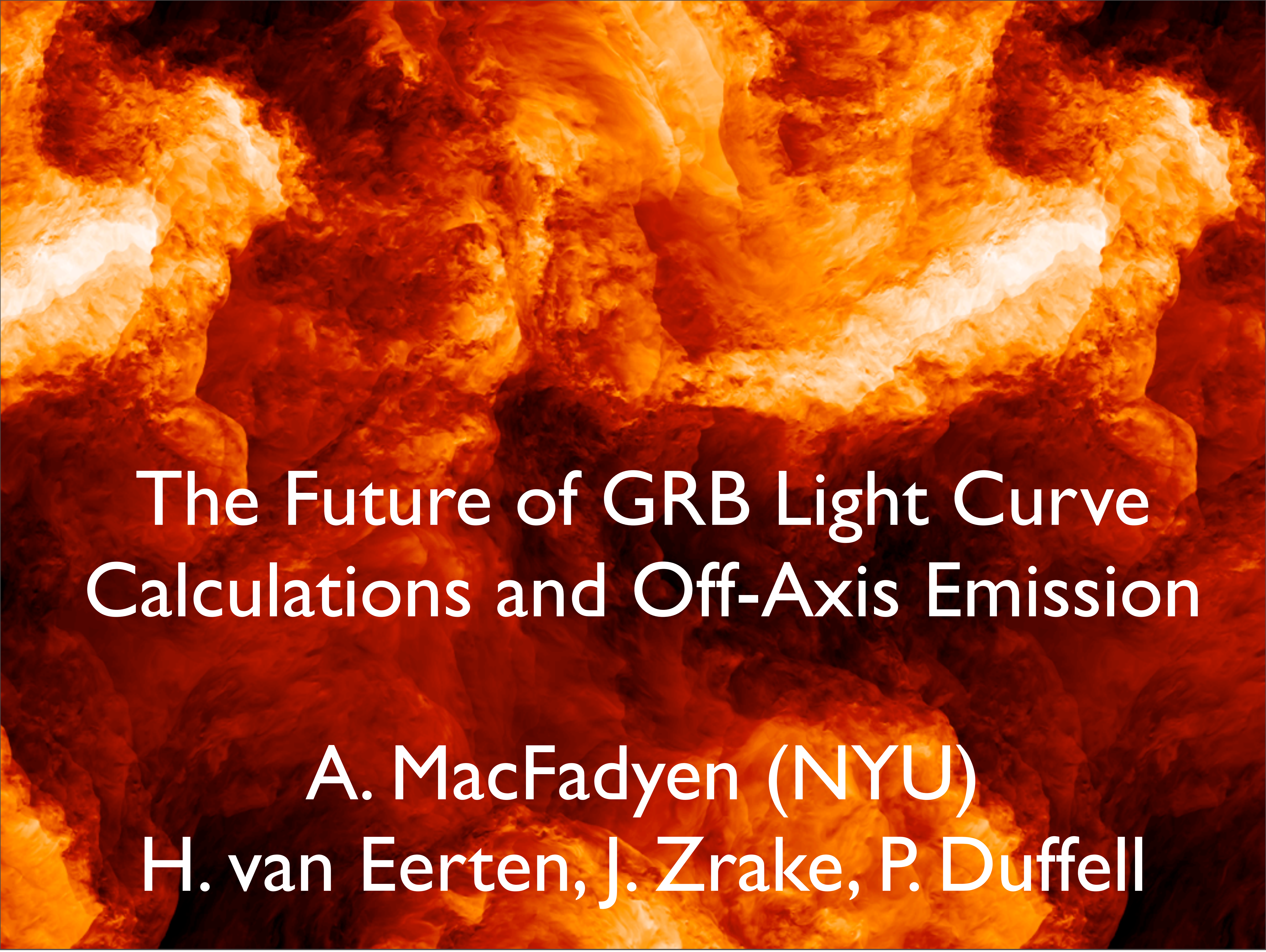
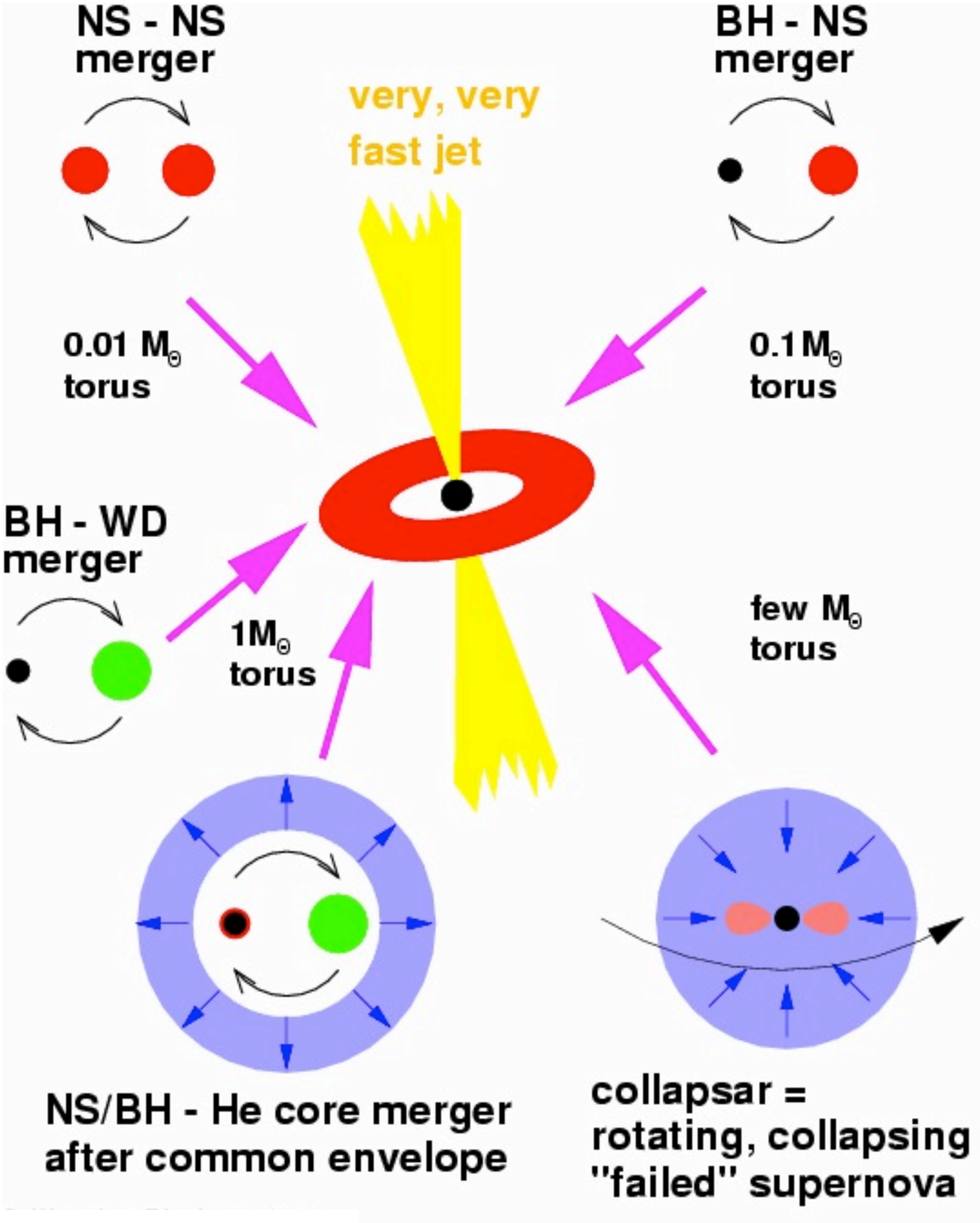


The Future of GRB Light Curve Calculations and Off-Axis Emission

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

Hyper-accreting black hole or ms magnetar



GRB photons are made far away from engine.

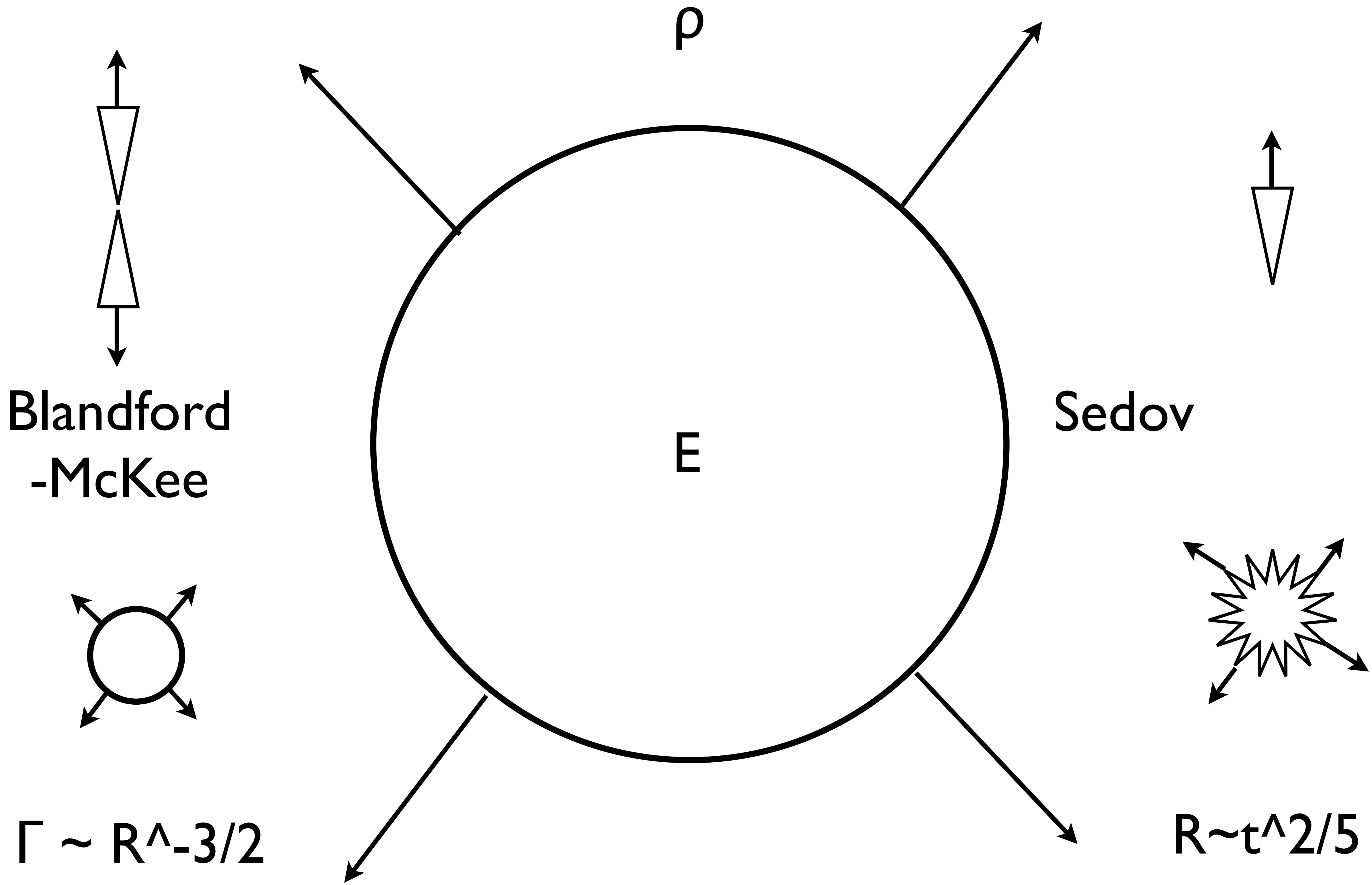
Can't observe engine directly with light. (neutrinos, gravitational waves?)

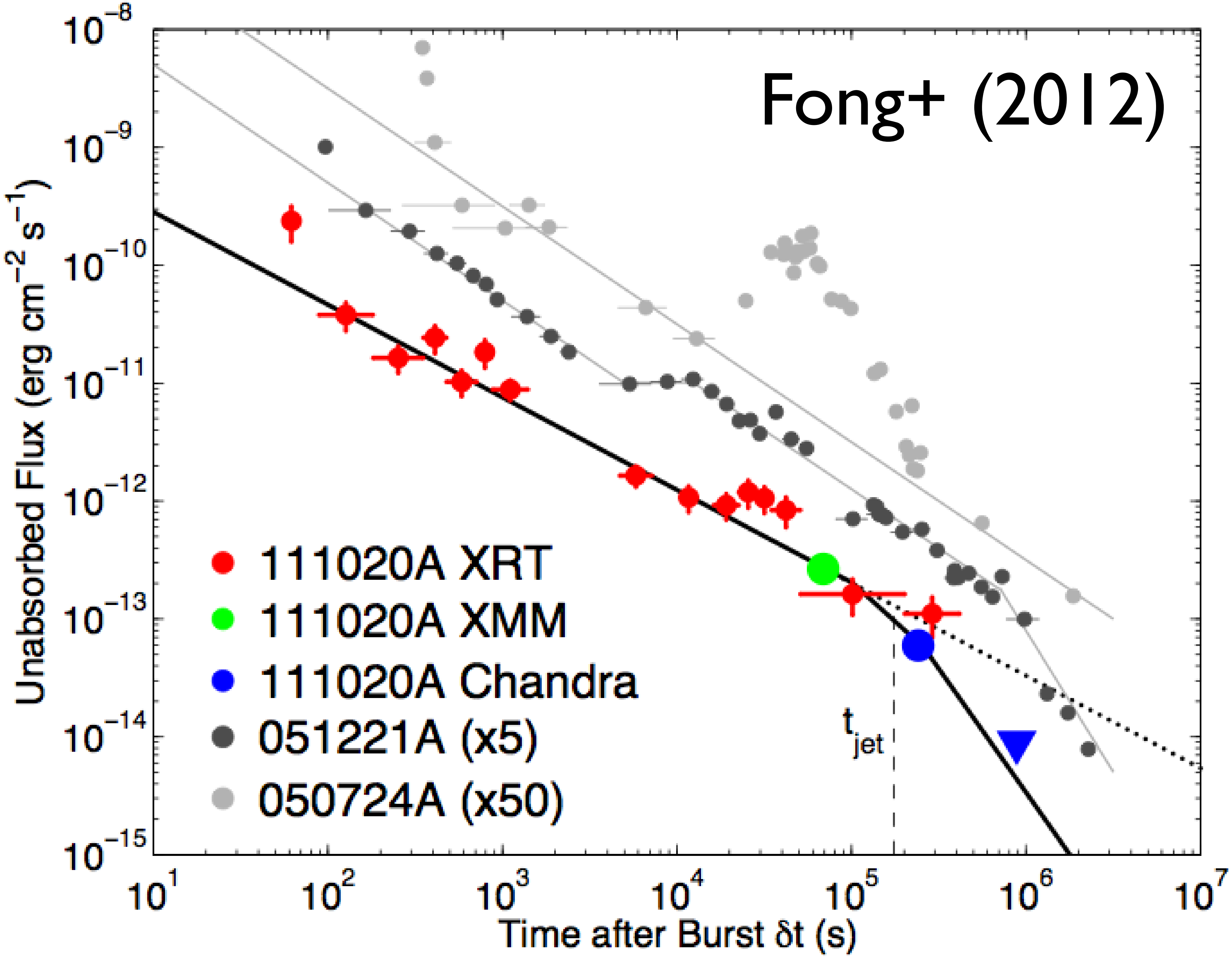
Electromagnetic process or neutrino annihilation to tap power of central compact object.

$\Gamma >> 1/\theta$

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

Spherical Attractor





Fong+ (2012)
Unabsorbed Flux (erg cm^{-2} s^{-1})
Time after Burst δt (s)
111020A XRT
111020A XMM
111020A Chandra
051221A (x5)
050724A (x50)
t_{jet}

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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•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

All these issues can be addressed by numerical simulations

•High-resolution relativistic hydrodynamics, adaptive mesh-refinement with RAM

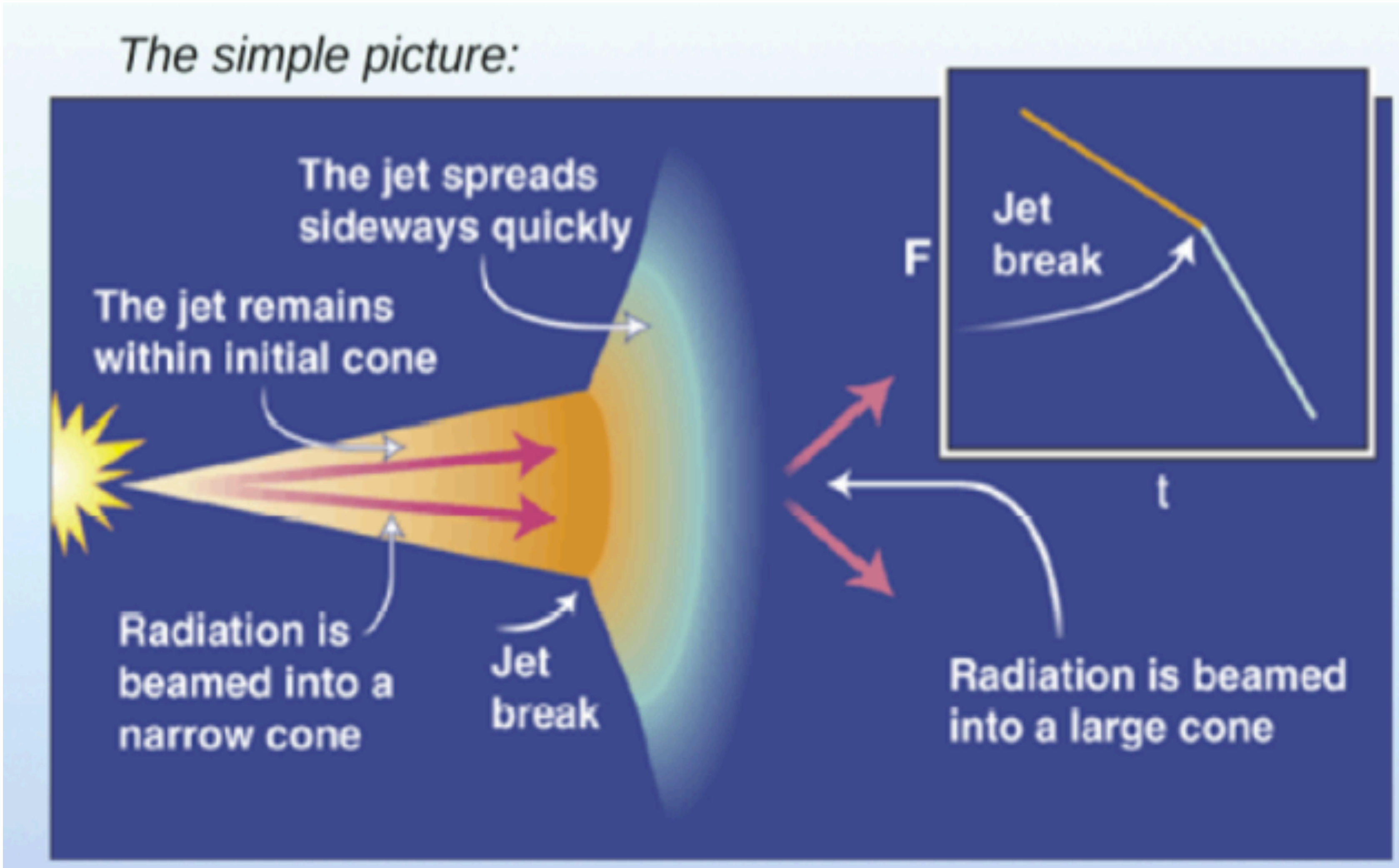
•radiative transfer for synchrotron radiation

•***This talk:*** even complex 2D simulation results are scalable

•***This talk:*** simulation-based broadband data fitting now possible

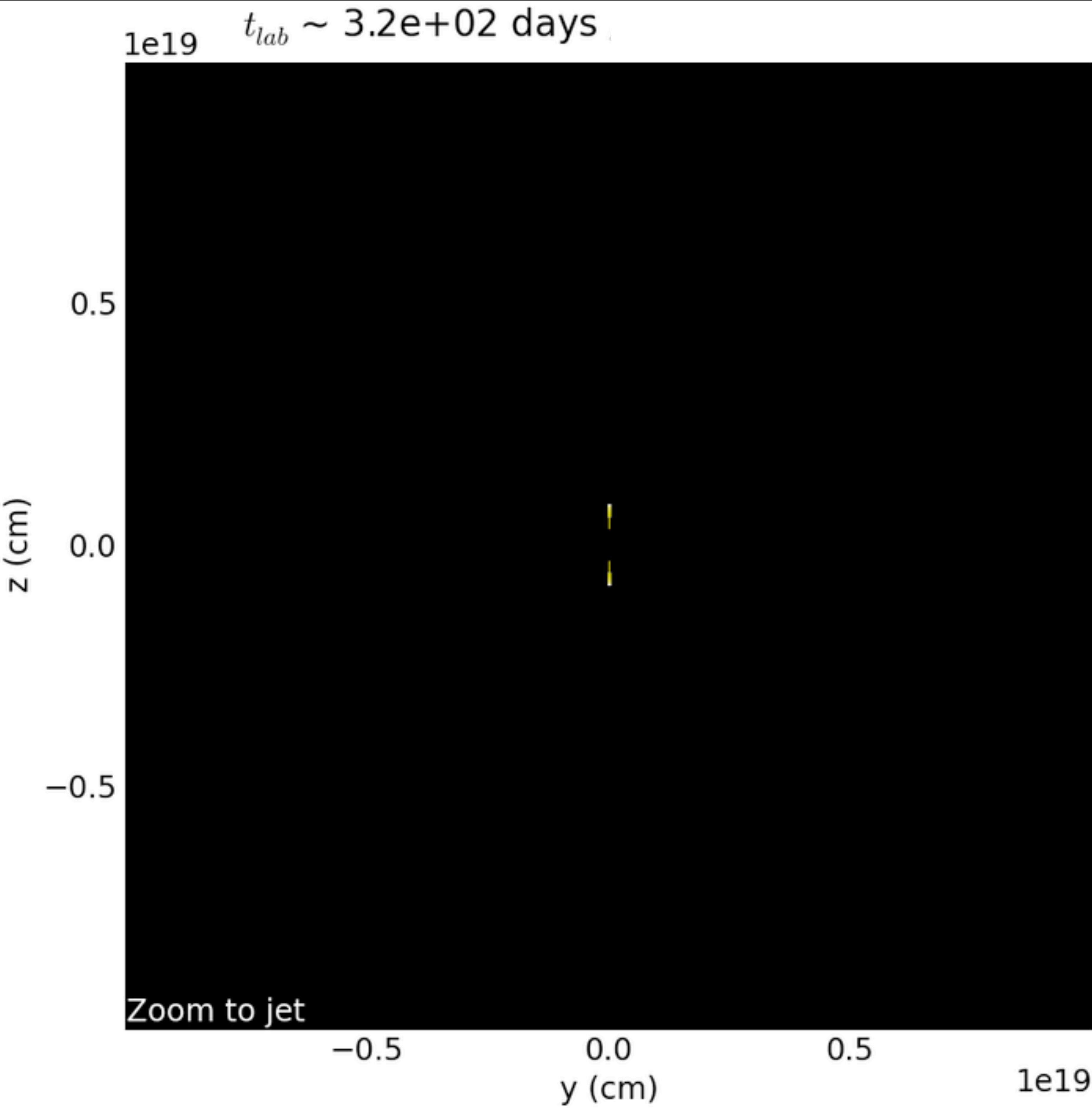
•***This talk:*** a tool for improved survey predictions

Afterglow Jet Dynamics



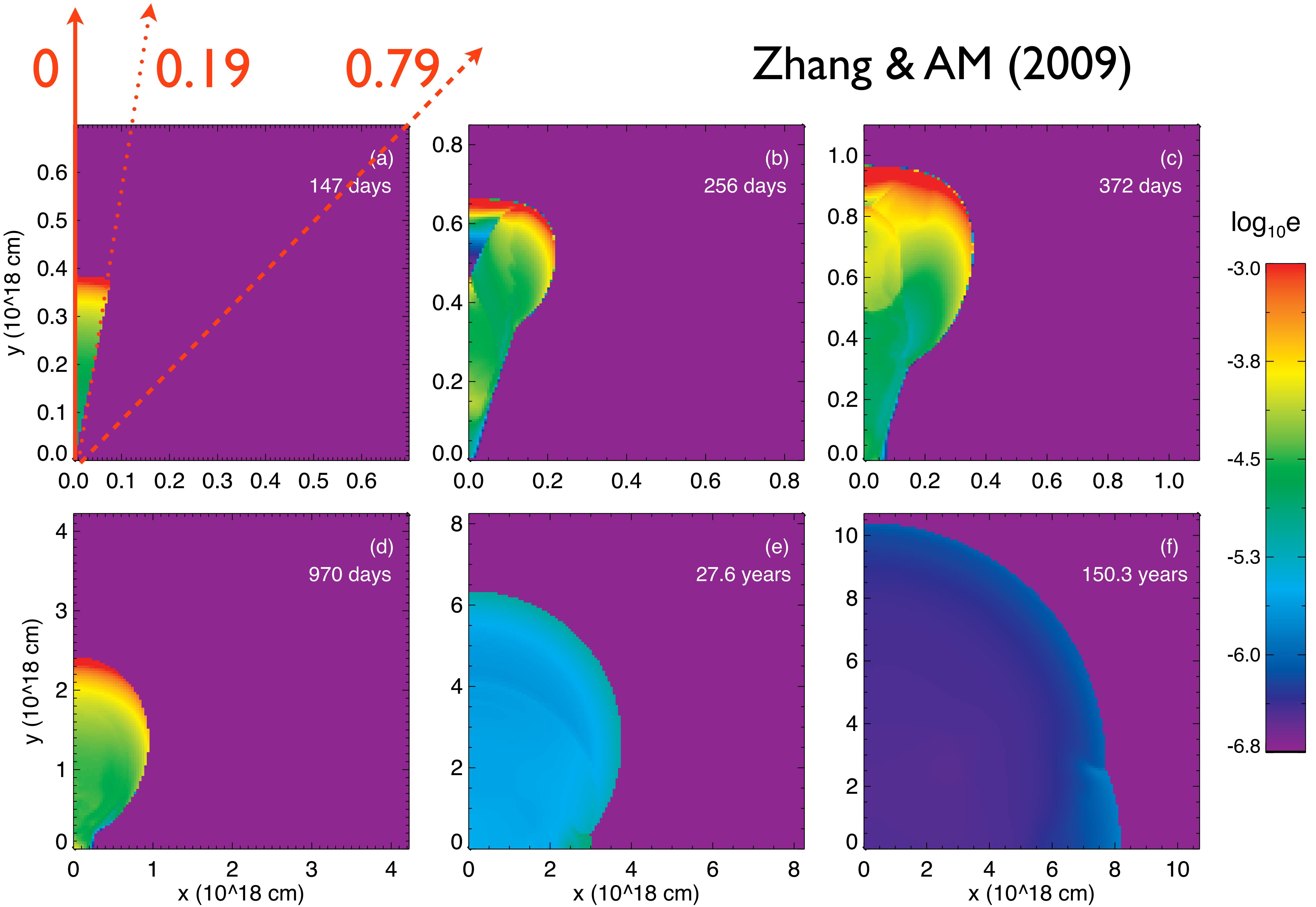
Model parameters:

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



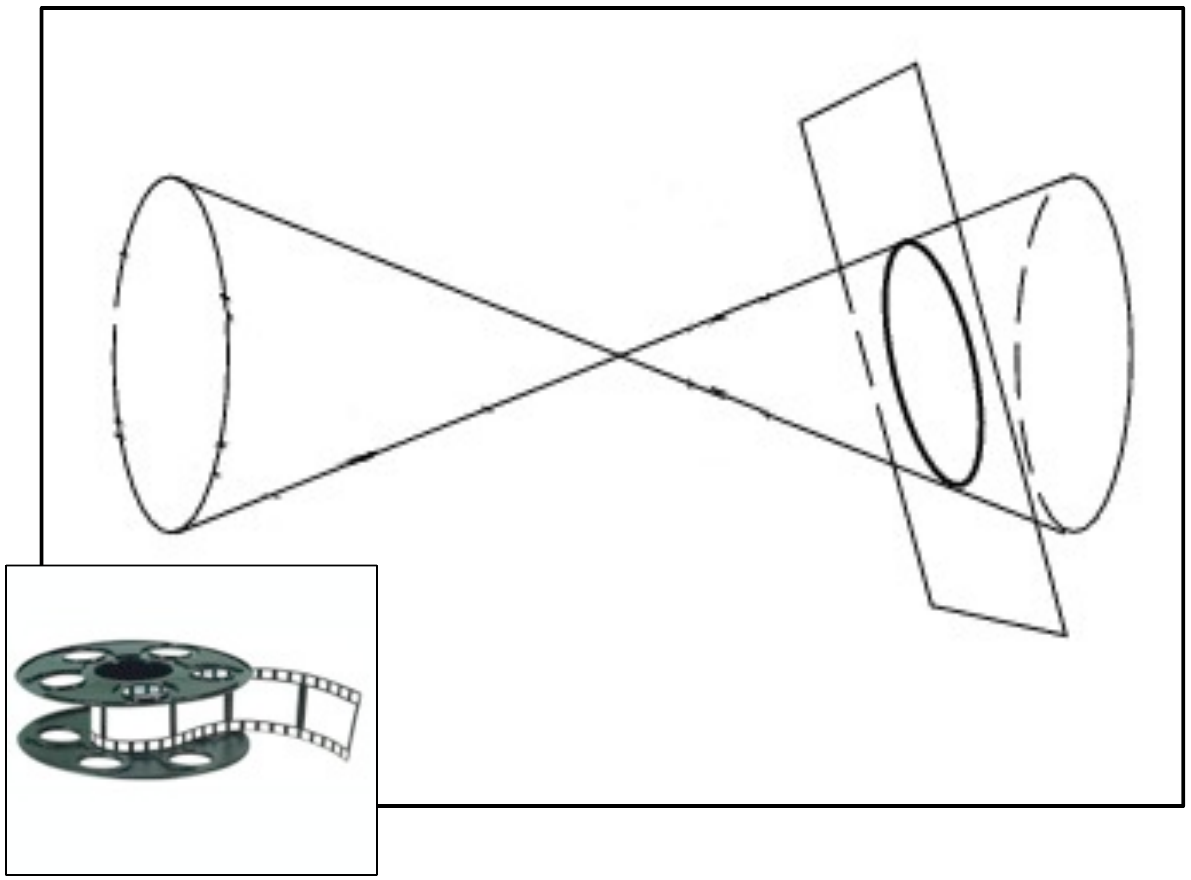
Ej = 2e52
θj=0.05
n=1cm^-3

van Eerten & AM (2011)


0
0.19
0.79
Zhang & AM (2009)
(a)
147 days
(b)
256 days
(c)
372 days
(d)
970 days
(e)
27.6 years
(f)
150.3 years
log10e
-3.0
-3.8
-4.5
-5.3
-6.0
-6.8
y (10^18 cm)
x (10^18 cm)

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

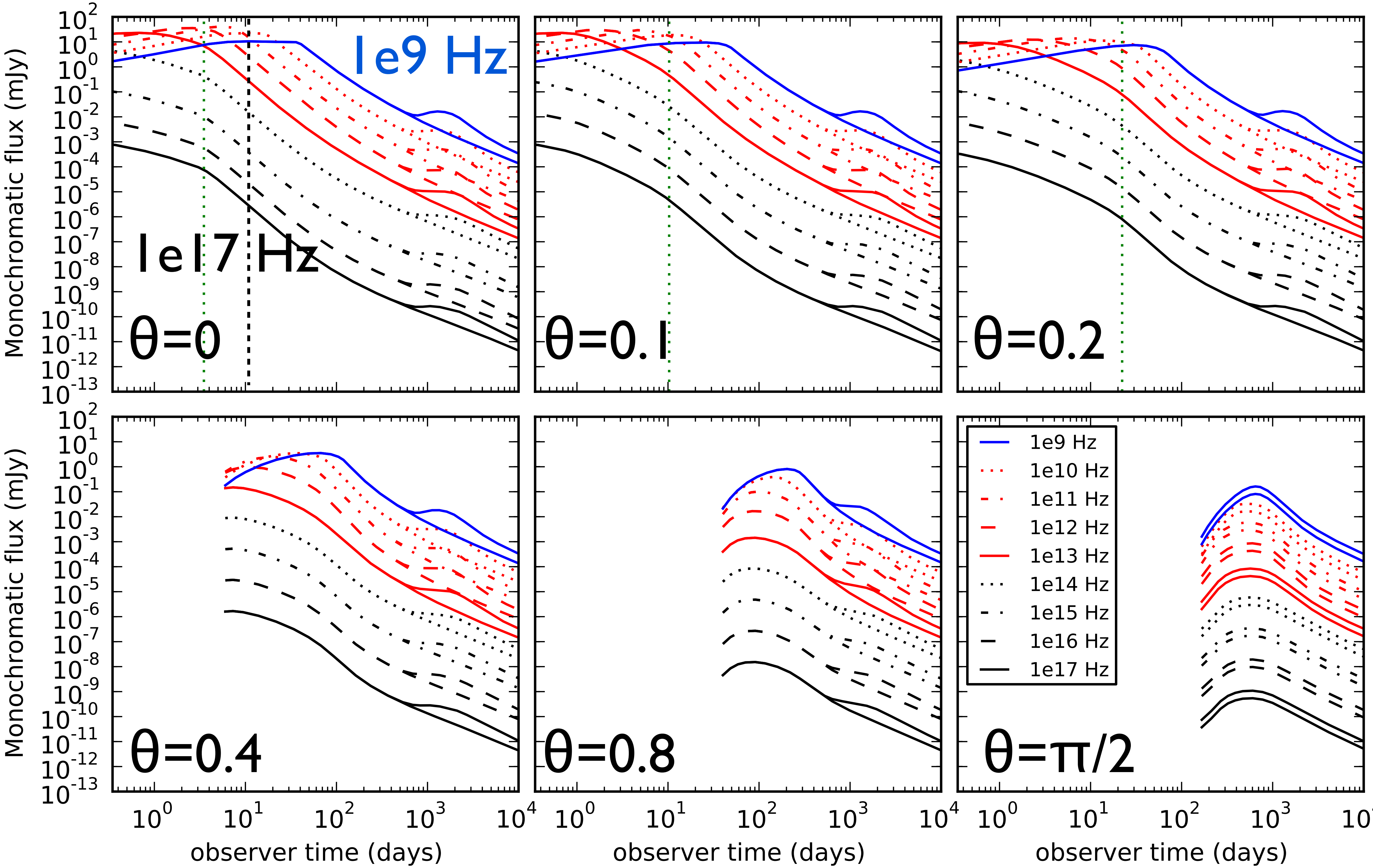
$$\frac{dI_\nu}{dz} = -\alpha_\nu I_\nu + j_\nu$$

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

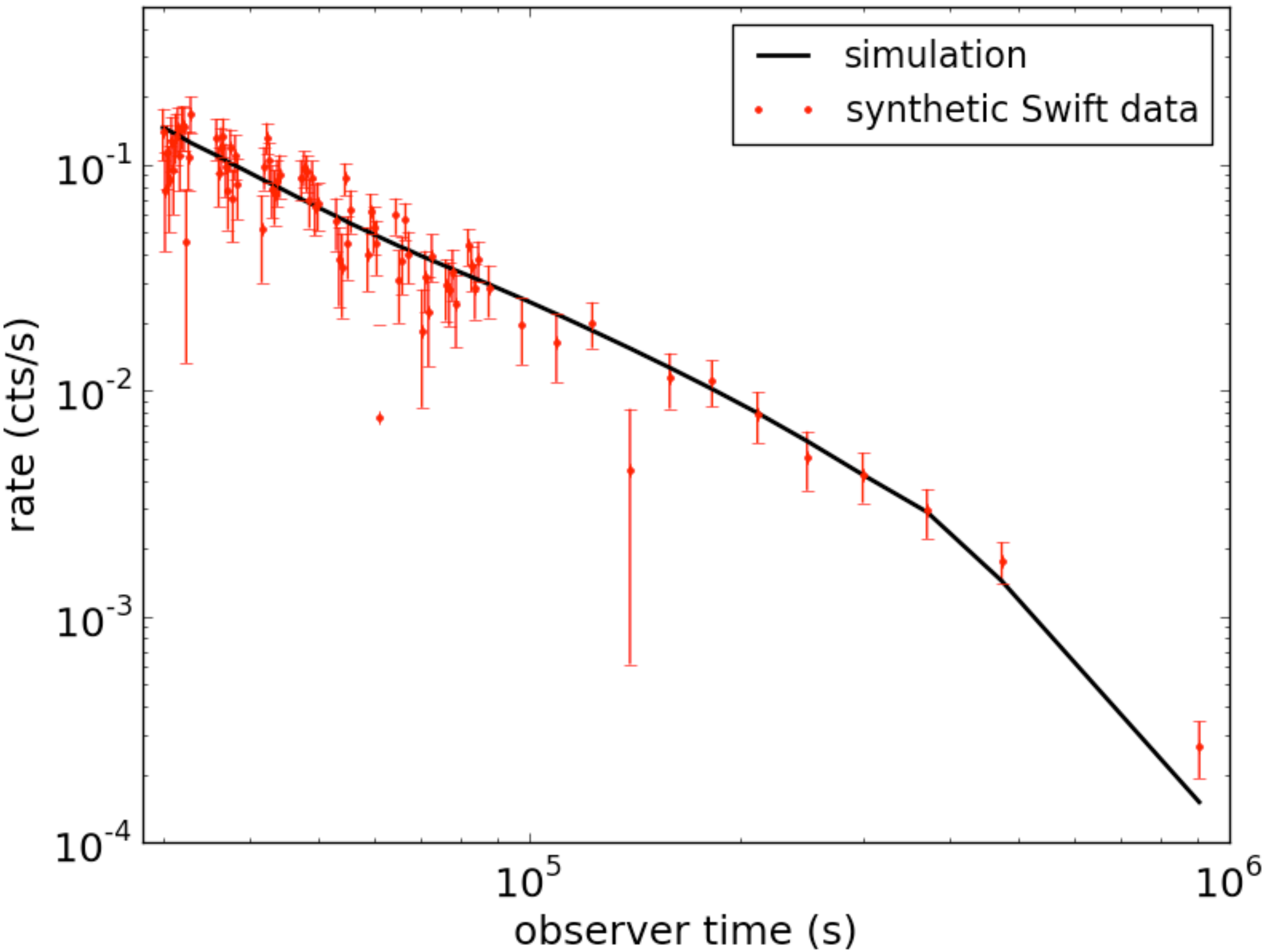
the challenge: *the jet nearly keeps up with its radiation*

Off-Axis Light Curves

van Eerten, Zhang & AM (ApJ, 2010)



On Axis



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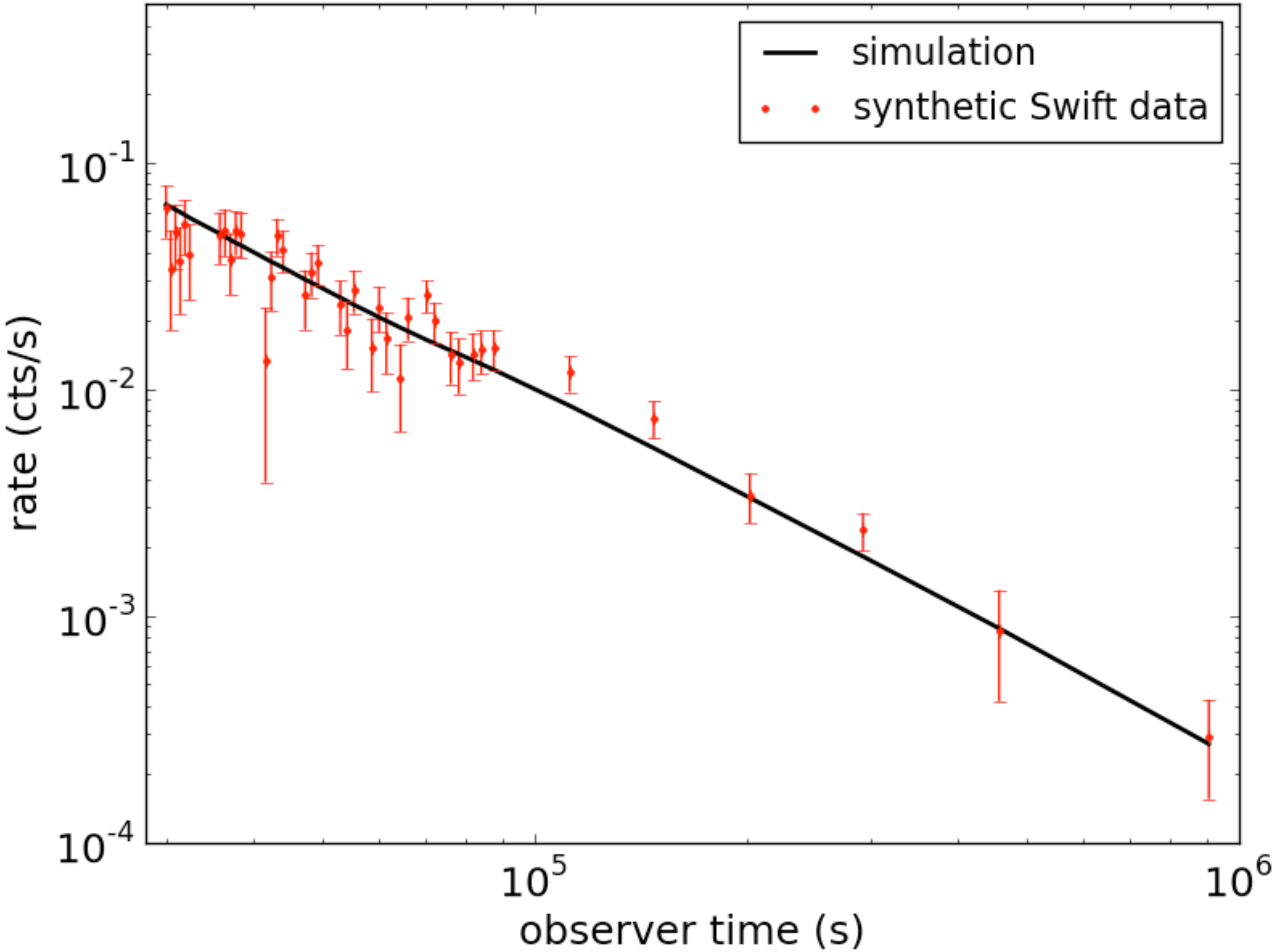
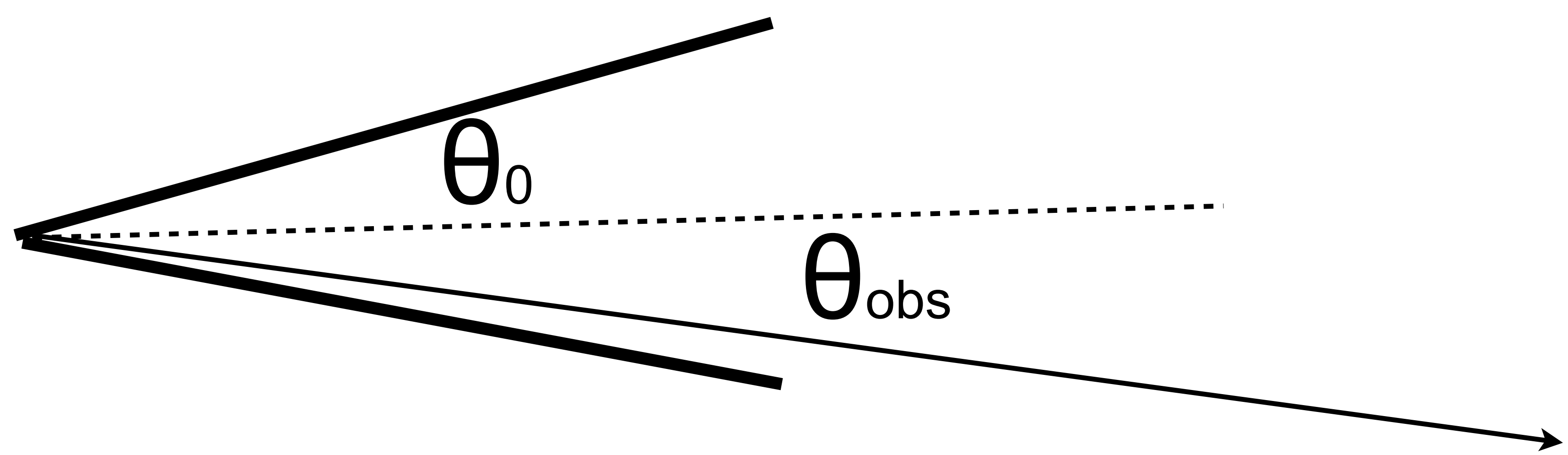
On Edge



A. MacFadyen (NYU)

Estimated Jet Break Time for Off-Axis Observer

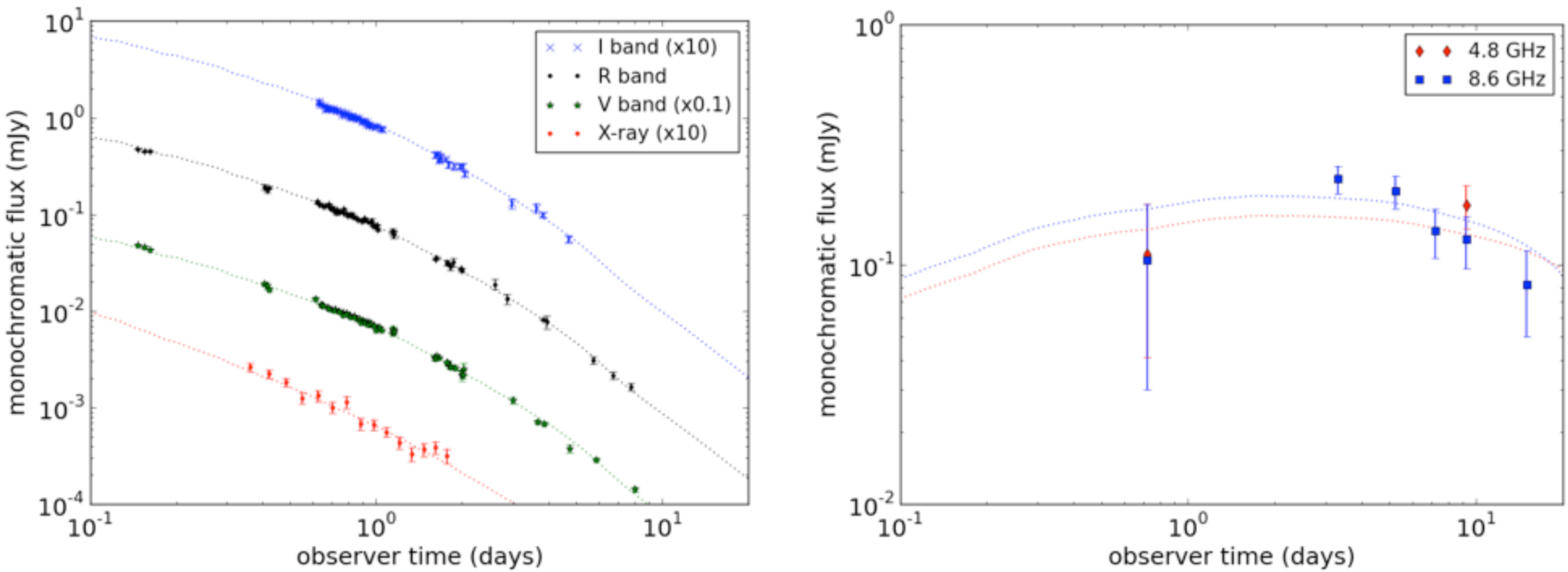
$$t_j = 3.5(1+z)E_{iso,53}^{1/3} n_1^{-1/3} \left(\frac{\theta_0 + \theta_{obs}}{0.2} \right)^{8/3} \text{ days,}$$



Theta_likely = 2/3 Theta_0

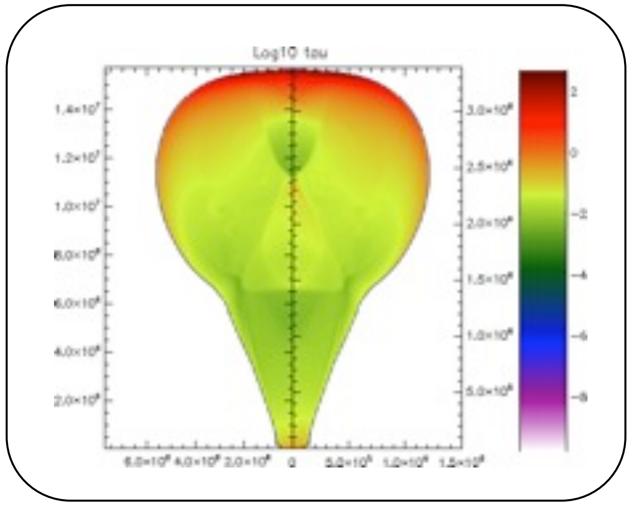
A. MacFadyen (NYU)

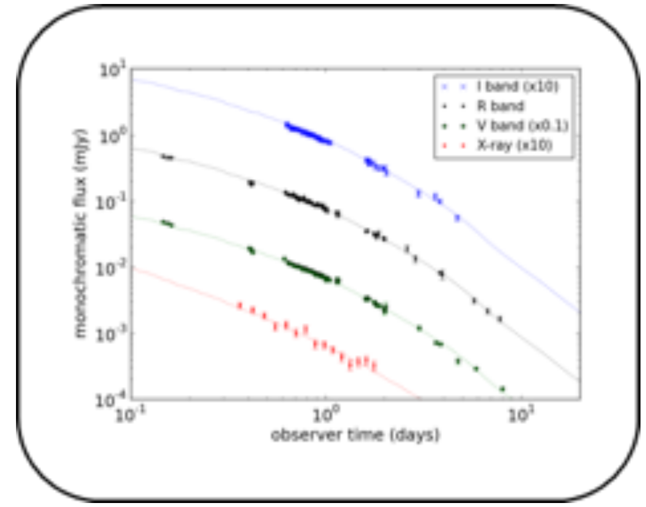
Example application: model fit to GRB 990510



- **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

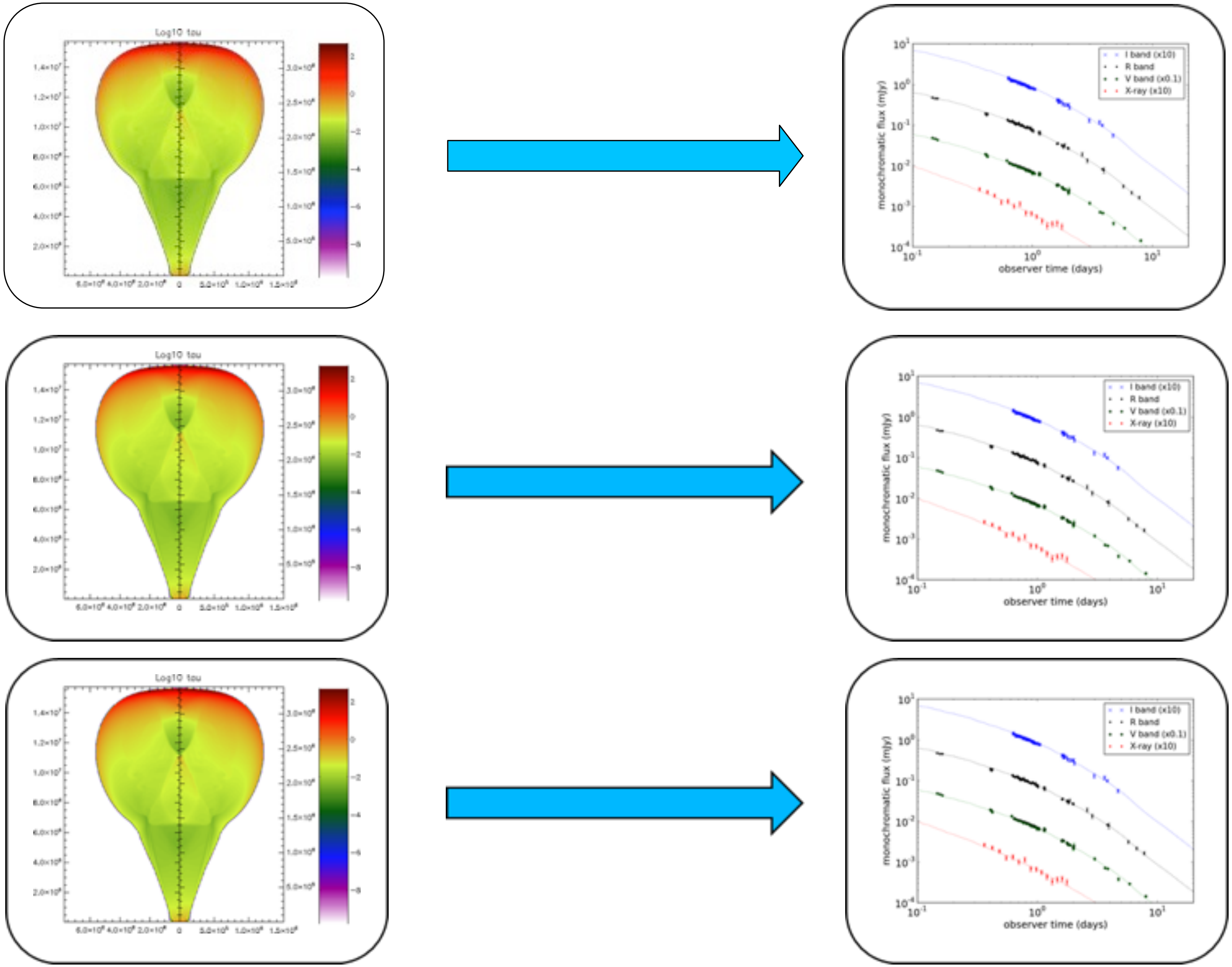
From AMR RHD simulation to light curve





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:

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

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)

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: $A \rightarrow 1$

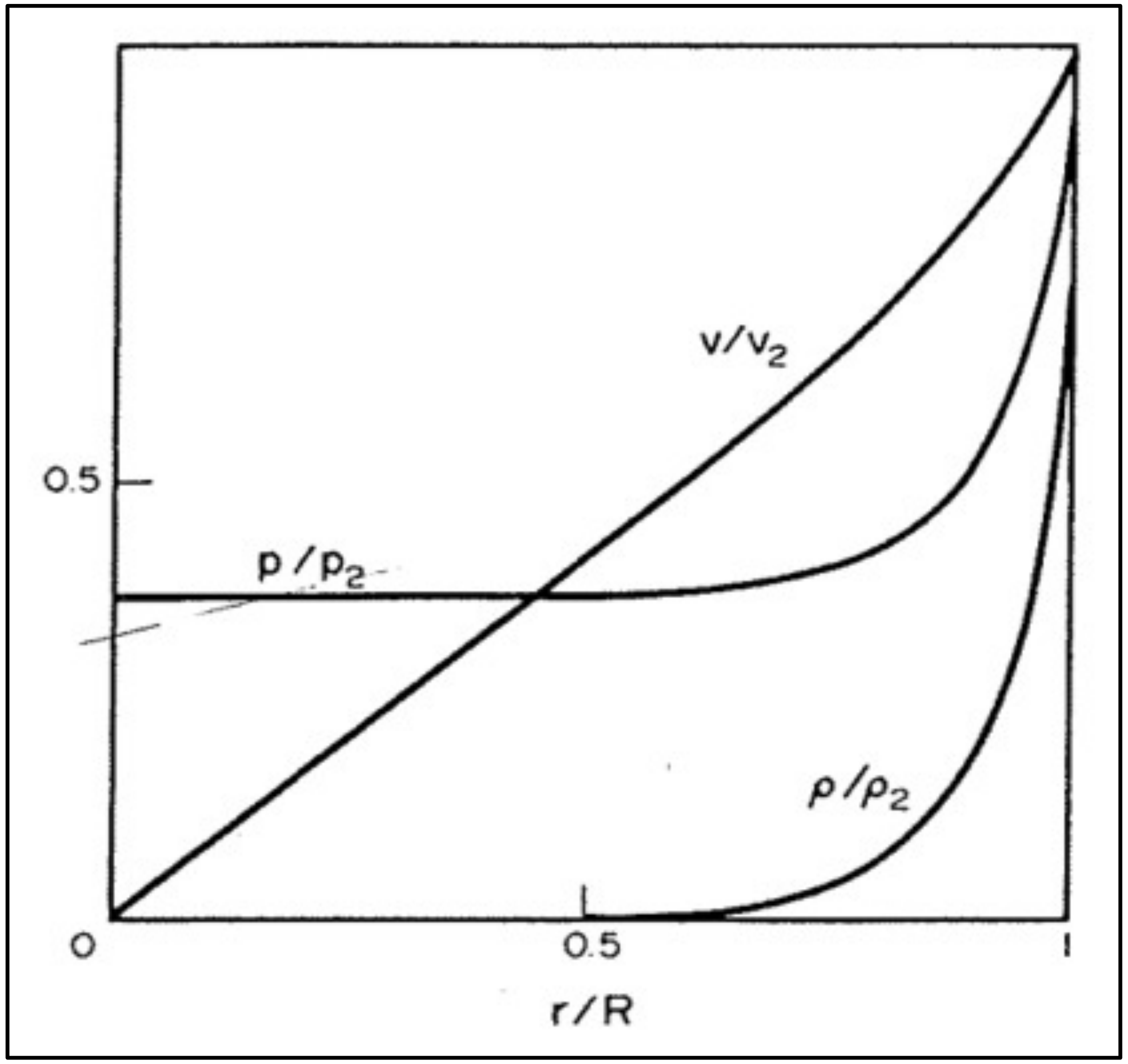
- nonrelativistic: $A \rightarrow \infty$

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

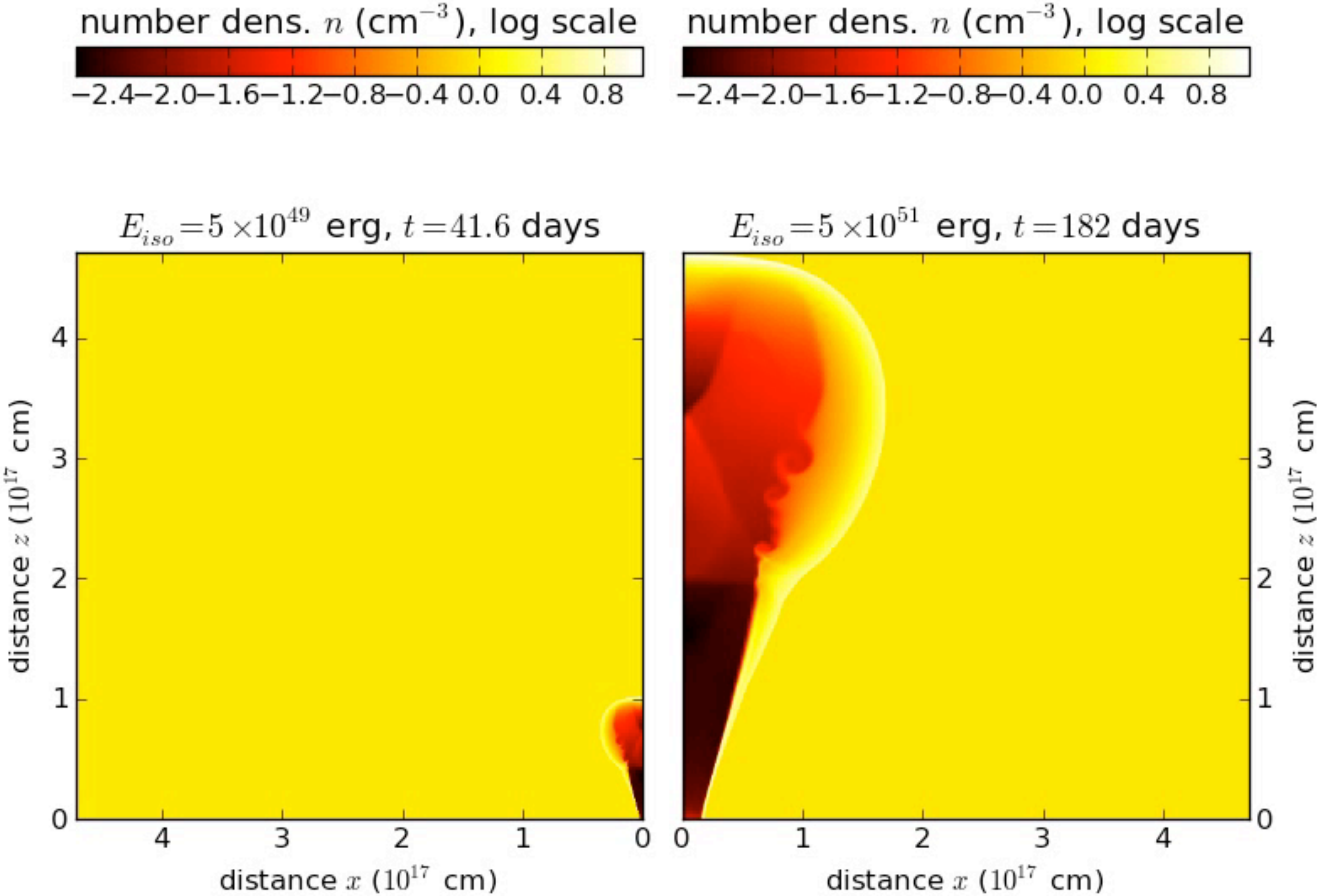
"Sedov-Taylor" non-relativistic



Sedov-Taylor blast wave
image: Landau & Lifshitz 1952

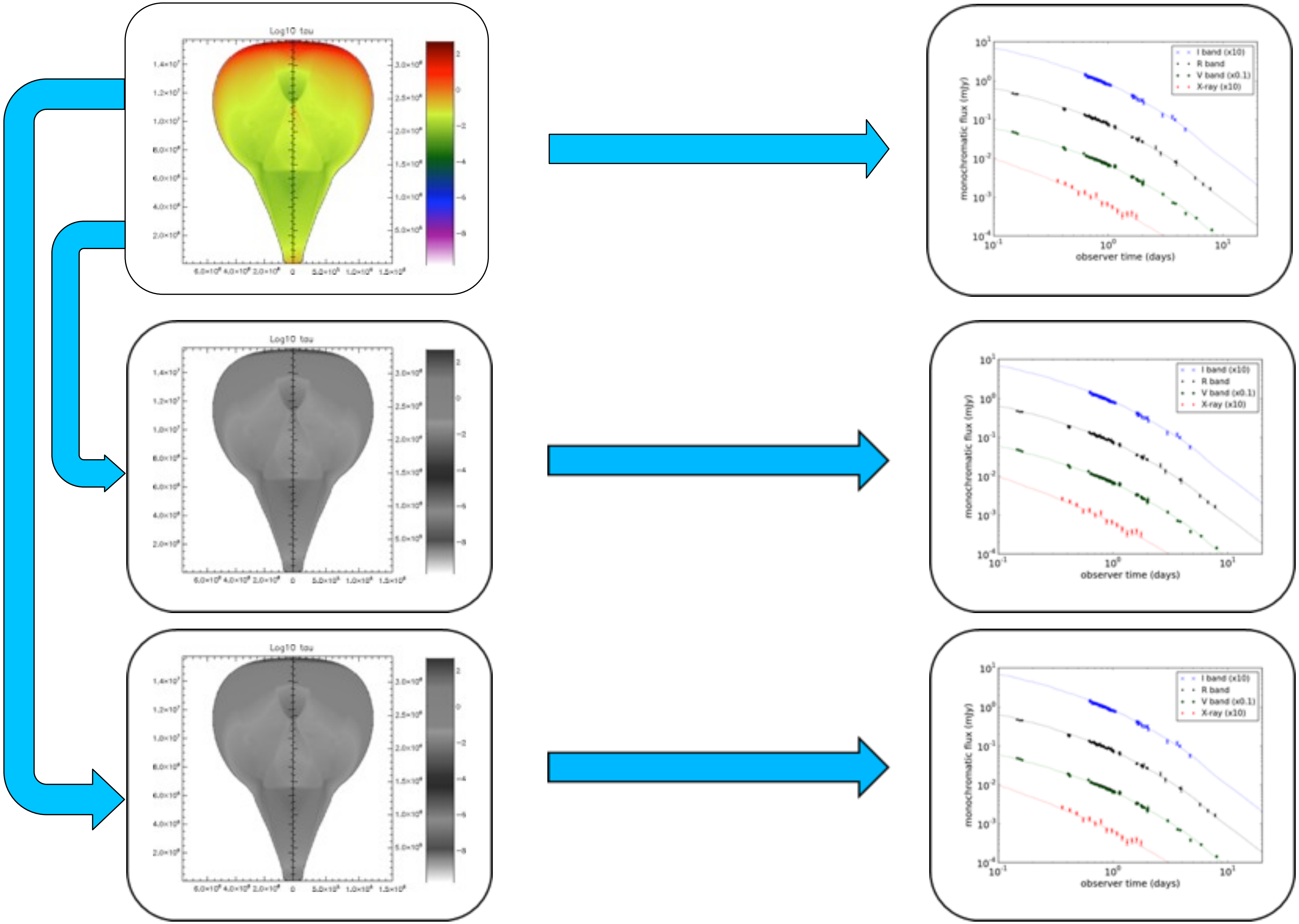
intermediate stage in 2D more complex

Scaling of Jet Dynamics

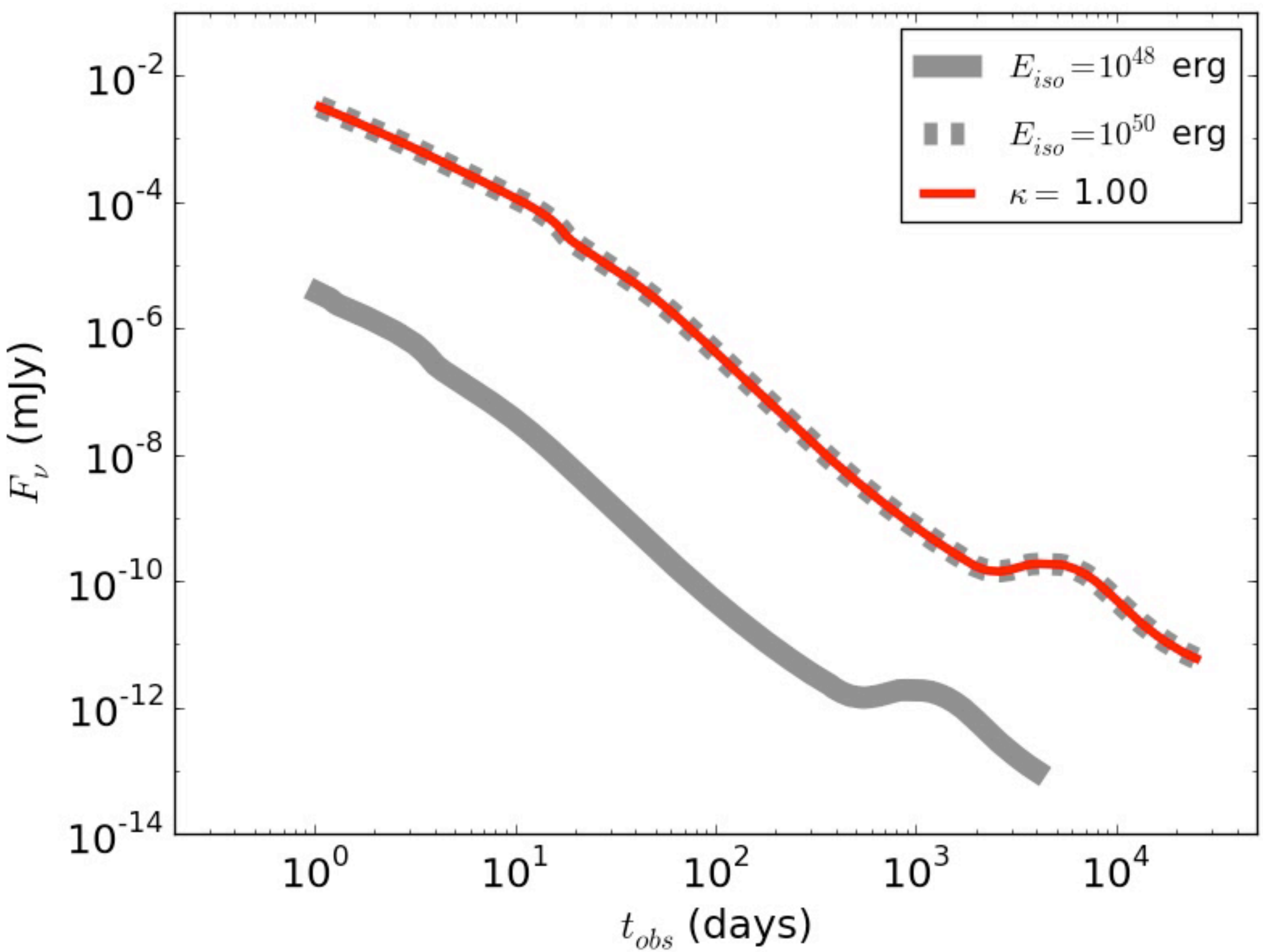


$$E'_{iso} = \kappa E_{iso}, \quad n' = \lambda n, \quad t' = (\kappa/\lambda)^{1/3} t, \quad r' = (\kappa/\lambda)^{1/3} r$$

Calculate jet dynamics by applying scaling



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

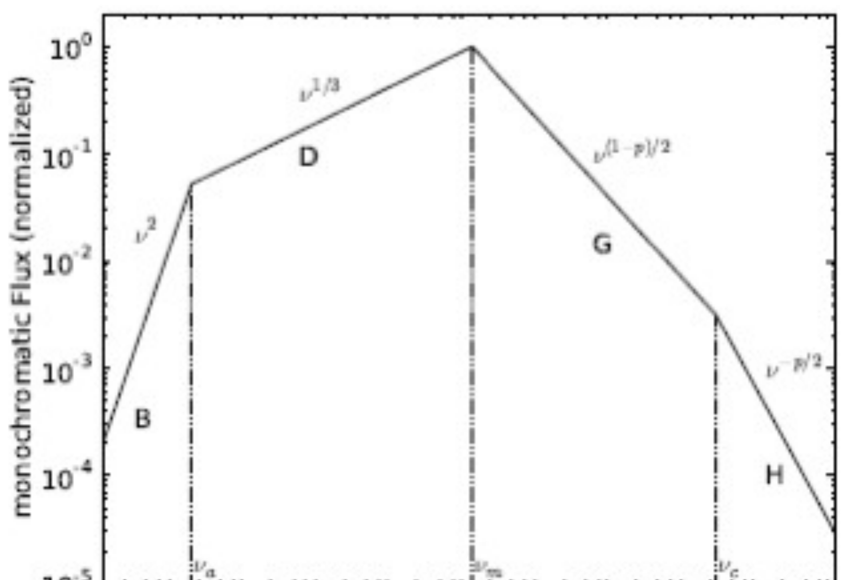


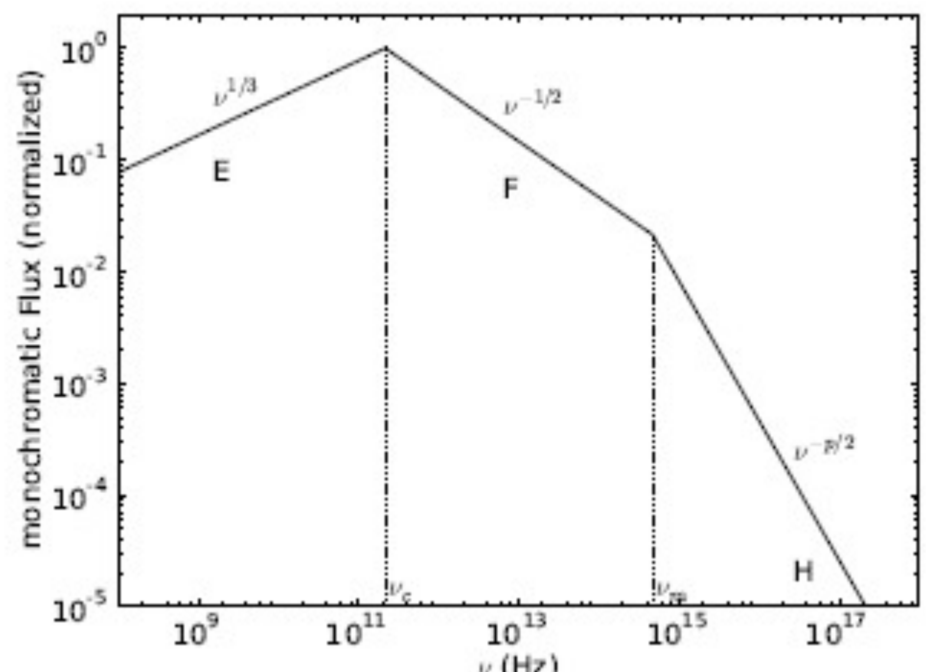
$$E'_{iso} = \kappa E_{iso}, \quad n' = \lambda n,$$

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

Scalings, the full formulae

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

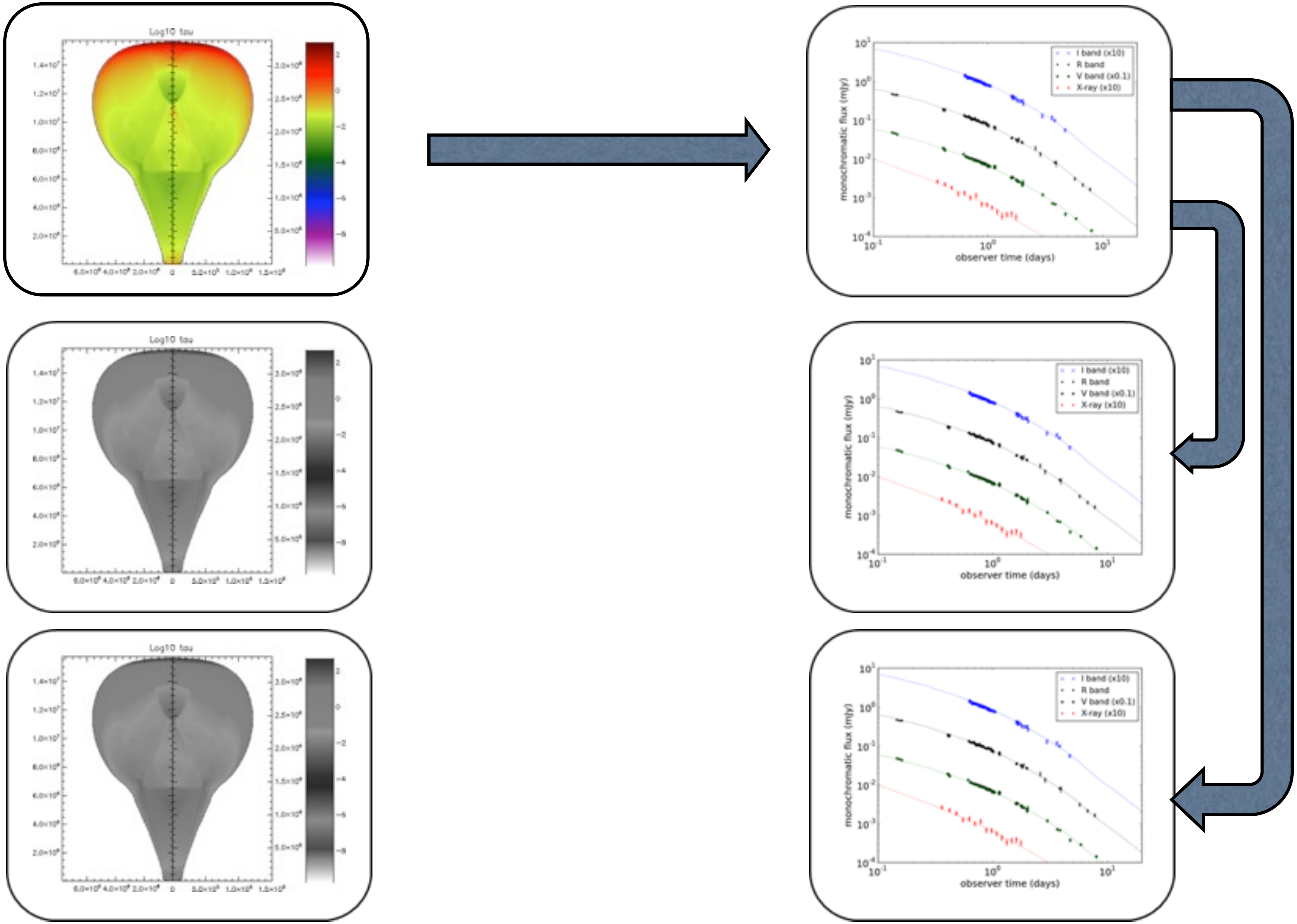




$$E'_{\rm iso} = \kappa E_{\rm iso}, \quad n' = \lambda n,$$

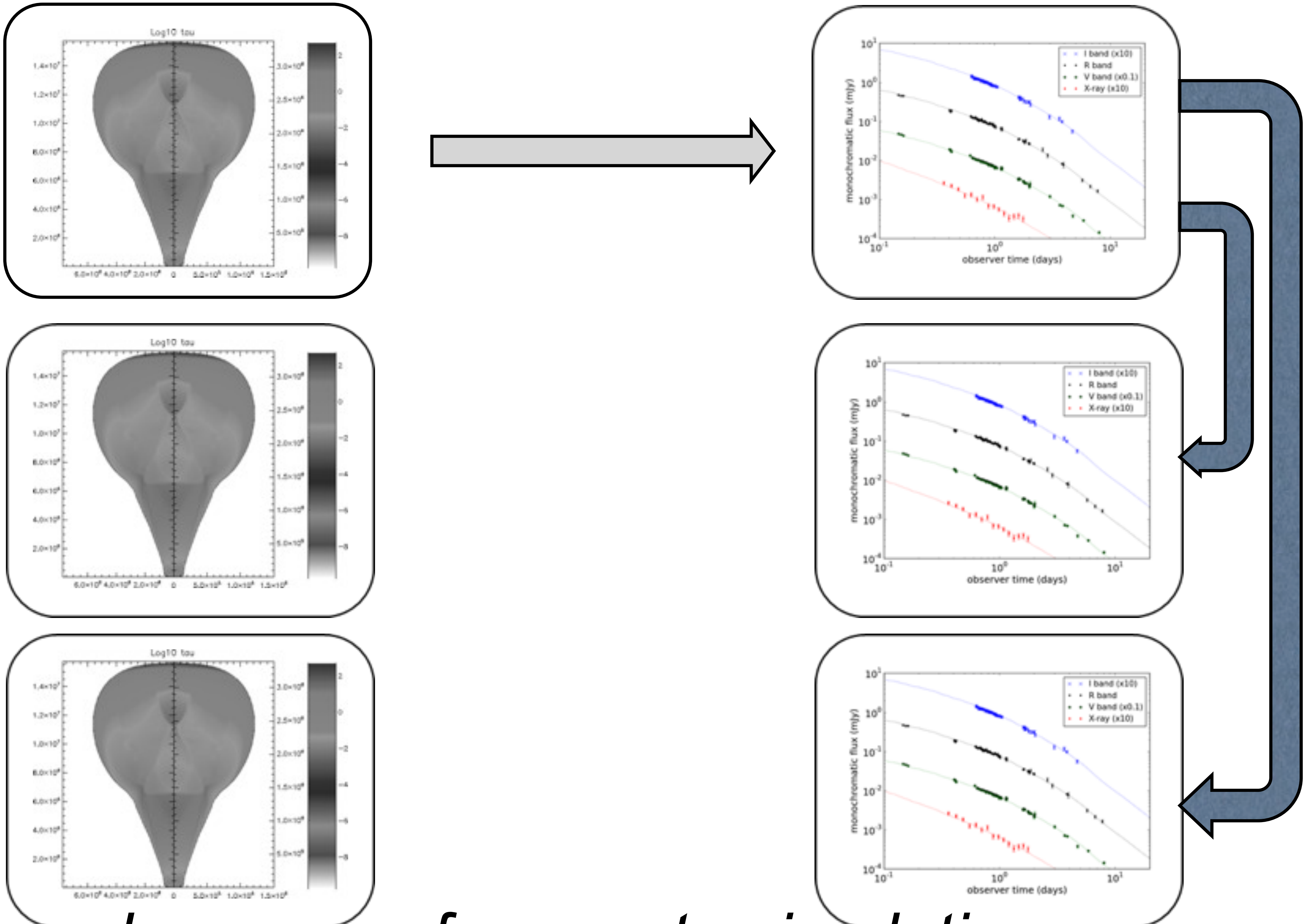
$$t'_{\rm obs} = (\kappa/\lambda)^{1/3} t_{\rm obs}, \quad F'_{\rm optical} = \kappa \lambda^{(1+p)/4} F_{\rm optical}$$

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!

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.

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)

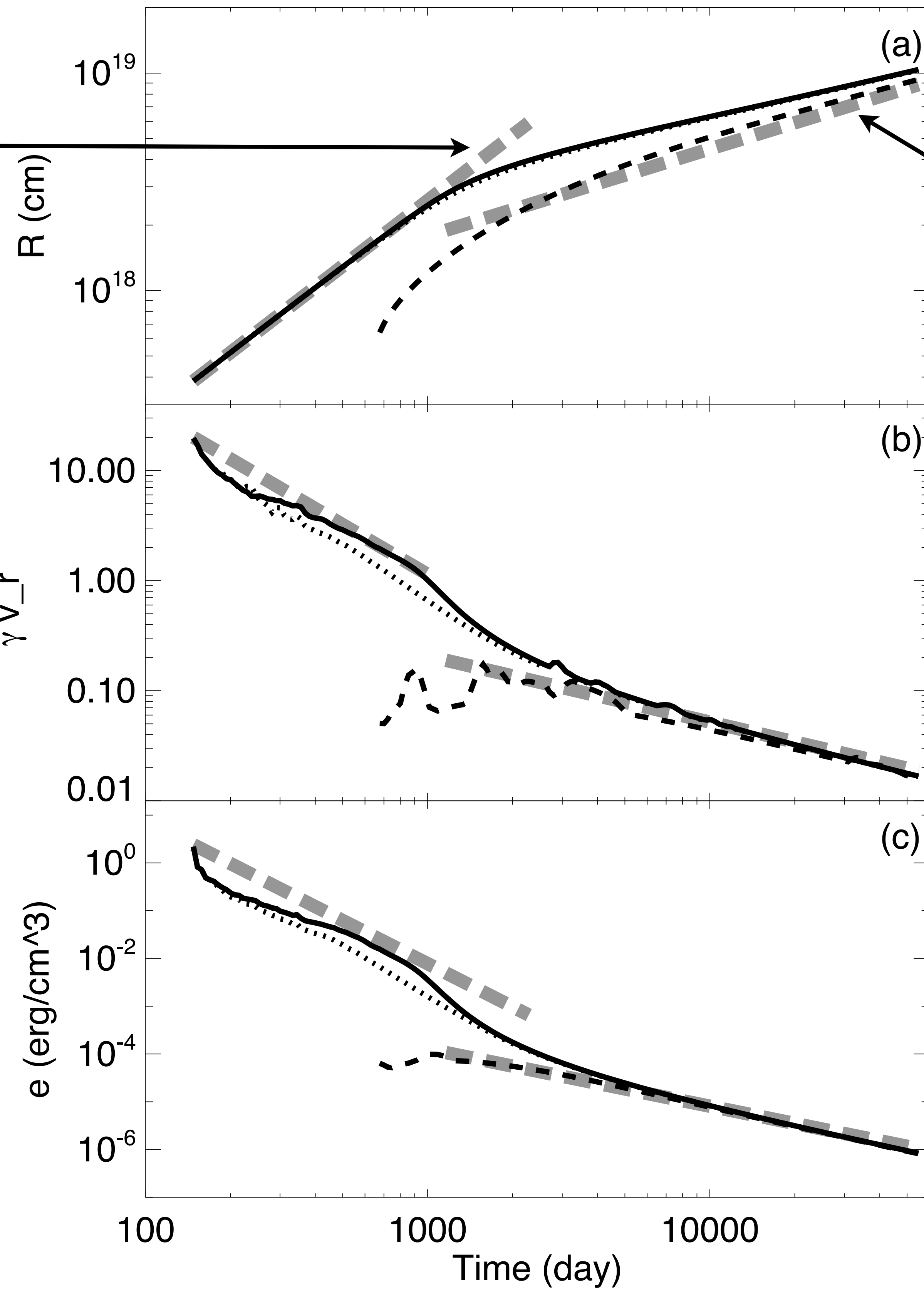
- calculate arbitrary parameter value light curves ‘on demand’

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
- 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



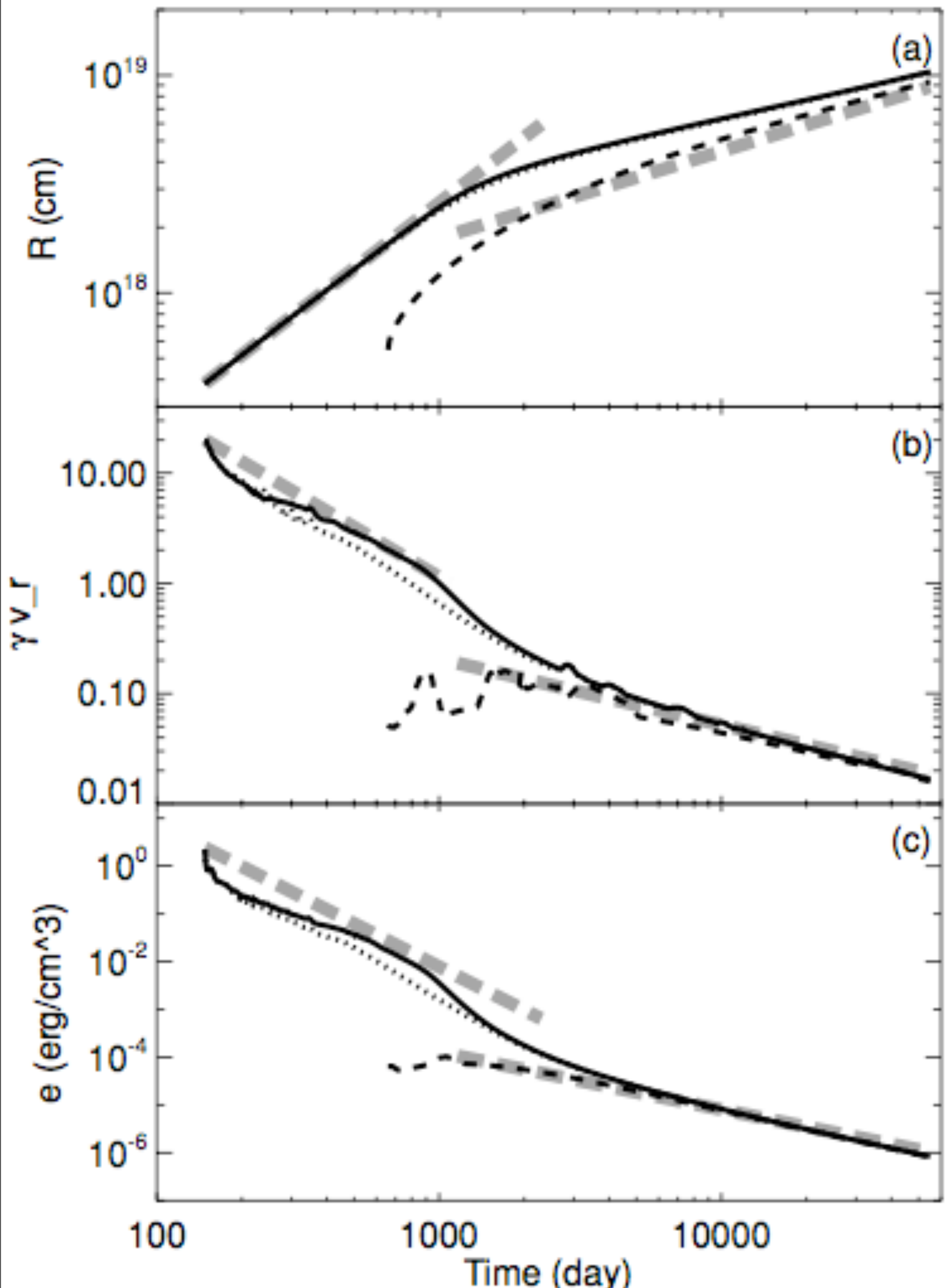
Blandford-McKee

Sedov

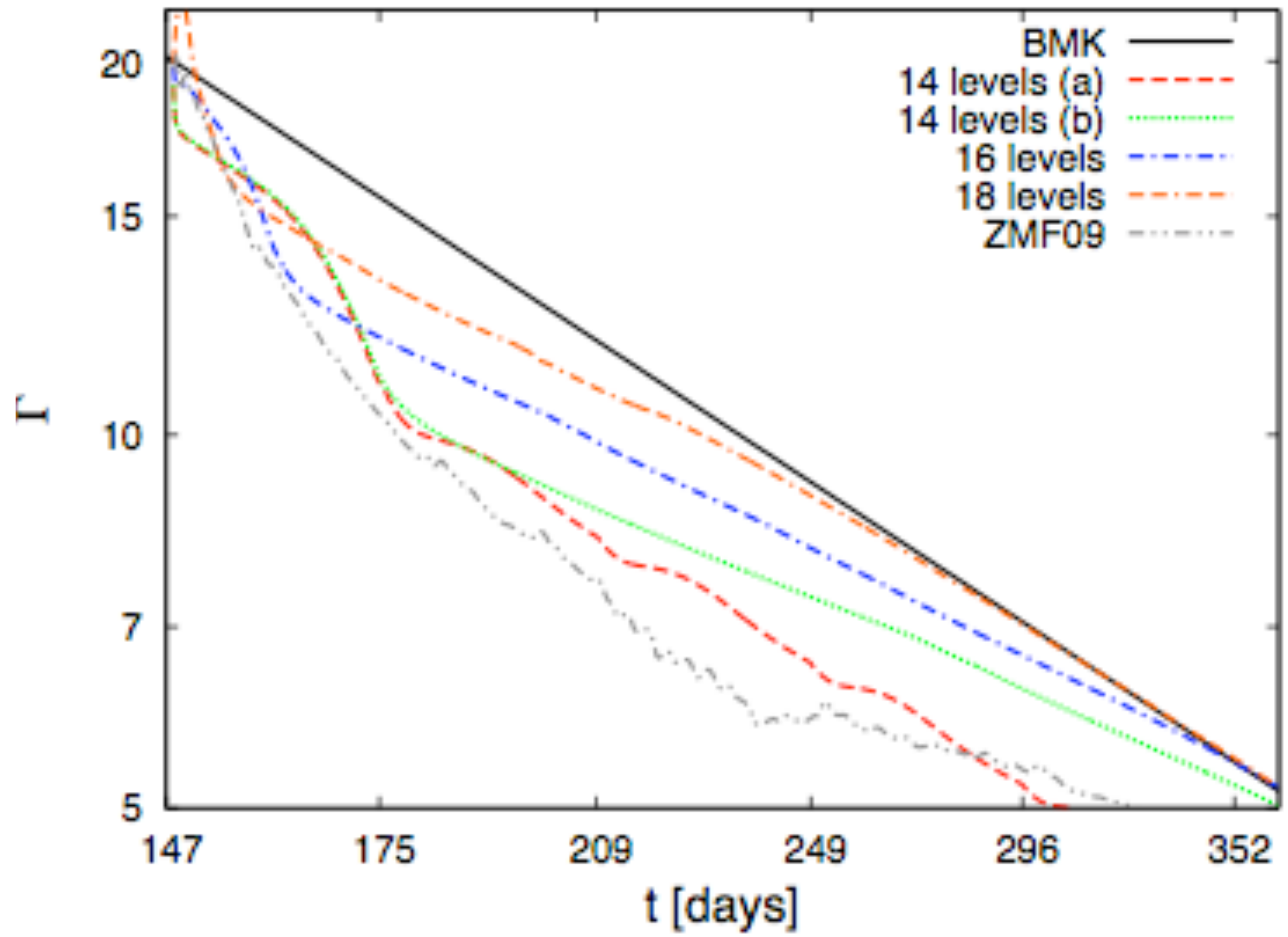
θj = 0.2

θ = 0,0.19,π/4

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



Zhang & AM (2009)

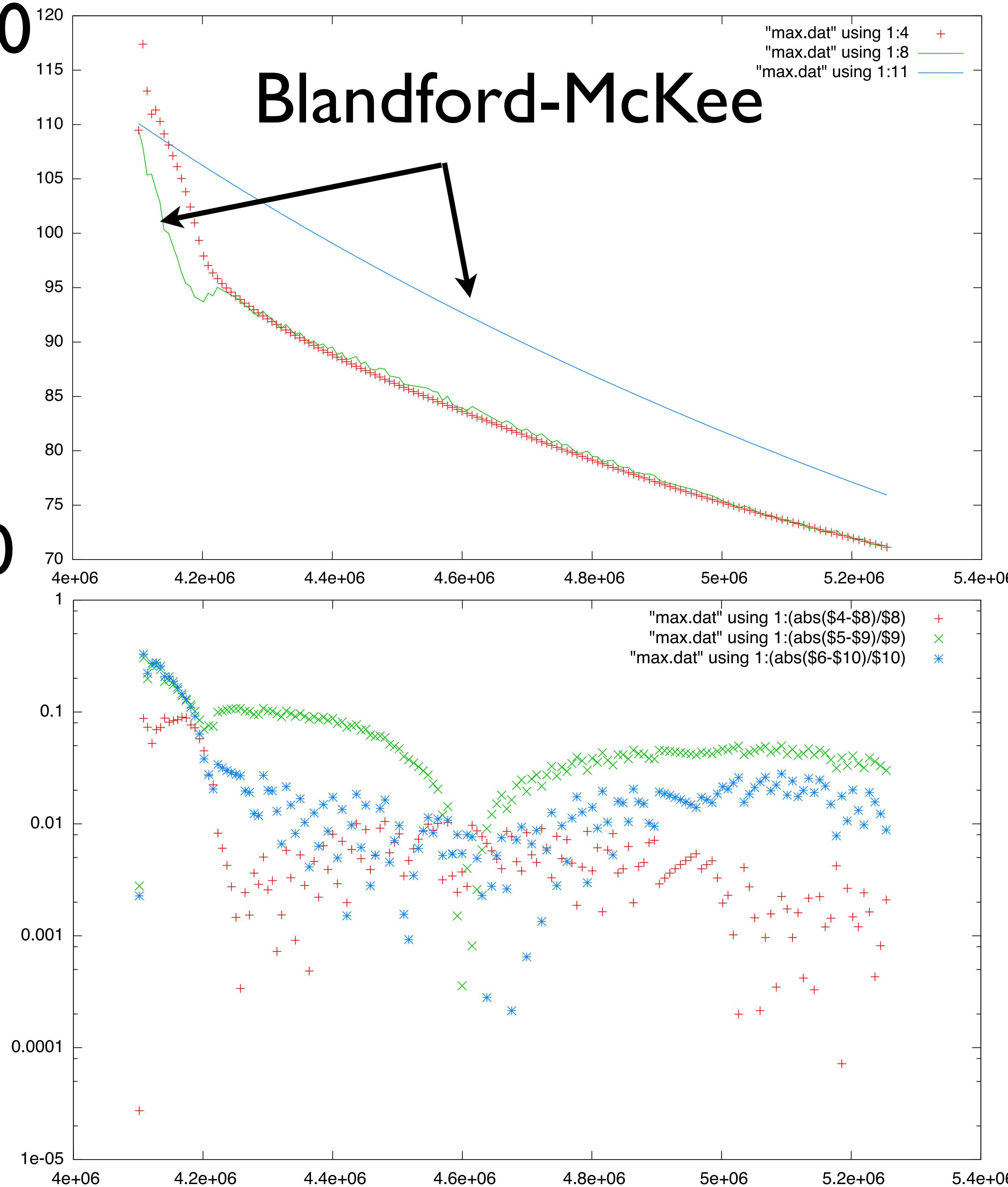


DeColle+ (2012)

θjet=0.05
Eiso=1e53
n=1

120
Γ
70

Blandford-McKee

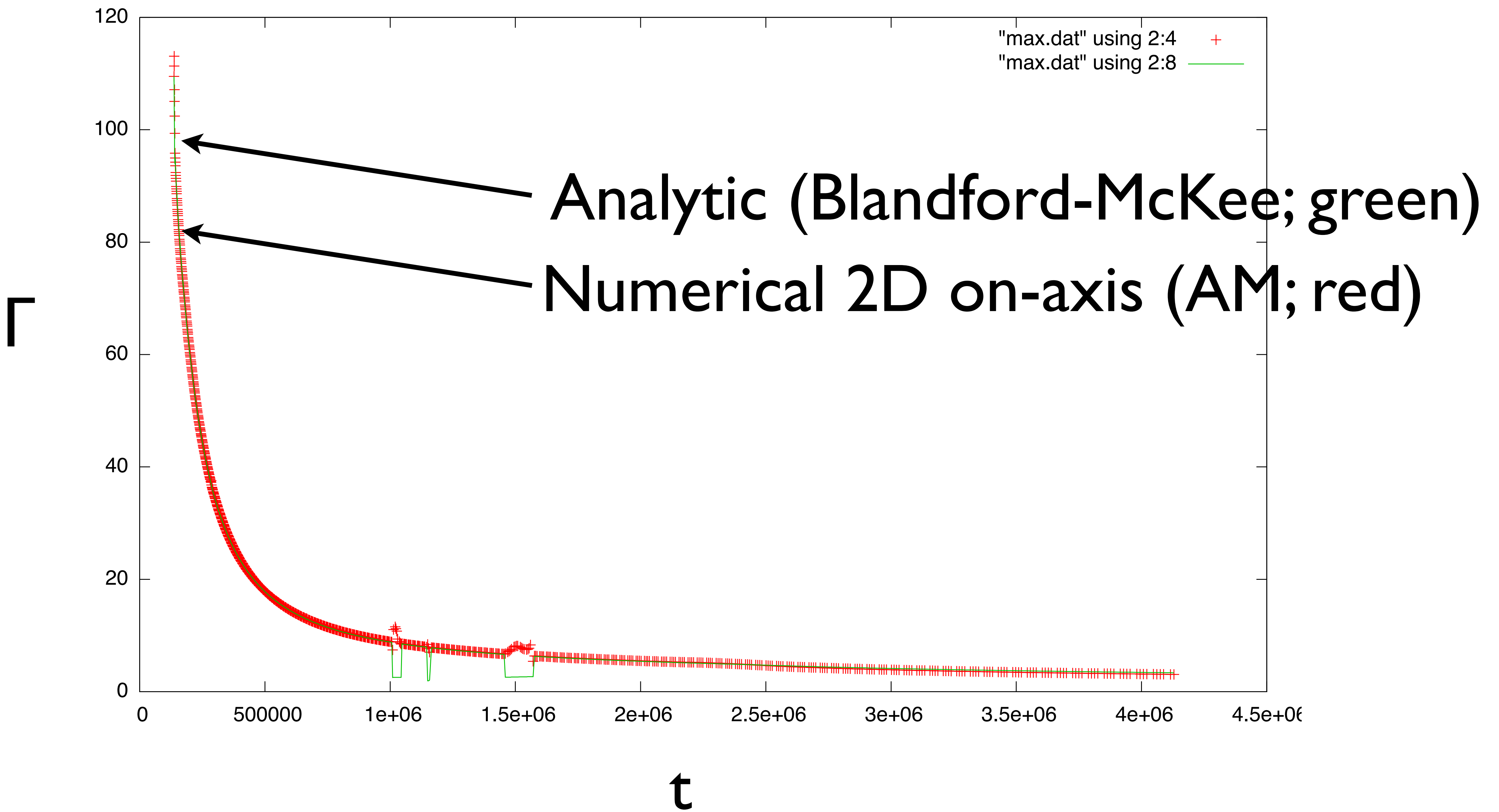


Fractional errors in Γ, P, ρ

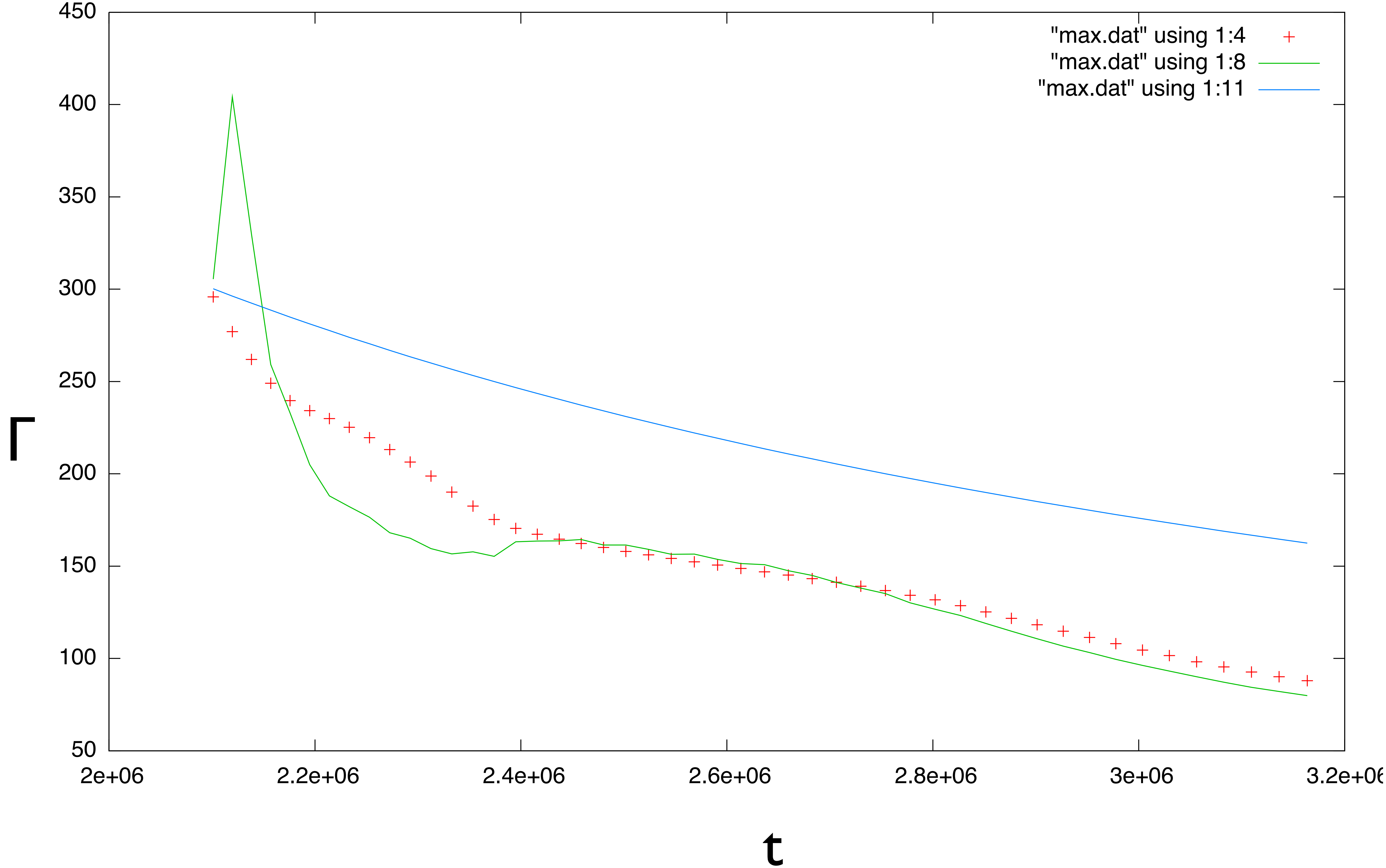
t (s)

AM (in prep, 2012)

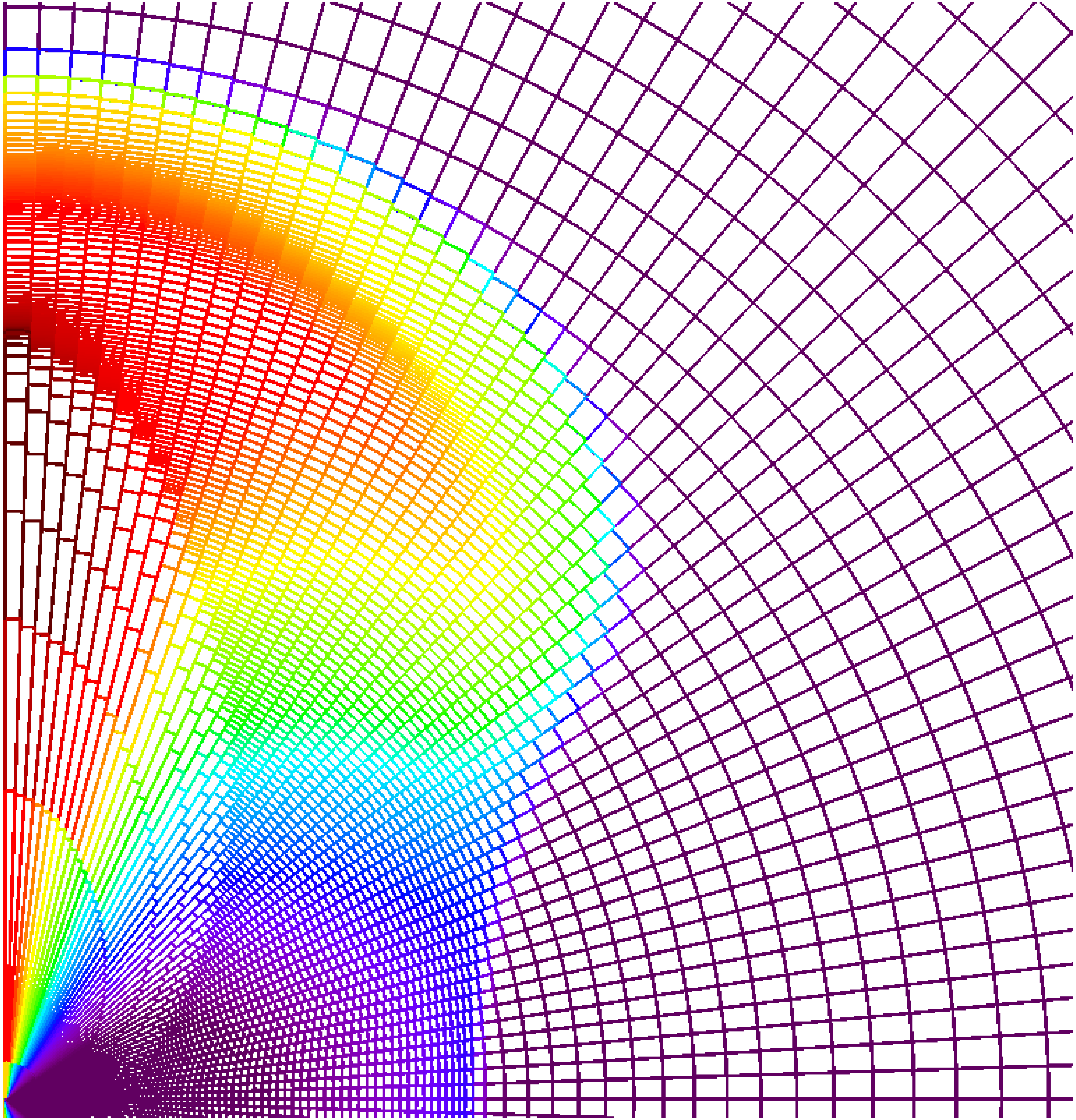
2D Moving Mesh: $\Gamma = 110$



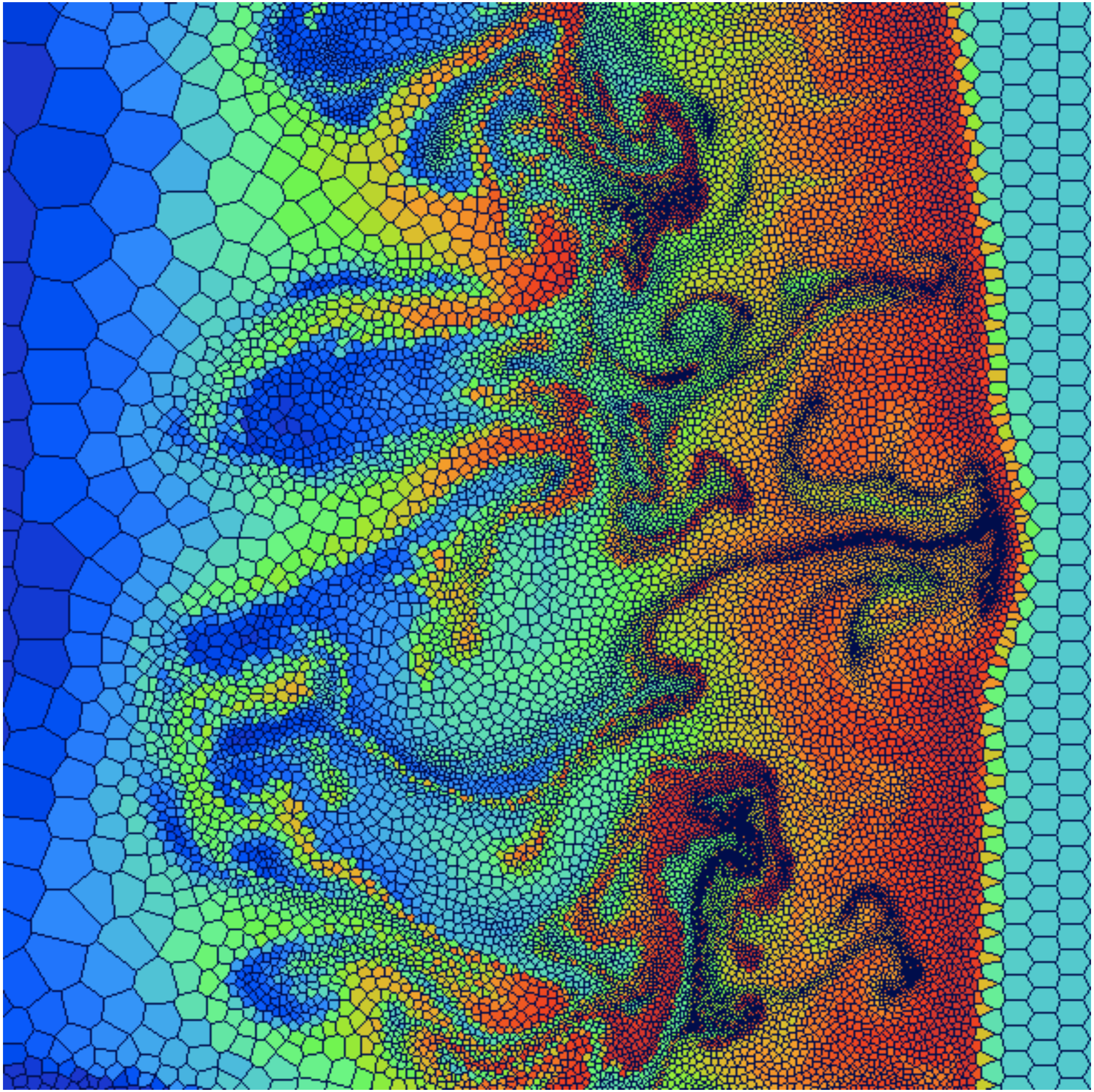
Γ = 300



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
"max.dat" using 1:4
"max.dat" using 1:8
"max.dat" using 1:11

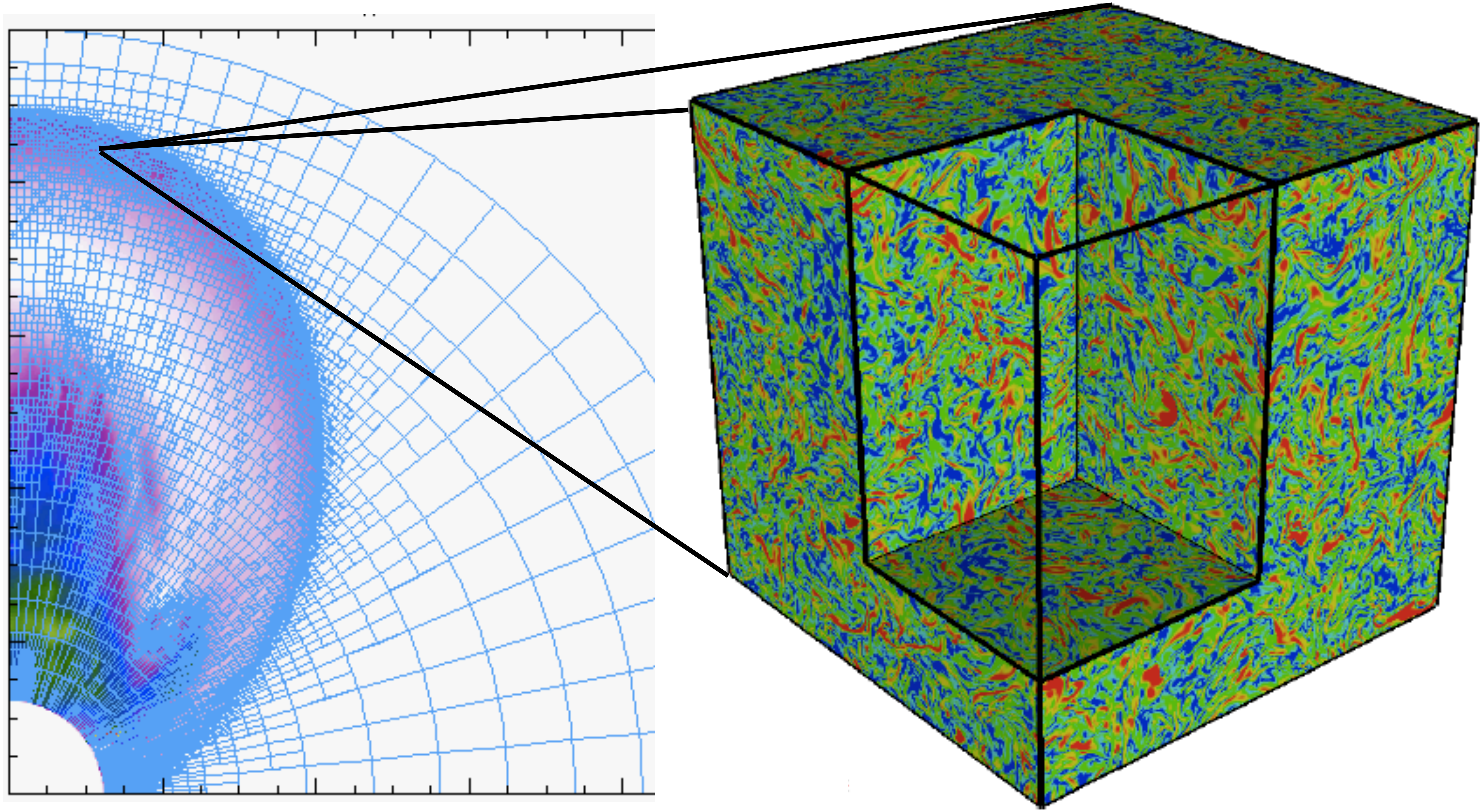


TESS
Duffel&AM
(2012)



TESS

Duffell&AM (2012)

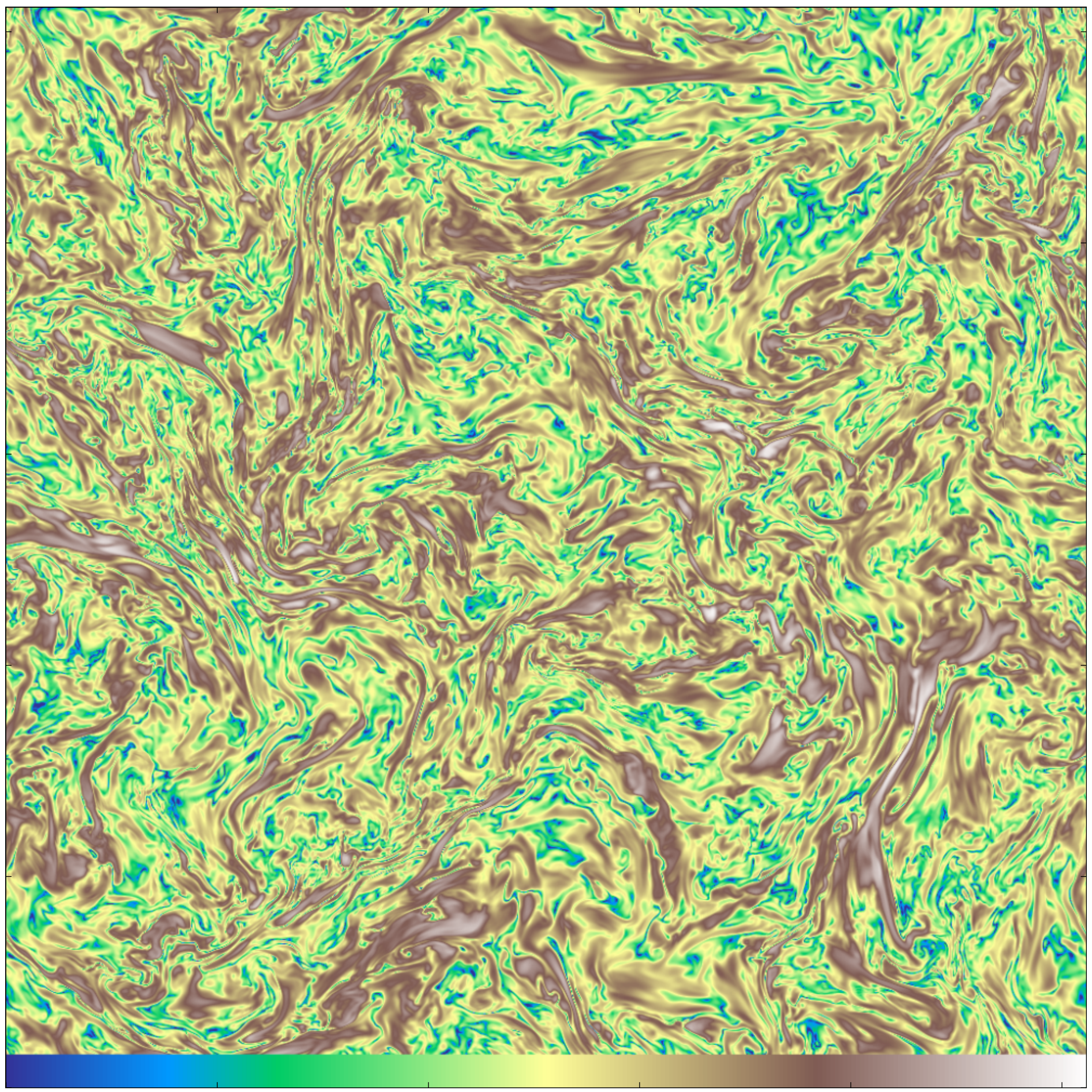


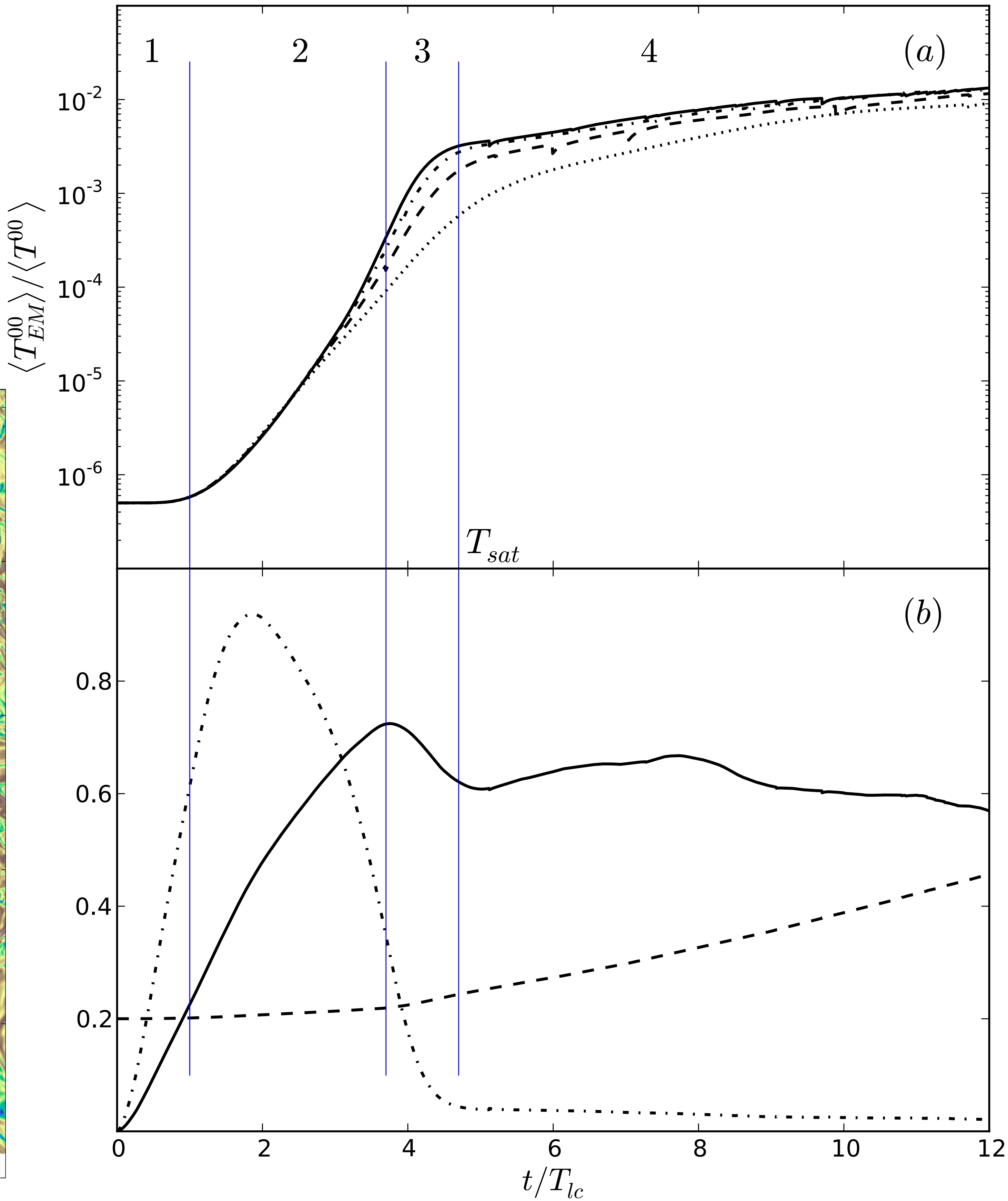
Zhang&AM (2009), van Eerten&AM (2011,2012)

Zhang, AM&Wang, ApJL (2009)

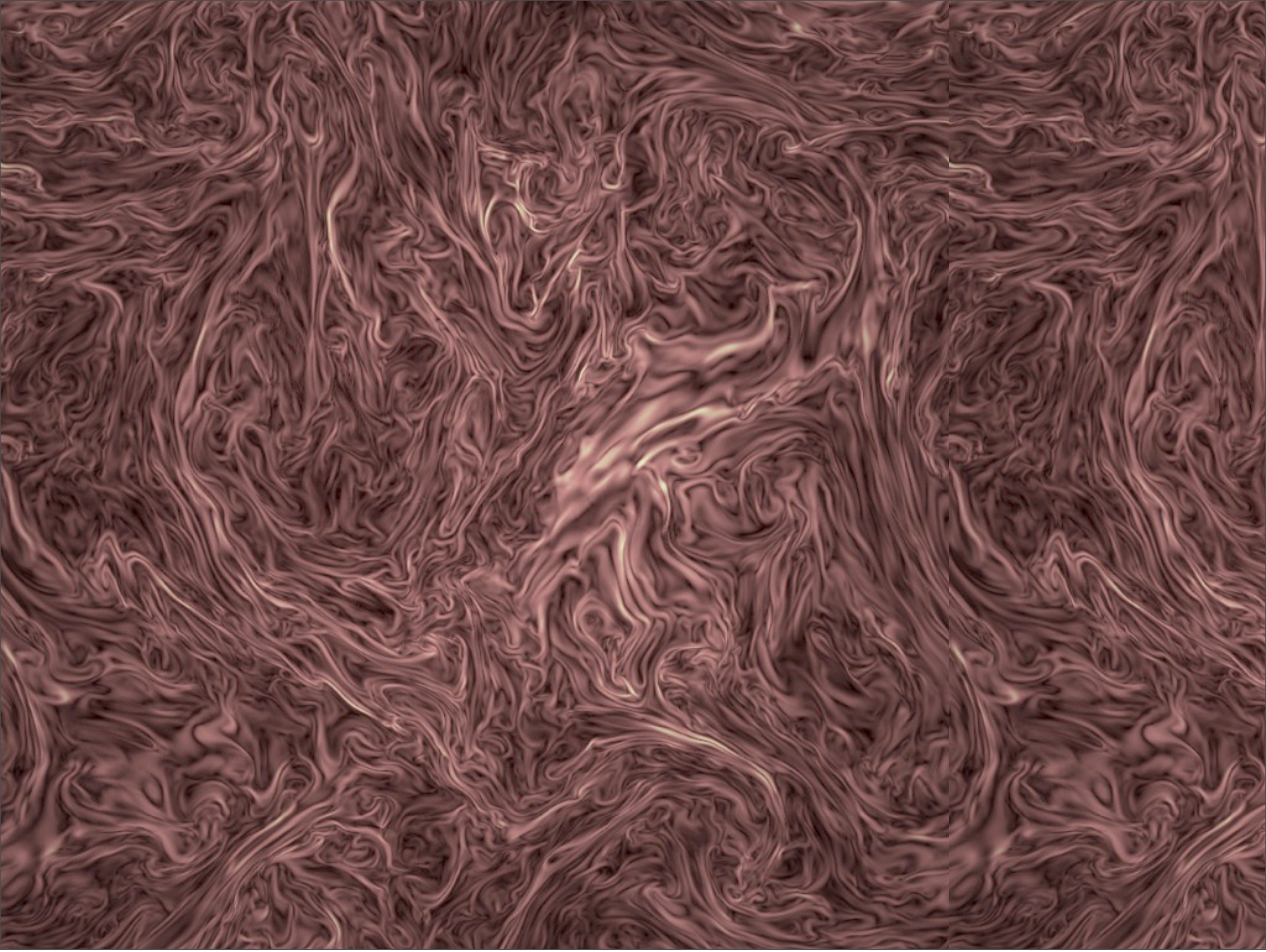
Turbulent amplification of Magnetic Field

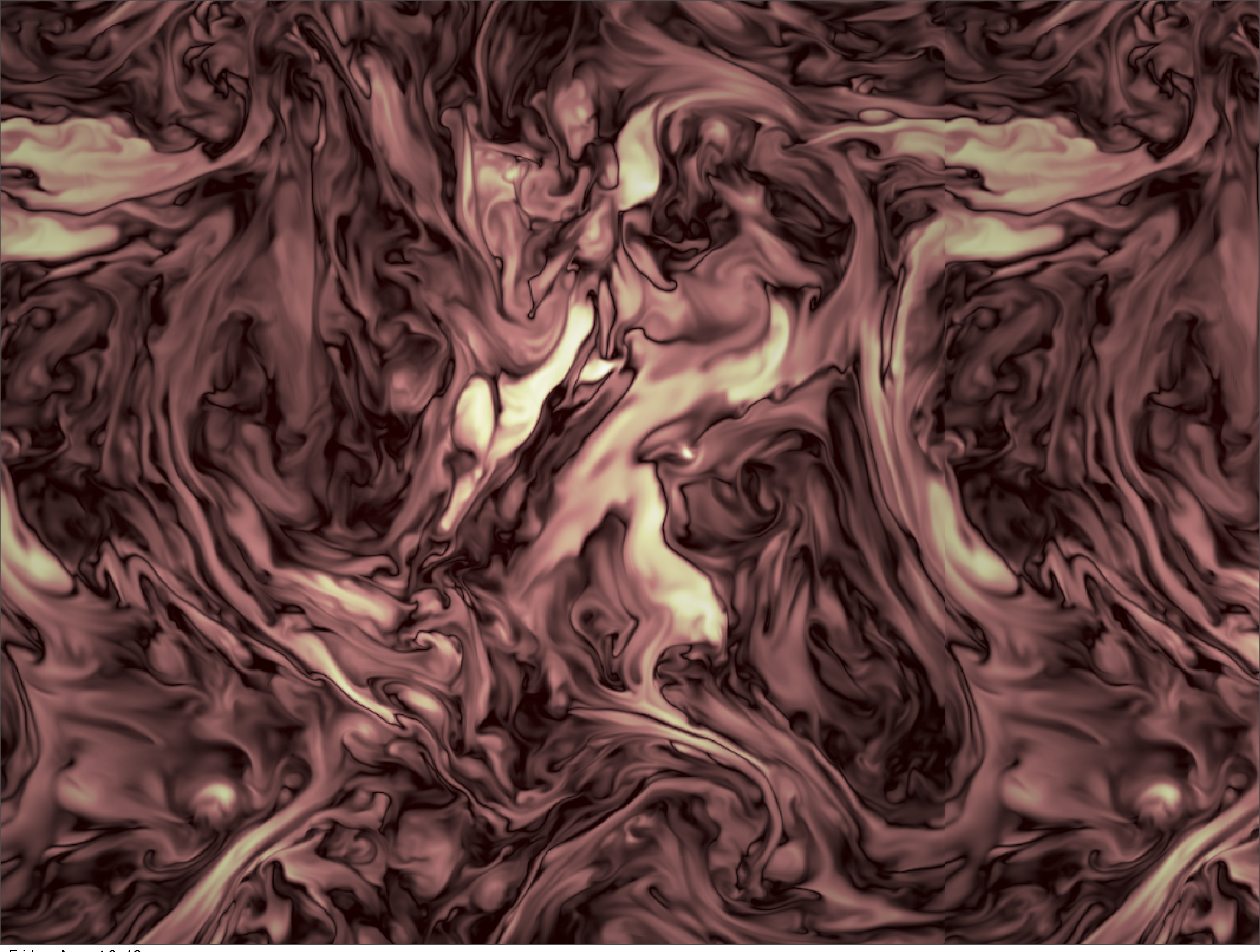
$\epsilon_B = 10^{-2}$



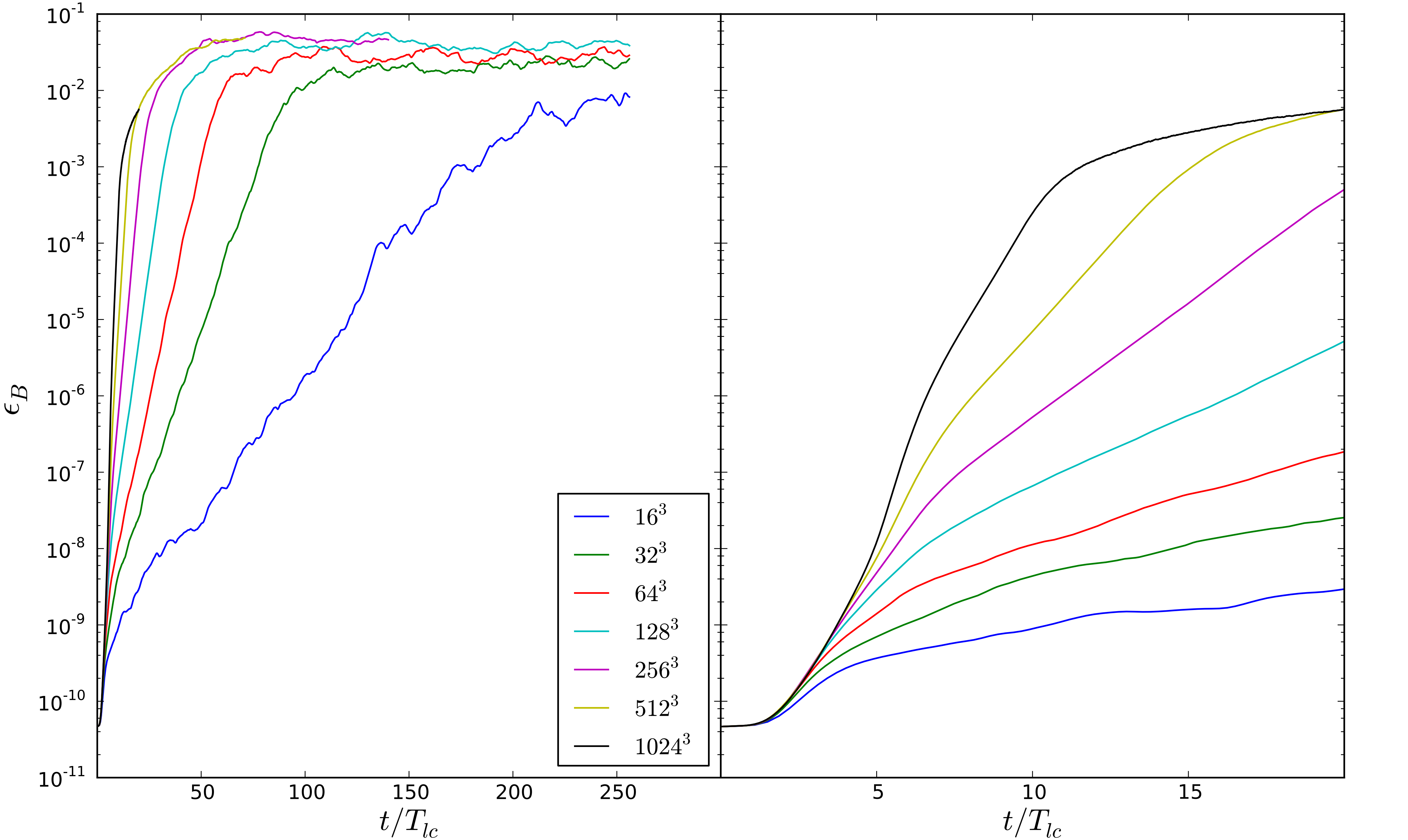


Zrake & AM (2012)



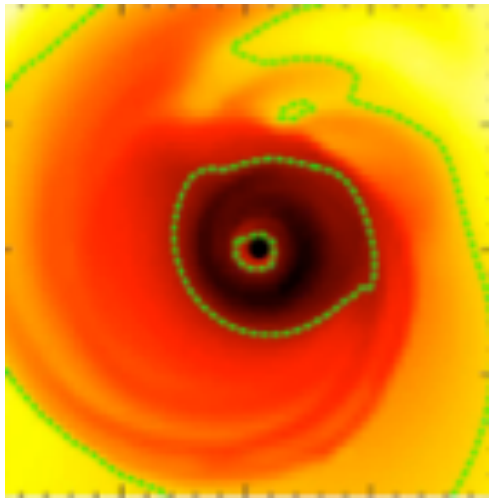


ε_B ~ 10^-2

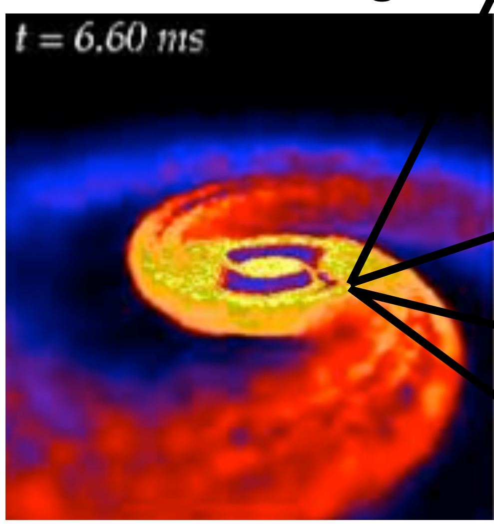


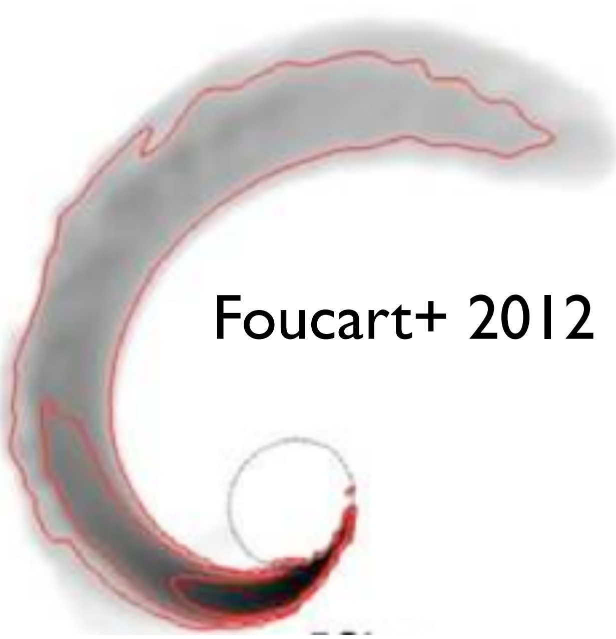
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
ϵ_B
50
100
150
200
250
t/T_{lc}
16^3
32^3
64^3
128^3
256^3
512^3
1024^3
5
10
15
t/T_{lc}

Kyutoku+ 2011

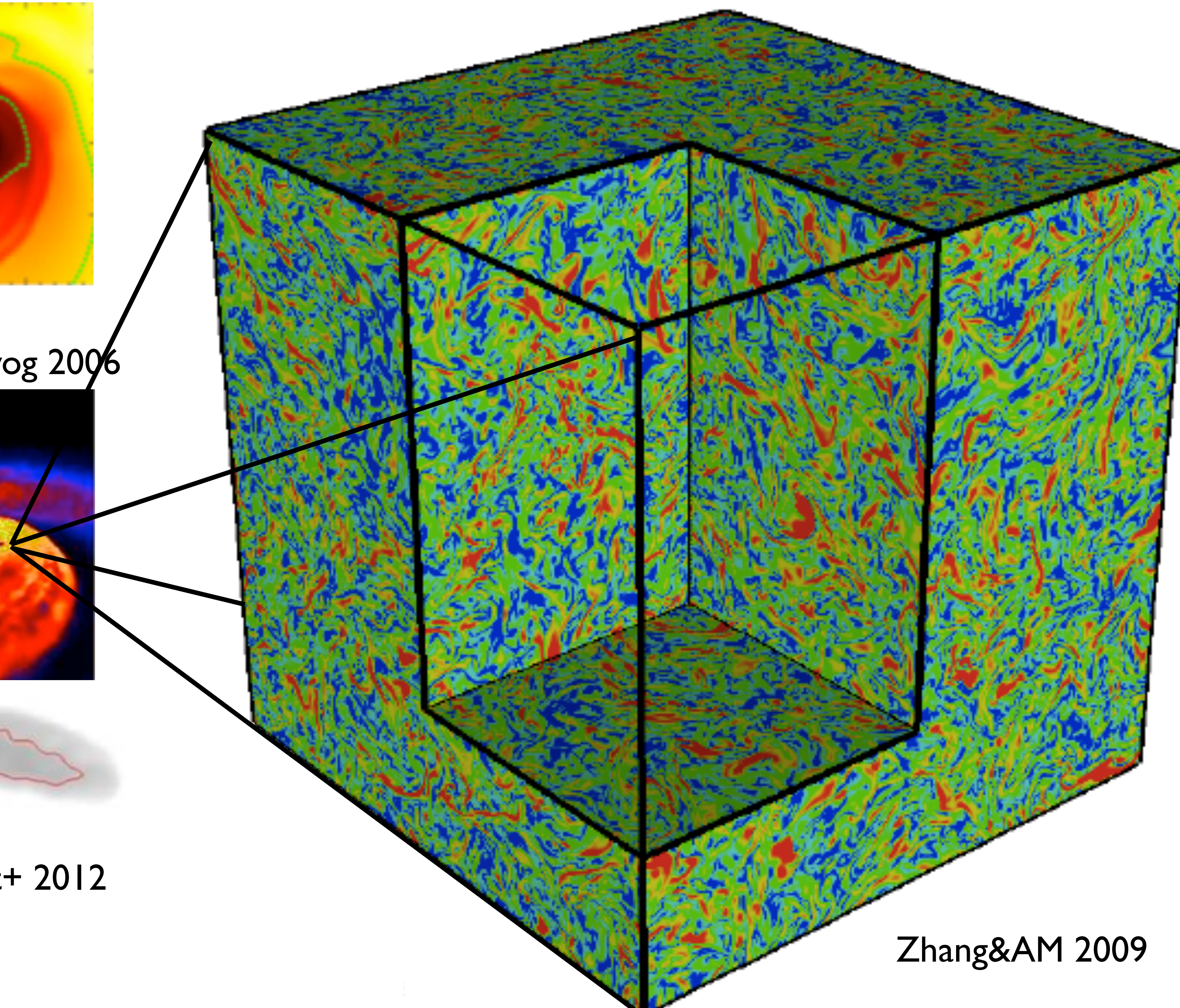


Price & Rosswog 2006

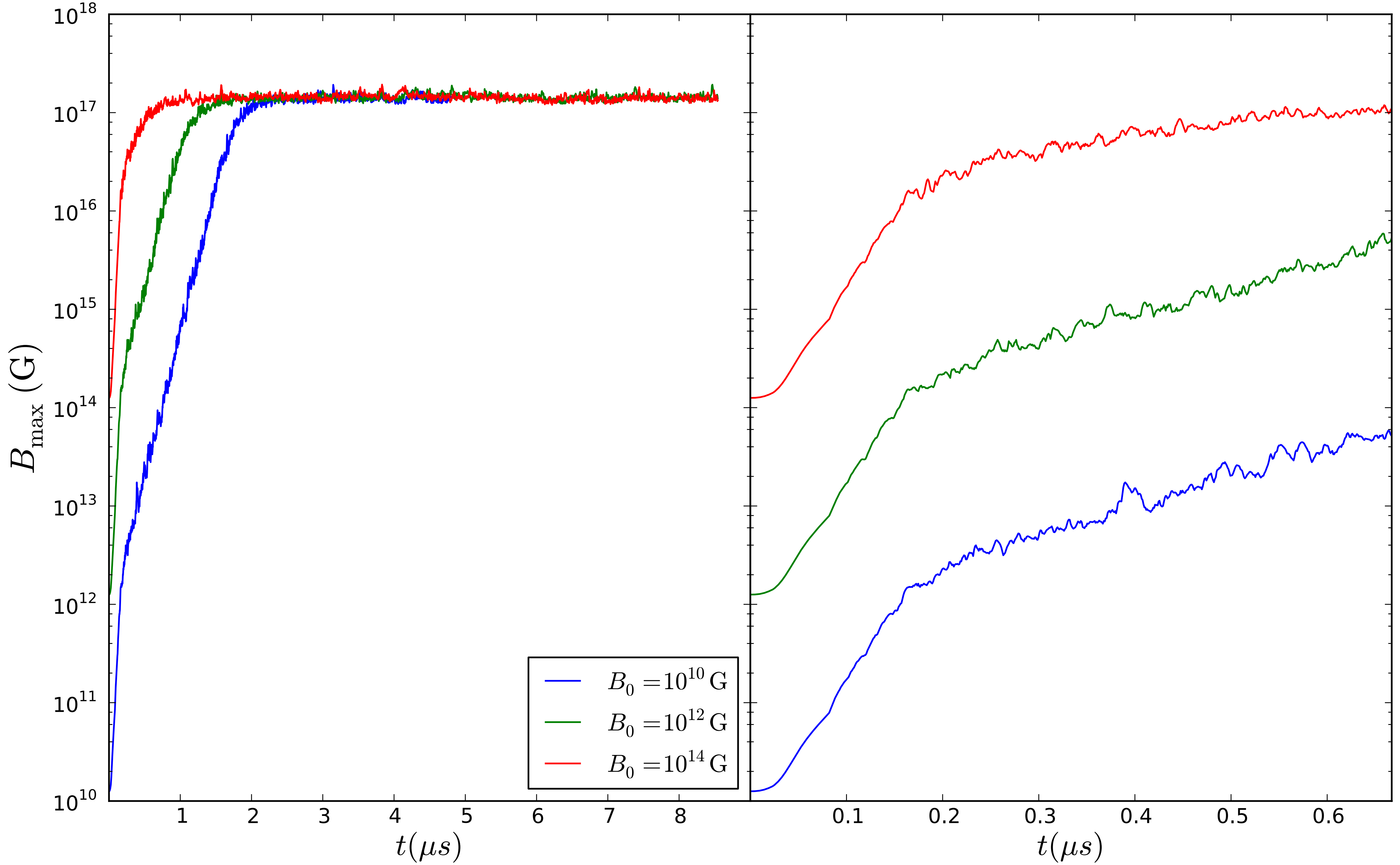




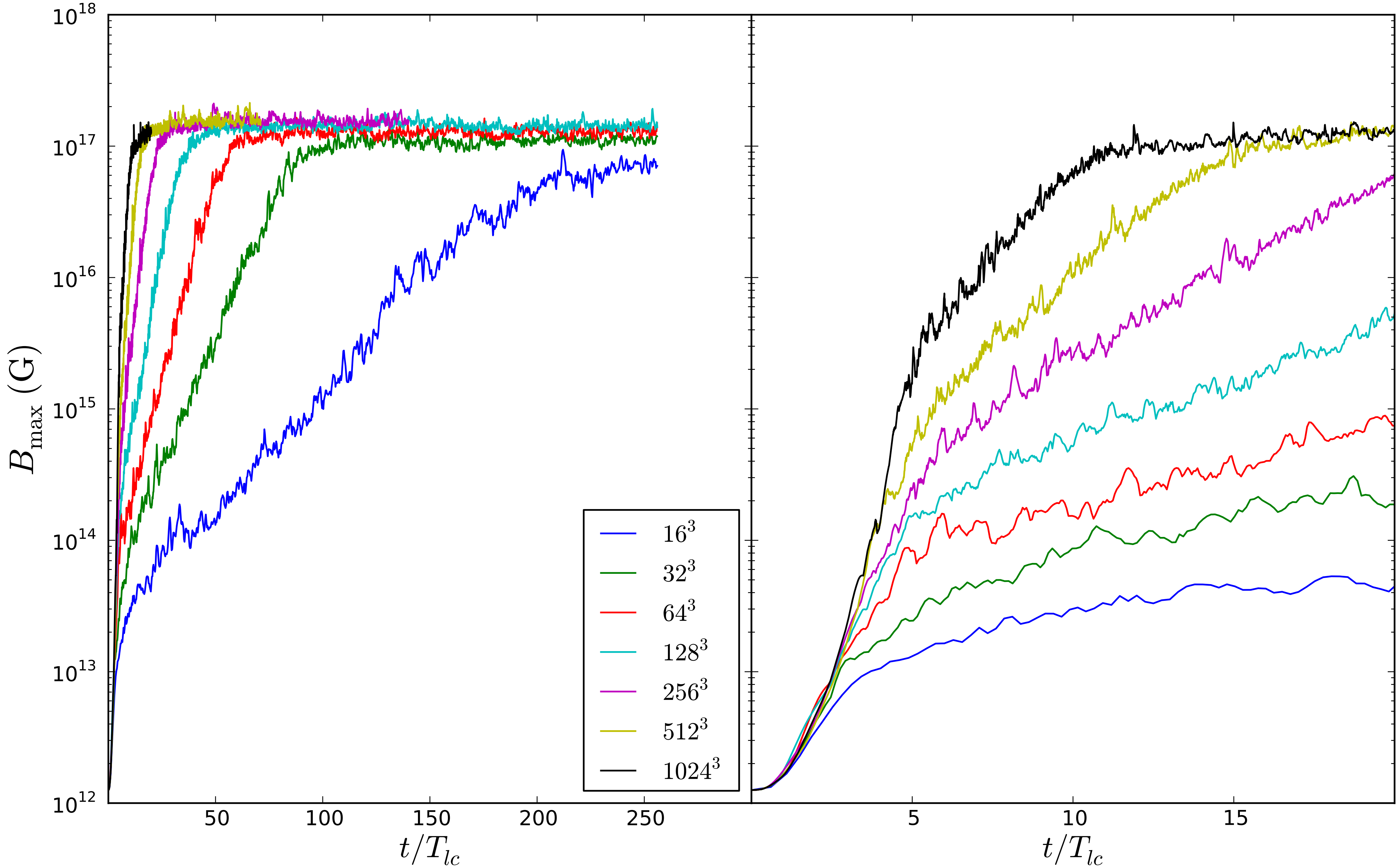
Foucart+ 2012



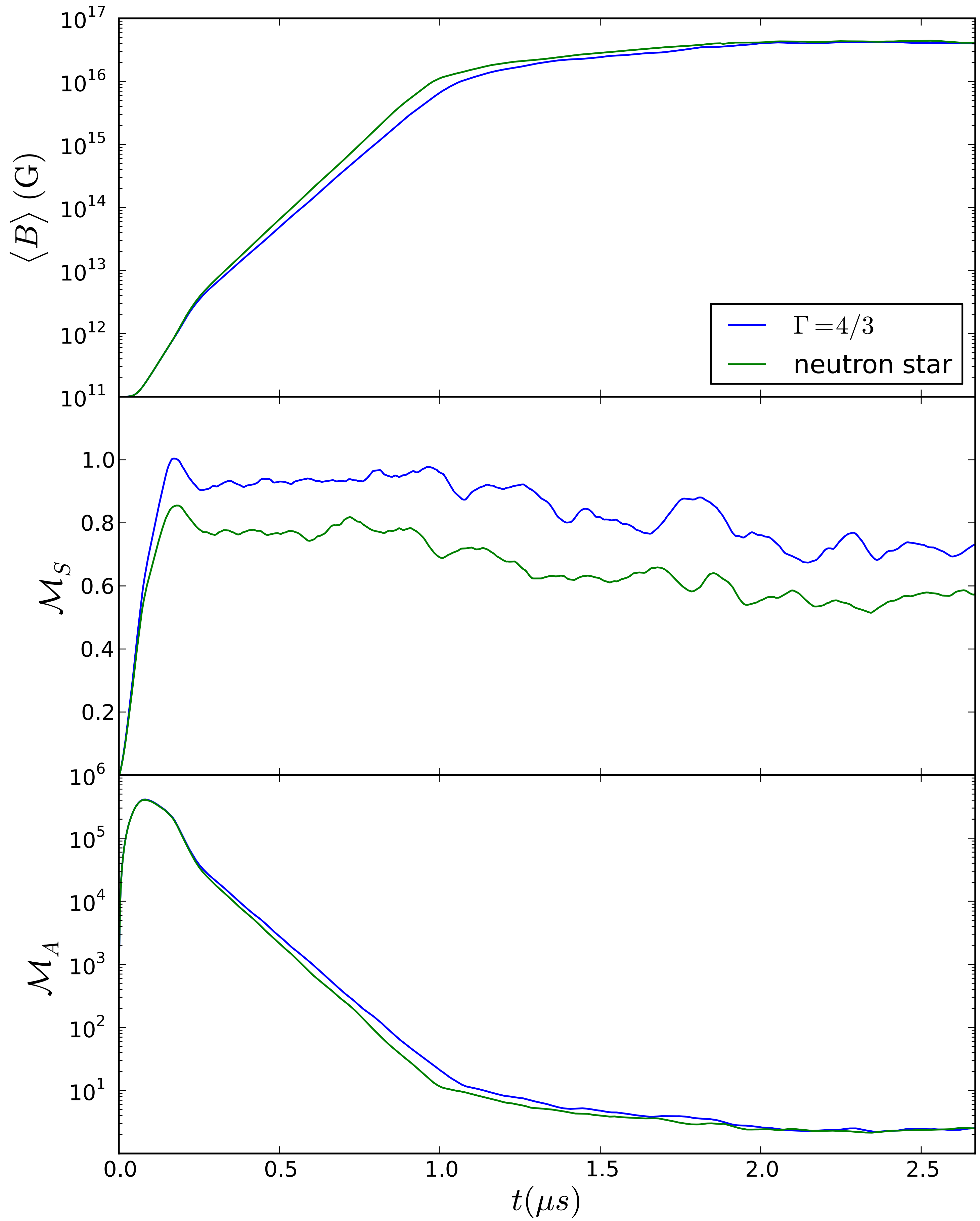
Zhang&AM 2009

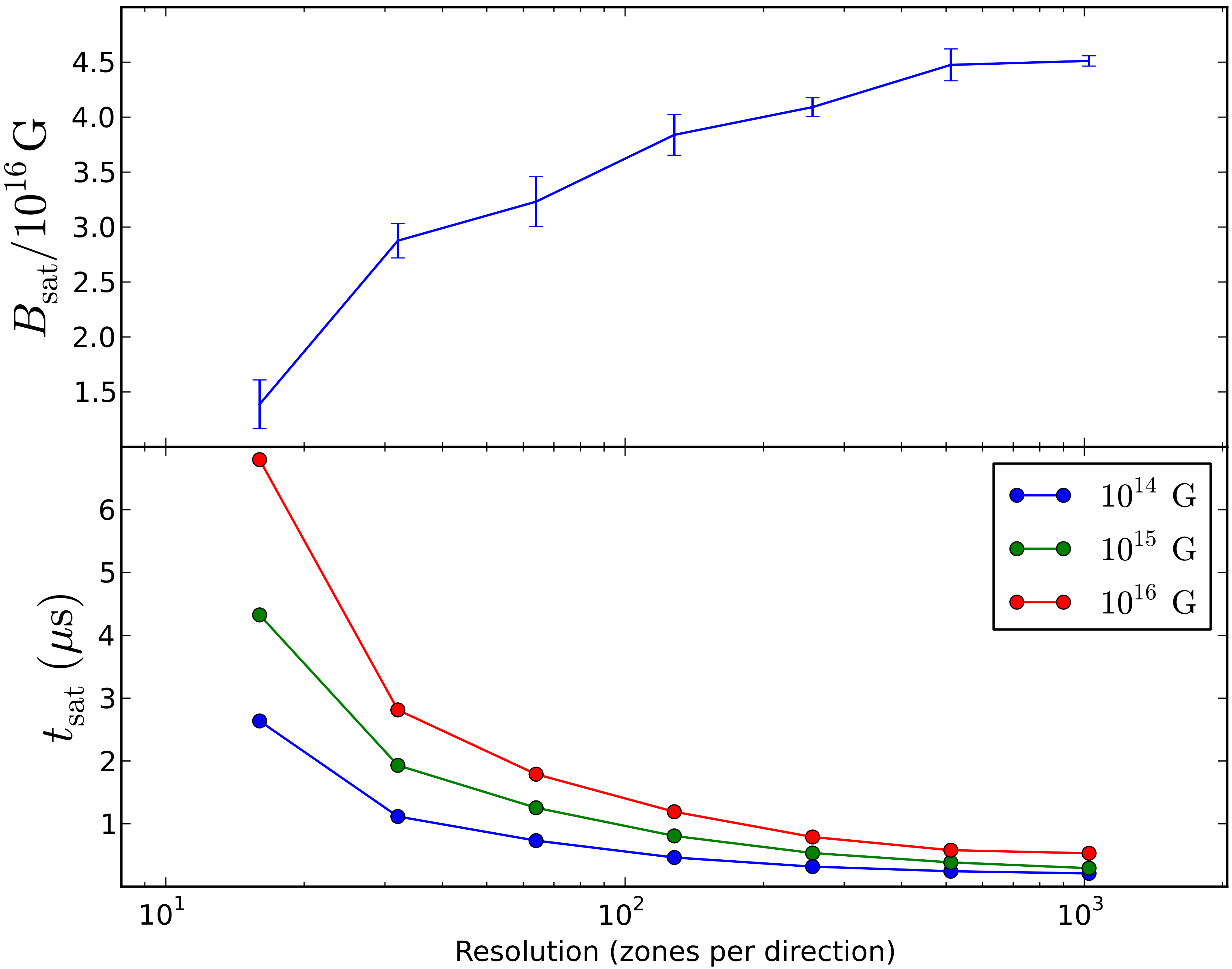


10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
$B_{\max}$ (G)
1 2 3 4 5 6 7 8
$t(\mu s)$
$B_0 = 10^{10}$ G
$B_0 = 10^{12}$ G
$B_0 = 10^{14}$ G
0.1 0.2 0.3 0.4 0.5 0.6
$t(\mu s)$

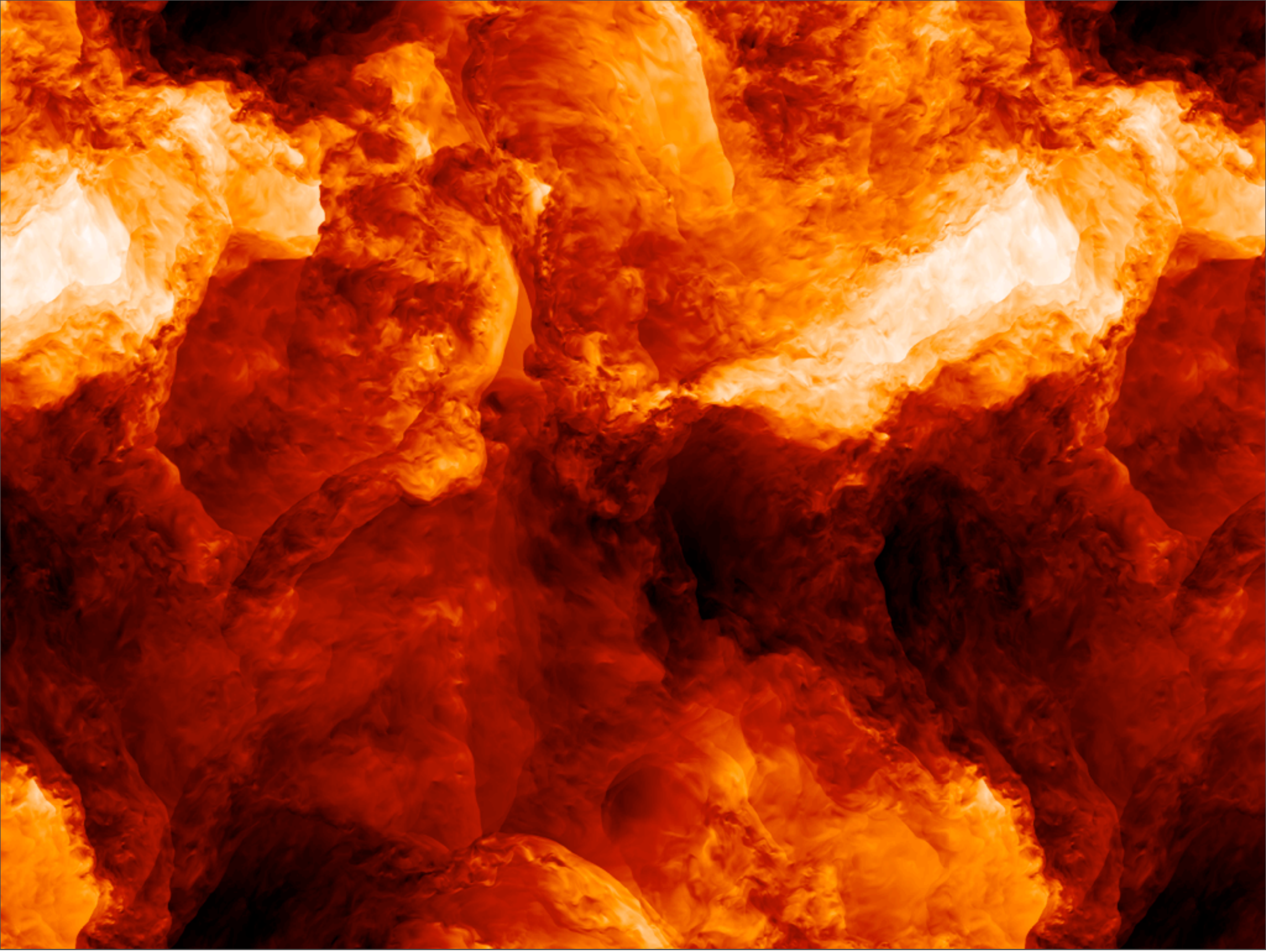

10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
$B_{\max}$ (G)
50
100
150
200
250
t/T_{lc}
5
10
15
t/T_{lc}
16^3
32^3
64^3
128^3
256^3
512^3
1024^3

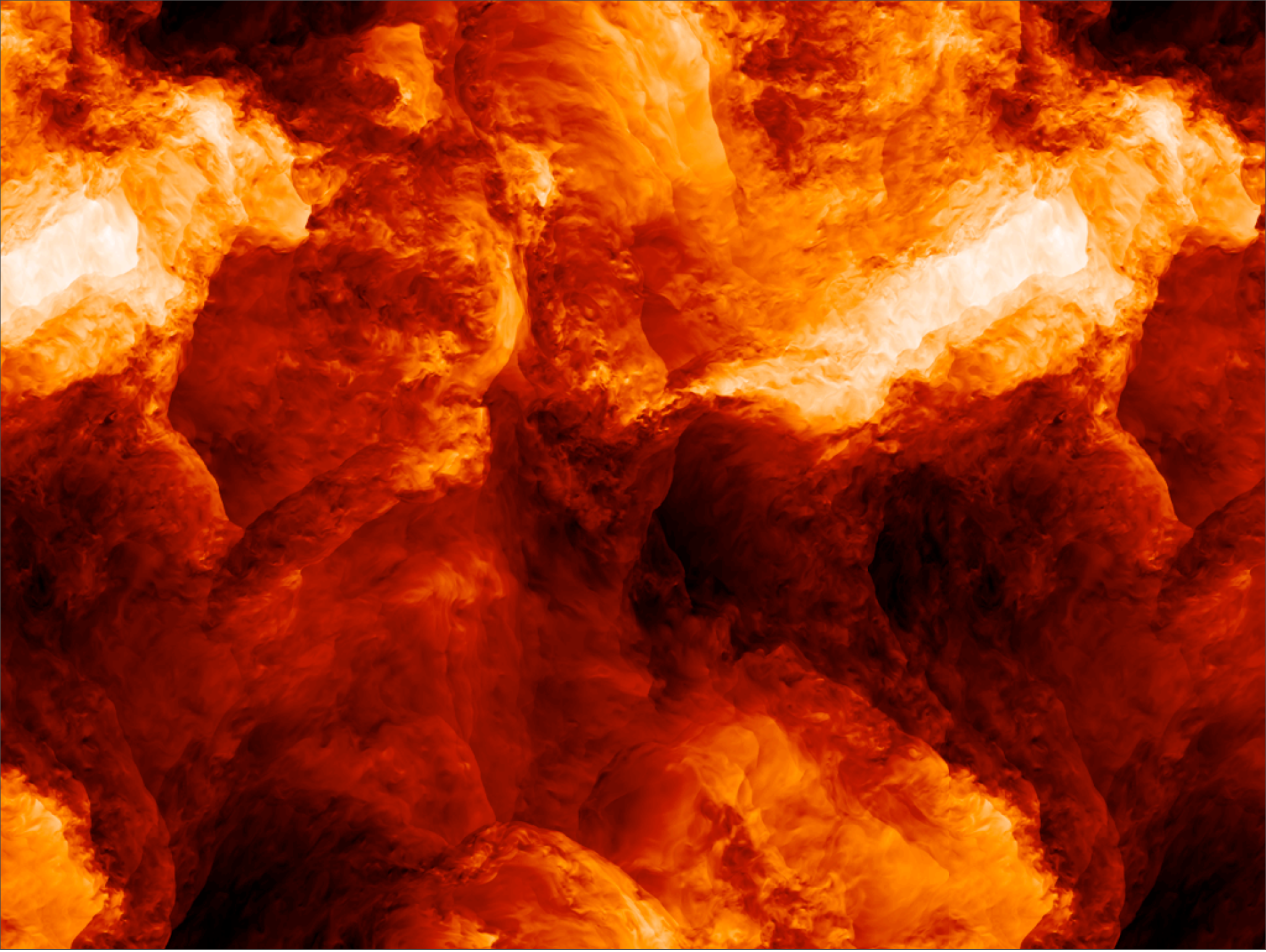
SRMHD
Shen EOS

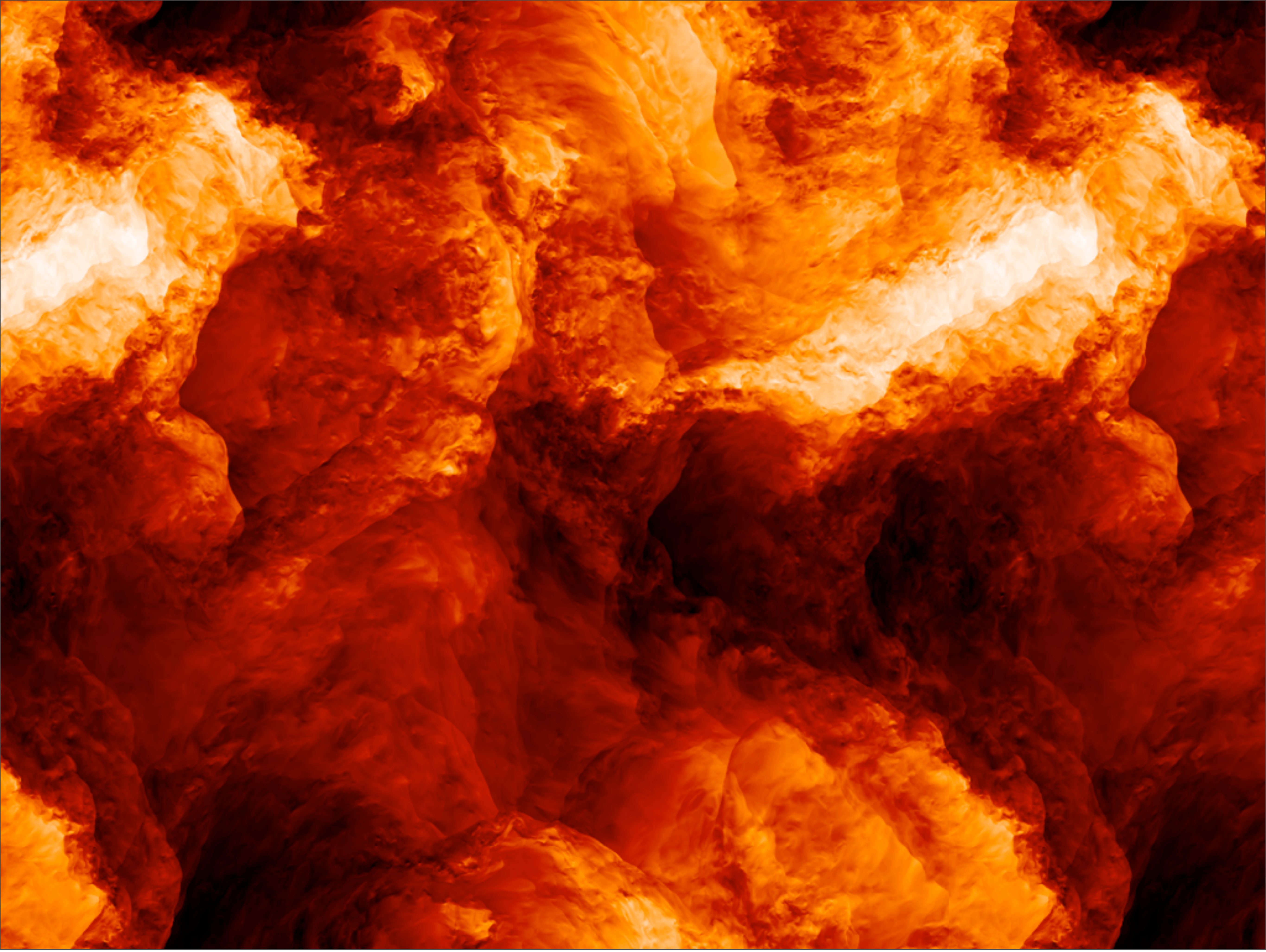


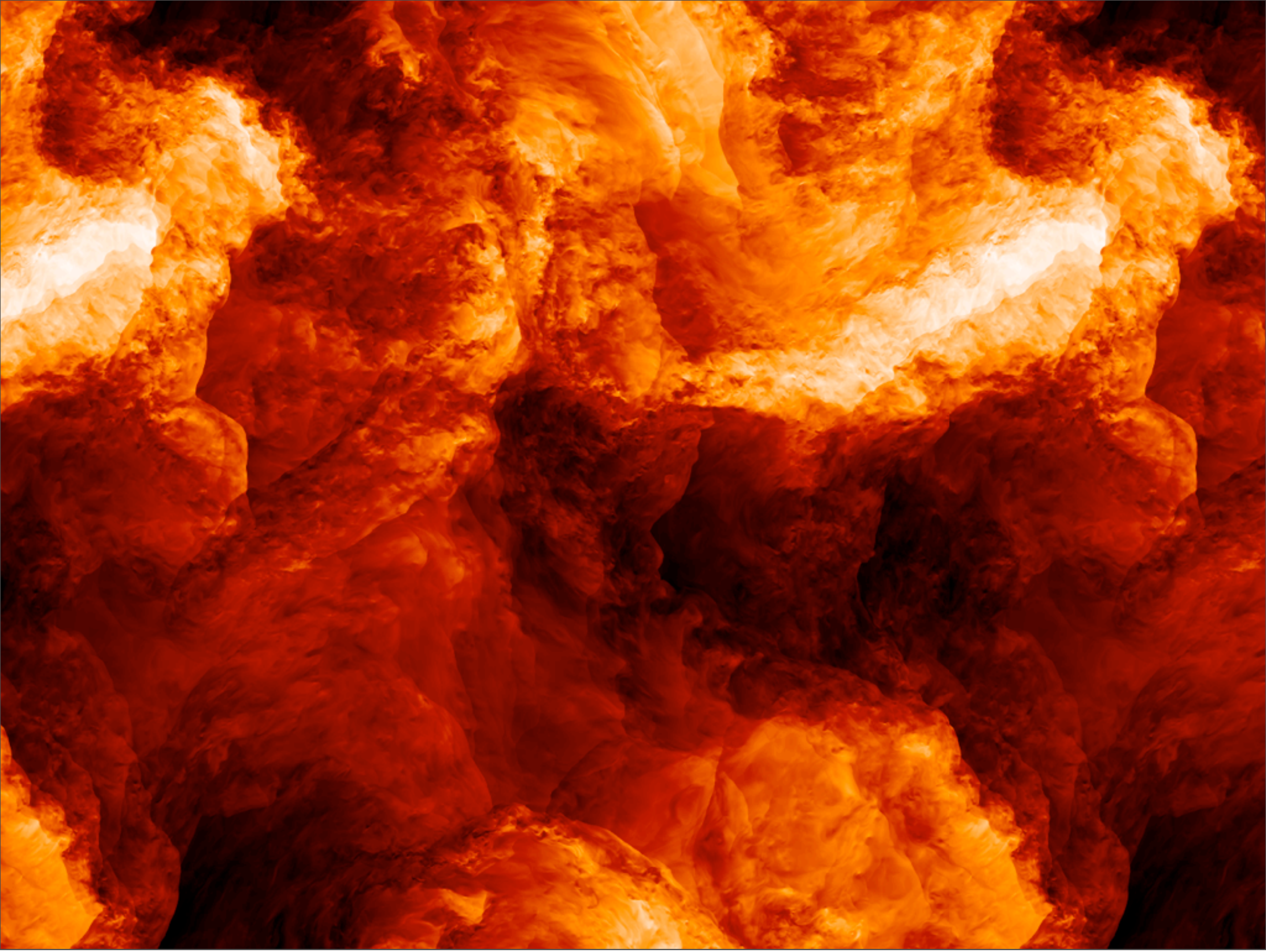


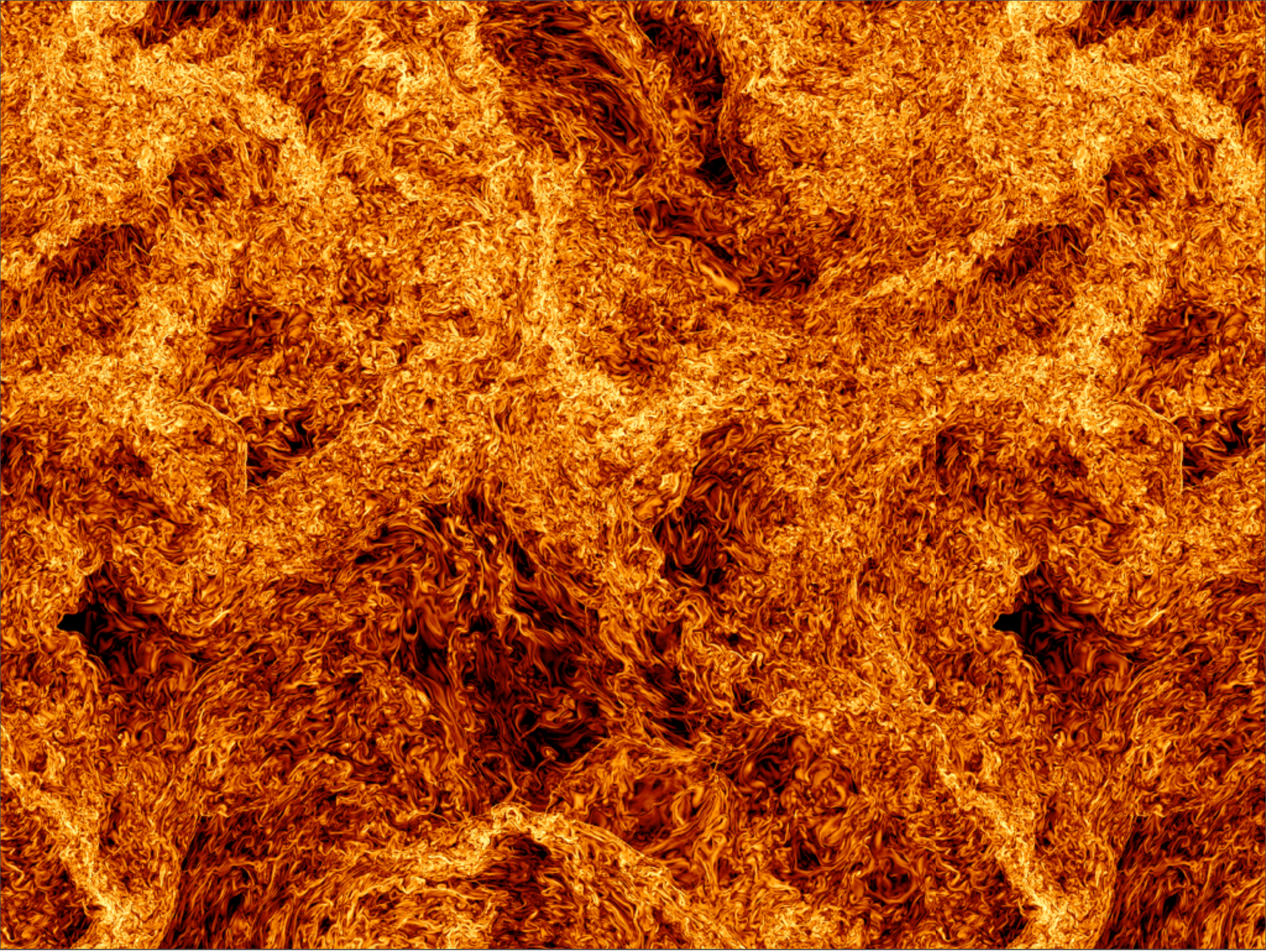
$B_{\rm sat}/10^{16}\,{\rm G}$
4.5
4.0
3.5
3.0
2.5
2.0
1.5
$t_{\rm sat}\ (\mu s)$
6
5
4
3
2
1
10^{14} G
10^{15} G
10^{16} G
10^1
10^2
10^3
Resolution (zones per direction)

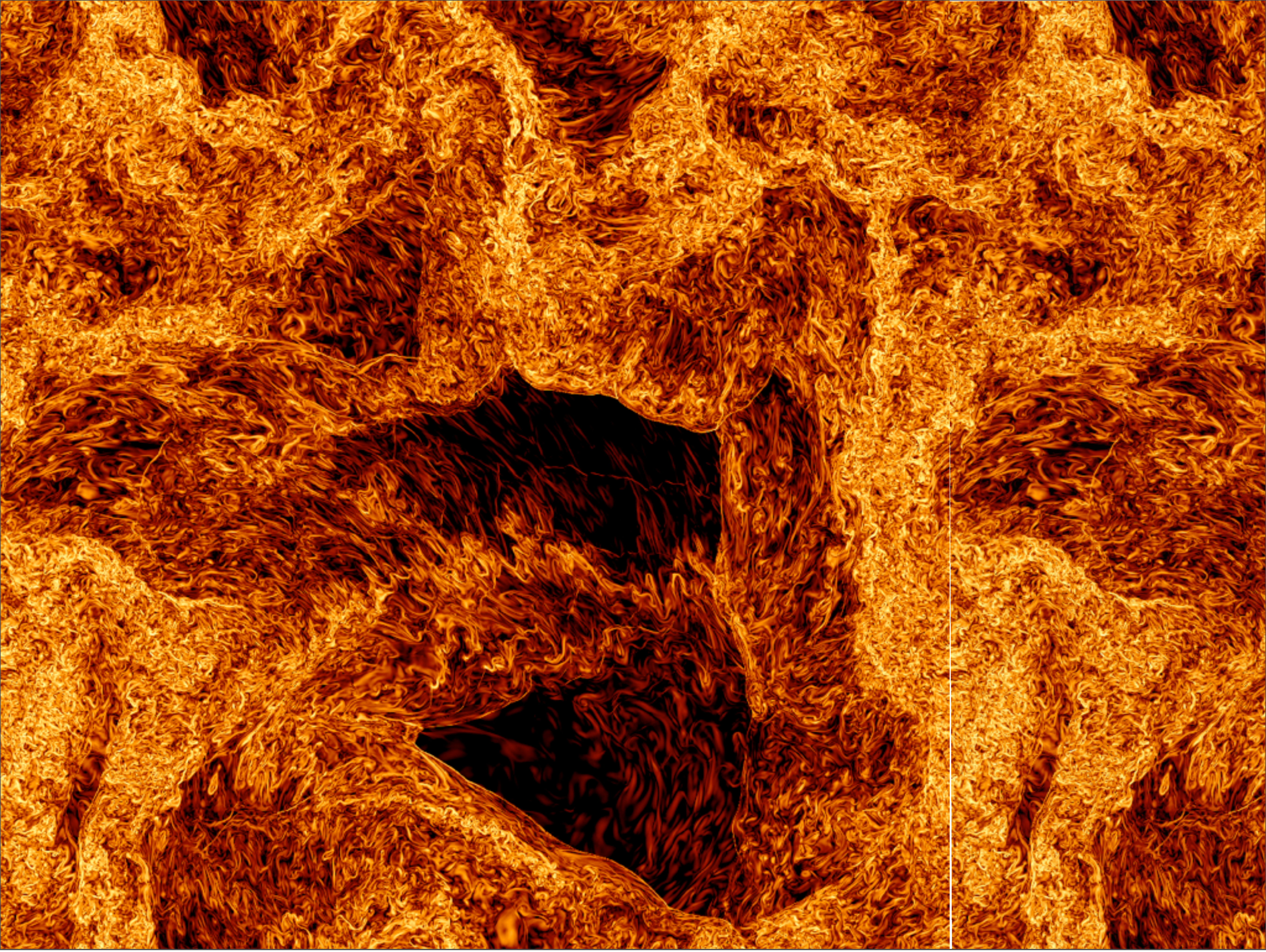


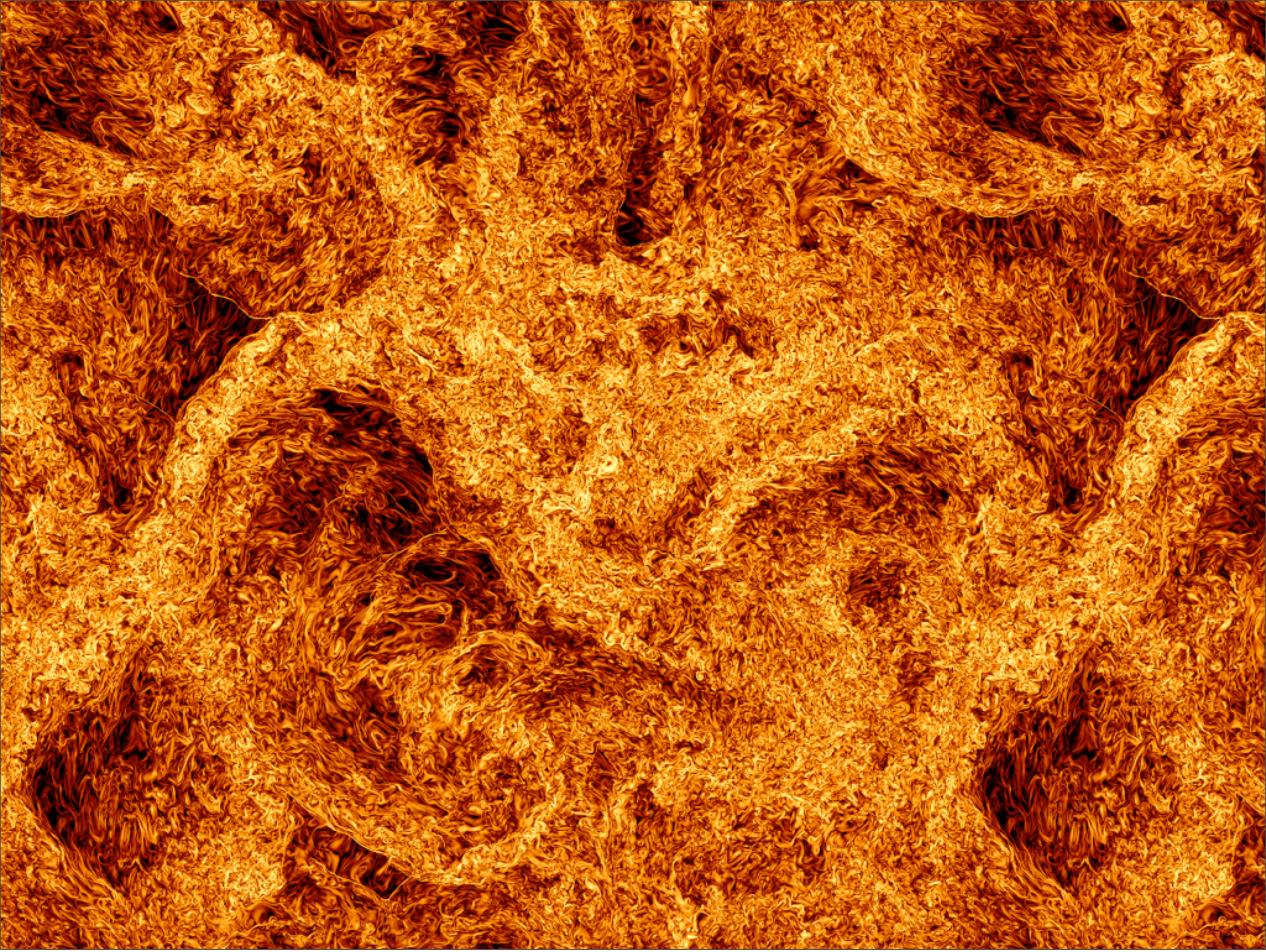












Conclusions

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