and spectra
- Ultra Fast Outflows

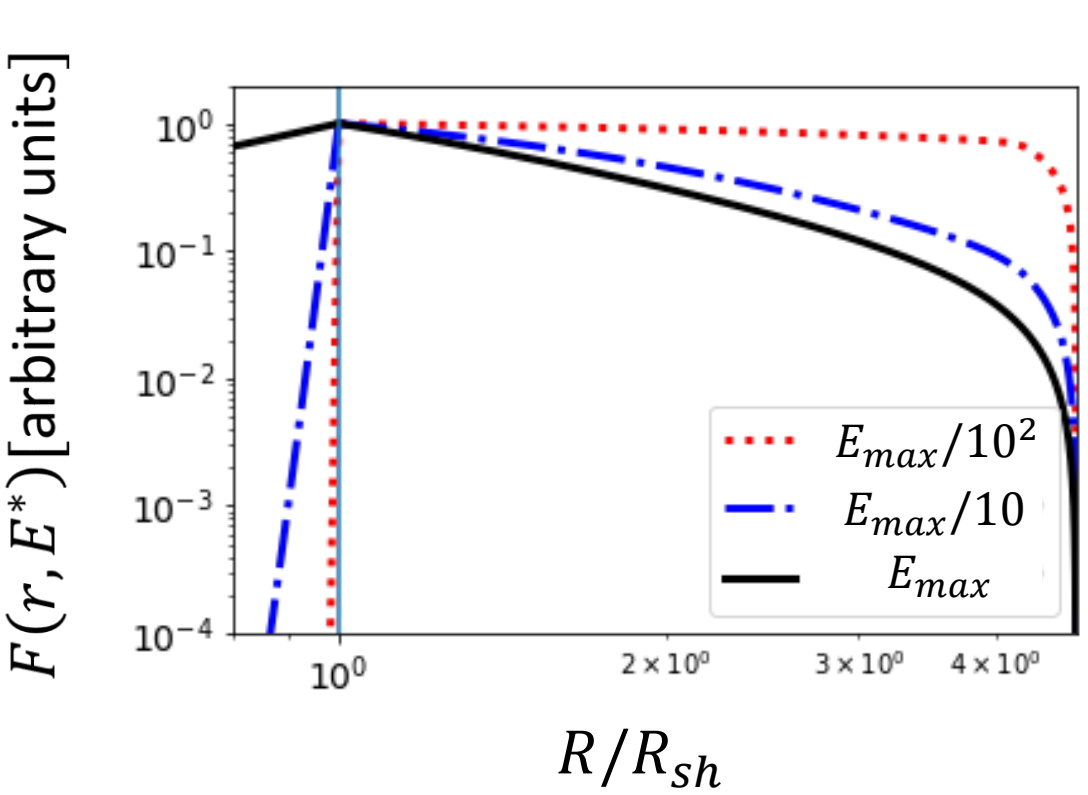
Solution: radial behavior and spectra

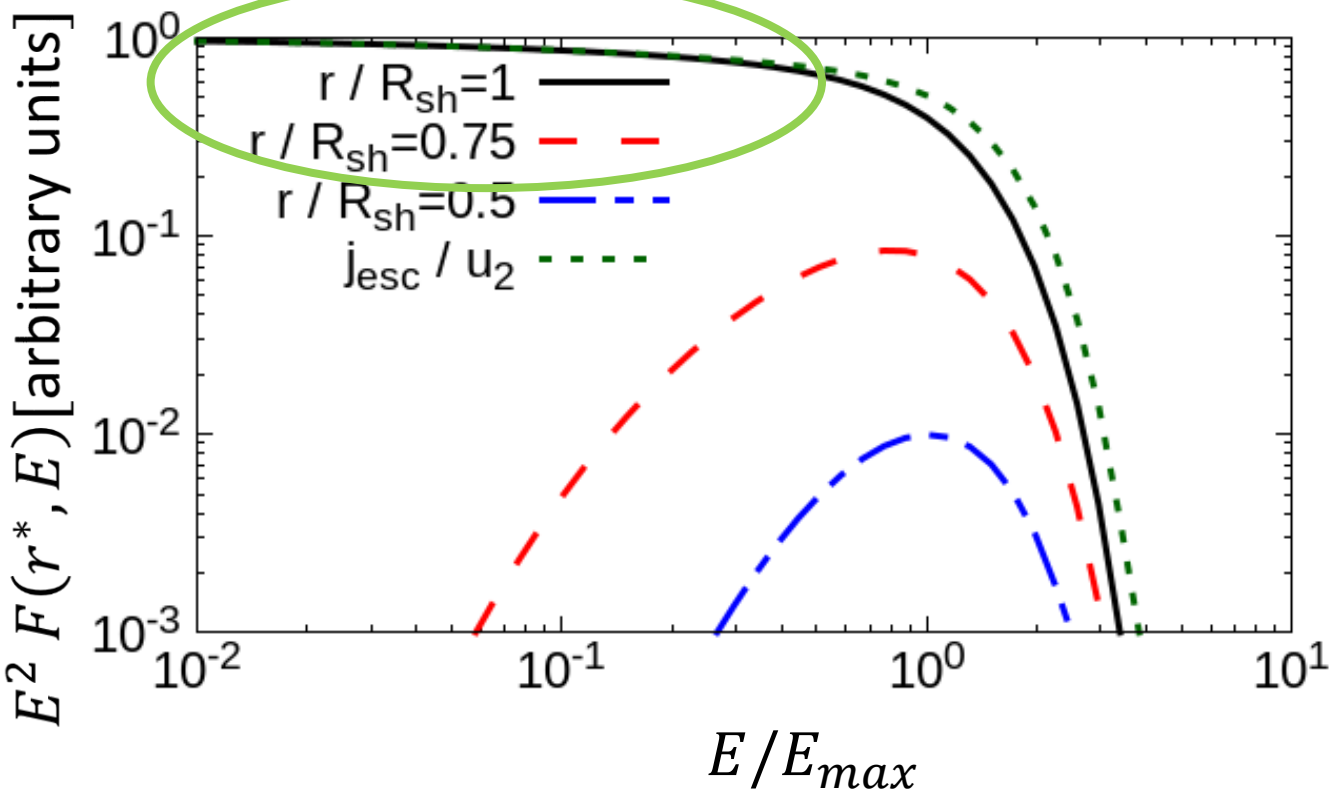




Solution: radial behavior and spectra

$F \sim E^{-2}$ ⇔ DSA

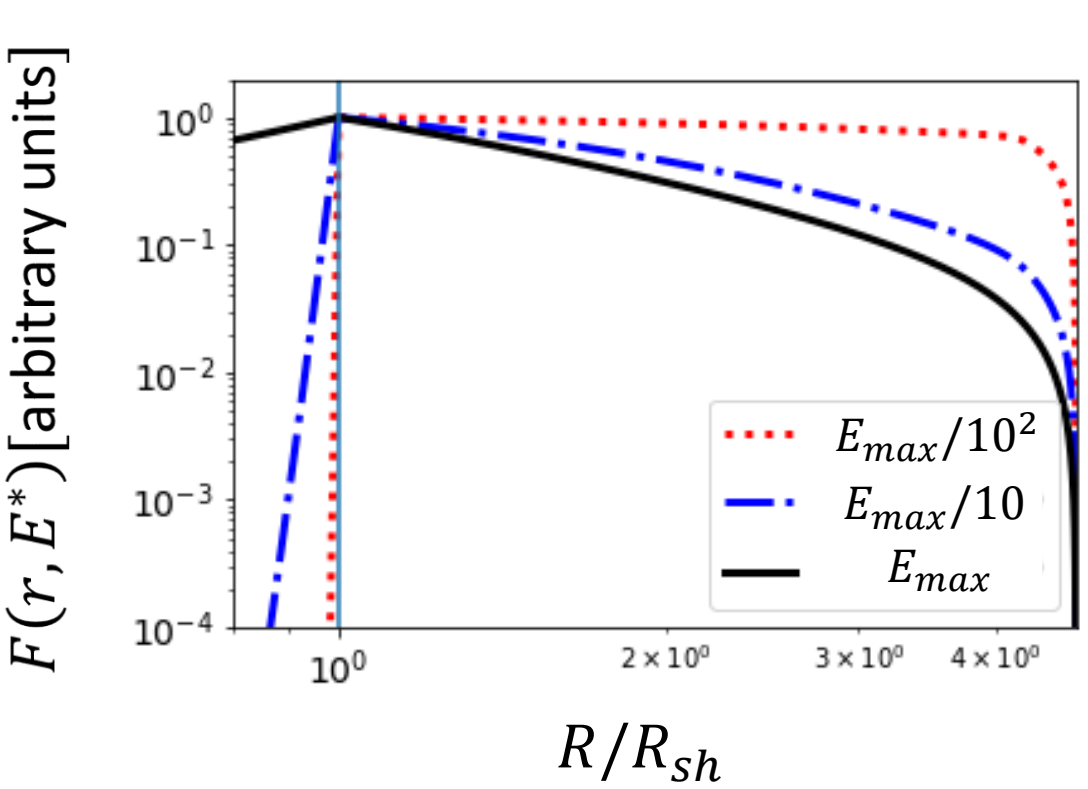


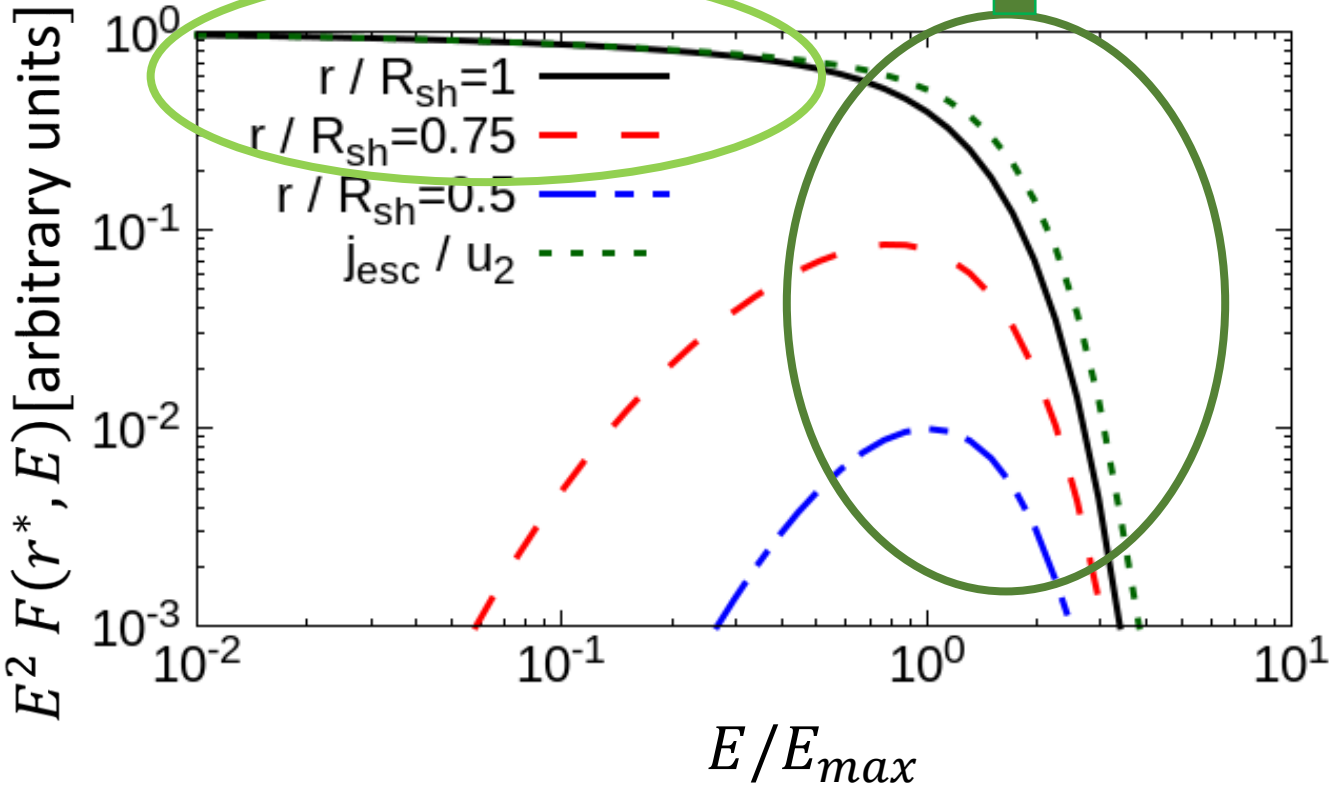


Solution: radial behavior and spectra

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

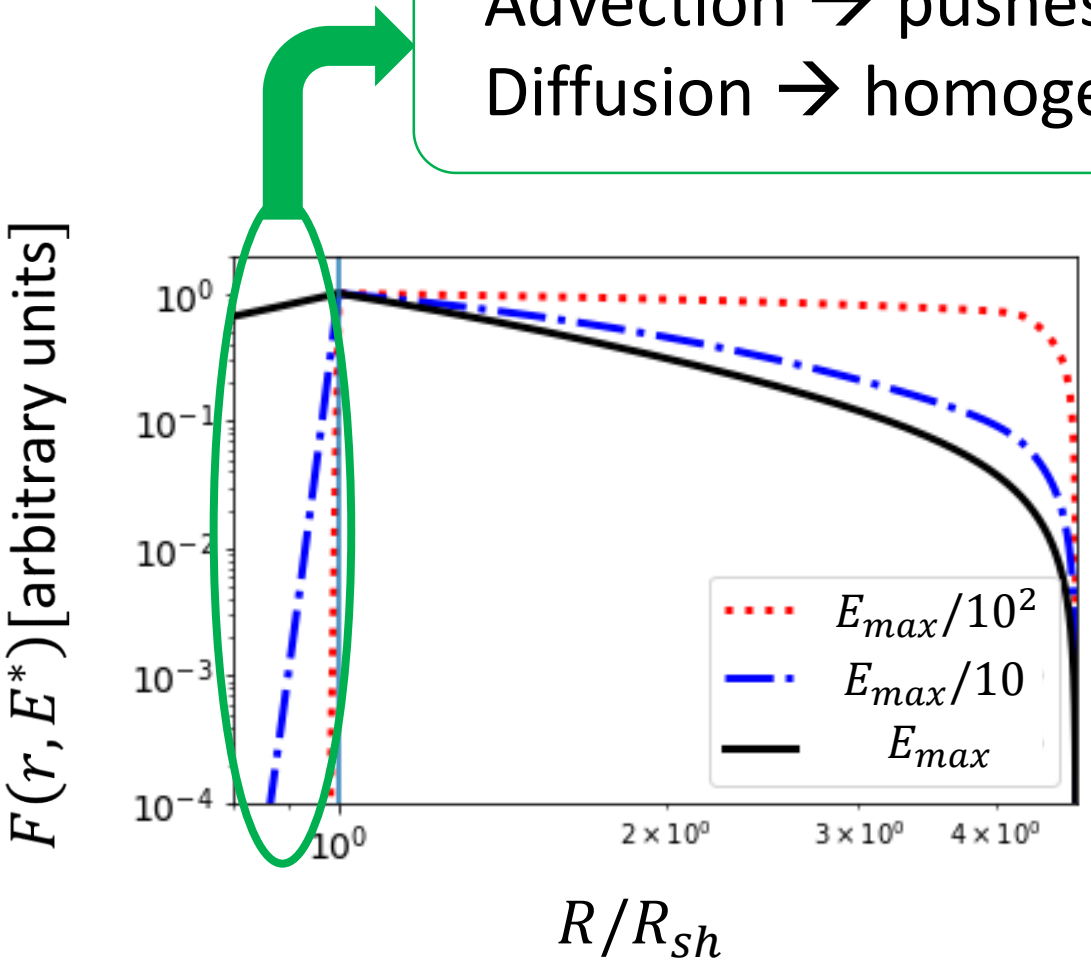
$F \sim E^{-2}$ ⇔ DSA

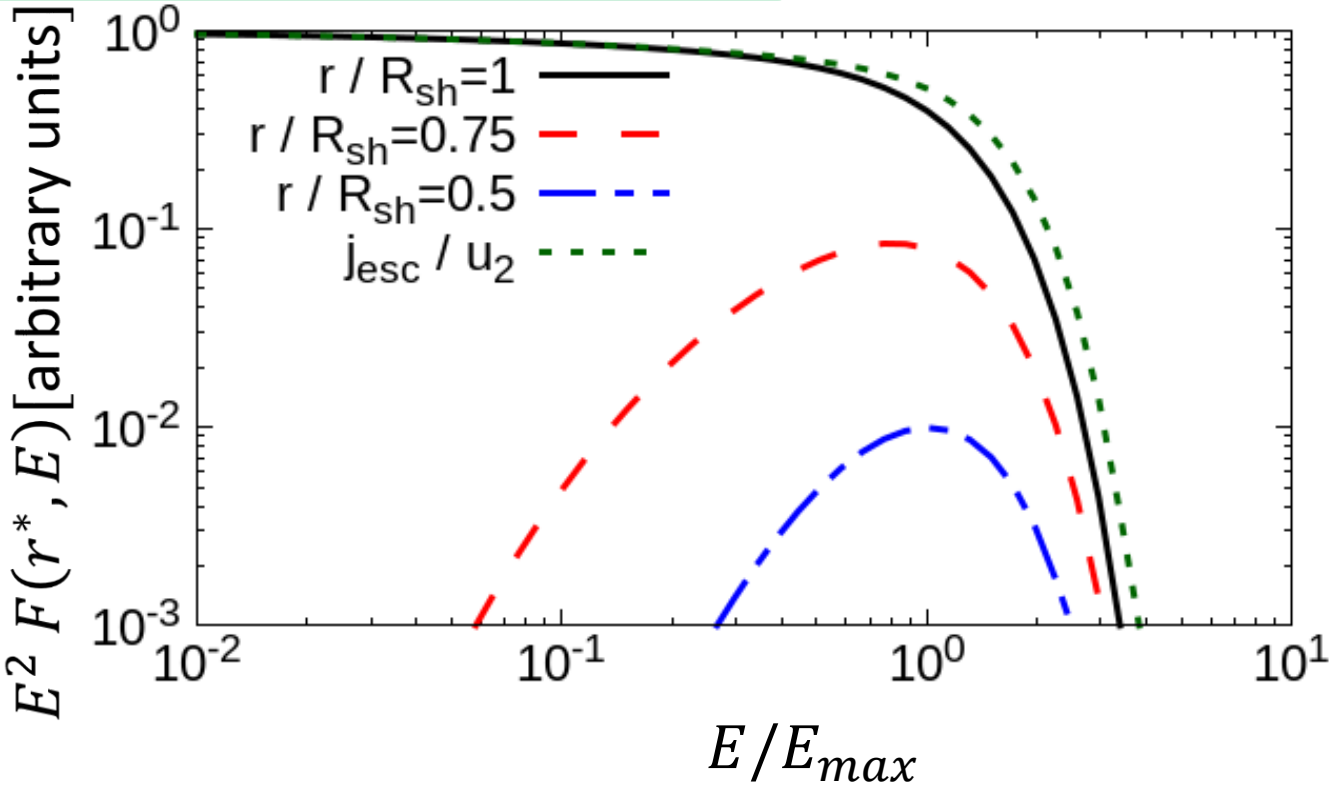




Solution: radial behavior and spectra

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





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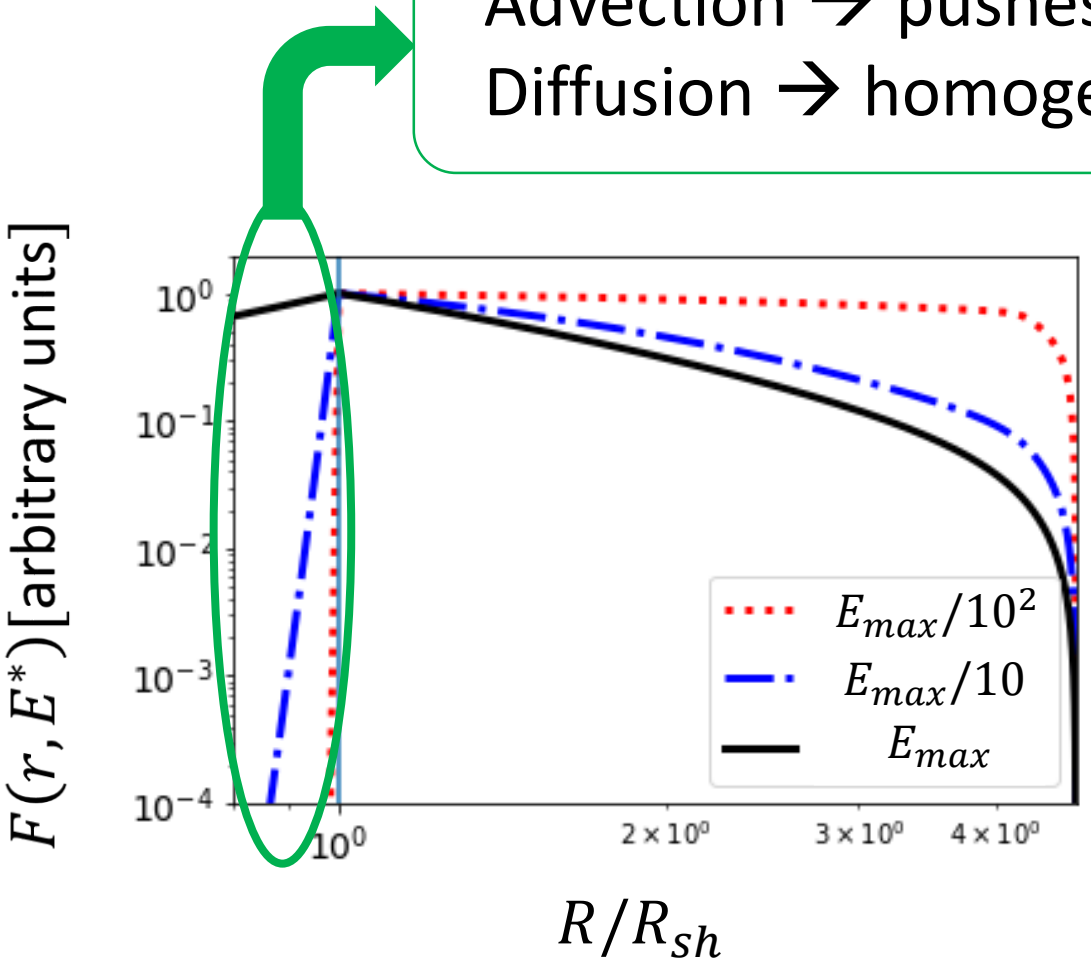
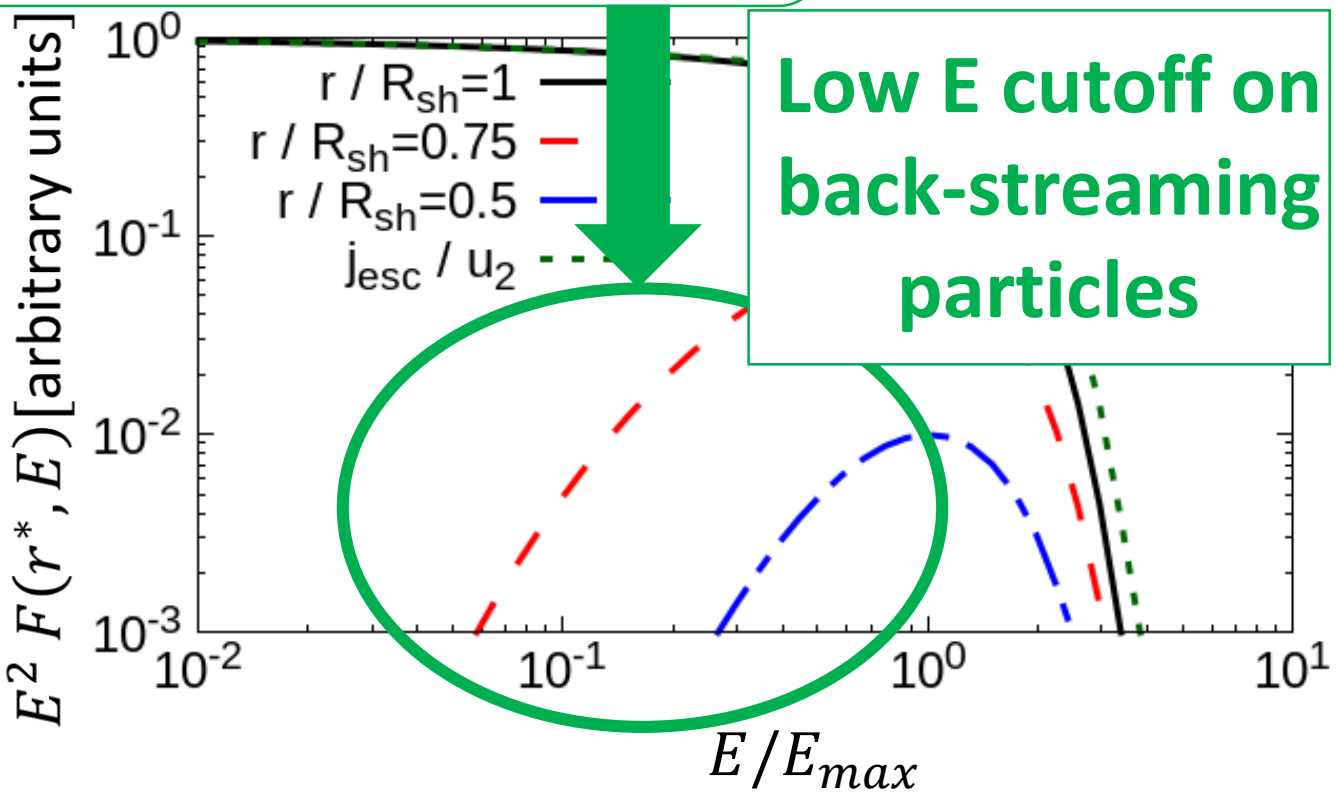
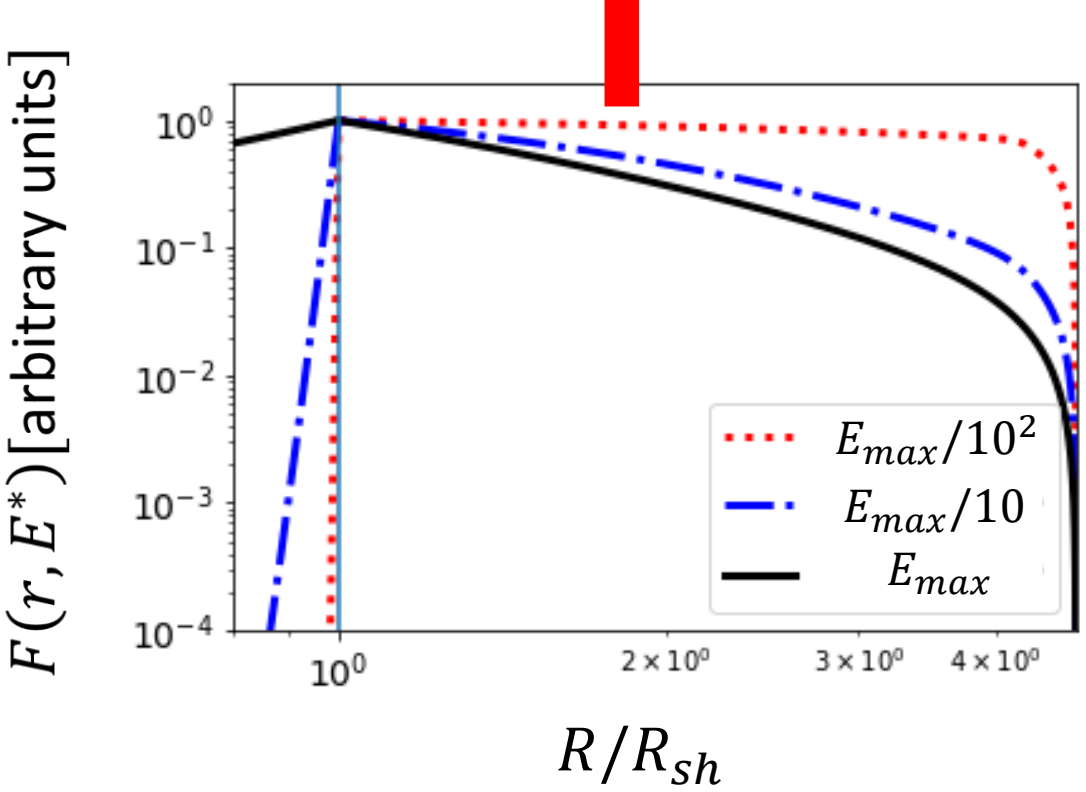


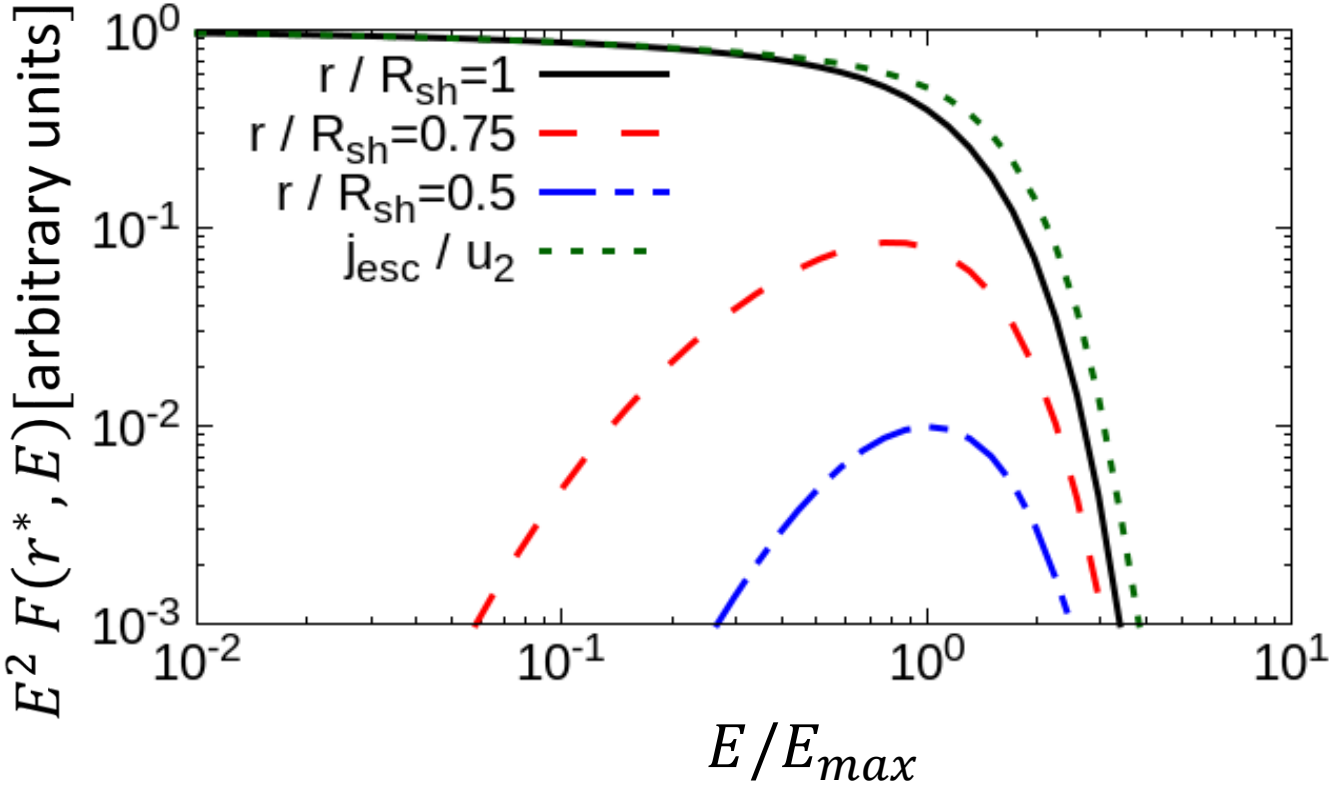


Low E cutoff on back-streaming particles

Solution: radial behavior and spectra

Advection dominated

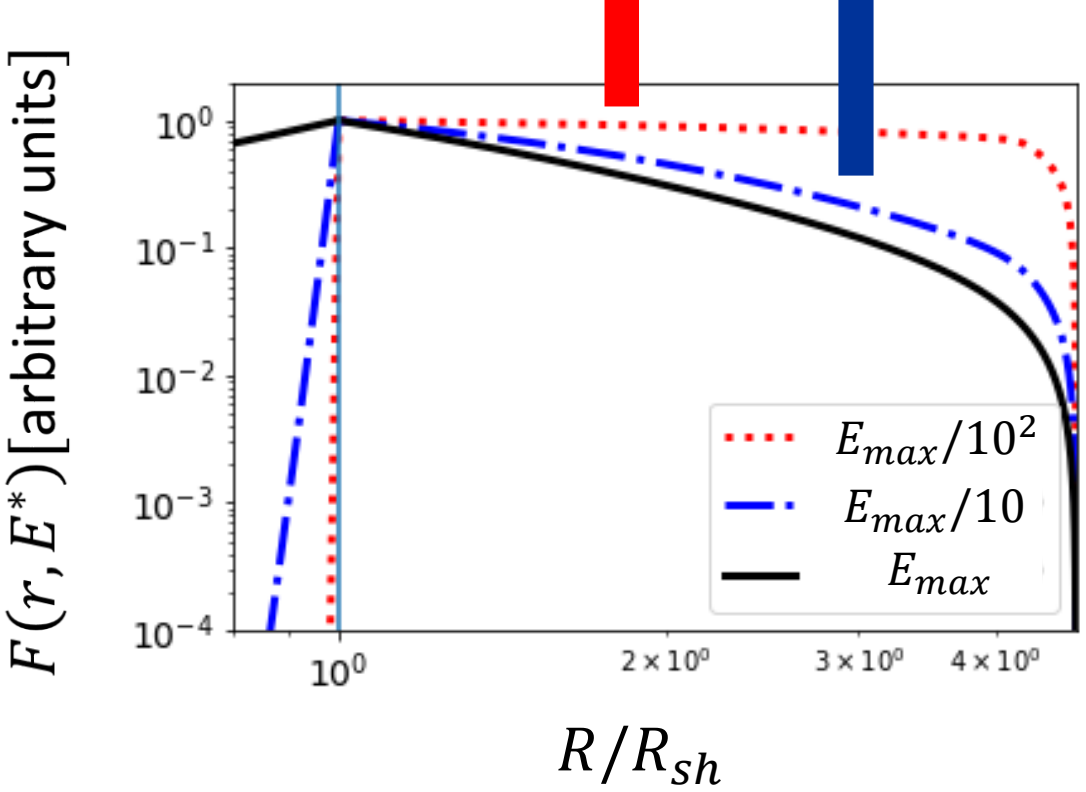


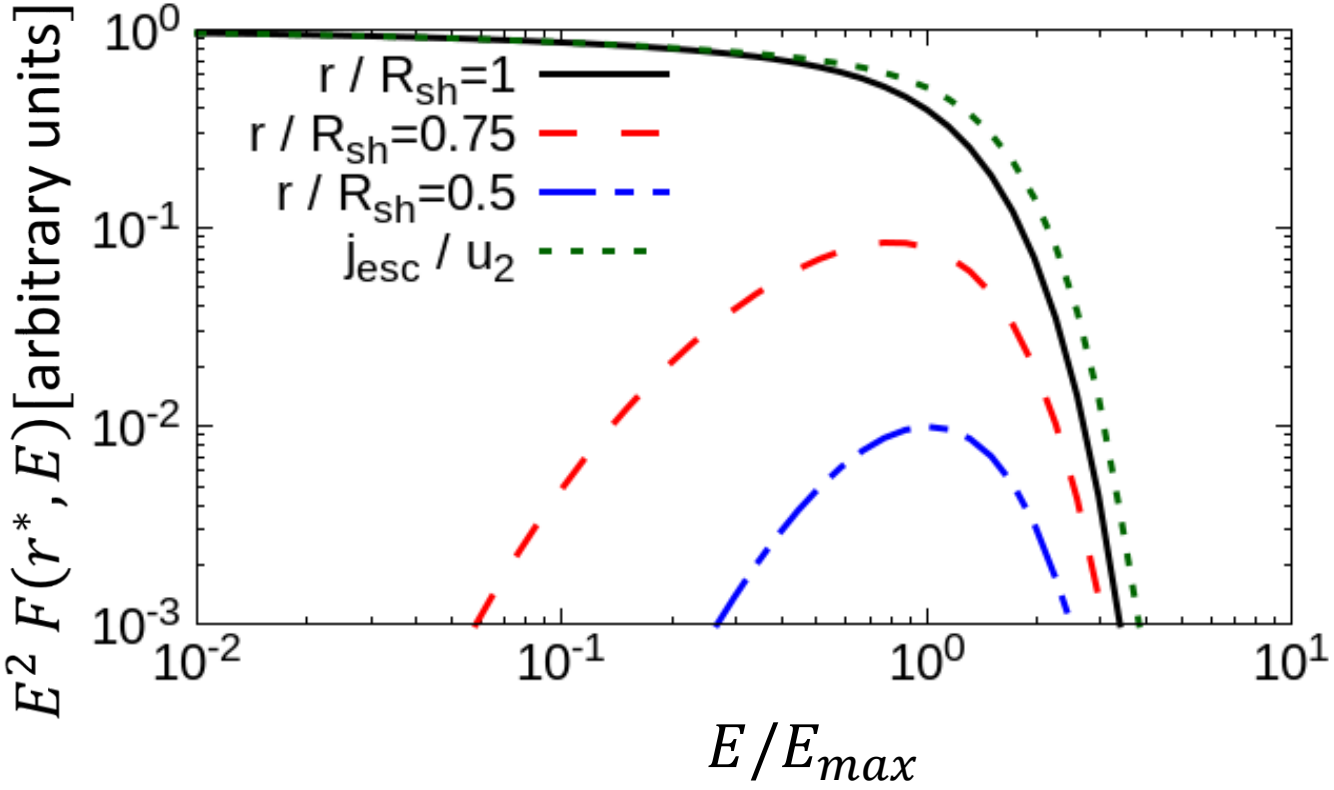


Solution: radial behavior and spectra

Advection dominated

Diffusion dominated



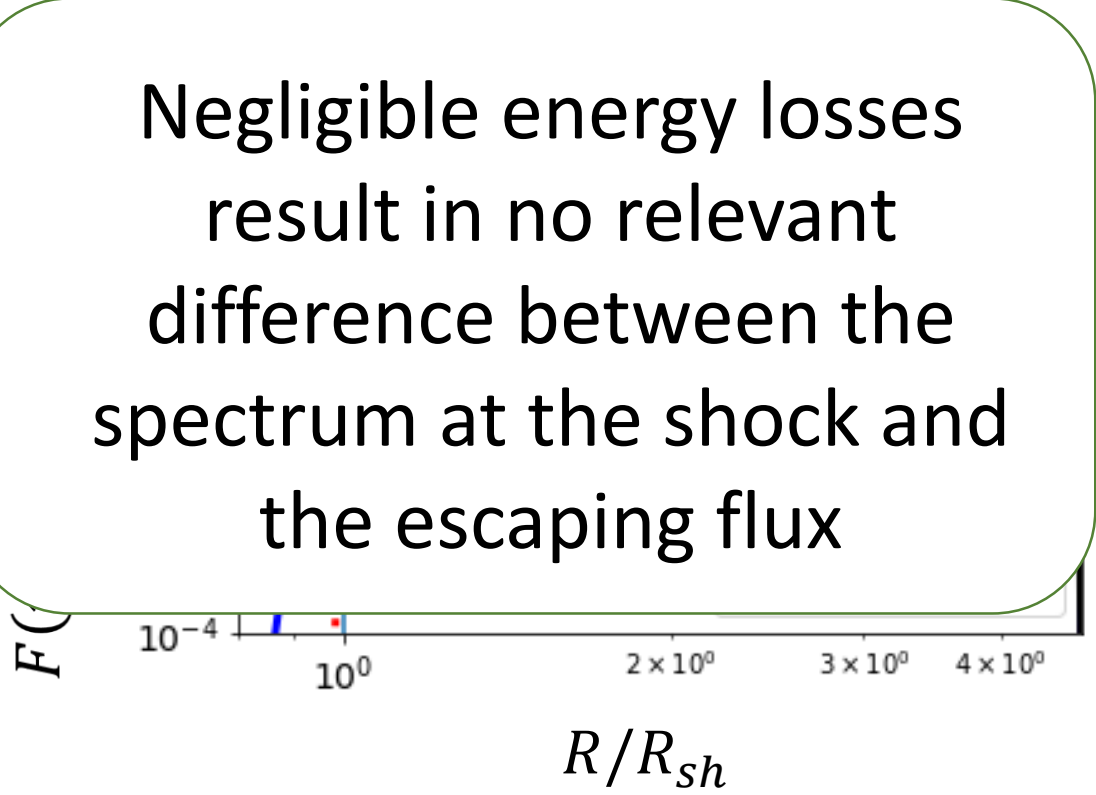


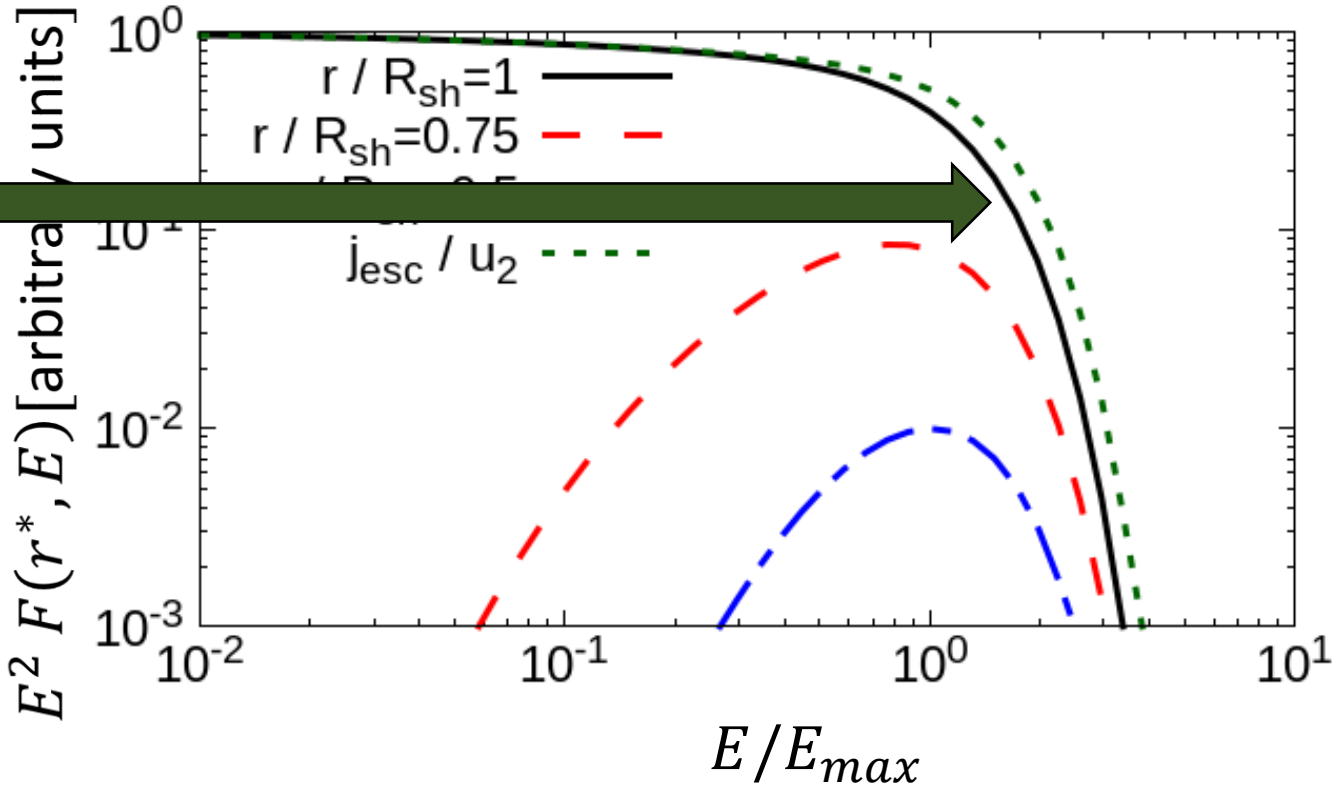
Solution: radial behavior and spectra

Advection dominated

Diffusion dominated

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

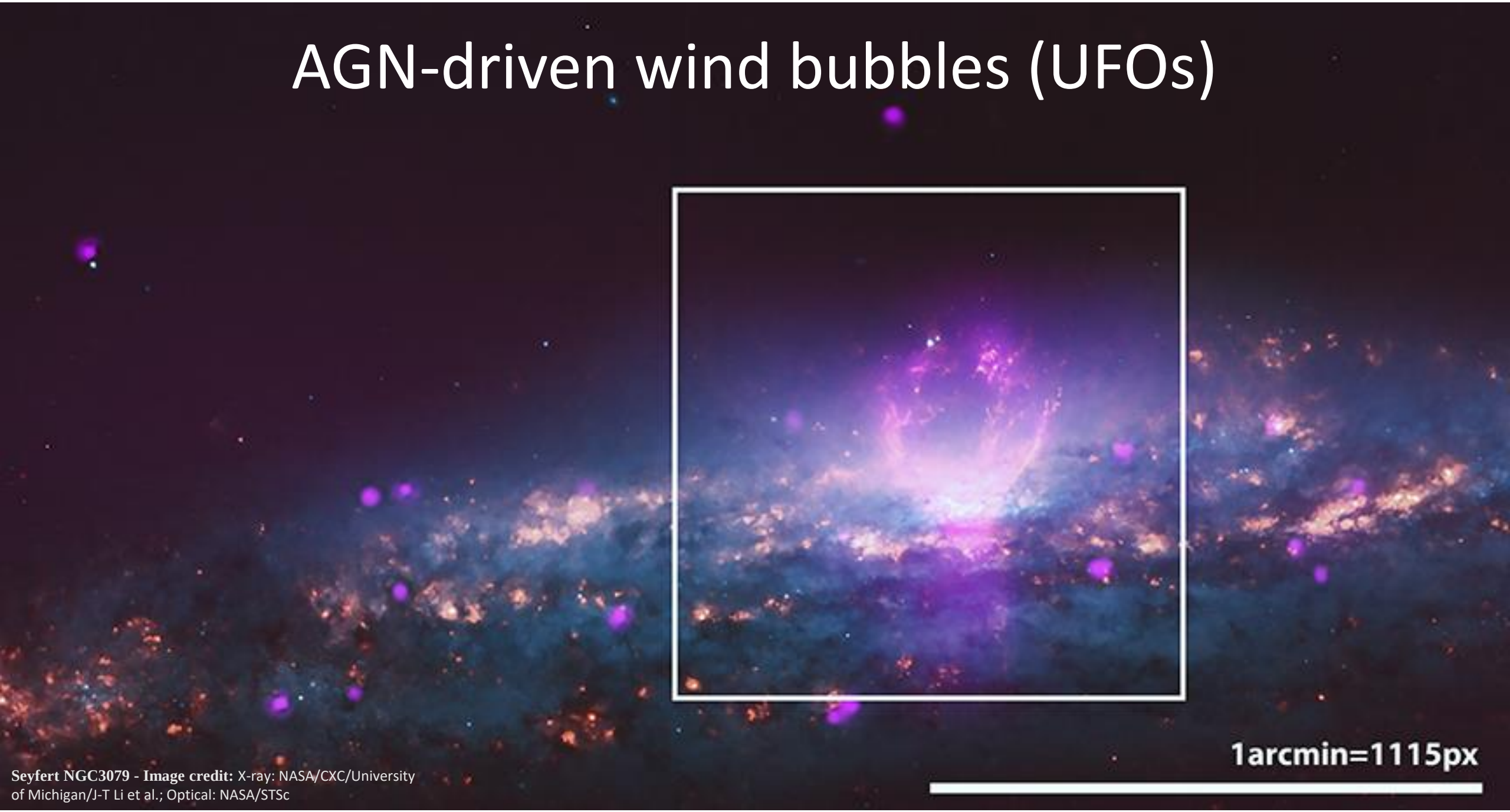




Outline

- Wind bubbles: structure and evolution
- Model for particle acceleration in wind bubbles
- Solution: radial distribution and spectra
- Ultra Fast Outflows

AGN-driven wind bubbles (UFOs)

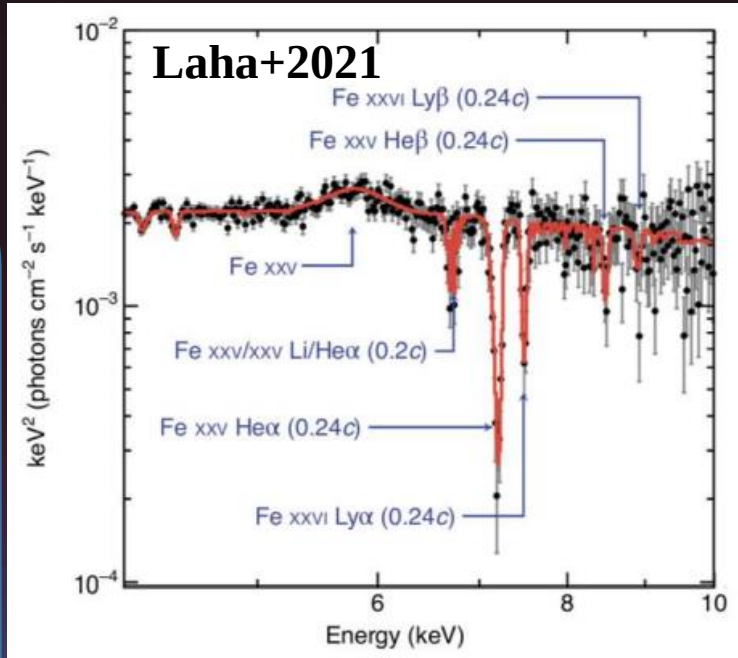


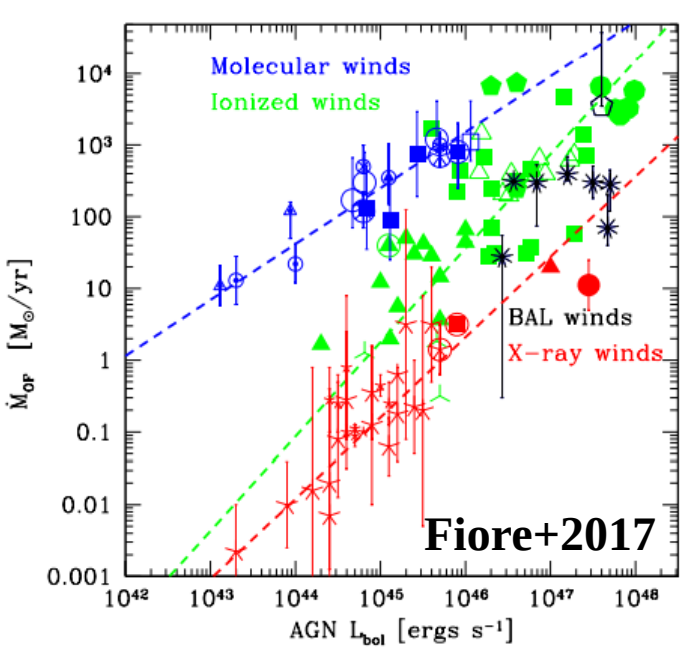
Seyfert NGC3079 - Image credit: X-ray: NASA/CXC/University of Michigan/J-T Li et al.; Optical: NASA/STSc

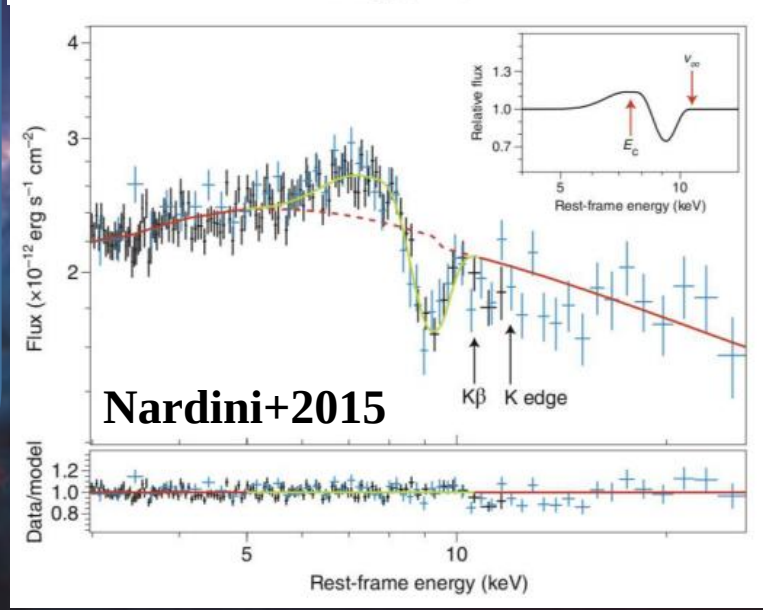
Seyfert NGC3079 - Image credit: X-ray: NASA/CXC/University of Michigan/J-T Li et al.; Optical: NASA/STSc

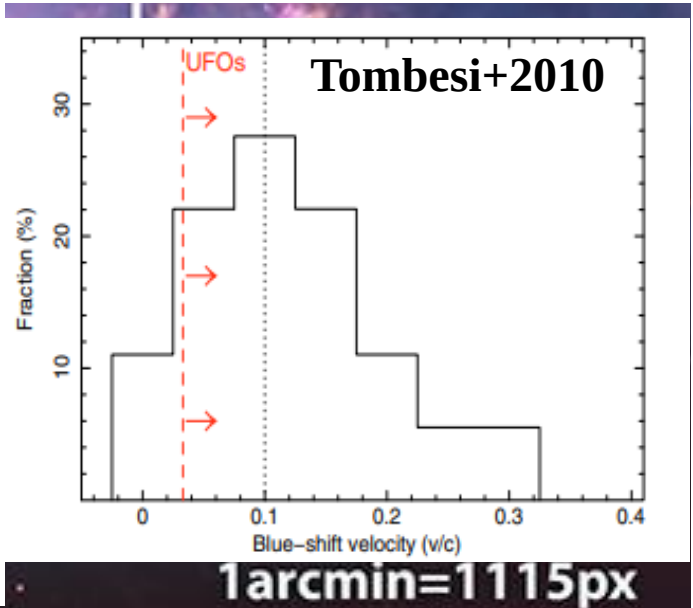
Ultra-Fast Outflows (UFOs)

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





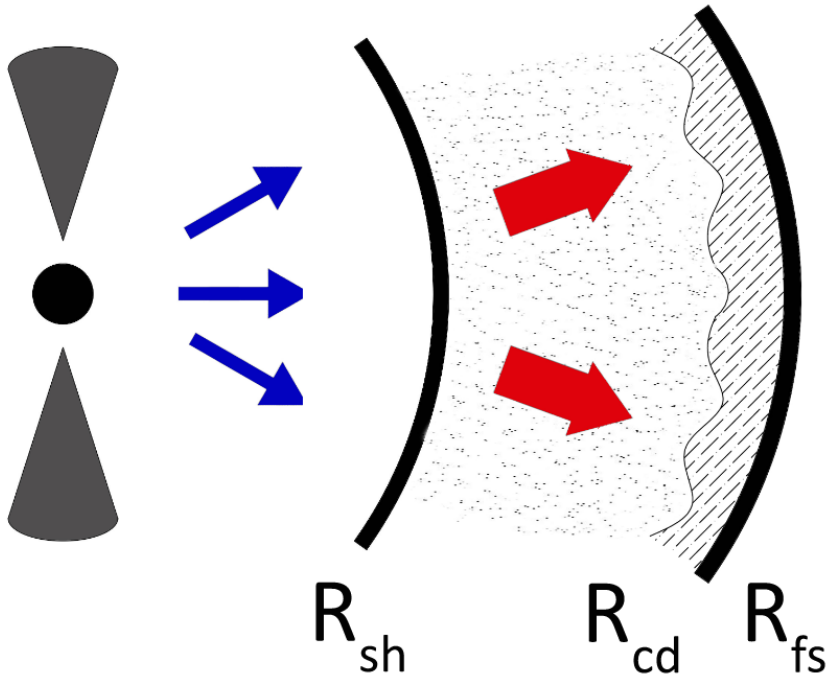




1arcmin=1115px

The UFO wind bubble

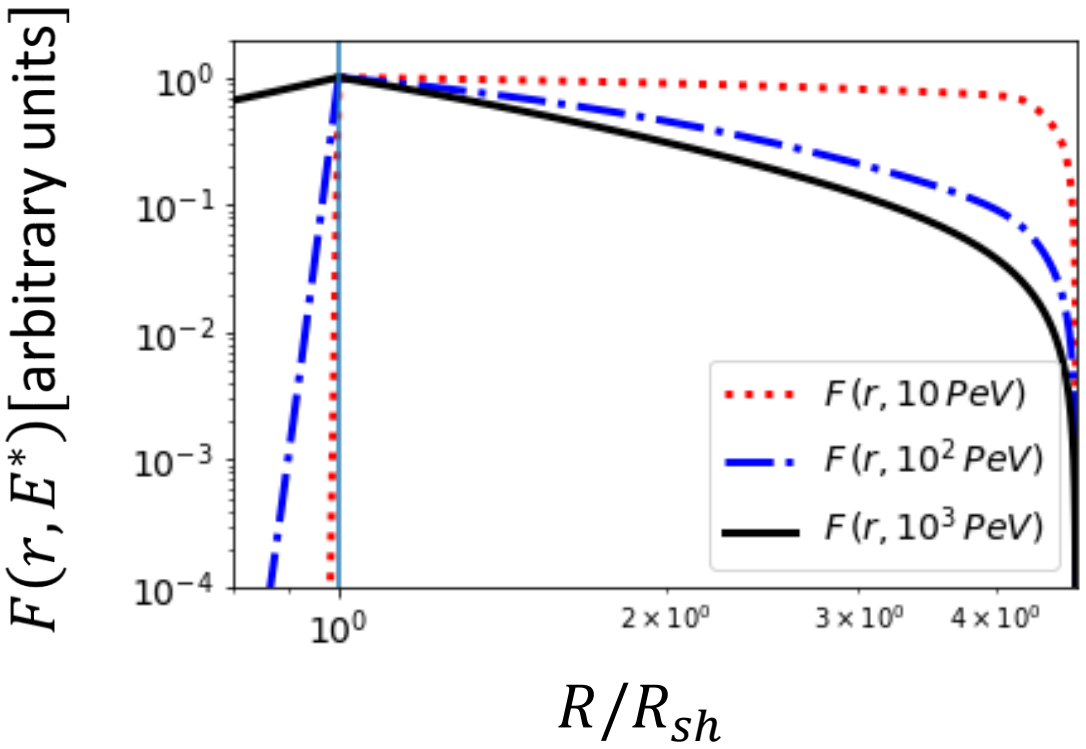
$$r^2 u(r)\partial_r f = \partial_r[r^2 D(r,p)\partial_r f] + \frac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p) - r^2 \Lambda(r,p)$$

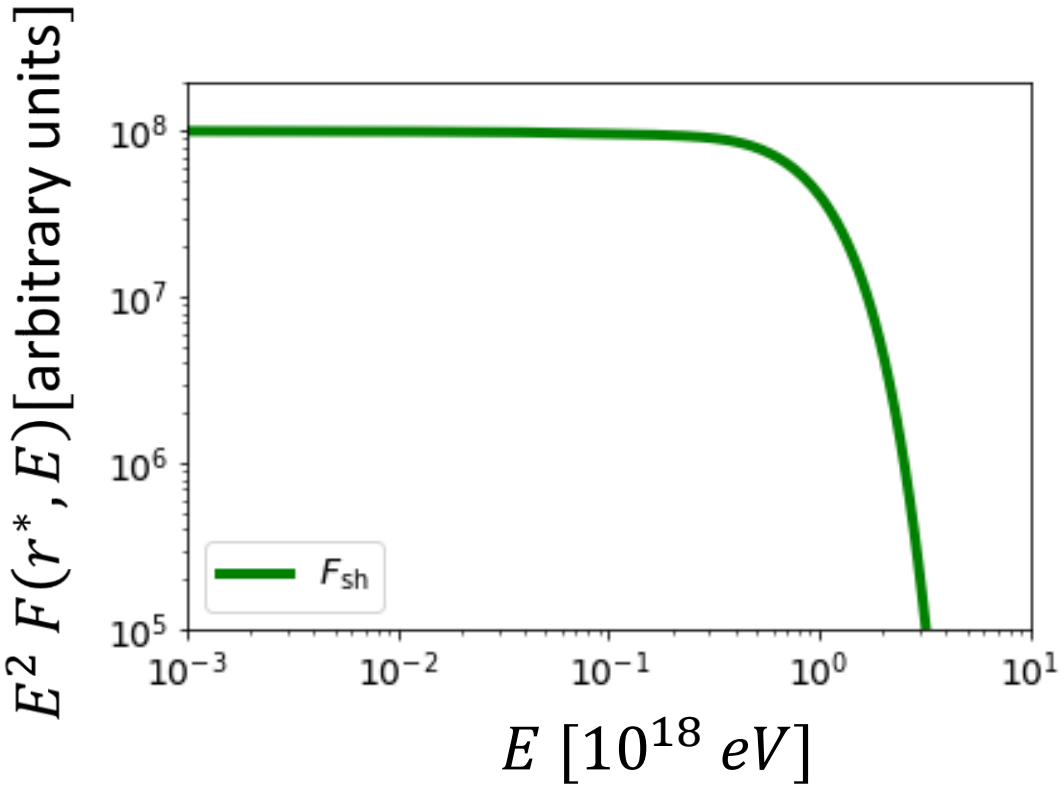


Parameters:

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

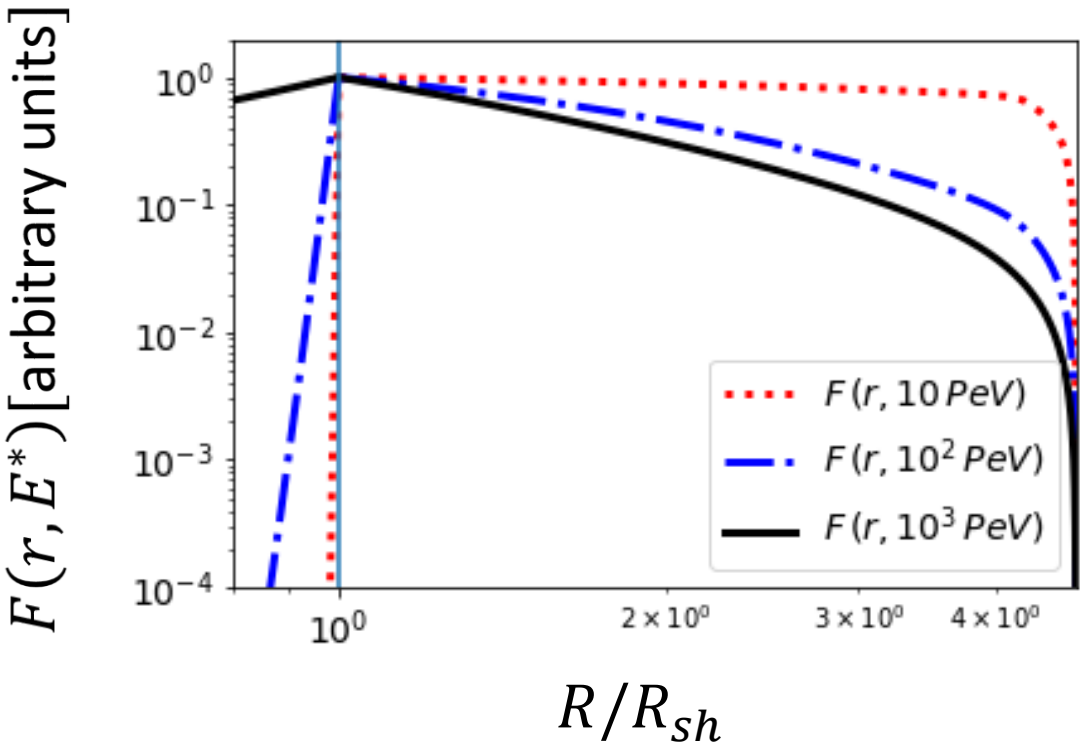
Solution: radial behavior and spectra

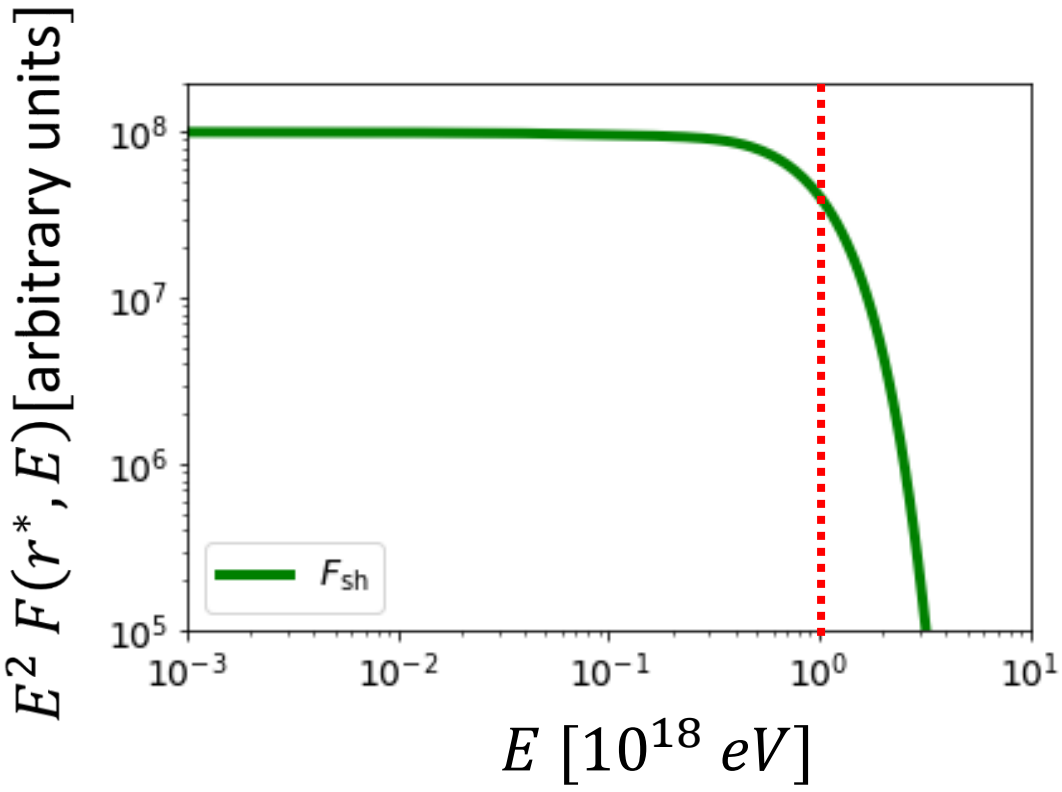




Solution: radial behavior and spectra

Maximum Energy in the EeV range
(for a Kraichnan D)





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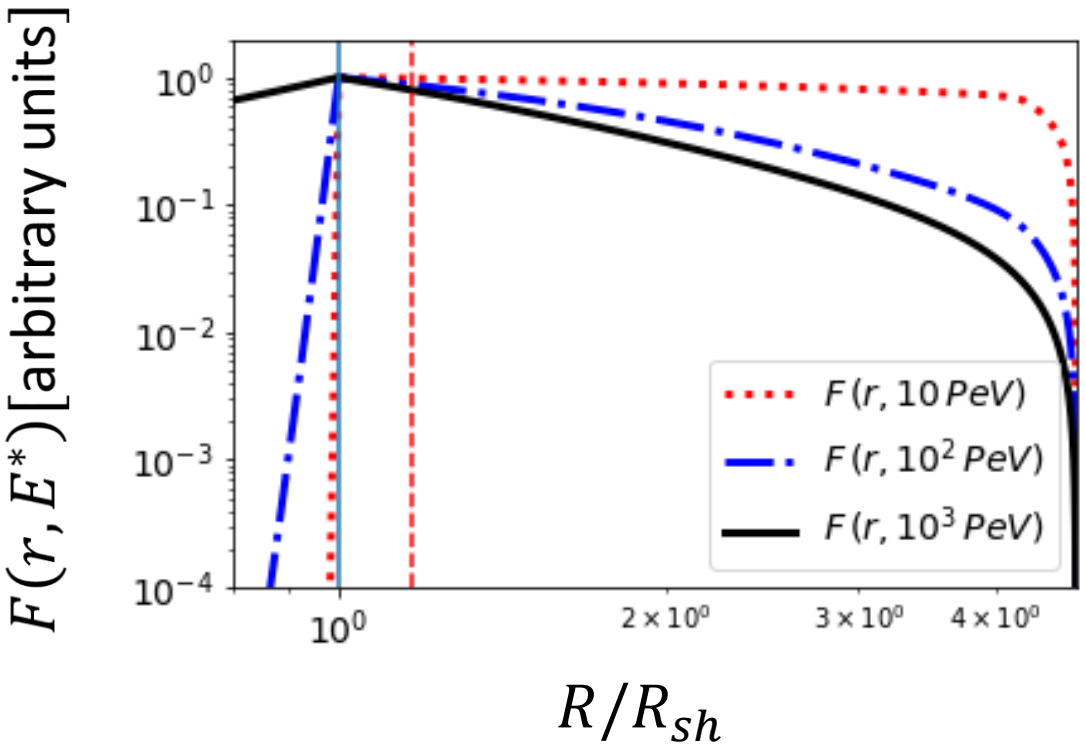
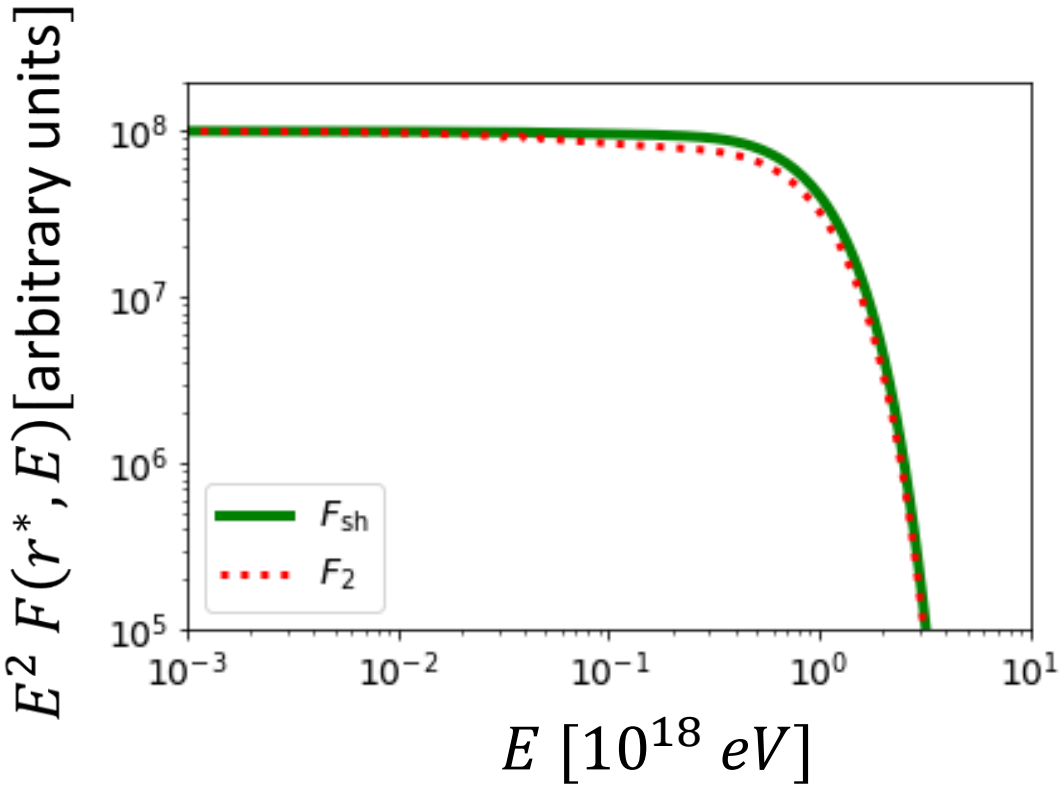
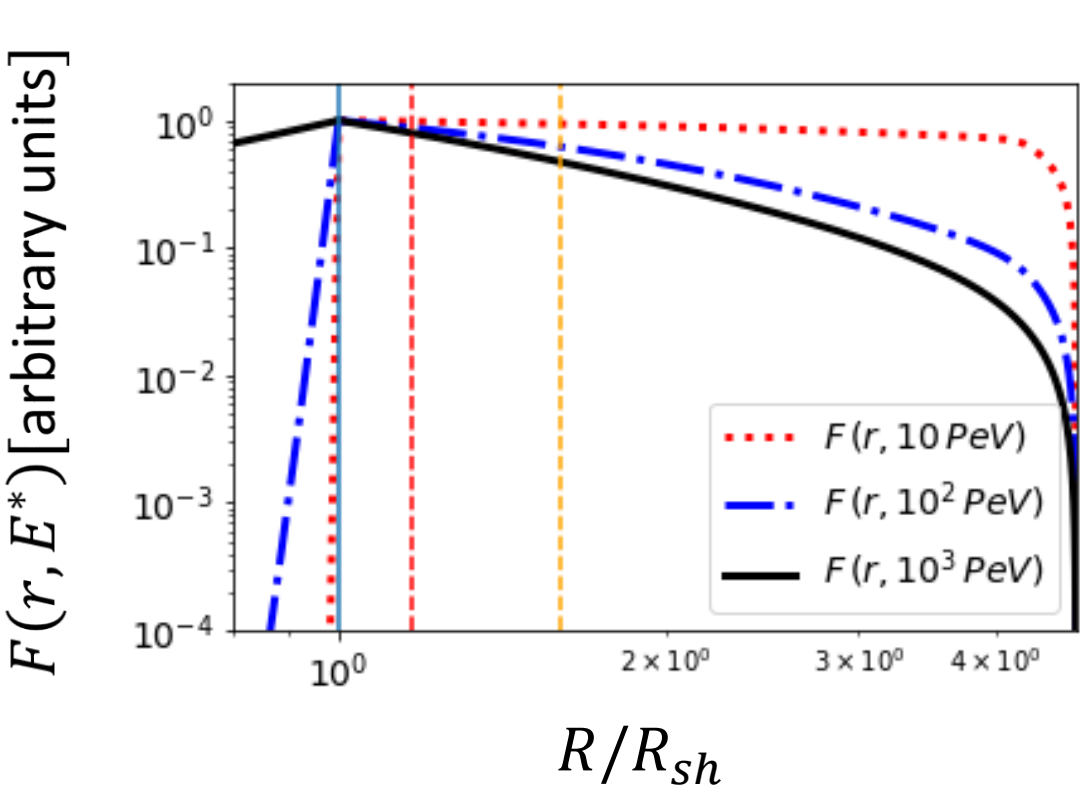
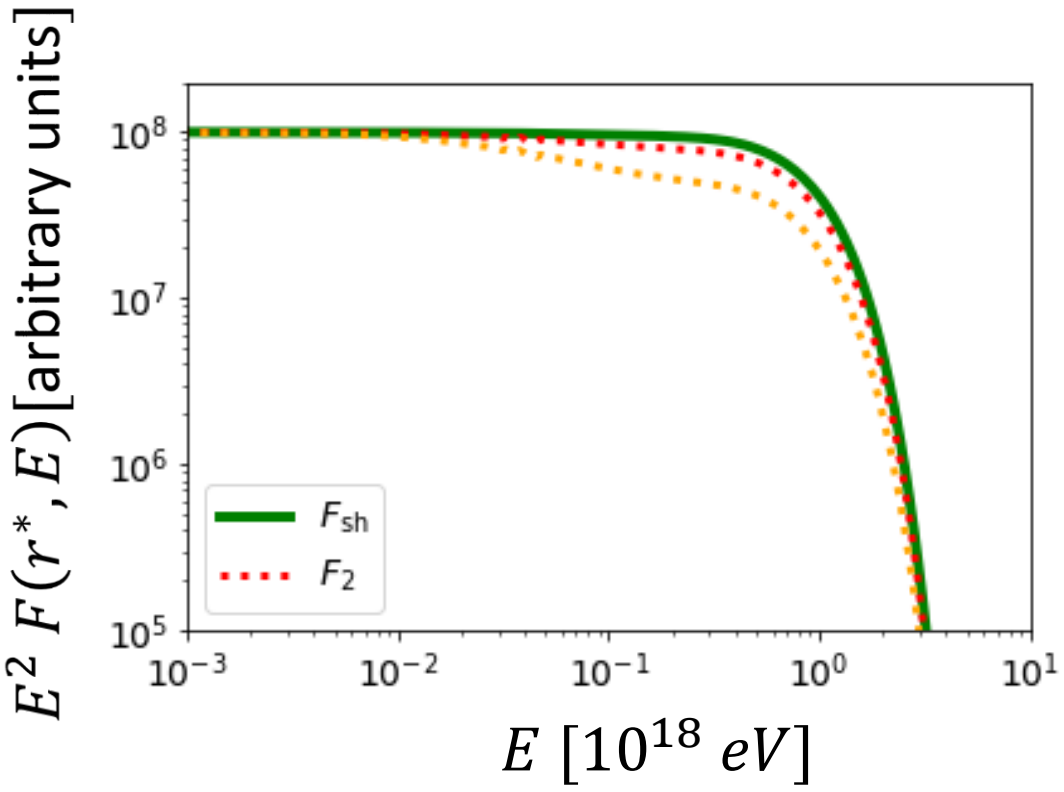


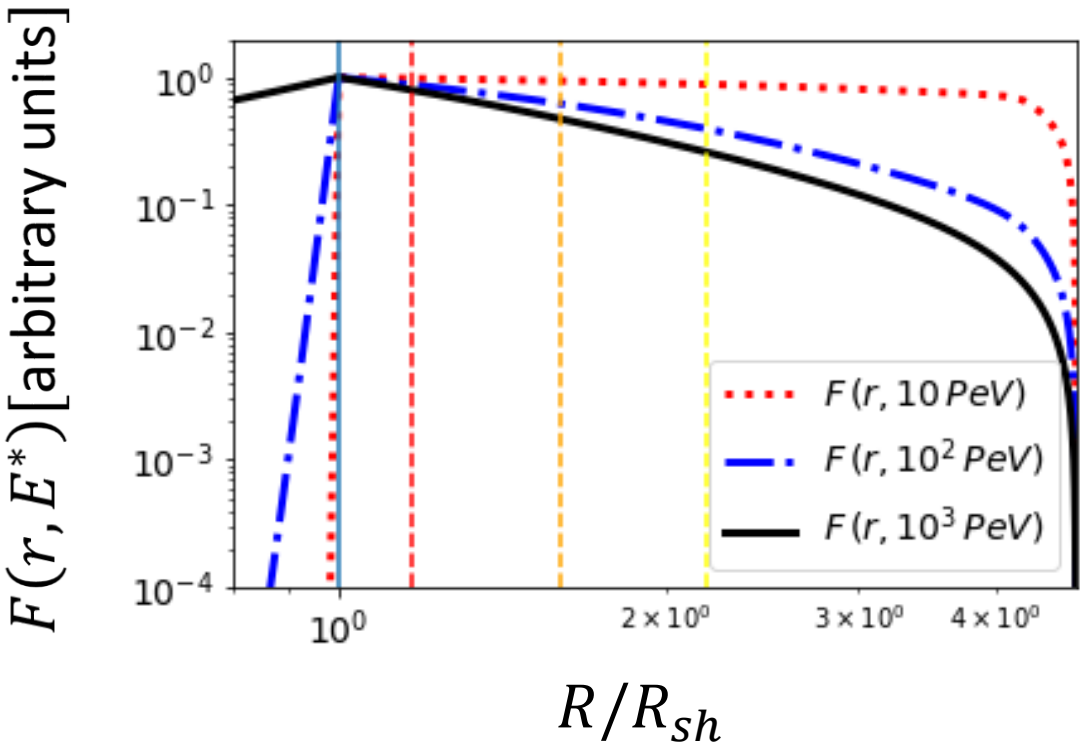


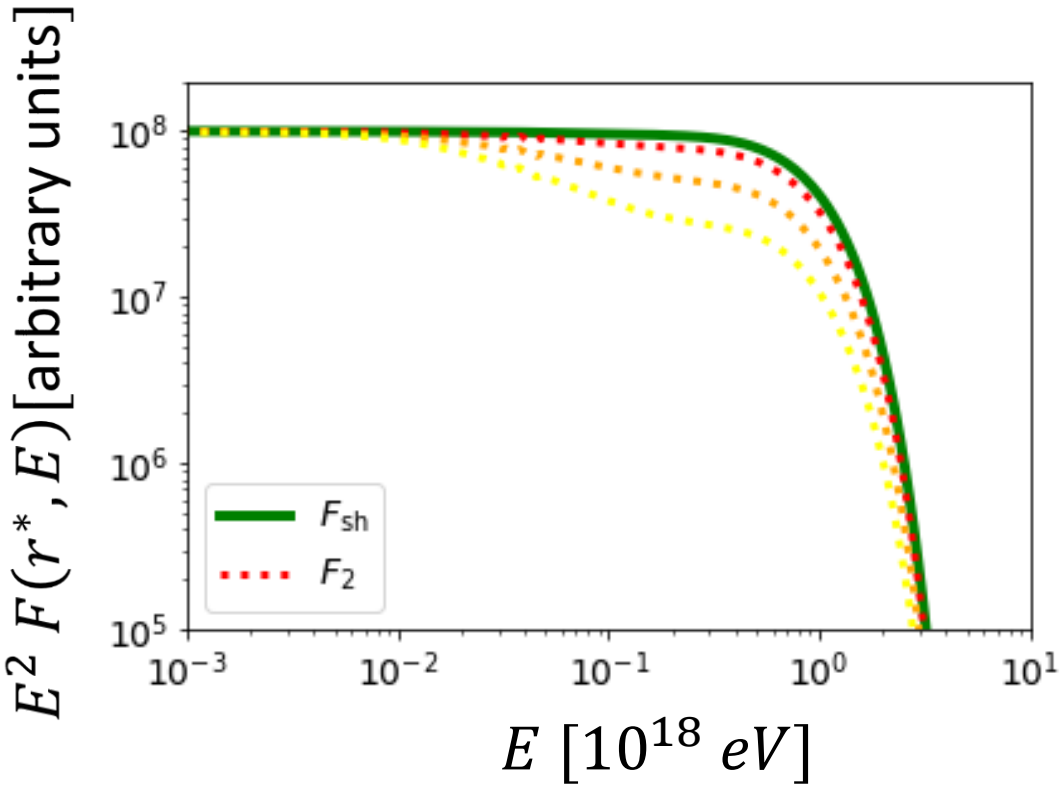
Solution: radial behavior and spectra



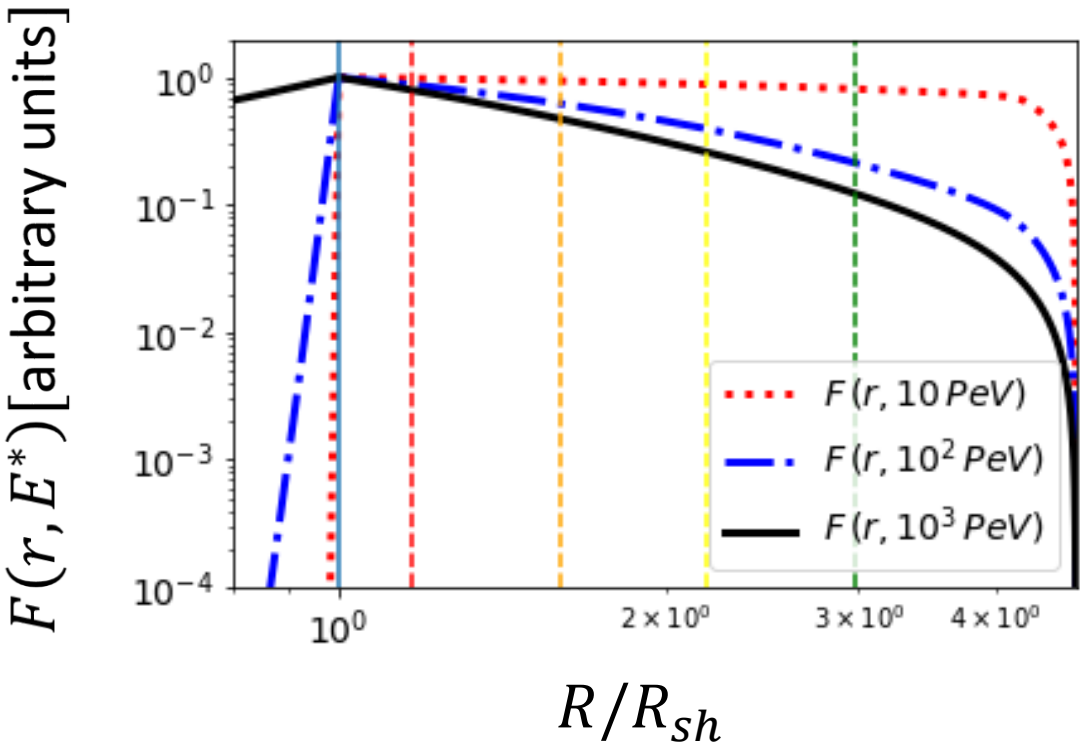


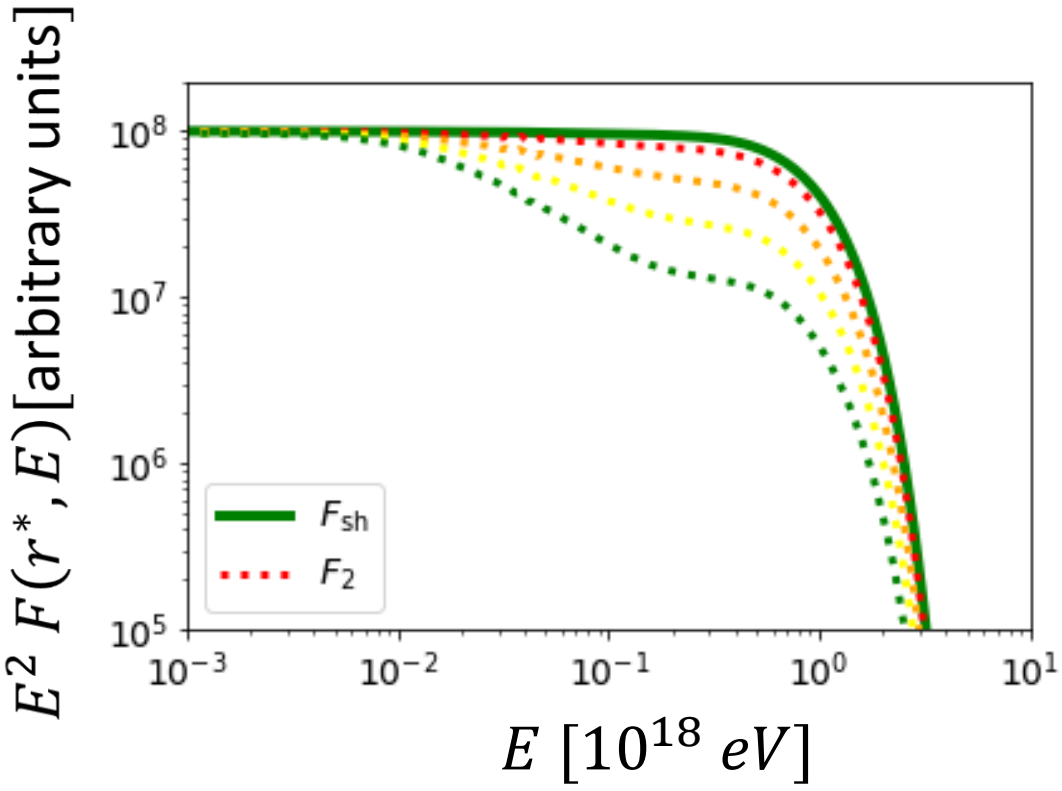
Solution: radial behavior and spectra



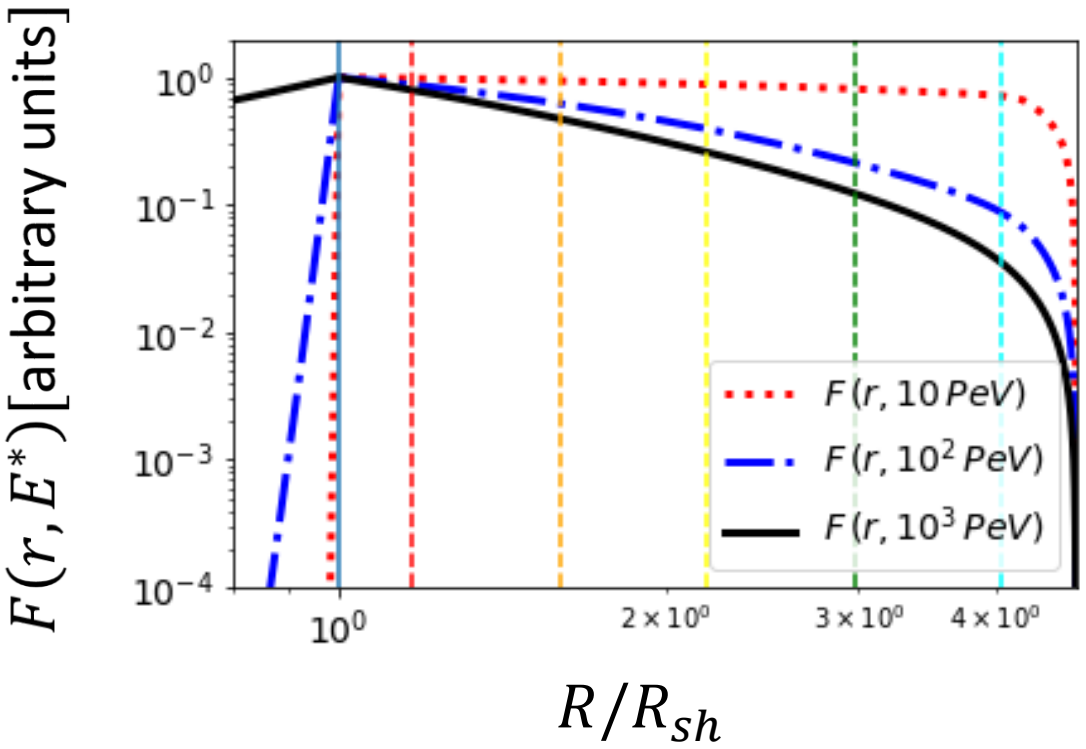


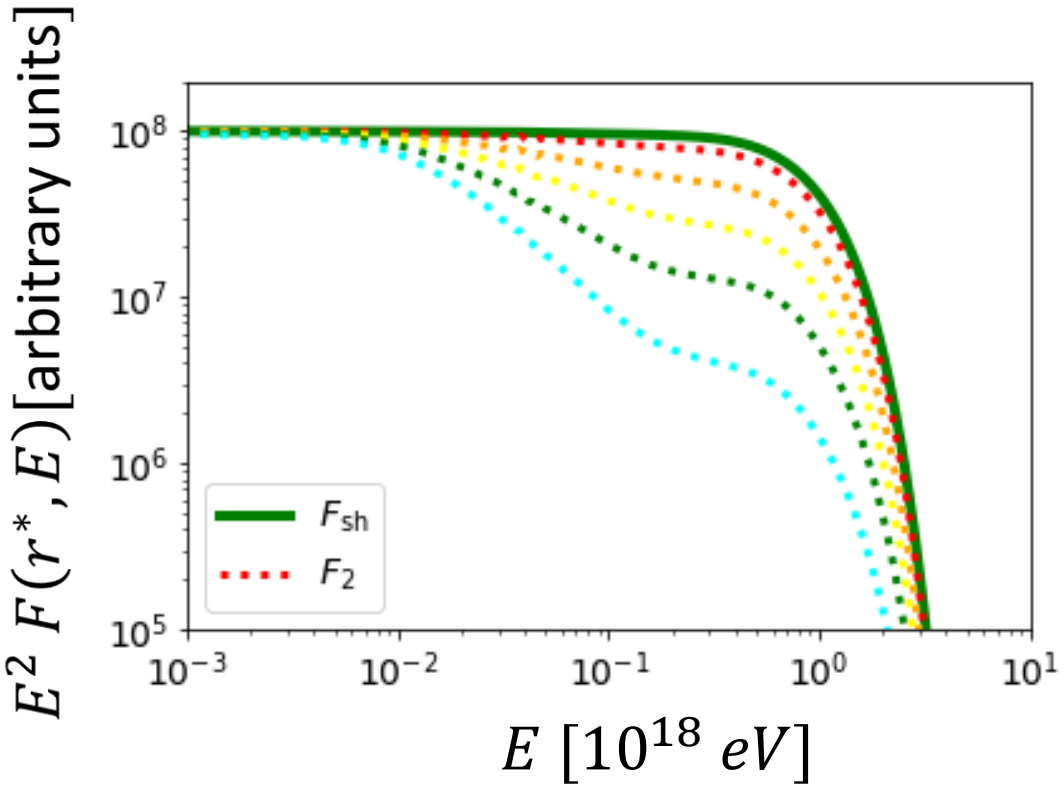
Solution: radial behavior and spectra



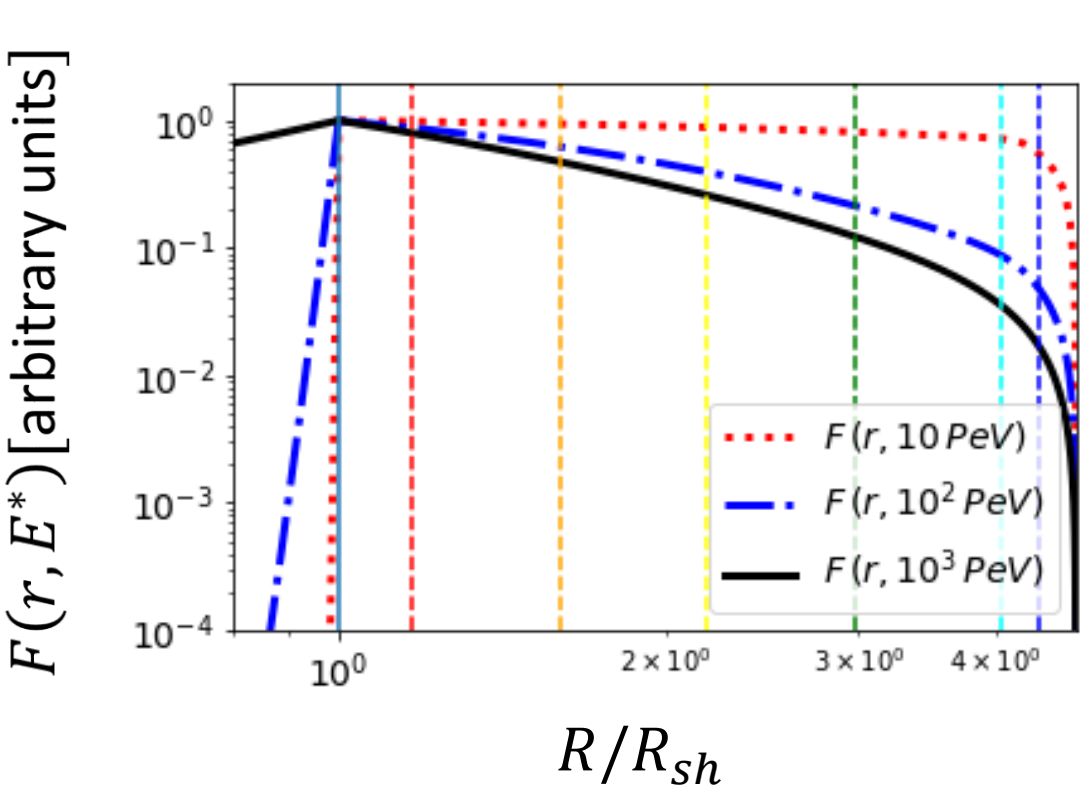


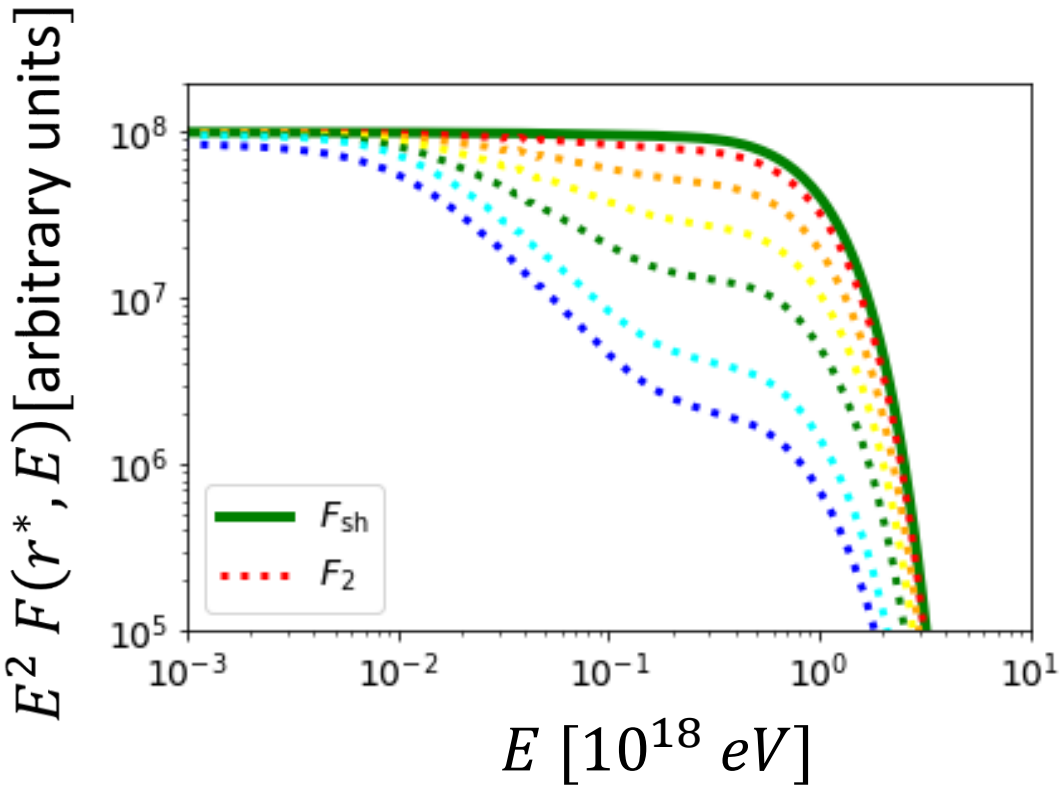
Solution: radial behavior and spectra



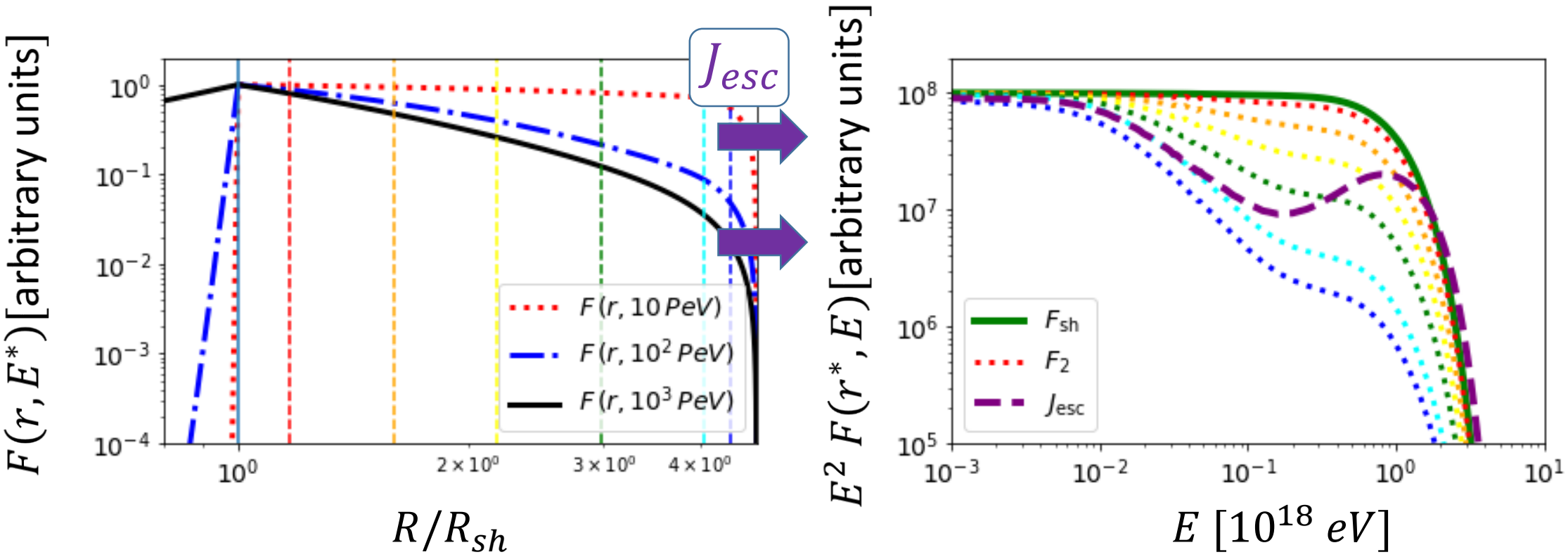


Solution: radial behavior and spectra



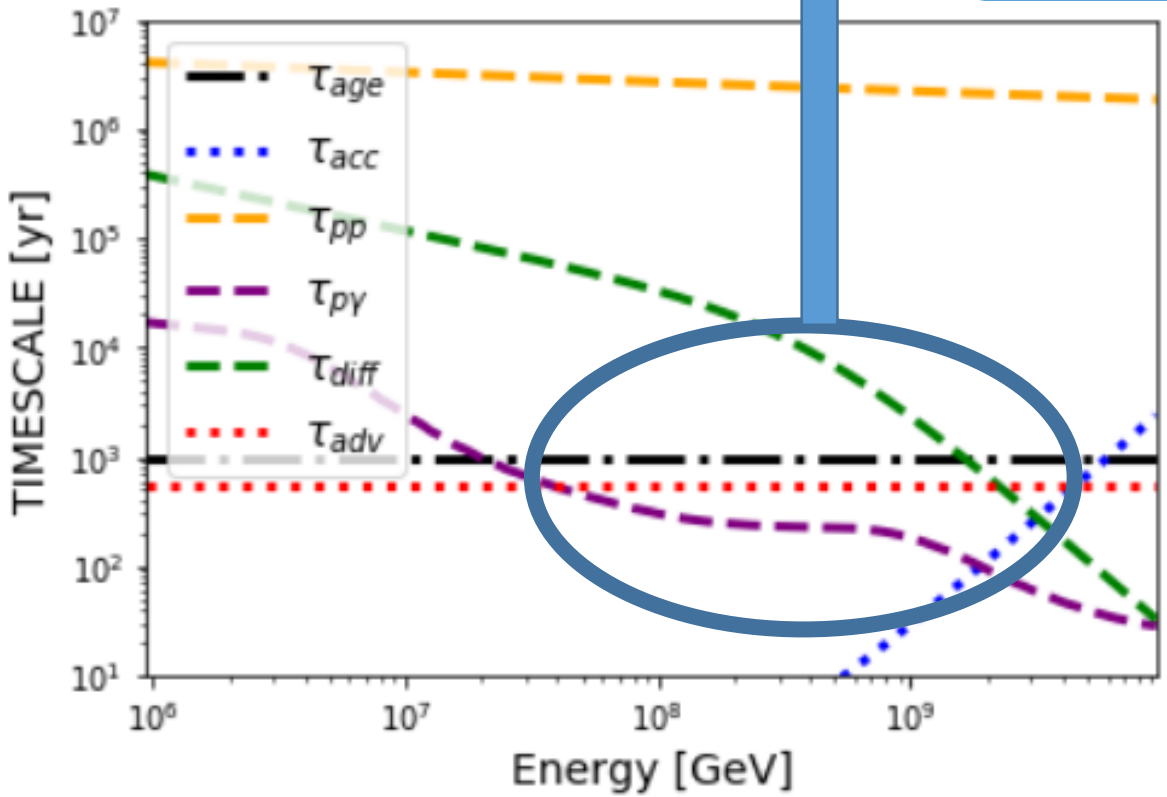


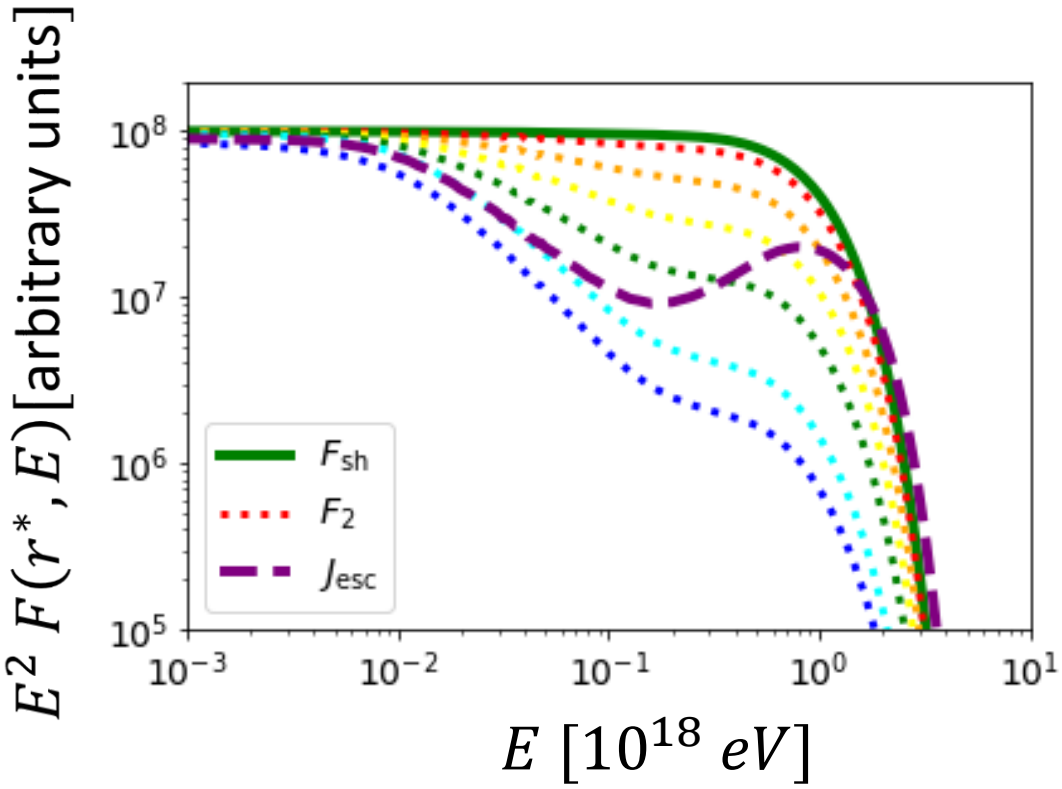
Solution: radial behavior and spectra



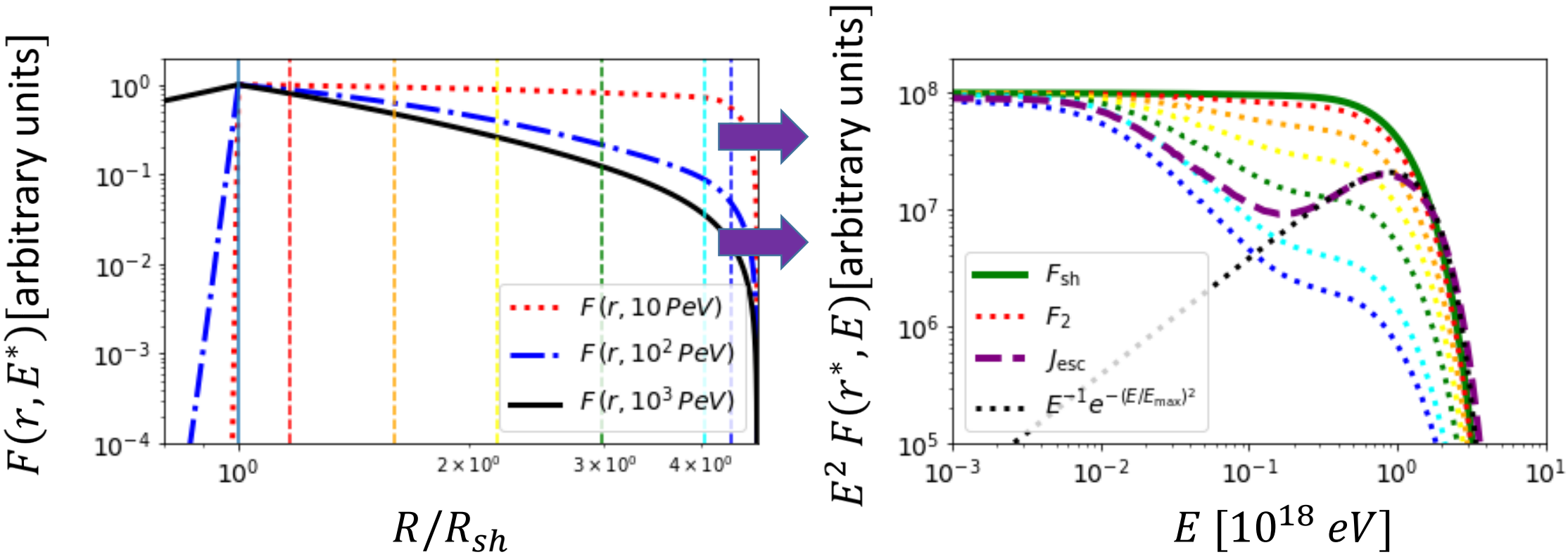
Solution: radial behavior and spectra

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





Solution: radial behavior and spectra



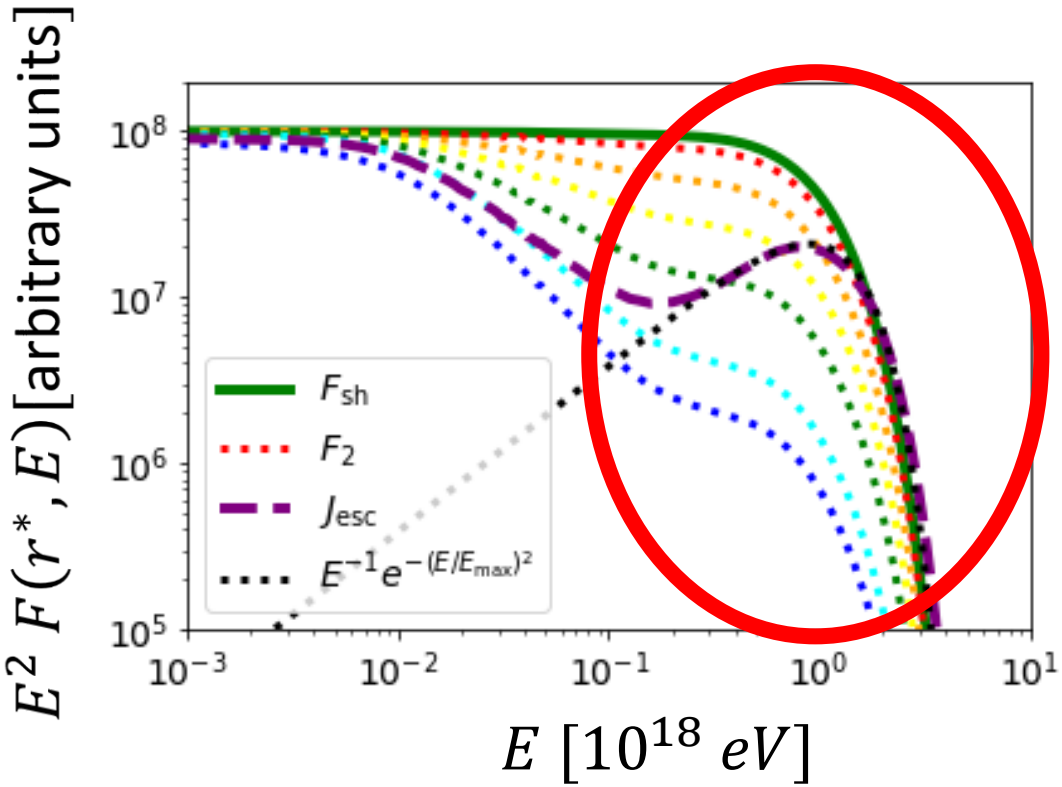
Solution: radial behavior and spectra

1. Standard $\sim E^{-2}$ acceleration spectrum

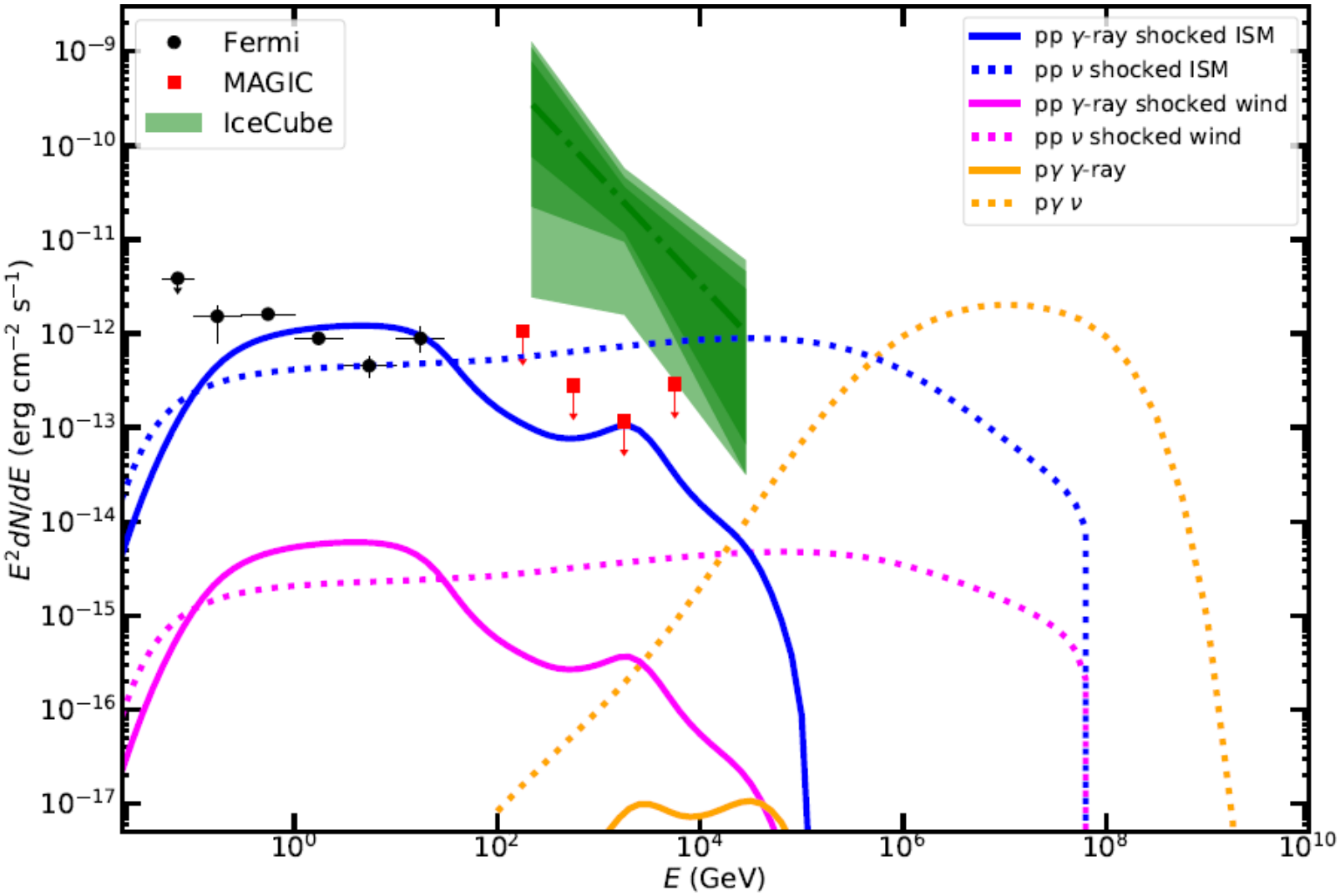
2. Hard spectrum injected in the host galaxy ISM

$F(r, E^*)$[arbitrary units]

R/R_{sh}

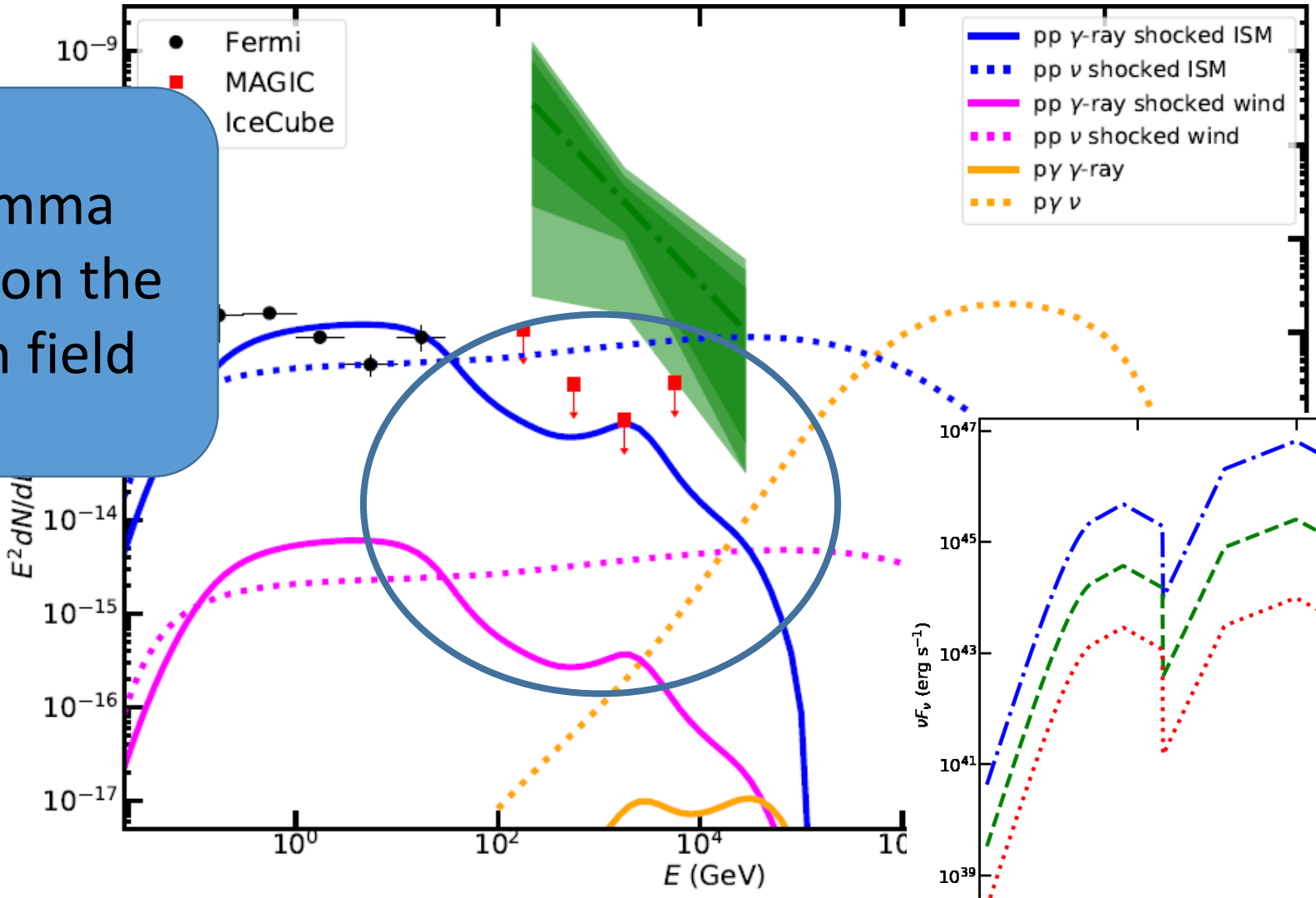


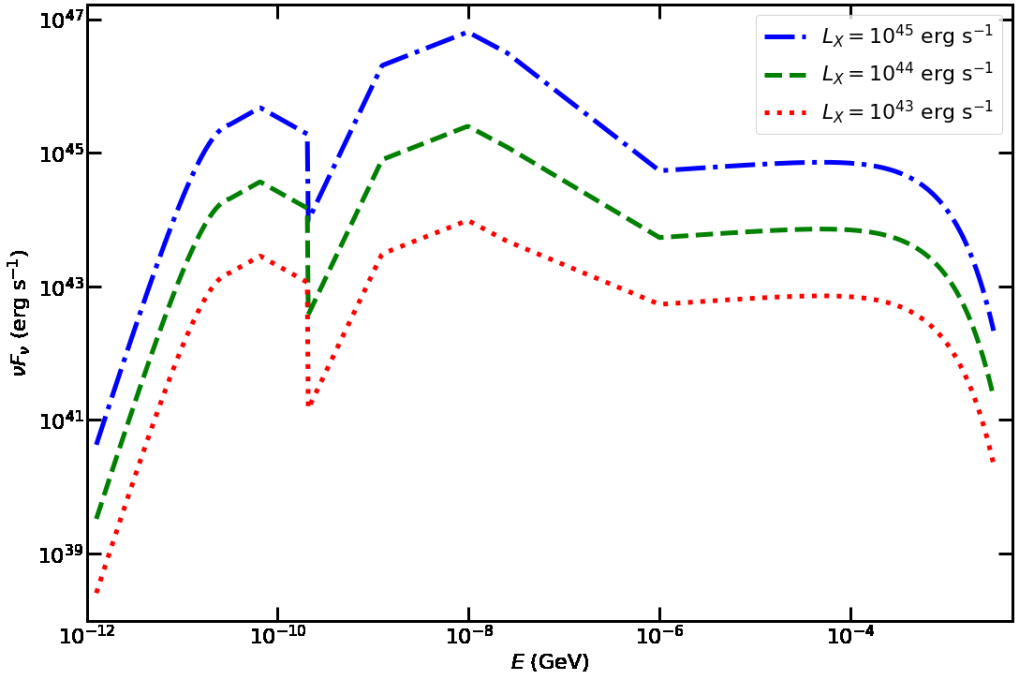
Multimessenger implications: NGC1068



Multimessenger implications: NGC1068

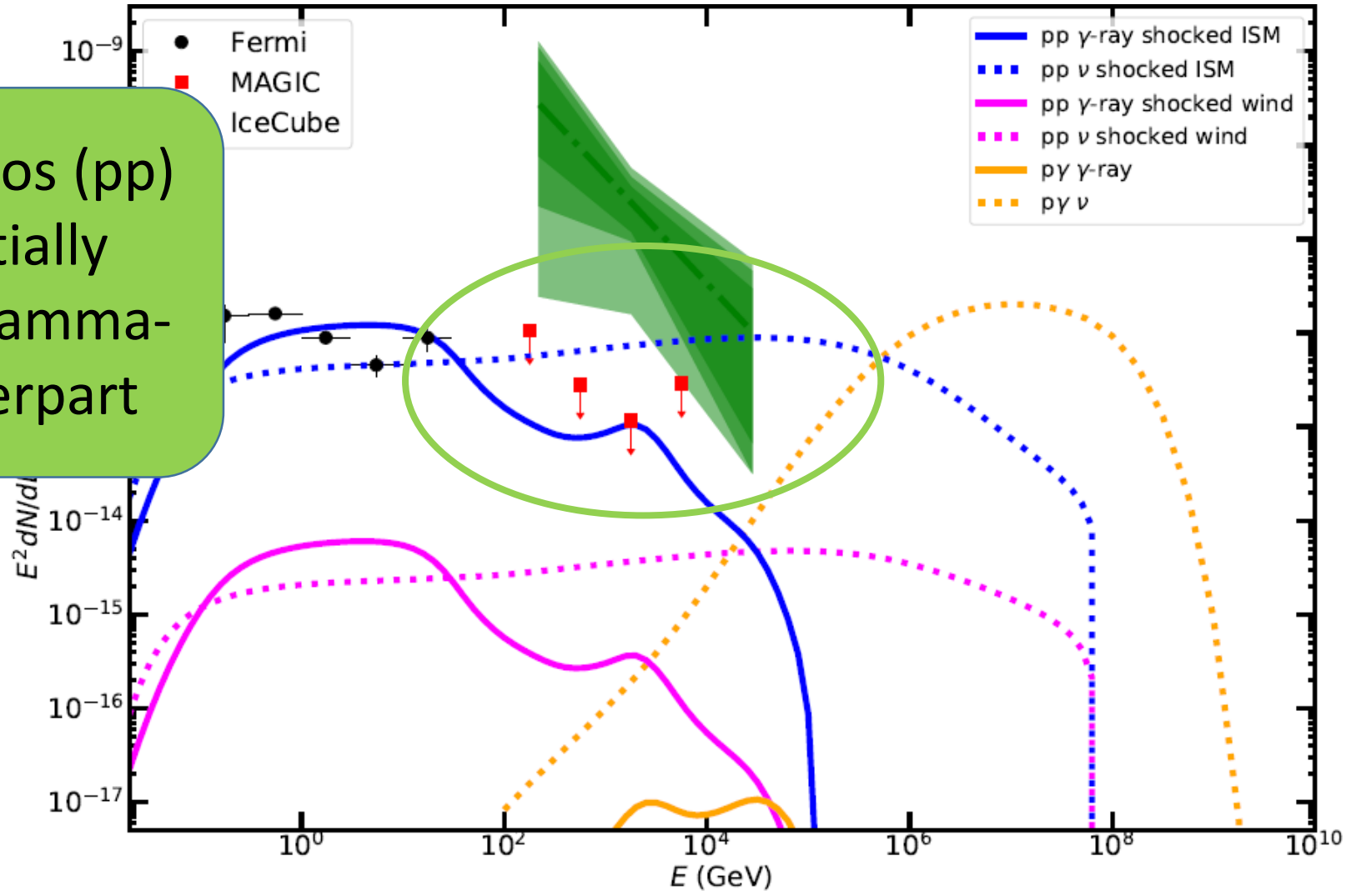
Gamma-gamma absorption on the BKG photon field





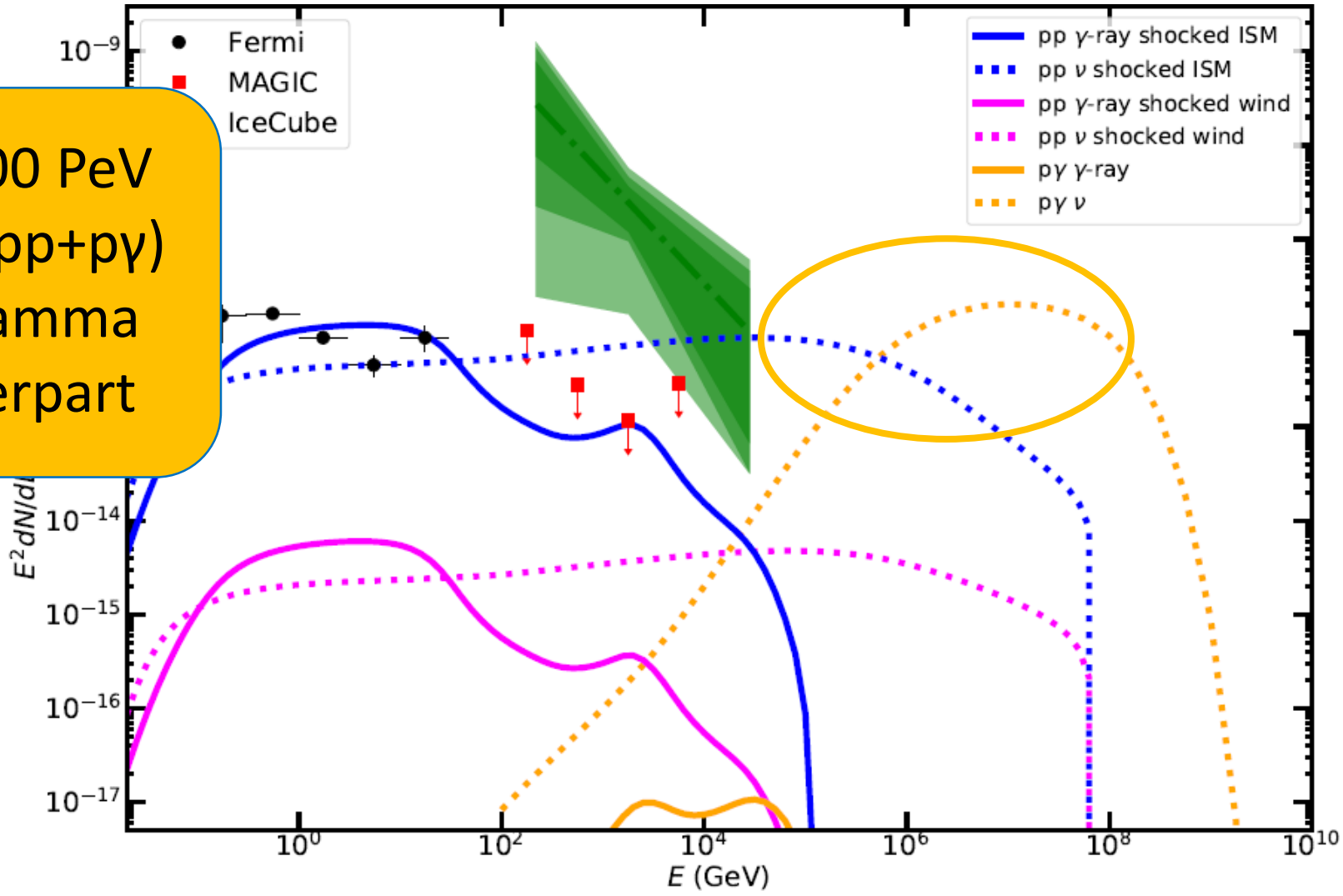
Multimessenger implications: NGC1068

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

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

- Maximum energy: PeV can be reached in SCs, 10^2 PeV in SBGs & EeV in AGN-driven winds (UFOs)

- UHECRs can be injected by UFOs in the host galaxy featuring a hard spectral slope at the highest energies

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

Take h[illegible] messages

- Diffusive sh[illegible] take place efficiently at wi[illegible] wind bubbles
- [illegible] eV can be reached in SC[illegible] EeV in AGN-driven wind[illegible]
- [illegible]CRs can be injected by U[illegible] featuring a hard spectral sl[illegible]ergies
- UFOs can be bright neutrin[illegible]es while being opaque to gamma rays

What about starbursts?

Where should we look to spot the sources of UHECRs?

Thanks for your attention!

Solution: radial behavior and spectra

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

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

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