Numerical Simulations of Relativistic Outflows in GRBs

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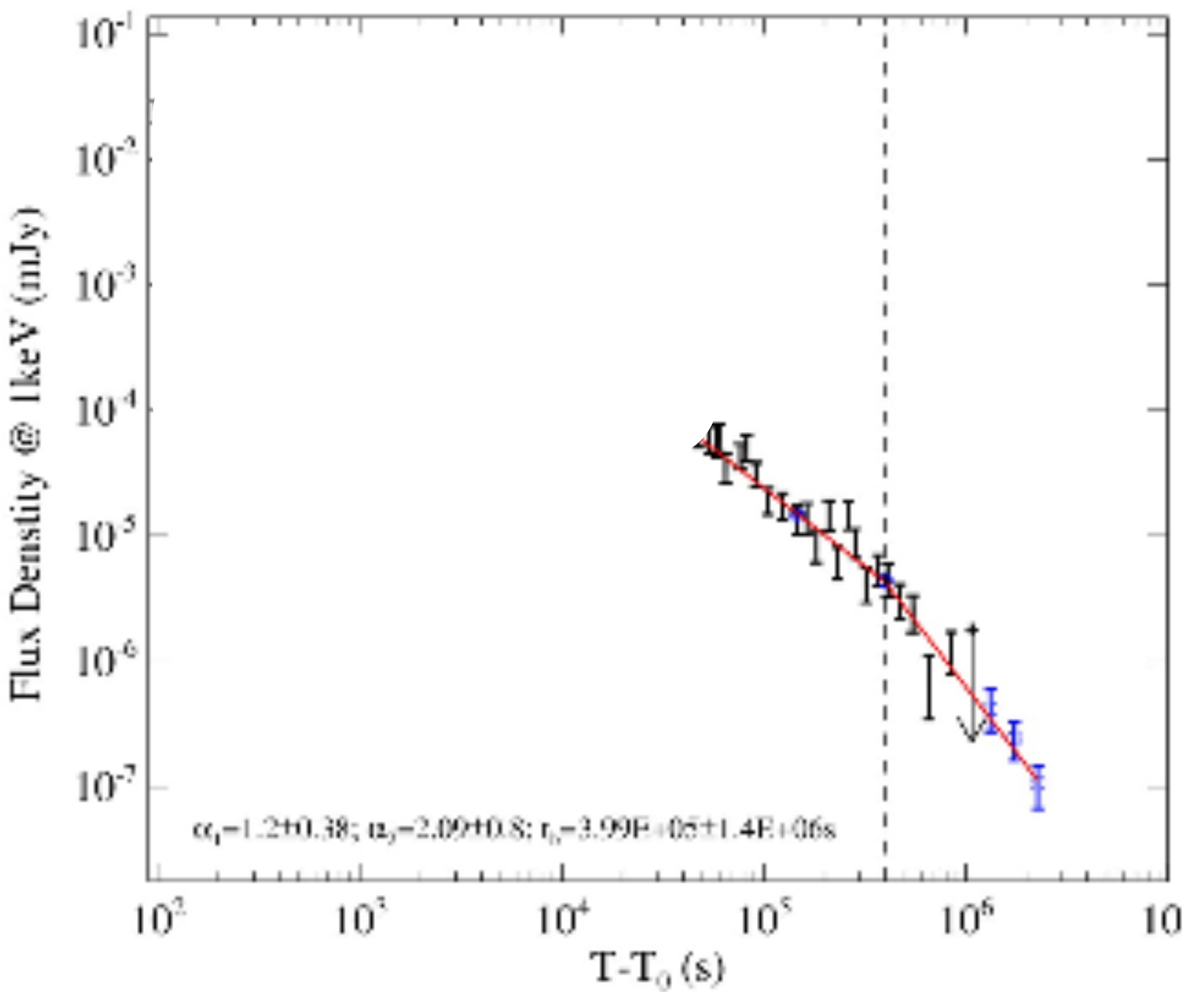
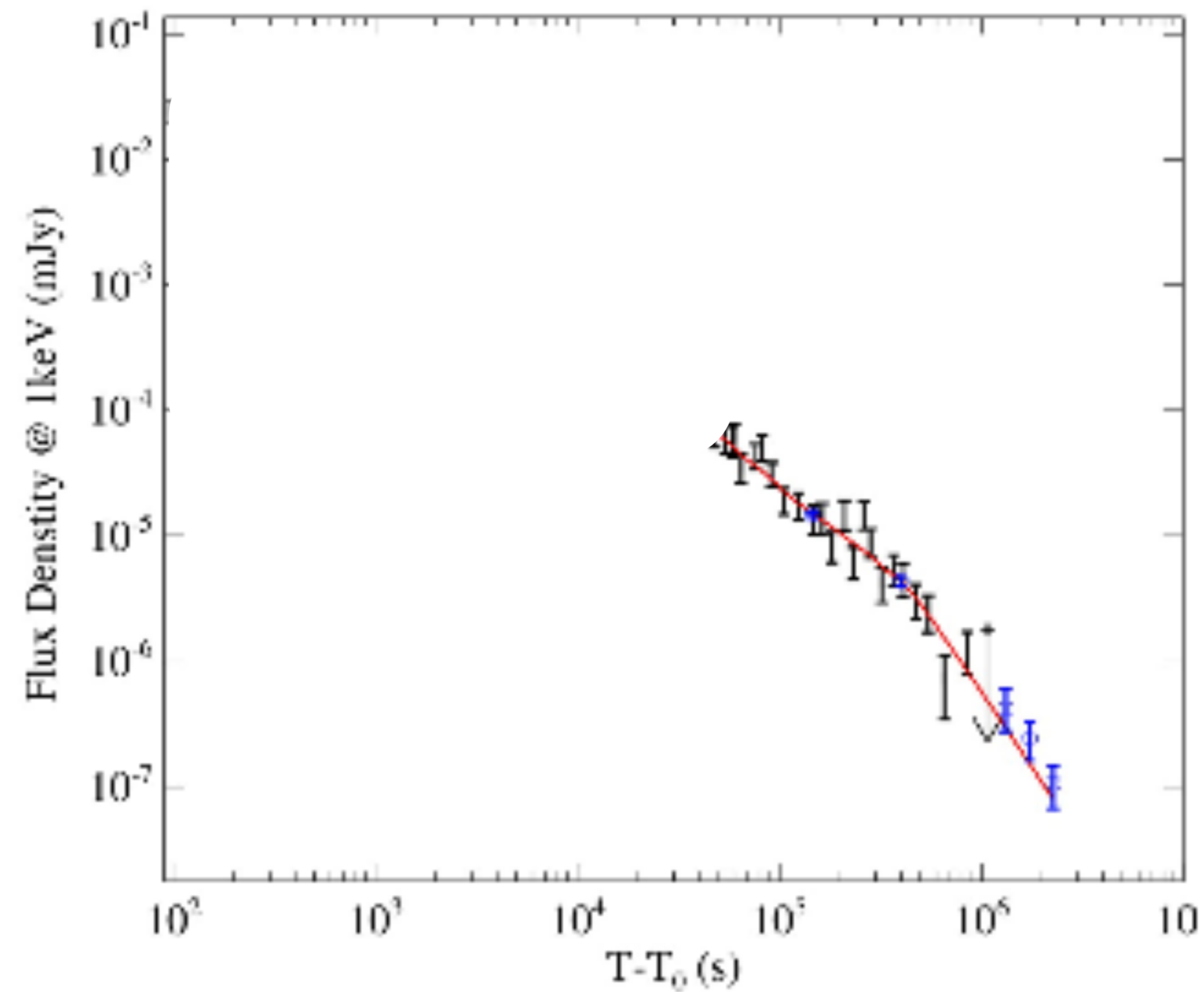
2nd Purdue Worskshop on Relativistic Plasma Astrophysics
May 11, 2016

GRB051221A
"Pre Swift"

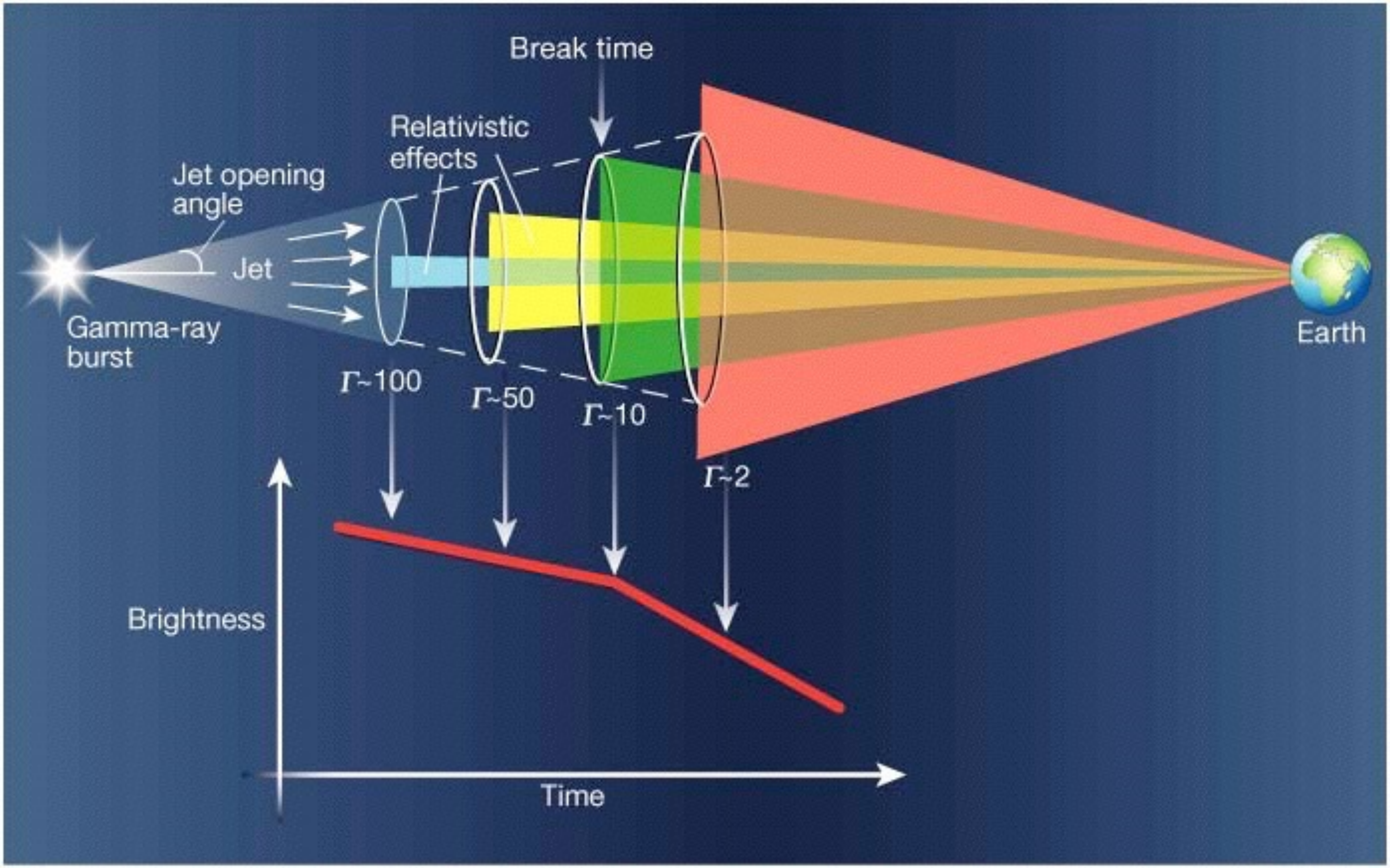


Zhang+ (2014)



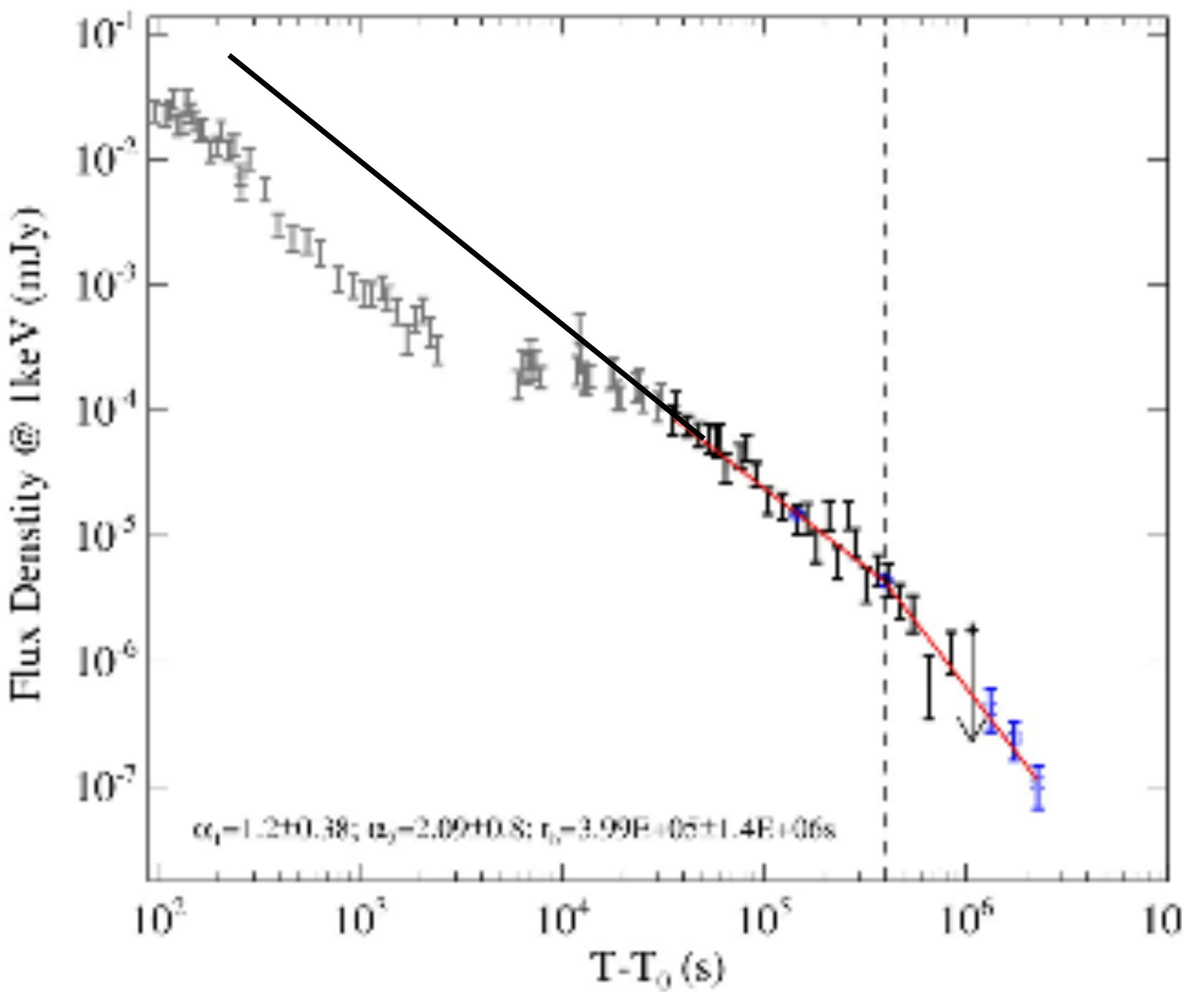
Ryan+ (2014)

Late GRB Afterglow

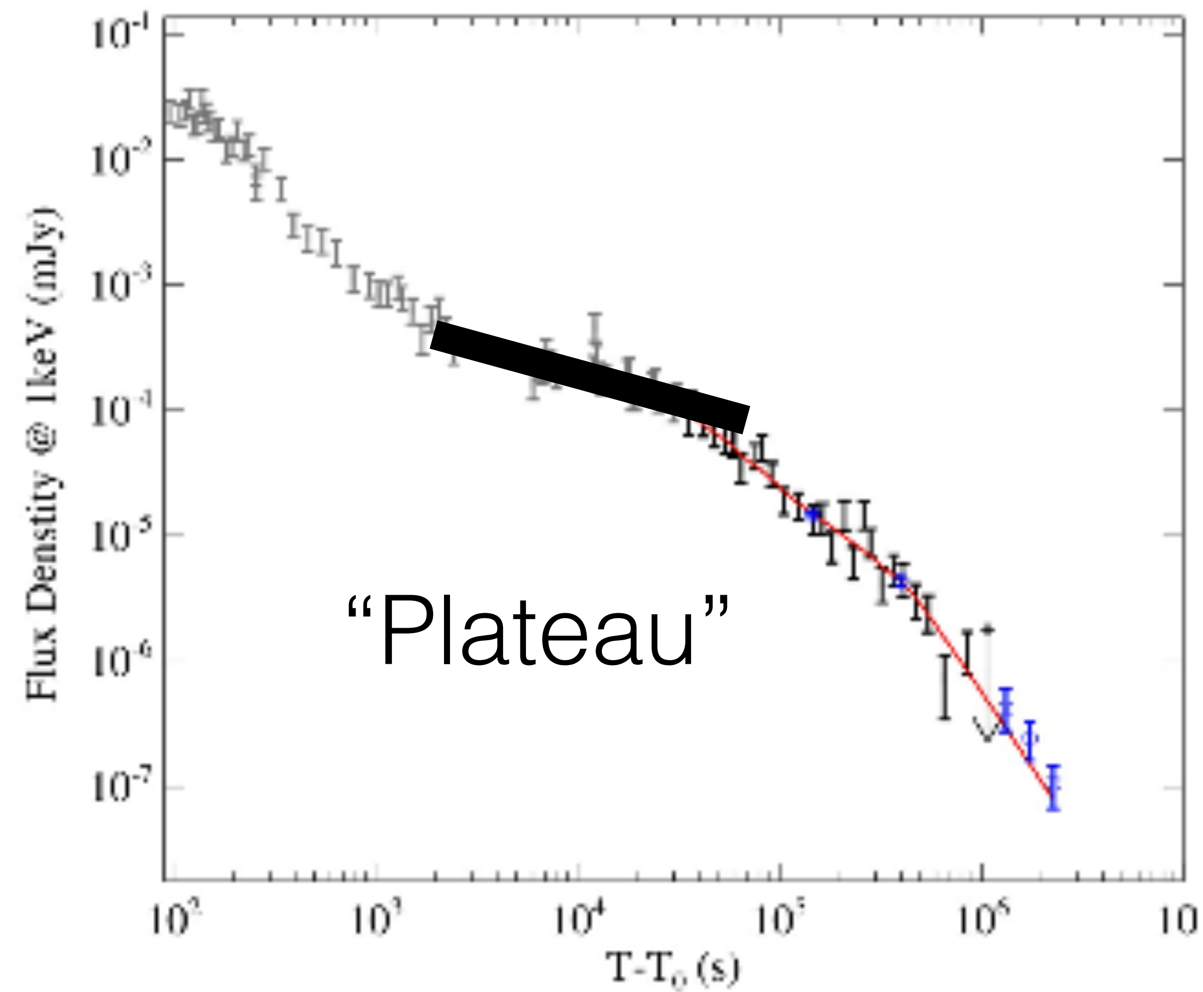


Need epsilon_b ~ 0.01 for synchrotron

GRB051221A
“Post Swift”



Zhang+ (2014)



Ryan+ (2014)

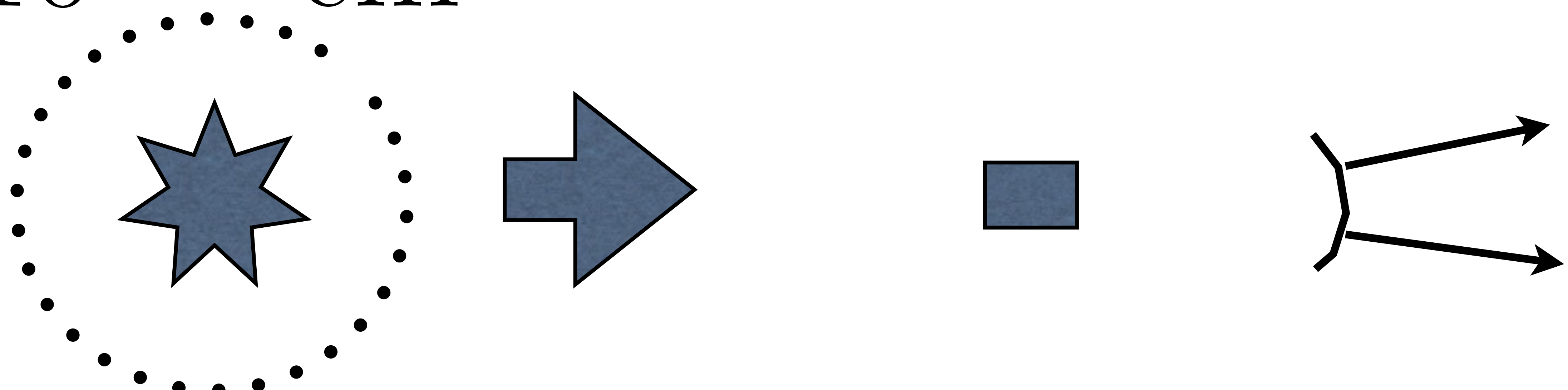
Over 10 orders of mag in length scale!

Engine

$10^{6-7}\mathrm{cm}$

Prompt + Early Afterglow

$10^{13-15}\mathrm{cm}$



$10^{11}\mathrm{cm}$

$10^{16-18}\mathrm{cm}$

Star or Cloud

Afterglow

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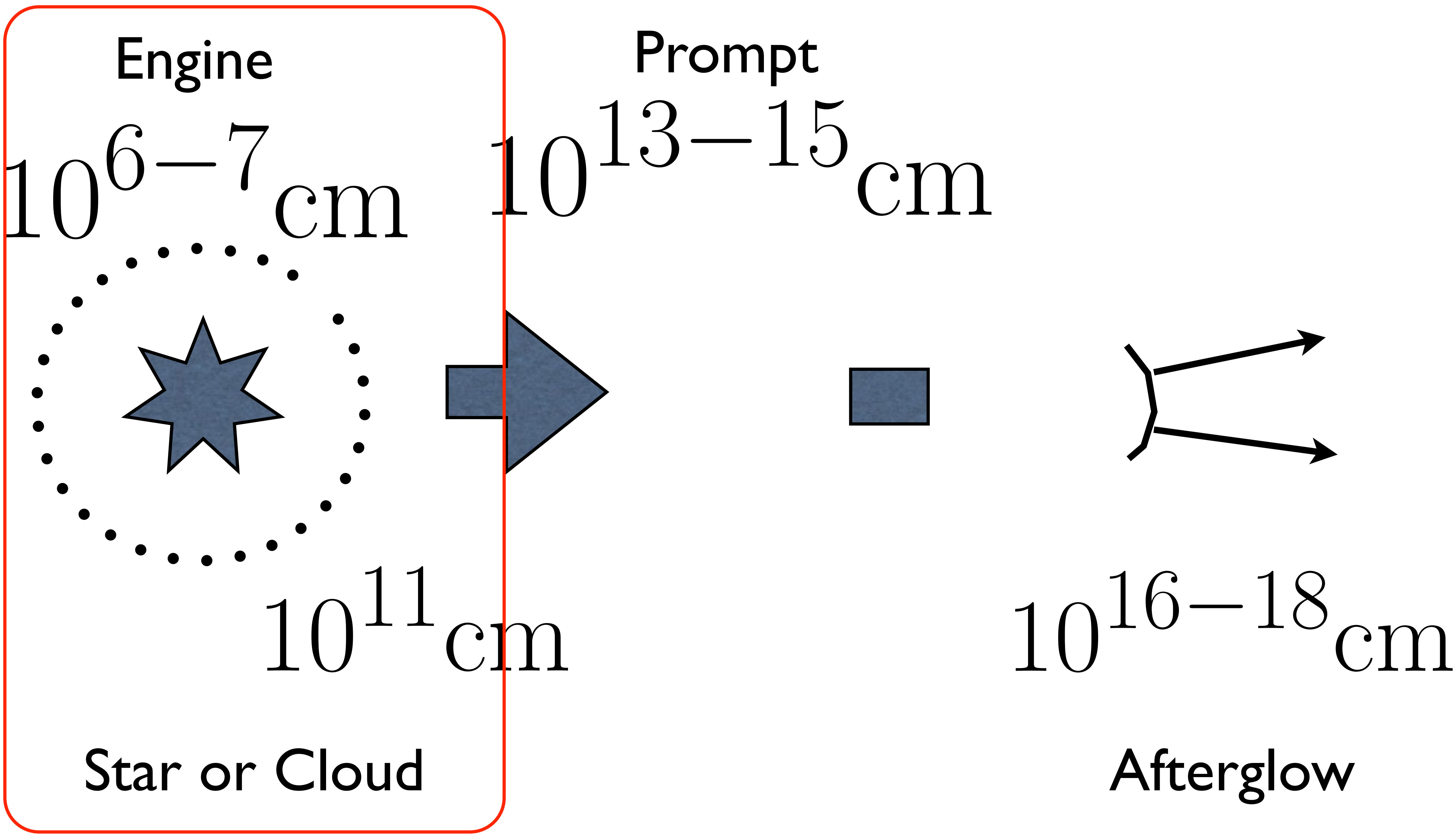
Over 10 orders of mag in length scale!



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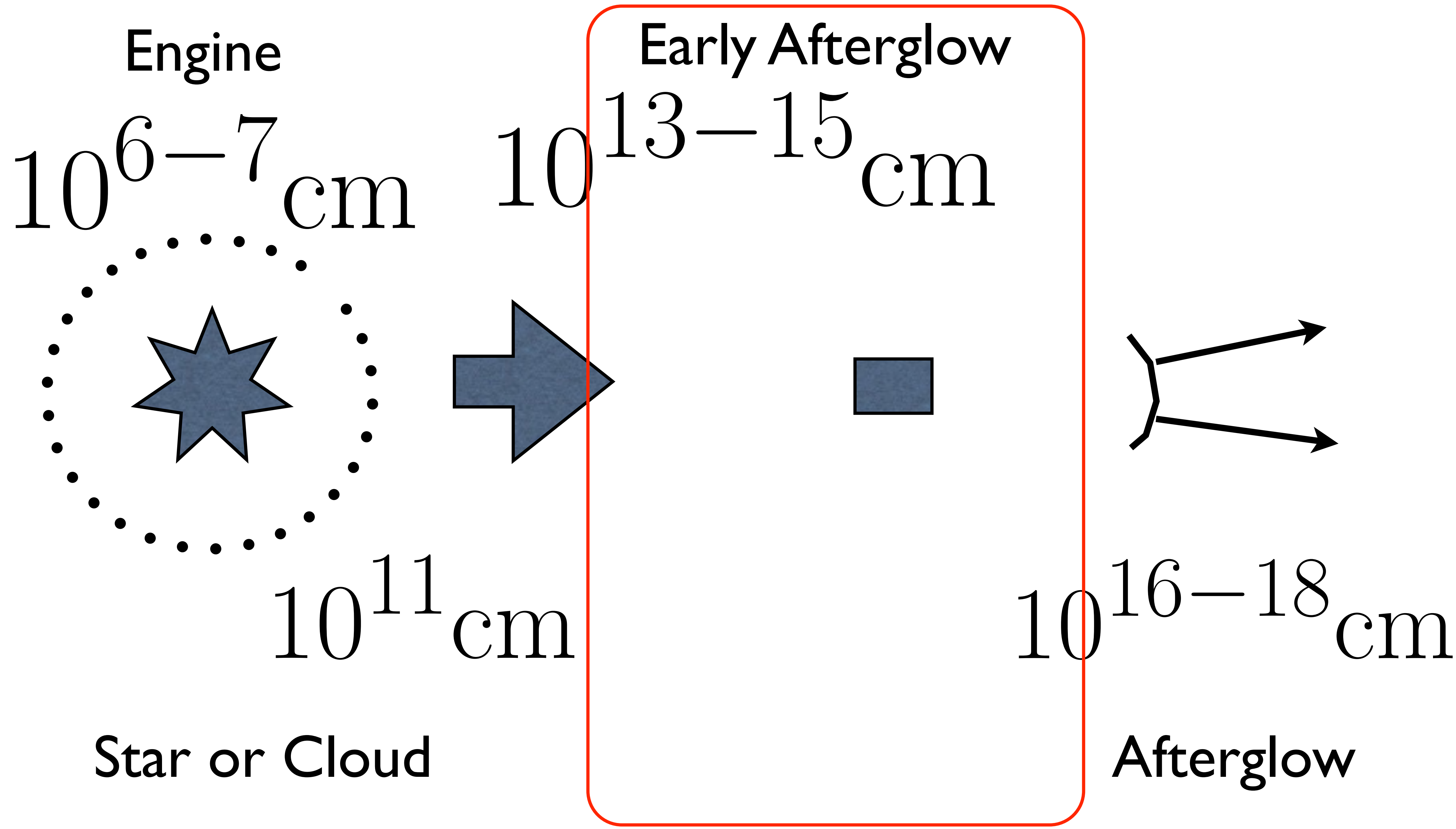
Over 10 orders of mag in length scale!



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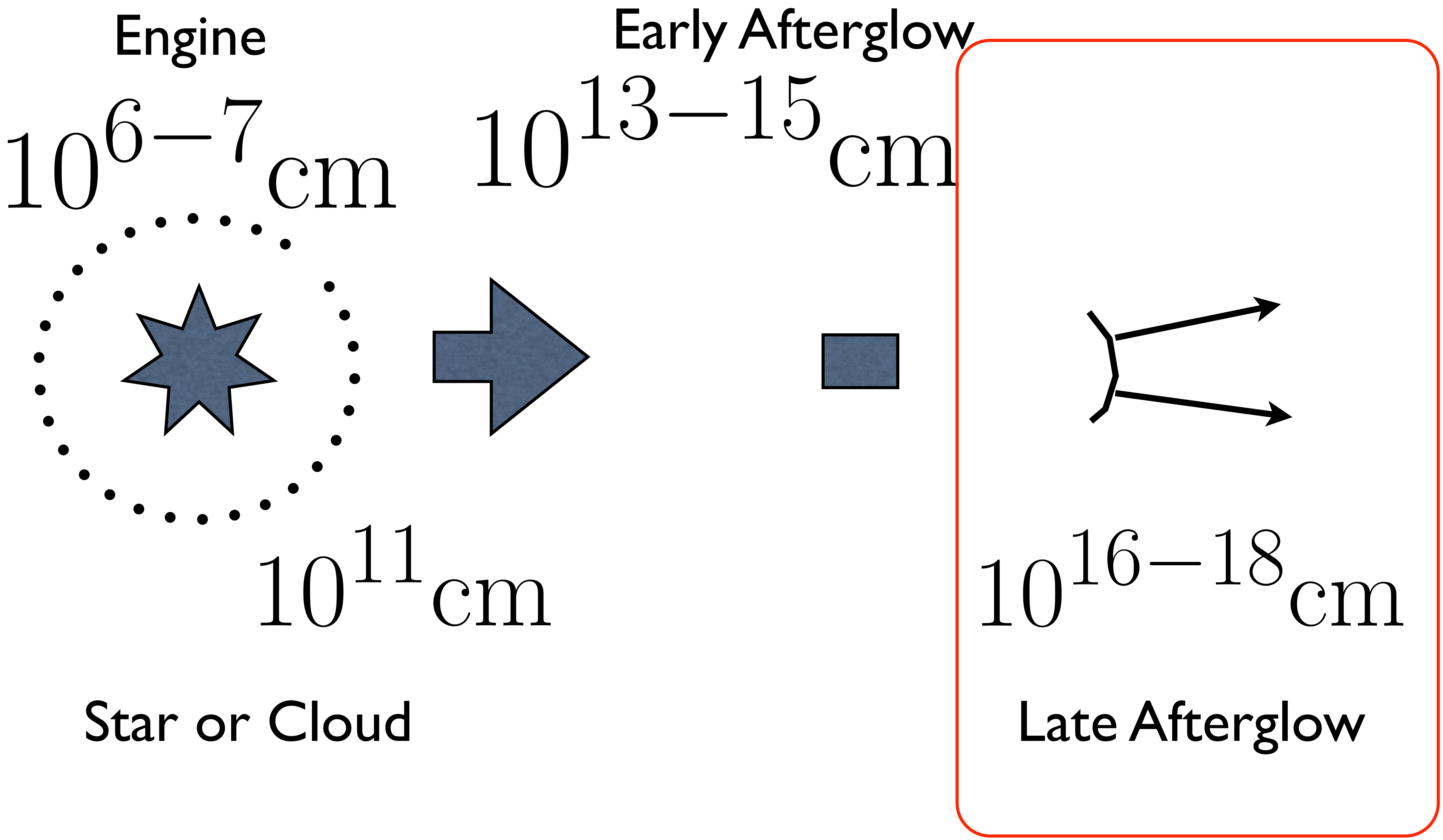
Over 10 orders of mag in length scale!



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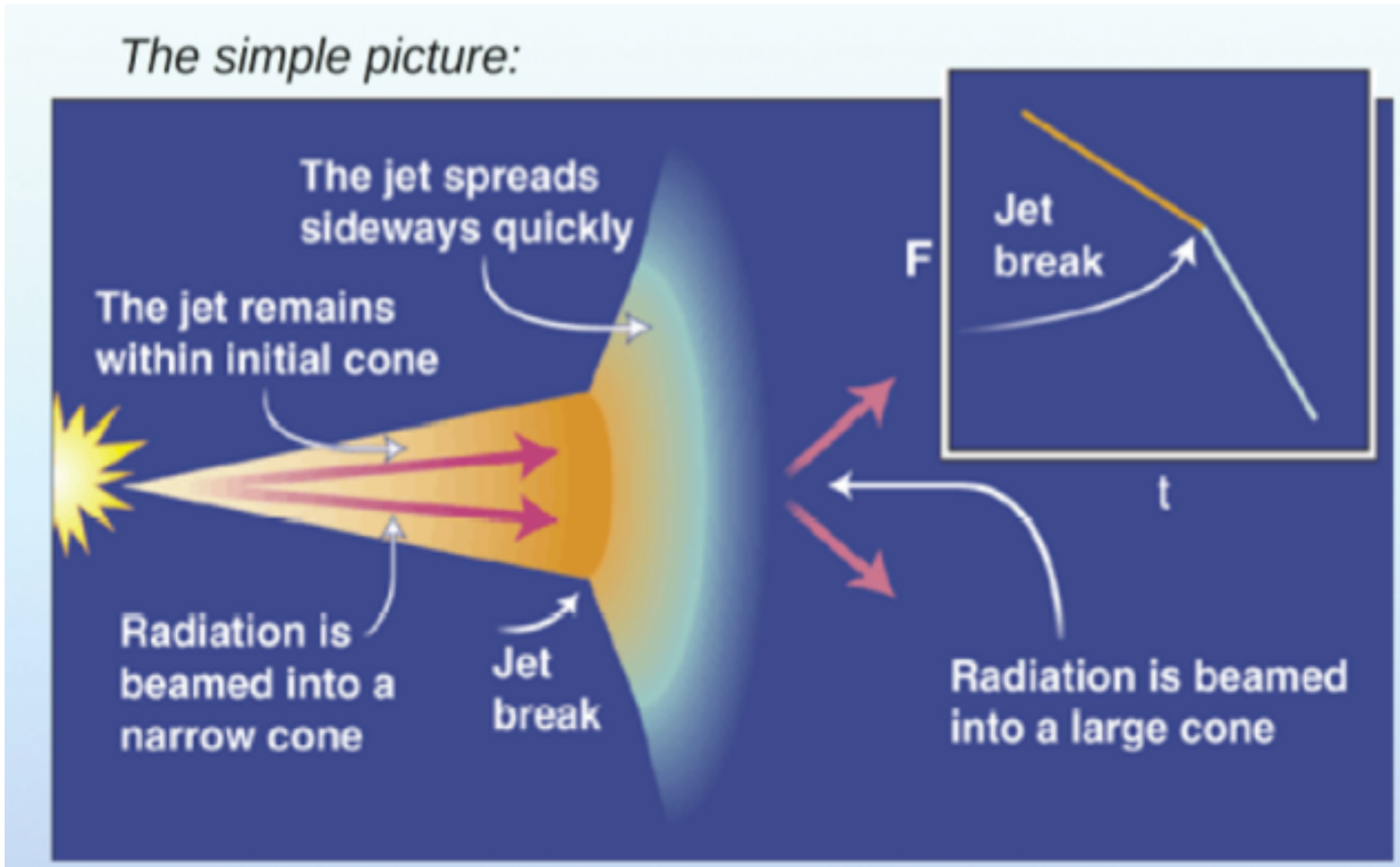
Afterglow Jet Dynamics



Model parameters:

dynamics:	Explosion energy E_{iso}, circumburst density $n \propto n_0 r^{-k}$, jet opening angle θ_{jet}
(synchrotron) radiation:	magnetic field fraction ε_B, particle energy fraction ε_E, particle number fraction ξ_N, synchrotron slope p
observer position	observer angle θ_{obs}, luminosity distance, redshift

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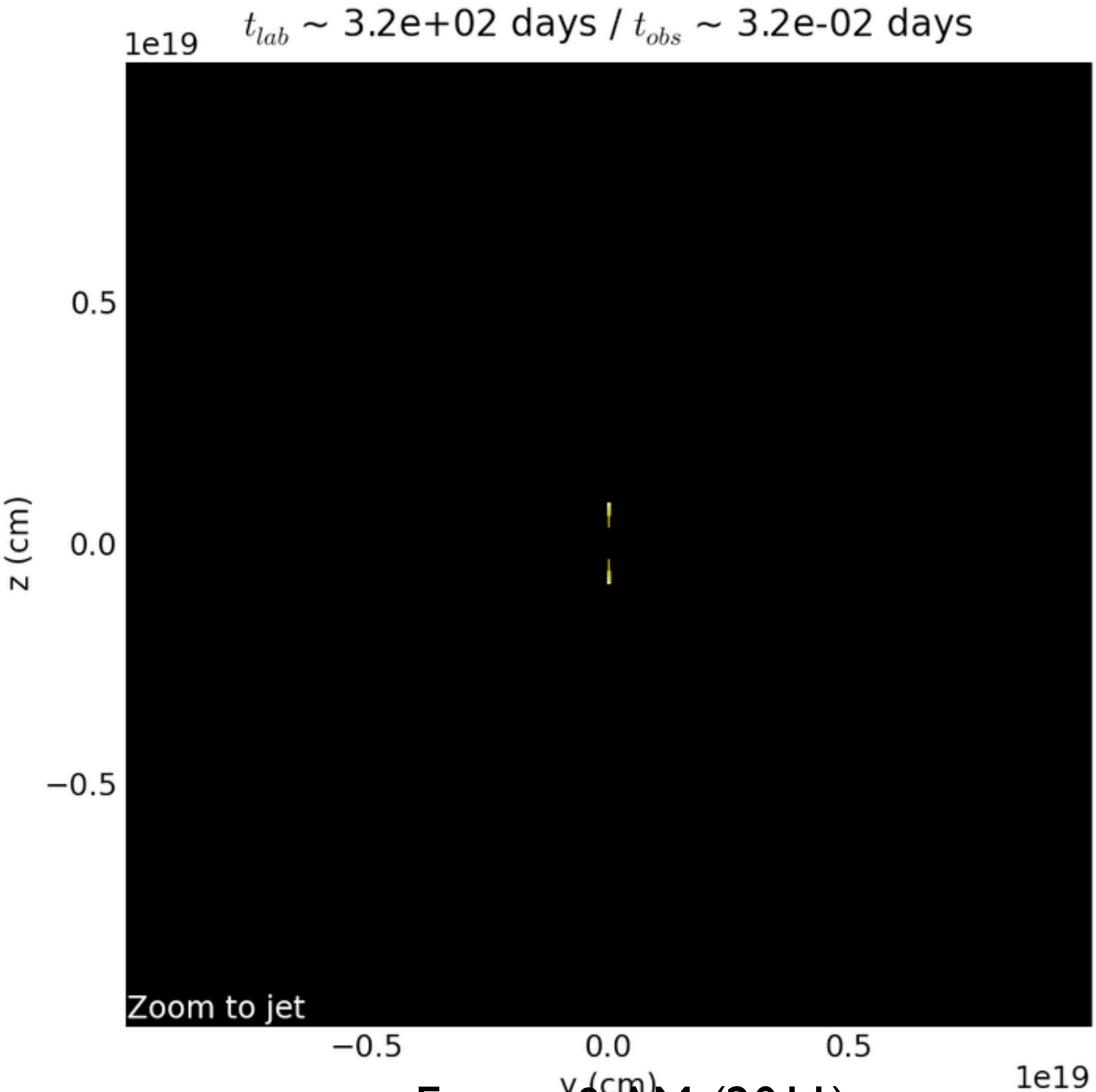


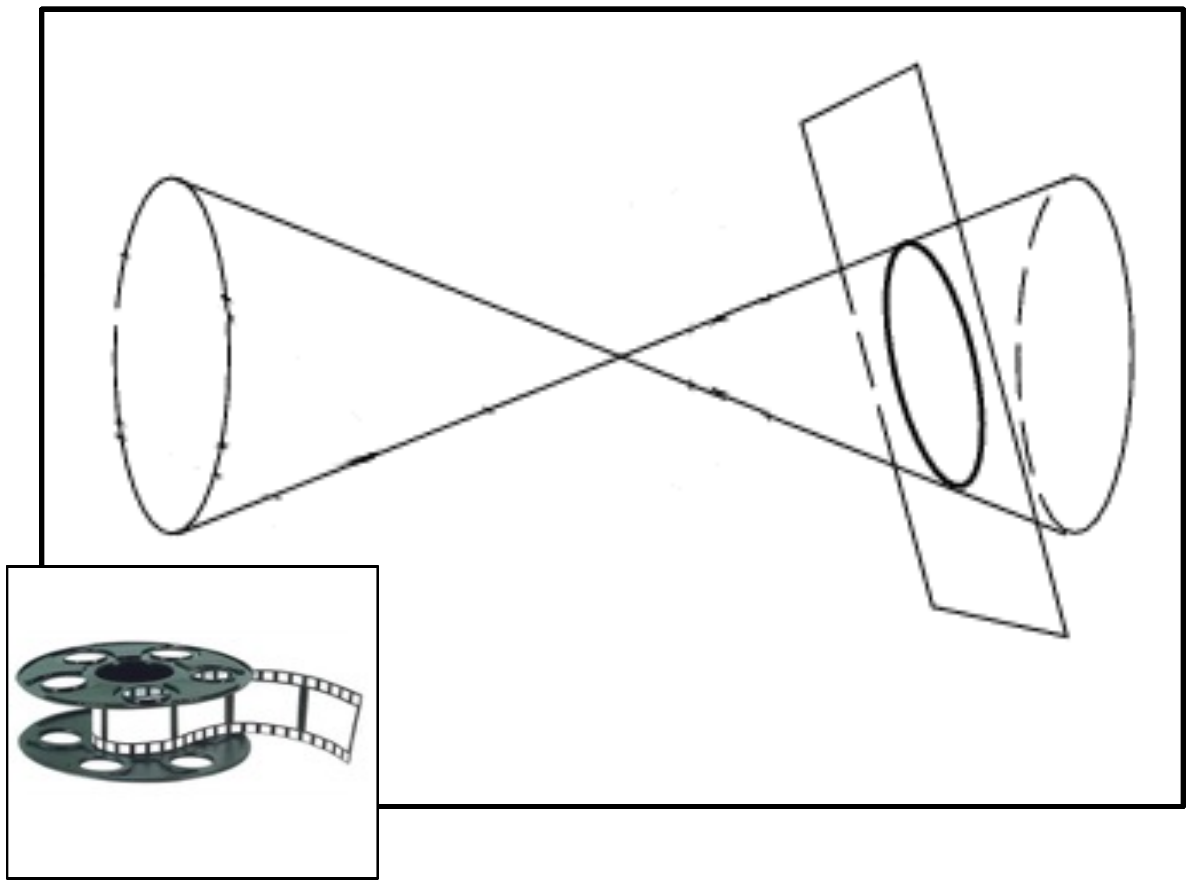
van Eerten & AM (2011)

Ej = 2e52
θj=0.05
n=1cm^-3

Granot+(01)
Granot+Kumar(03,06)
Zhang&AM(09)
vanEerten+(10,11,12,13ab)
Wygoda+(11)
deColle+(12)
Vlasis+ (12)

Synchrotron linear radiative transfer

For a given observer / arrival time,
a single intersecting plane at each emission time



- Optically thin limit:

Just count all emission

- Emission & absorption, no scattering (i.e. synchrotron radiation):

linear radiative transfer for all rays perpendicular to intersecting plane

$$\frac{dI_\nu}{dz} = -\alpha_\nu I_\nu + j_\nu$$

$$t_{obs} = t_{travel} + t_e - R/c$$
$$\mathrm{d}t_e \sim \Gamma^2 \mathrm{d}t_{obs}, \qquad \Gamma \sim 100$$

the challenge: *the jet nearly keeps up with its radiation*

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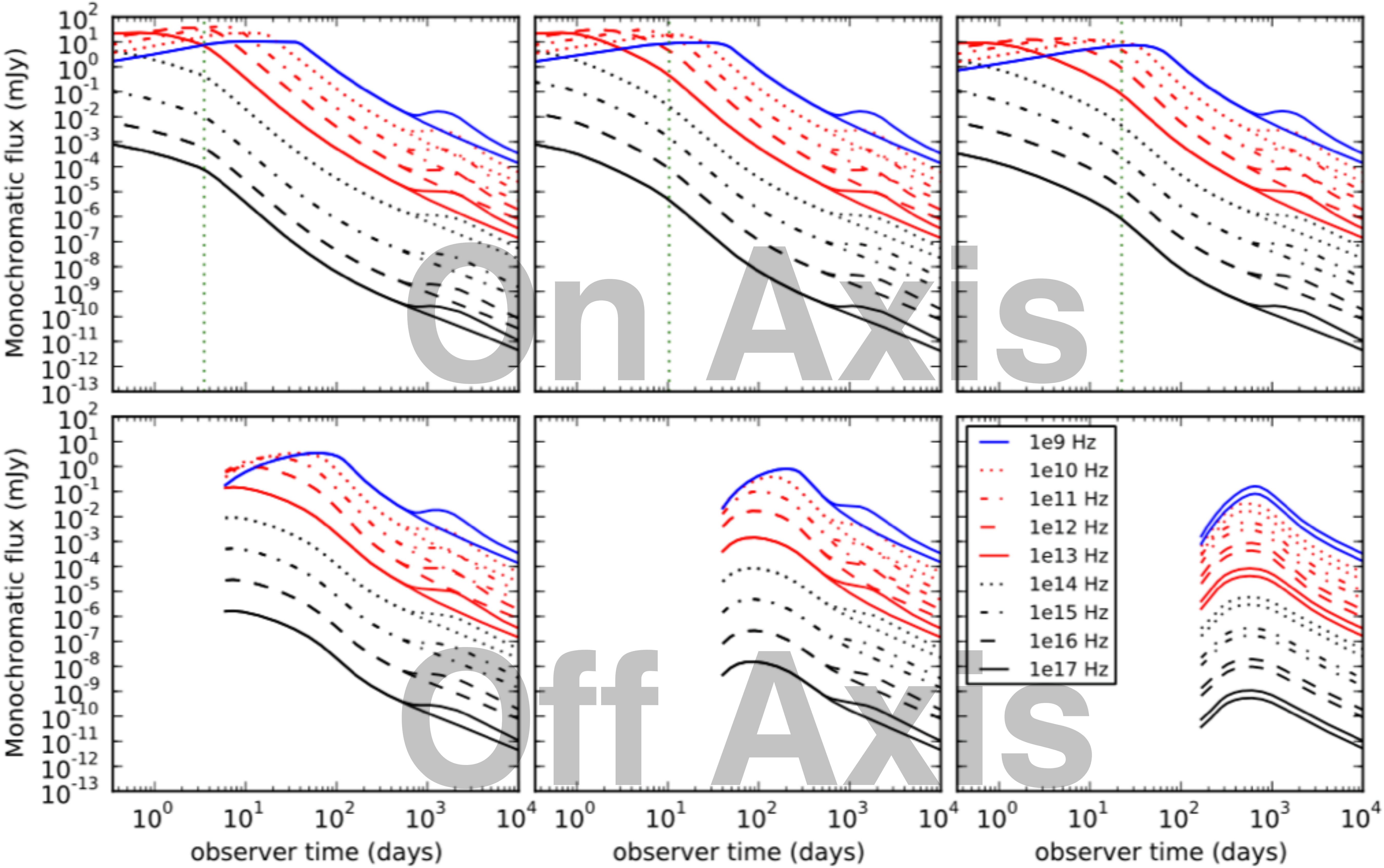

http://cosmo.nyu.edu/afterglowlibrary

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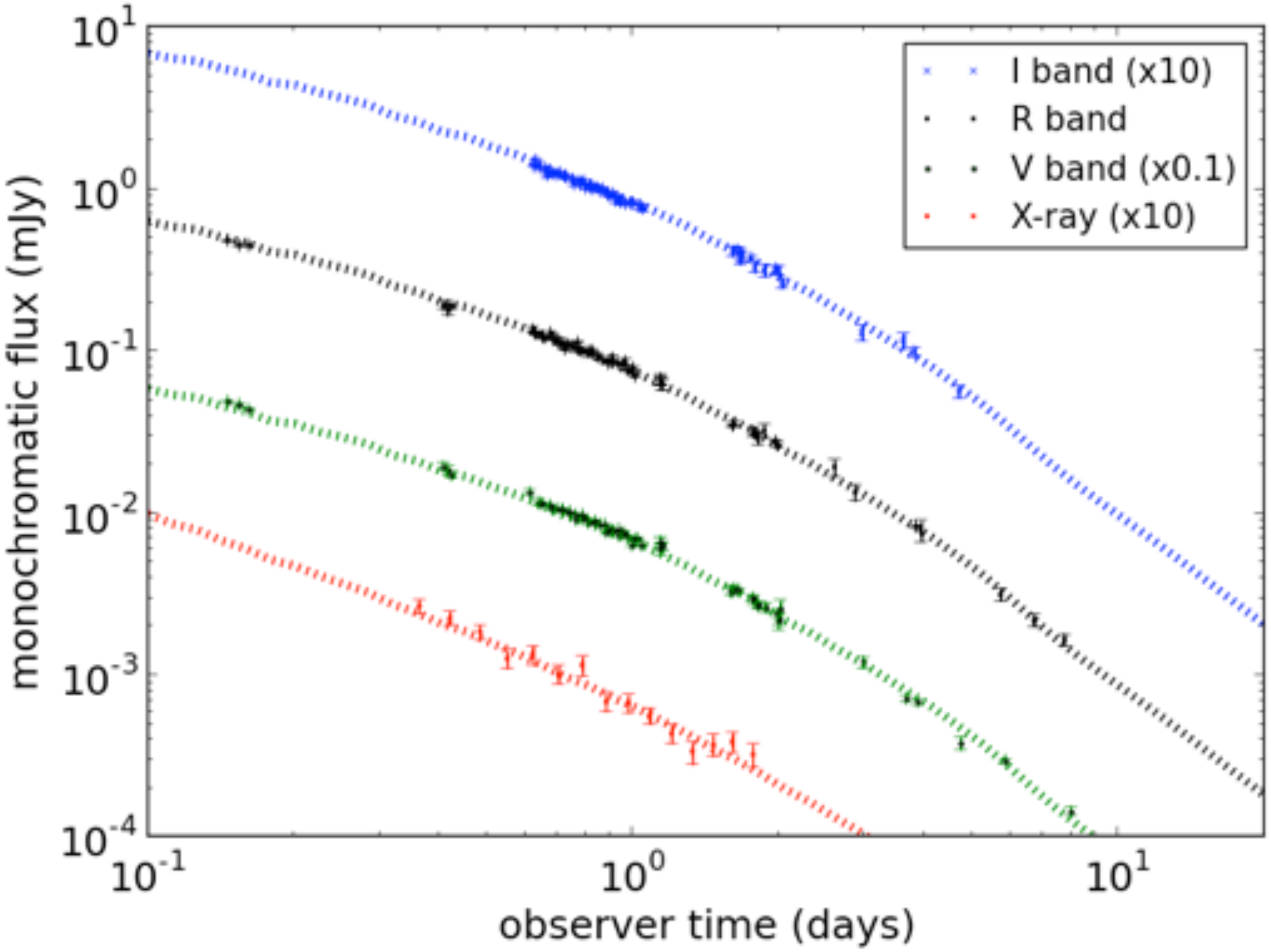
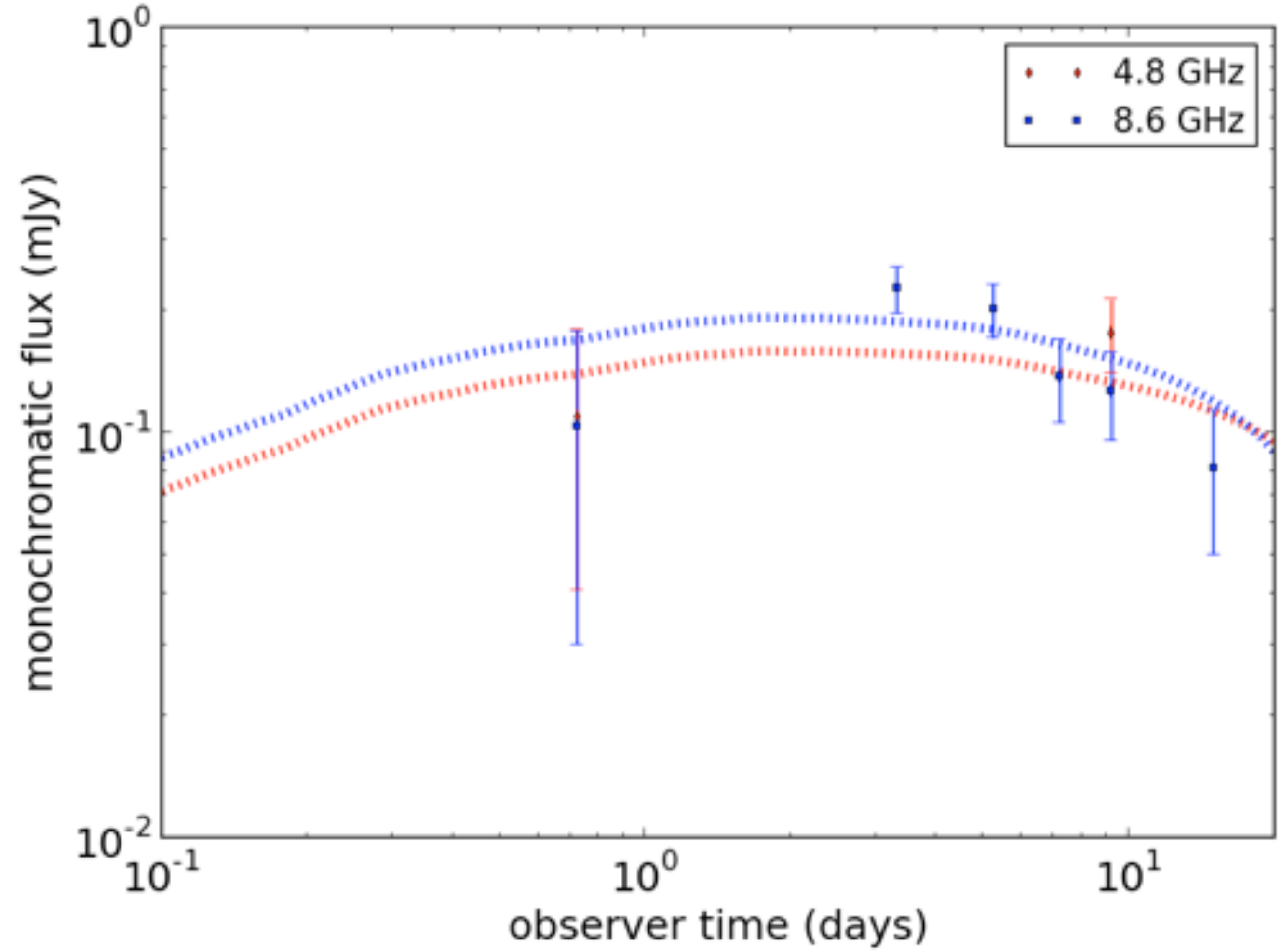
Example application: model fit to GRB 990510





- **Iterative fit** to radio, optical & X-ray data, based on 2D jet simulations
- Synchrotron slope $p > 2$, in contrast to 1.8 from Panaitescu & Kumar (2002)
- reduced χ-squared 3.235 for off-axis observer, while 5.389 on-axis
- observer angle θ is 0.016 rad, one third of jet angle 0.048 rad

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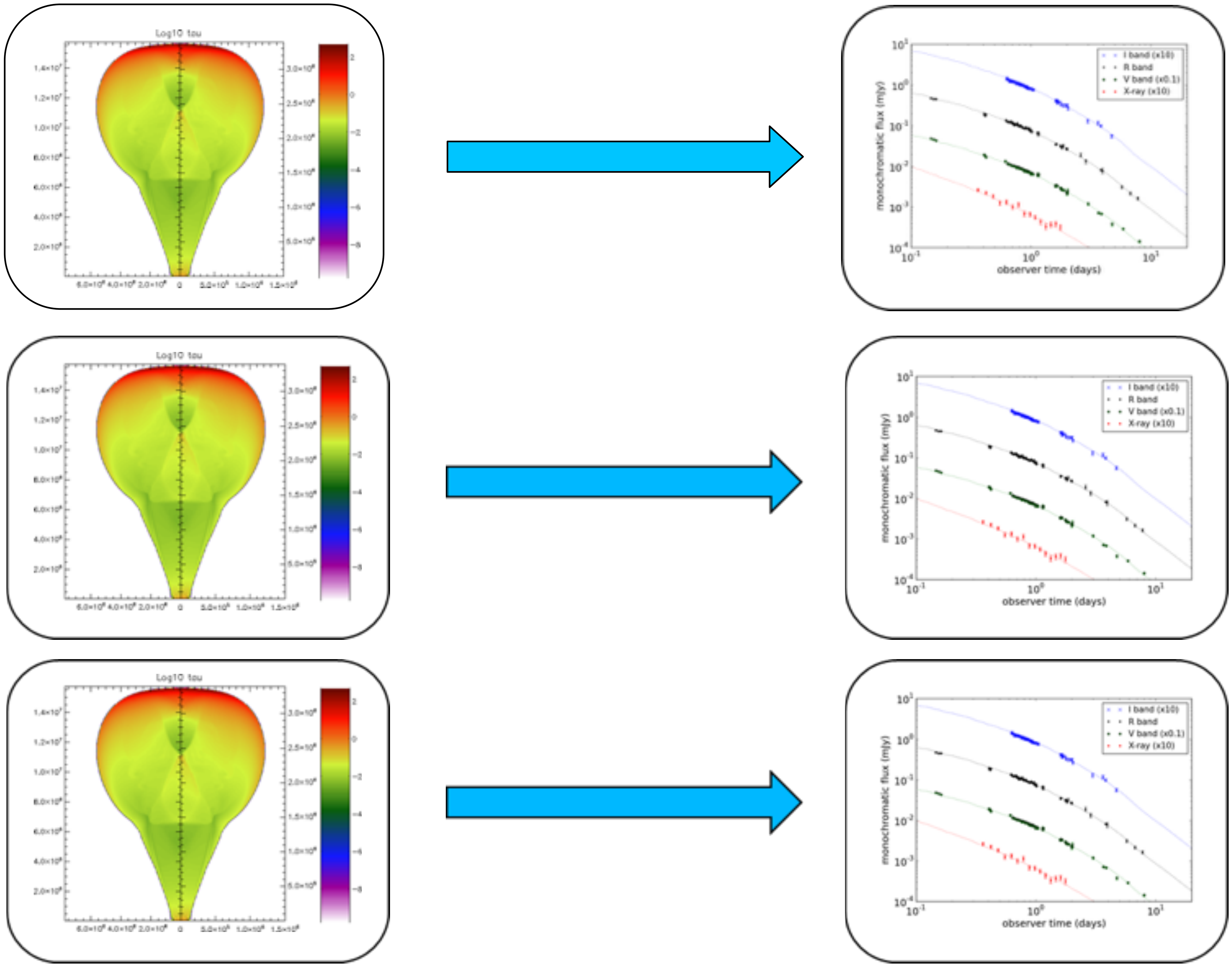
From AMR RHD simulation to light curve



Simulate for energy E, density n, opening angle θ, then synchrotron radiative transfer calculation

Business as usual: rerun simulation for different E, n

More on scalings 1 / 2

some observations...

blast wave variables:

$$E_{\rm iso}/\rho_0, \theta_0; r, t, \theta \rightarrow \rho(E_{\rm iso}/\rho_0; r, t, \theta), p(.), \gamma(.), R(.), \ldots$$

fluid equations can be rewritten in terms of dimensionless parameters:

$$r, t, \theta \rightarrow A = ct/r, B = E_{\rm iso} t^2 / R^5 \rho_0, \theta$$

dynamics invariant under transform of $E_{\rm iso}/\rho$

$$E_{\rm iso}/\rho_0 \rightarrow \alpha E_{\rm iso}/\rho_0, \quad t \rightarrow \alpha^{1/3} t, \quad r \rightarrow \alpha^{1/3}$$

$$A \rightarrow A, \quad B \rightarrow B$$

In other words, only one (numerically challenging!) simulation needed.

(*A* and *B* not explicitly required. Just compensate in *r* and *t,* since energy over density is a combination of cm and s)

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More on scalings 2 / 2

$$r, t, \theta \rightarrow A = ct/r, B = E_{\rm iso} t^2 / R^5 \rho_0, \theta$$

limiting cases:

- ultrarelativistic: $A \rightarrow 1$

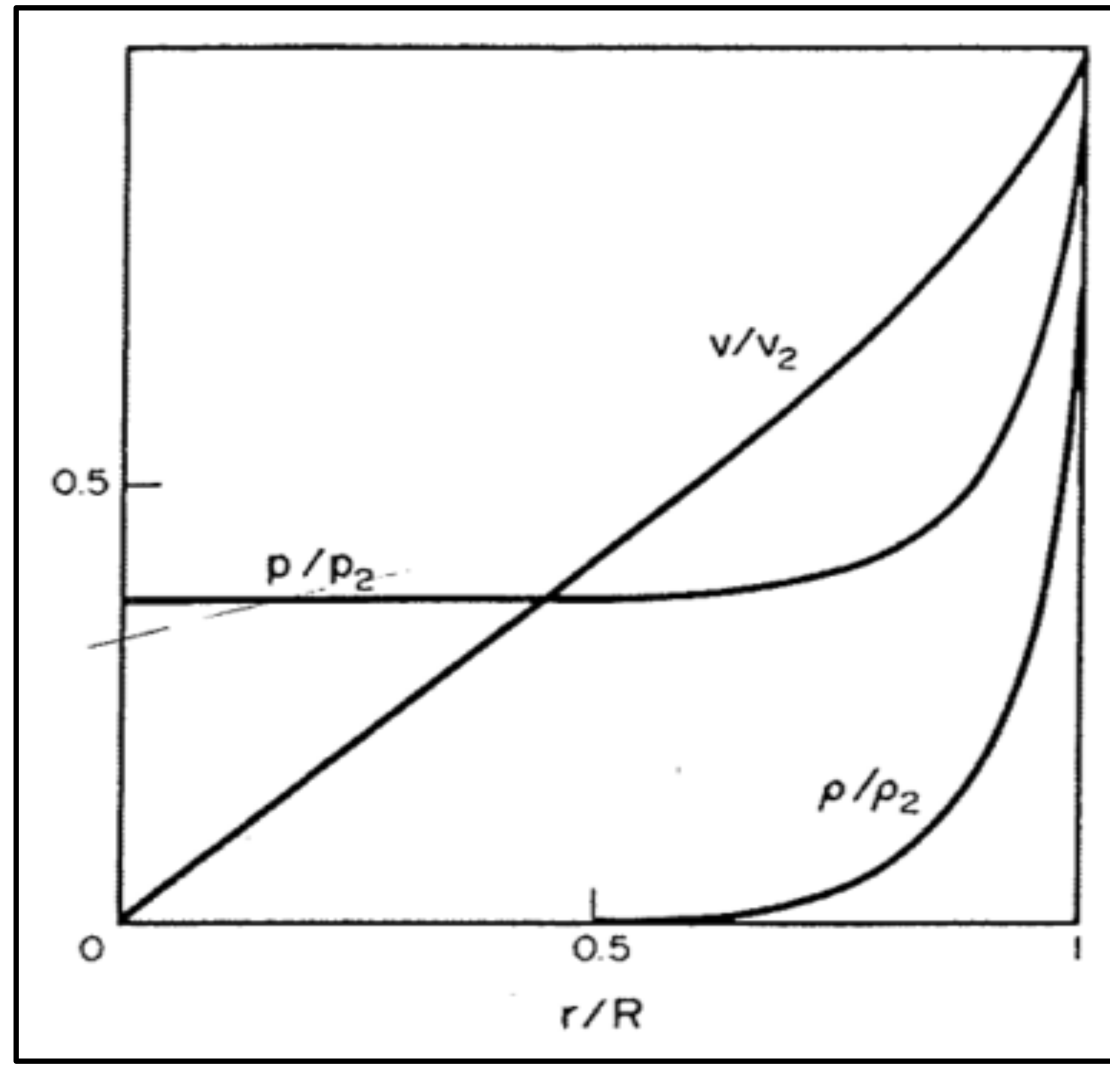
- nonrelativistic: $A \rightarrow \infty$

so spherical (no θ) blast waves are *self-similar* in these limits:

$$\rho(r,t,\theta) \rightarrow \rho(B), \qquad \text{etc...}$$

"Blandford-McKee" relativistic

"Sedov-Taylor" non-relativistic



Sedov-Taylor blast wave
image: Landau & Lifshitz 1952

intermediate stage in 2D more complex

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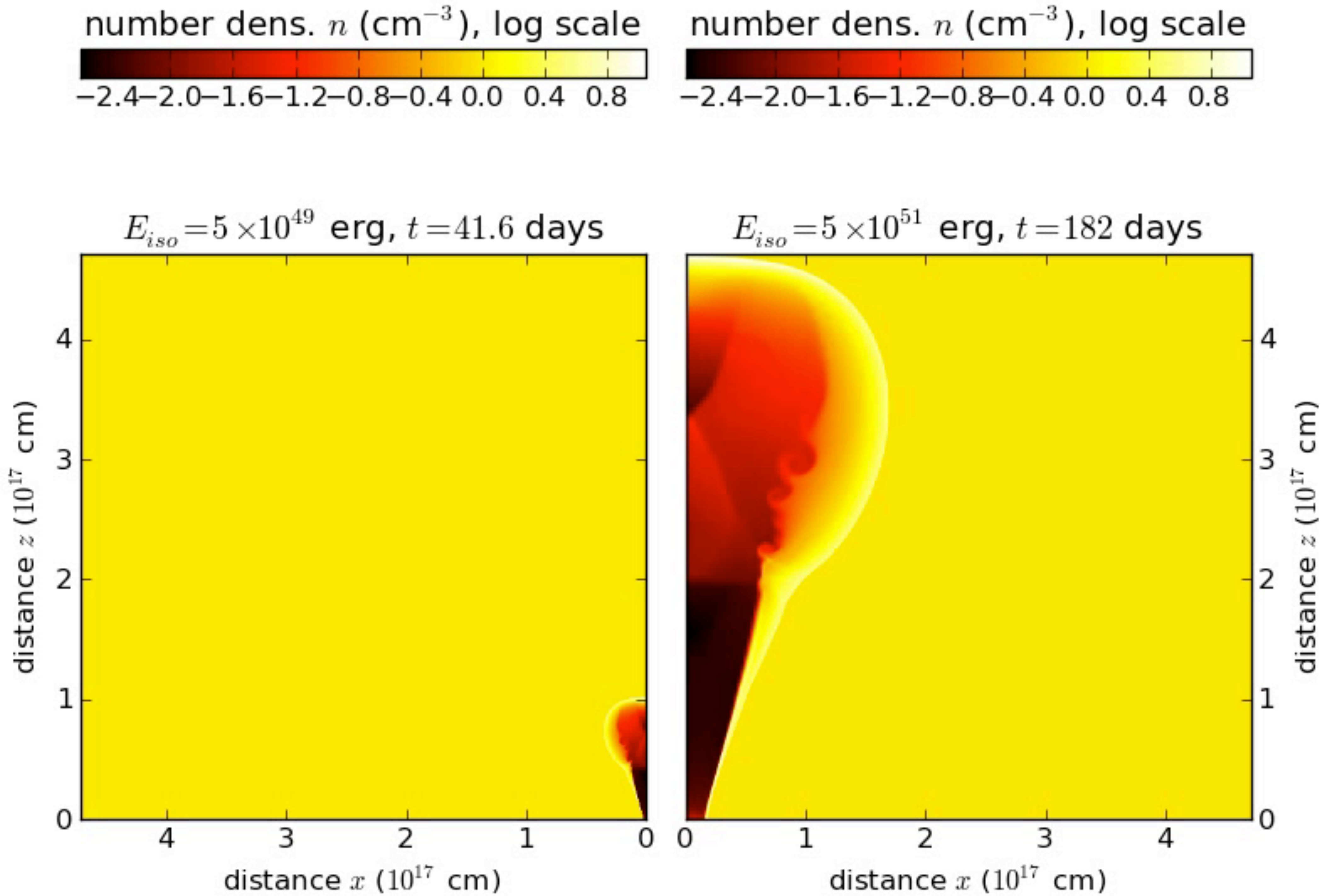
Scaling of Jet Dynamics



$$E'_{iso} = \kappa E_{iso}, \quad n' = \lambda n, \quad t' = (\kappa/\lambda)^{1/3} t, \quad r' = (\kappa/\lambda)^{1/3} r$$

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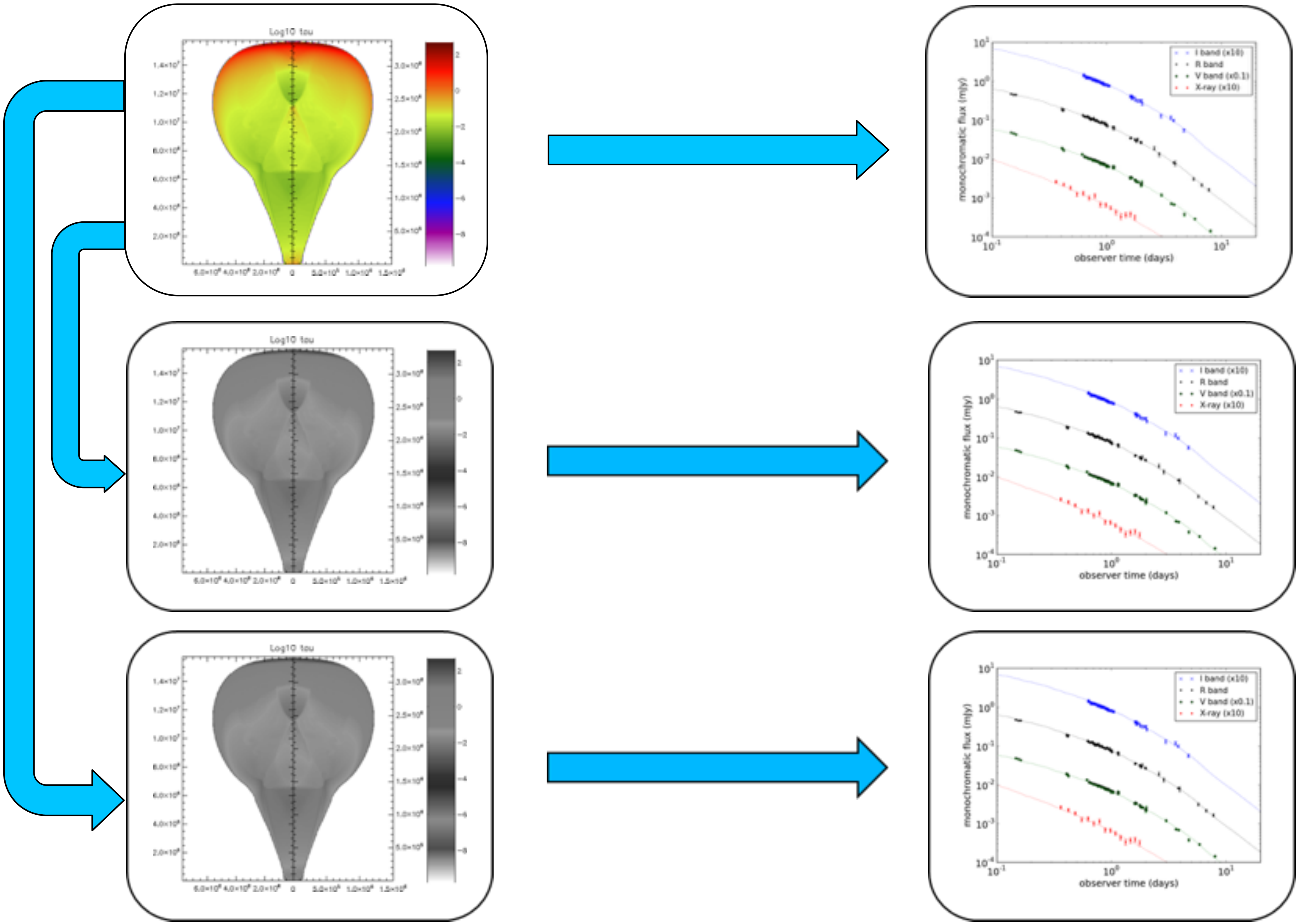
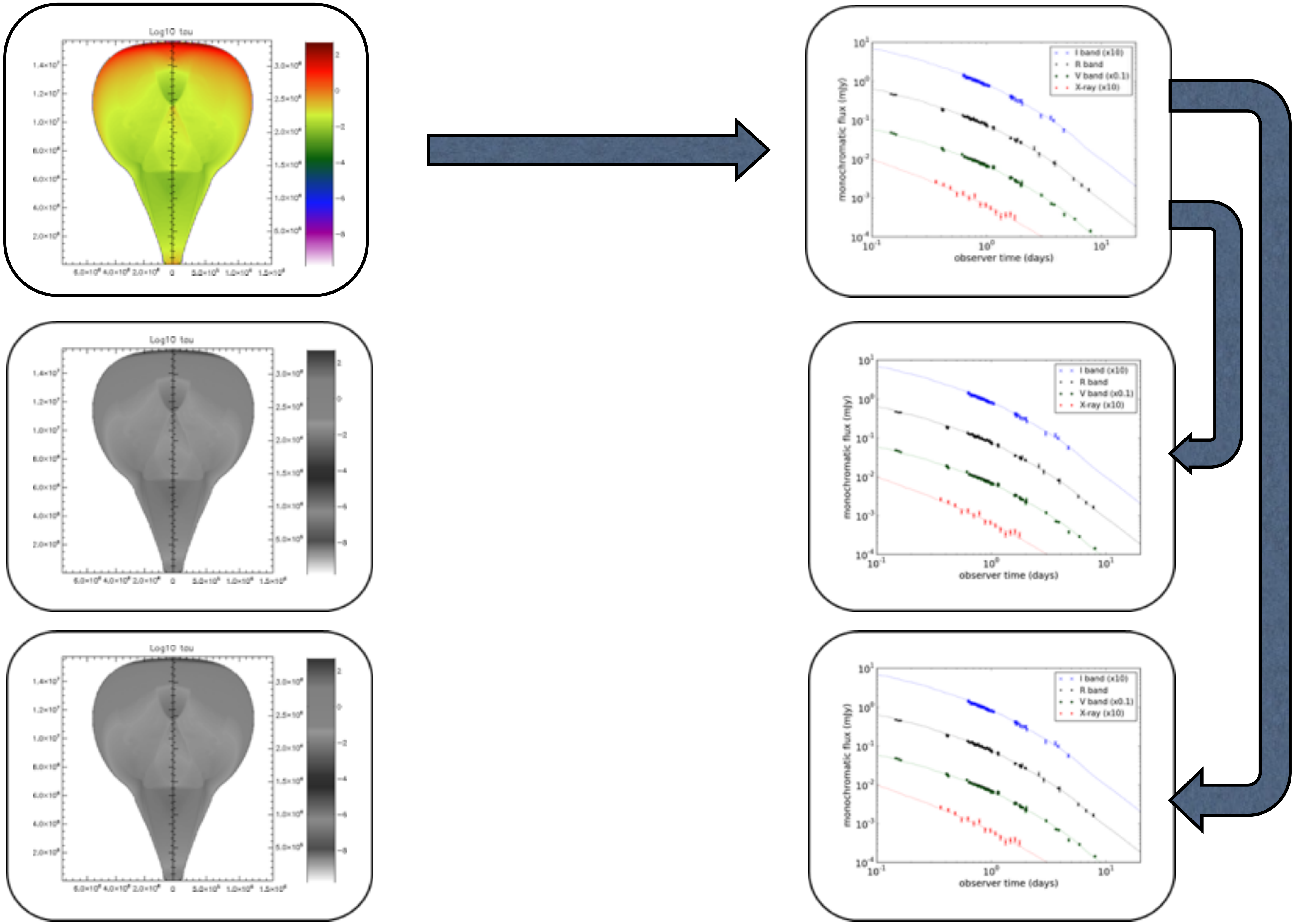
Calculate jet dynamics by applying scaling



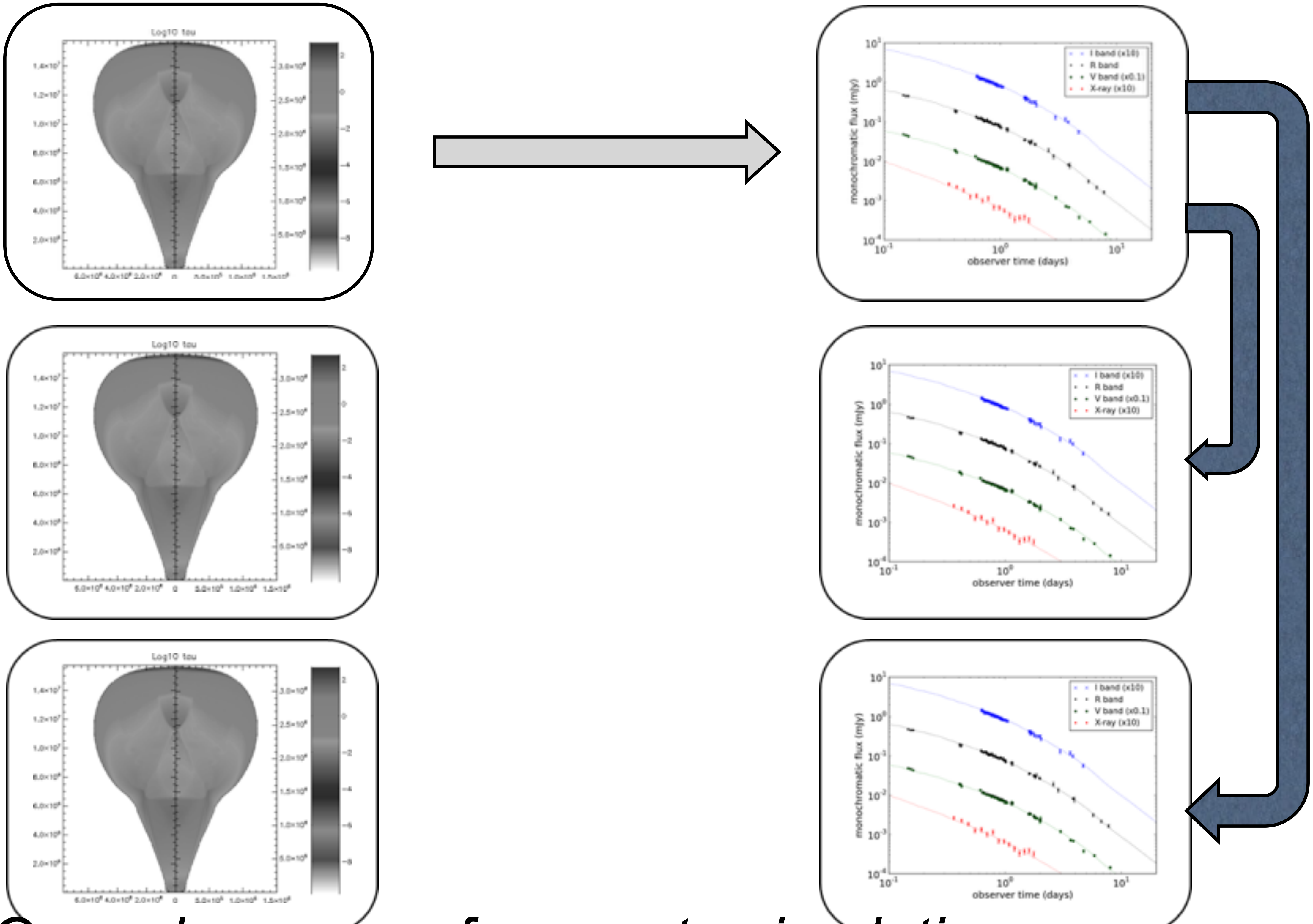
Different *E* and *n* can be obtained by scaling: *greatly reduces parameter space*

Calculate light curves by applying scaling



All light curves can be calculated by scaling a basic set for E and n

Calculate light curves by applying scaling



Once done, no reference to simulations necessary anymore!

BoxFit &ScaleFit

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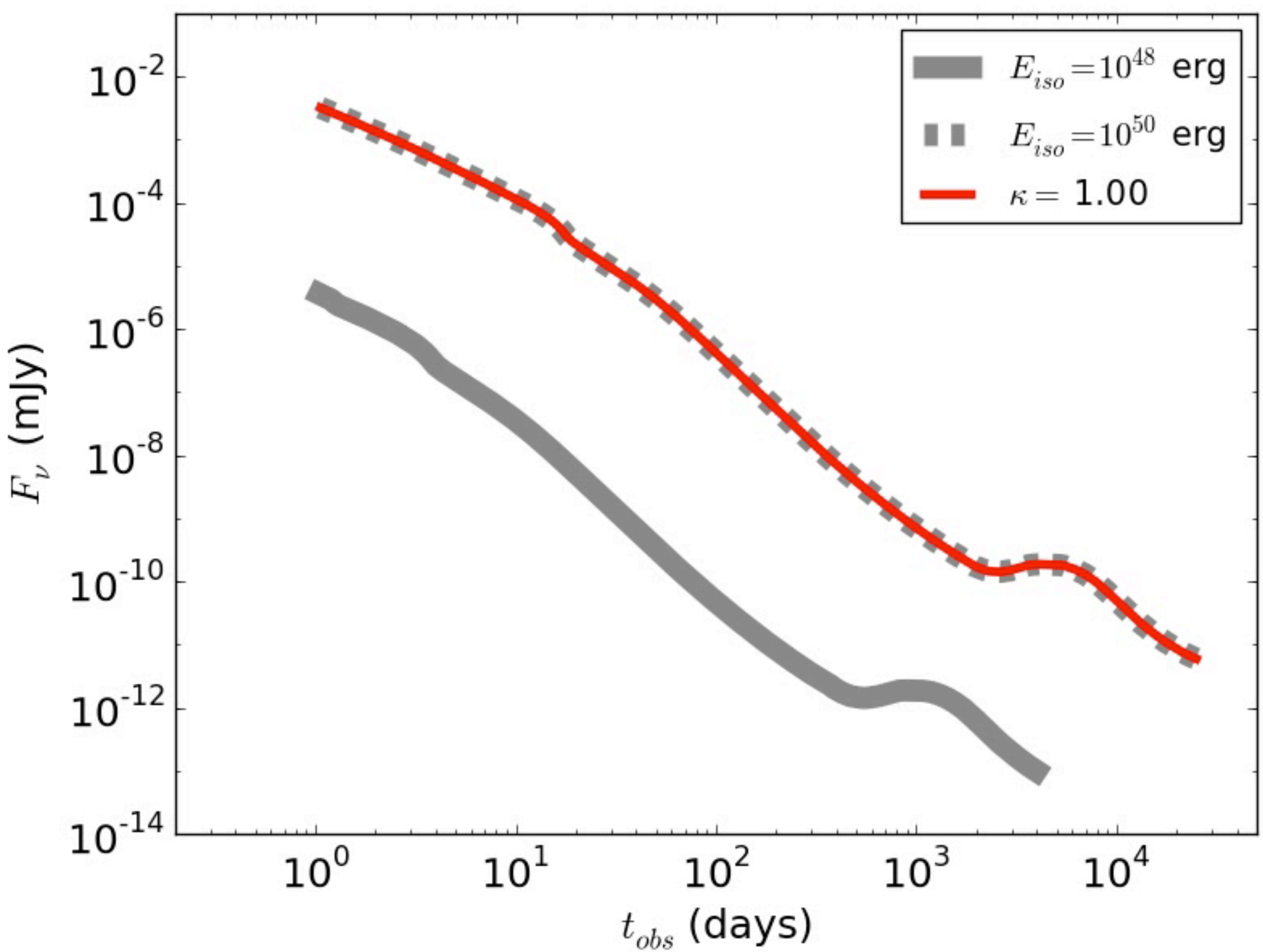

$$E'_{iso} = \kappa E_{iso}, \quad n' = \lambda n,$$

$$t'_{obs} = (\kappa/\lambda)^{1/3} t_{obs}, \quad F'_{optical} = \kappa \lambda^{(1+p)/4} F_{optical}$$

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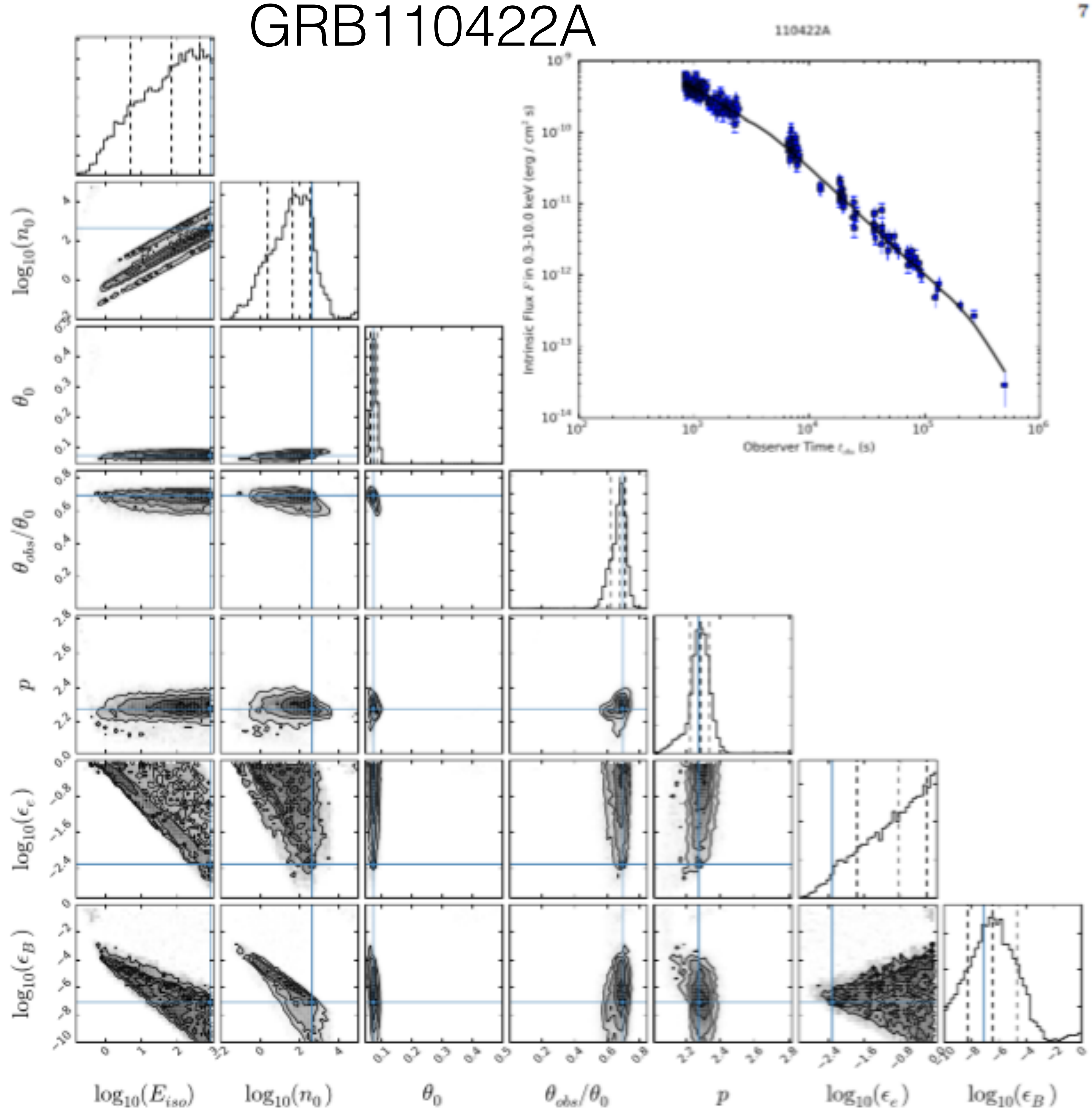
$$\Theta \equiv \{z, d_L, E_{iso}, n_0, \theta_0, \theta_{obs}, p, \epsilon_e, \epsilon_B, \xi_N\}$$

$$\Theta_{fit} \equiv \{\log_{10}\kappa,\ \log_{10}\lambda,\ \theta_0,\ \theta_{obs}/\theta_0,\ p,\ \log_{10}\epsilon_e,\ \log_{10}\epsilon_B\}\ .$$

GRB110422A



Ryan et al (2015)

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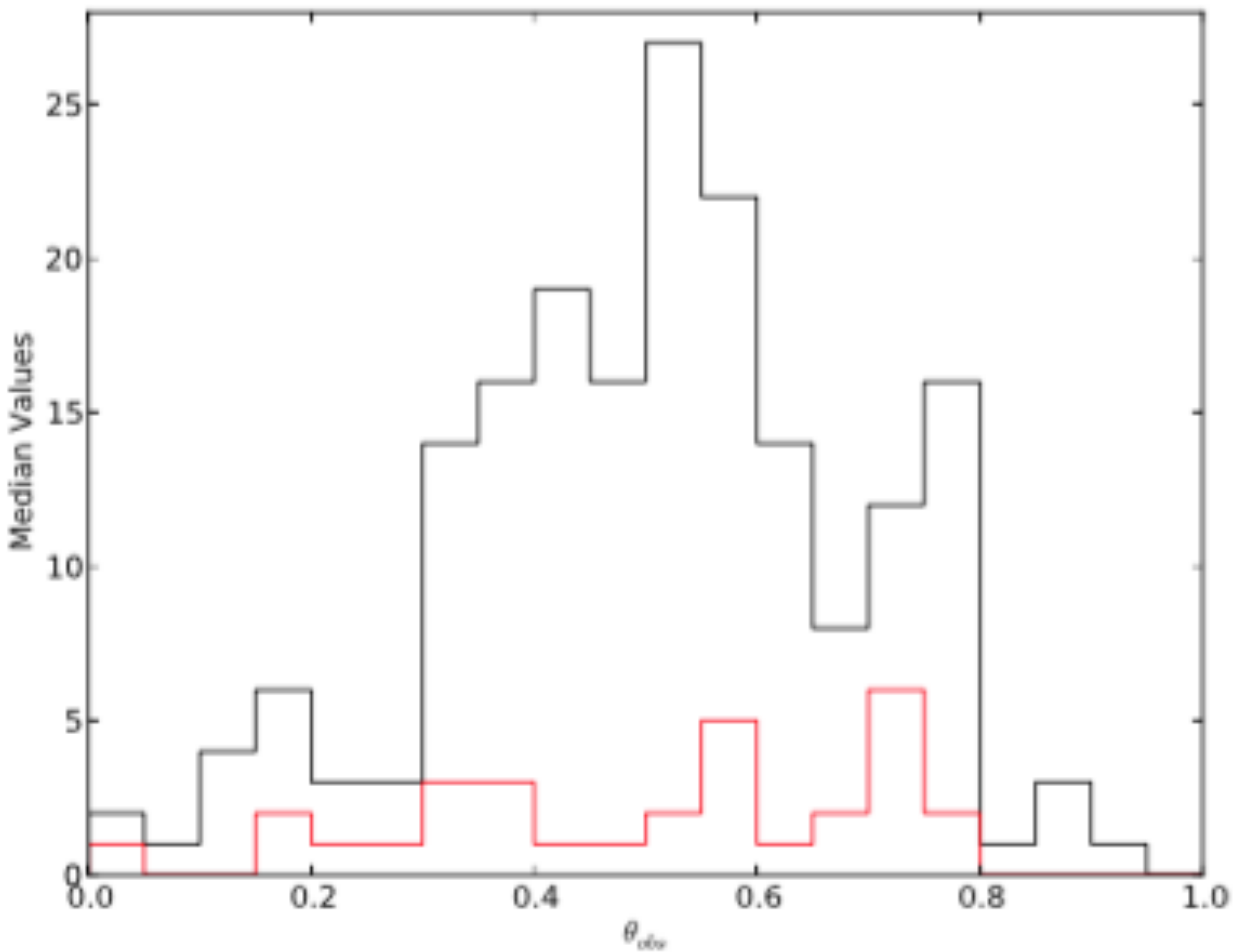
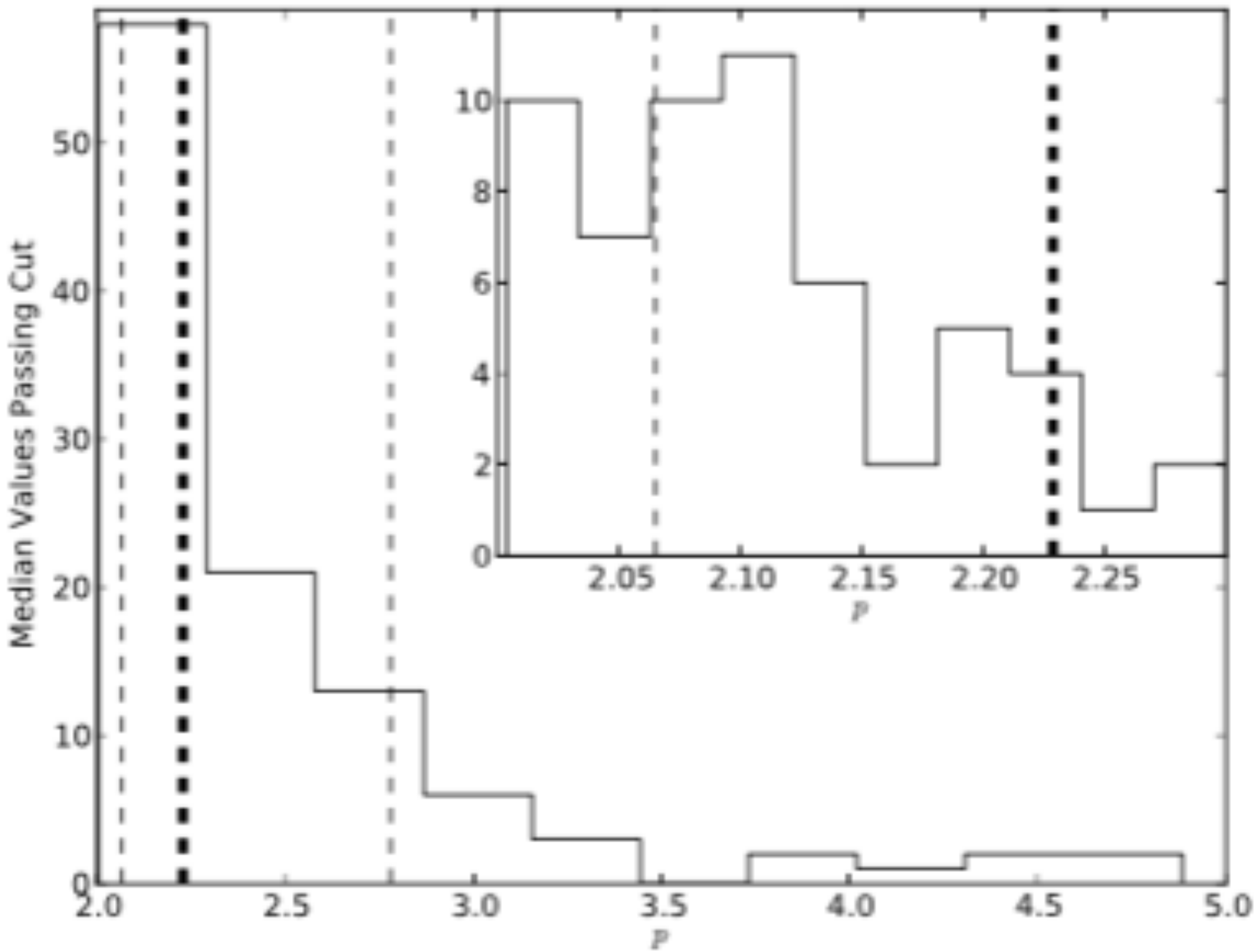
Observer Angle



Ryan et al (2015)

Electron slope p



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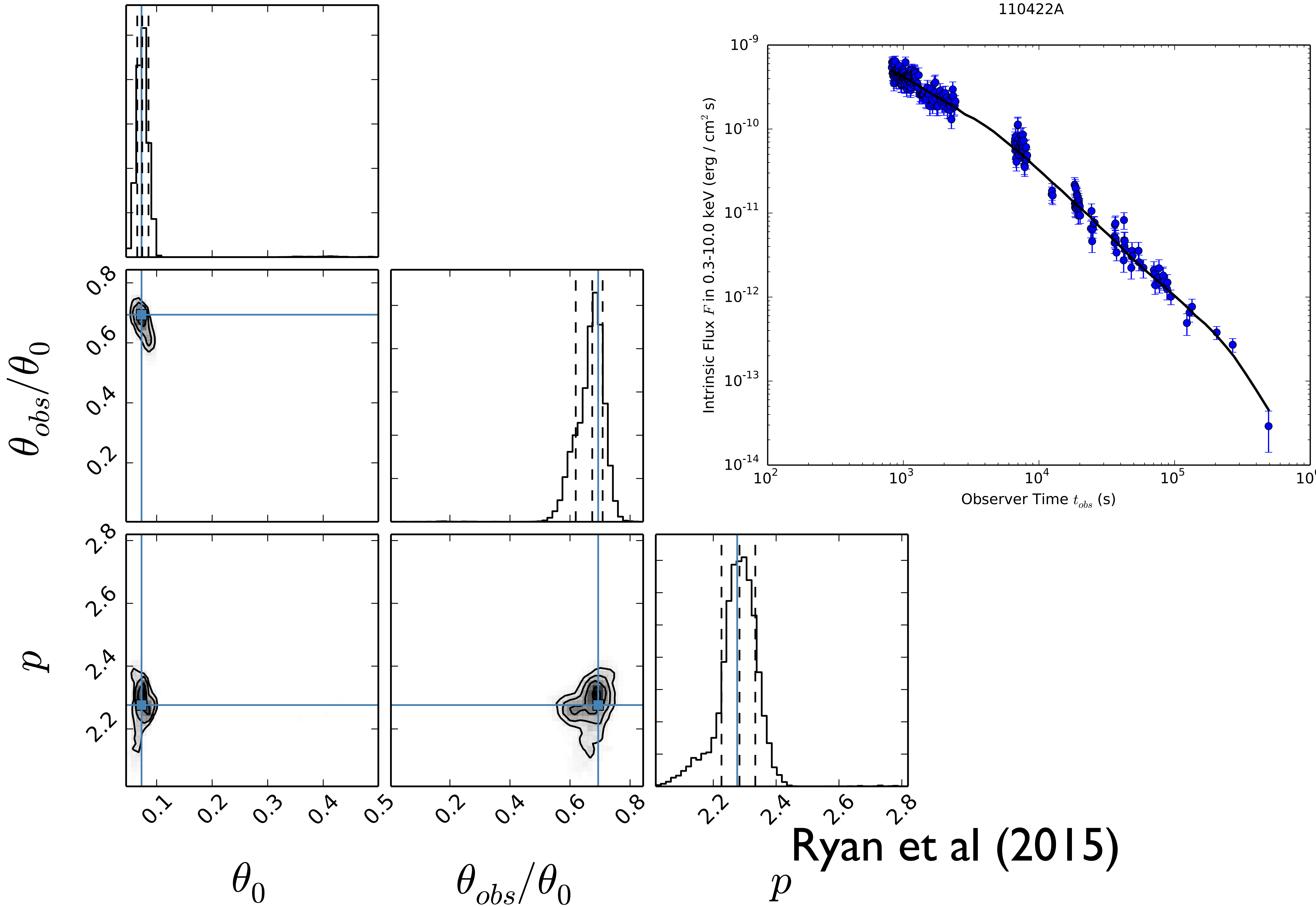
GRB110422A



Ryan et al (2015)

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Supported by NASA NNX10AF62G

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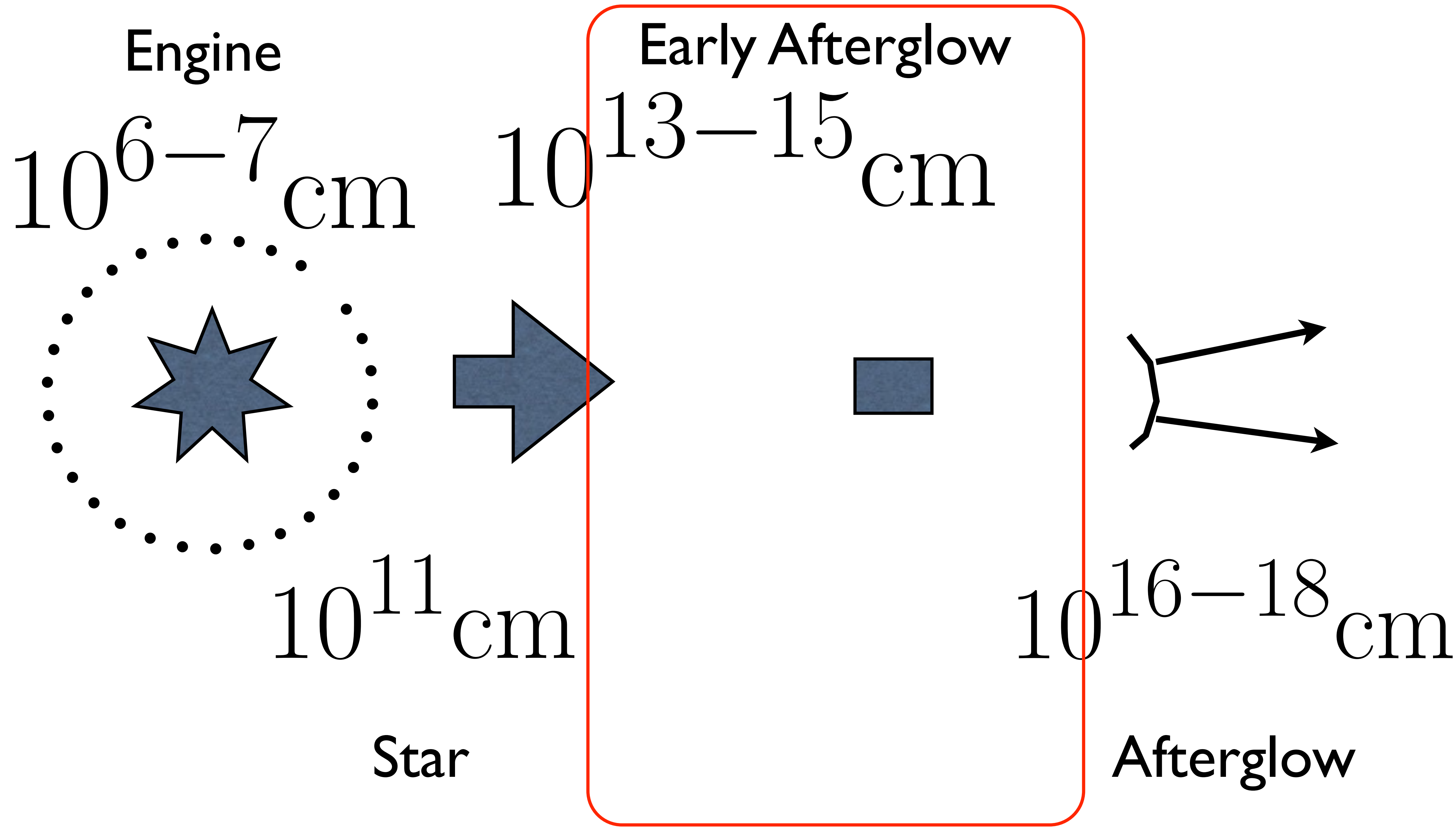
Over 10 orders of mag in length scale!



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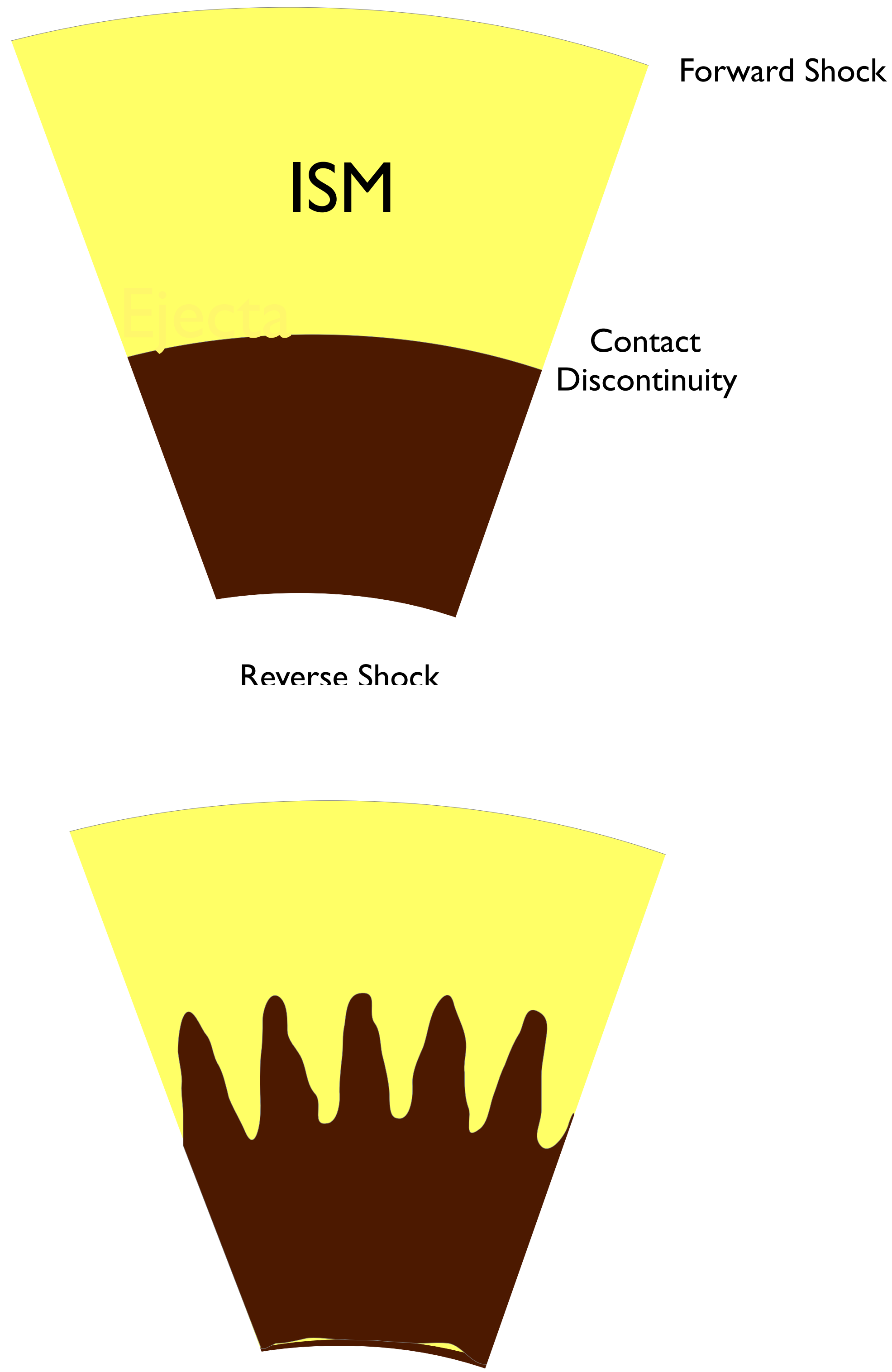


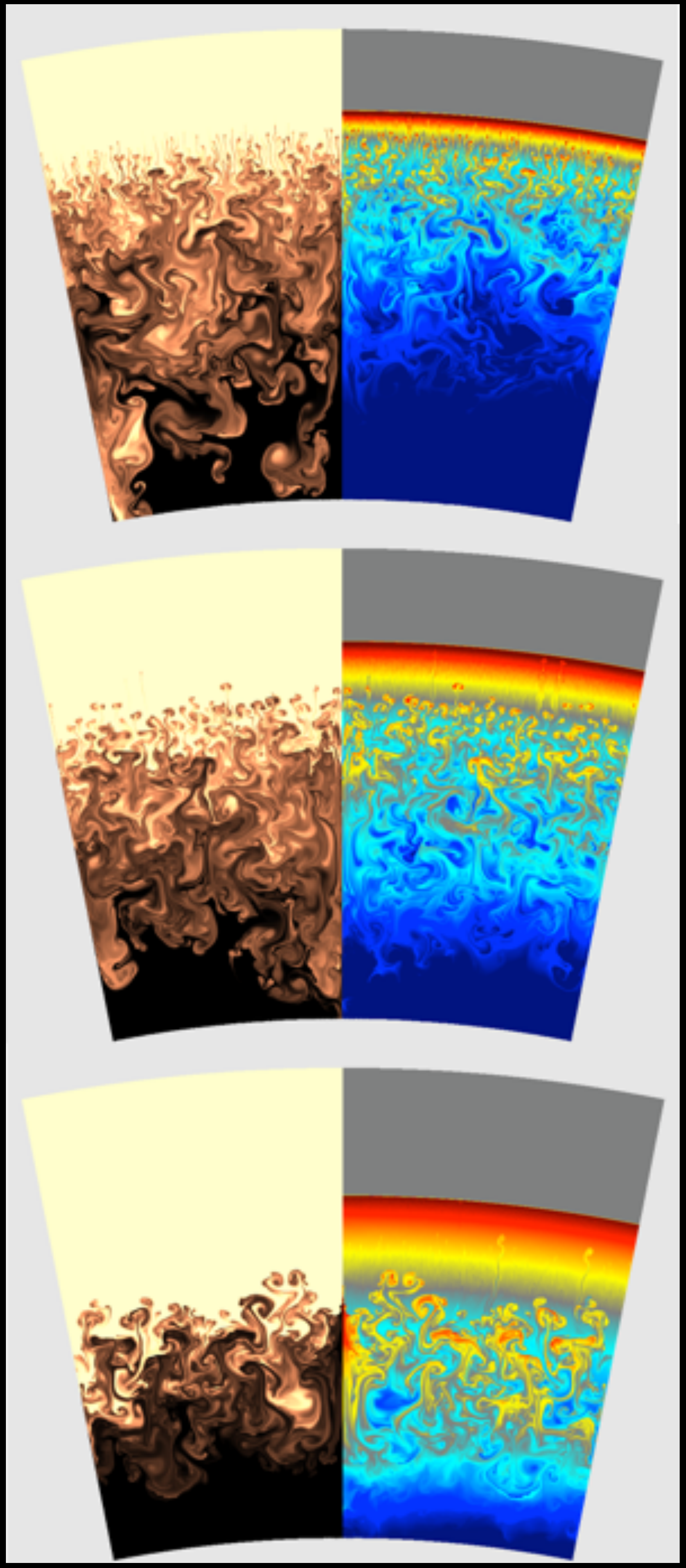
Forward Shock
ISM
Ejecta
Contact
Discontinuity
Reverse Shock

Rayleigh-Taylor Instability

100

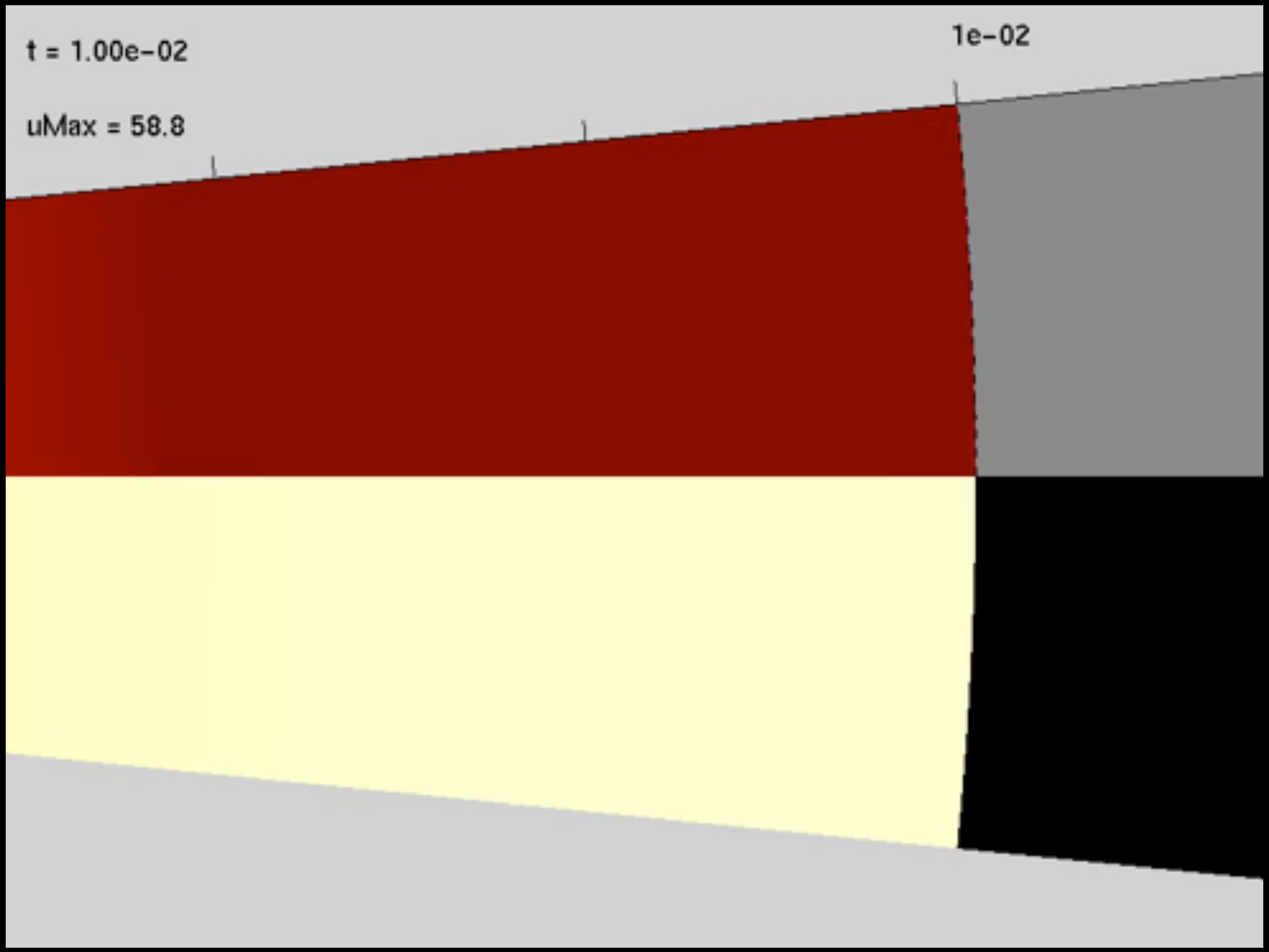
30

Lorentz Factor = 10

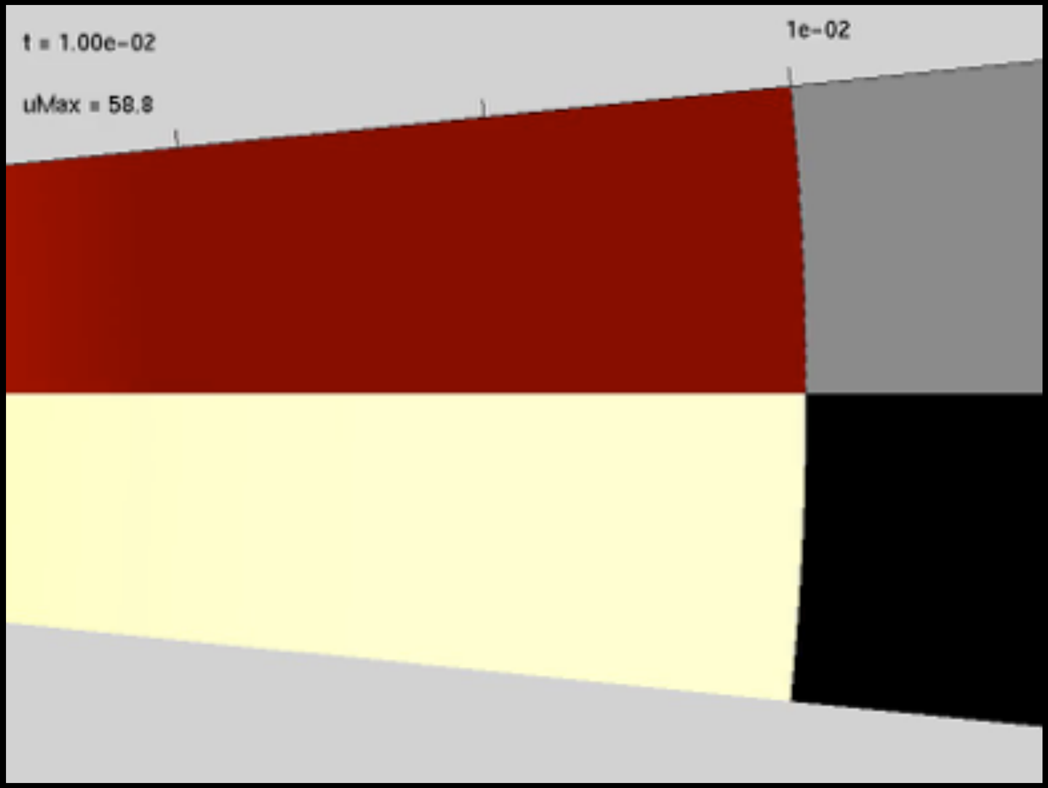


Duffell & AM (2014)

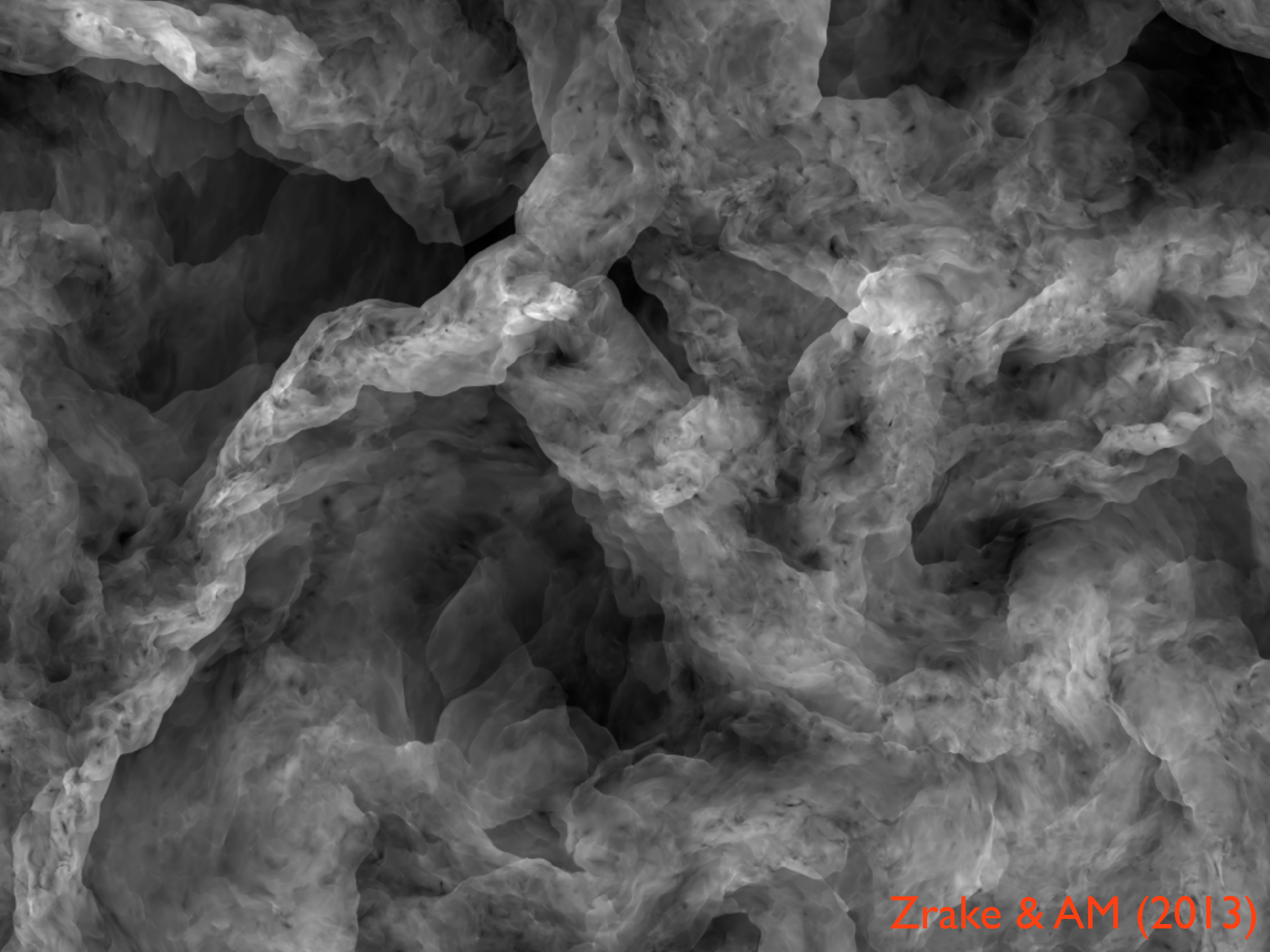
Adiabatic Index = 4/3



Adiabatic Index = 1.1



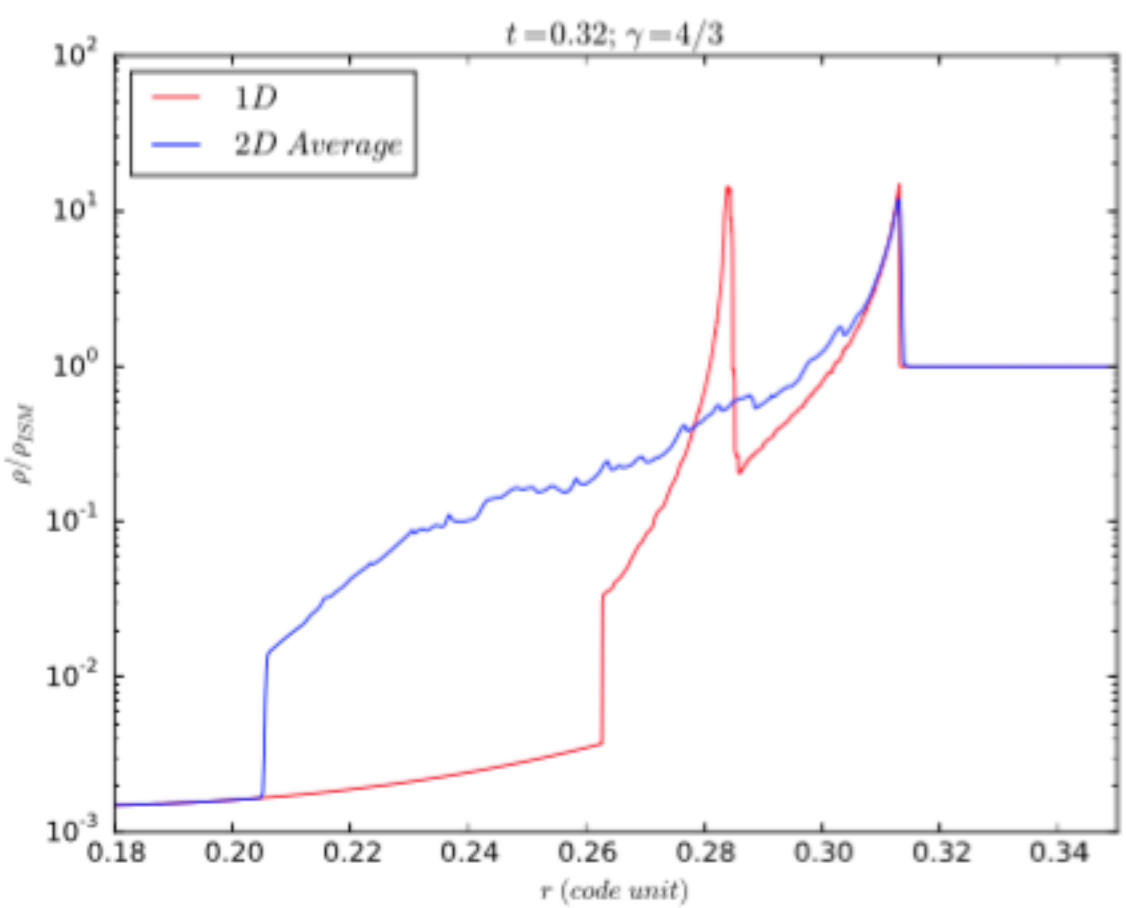
Duffell & AM (2014)

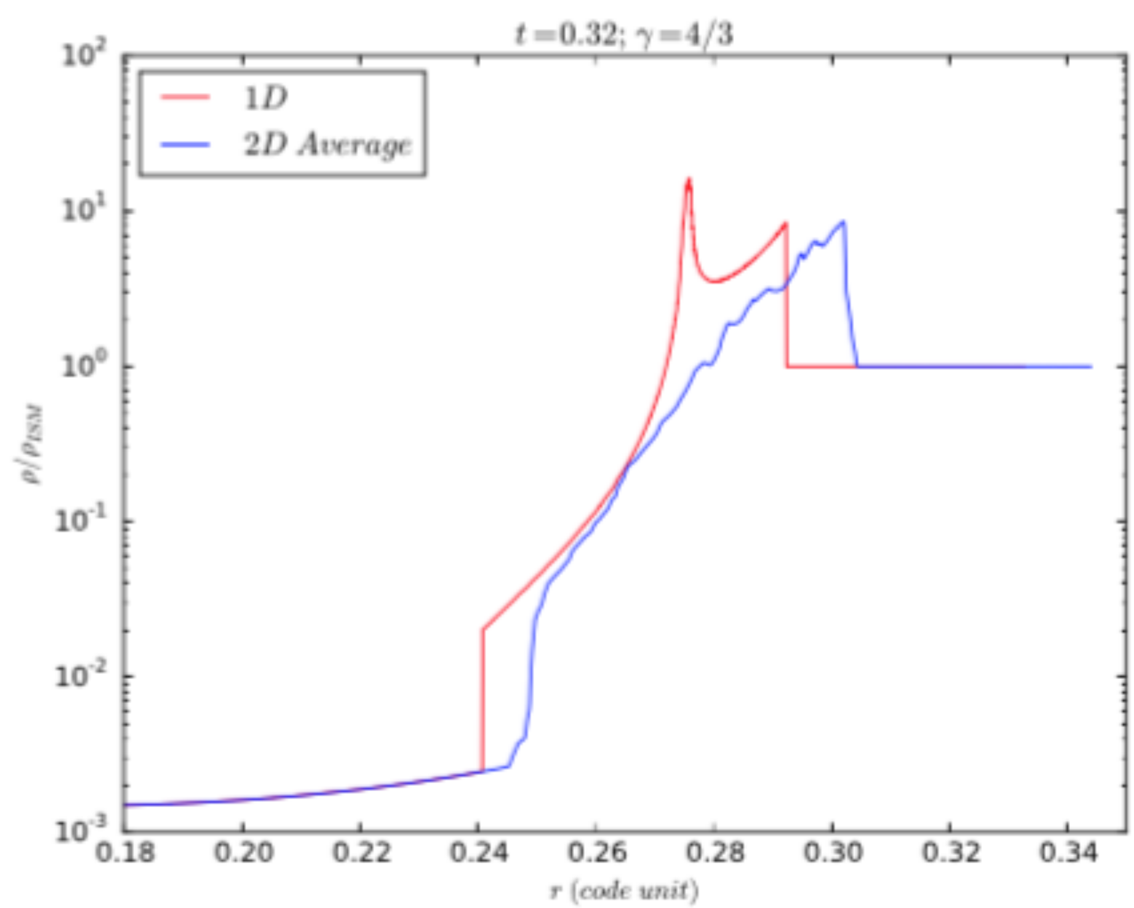

Zrake & AM (2013)

$$P_{syn} = \frac{36\sigma_T m_p}{m_e^2 c^3} \cdot (\epsilon_e^2 \epsilon_B \frac{P^3}{\rho})$$

$$\gamma = 4/3$$

$$\epsilon_e^2 \epsilon_B = 0.05$$





Yiyang Wu et al (2016)

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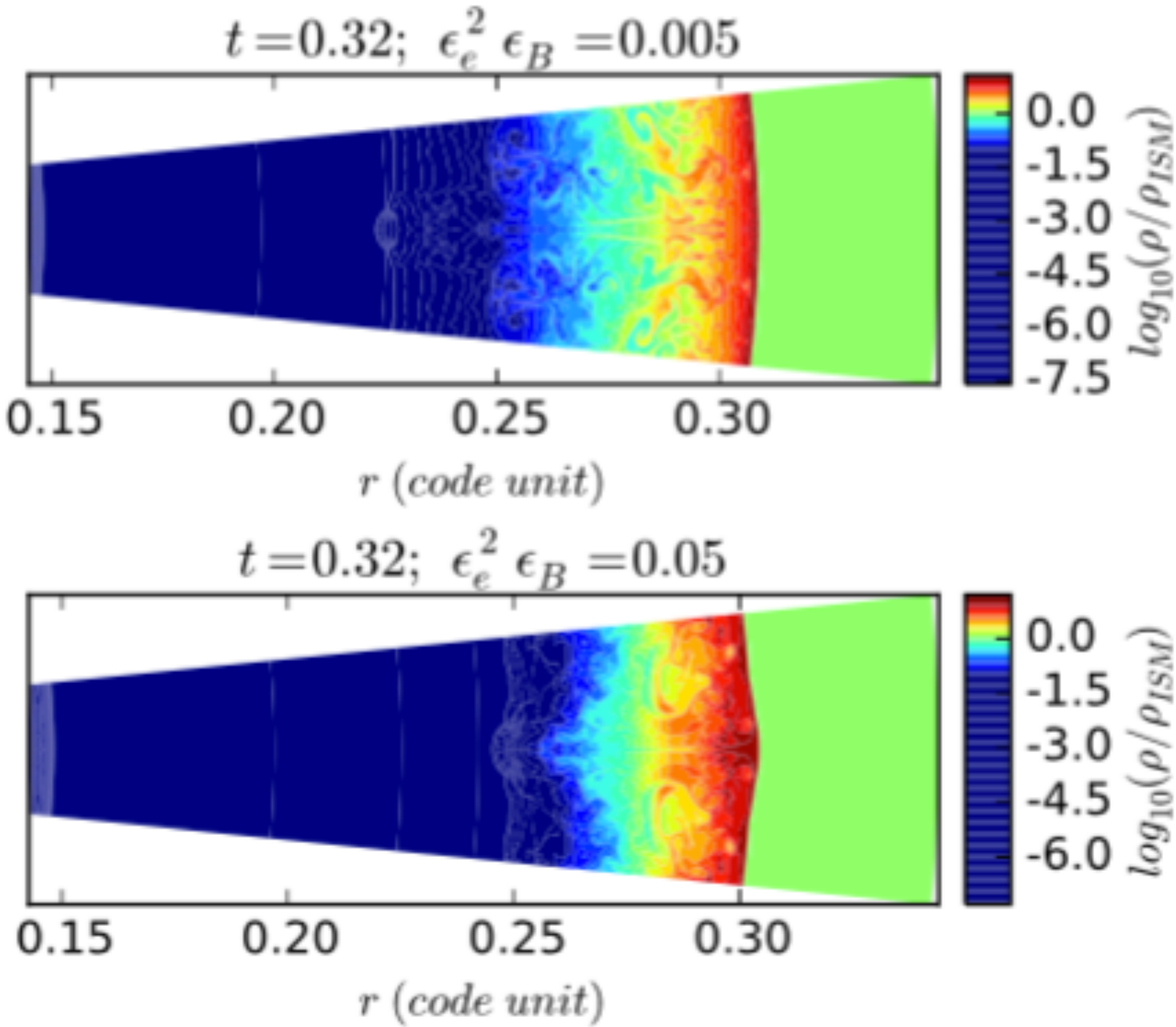

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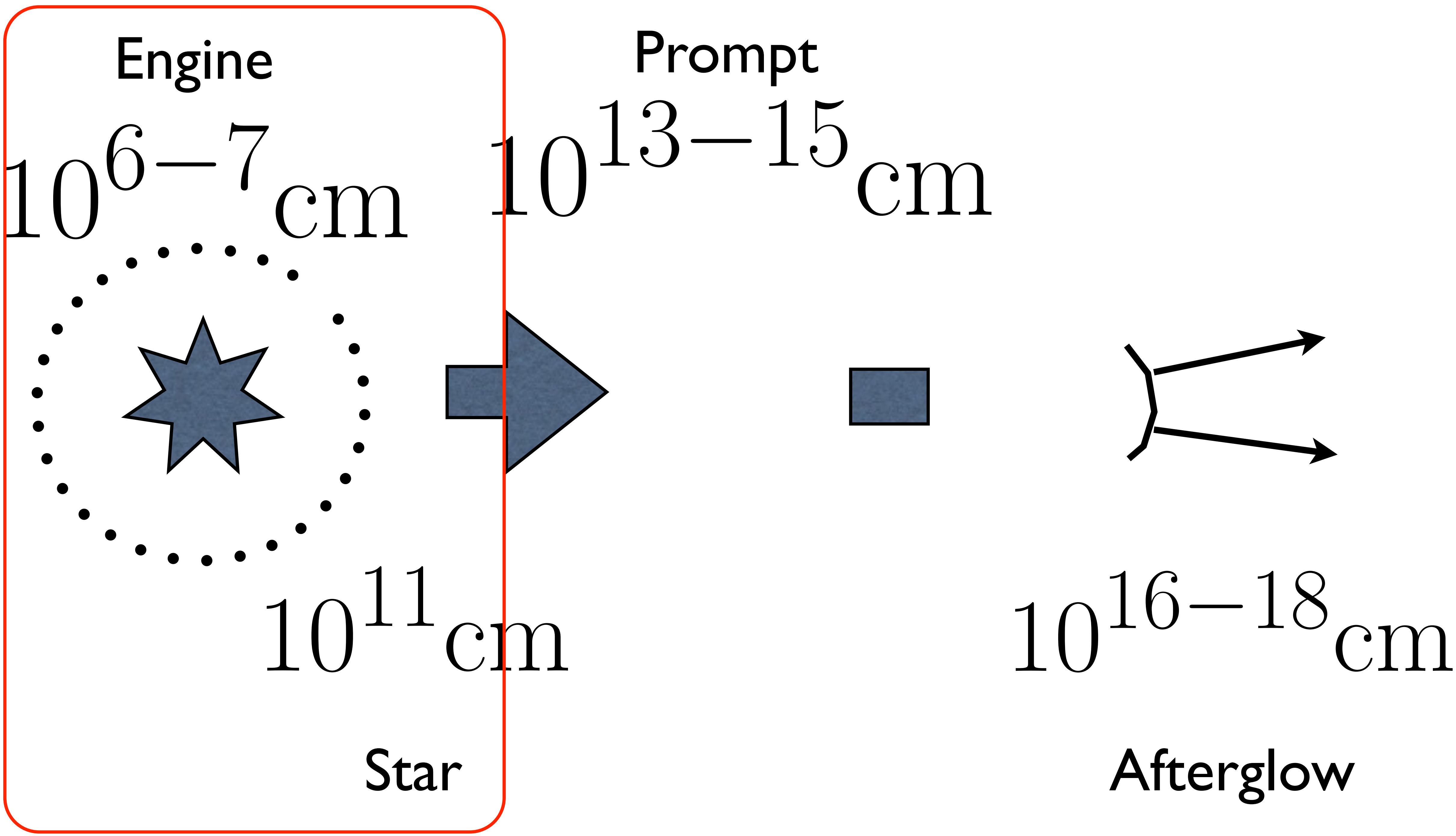
Over 10 orders of mag in length scale!



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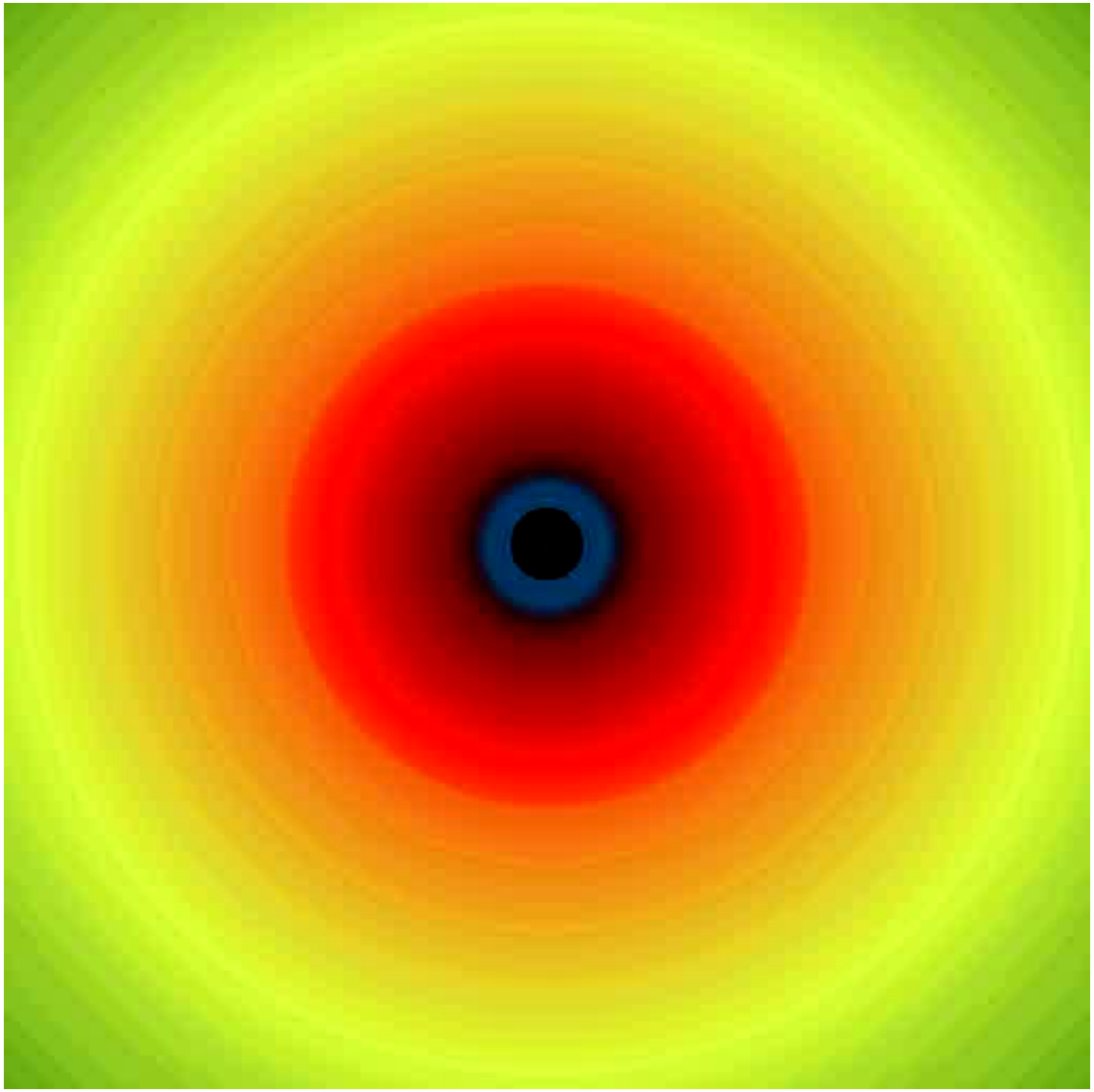
Relativistic Jets Can Escape Stars

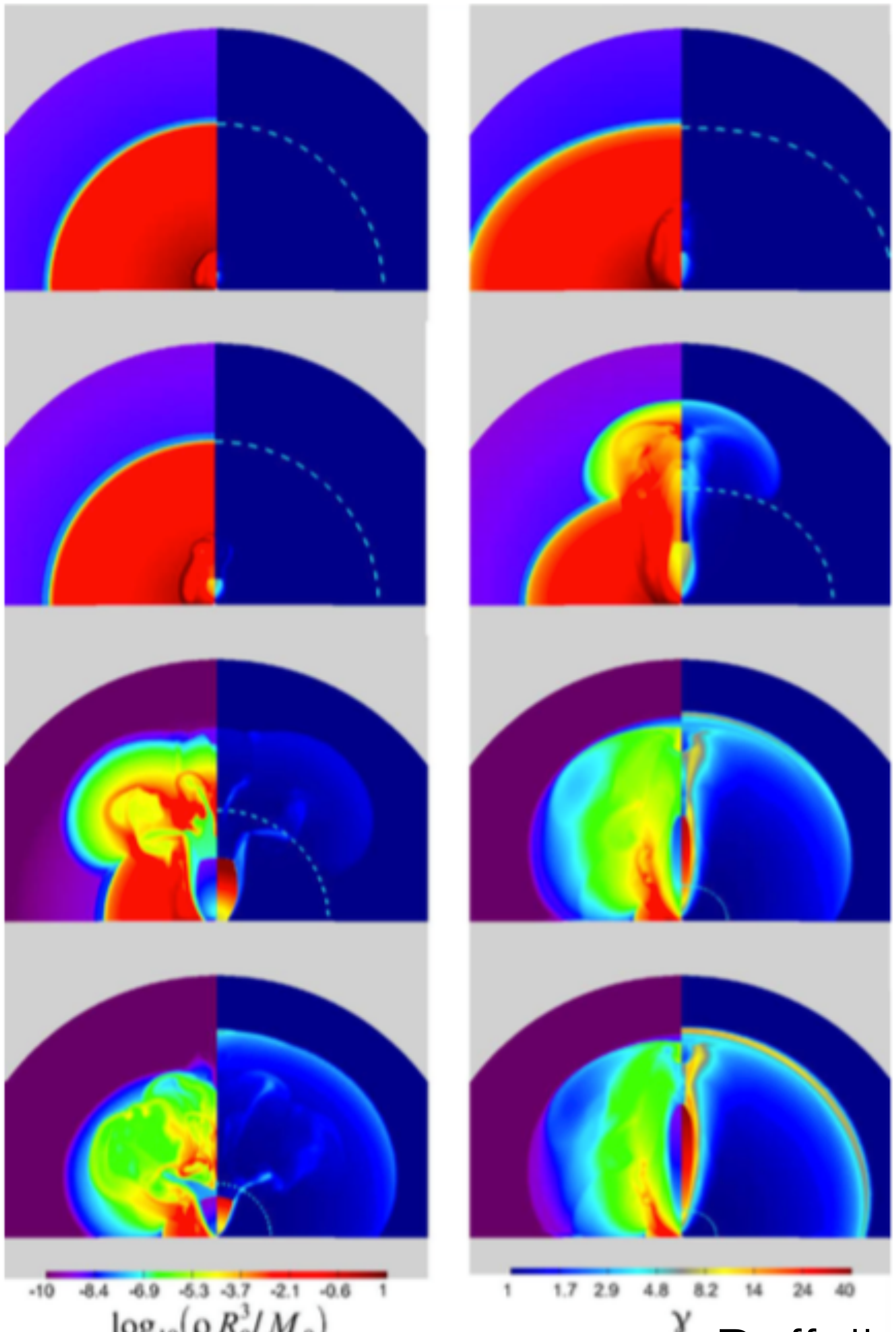


Binary Black Hole Case e.g. Loeb (2016)?

Expect gamma ray variability at ~ binary frequency?

Baryons aren't a problem!

Baryons can help collimate a jet..



Short Burst in pre NS merger Ejecta Cloud

Left: Spherical Cloud

Right: Flat cloud

Duffell, Quataert & AM (2015)

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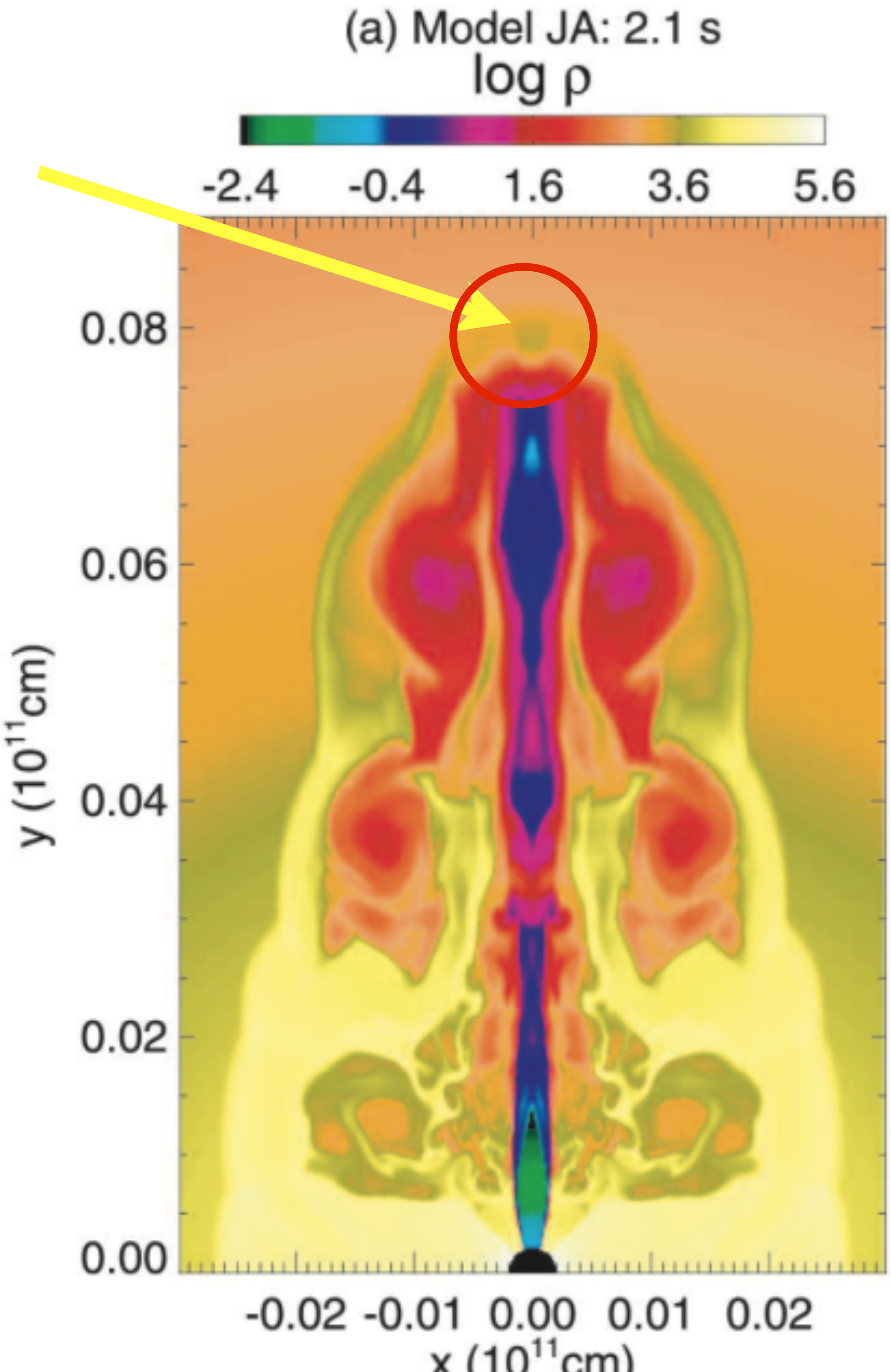
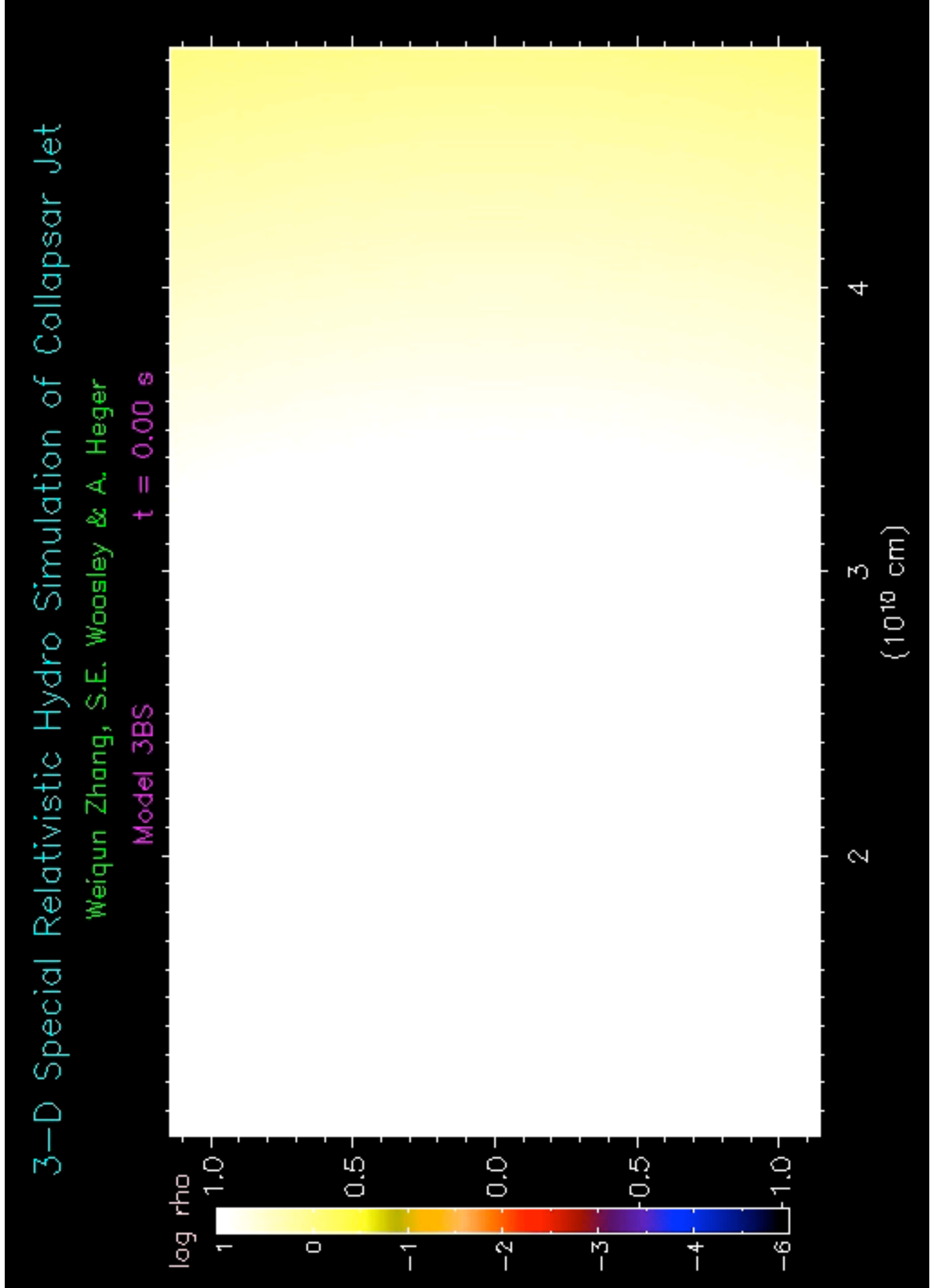
2D SRHD

“Plug”



Zhang, Woosley & MacFadyen (2003)

3D SRHD



Zhang+ (2004)

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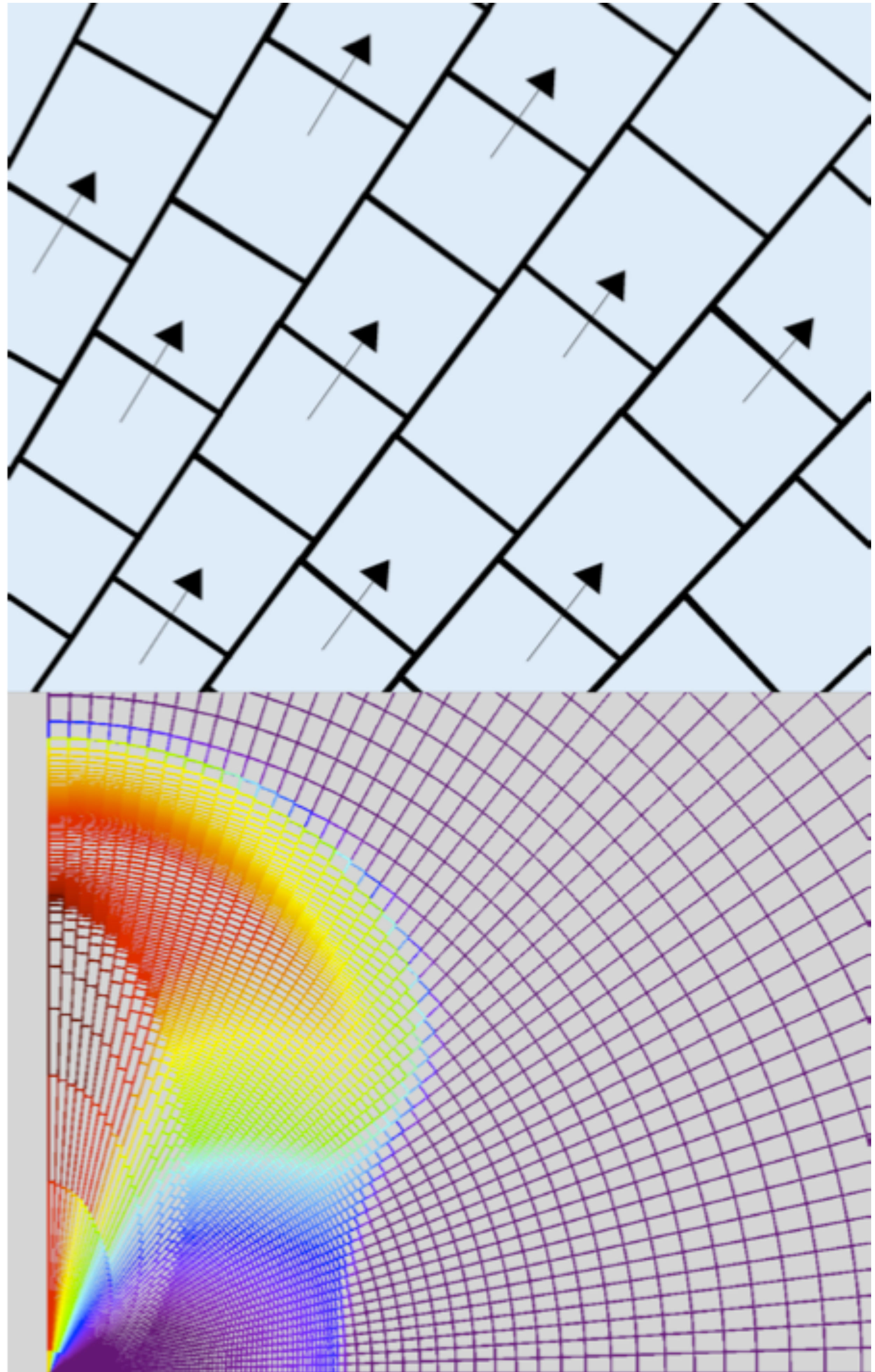
“JET”
Moving Mesh
Code

Relativistic
MHD

Duffell &
MacFadyen
(2011,2013,
2014)



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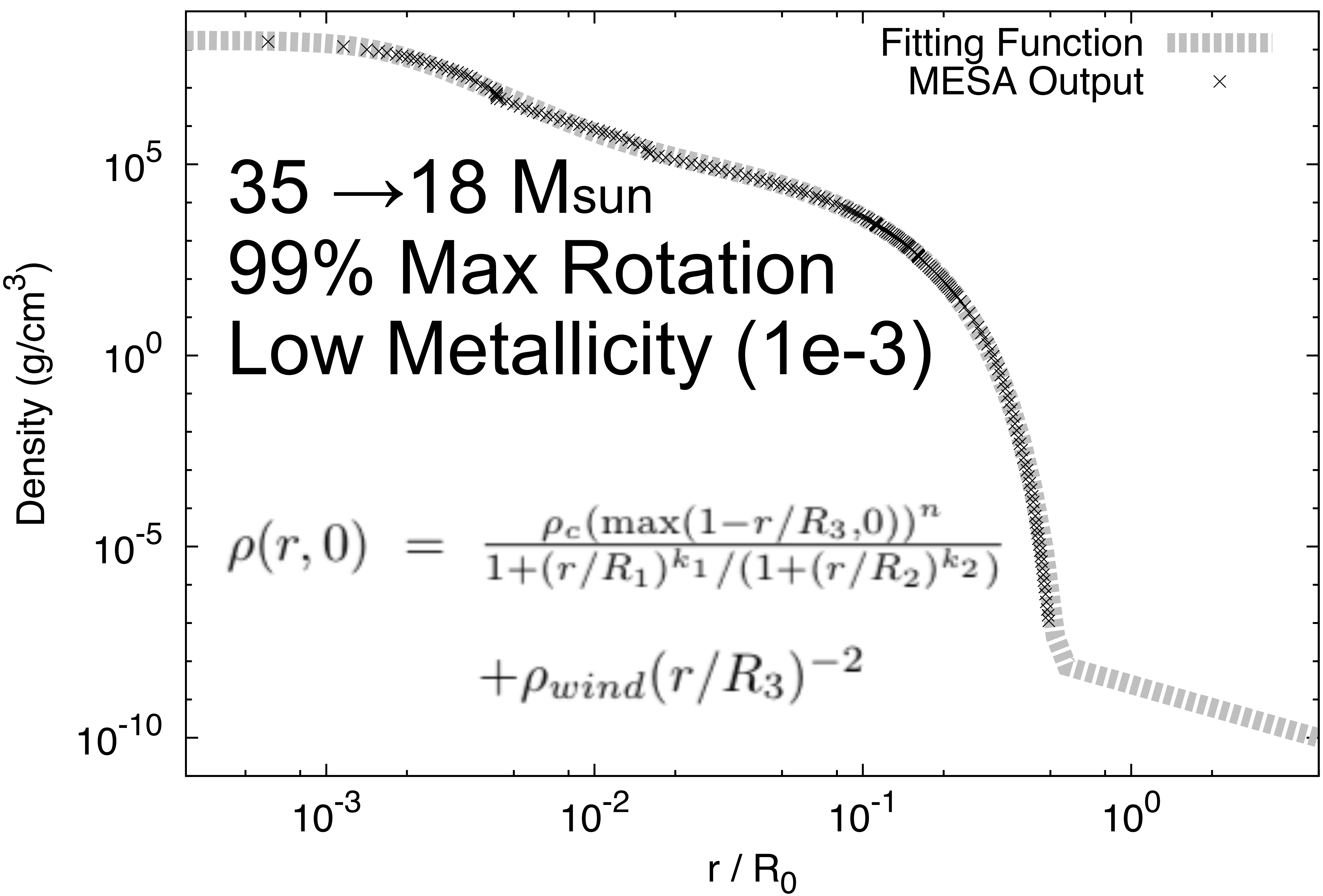
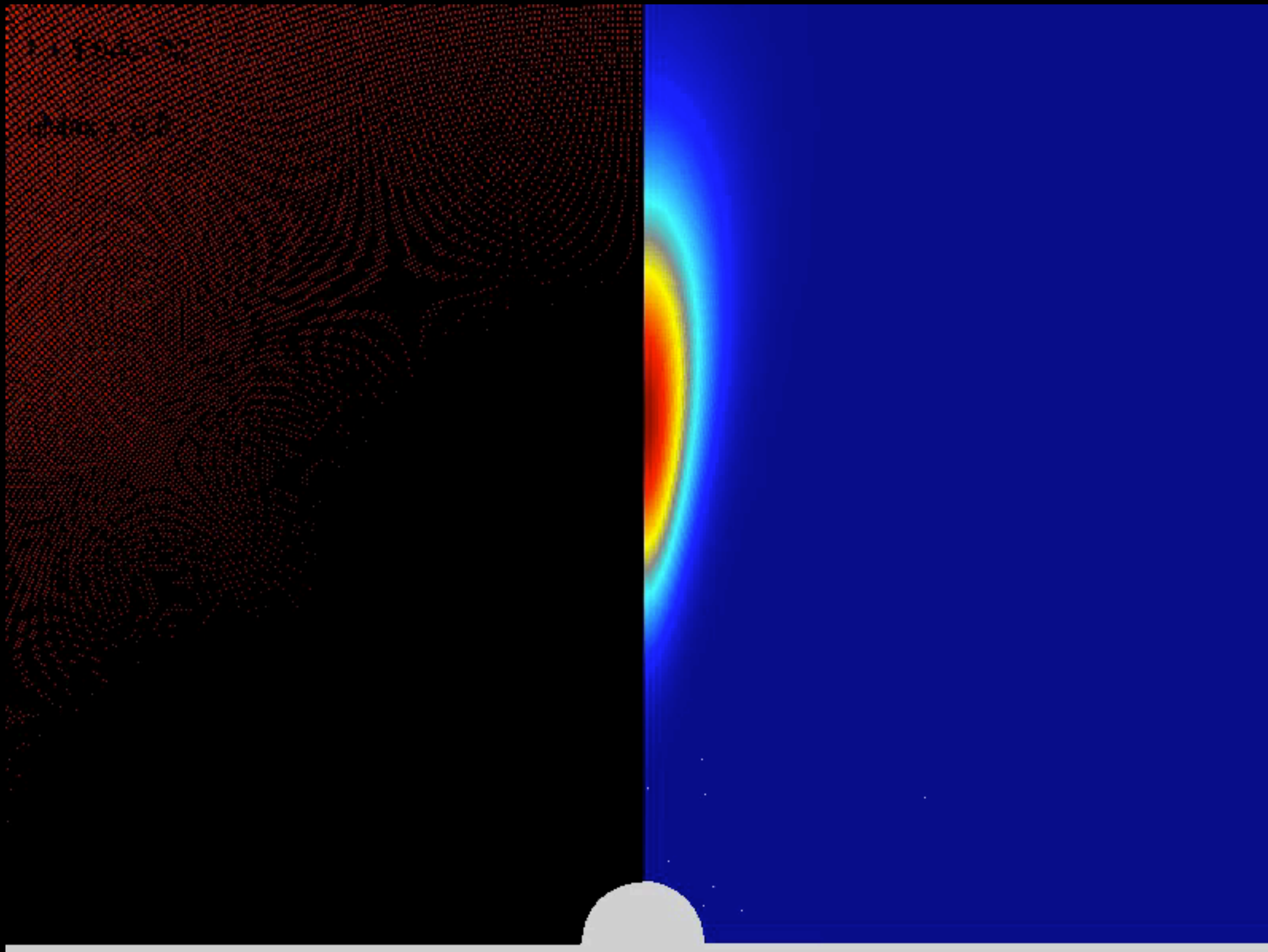
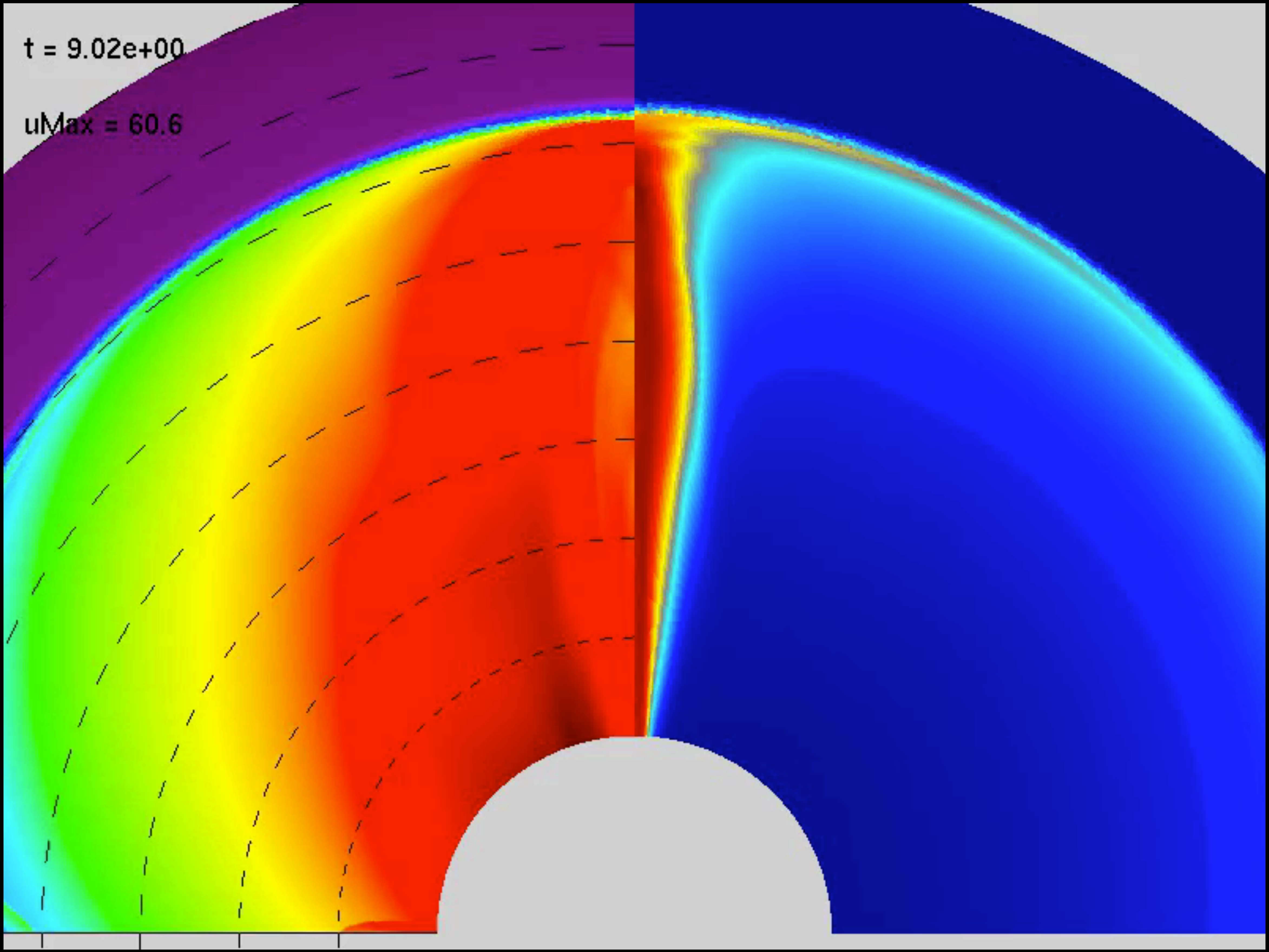


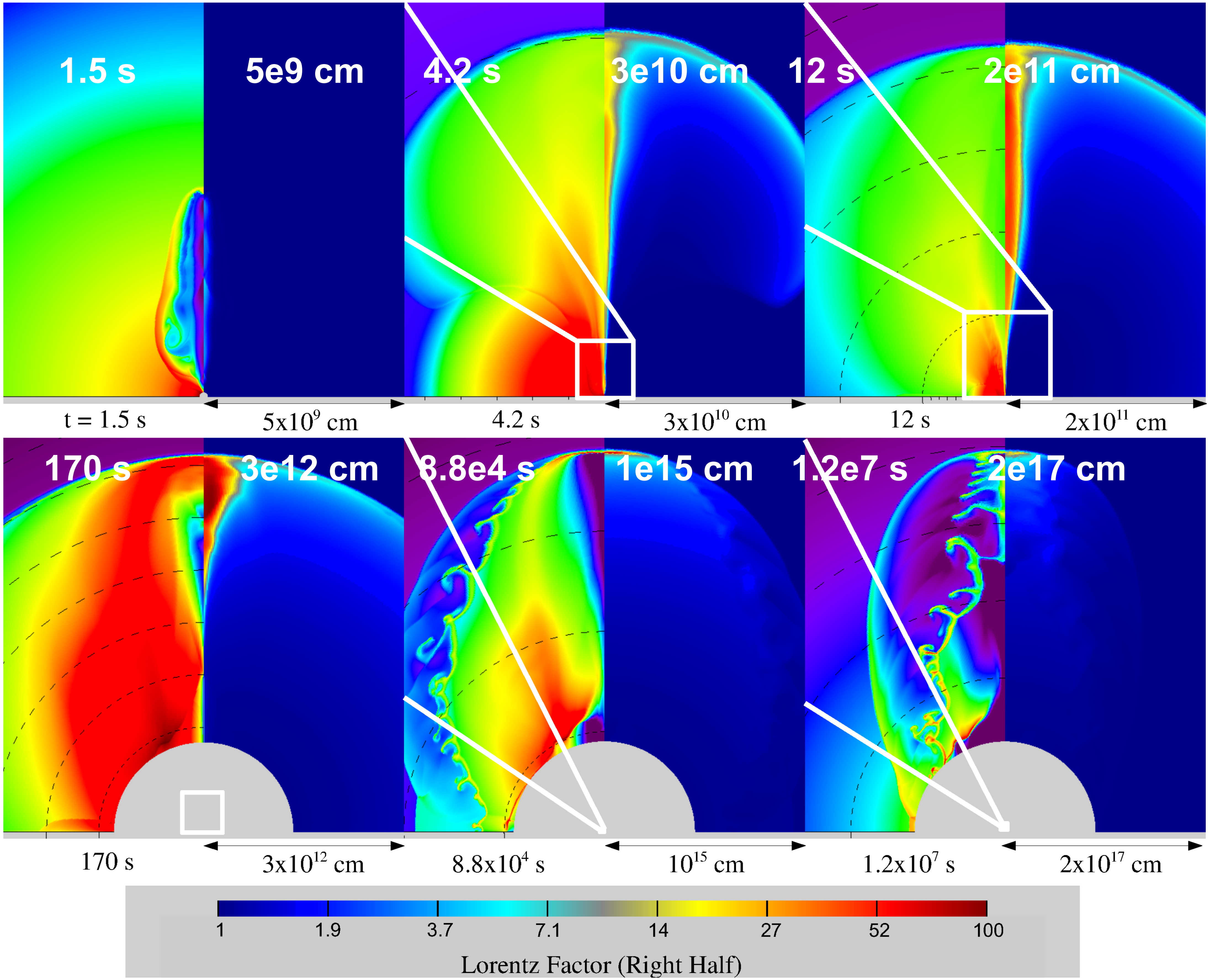
Duffell & MacFadyen (2015)



Duffell & MacFadyen (2014)



Duffell & MacFadyen (2014)



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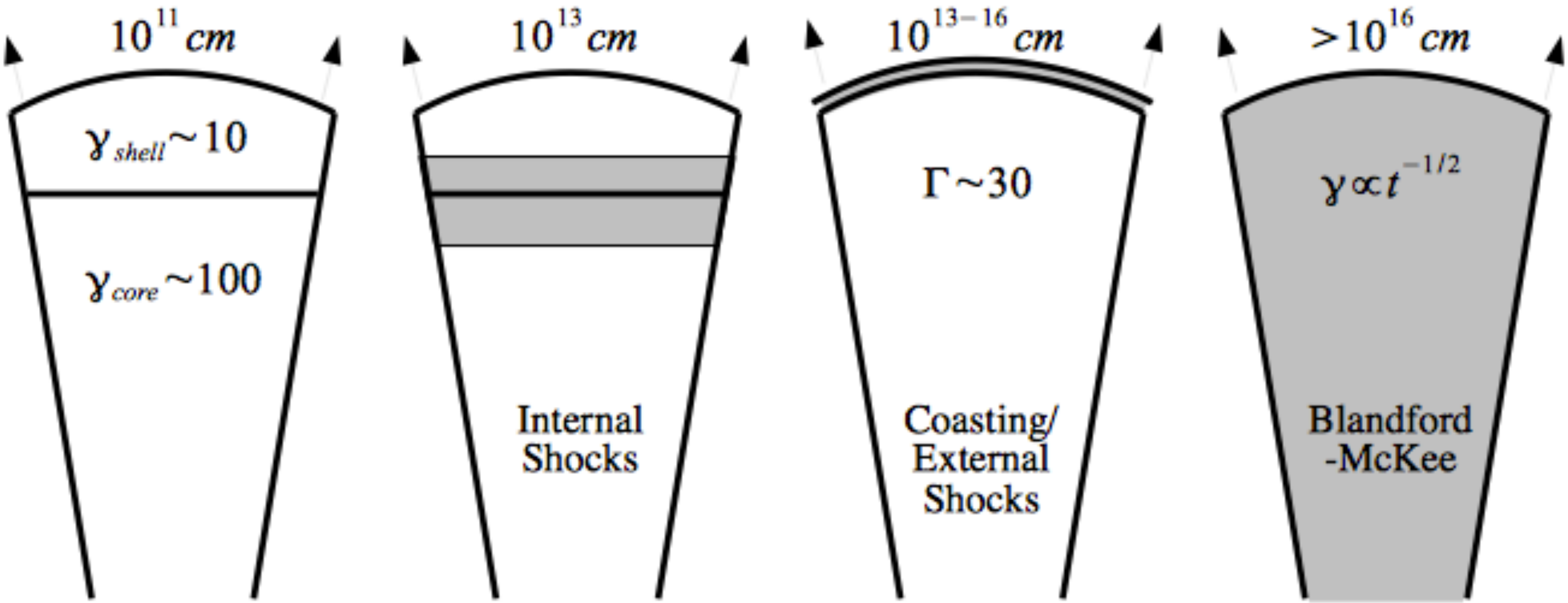
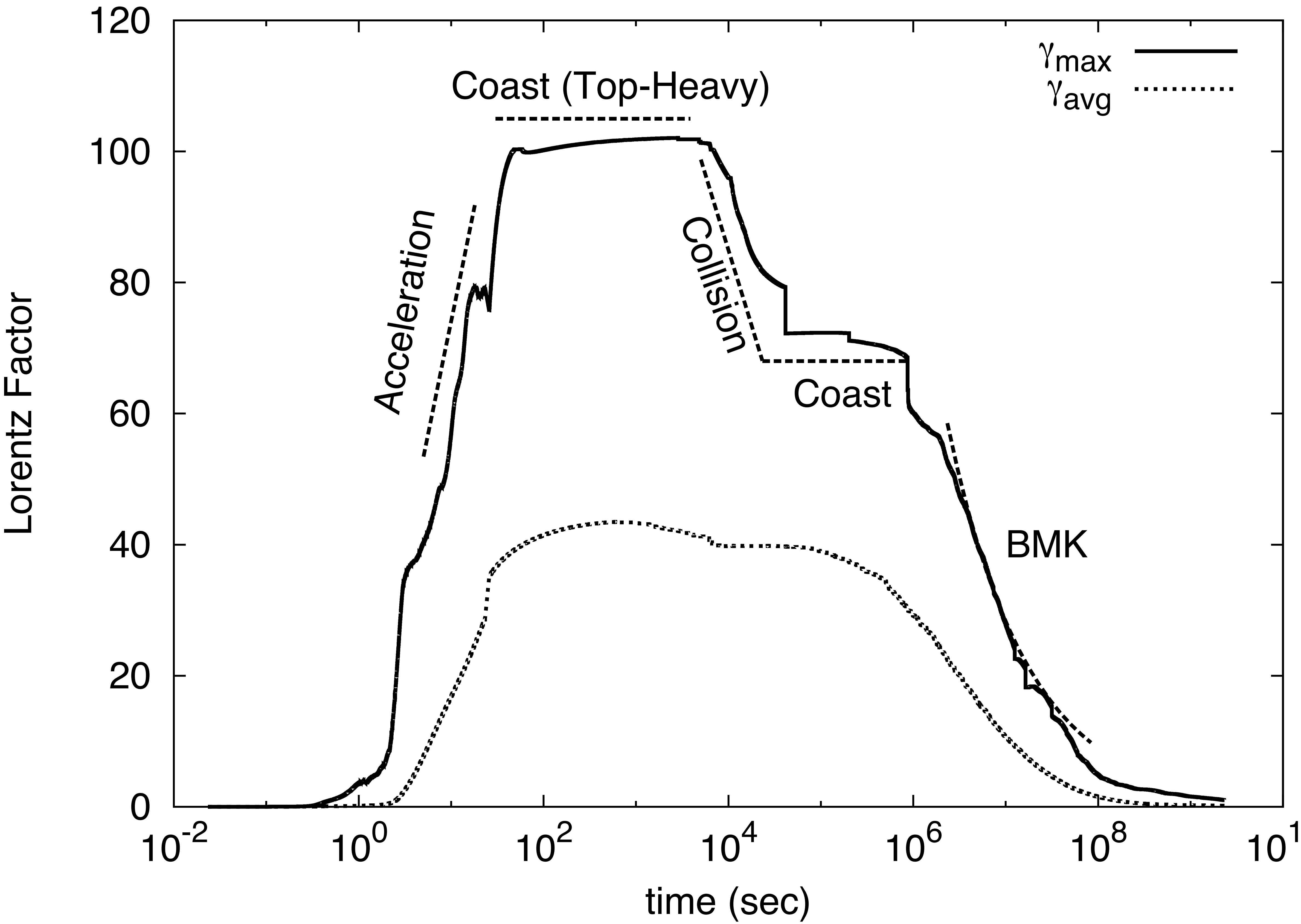


Duffel & AM (2015)



Duffell & AM (2015)

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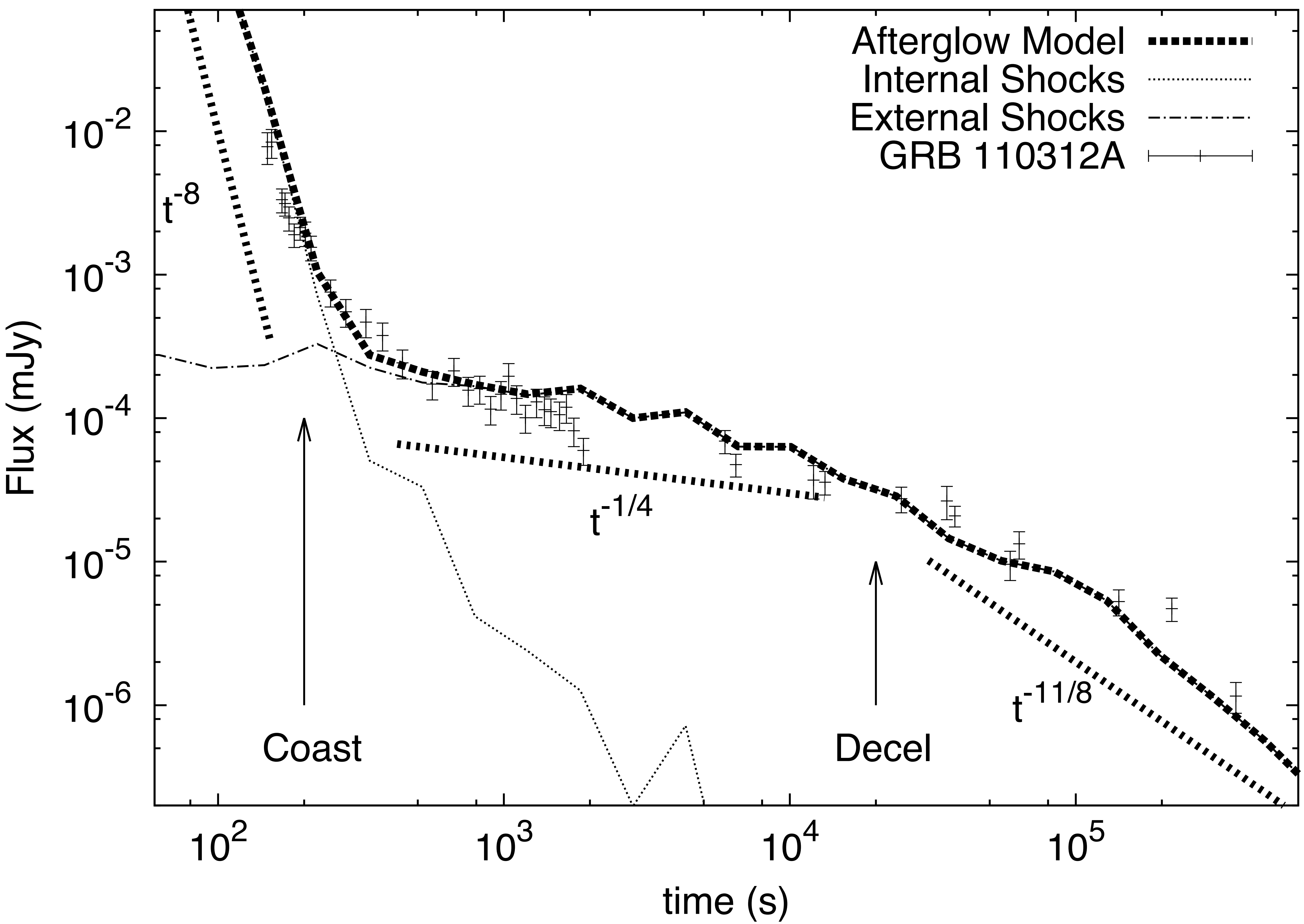

Duffell & AM (2015)

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$$\alpha_{op} = -3 + k(p+5)/4 \quad \nu_m < \nu < \nu_c$$

$$\alpha_{op} = (p-1)/2 = 3/4 \text{ for } p = 2.5$$

Independent of p:

$$\Delta\alpha \equiv \alpha_{op} - \alpha_X = 3k/4 - 1 \approx 1/2$$

In contrast, decelerating blast wave predicts (eg Sari et al, 1998):

$$\Delta\alpha = 1/4$$

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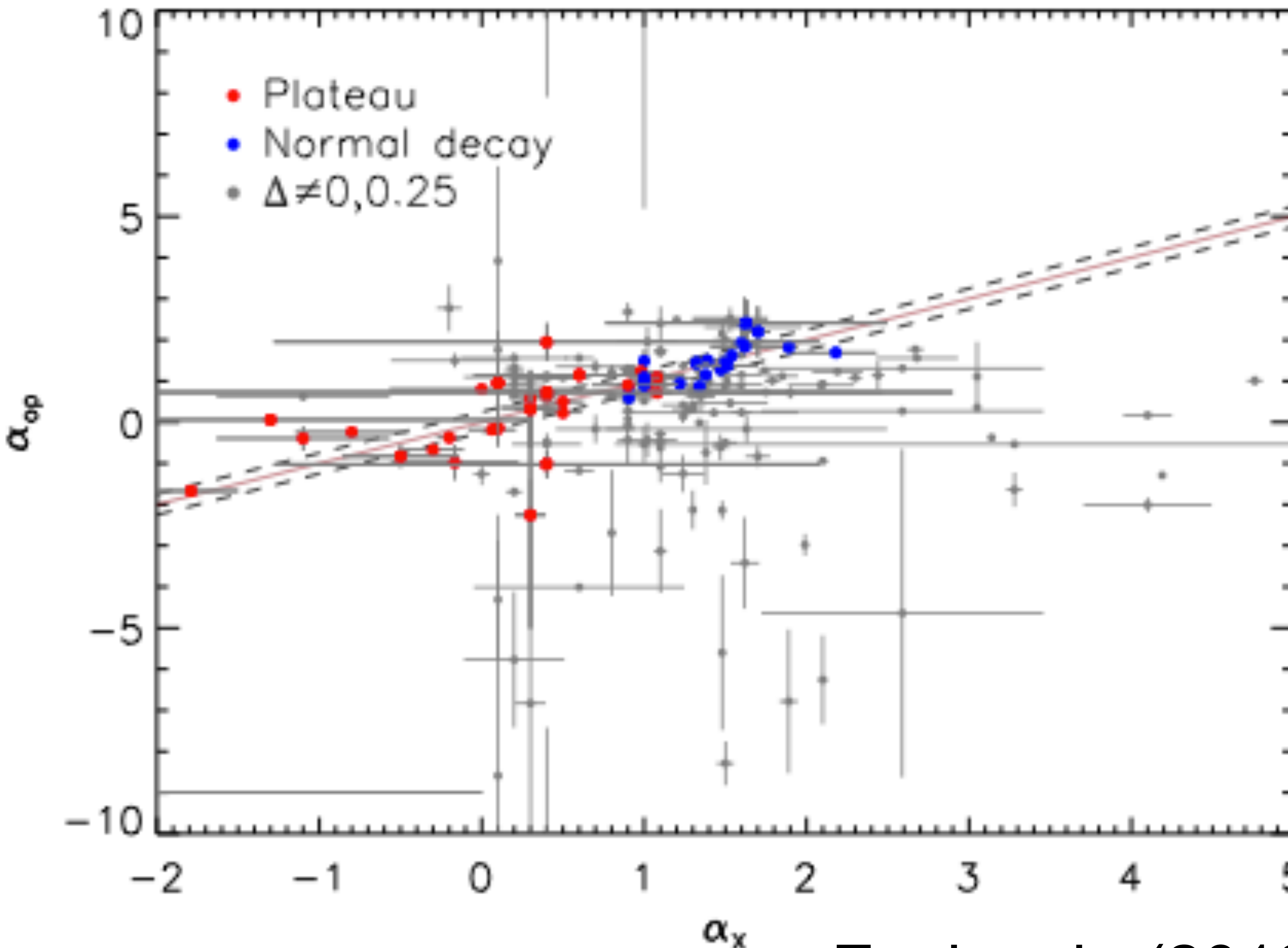

Zaninoni+ (2013)

A. MacFadyen (NYU)

Conclusions

- GRB afterglows p ~ 2.2
- OFF AXIS viewing $\longrightarrow$ "Magnetars" possible
- Jets are "top heavy"
- Internal collision $\longrightarrow$ steep decay
- Coasting amalgamated jet $\longrightarrow$ plateau
- Decaying plateau $\longrightarrow$ wind medium
- $\boldsymbol{\Delta\alpha}$ = 1/2
- Jets & Fireballs are RT Unstable $\longrightarrow$ B field