Diffusive shock acceleration and multi-messenger radiation from wind bubbles

Enrico Peretti

peretti@nbi.ku.dk

Topical Seminar at «Here, There & Everywhere»
PhD Summer School on Neutrinos, NBI, Copenhagen

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

- Transport equation of Cosmic Rays
- Transport approach to diffusive shock acceleration
- Wind blown bubbles
- Modeling acceleration and multi-messenger radiation

Outline

- Transport equation of Cosmic Rays
- Transport approach to diffusive shock acceleration
- Wind blown bubbles
- Modeling acceleration and multi-messenger radiation

Cosmic Rays

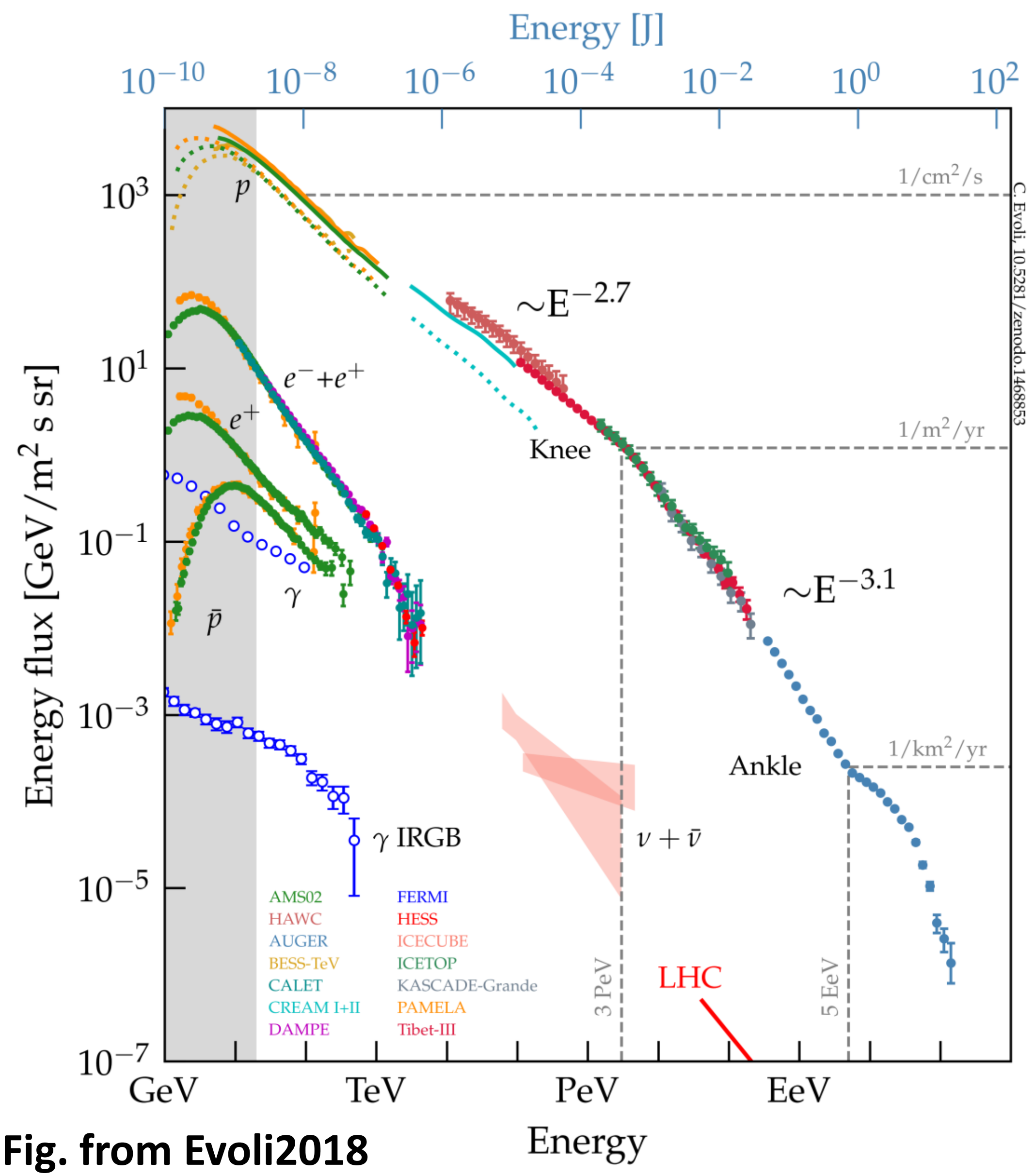
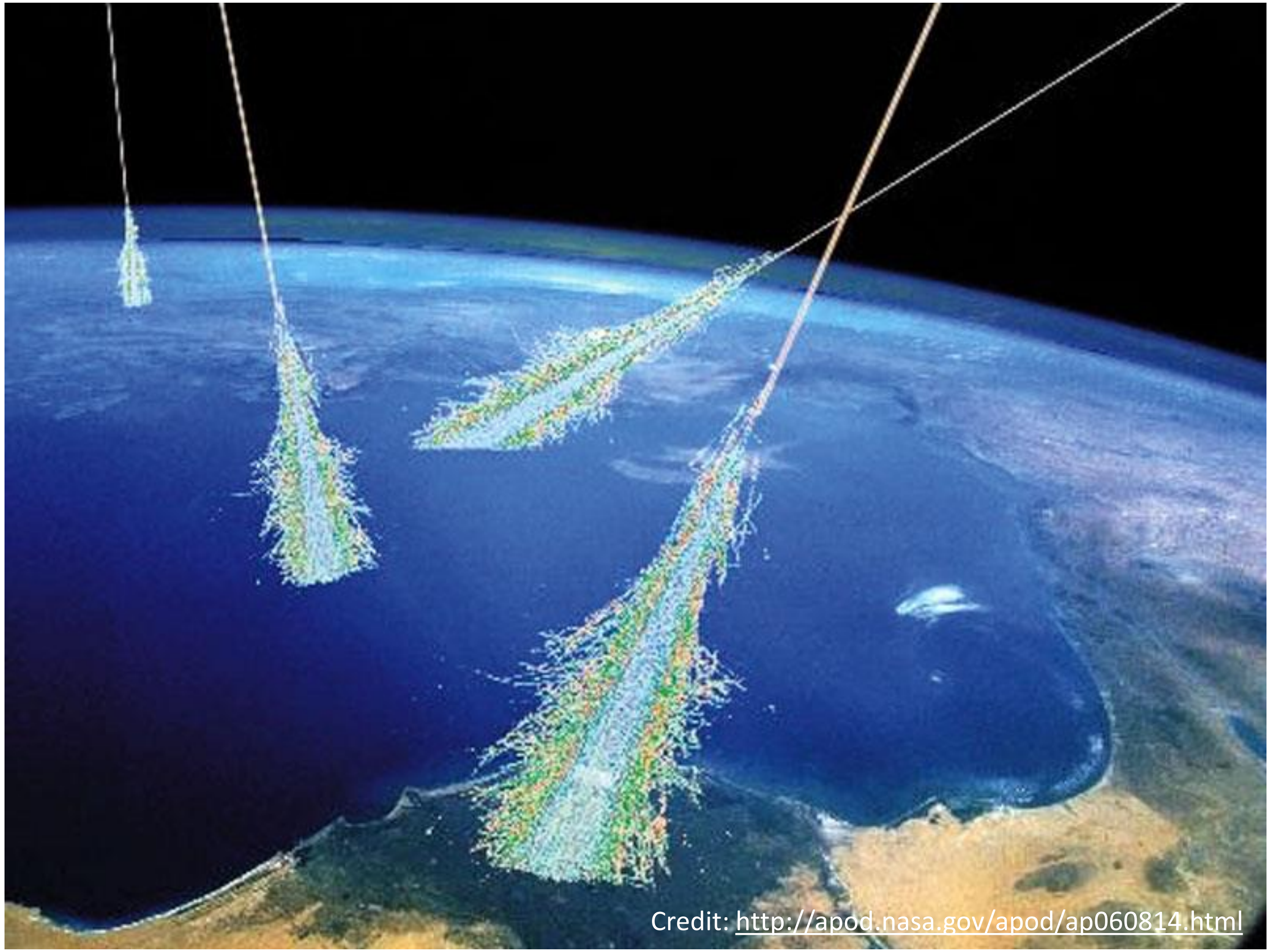


Fig. from Evoli2018


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

Cosmic Rays

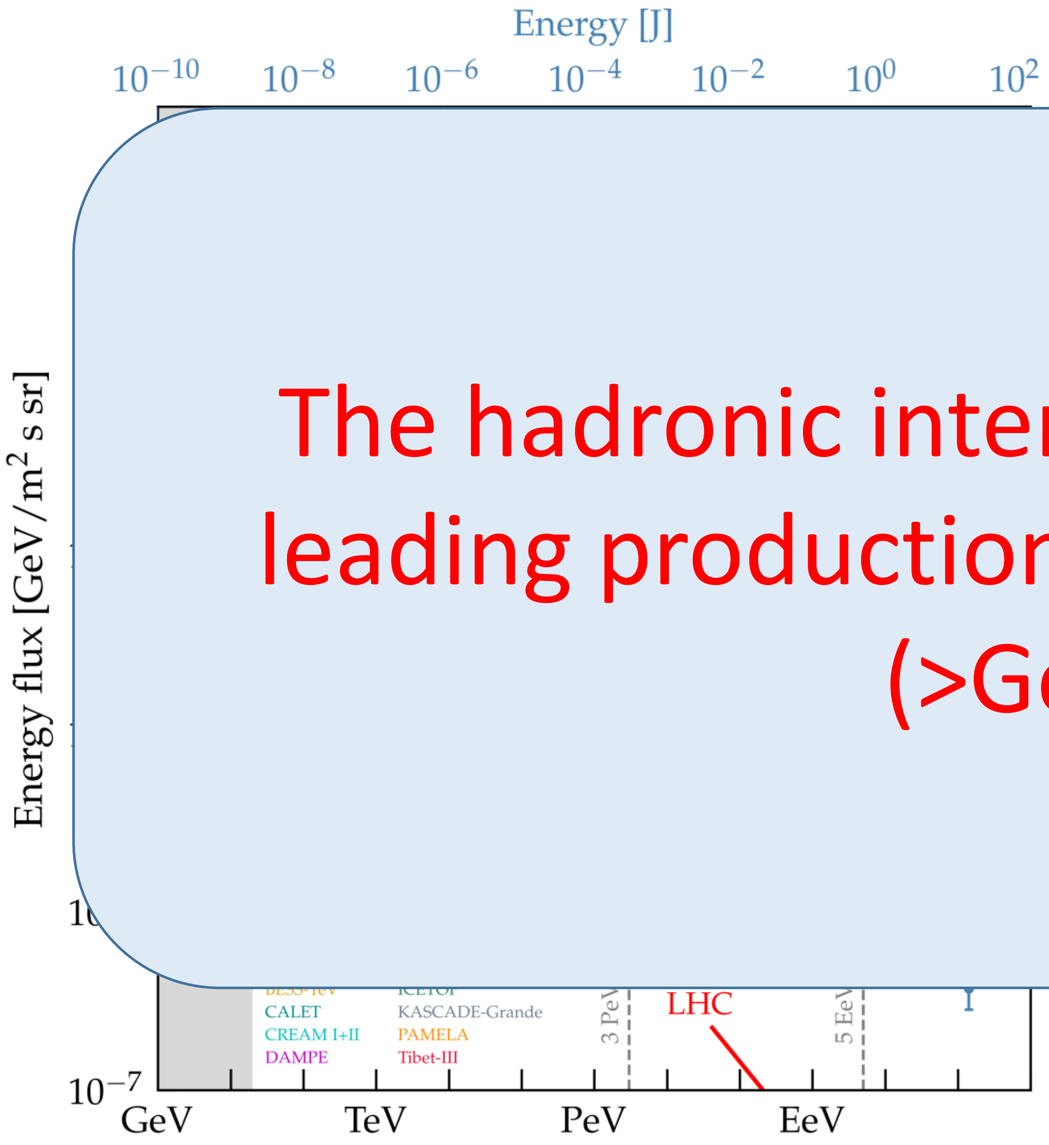
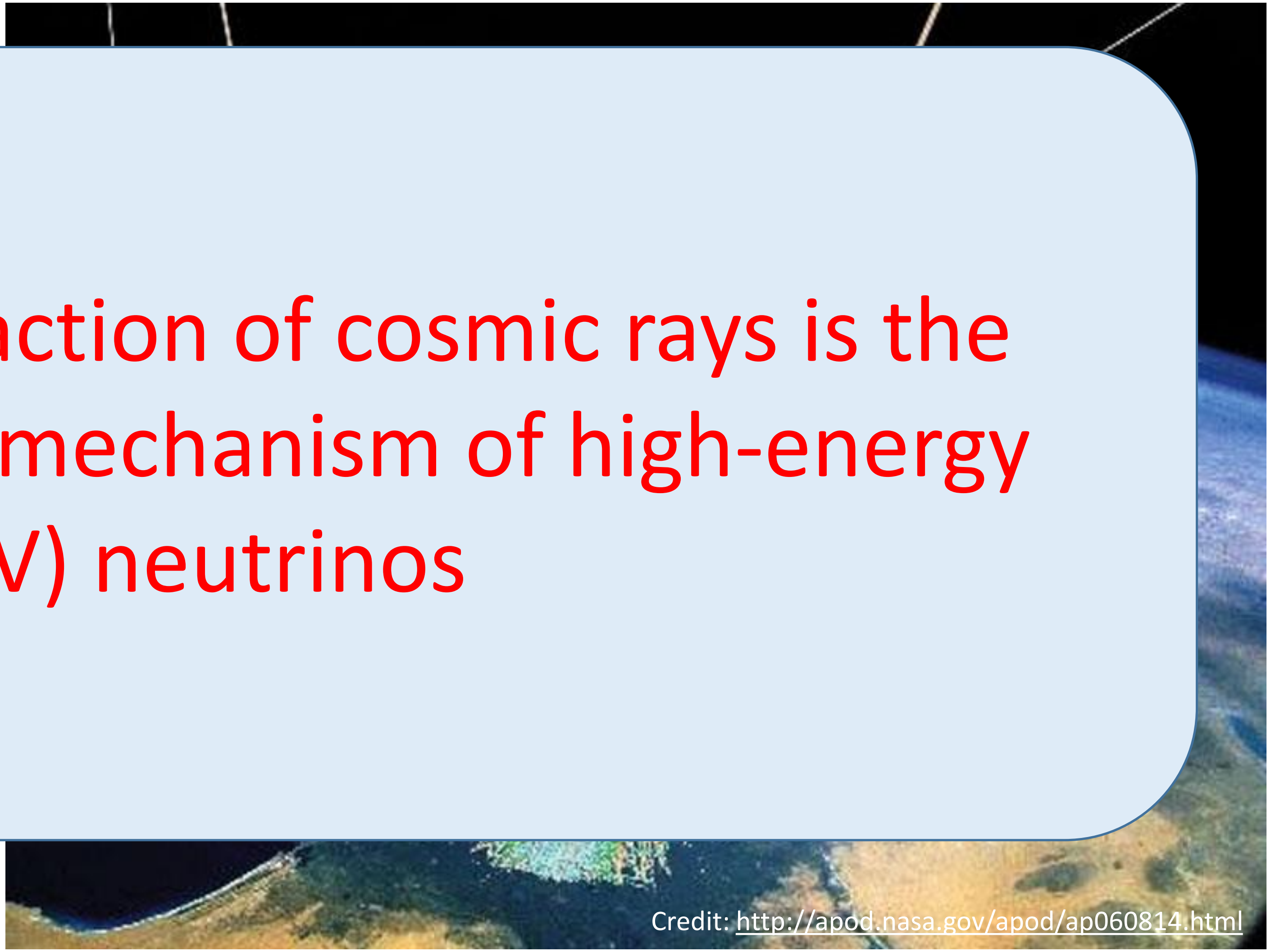


Fig. from Evoli2018

The hadronic interaction of cosmic rays is the leading production mechanism of high-energy (>GeV) neutrinos



Cosmic Rays

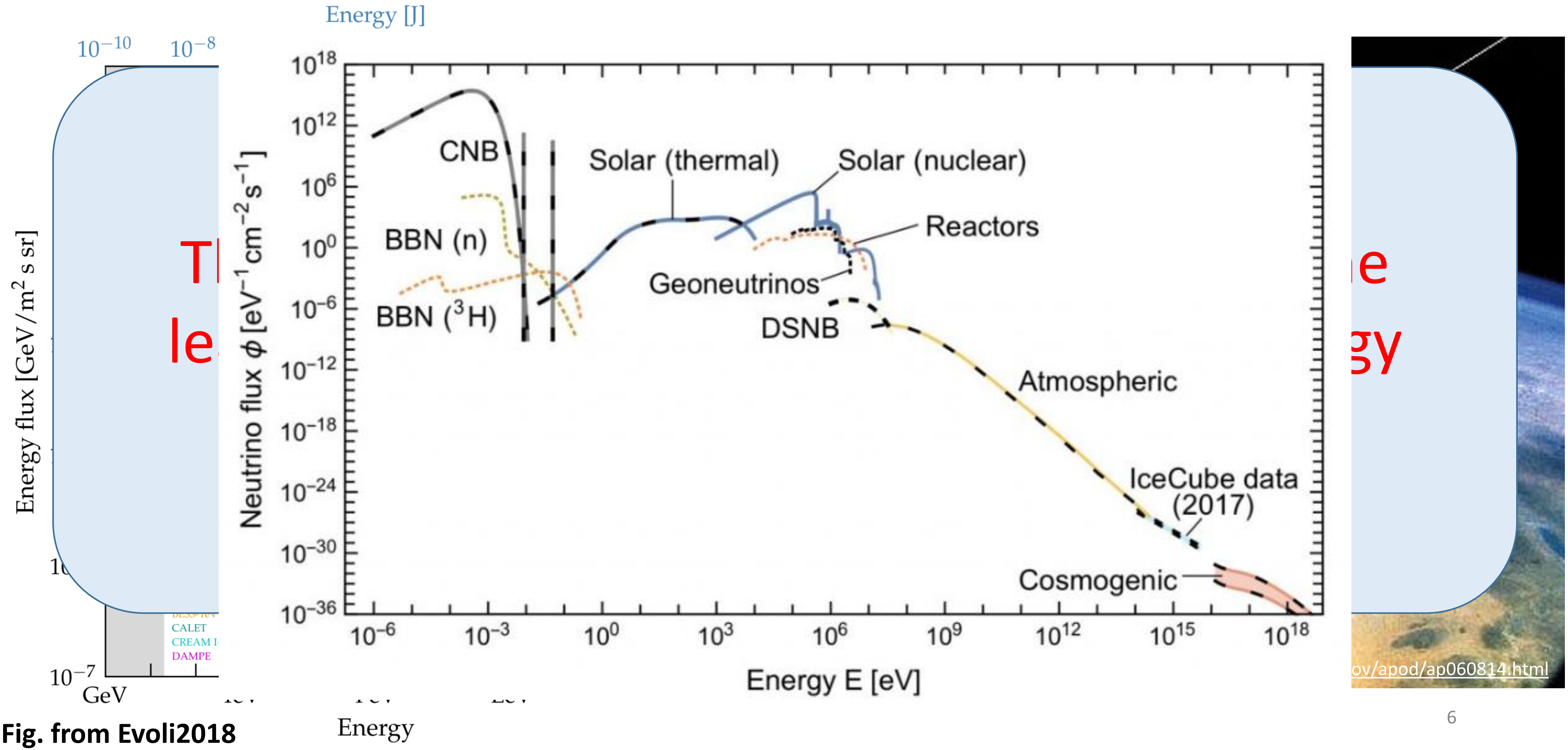


Fig. from Evoli2018

Cosmic Rays

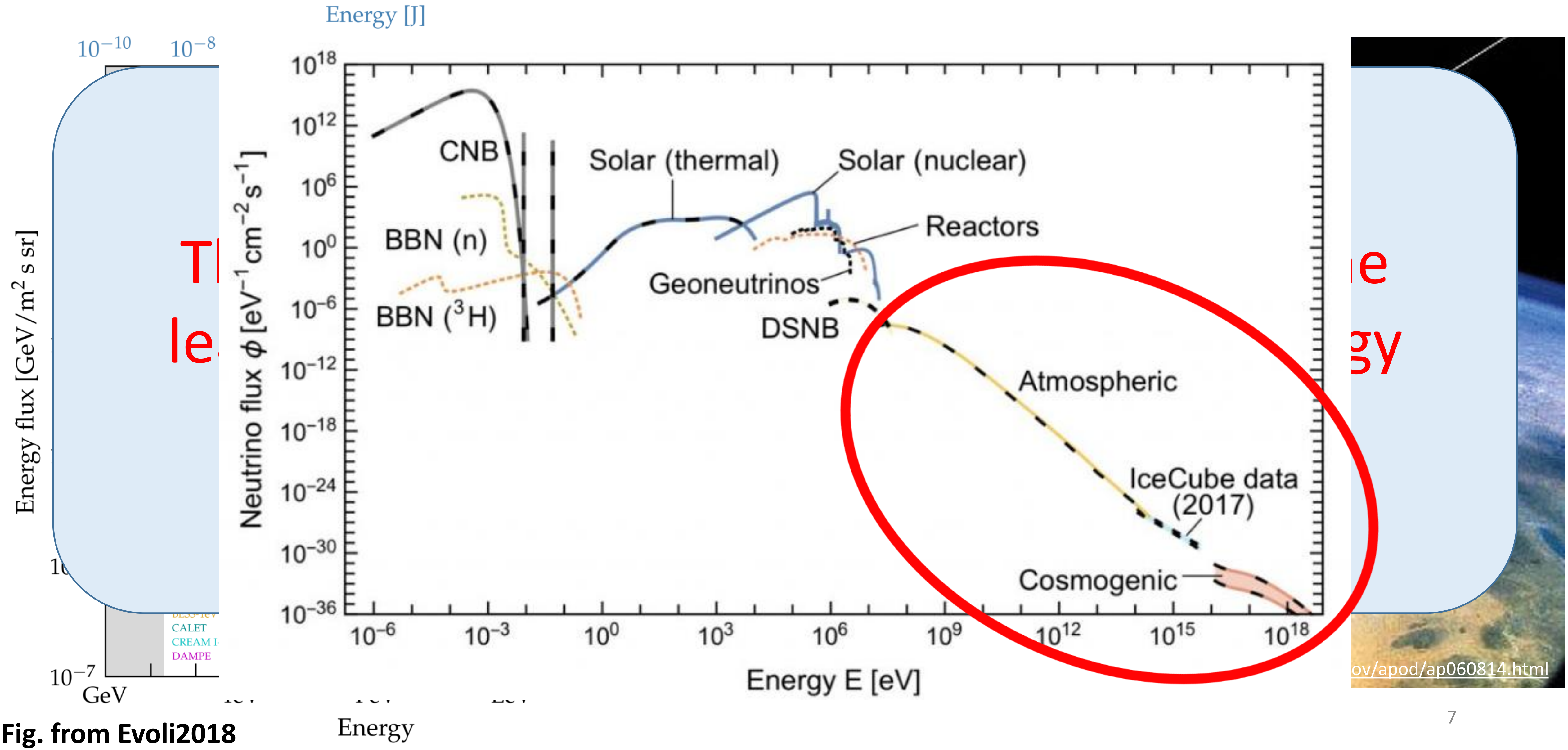
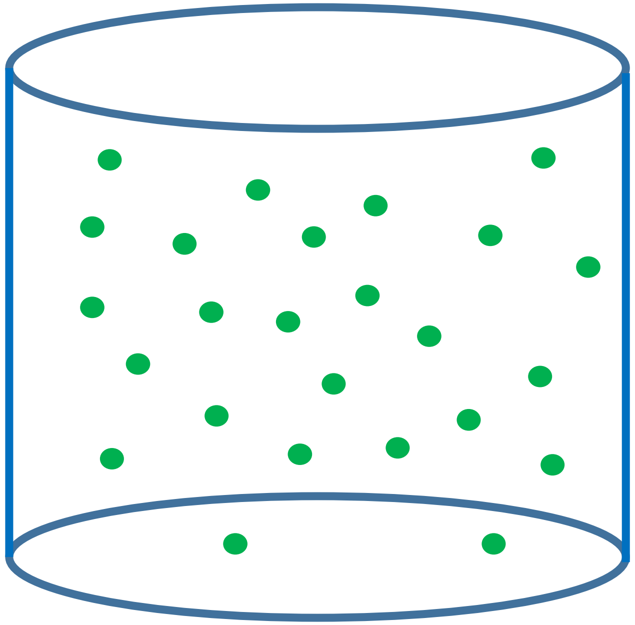


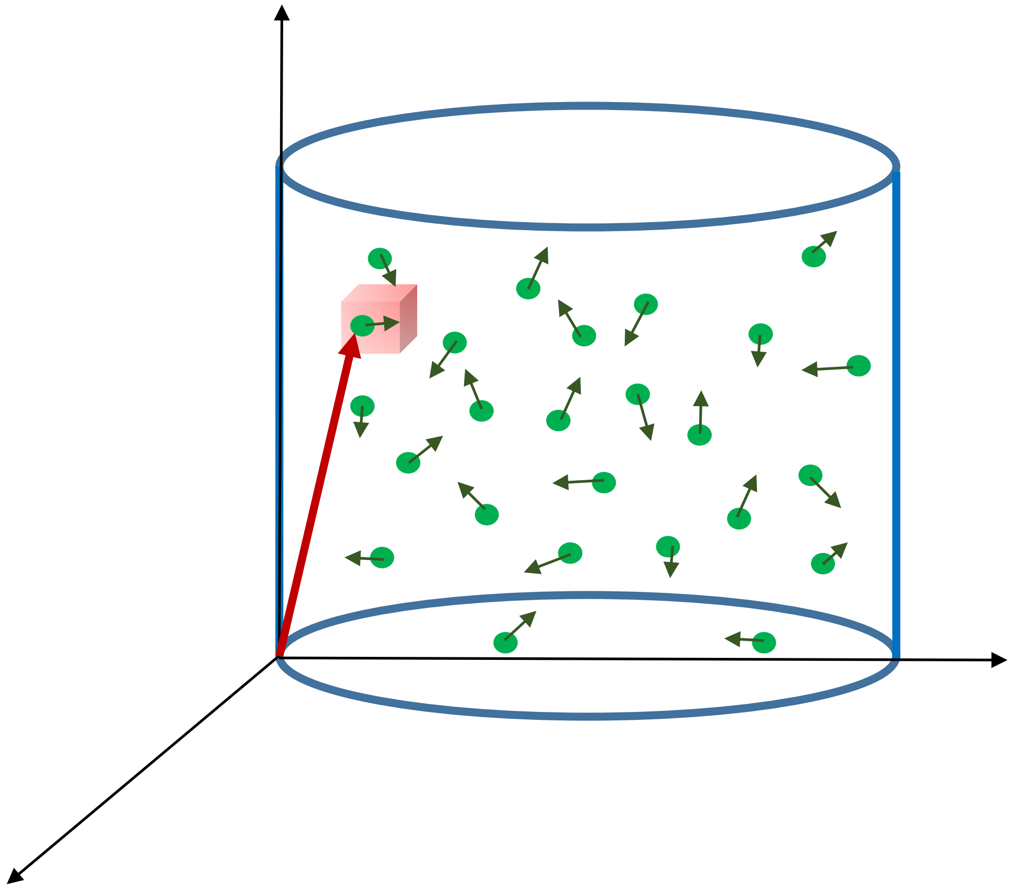
Fig. from Evoli2018

Transport equation of Cosmic Rays



Transport equation of Cosmic Rays

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



Transport equation of Cosmic Rays

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

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

Transport equation of Cosmic Rays

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

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

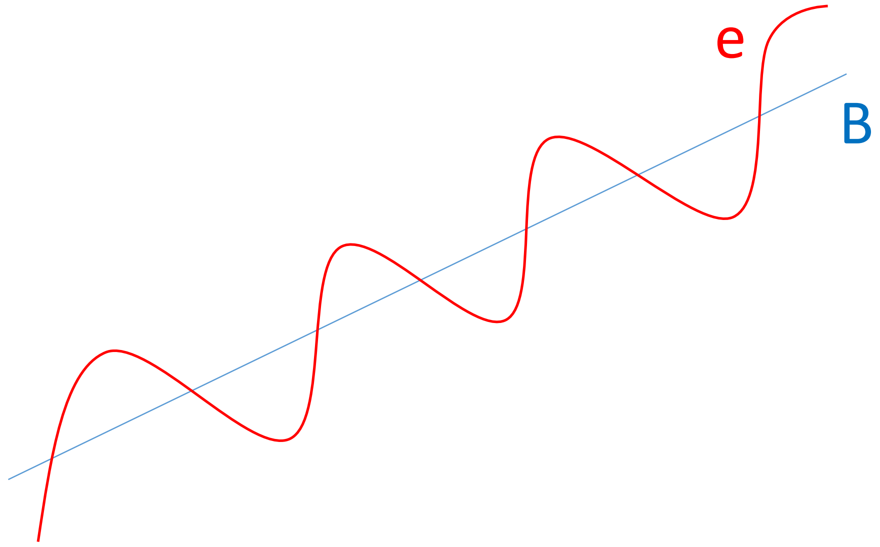
Topic of the upcoming slides

Transport equation of Cosmic Rays

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

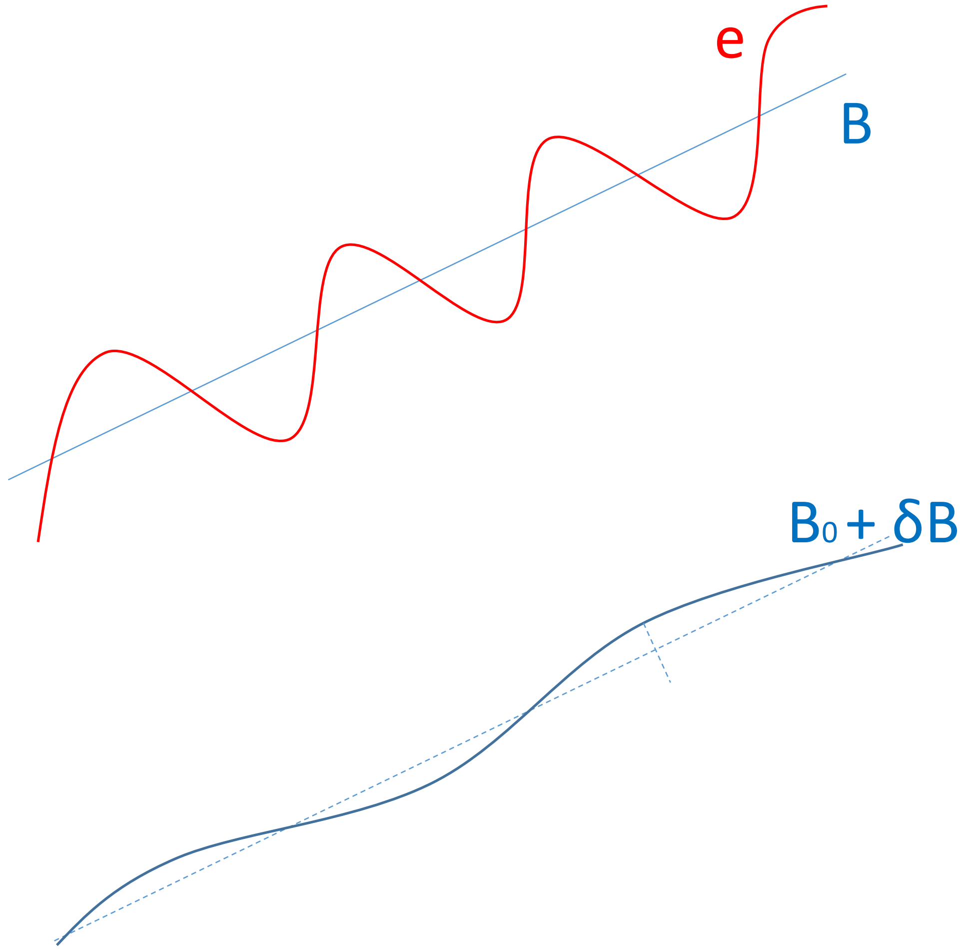
$$Time\ evolution = Injection + diff. + adv. + adb. + loss.$$

Physics of cosmic rays: Diffusion - 1



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

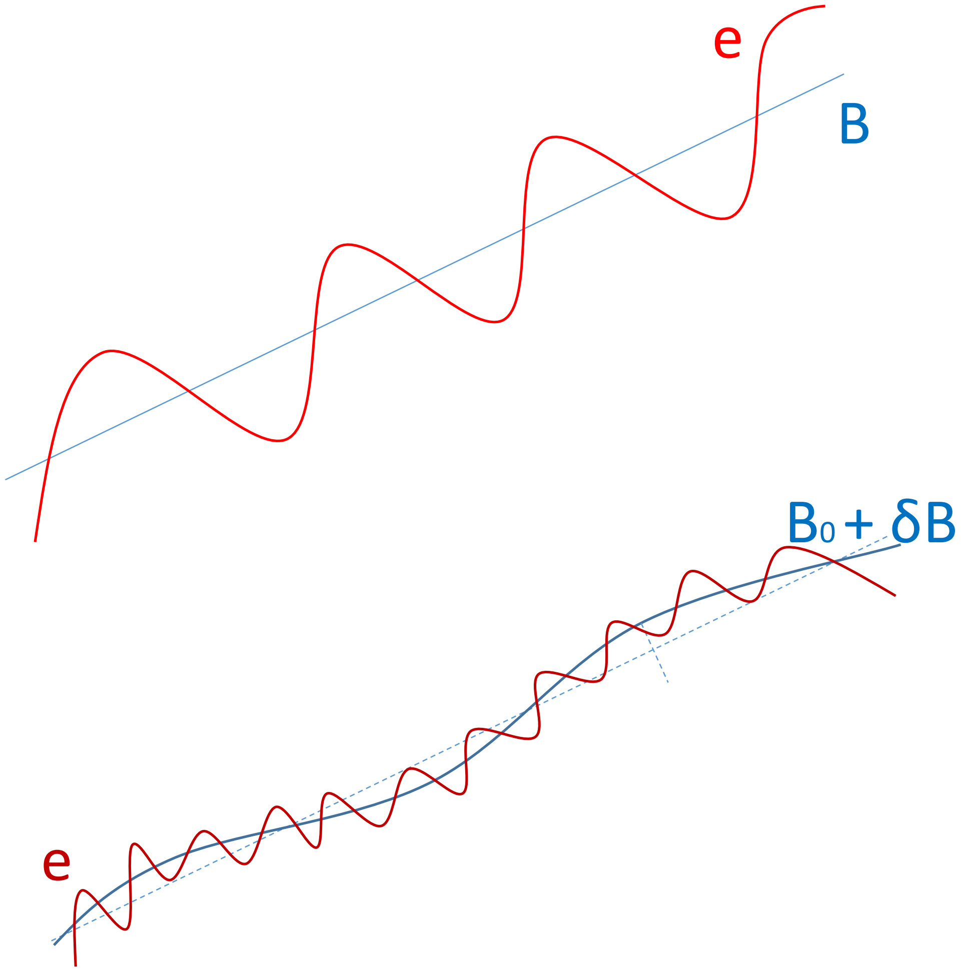
Physics of cosmic rays: Diffusion - 1



- The ISM is a turbulent plasma

- The magnetic field is also turbulent (δB)

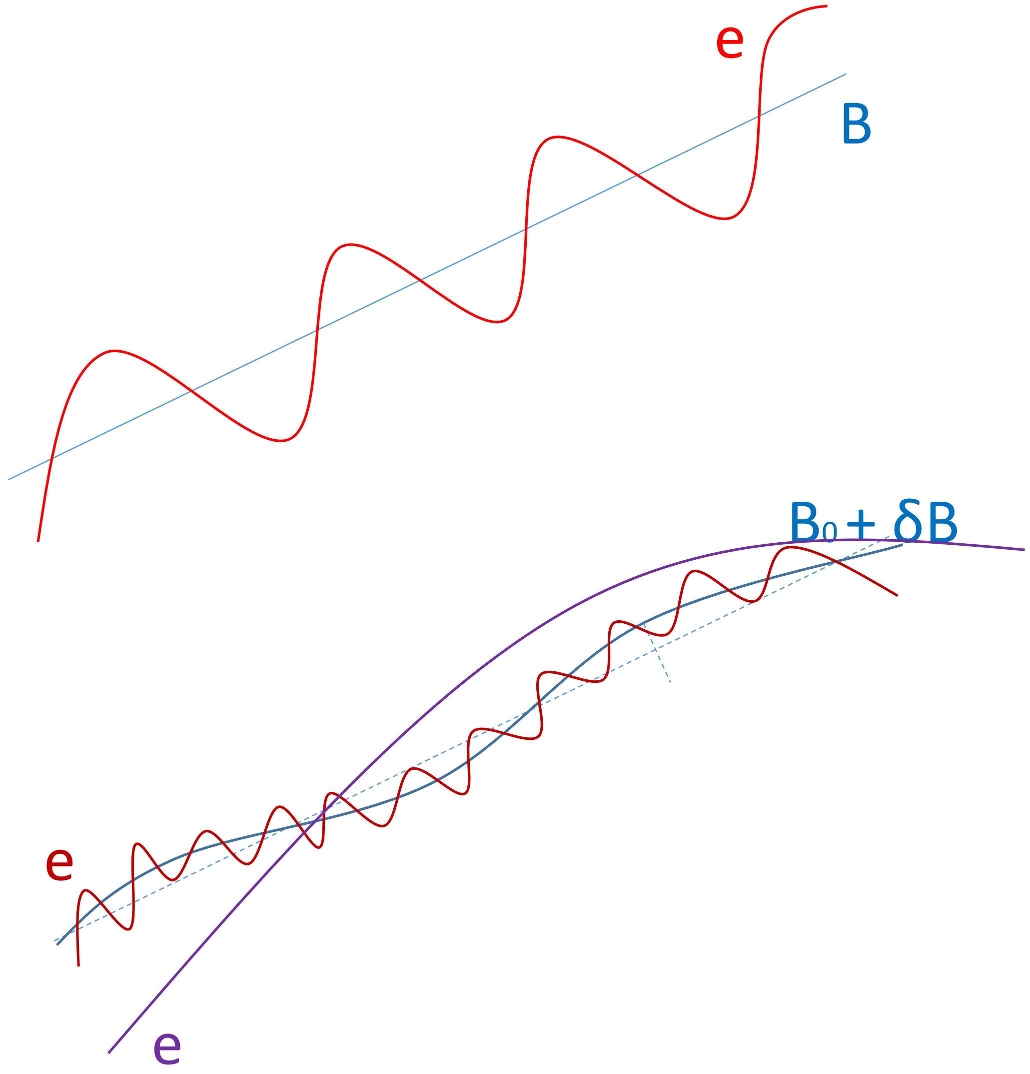
Physics of cosmic rays: Diffusion - 1



- The ISM is a turbulent plasma

- The magnetic field is also turbulent (δB)

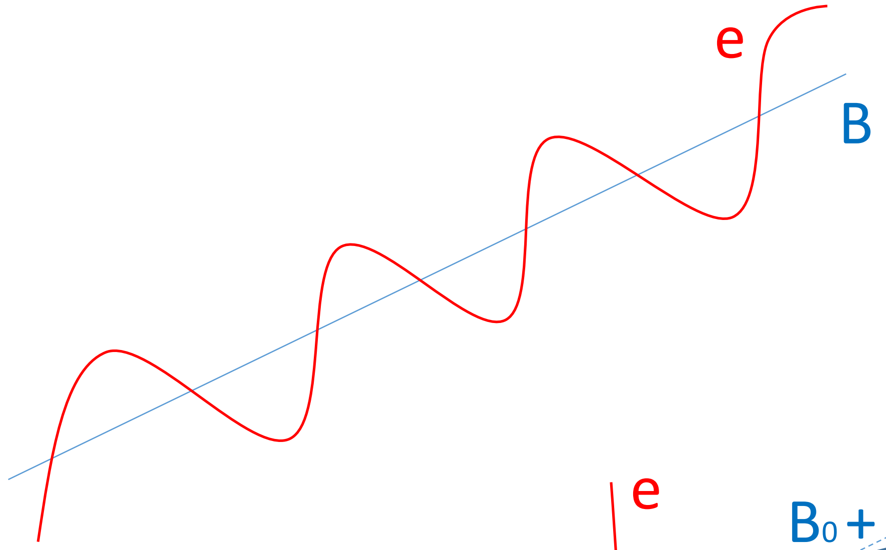
Physics of cosmic rays: Diffusion - 1

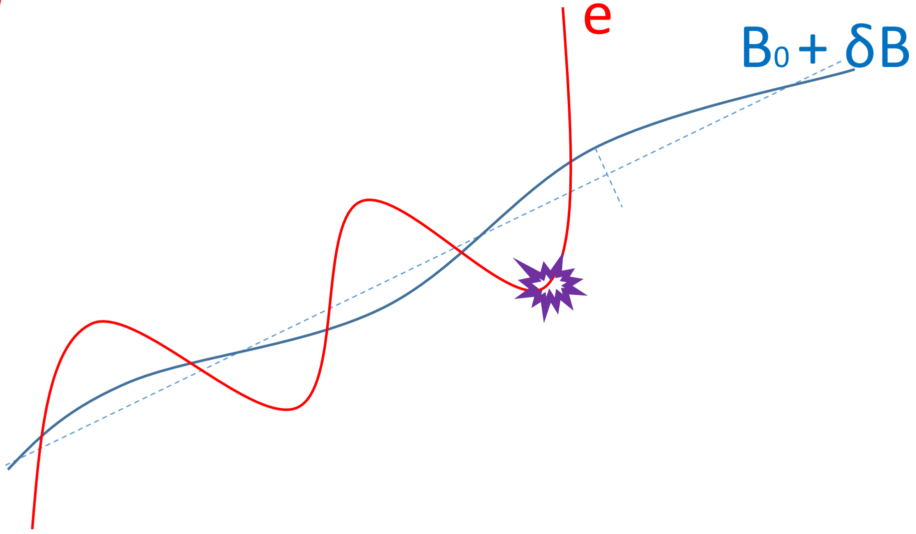


- The ISM is a turbulent plasma

- The magnetic field is also turbulent (δB)

Physics of cosmic rays: Diffusion - 1

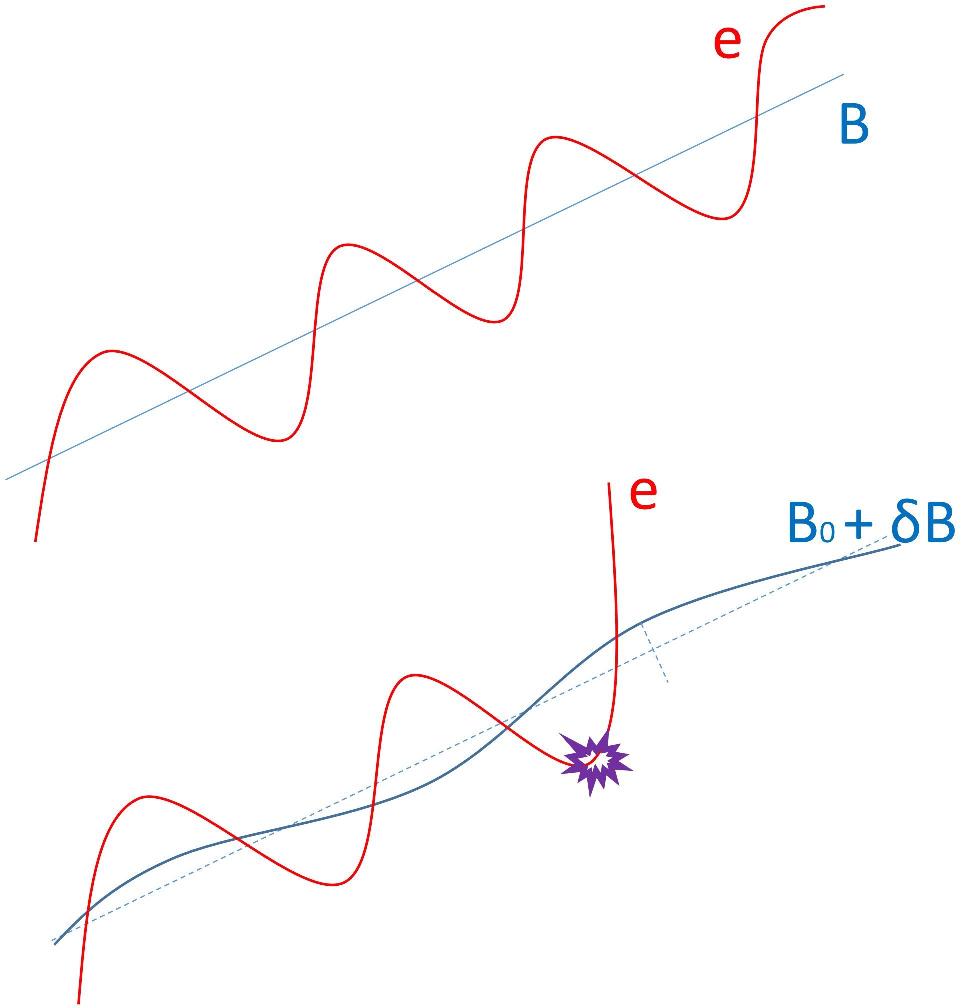




- The ISM is a turbulent plasma
- The magnetic field is also turbulent (δB)
- Particles pitch angle evolves in time when in presence of magnetic field disturbances

Helical motion→ Spatial diffusion

Physics of cosmic rays: Diffusion - 1

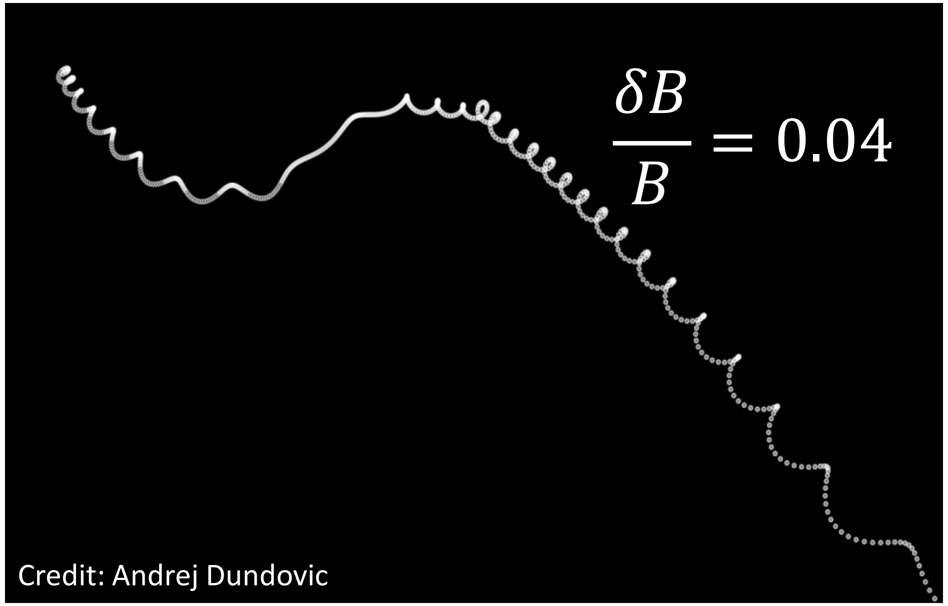


- The ISM is a turbulent plasma
- The magnetic field is also turbulent (δB)
- Particles pitch angle evolves in time when in presence of magnetic field disturbances

Helical motion→ Spatial diffusion

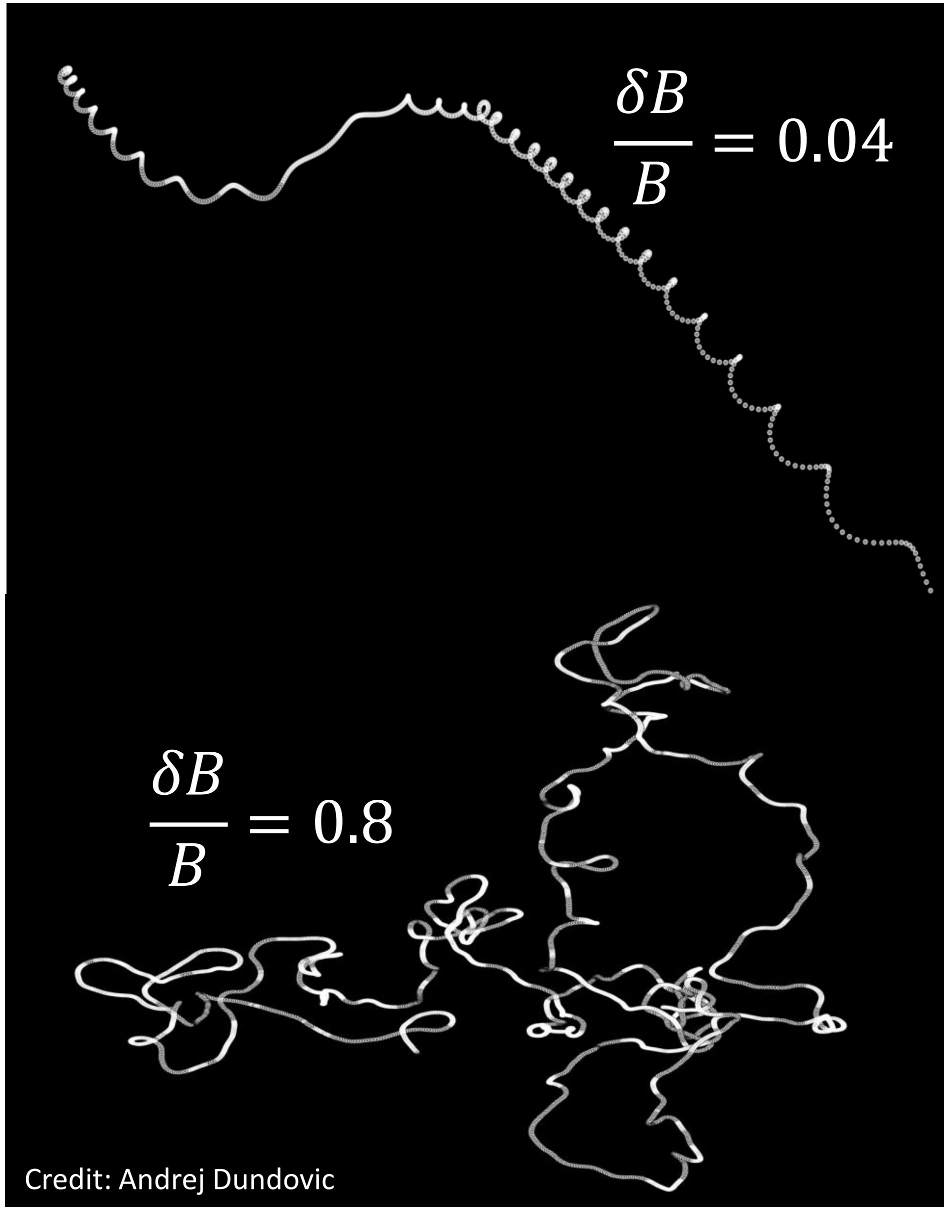
- Diffusion tensor/coefficient: $D(\vec{x}, \vec{p})$

Physics of cosmic rays: Diffusion - 2



- Low turbulence environment allows to observe standard helical motions

Physics of cosmic rays: Diffusion - 2



- Low turbulence environment allows to observe standard helical motions

- When the turbulence is strong the motion of particles from helicoidal becomes diffusive

$$\tau_{diff} \approx \frac{H^2}{D(E)}$$

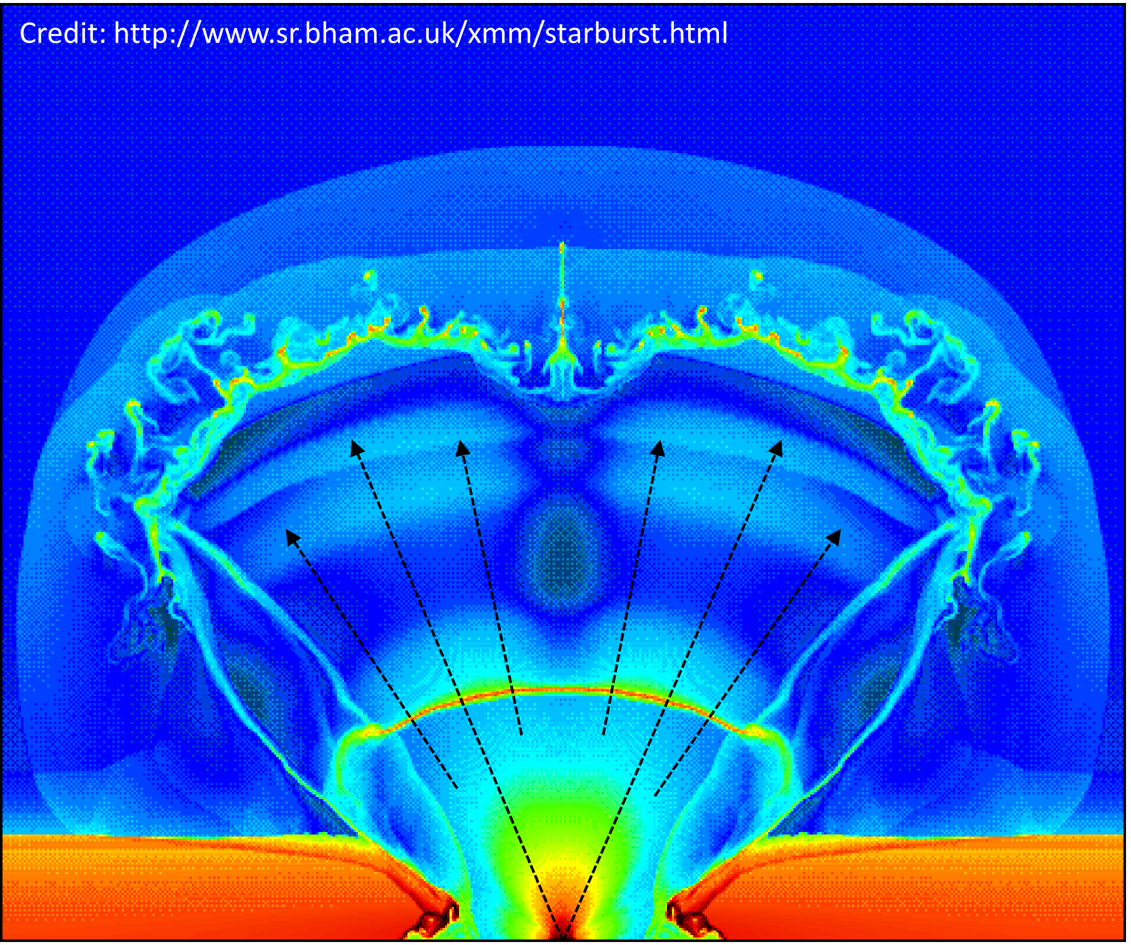
Jokipii1966, Blandford+1987, Blasi2013, Snodin+2016, Subedi+2017, Dundovic+2020, Kuhlen+2022

Transport equation of Cosmic Rays

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

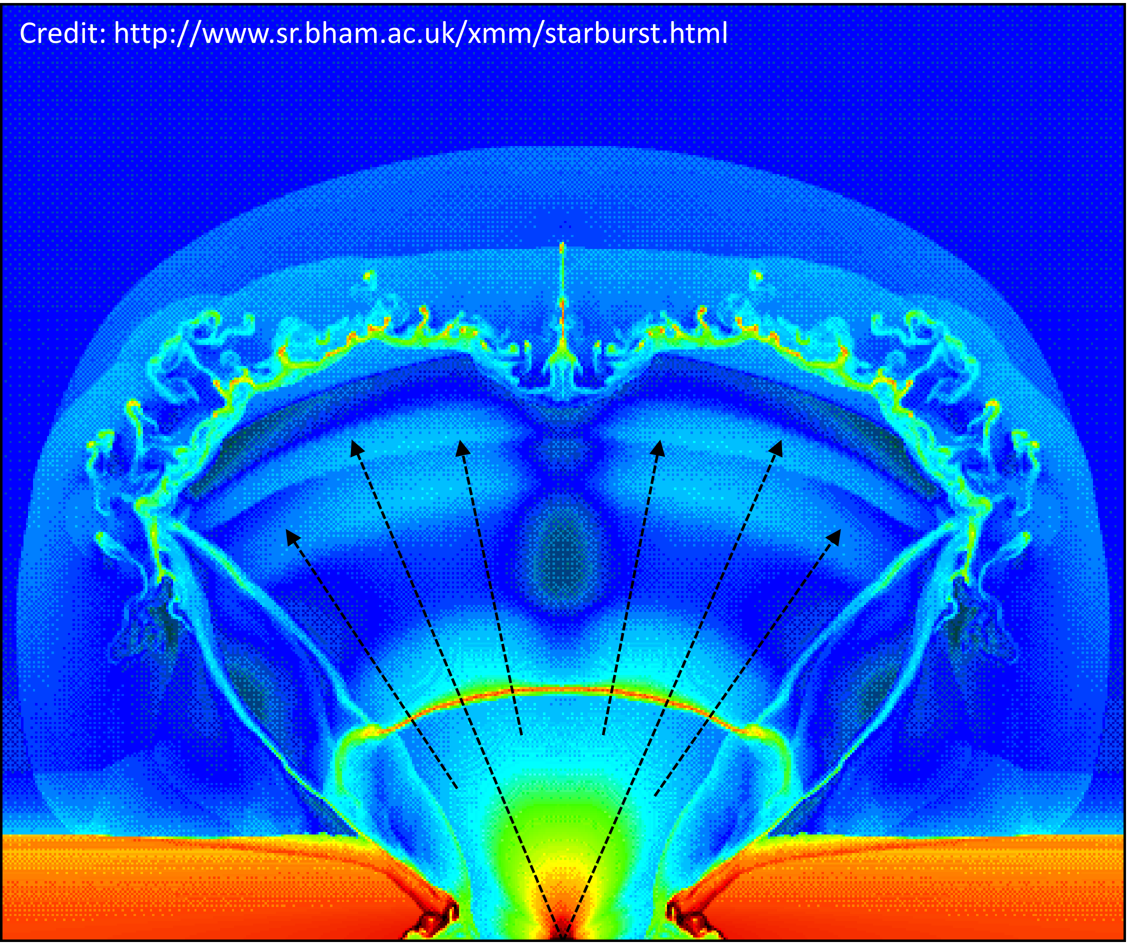
$$Time\ evolution = \ Injection + diff. + adv. + adb. + loss.$$

Physics of cosmic rays: Advection and Adbiabatic losses



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

Physics of cosmic rays: Advection and Adbiabatic losses

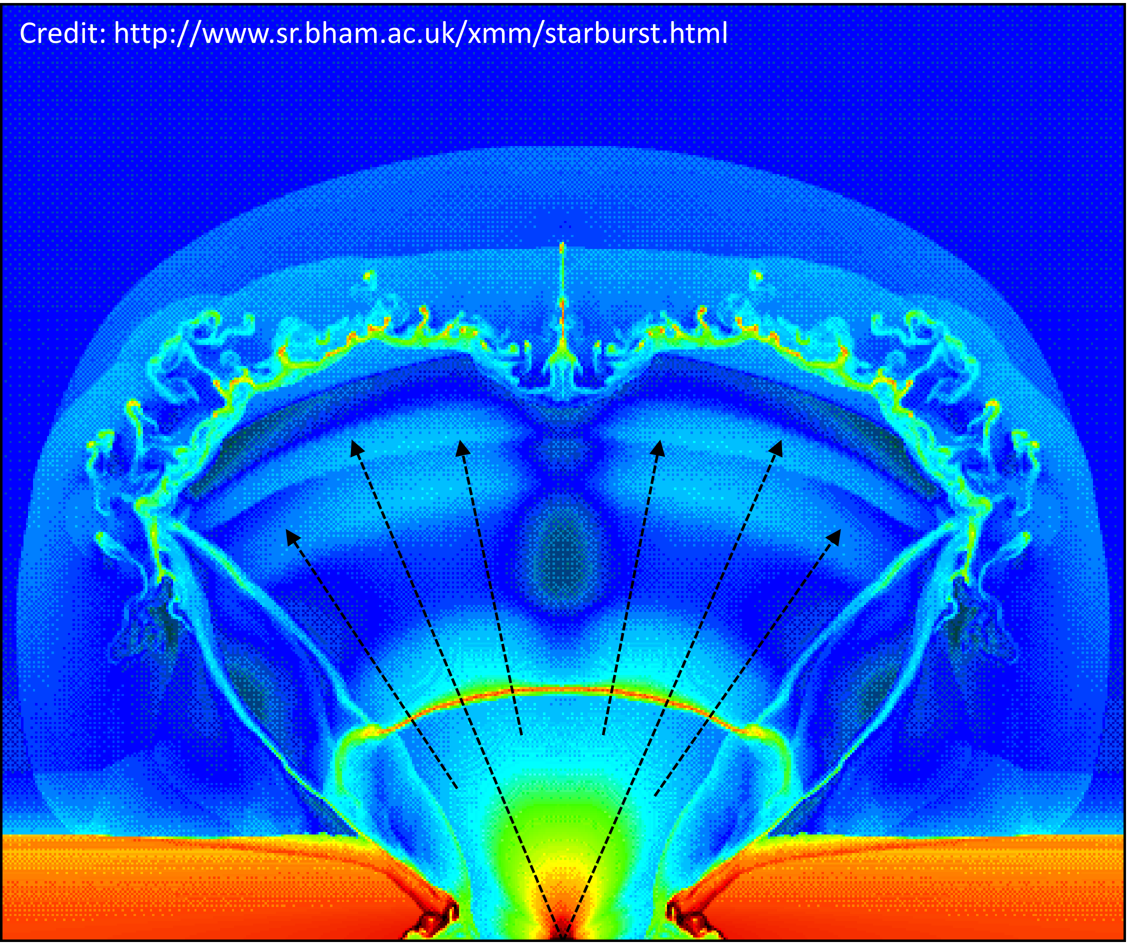


- The interstellar medium (ISM) can be characterized by large scale bulk motions

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

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

Physics of cosmic rays: Advection and Adbiabatic losses



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

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

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

- CRs can lose or gain energy adiabatically

Transport equation of Cosmic Rays

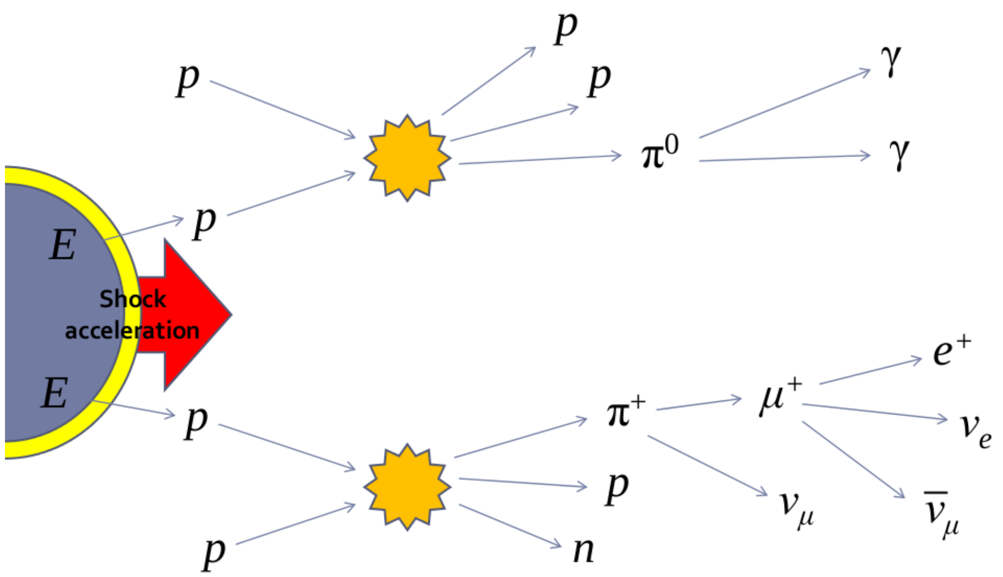
- Cosmic rays → phase space density → $f(t, \vec{x}, \vec{p}) = \frac{dN}{dV \cdot d^3p}$

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

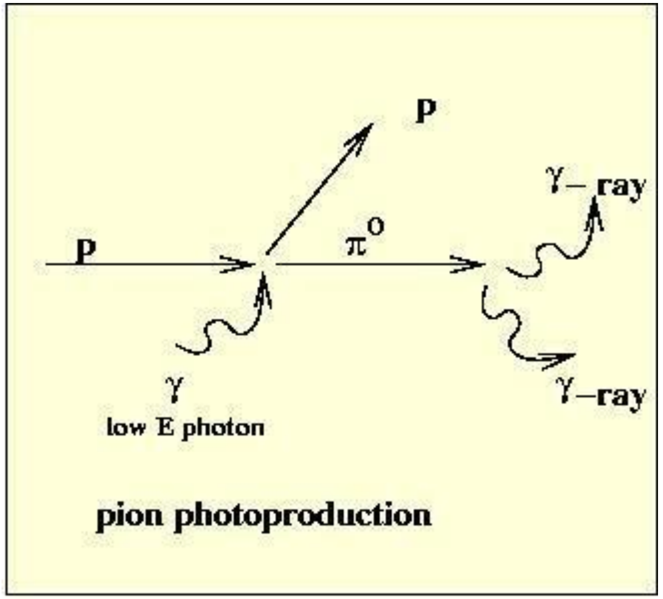
Transport equation of Cosmic Rays

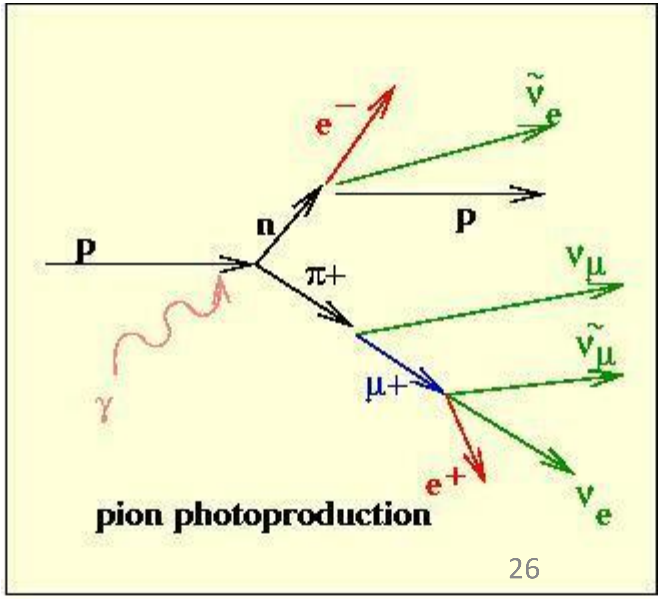
- Cosmic rays → phase space density → $f(t,\vec{x},\vec{p}) = \frac{dN}{dV \cdot d^3p}$

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



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





Website: https://www.uibk.ac.at/projects/he-cosmic-sources/tools/sophia/index.html.en

Transport equation of Cosmic Rays

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

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

Transport equation of Cosmic Rays

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

$$\frac{\partial f}{\partial t} = Q + \nabla \cdot [D \nabla f] - \vec{u} \cdot \nabla f + \frac{\nabla \cdot \vec{u}}{3} p \frac{\partial f}{\partial p} - L$$

Transport equation of Cosmic Rays

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

$$\frac{\partial f}{\partial t} = Q + \nabla \cdot [D \nabla f] - \vec{u} \cdot \nabla f + \frac{\nabla \cdot \vec{u}}{3} p \frac{\partial f}{\partial p} - L$$

- When the transport is stationary, homogeneous and isotropic:

Transport equation of Cosmic Rays

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

$$\frac{\partial f}{\partial t} = Q + \nabla \cdot [D \nabla f] - \vec{u} \cdot \nabla f + \frac{\nabla \cdot \vec{u}}{3} p \frac{\partial f}{\partial p} - L$$

- When the transport is stationary, homogeneous and isotropic:

Transport equation of Cosmic Rays

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

$$\frac{\partial f}{\partial t} = Q + \nabla \cdot [D \nabla f] - \vec{u} \cdot \nabla f + \frac{\nabla \cdot \vec{u}}{3} p \frac{\partial f}{\partial p} - L$$

- When the transport is stationary, homogeneous and isotropic:

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

Outline

- Transport equation of Cosmic Rays
- Transport approach to diffusive shock acceleration
- Wind blown bubbles
- Modeling acceleration and multi-messenger radiation

Diffusive Shock Acceleration

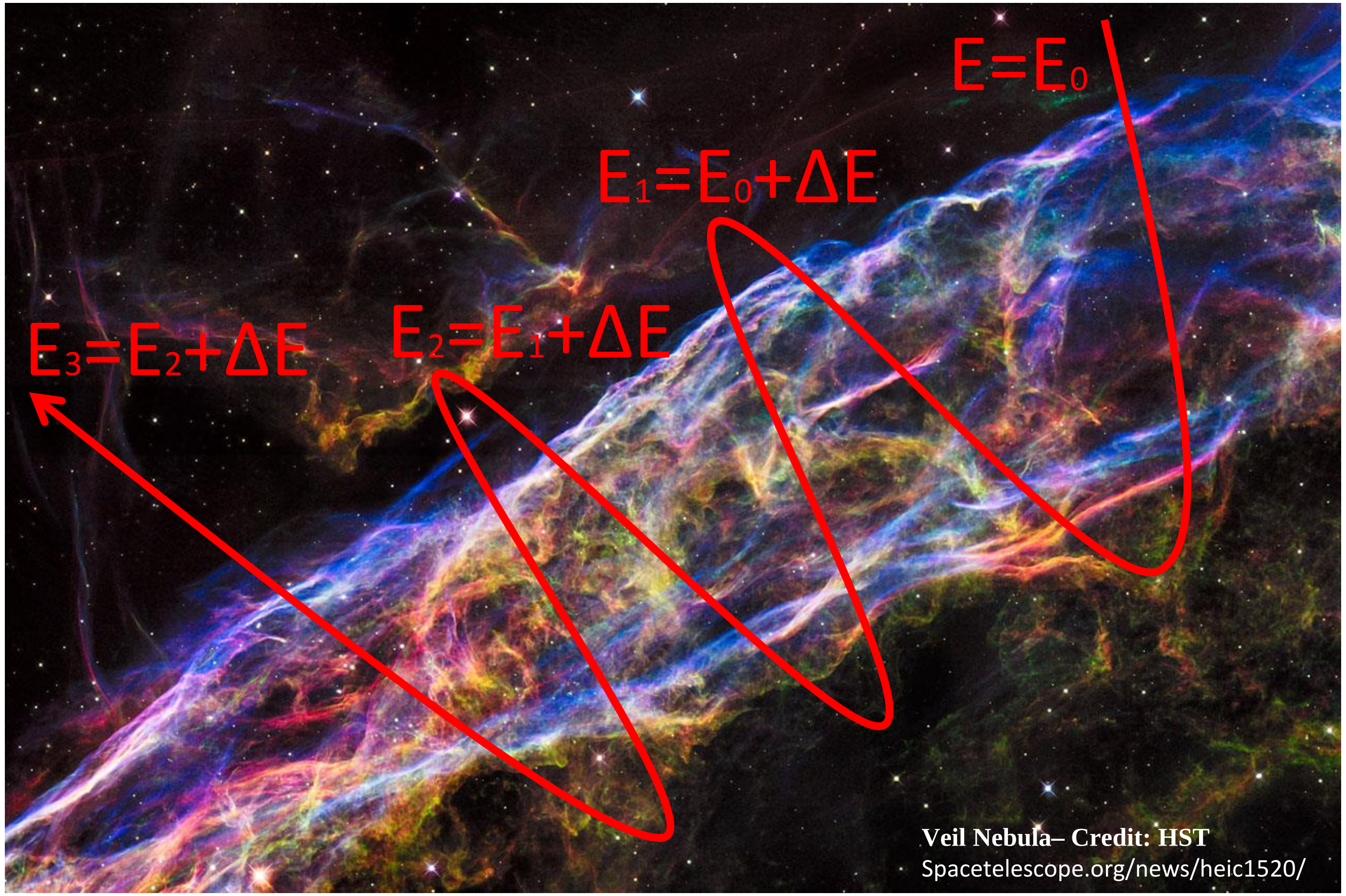
- Shocks are the result of explosions or motion of supersonic flows → very common in astrophysical environments

Diffusive Shock Acceleration

- Shocks are the result of explosions or motion of supersonic flows → very common in astrophysical environments

- One of the most simple and efficient first order Fermi mechanism we know in Nature

Diffusive Shock Acceleration



- Shocks are the result of explosions or motion of supersonic flows → very common in astrophysical environments

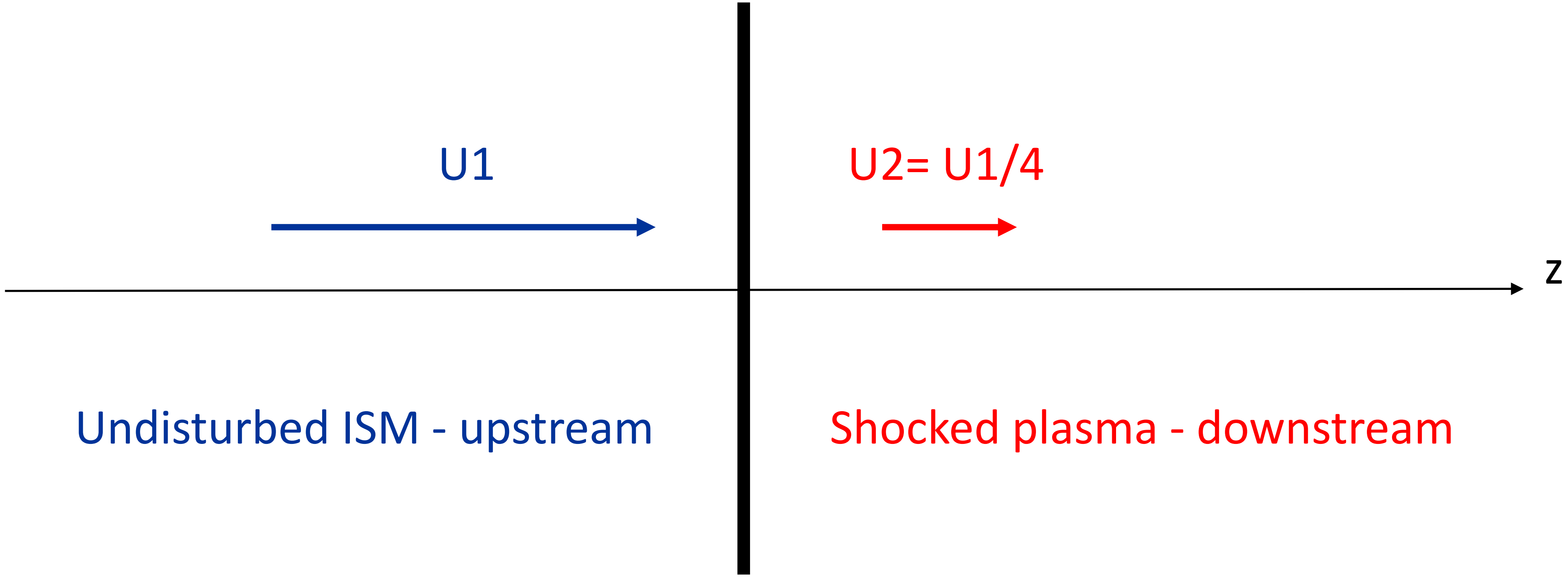
- One of the most simple and efficient first order Fermi mechanism we know in Nature

- Particles diffuse across shock waves gaining energy at each cycle

$$\Delta E/E \propto \beta_{sh}$$

Transport approach to DSA

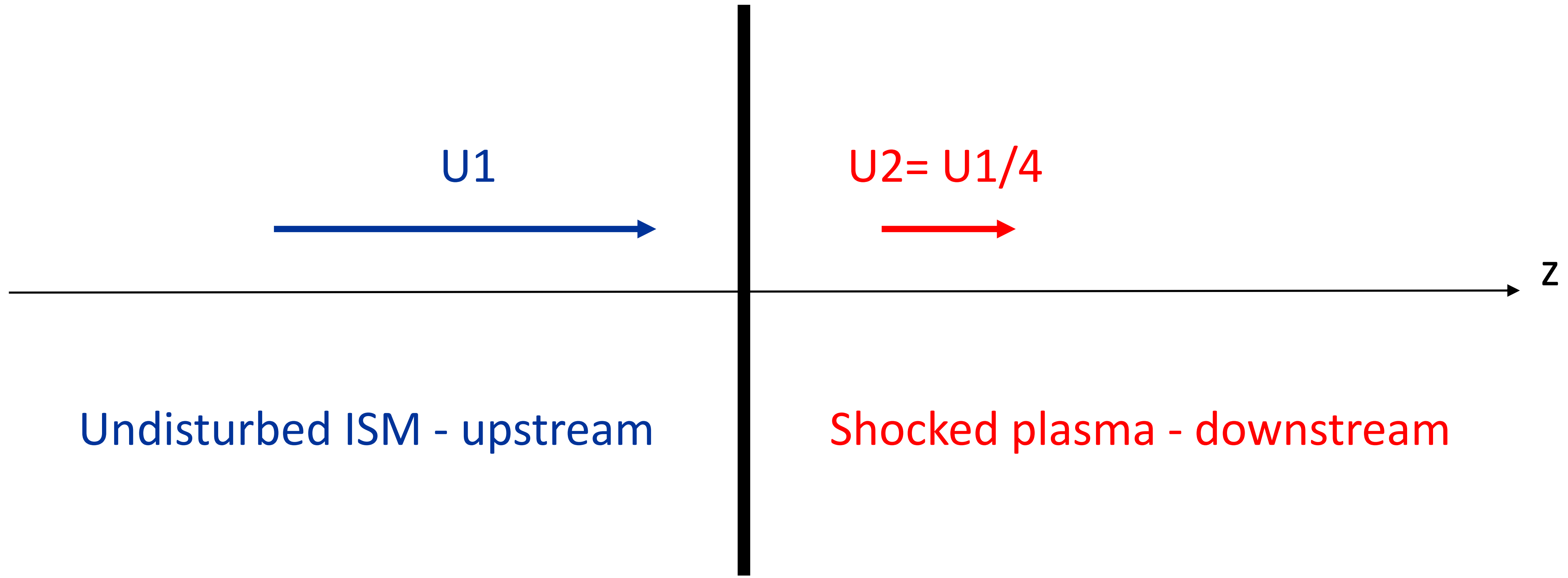
$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial z} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] + \frac{1}{3}\frac{\partial v}{\partial z}p\frac{\partial f}{\partial p} + Q - \frac{f}{\tau_{loss}}$$



Transport approach to DSA

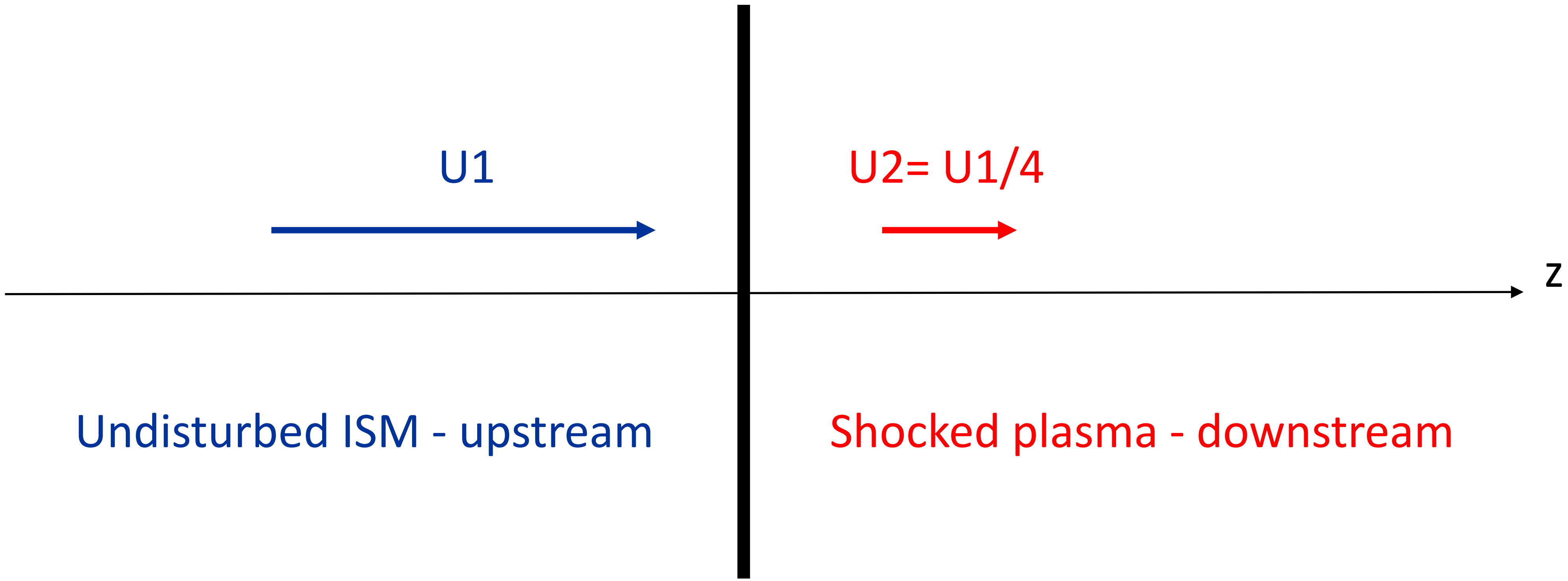
STATIONARY NEGLIGIBLE

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



Boundary conditions

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



Boundary conditions

Far upstream the particle distribution function as well as the associated flux are negligible

z

Undisturb

vnstream

Boundary conditions

$$f(-\infty) = \partial_z f|_{-\infty} = 0$$

The strong turbulence homogenizes the particle distribution function in the downstream region

z

Undisturb

vnstream

Boundary conditions

$$f(-\infty) = \partial_z f|_{-\infty} = 0$$

$$\partial_z f|_{z>0} = 0$$

The injection of high energy particles takes place only at the shock

z

Undisturb

vnstream

Boundary conditions

$$f(-\infty) = \partial_z f|_{-\infty} = 0$$

$$\partial_z f|_{z>0} = 0$$

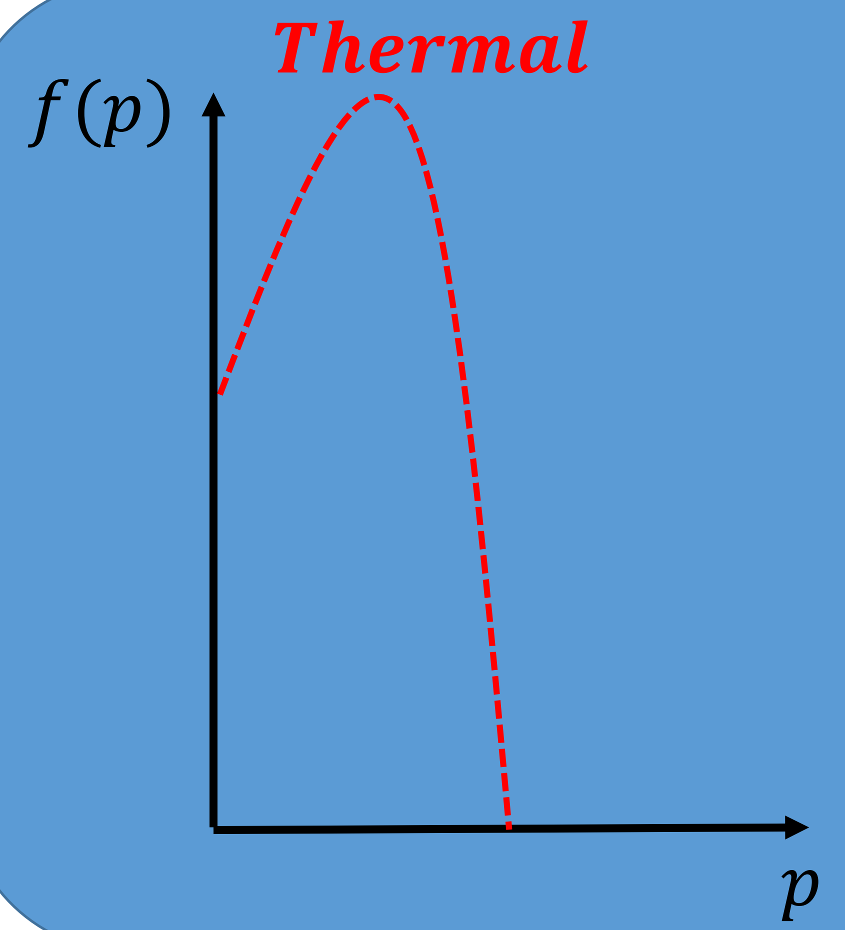
z

Undisturb

$$Q(z,p) = \xi_{CR}\frac{n_1 u_1}{4\pi p^2}\delta[p - p_{inj}]\delta[z]$$

vnstream

Boundary conditions



$f(-\infty) = \partial_z f$

$\partial_z f|_{z>0} =$

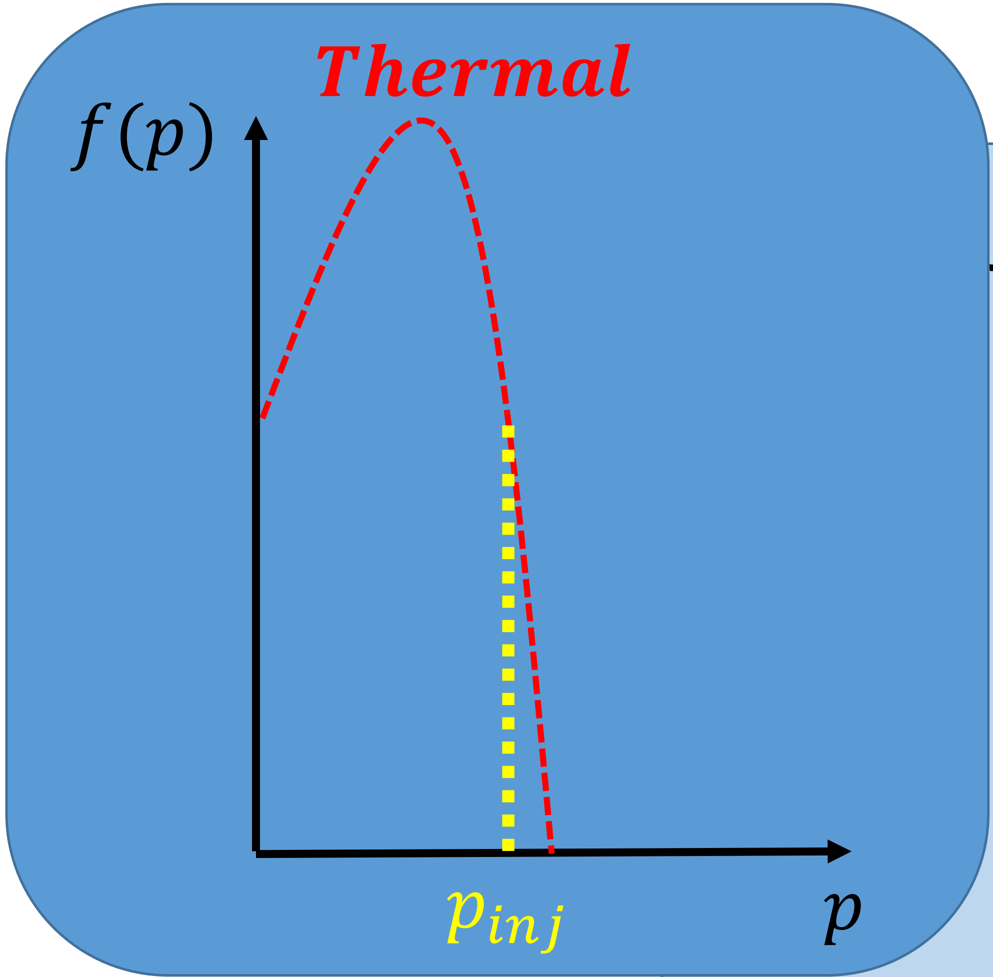
z

Undisturb

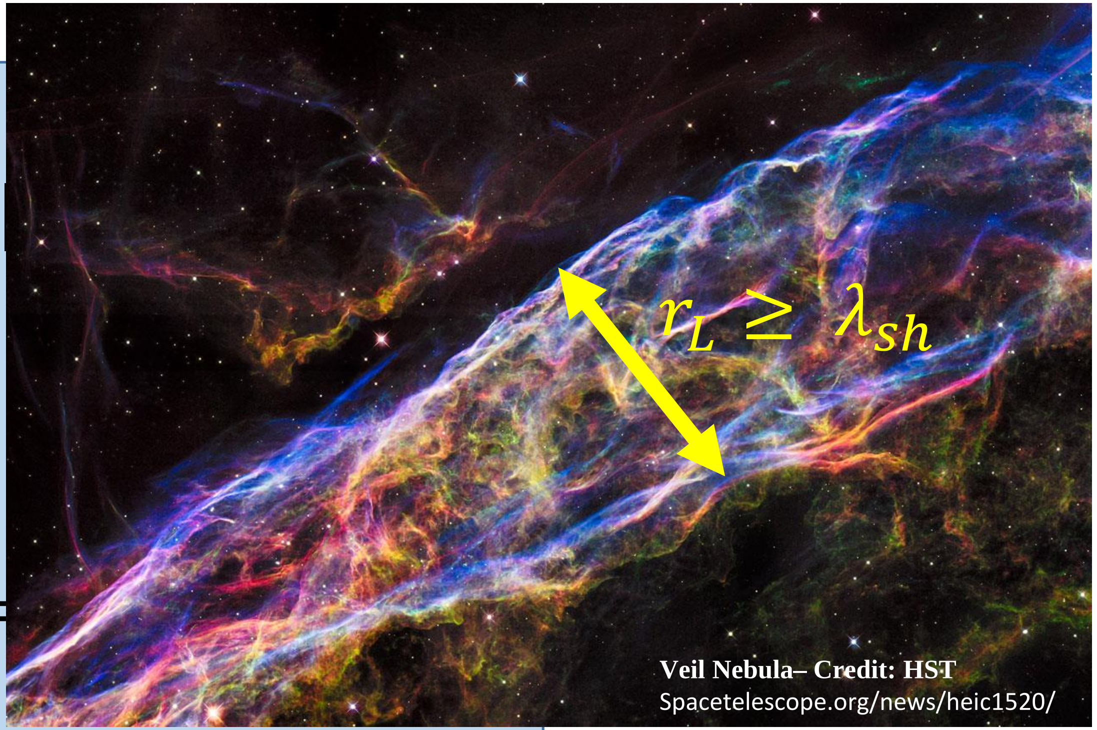
$$Q(z,p) = \xi_{CR} \frac{n_1 u_1}{4\pi p^2} \delta[p - p_{inj}]\delta[z]$$

wnstream

Boundary conditions



$f(-\infty) = \partial_z f$



$\partial_z f|_{z>0} =$

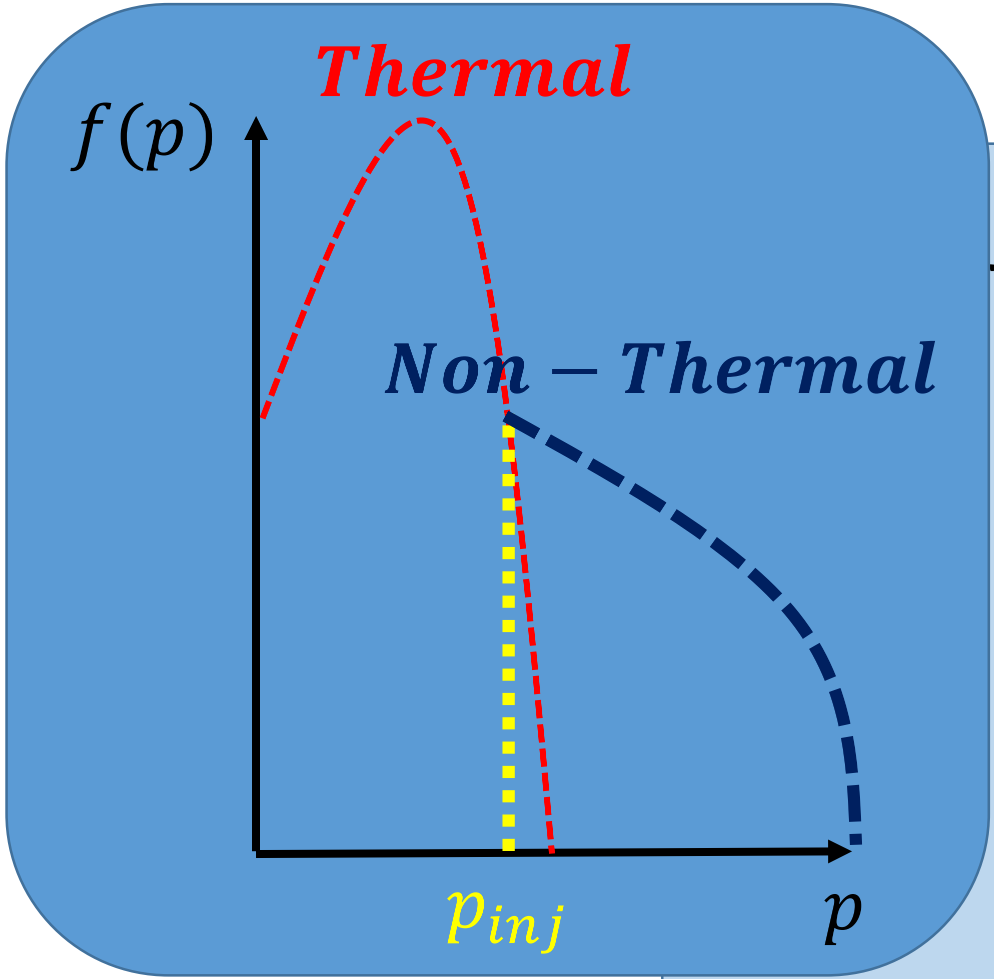
z

Undisturb

vnstream

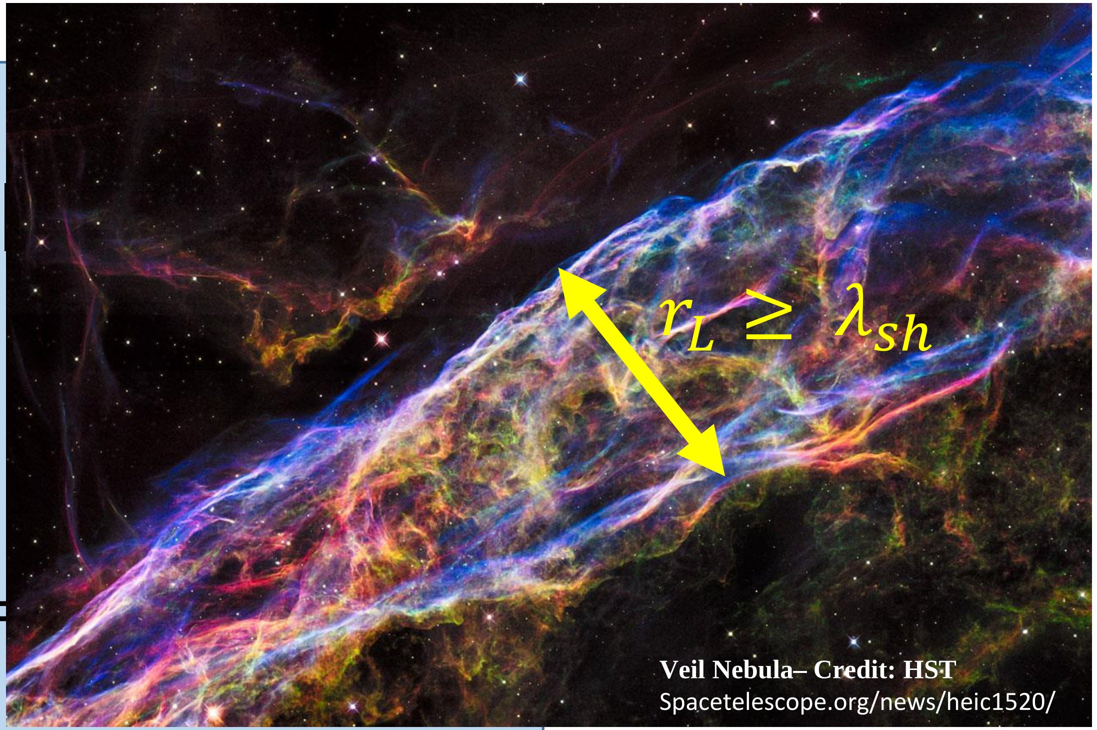
$$Q(z,p) = \xi_{CR} \frac{n_1 u_1}{4\pi p^2} \delta[p - p_{inj}] \delta[z]$$

Boundary conditions



$(-\infty) = \partial_z f$

$\partial_z f|_{z>0} =$



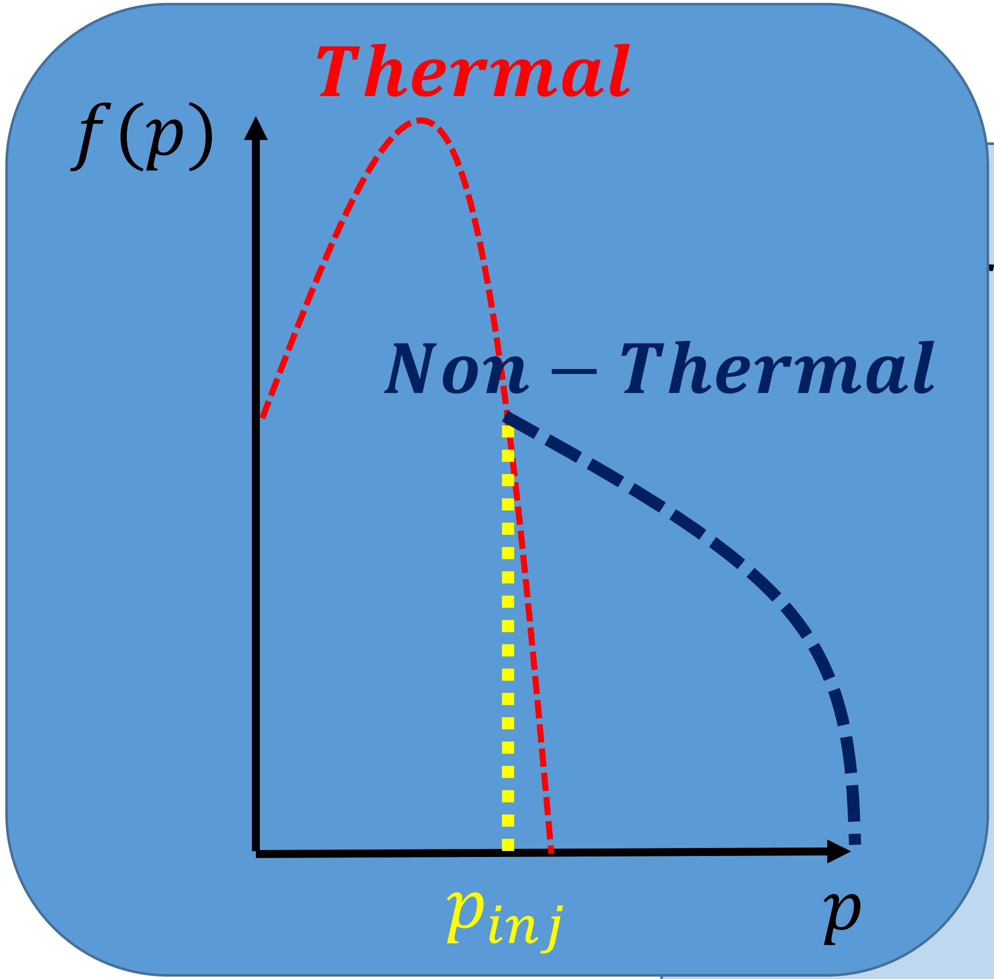
z

Undisturb

vnstream

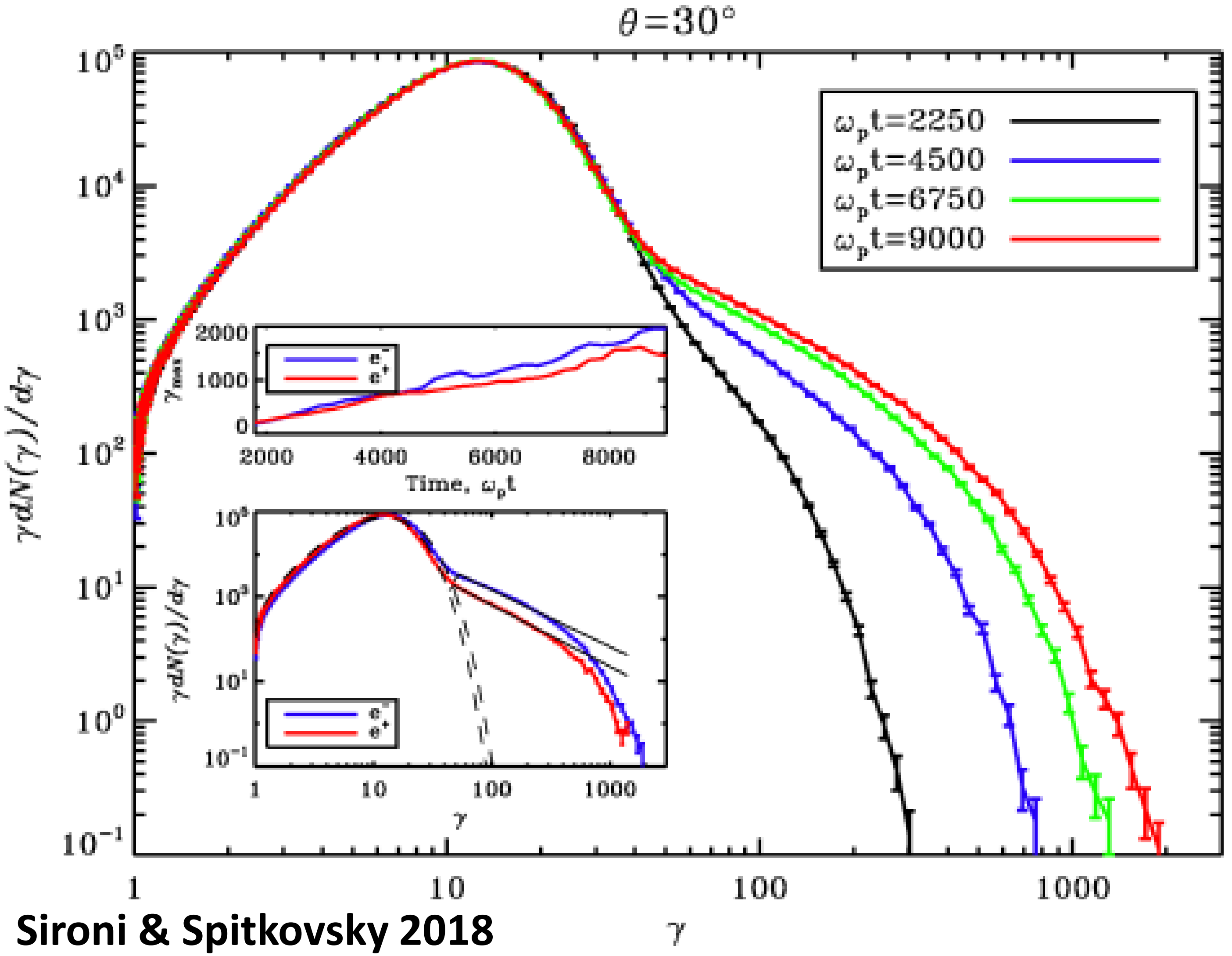
$$Q(z,p) = \xi_{CR} \frac{n_1 u_1}{4\pi p^2} \delta[p - p_{inj}] \delta[z]$$

Boundary conditions



Undisturb

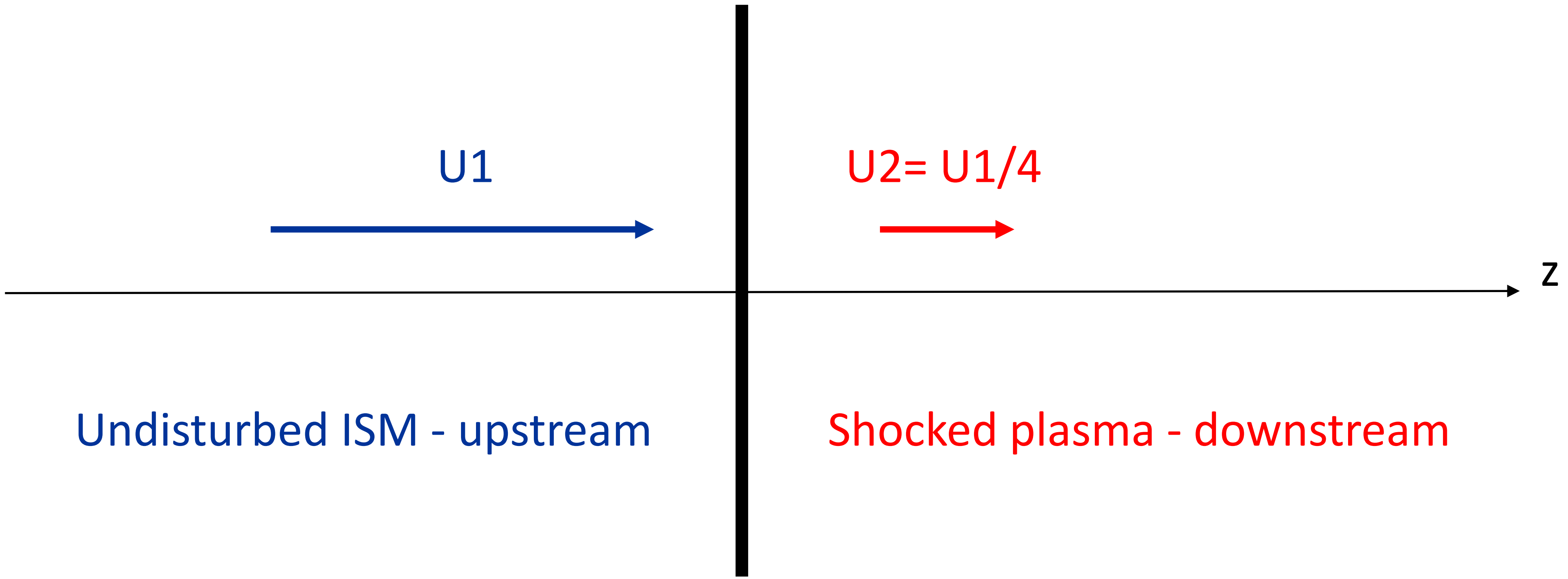
$Q(z,p) =$



Sironi & Spitkovsky 2018

Upstream solution

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



Upstream solution

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

$$\int_{-\infty}^{z} dz'\ T.E. \rightarrow\ \ vf|_{-\infty}^{z} = D\partial_z f|_{-\infty}^{z} + 0 + 0$$

Upstream solution

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

$$\int_{-\infty}^{z}dz'\ T.E.\ \rightarrow\ \ vf|_{-\infty}^{z}=D\partial_z f|_{-\infty}^{z}+0+0$$

$$vf=D\partial_z f$$

Upstream solution

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

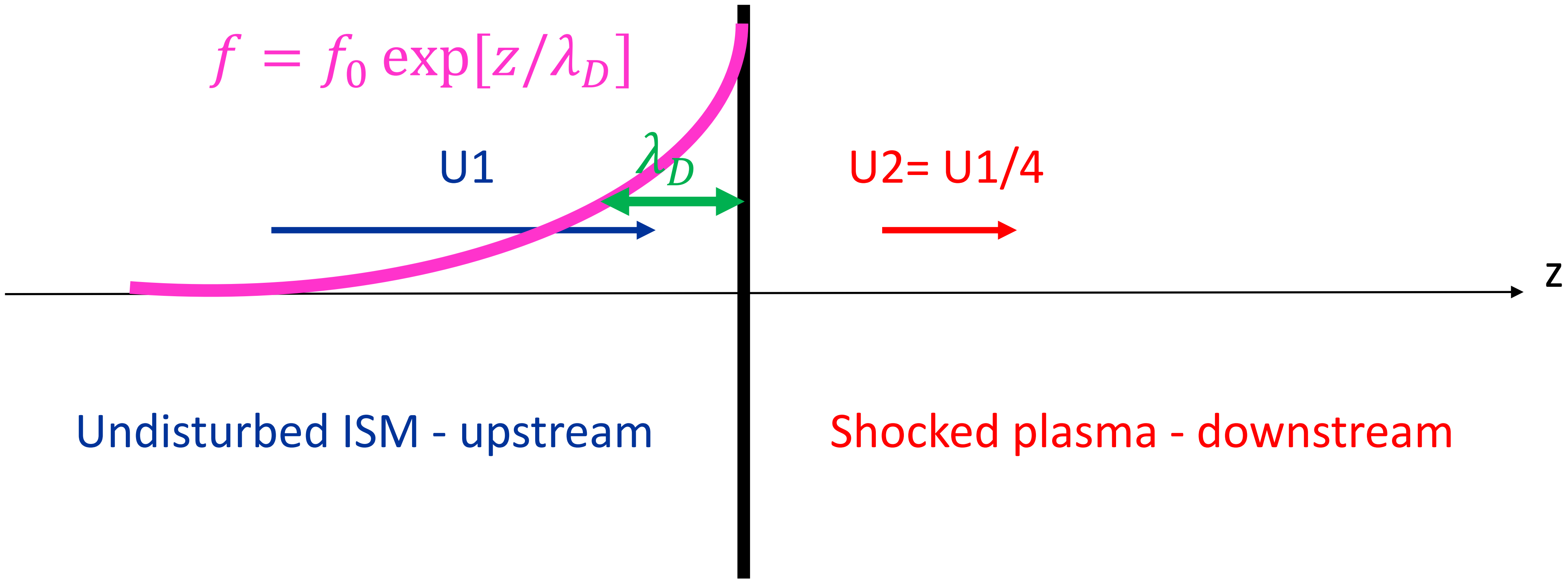
$$\int_{-\infty}^{z} dz' \ T.E. \rightarrow \ \ vf|_{-\infty}^{z} = D\partial_z f|_{-\infty}^{z} + 0 + 0$$

$$vf = D\partial_z f$$

$$f = f_0 \exp[z/\lambda_D] \qquad \lambda_D = D/U_1$$

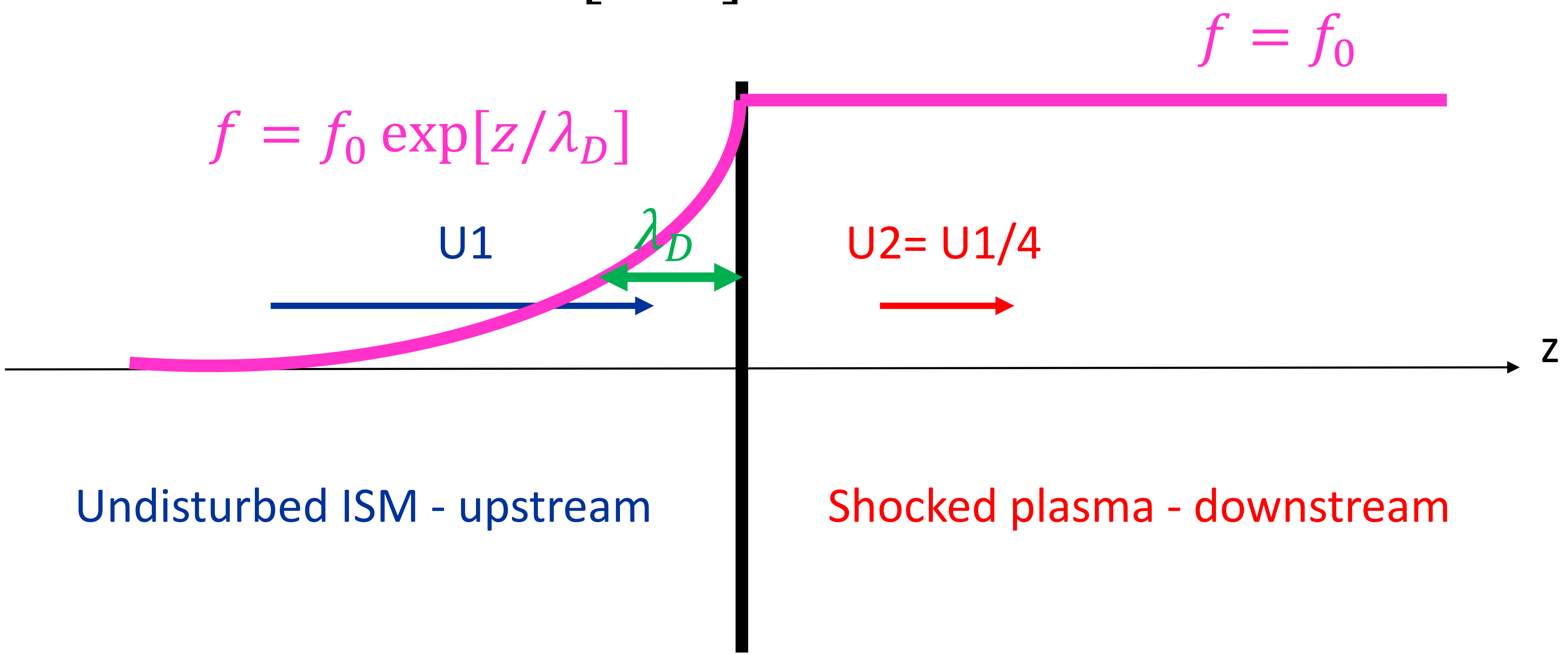
Radial distribution

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



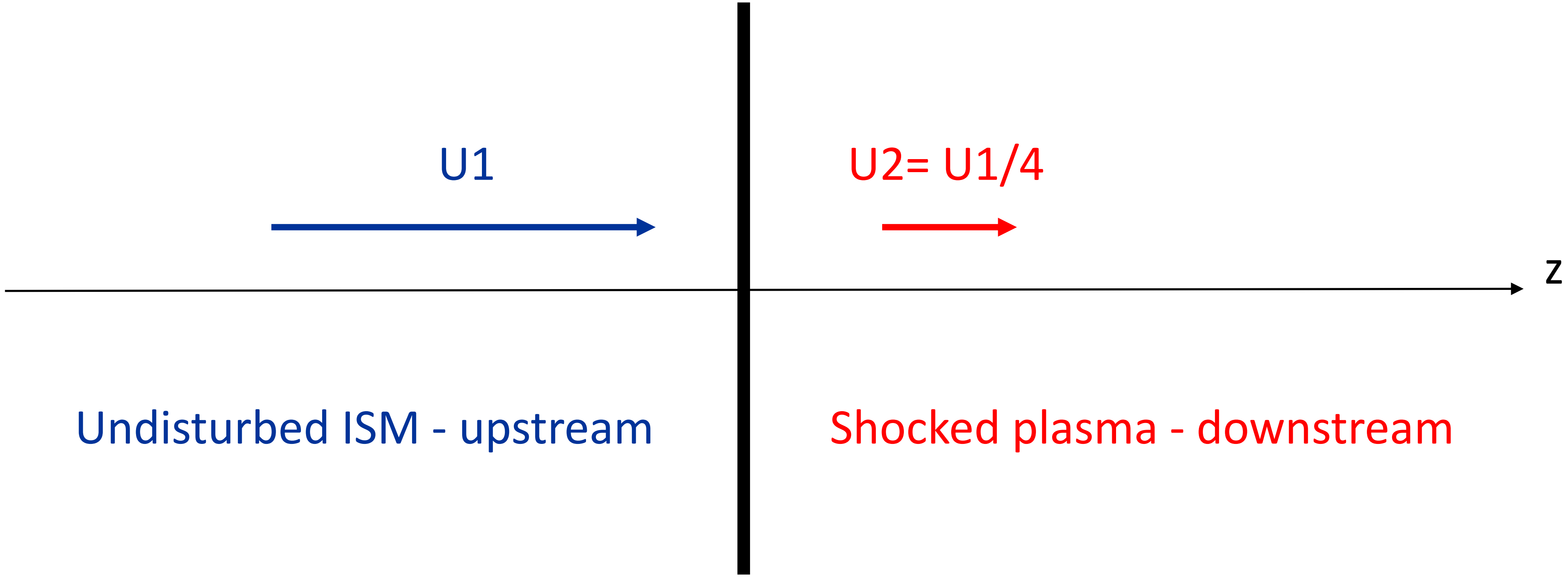
Radial distribution

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



Solution at the shock

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



Solution at the shock

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

$$\int_{0^-}^{0^+} dz' \;\; T.E.$$

Solution at the shock

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

$$\int_{0^-}^{0^+} dz' \;\; T.E.$$

$$v(z) = U_1 + (U_2 - U_1)\,\theta[z]$$

Solution at the shock

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

$$\int_{0^-}^{0^+} dz' \;\, T.E.$$

$$v(z) = U_1 + (U_2 - U_1)\,\theta[z]$$

$$\frac{\partial v}{\partial z} = (U_2 - U_1)\,\delta[z]$$

Solution at the shock

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

$$\int_{0^-}^{0^+} dz'\, v\frac{\partial f}{\partial z'} = \quad 0$$

Solution at the shock

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

$$\int_{0^-}^{0^+} dz' \, v \frac{\partial f}{\partial z'} = \; 0$$

$$\int_{0^-}^{0^+} dz' \; T.E. \; \rightarrow \; 0 =$$

Solution at the shock

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

$$\int_{0^-}^{0^+} dz'\,\frac{\partial}{\partial z'}\left[D\frac{\partial f}{\partial z'}\right] = D\partial_z f|_{0^-}^{0^+} = -D\partial_z f_0$$

$$\int_{0^-}^{0^+} dz'\;\; T.E. \;\rightarrow\;\; 0 = -D\partial_z f_0$$

Solution at the shock

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

$$\int_{0^-}^{0^+} dz' \, \frac{1}{3}\frac{\partial v}{\partial z'} p \frac{\partial f}{\partial p} = \frac{(U_2 - U_1)}{3} p \partial_p f_0$$

$$\int_{0^-}^{0^+} dz' \;\; T.E. \;\rightarrow\;\; 0 = -D\partial_z f_0 + \frac{(U_2 - U_1)}{3} p \partial_p f_0$$

Solution at the shock

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

$$\int_{0^-}^{0^+} dz' Q(z', p) = \int_{0^-}^{0^+} dz' Q_0(p)\delta[z'] = Q_0(p)$$

$$\int_{0^-}^{0^+} dz' \ T.E. \rightarrow \ 0 = -D\partial_z f_0 + \frac{(U_2 - U_1)}{3} p\partial_p f_0 + Q_0(p)$$

Solution at the shock

$$0 = -D\partial_z f_0 + \frac{(U_2 - U_1)}{3} p\partial_p f_0 + Q_0(p)$$

$U_1 f_0 = D\partial_z f_0$ - Upstream flux conservation

Solution at the shock

$$0 = -U_1 f_0 + \frac{(U_2 - U_1)}{3} p \partial_p f_0 + Q_0(p)$$

Solution at the shock

$$0 = -U_1 f_0 + \frac{(U_2 - U_1)}{3} p\partial_p f_0 + Q_0(p)$$

$$0 = -s f_0 - p\partial_p f_0 + s\,\frac{Q_0(p)}{U_1}$$

$$s = \frac{3U_1}{(U_1 - U_2)}$$

Solution at the shock

$$0 = -U_1 f_0 + \frac{(U_2 - U_1)}{3} p \partial_p f_0 + Q_0(p)$$

$$0 = -s f_0 - p \partial_p f_0 + s \frac{Q_0(p)}{U_1}$$

$$s = \frac{3U_1}{(U_1 - U_2)}$$

$$\partial_p f_0 + \frac{s}{p} f_0 = \frac{s}{p} \frac{Q_0(p)}{U_1}$$

$$\partial_p [f_0 p^s] = \frac{s}{p} \frac{Q_0(p)}{U_1} p^s$$

Solution at the shock

$$\partial_p [f_0 p^s] = \frac{s}{p} \frac{Q_0(p)}{U_1} p^s$$

Solution at the shock

$$\partial_p[f_0 p^s] = \frac{s}{p}\frac{Q_0(p)}{U_1}p^s$$

$$f_0 p^s = C + \int dp' \frac{s}{p'}\frac{Q_0(p')}{U_1}p'^s$$

Solution at the shock

$$\partial_p[f_0 p^s] = \frac{s}{p}\frac{Q_0(p)}{U_1}p^s$$

$$f_0 p^s = C + \int dp' \frac{s}{p'}\frac{Q_0(p')}{U_1}p'^s$$

$$f_0(p) = \frac{s\xi_{CR} n_1}{4\pi p_{inj}^3}(\frac{p_{inj}}{p})^s$$

General considerations on the solution

$$f_0(p) = \frac{s\xi_{CR}n_1}{4\pi p_{inj}^3}(\frac{p_{inj}}{p})^s$$

General considerations on the solution

$$f_0(p) = \frac{s\xi_{CR} n_1}{4\pi p_{inj}^3} (\frac{p_{inj}}{p})^s$$

$$s = \frac{3U_1}{(U_1 - U_2)} = 4 \ (Strong\ shock)$$

General considerations on the solution

$$f_0(p) = \frac{s\xi_{CR}n_1}{4\pi p_{inj}^3}(\frac{p_{inj}}{p})^s$$

$$s = \frac{3U_1}{(U_1 - U_2)} = 4\ (Strong\ shock)$$

$$f_0(p) \sim p^{-4}\ \rightarrow f_0(E) = 4\pi p^2 f_0(p)\frac{dp}{dE} \sim E^{-2}\ (pc \approx E)$$

General considerations on the solution

CR pressure divergence

$$P_{CR} = \frac{1}{3}\int dp\; 4\pi p^2\, [pv(p)] f(p) \sim \int dp\; p^{3-s} \sim \ln(p) \to \infty$$

$$f_0(p) \sim p^{-4} \;\to f_0(E) = 4\pi p^2 f_0(p)\frac{dp}{dE} \sim E^{-2}\; (pc \approx E)$$

On the maximum energy

The existence of a maximum energy can solve the problem of the divergence in the pressure

On the maximum energy

The existence of a maximum energy can solve the problem of the divergence in the pressure

A revision in the boundary conditions is required

On the maximum energy

The existence of a maximum energy can solve the problem of the divergence in the pressure

A revision in the boundary conditions is required

Possibilities:

On the maximum energy

The existence of a maximum energy can solve the problem of the divergence in the pressure

A revision in the boundary conditions is required

Possibilities:

1. The transport is time-dependent
2. The size of the system is finite

On the maximum energy

The existence of a maximum energy can solve the problem of the divergence in the pressure

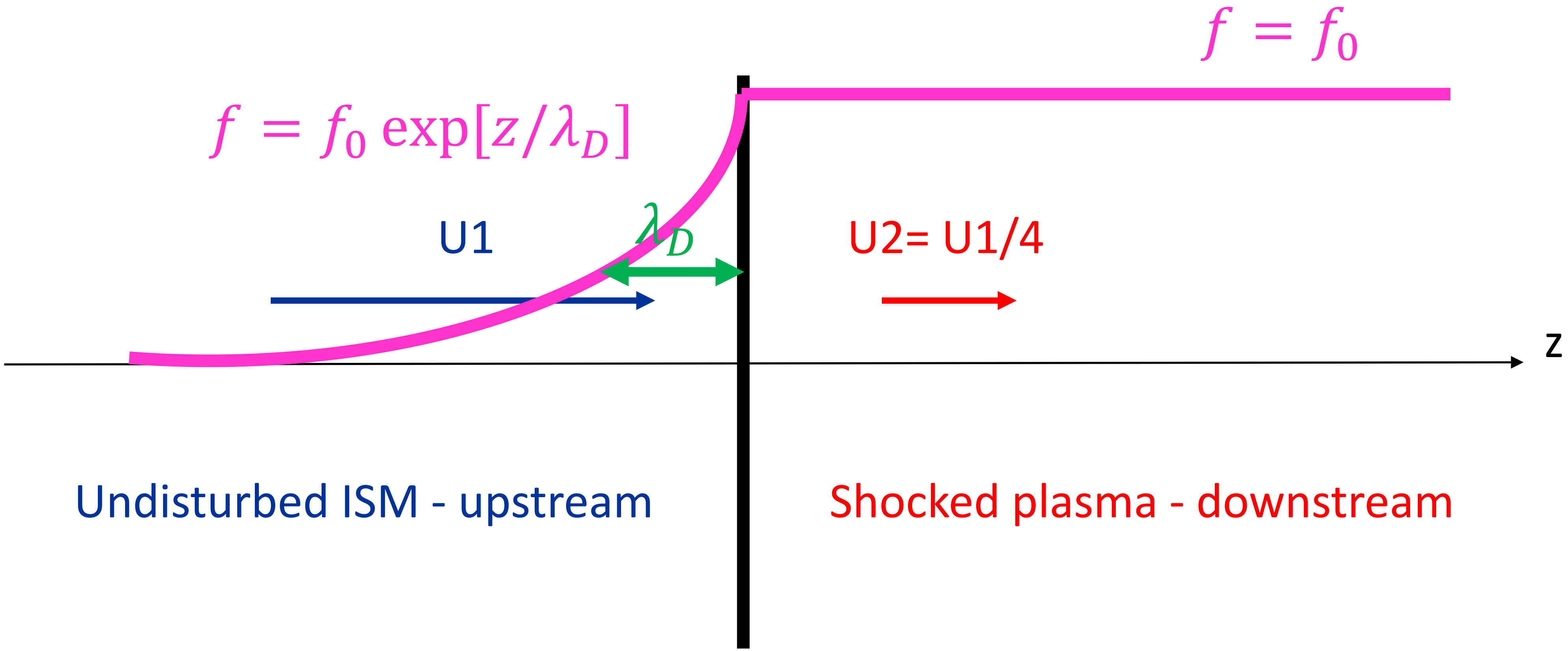
A revision in the boundary conditions is required

Possibilities:

1. The transport is time-dependent
2. The size of the system is finite

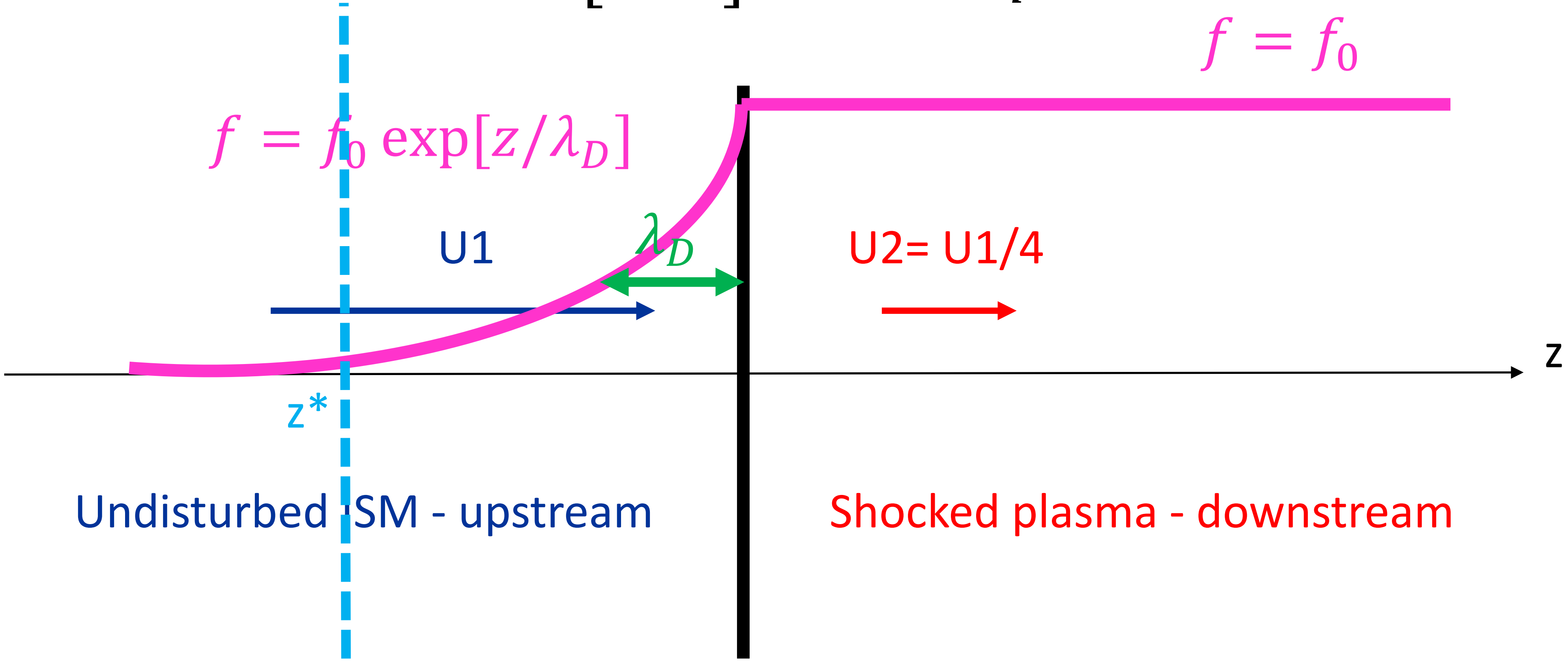
On the maximum Energy

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



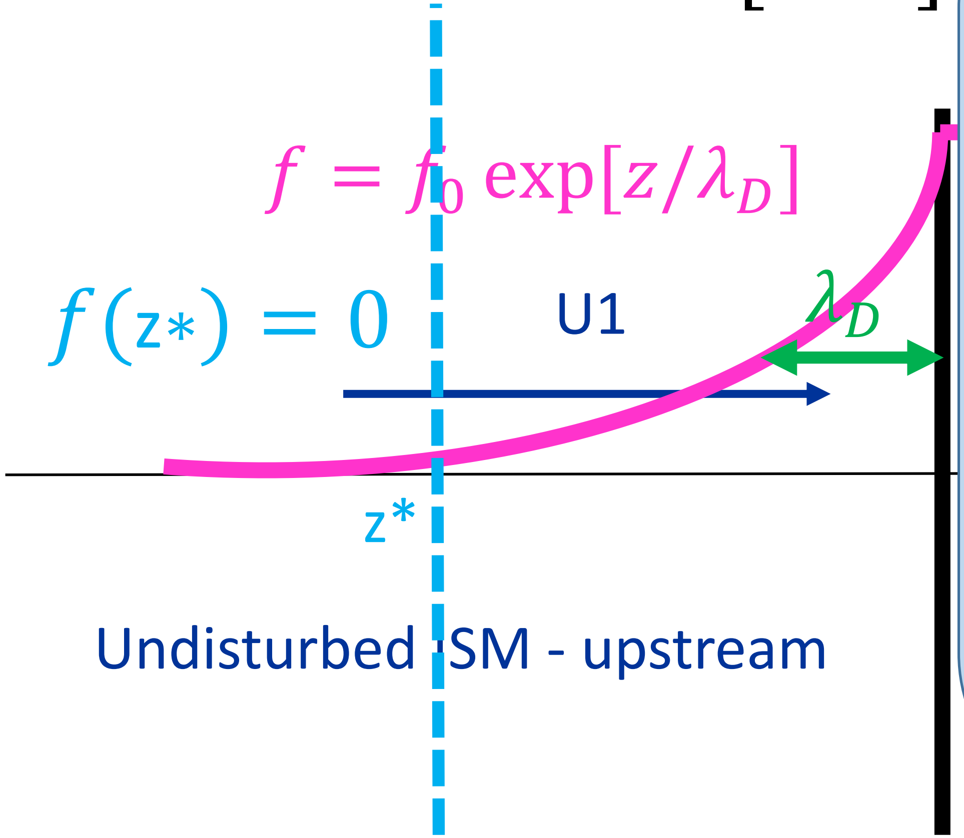
On the maximum Energy

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



On the maximum Energy

$$v\frac{\partial f}{\partial z} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] + \ldots$$



$$\lambda_D(E^*) \approx |z^*|$$

Particles with energy E>E* will start diffusing away from the system

E* is the Maximum Energy

On the maximum Energy

Possible exercise:

Try to solve the transport equation at the infinite planar shock introducing the free escape boundary condition

What is the mathematical expression of the HE cutoff?

$(E^*) \approx |z^*|$

energy E>E* will start

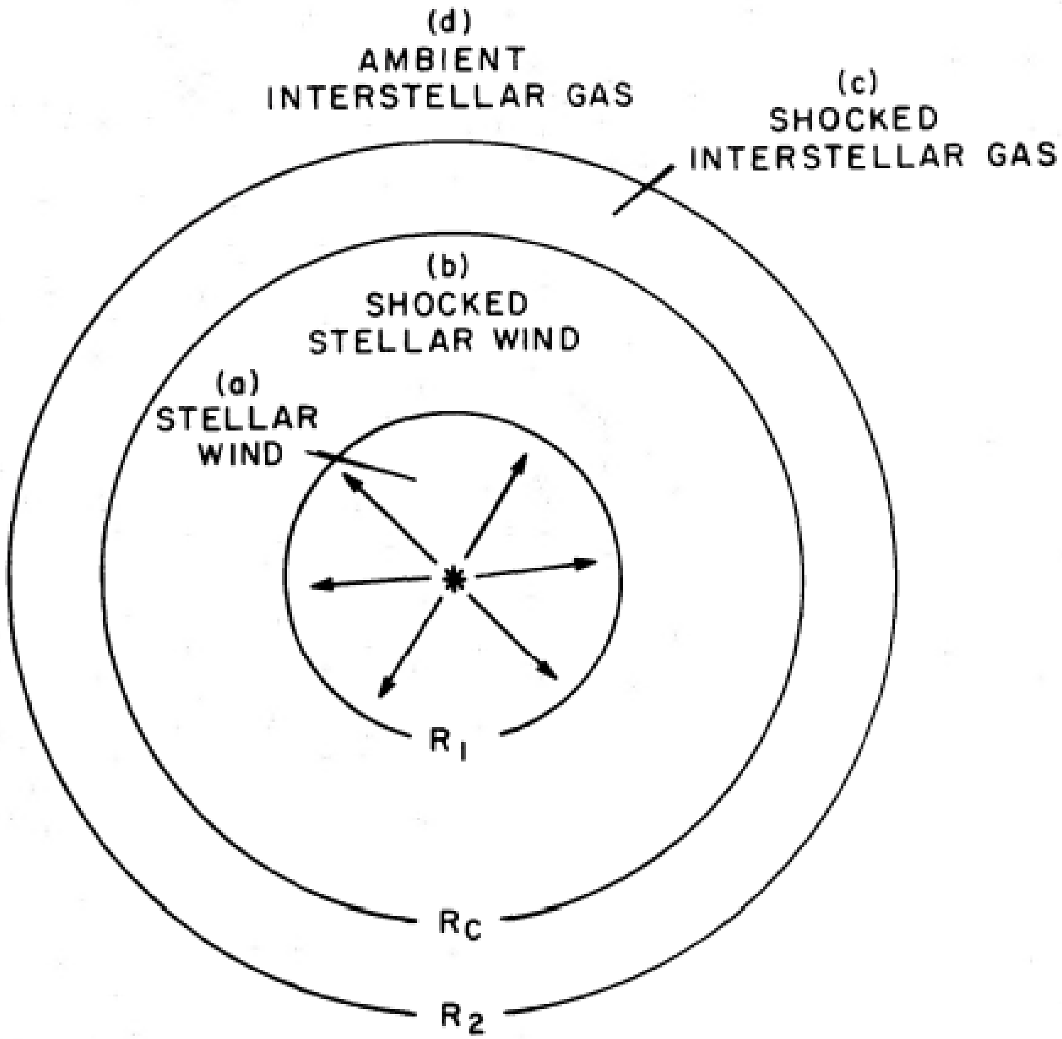
away from the system

E* is the Maximum Energy

Outline

- Transport equation of Cosmic Rays
- Transport approach to diffusive shock acceleration
- Wind blown bubbles
- Modeling acceleration and multi-messenger radiation

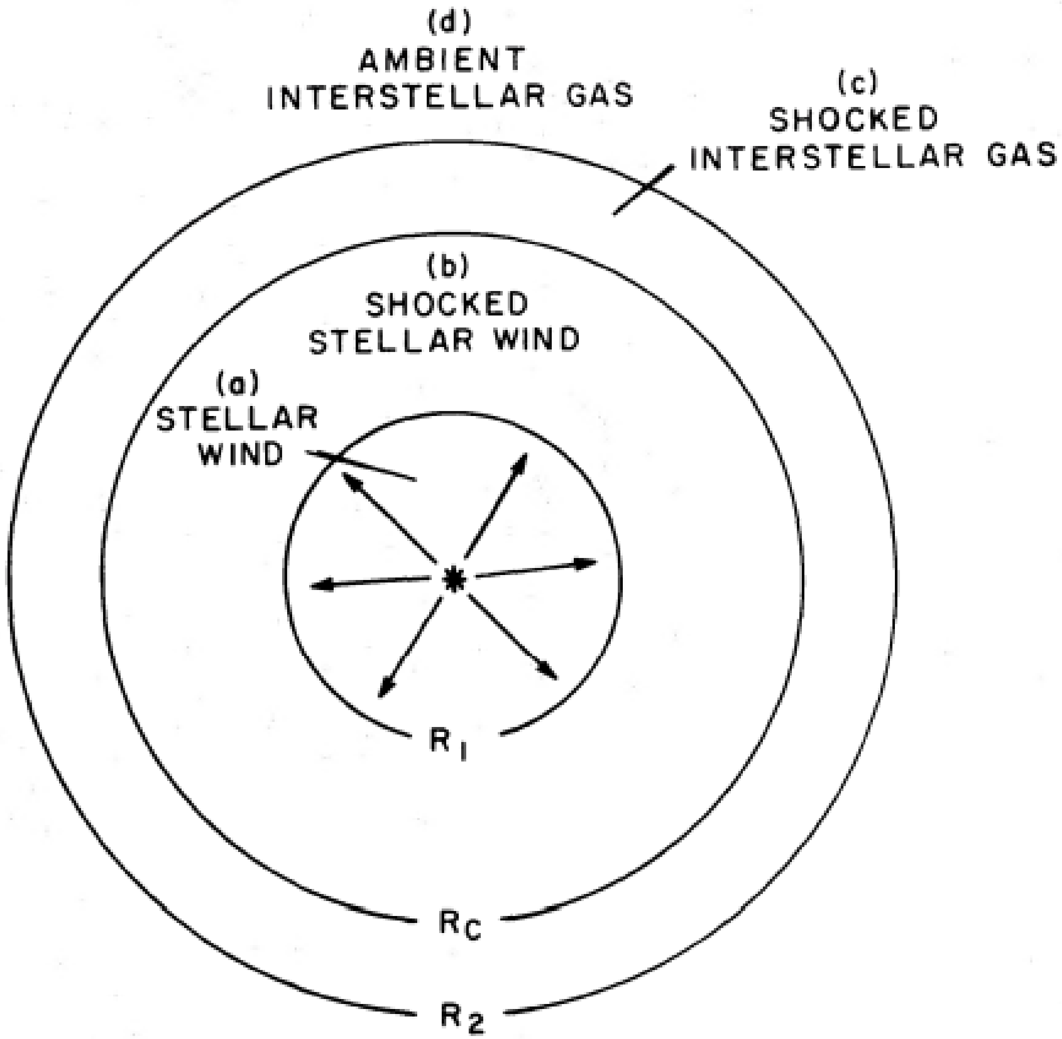
Diverging flows (wind bubbles)



Weaver+1977

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

Diverging flows (wind bubbles)



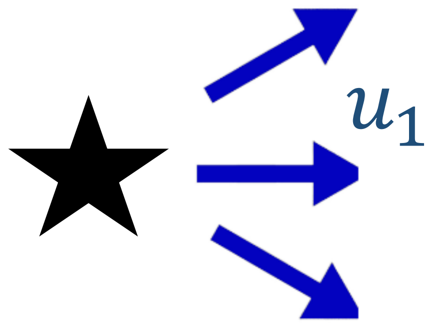
Weaver+1977

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

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

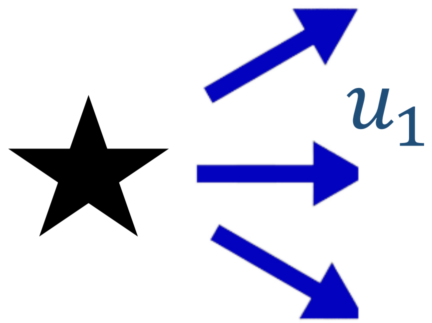
Structure and Evolution

1. The outflow is launched - t_0



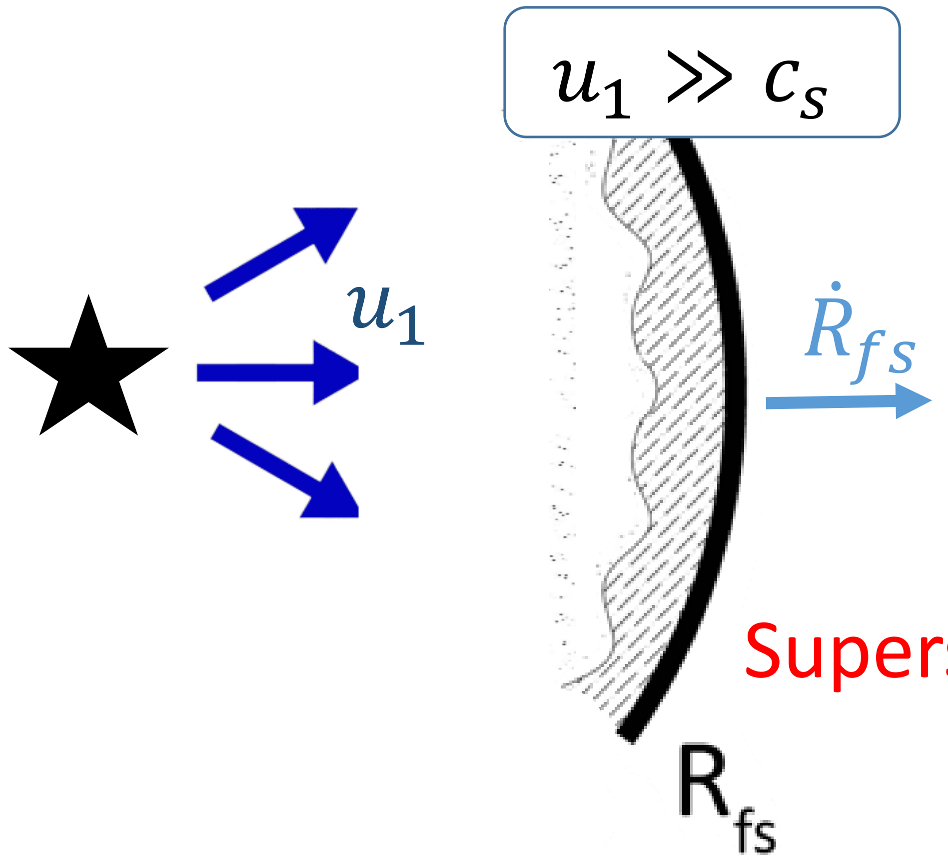
Structure and Evolution

$u_1 \gg c_s$



1. The outflow is launched - t_0

Structure and Evolution

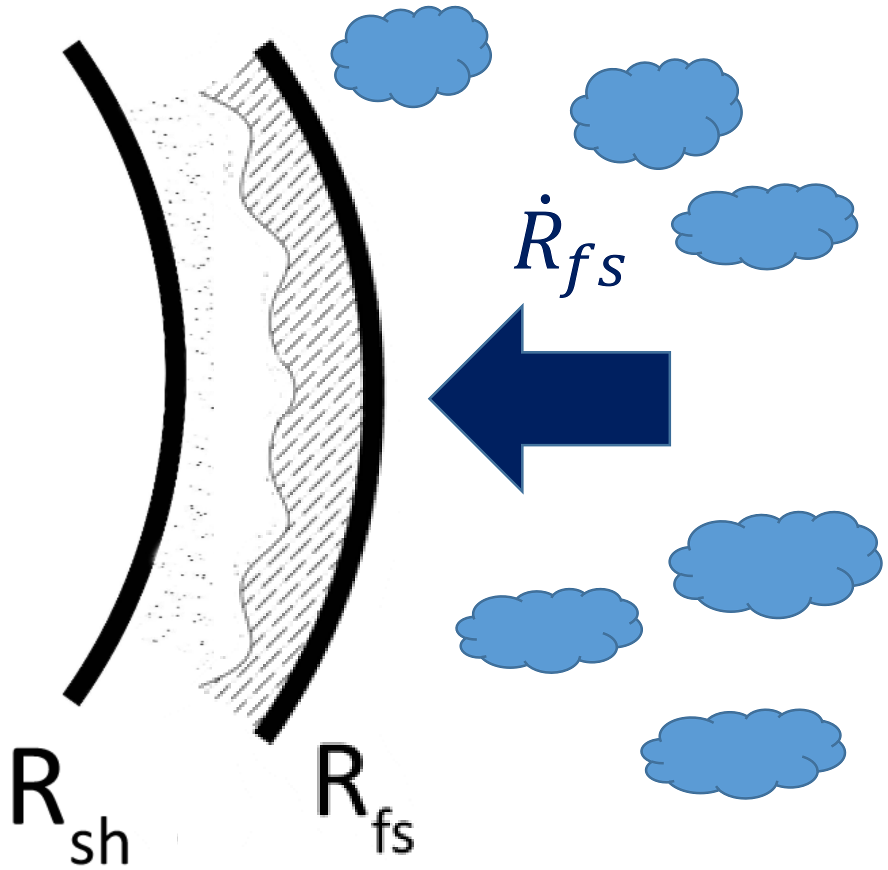


1. The outflow is launched - t_0

Supersonic → forward shock

Structure and Evolution

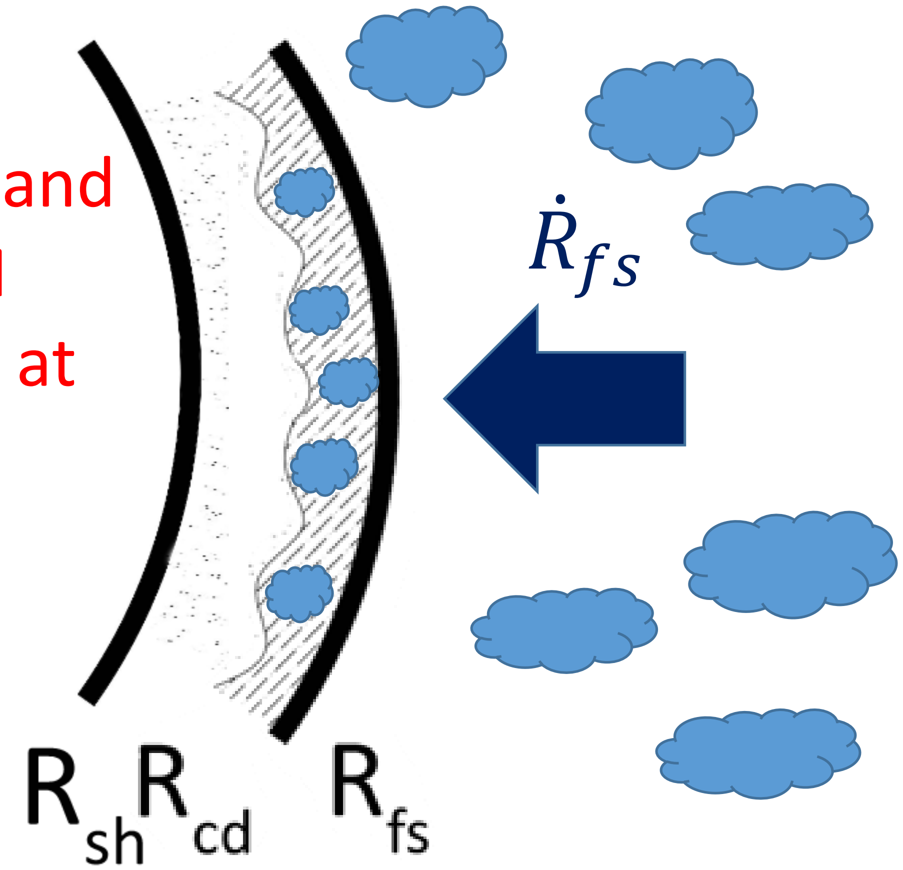
Collision with ISM → wind shock



1. The outflow is launched - t_0

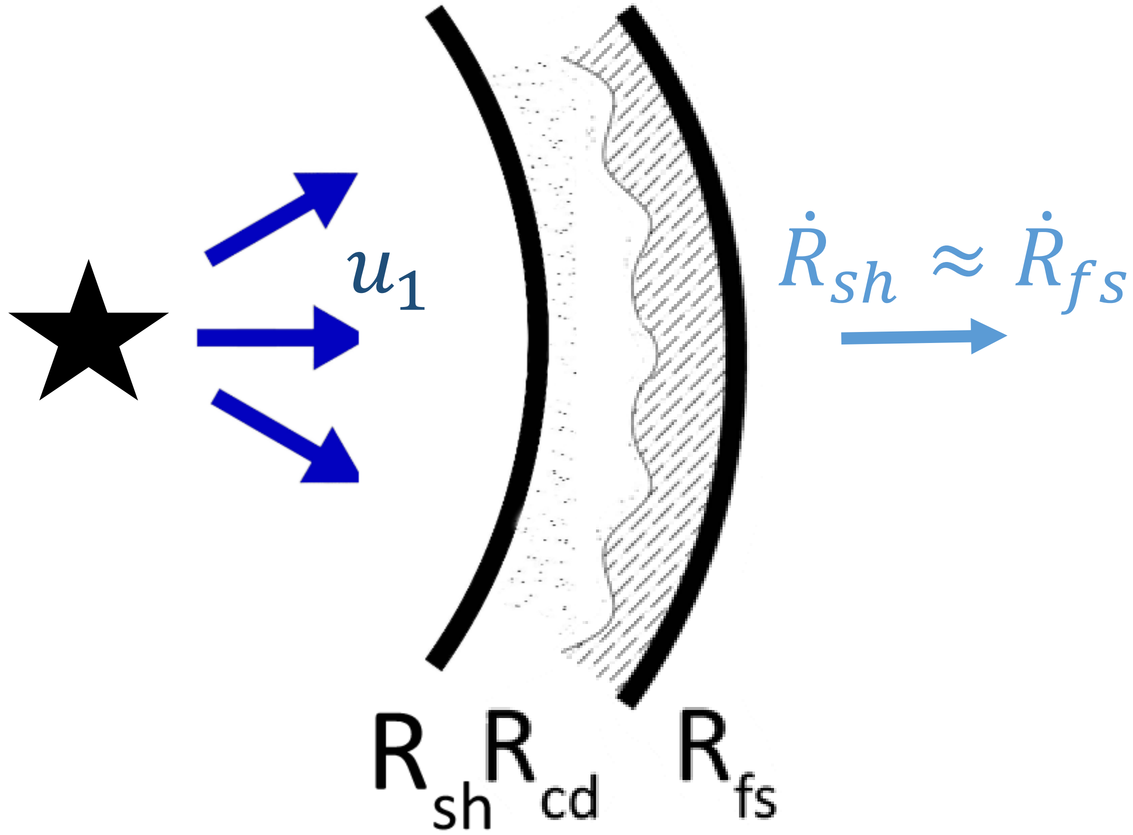
Structure and Evolution

Compressed and shocked ISM accumulated at the contact discontinuity



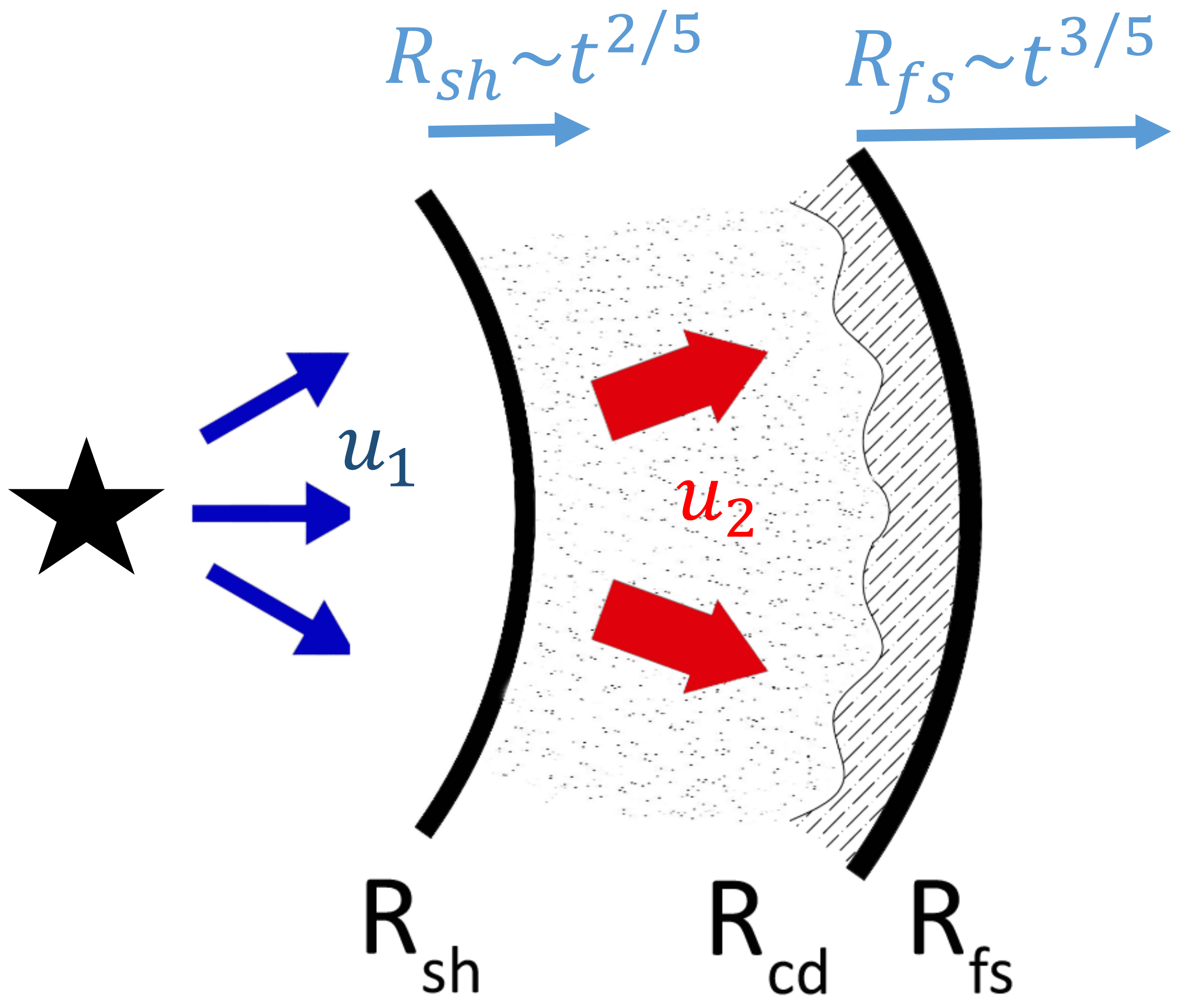
1. The outflow is launched - t_0

Structure and Evolution



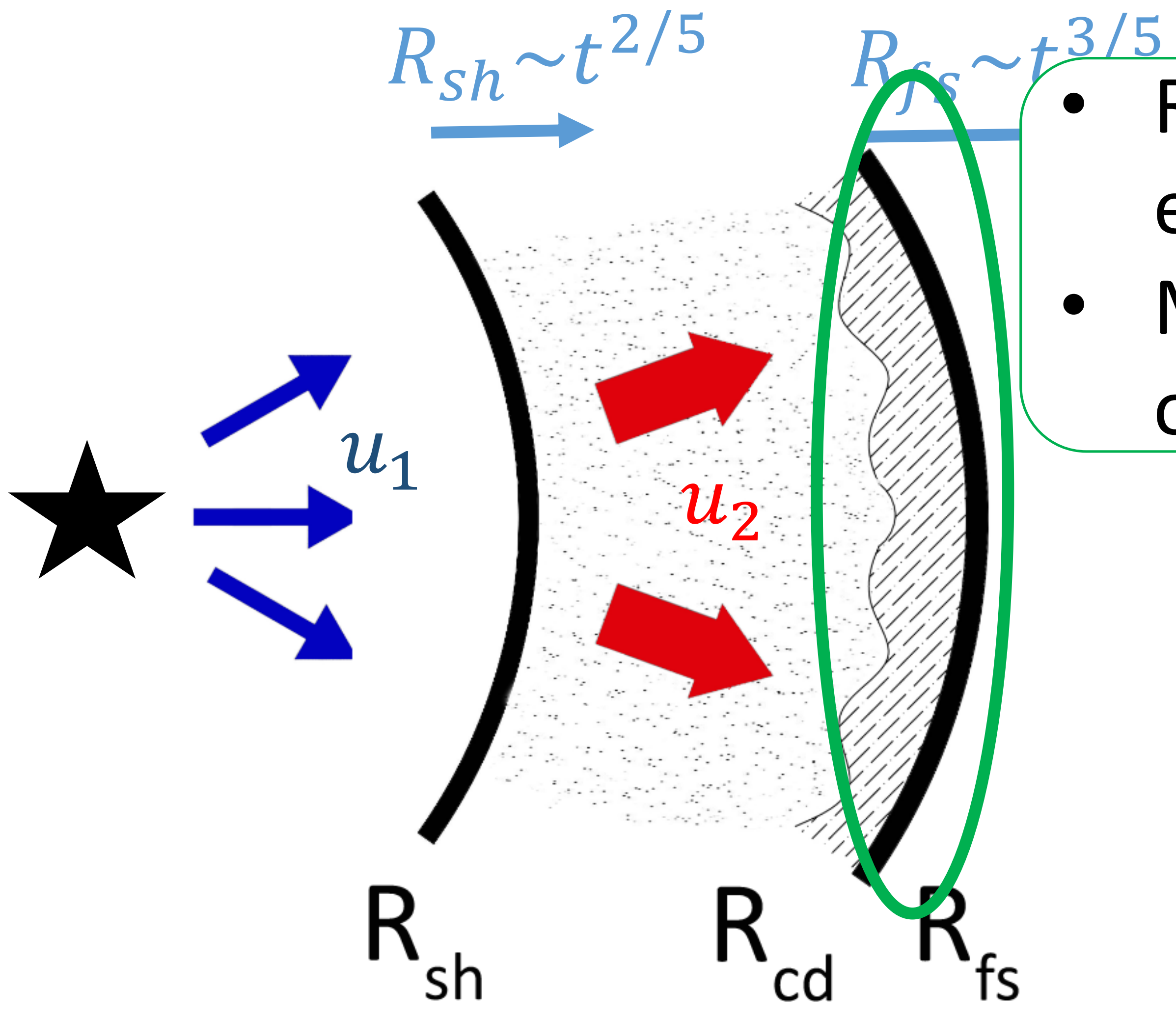
1. The outflow is launched - t_0
2. Free expansion phase - t_1

Structure and Evolution



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

Characterizing the accelerator



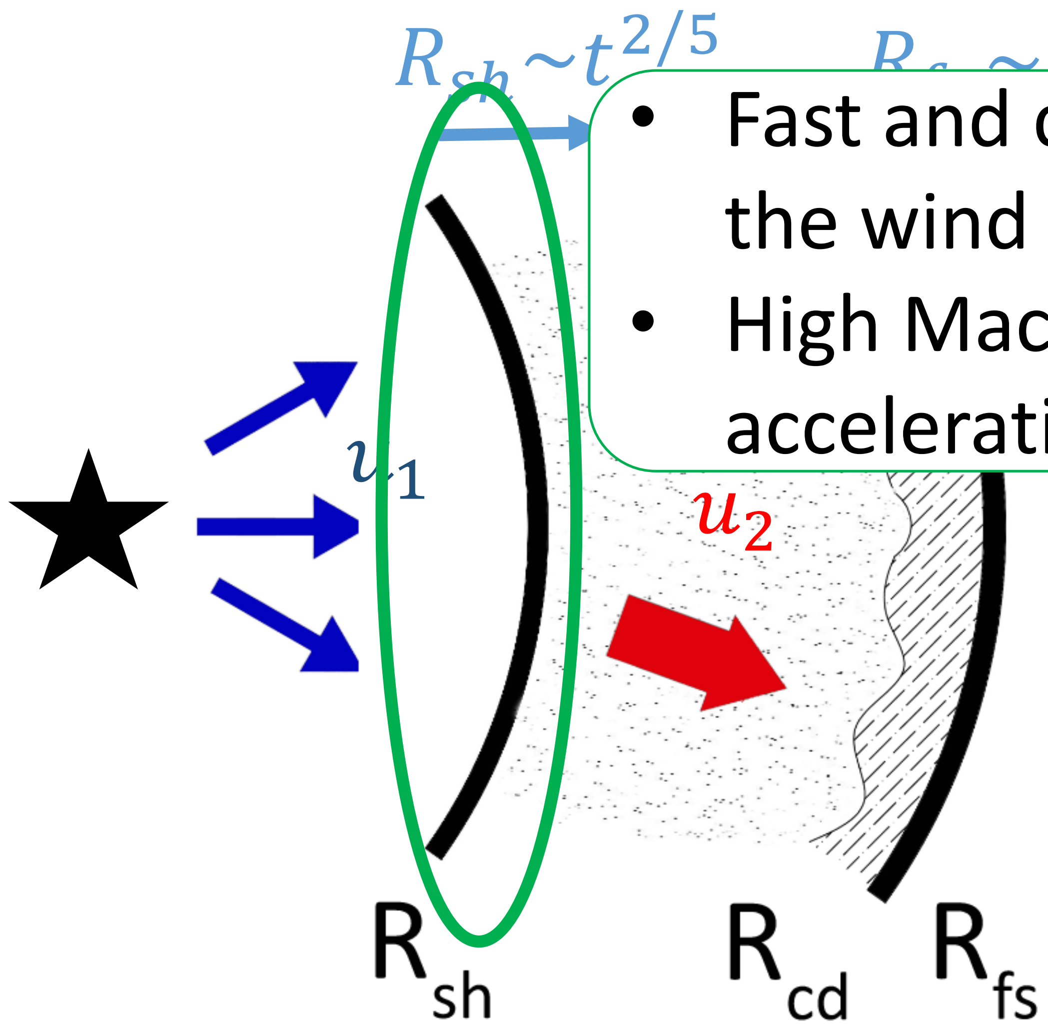
- Rapid fall of acceleration efficiency in time
- Mach number dependent on the external medium

hed - t_0

2. Free expansion phase - t_1

3. Deceleration phase - $t > t_1$

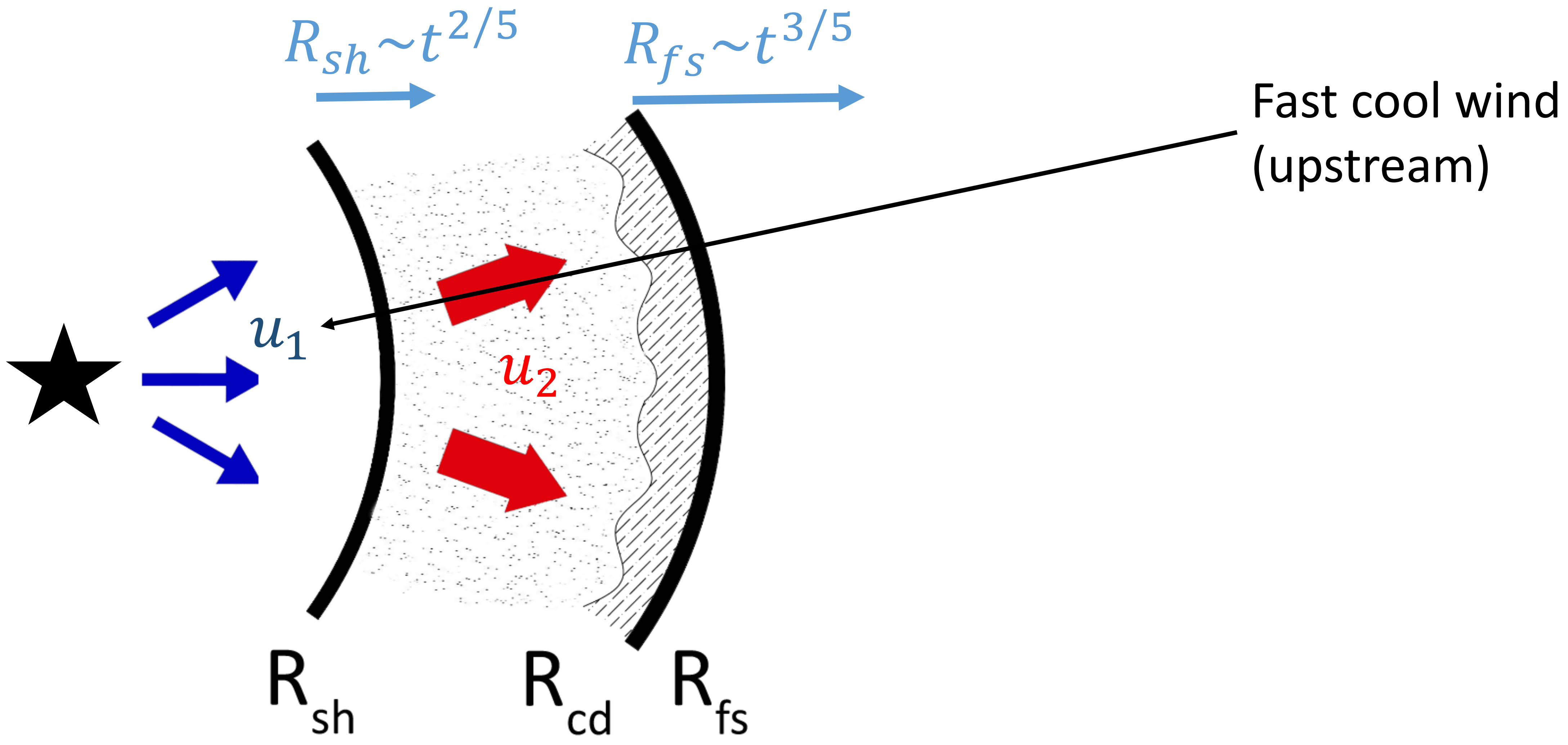
Characterizing the accelerator



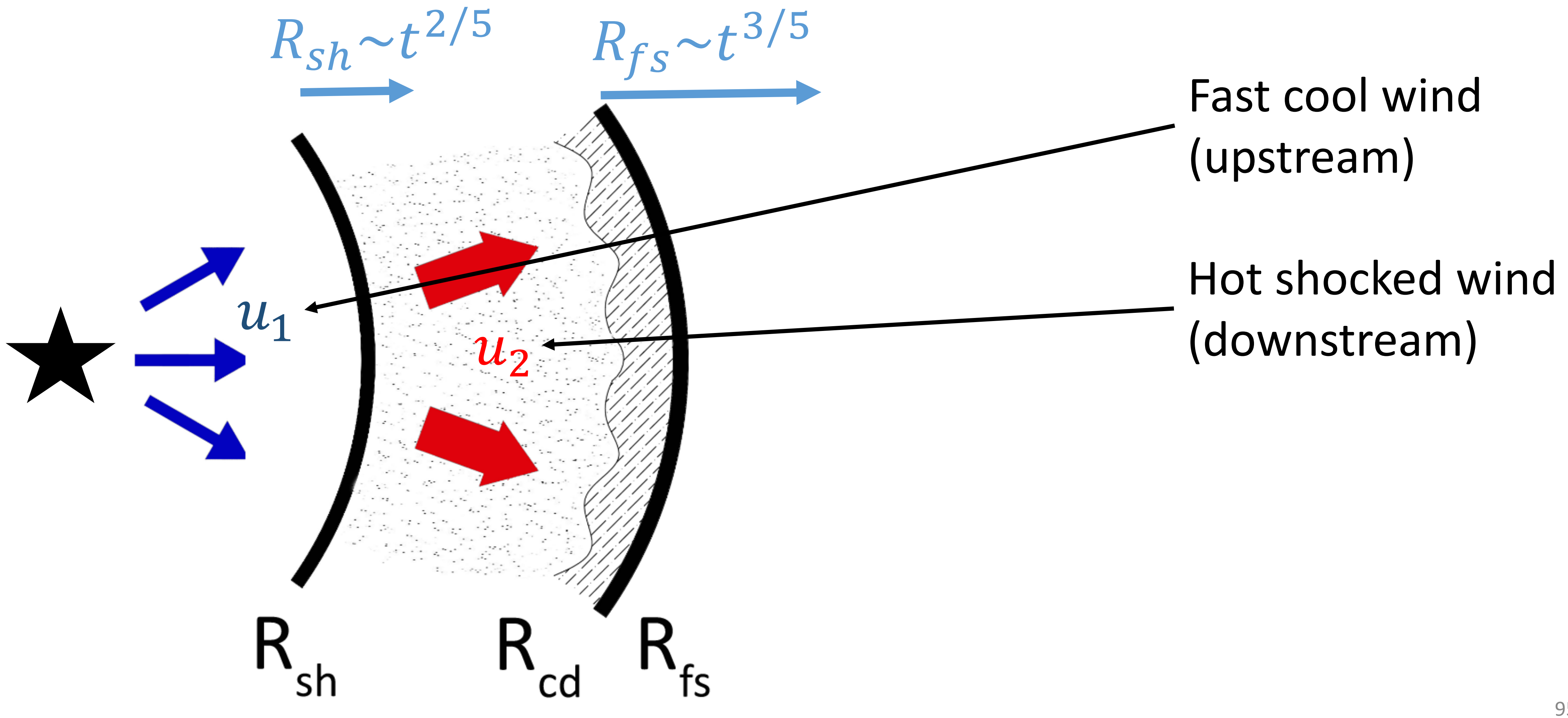
- Fast and cool plasma at the wind shock
- High Mach number and acceleration efficiency

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

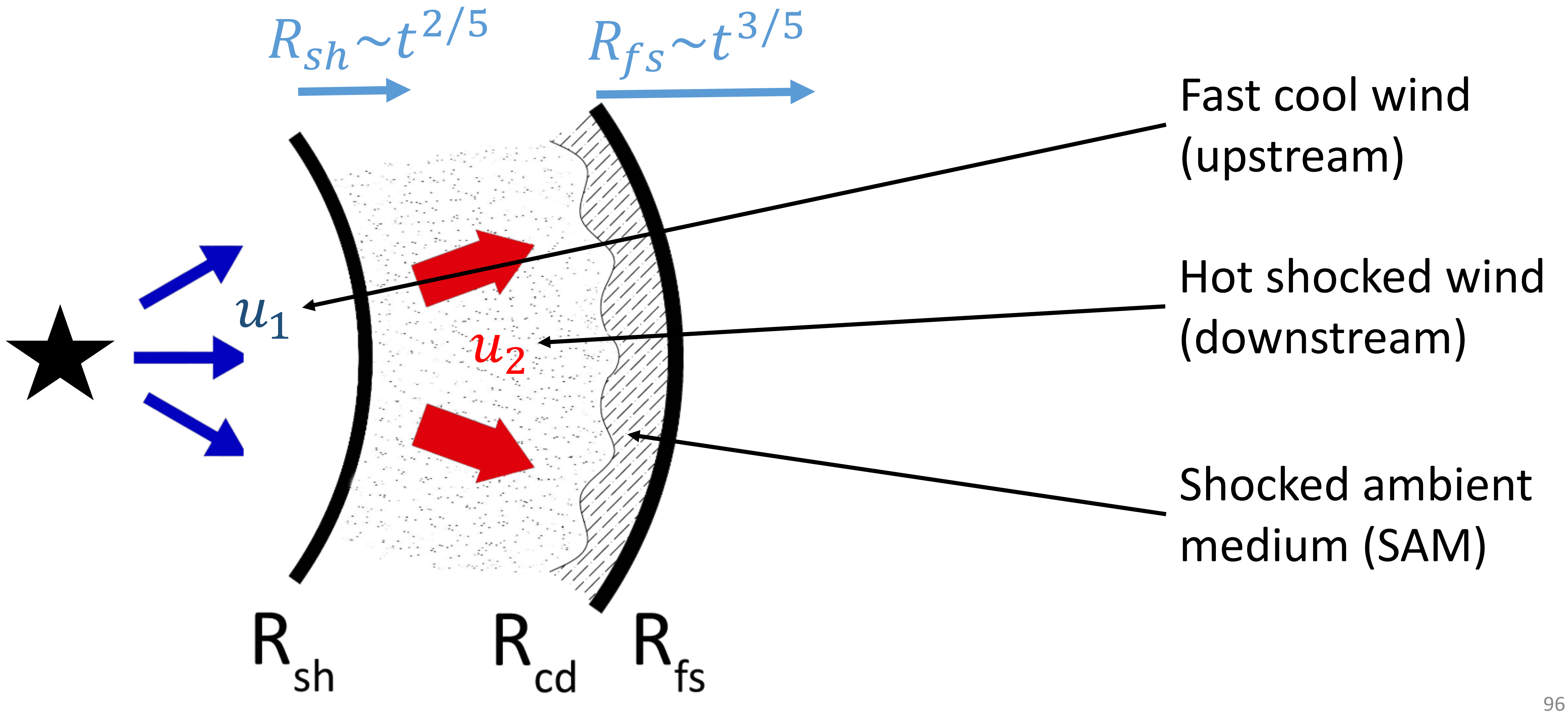
Characterizing the accelerator



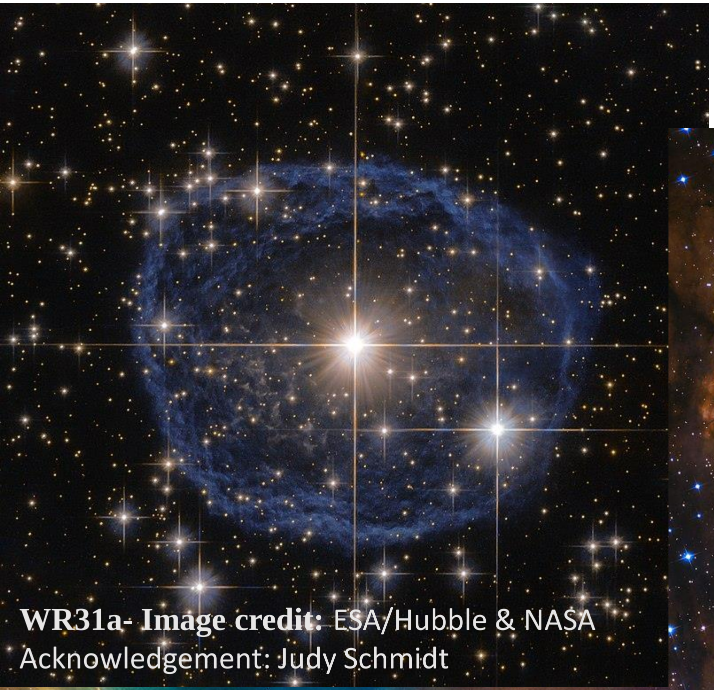
Characterizing the accelerator



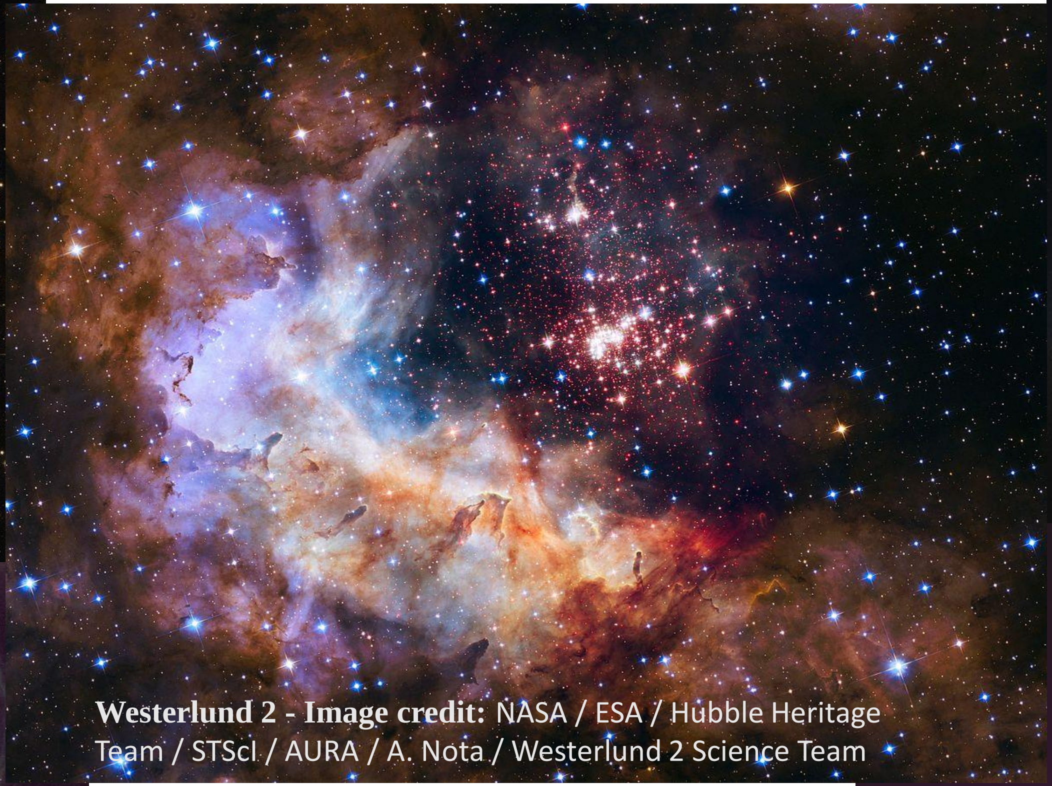
Characterizing the accelerator

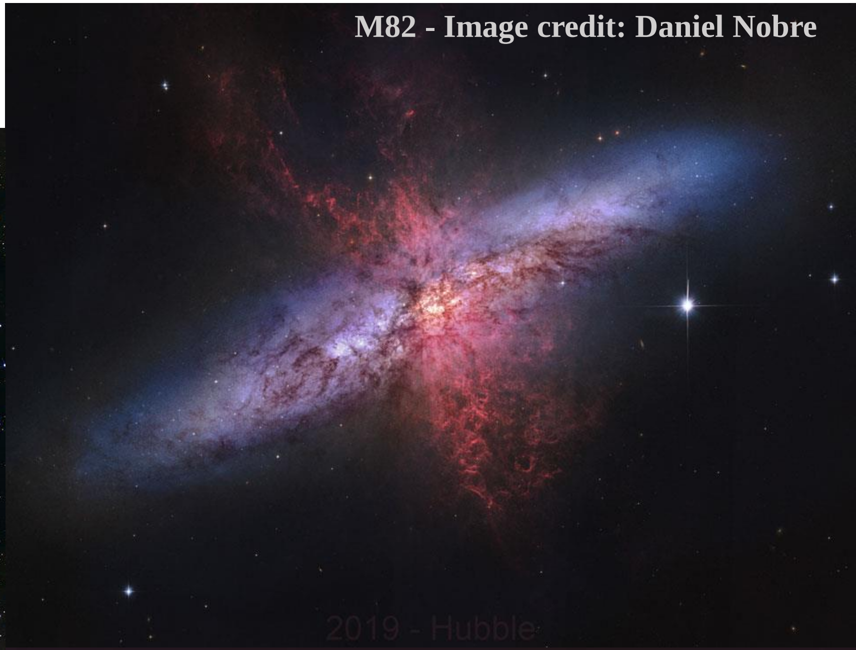


Scale and power

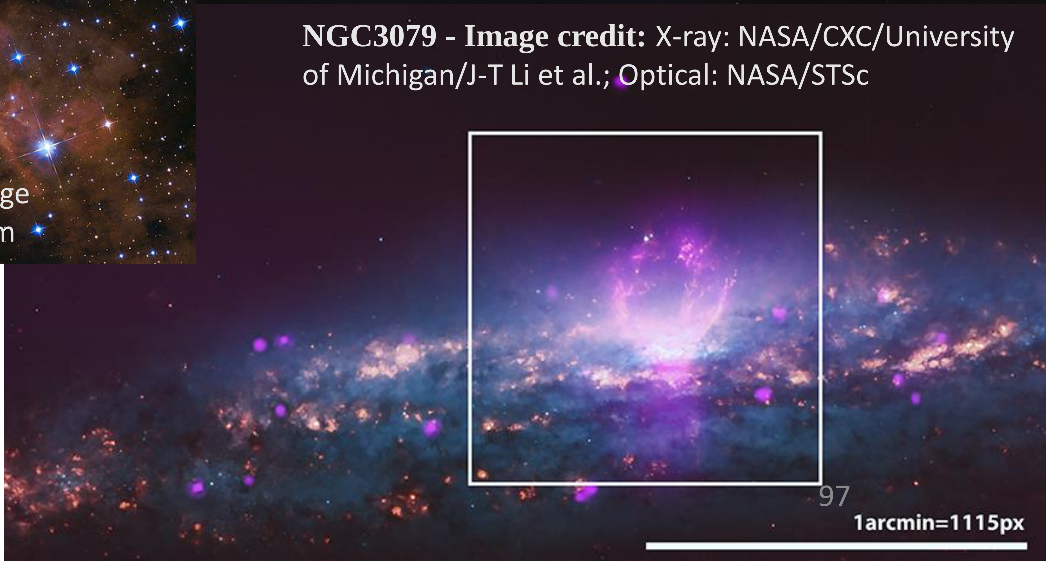

WR31a- Image credit: ESA/Hubble & NASA
Acknowledgement: Judy Schmidt


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



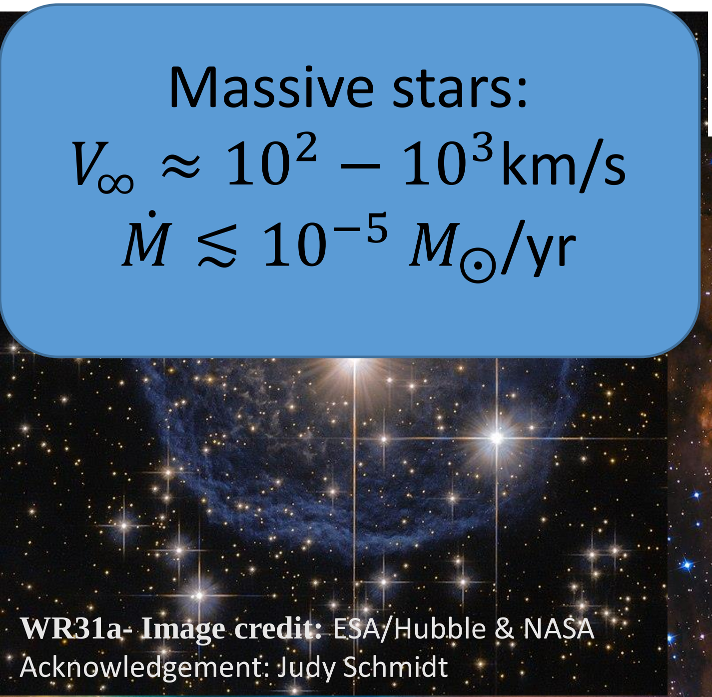
M82 - Image credit: Daniel Nobre



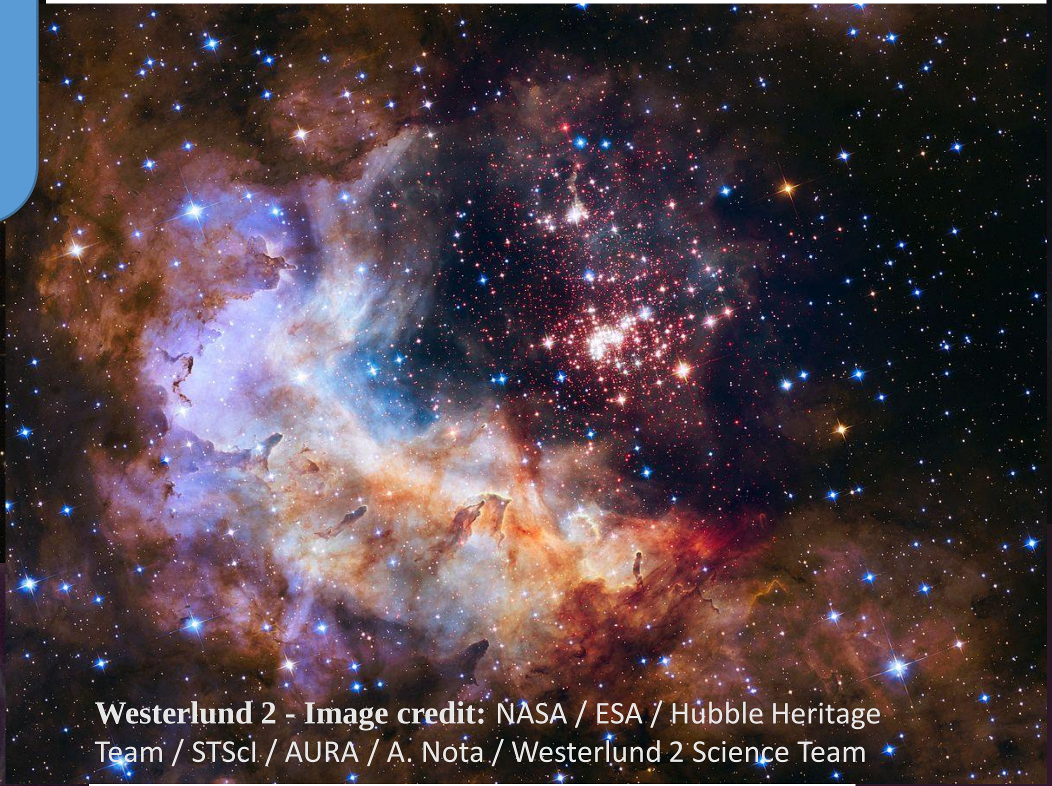
NGC3079 - Image credit: X-ray: NASA/CXC/University of Michigan/J-T Li et al.; Optical: NASA/STSc

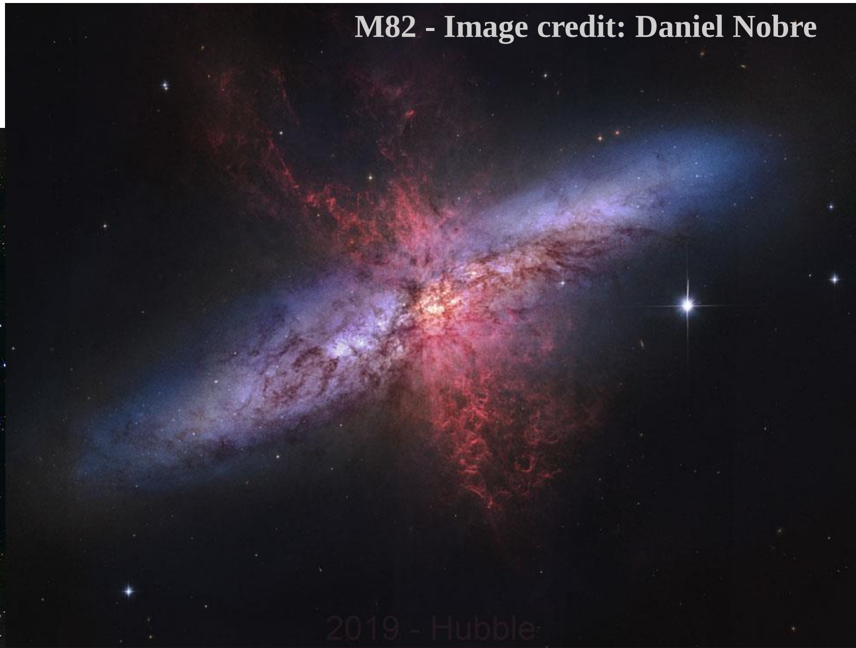
Scale and power

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

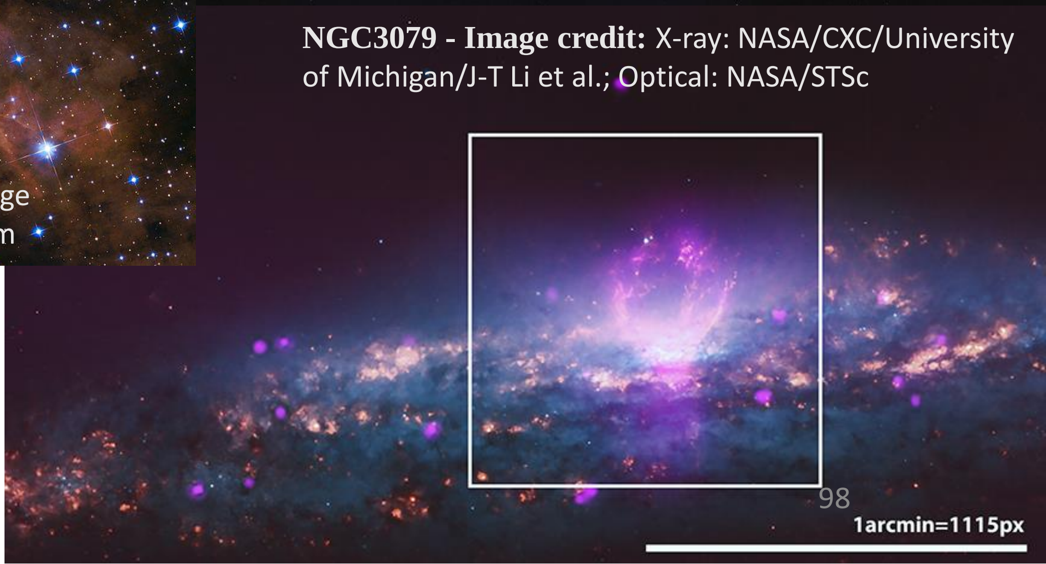

WR31a- Image credit: ESA/Hubble & NASA
Acknowledgement: Judy Schmidt


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


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



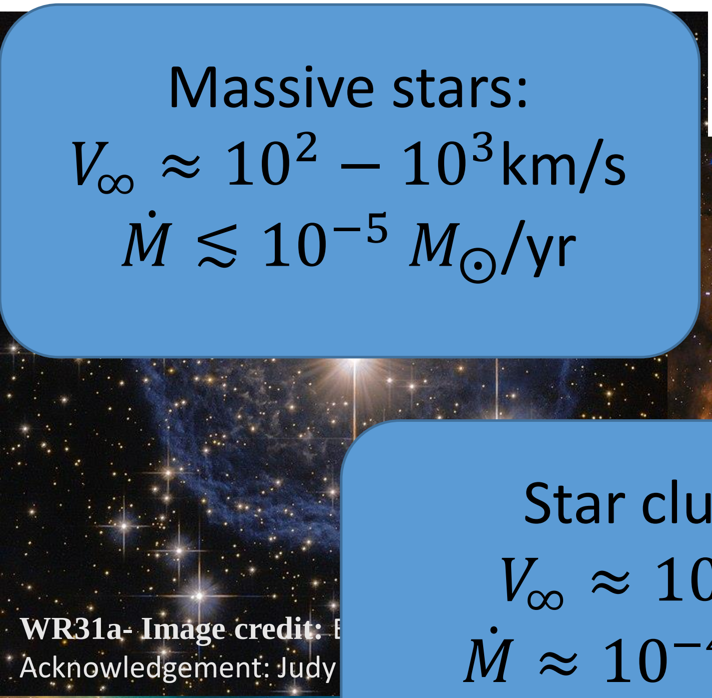
M82 - Image credit: Daniel Nobre



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

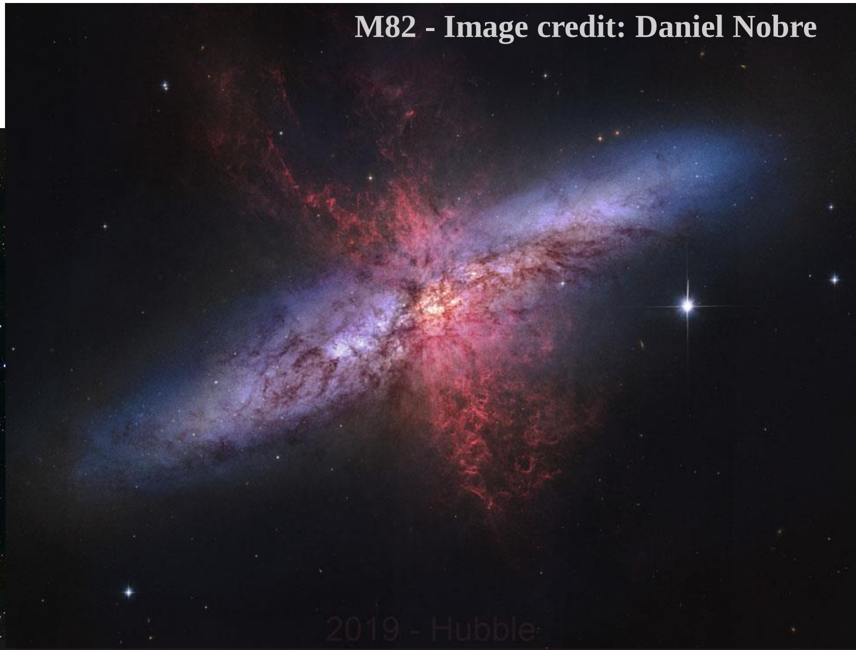
Scale and power

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


WR31a- Image credit: E
Acknowledgement: Judy

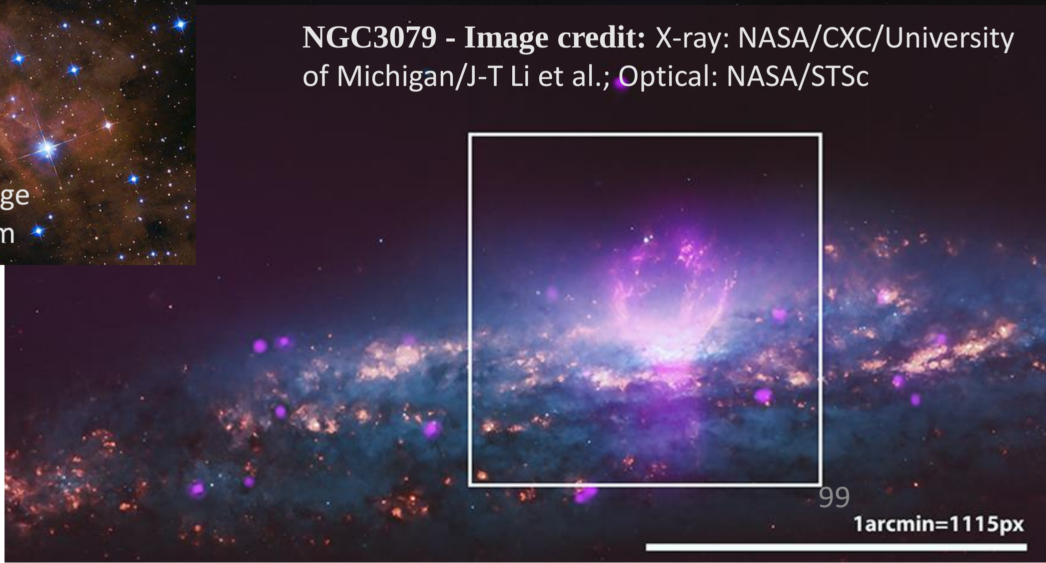
Star clusters:
$V_\infty \approx 10^3 \mathrm{km/s}$
$\dot{M} \approx 10^{-4}\ M_\odot/\mathrm{yr}$


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



M82 - Image credit: Daniel Nobre


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



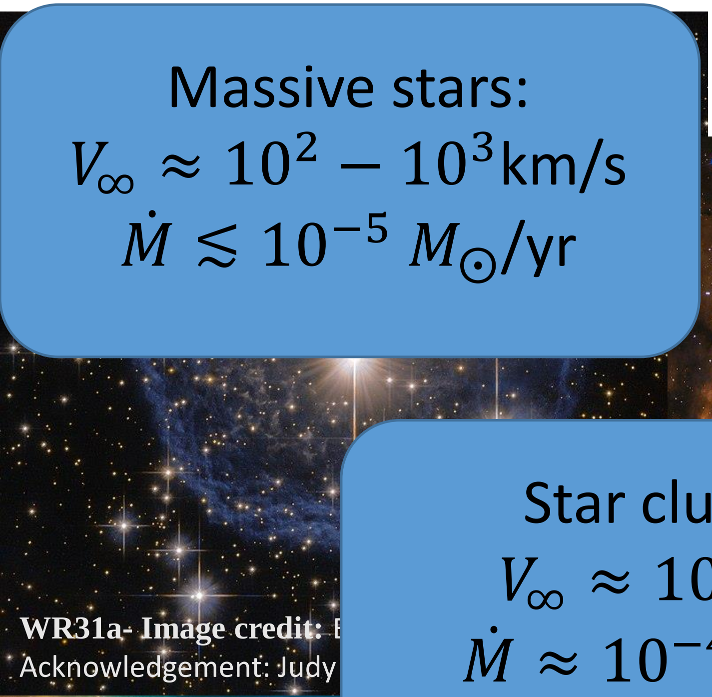
NGC3079 - Image credit: X-ray: NASA/CXC/University of Michigan/J-T Li et al.; Optical: NASA/STSc

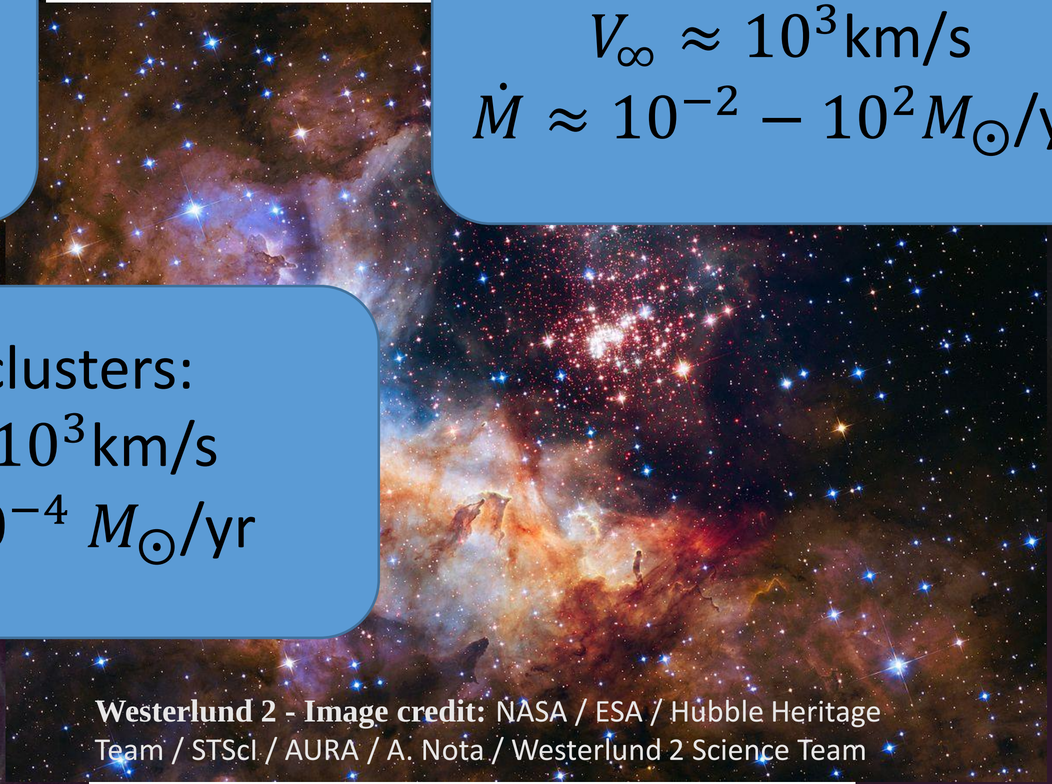
Scale and power

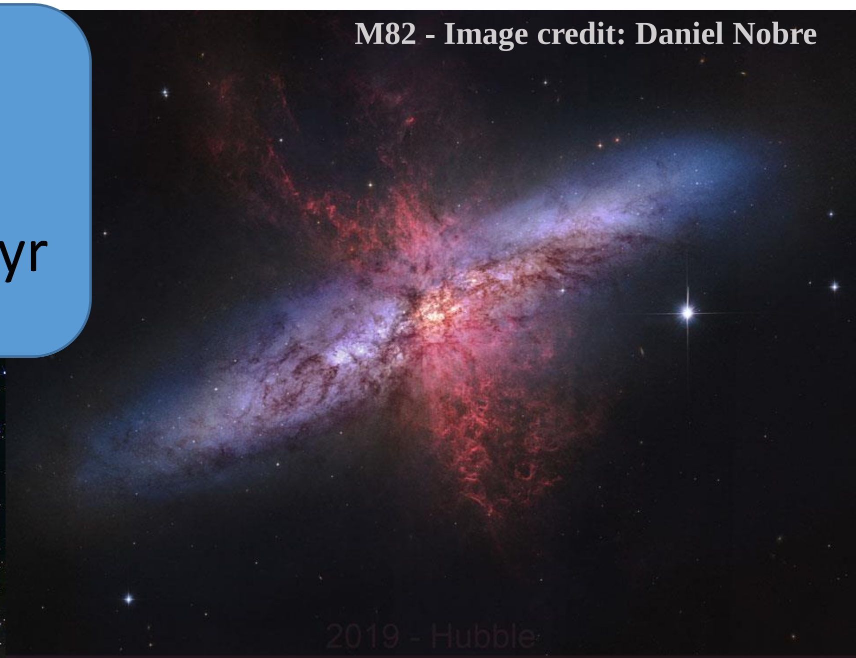
Massive stars:
$V_\infty \approx 10^2 - 10^3 \text{km/s}$
$\dot{M} \lesssim 10^{-5}\ M_\odot/\text{yr}$

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

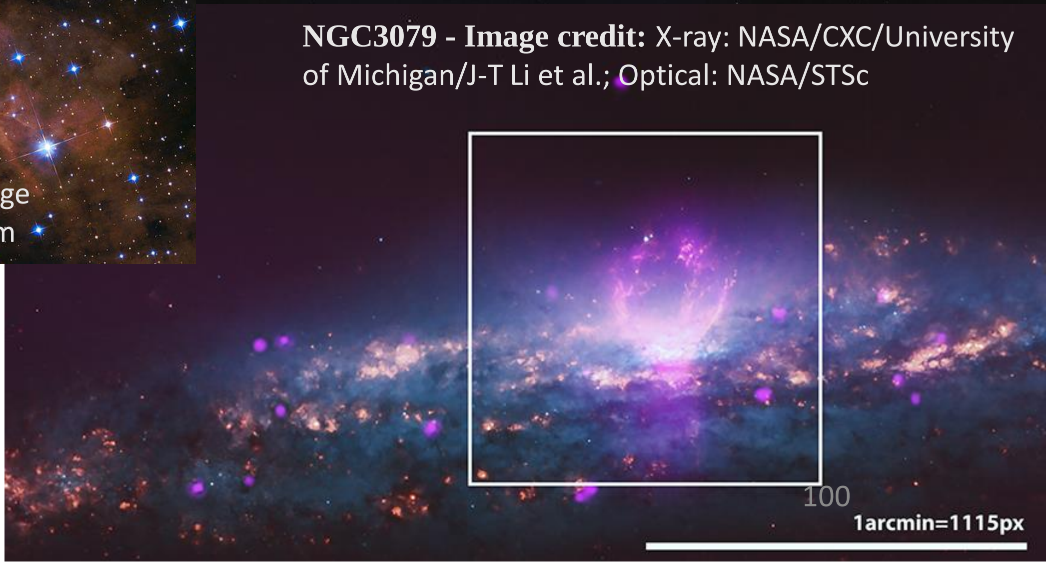
Star clusters:
$V_\infty \approx 10^3 \text{km/s}$
$\dot{M} \approx 10^{-4}\ M_\odot/\text{yr}$


WR31a- Image credit: E
Acknowledgement: Judy


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


M82 - Image credit: Daniel Nobre


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



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

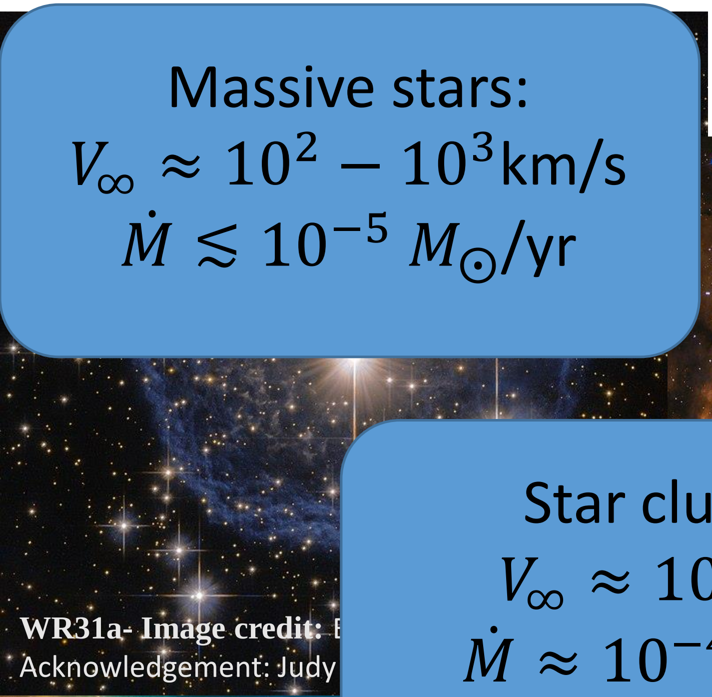
Scale and power

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

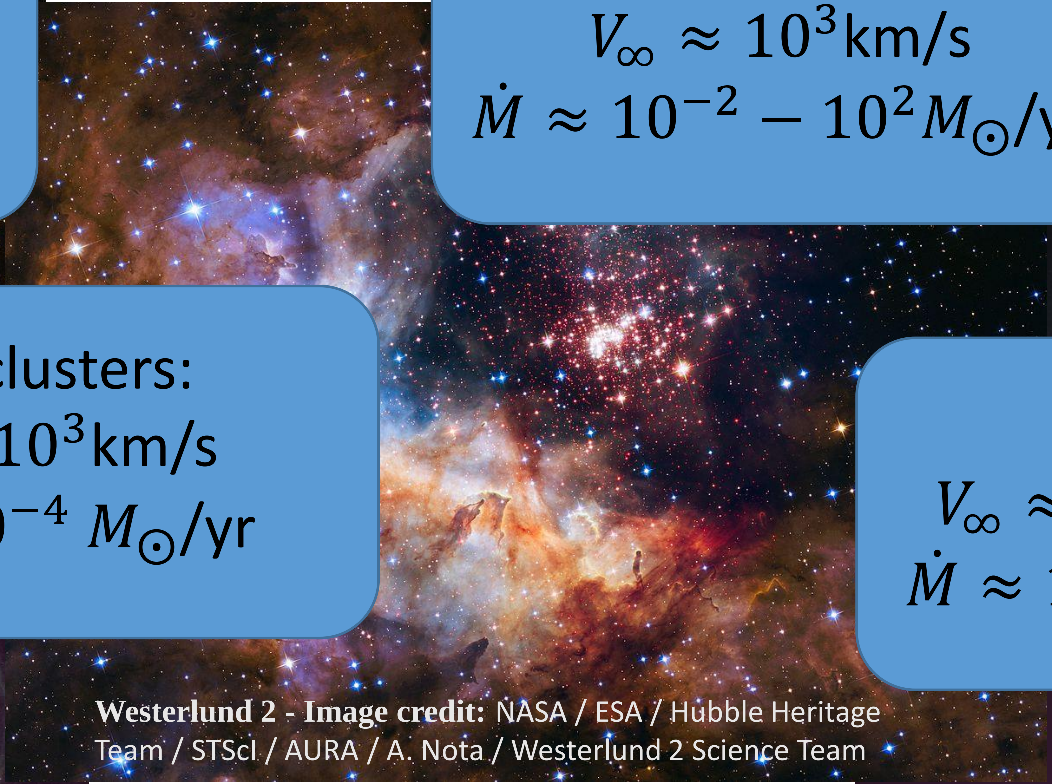
Starbursts:
$V_\infty \approx 10^3$km/s
$\dot{M} \approx 10^{-2} - 10^2 M_\odot$/yr

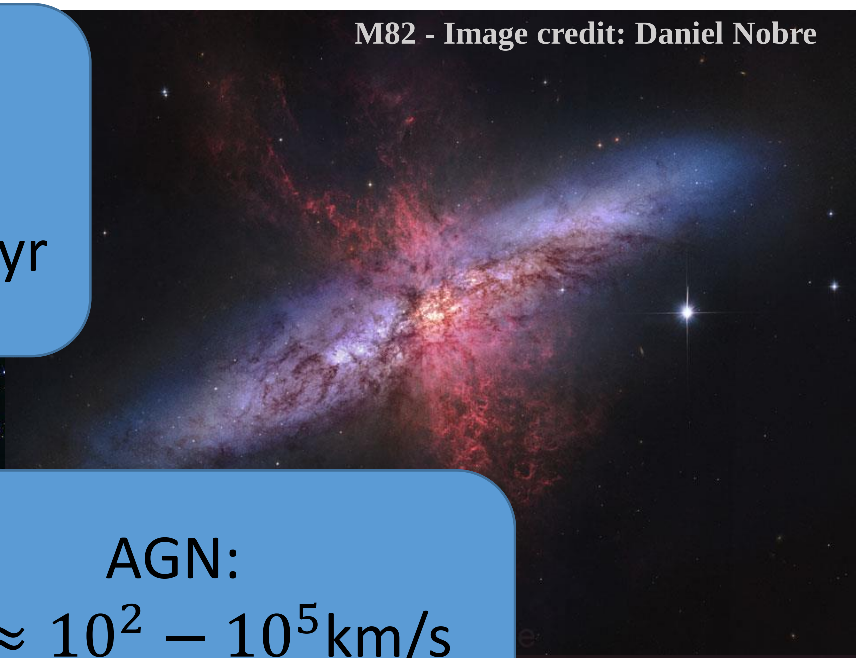
Star clusters:
$V_\infty \approx 10^3$km/s
$\dot{M} \approx 10^{-4}\ M_\odot$/yr

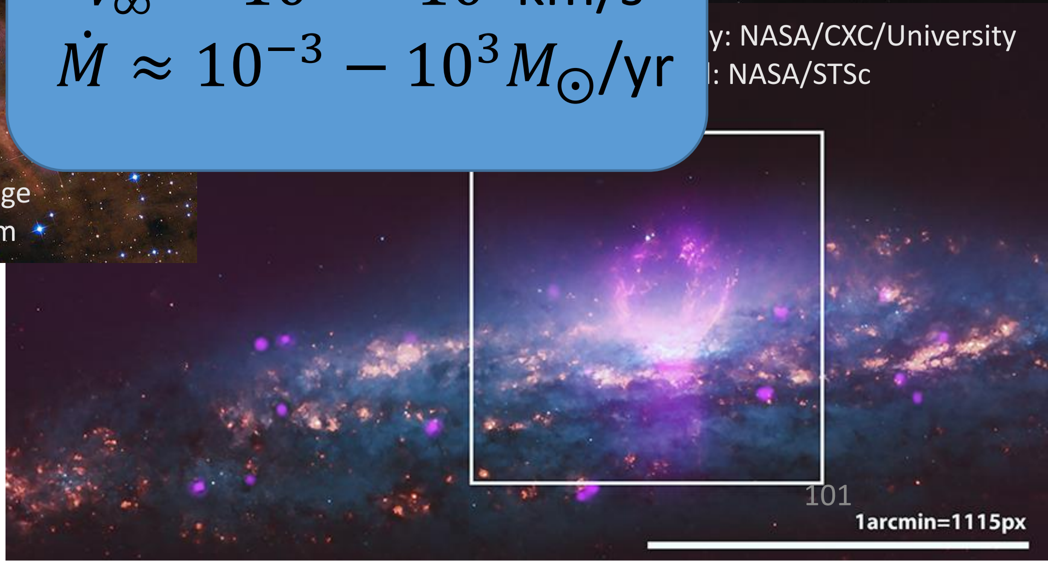
AGN:
$V_\infty \approx 10^2 - 10^5$km/s
$\dot{M} \approx 10^{-3} - 10^3 M_\odot$/yr


WR31a- Image credit: E
Acknowledgement: Judy


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



y: NASA/CXC/University
: NASA/STSc

Maximum Energy: a first guess

$$\lambda_D(E_{max}) \approx R_{sh}$$

$$D(E_{max})/U_1 \approx R_{sh}$$

$$\xi^{-1}\, R_L(E_{max})c/U_1 \approx R_{sh}$$

$$\xi^{-1}\, E_{max}c/qBU_1 \approx R_{sh}$$

Maximum Energy: a first guess

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

Maximum Energy: a first guess

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

$$U_B = \epsilon_B P_{ram} = \epsilon_B \frac{\dot{M}}{4\pi R_{sh}^2} u_1$$

Maximum Energy: a first guess

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

$$U_B = \epsilon_B P_{ram} = \epsilon_B \frac{\dot{M}}{4\pi R_{sh}^2} u_1$$

$$E_{max} = E_{max}\left(u_1, \dot{M}\right) = E_{max}(\dot{E}, \dot{P})$$

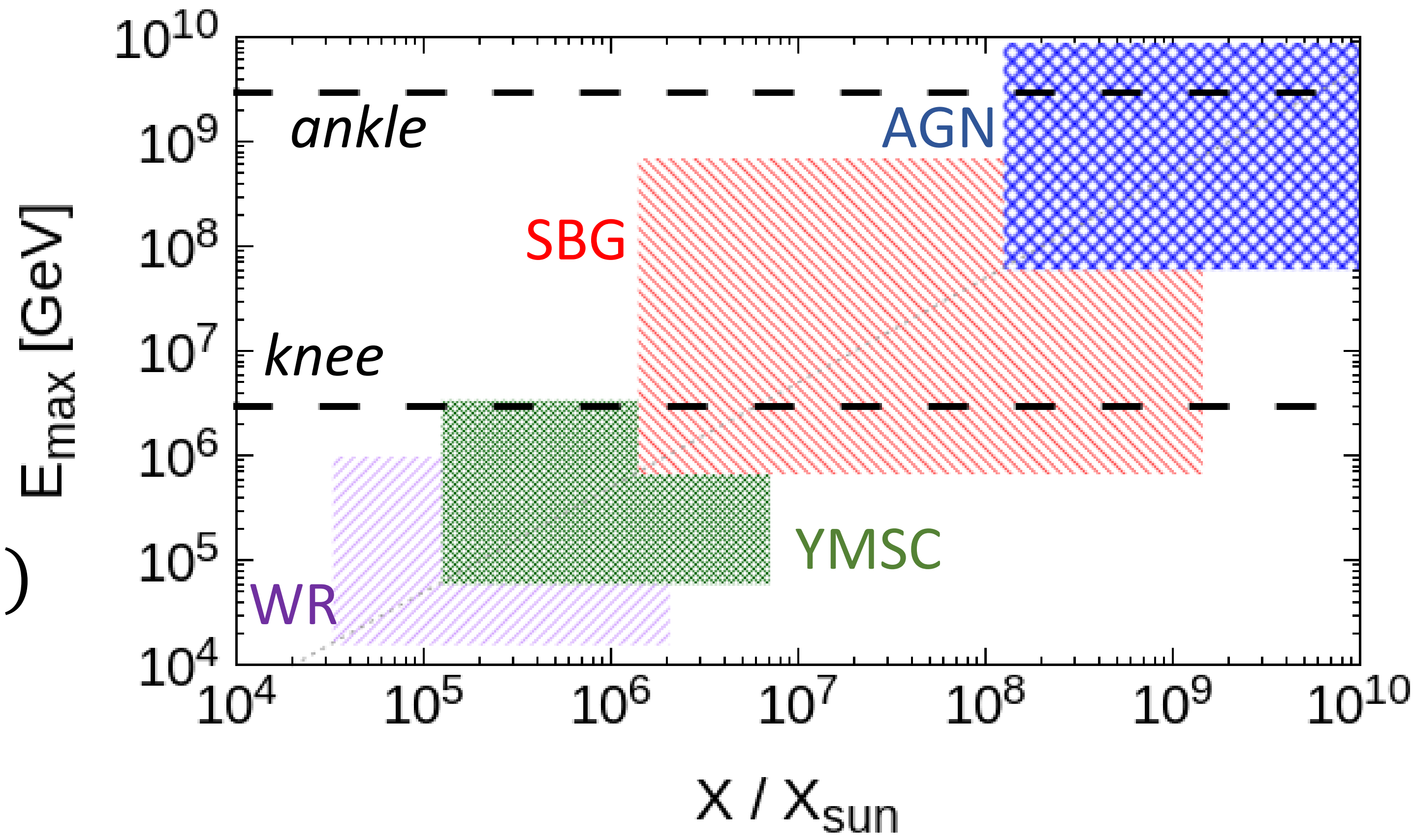
Maximum Energy: a first guess

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

$$U_B = \epsilon_B P_{ram} = \epsilon_B \frac{\dot{M}}{4\pi R_{sh}^2} u_1$$

$$E_{max} = E_{max}\left(u_1, \dot{M}\right) = E_{max}(\dot{E}, \dot{P})$$

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



Diverging flows as cosmic-ray sources

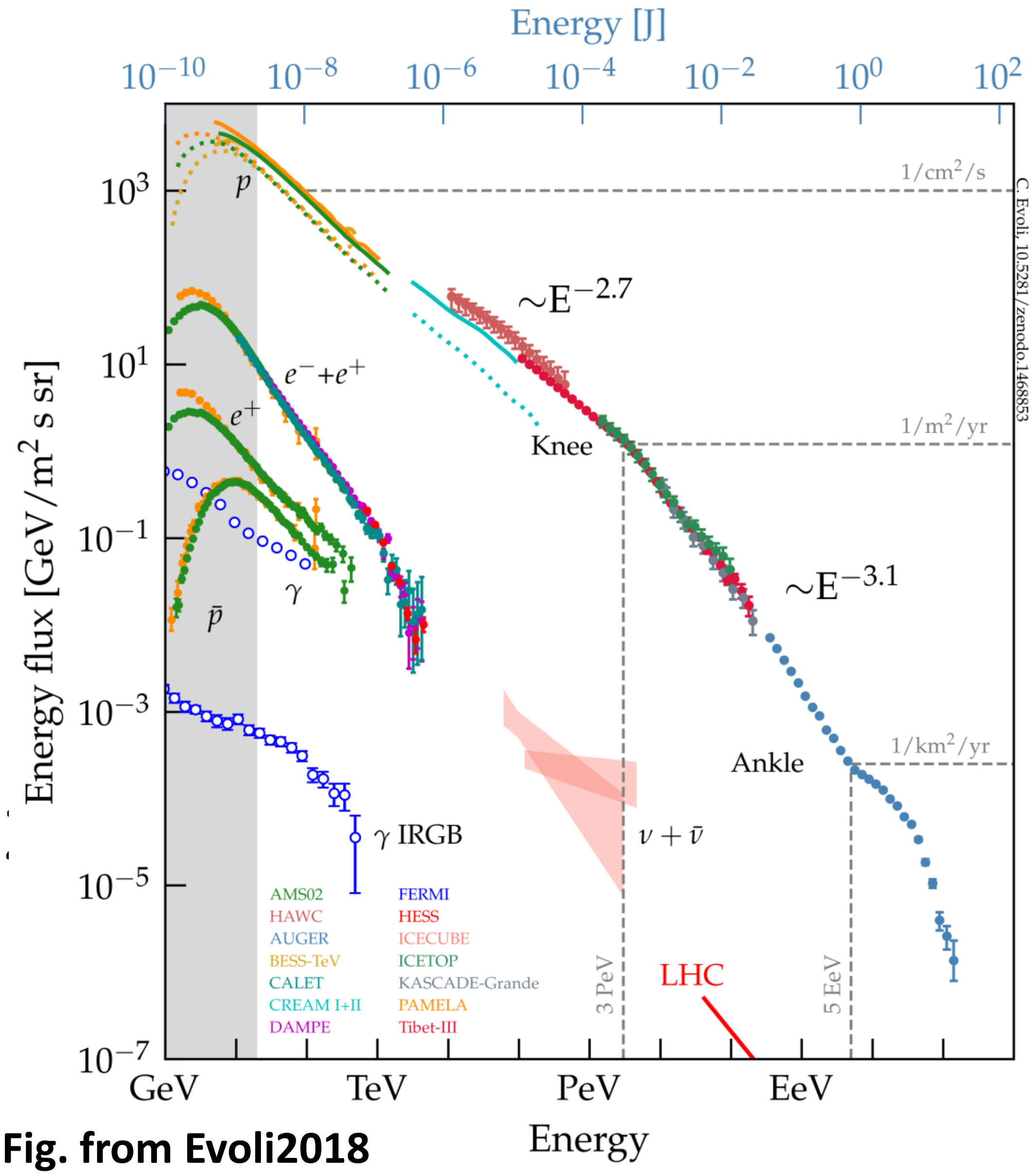
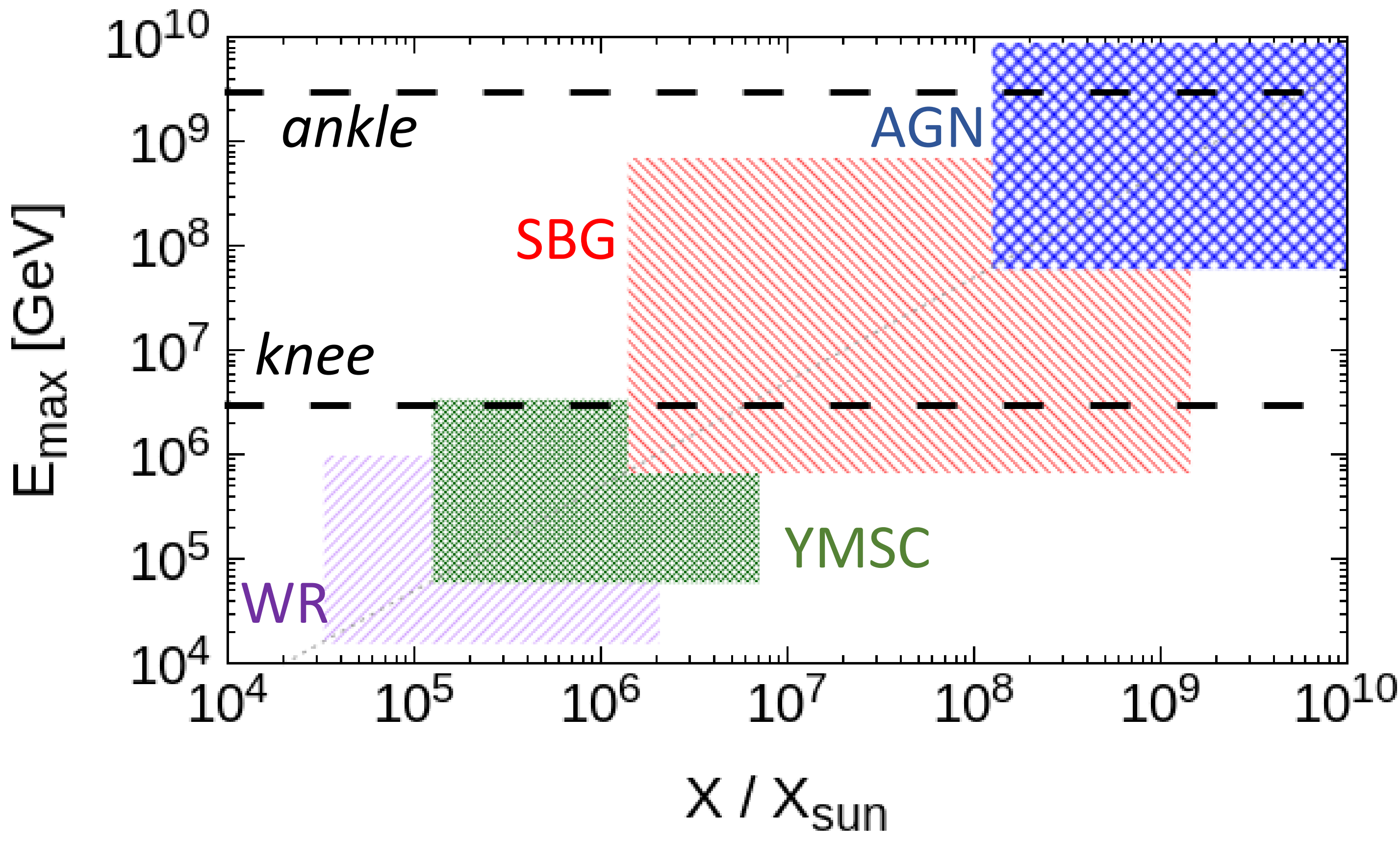


Fig. from Evoli2018



Diverging flows as cosmic-ray sources

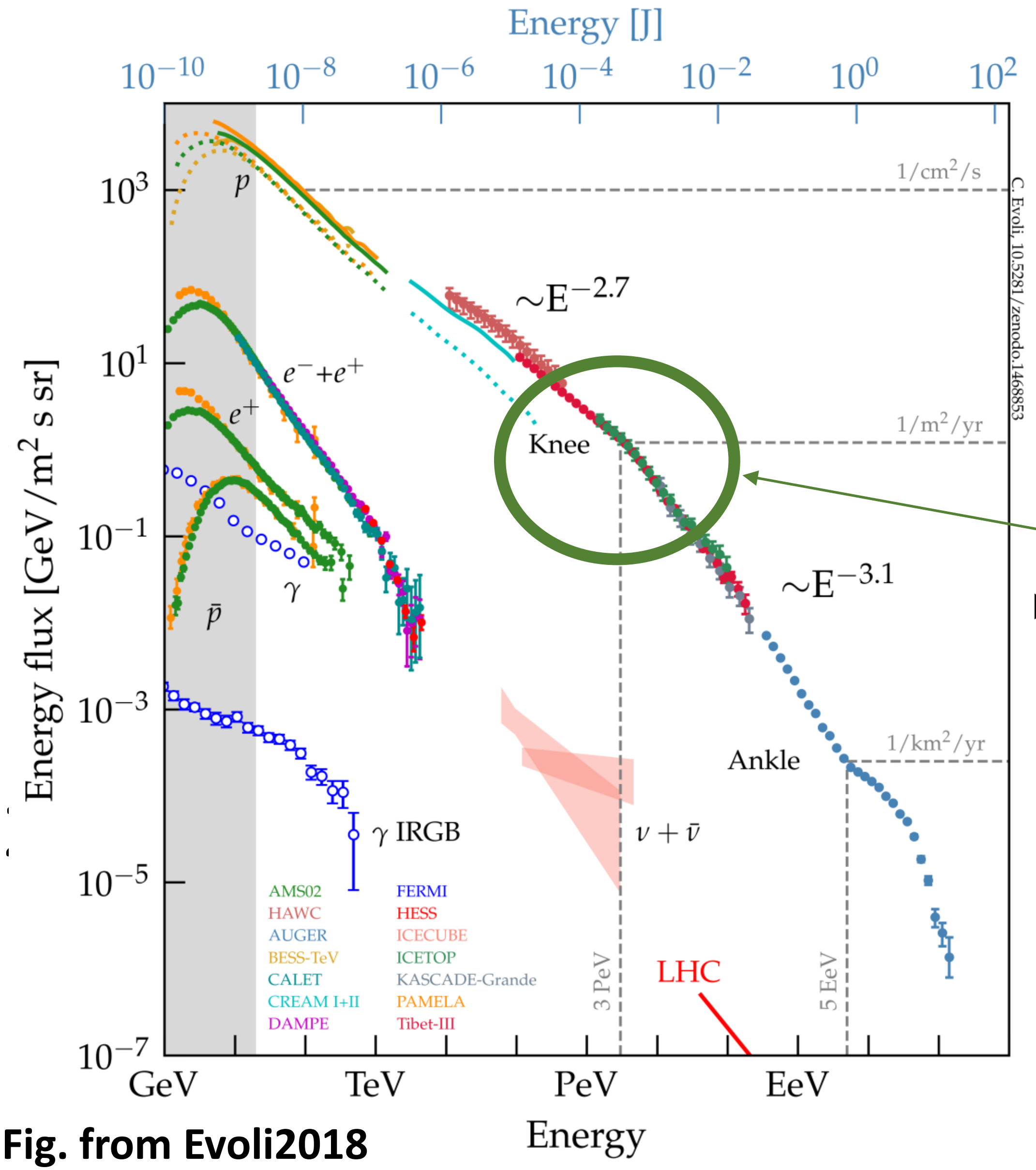
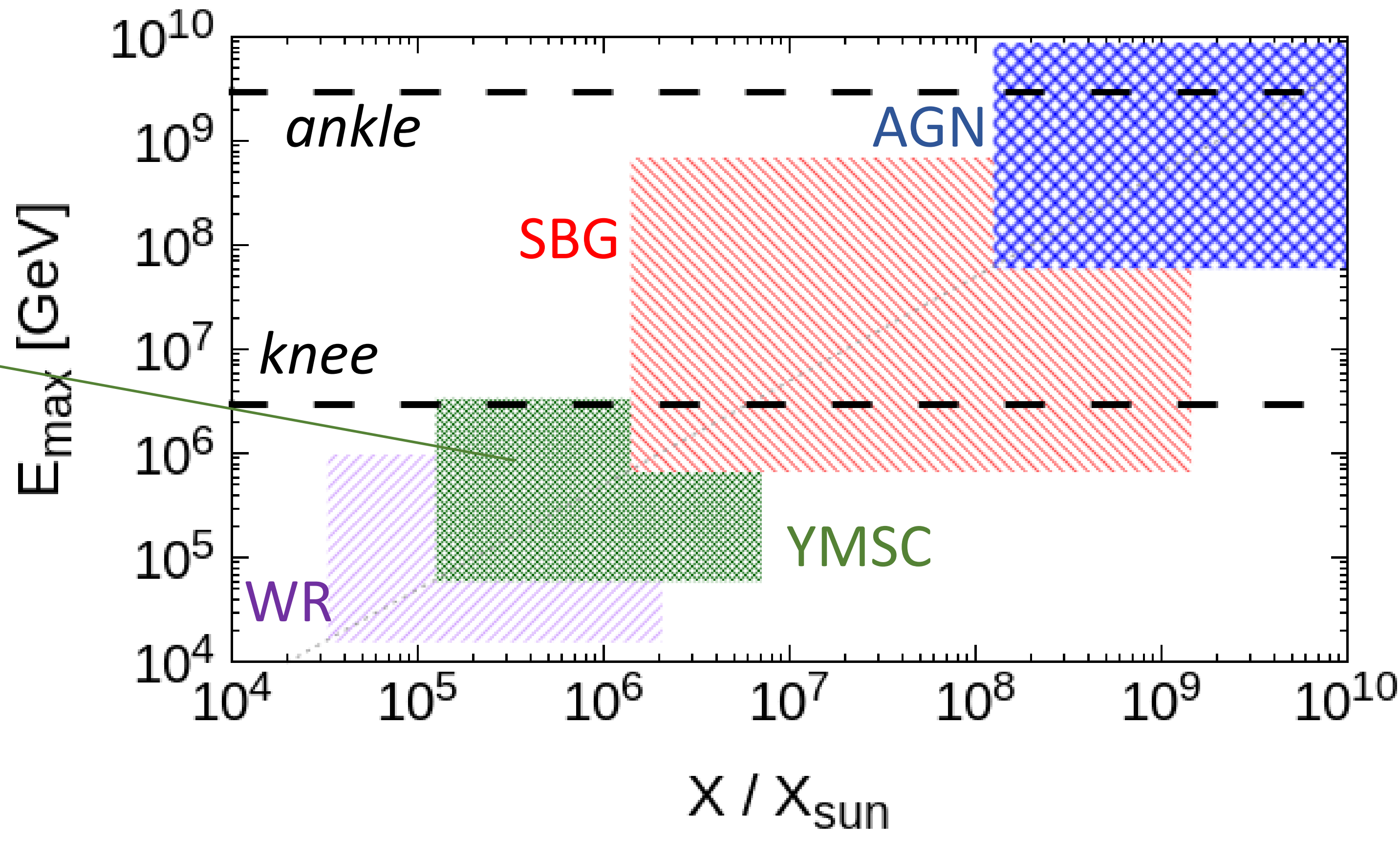


Fig. from Evoli2018



Diverging flows as cosmic-ray sources

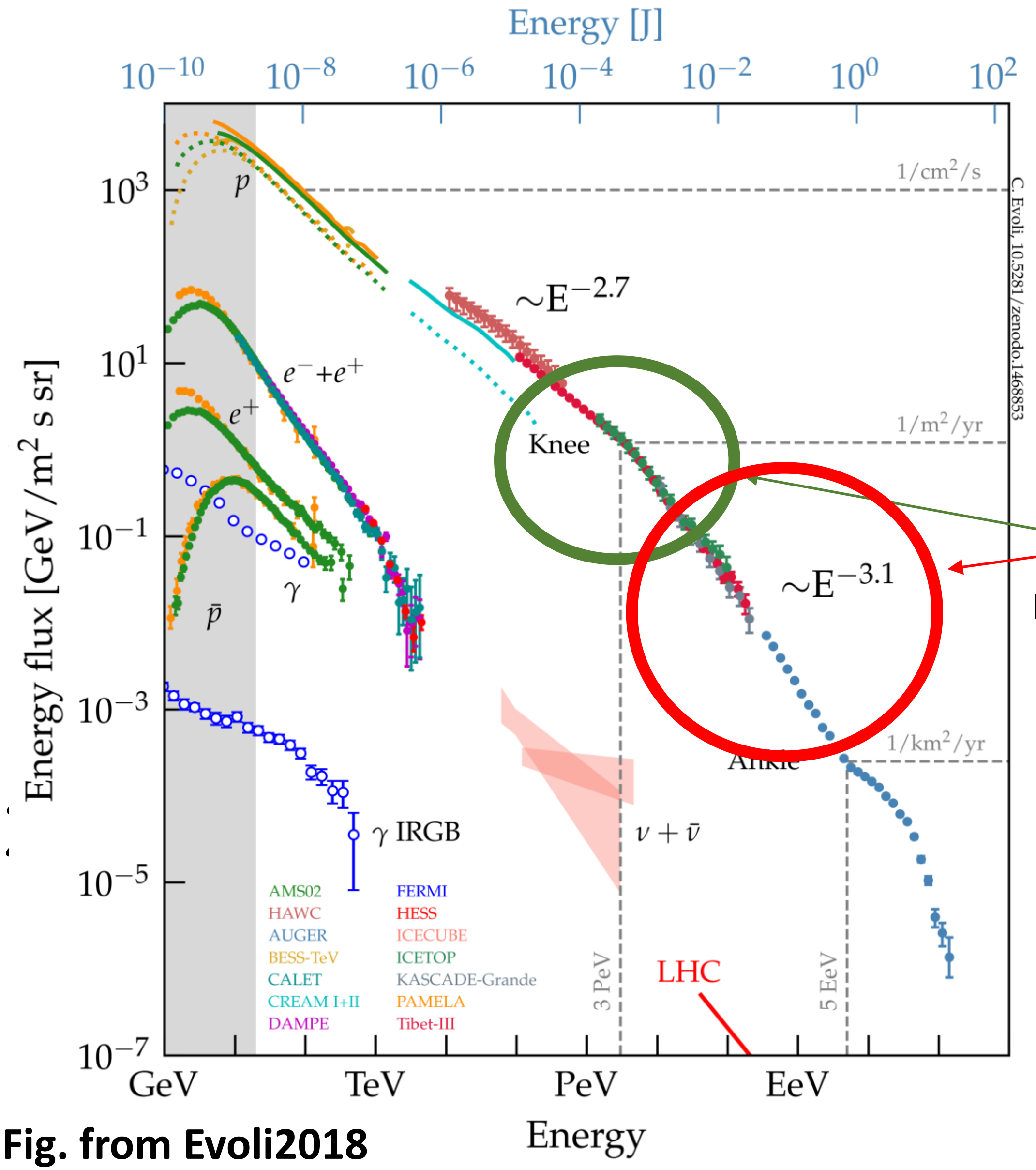
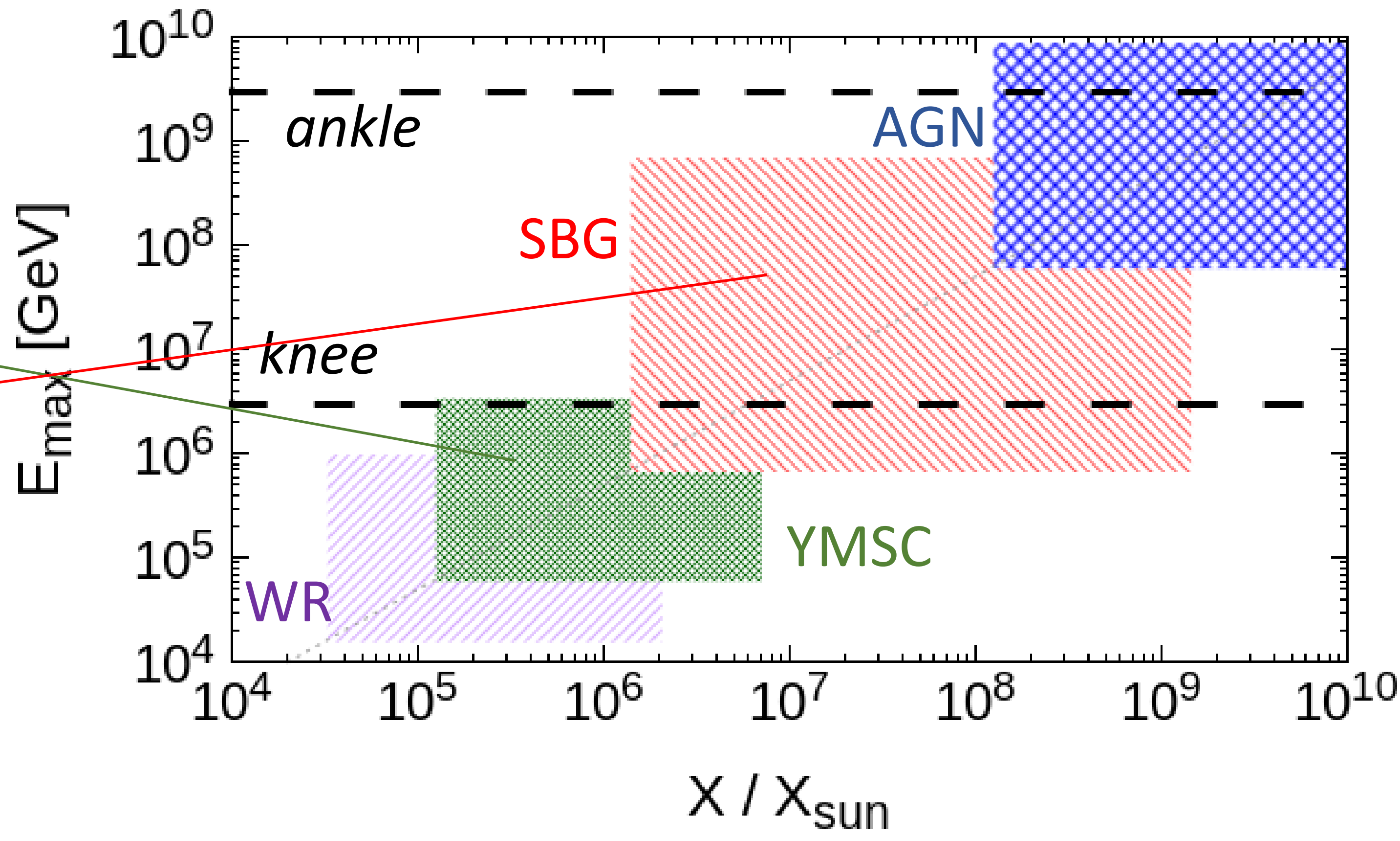


Fig. from Evoli2018



Diverging flows as cosmic-ray sources

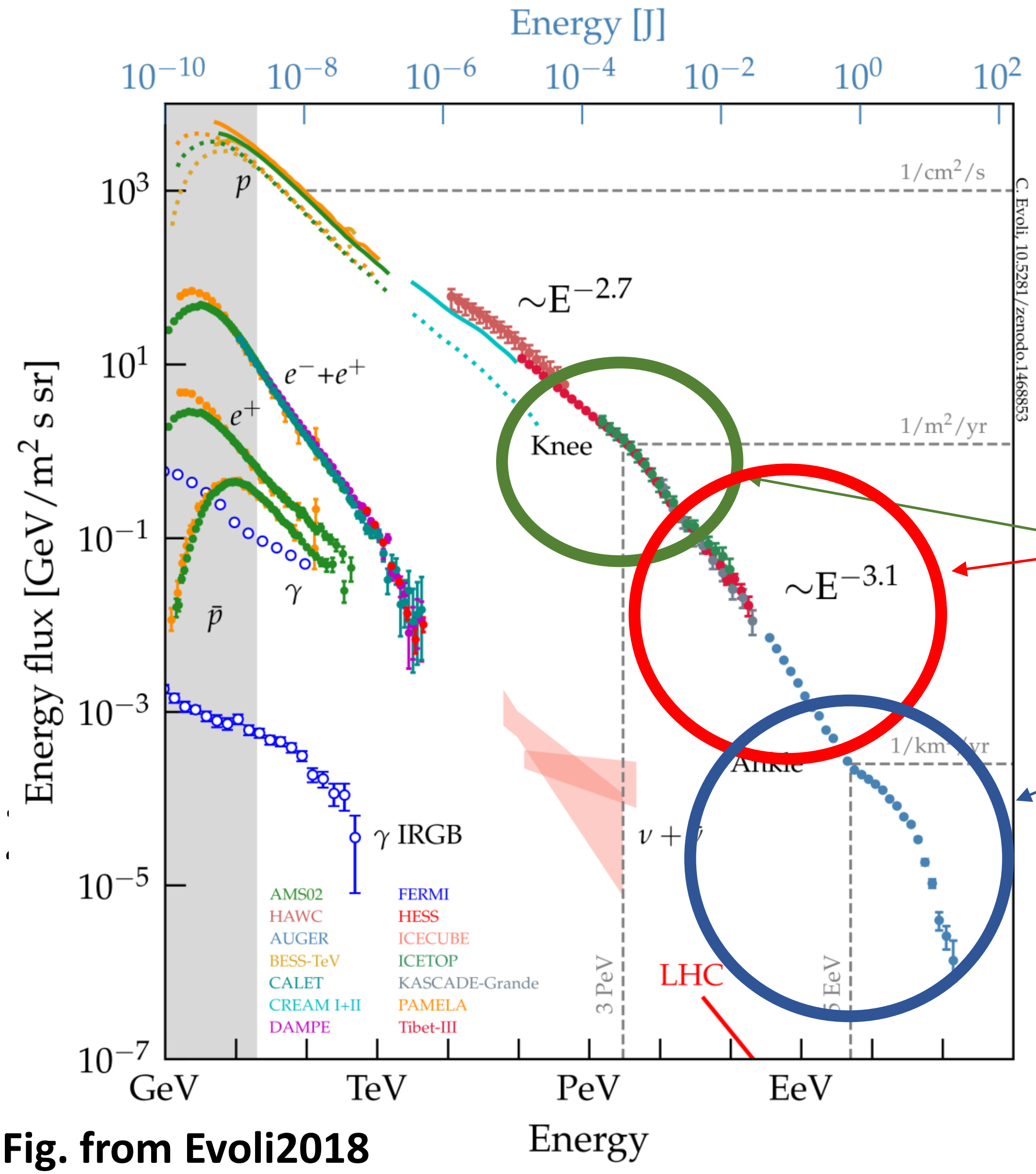
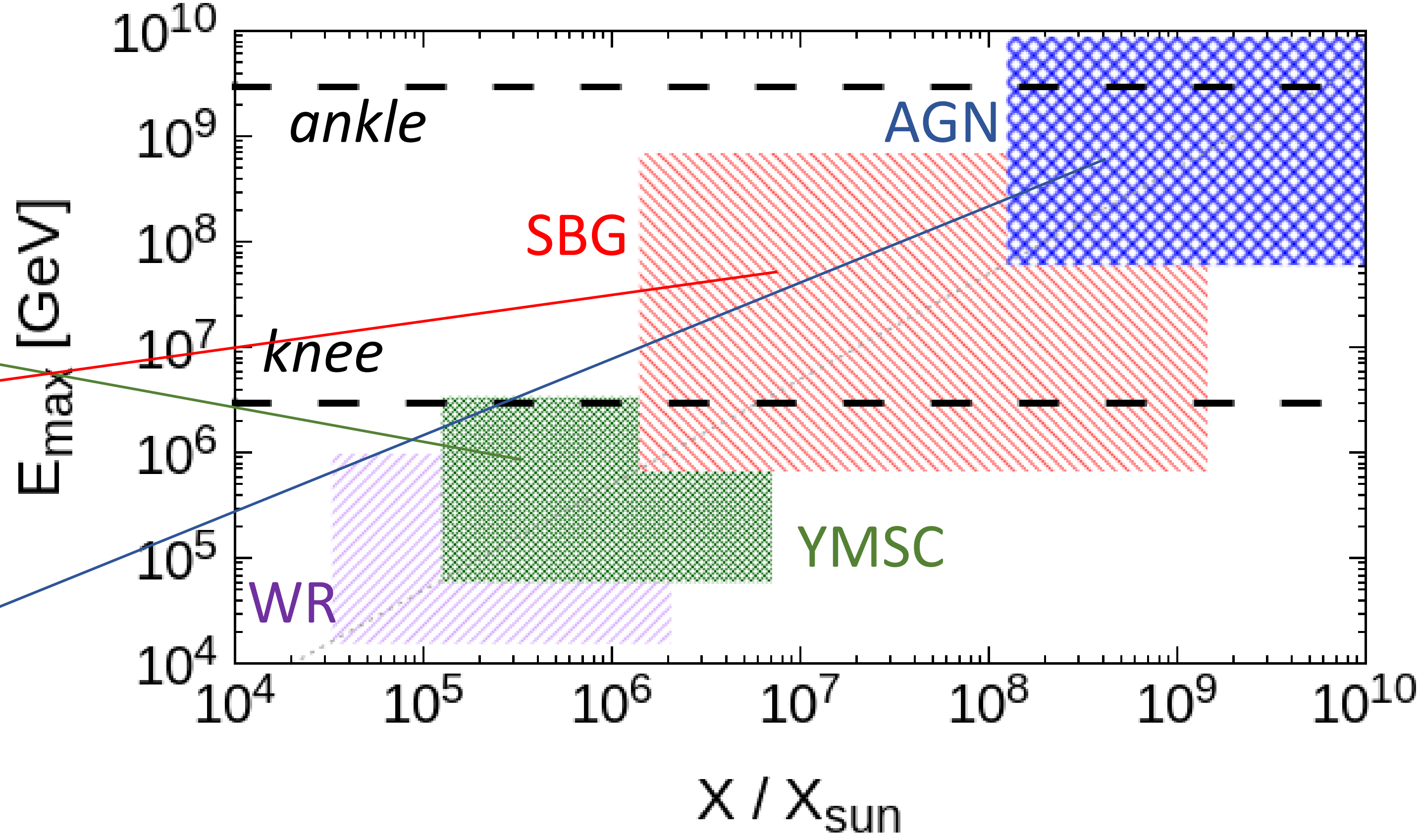


Fig. from Evoli2018

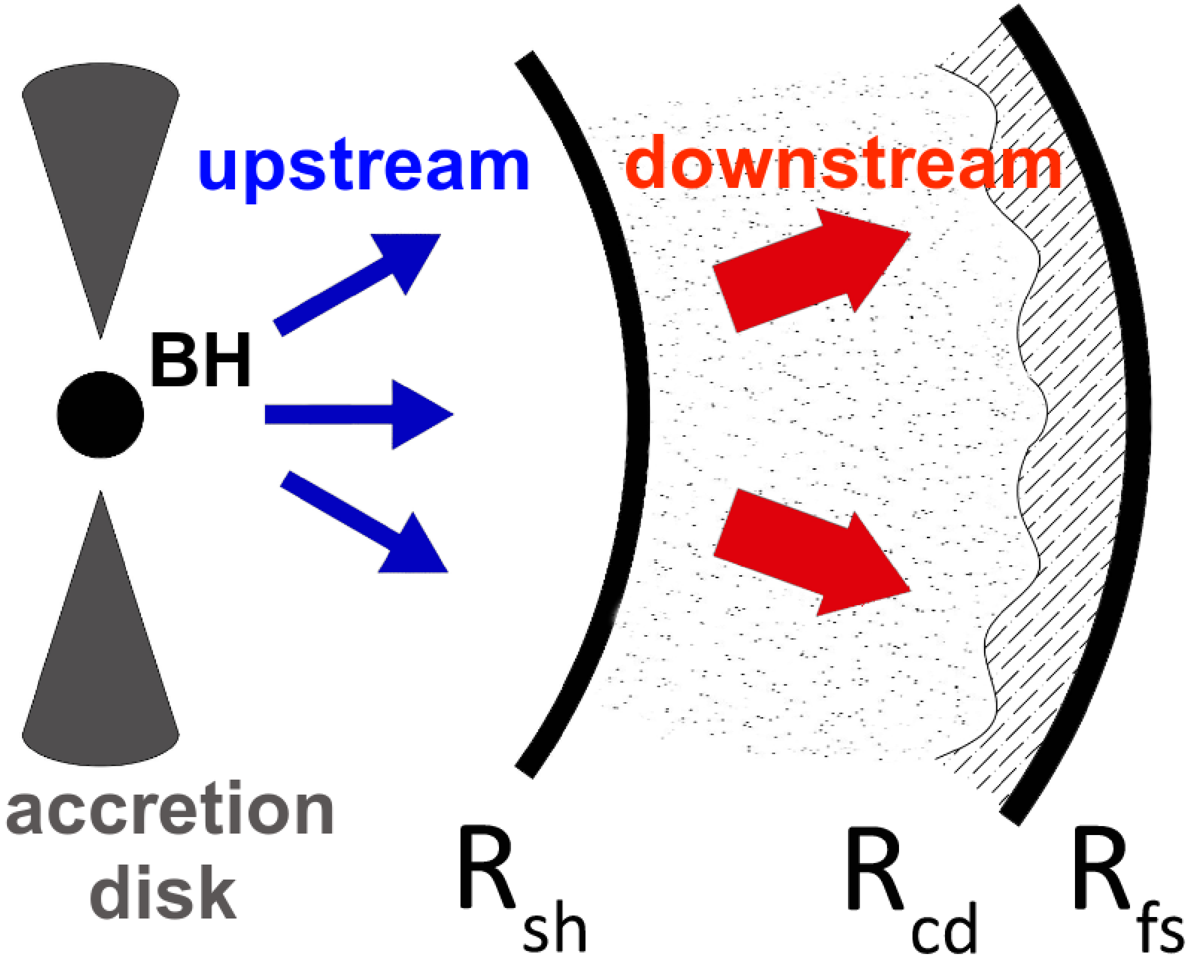


Outline

- Transport equation of Cosmic Rays
- Transport approach to diffusive shock acceleration
- Wind blown bubbles
- Modeling acceleration and multi-messenger radiation

Acceleration and transport model

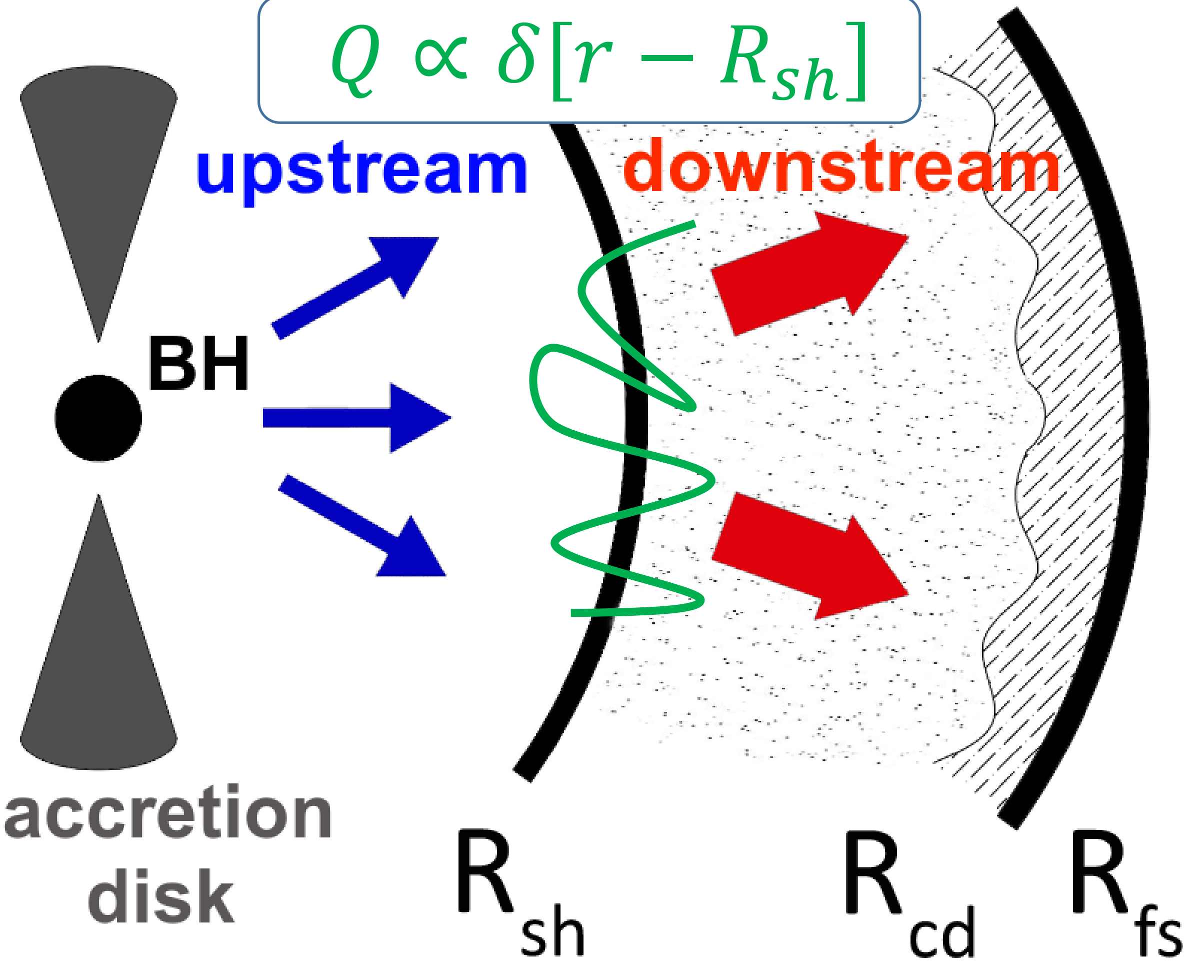
$$r^2 u(r)\partial_r f = \partial_r[r^2 D(r,p)\partial_r f] + \frac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p) - r^2 \Lambda(r,p)$$



Acceleration and transport model

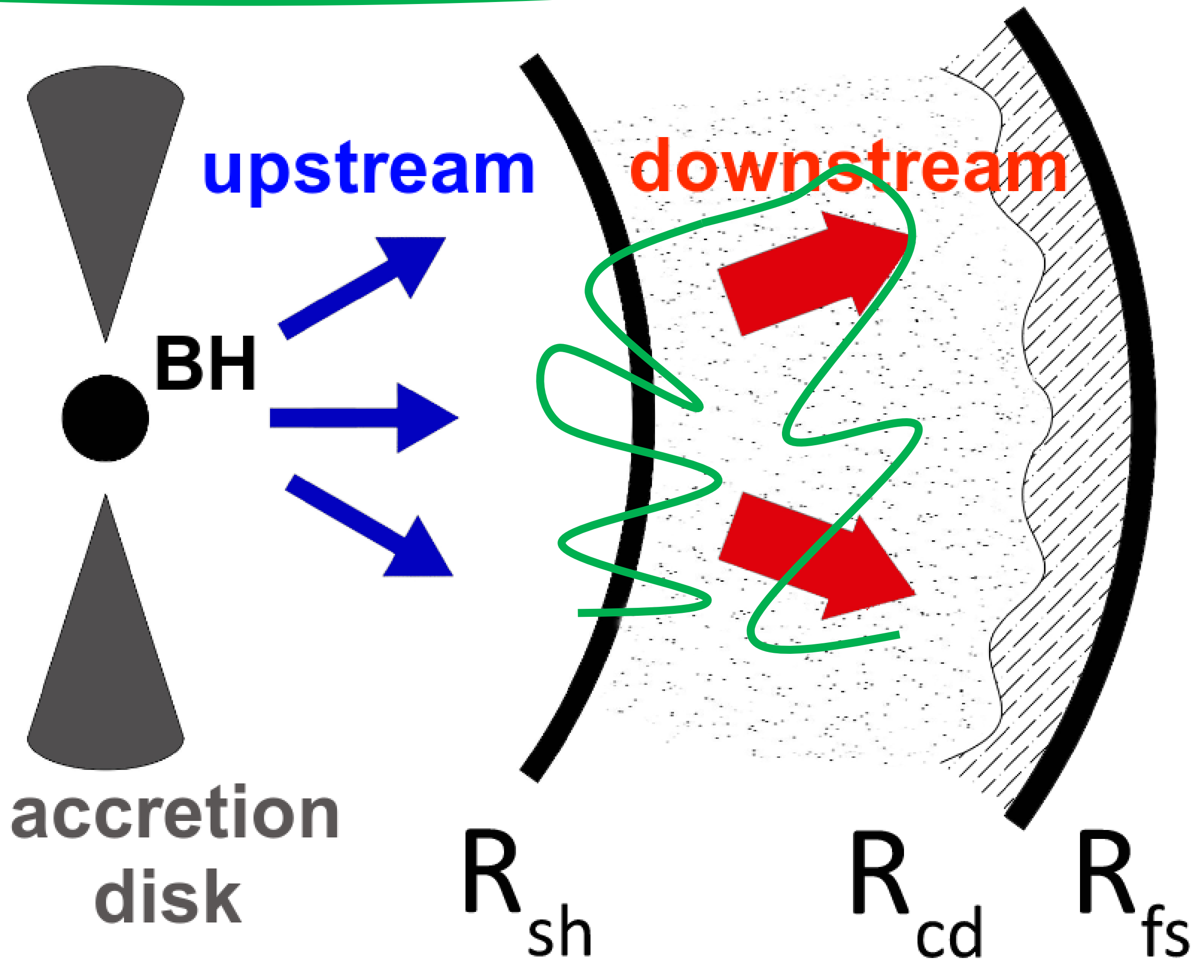
$$r^2u(r)\partial_r f = \partial_r[r^2D(r,p)\partial_r f] + \frac{1}{3}\partial_r[r^2u(r)]p\partial_p f + r^2Q(r,p) - r^2\Lambda(r,p)$$

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



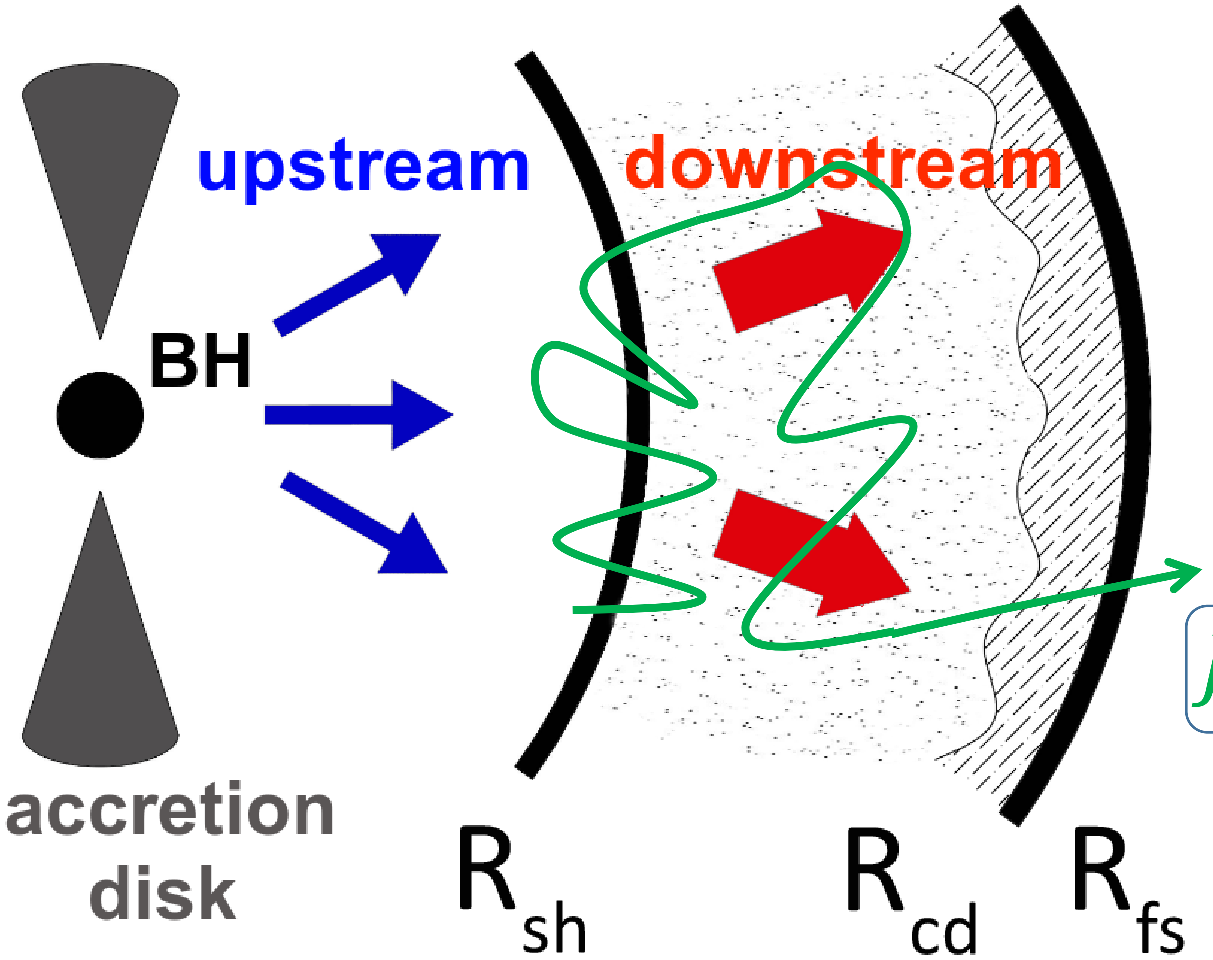
Acceleration and transport model

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



Acceleration and transport model

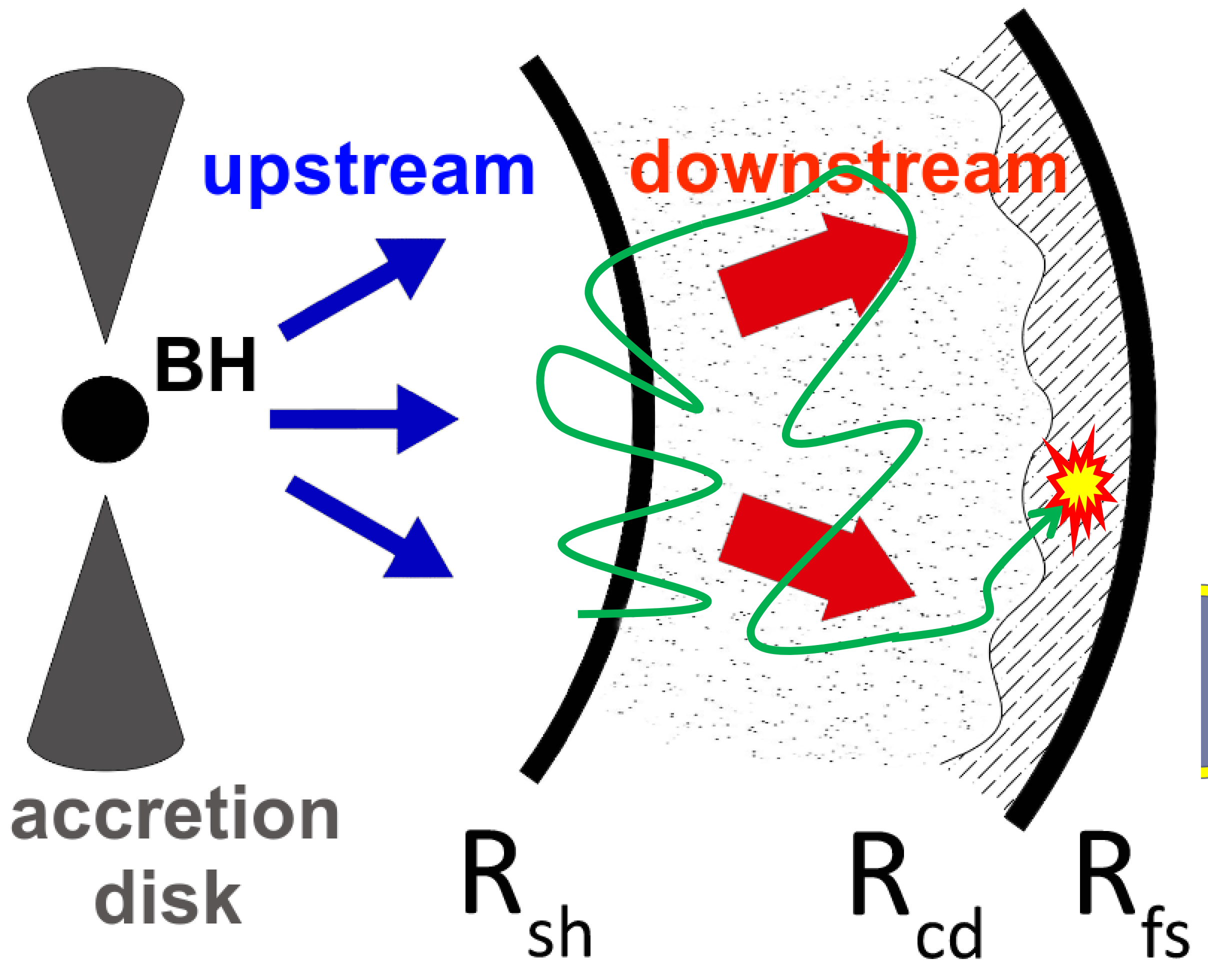
$$r^2 u(r)\partial_r f = \partial_r[r^2 D(r,p)\partial_r f] + \frac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p) - r^2 \Lambda(r,p)$$

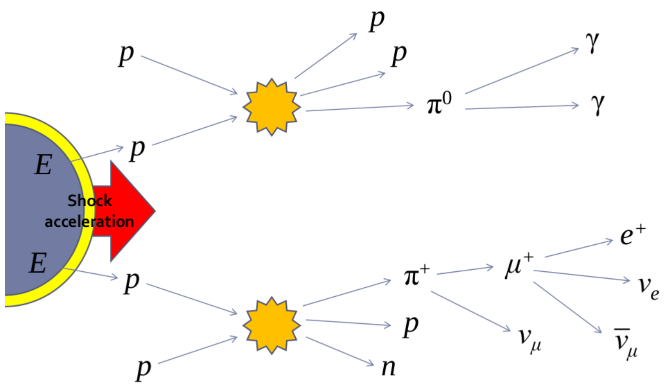


$J_{esc} \propto -D\partial_r f|_{R_{esc}}$

Acceleration and transport model

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

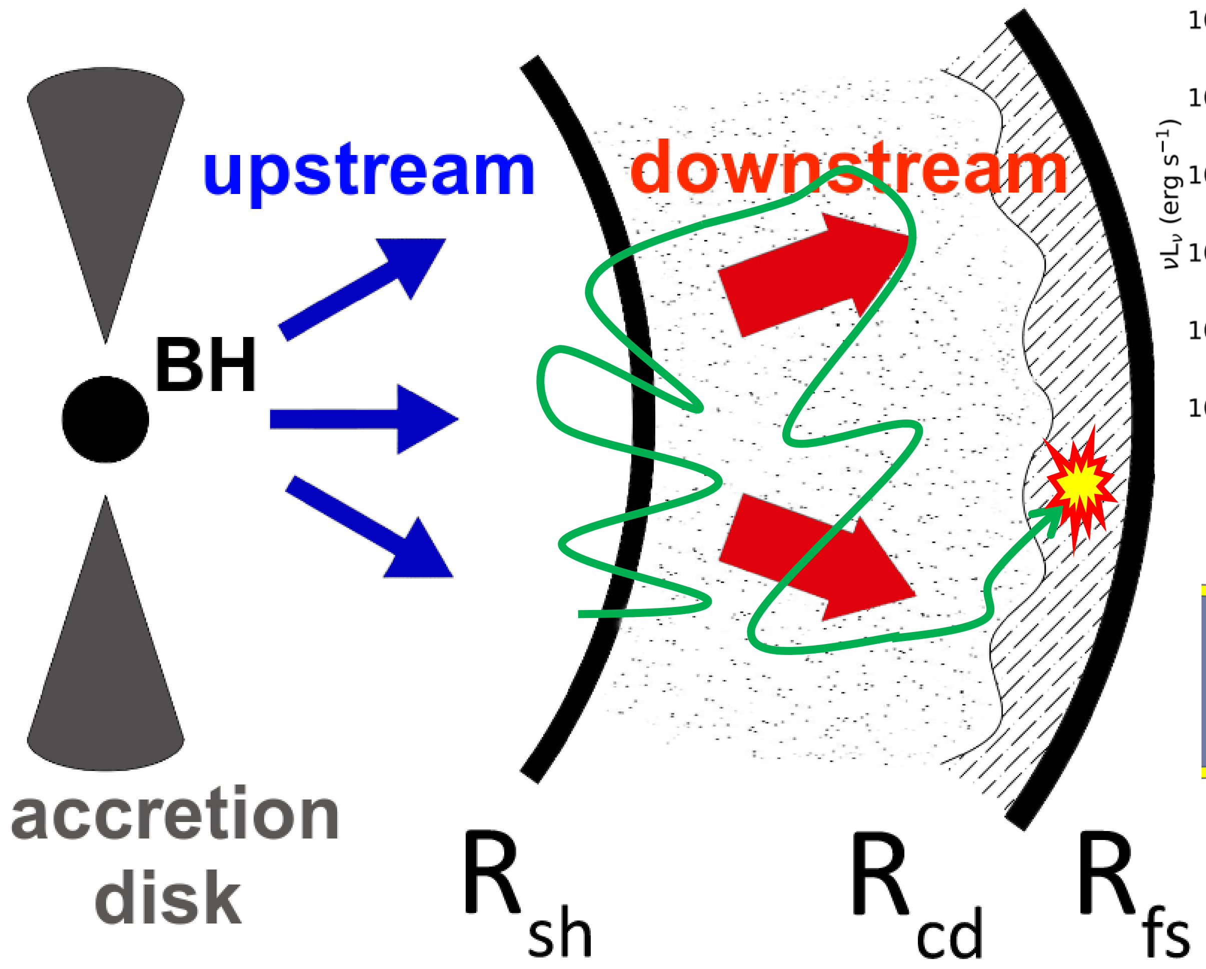


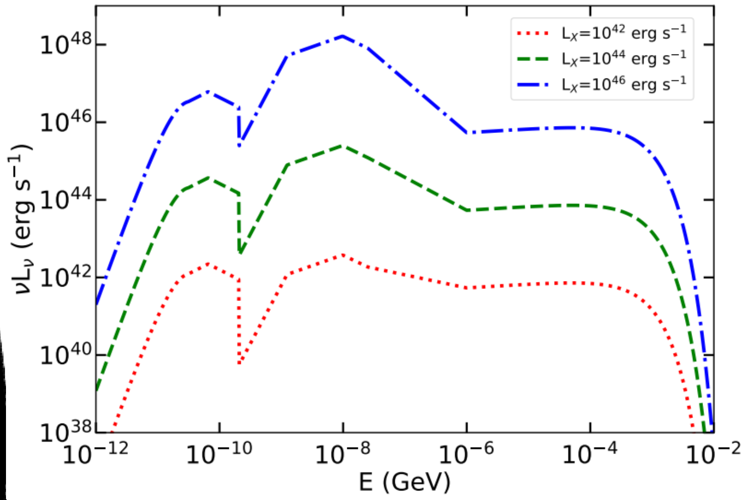


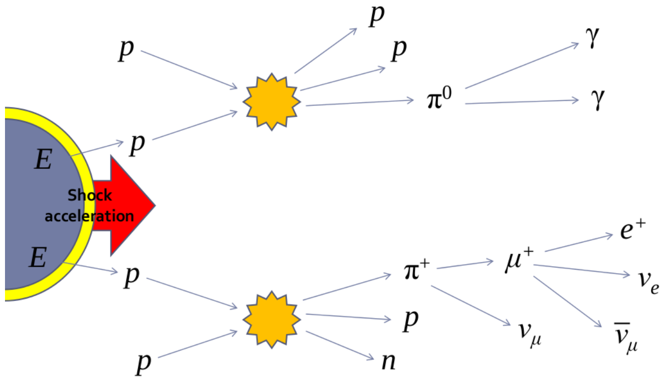
Website: http://www.astro.wisc.edu/~gvance/index.html

Acceleration and transport model

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

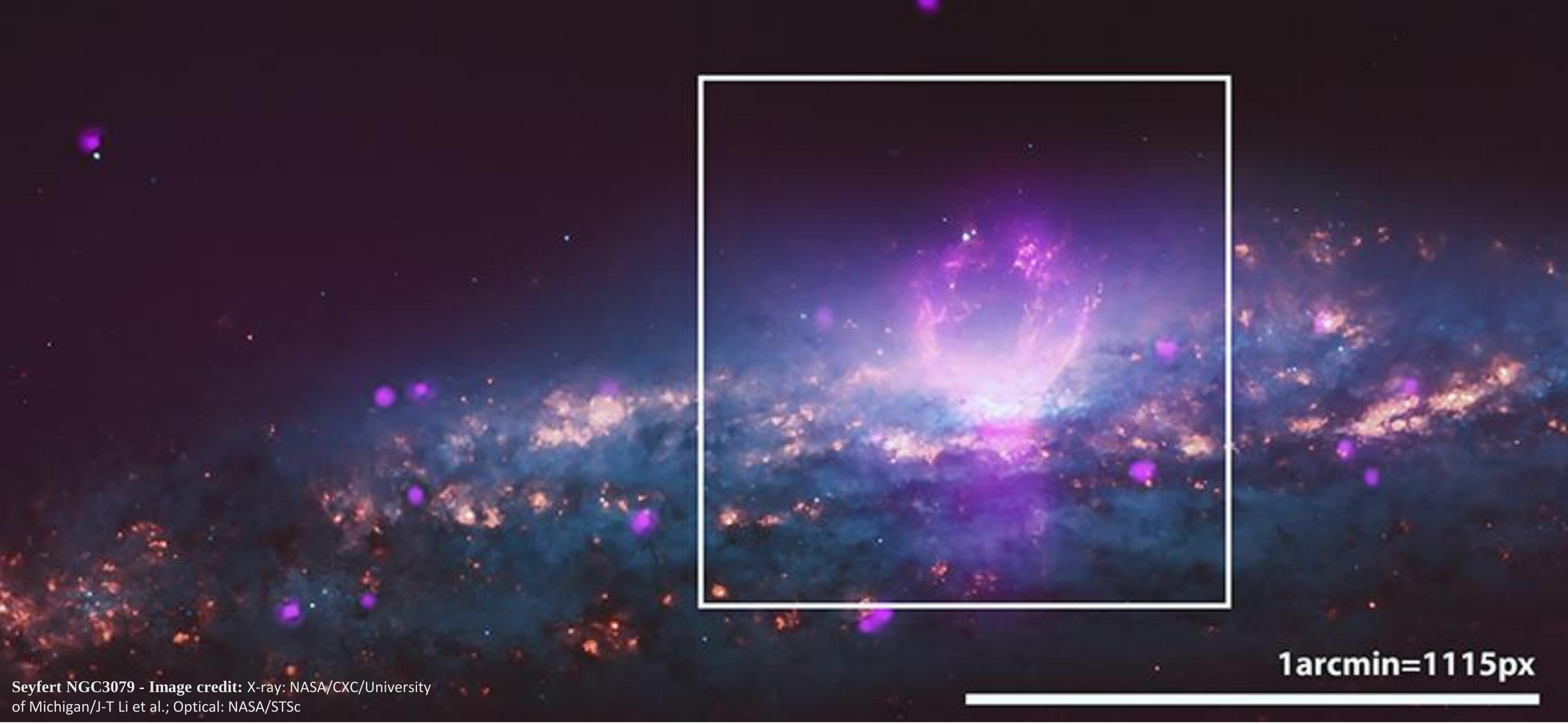






Website: http://www.astro.wisc.edu/~gvance/index.html

AGN-driven wind bubbles (UFOs)

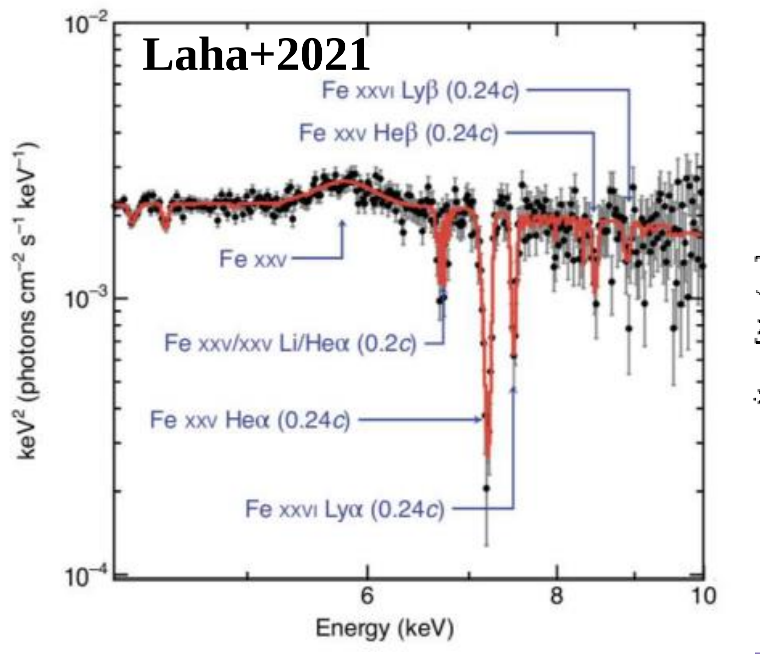


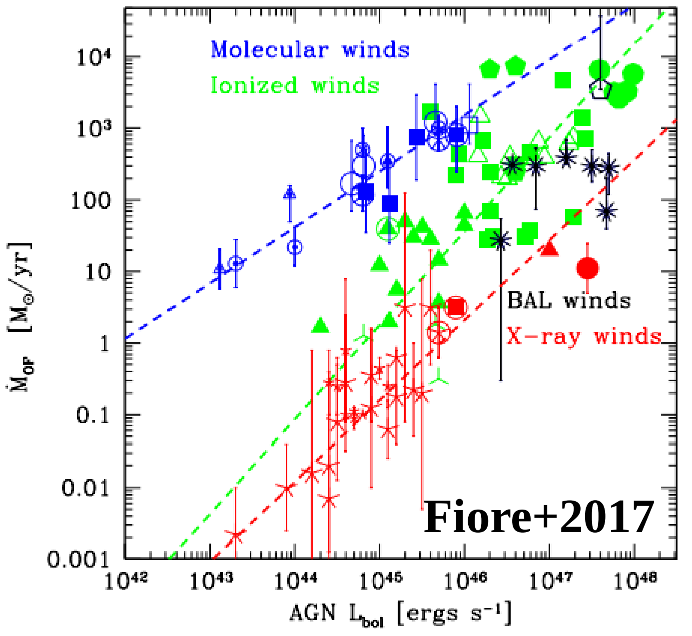
Seyfert NGC3079 - Image credit: X-ray: NASA/CXC/University of Michigan/J-T Li et al.; Optical: NASA/STSc

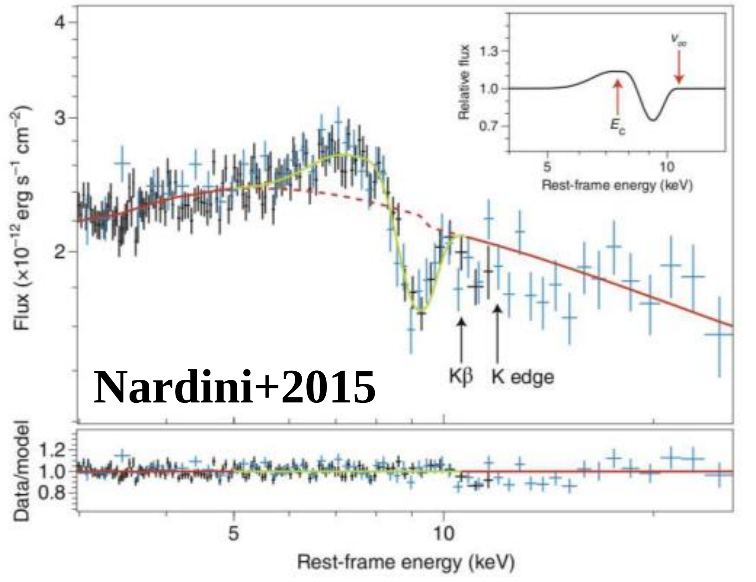
Seyfert NGC3079 - Image credit: X-ray: NASA/CXC/University of Michigan/J-T Li et al.; Optical: NASA/STSc

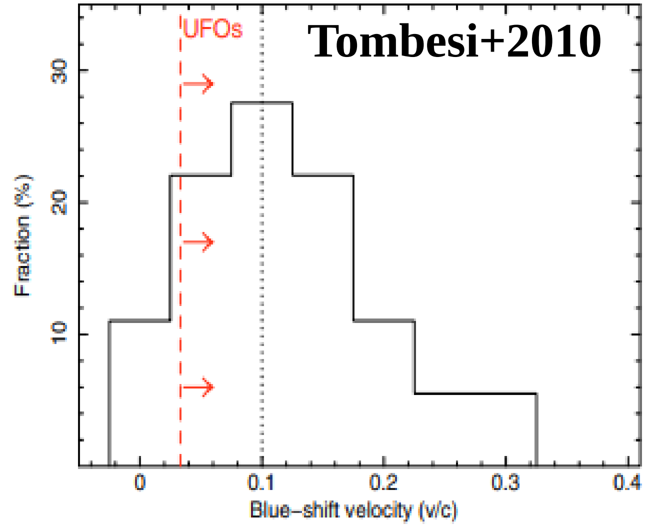
Ultra-Fast Outflows (UFOs)

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



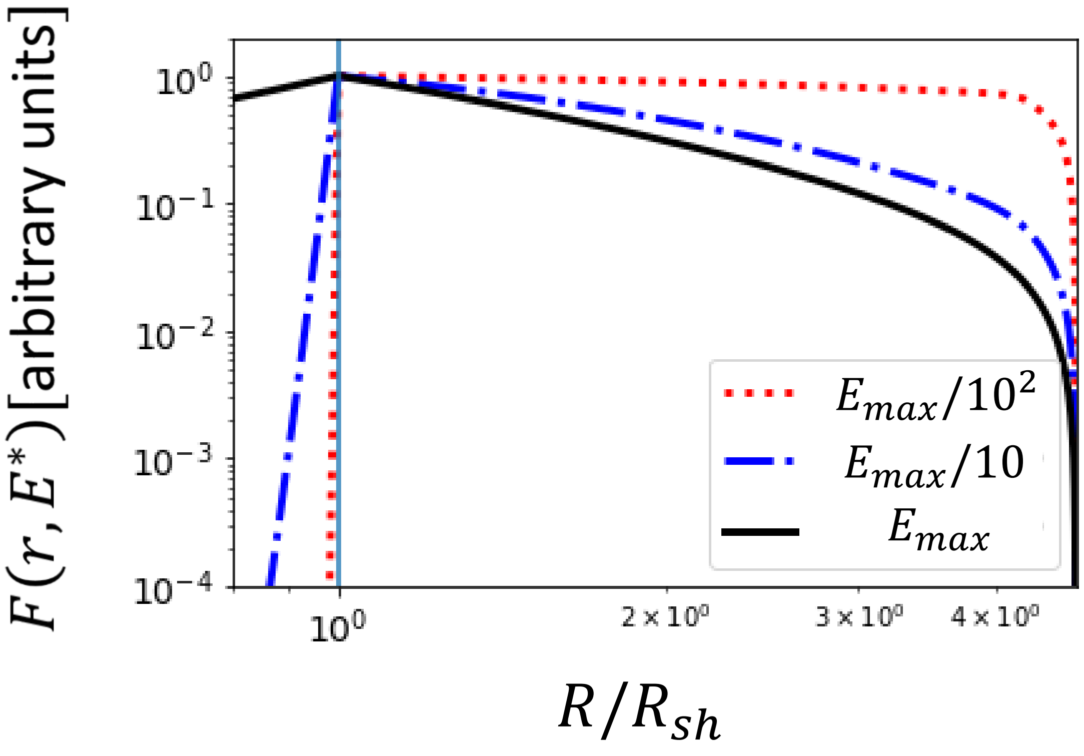


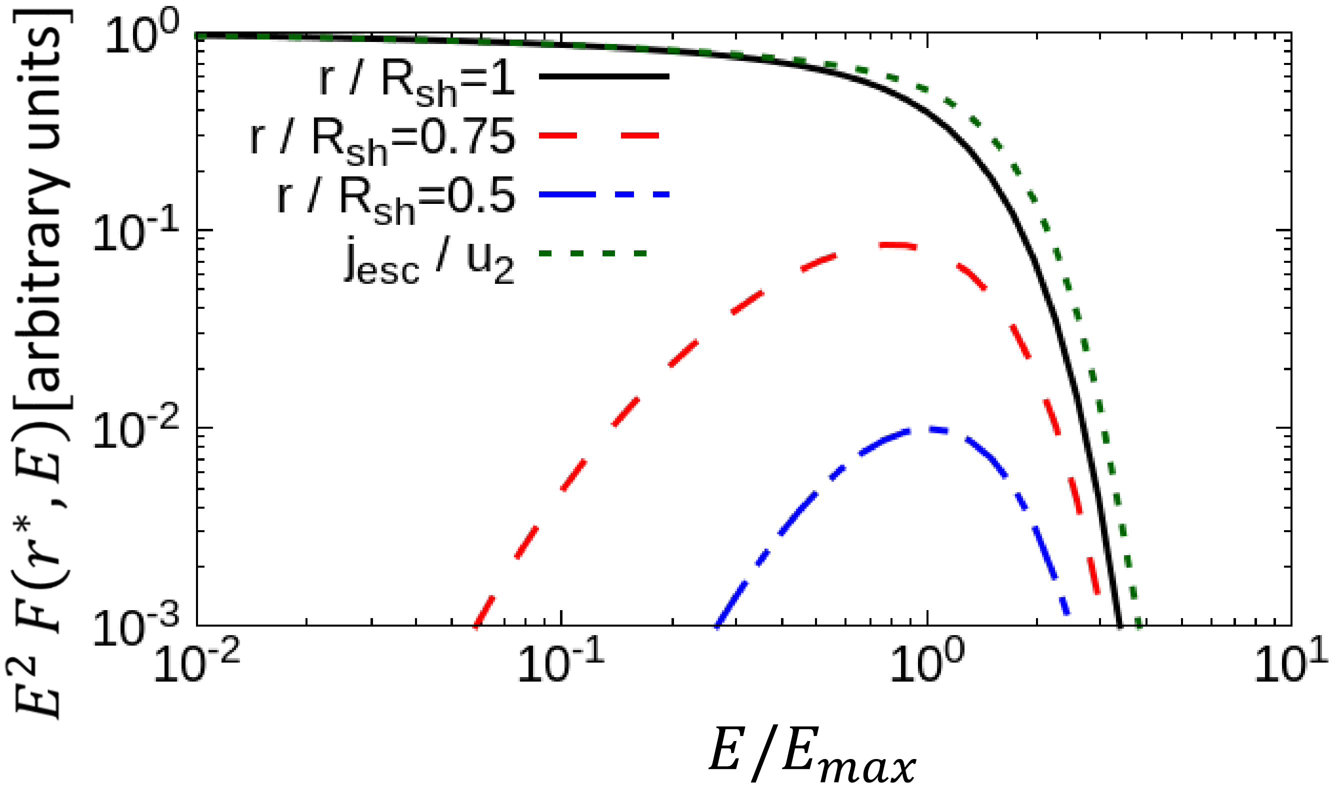




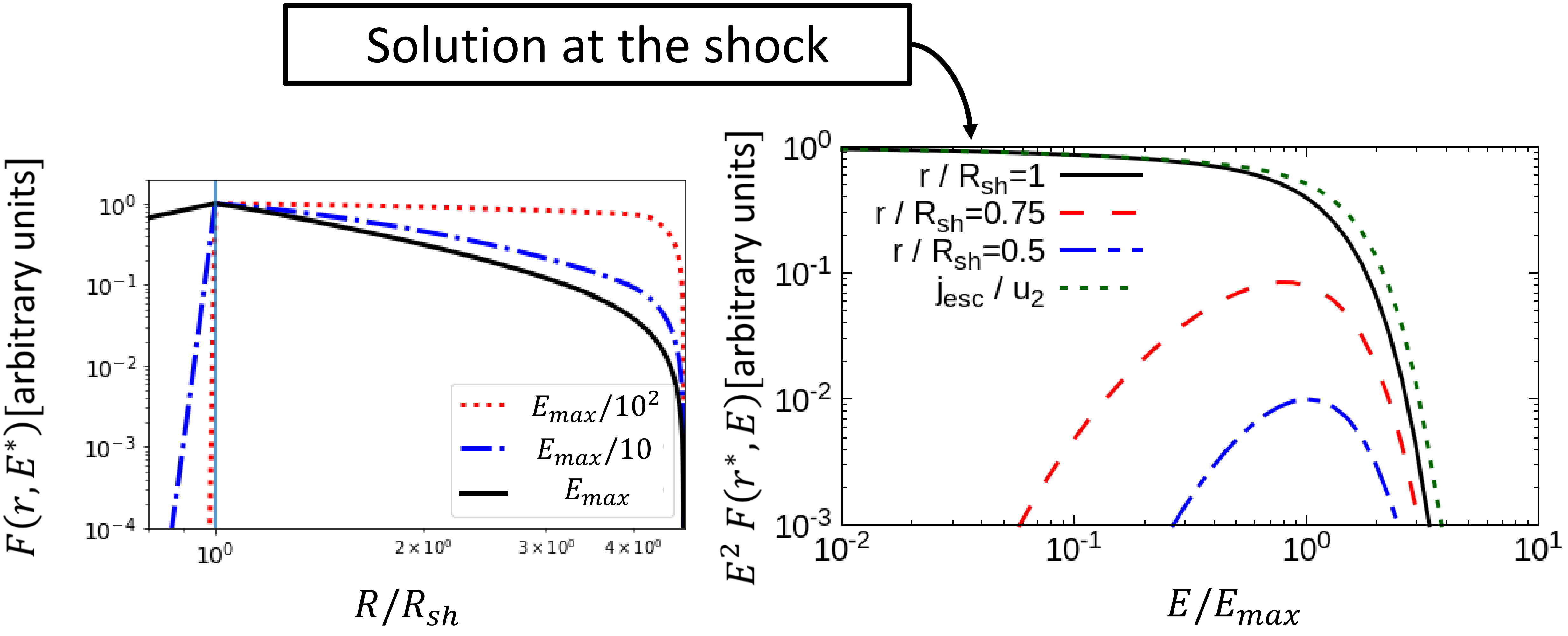
1arcmin=1115px

Solution: radial behavior and spectra

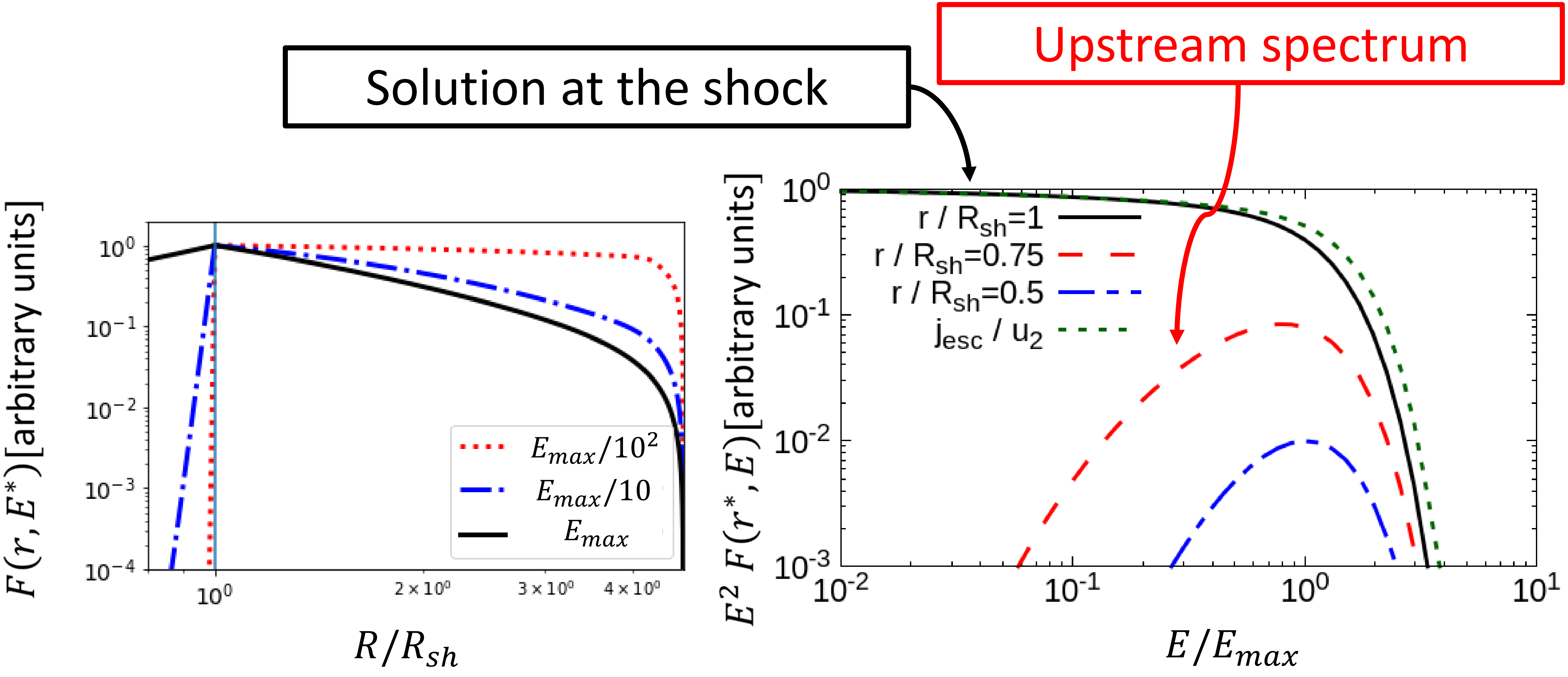




Solution: radial behavior and spectra

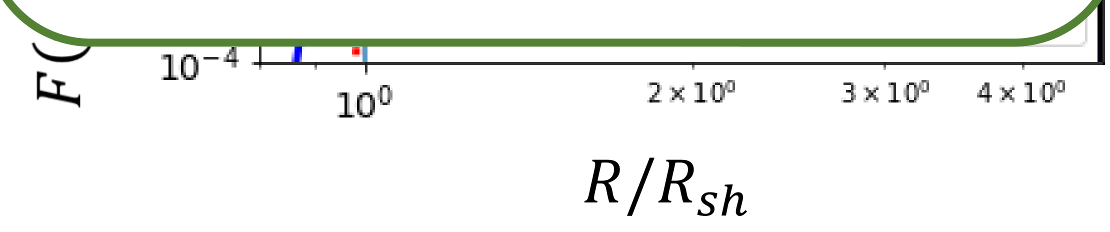


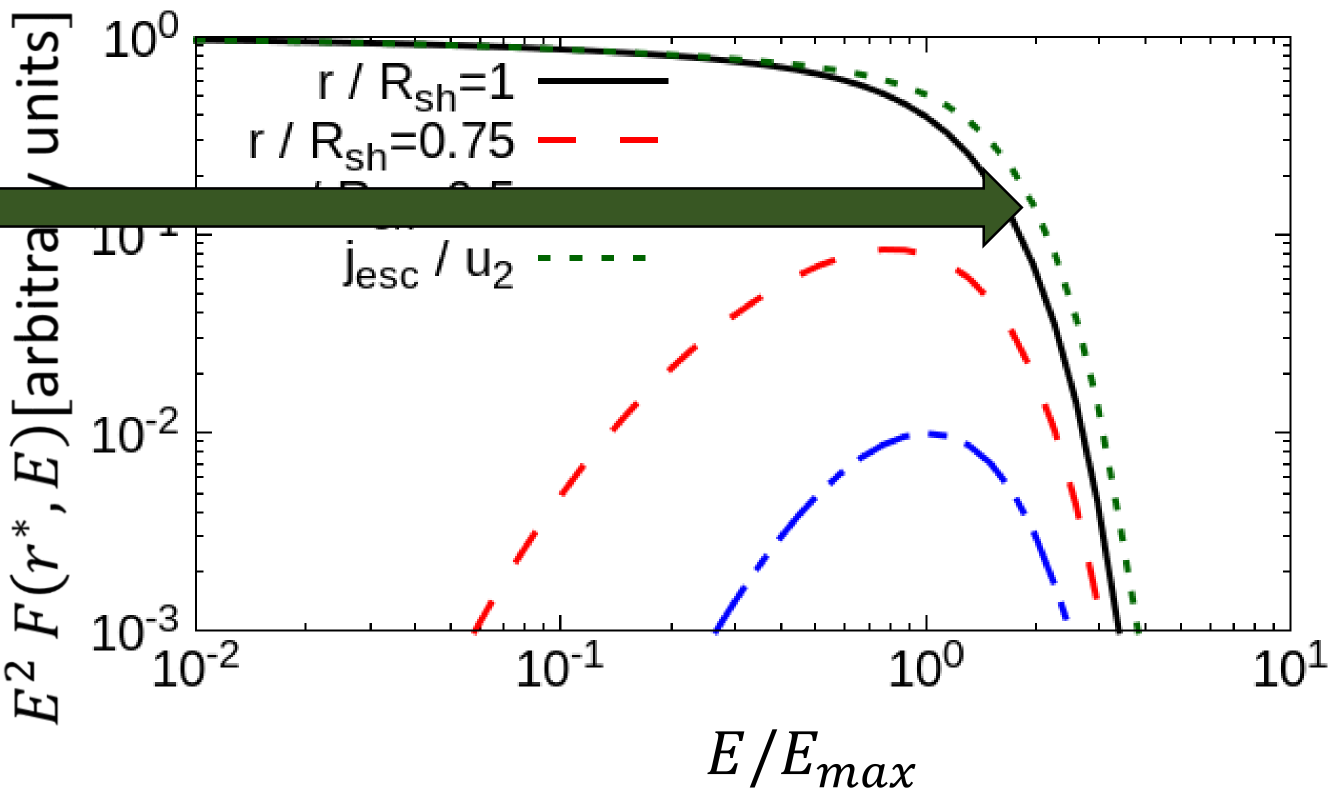
Solution: radial behavior and spectra



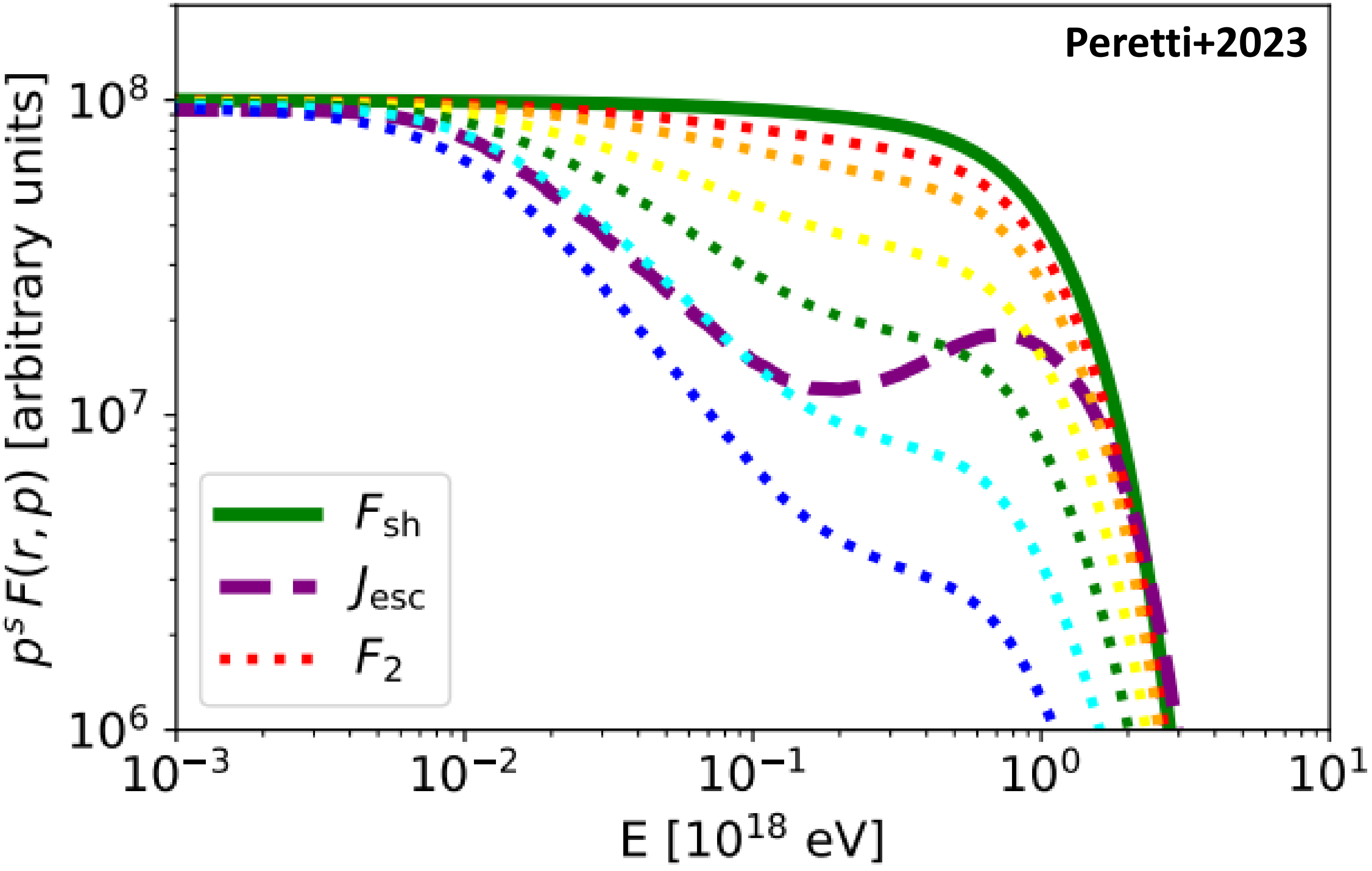
Solution: radial behavior and spectra

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



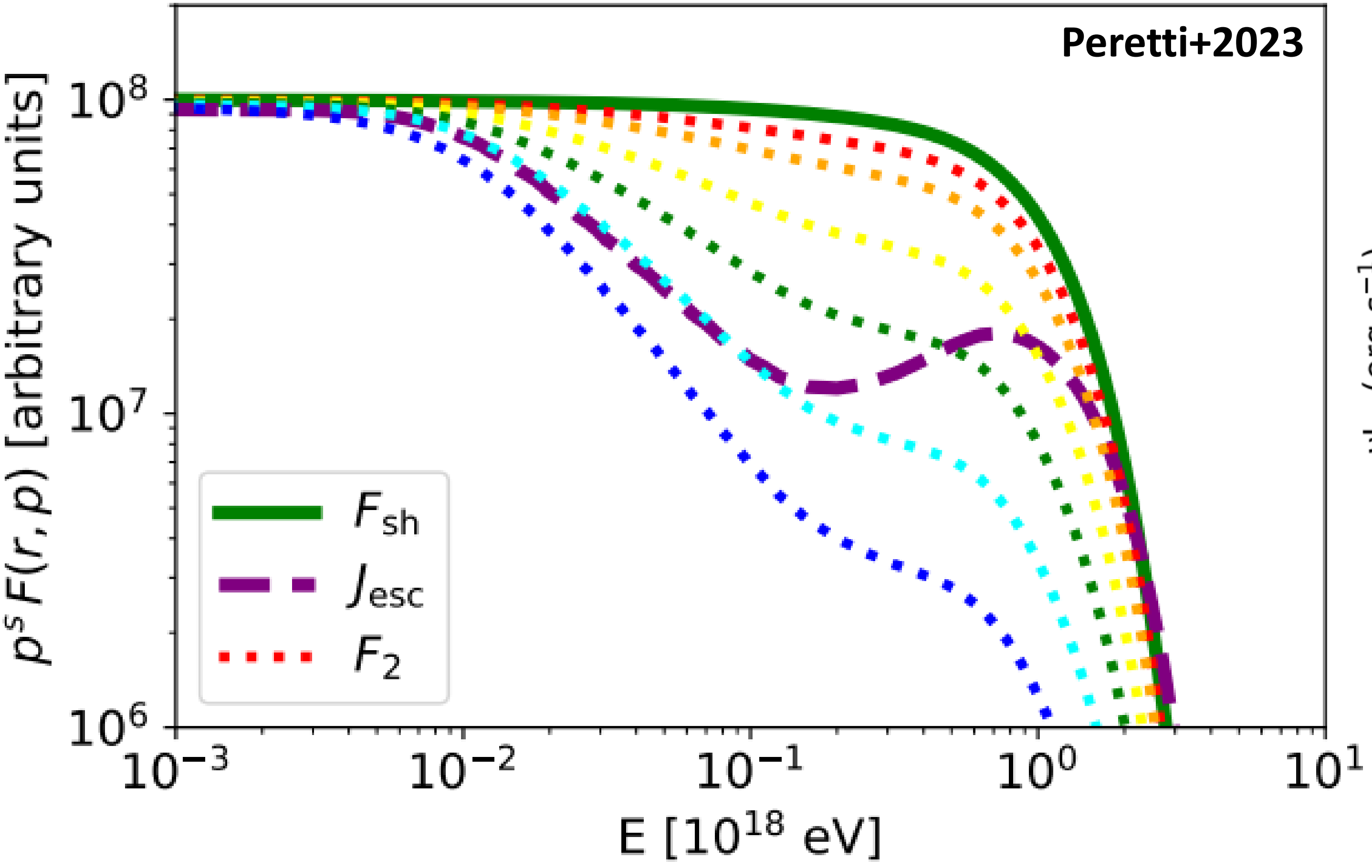


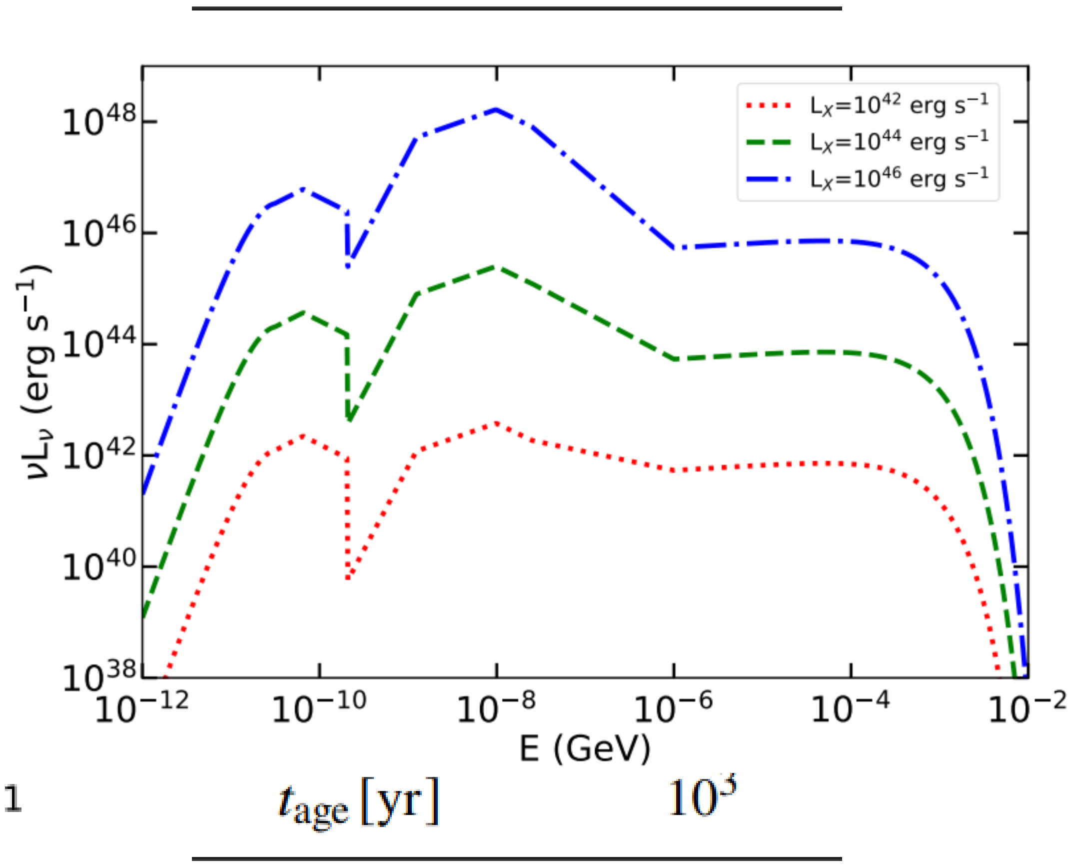
The prototype UFO



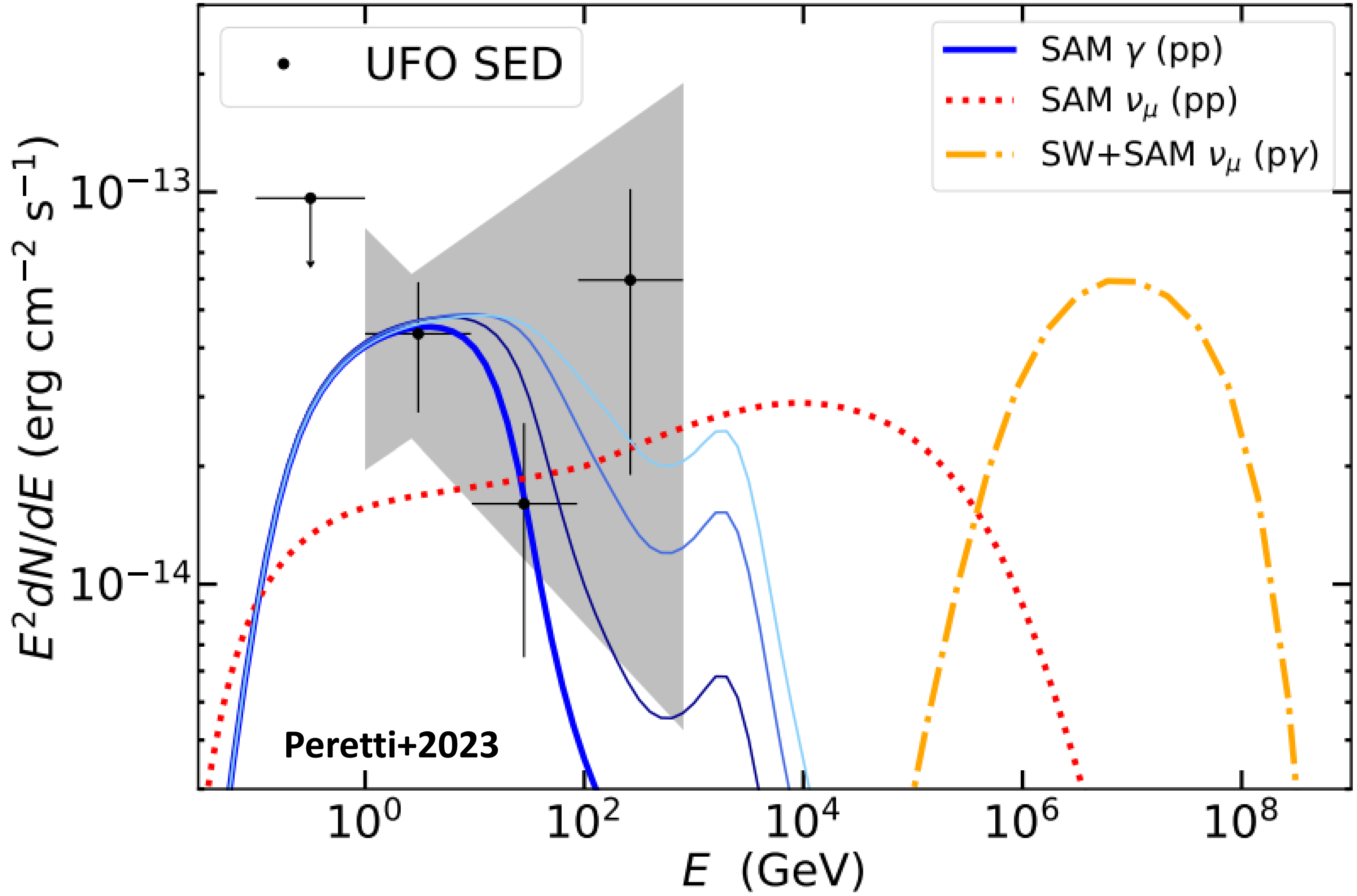
Parameter	benchmark
u_1/c	0.2
$\dot{M}\,[\mathrm{M_\odot\,yr^{-1}}]$	10^{-1}
ξ_{CR}	0.05
ϵ_B	0.05
l_c [pc]	10^{-2}
δ	3/2
$L_X\,[\mathrm{erg\,s^{-1}}]$	10^{44}
$n_{ISM}\,[\mathrm{cm^{-3}}]$	10^4
t_{age} [yr]	10^3

The prototype UFO



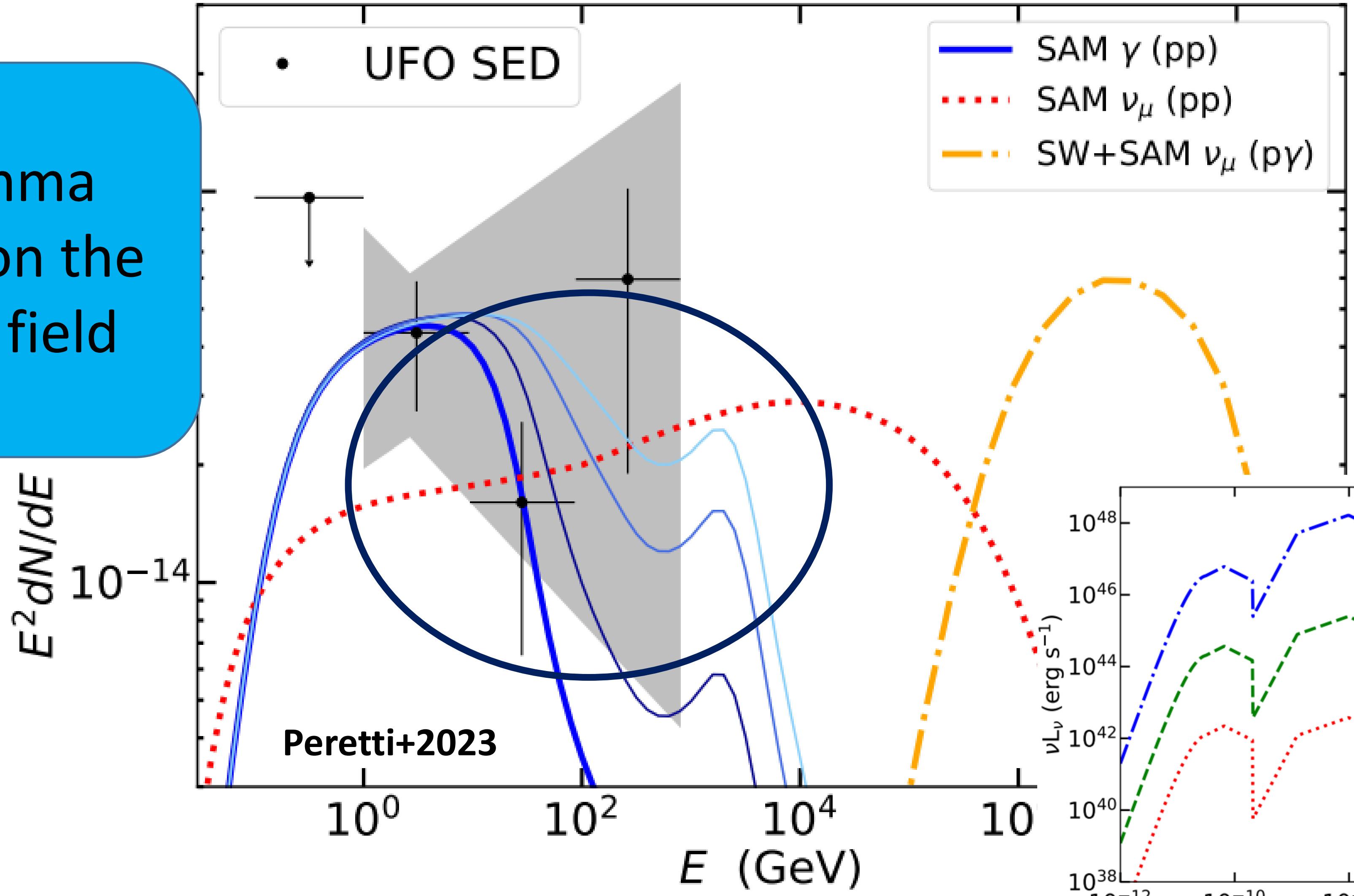


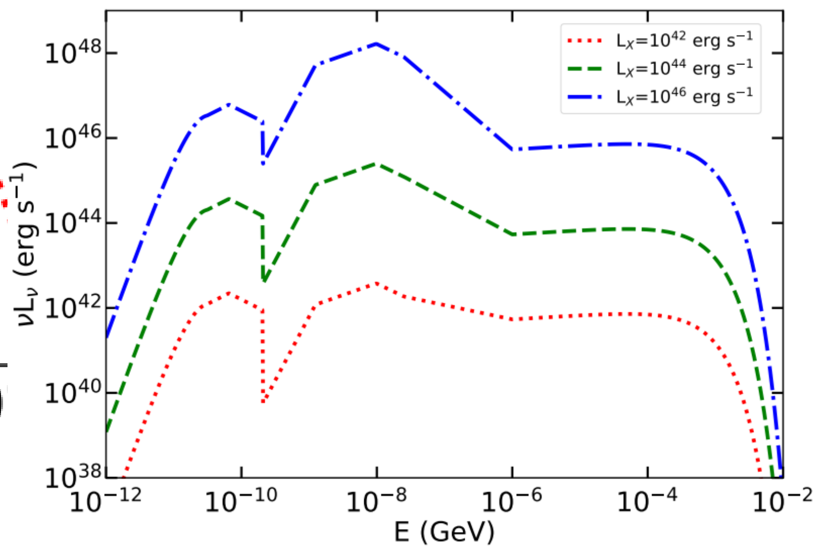
UFO model applied to Fermi-LAT results



UFO model applied to Fermi-LAT results

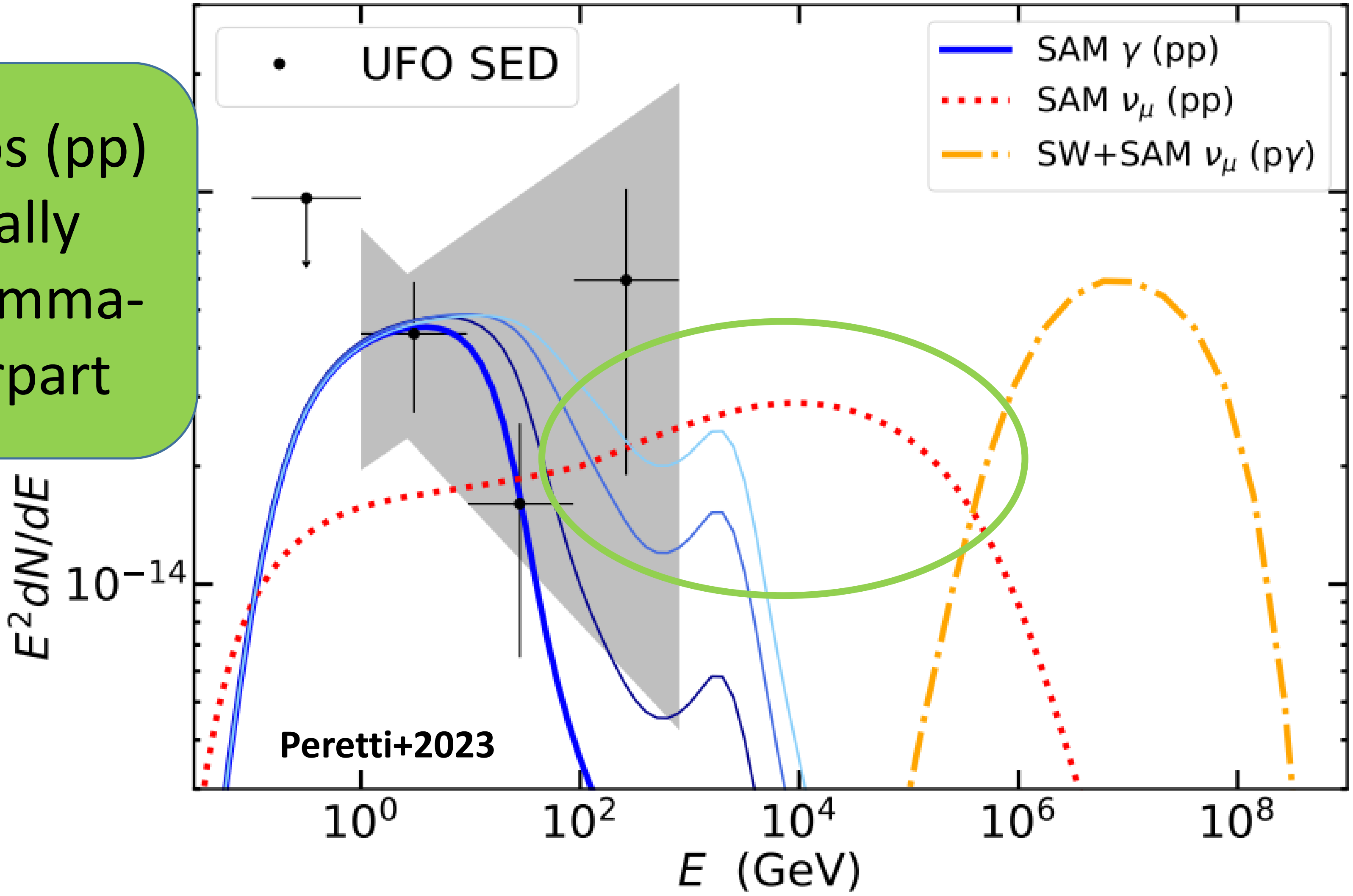
Gamma-gamma absorption on the BKG photon field





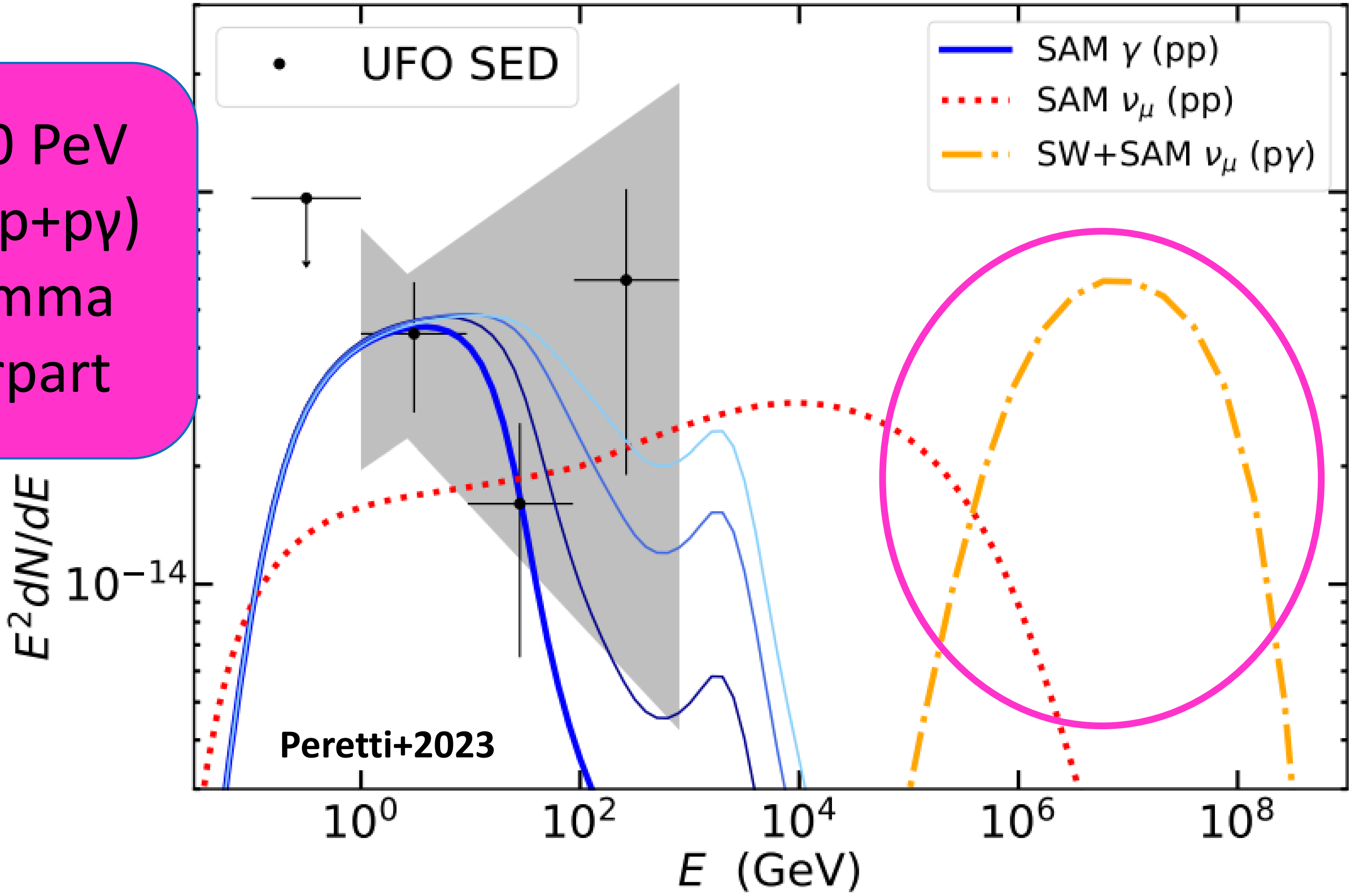
UFO model applied to Fermi-LAT results

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



UFO model applied to Fermi-LAT results

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



Take home message

- Diffusive shock acceleration is an evergreen mechanism

- Wind bubbles are promising sites for DSA

- Multi-messenger radiation is efficiently produced in WBs

- Energies as high as EeV can be produced in UFOs

Thanks for your attention!

BACK UP

Wind Bubble dynamics – Forward shock

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

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

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

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

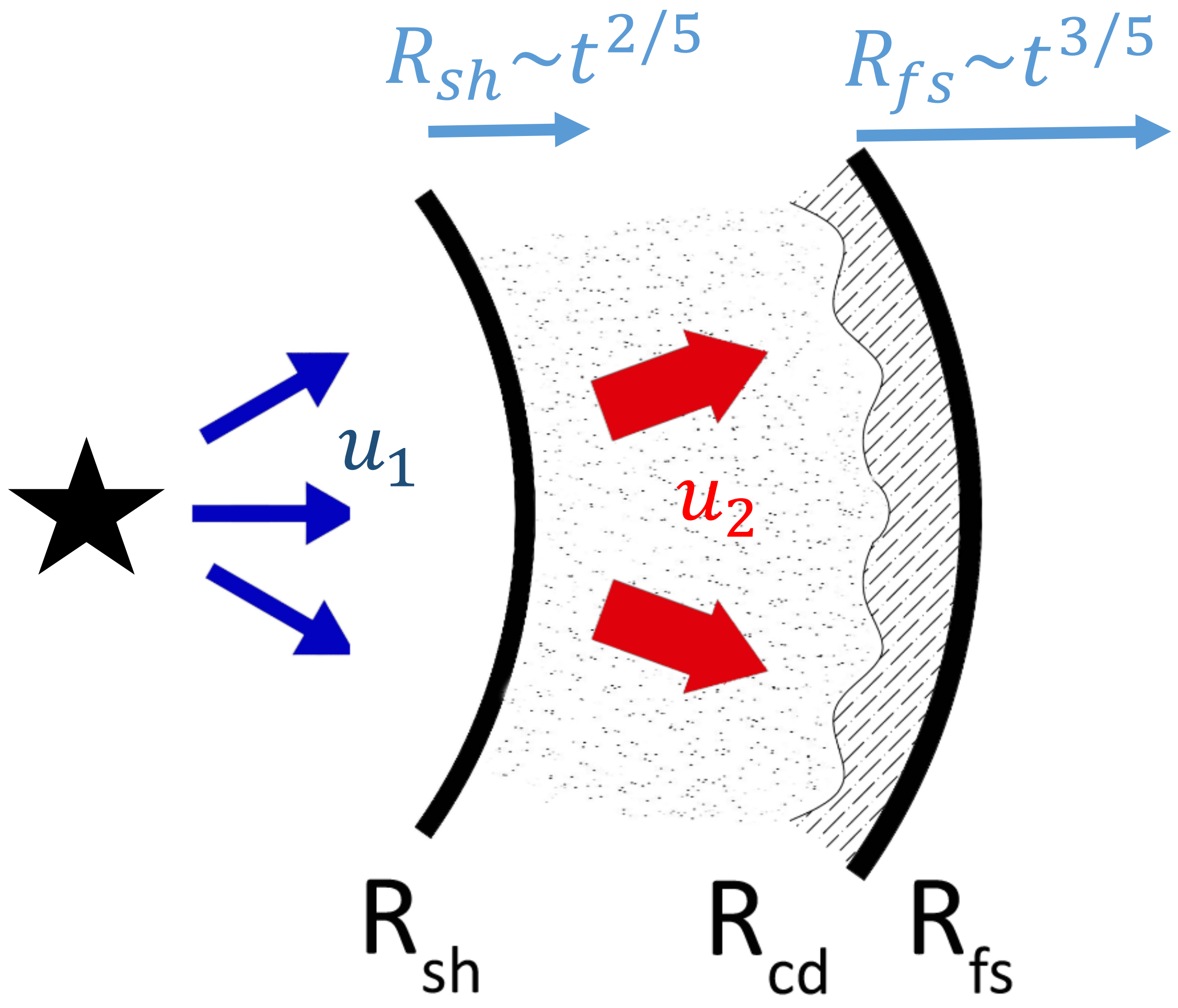
Wind Bubble dynamics – Wind termination shock

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

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

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

Characterizing the accelerator



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

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

Characterizing the accelerator

<u>Time (in)dependence of the accelerator:</u>

Sitting in the reference frame of the central engine the velocity of the fast cool wind is much larger than the shock velocities.
The timescales for HE particles are shorter than the dynamical time of the system.

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

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

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

Characterizing the accelerator

<u>Time (in)dependence of the accelerator:</u>

Stationary diffusive shock acceleration is a good approximation.

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

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

sh cd fs