# The Dynamics and Radiation of Relativistic Jets

Andrew MacFadyen (New York University)

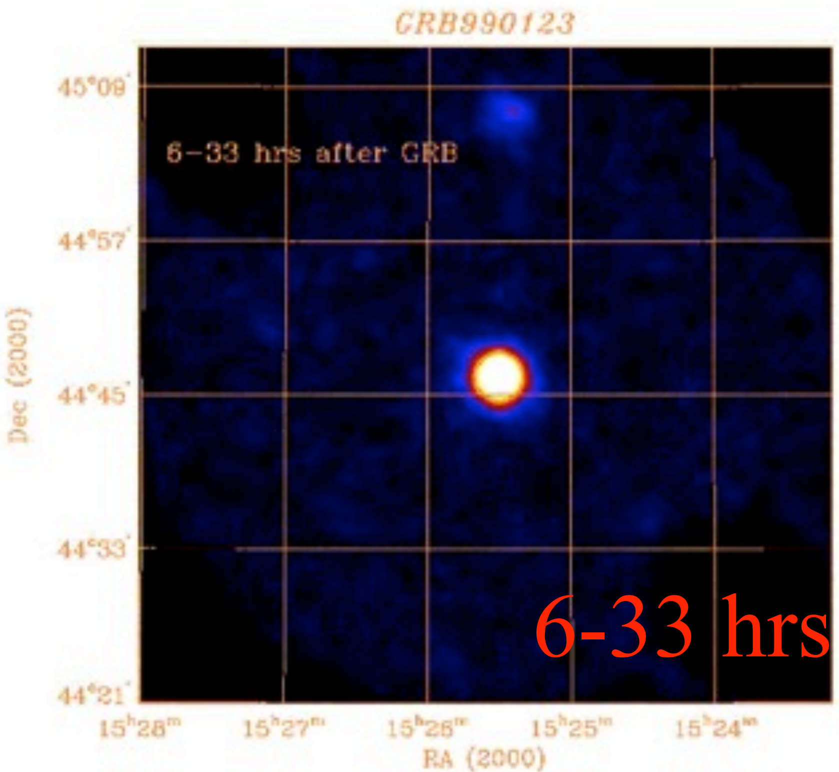
Paul Duffell, Geoff Ryan, Hendrik van Eerten

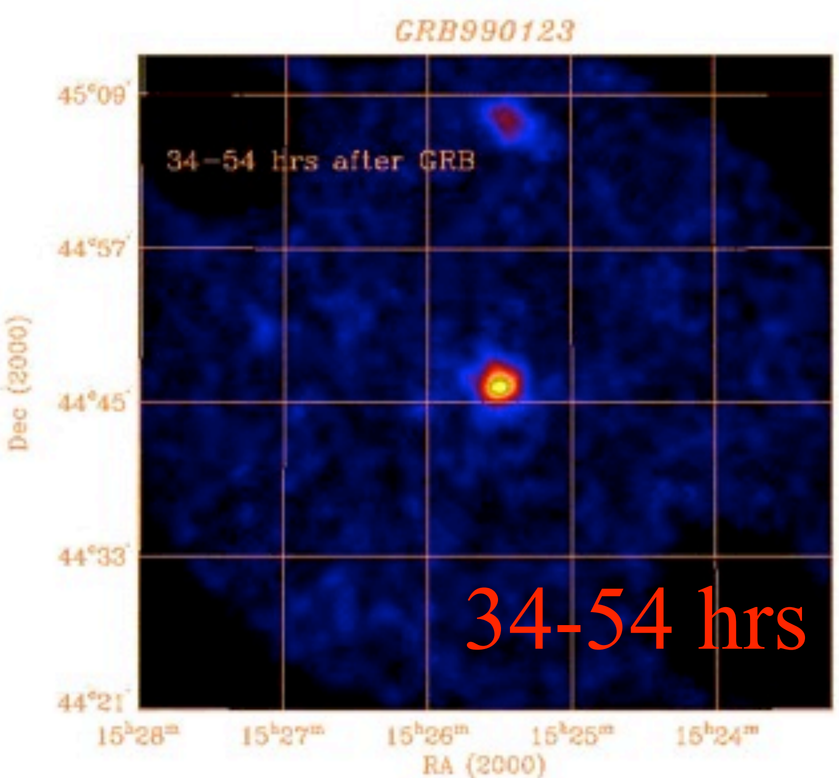


Duffell&AM (2011,2012,2014ab),
Ryan, van Eerten &AM (2014)

# GRB 990123

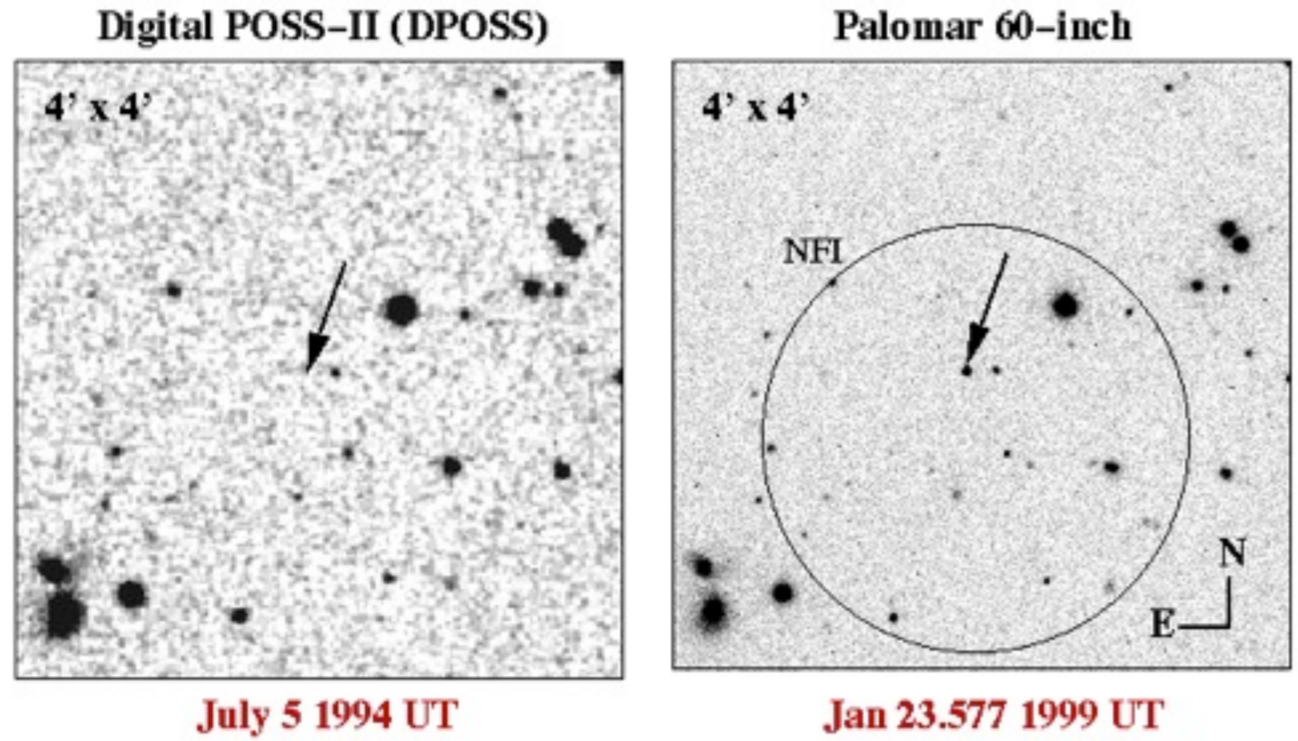
## 2. BeppoSAX (X-ray)




~ 1'

## 3. Palomar < 1 day




Keck spectrum

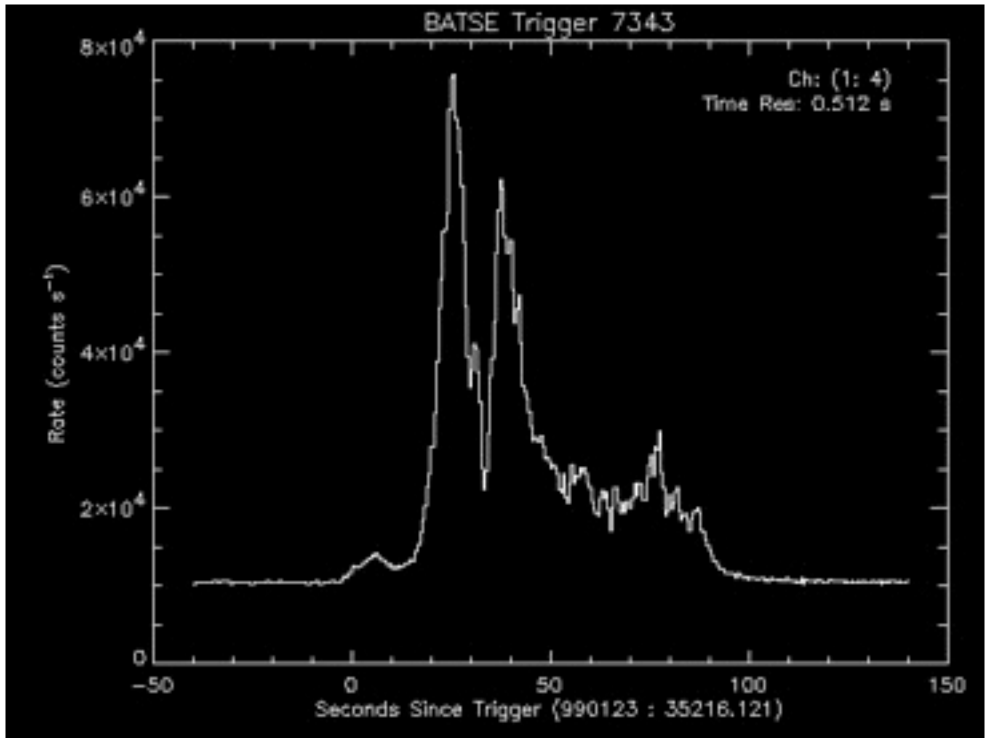
z=1.60

$E_{iso}$ =

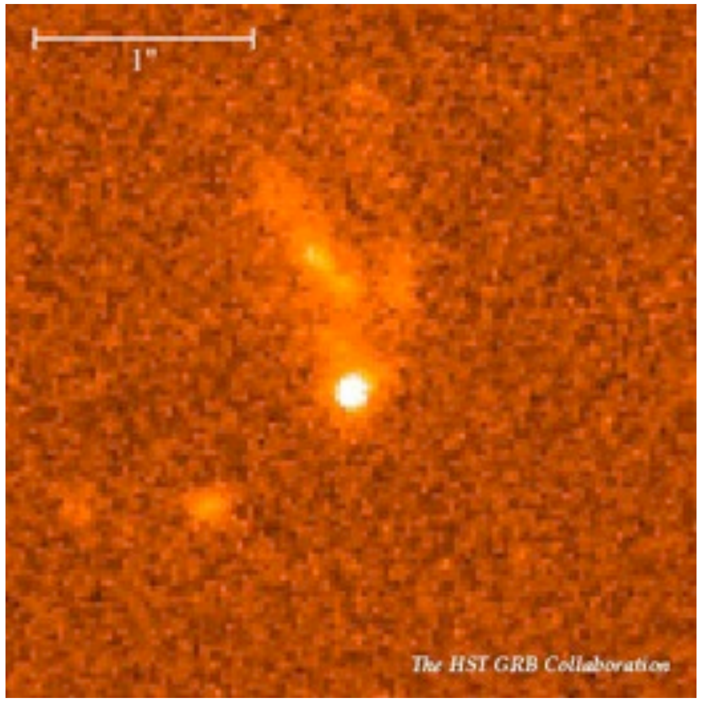
$3 \times 10^{54}$ erg

~ $M_{sun}c^2$

9th mag flash

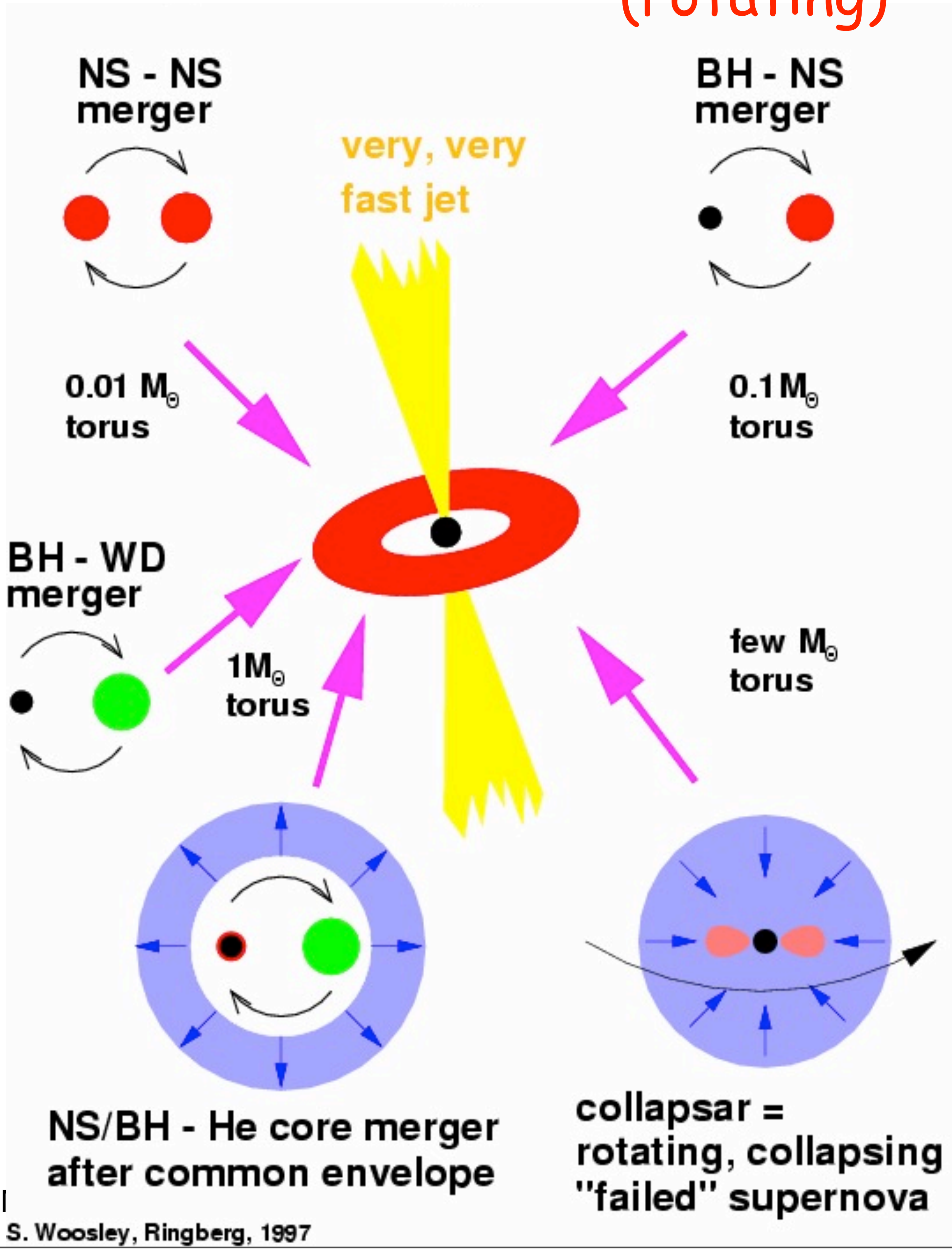



1. CGRO ~1°




4. HST 17 days

# Hyper-accreting black hole or high field neutron star (rotating)

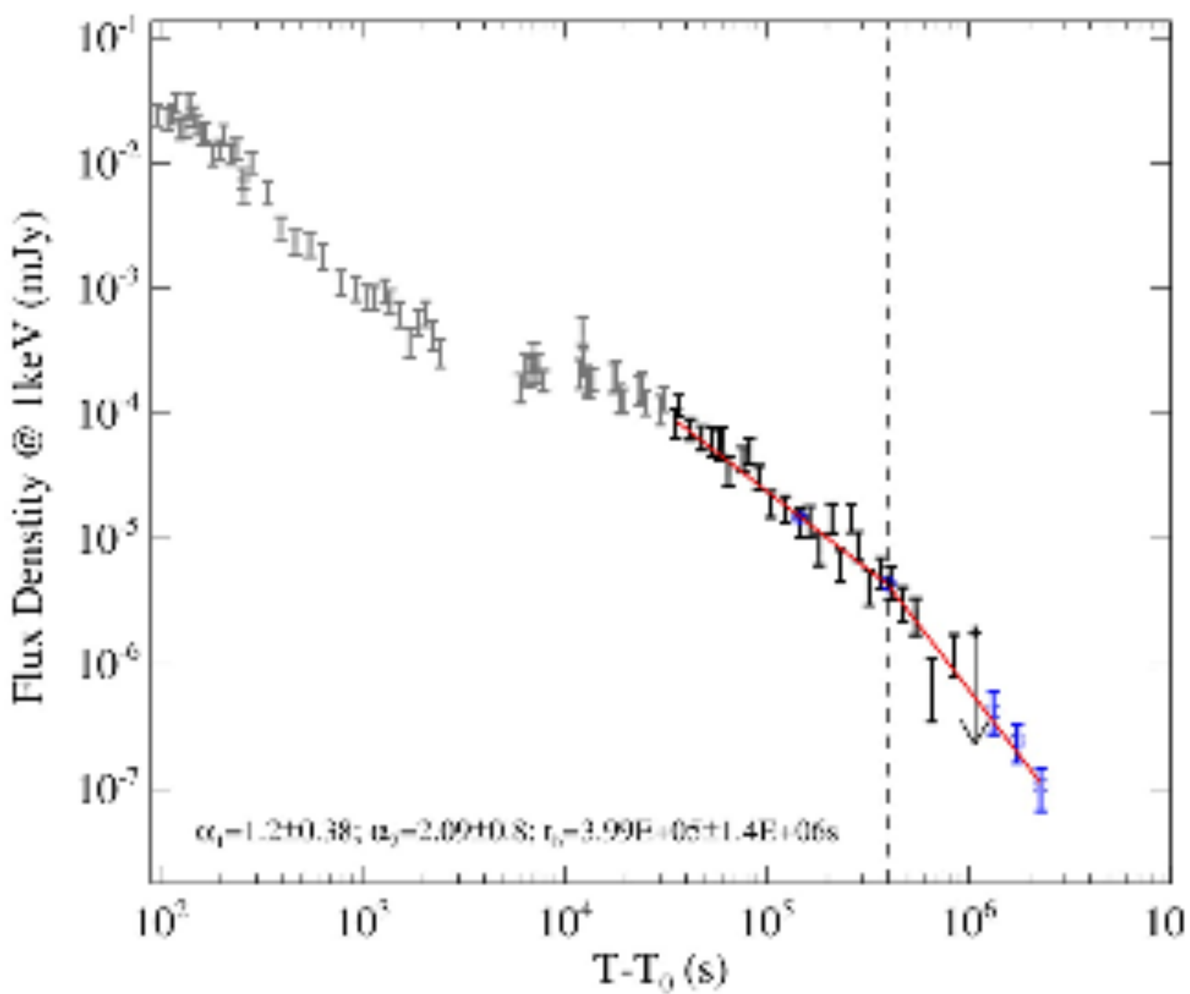


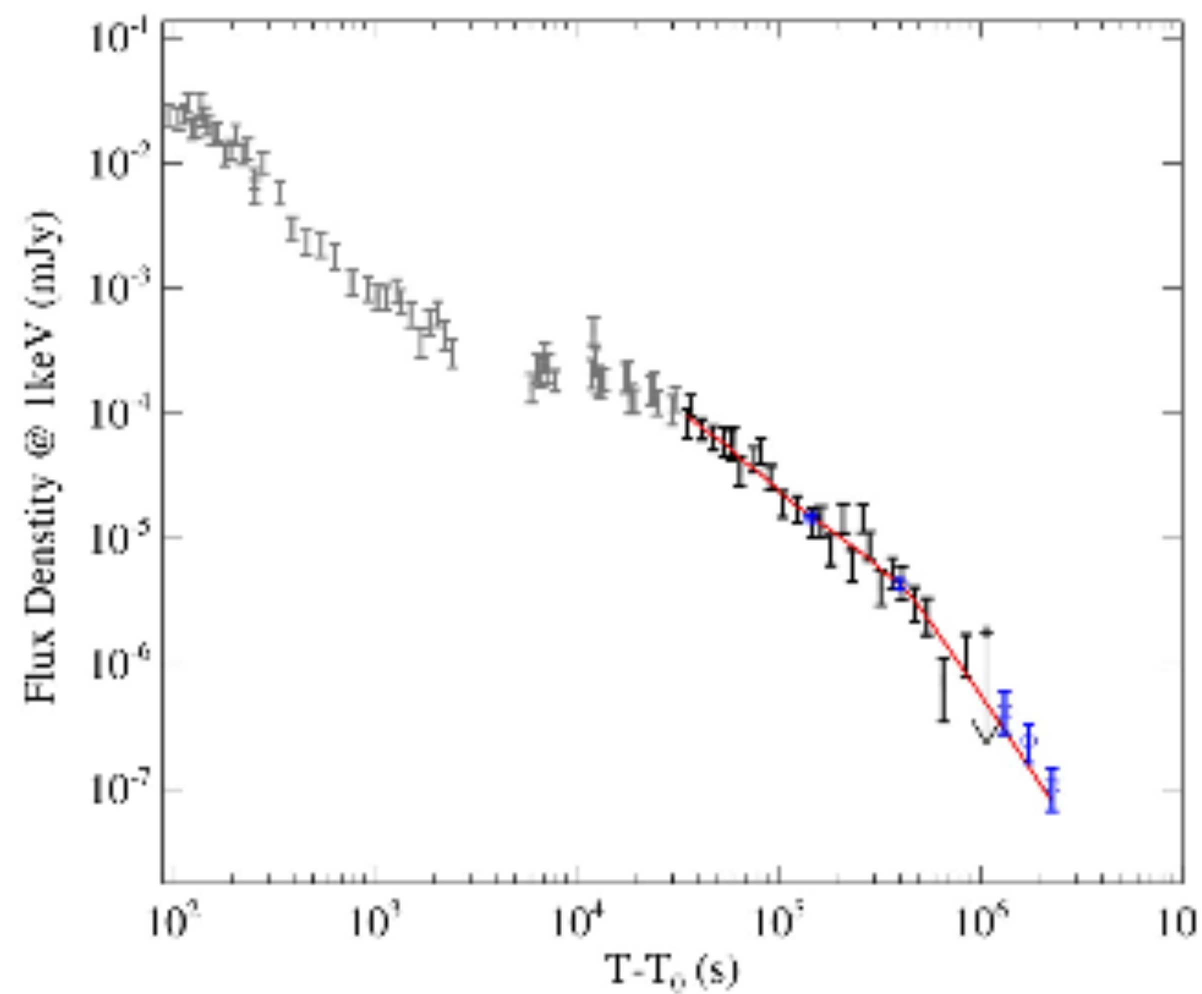

GRB photons are made far away from engine.

Can't observe engine directly with light. (neutrinos, gravitational waves?)

Electromagnetic process or neutrino annihilation to tap power of central compact object.

# GRB051221A




Zhang+ (2014), Ryan+(2014)

A. MacFadyen (NYU)

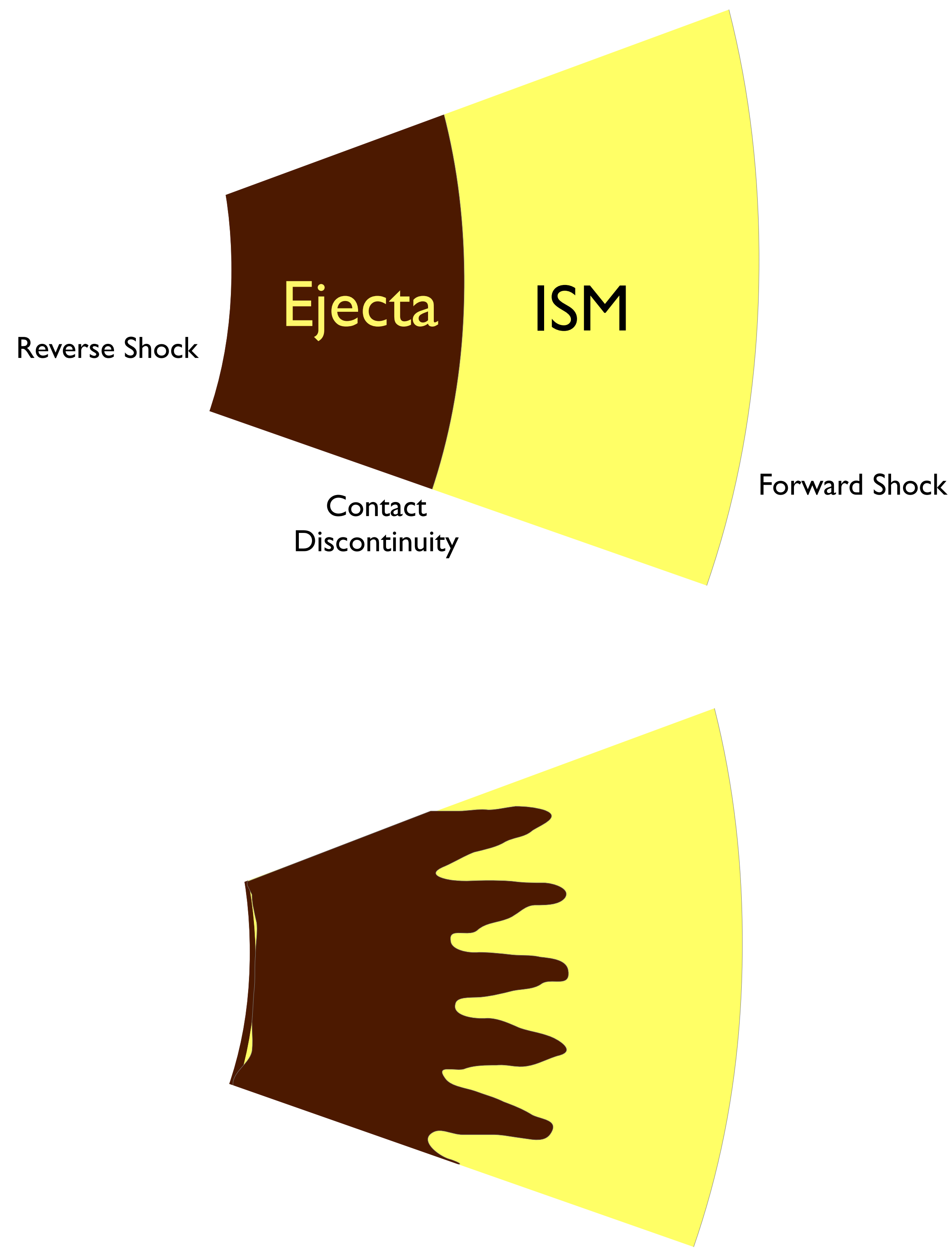
10^7 cm 10^15 cm 10^18 cm

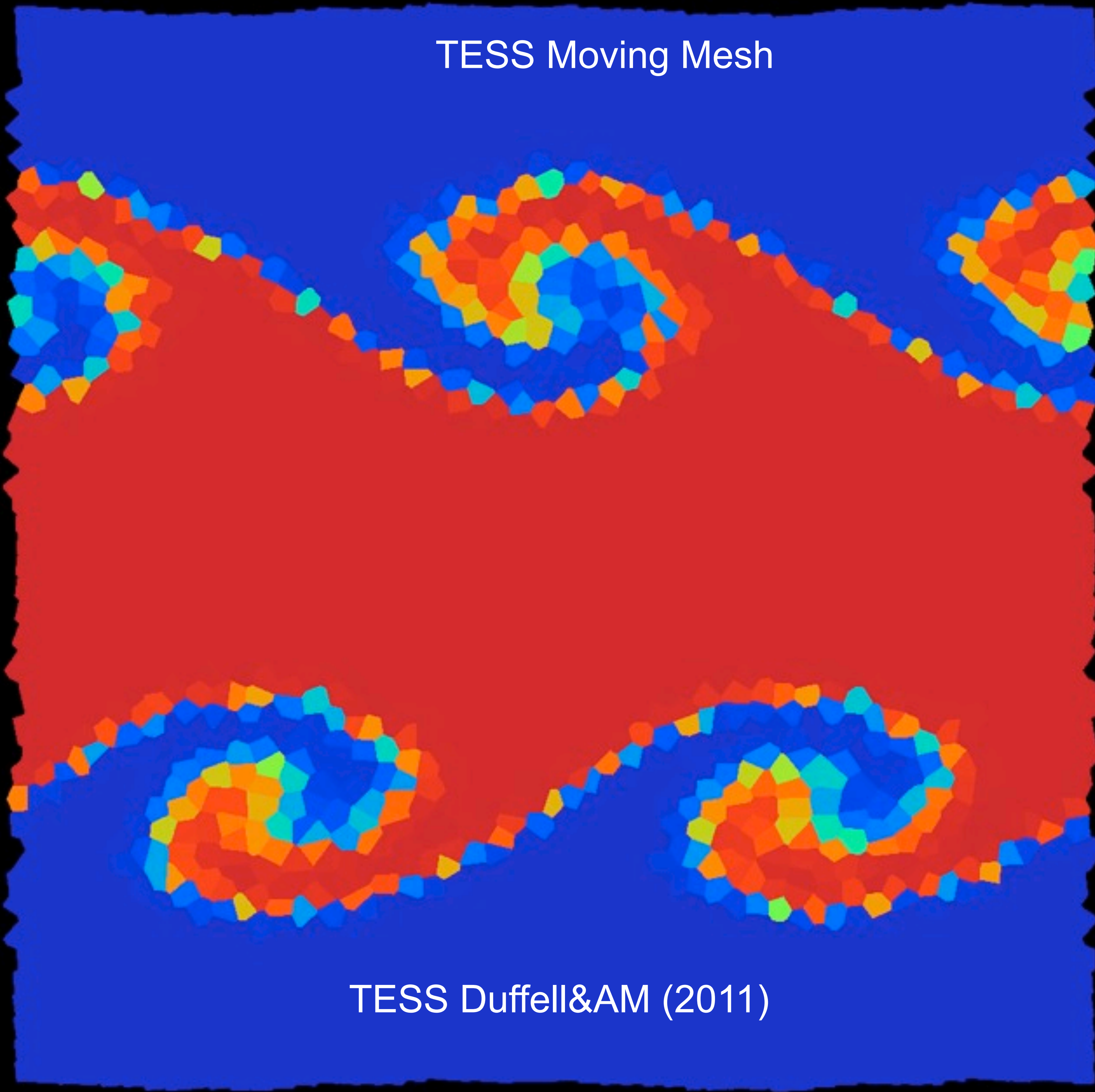

1. RT Instability

2. Afterglow Fits

This Talk

A. MacFadyen (NYU)


Ejecta
ISM
Reverse Shock
Contact
Discontinuity
Forward Shock


TESS Moving Mesh
TESS Duffell&AM (2011)

## Numerical Methods for Solving Conservation Laws

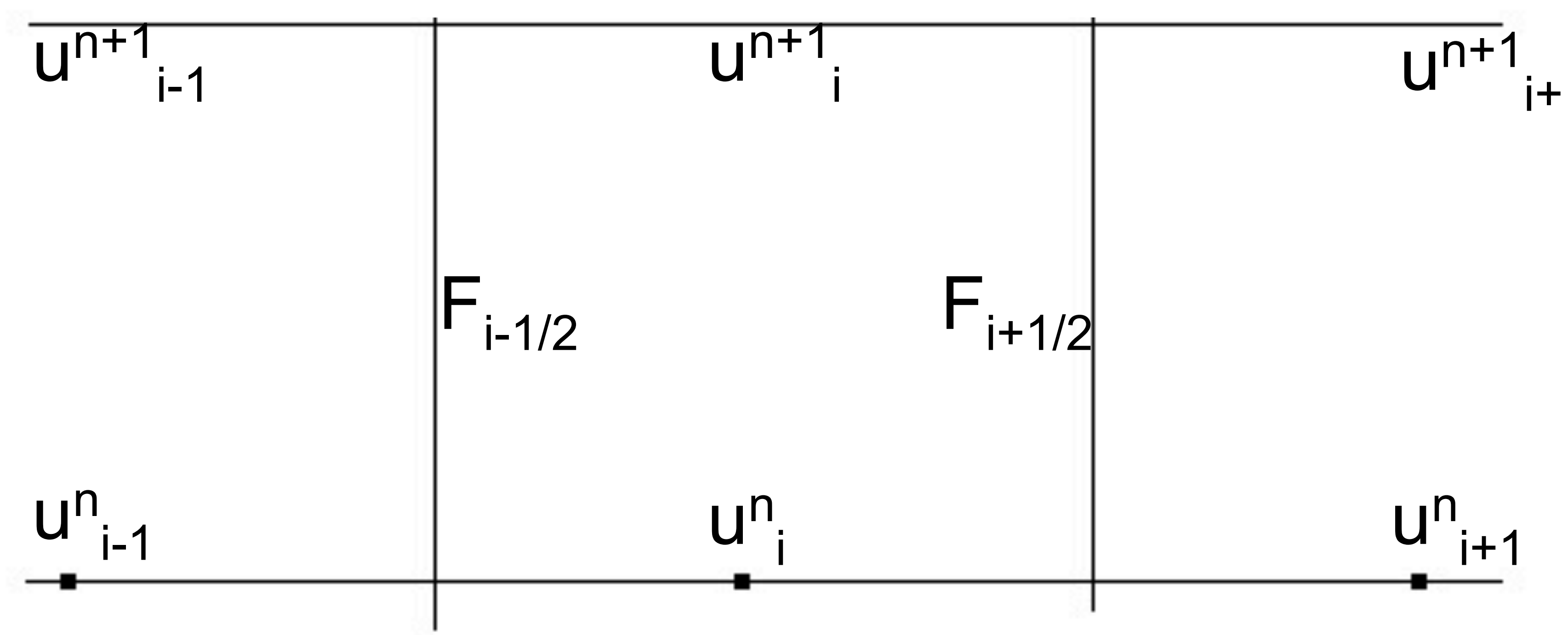
$$\frac{\partial u}{\partial t} + \frac{\partial F}{\partial x} = 0$$

$$\int dx\, dt \frac{\partial u}{\partial t} + \int dx\, dt \frac{\partial F}{\partial x} = 0$$

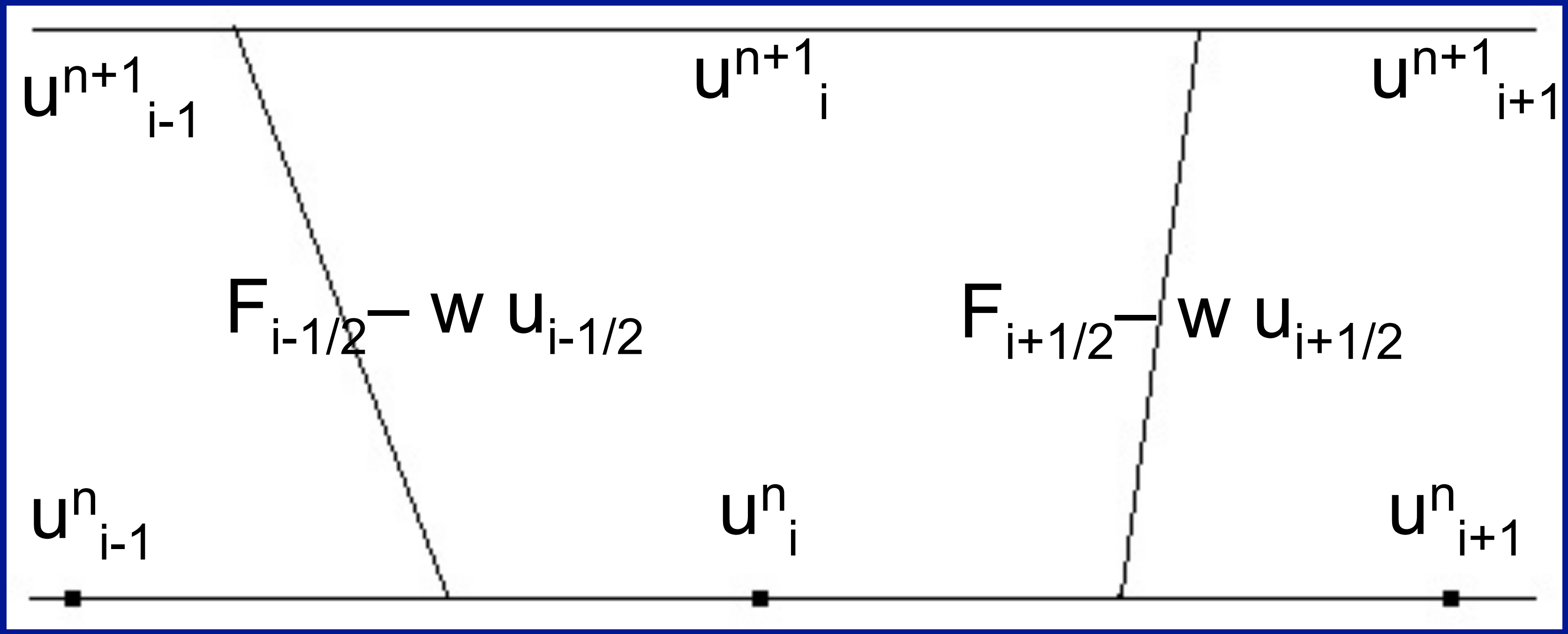
$$\left[\int dx\, u\right]_n^{n+1} + \left[\int dt\, F\right]_{i-1/2}^{i+1/2} = 0$$

$$\Delta x (u_i^{n+1} - u_i^n) + \Delta t (F_{i+1/2} - F_{i-1/2}) = 0$$

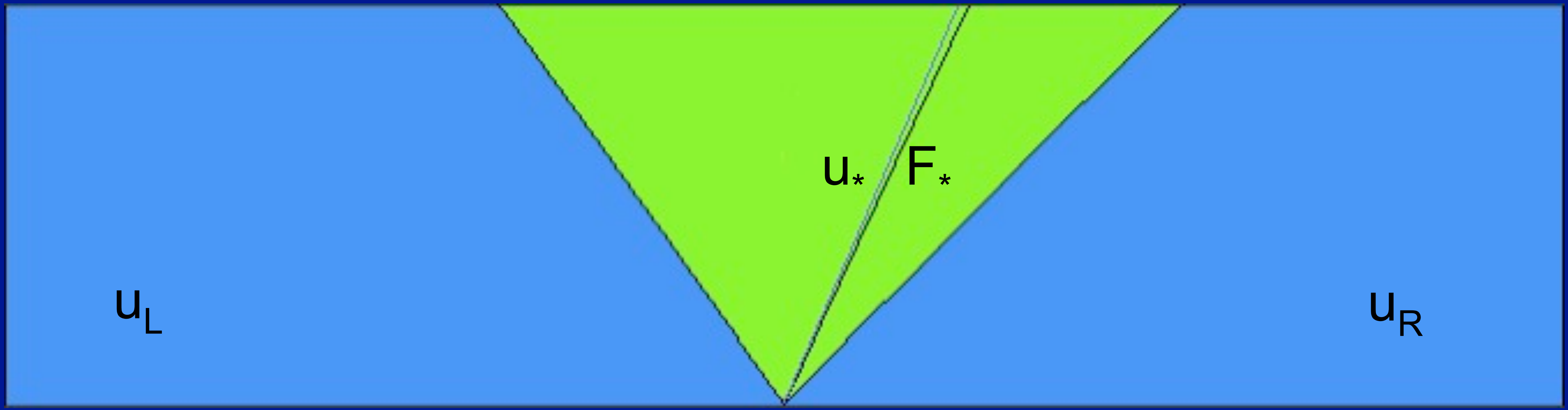
$$u_i^{n+1} = u_i^n - \frac{\Delta t}{\Delta x} (F_{i+1/2} - F_{i-1/2})$$

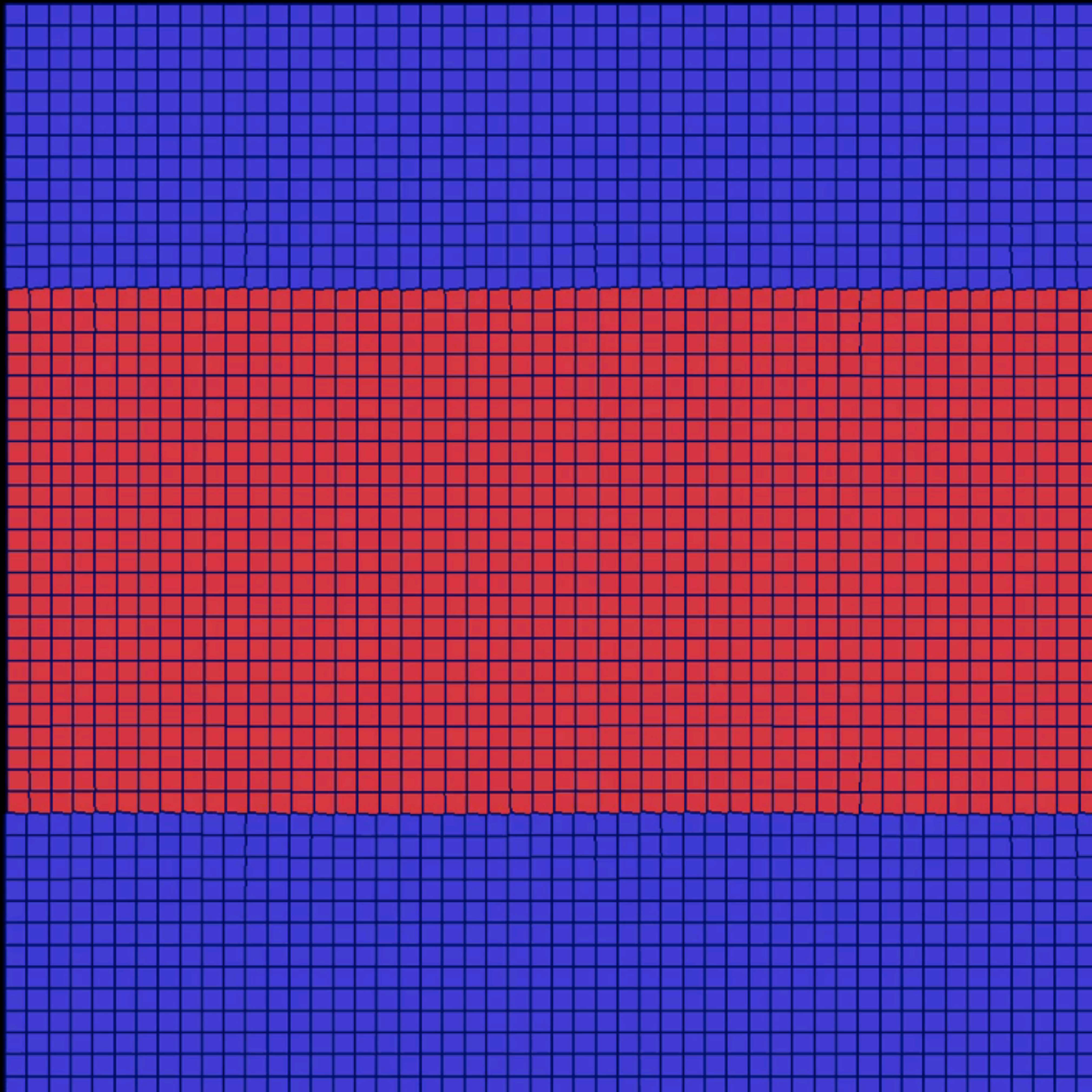


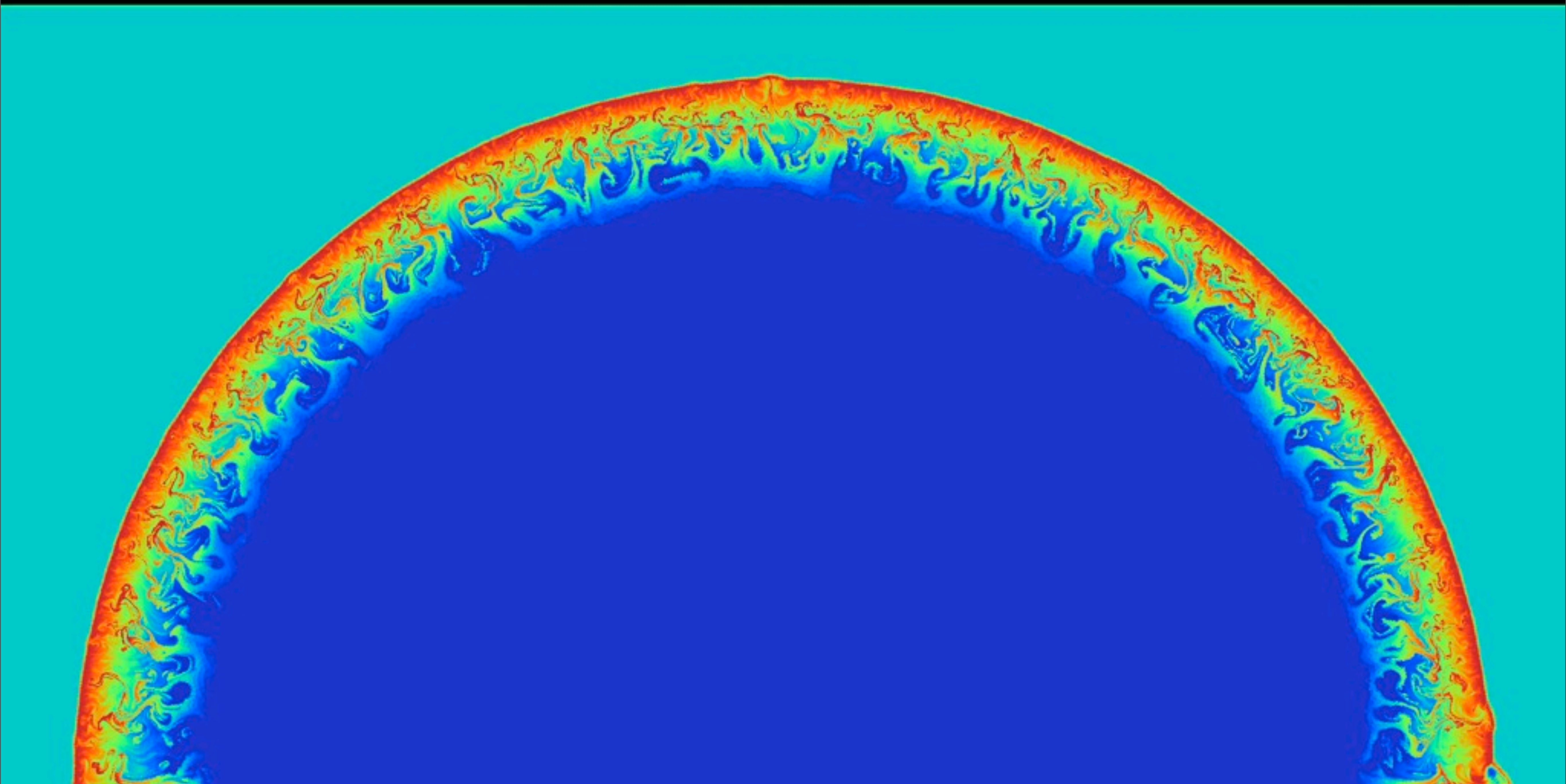
## TESS: Lagrangian Hydrodynamics using a Dynamic Voronoi Mesh



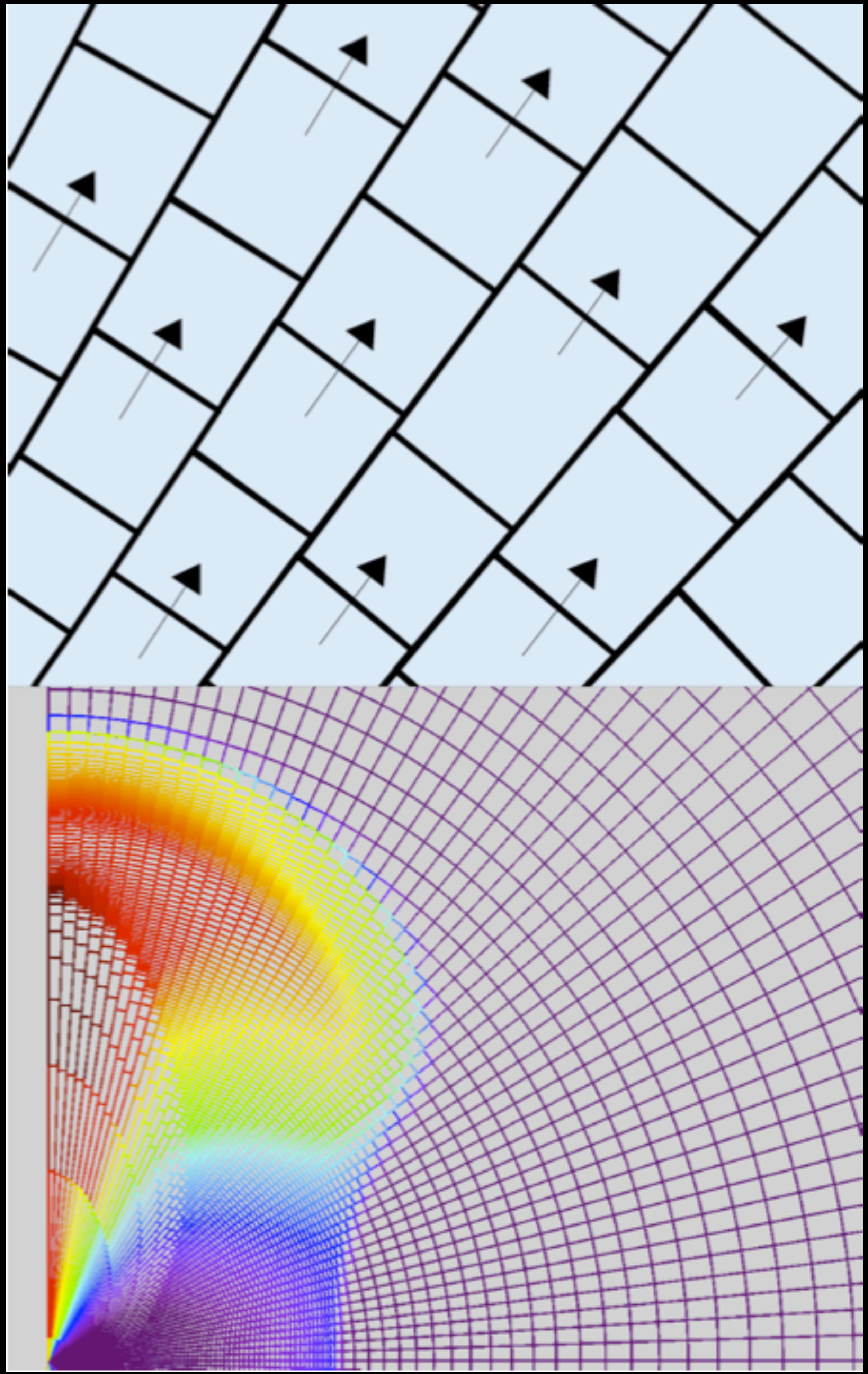

$$\vec{F}_* \rightarrow \vec{F}_* - \vec{w}\, u_*$$



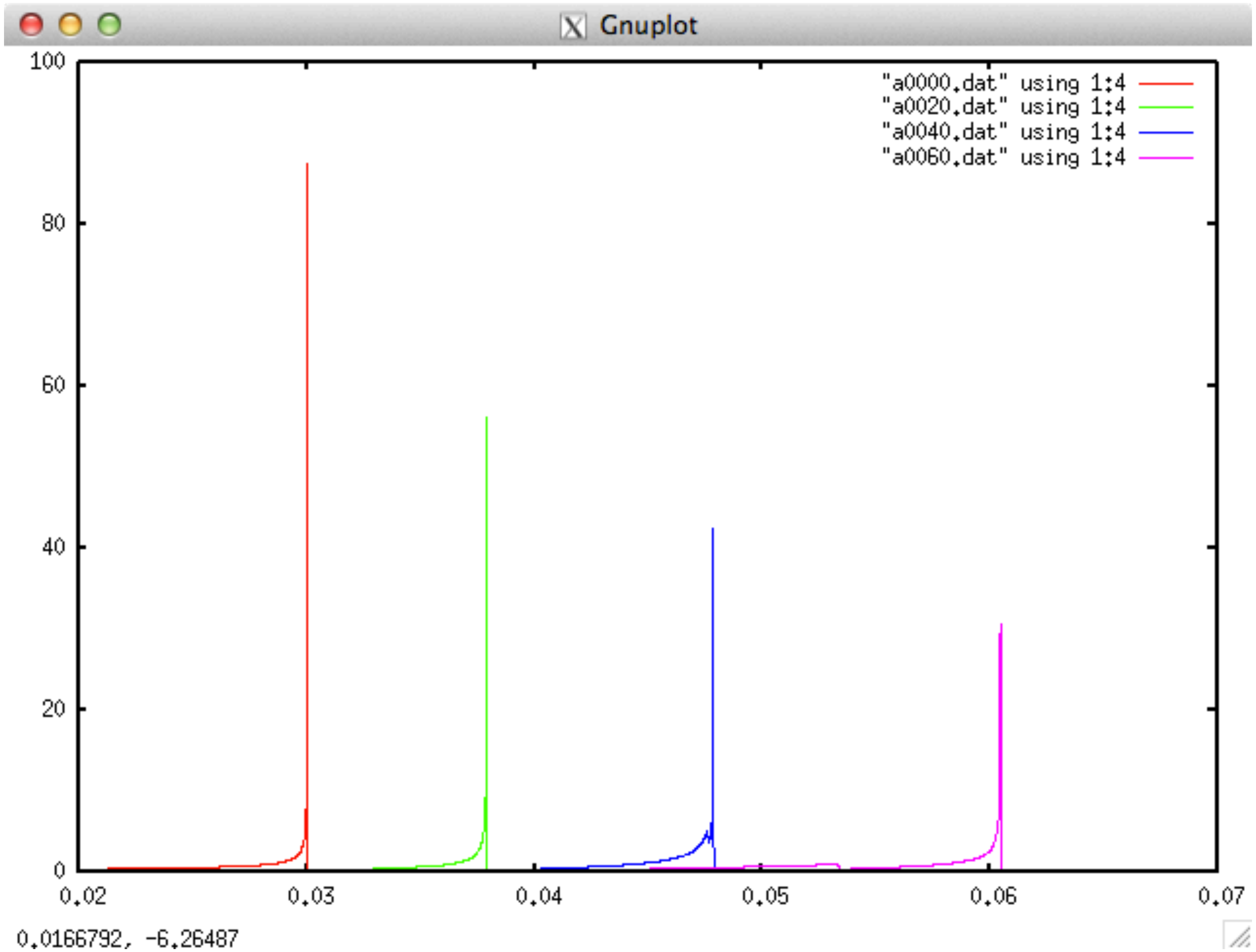




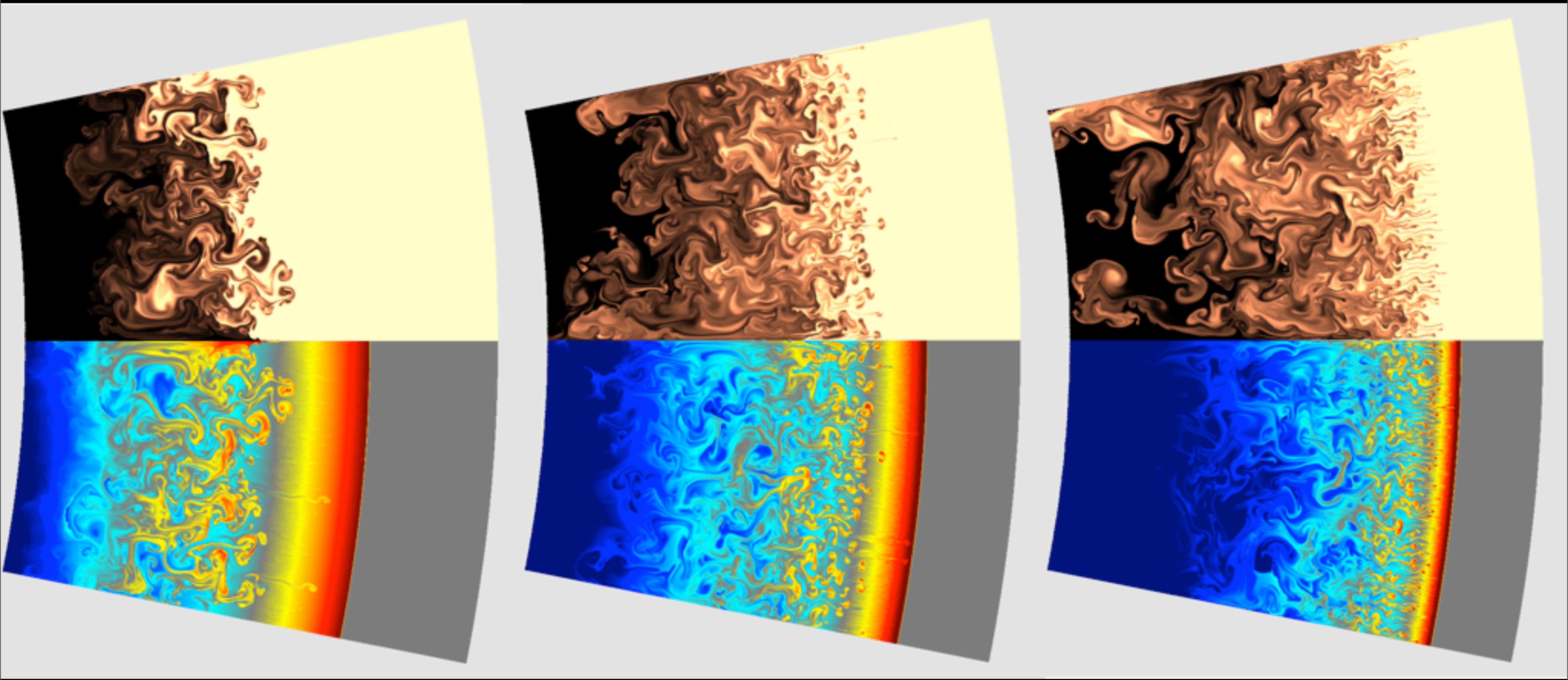
JET Code
Duffell&AM (2013)



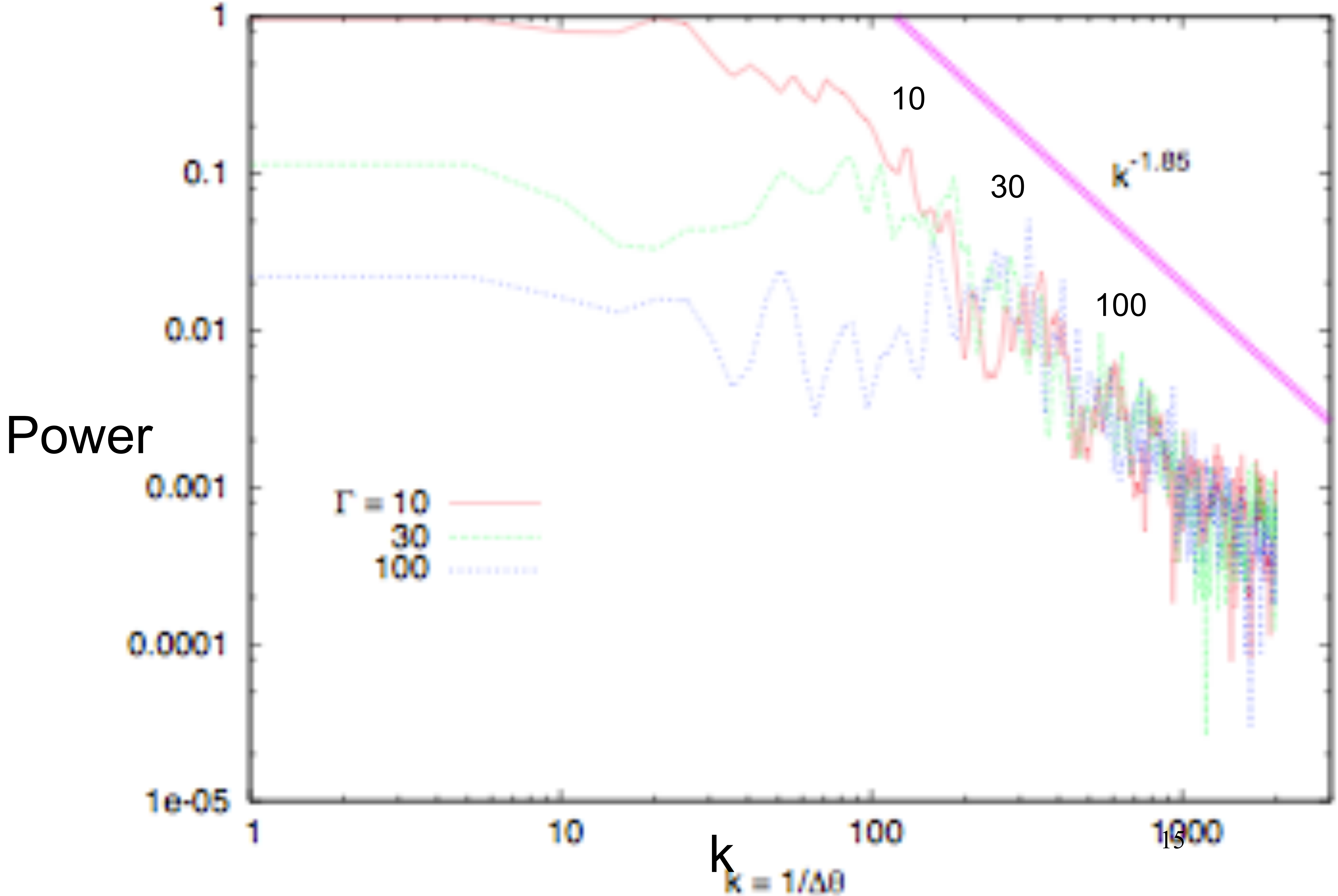
# TESS: Blandford-McKee

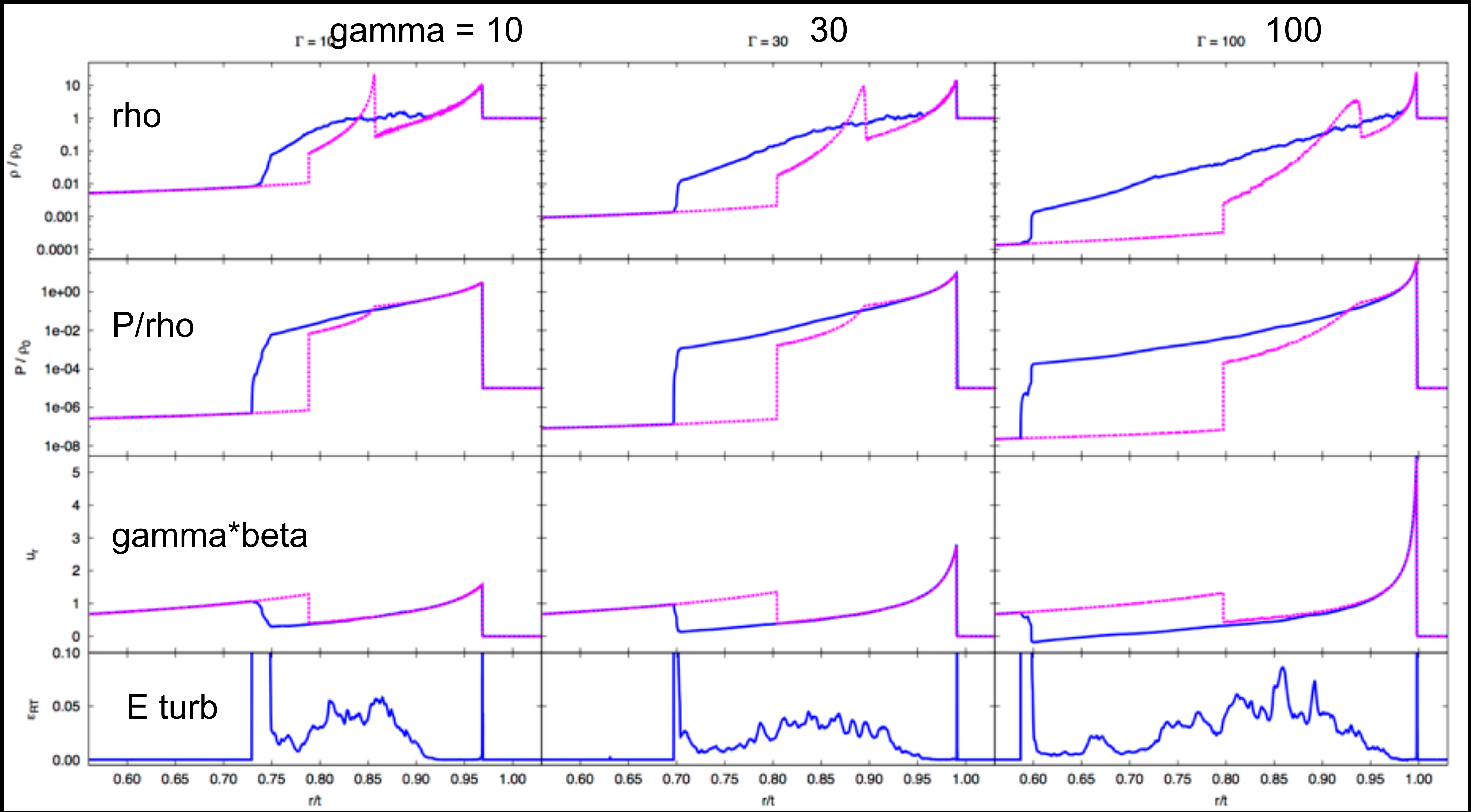


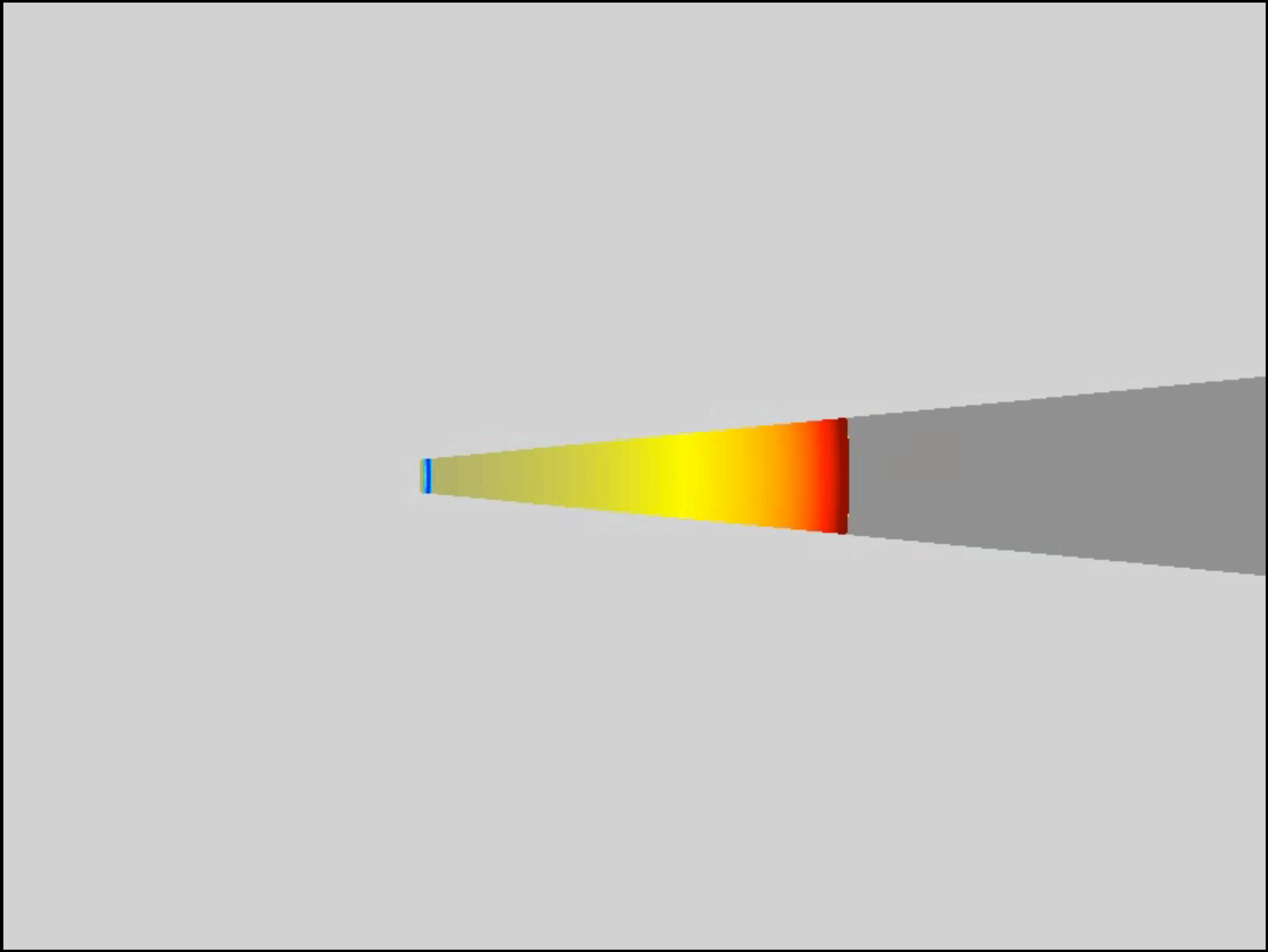
Lorentz Factor = 10 30 100

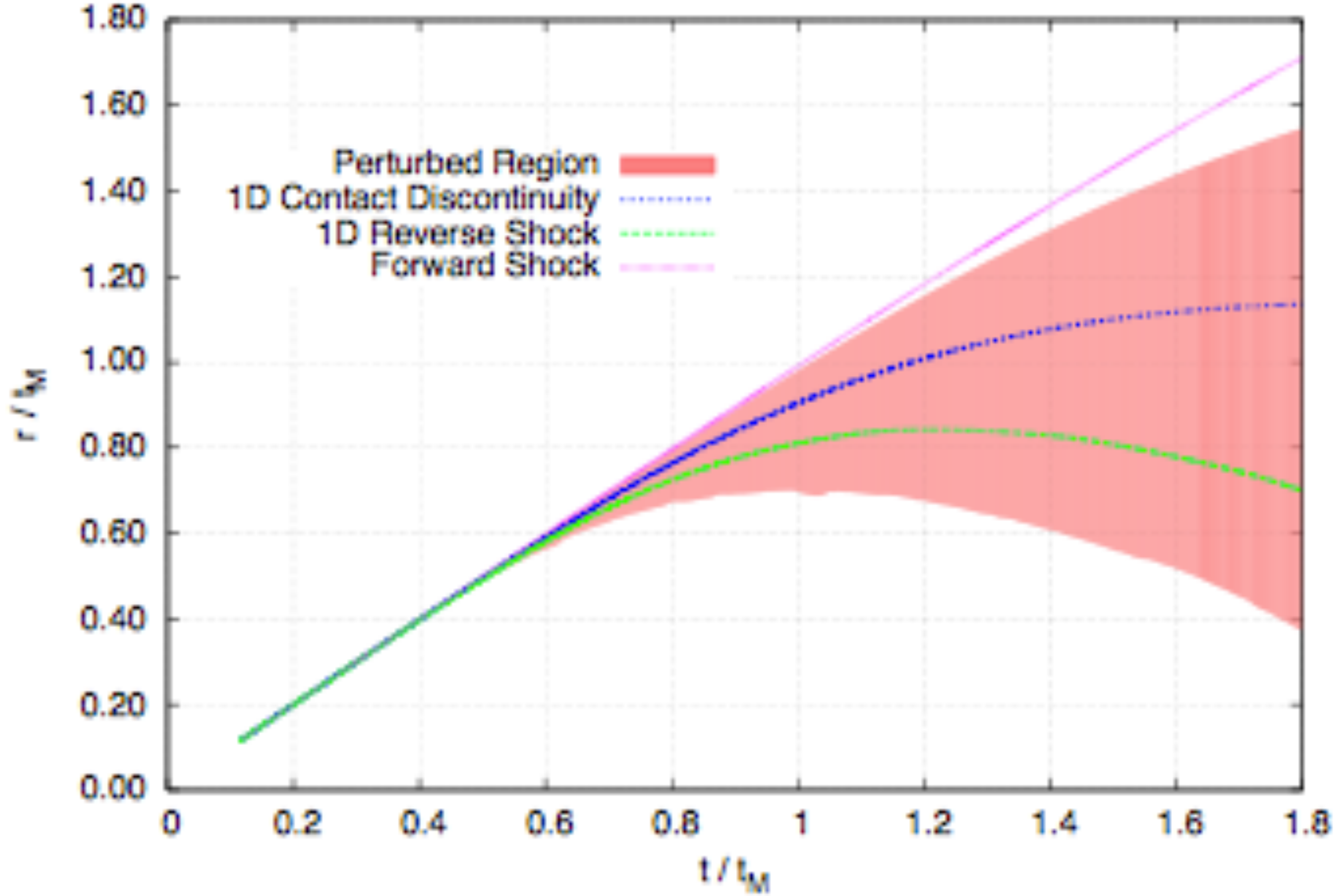


# RT Turbulence Spectrum




gamma = 10
30
100
Γ = 10
Γ = 30
Γ = 100
rho
P/rho
gamma*beta
E turb
ρ / ρ0
P / ρ0
ur
εRT
r/t



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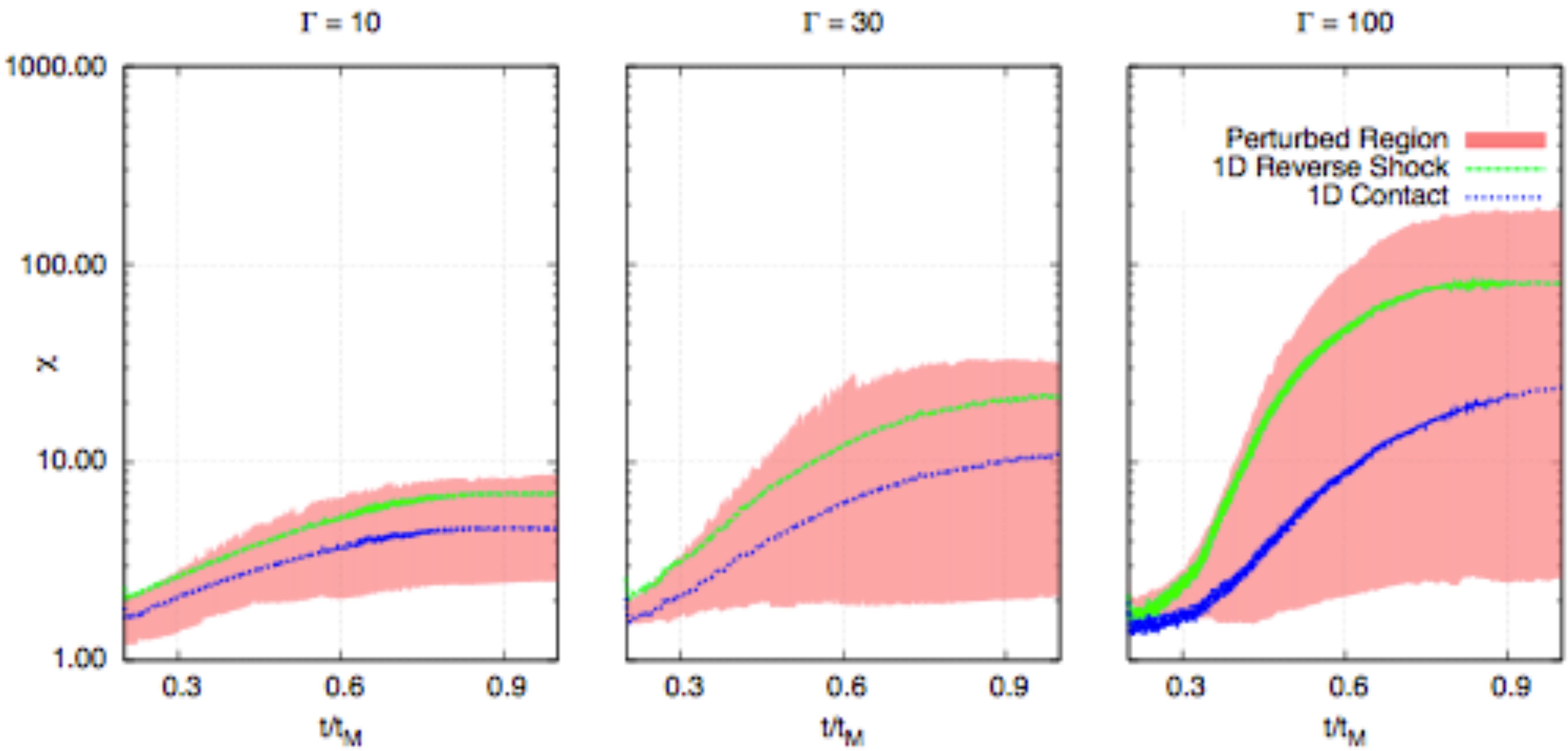
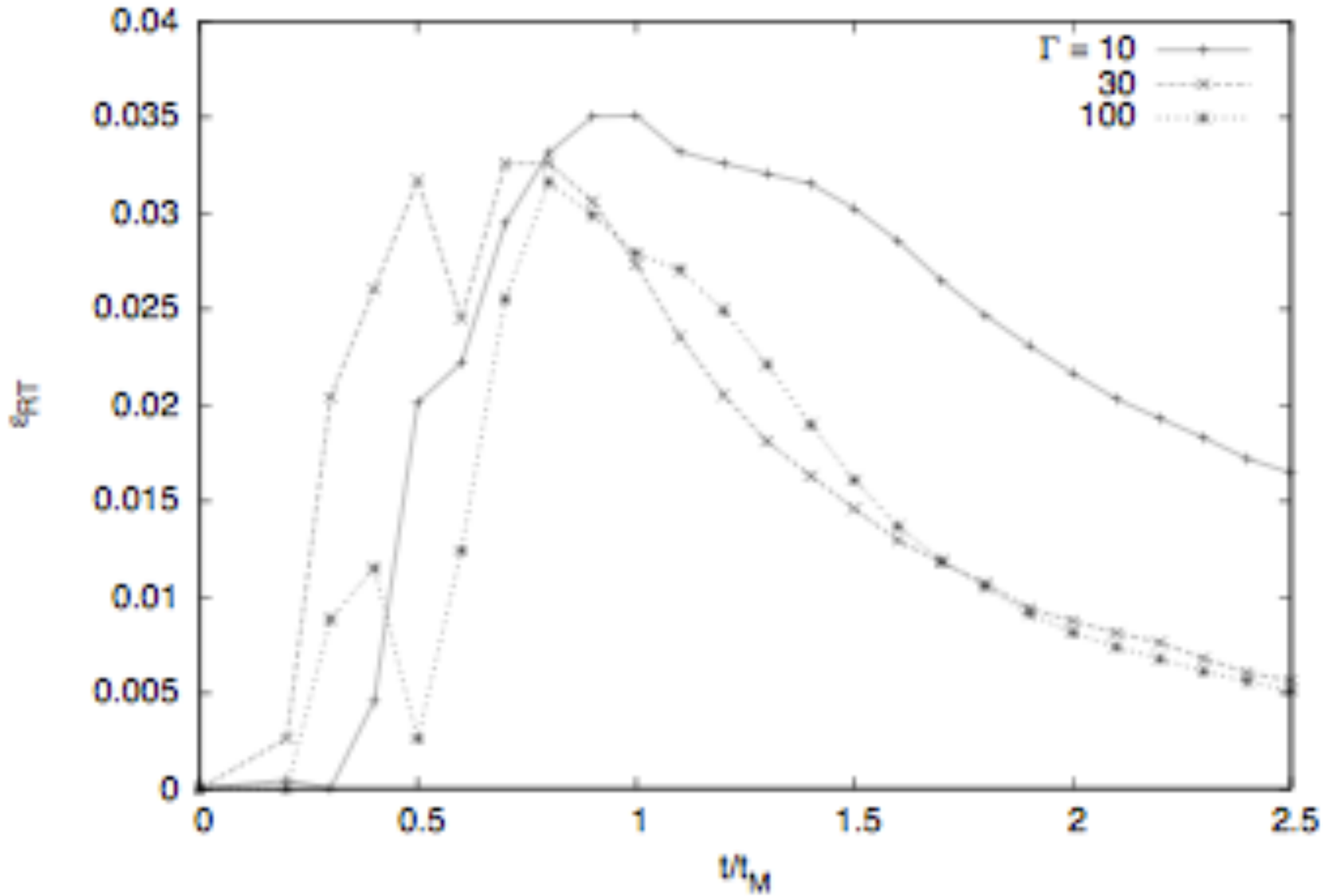



A. MacFadyen (NYU)

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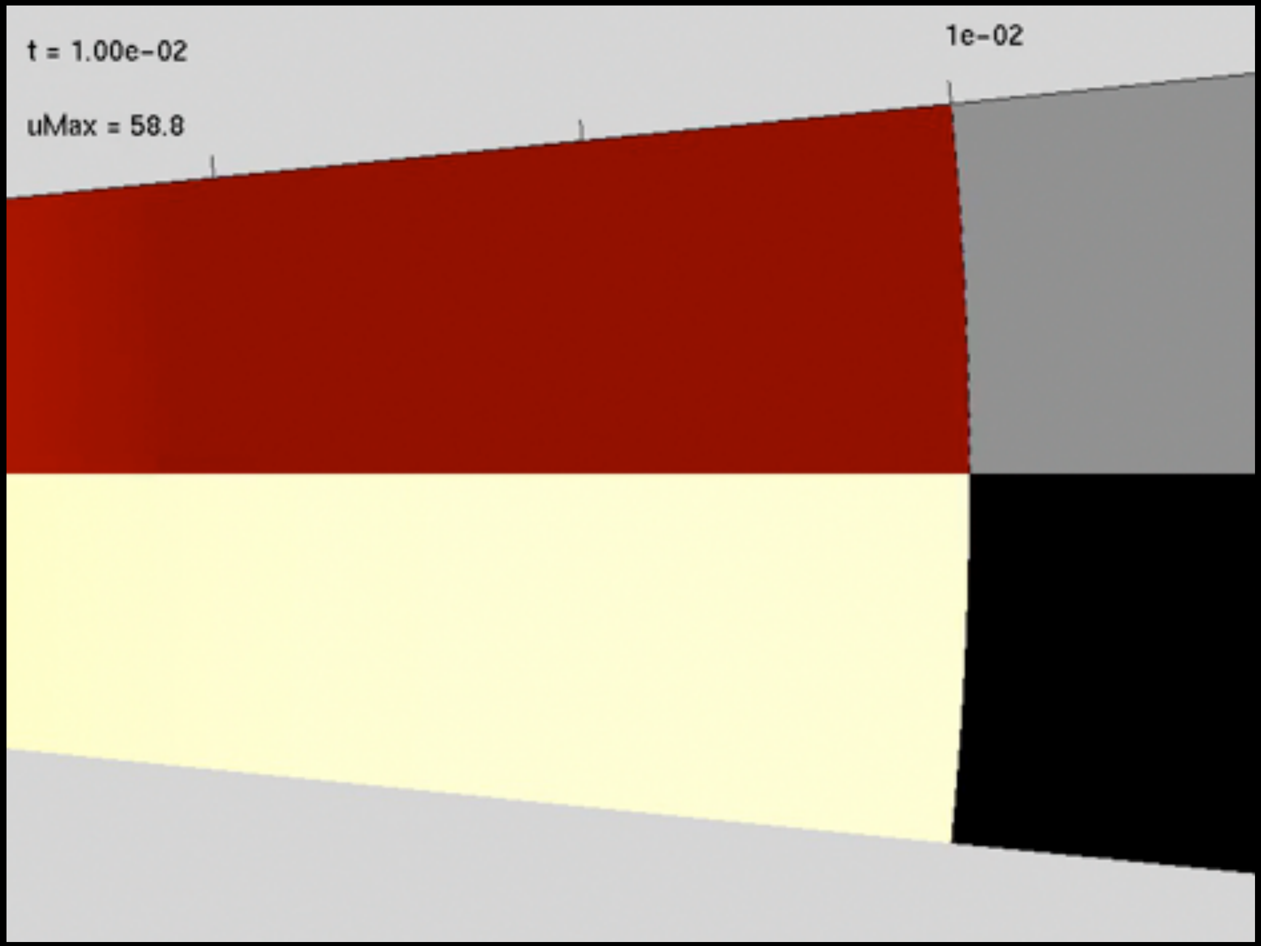
Adiabatic Index = 4/3

Adiabatic Index = 1.1

Duffel & MacFadyen (2013)

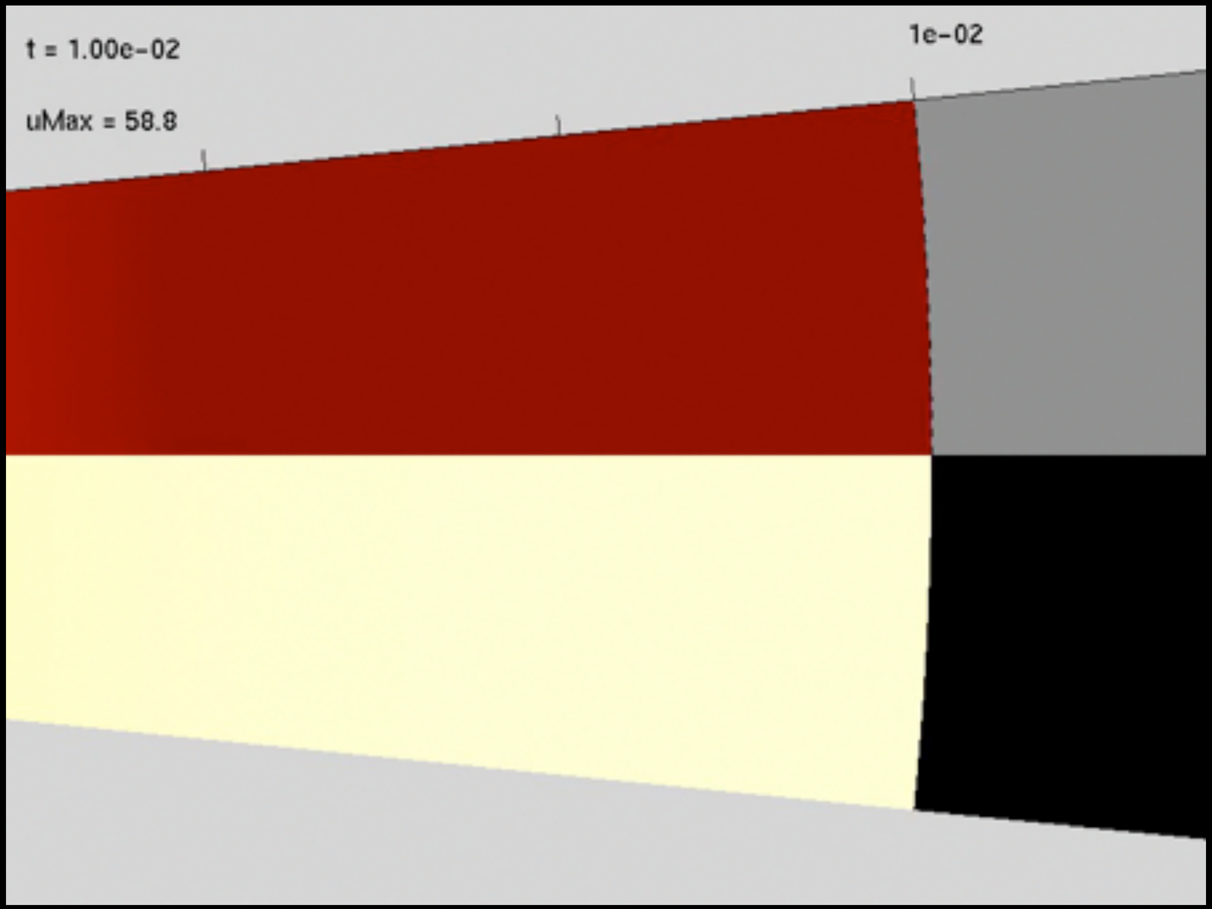
Duffel & MacFadyen (2014)

Adiabatic Index = 4/3



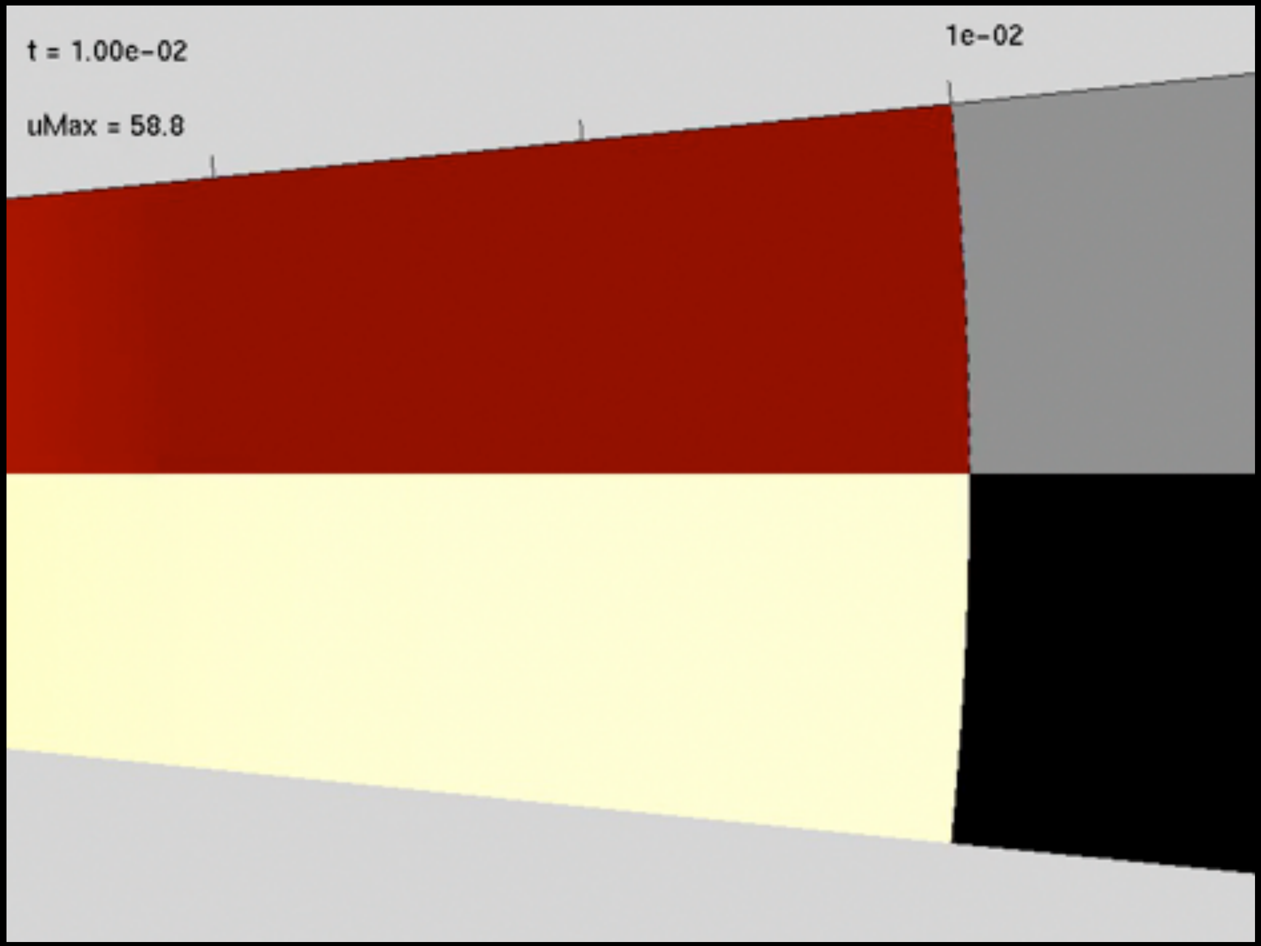

Duffel & MacFadyen (2013)

Adiabatic Index = 1.1



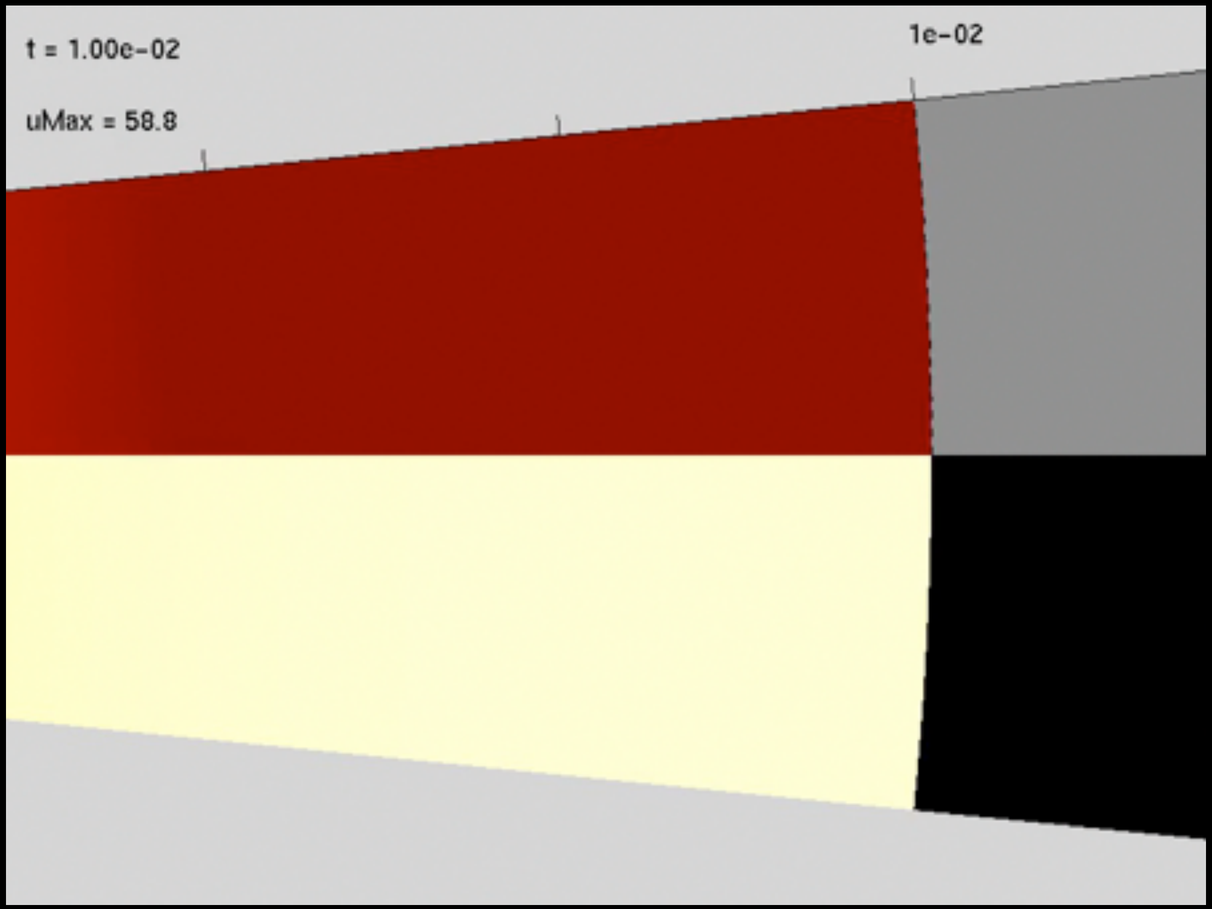

Duffel & MacFadyen (2014)

Adiabatic Index = 4/3




Duffel & MacFadyen (2013)

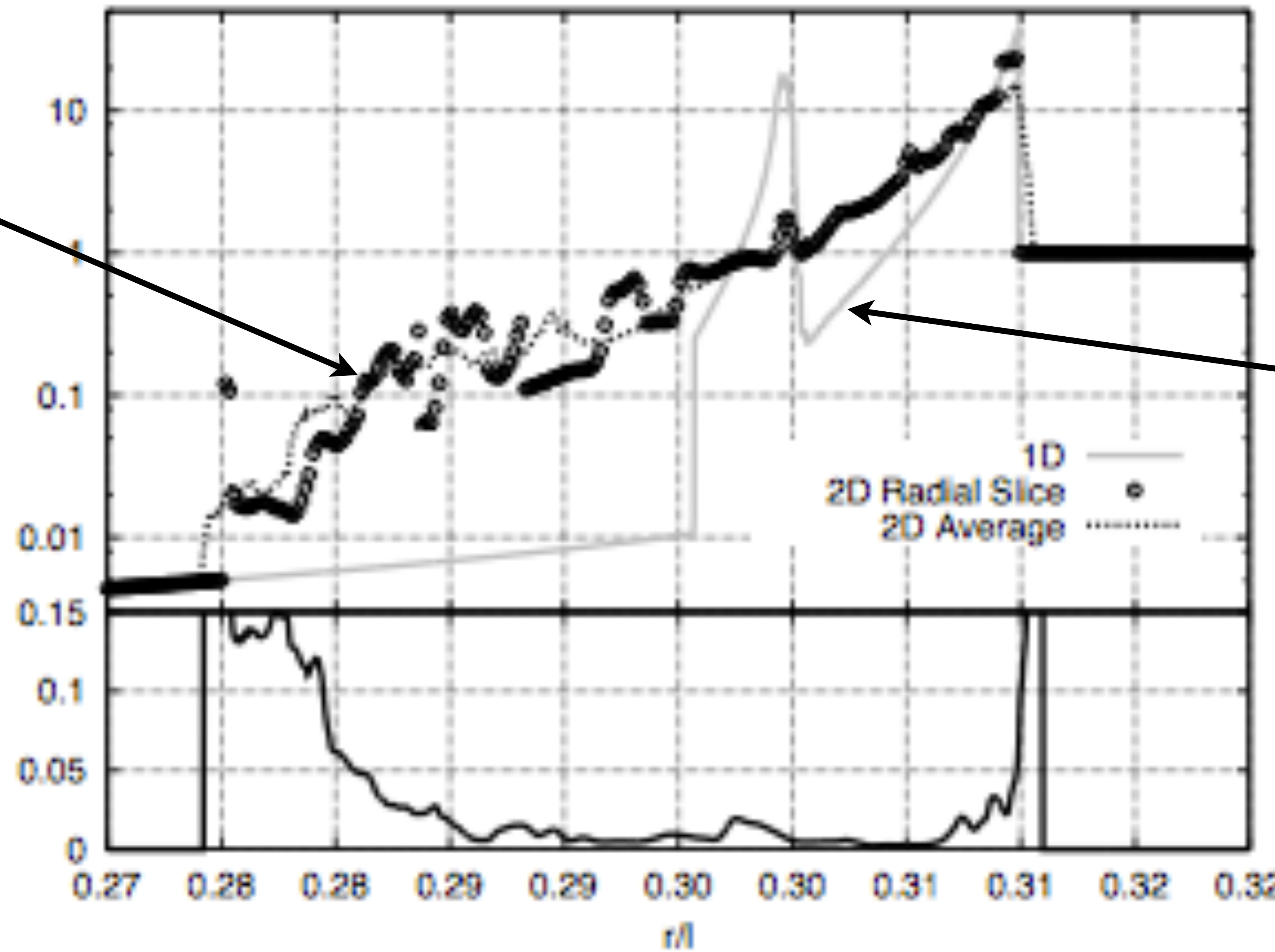
Adiabatic Index = 1.1




Duffel & MacFadyen (2014)

2D

P/rho




1D

Turbulent Energy

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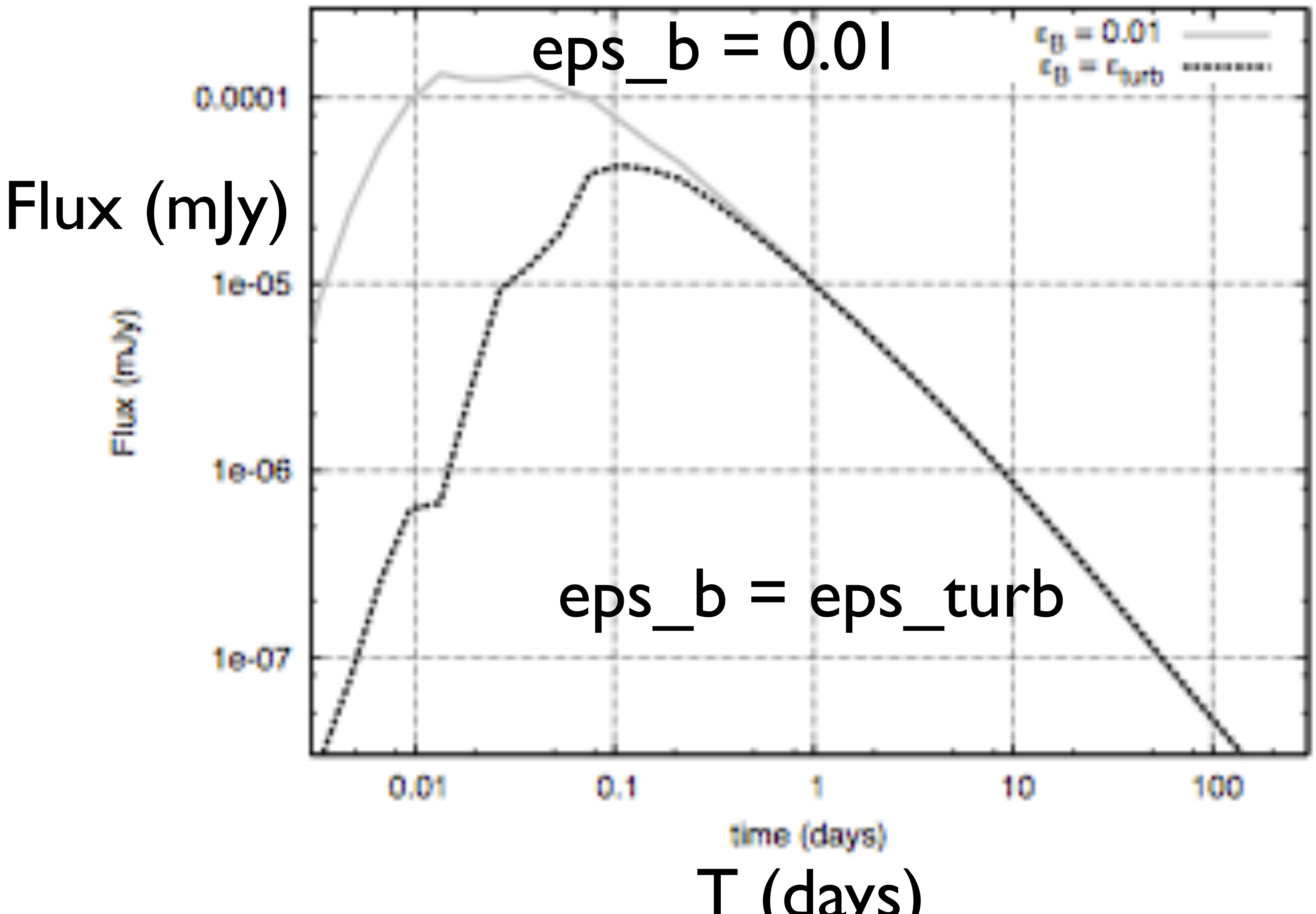
# Light Curves




Duffell & AM (2014)

10^7 cm 10^15 cm 10^18 cm


1. RT Instability

2.Afterglow Fits

This Talk

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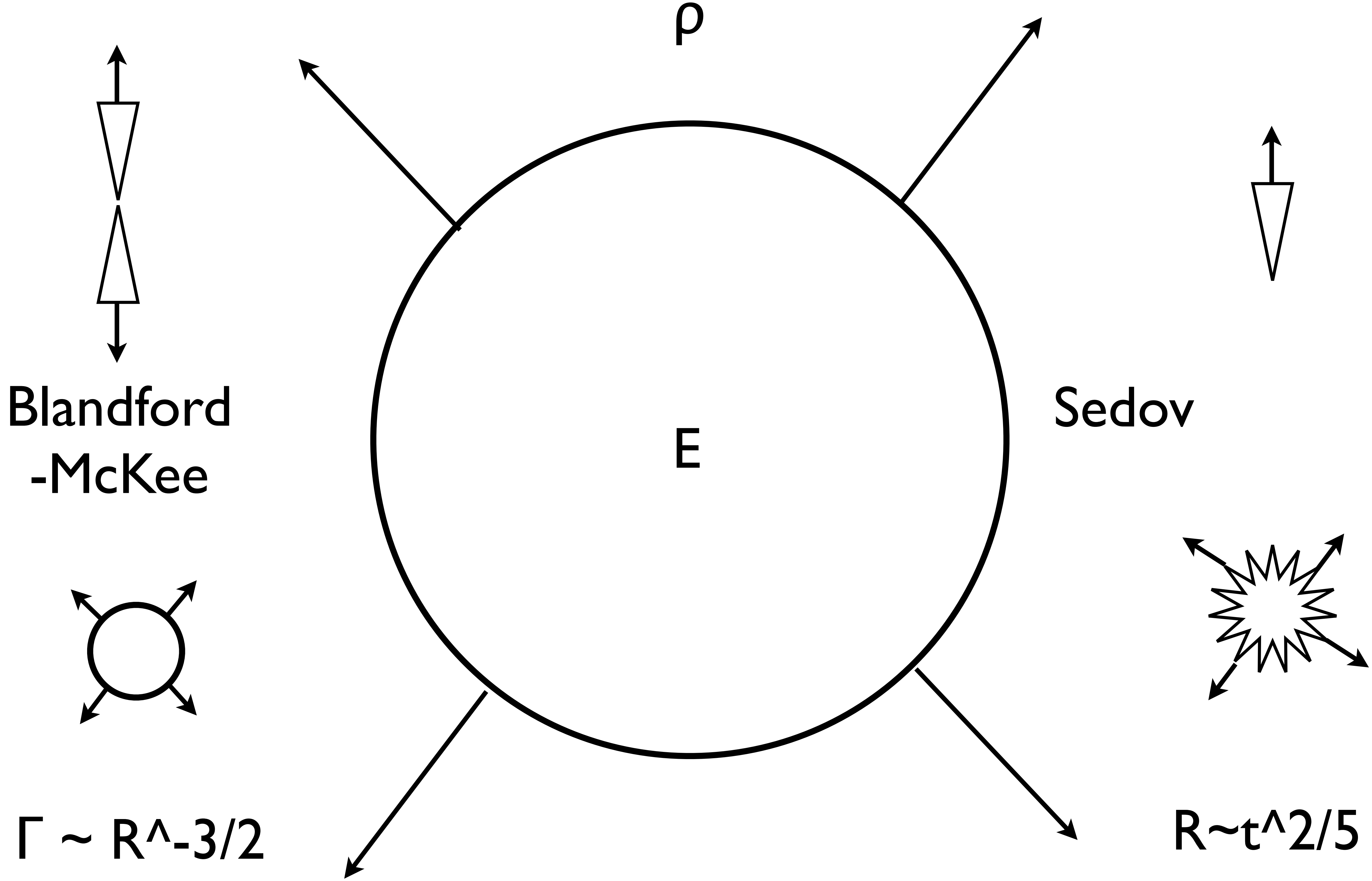
# Spherical Attractor

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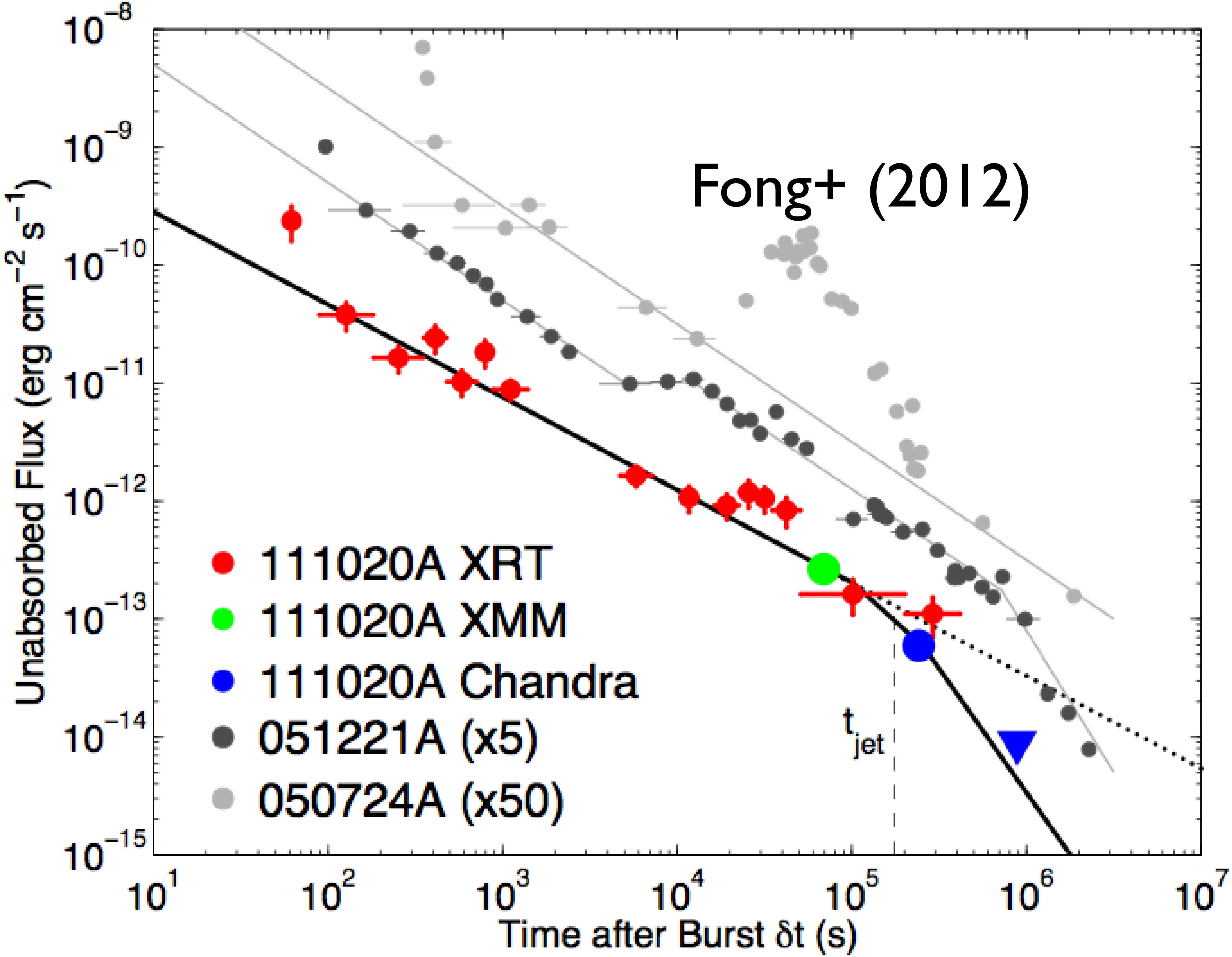


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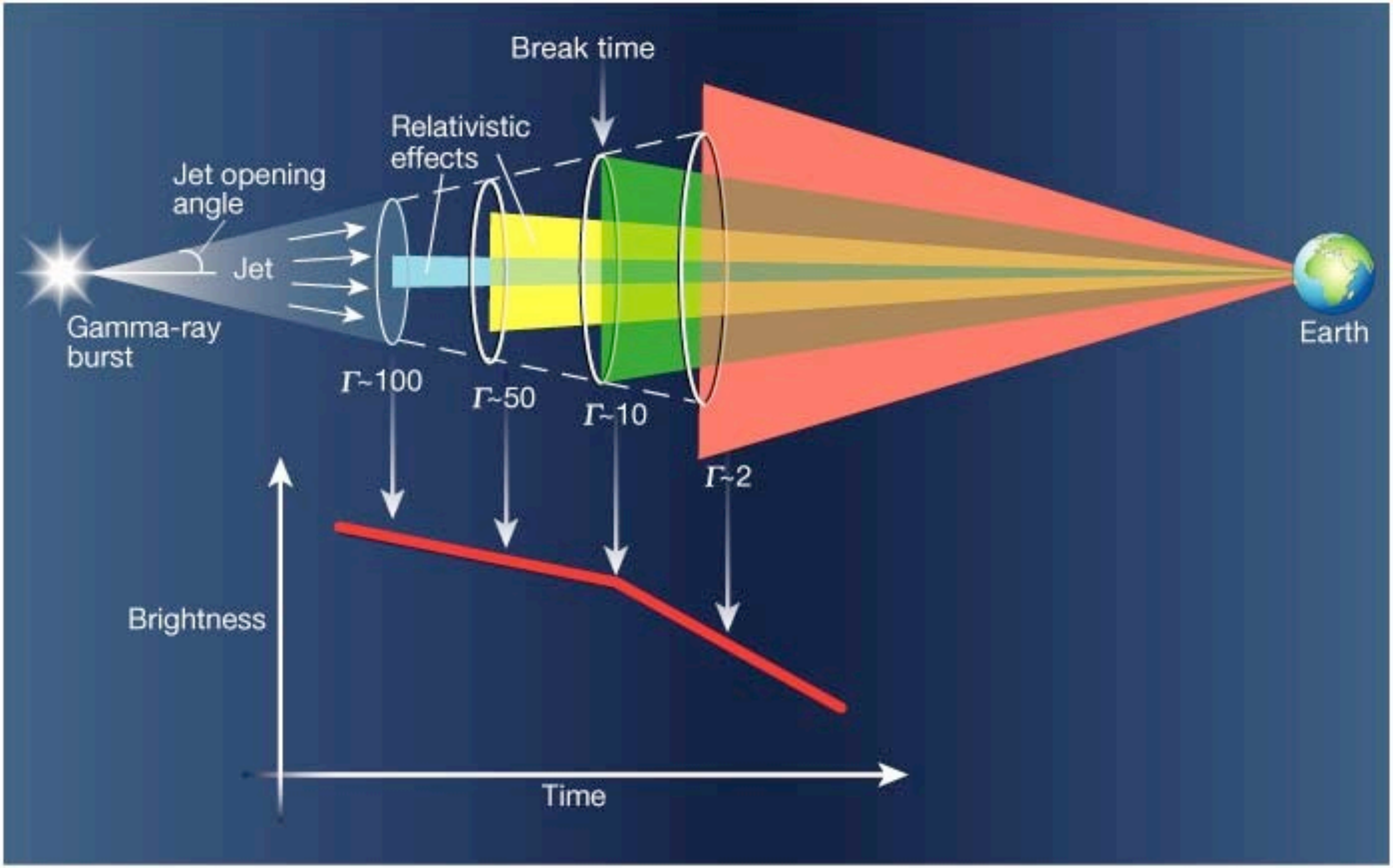
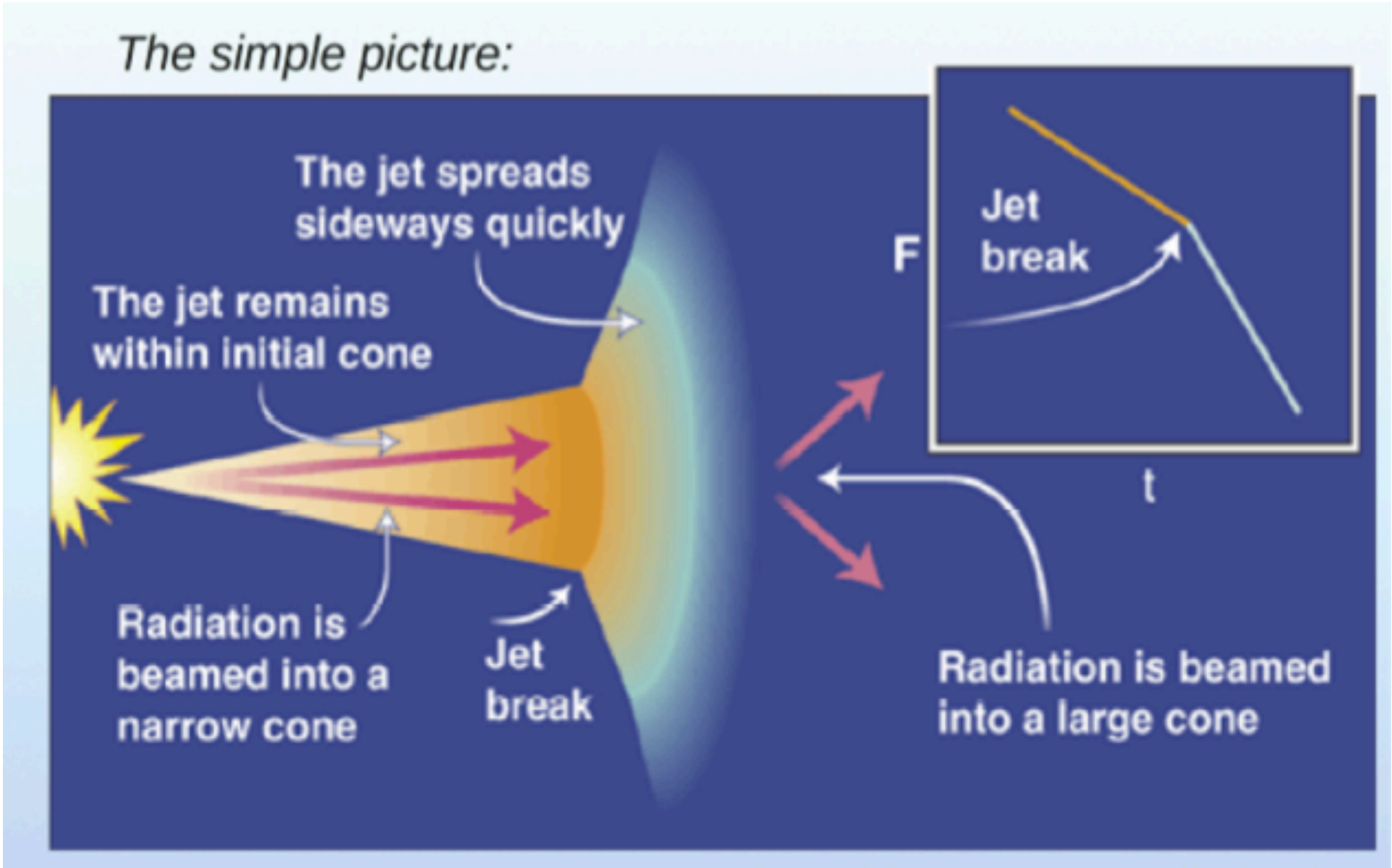
# GRB AFTERGLOWs




Need epsilon_b ~ 0.01 for synchrotron

# Afterglow Jet Dynamics




**Model parameters:**

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

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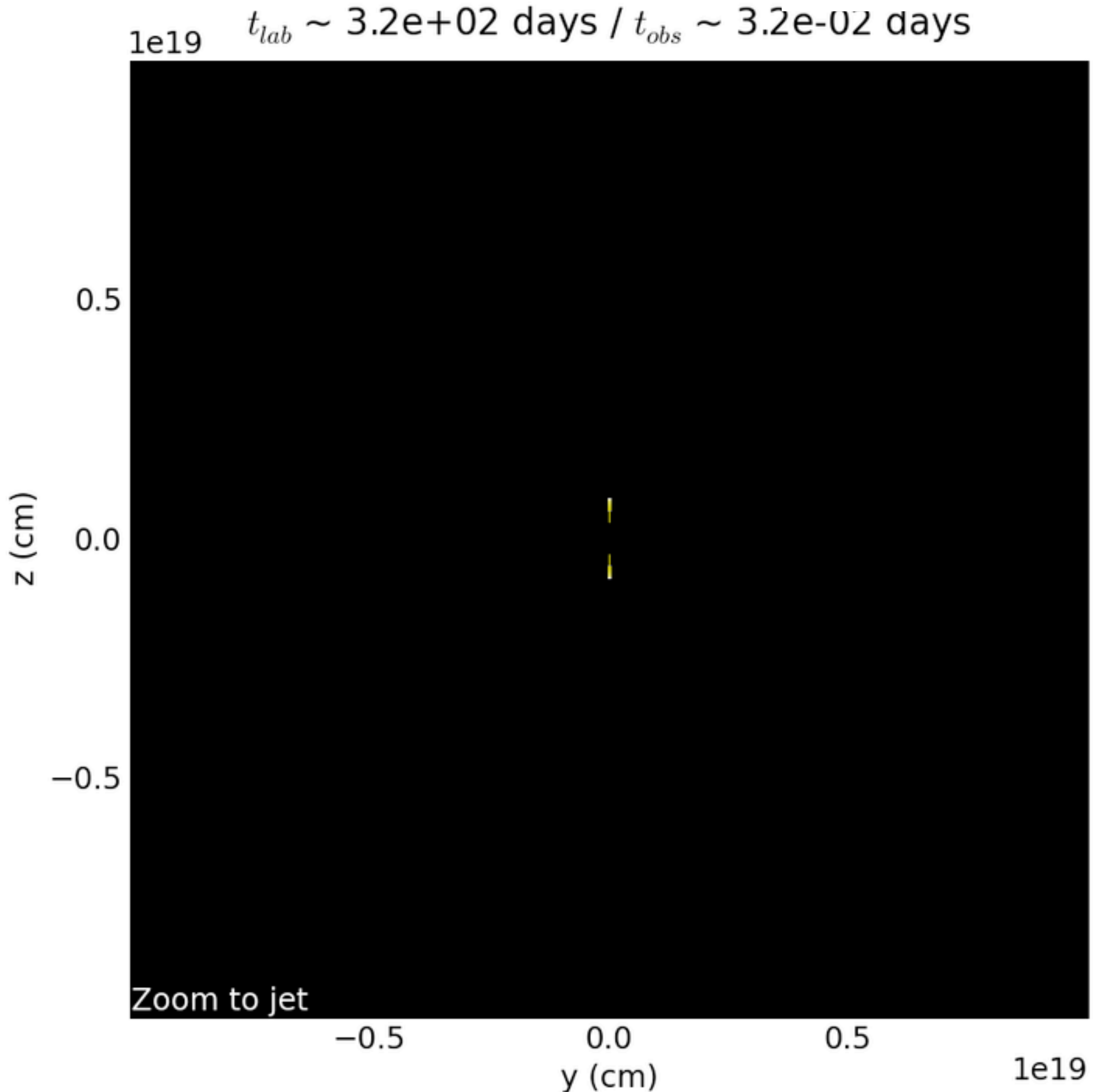
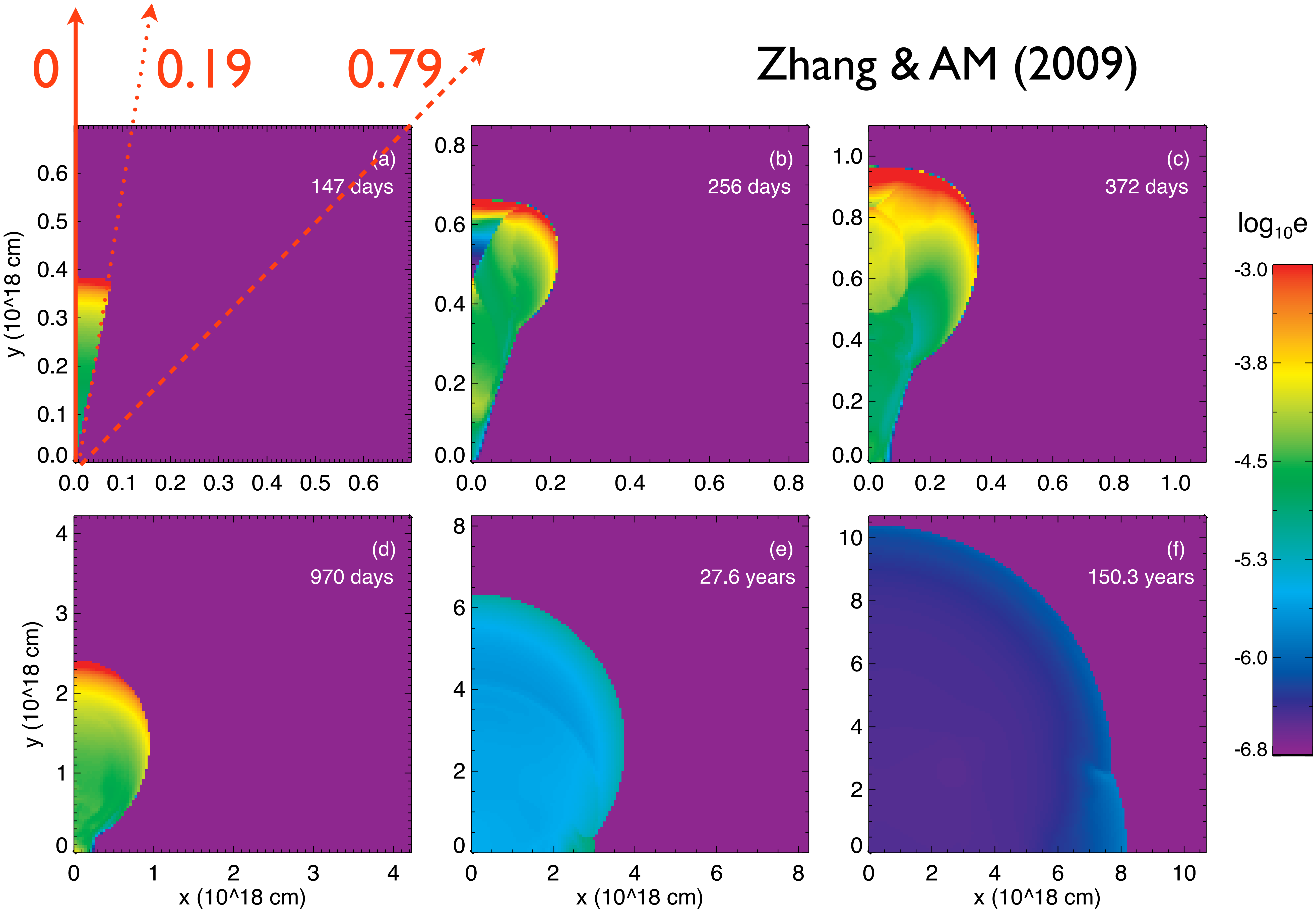



Ej = 2e52
θj=0.05
n=1cm^-3

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

van Eerten & AM (2011)

Zhang & AM (2009)

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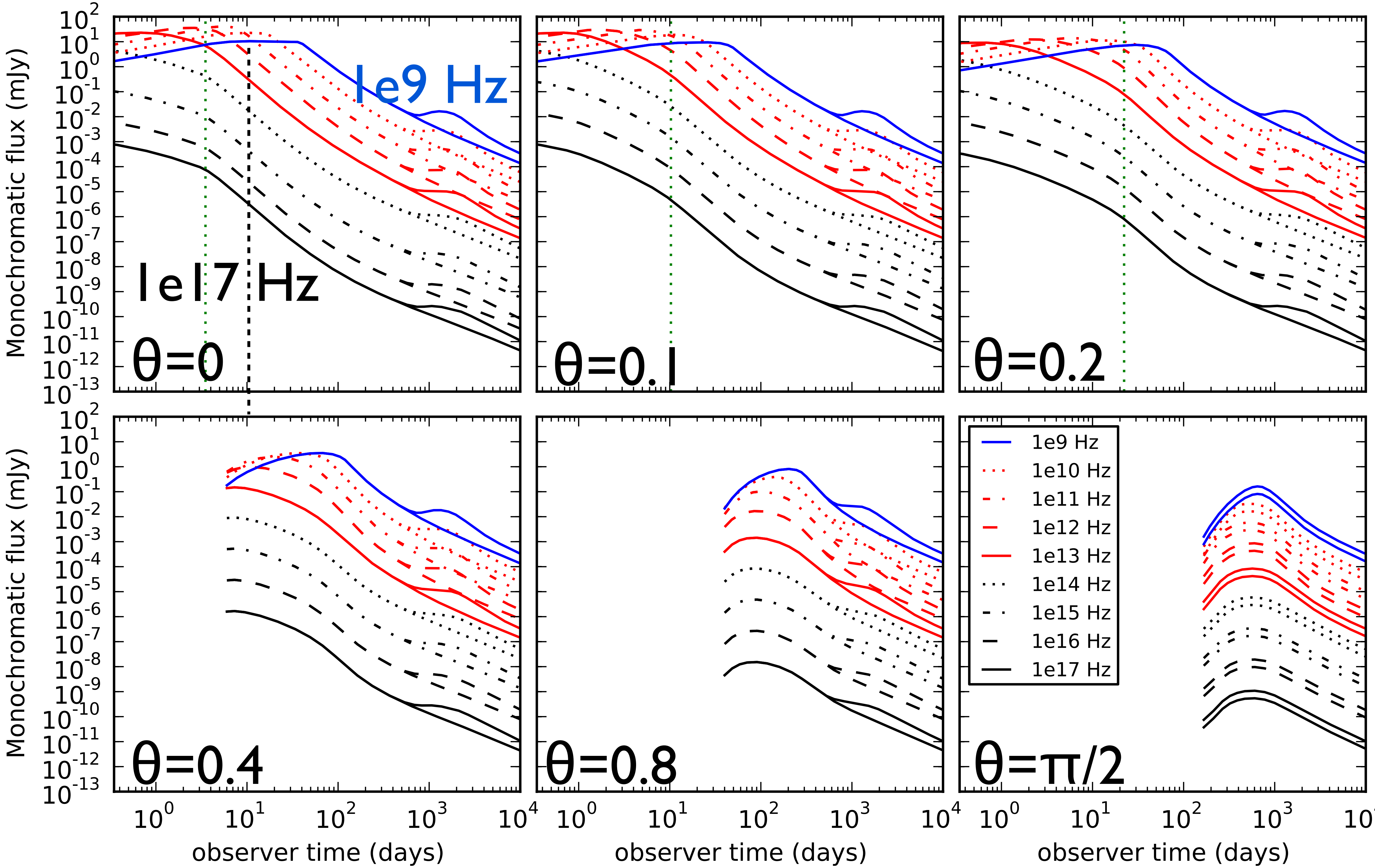
# Off-Axis Light Curves

## van Eerten, Zhang & AM (ApJ, 2010)

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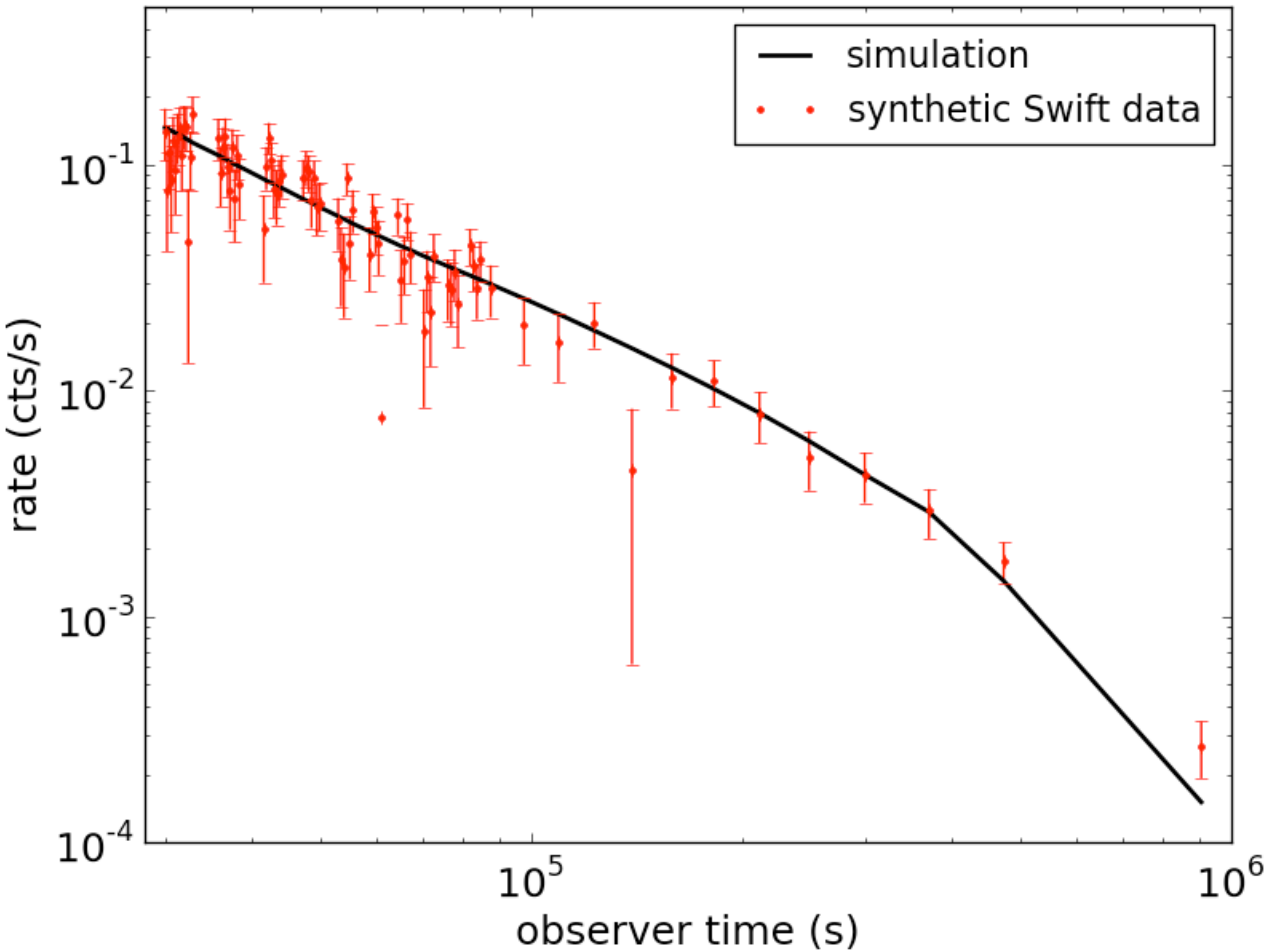
# On Axis

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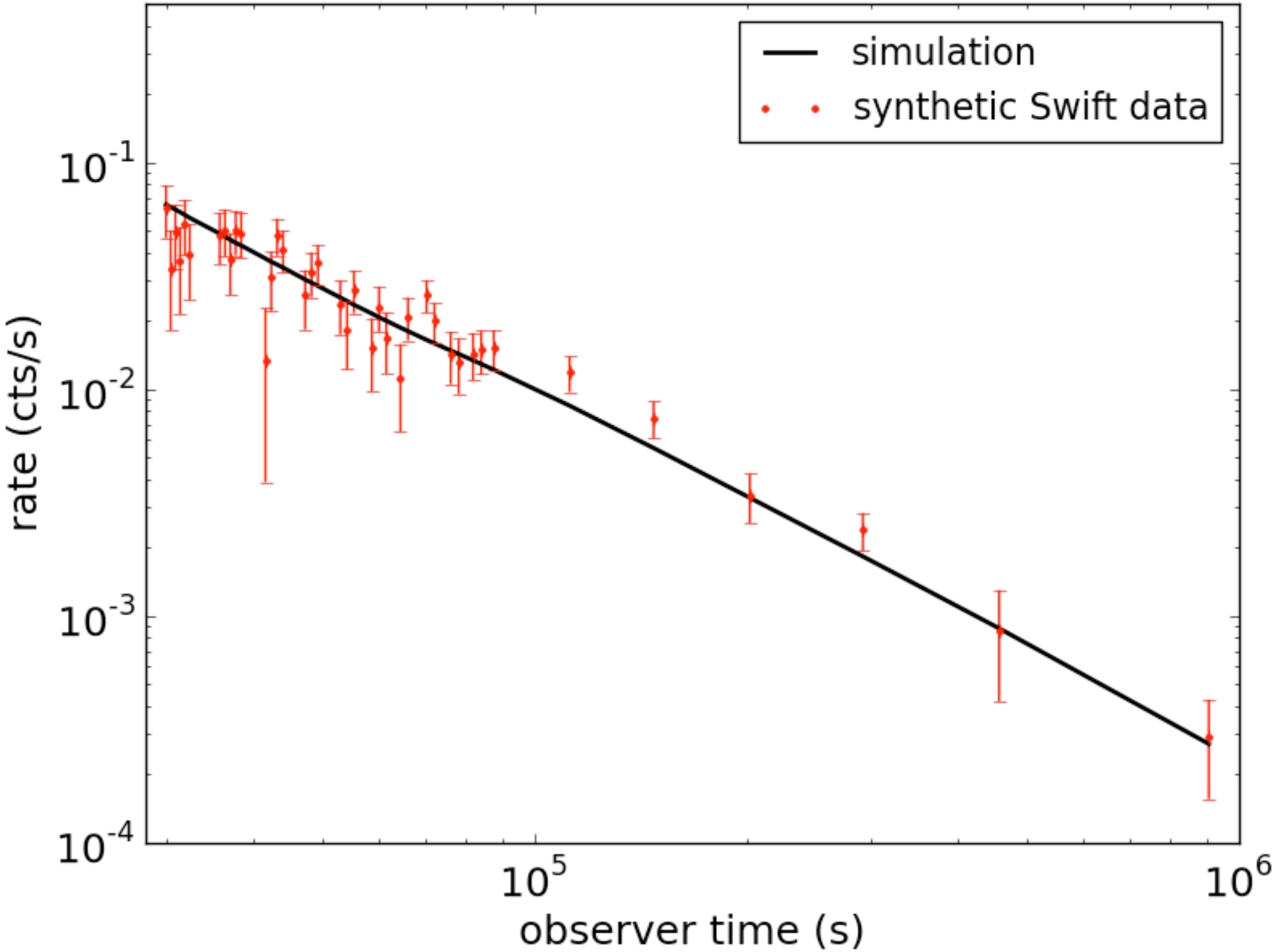
# On Edge

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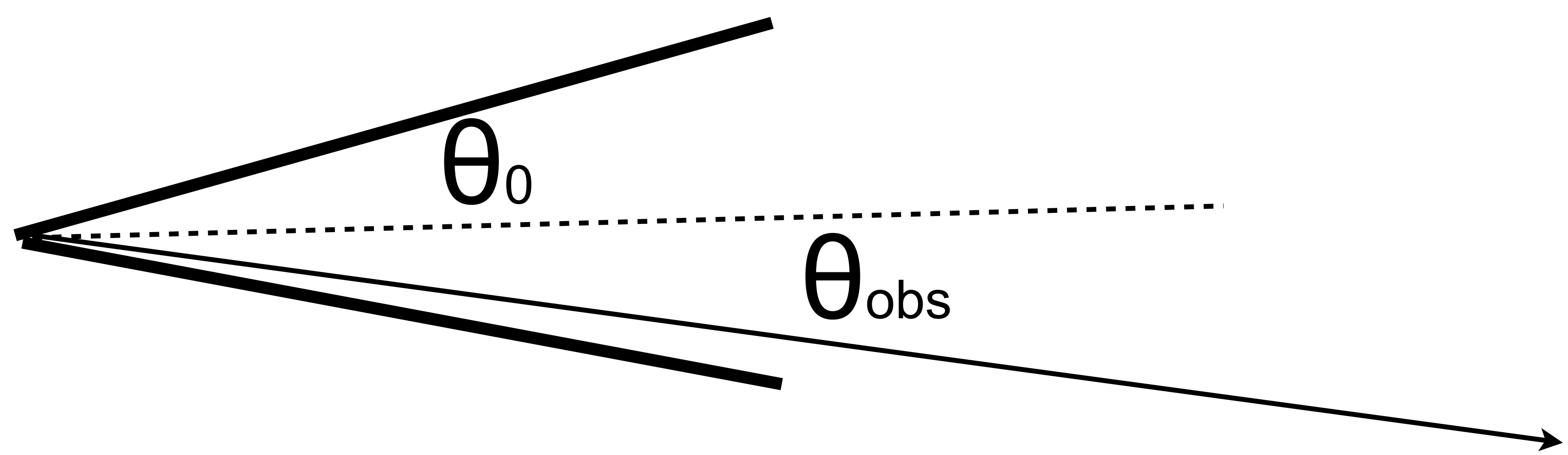
# Estimated Jet Break Time for Off-Axis Observer

$$t_j = 3.5(1+z)E_{iso,53}^{1/3} n_1^{-1/3} \left( \frac{\theta_0 + \theta_{obs}}{0.2} \right)^{8/3} \text{ days},$$




Theta_likely = 2/3 Theta_0

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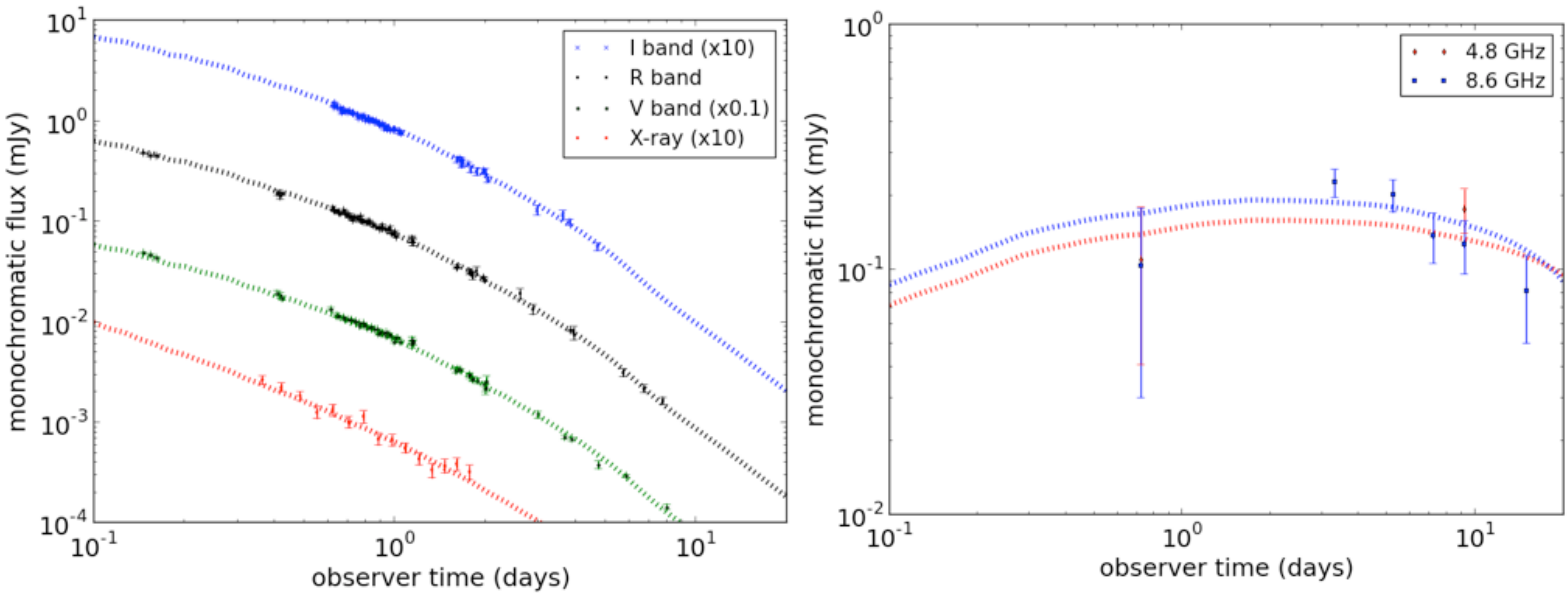
# Example application: model fit to GRB 990510




- **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 $\chi$-squared 3.235 for off-axis observer, while 5.389 on-axis
- observer angle $\theta$ is 0.016 rad, one third of jet angle 0.048 rad

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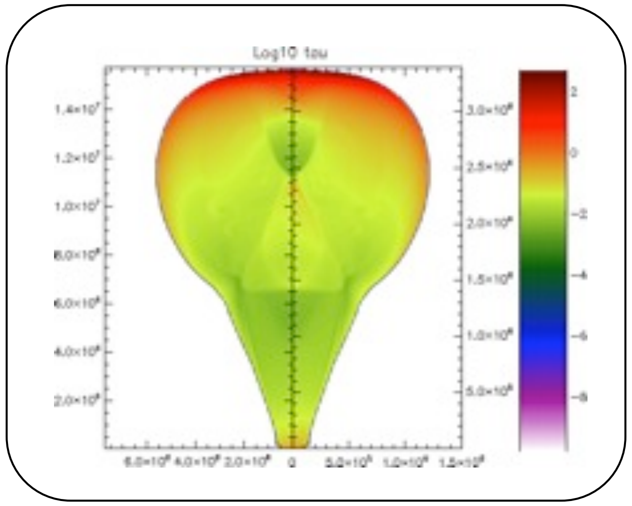
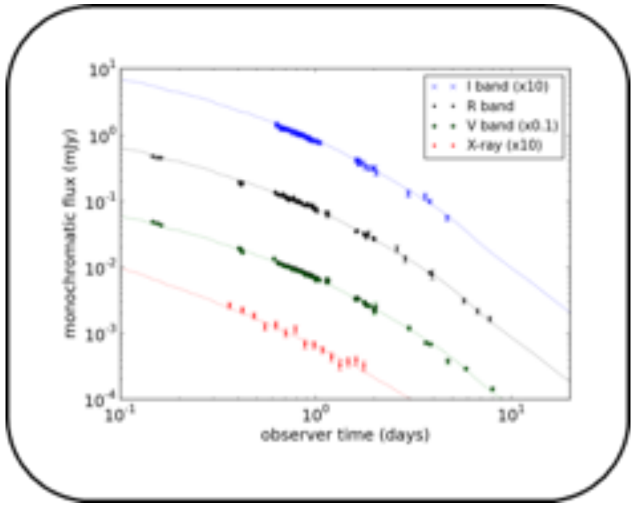
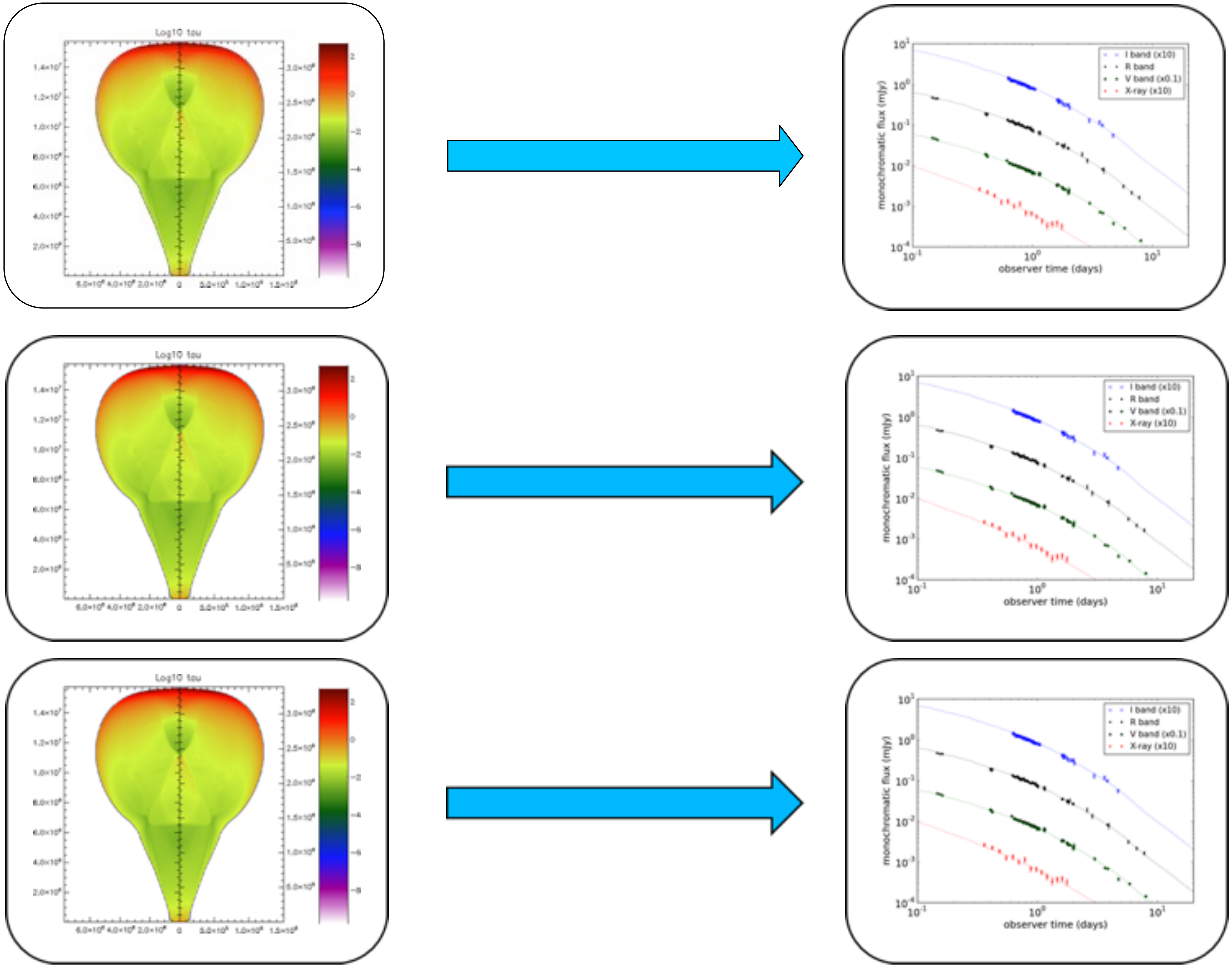
# From AMR RHD simulation to light curve




Simulate for energy $E$, density $n$, opening angle $\theta$, then synchrotron radiative transfer calculation

# From AMR RHD simulation to light curve




Simulate for energy *E*, density *n*, opening angle $\theta$, 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: $A \rightarrow 1$

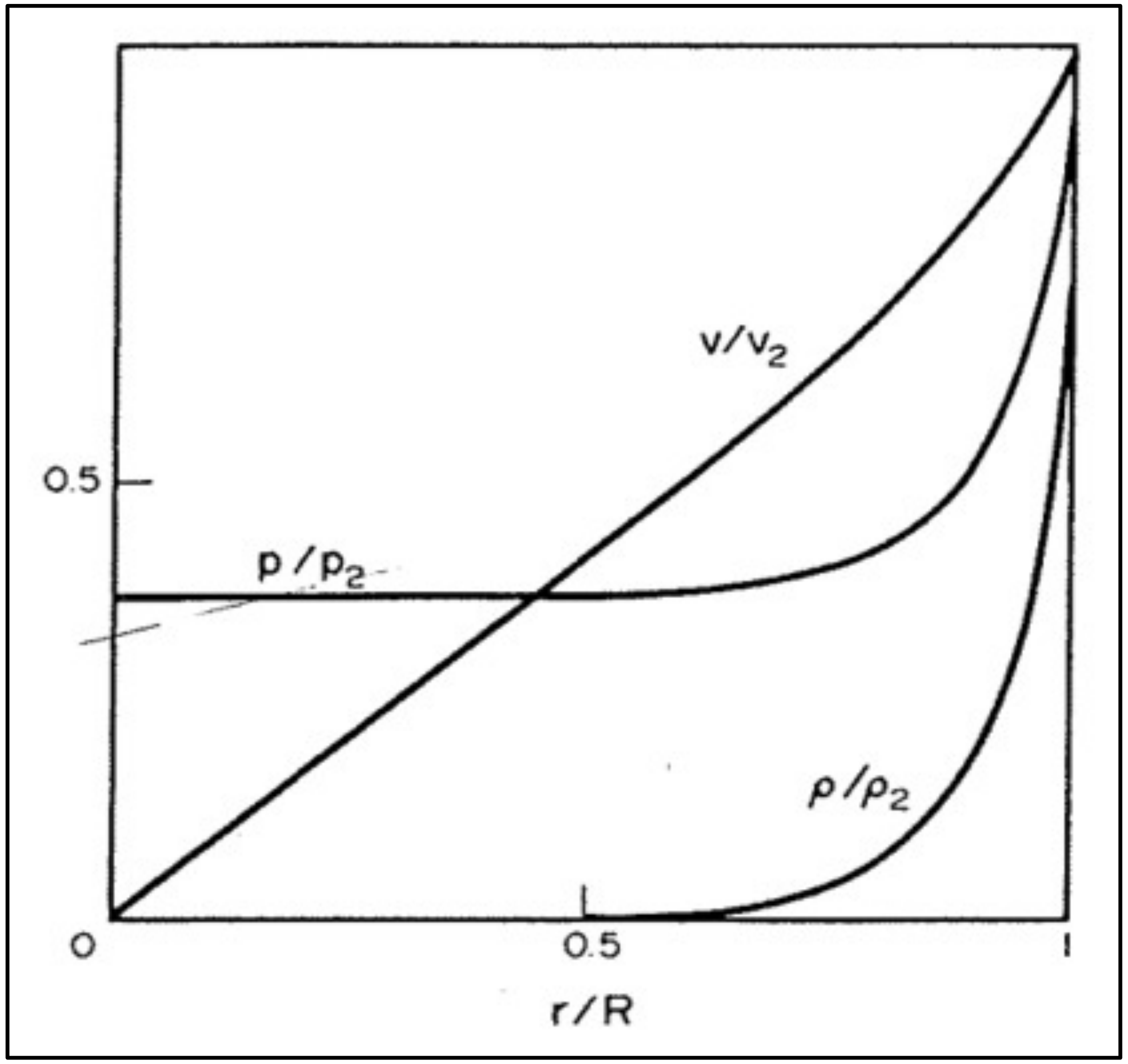
- nonrelativistic: $A \rightarrow \infty$

so spherical (no $\theta$) 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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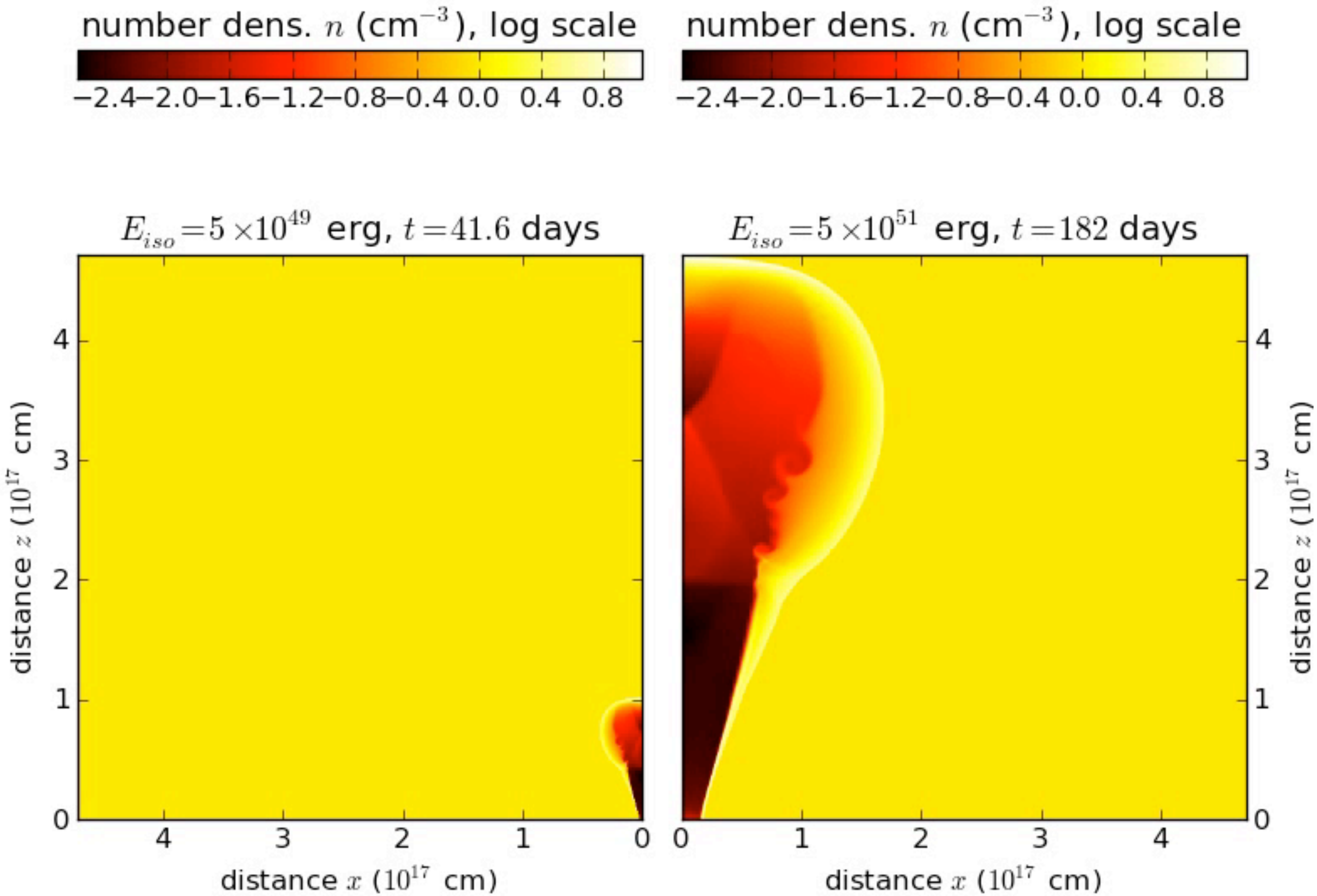
# Scaling of Jet Dynamics




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

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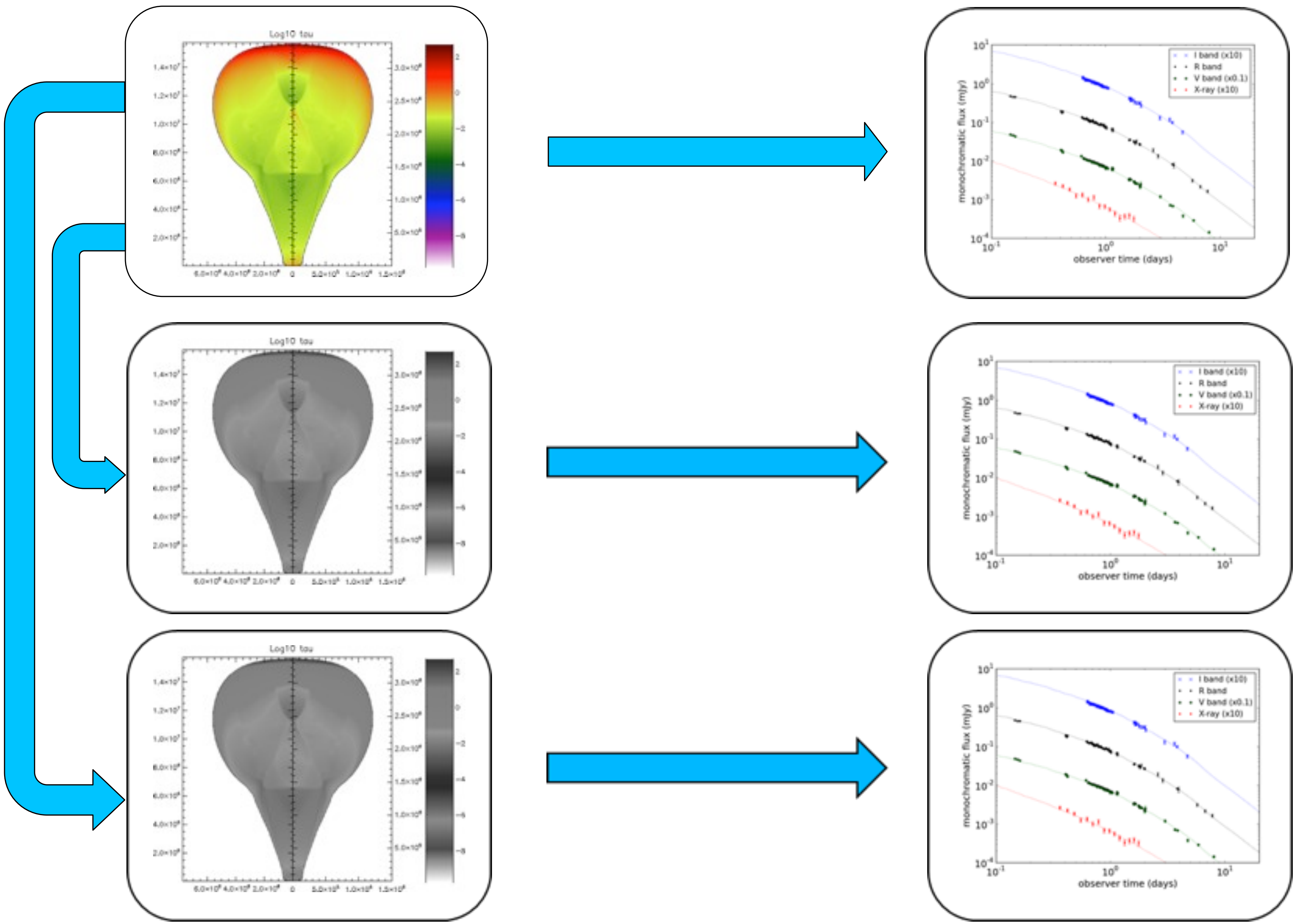
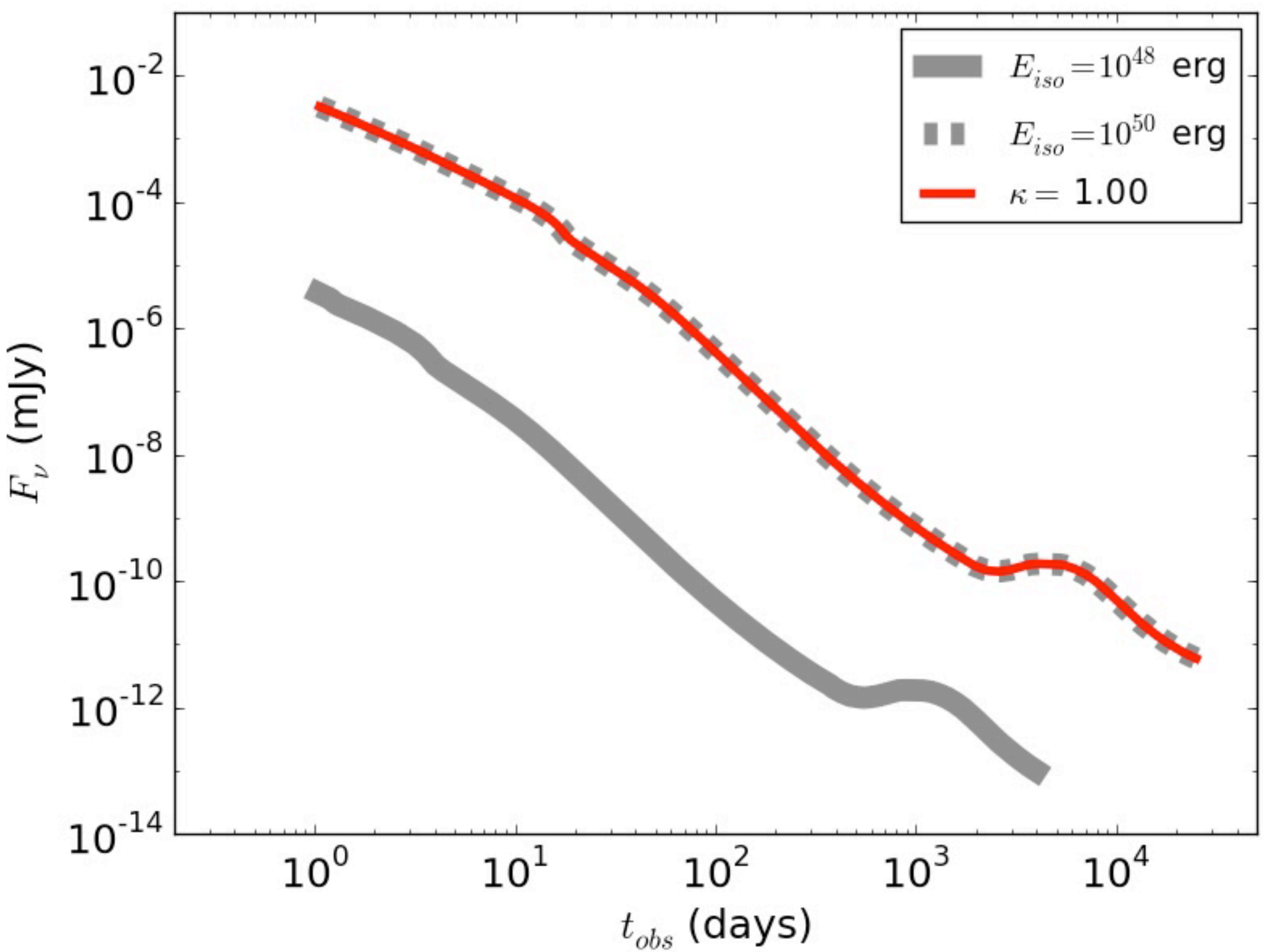
# Calculate jet dynamics by applying scaling




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




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

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

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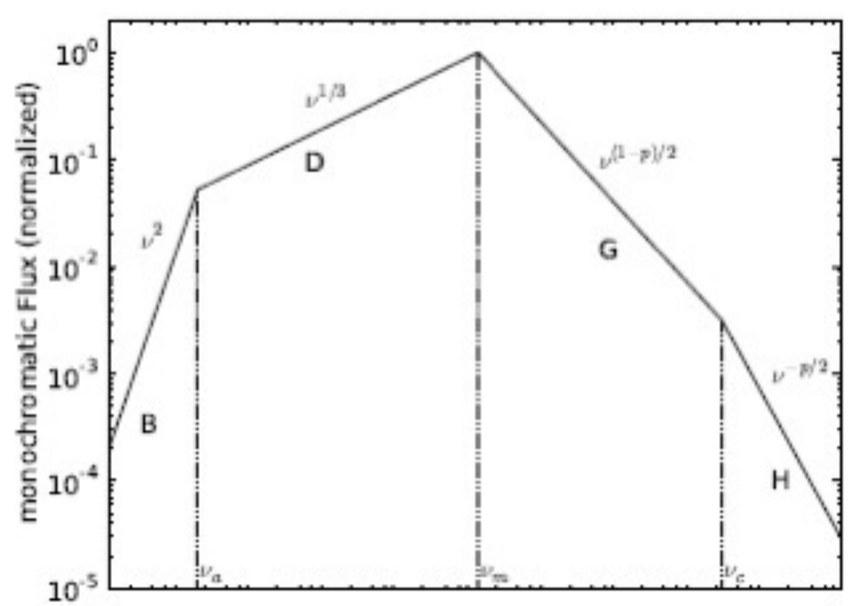
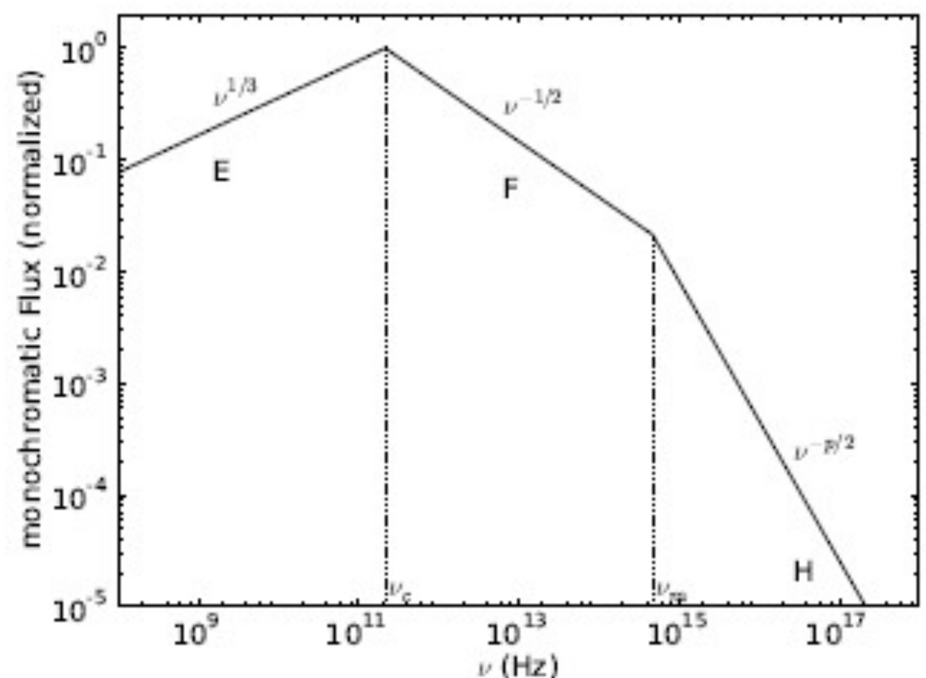
# Scalings, the full formulae

| $F$ or $\nu$ | leading order scalings | $\kappa$ | $\lambda$ |
|---|---|---|---|
| $F_{B,BM}$ | $(1+z)E_{\rm iso}^{1/2} n_0^{-1/2} \epsilon_e^1 \epsilon_B^0 \xi_N^{-1} t^{1/2} \nu^2$ | $\kappa^{2/3}$ | $\lambda^{-2/3}$ |
| $F_{B,ST}$ | $(1+z)E_{\rm iso}^{4/5} n_0^{-4/5} \epsilon_e^1 \epsilon_B^0 \xi_N^{-1} t^{-2/5} \nu^2$ | | |
| $F_{D,BM}$ | $(1+z)E_{\rm iso}^{5/6} n_0^{1/2} \epsilon_e^{-2/3} \epsilon_B^{1/3} \xi_N^{5/3} t^{1/2} \nu^{1/3}$ | $\kappa^1$ | $\lambda^{1/3}$ |
| $F_{D,ST}$ | $(1+z)E_{\rm iso}^{7/15} n_0^{13/15} \epsilon_e^{-2/3} \epsilon_B^{1/3} \xi_N^{5/3} t^{8/5} \nu^{1/3}$ | | |
| $F_{E,BM}$ | $(1+z)E_{\rm iso}^{7/6} n_0^{5/6} \epsilon_e^0 \epsilon_B^1 \xi_N^1 t^{1/6} \nu^{1/3}$ | $\kappa^{11/9}$ | $\lambda^{7/9}$ |
| $F_{E,ST}$ | $(1+z)E_{\rm iso}^1 n_0^1 \epsilon_e^0 \epsilon_B^1 \xi_N^1 t^{2/3} \nu^{1/3}$ | | |
| $F_{F,BM}$ | $(1+z)E_{\rm iso}^{3/4} n_0^0 \epsilon_e^0 \epsilon_B^{-1/4} \xi_N^1 t^{-1/4} \nu^{-1/2}$ | $\kappa^{2/3}$ | $\lambda^{1/12}$ |
| $F_{F,ST}$ | $(1+z)E_{\rm iso}^{1/2} n_0^{1/4} \epsilon_e^0 \epsilon_B^{-1/4} \xi_N^1 t^{1/2} \nu^{-1/2}$ | | |
| $F_{G,BM}$ | $(1+z)E_{\rm iso}^{(p+3)/4} n_0^{1/2} \epsilon_e^{p-1} \epsilon_B^{(1+p)/4} \xi_N^{2-p} t^{3(1-p)/4} \nu^{(1-p)/2}$ | $\kappa^1$ | $\lambda^{(1+p)/4}$ |
| $F_{G,ST}$ | $(1+z)E_{\rm iso}^{(5p+3)/10} n_0^{(19-5p)/20} \epsilon_e^{p-1} \epsilon_B^{(1+p)/4} \xi_N^{2-p} t^{(21-15p)/10} \nu^{(1-p)/2}$ | | |
| $F_{H,BM}$ | $(1+z)E_{\rm iso}^{(p+2)/4} n_0^0 \epsilon_e^{p-1} \epsilon_B^{(p-2)/4} \xi_N^{2-p} t^{(2-3p)/4} \nu^{-p/2}$ | $\kappa^{2/3}$ | $\lambda^{(3p-2)/12}$ |
| $F_{H,ST}$ | $(1+z)E_{\rm iso}^{(p)/2} n_0^{(2-p)/4} \epsilon_e^{p-1} \epsilon_B^{(p-2)/4} \xi_N^{2-p} t^{(4-3p)/2} \nu^{-p/2}$ | | |

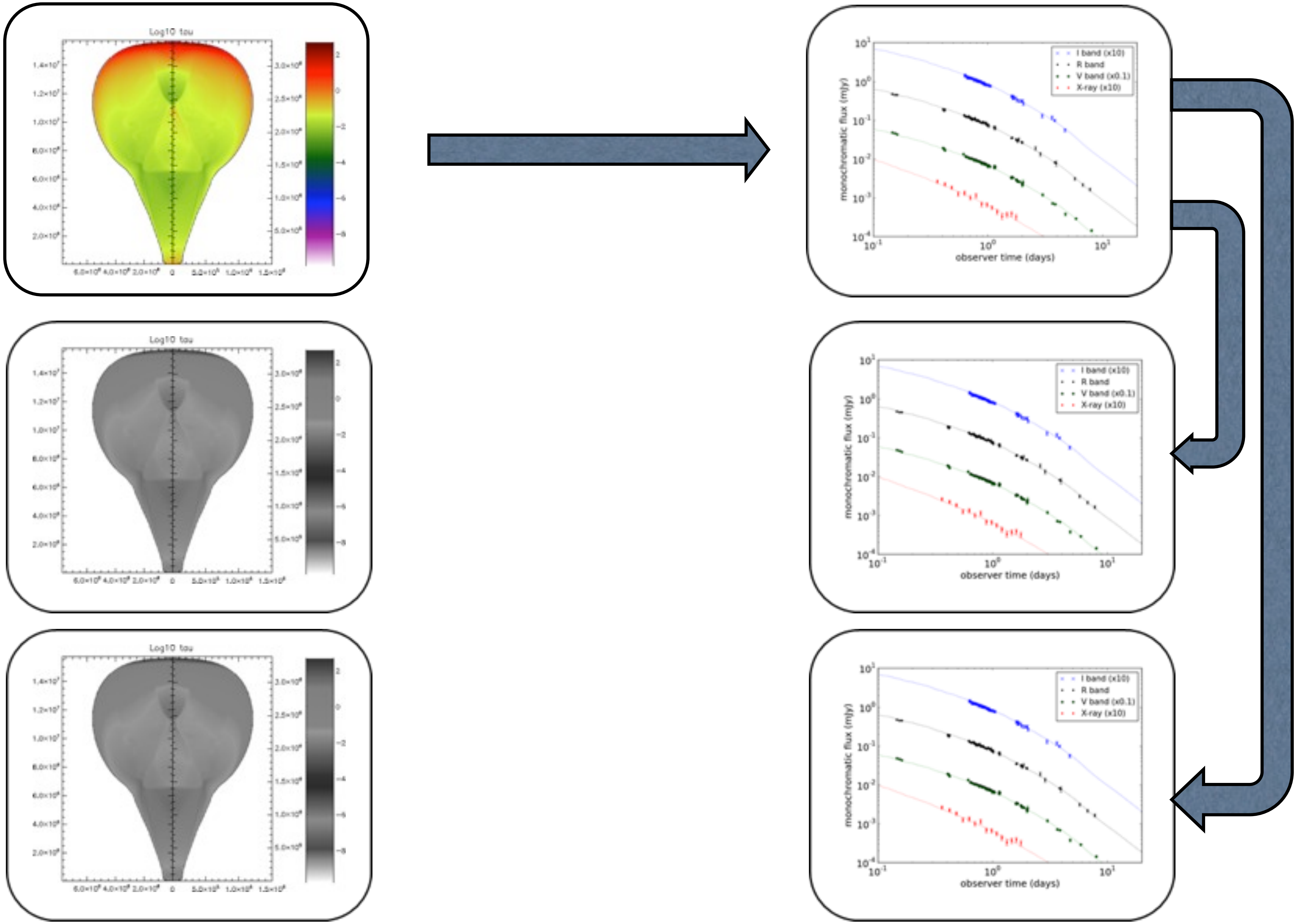



$$E'_{\rm iso} = \kappa E_{\rm iso}, \quad n' = \lambda n,$$

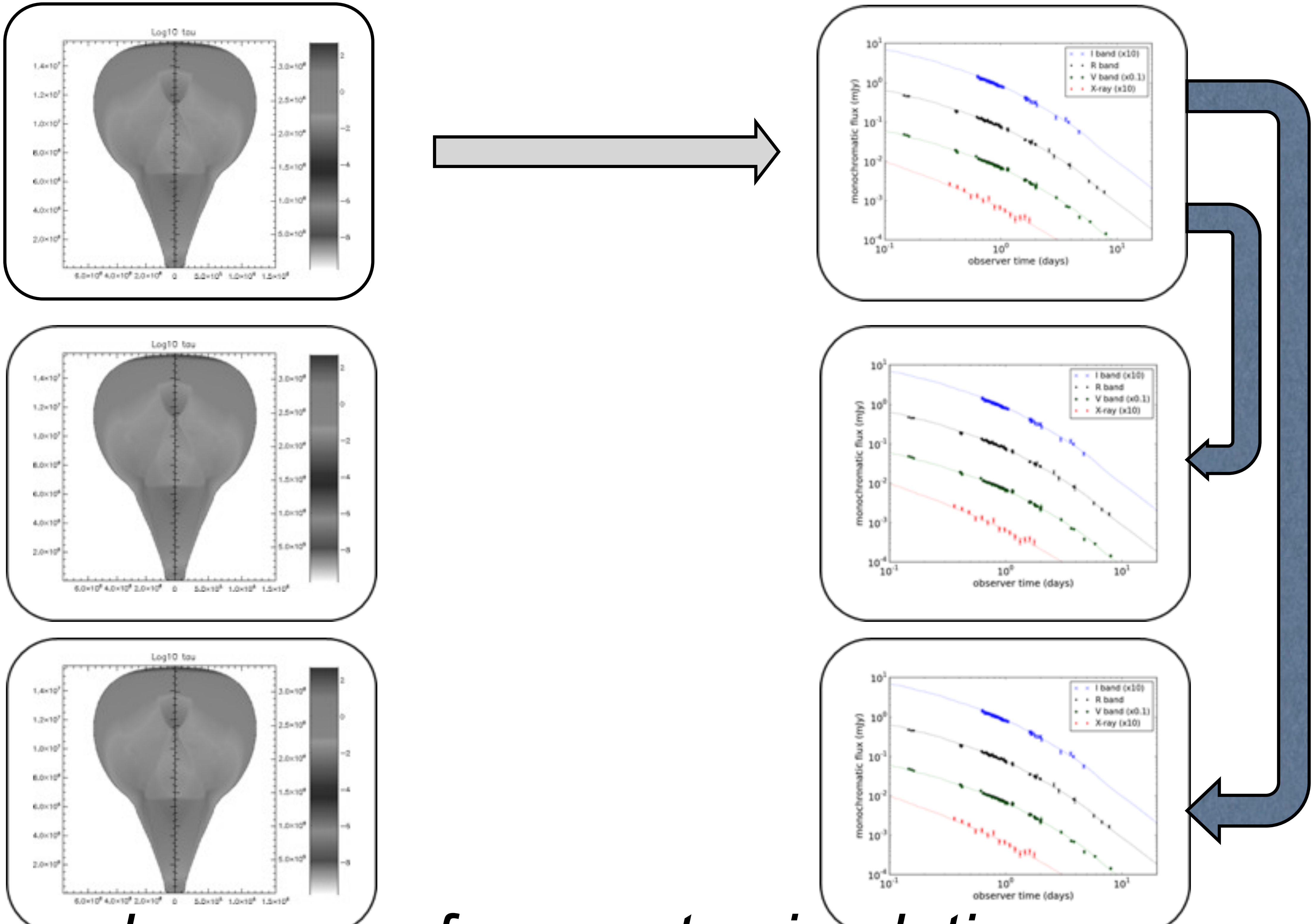
$$t'_{\rm obs} = (\kappa/\lambda)^{1/3} t_{\rm obs}, \quad F'_{\rm optical} = \kappa \lambda^{(1+p)/4} F_{\rm optical}$$

# 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!*

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# summarizing: what scales and what doesn't?

## Scales throughout the ejecta evolution:

**Dynamics:**
Explosion energy (through observer time)
Circumburst medium density (through observer time)

**Radiation:**
magnetic field, particle energy, particle number fraction
(i.e. they all scale, this is neither new nor unexpected)

## Left in parameter space:

**Dynamics:**
initial jet opening angle
circumburst density structure (‘*k*’ )

**Radiation / observer position:**
observer angle
[ transitions between spectral regimes, use sharp / smooth spectral powerlaws ]

## This implies:

1. Run simulations for different jet opening angles, and for wind and ISM
2. calculate light curve characteristics for different observer angles
3. collect resulting overview of parameter space and link to fit code / rate predictions etc.

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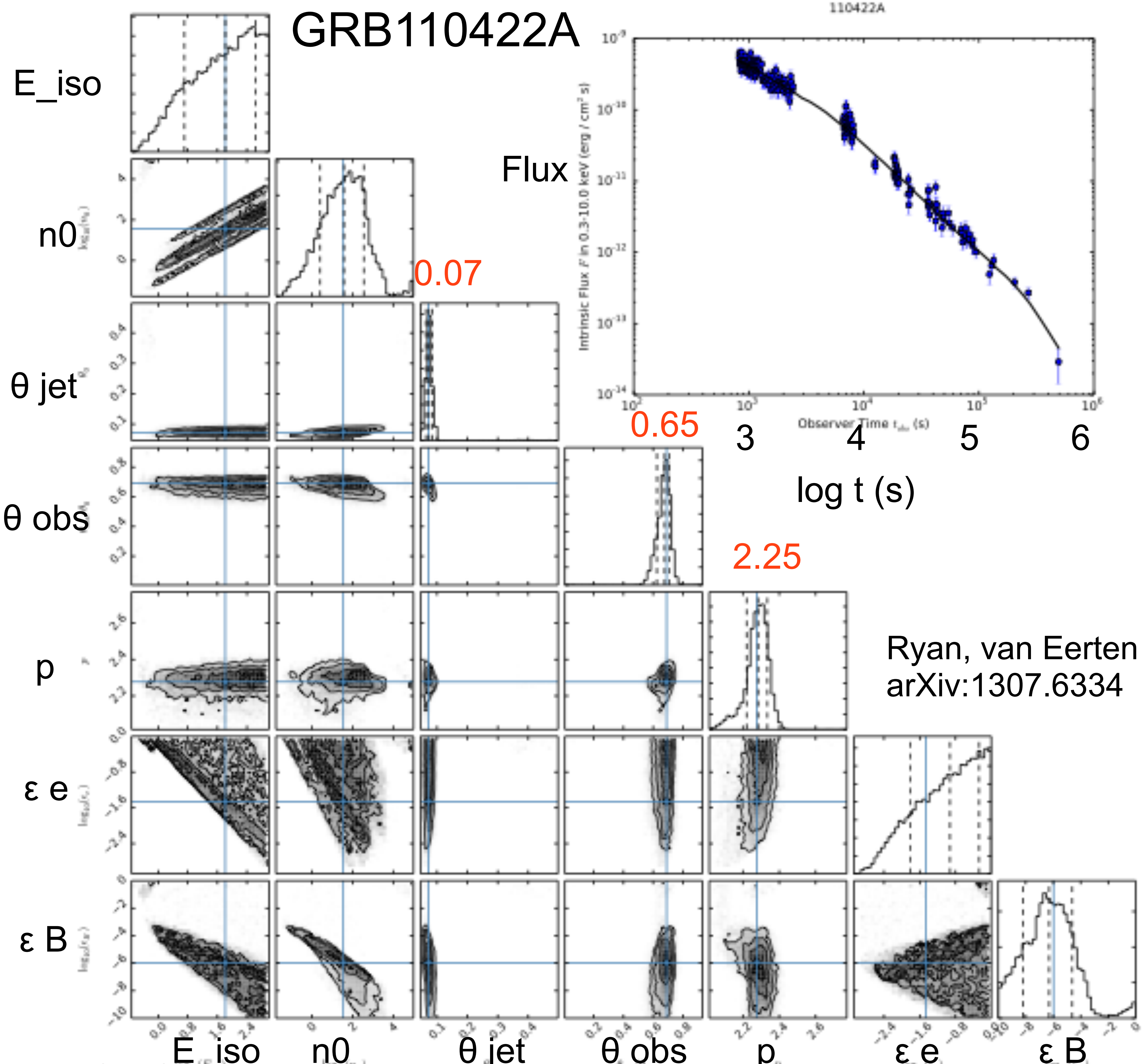
# GRB110422A




Ryan, van Eerten & AM (2014)
arXiv:1307.6334

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http://cosmo.nyu.edu/afterglowlibrary/

Supported by NASA NNX10AF62G

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# Summary

- Both jet dynamics and broadband light curves are scalable in energy in density

***as a result we now can***

- iteratively fit complex 2D simulation results to data (e.g. grb990510)
- calculate arbitrary parameter value light curves ‘on demand’

*which is useful for exploring parameter space (i.e. surveys)*
*and readily generalized to similar blast wave / jet phenomena:*
- *both long and short GRB’s*
- *supernova blast waves*
- *tidal disruption jets (talk Brian Metzger)*
- *....?*

***all light curves, spectra, fit codes etc. available on-line:***

*(in the [near] future also fit code and continuous parameter space light curves)*

**http://cosmo.nyu.edu/afterglowlibrary**

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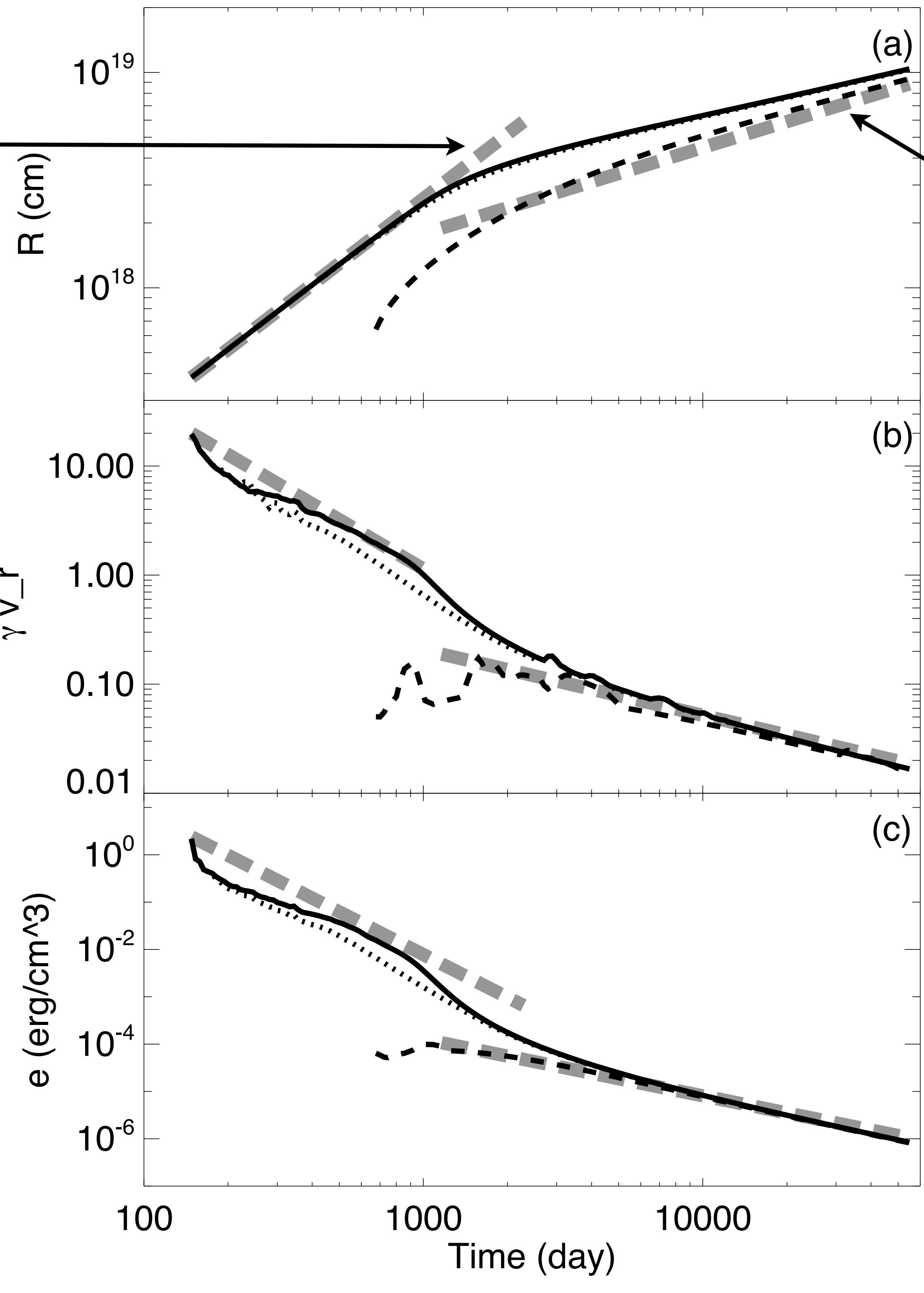
Blandford-McKee

Sedov

θj = 0.2

θ = 0,0.19,π/4




Granot+(2001)
Zhang&AM(2009)
vanEerten+(2010)
Wygoda+(2011)
deColle+(2012)
Vlasis+ (2012)

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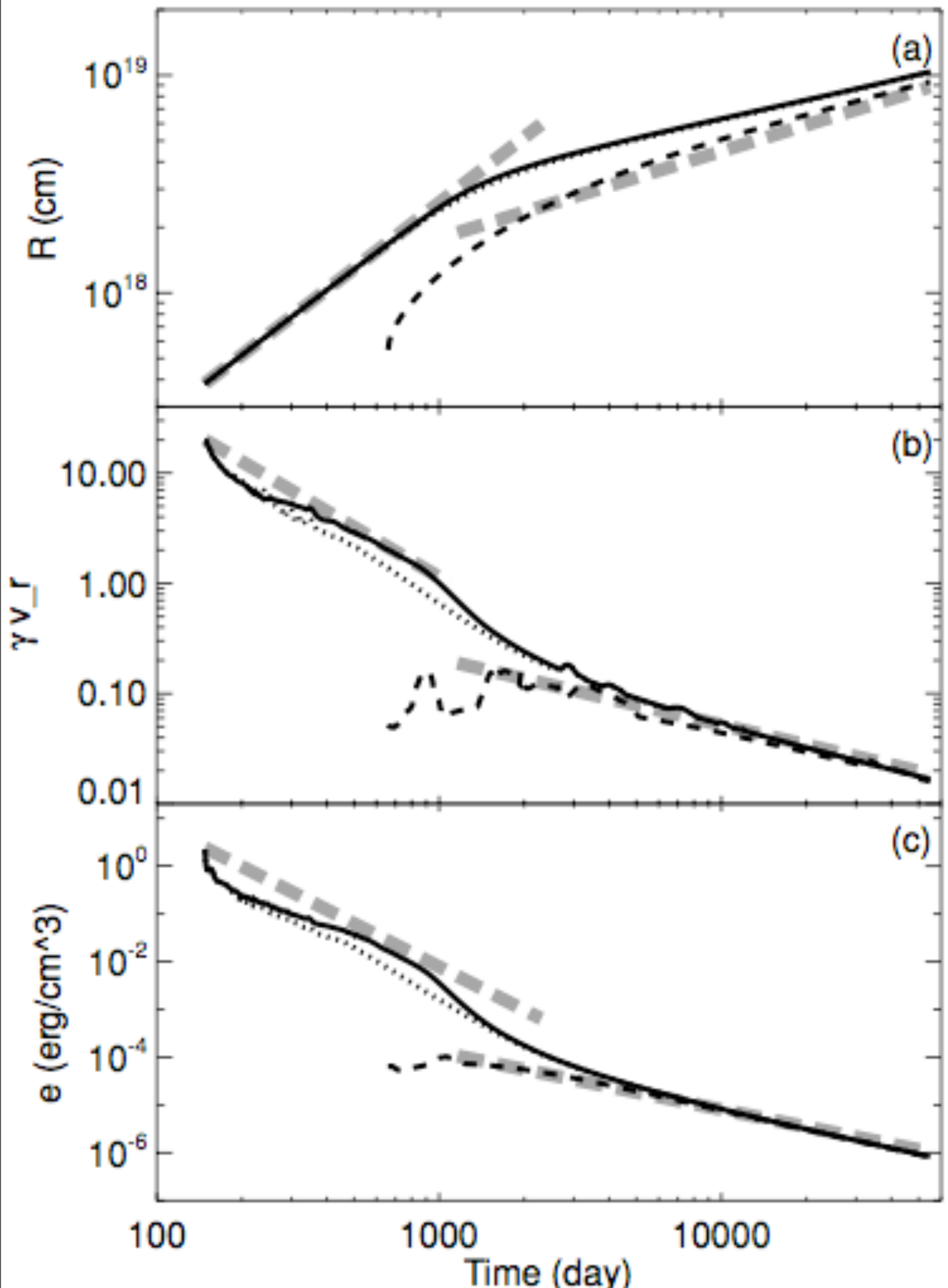
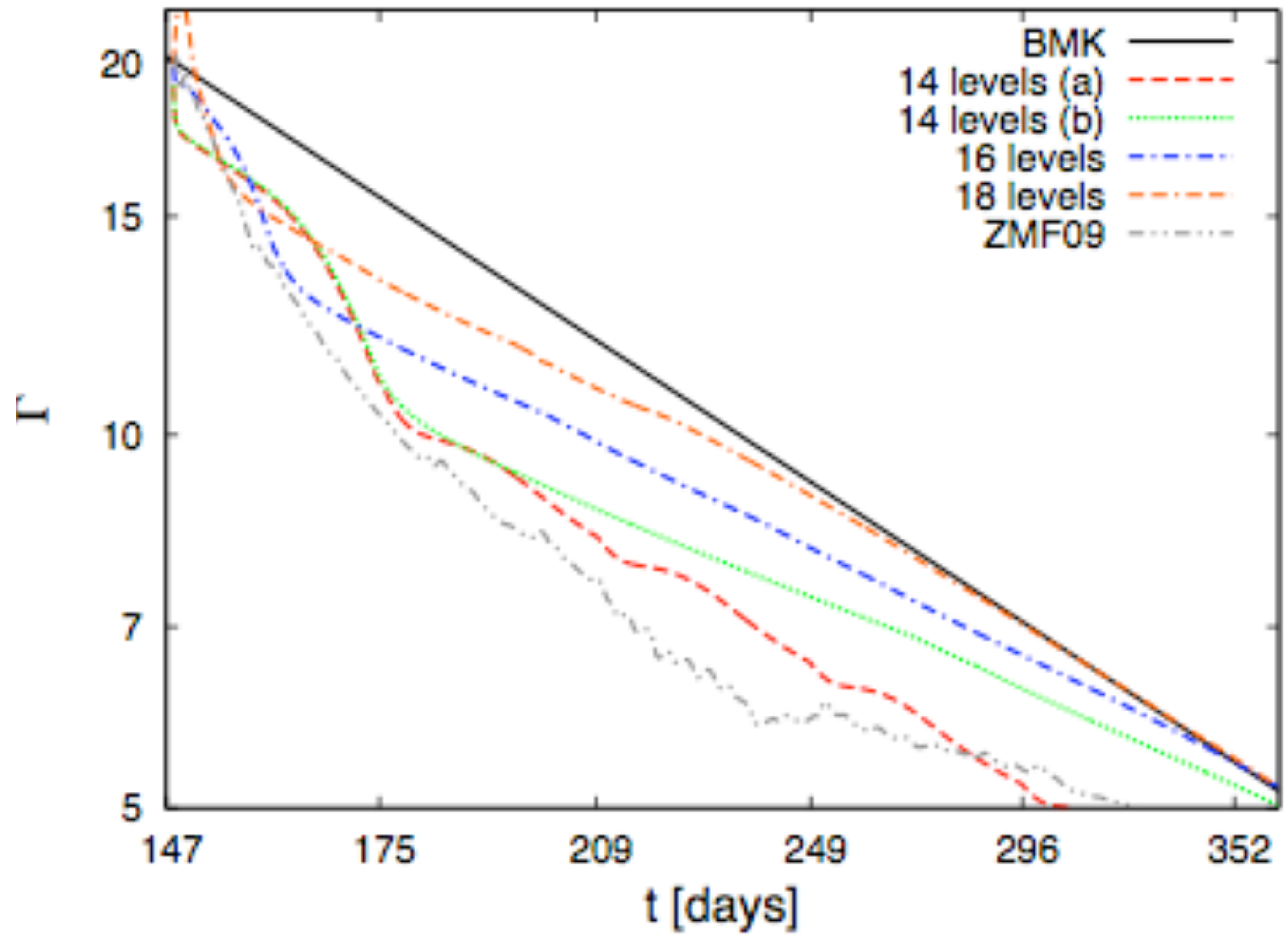



Zhang & AM (2009)




DeColle+ (2012)

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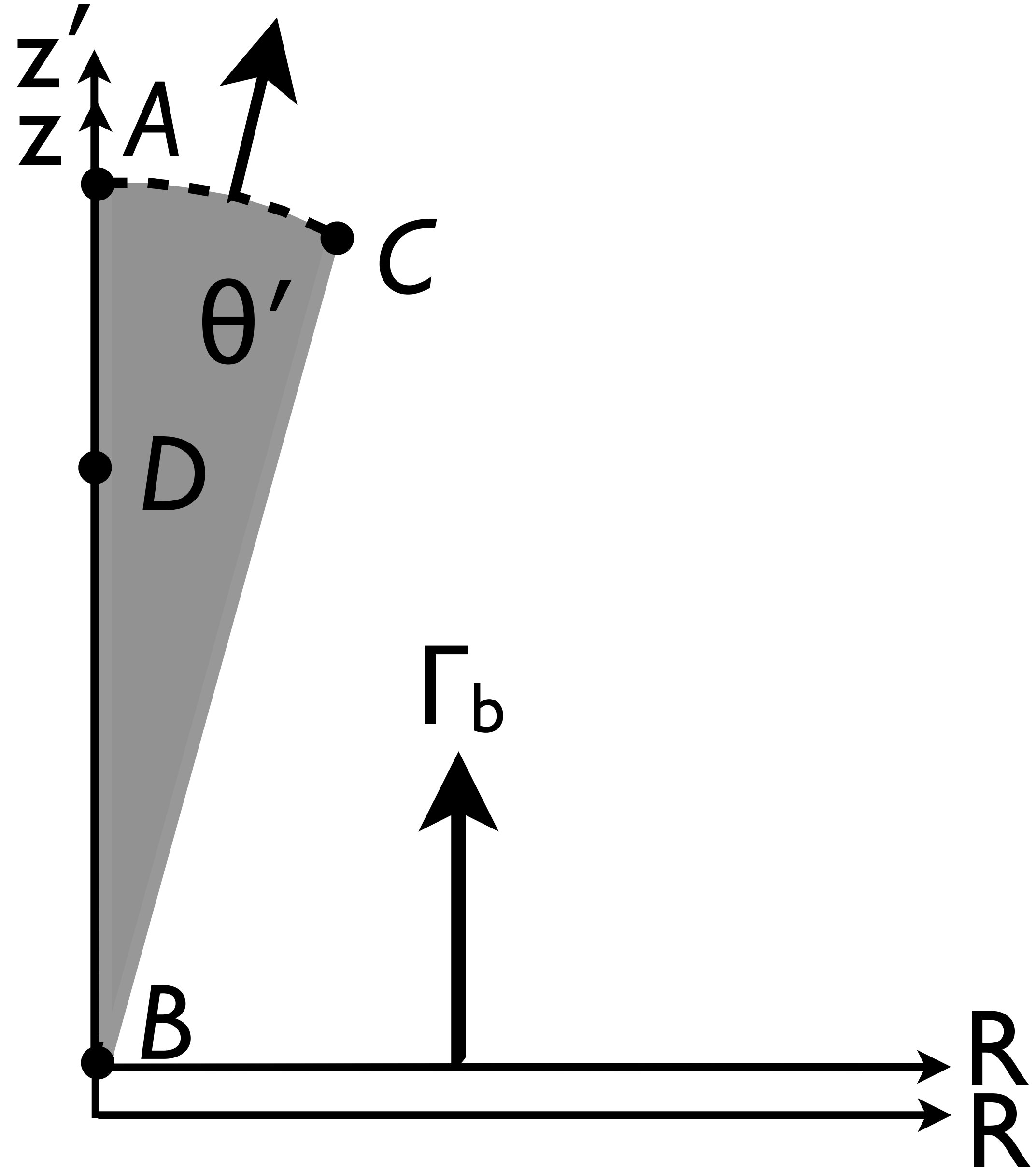
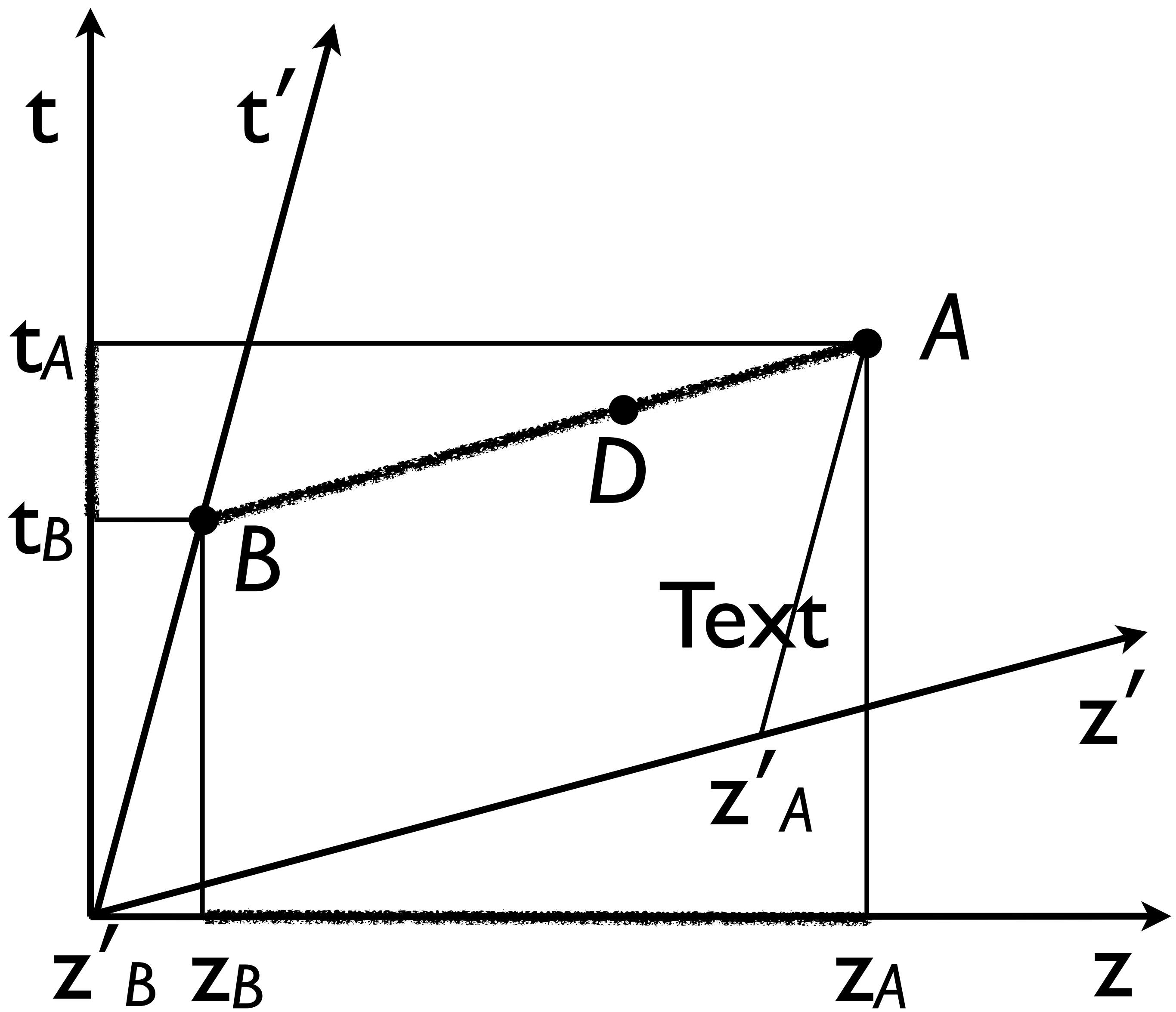
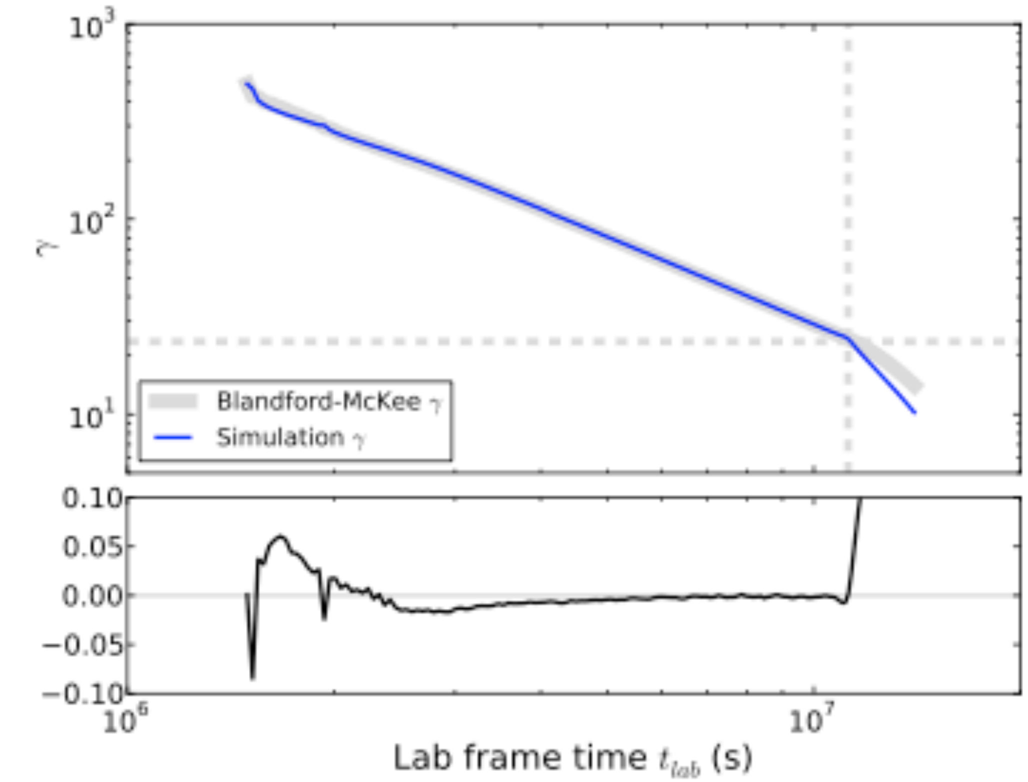
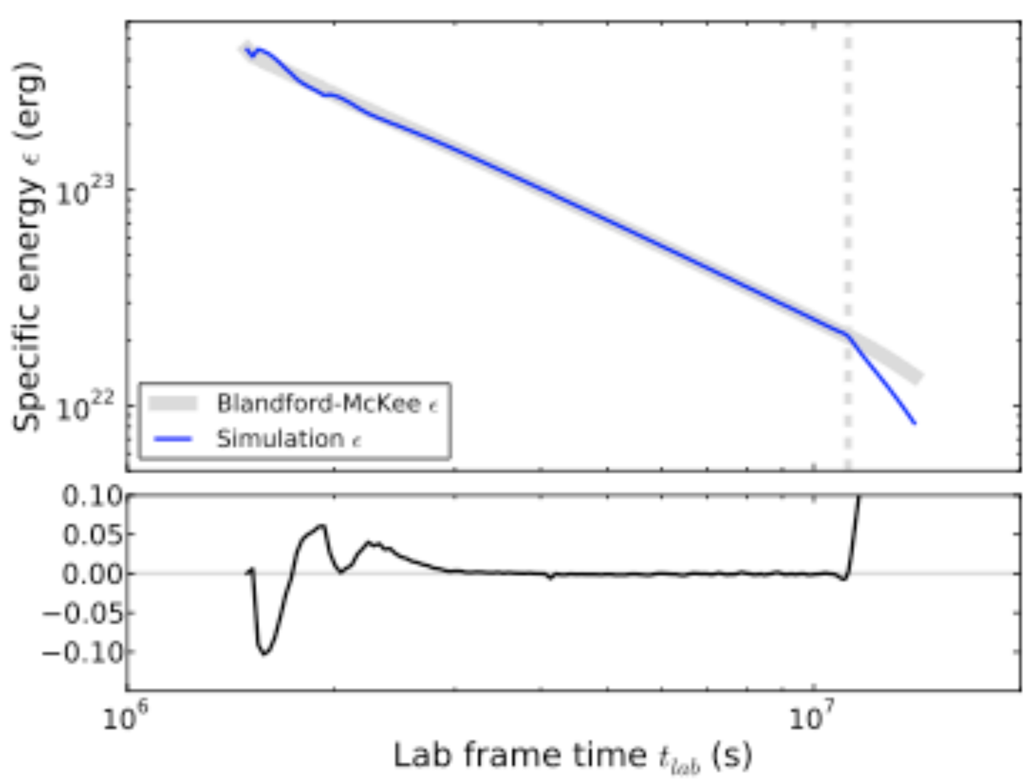



AM & van Eerten (2013, in prep)




Blandford-McKee: P(r,t), ρ(r,t), Γ(r,t)

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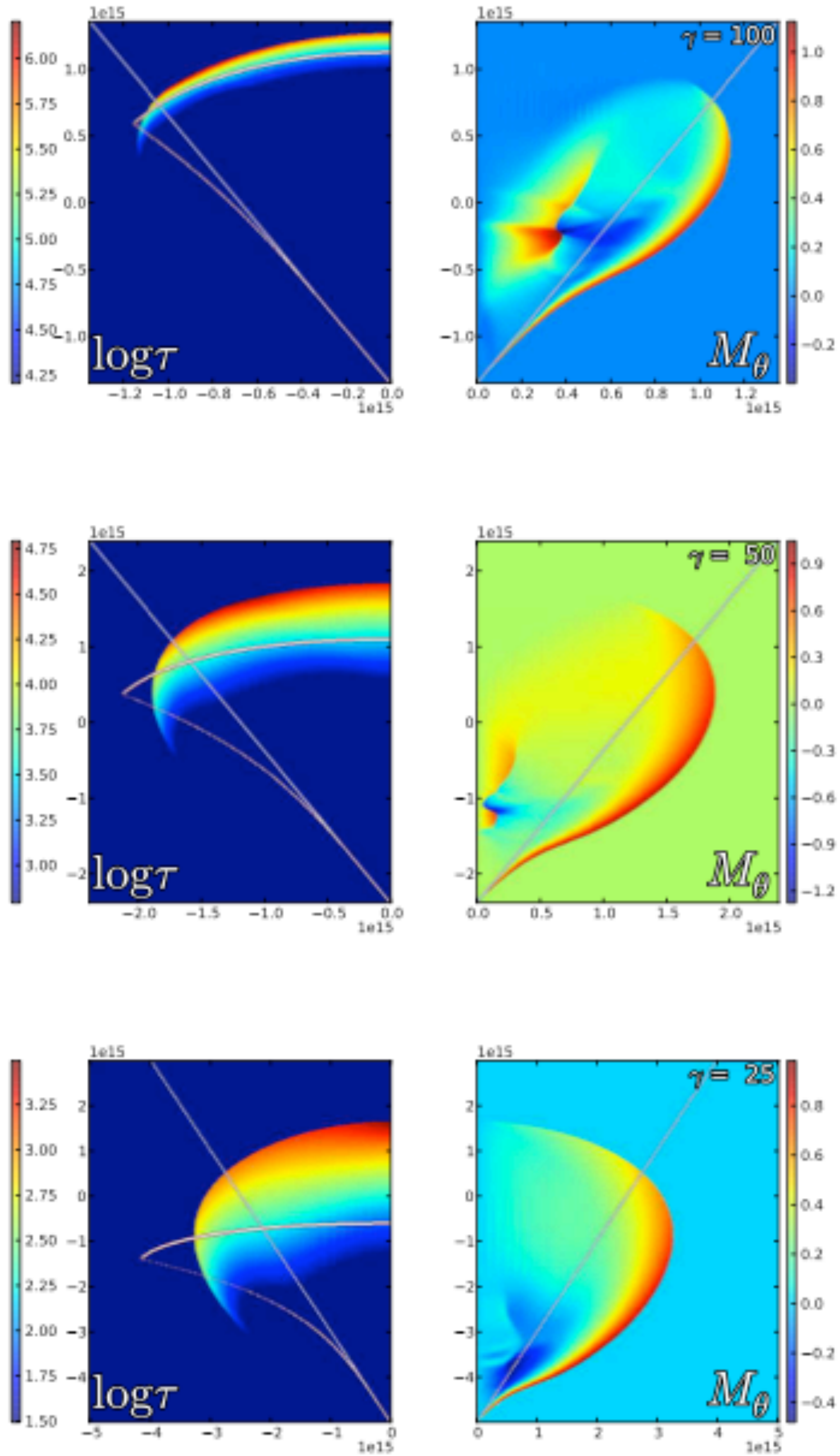
$\theta_0 = 0.01$

$\Gamma_0 = 500$




$\Gamma = 100$

$\Gamma = 50$

$\Gamma = 25$

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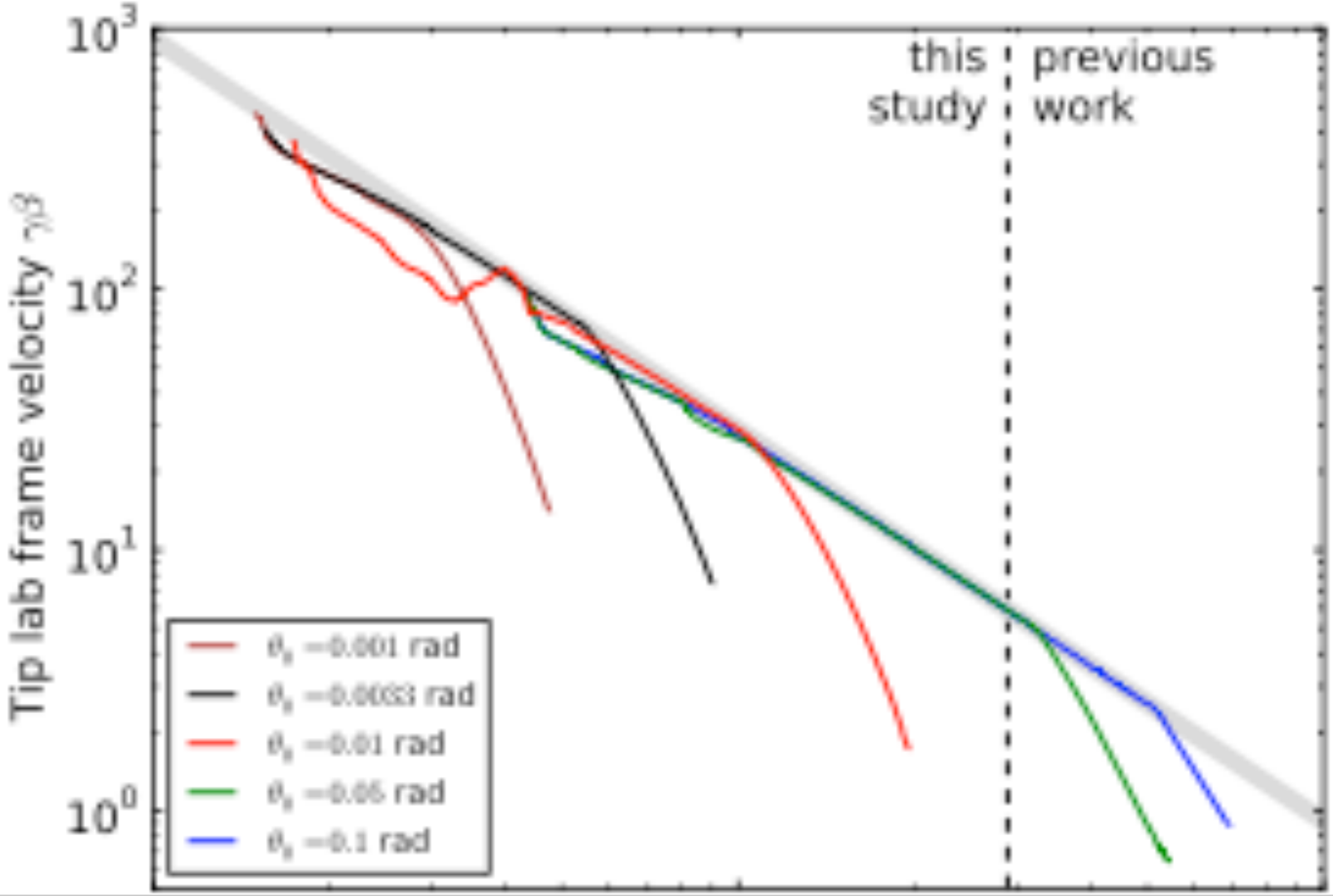
# Jet Spreading

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10^7 cm 10^15 cm 10^18 cm


1. RT Instability

2. Afterglow Fits

This Talk

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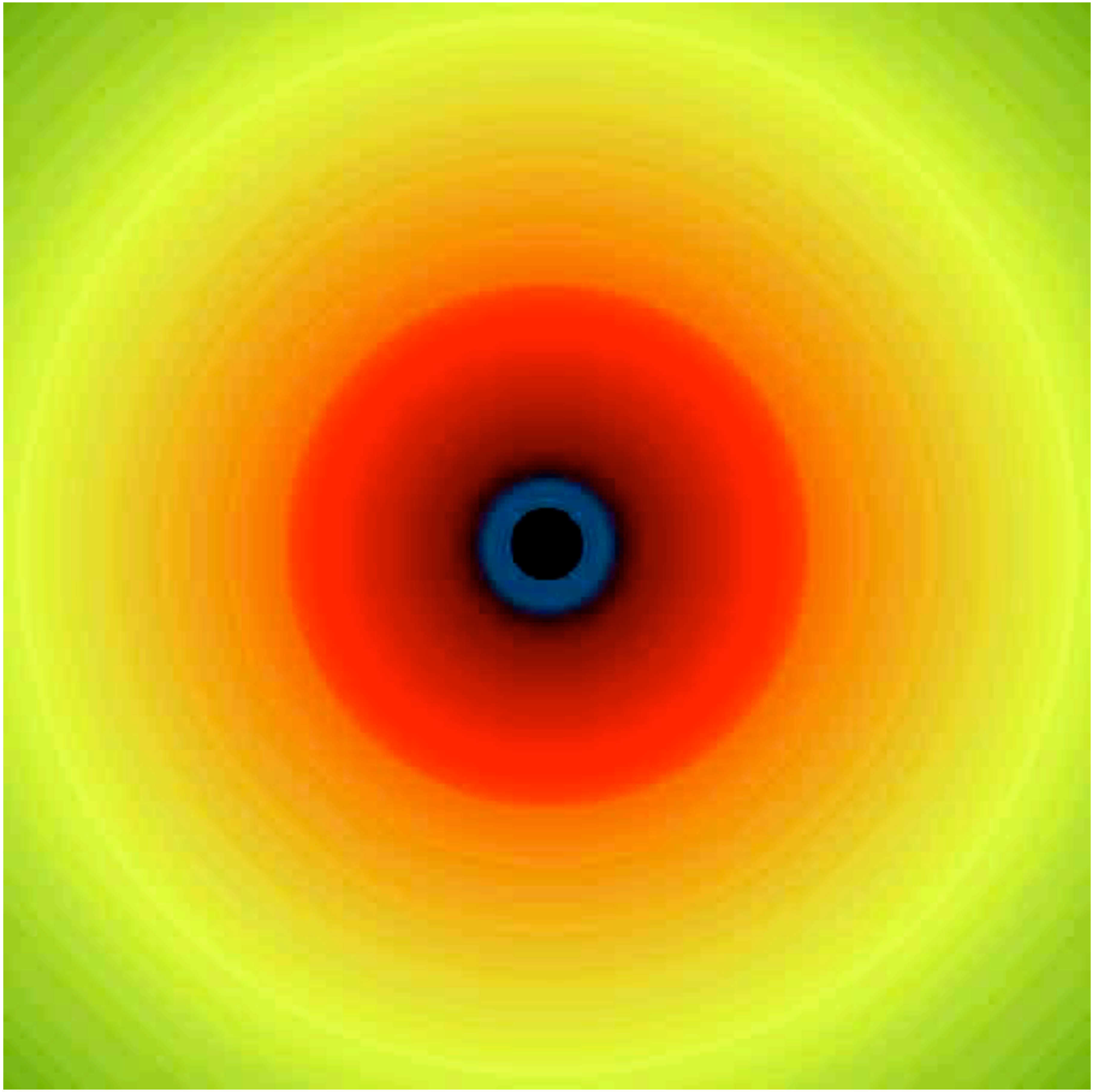
AMR
jet+wind

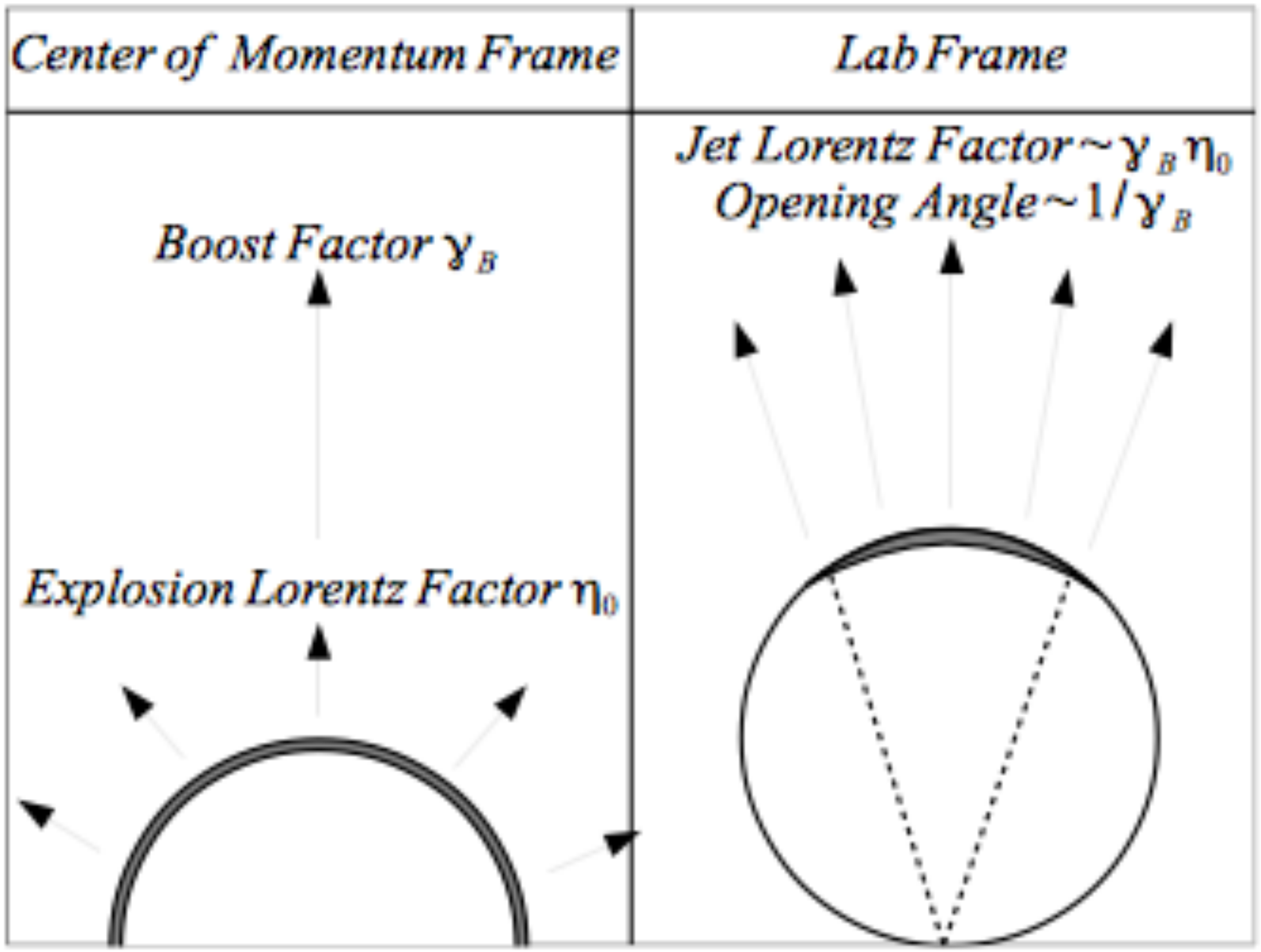
AM&Zhang
(2009)



AMR
jet+wind

AM&Zhang
(2009)

# Boosted Fireball

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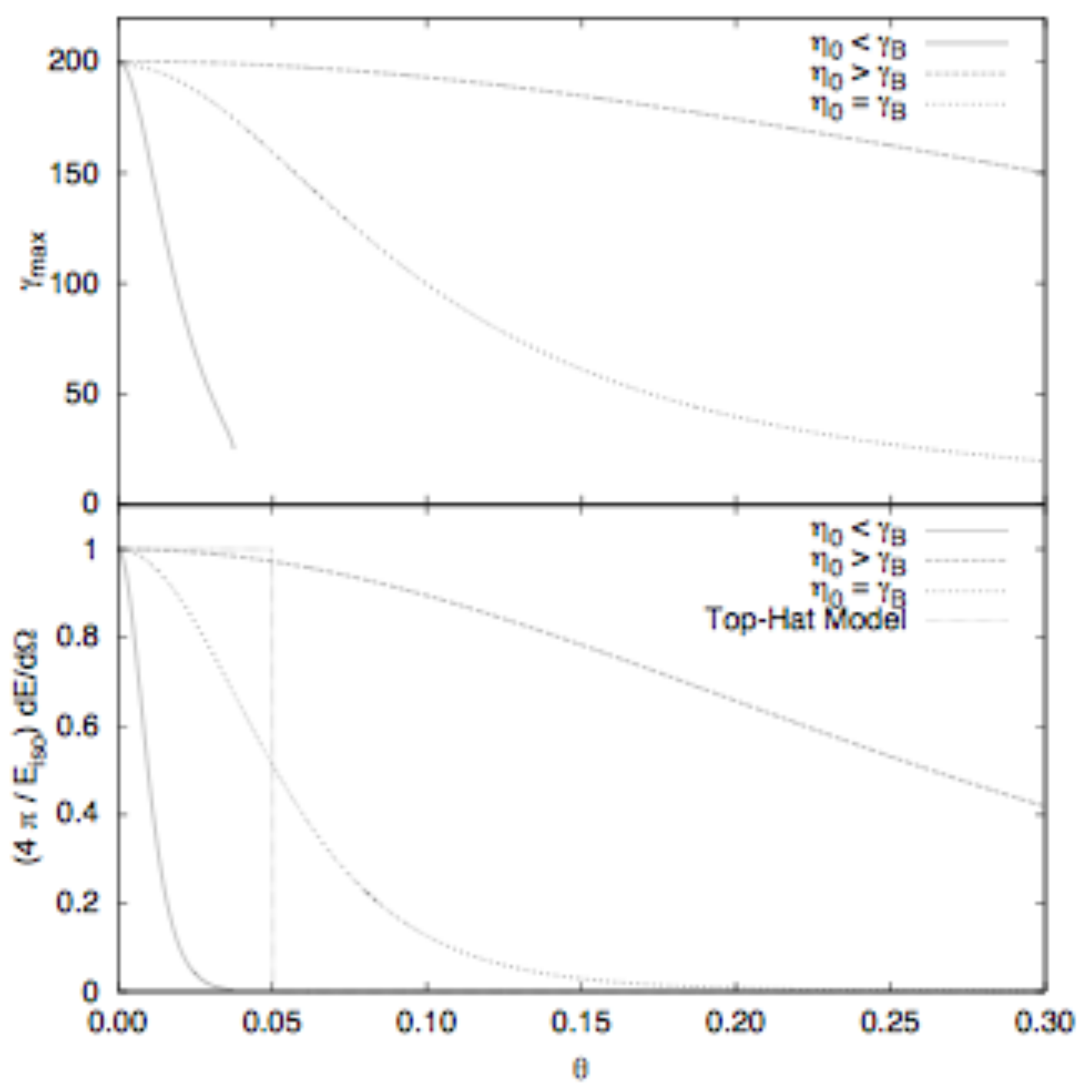
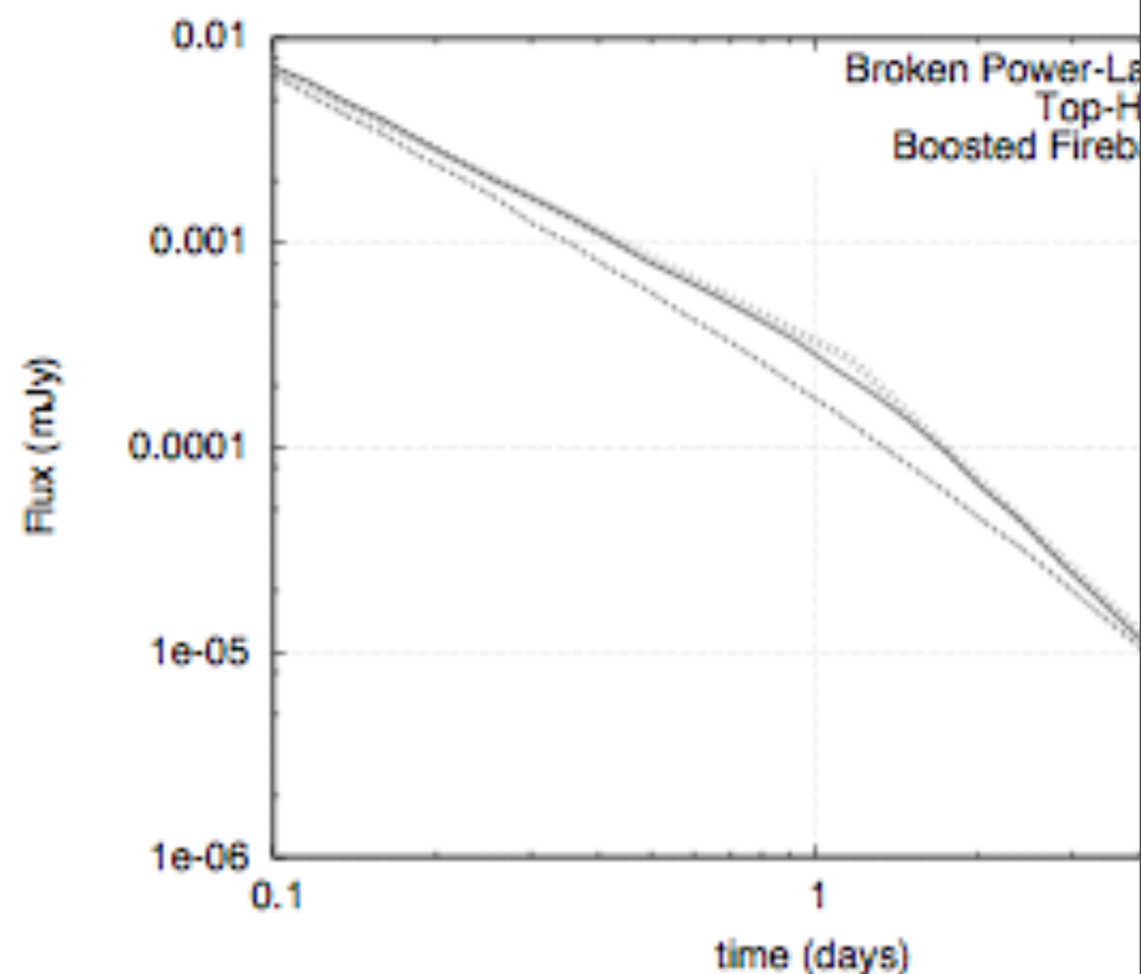
# Boosted Fireball

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# Summary

- 2D Hi-res simulations scale in E and ρ
- AG data fit with sims inc. off-axis observers
- Narrow UR, jets; BF; Exponential Spreading
- "Boosted Fireball" jet structure Duffell & MacFadyen (2013a)
- Fireballs are RT Unstable; Turbulent $\varepsilon_B$ (t)~.01
- RT disrupts CD, pushes back & slows RS Duffell & MacFadyen (2013b)