Diffusive Shock Acceleration at wind shocks in AGN-driven outflows

Enrico Peretti

Co-authors: M. Ahlers & A. Lamastra

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

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Outline

- Ultra Fast Outflows
- Acceleration and transport at wind shocks in UFOs
- Solution: radial behavior and spectra
- Multimessenger implications

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


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Outflows are detected in ≥ 50% of nearby AGNi
1arcmin=1115px

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Ultra-Fast Outflows (UFOs)

1arcmin=1115px

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Ultra-Fast Outflows (UFOs)

- Dist. scale = $10^{-3} - 10$ pc

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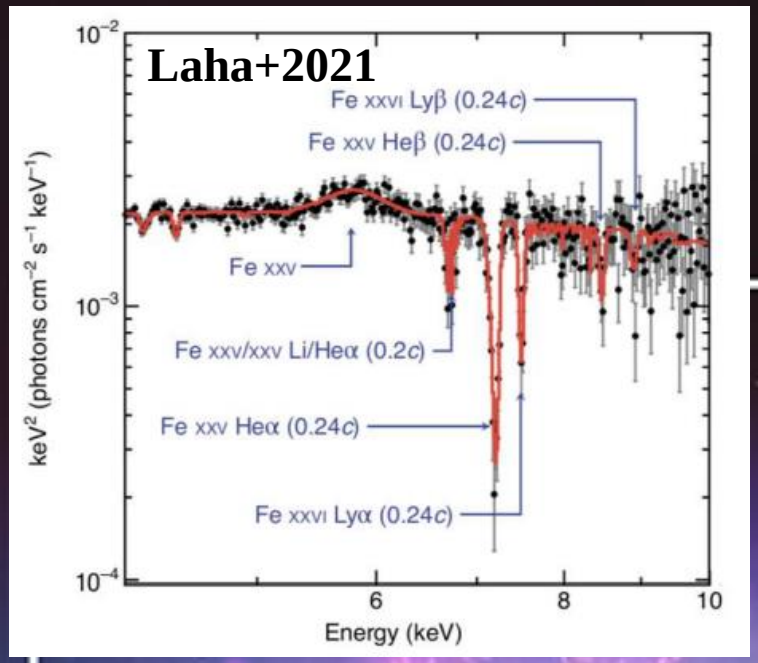
Ultra-Fast Outflows (UFOs)

- Dist. scale = $10^{-3} - 10$ pc
  - $v \approx 0.03\,c\ - 0.3\,c$



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Ultra-Fast Outflows (UFOs)

- Dist. scale = $10^{-3} - 10$ pc
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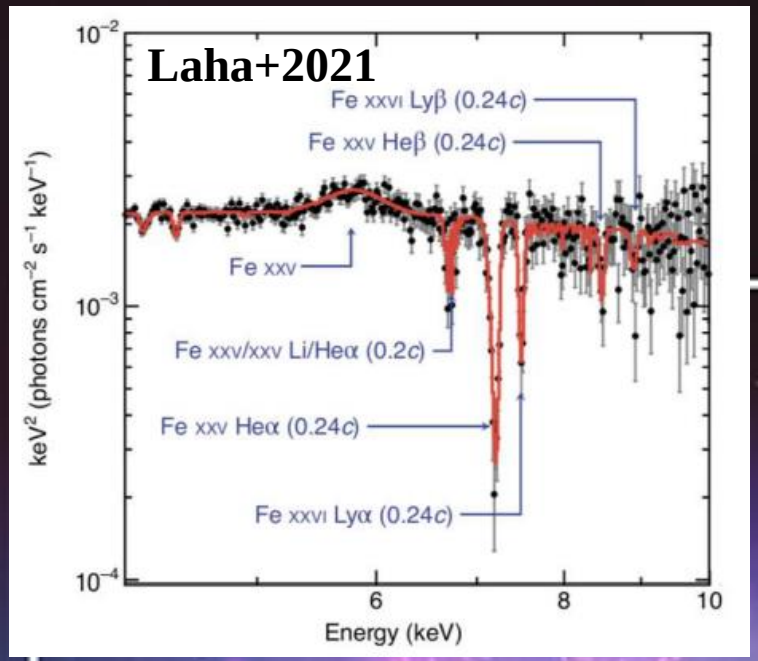
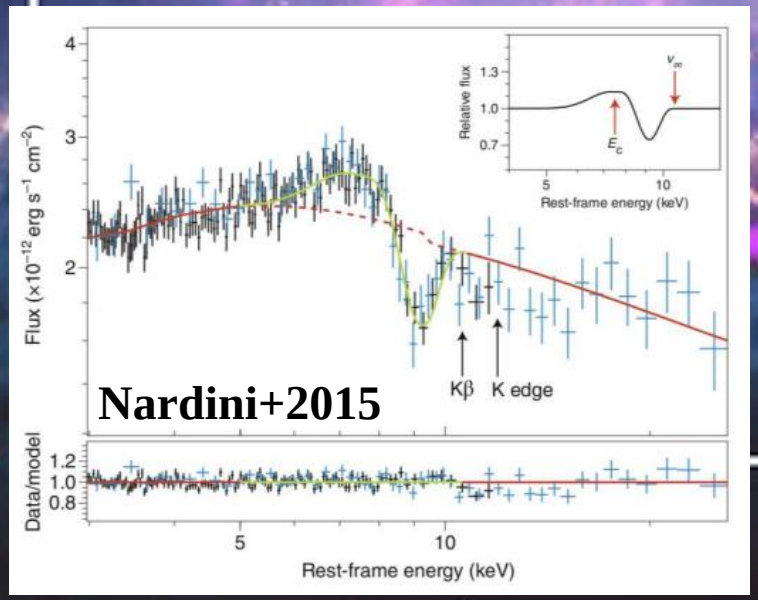
- $\Omega \gtrsim 3\pi$ sr





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Ultra-Fast Outflows (UFOs)

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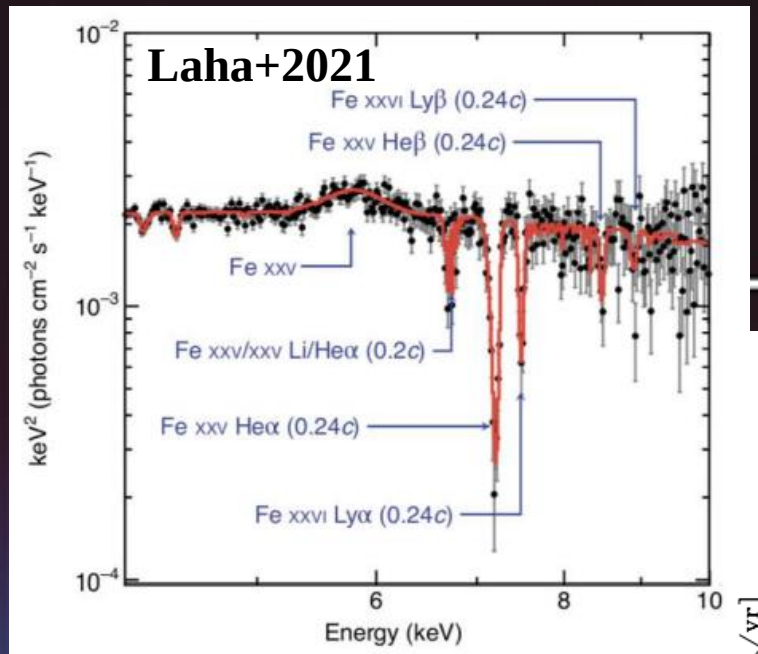
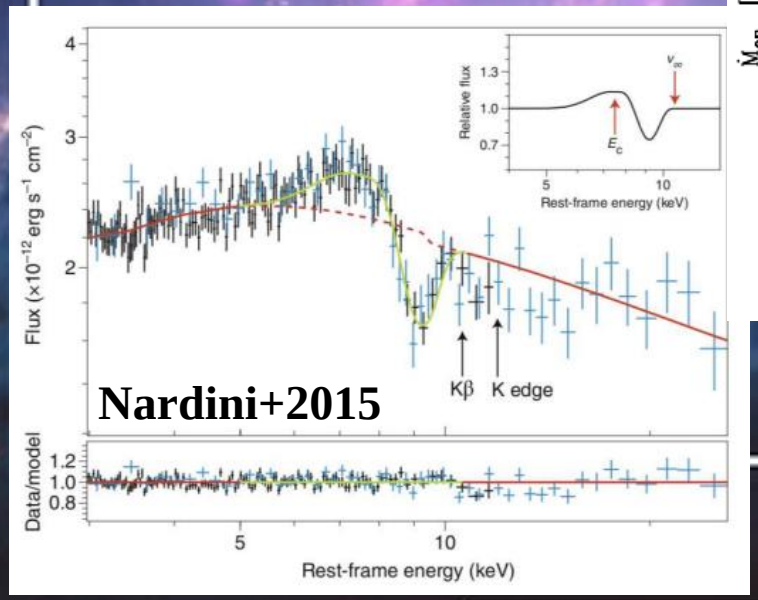
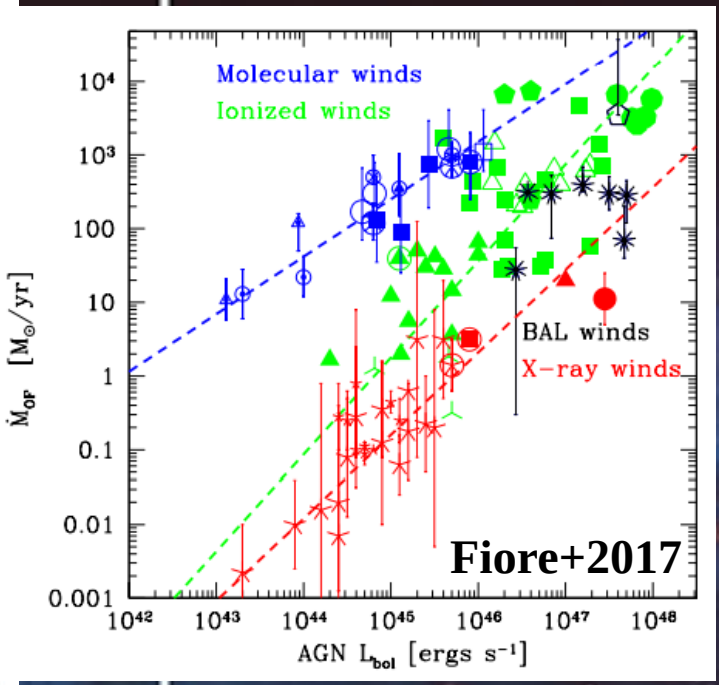
  - $v \approx 0.03\,c\ - 0.3\,c$
    - $\Omega \gtrsim 3\pi$ sr
- $\dot{M} \approx 10^{-3} - 10\ M_{\odot} yr^{-1}$







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- Solution: radial behavior and spectra
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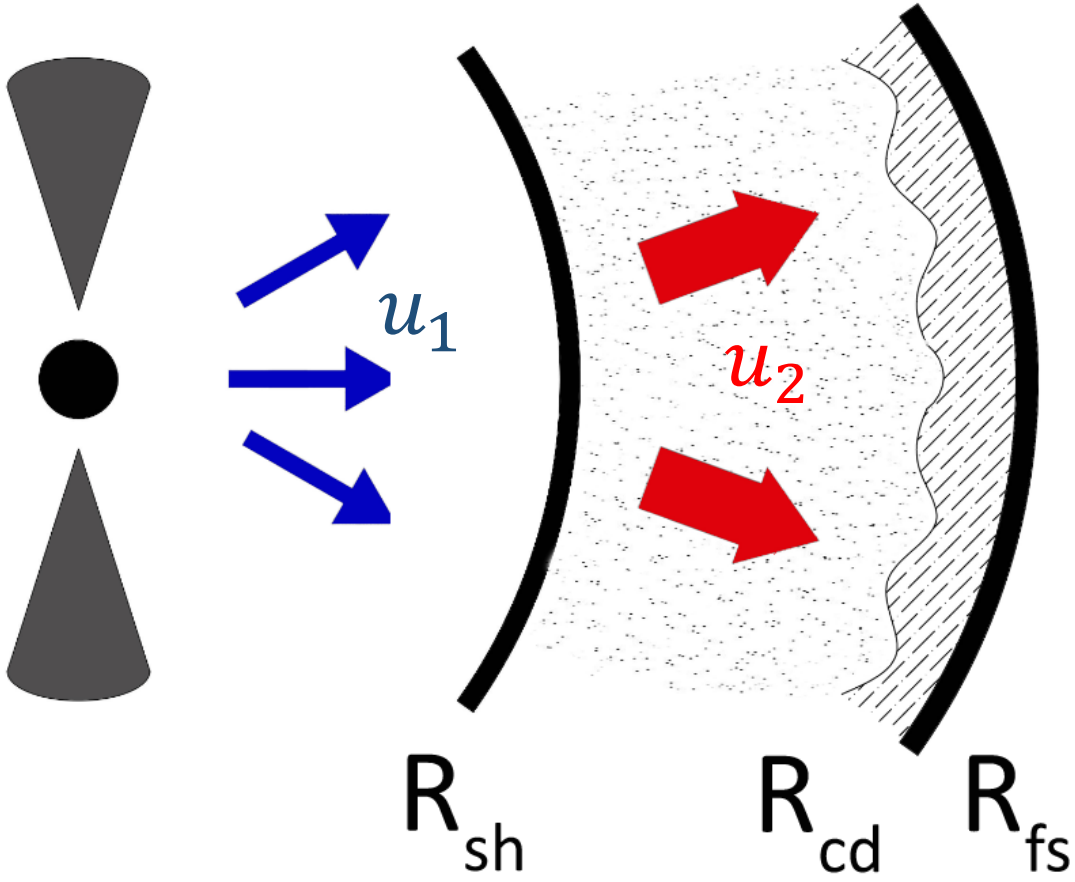
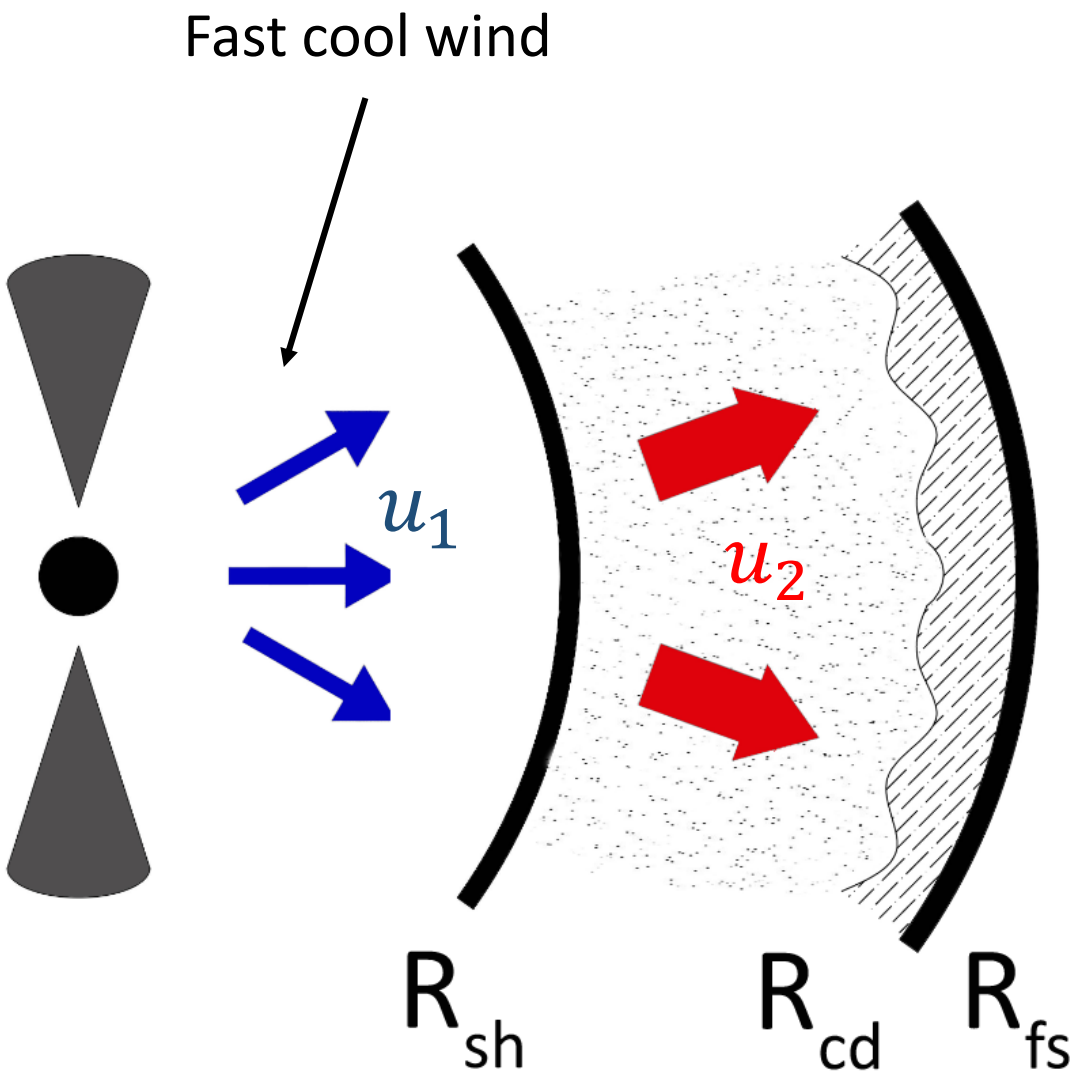
Wind bubble structure and evolution



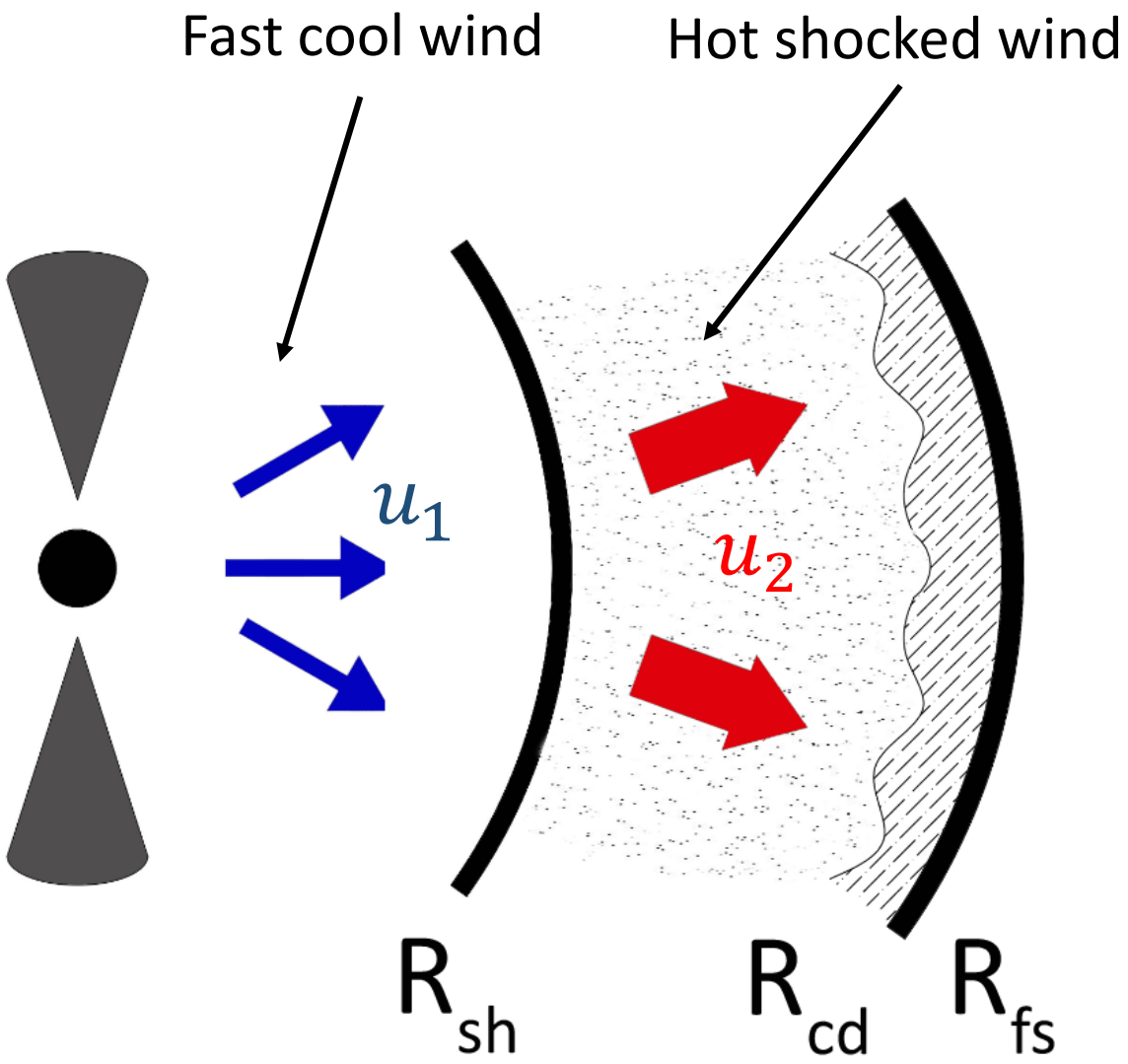
1. The outflow is launched - t_0
2. Free expansion phase - t_1
3. Deceleration phase - $t > t_1$

Wind bubble structure and evolution



- R_{sh} → Wind shock (high Mach n.)

Wind bubble structure and evolution



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

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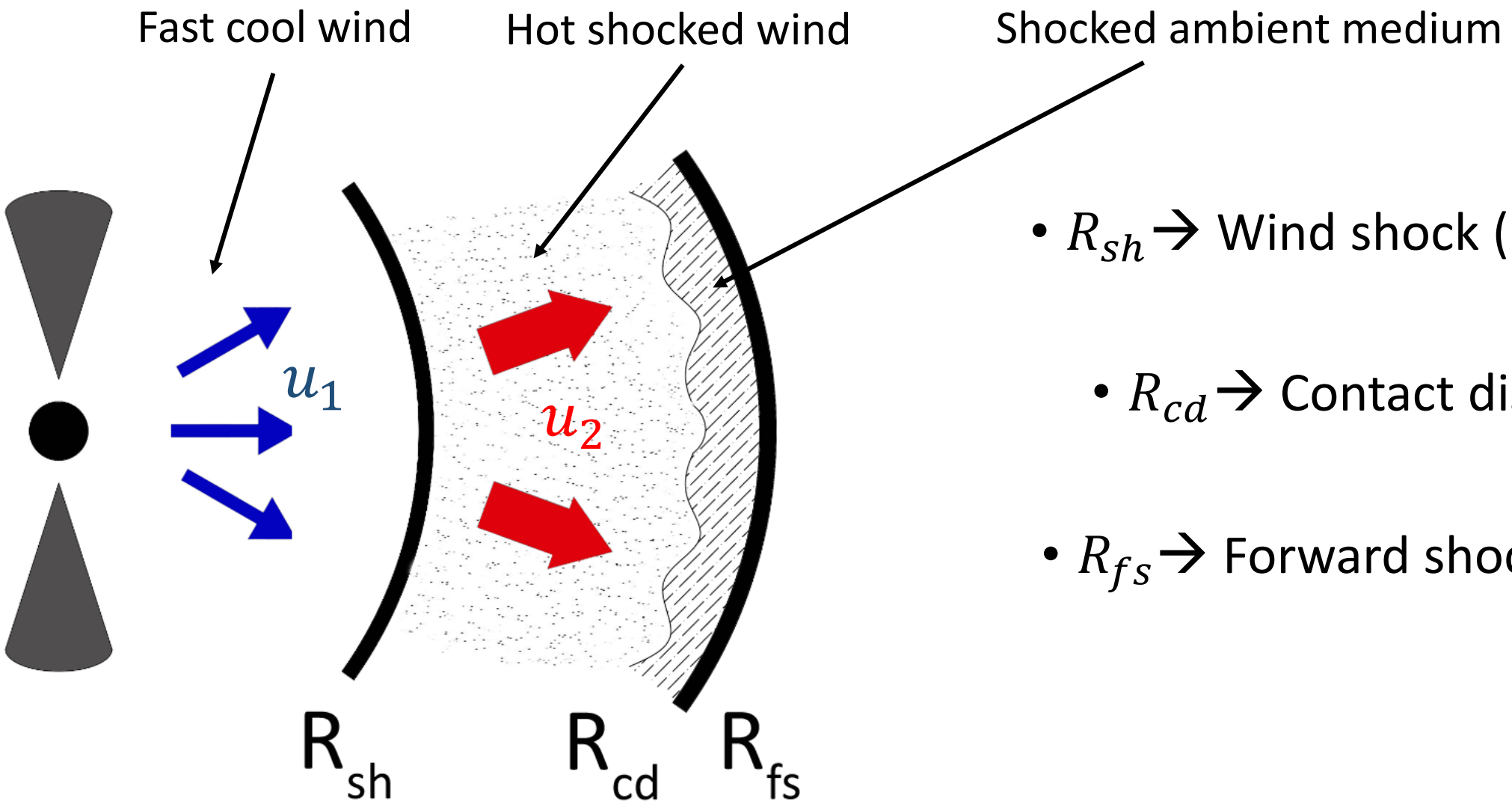

- R_{sh} → Wind shock (high Mach n.)
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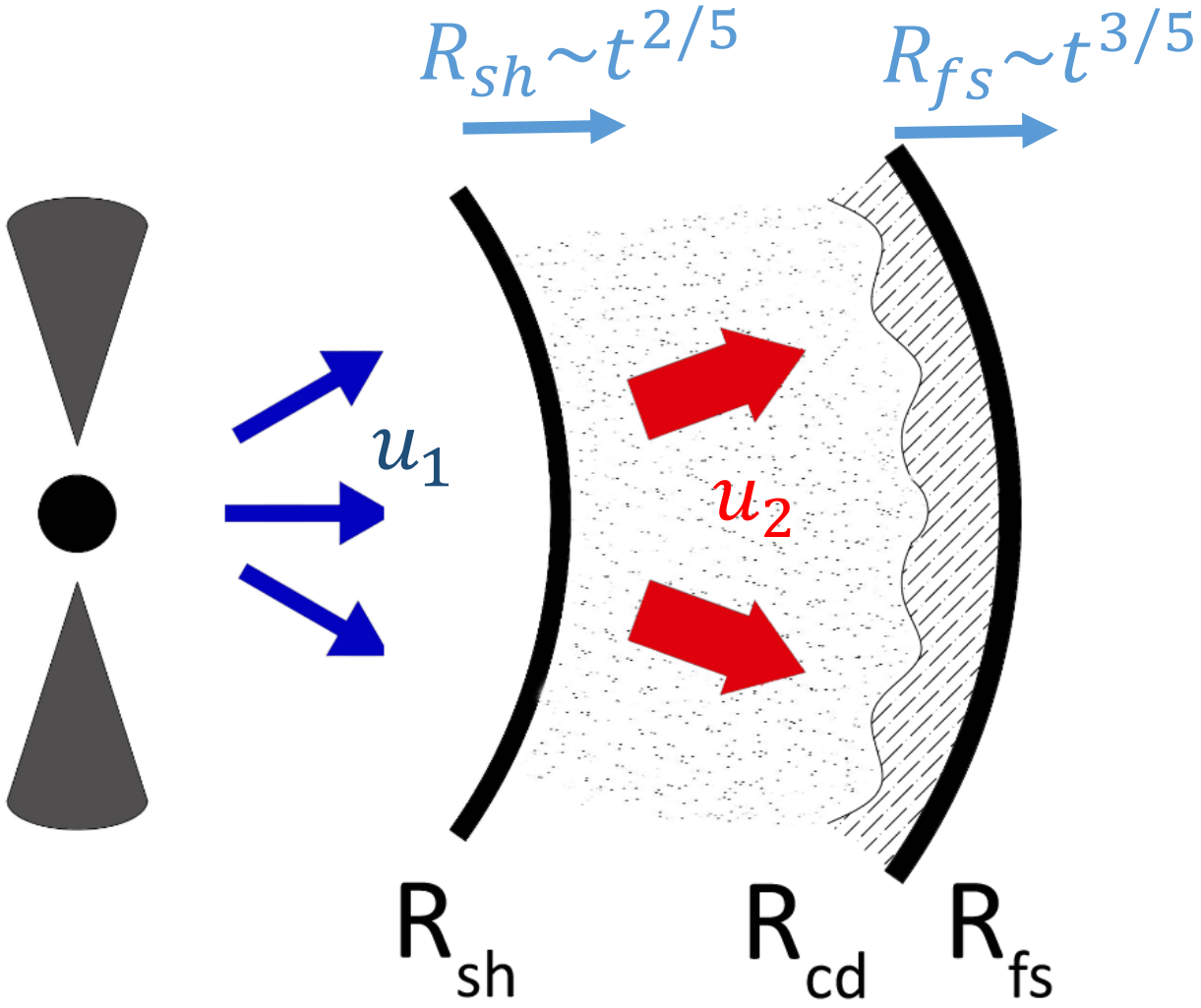
- R_{fs} → Forward shock (Mach n.?)

Wind bubble structure and evolution



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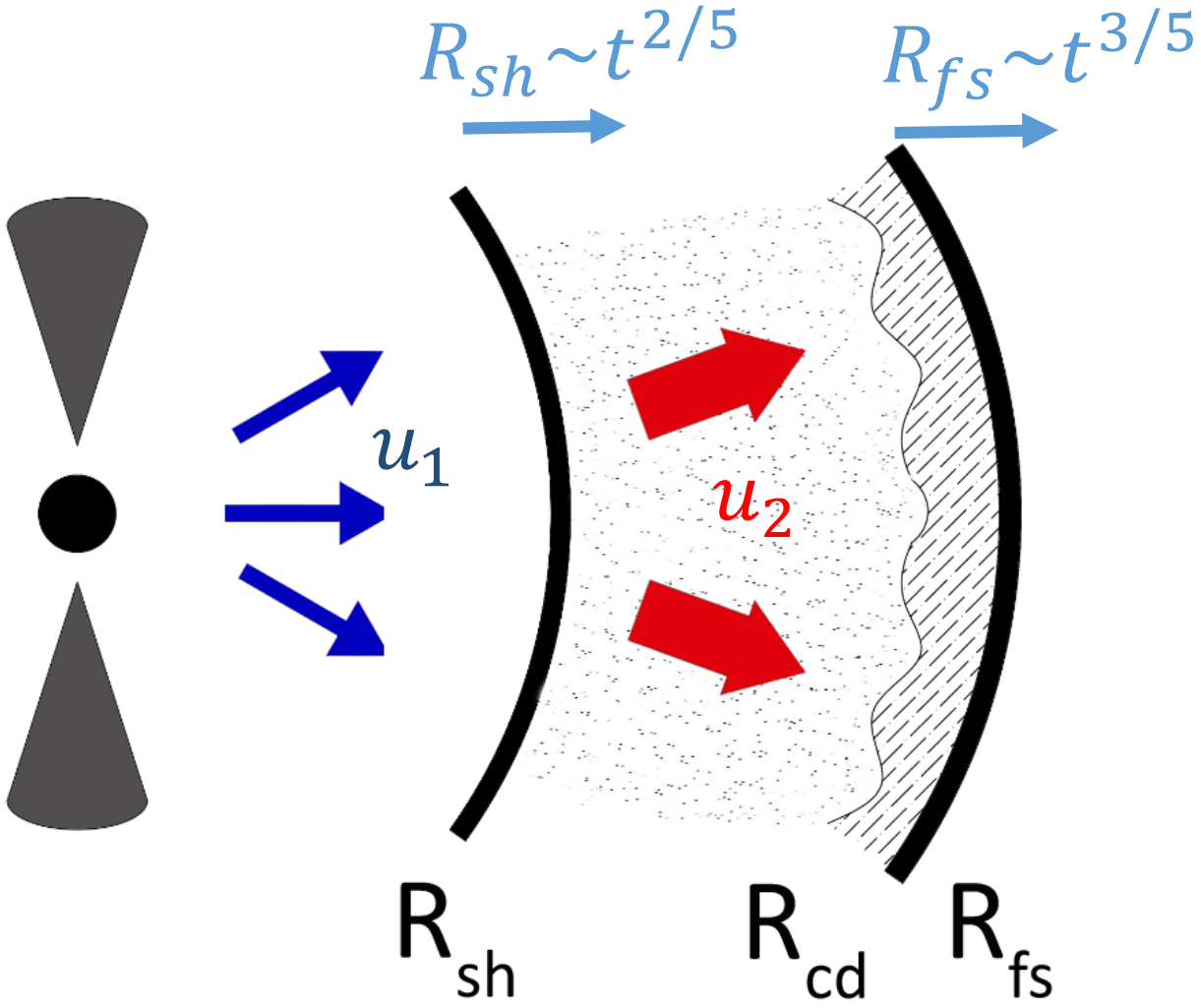
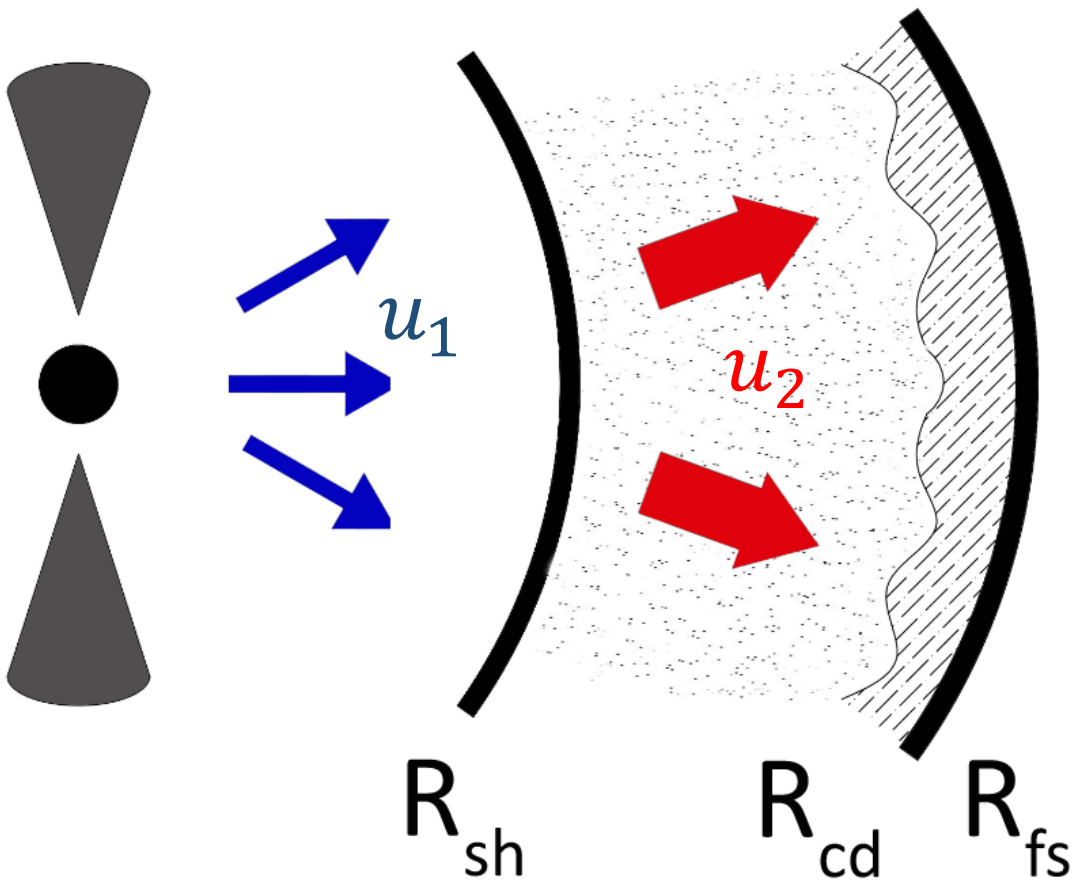


- $u_1 \approx 0.1\,c \gg \dot{R}_{sh}$
- The shocked wind is adiabatic
- The shocked wind region grows in t

Building the model

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



- Spherically symmetric

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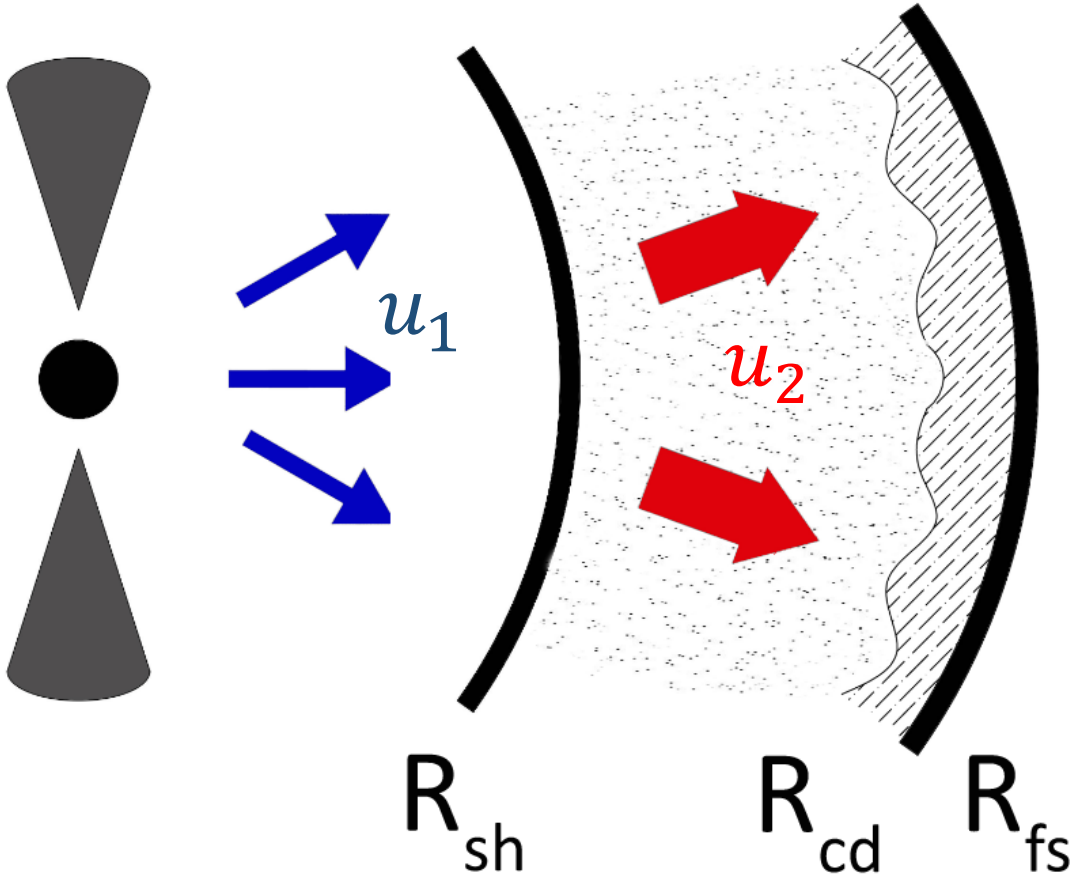

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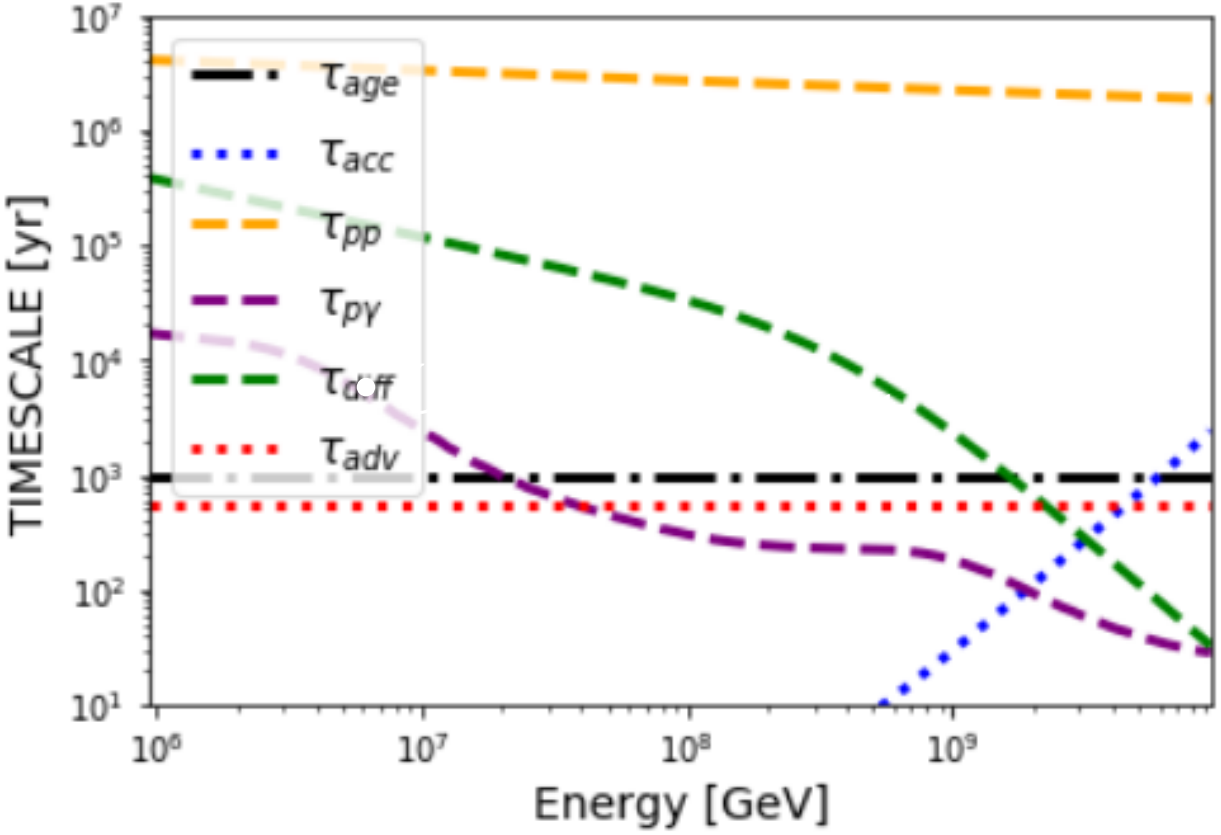

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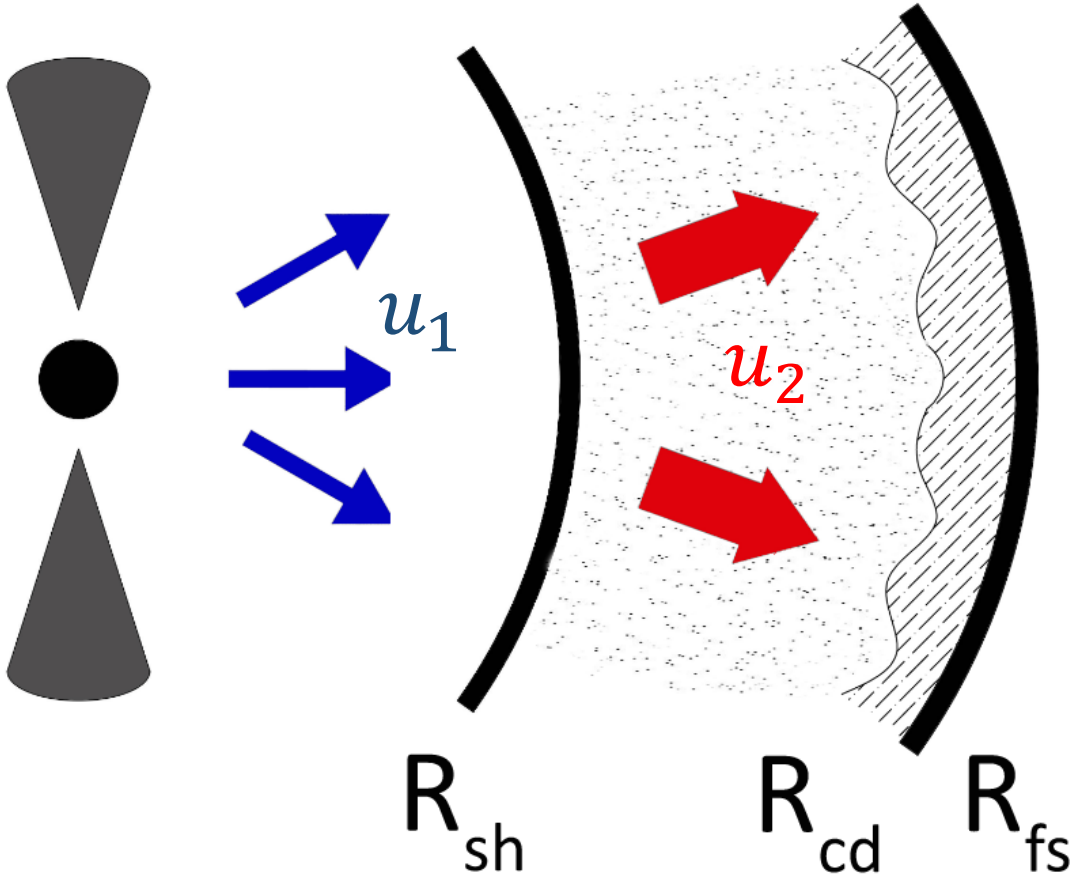

- Spherically symmetric
- Stationary

Building the model

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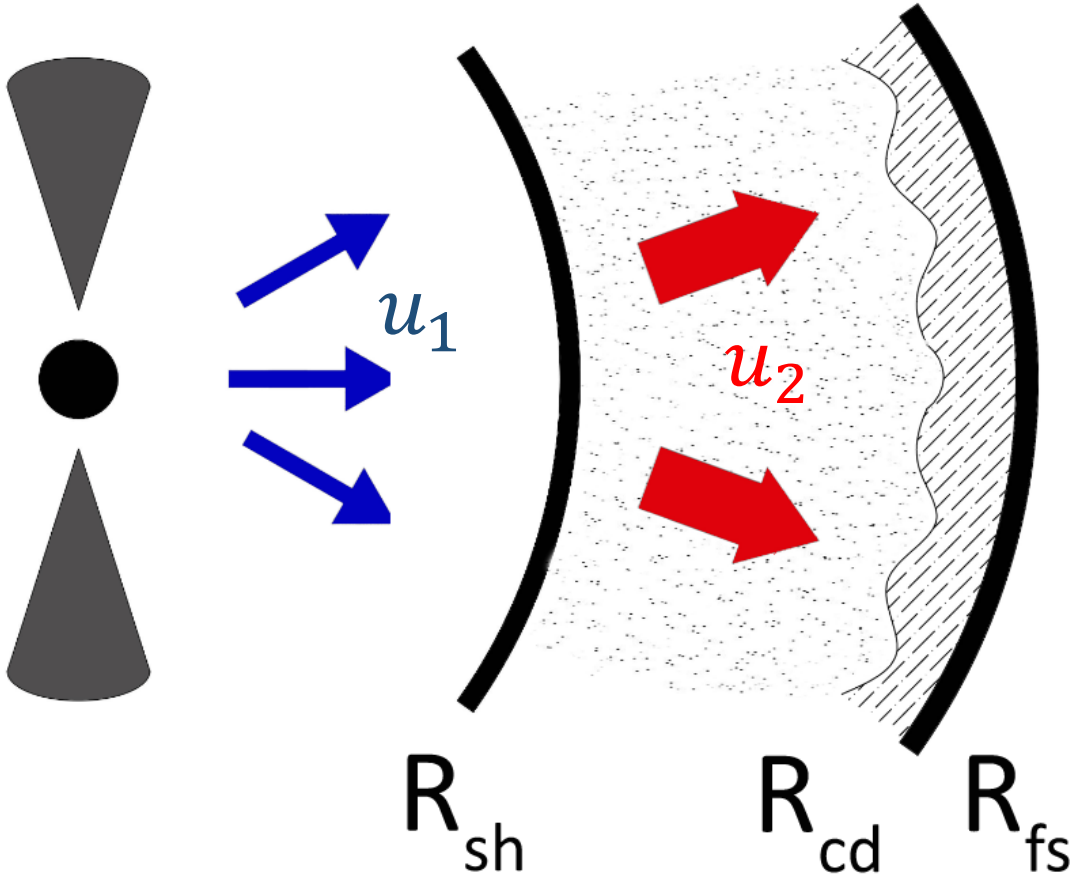
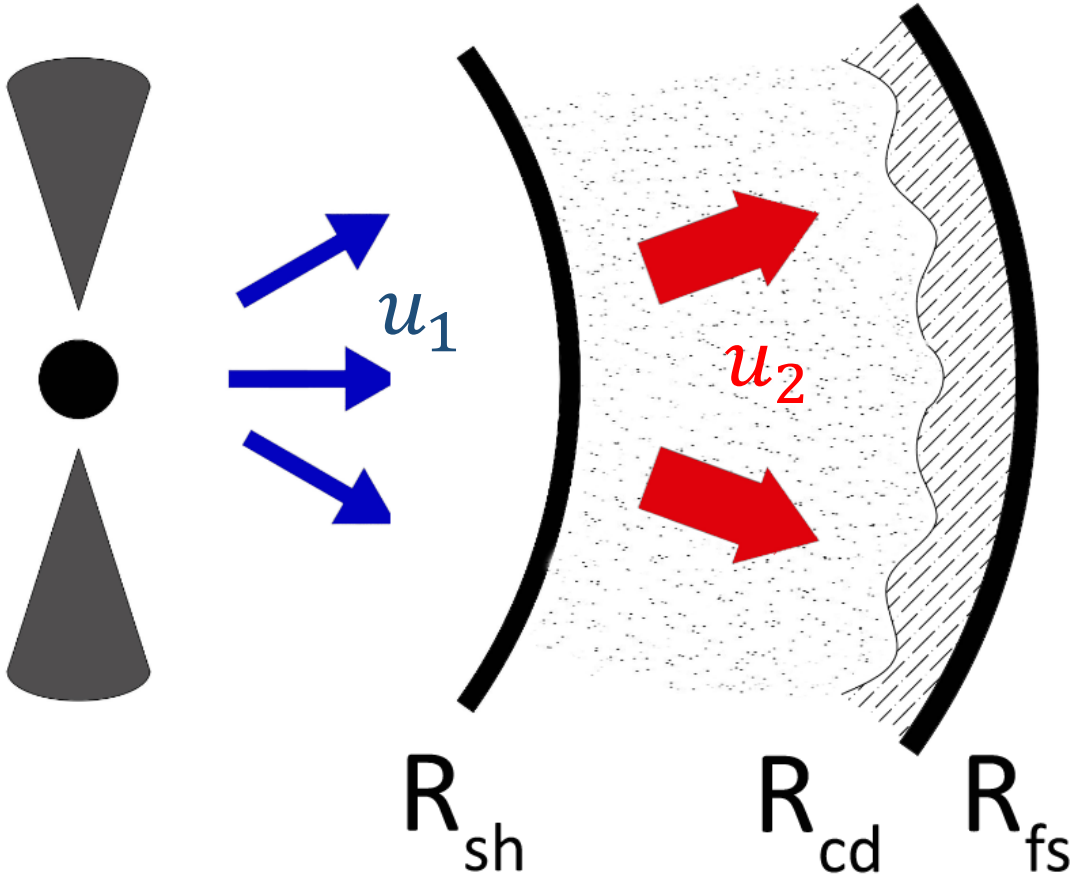


- Spherically symmetric
- Stationary
- $U_{B,1} = \epsilon_B P_{ram,1}$
- $D = \frac{1}{3} v r_L^{2-\delta} l_c^{\delta-1}$

Building the model

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

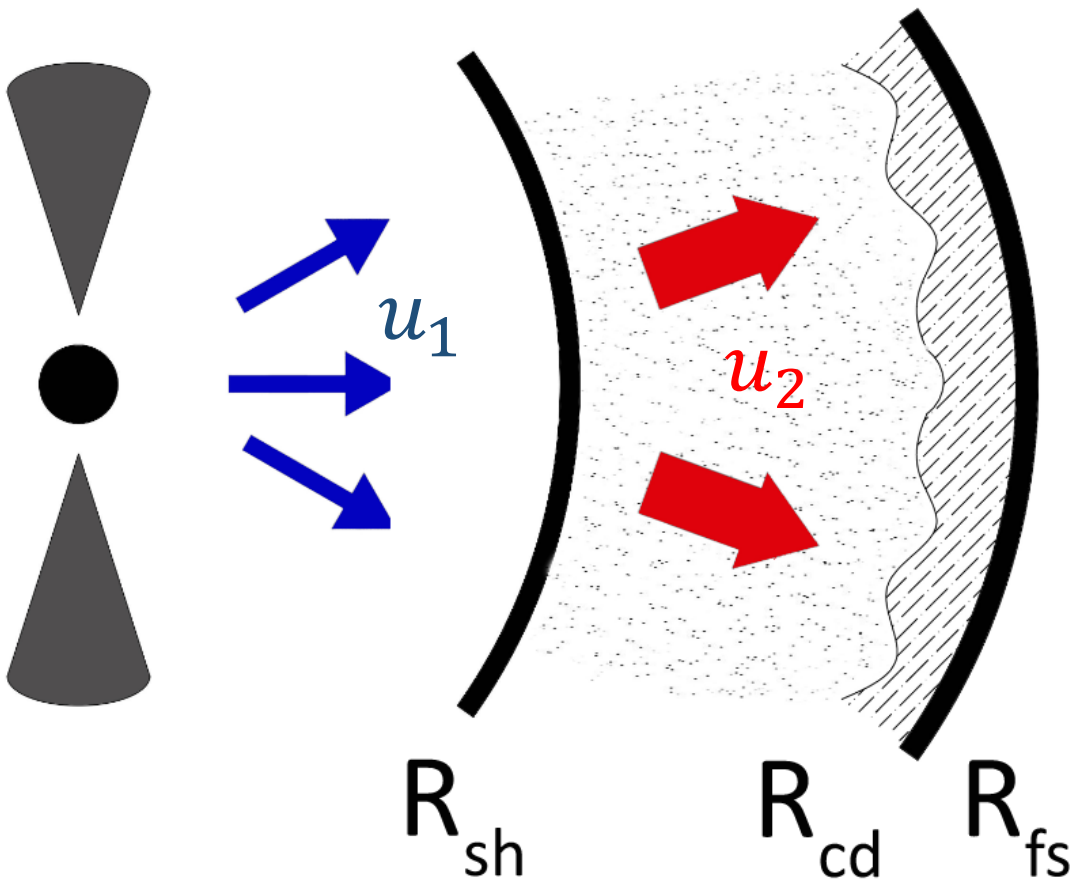


Boundary conditions:

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

Building the model

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



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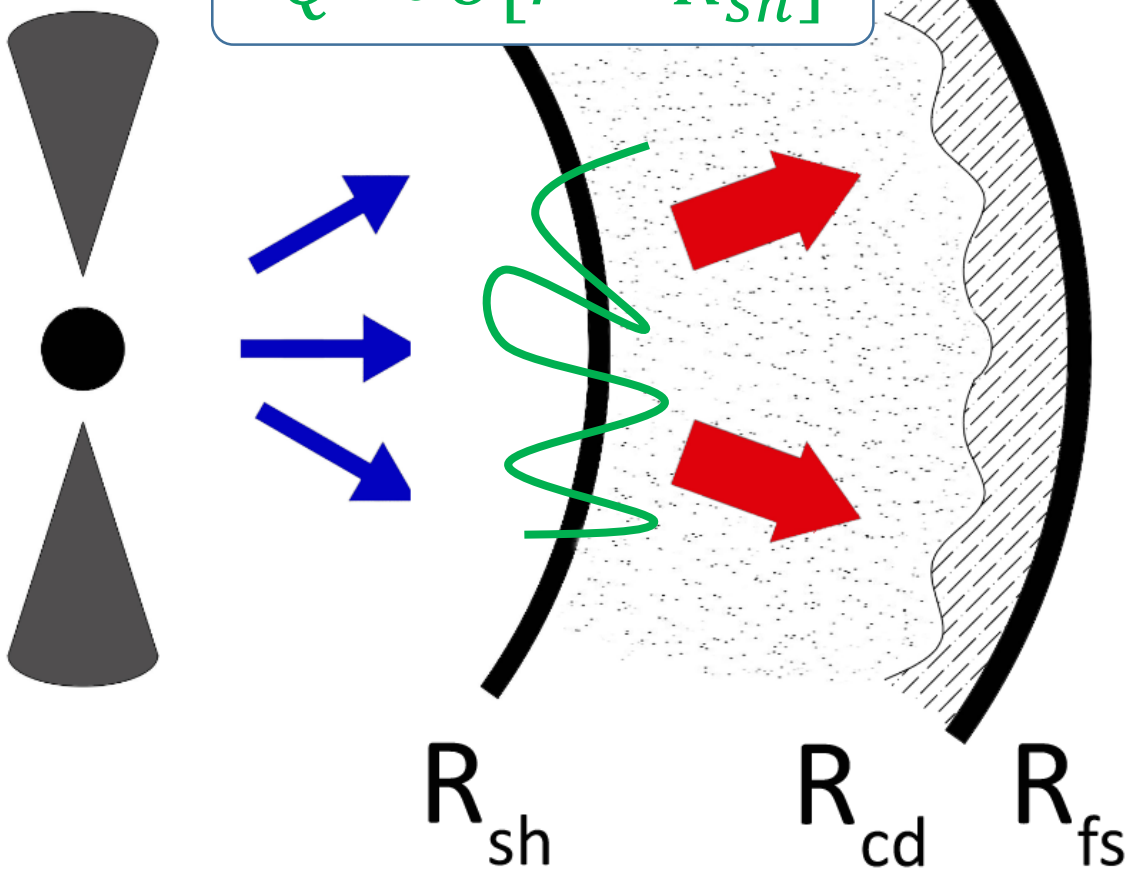
Acceleration-transport model

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

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



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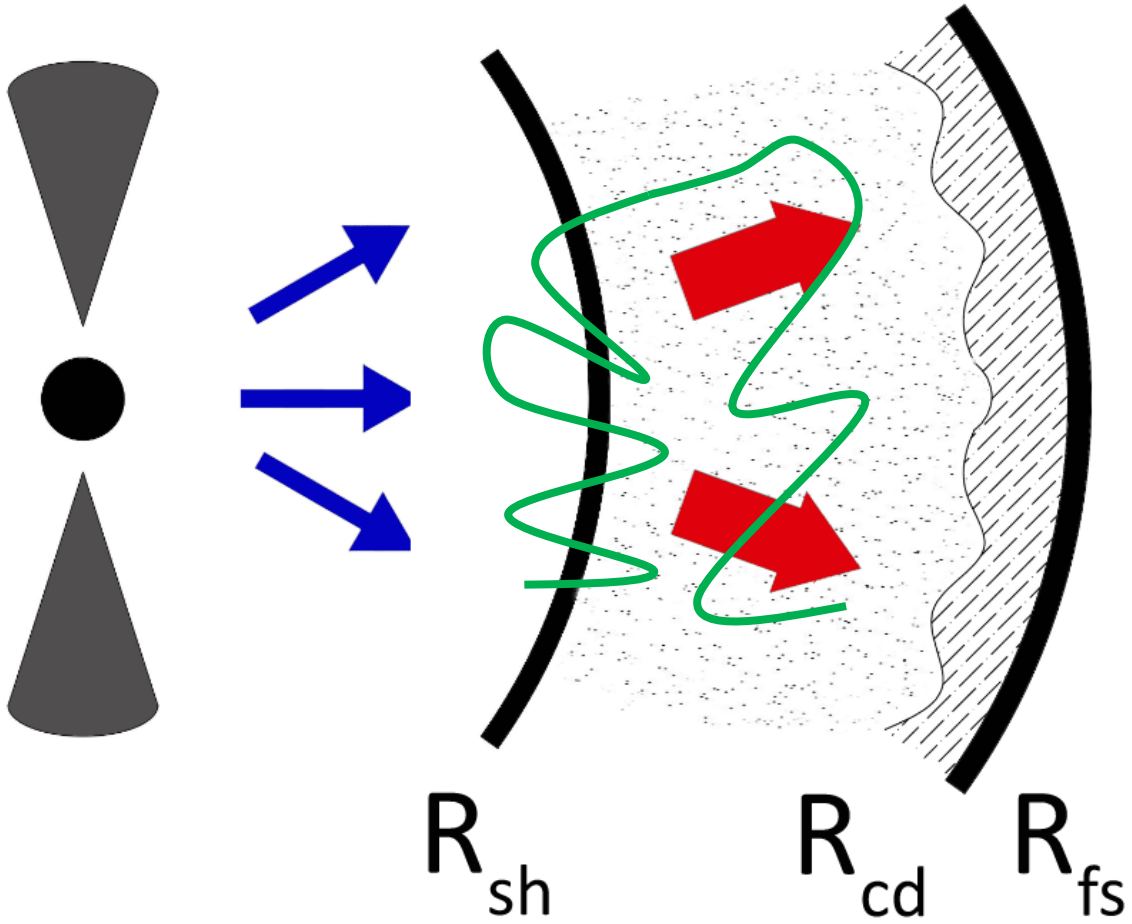

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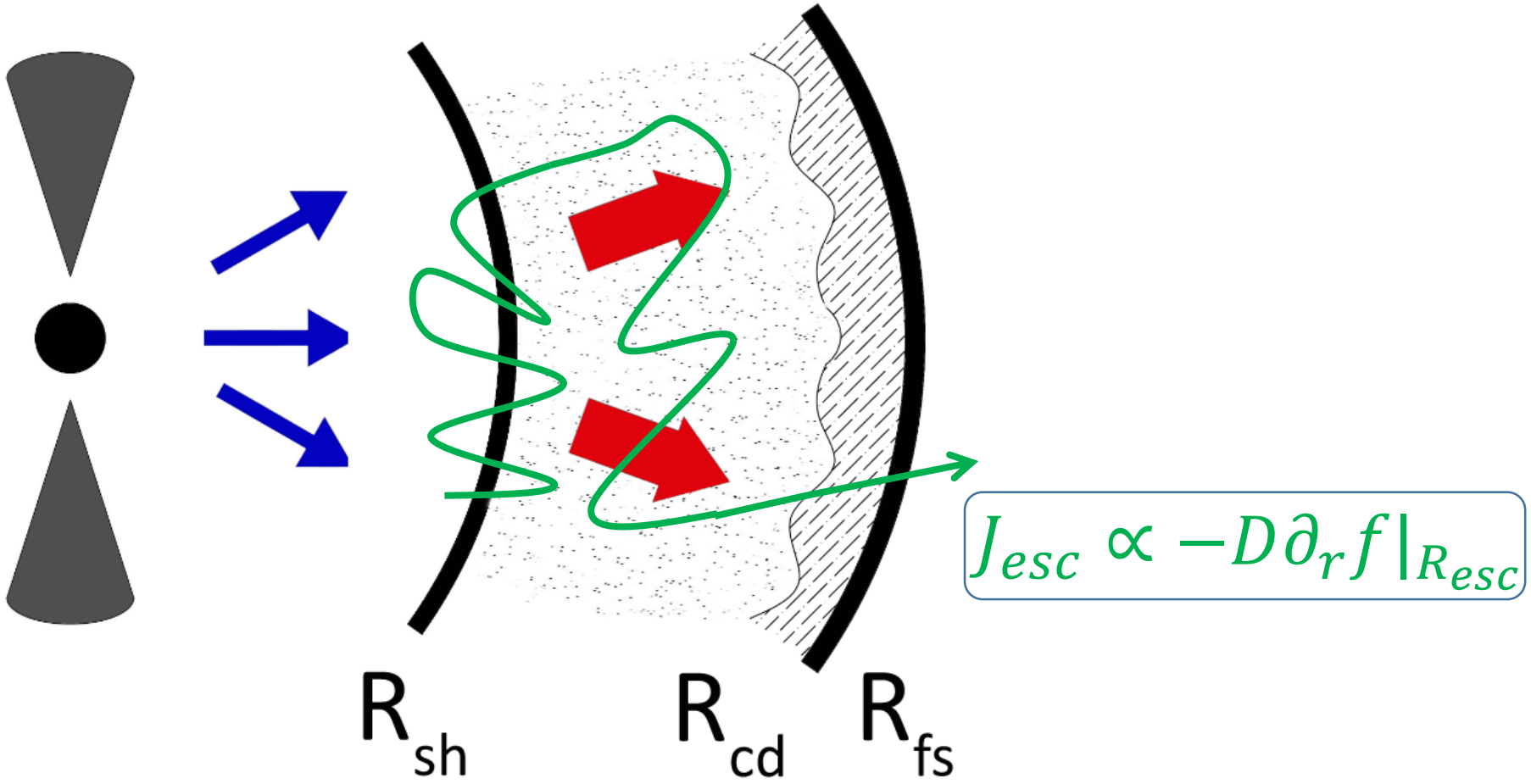

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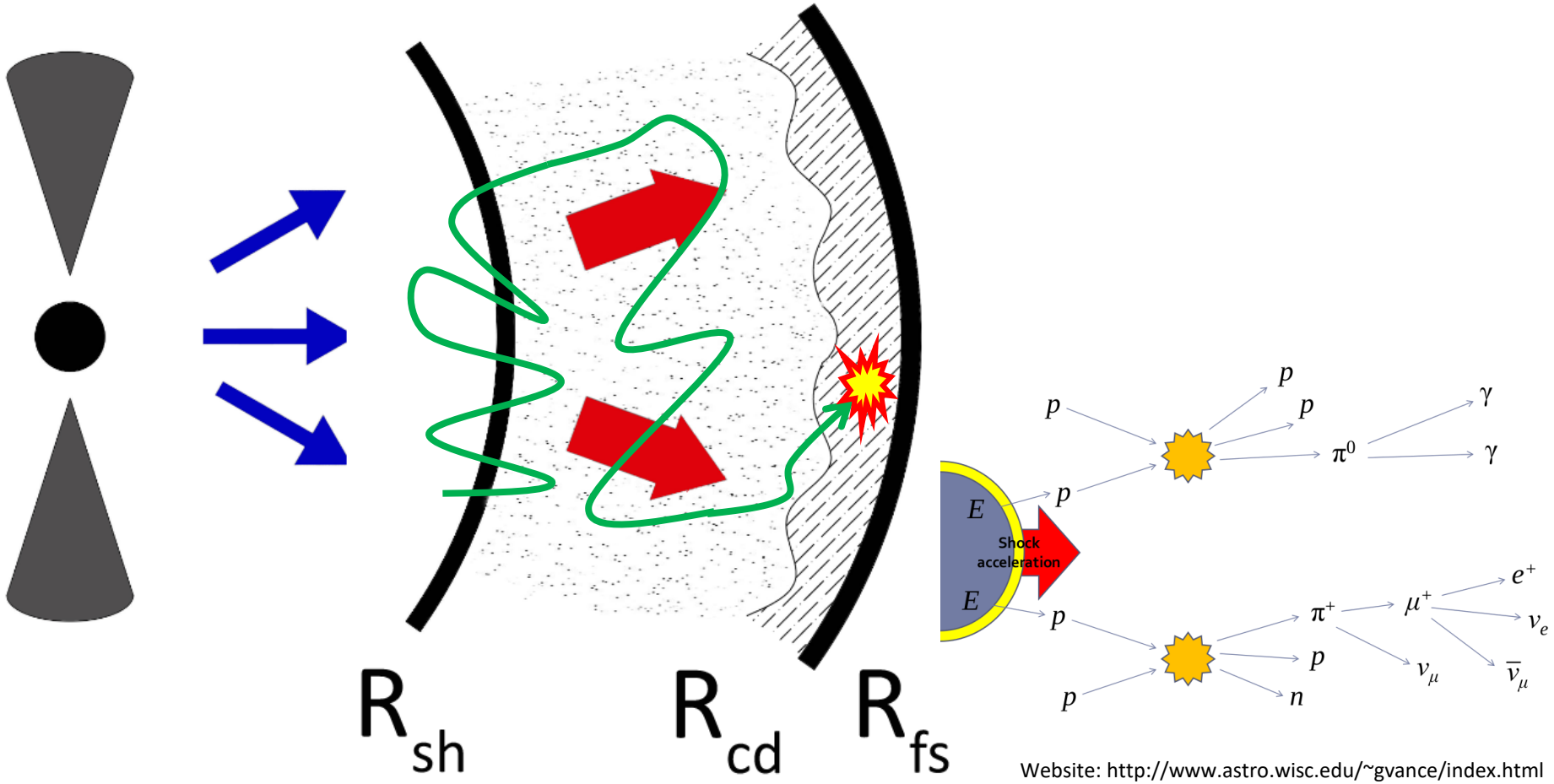

Website: http://www.astro.wisc.edu/~gvance/index.html

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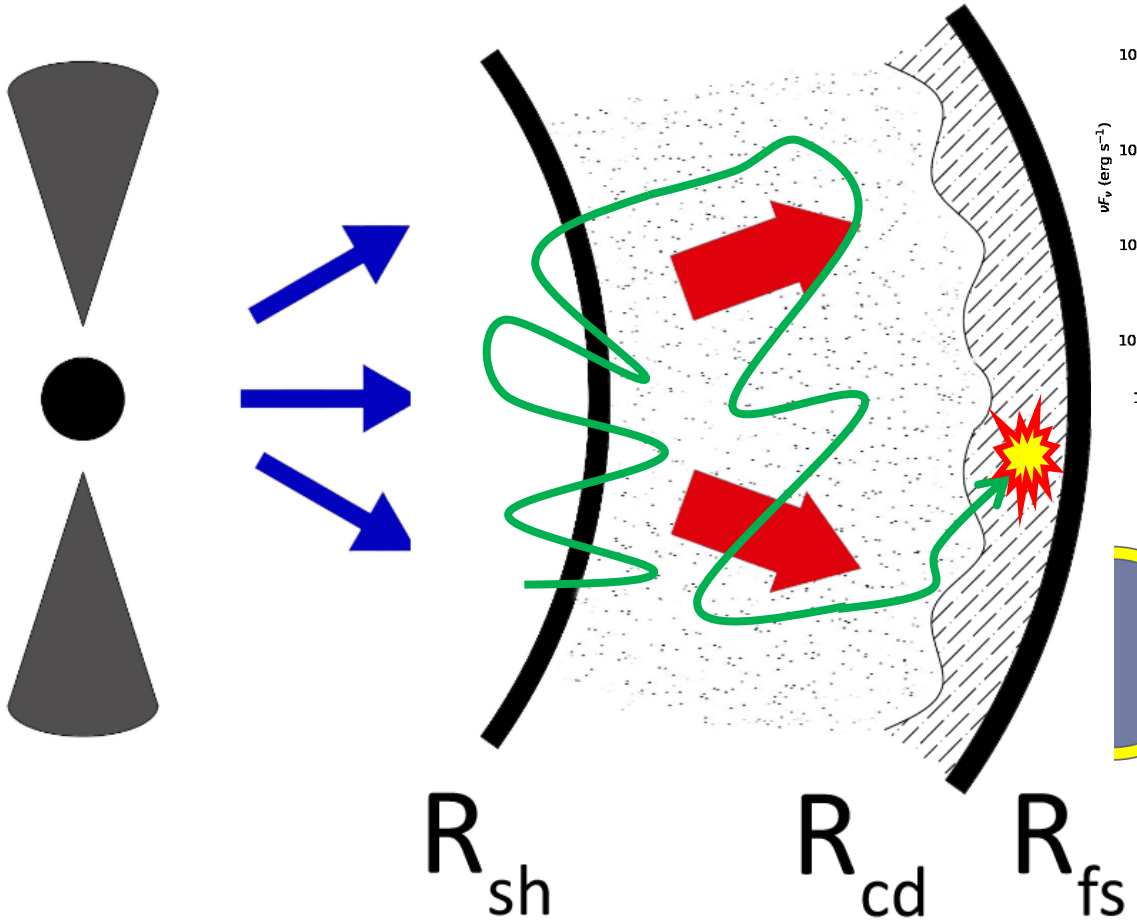

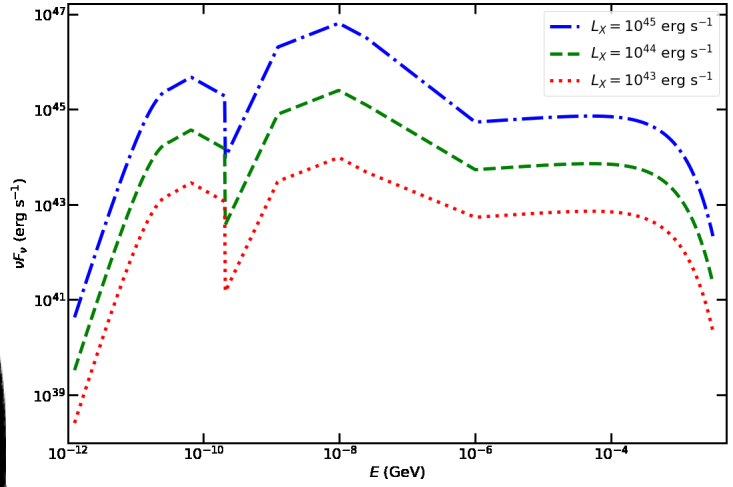

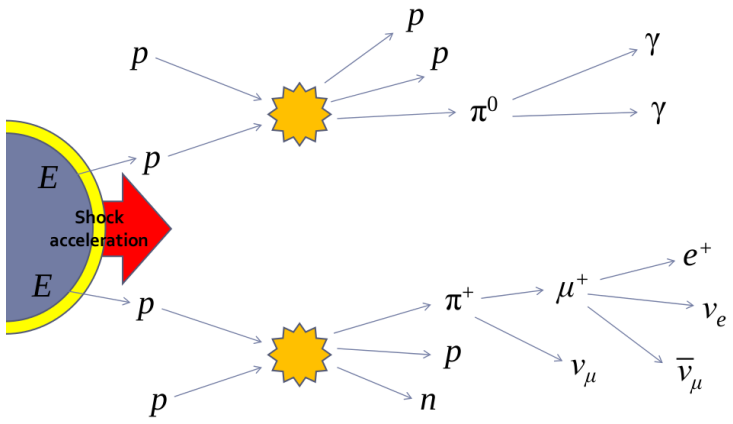

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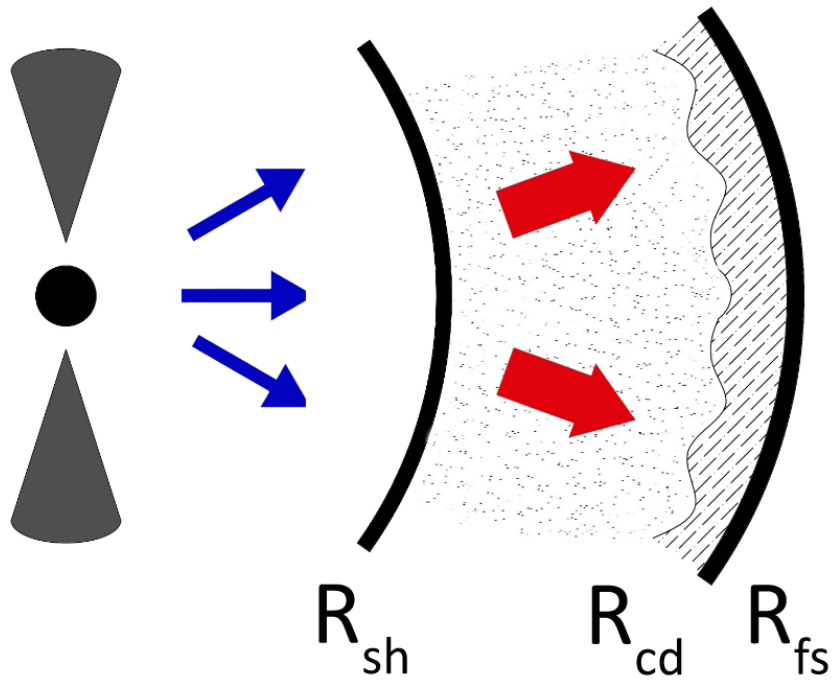
Solving the transport equation 1

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

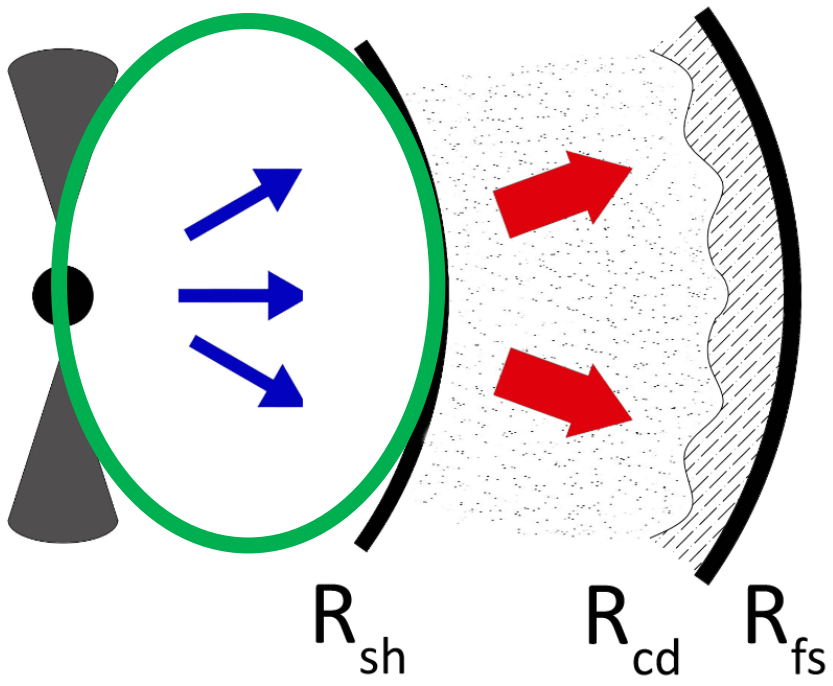


Parameters:

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

Solving the transport equation 2

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



- $\int_0^{R_{sh}} dr\, T.E.$ → upstream solution

Solving the transport equation 2

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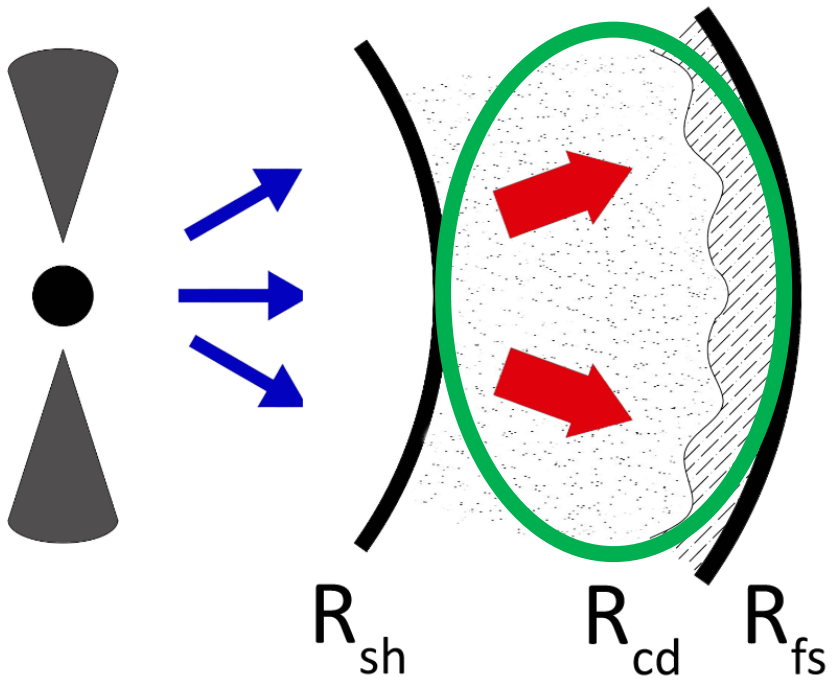

- $\int_0^{R_{sh}} dr\, T.E.$ → upstream solution
- $\int_{R_{sh}}^{R_{fs}} dr\, T.E.$ → downstream solution

Solving the transport equation 2

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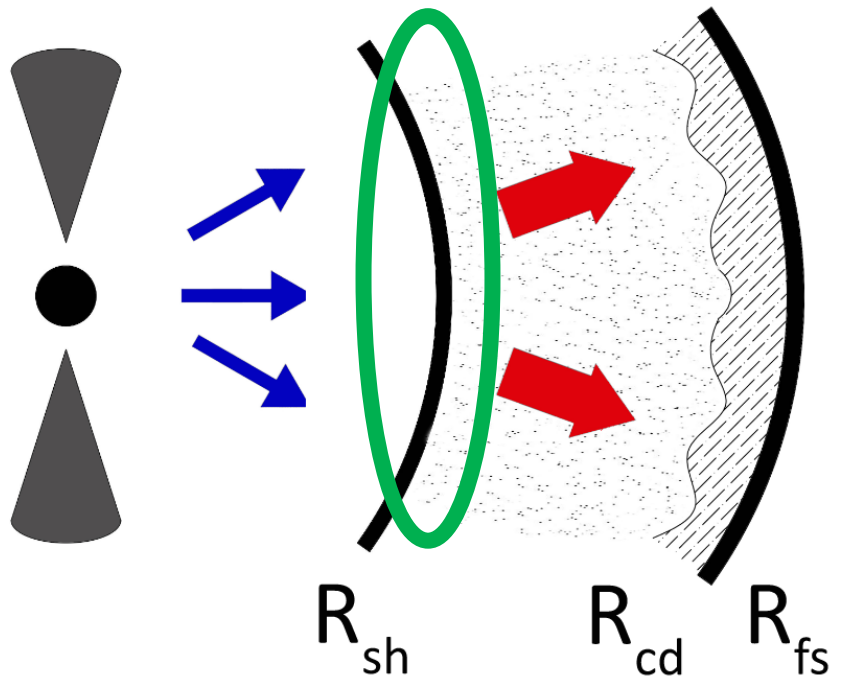


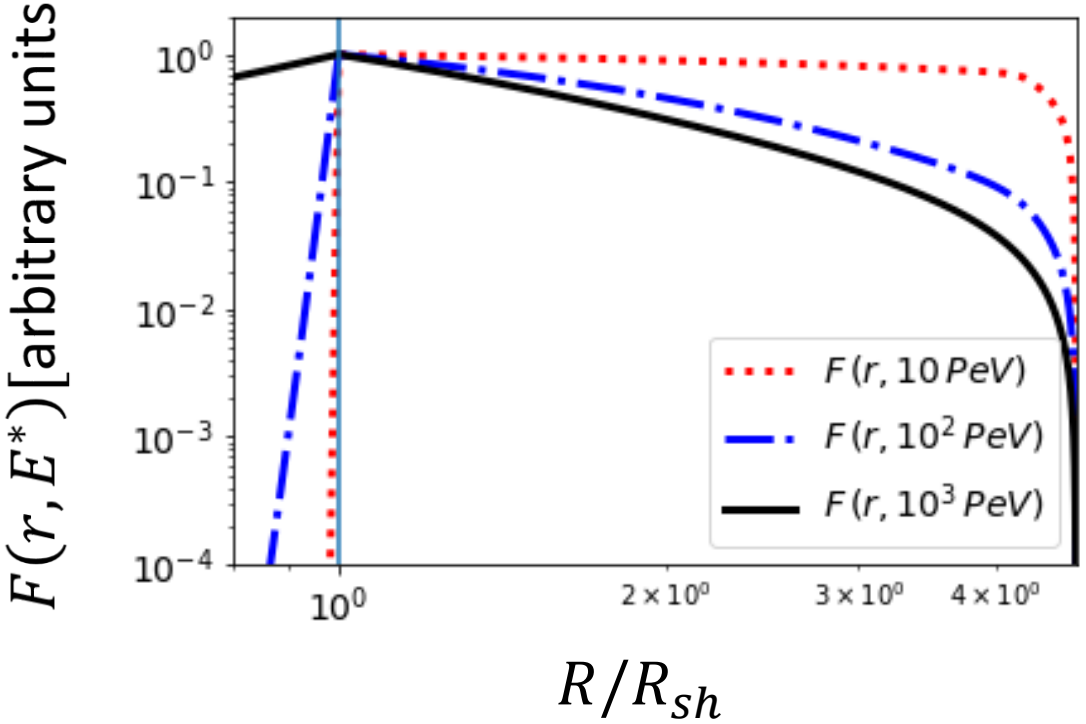
- $\int_0^{R_{sh}} dr\, T.E.$ → upstream solution
- $\int_{R_{sh}}^{R_{fs}} dr\, T.E.$ → downstream solution
- $\int_{R_{sh}^-}^{R_{sh}^+} dr\ \ T.E.$ → solution at the shock

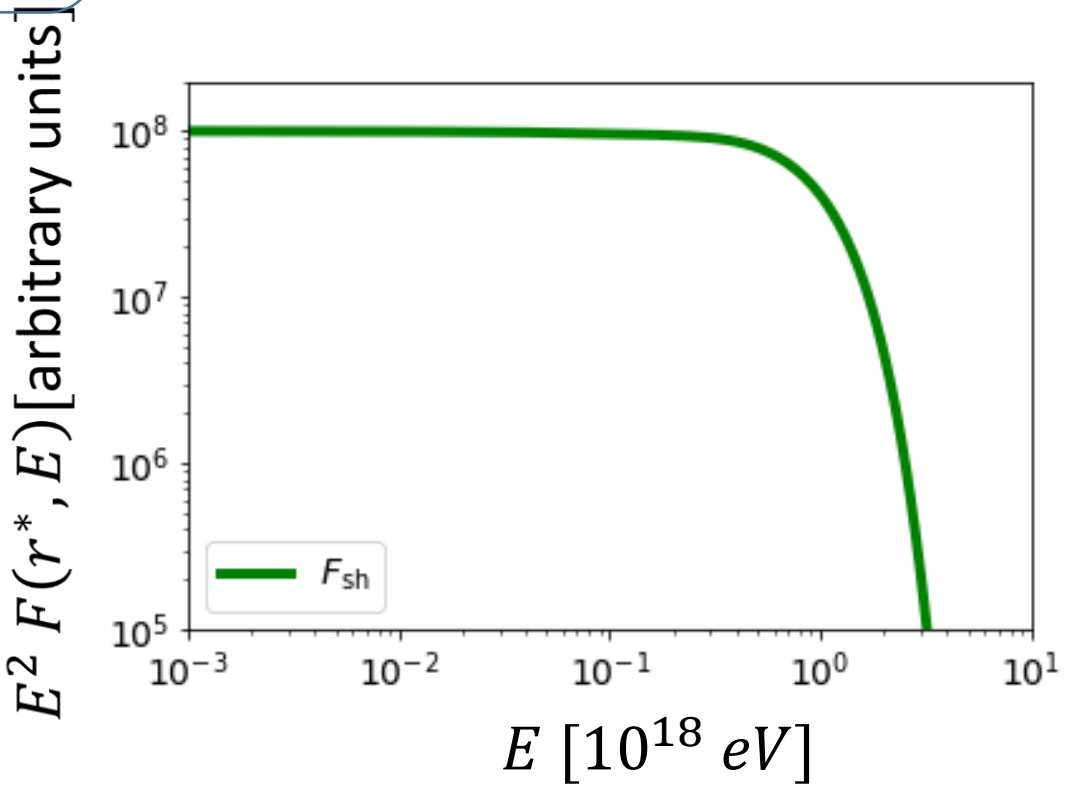
Solution: radial behavior and spectra

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

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

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





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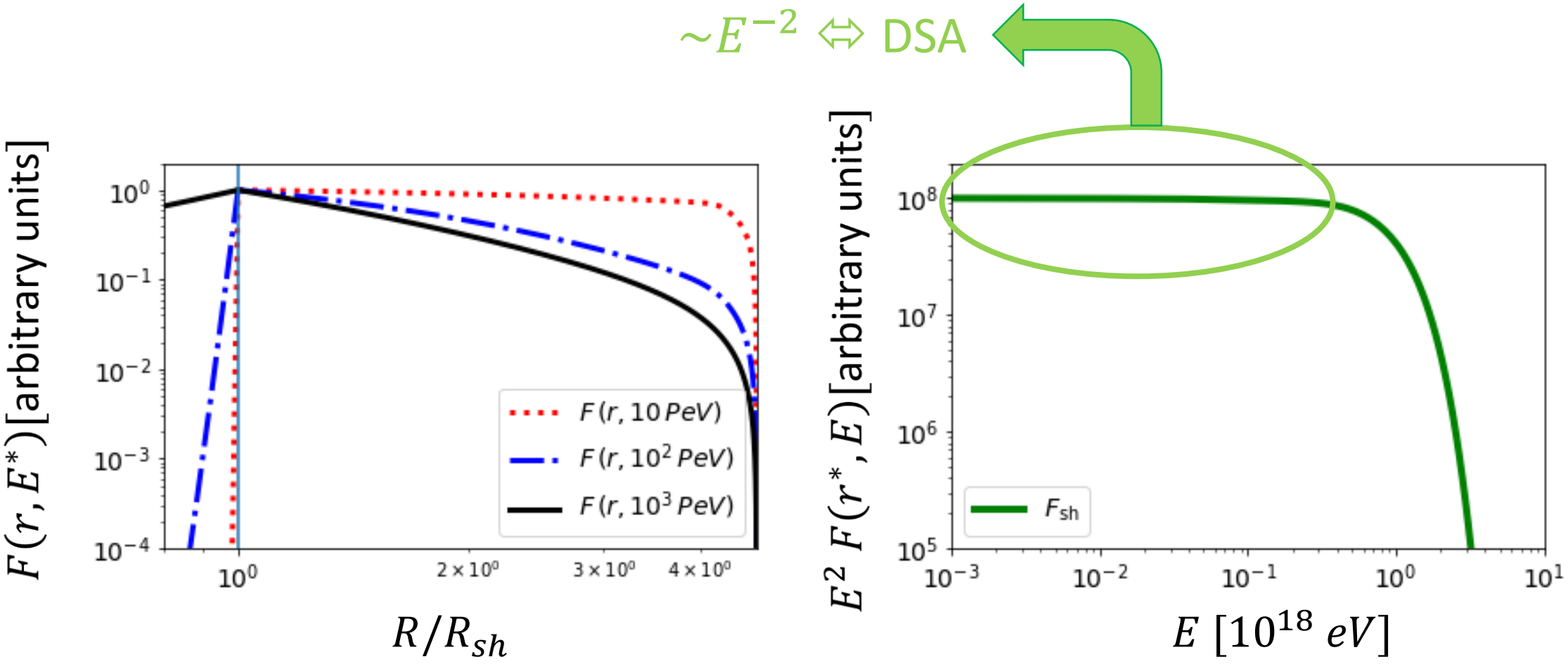
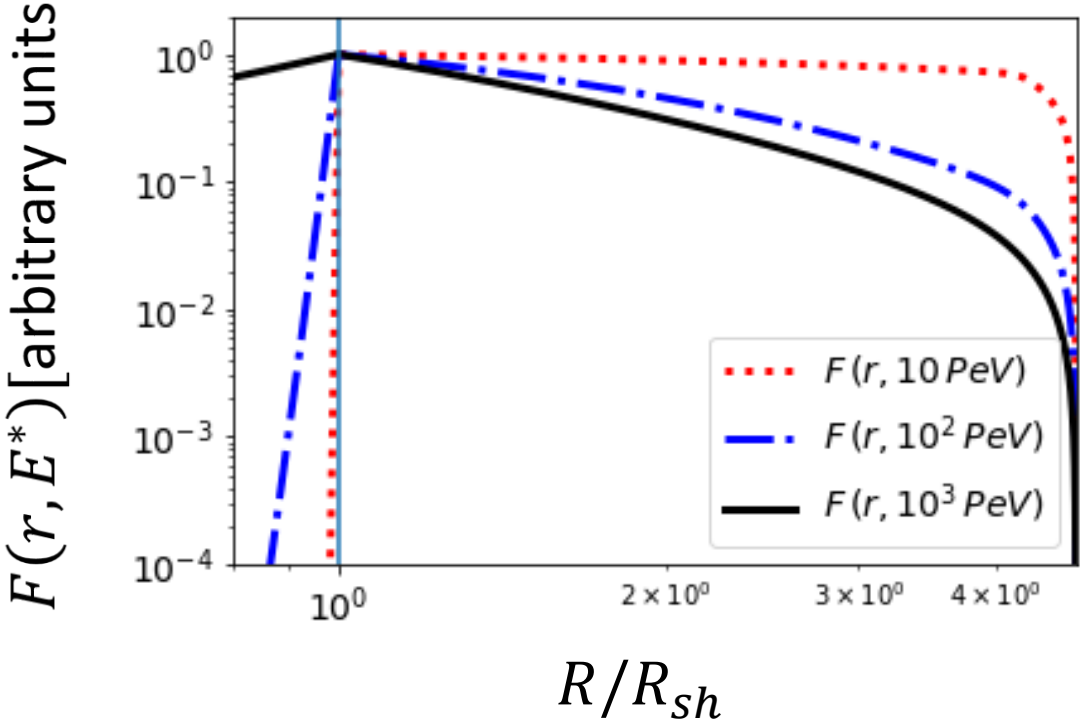
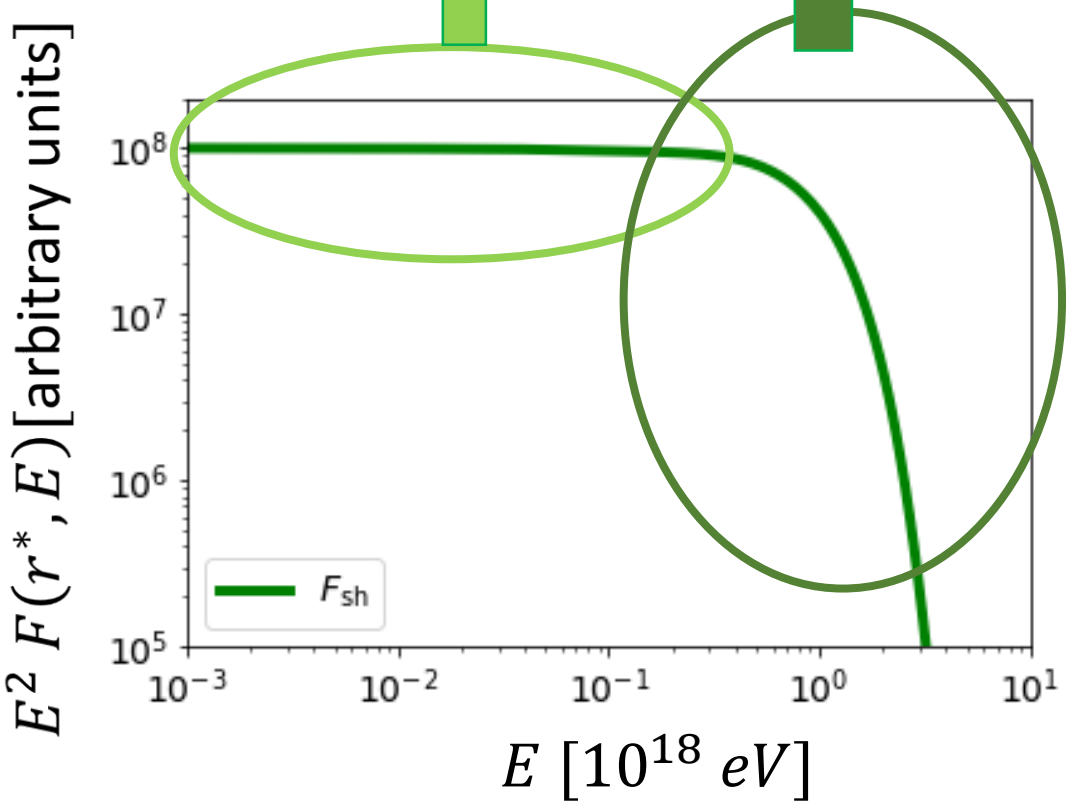


Solution: radial behavior and spectra

Maximum Energy ~ EeV

$\sim E^{-2}$ ⇔ DSA





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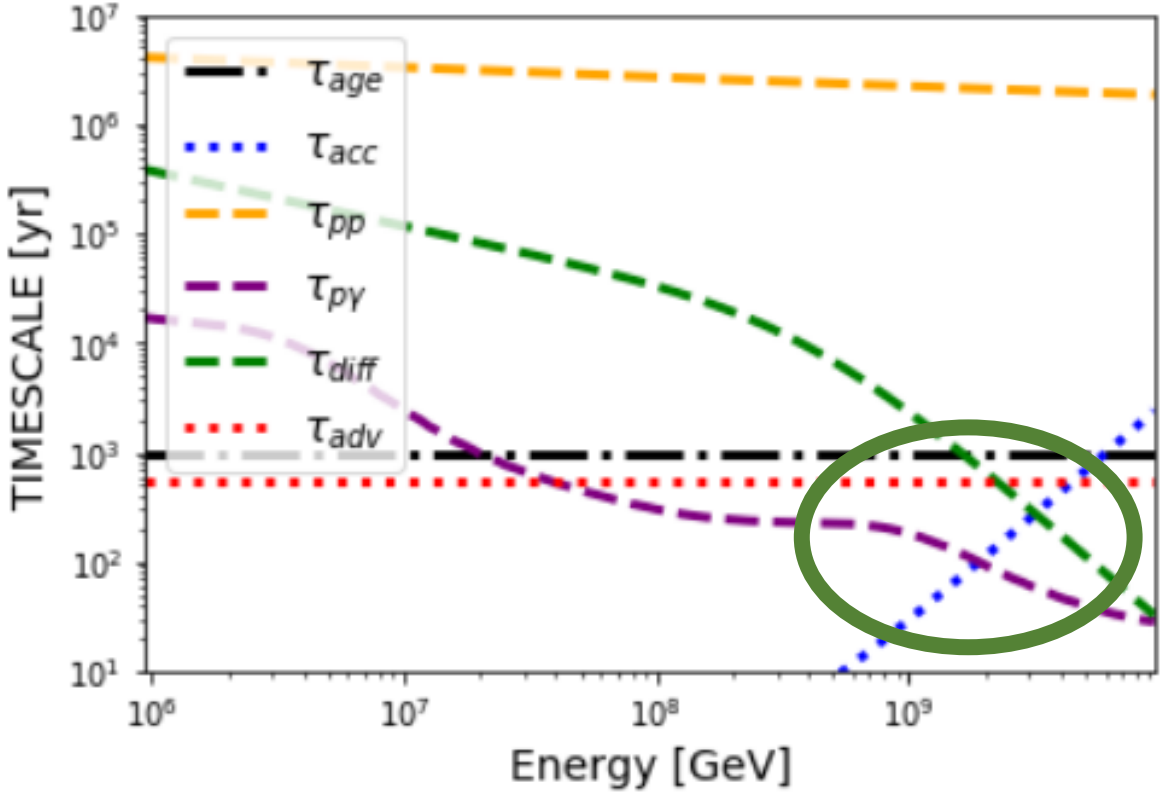

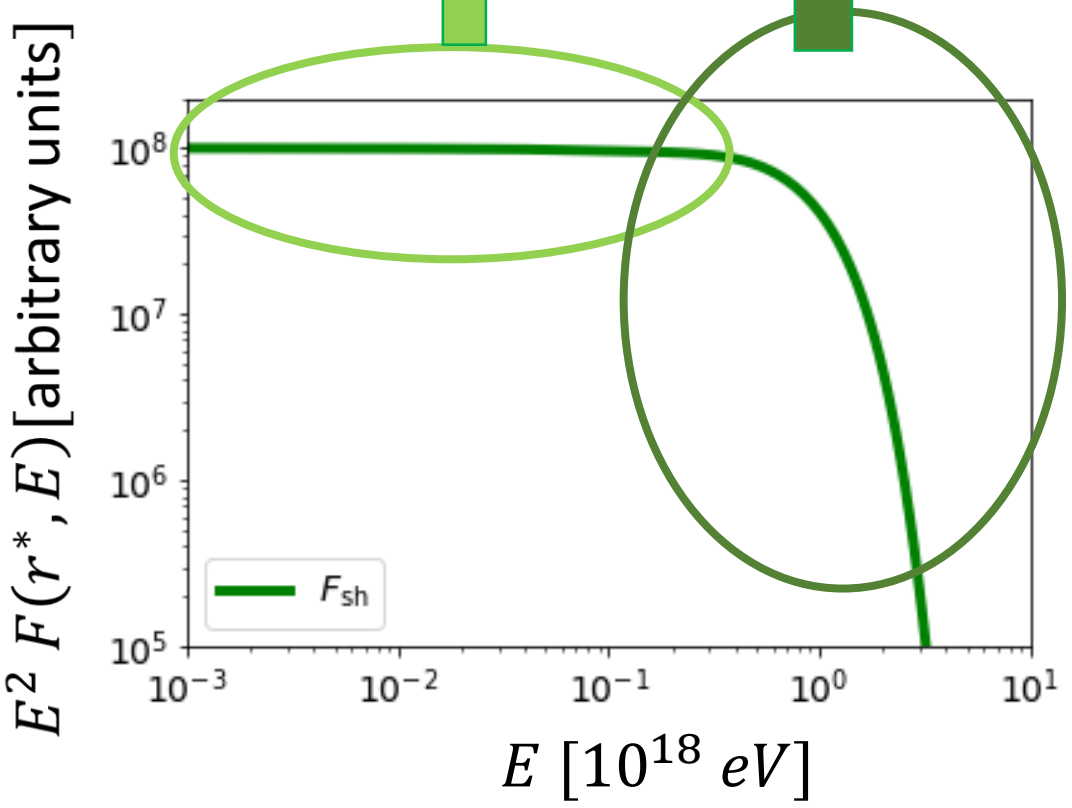

Solution: radial behavior and spectra

Maximum Energy ~ EeV

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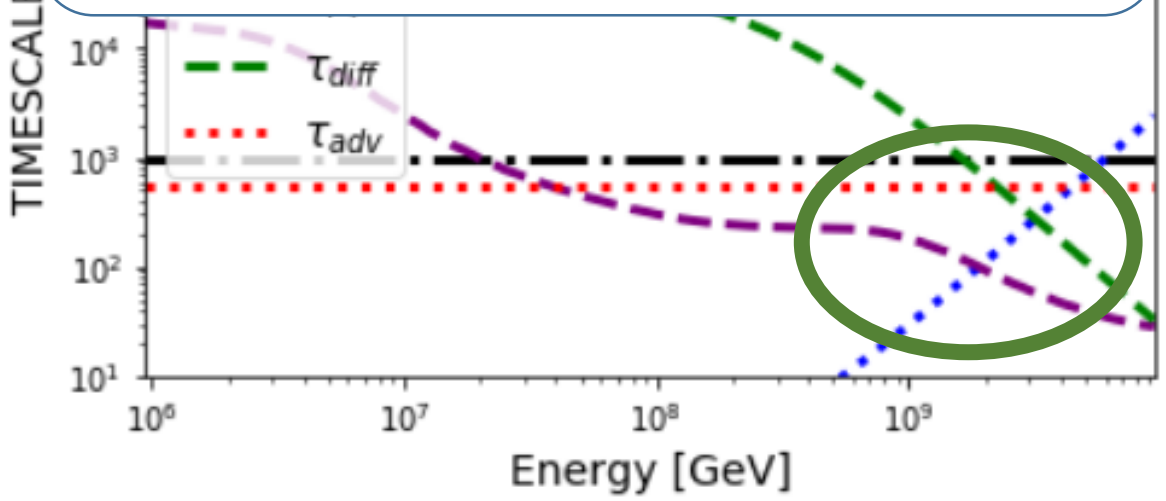
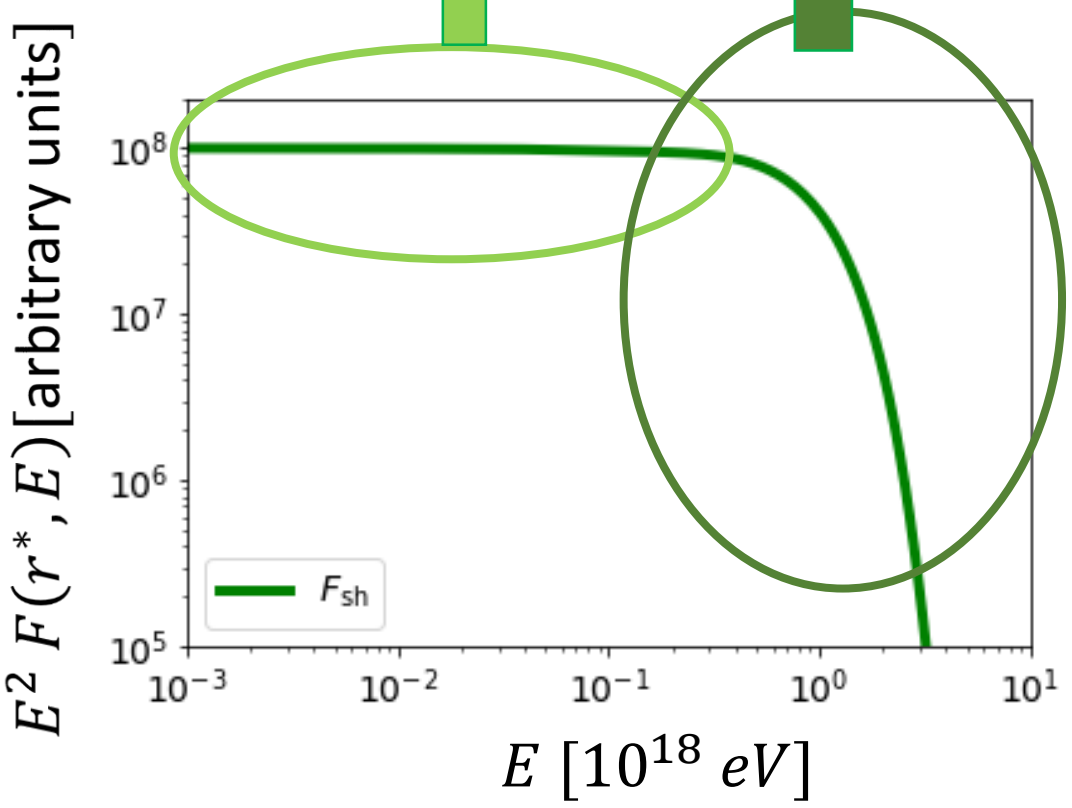
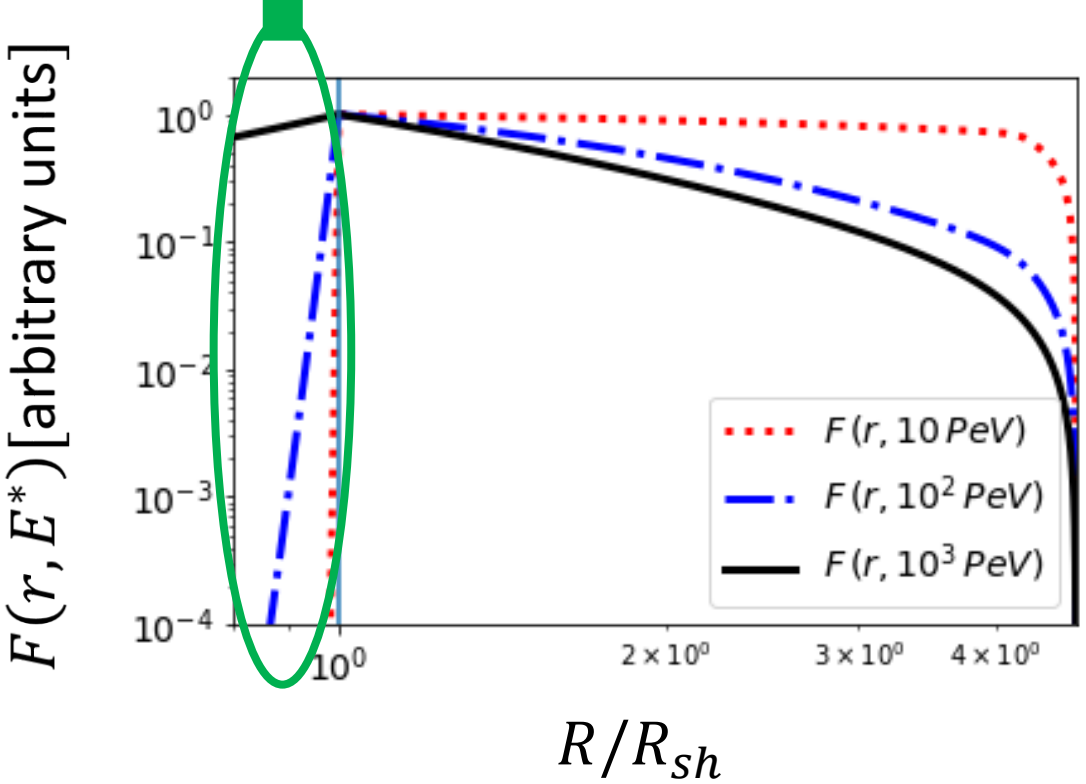
- Photomeson interaction (torus)
- Diffusion (escape)

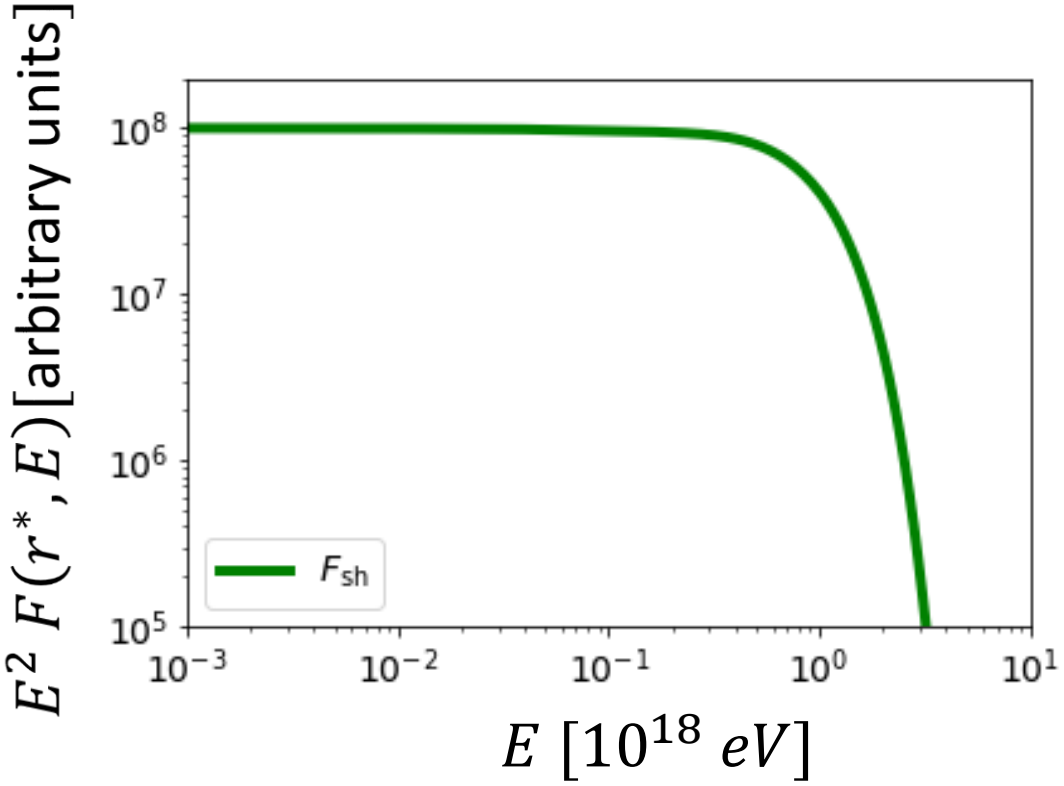




Solution: radial behavior and spectra

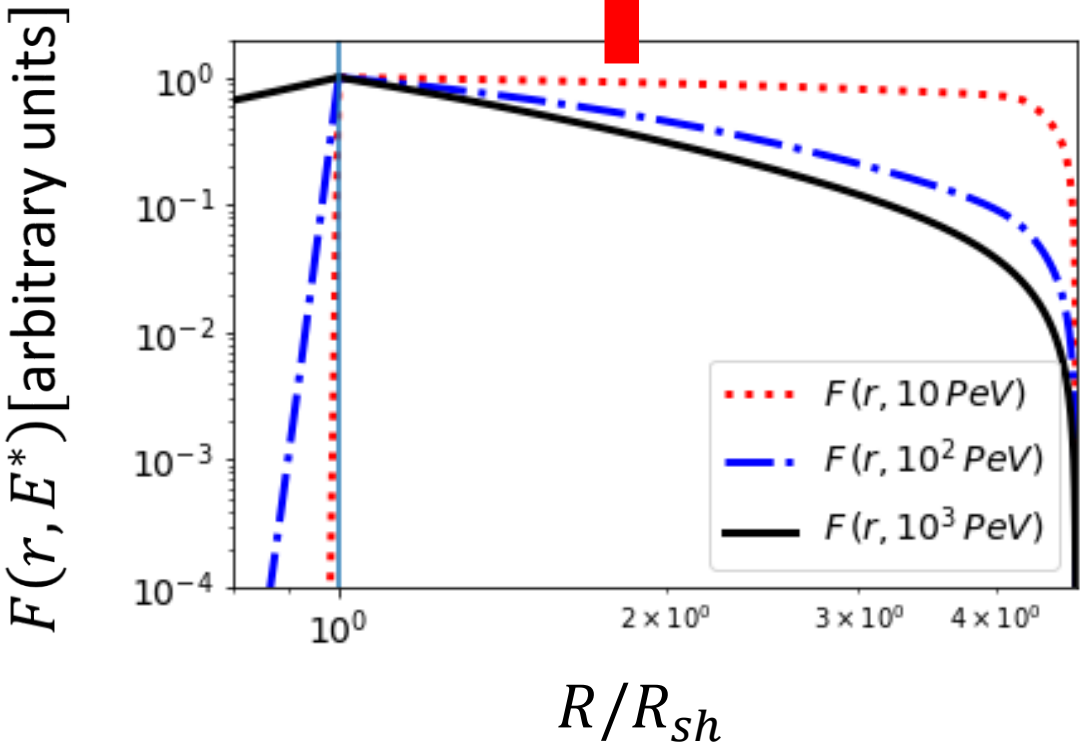
Advection → pushes particle towards R_{sh}
Diffusion → homogenizes particles

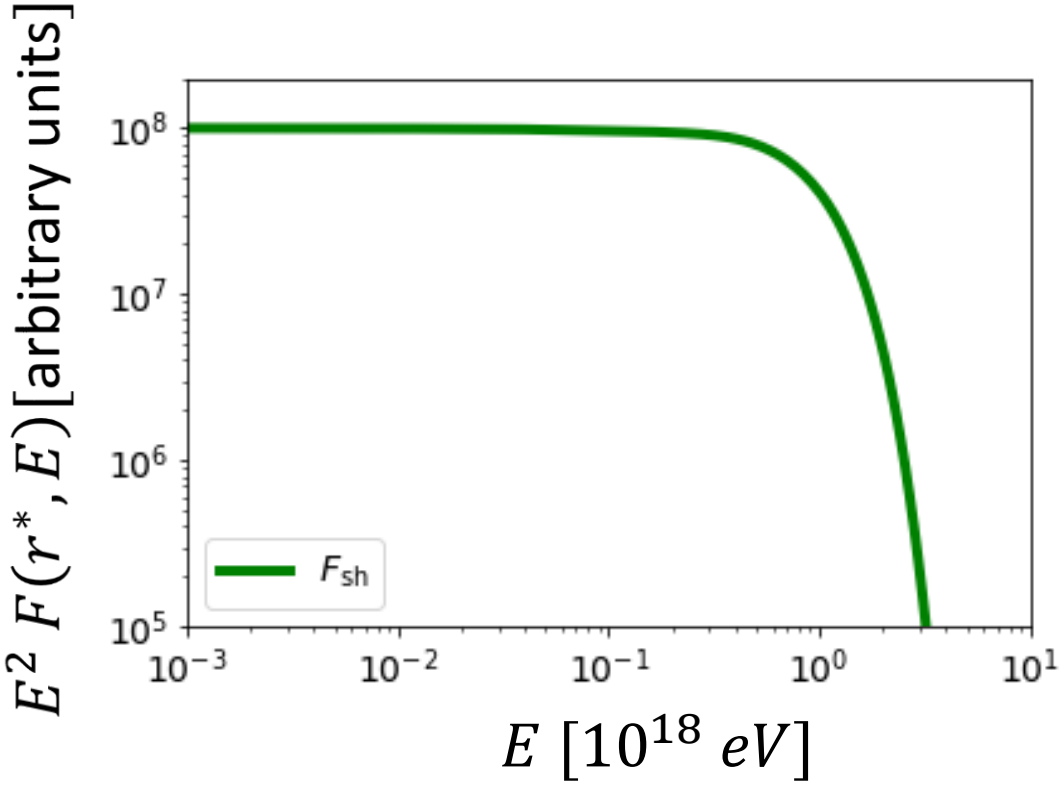




Solution: radial behavior and spectra

Advection dominated

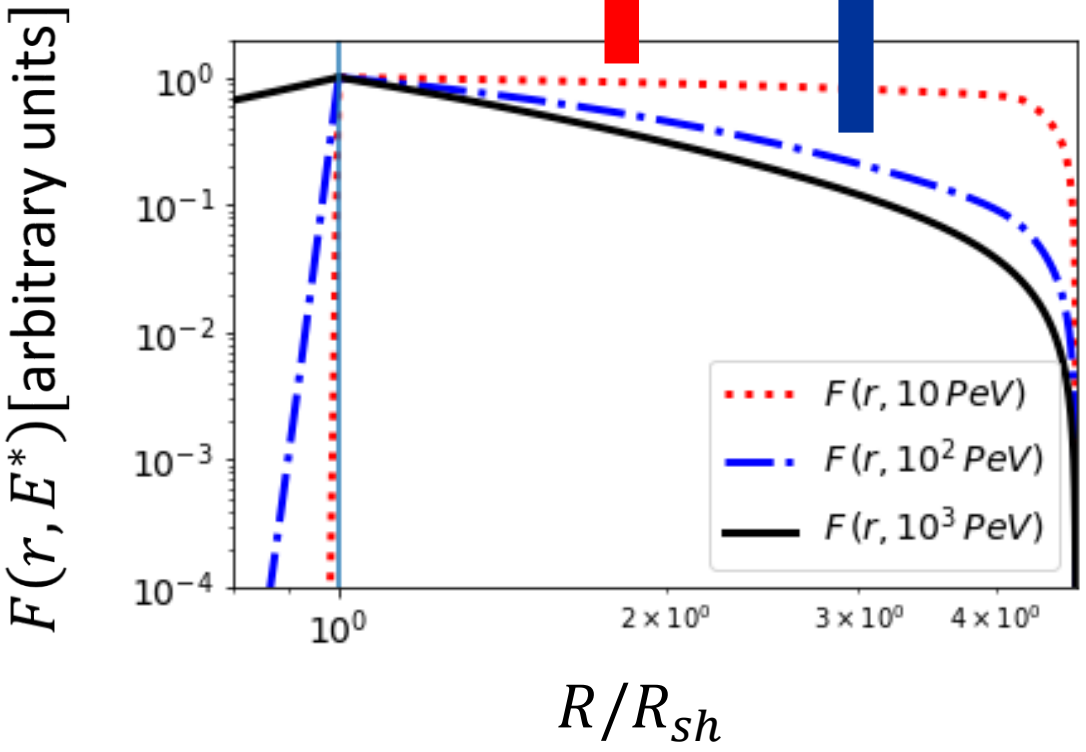


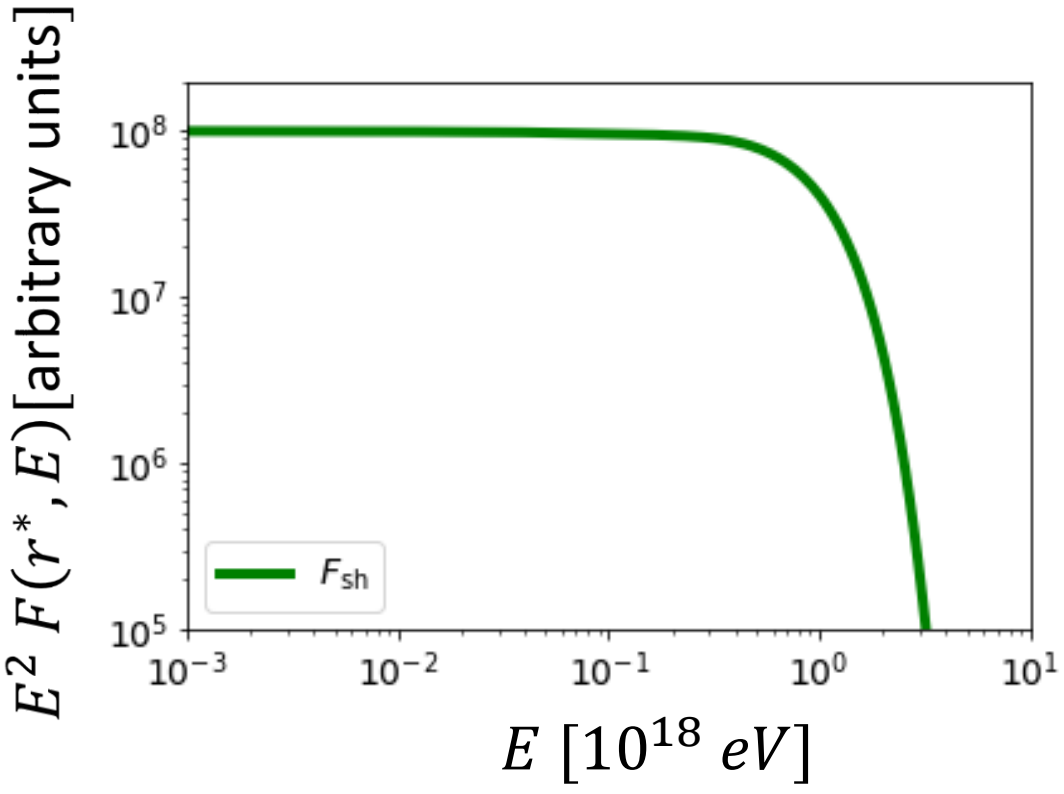


Solution: radial behavior and spectra

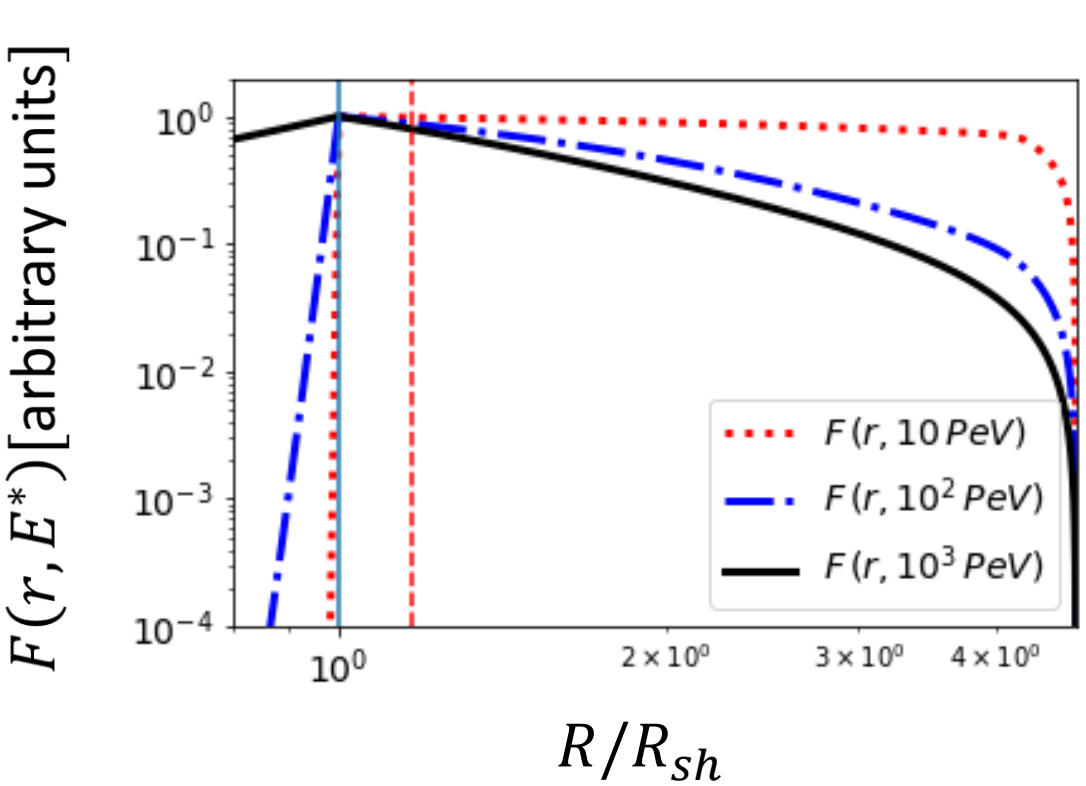
Advection dominated

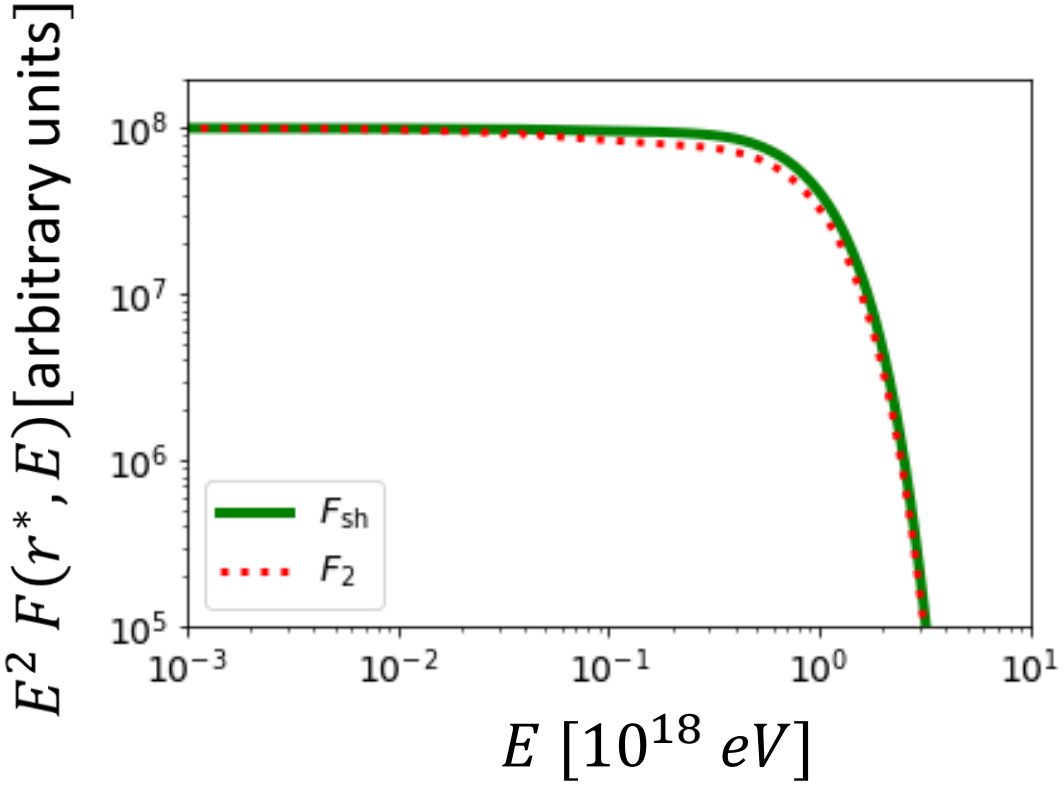
Diffusion dominated



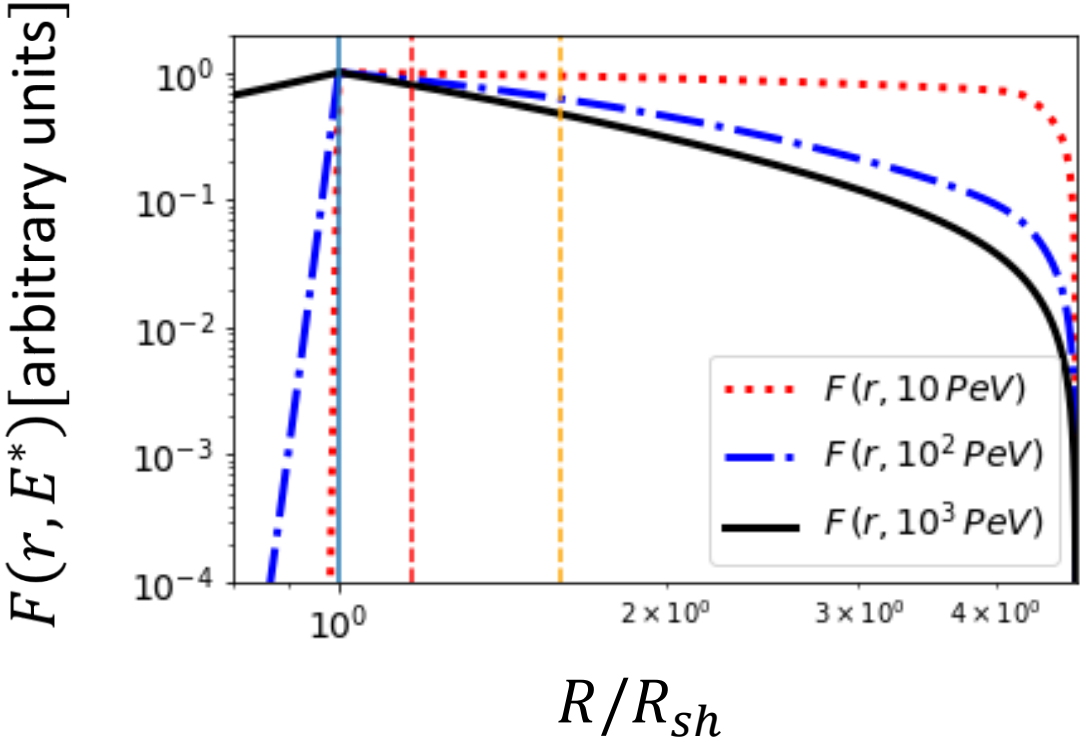


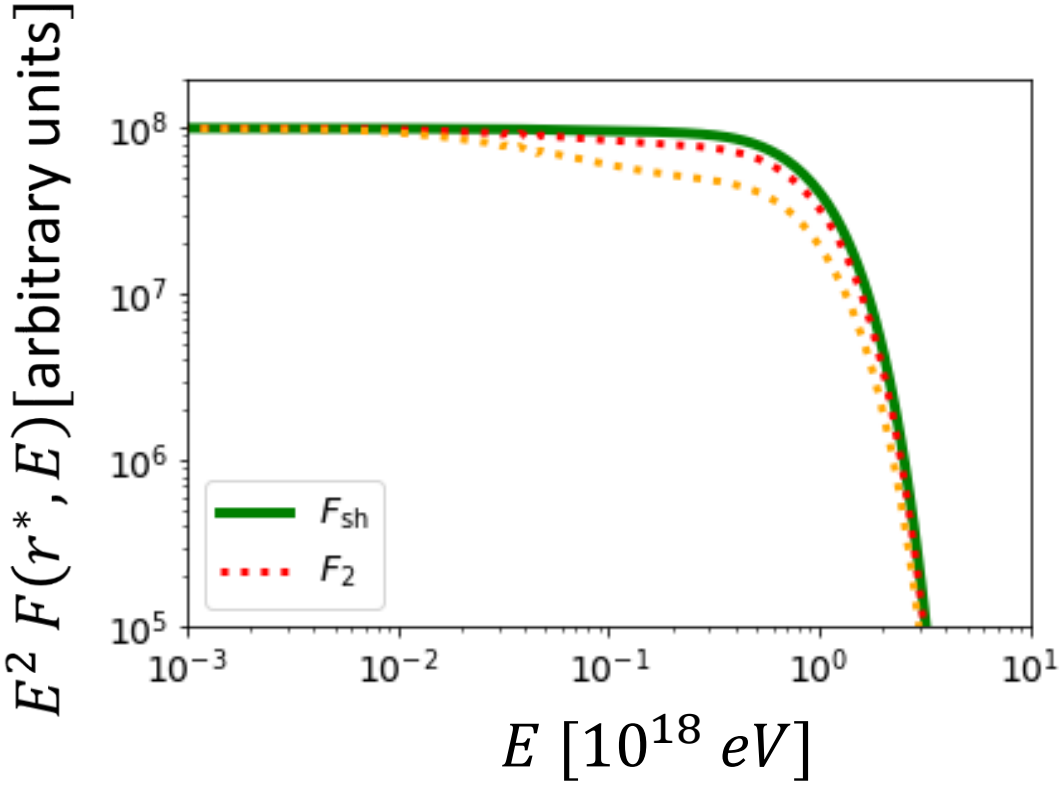
Solution: radial behavior and spectra



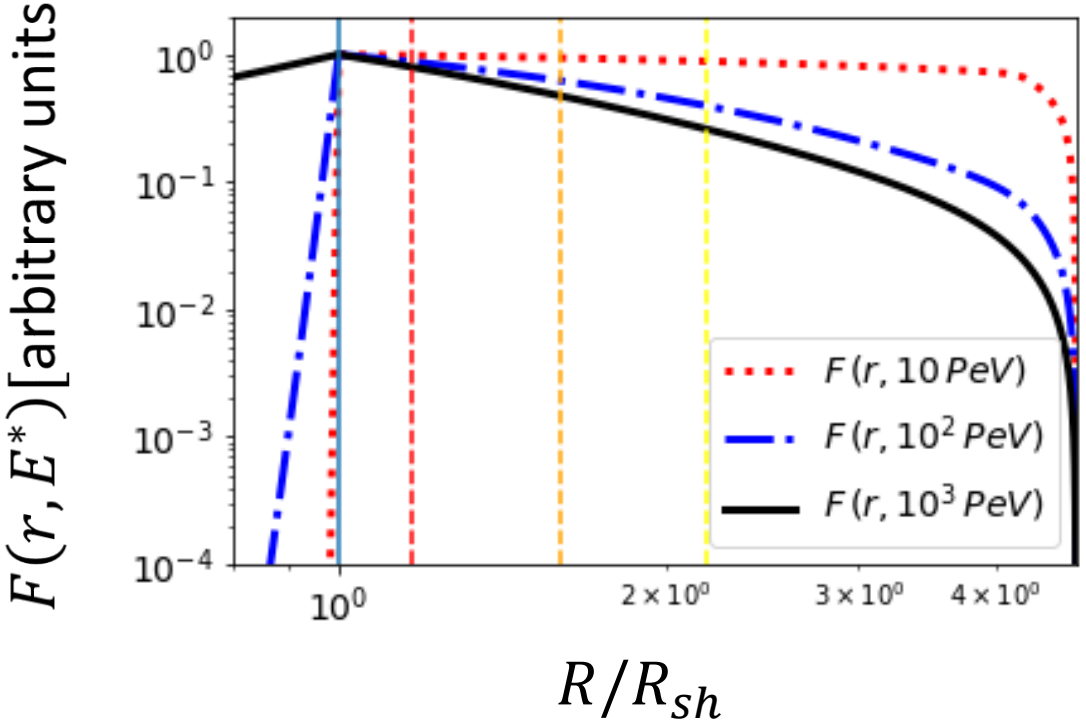


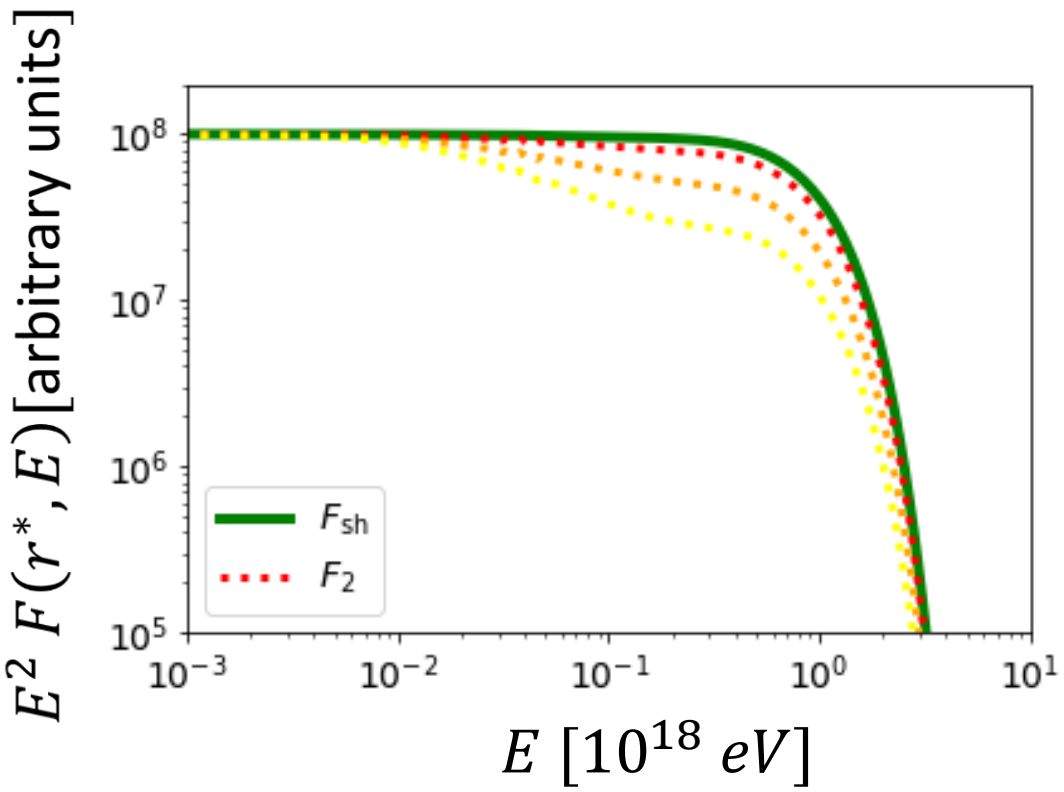
Solution: radial behavior and spectra



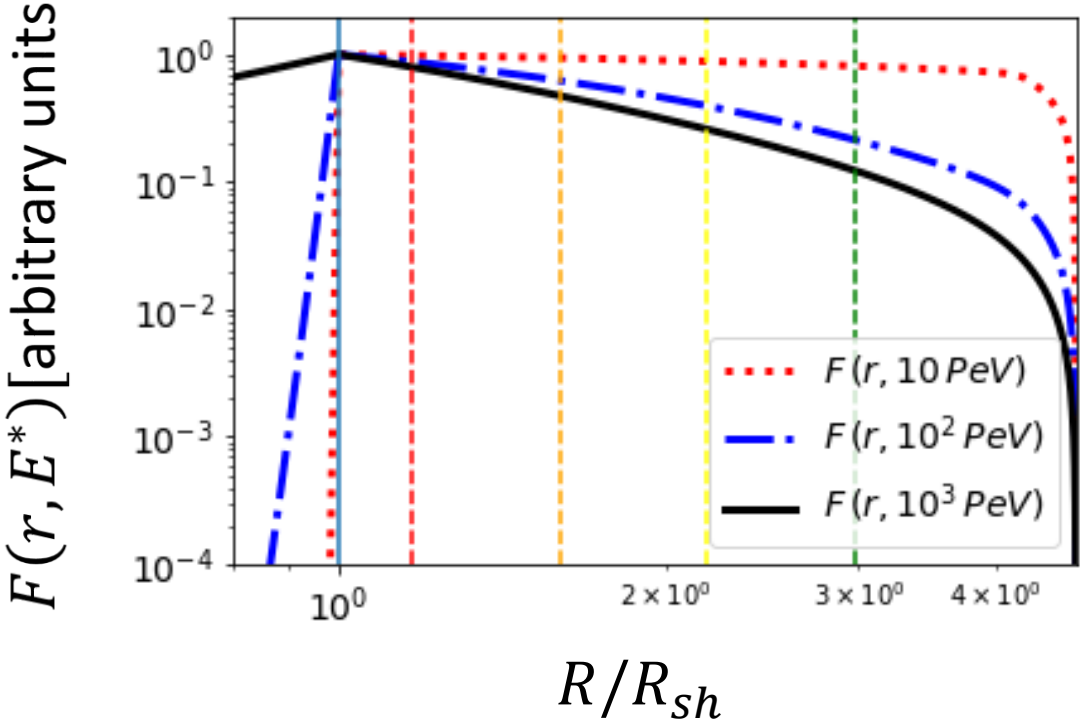


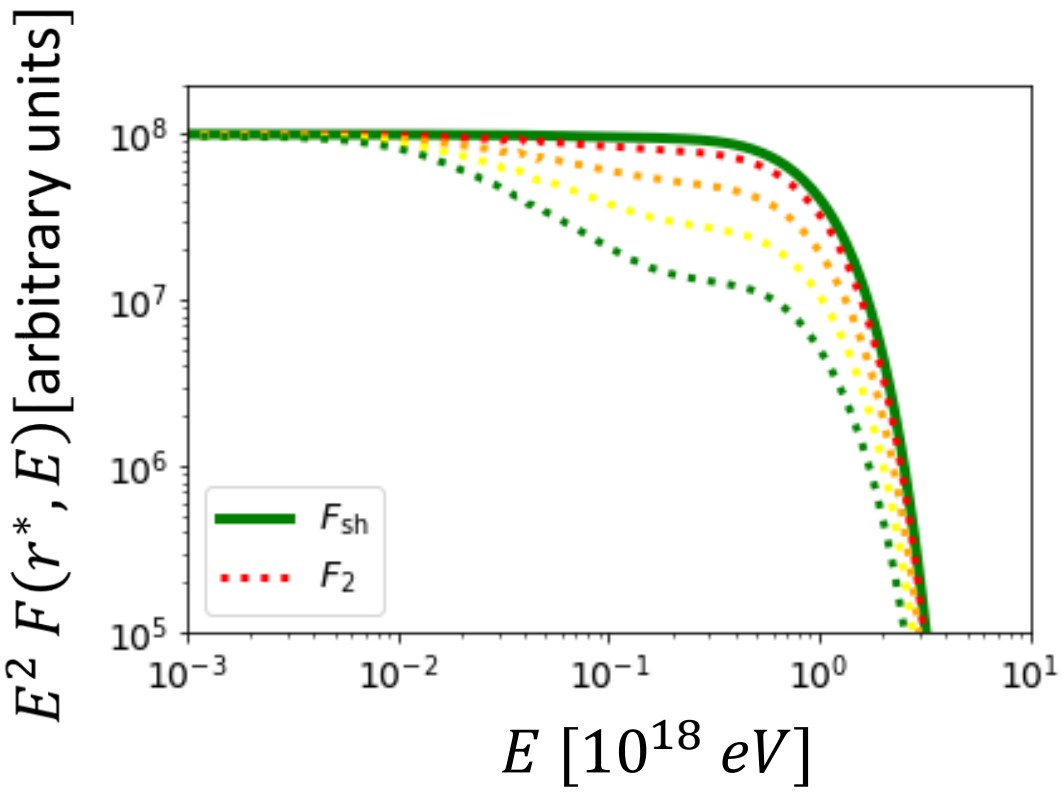
Solution: radial behavior and spectra



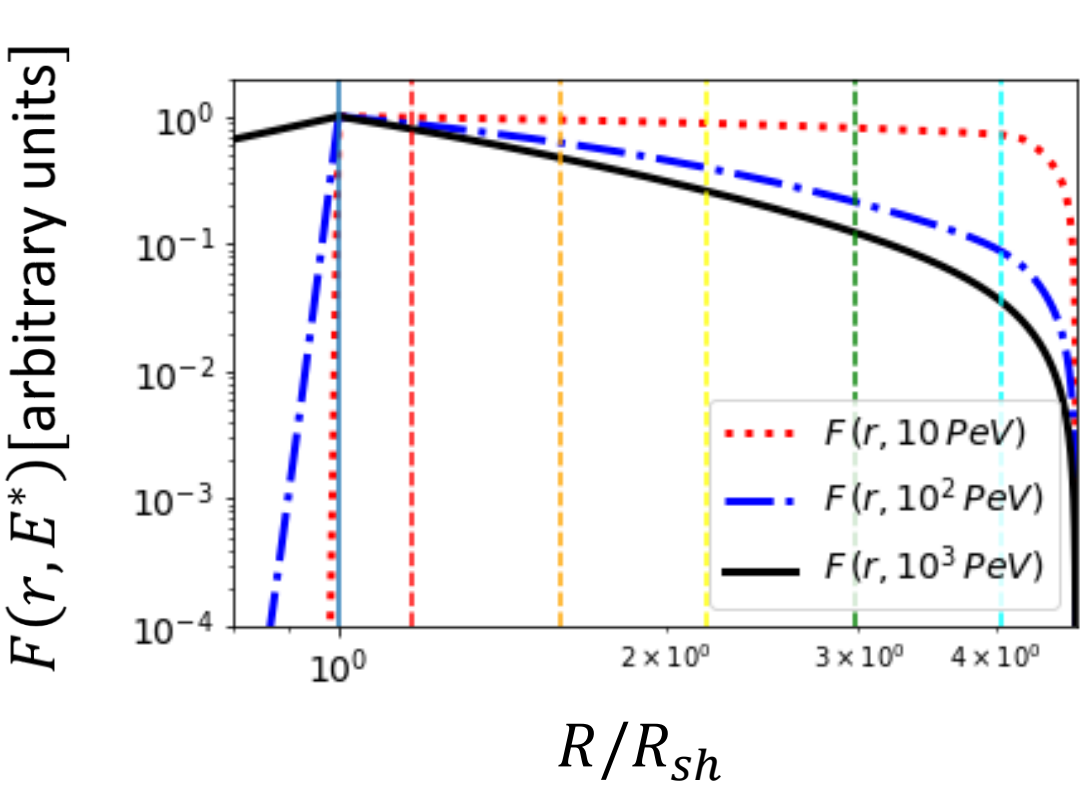


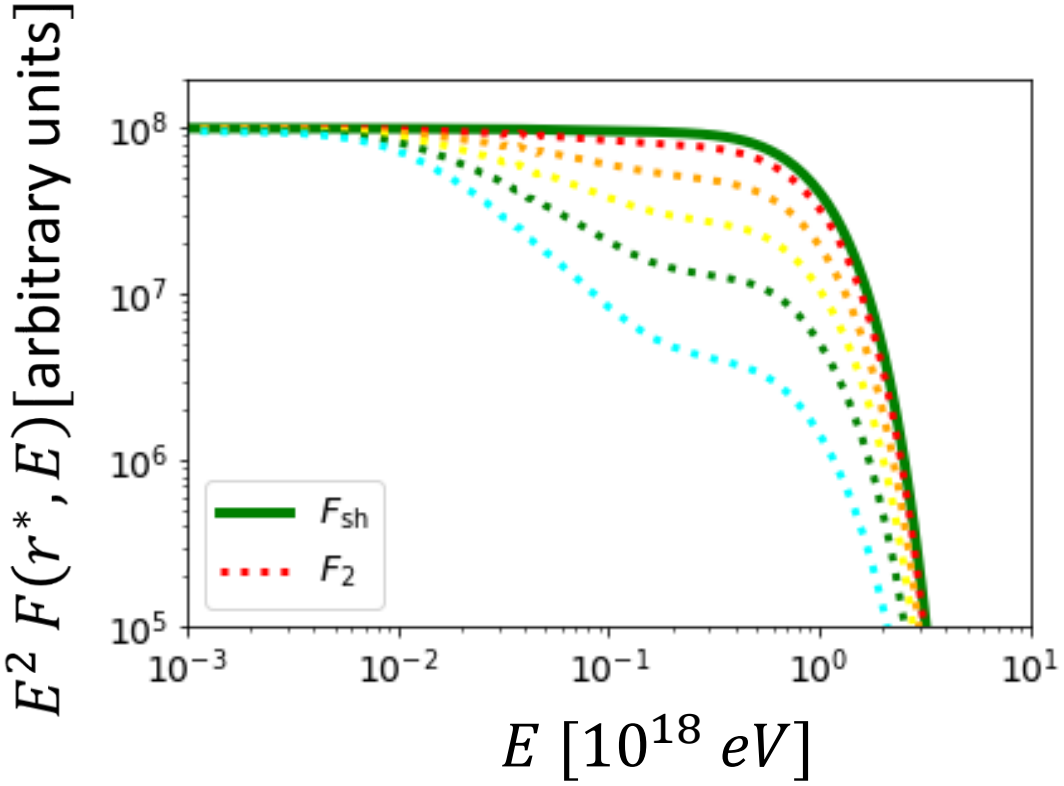
Solution: radial behavior and spectra



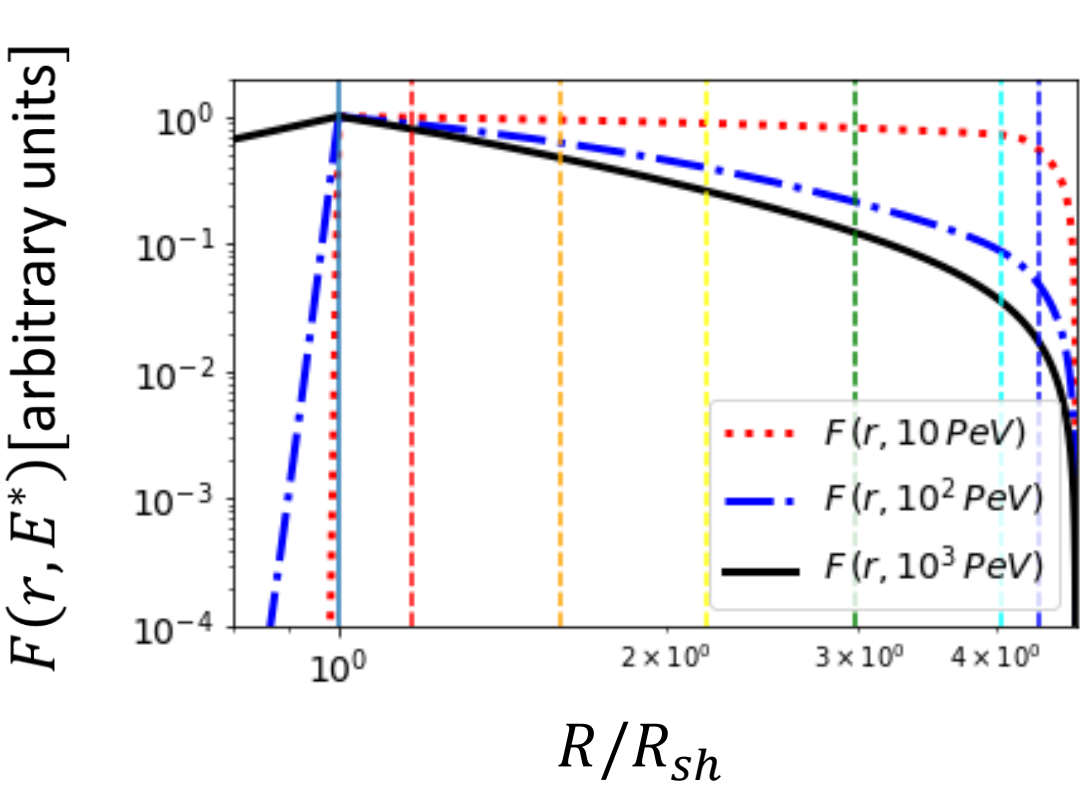


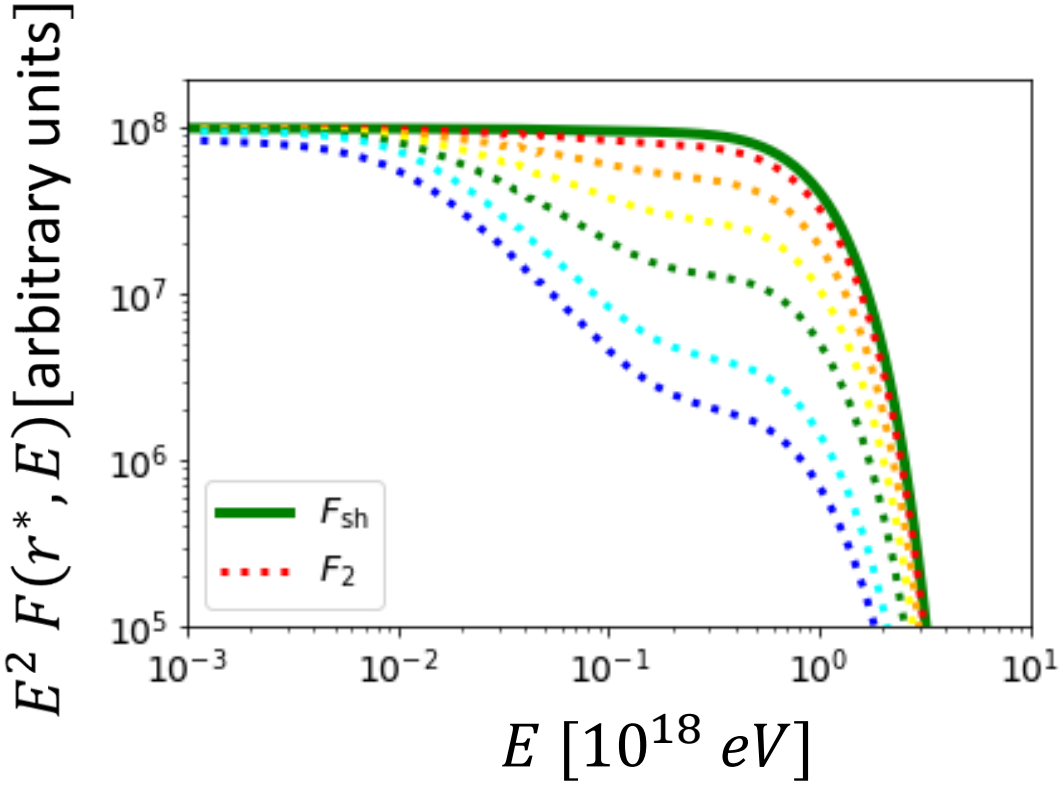
Solution: radial behavior and spectra



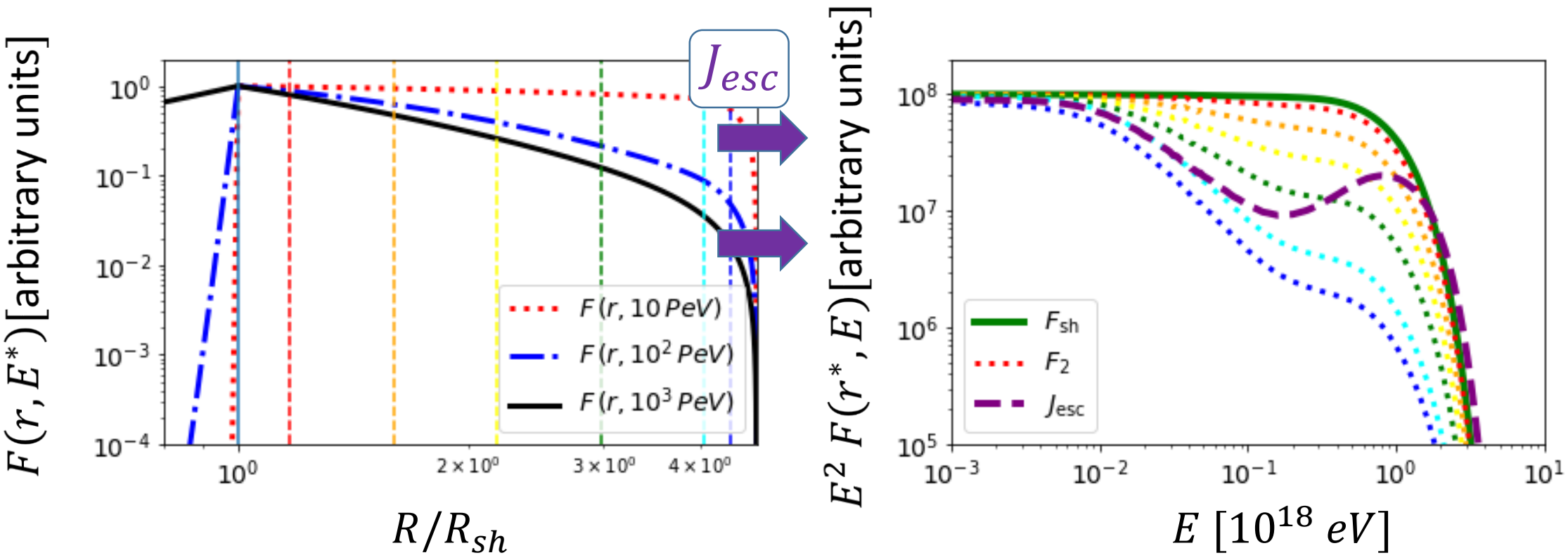


Solution: radial behavior and spectra



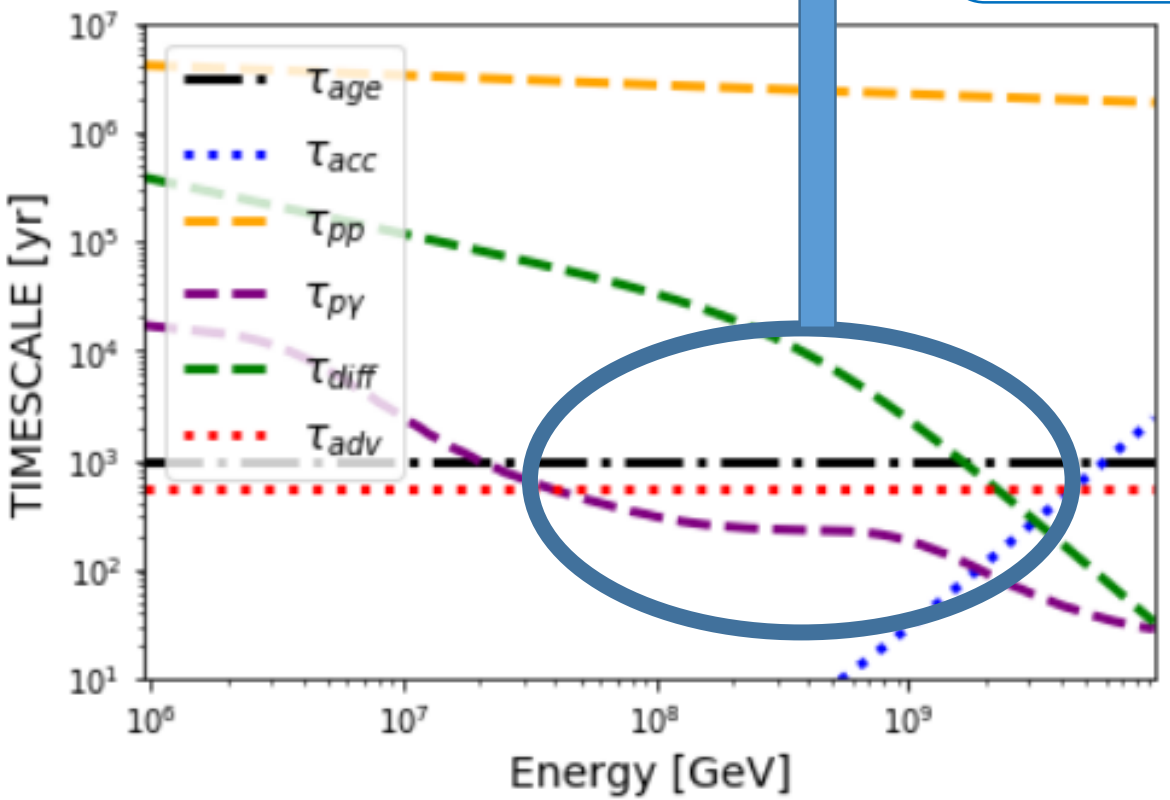


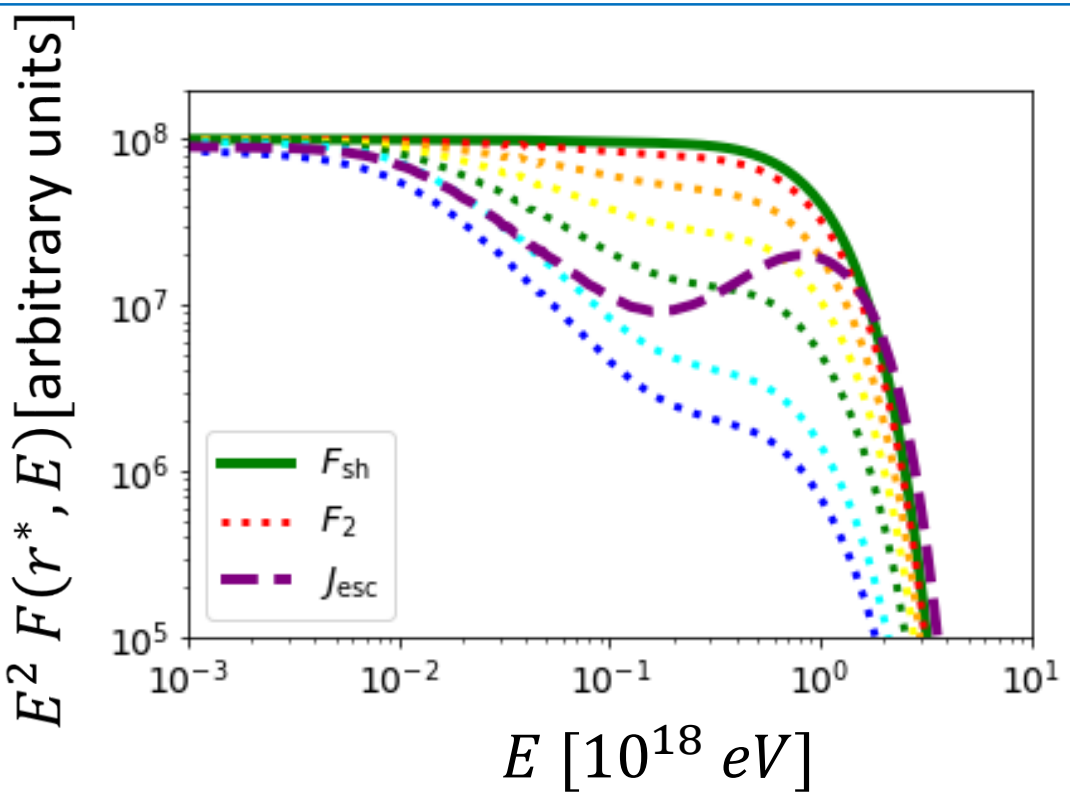
Solution: radial behavior and spectra



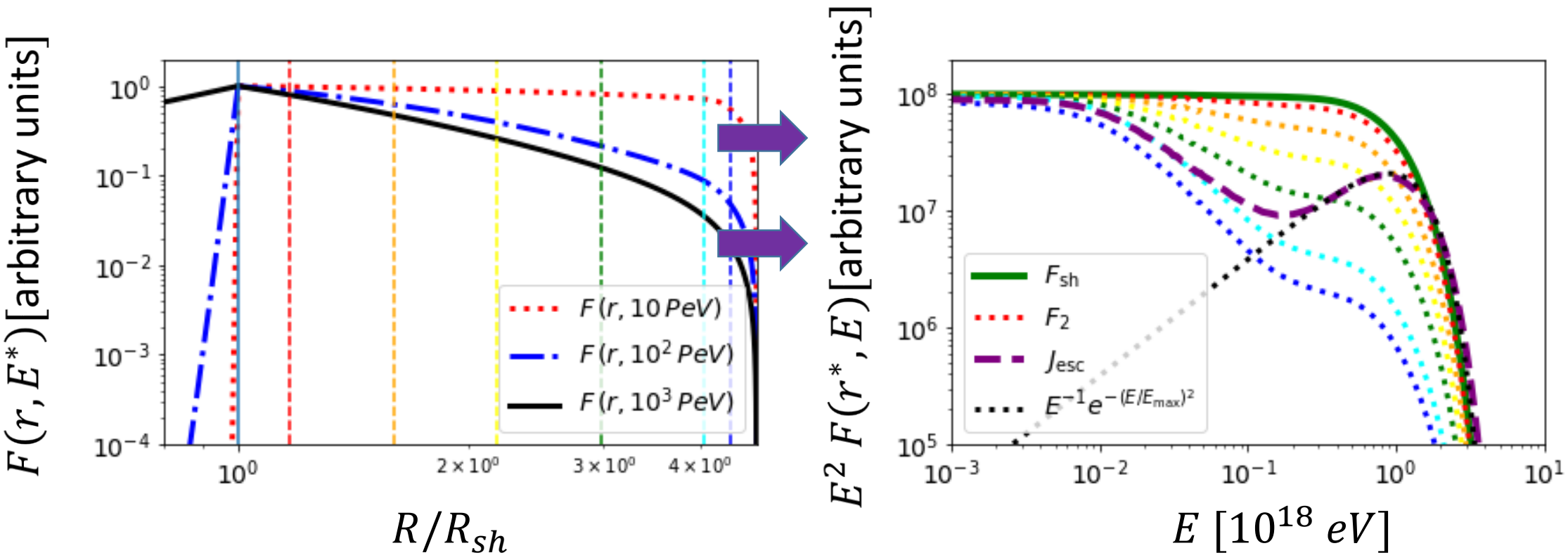
Solution: radial behavior and spectra

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

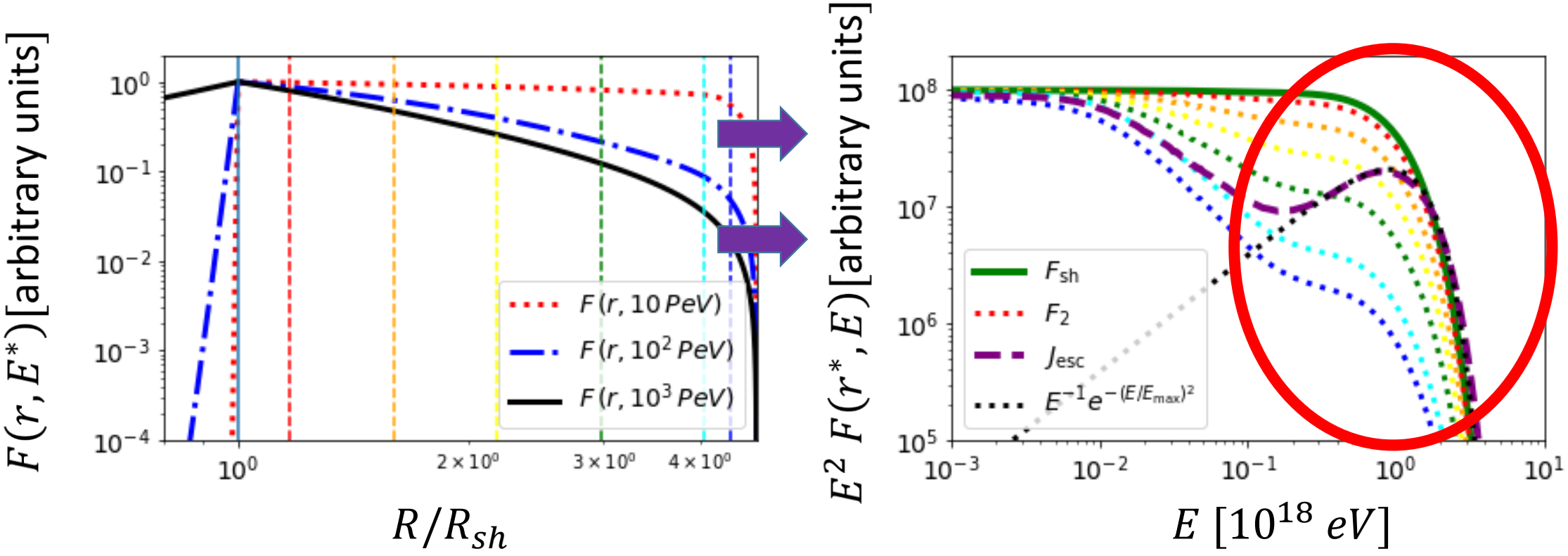




Solution: radial behavior and spectra



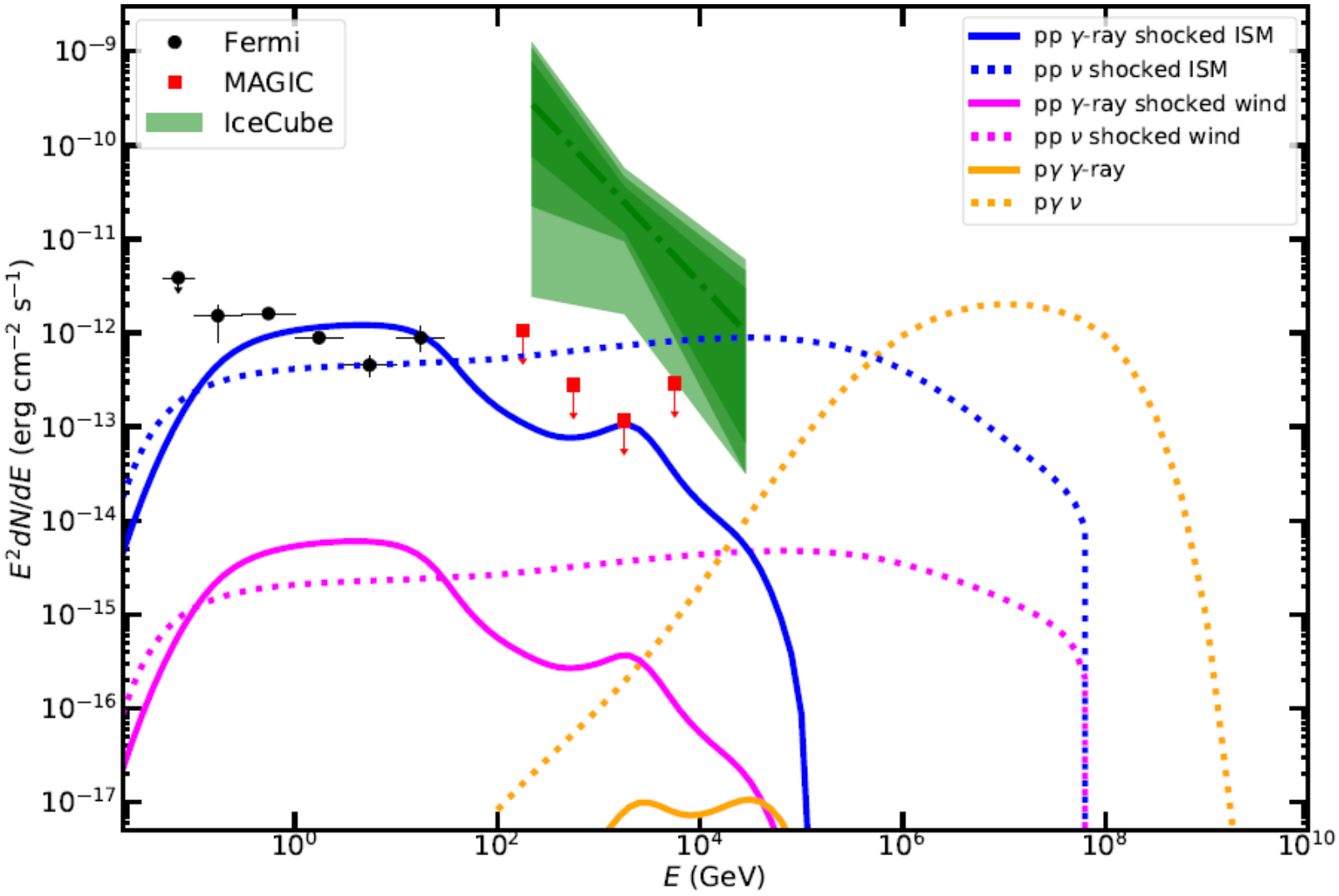
Solution: radial behavior and spectra



Outline

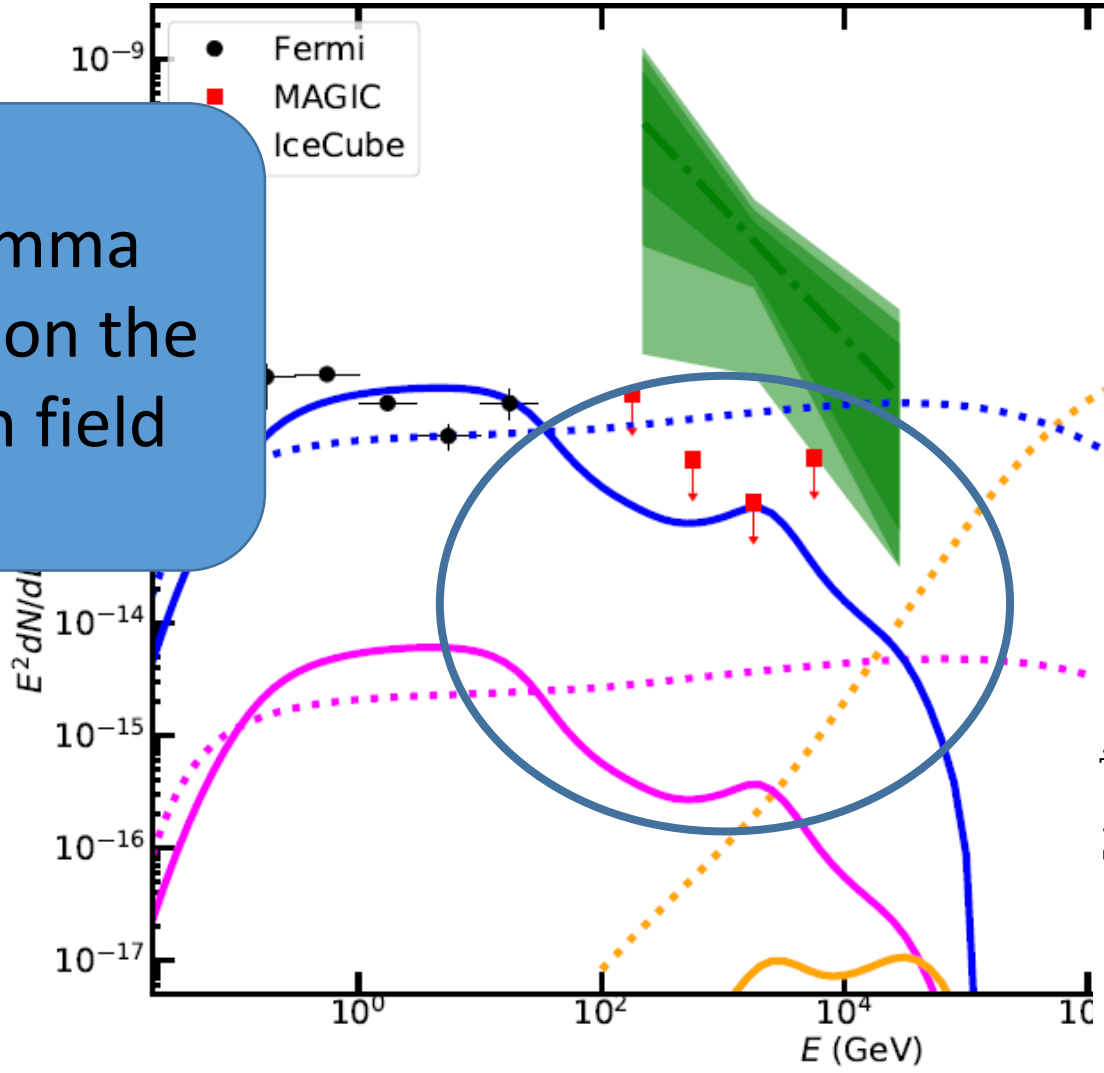
- Ultra Fast Outflows
- Acceleration and transport at wind shocks in UFOs
- Solution: radial behavior and spectra
- Multimessenger implications

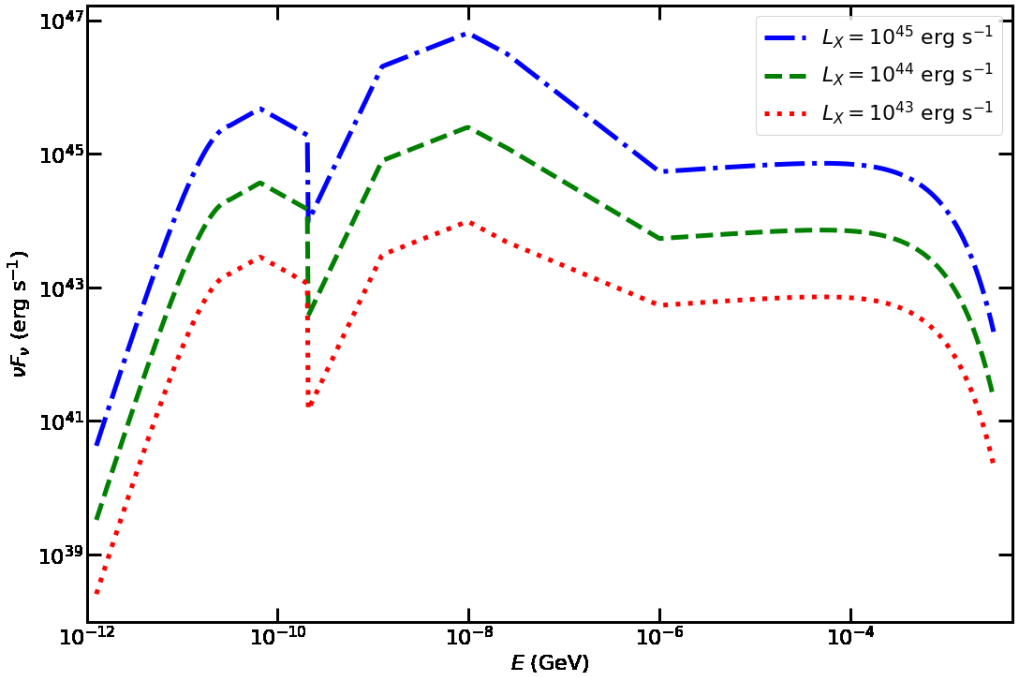
Multimessenger implications: NGC1068



Multimessenger implications: NGC1068

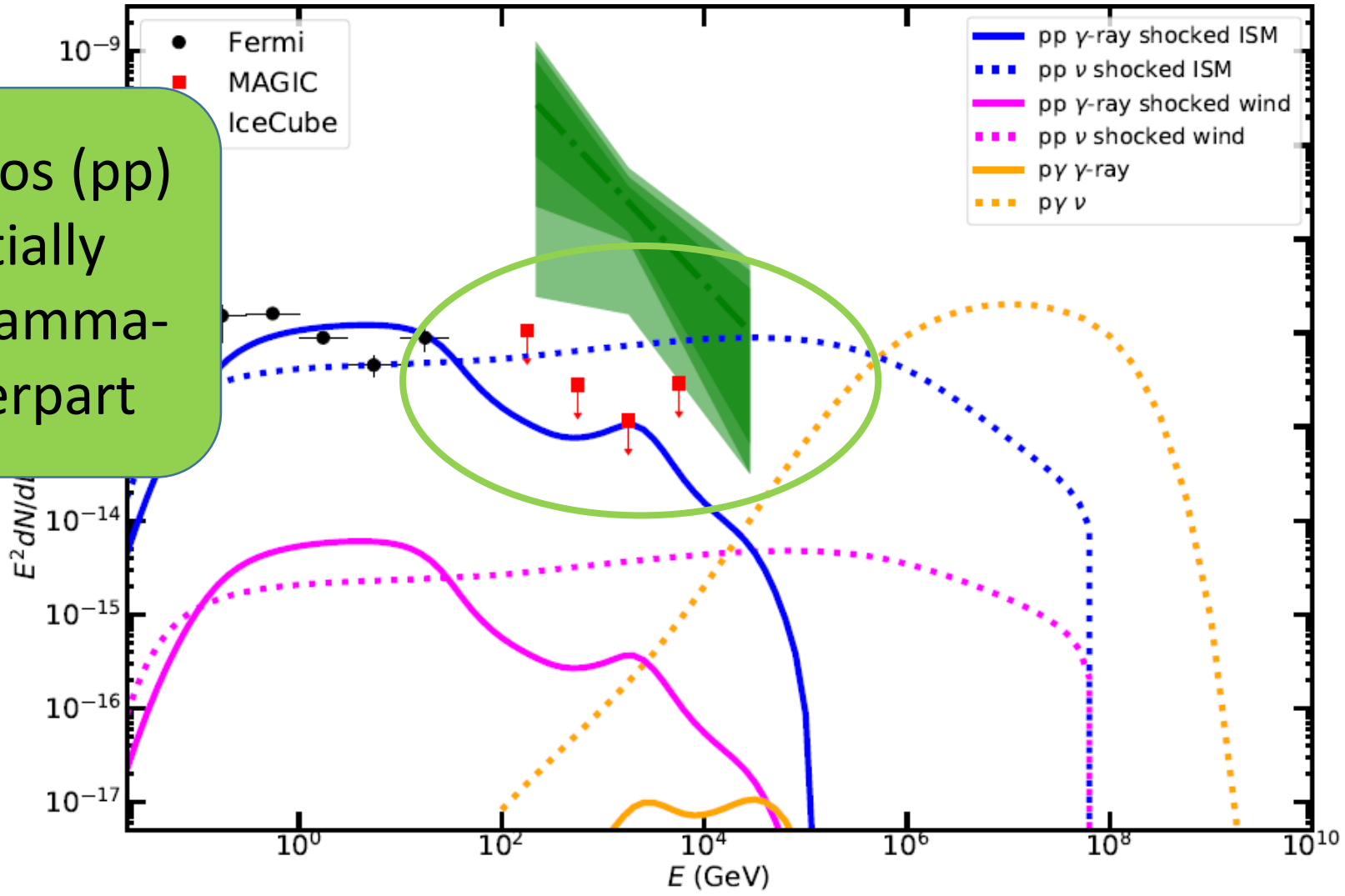
Gamma-gamma absorption on the BKG photon field





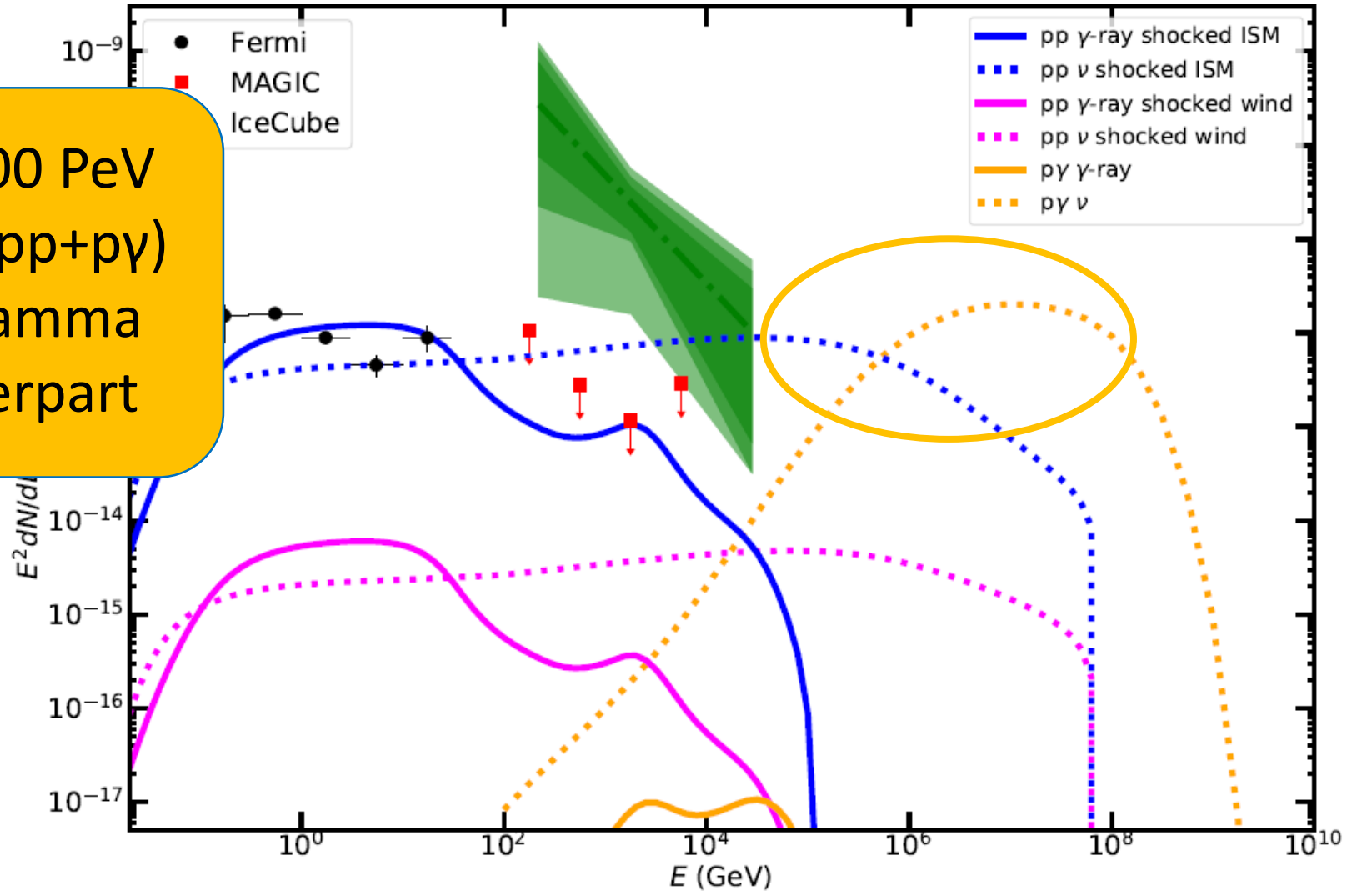
Multimessenger implications: NGC1068

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 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!

Back up

DSA idea – infinite planar shock

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

DSA idea – infinite planar shock

STATIONARY

NEGLIGIBLE

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

DSA idea – infinite planar shock

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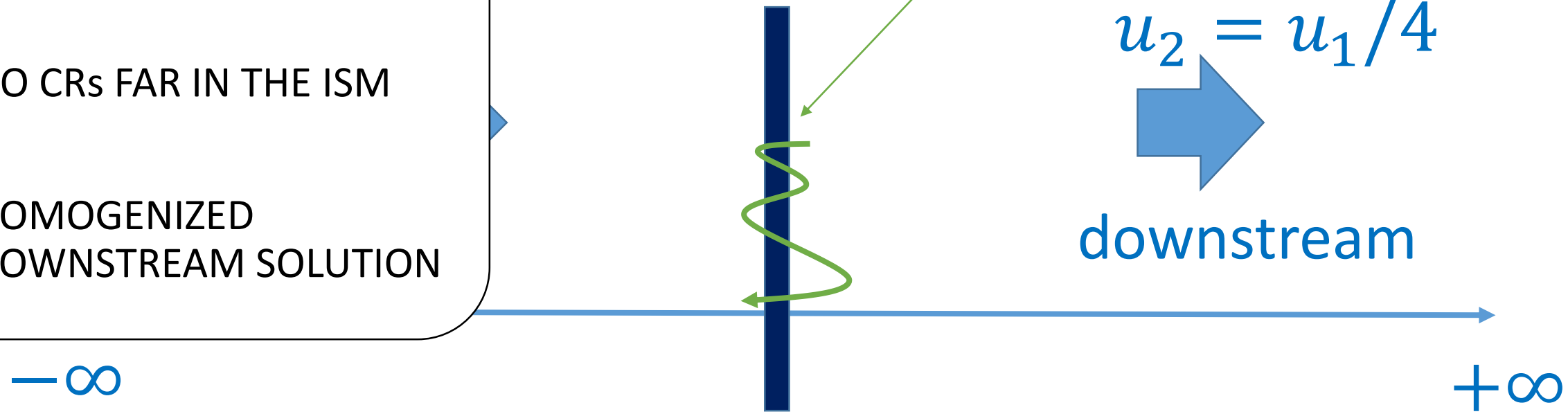
INJECTION LOCALIZED AT THE SHOCK

BOUNDARY CONDITIONS:

- NO CRs FAR IN THE ISM
- HOMOGENIZED DOWNSTREAM SOLUTION



DSA idea – infinite planar shock

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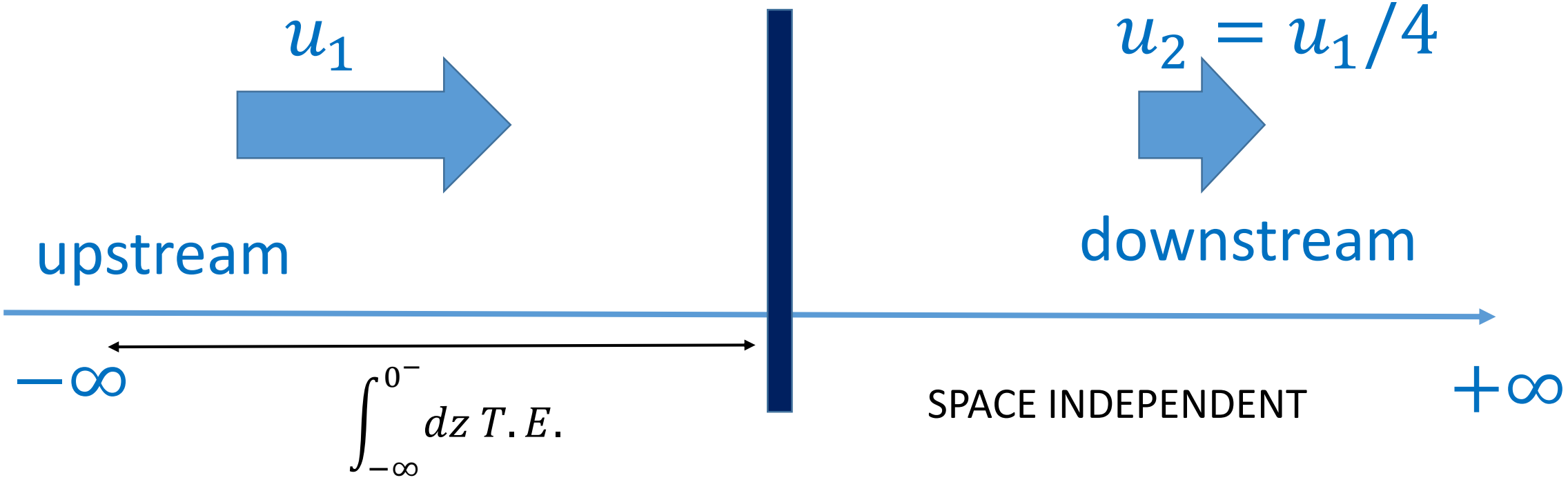

DSA idea – infinite planar shock

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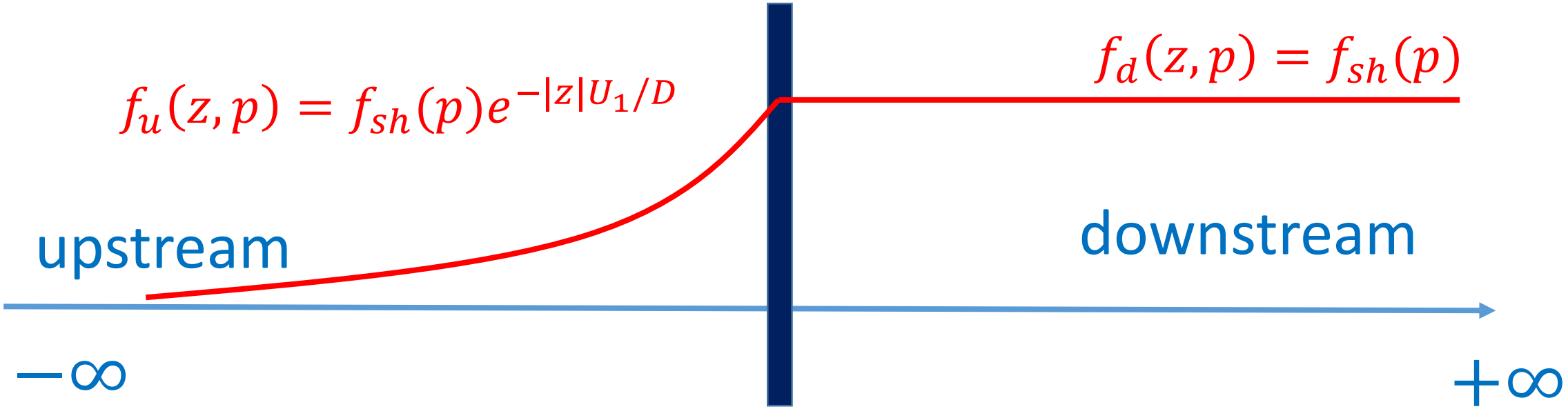

DSA idea – infinite planar shock

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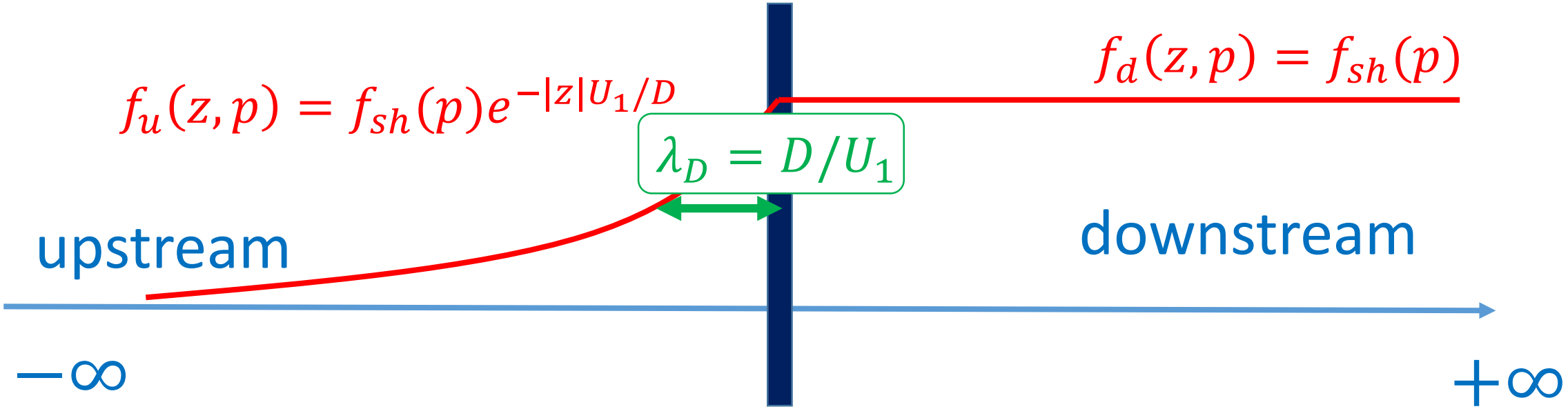

DSA idea – infinite planar shock

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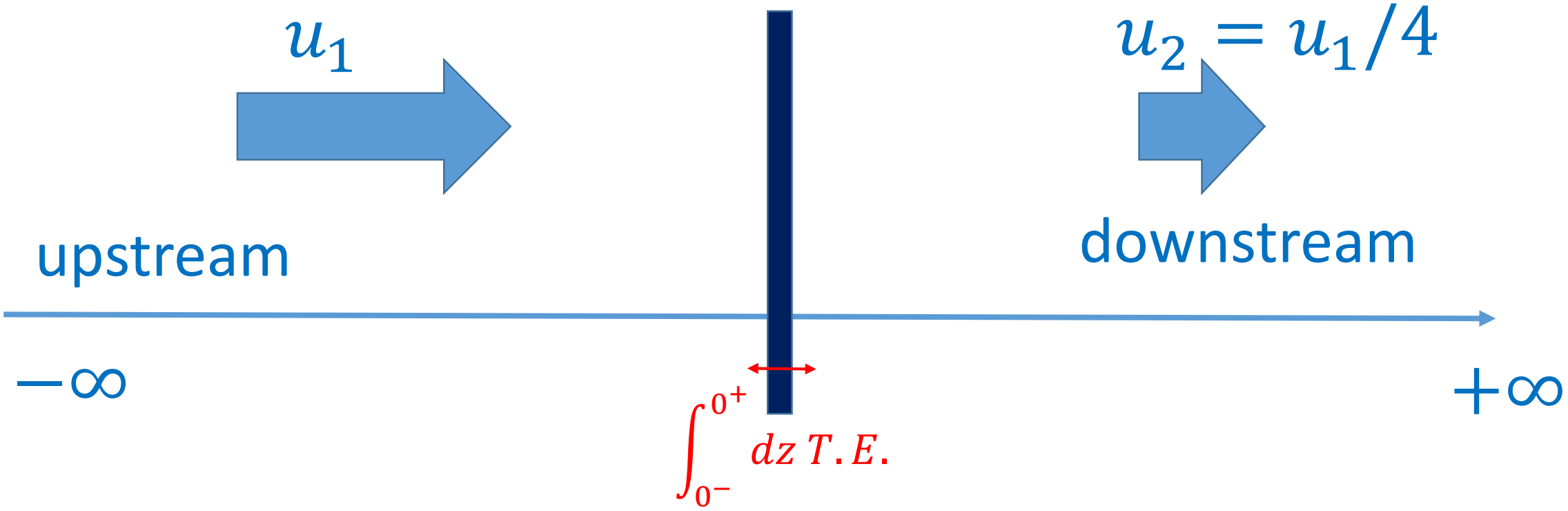

DSA idea – infinite planar shock

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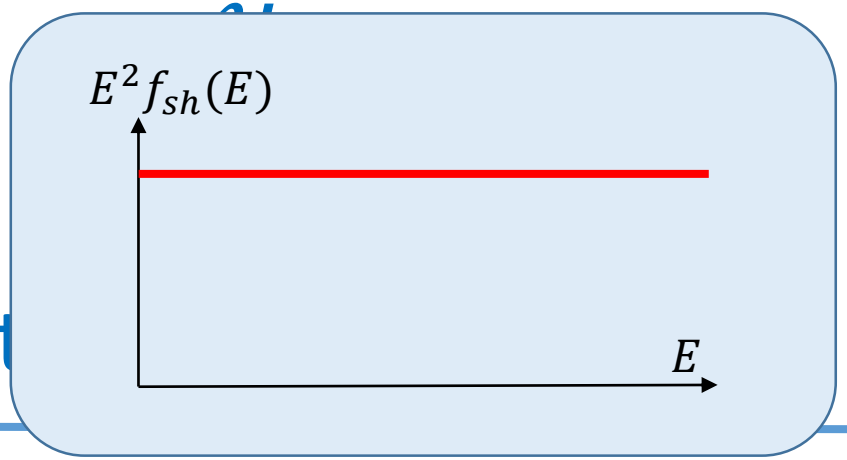


$$s = \frac{3U_1}{U_1 - U_2} \rightarrow strong\ shock\ \rightarrow 4$$

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

upst

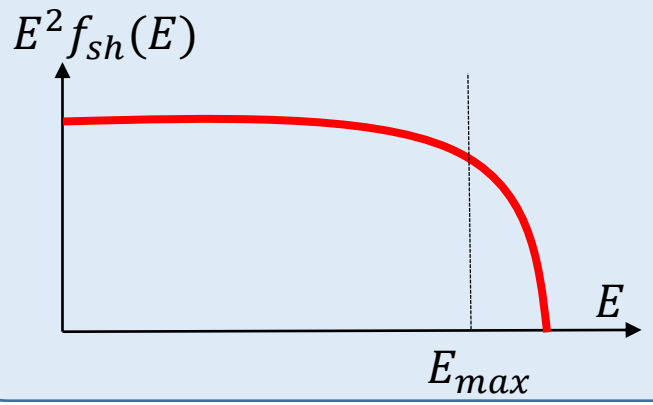
$-\infty$

$+\infty$

DSA idea – infinite planar shock

Finite size of the system → Escape z* → E_{max}

$$\lambda_D(E_{max}) = D(E_{max})/u_1 \approx |z^*|$$



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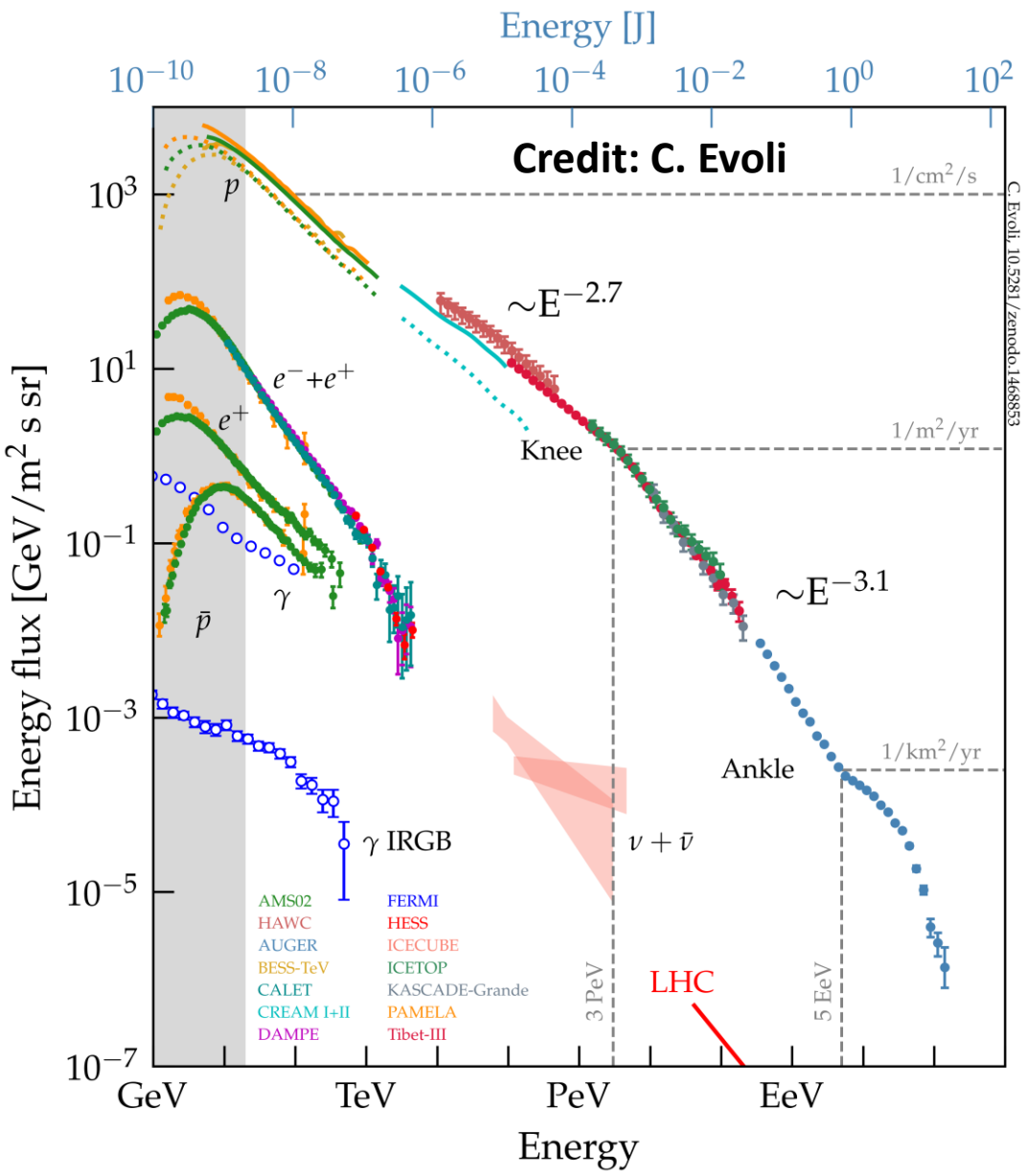
upst

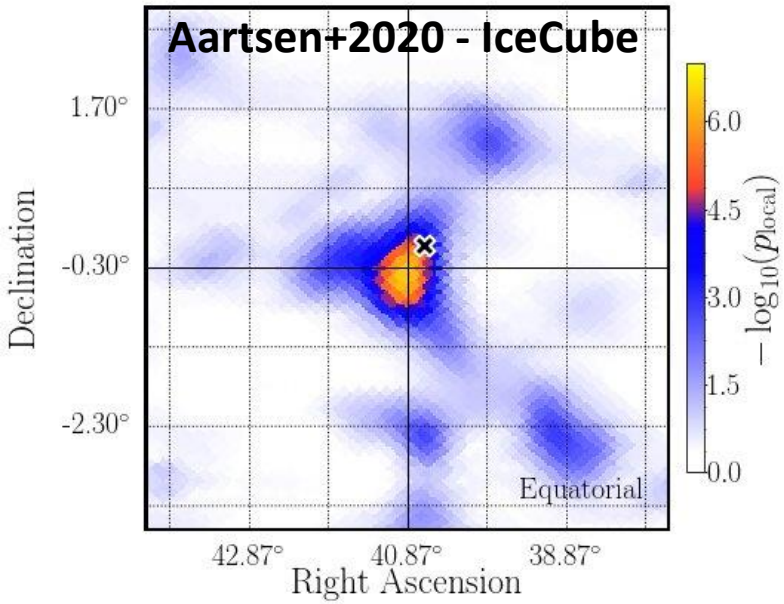
$-\infty$

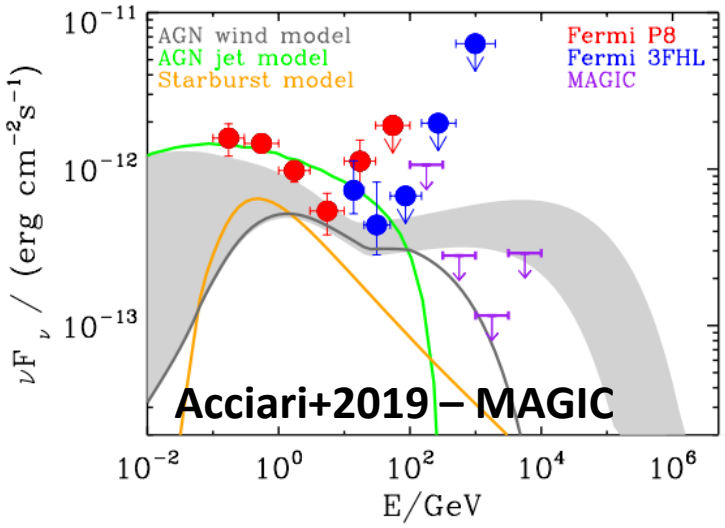
$+\infty$

Particle Multimessenger plot



NGC1068





Indications of neutrino production at TeV in the nearby NGC1068 while gamma is limited below 10^2 GeV

- Starburst emission?
- AGN jet? AGN wind?
- Other sources?

Maximum Energy & Luminosity (SB-Wind)