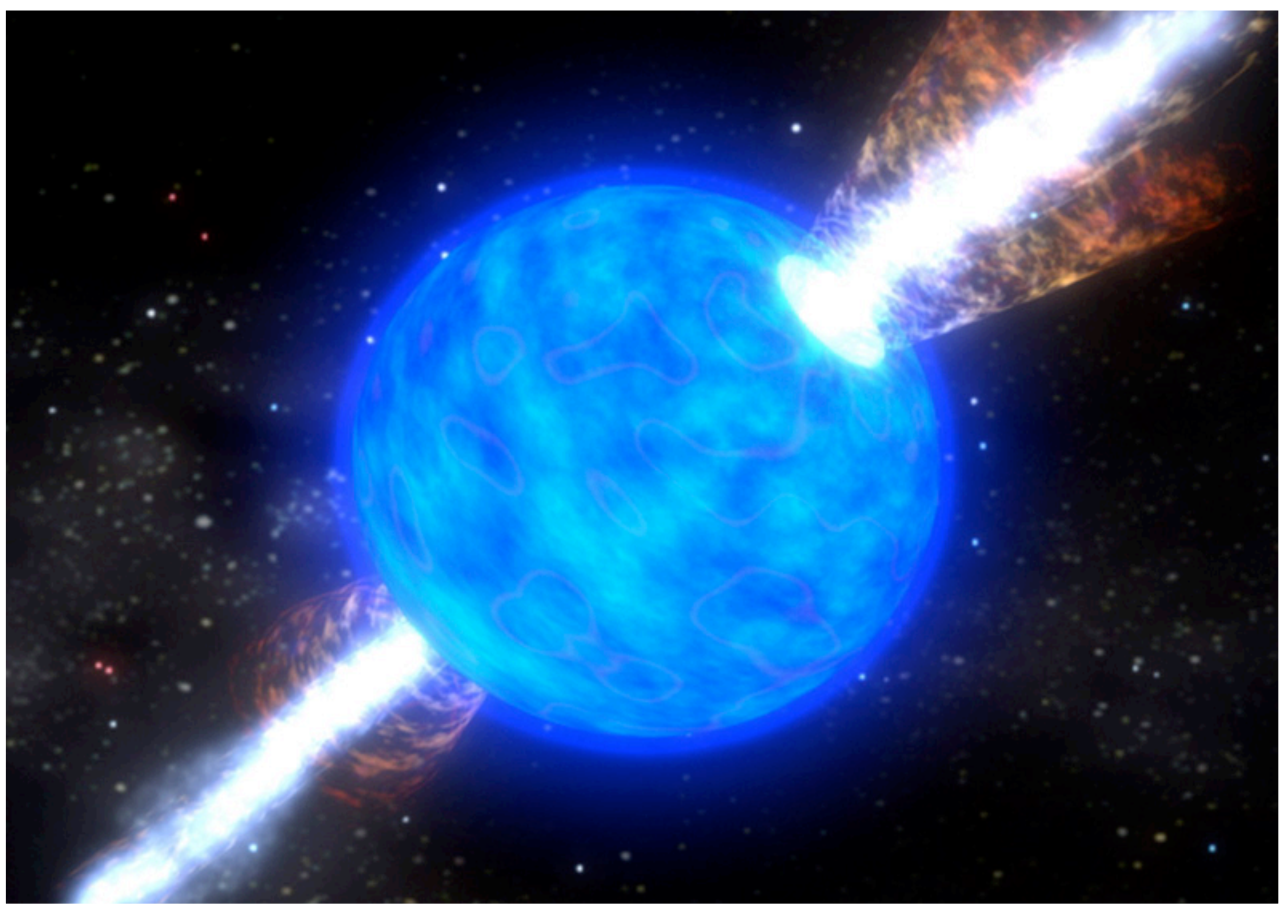
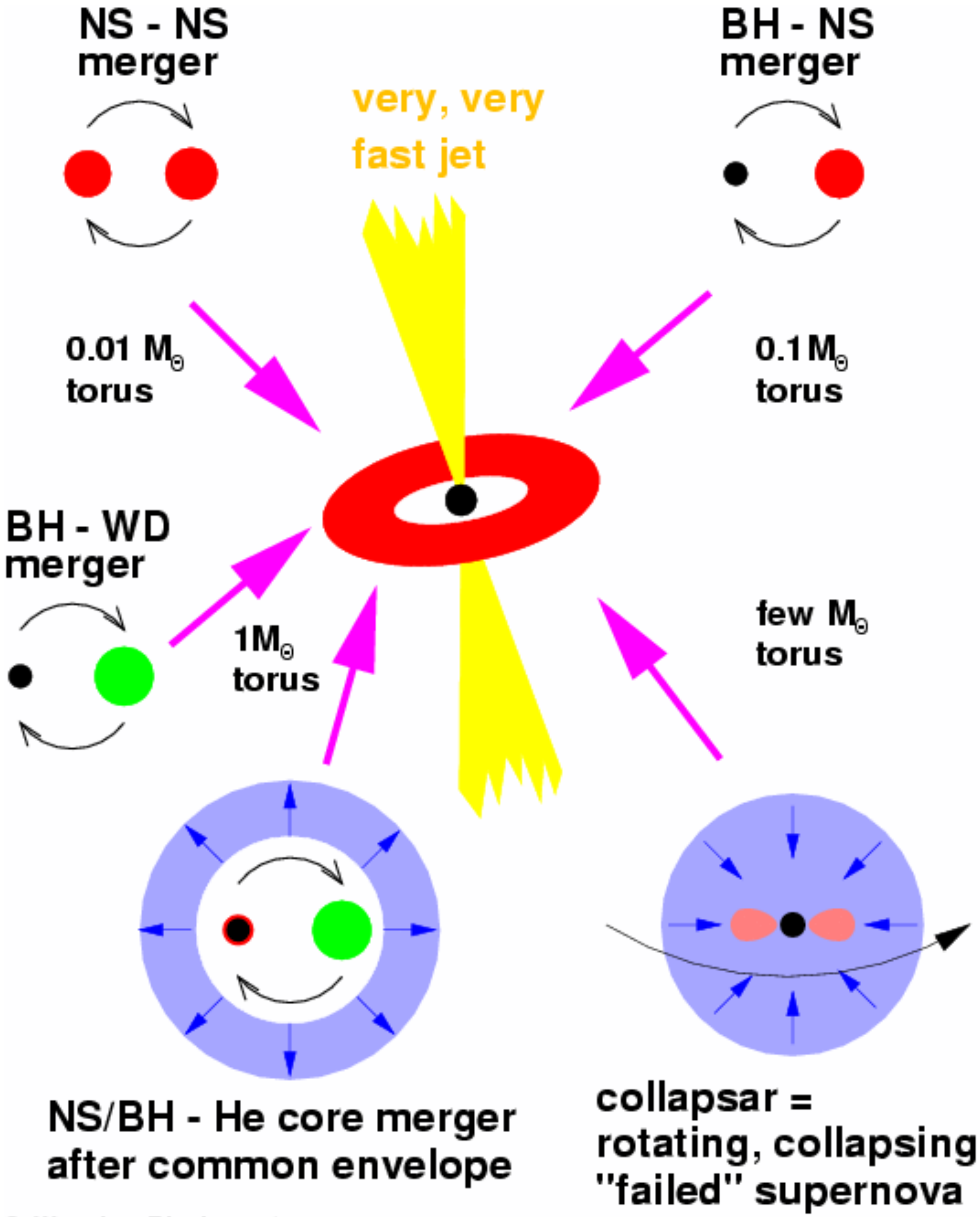
Scaling Properties of Afterglow Radiation



A. MacFadyen
H. van Eerten
P. Duffel
J. Zrake
(NYU)

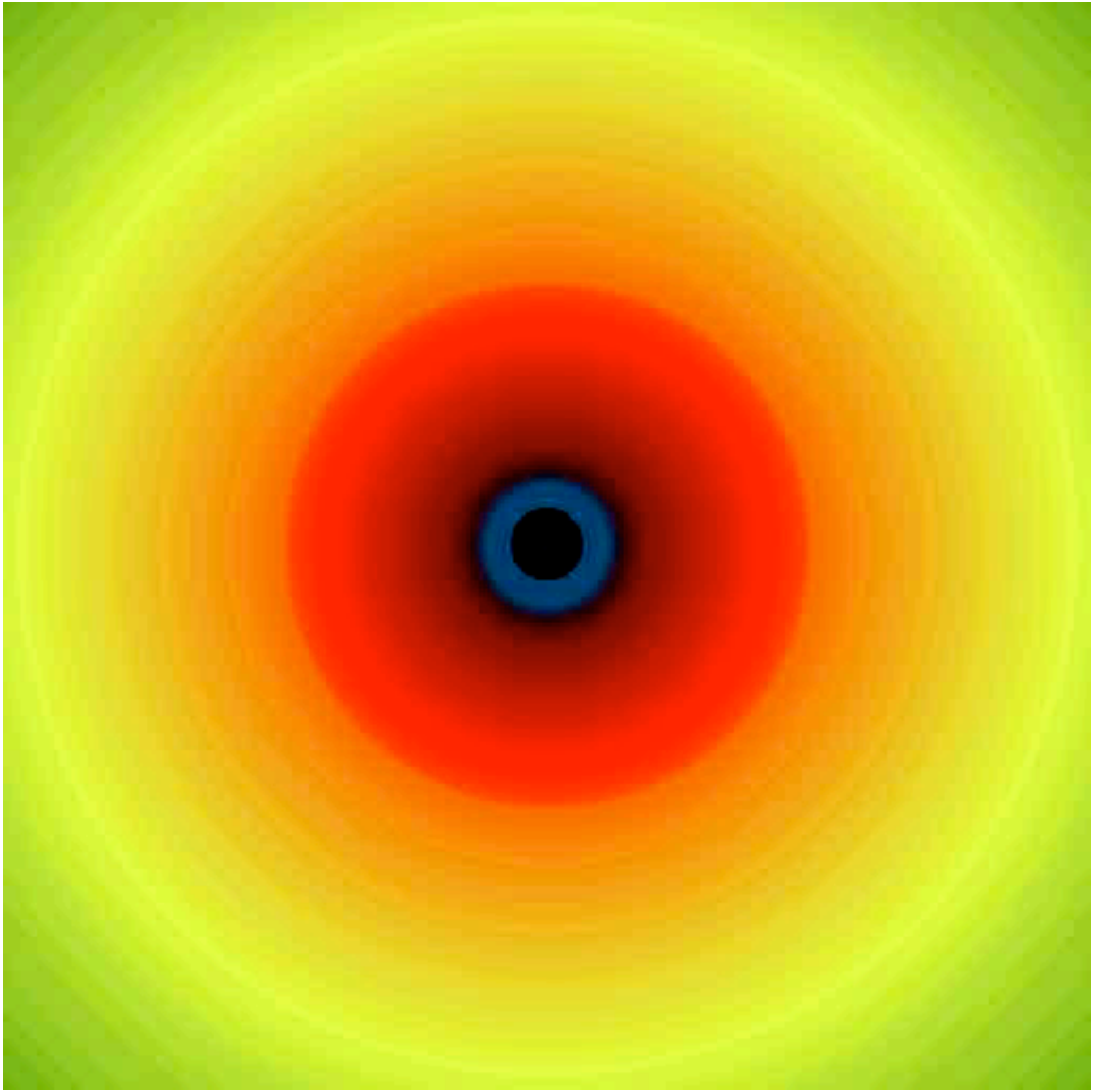
Hyper-accreting black hole or ms magnetar

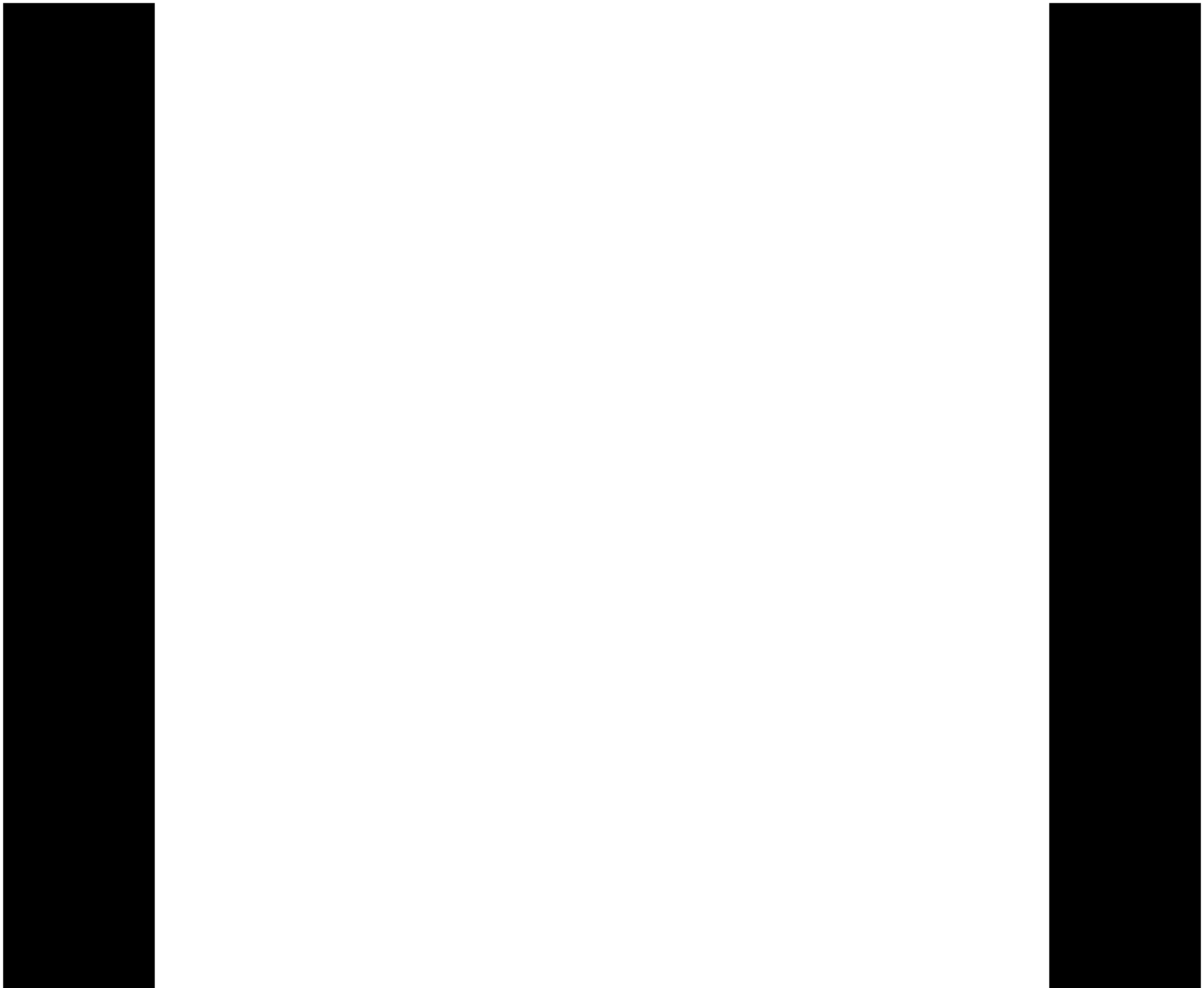


GRB photons are made far away from engine.

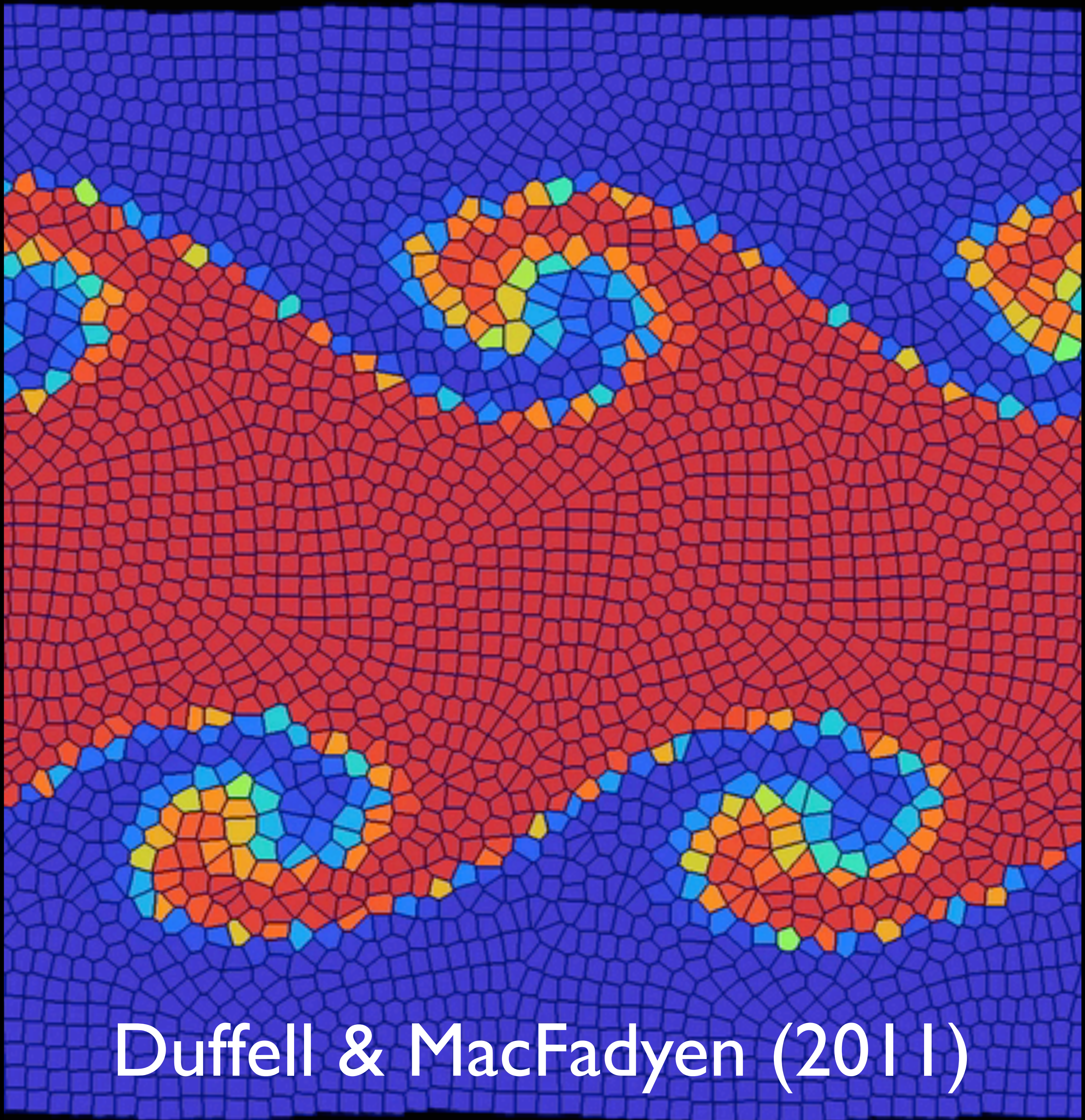
Can't observe engine directly with light. (neutrinos, gravitational waves?)

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



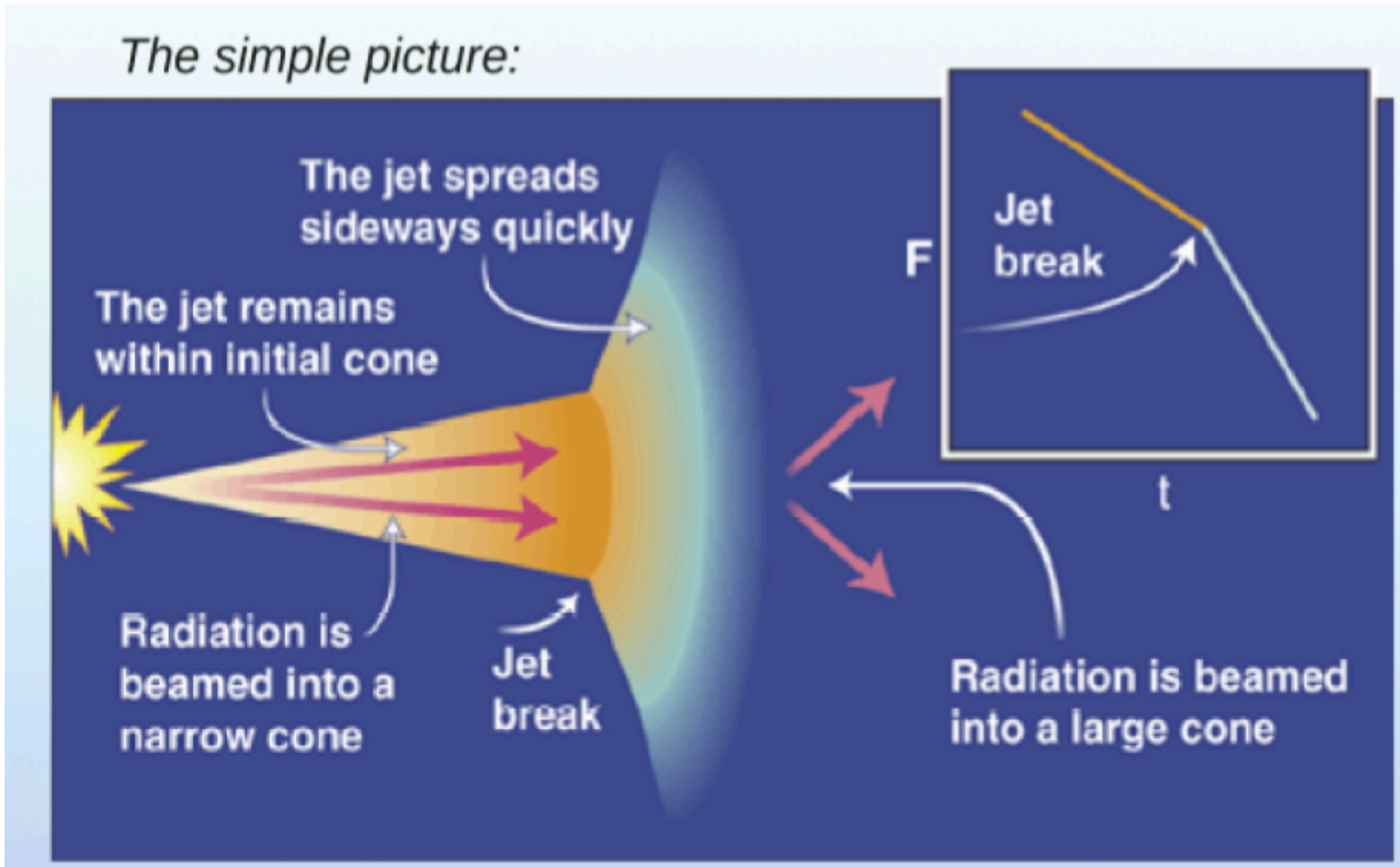


Tess



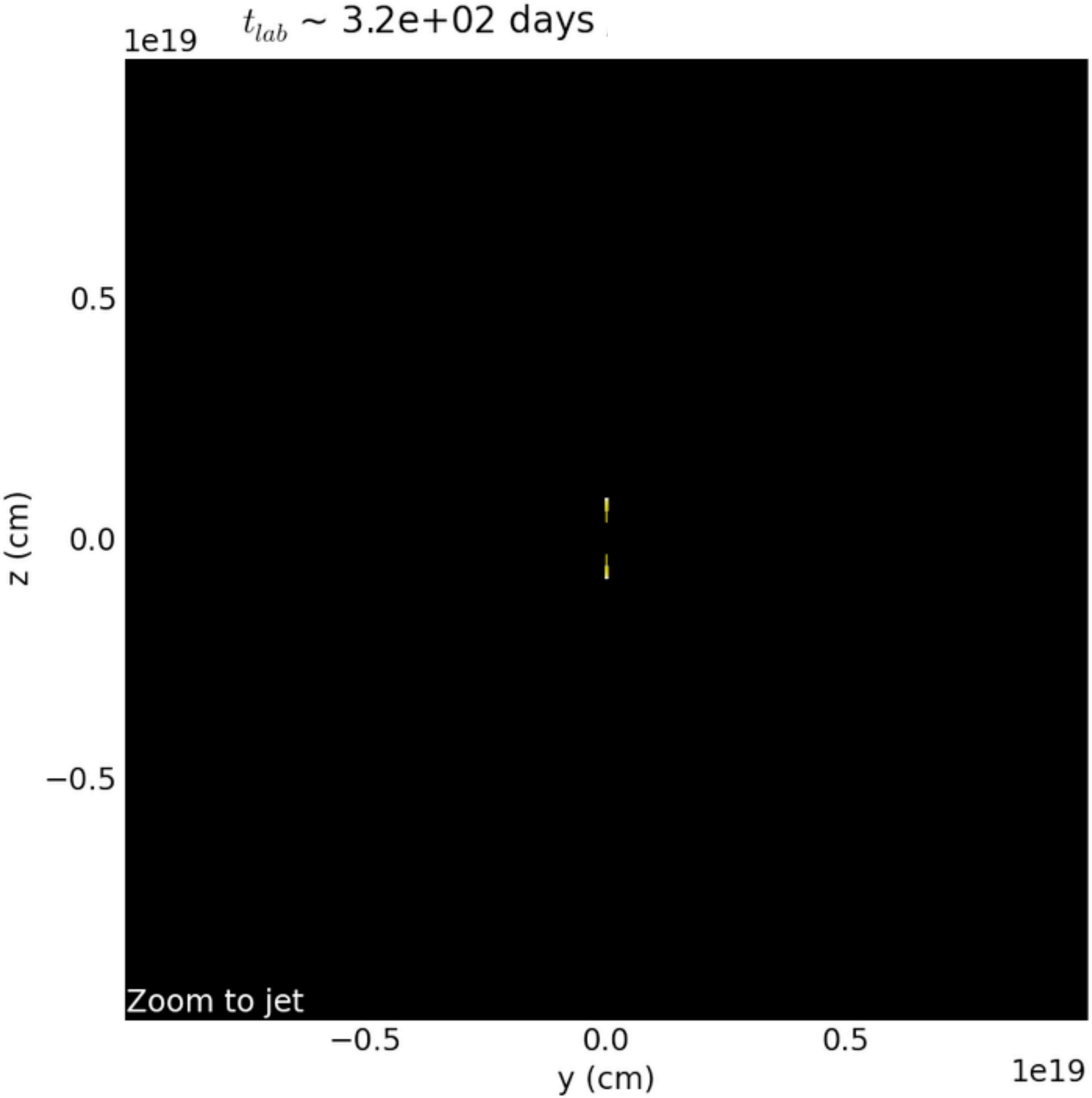
Duffell & MacFadyen (2011)

Afterglow Jet Dynamics



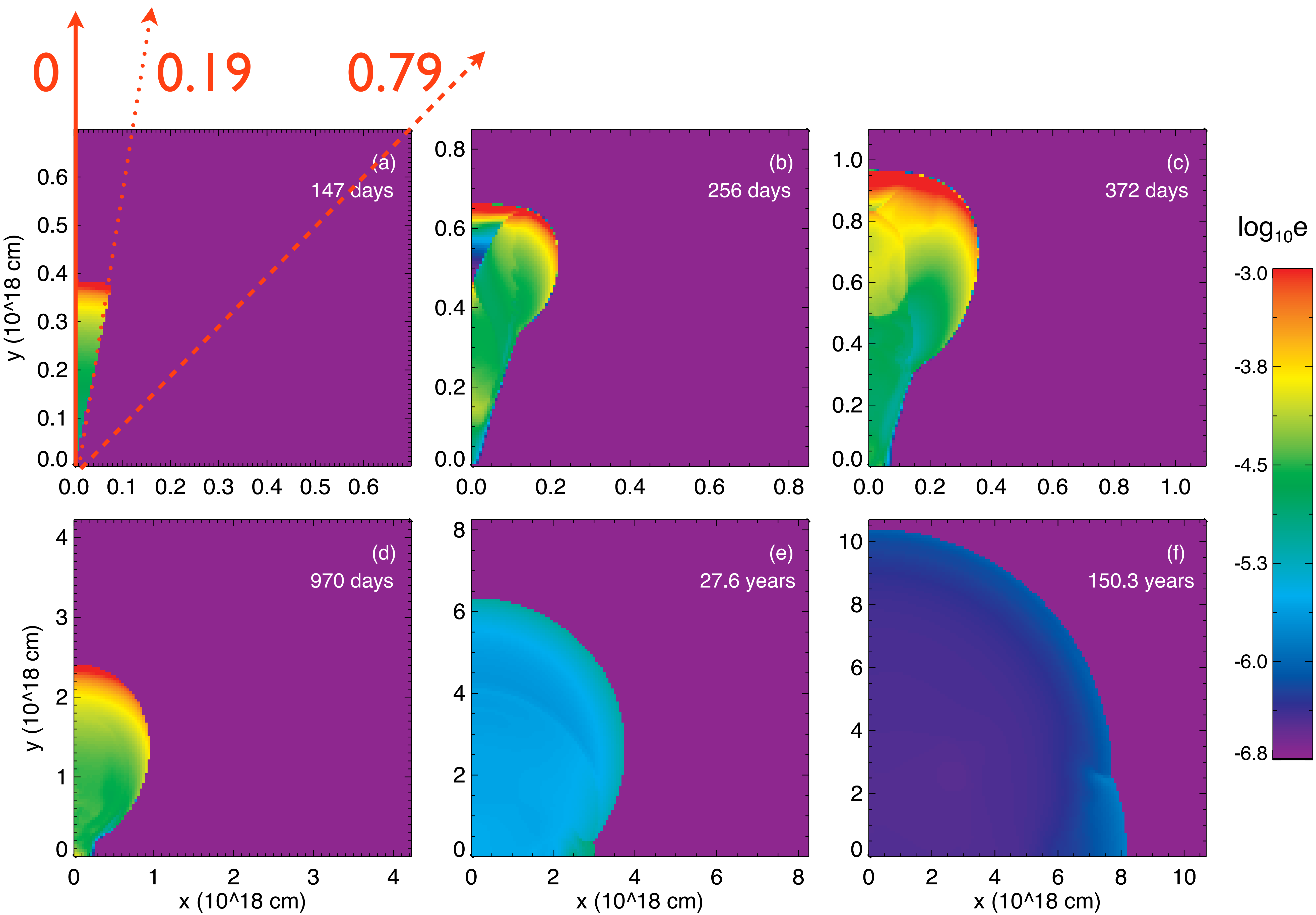
Model parameters:

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



Ej = 2e52
θj=0.05
n=1cm^-3

van Eerten & AM (2011)

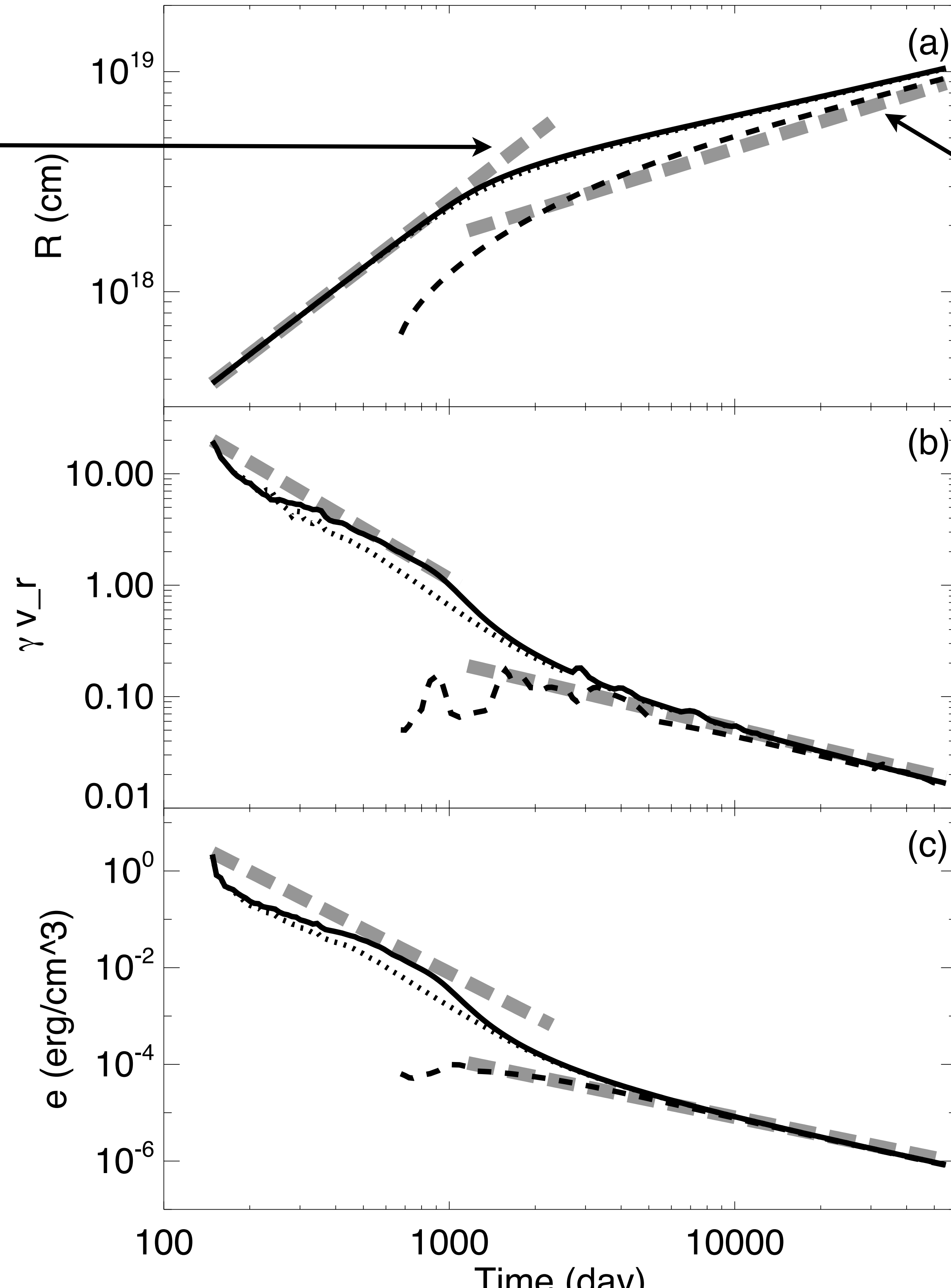


0
0.19
0.79
(a)
147 days
(b)
256 days
(c)
372 days
(d)
970 days
(e)
27.6 years
(f)
150.3 years
y (10^18 cm)
x (10^18 cm)
log10e
-3.0
-3.8
-4.5
-5.3
-6.0
-6.8

Blandford-McKee

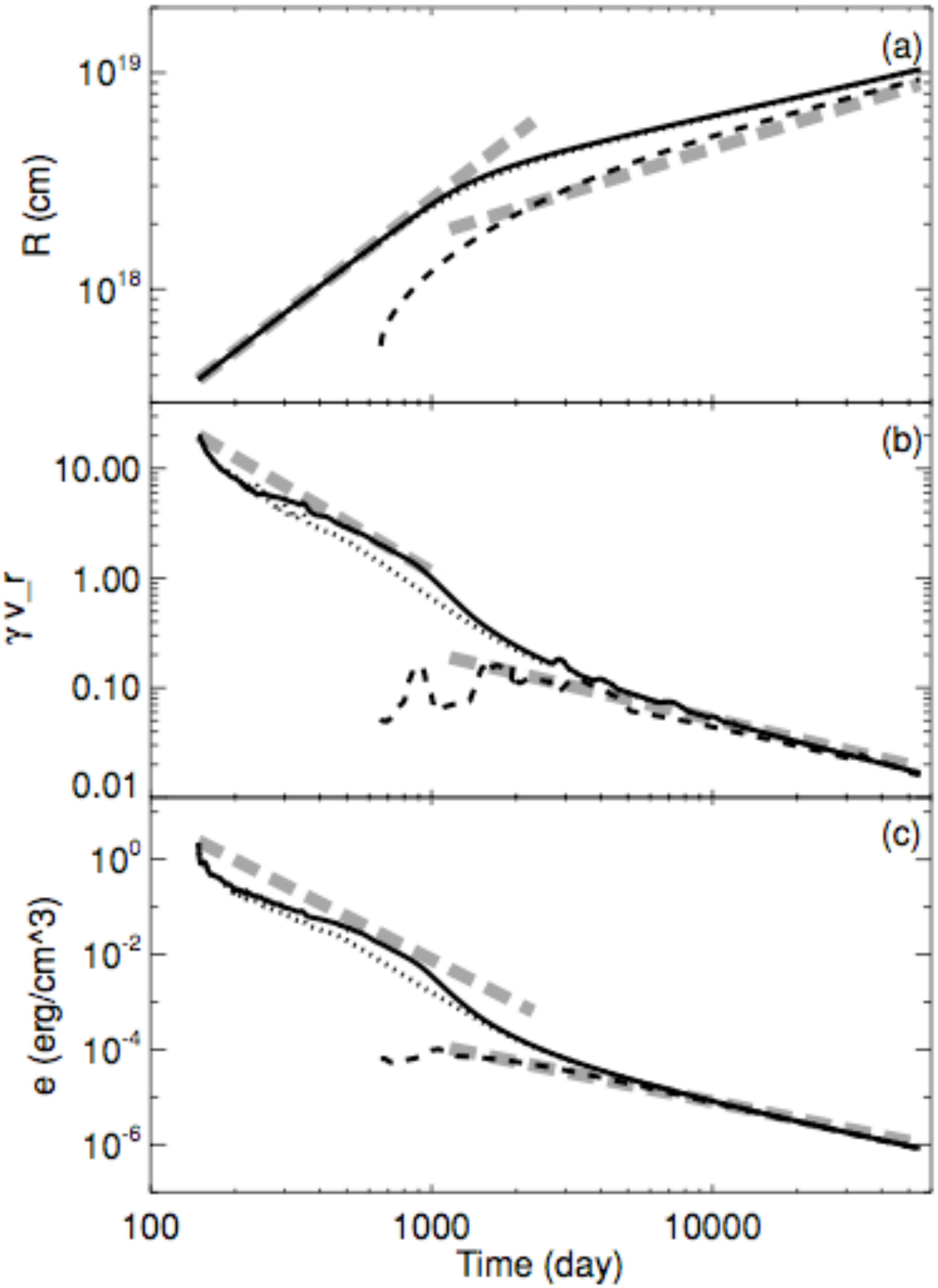
Sedov

$\theta j = 0.2$

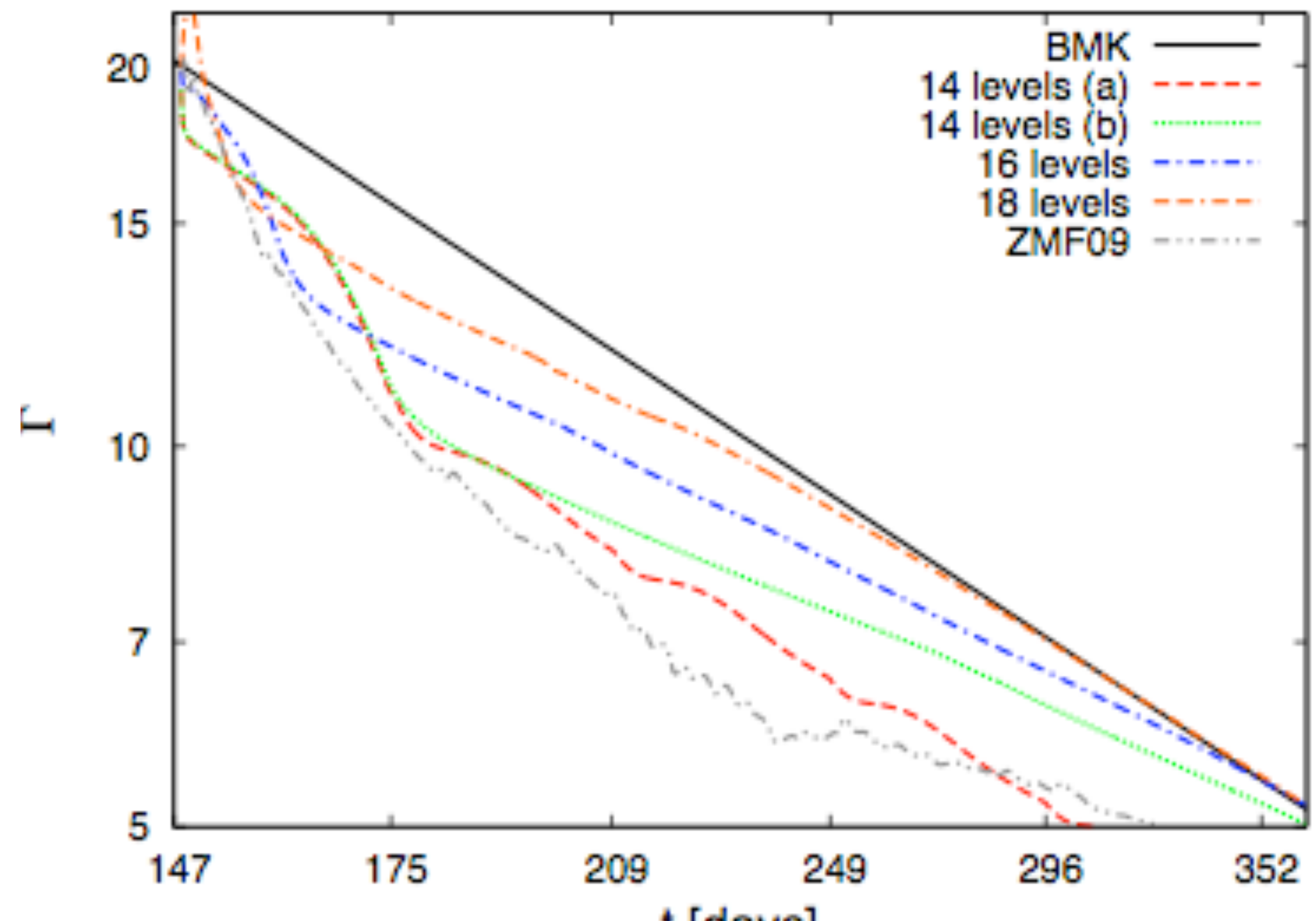


$\theta = 0, 0.19, \pi/4$

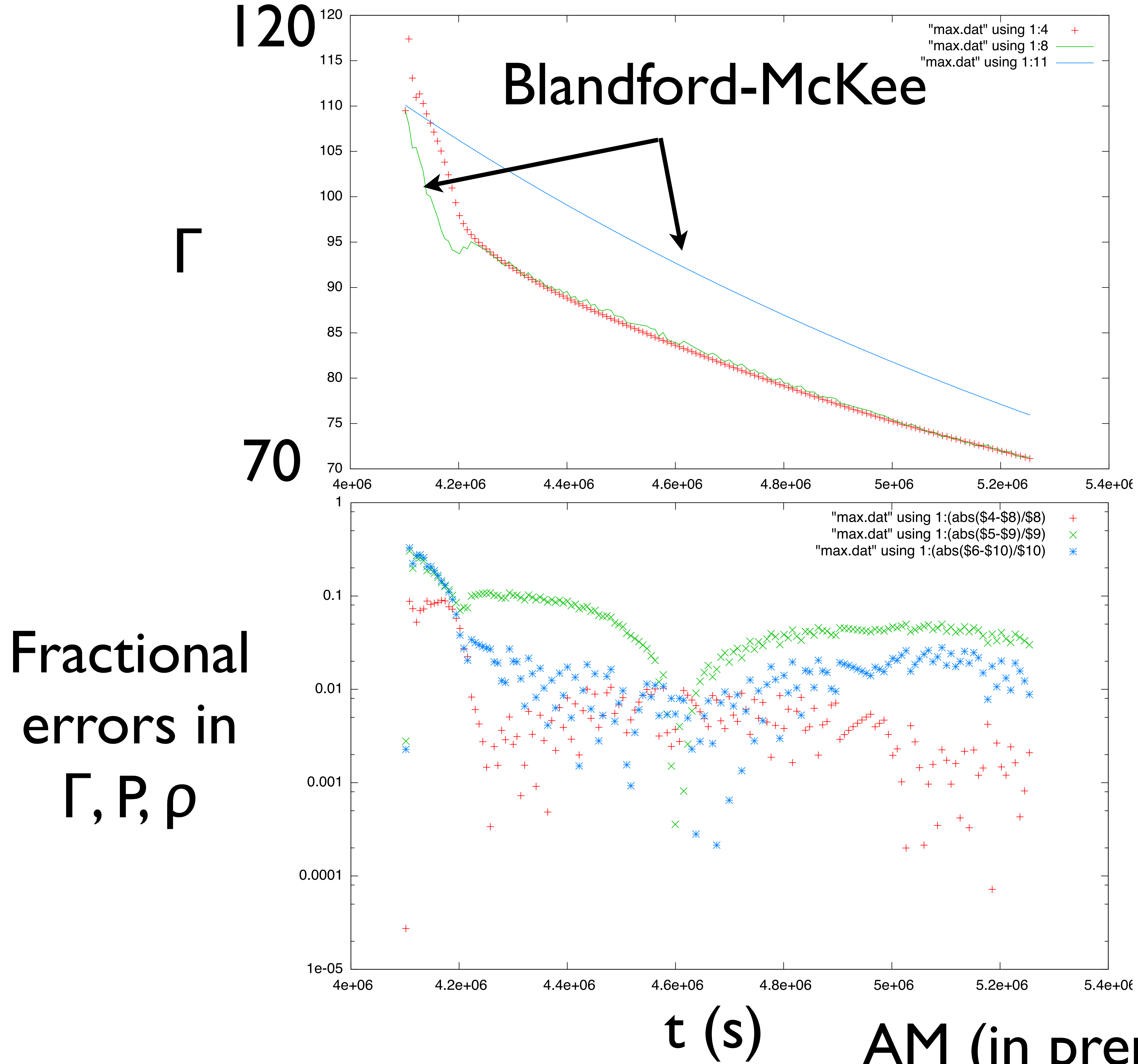
Granot+(2001)
Zhang&AM(2009)
vanEerten+(2010)
Wygoda+(2011)
deColle+(2012)
Vlasis+ (2012)



Zhang & AM (2009)



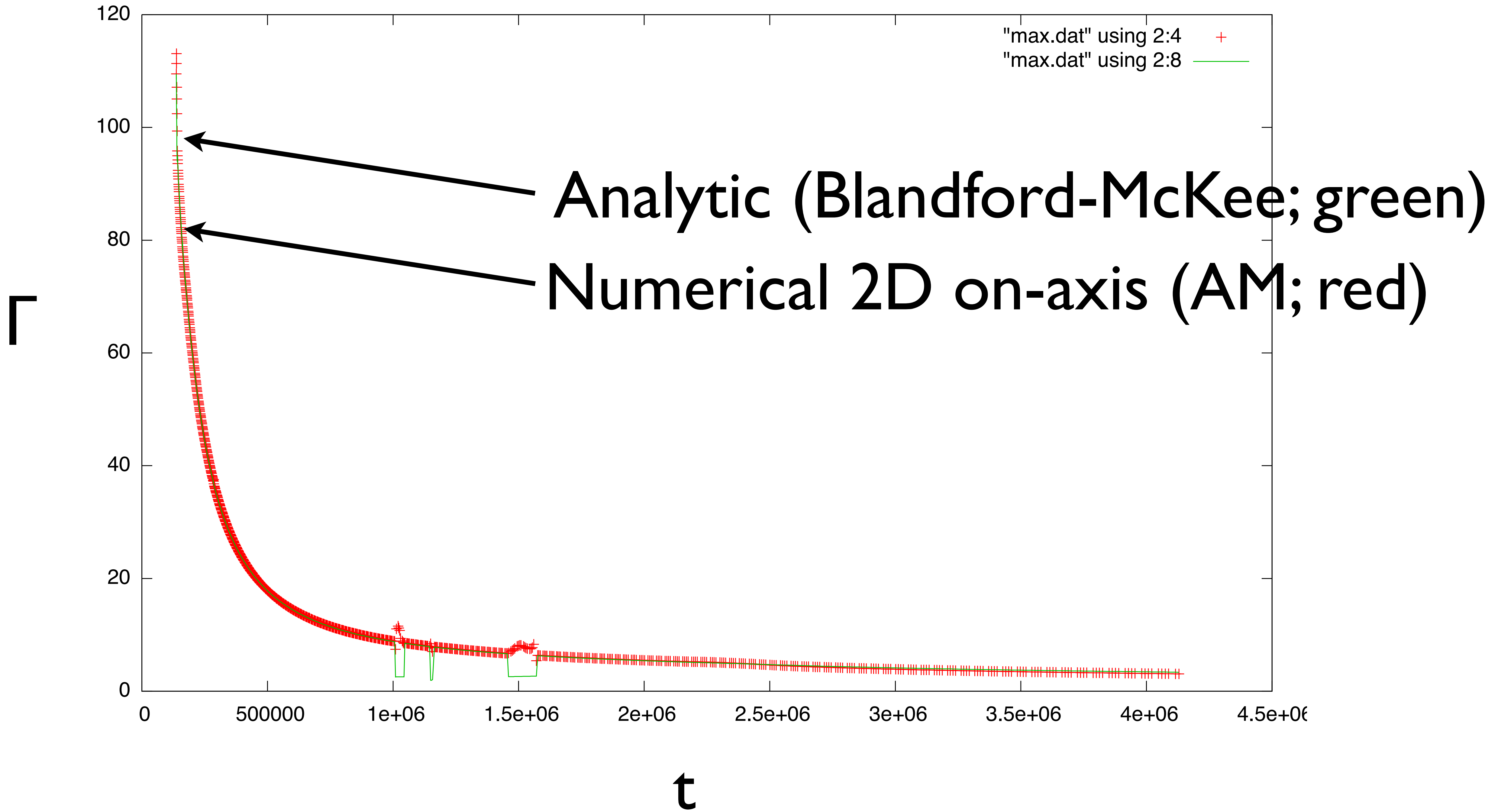
DeColle+ (2012)



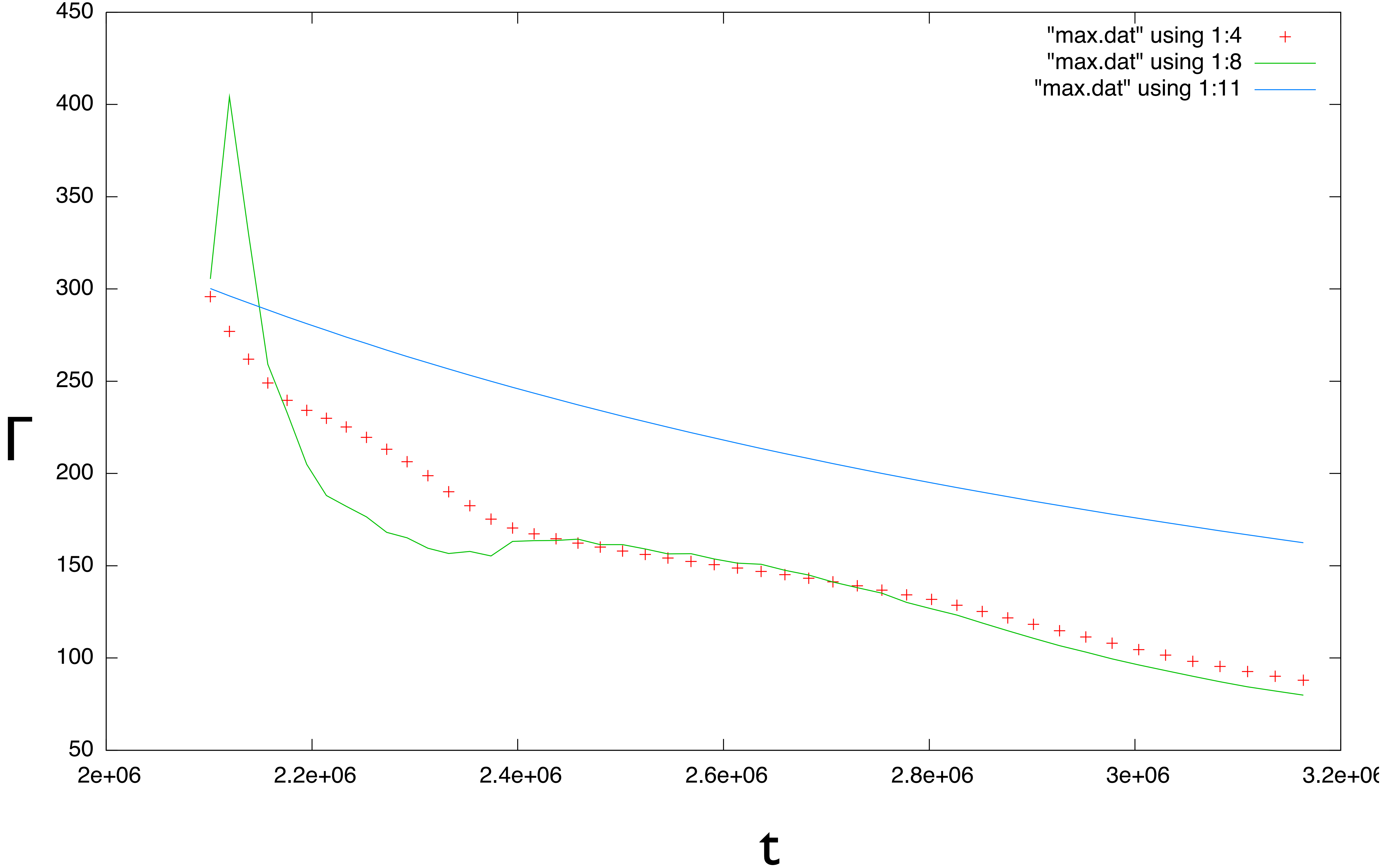
θjet=0.05
Eiso=1e53
n=1

AM (in prep, 2012)

2D Moving Mesh: Γ = 110



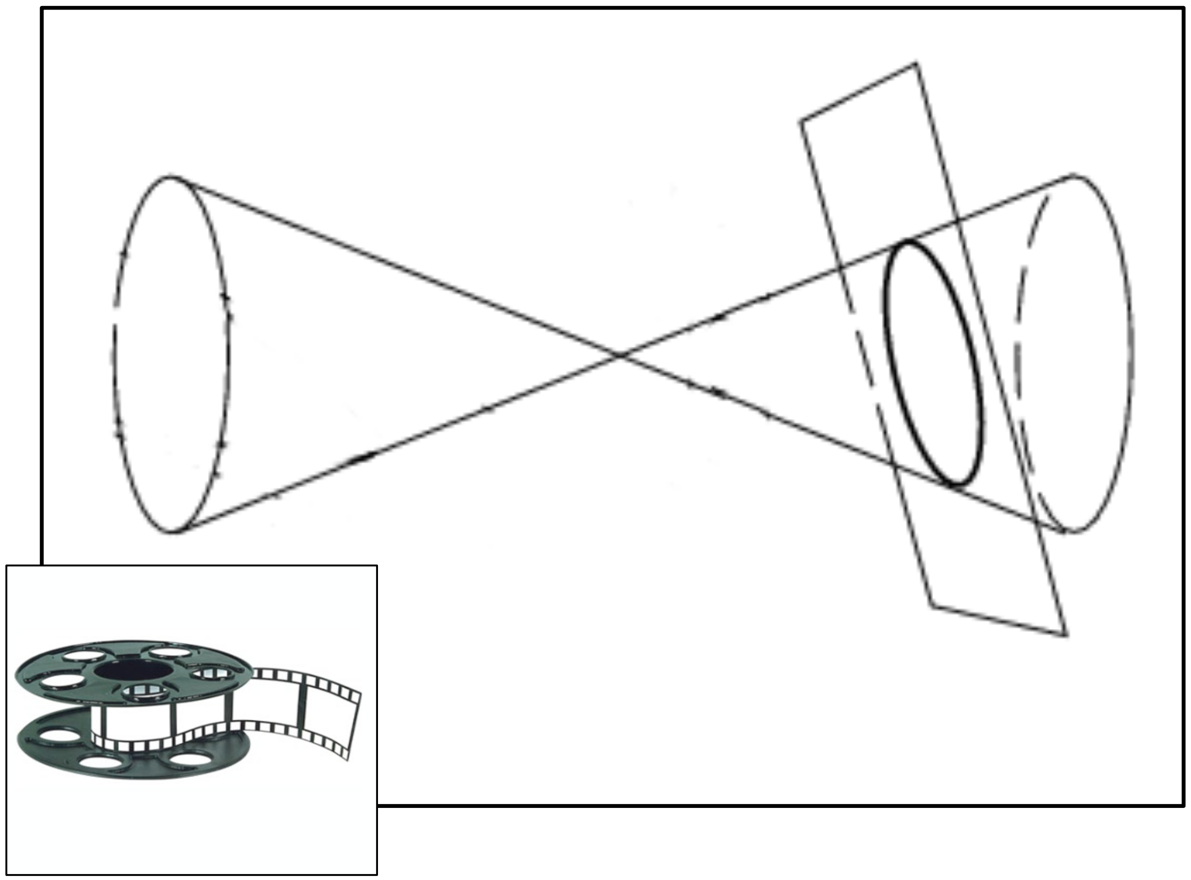
Γ = 300



"max.dat" using 1:4
"max.dat" using 1:8
"max.dat" using 1:11
450
400
350
300
250
200
150
100
50
Γ
2e+06
2.2e+06
2.4e+06
2.6e+06
2.8e+06
3e+06
3.2e+06
t

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

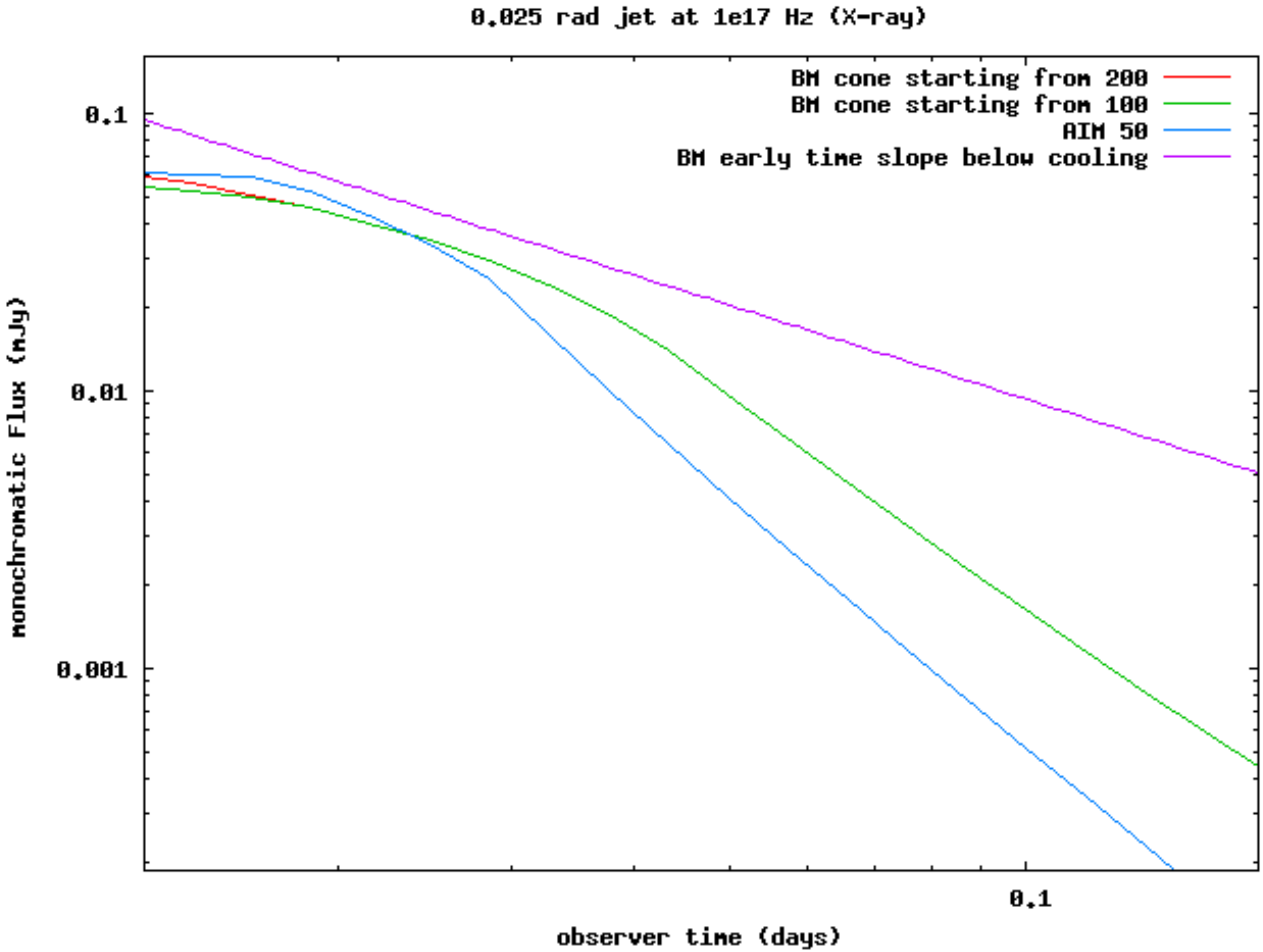
- Emission & absorption, no scattering (i.e. synchrotron radiation):

linear radiative transfer for all rays perpendicular to intersecting plane

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

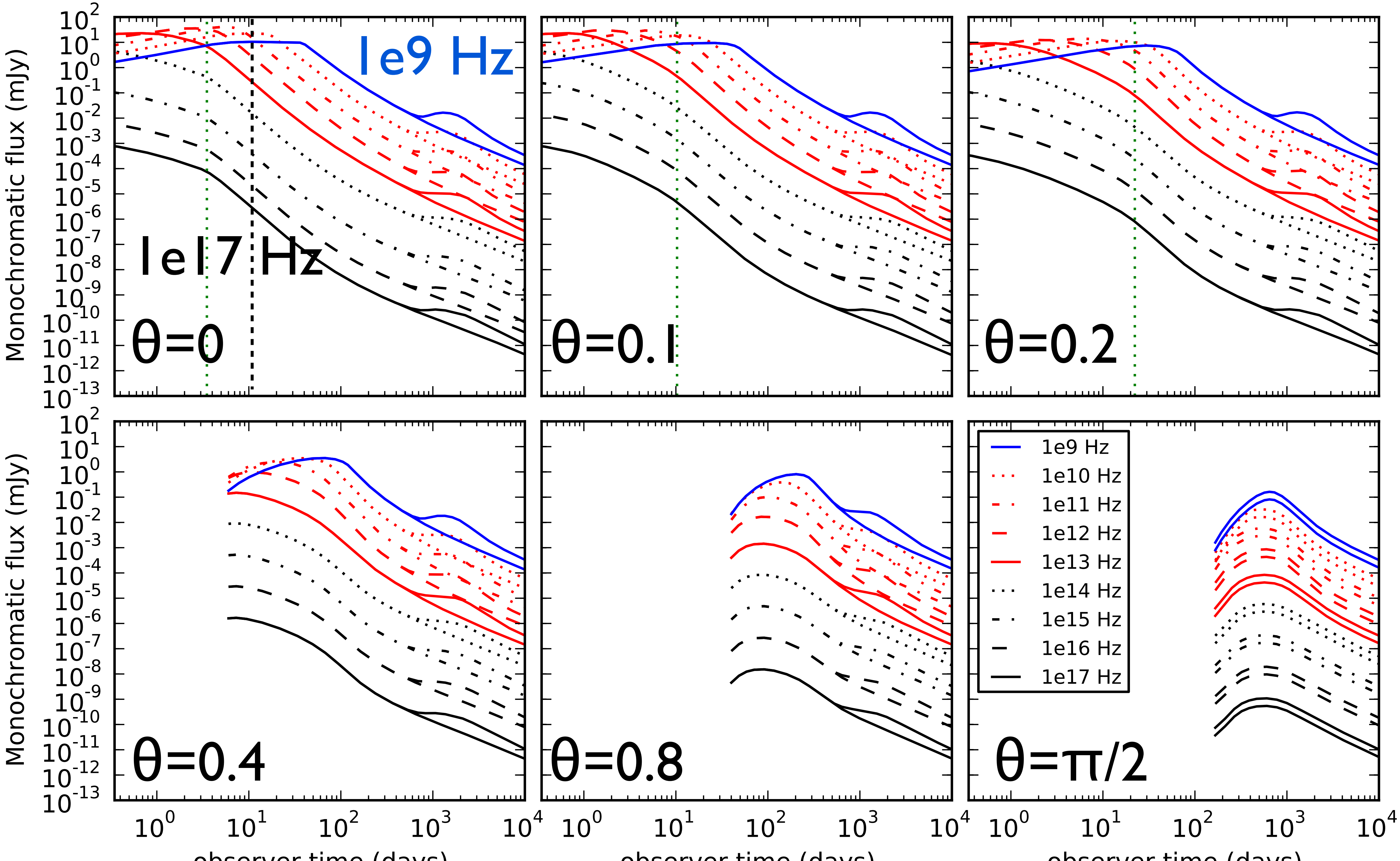
$$t_{obs} = t_{travel} + t_e - R/c$$
$$\mathrm{d}t_e \sim \Gamma^2 \mathrm{d}t_{obs}, \qquad \Gamma \sim 100$$

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

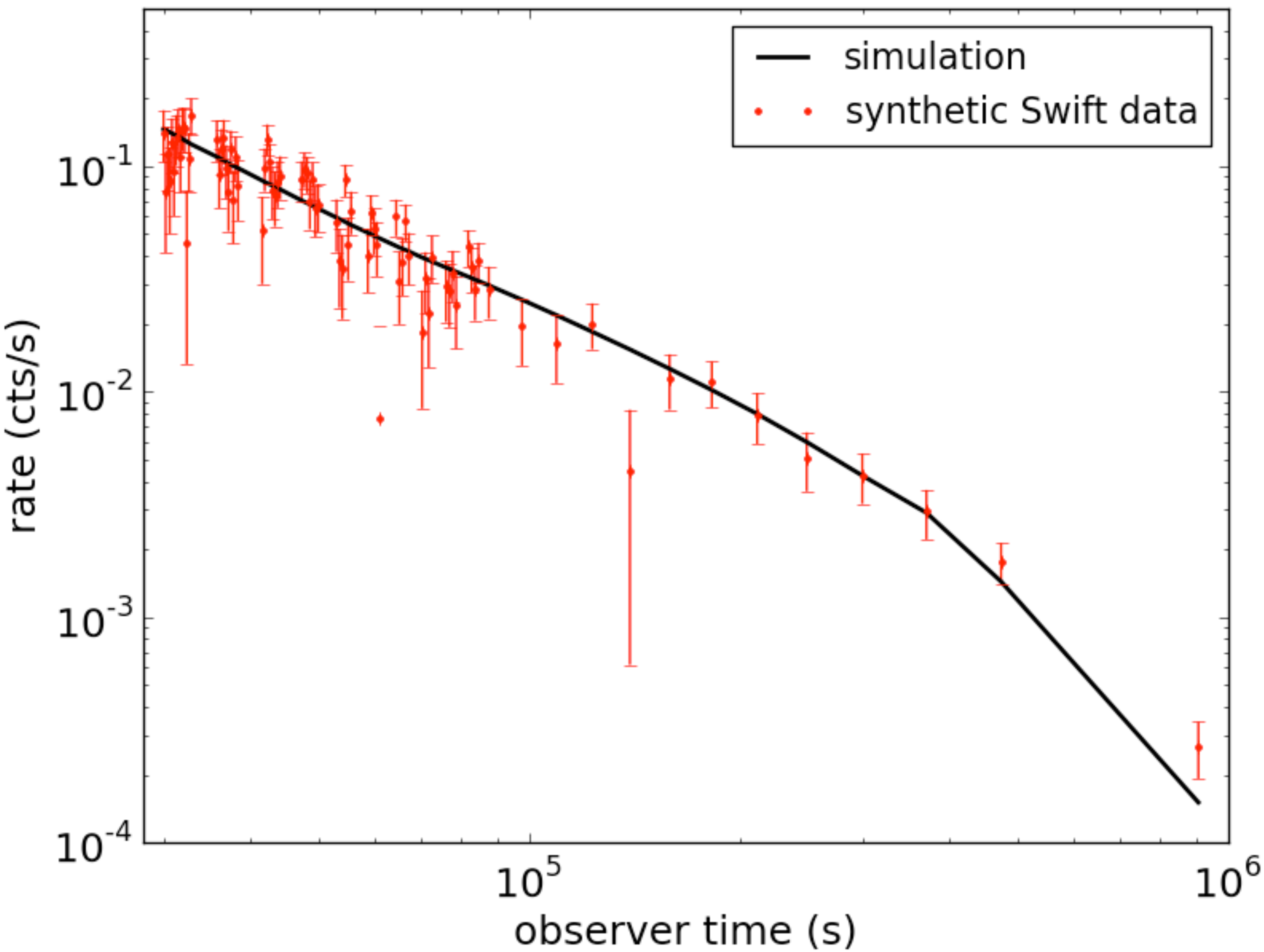

0.025 rad jet at 1e17 Hz (X-ray)
BM cone starting from 200
BM cone starting from 100
AIM 50
BM early time slope below cooling
monochromatic Flux (mJy)
0.1
0.01
0.001
0.1
observer time (days)

Off-Axis Light Curves

van Eerten, Zhang & AM (ApJ, 2010)

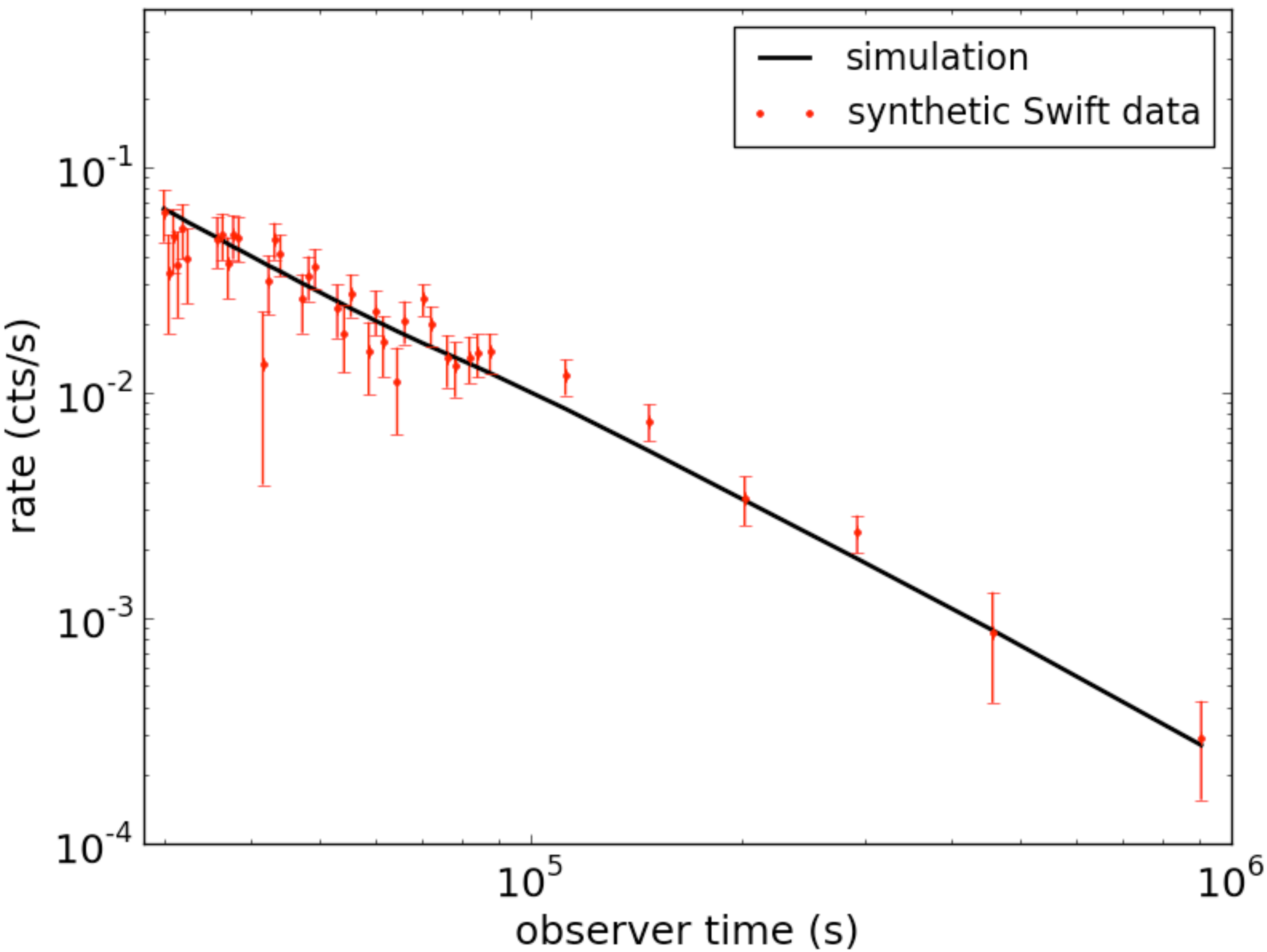


On Axis



A. MacFadyen (NYU)

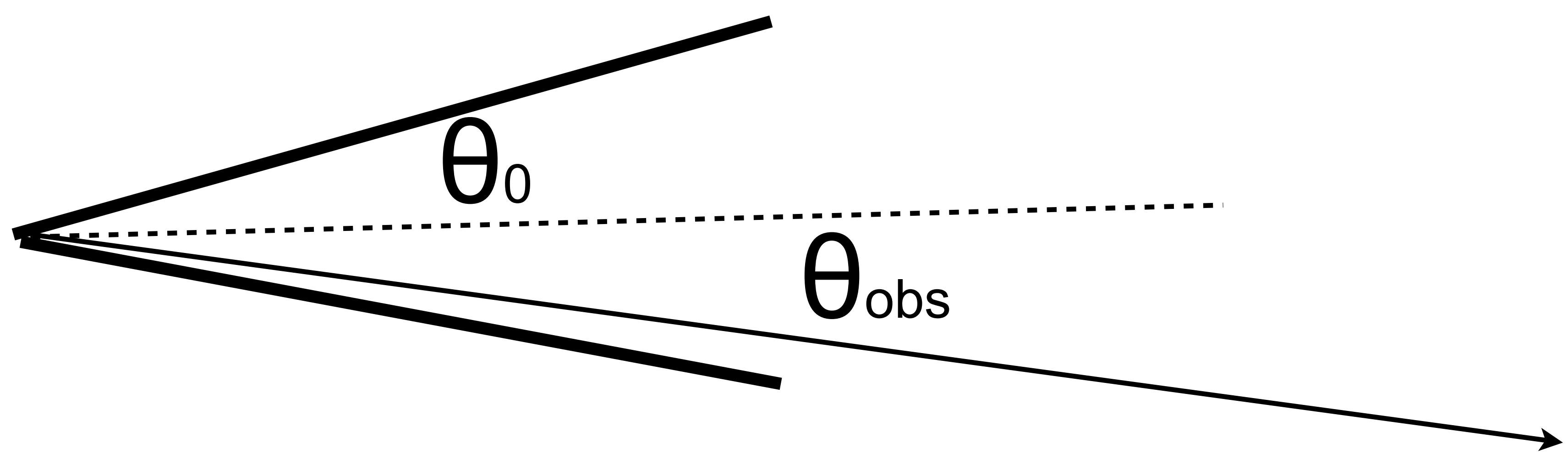
On Edge



A. MacFadyen (NYU)

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

A. MacFadyen (NYU)

Analytical models vs. numerical jet simulations

Analytical jet models are limited when it comes to e.g.:

- Trans-relativistic deceleration of jets and emergence of the counterjet
- Fluid profile of spreading jets
- Off-axis observations (including orphan afterglows & slightly off-axis)
- Shape of the jet break in the light curve

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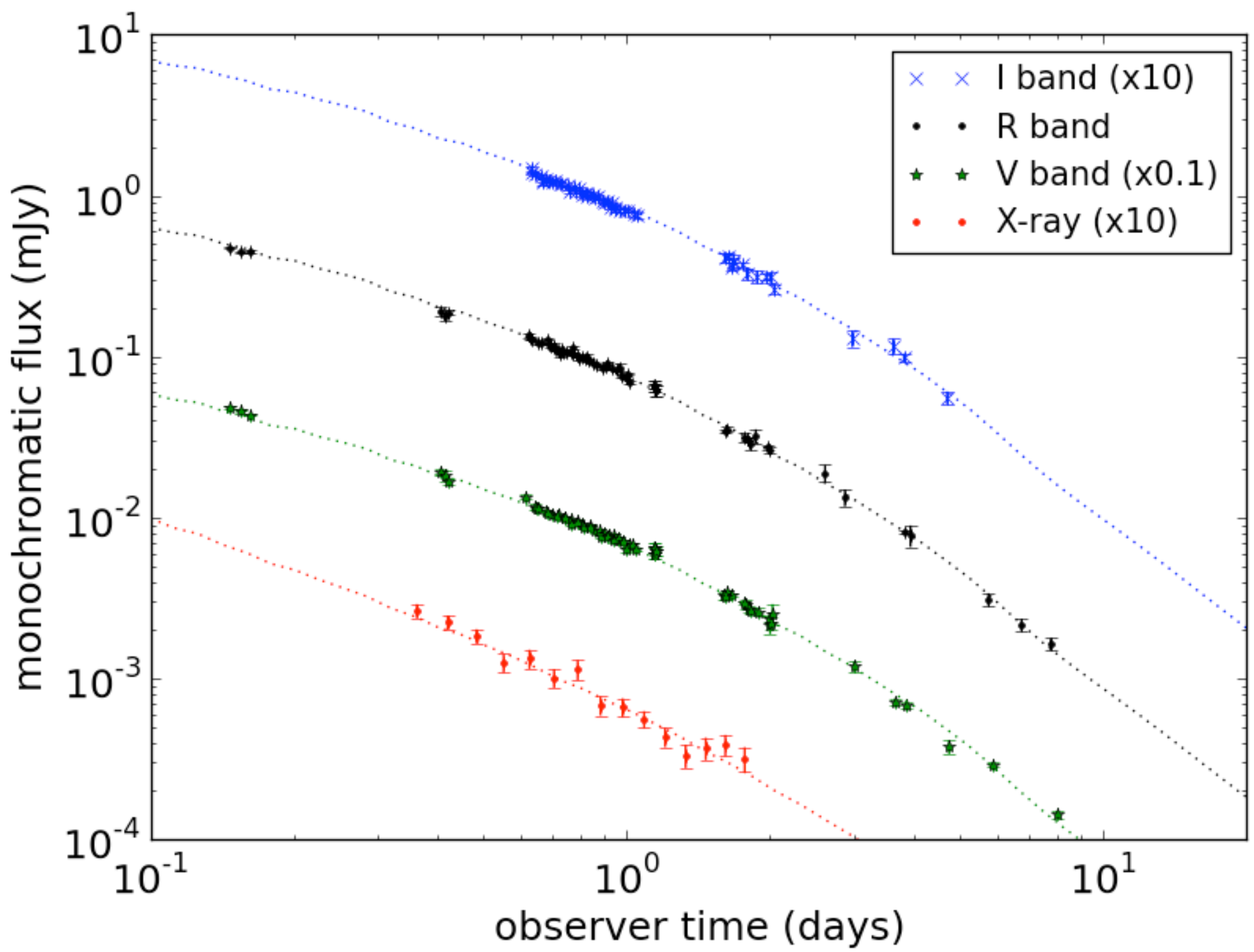
All these issues can be addressed by numerical simulations

- High-resolution relativistic hydrodynamics, adaptive mesh-refinement with RAM
- radiative transfer for synchrotron radiation
- ***This talk:*** even complex 2D simulation results are scalable
- ***This talk:*** simulation-based broadband data fitting now possible
- ***This talk:*** a tool for improved survey predictions

Examples of afterglow light curves

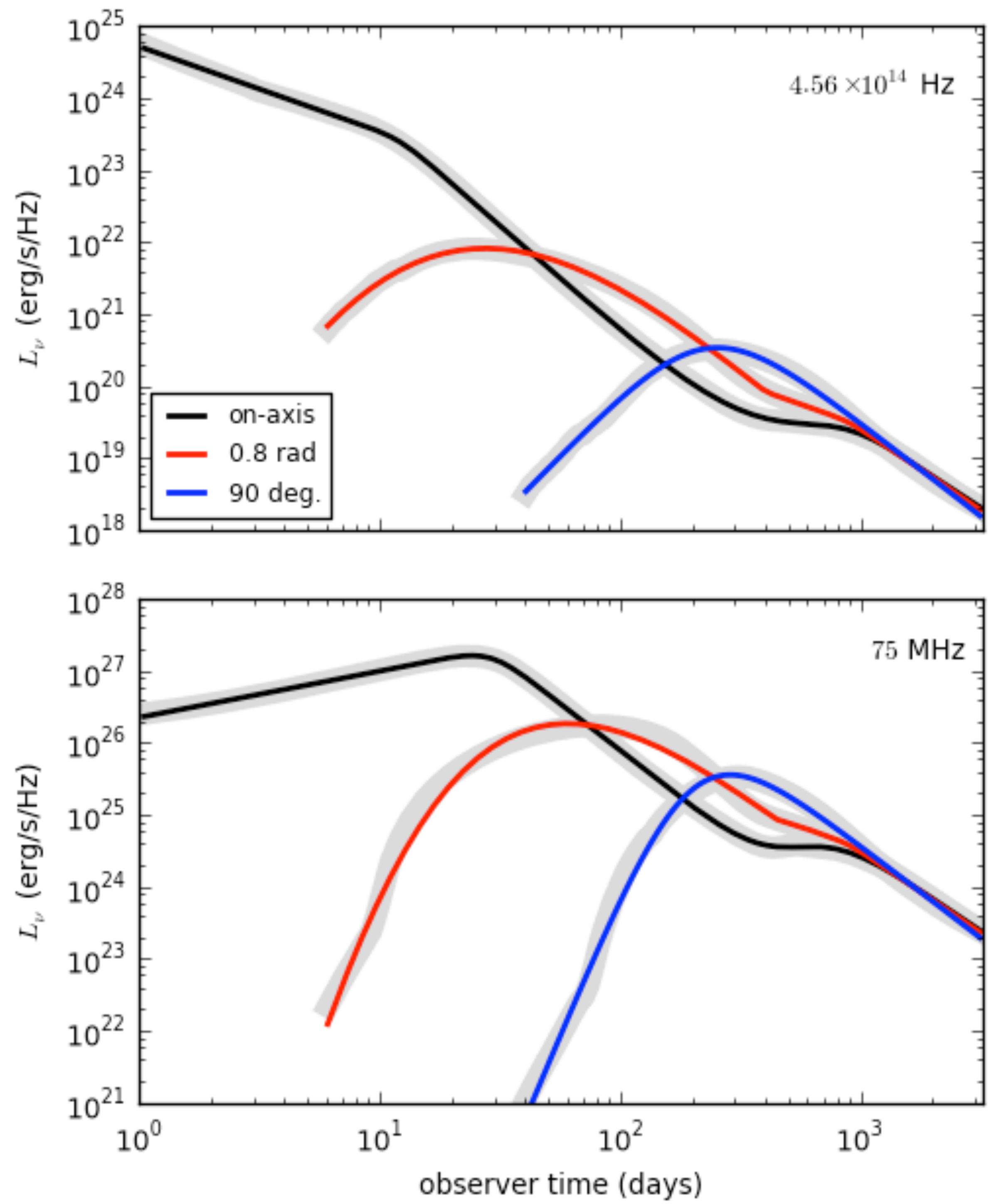


GRB 990510 plus best fit

These are calculated by applying radiative transfer to the jet simulation results

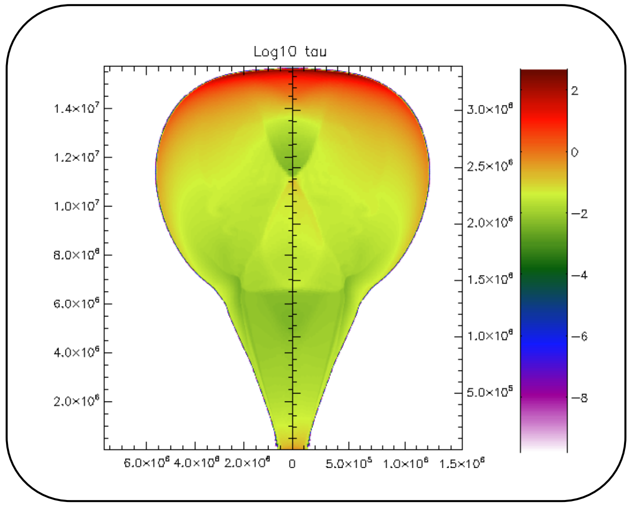
$$\frac{dI_\nu}{dz} = -\alpha_\nu I_\nu + j_\nu$$

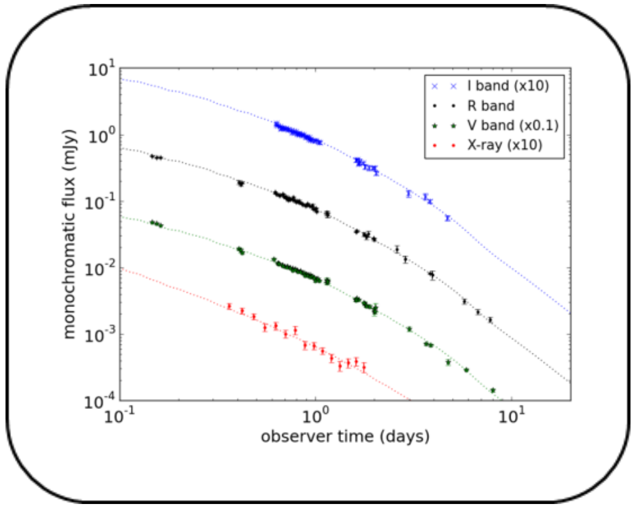
$$t_{obs} = t_{travel} + t_e - R/c$$



Generic light curves optical & low radio
jet has opening angle of 0.4 rad

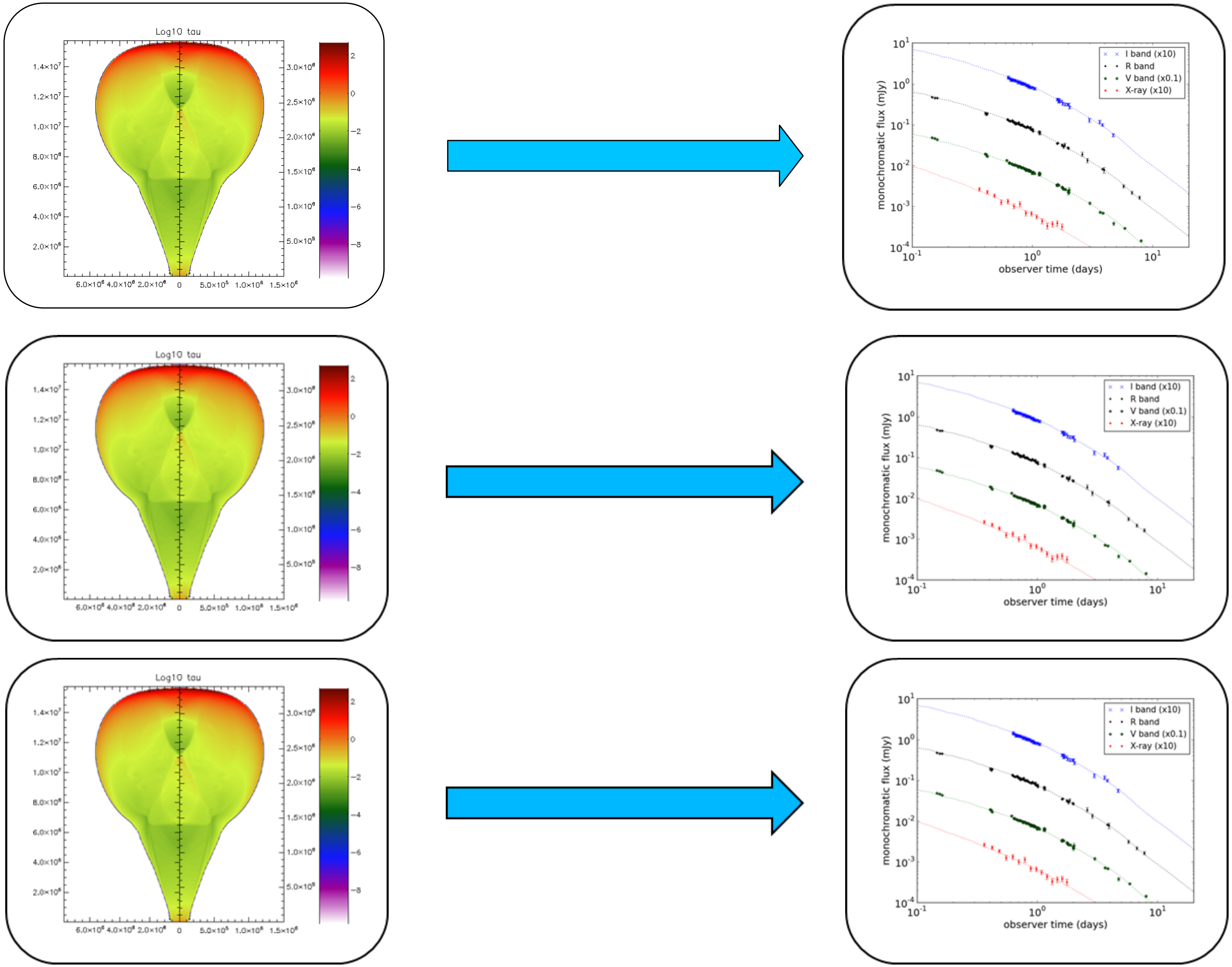
From AMR RHD simulation to light curve





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

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:

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

fluid equations can be rewritten in terms of dimensionless parameters:

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

dynamics invariant under transform of E_{iso}/ρ

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

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

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)

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: $A \rightarrow \infty$

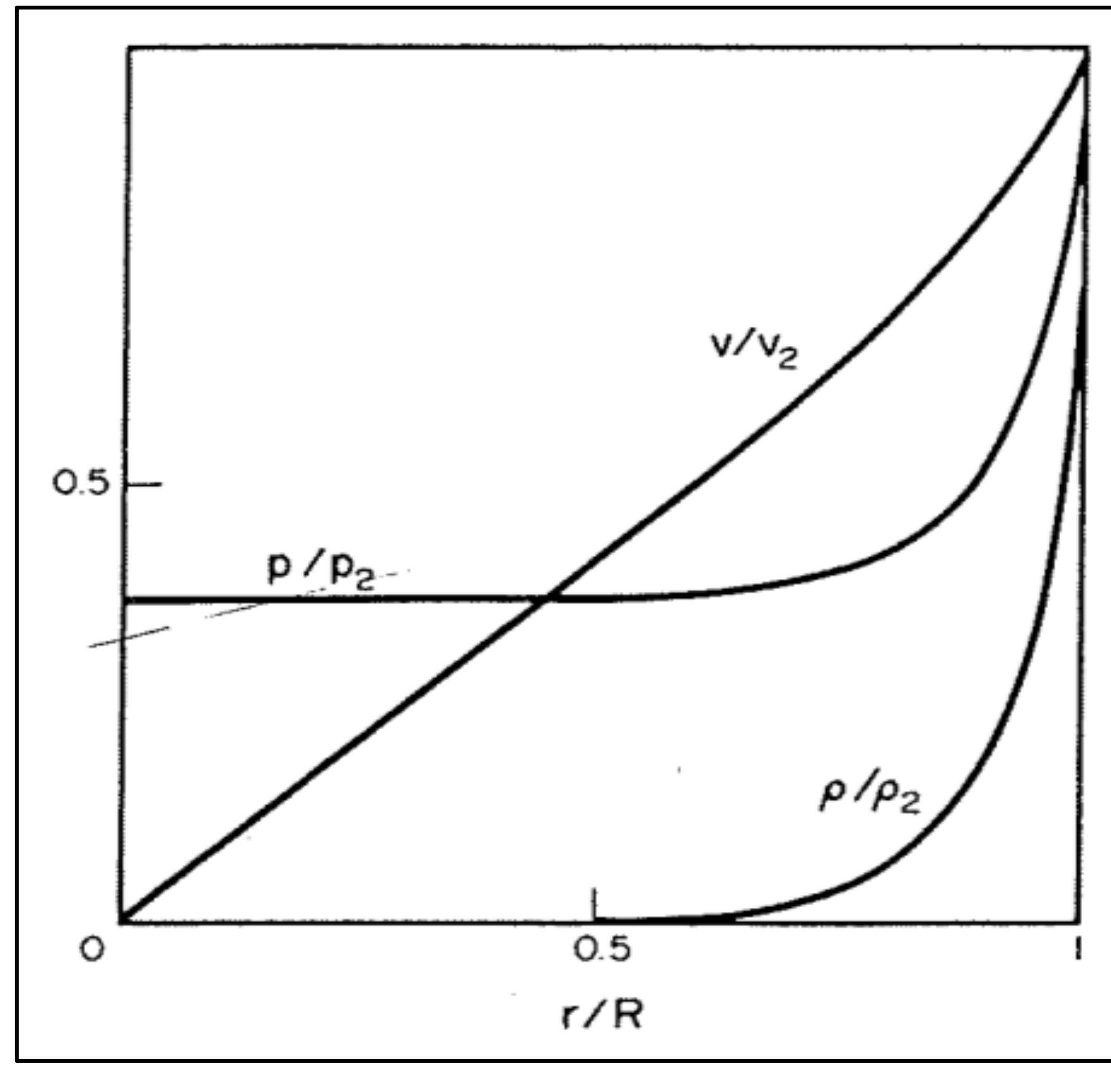
so spherical (no θ) blast waves are *self-similar* in these limits:

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

"Blandford-McKee" relativistic

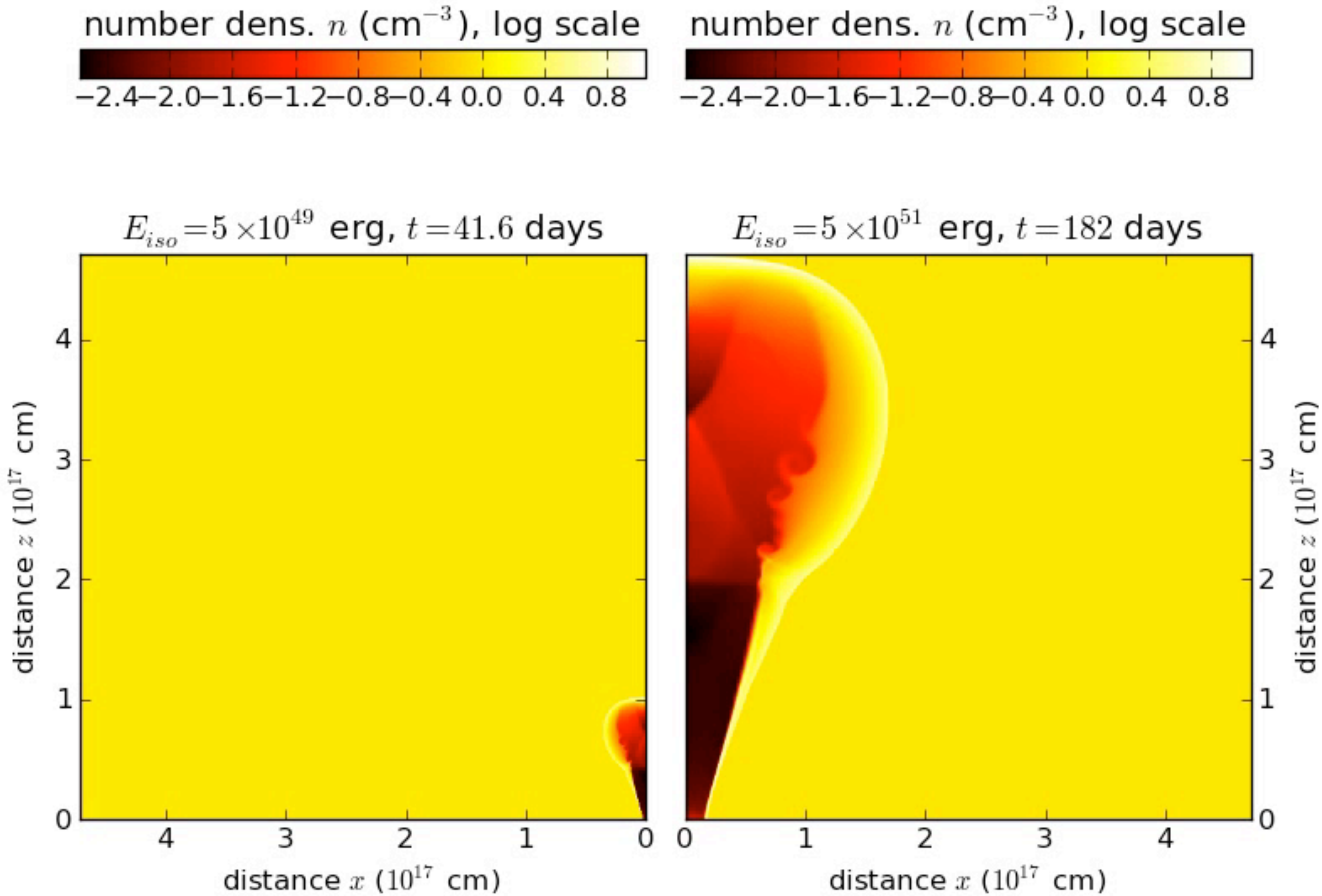
"Sedov-Taylor" non-relativistic

intermediate stage in 2D more complex



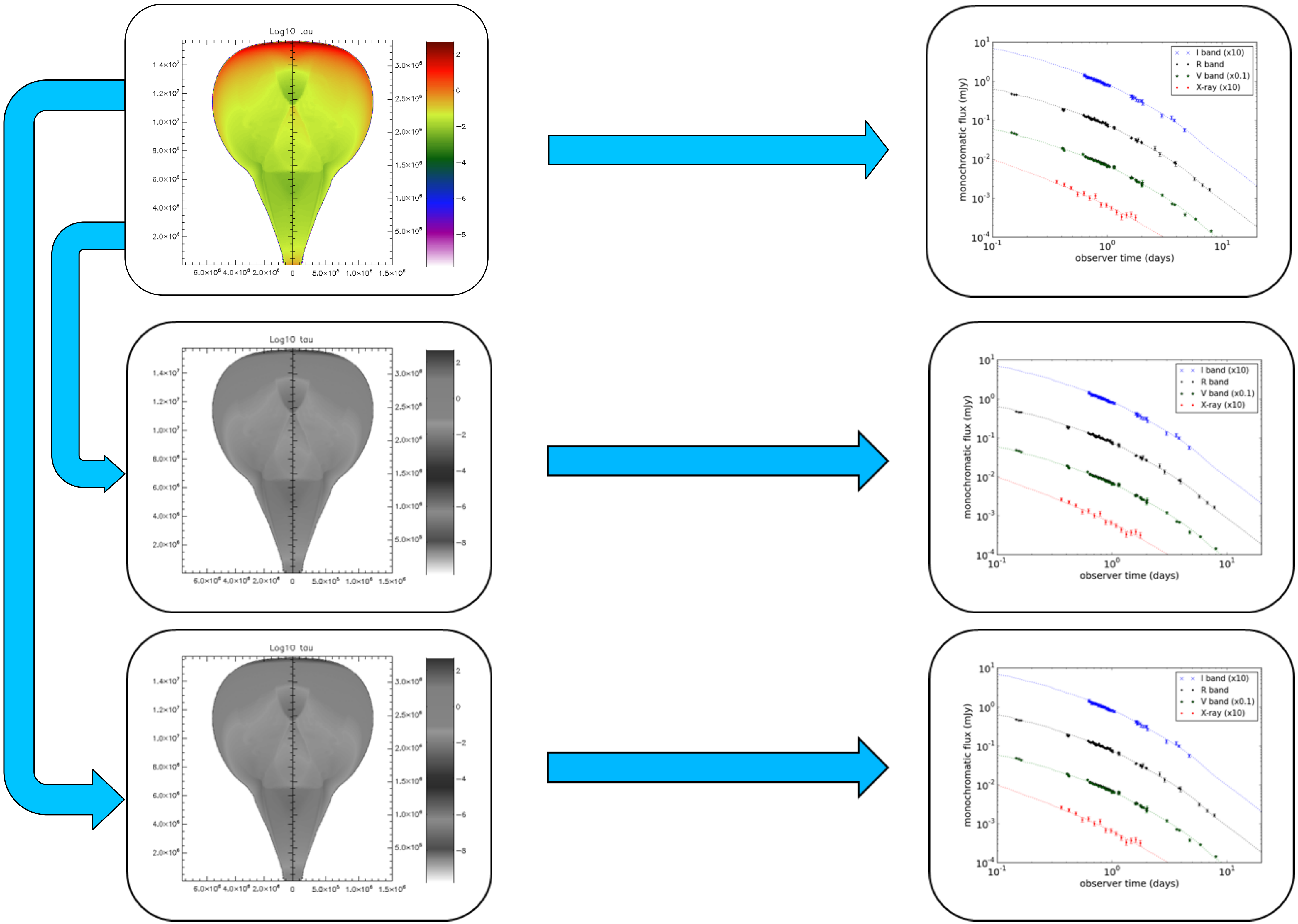
Sedov-Taylor blast wave
image: Landau & Lifshitz 1952

Scaling of Jet Dynamics

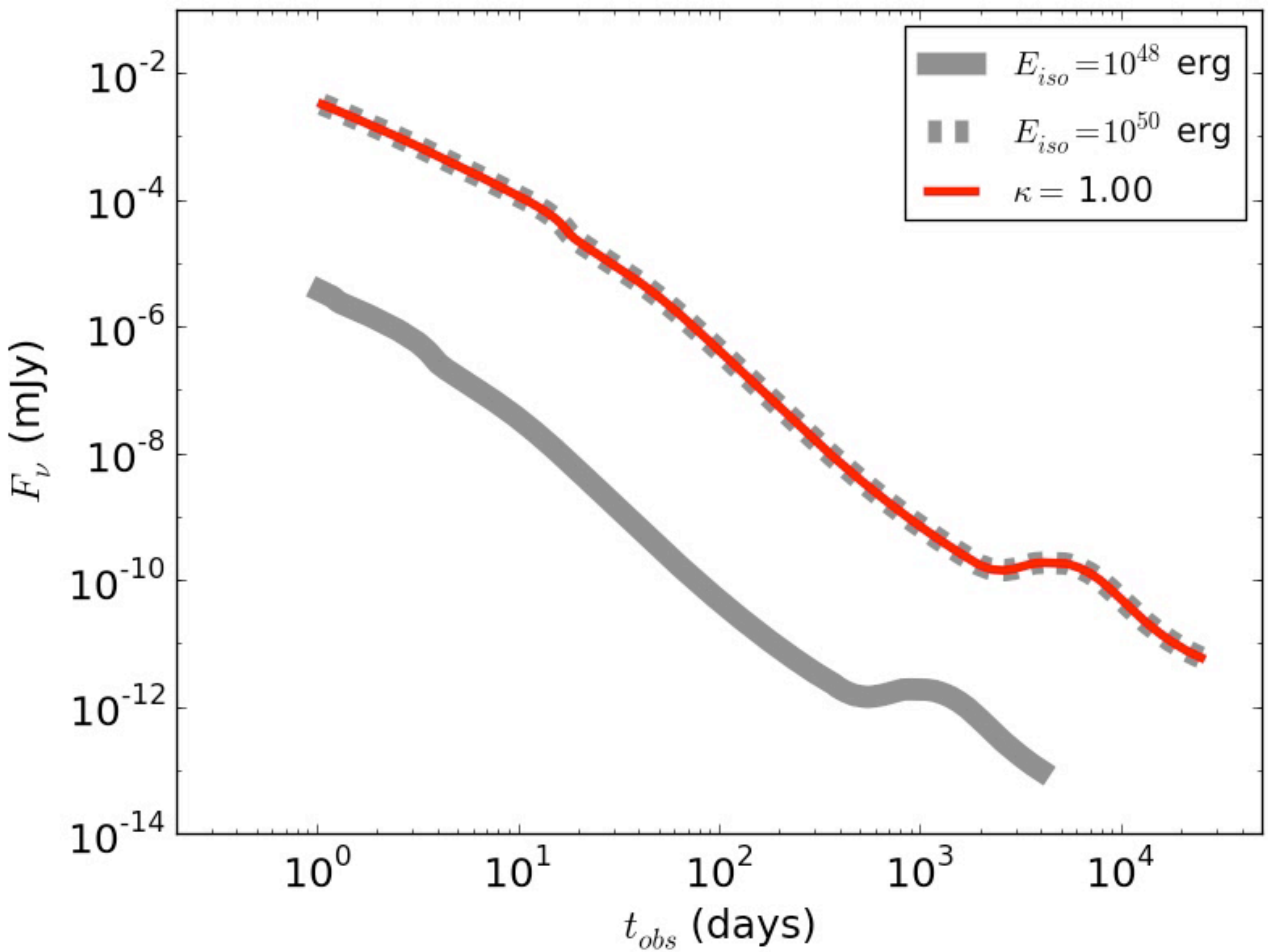


$$E'_{iso} = \kappa E_{iso}, \quad n' = \lambda n, \quad t' = (\kappa/\lambda)^{1/3} t, \quad r' = (\kappa/\lambda)^{1/3} r$$

Calculate jet dynamics by applying scaling



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

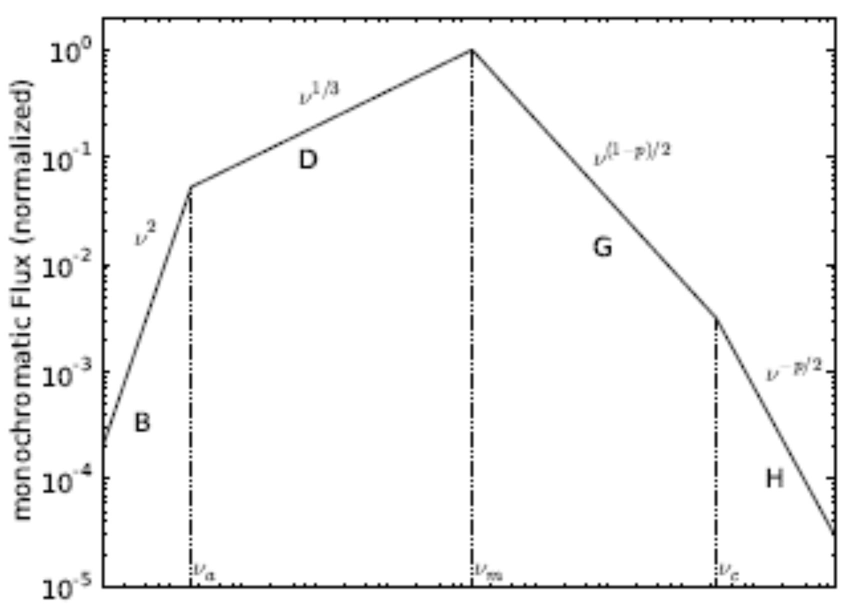


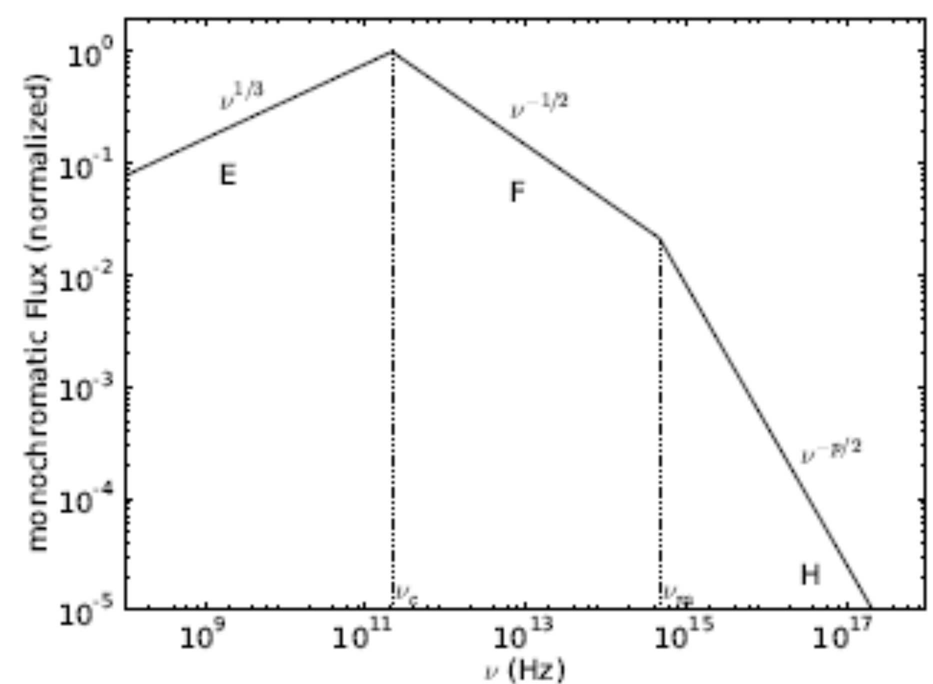
$$E'_{iso} = \kappa E_{iso}, \quad n' = \lambda n,$$

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

Scalings, the full formulae

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

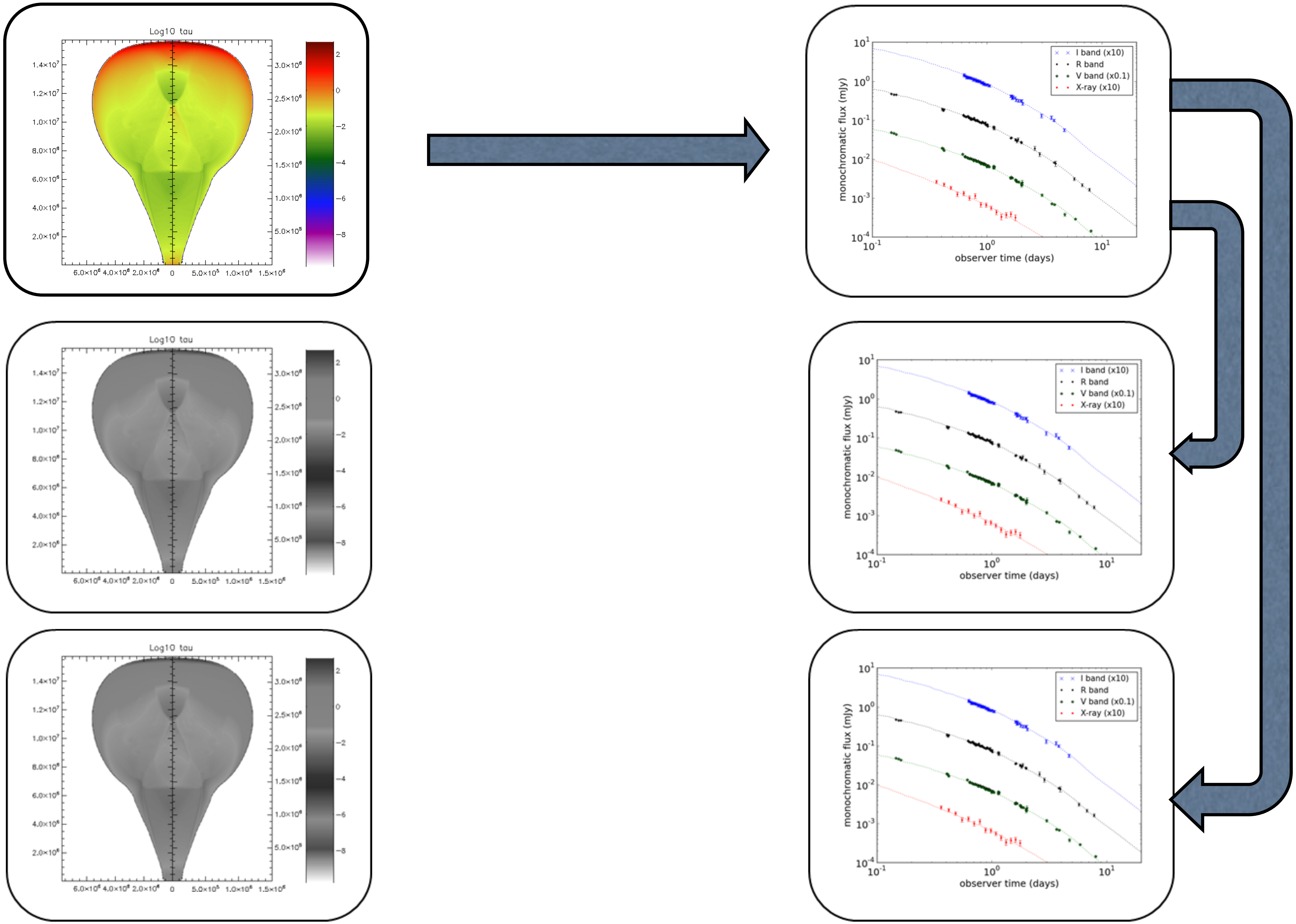




$$E'_{iso} = \kappa E_{iso}, \quad n' = \lambda n,$$

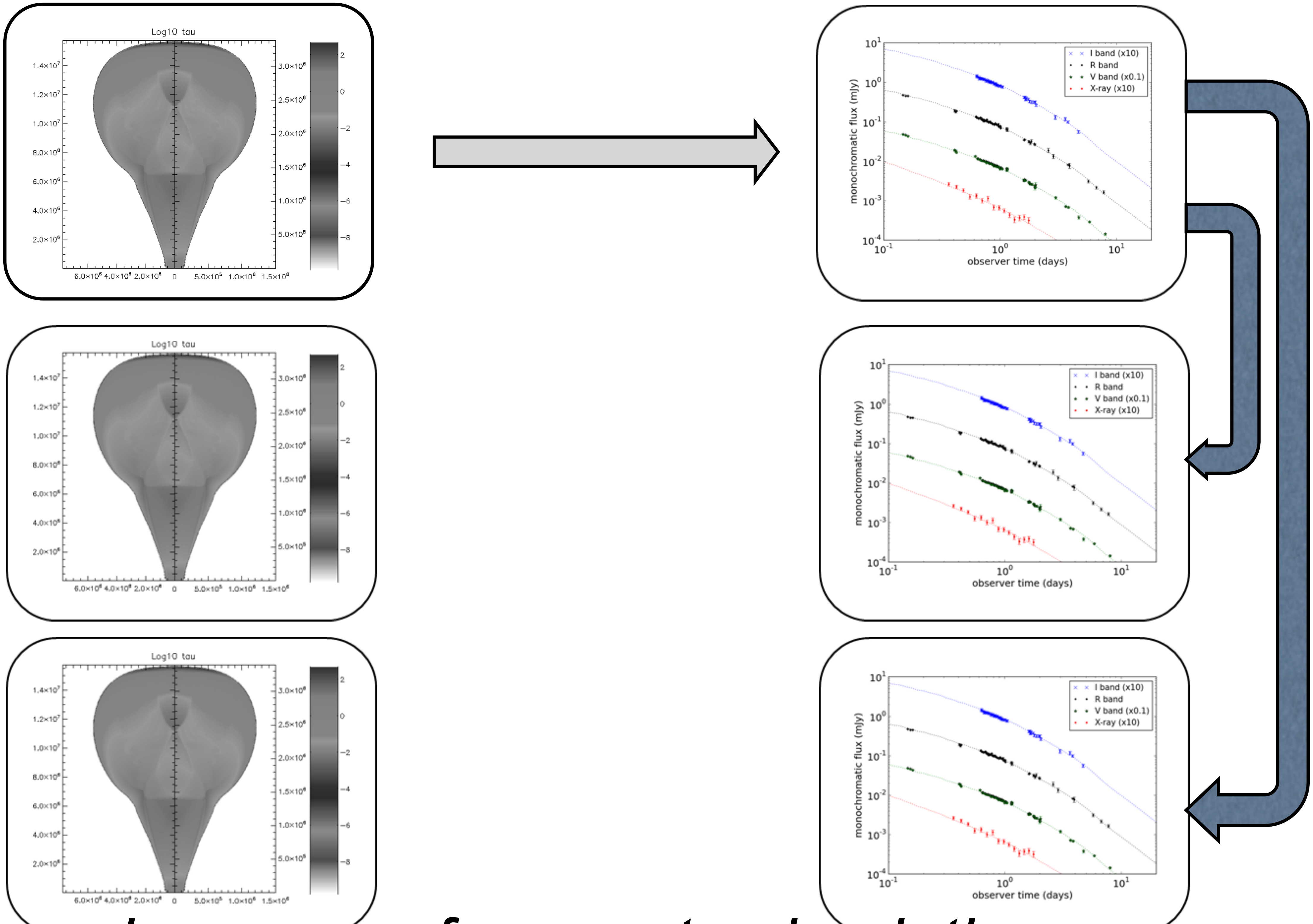
$$t'_{obs} = (\kappa/\lambda)^{1/3} t_{obs}, \quad F'_{optical} = \kappa \lambda^{(1+p)/4} F_{optical}$$

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!

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:

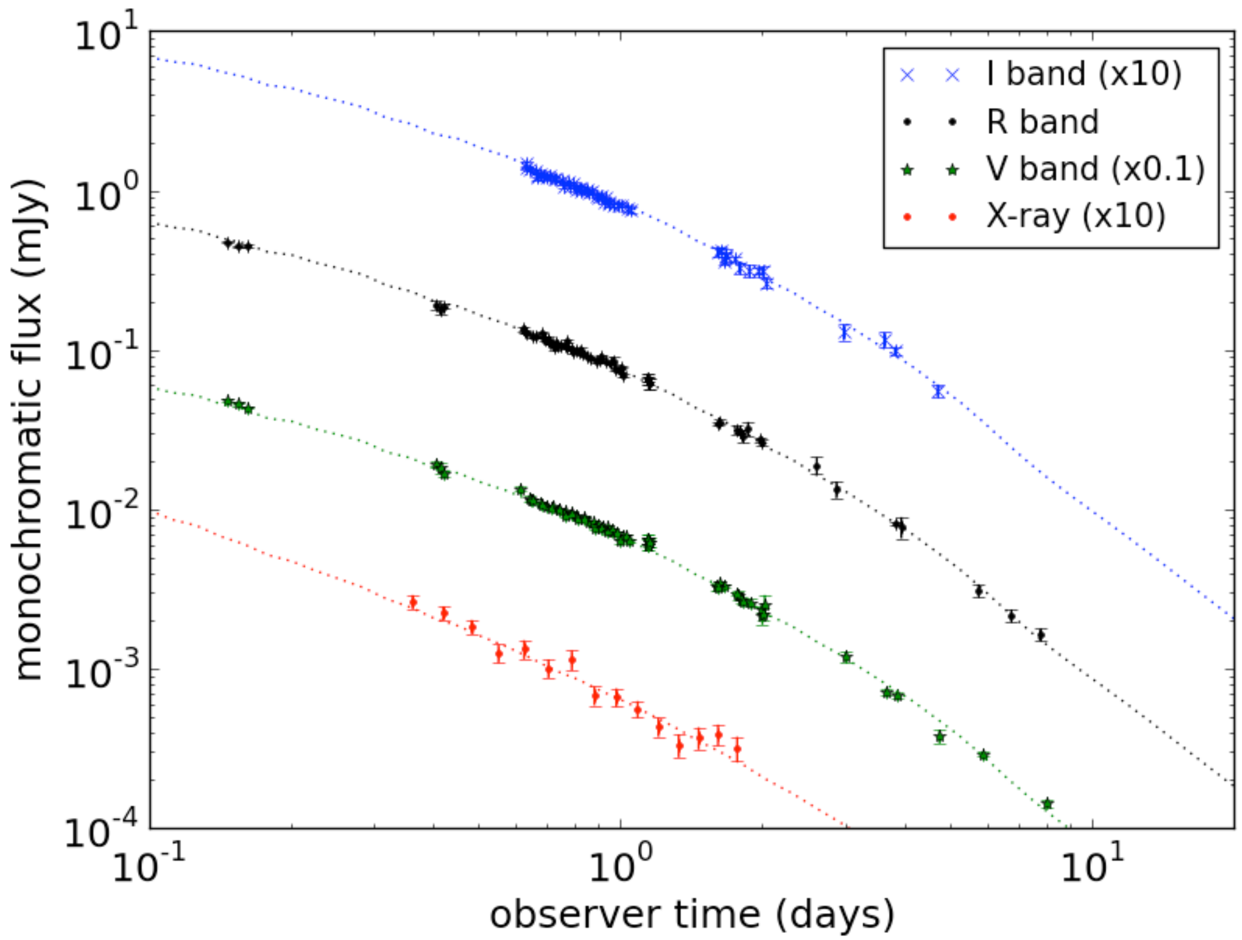
Dynamics:
initial jet opening angle
circumburst density structure ('*k*')

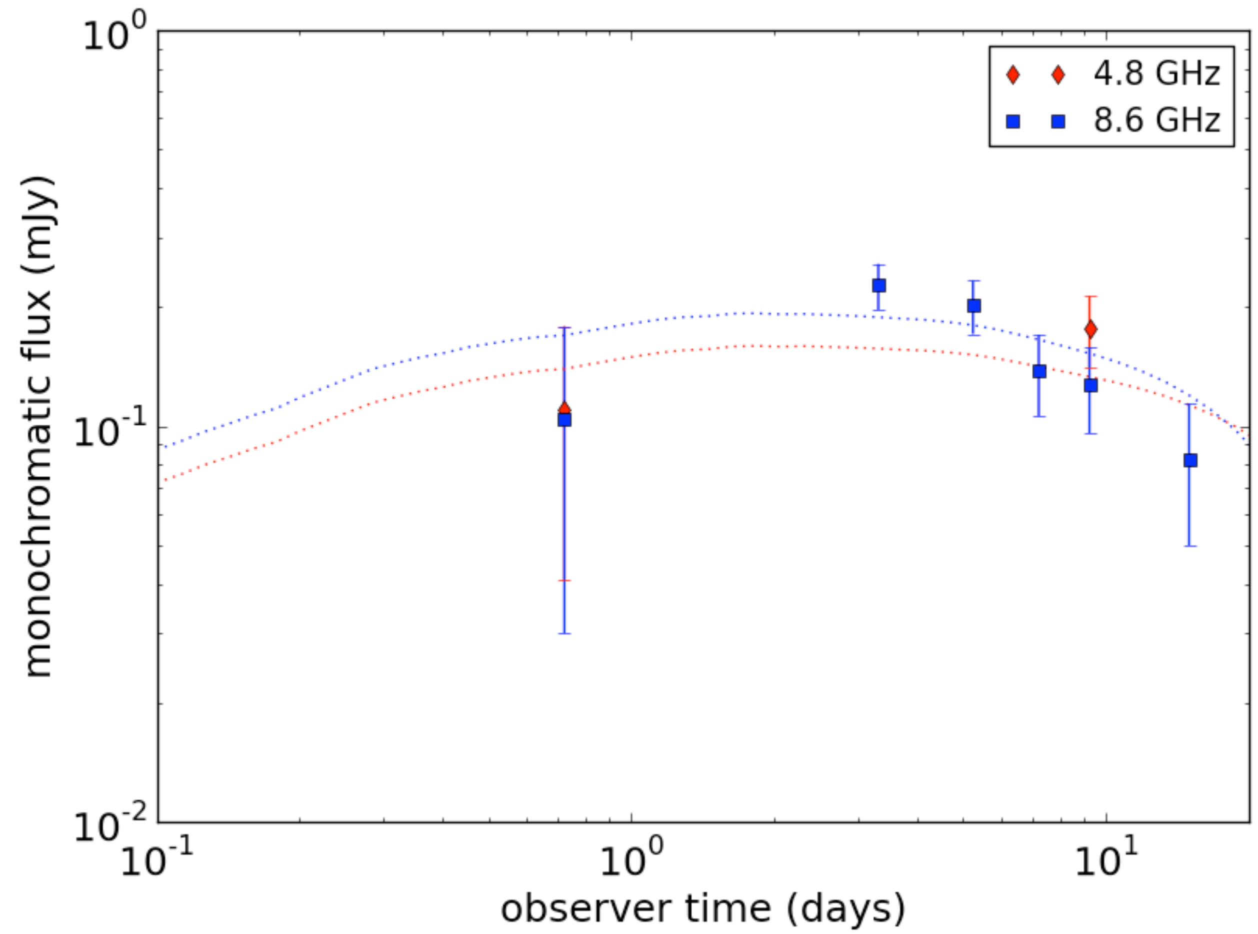
Radiation / observer position:
observer angle
[transitions between spectral regimes, use sharp / smooth spectral powerlaws]

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.

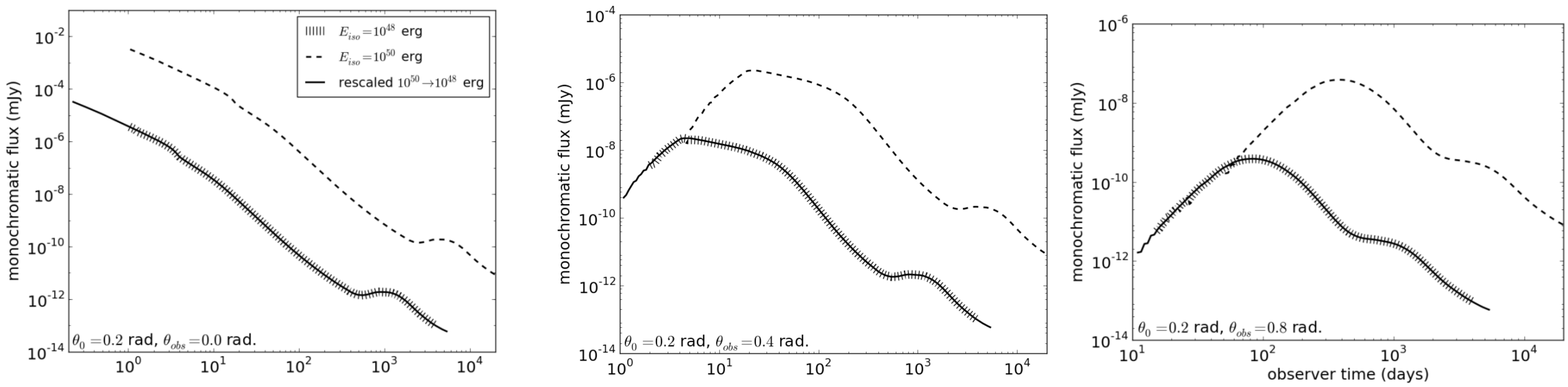
Example application: model fit to GRB 990510





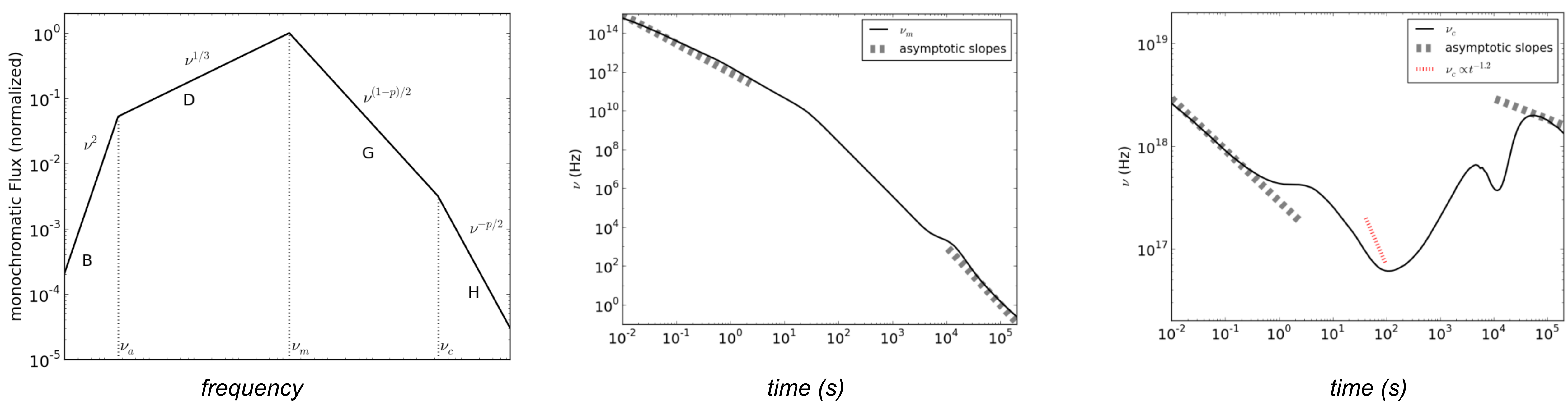
- **Iterative fit** to radio, optical & X-ray data, based on 2D jet simulations
- Synchrotron slope $p > 2$, in contrast to 1.8 from Panaitescu & Kumar (2002)
- reduced χ-squared 3.235 for off-axis observer, while 5.389 on-axis
- observer angle θ is 0.0016 rad, one third of jet angle 0.0048 rad

Example application: characteristic behavior



In the top row: *scaling works for all observer angles*

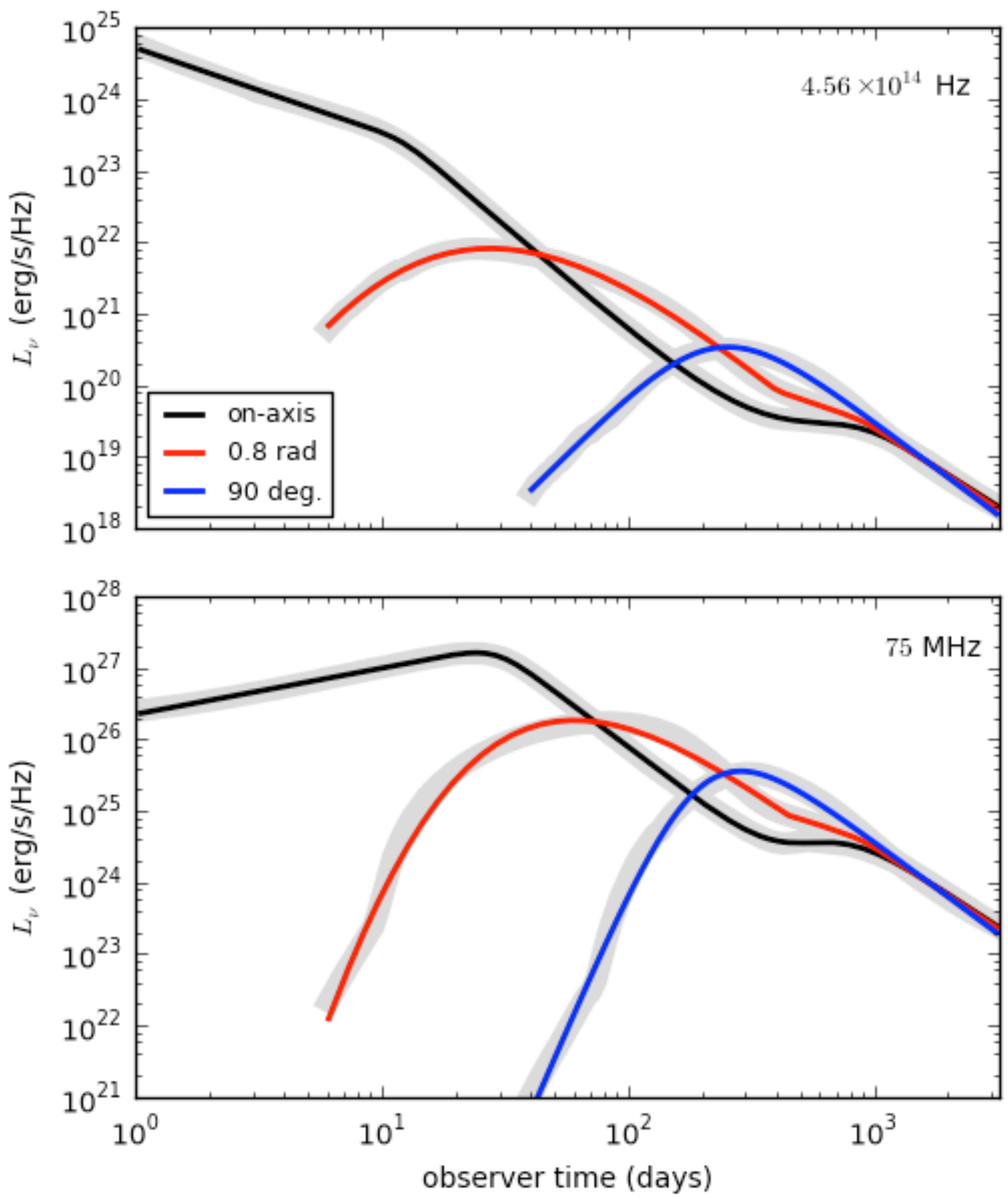
In the bottom row: *schematic synchrotron, synchrotron break frequency, cooling break frequency*



new insight: characteristics change quickly following jet break

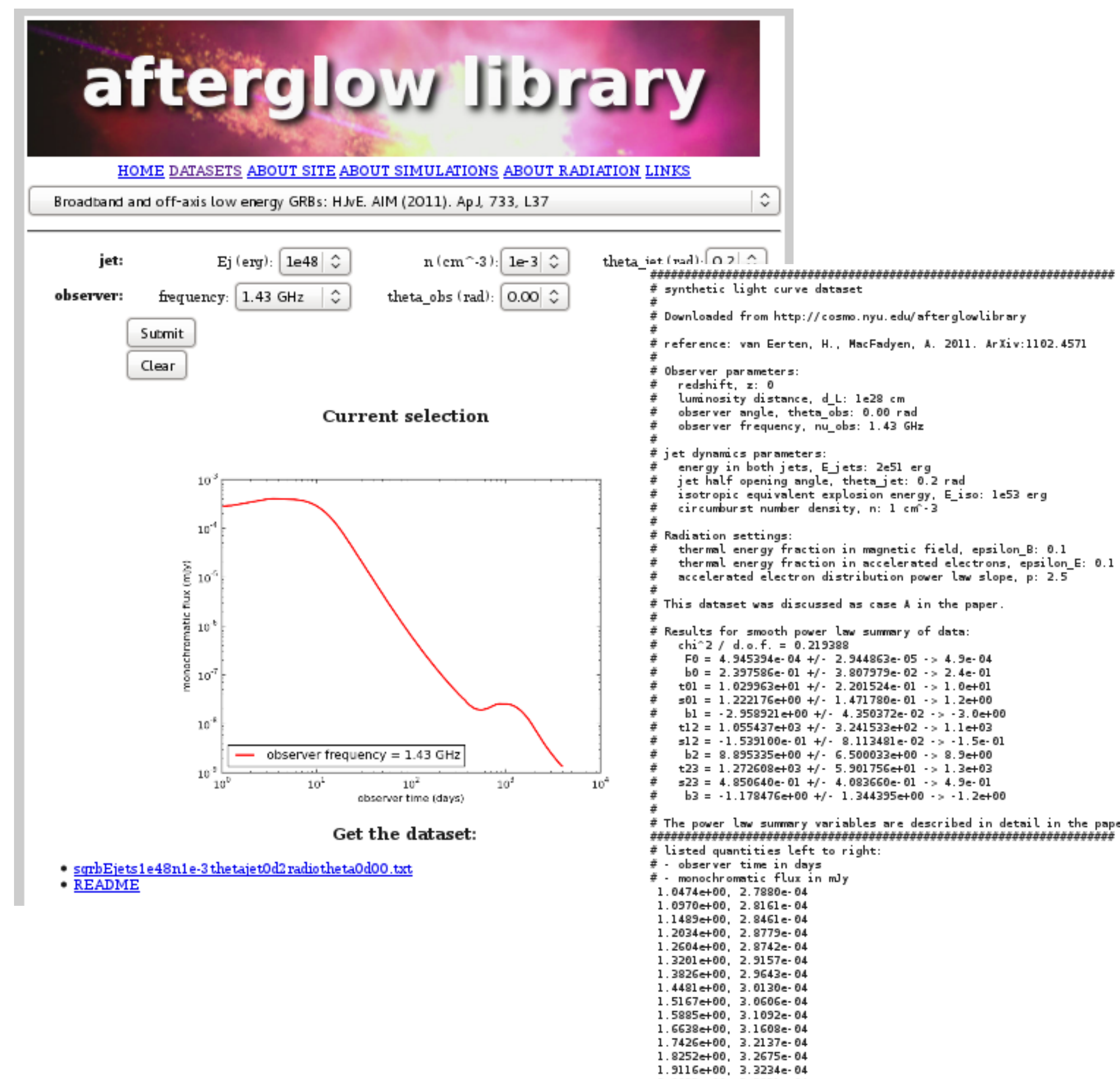
Example application: generic light curves on-line

The ability to quickly generate light curves and GRB afterglows to probe parameter space...



On-line website with downloadable light curves:

http://cosmo.nyu.edu/afterglowlibrary



generic low energy light curves
for different angles and frequencies

(orphan afterglows? LOFAR, SKA? etc.)

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

Supported by NASA NNX10AF62G

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’

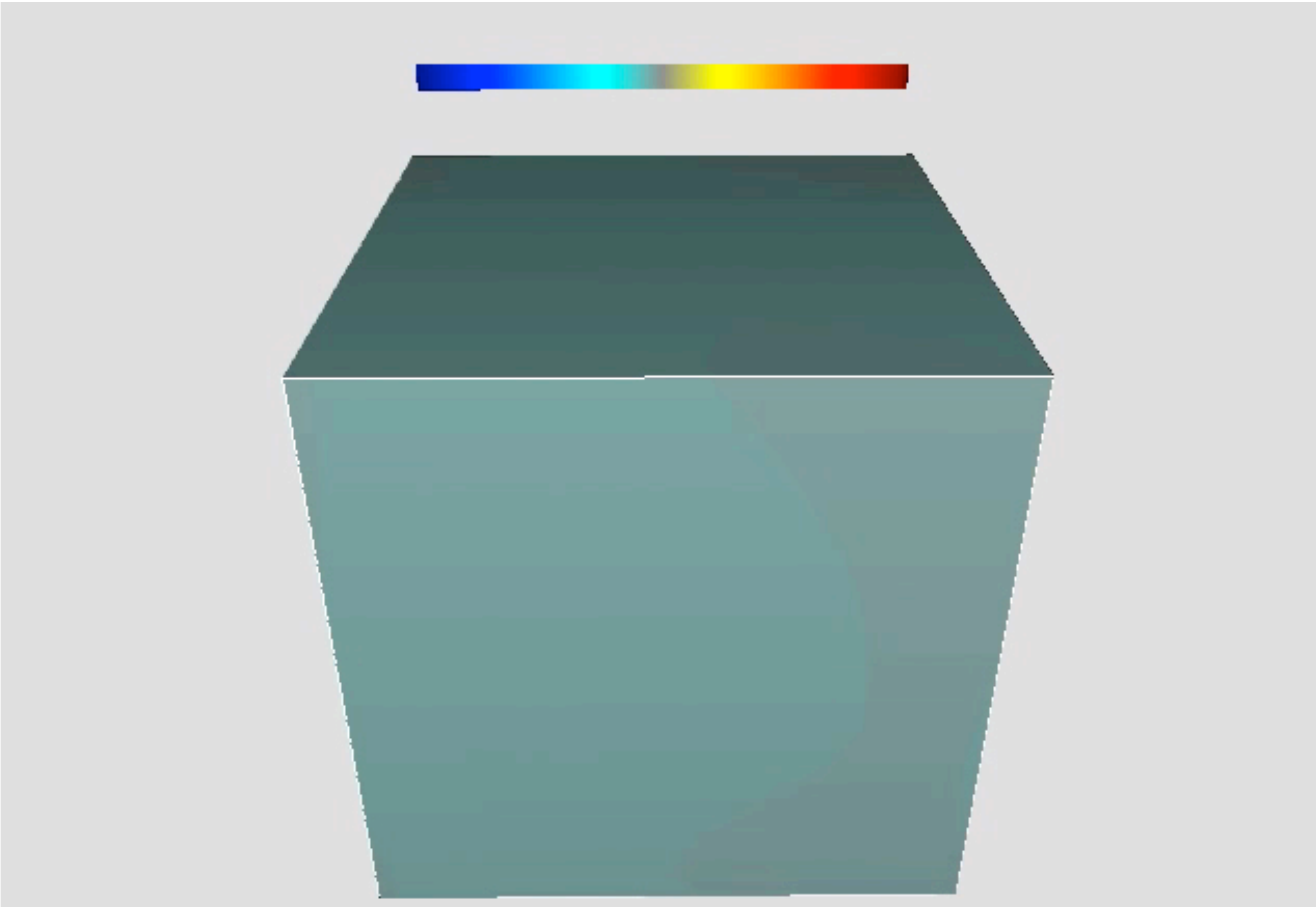
which is useful for exploring parameter space (i.e. surveys)
and readily generalized to similar blast wave / jet phenomena:
- both long and short GRB’s
- supernova blast waves (talks Assaf Horesh, Laura Chomiuk)
- tidal disruption jets (talk Brian Metzger)
- ....?

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

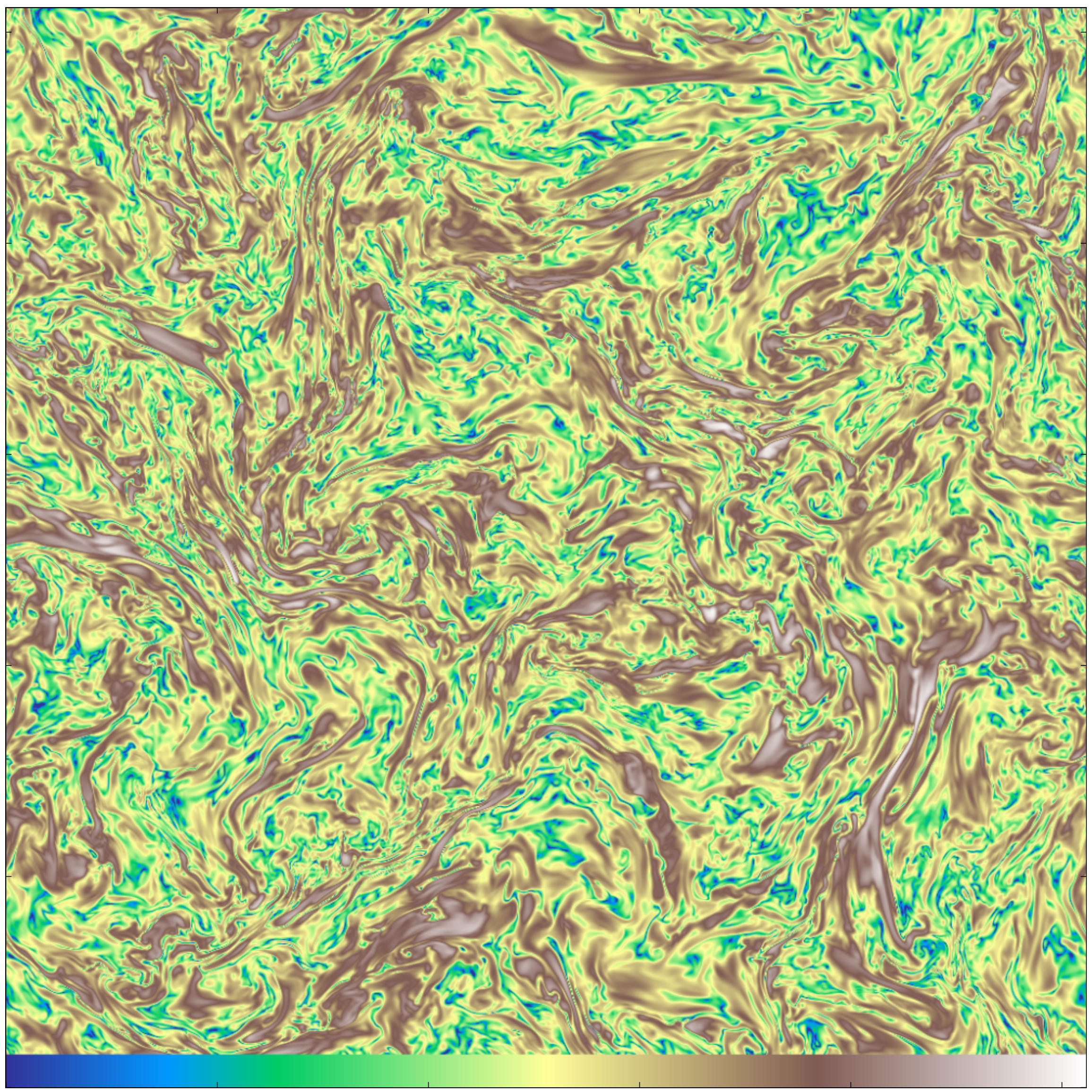
MARA

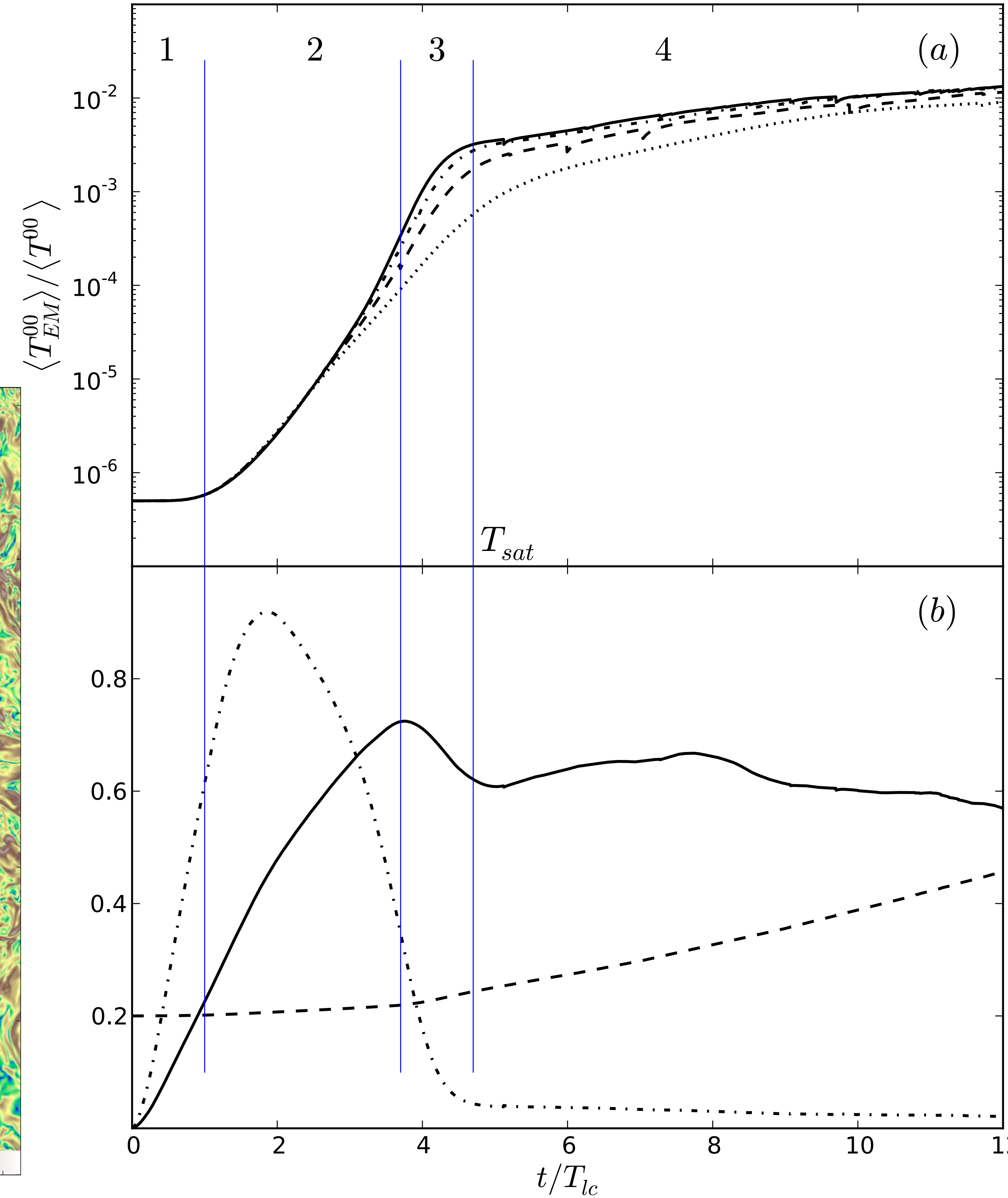


Zrake & MacFadyen (2011)

Turbulent amplification of Magnetic Field

□$_B$= 10^{-2}



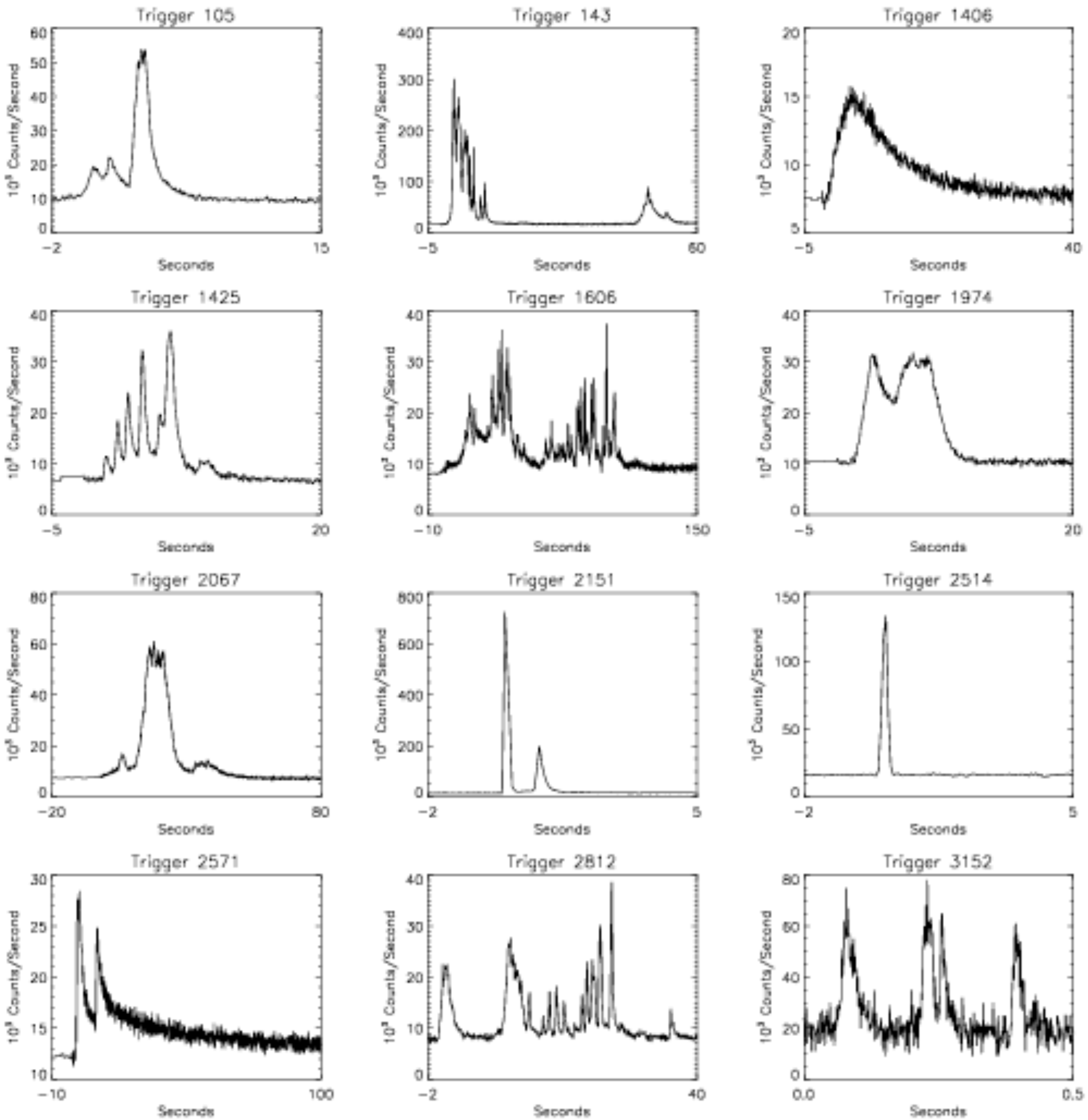


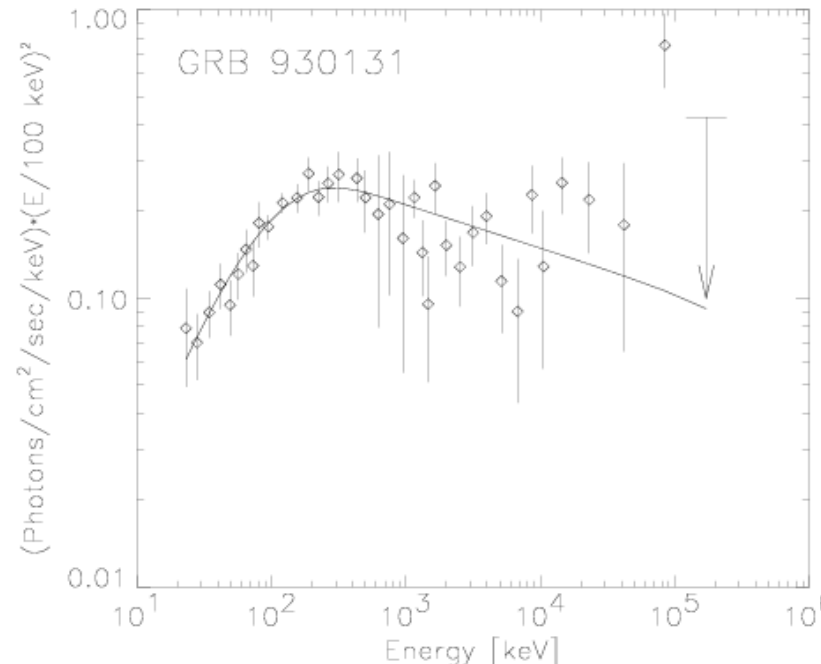
Zrake & AM (2012)

Conclusions

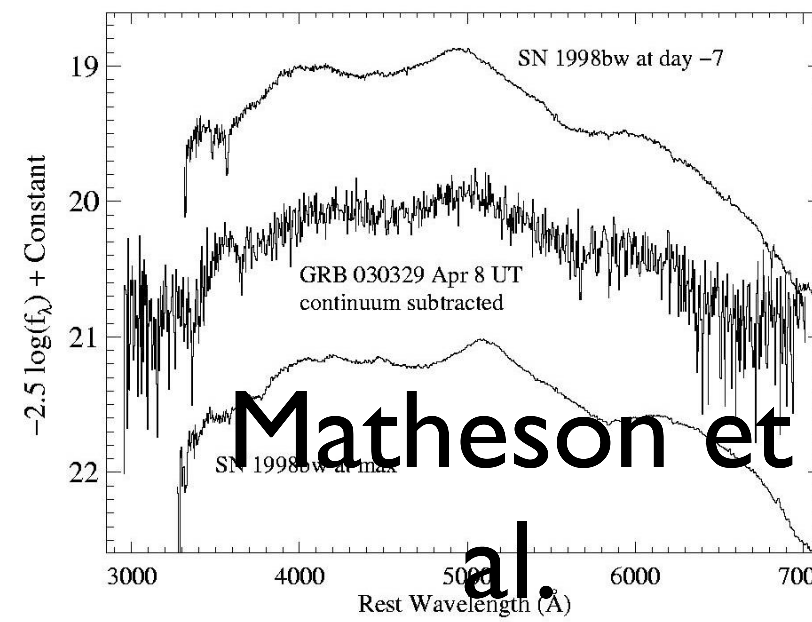
- Jet Dynamics Scale
- Light Curves Scale
- Γ numerical $\gtrsim 200$ ($\gg 1/\theta_{jet}$)
- Fit data with full dynamics
- $t_{jet} \Rightarrow \theta_{jet} + \theta_{obs} \Rightarrow E_{jet} \downarrow$
- http://cosmo.nyu.edu/afterglowlibrary
- Turbulence $\Rightarrow \varepsilon_B = 10^{-2}$

GRB Light Curves





SN2003dh



~0.5 Msun Ni56

Matheson et al.

ms variability + non-thermal spectrum

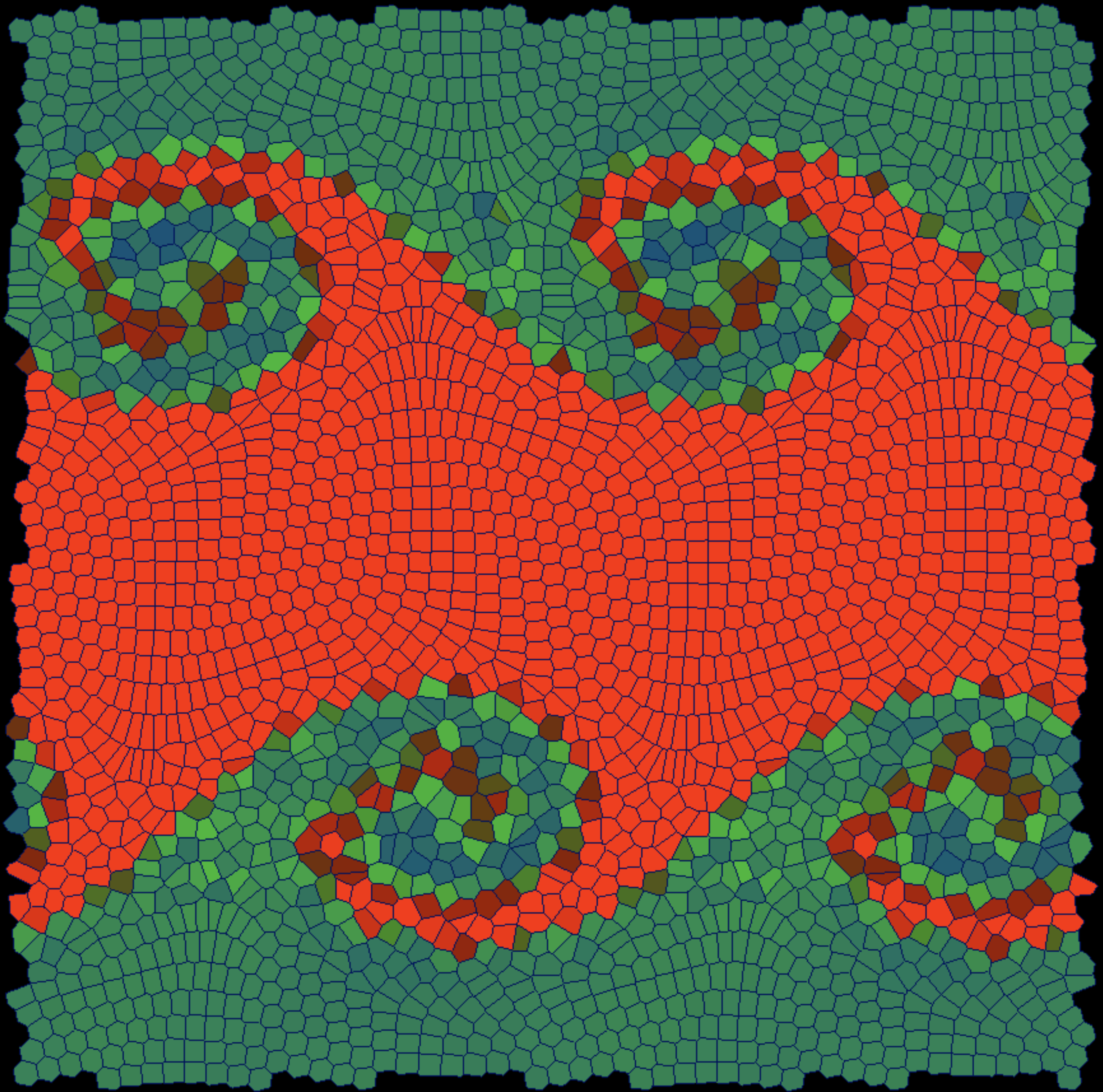
$M = E/ \Gamma c^2 \sim 10^{-6} M_{sun}$

Compactness -> $\Gamma \geq 100$

Ultra-relativistic

Ultra-clean

Tess

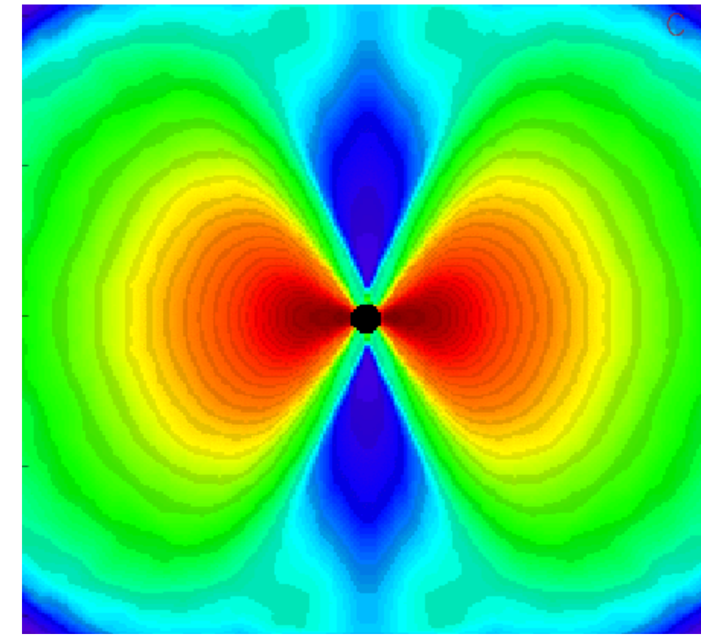


Duffel & AM (2011)

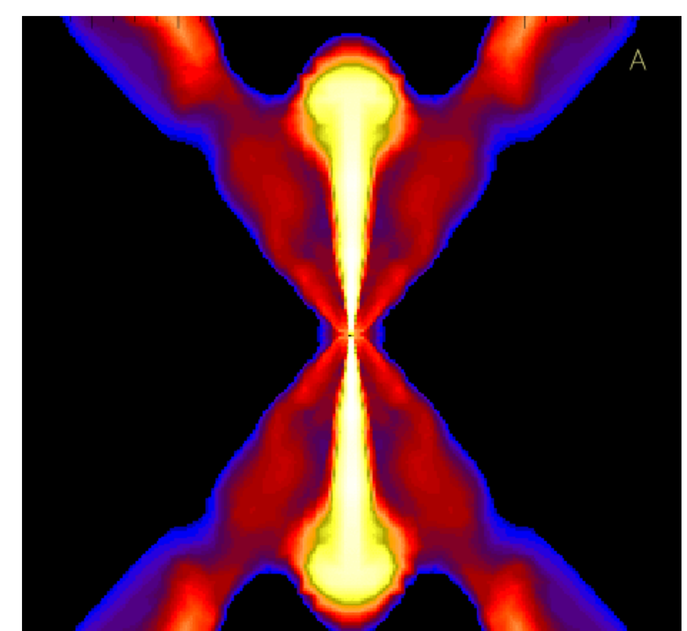
GRBs from Stars

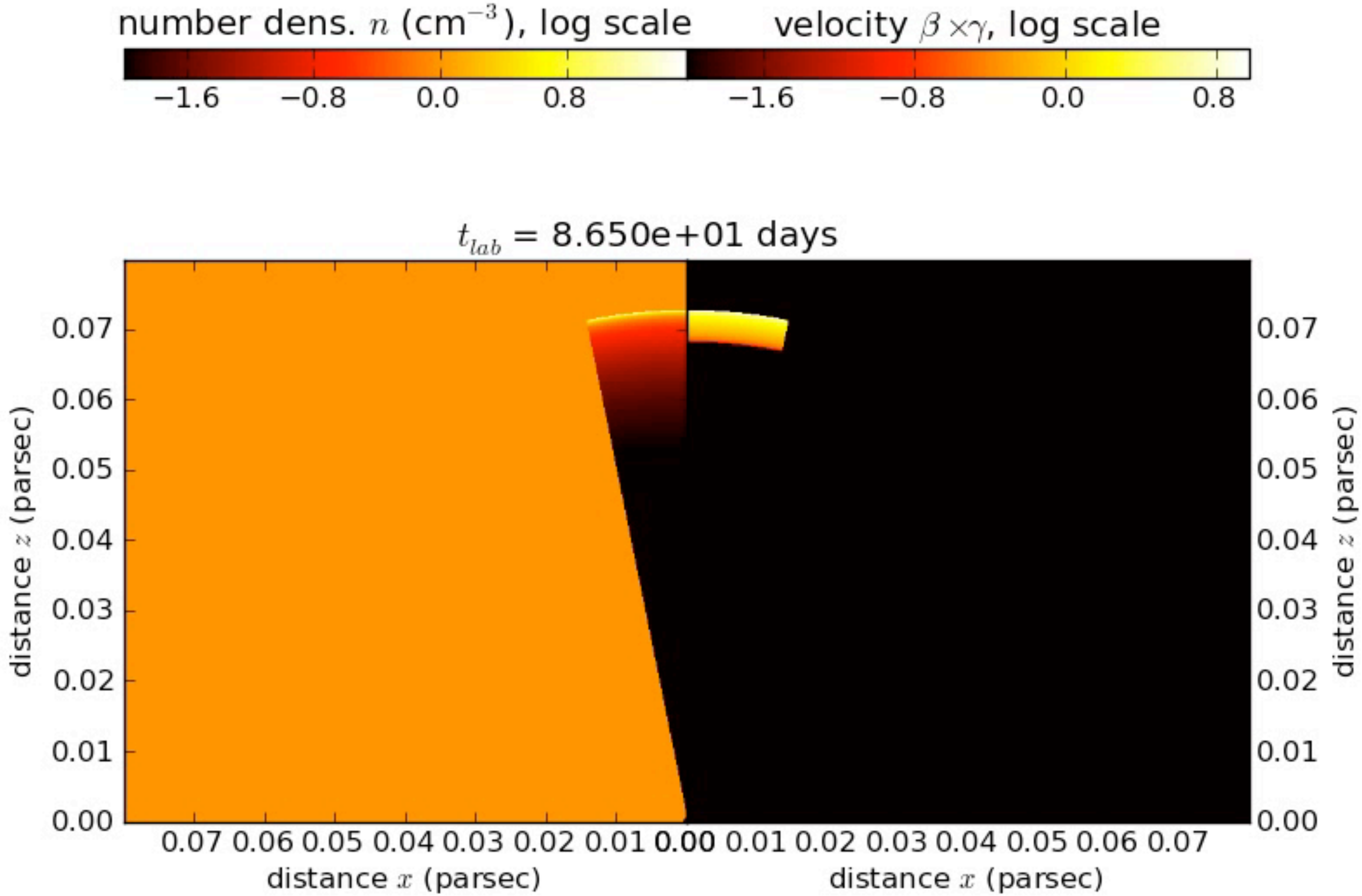
- Need ejecta to escape star before engine dies. T_engine > T_escape
- T_escape ~ 2 x T_light (~3 s = 10^11 cm)
- T_engine >> T_dyn for BH or NS
- T_ACCRETE ~ 20-100s s for massive star
- Need angular momentum (not too much)
- Need to lose H envelope -> WR progenitor and Type Ibc supernova (if Ni56)

Collapsar - Disk and Jet



- pre-SN 15 Msun Helium star
- Newtonian Hydrodynamics (PPM)
- alpha viscosity
- rotation
- photodisintegration (NSE alpha, n, p)
- neutrino cooling, thermal + URCA optically thin
- Ideal nucleons, radiation, relativistic degenerate electrons, positions
- 2D axisymmetric, spherical grid
- self gravity
- $R_{in} = 9\ R_s\ R_{out} = 9000\ R_s$




number dens. n (cm^{-3}), log scale
velocity $\beta\times\gamma$, log scale
−1.6
−0.8
0.0
0.8
−1.6
−0.8
0.0
0.8
t_{lab} = 8.650e+01 days
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
distance z (parsec)
distance x (parsec)
distance x (parsec)
distance z (parsec)