Selected Topics in Relativistic Jets Simulations

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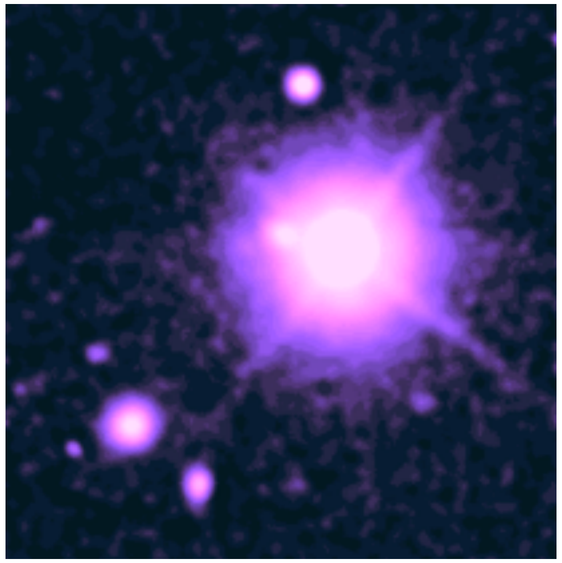
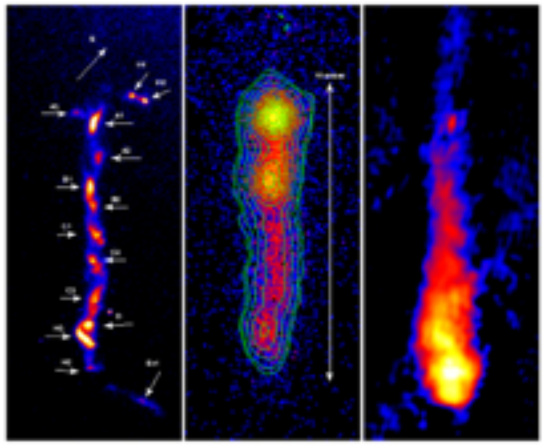
Outline

- Introduction
- Simulations of dynamics and emission from:
    - internal shocks in blazars (X-ray)
    - external shocks in GRB afterglows (optical)
    - parsec-scale jets (radio)
- Summary and more

Hydrodynamic simulation: an indispensable tool



- events taking place in jets extraordinarily dynamic and complex
- jet physics: interplay of processes on a large range of length and time scales
- (magneto)hydrodynamical viewpoint accurate enough
- jets modelled as fluids: relativistic generalisation of Euler equations appropriate
- most commonly used systems of equations:
  - relativistic hydrodynamics (RHD)
  - relativistic magnetohydrodynamics (RMHD)
  - general relativistic hydrodynamics (GRHD)
  - general relativistic magnetohydrodynamics (GRMHD)
  - resistive relativistic magnetohydrodynamics (RRMHD)
  - ...
- advances in numerical techniques and supporting hardware and software make it possible to simultaneously perform *HD simulations *and* compute corresponding synthetic images, spectra and light curves



Example: RHD Equations

$$\frac{\partial D}{\partial t} + \nabla \cdot (D\mathbf{v}) = 0$$

mass conservation

$$\frac{\partial \mathbf{S}}{\partial t} + \nabla \cdot (\mathbf{S} \otimes \mathbf{v} + p\mathbf{I}) = 0$$

momentum conservation

$$\frac{\partial \tau}{\partial t} + \nabla \cdot (\mathbf{S} - D\mathbf{v}) = 0$$

energy conservation

equations of RHD

$$h = \frac{5}{2}\frac{P}{\rho c^2} + \sqrt{\frac{9}{4}\left(\frac{P}{\rho c^2}\right)^2 + 1}$$

TM approximation to Synge equation of state

Mignone et al. Astrophys. J. Supplement **160** (2005) 199

de Berredo-Peixoto et al. Modern Phys. Lett. A **20** (2005) 2723

ρ rest-mass density

P pressure

$\mathbf{v}$ fluid velocity

primitive variables

$$W := \frac{1}{\sqrt{1 - \mathbf{v}^2/c^2}}$$ Lorentz factor

$$h := 1 + \frac{\varepsilon}{c^2} + \frac{p}{\rho c^2}$$ specific enthalpy

$$D := \rho W$$

relativistic rest-mass density

$$\mathbf{S} := \rho h W^2 \mathbf{v}$$

relativistic momentum density

$$\tau := \rho h W^2 c^2 - p - \rho W c^2$$

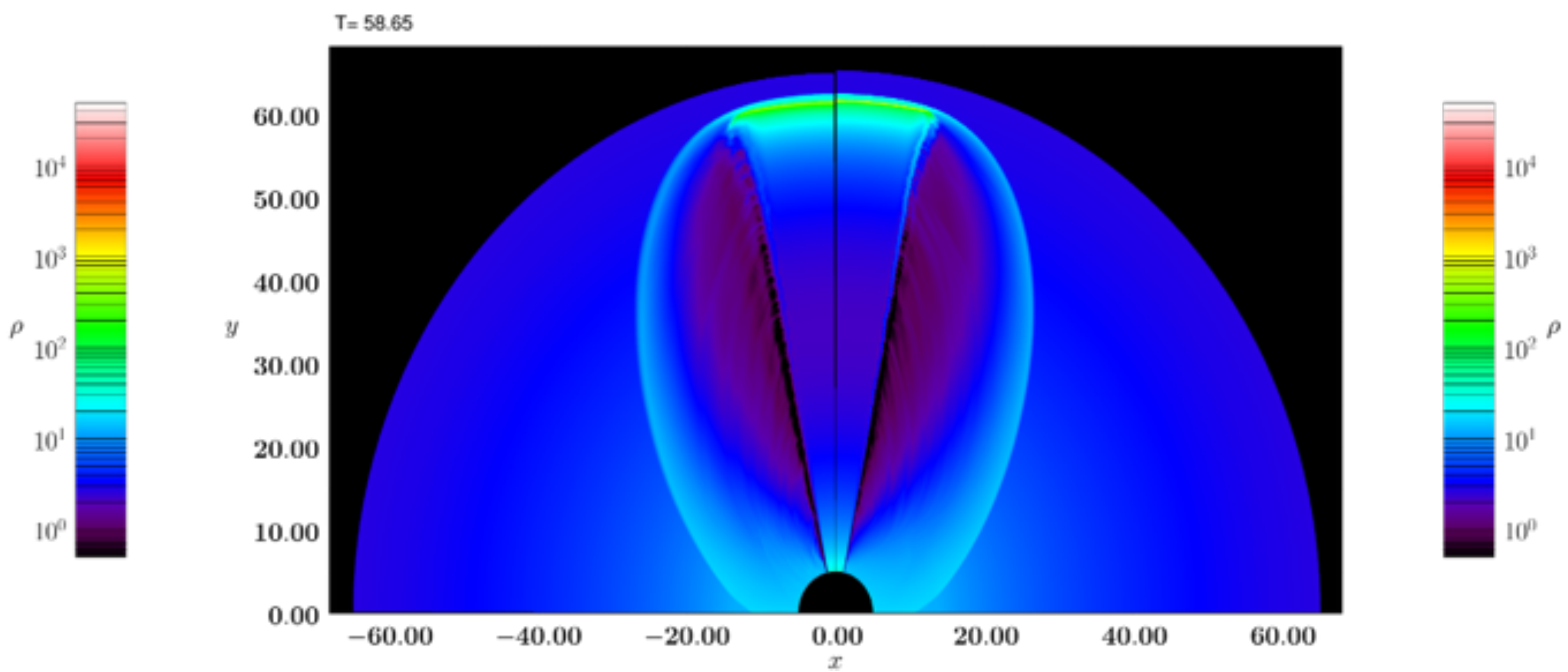
relativistic energy density

conserved variables

- primitive variables must be obtained ("recovered") from the conserved ones
- no analytic solution in general, numerical procedure must be used (and it can fail!)

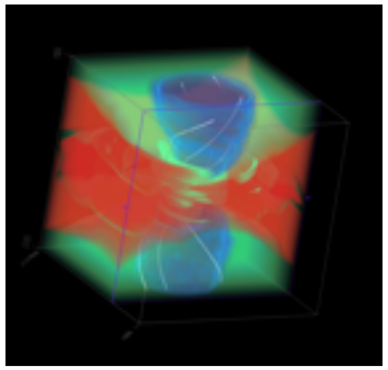
Simulating Jet Evolution

- equations solved after specifying initial and boundary conditions
- spacetime discretization: numerical solution computed at a finite number of spatial and temporal points $U^n_{i,j,k}=U(t^n,x^1_i,x^2_j,x^3_k)$
- spatial grid: typically uniform or AMR (adaptive mesh refinement)
- numerical dissipation included to keep non-smooth flows under control (e.g, properly treat shock waves, contact discontinuities)
- special considerations of (G)RMHD: finite accuracy (truncation errors) means that codes need to include explicit enforcement of the constraint equation (divergence cleaning or constraint transport)

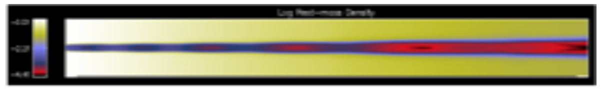


Jet Simulations on Different Scales

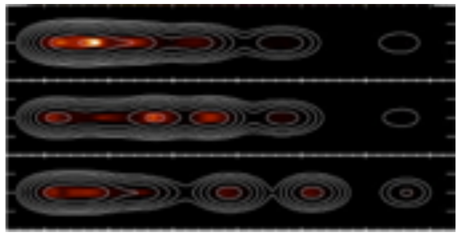
- AGN jets:
  - launching and collimation (subpc scales)
  - VLBI jets, superluminal components (pc scales)
  - jet-environment interaction (kilopc scales)



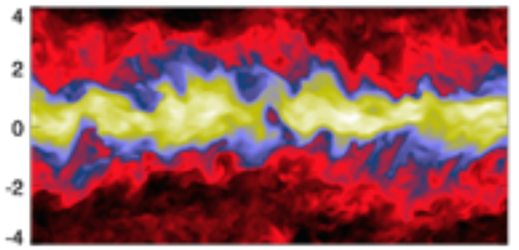
McKinney *et al.* 2014
(BZ, launching)



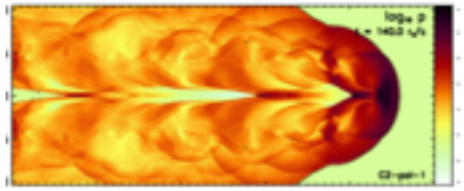
Agudo *et al.* 2001
(AGN, pc-scale, recollimation)



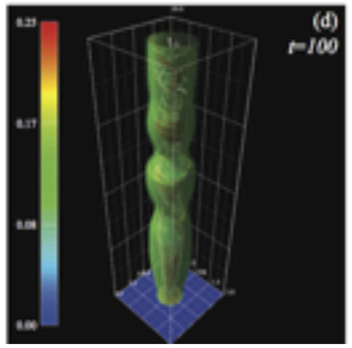
Mimica *et al.* 2009
(AGN, pc-scale, radio)



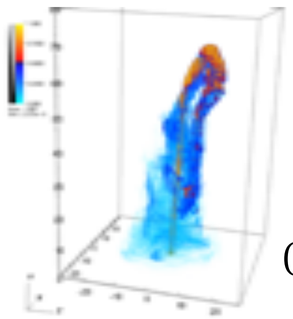
Perucho *et al.* 2010
(KH, stability)



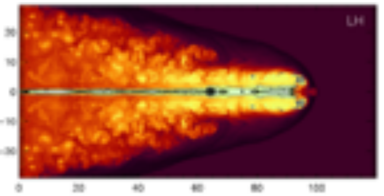
Leismann *et al.* 2005
(AGN, magnetized jet)



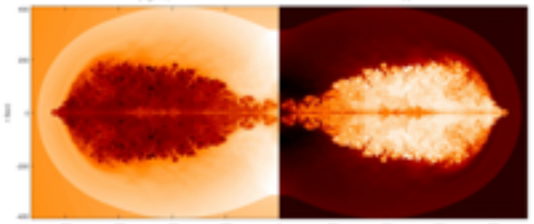
Mizuno *et al.* 2014
(CD kink, stability)



Mignone *et al.* 2009
(AGN, magnetized jet)

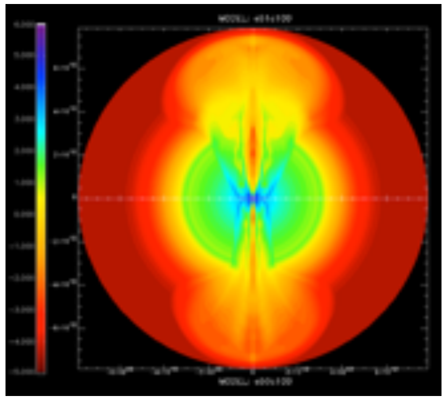


Scheck *et al.* 2002
(AGN, long-term evolution)

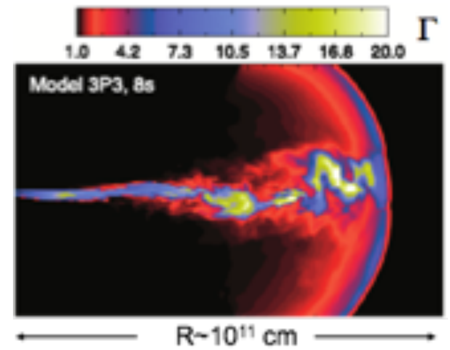


Perucho *et al.* 2014
(AGN, jet-ICM interaction)

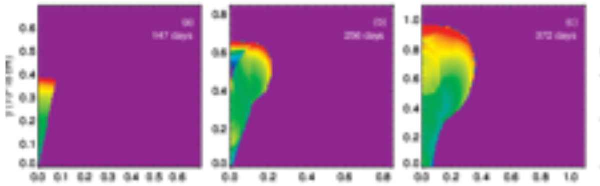
- GRB jets:
  - jet formation (<10^8 cm)
  - interaction with(in) the progenitor (10^8-10^{11} cm)
  - interaction with the circumburst medium (>10^{14} cm)



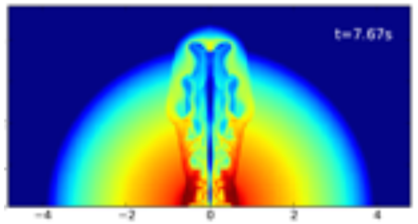
Aloy *et al.* 2000
(GRB, fireball, launching)



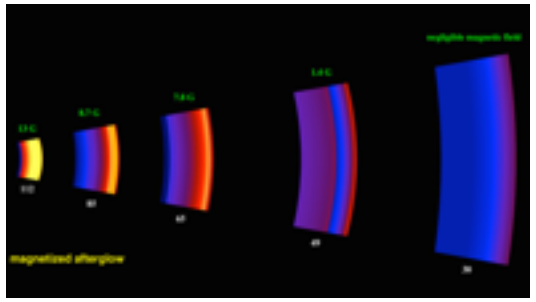
Zhang *et al.* 2004
(GRB, interaction with progenitor)



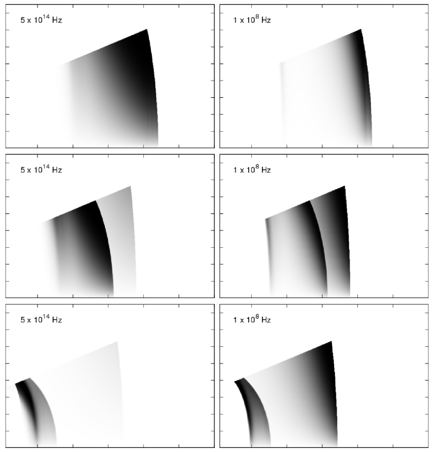
Zhang & MacFadyen 2009
(GRB, afterglows)



Lazzati *et al.* 2009
(GRB, interaction with progenitor)



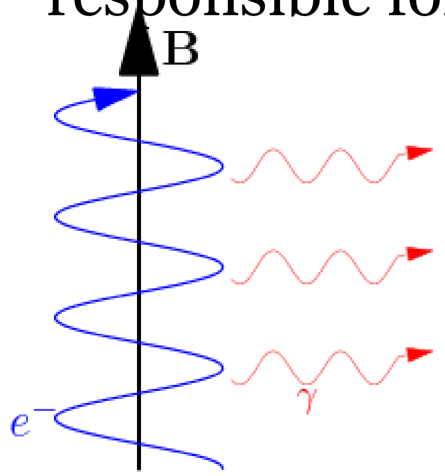
Mimica et al. 2009
(GRB, magnetized afterglows)

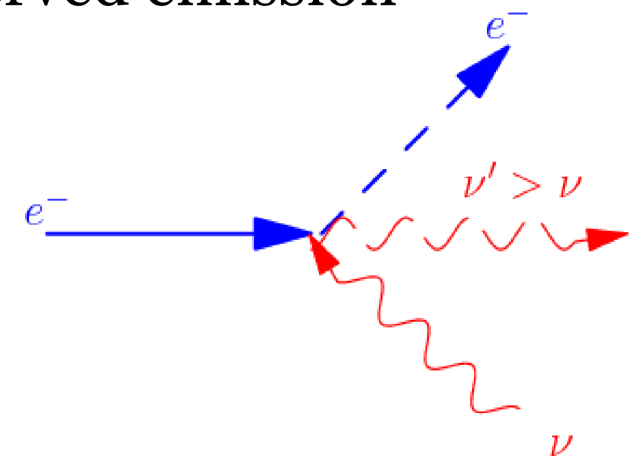


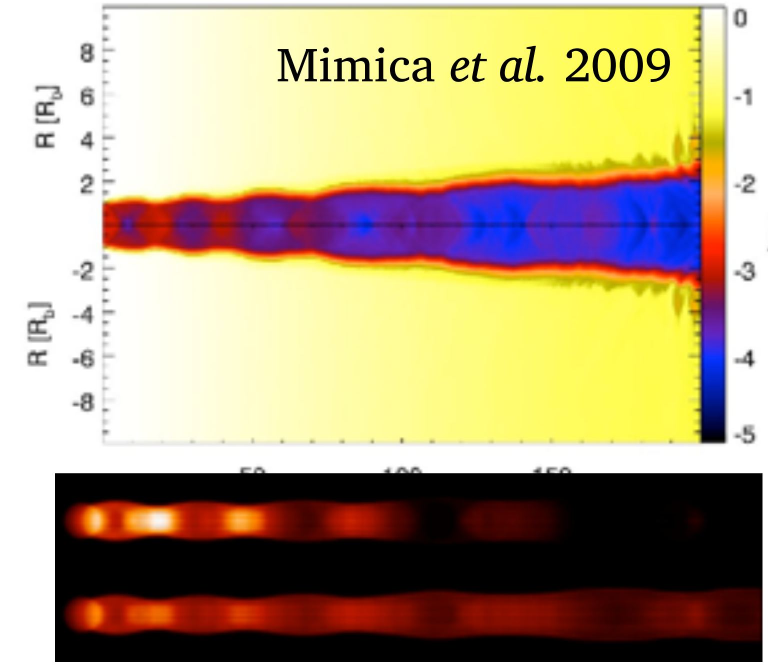
Vlasis et al. 2011
(GRB, radio afterglows)

Simulating Jet Emitted Radiation

- underlying jet fluid ("thermal plasma") not directly observable from Earth
- population of high-energy non-thermal particles in the jet responsible for observed emission



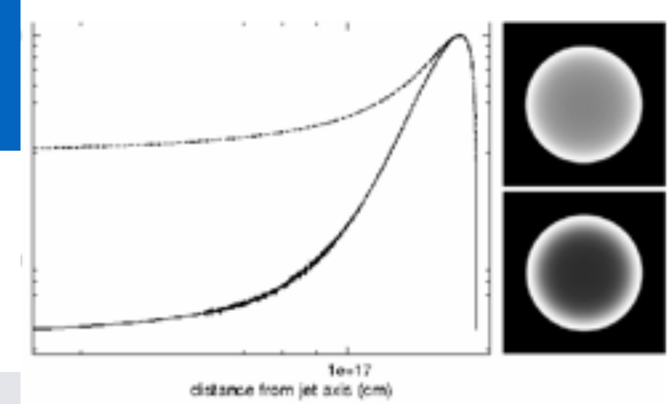




Mimica *et al.* 2009

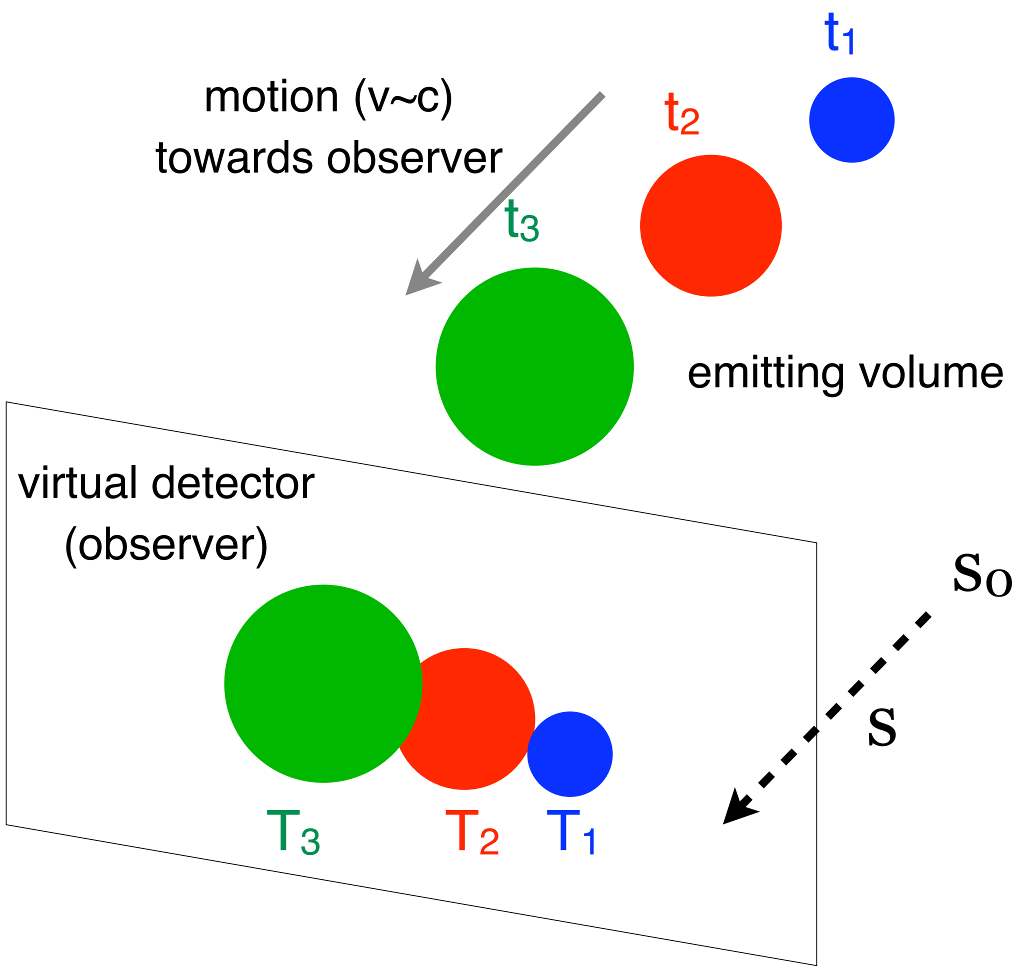
Algorithm Classification

	τ≪1	τ≳1
local	• X & γ-ray afterglows • blazars emission	• stationary radio emission
transport	• opt. & UV afterglows • X-ray TDE jets	• radio jets • late-time radio afterglows



van Eerten *et al.* 2011

Simulating Jet Observed Radiation



- for a fixed observer time T, need to process the **whole** spacetime evolution to compute a **single** virtual image
- tightly coupled, highly non-local problem
- **5D problem**:
  - virtual detector image **(x, y)**
  - observation time **T**
  - observation frequency **v**
  - contributions along the line of sight **s**

synchrotron, inverse-Compton

synchrotron self-absorption

I_ν : intensity j_ν α_ν : emission, absorption

T : observer time t : jet evolution time

s : path towards the detector

radiation transfer equation:

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = j_\nu + \alpha_\nu I_\nu$$

$$s = c(t - T) + s_0$$

for a fixed T, equation gives an isochrone (s, t) along each line of sight

Jet Simulations Building Blocks

easy — difficult — very difficult

treatment of hydrodynamic evolution

- **Riemann solver** *(blazar, GRB internal shocks)*
- **RHD** *(AGN jets, TDE jets)*
- **RMHD** *(GRBs, blazars)*
- **RRMHD** *(non-ideal dissipative processes in blazars)*

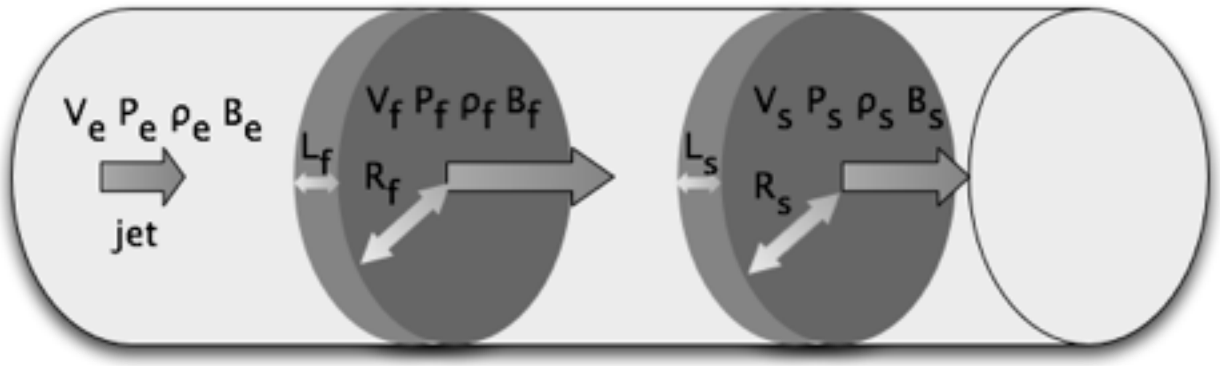
treatment of non-thermal particles

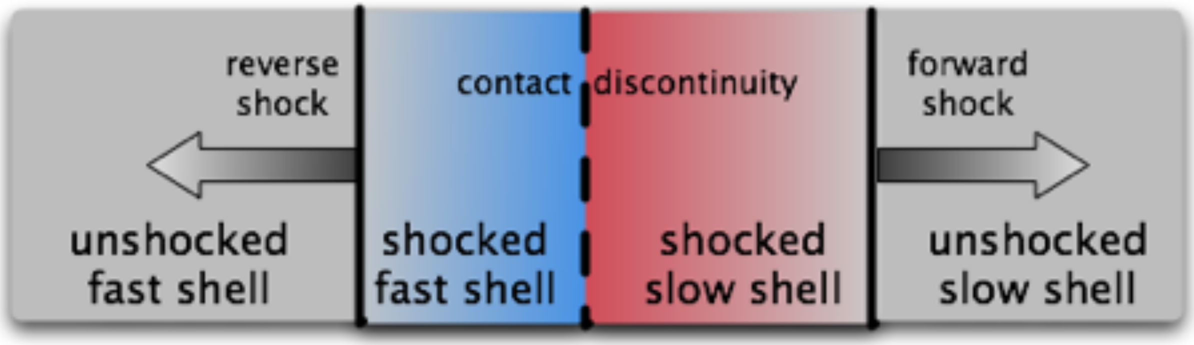
- **1D transport** *(blazar/GRB internal shocks, on-axis GRB blast wave)*
- **2D transport** *(radio maps, off-axis light curves)*
- **3D transport** *(?)*

treatment of radiative processes

- **Synchrotron + EC** *(radio maps, blazar X light curves, GRB afterglows, TDE radio transients)*
- **Syn. + EC + SSC** *(blazar radio-to-γ-ray light curves and spectra)*
- **additional** *(blazar leptonic-hadronic models?)*

Internal Shocks: Colliding Shell Hydrodynamics





- model: steady jet (background) with embedded density and velocity perturbations (shells)
- shells: initially cold, relativistic, possibly magnetised
- two shocks form upon contact
- **forward shock:** compresses and accelerates slower shell
- **reverse shock:** compresses and decelerates faster shell

Colliding shell models classification

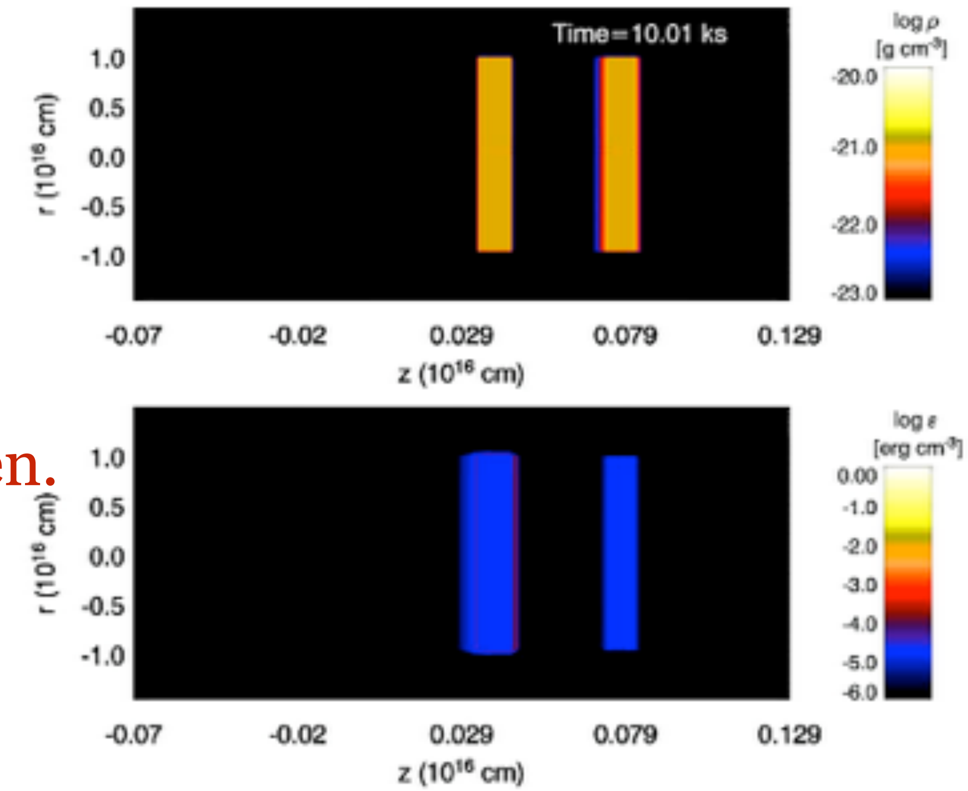
model type	advantage	disadvantage
1- or 2-zone	• treatment of large number of shell collisions possible	• very simple shell evolution and emission calculation
multi-zone	• detailed treatment of radiation processes	• simplified treatment of hydrodynamics
simulations	• detailed hydrodynamic evolution and emission	• computationally expensive, inefficient for parameter scans

2D RHD Colliding Shell Simulations

Mimica *et al.* 2004
(cylindrical shells, *MRGENESIS code*)

fluid density

internal en. density

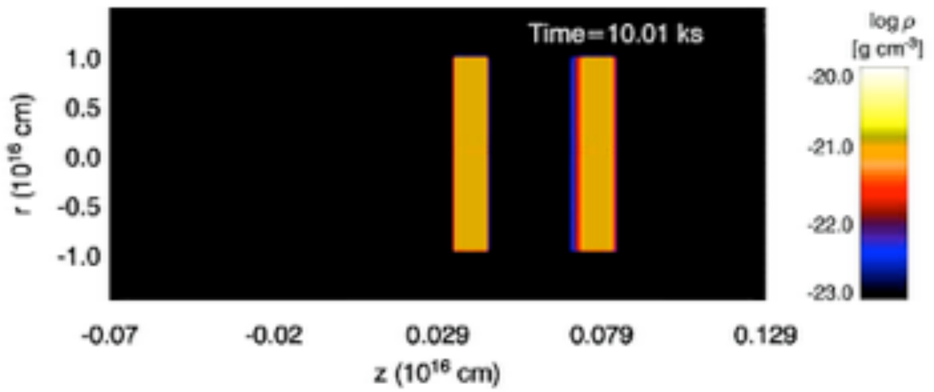


- model: aligned cylindrical shells with same initial ρ
- very little lateral expansion
- shells pre-heated prior to collision
- merged shell wider and hotter than the initial shells
- 2D simulations expensive, little or no lateral expansion => 1D simulations probably good enough

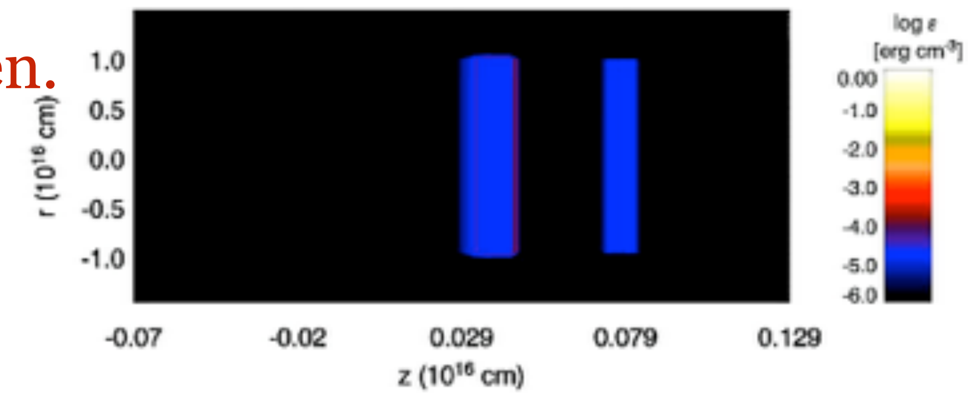
2D RHD Colliding Shell Simulations

Mimica *et al.* 2004
(cylindrical shells, *MRGENESIS code*)

fluid density



internal en. density



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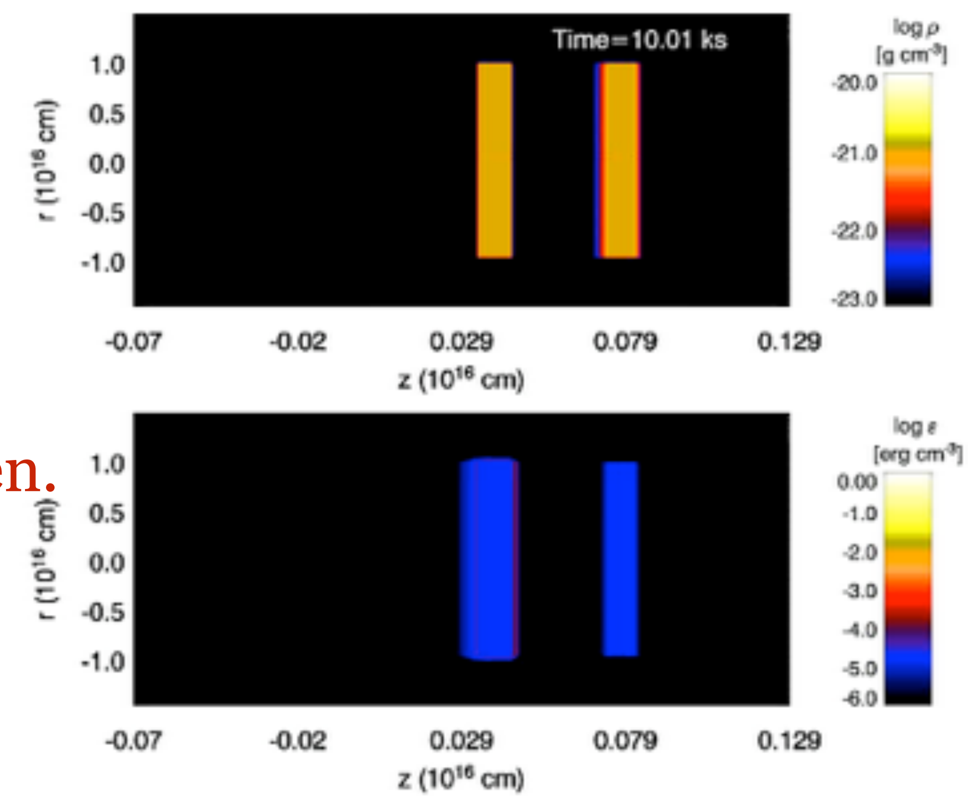
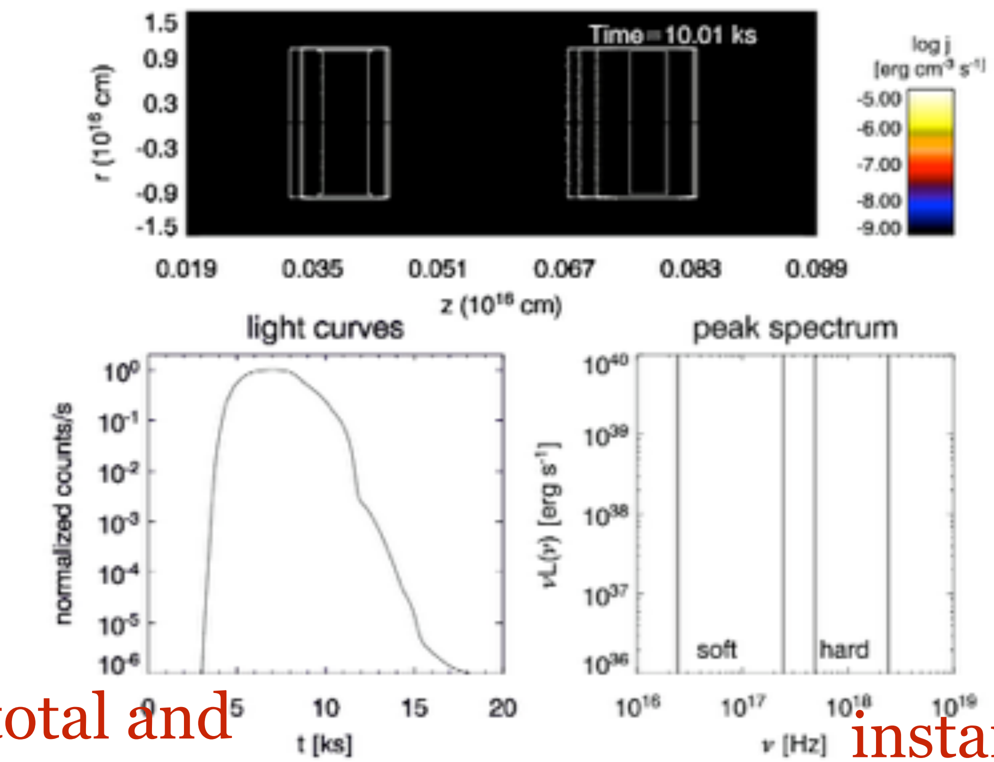


syn. emissivity



total and instantaneous LC

instantaneous spectrum

- model: aligned cylindrical shells with same initial ρ
- very little lateral expansion
- shells pre-heated prior to collision
- merged shell wider and hotter than the initial shells
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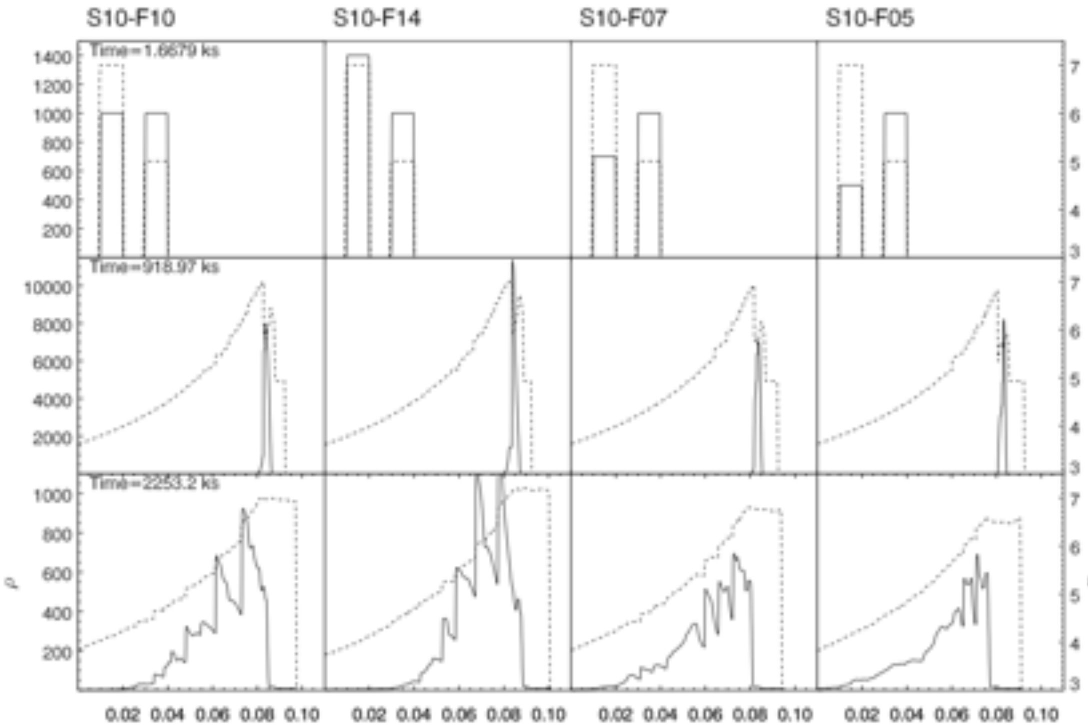
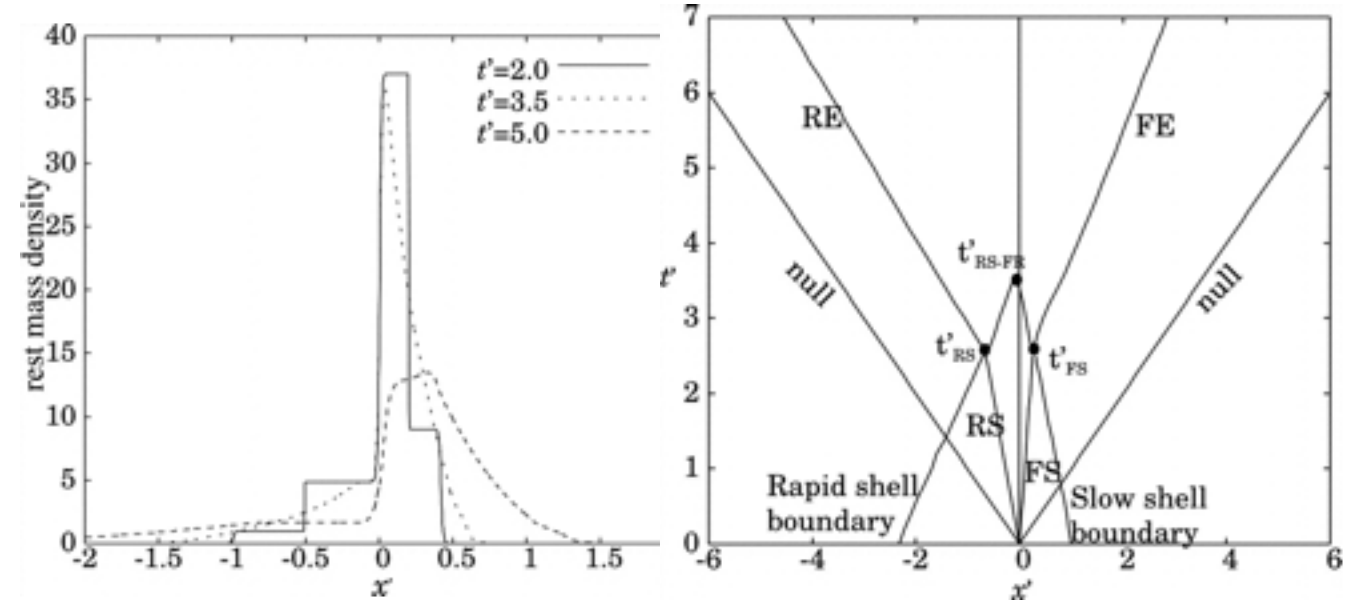
- electrons accelerated at FS and RS
- electrons advected with the fluid
- synchrotron cooling
- on-axis synchrotron emission
- back-reaction (thermal energy subtracted from shocks)
- expensive simulations: any change of microphysical parameters requires new run

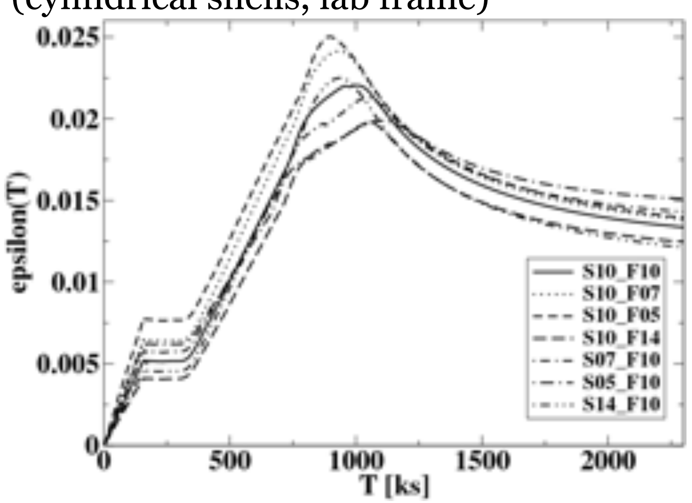
1D RHD & RMHD Colliding Shell Simulations



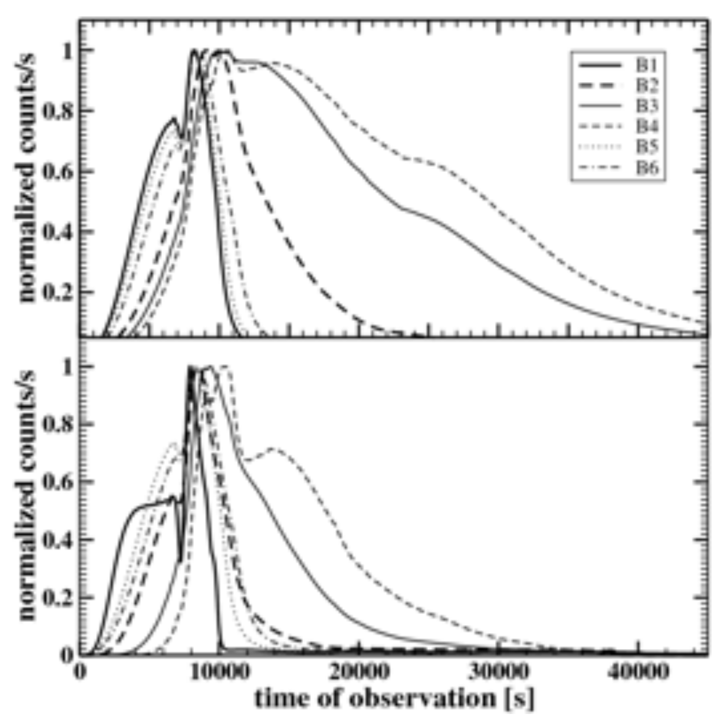
Mimica et al. 2005
(cylindrical shells, lab frame)



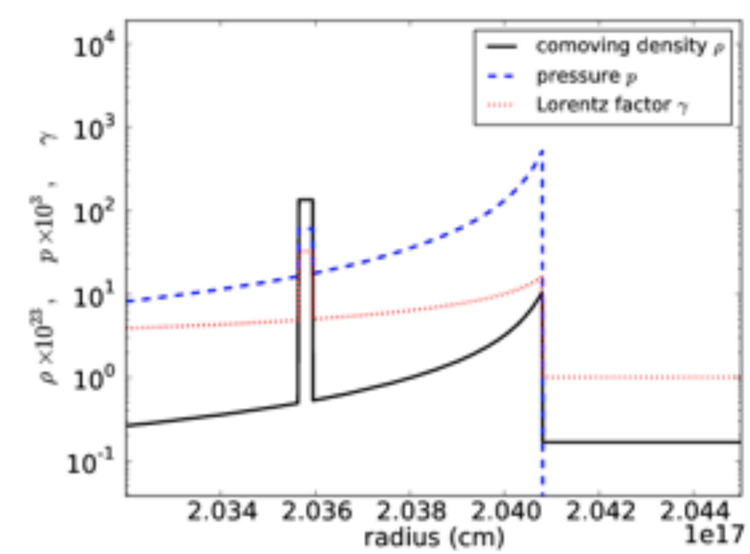
Kino *et al.* 2004
(cylindrical shells, CD frame)



kinetic-to-thermal energy conversion efficiency



Mimica *et al.* 2007
(magnetised shells, *MRGENESIS code*)



Vlasis *et al.* 2011
(spherical shells, GRB afterglows)

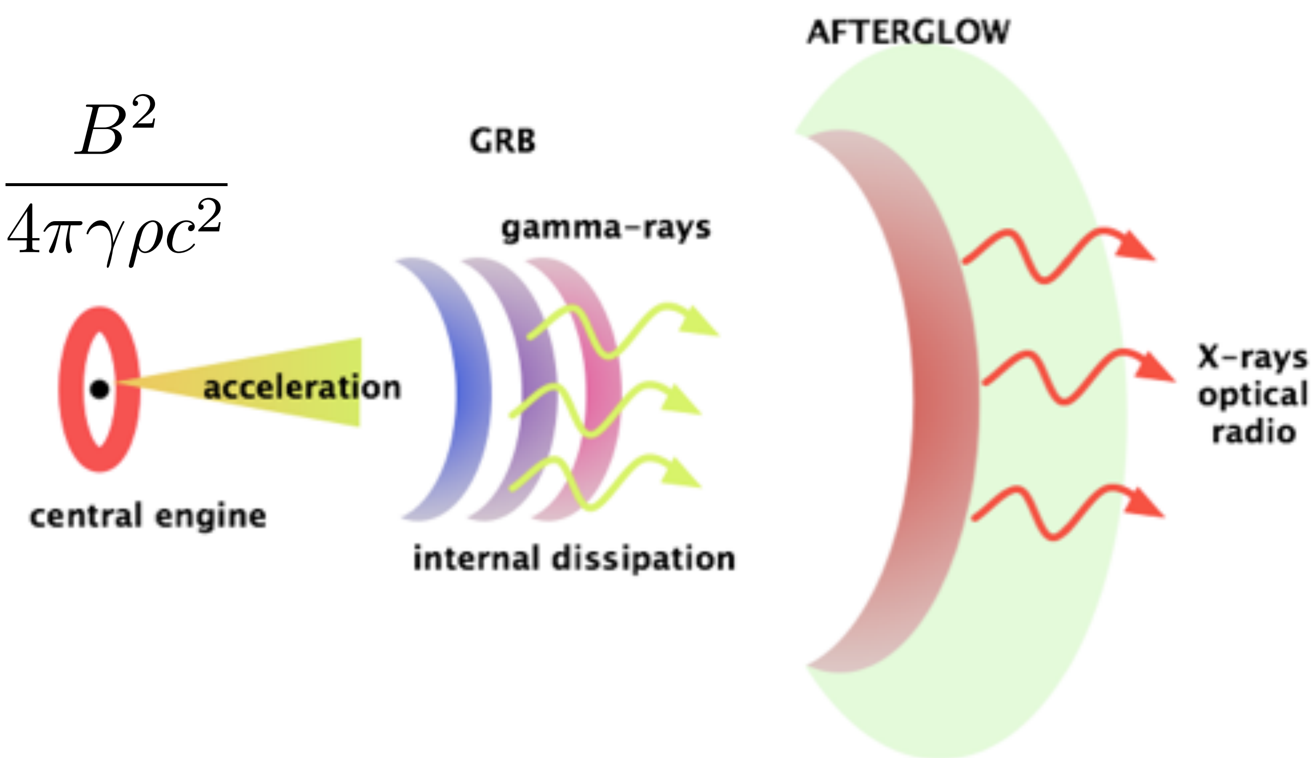
Overview of Multi-zone Semi-Analytic Models

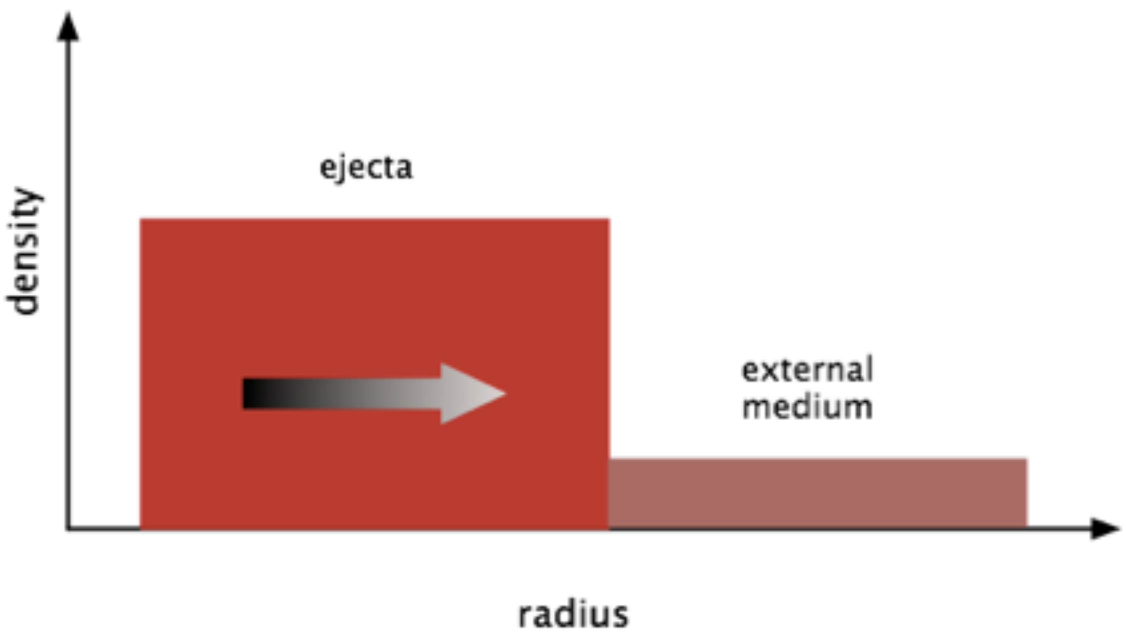
- characteristics: approximate hydrodynamics, detailed calculation of emission
- Sokolov et al. (2004): synchrotron + SSC, includes synchrotron cooling
- **Böttcher** & Dermer (2010): synchrotron + EC + SSC emission includes synchrotron + EC cooling, large parameter space scan, focus on inter-band lags
- **Chen** et al. (2011): Fokker-Planck (electrons) + Monte Carlo (photons)
- Joshi & **Böttcher** (2011): inhomogeneous particle and photon distributions (slicing of the emitting regions), includes SSC cooling
- **Zacharias** & Schlickeiser (2012, 2013): nonlinear SSC cooling, strong influence on variability timescales
- Mimica & Aloy (2012): exact solution of RP, synchrotron + EC + SSC including synchrotron + EC cooling, scans magnetisation parameter space
- **Rueda-Becerril** et al. (2014): variation of bulk and relative Γ and θ_{obs}
- Joshi et al. (2014): includes accretion disk, BLR and DT as sources of seed photons for EC, full Klein-Nishina treatment
- Marscher (2014): turbulent magnetized plasma, syn. + IC cooling, polarization
- Jamil & **Böttcher** (2012), **Chen** et al. (2014), Zhang et al. (2014): ordered magnetic fields (angle dependent synchrotron emissivity), polarisation

(more details in talks by M. Böttcher, X. Chen, M. Zacharias, J. Rueda-Becerril)

GRB Ejecta-Medium Interaction

- ejecta at the onset of the afterglow:
  - cold $P \ll \rho c^2$
  - highly relativistic $\gamma \gg 1$
  - total energy $E_K(1+\sigma)$
  - (unknown) magnetisation $\sigma := \dfrac{B^2}{4\pi\gamma\rho c^2}$



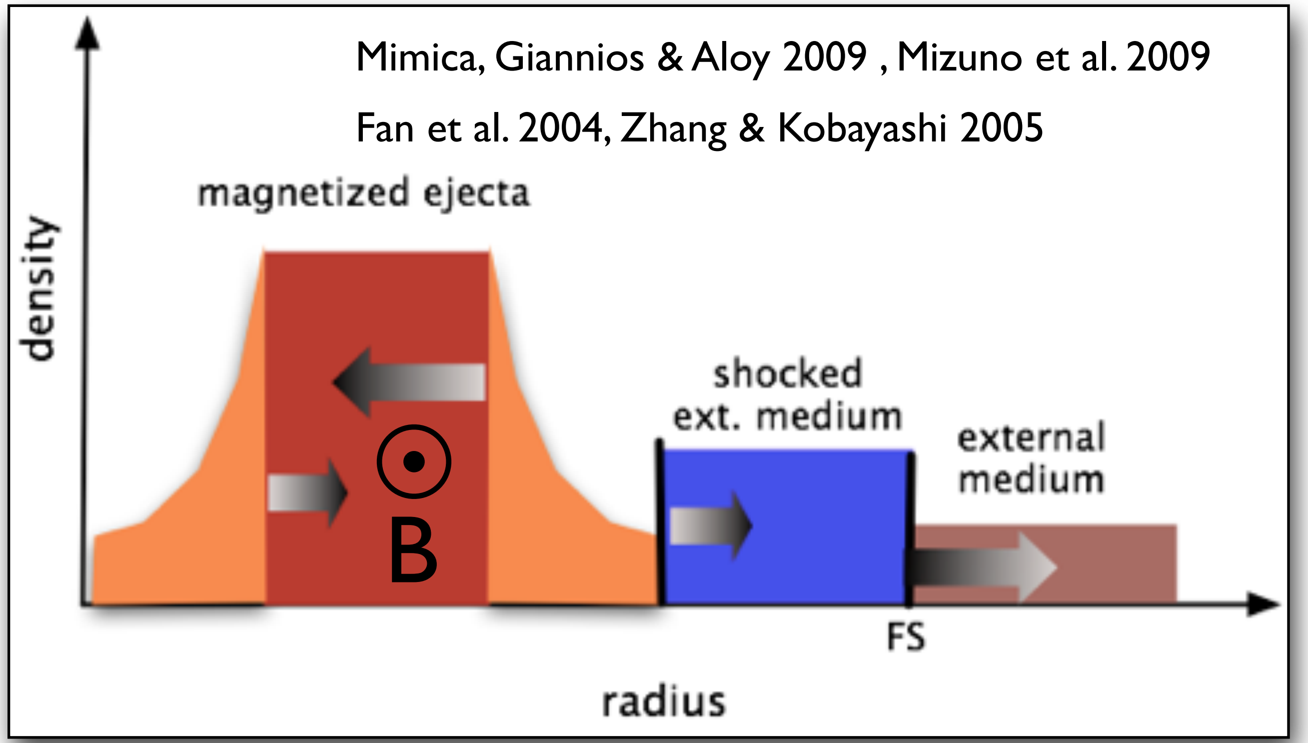


Afterglow simulations classification

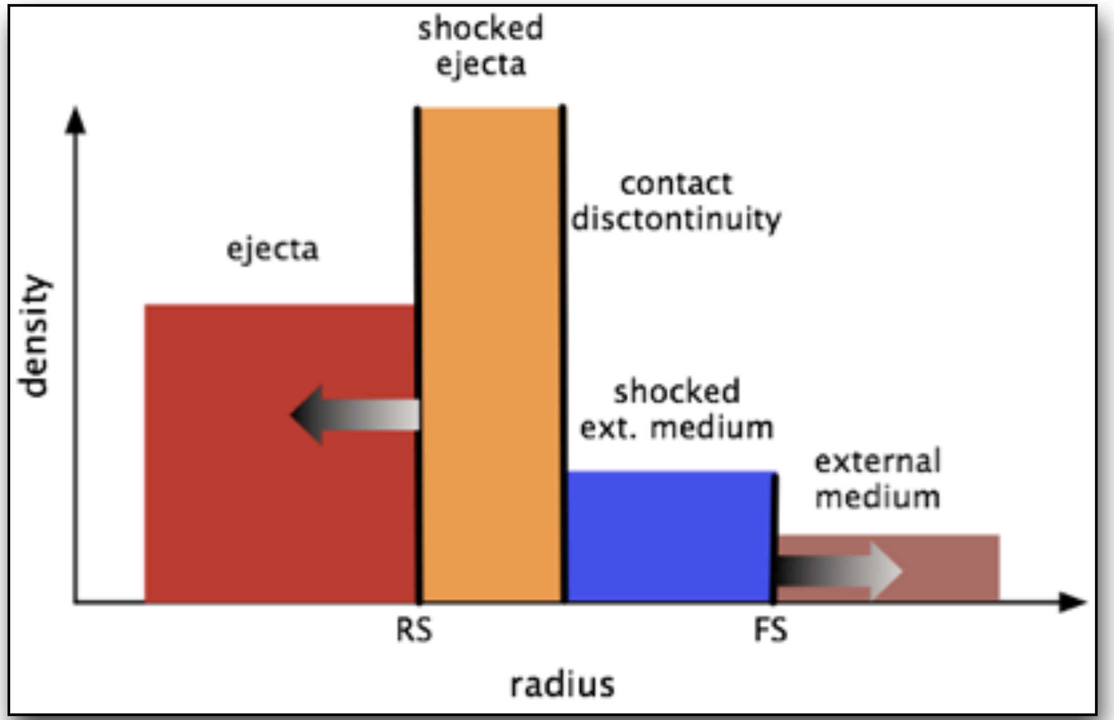
	early afterglow	late afterglow
properties	• probe ejecta properties (σ, γ, Δ) • typically 1D • RHD & RMHD	• probe global properties (E, n ext. medium structure) • 1D and 2D RHD

Magnetized vs. Hydrodynamic Ejecta

$\sigma \simeq 1$



$\sigma \ll 1$



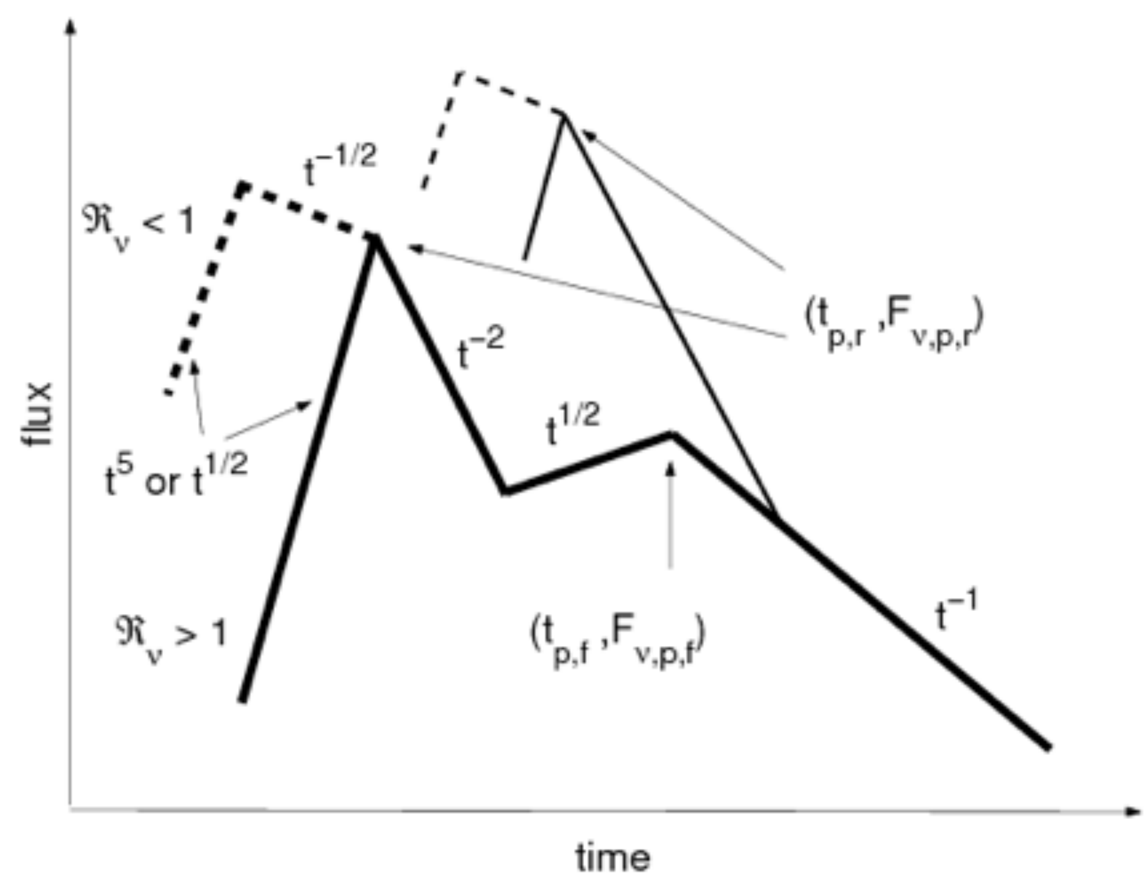
<u>What should be the shell magnetization at the onset of the afterglow?</u>

- impulsive acceleration of very magnetised shell has been studied in detail (e.g., Granot, Komissarov & Spitkovsky 2011; Lyutikov 2011; Levinson 2011; Granot 2012; Komissarov 2012)
- a $\sigma \gg 1$ shell accelerates until $\sigma \approx 1$
- longitudinal expansion converts Poynting flux into kinetic energy
- jet might be Poynting dominated beyond prompt emission zone (e.g., Komissarov 2012)

Why Are Early Afterglow Simulations Important?

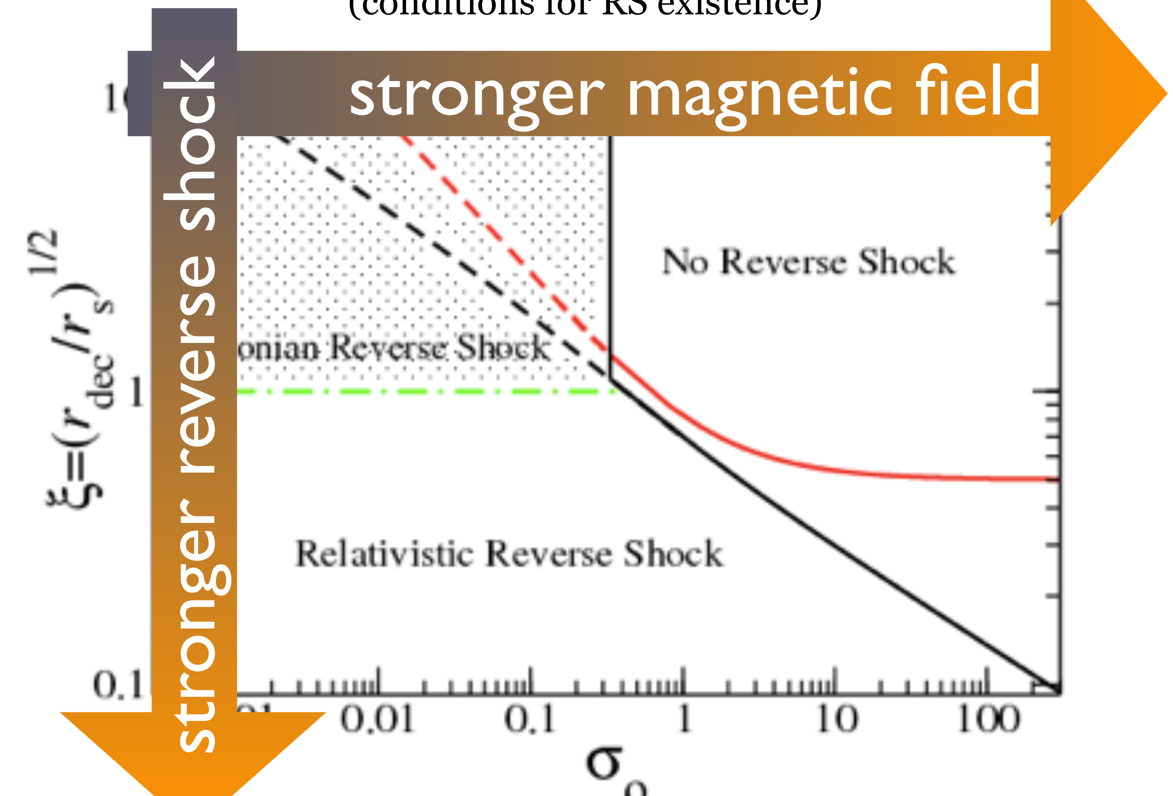
- (possible) RS detections in the *Swift* era (Gomboc et al. 2009)
  041219A, 050525A, 050904, 060111B, 060117, 061126, 080319B
- no reverse shock optical component detected in most early afterglows (Roming et al. 2006, Gomboc et al. 2009)

- strong magnetic fields affect shock conditions
- RS forms only if: $\sigma < 0.6 n_0^{1/2}\ \Delta_{12}^{3/2}\ \gamma_{2.5}^{4}\ E_{53}^{-1/2}$
- no RS -> no early optical flash



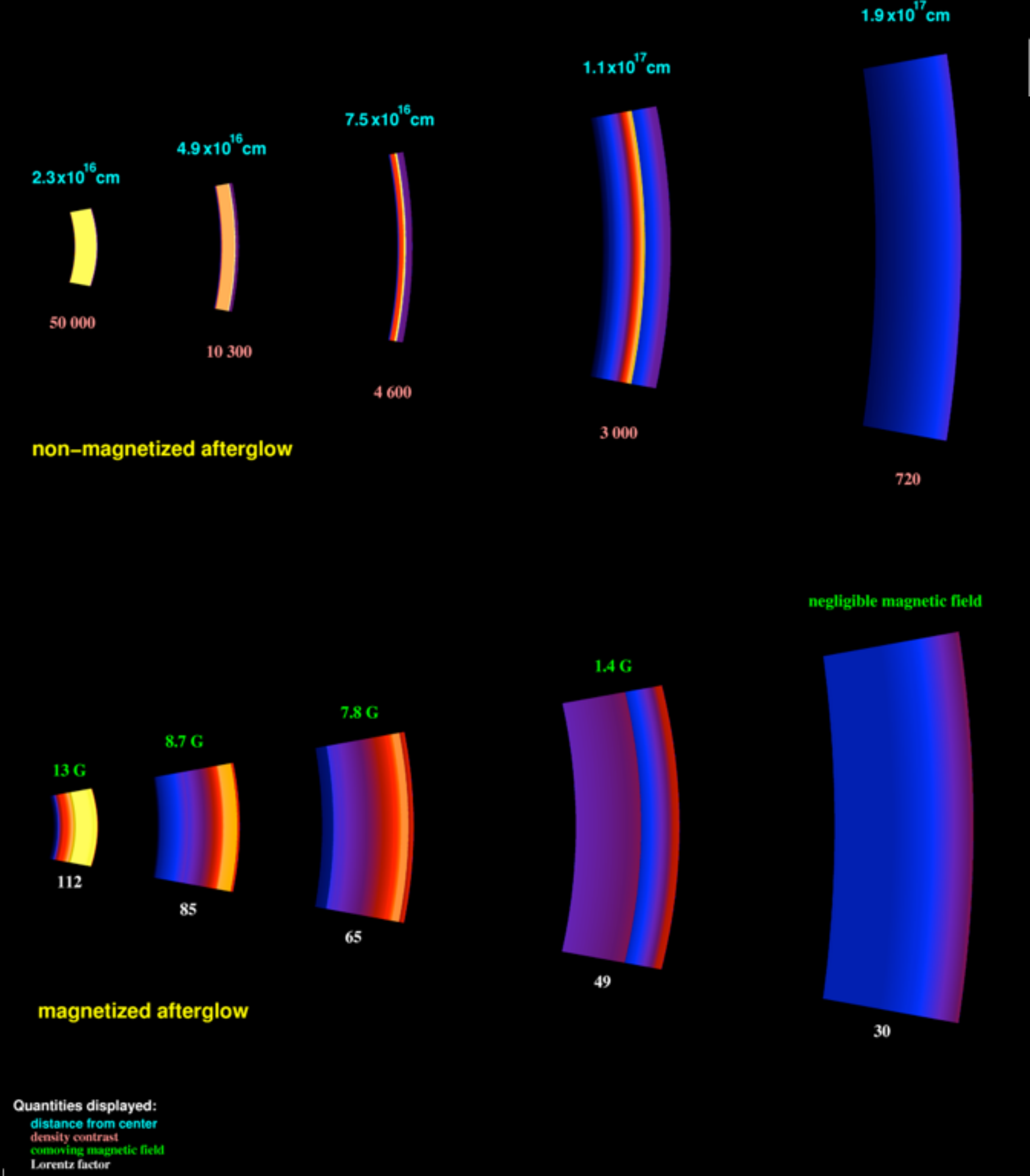
Zhang et al. 2003
(optical flash)

Giannios *et al.* 2008
(conditions for RS existence)



$$\xi \approx 0.73\ E_{53}^{1/6}\ n_0^{-1/6}\ \Delta_{12}^{-1/2}\ \gamma_{2.5}^{-4/3}$$

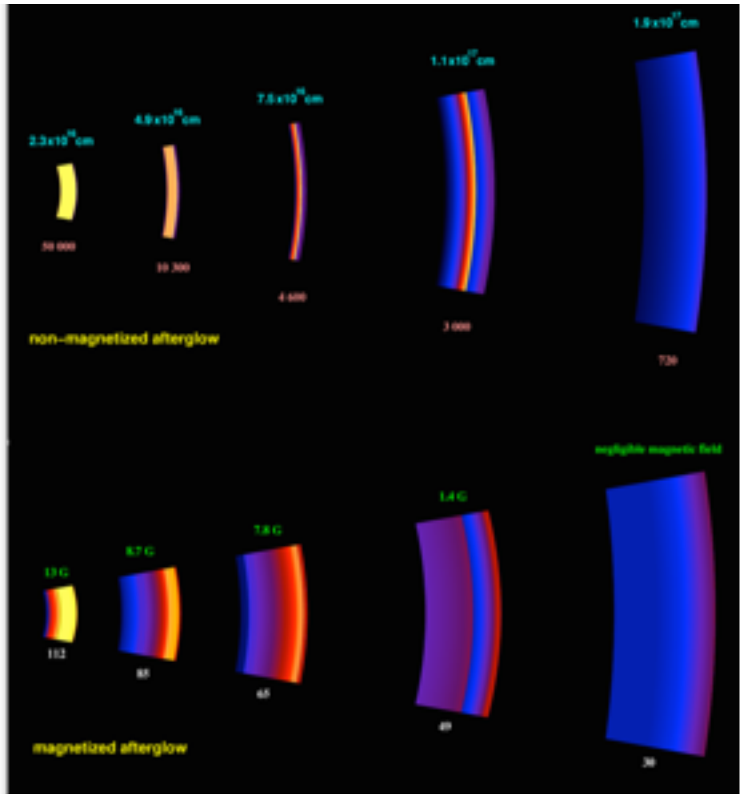
(Sari & Piran 1995)



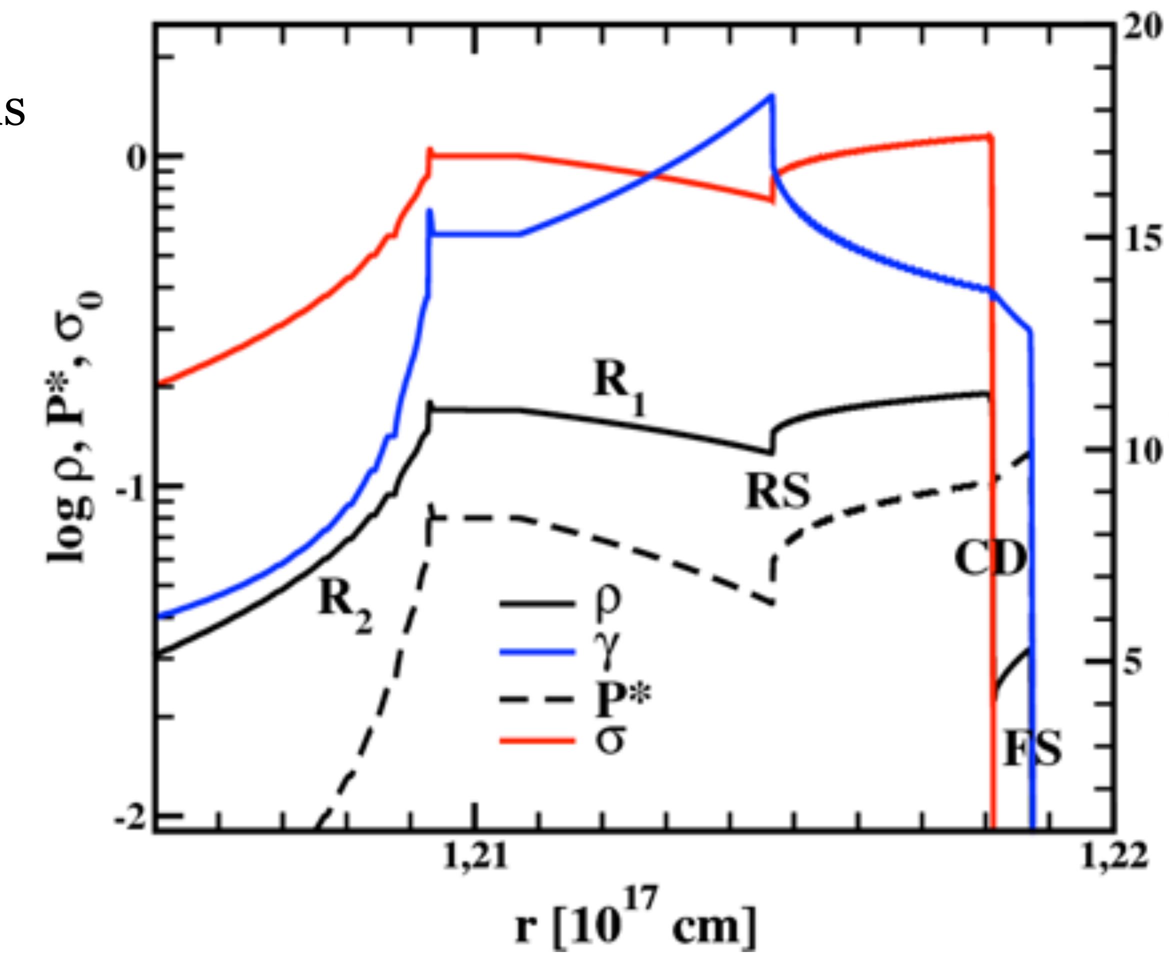
2.3x10^{16}cm
4.9x10^{16}cm
7.5x10^{16}cm
1.1x10^{17}cm
1.9x10^{17}cm
50 000
10 300
4 600
3 000
720
non-magnetized afterglow
negligible magnetic field
13 G
8.7 G
7.8 G
1.4 G
112
85
65
49
30
magnetized afterglow
Quantities displayed:
distance from center
density contrast
comoving magnetic field
Lorentz factor

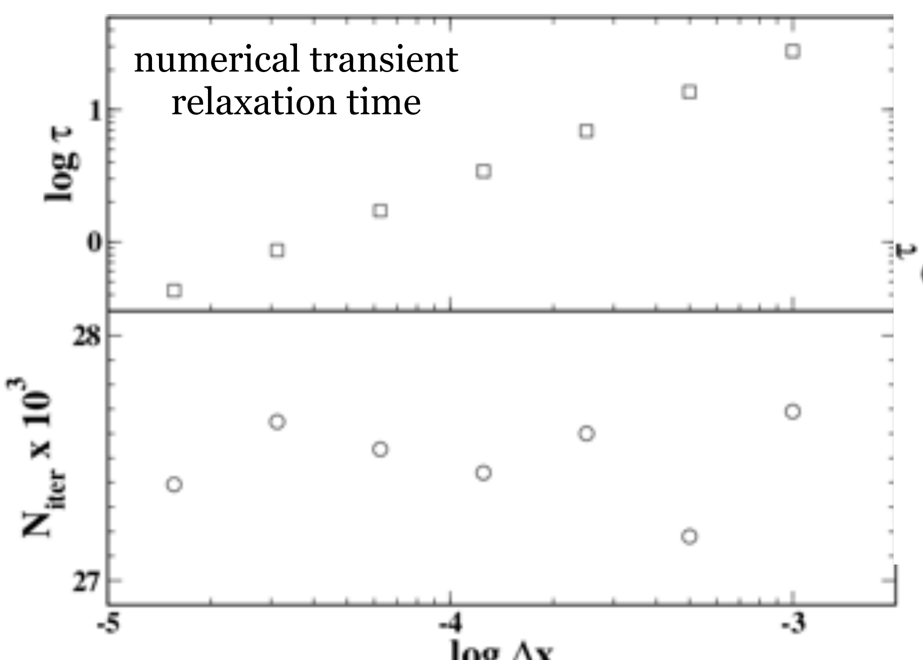
RMHD Early Afterglow Simulations Difficulties

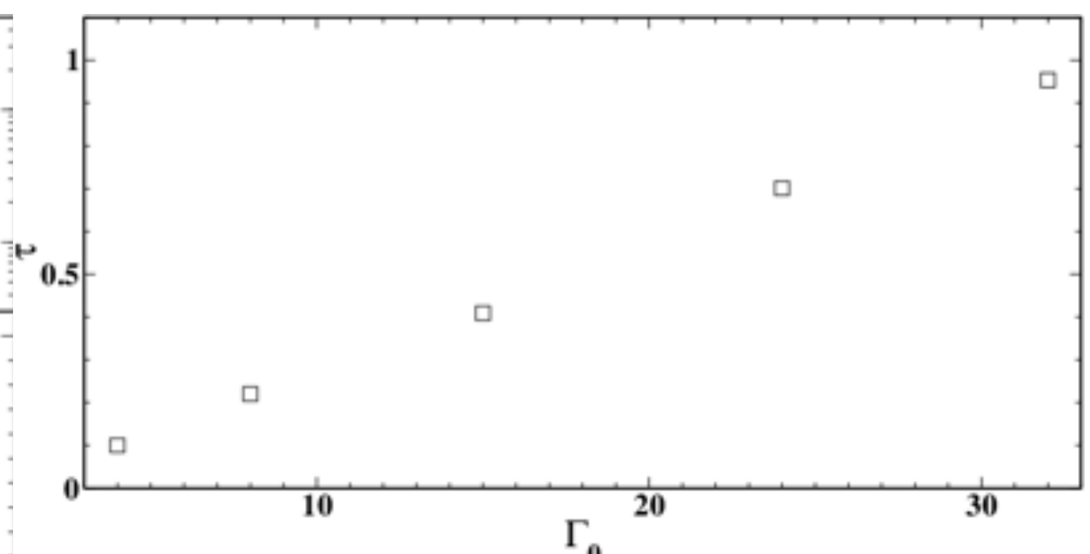
Mimica, Giannios & Aloy 2009
(deceleration of magnetised shells)



- early afterglow simulations require prohibitively high resolution





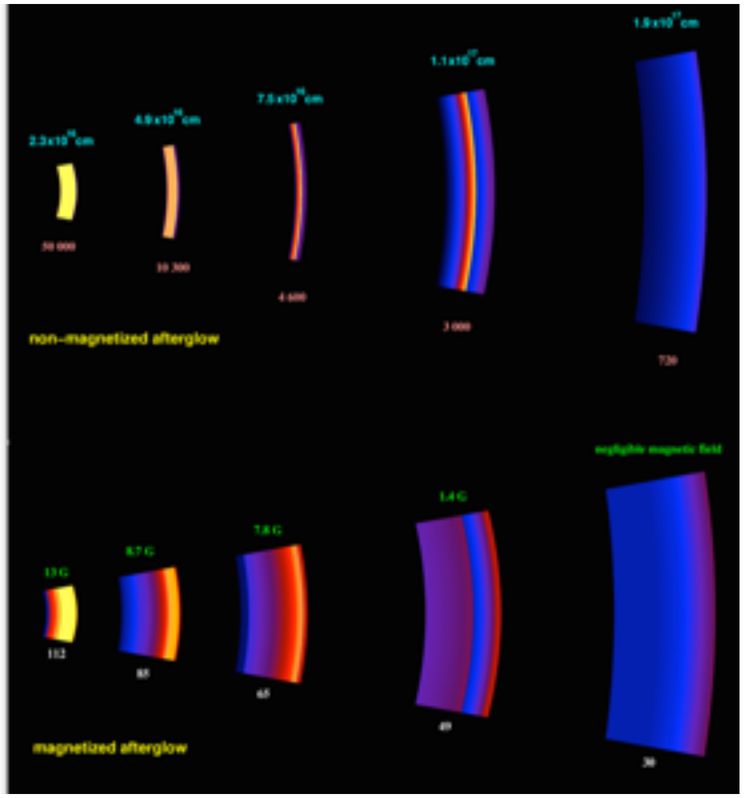


dependence of relaxation time on initial Lorentz factor

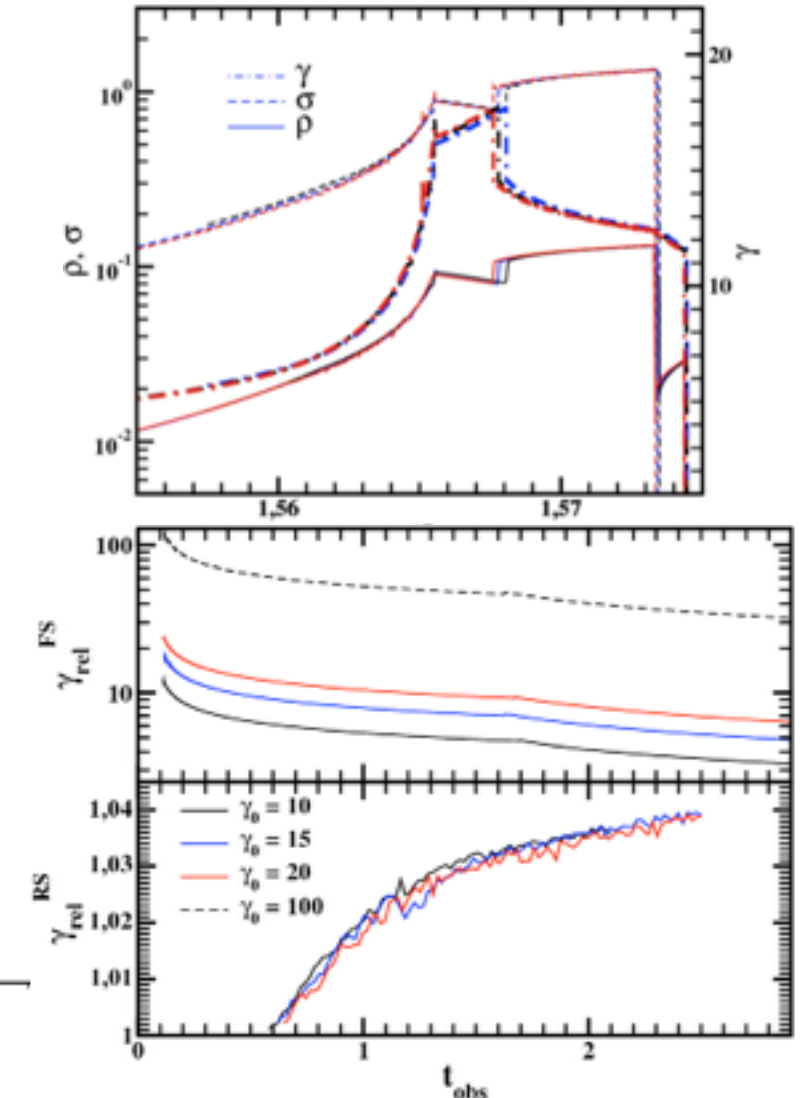
$$\text{resolution} \propto \Gamma_0/\tau_{\text{relaxation}}$$

RMHD Early Afterglow Simulations Difficulties

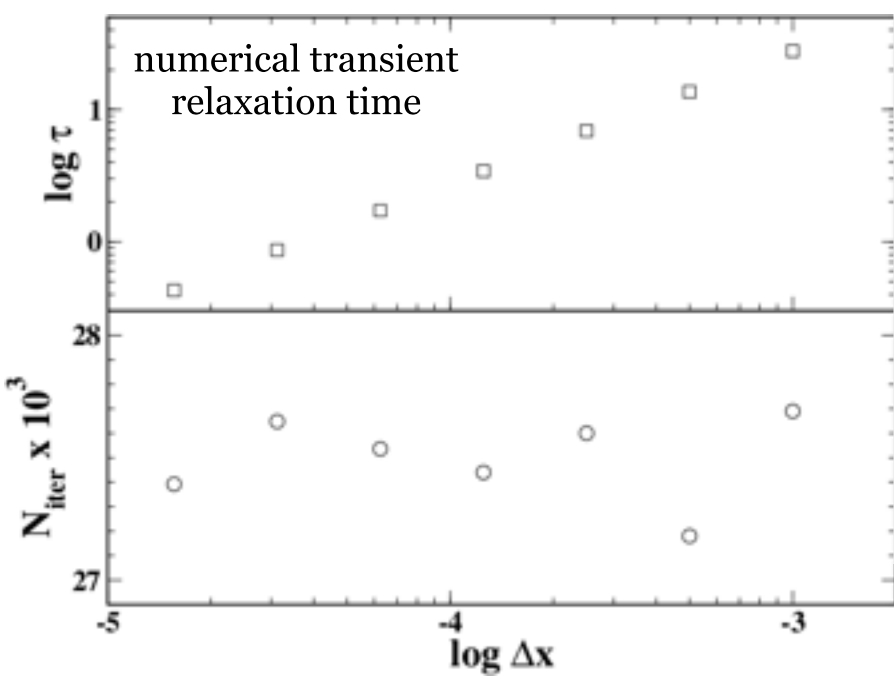
Mimica, Giannios & Aloy 2009
(deceleration of magnetised shells)

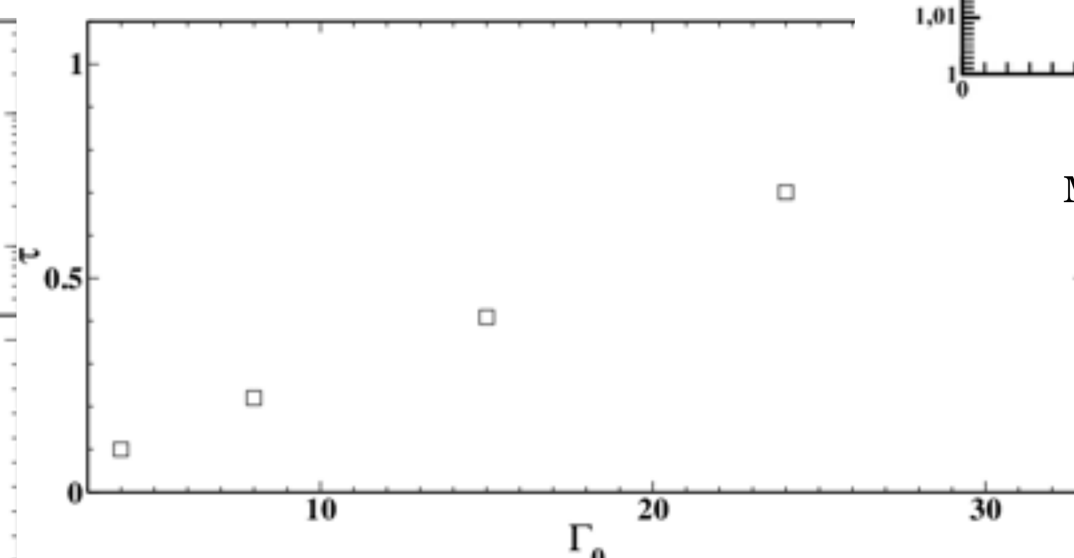


- early afterglow simulations require prohibitively high resolution
- idea: run at lower Γ, but rescale shell and ext. medium properties, keep ξ constant
- numerical tests confirm: once performed, a single simulation can be rescaled to arbitrary Γ!
- (other scaling relations possible: van Eerten & MacFadyen 2012; Granot 2012)



Mimica, Giannios & Aloy 2009
(rescaling tests)





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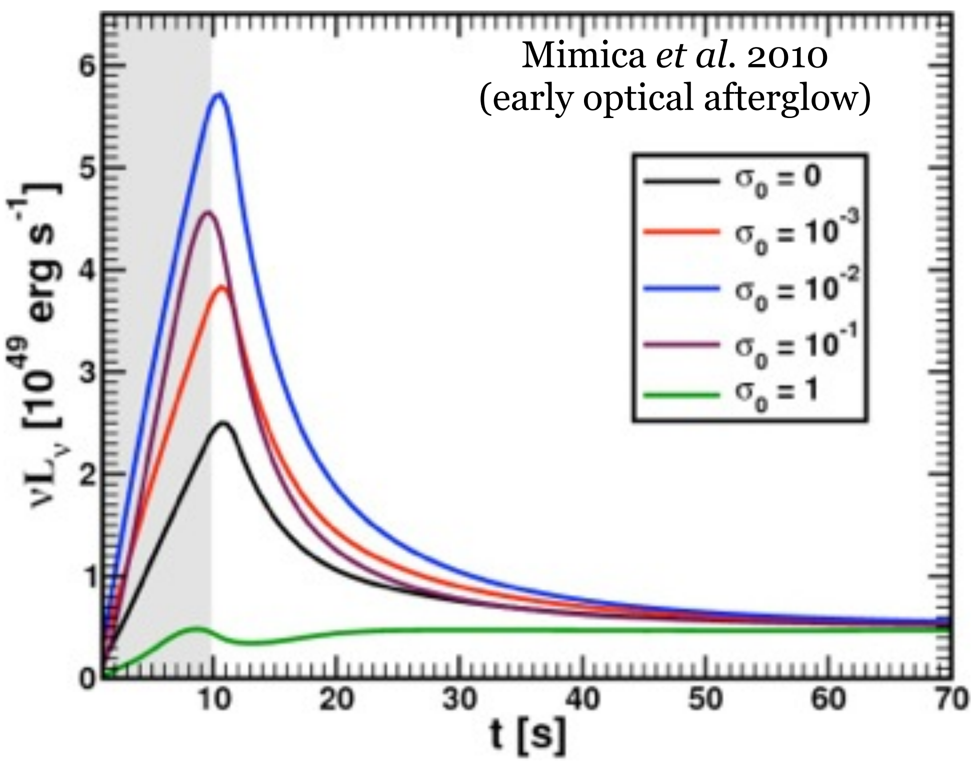
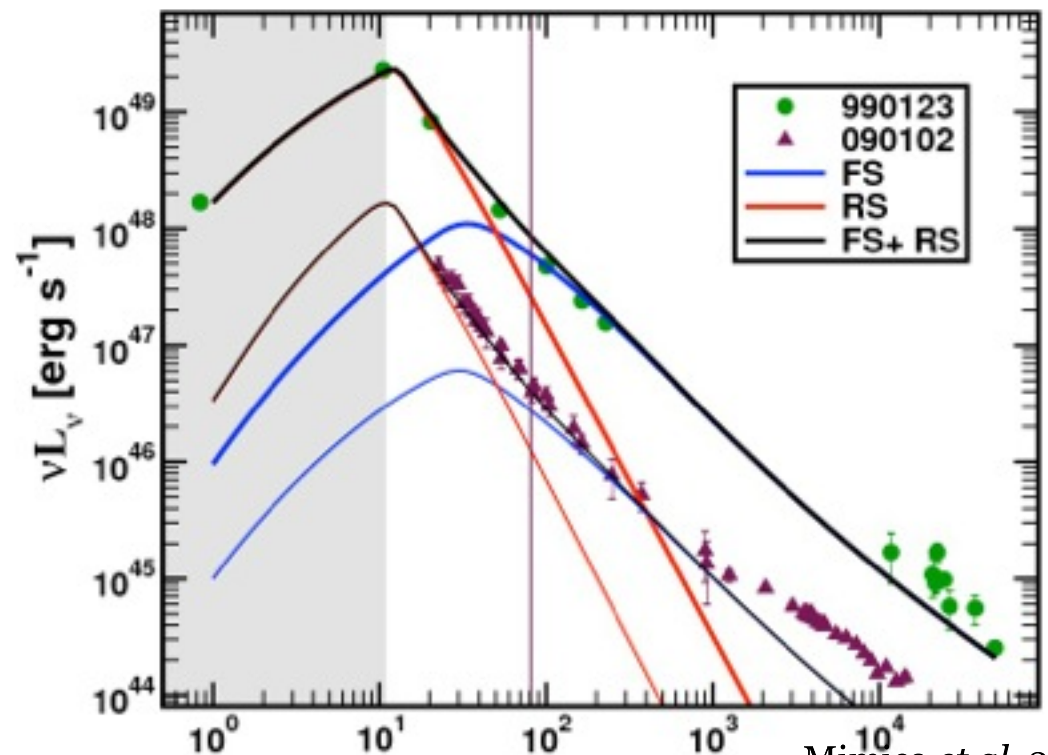
Early Afterglow Optical Emission

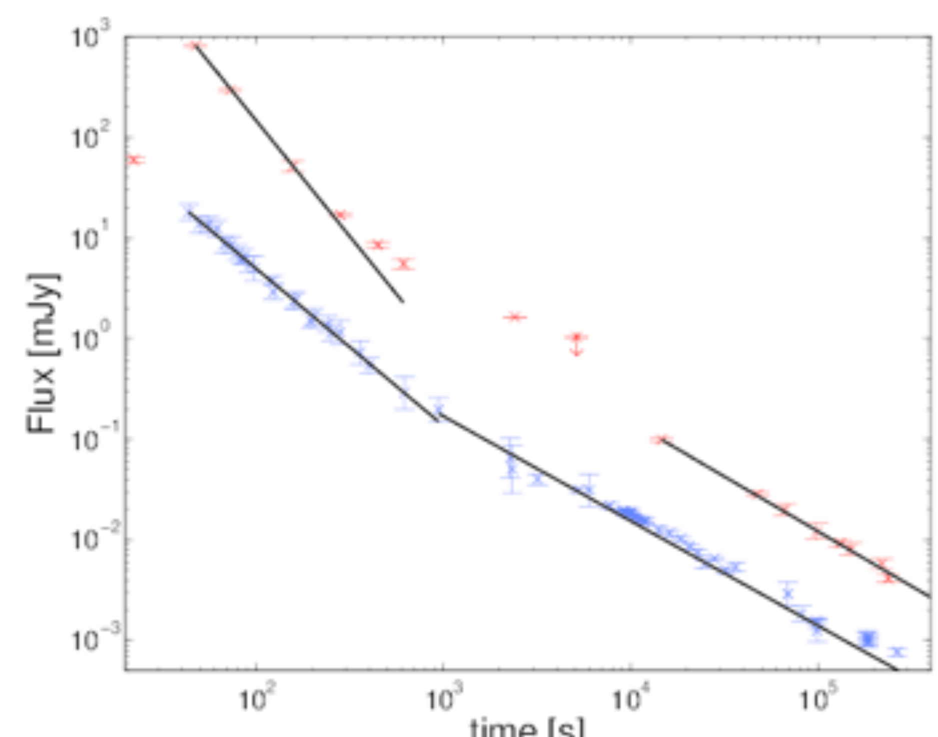




Mimica *et al.* 2010
(RMHD, GRBs 990123, 090102 optical light curves)

- generic simulations: moderate σ increases optical flash luminosity, σ > 0.1 suppresses RS & optical flash

- modeling of two GRBs with a strong optical flash yields consistent parameters:
  - GRB 990123: $\Gamma_0 = 640$, $\sigma_0 = 0.01$
  - GRB 090102: $\Gamma_0 = 940$, $\sigma_0 = 0.1$
- Harrison & Kobayashi (2013): $\sigma_{990123}/\sigma_{090102} \approx 30$
- difference between two results probably due to pure RHD treatment in H&K (2013)

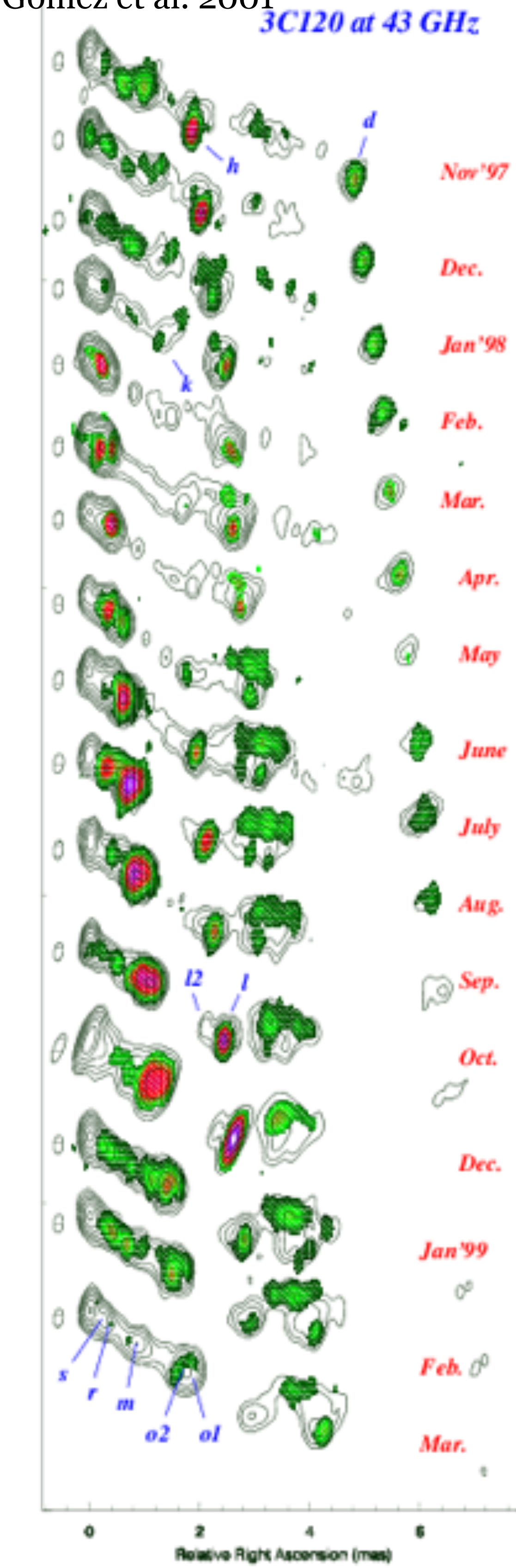


Harrison & Kobayashi 2013
(RHD, GRBs 990123, 090102 optical light curves)

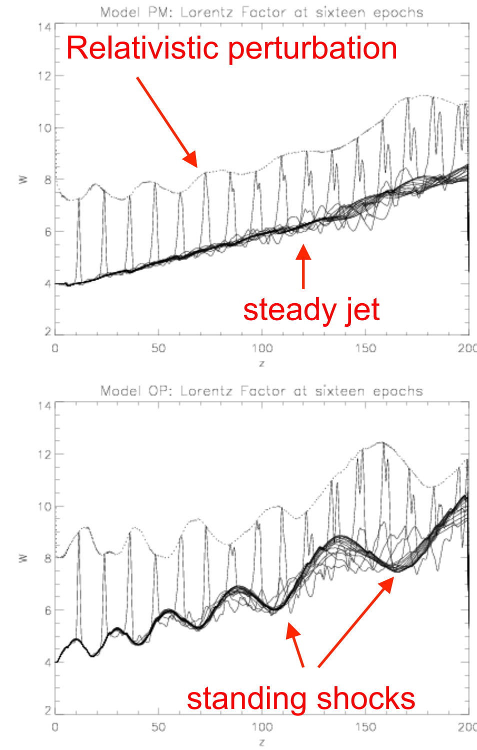
Emission from Parsec-scale Jets

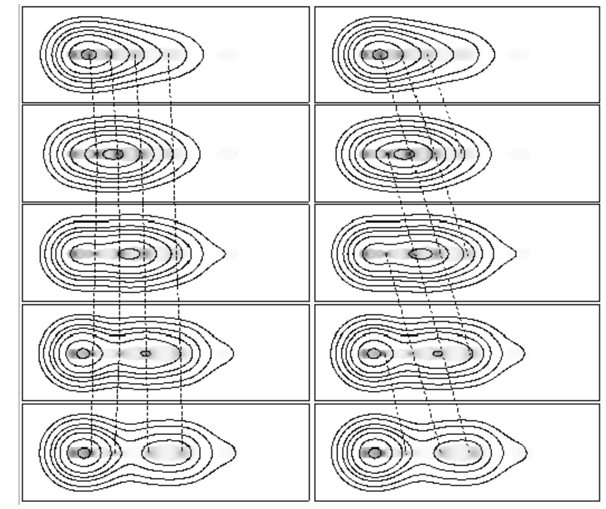
- intensive VLBI monitoring of innermost regions of relativistic jets reveals rich emission structure and variability, e.g.:
  - **stationary features:** standing knots of increased radio emission associated with the internal oblique shocks
  - **superluminal components:** radio emitting plasma moving at apparent superluminal velocities, associated with injection of material into the jet
  - **trailing components:** slow or quasi-stationary features trailing superluminal components
- observed emission influenced by a number of effects (time delays, Doppler boost, light abberation, opacity, Faraday rotation, ...) and not a direct map of jet physical state
- comparisons with relativistic (magneto)hydrodynamics and emission simulations needed to understand the inner jet dynamics

Gomez et al. 2001

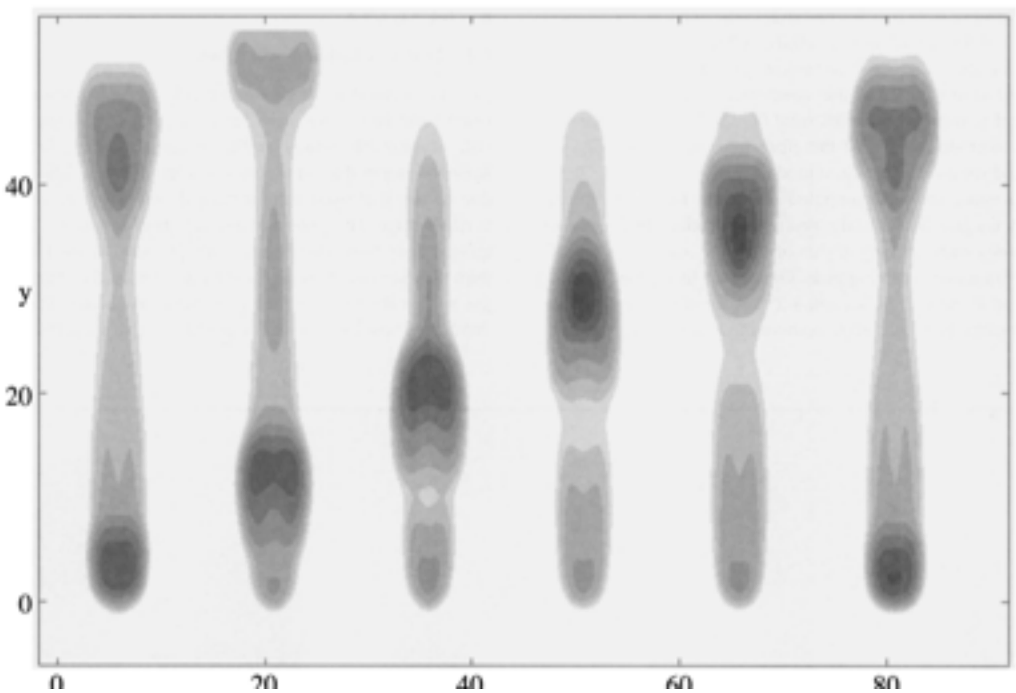


Numerical Hydrodynamic Models

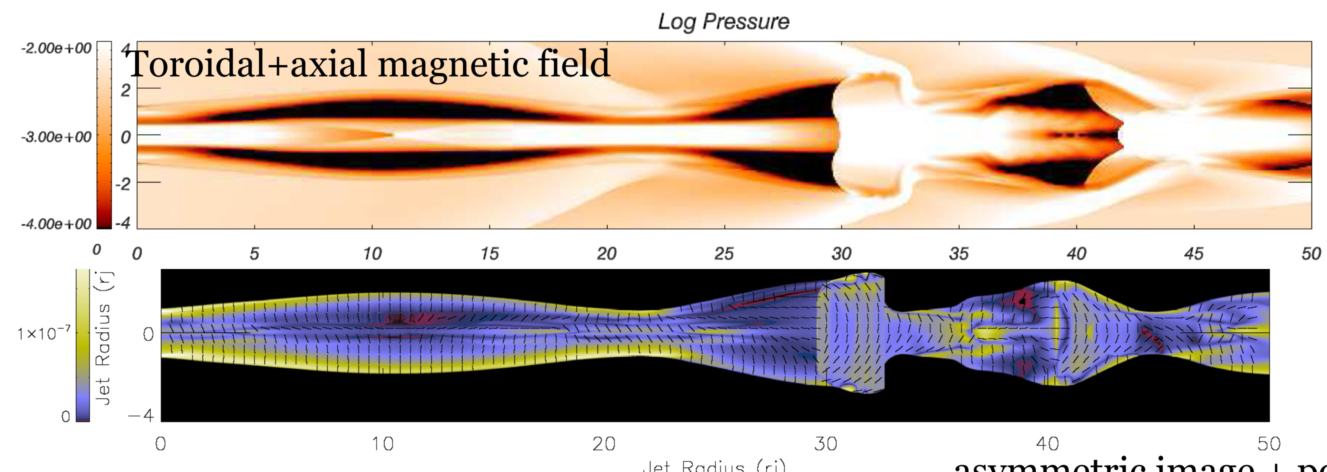




Gomez *et al.* 1997
(perturbation of steady jets, emission)



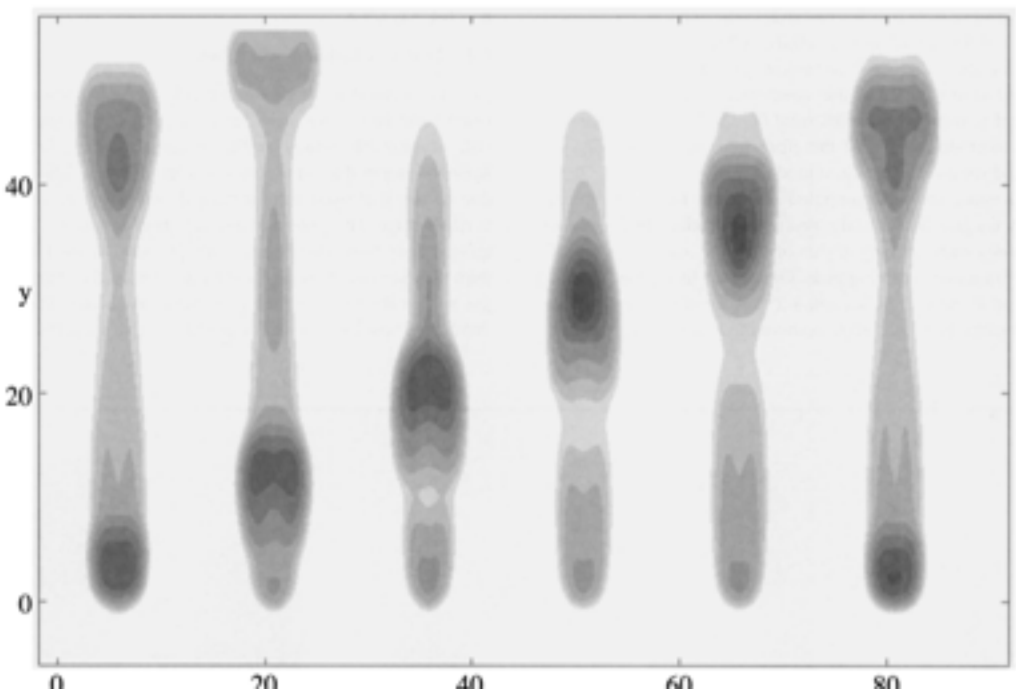
Komissarov & Falle 1997
(perturbation of steady jets, emission)



asymmetric image + polarisation

Roca-Sogorb *et al.* 2008
(steady magnetized jets, emission, polarization)

Numerical Hydrodynamic Models



Komissarov & Falle 1997
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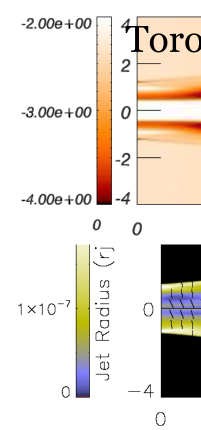
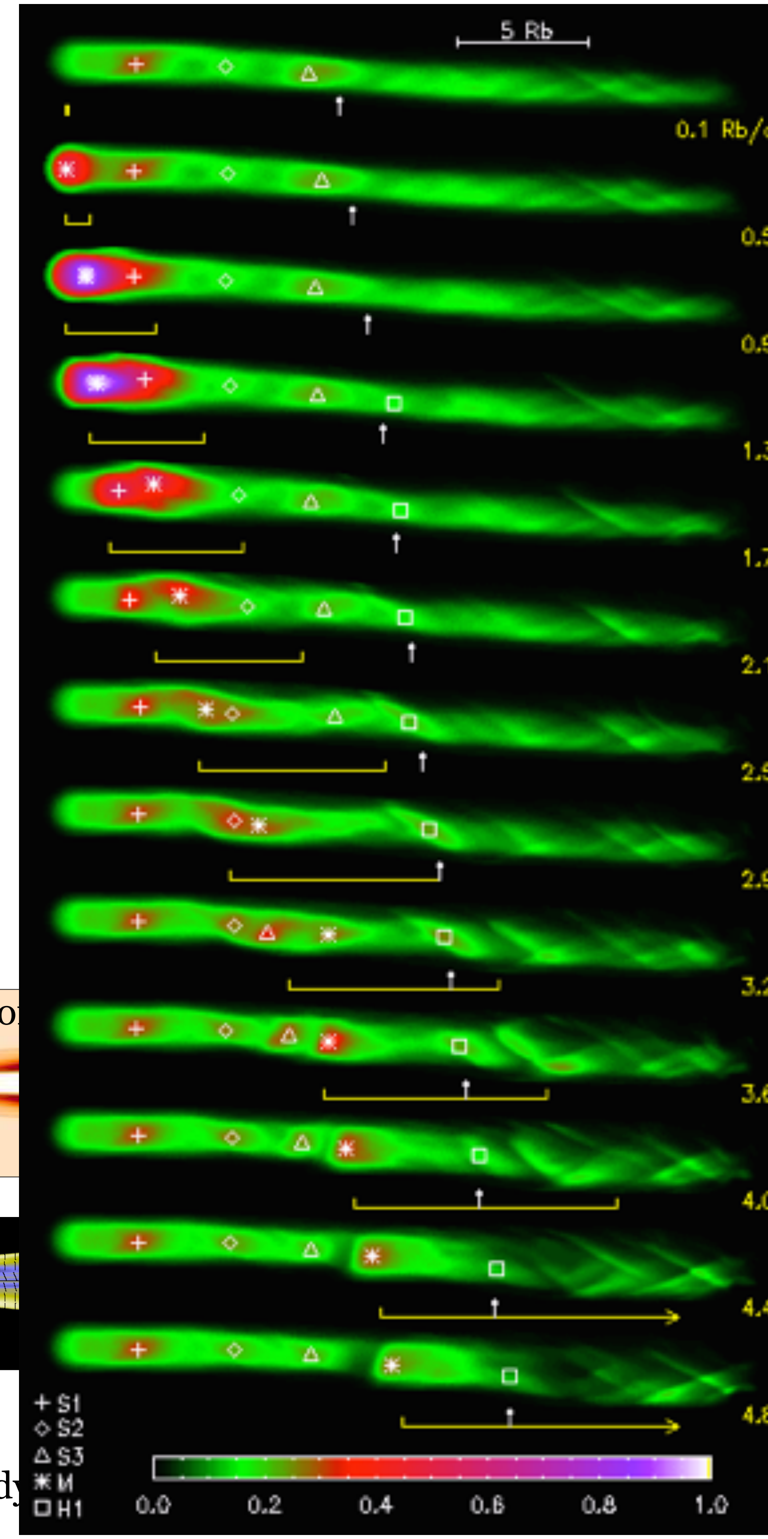
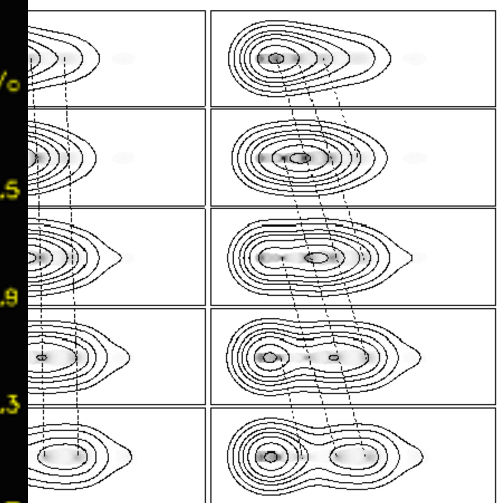


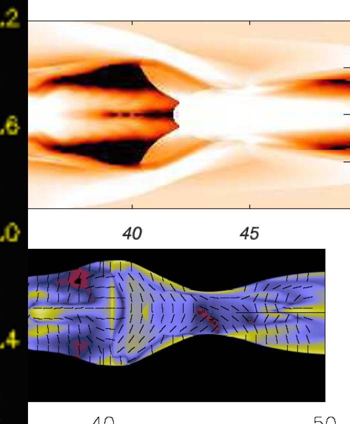
(steady



Aloy et al. 2003
(3D jets, emission)

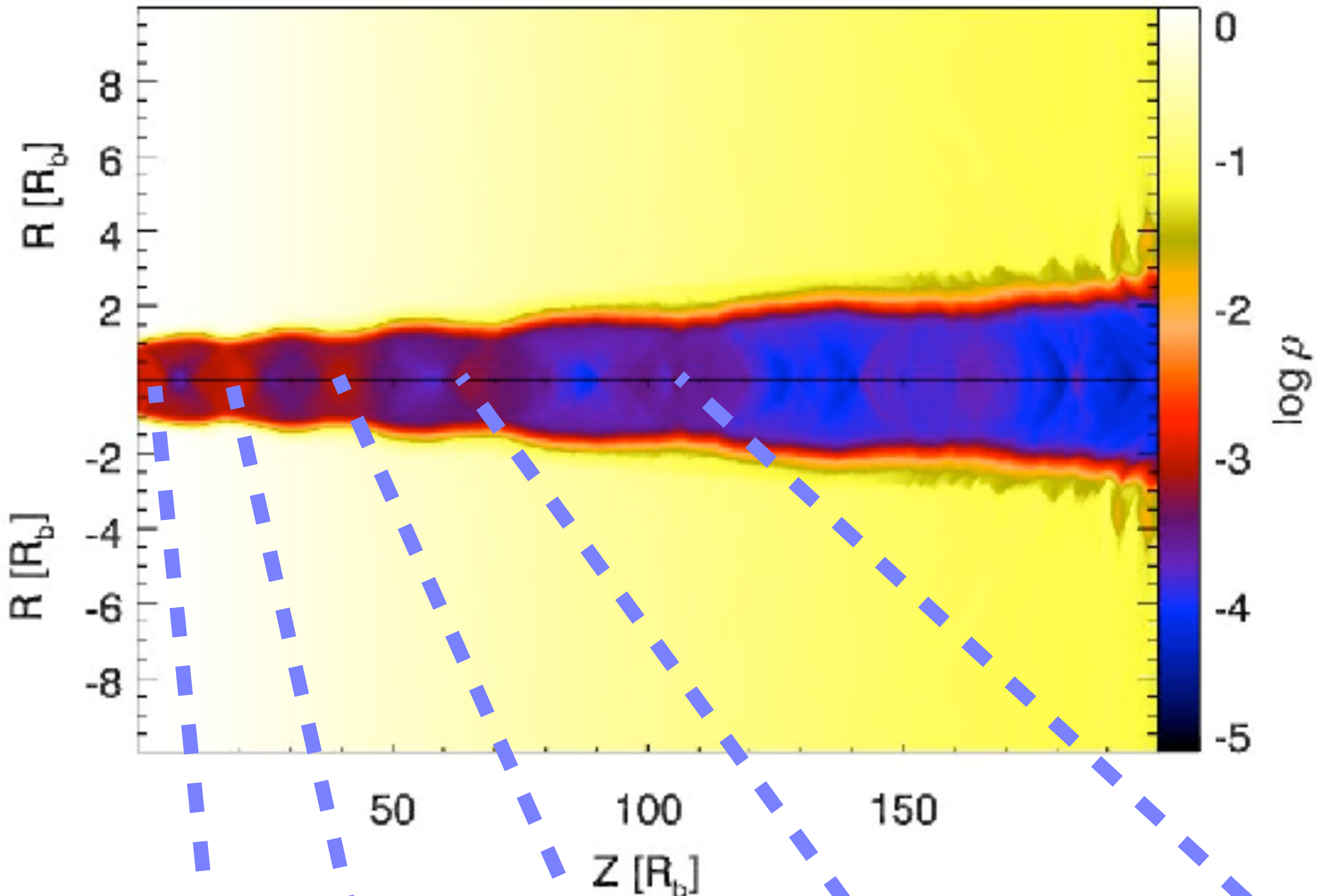


Gomez *et al*. 1997
ion of steady jets, emission)



symmetric image + polarisation

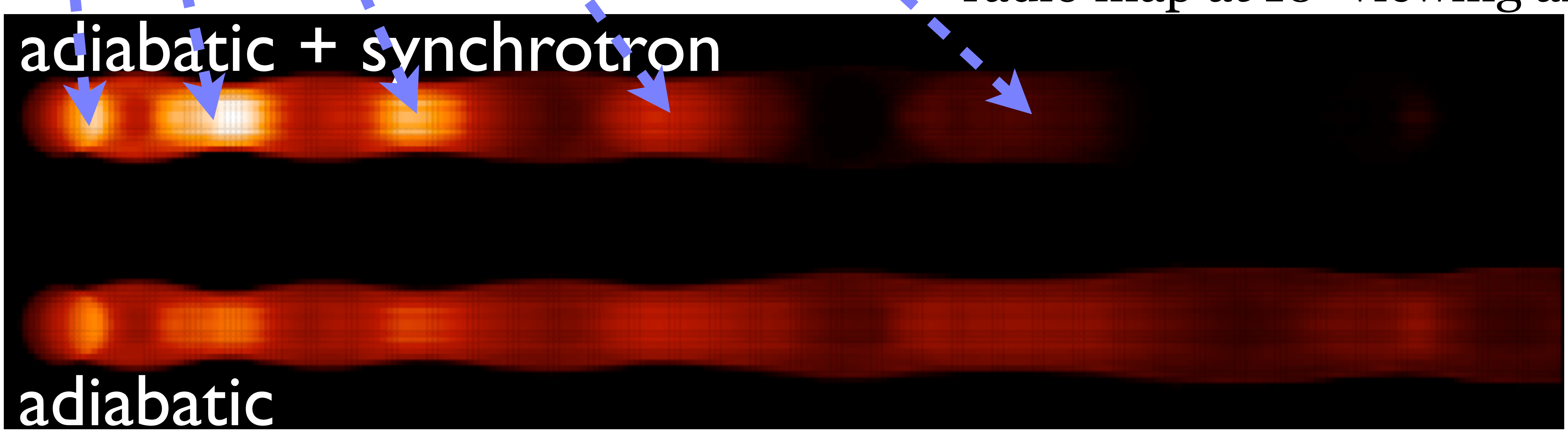
Simulated Radio Emission from Stationary Jet



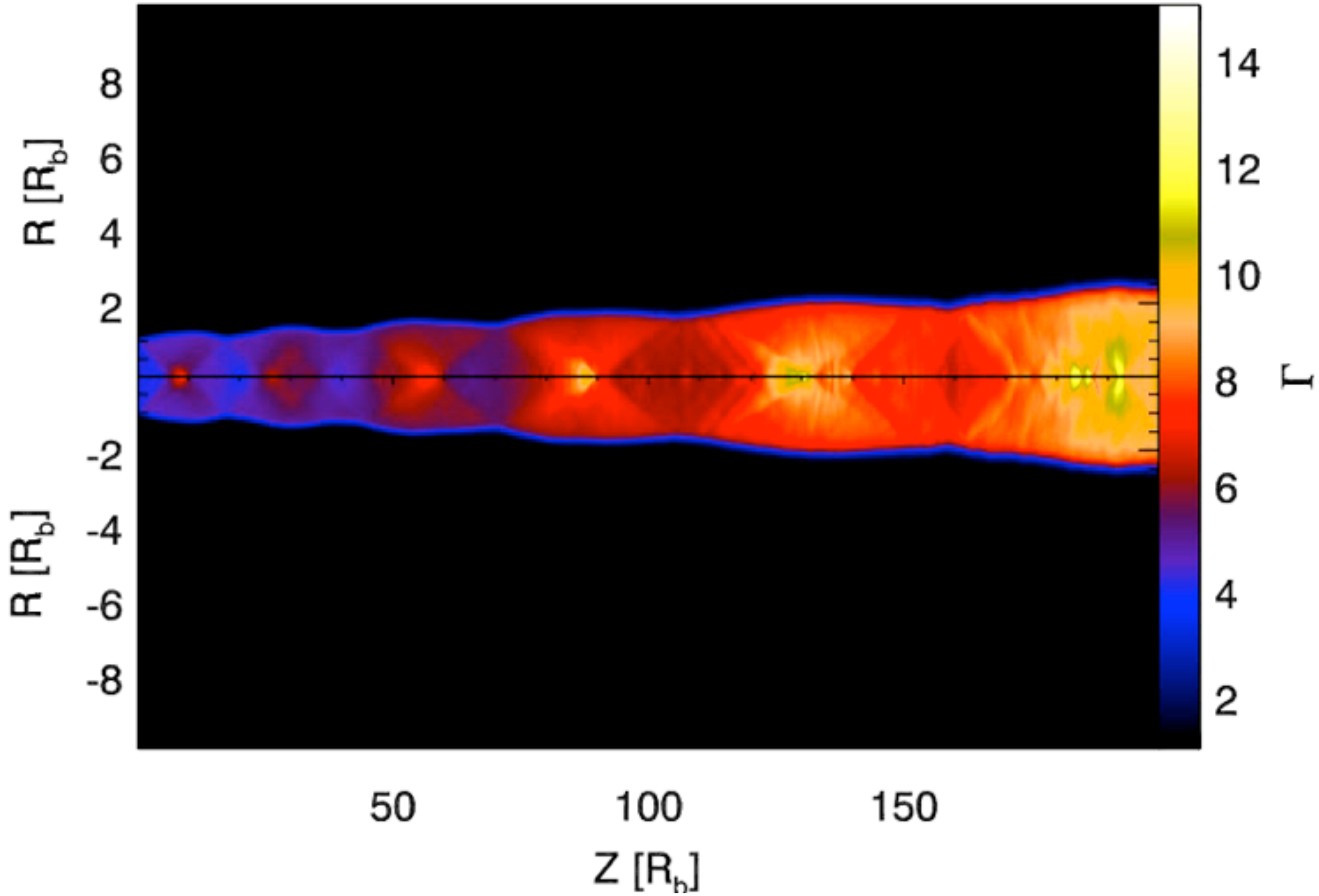
- inclusion of synchrotron losses *crucial* for obtaining correct radio images

RHD | 2D transport | Synchrotron

radio map at 10° viewing angle

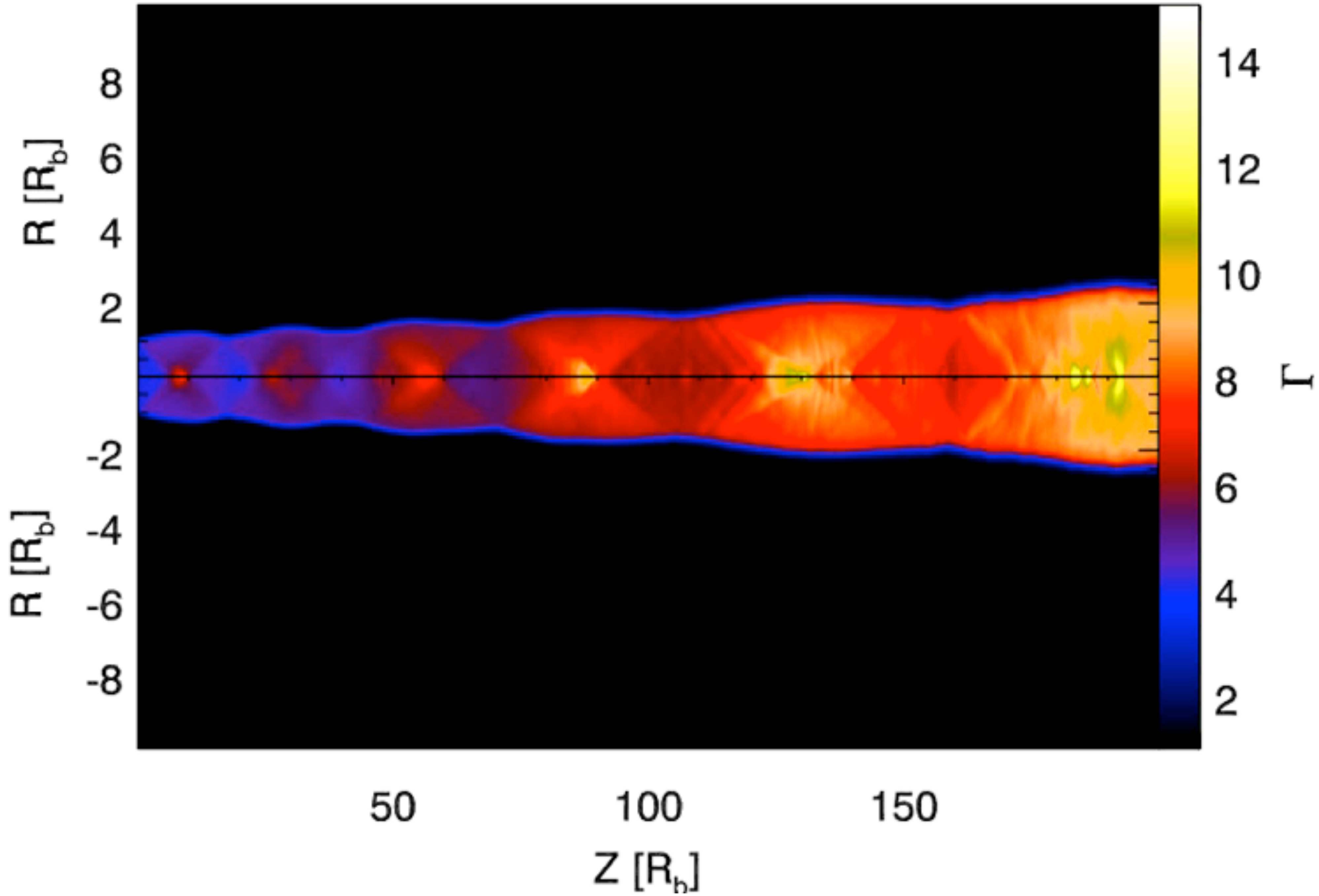


Perturbation of Stationary Jet



- component: velocity perturbation at jet nozzle
- component interacts with recollimation shocks
- simulation: `MRGENESIS`, 2D cylindrical, 1600 x 80 zones, 5×10^4 snapshots

Perturbation of Stationary Jet



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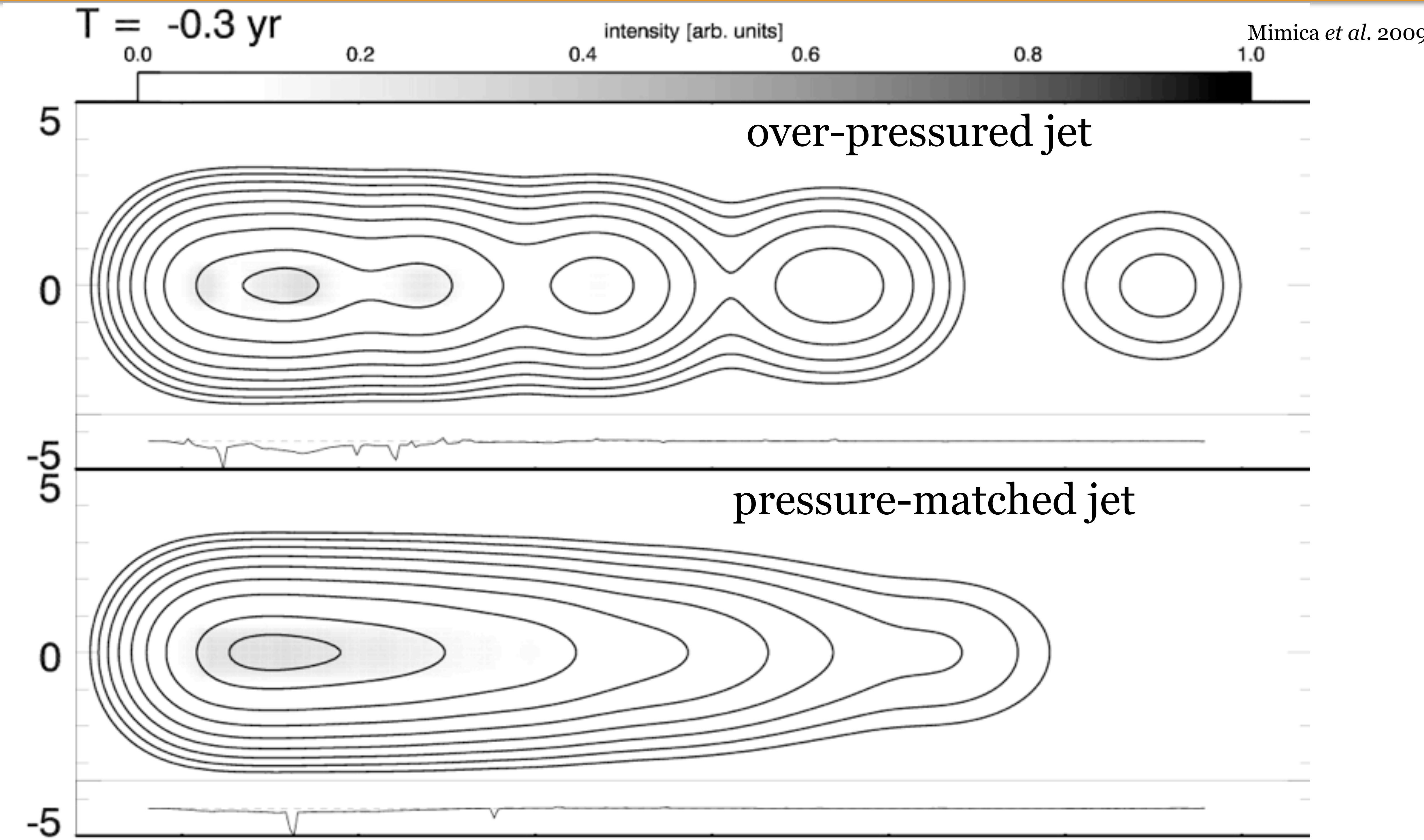
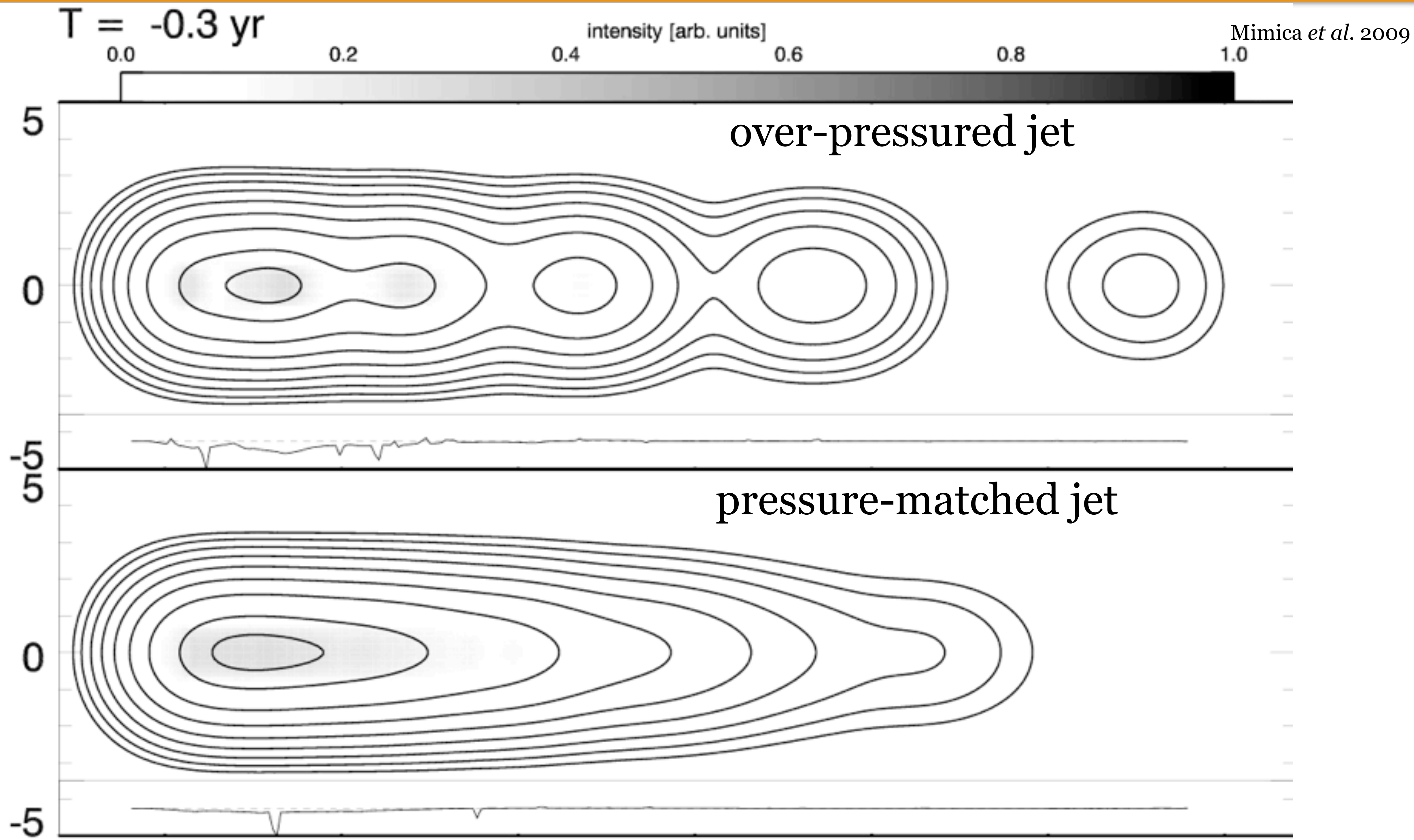
Time-Dependent Radio Emission



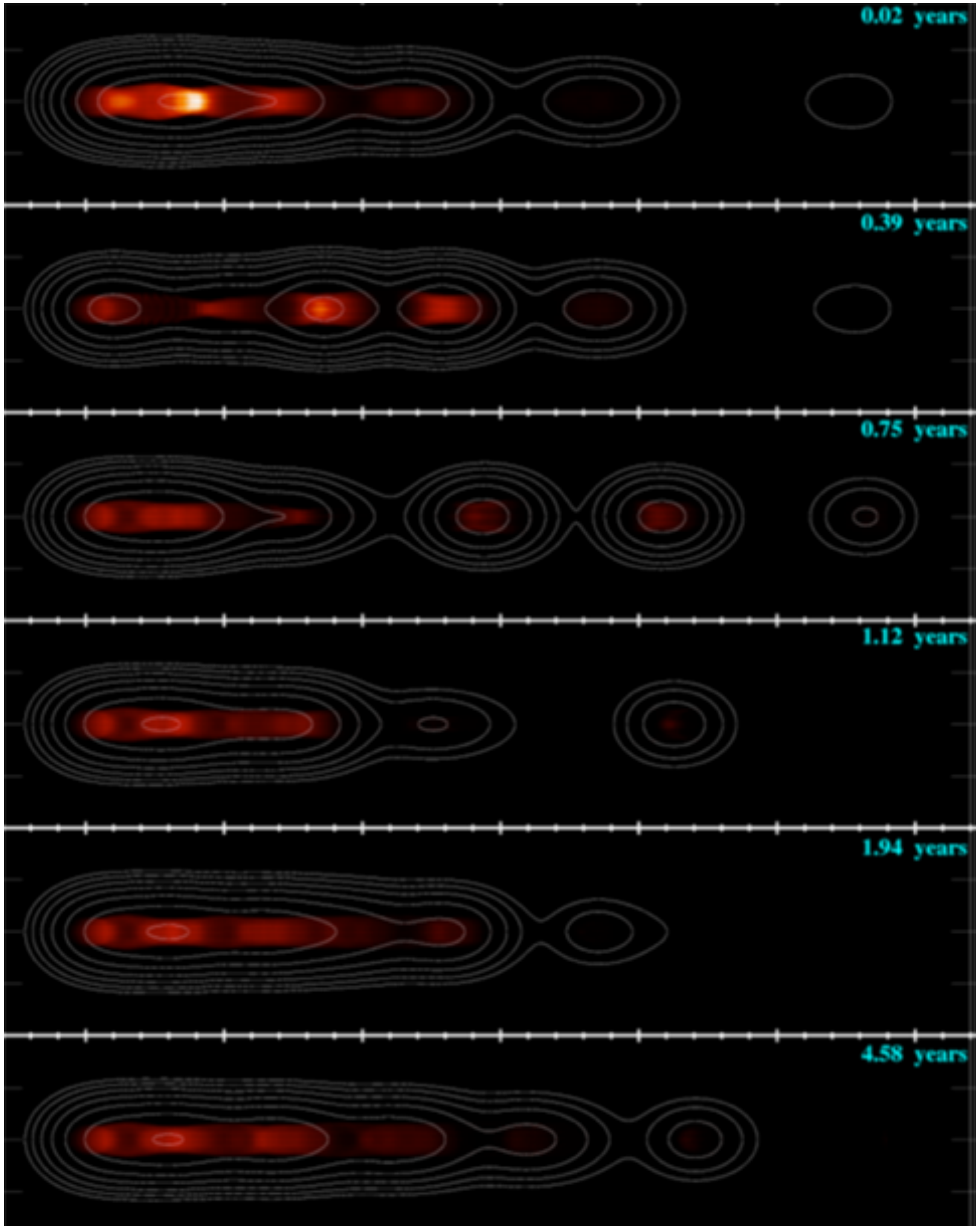
simulation: SPEV, 128 frames, 270 x 18 pixels, 3 frequencies, 100 Kh / model
0.5 Tb hydro data, 2×10^5 Lagrangian particles, 2×10^6 line-of-sight segments

Time-Dependent Radio Emission

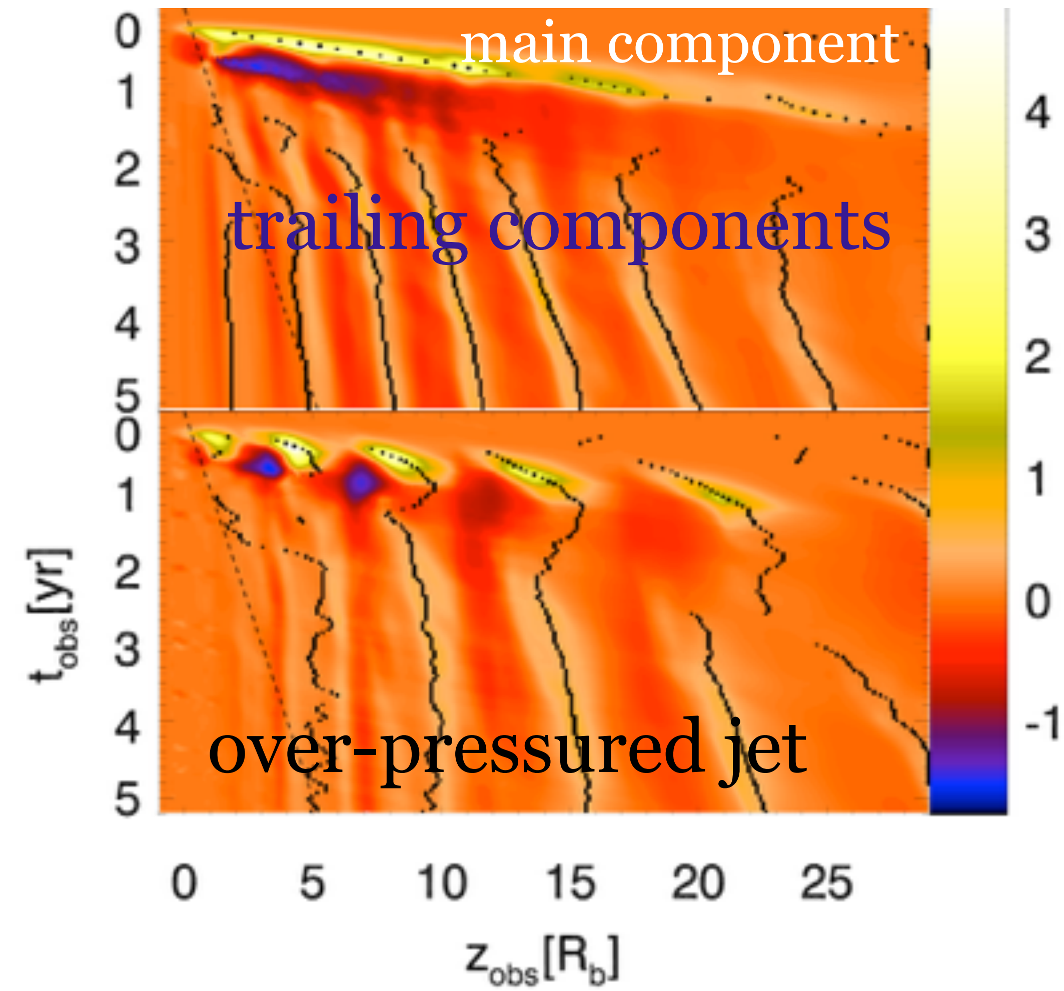


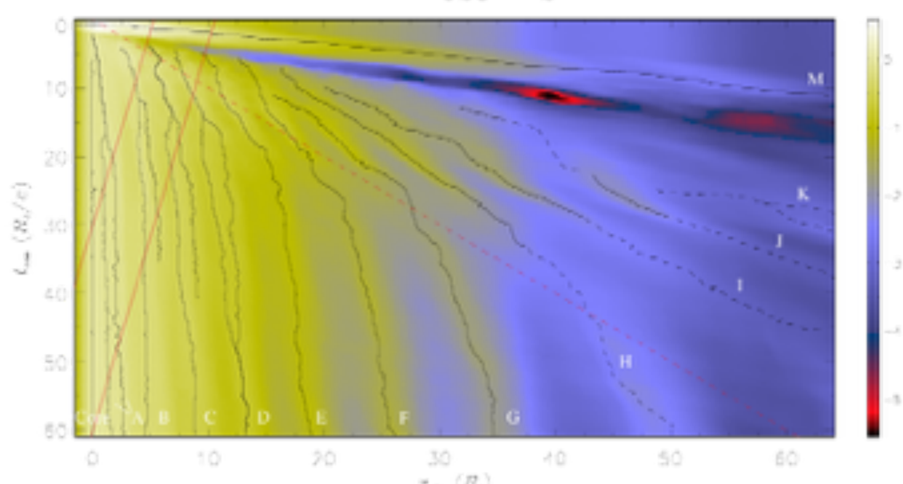
simulation: SPEV, 128 frames, 270 x 18 pixels, 3 frequencies, 100 Kh / model
0.5 Tb hydro data, 2×10^5 Lagrangian particles, 2×10^6 line-of-sight segments

Simulated Superluminal and Trailing Components



pressure-matched jet Mimica *et al.* 2009

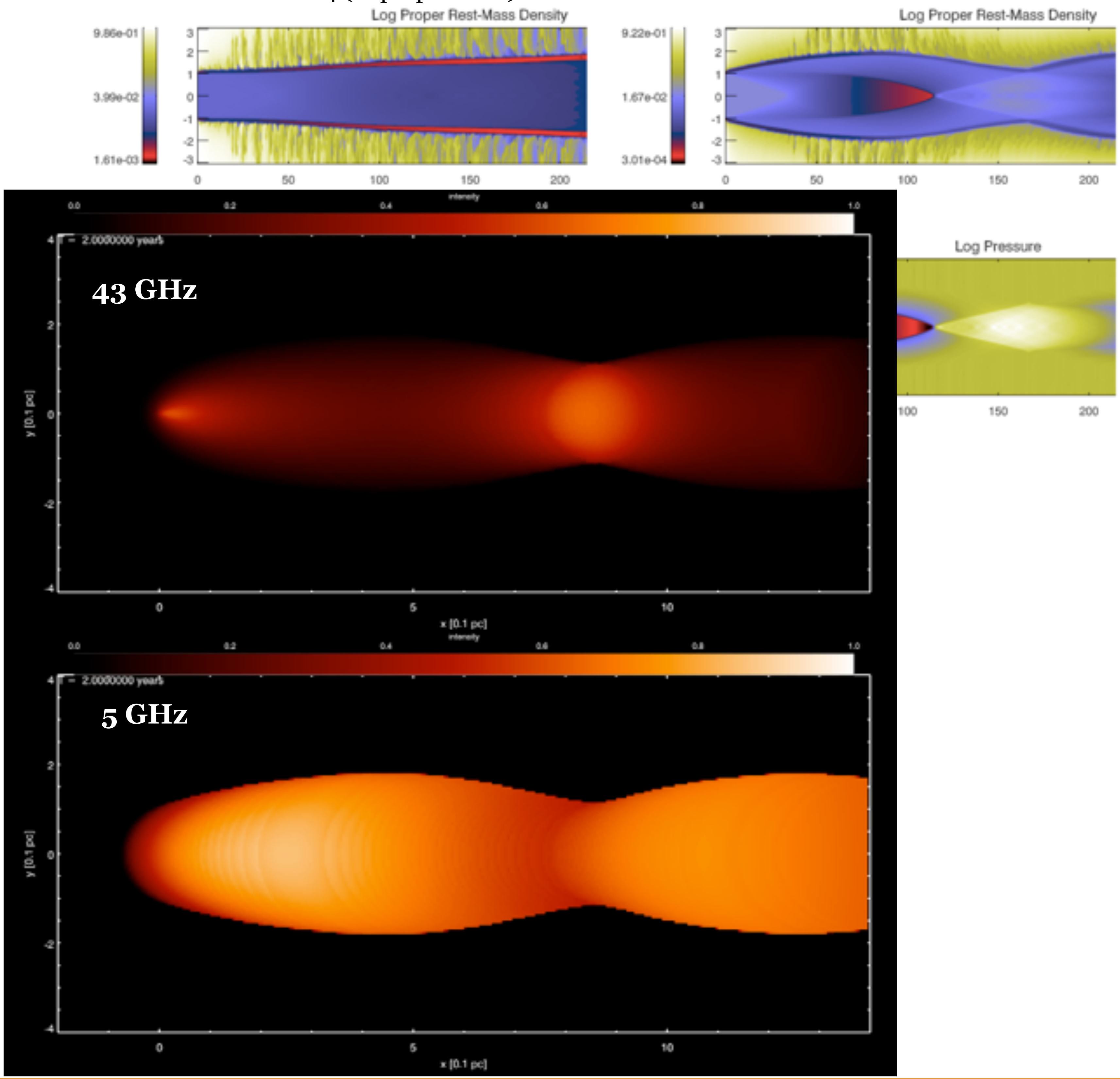


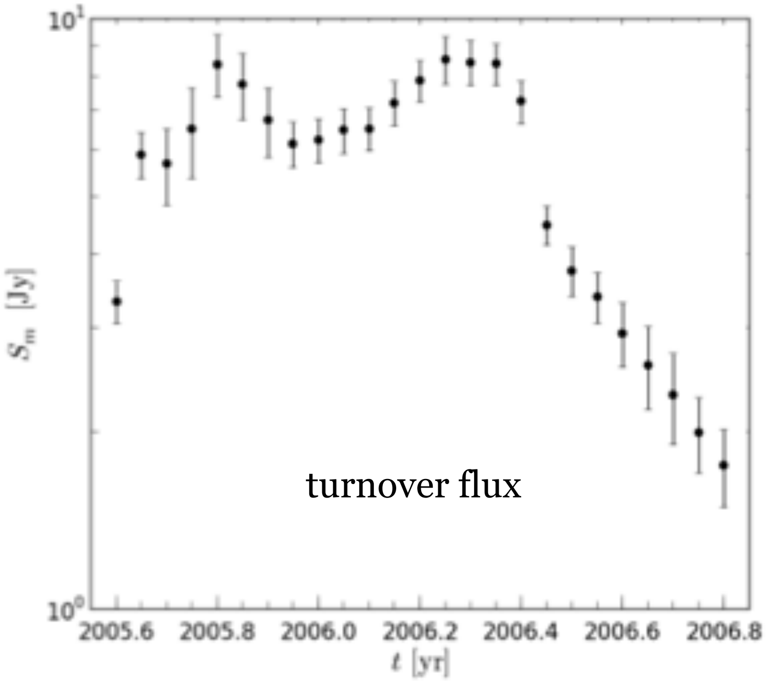


Agudo *et al.* 2001
pressure-matched jet

Shock-shock Interaction: Flare in CTA 102

Fromm *et al*. 2014 (in preparation)





Fromm *et al*. 2013
("catching the flare in CTA 102")

Fromm *et al*. 2014 (in preparation)

Shock-shock Interaction: Flare in CTA 102

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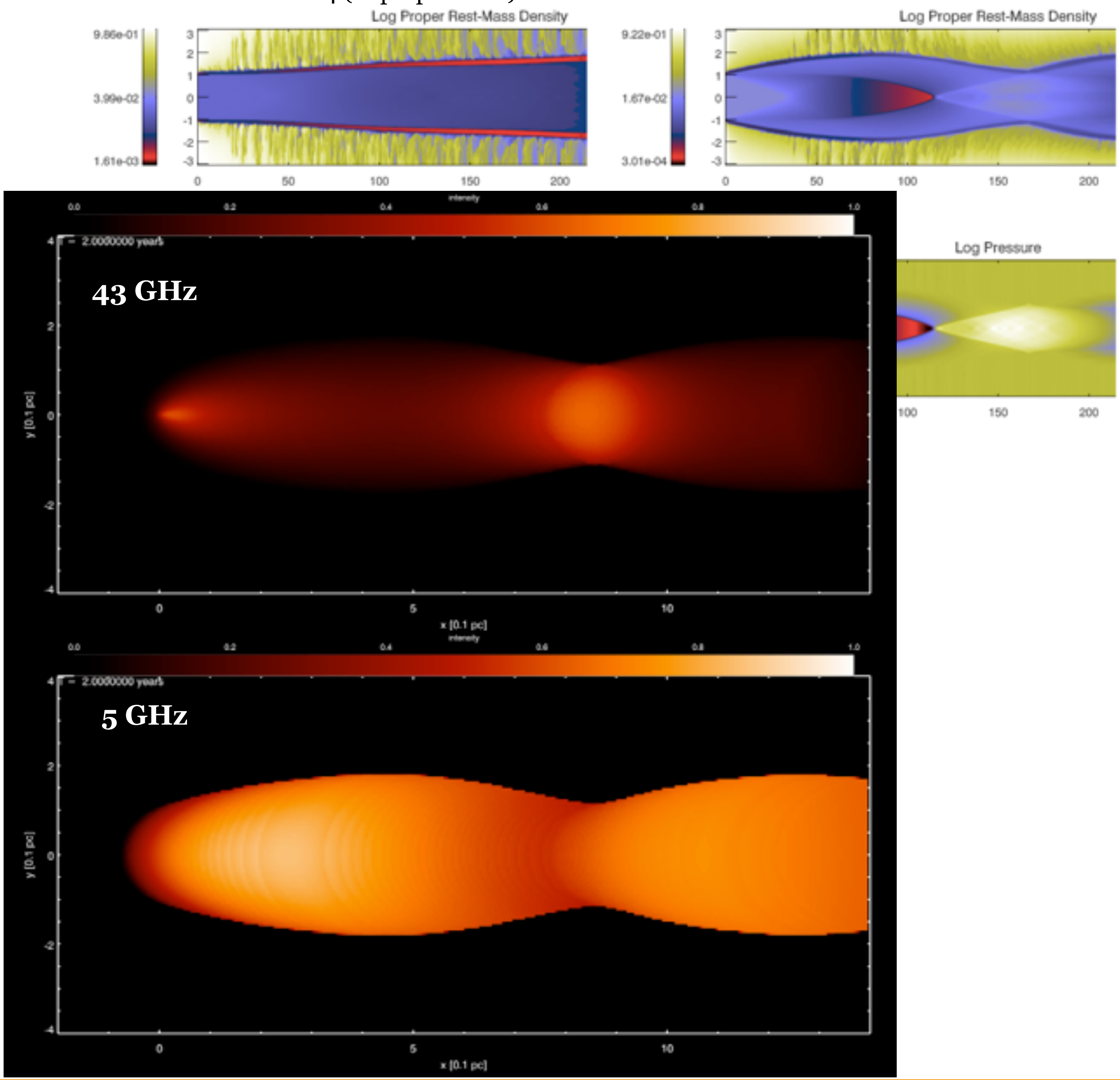

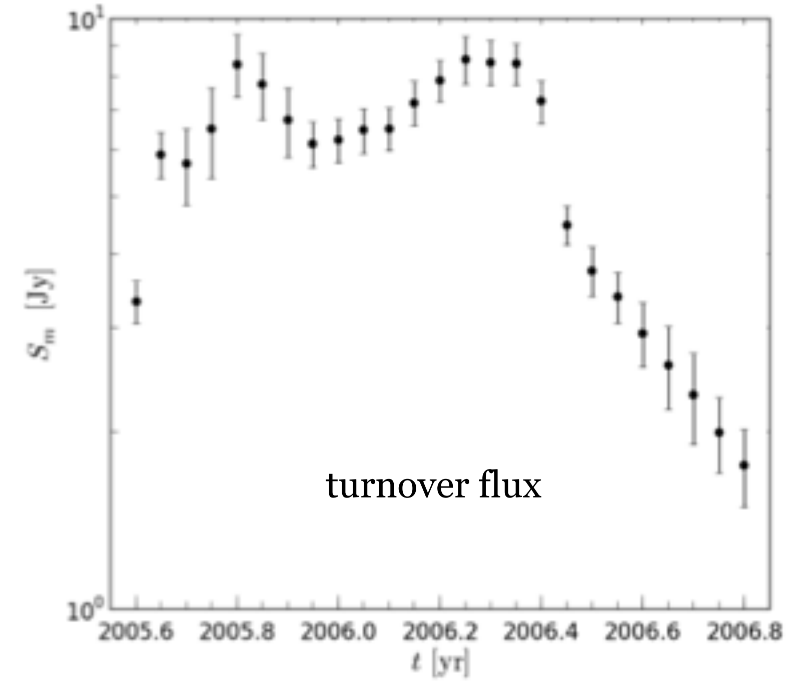

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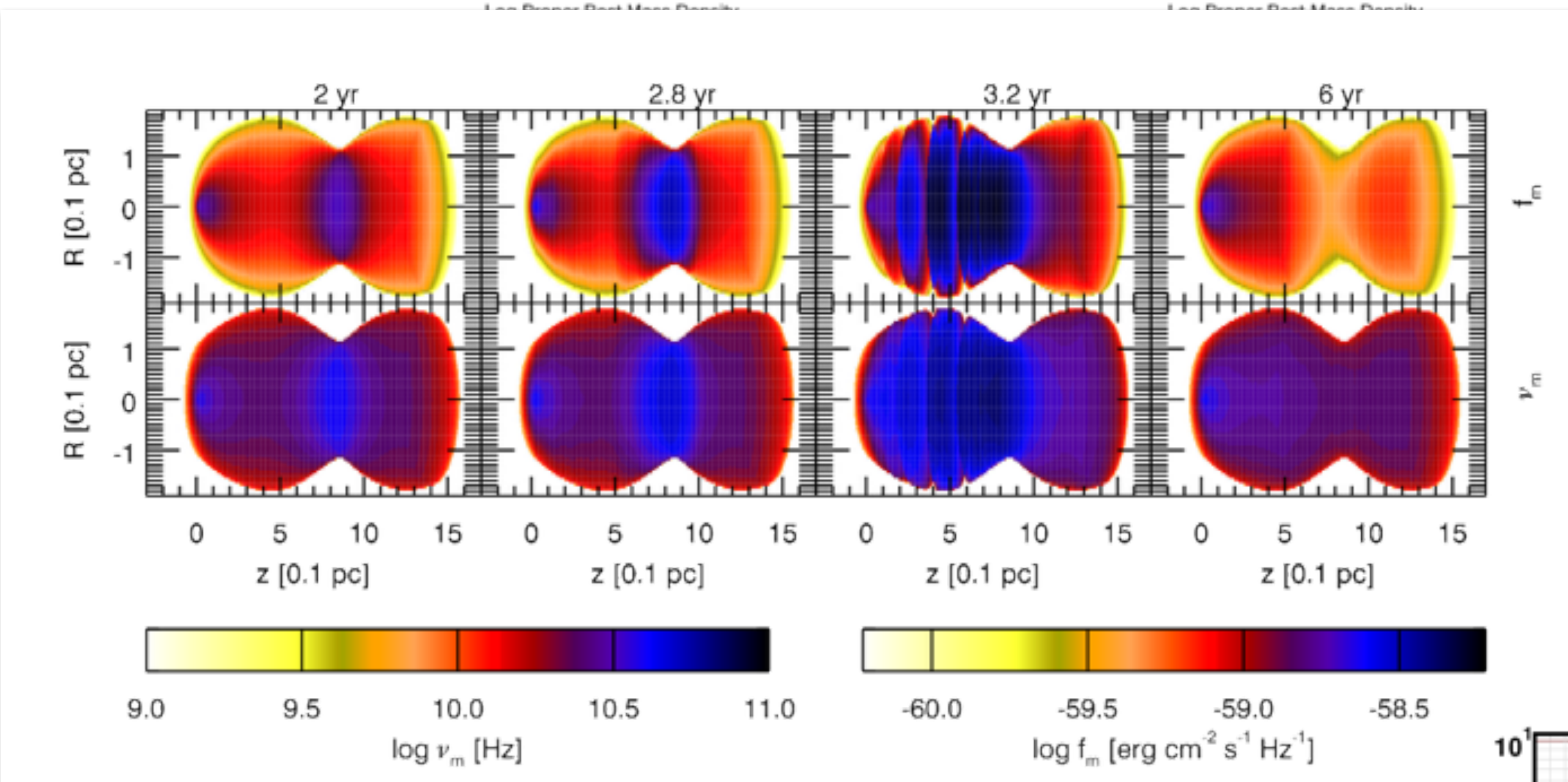

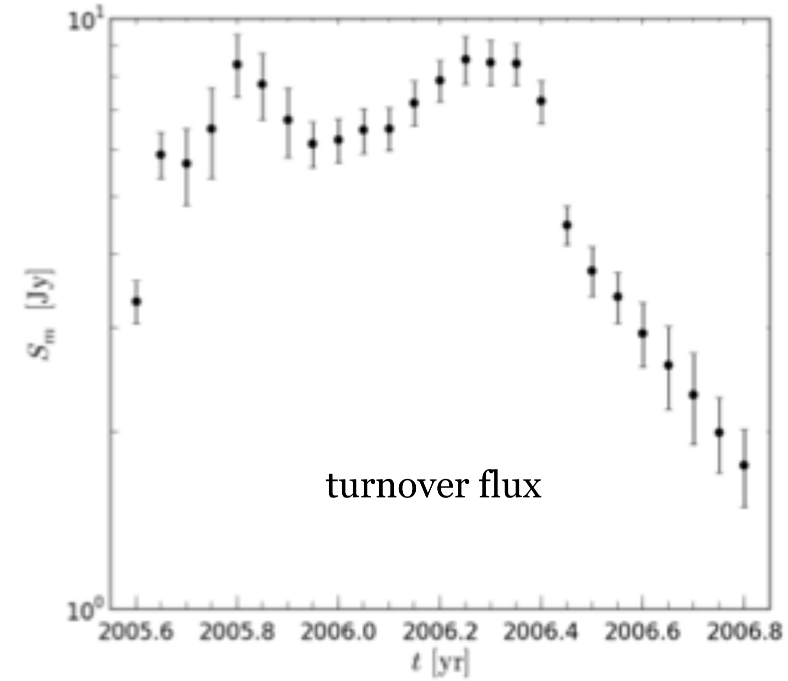

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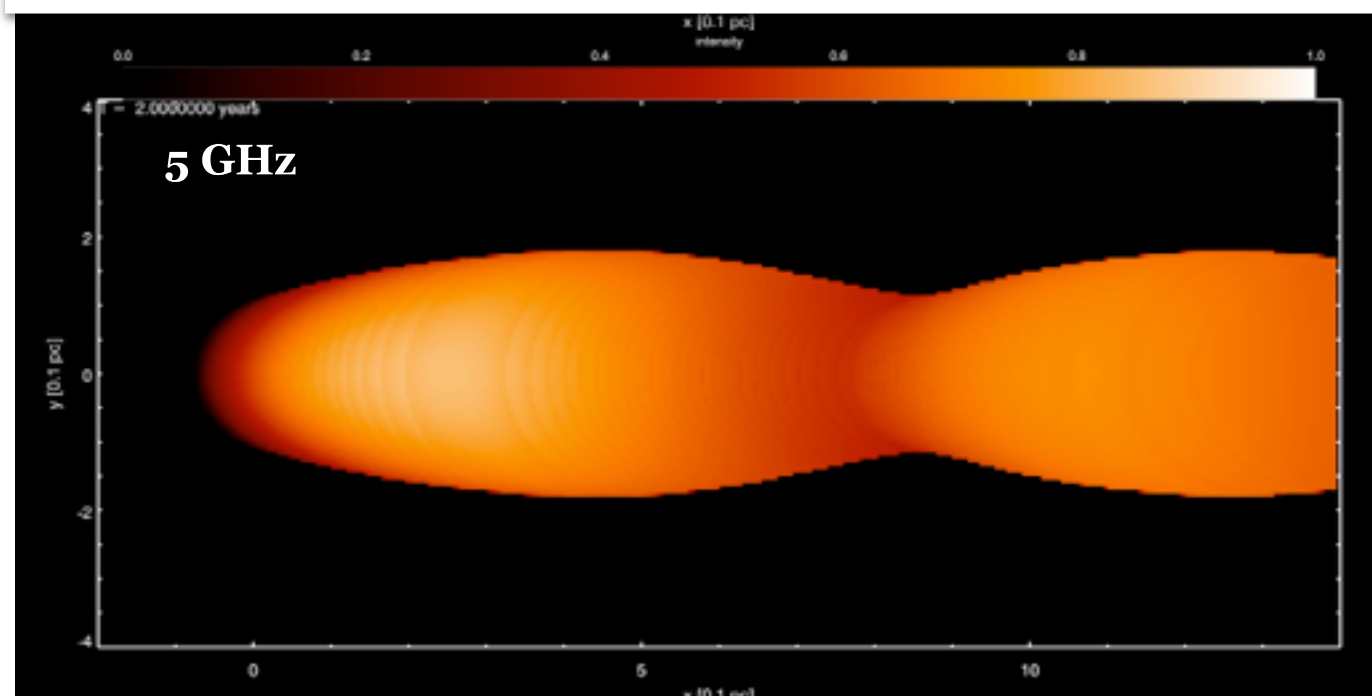

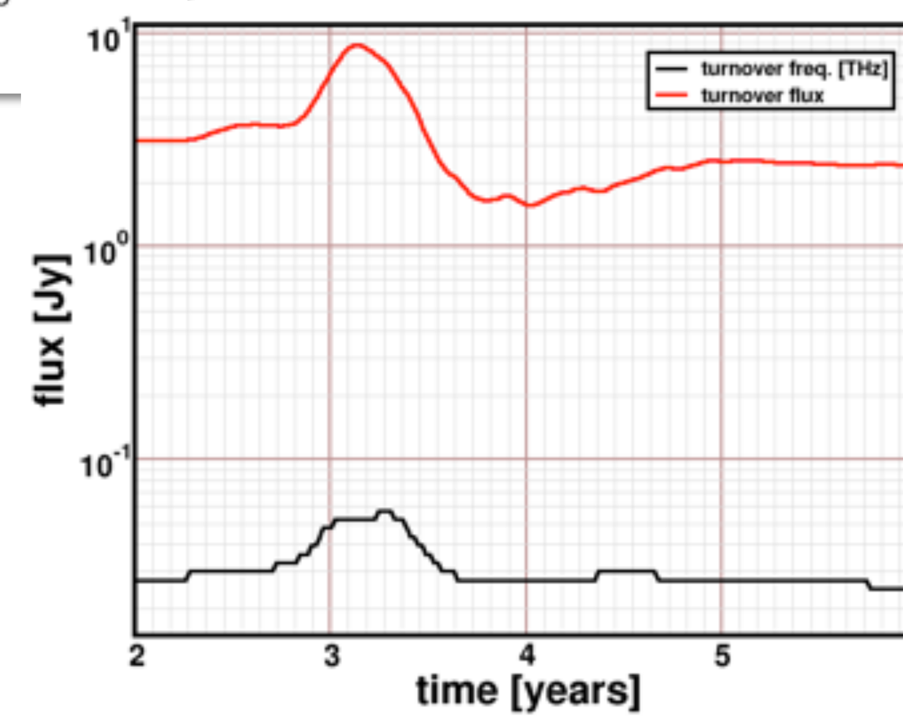

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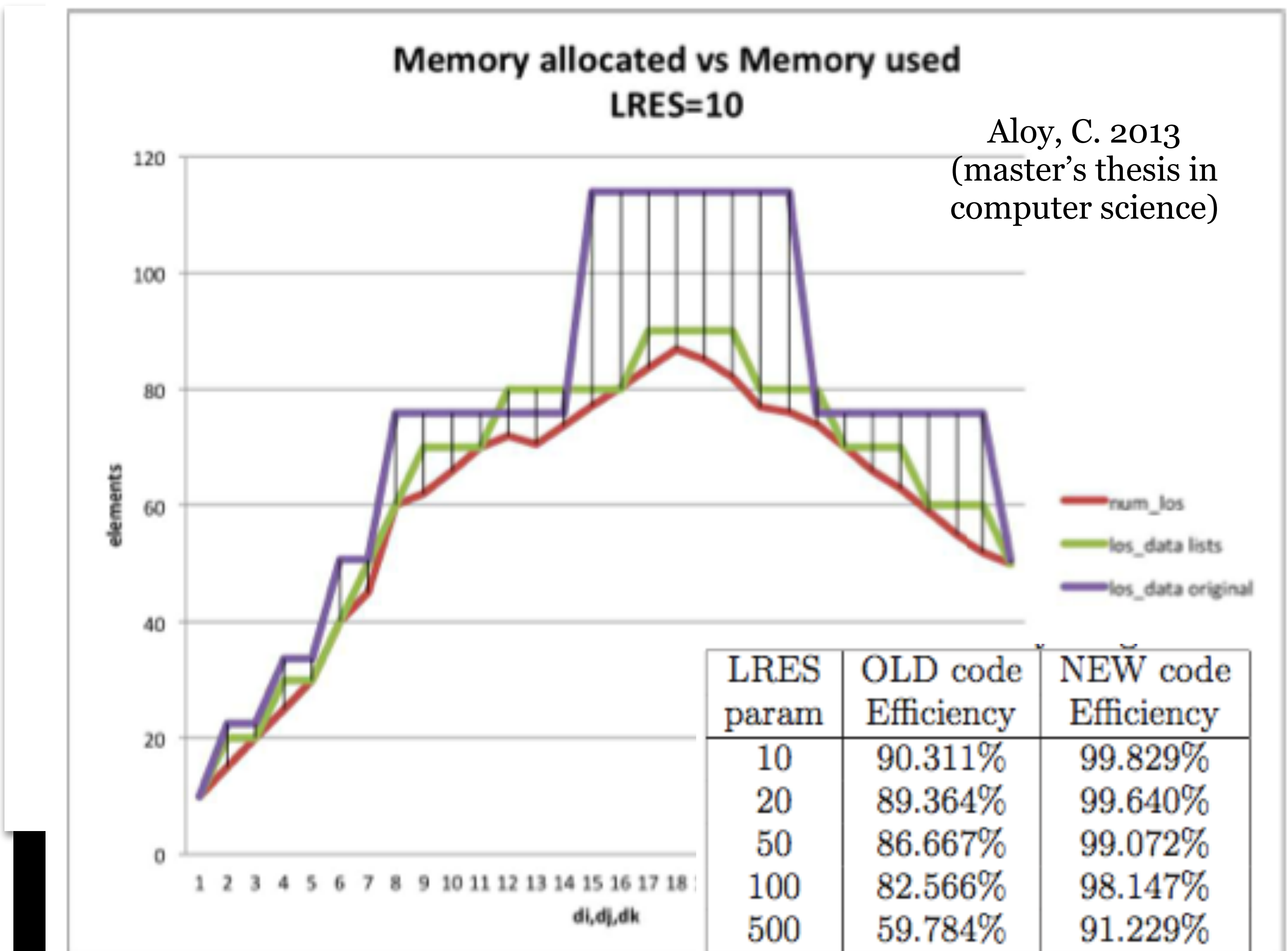
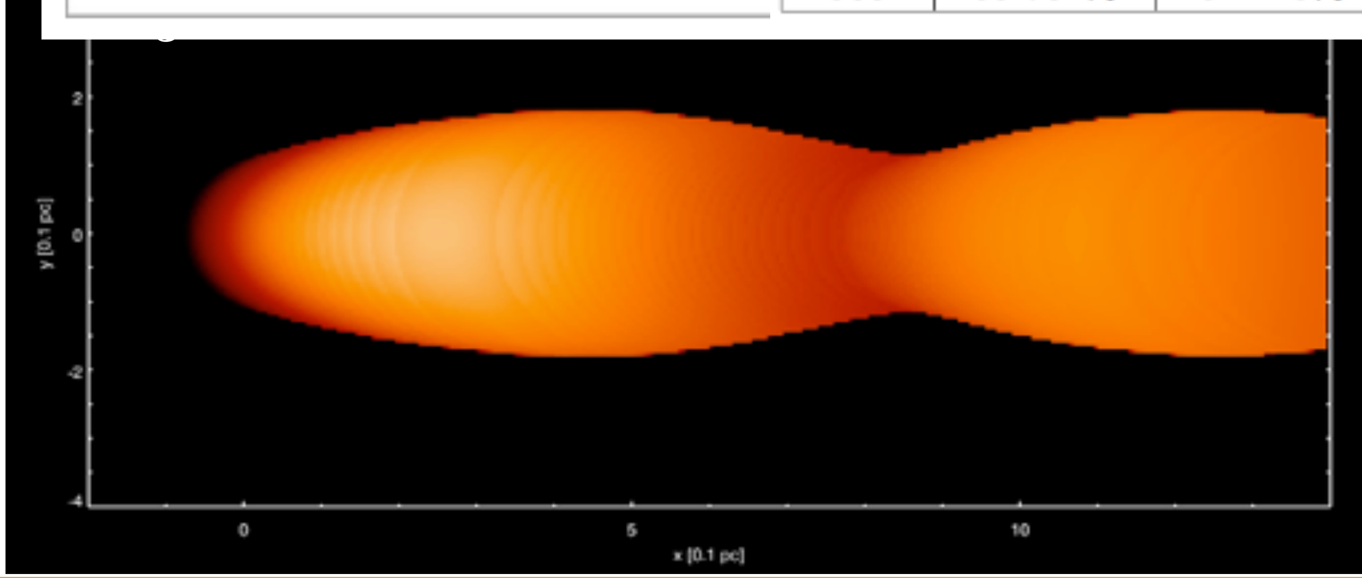
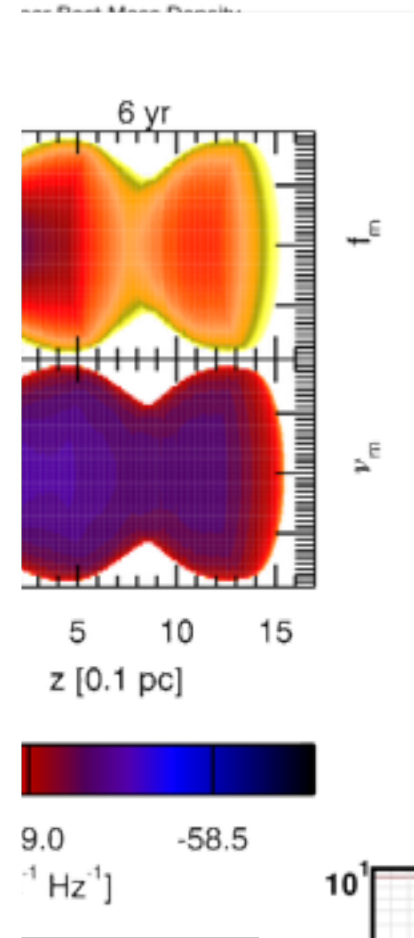
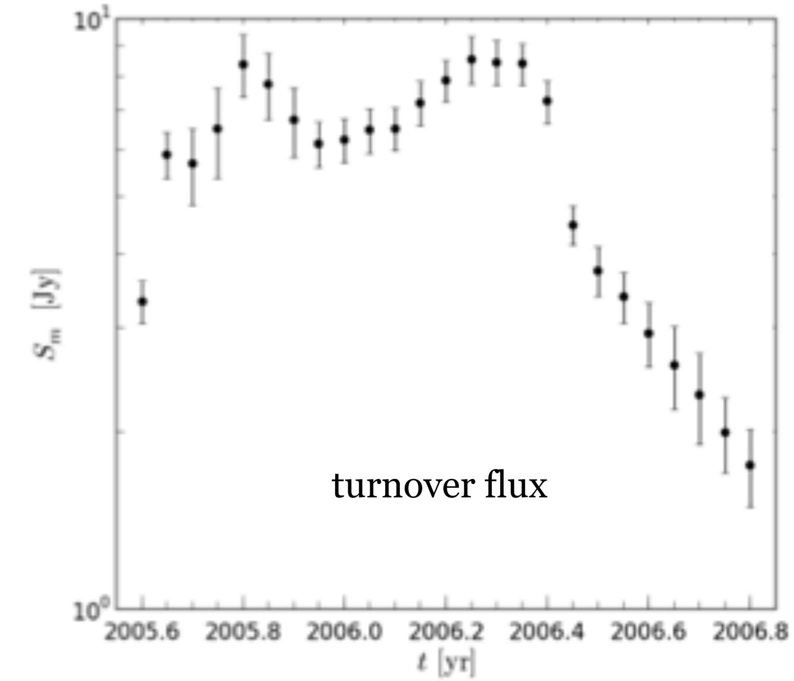


Aloy, C. 2013
(master's thesis in computer science)

LRES param	OLD code Efficiency	NEW code Efficiency
10	90.311%	99.829%
20	89.364%	99.640%
50	86.667%	99.072%
100	82.566%	98.147%
500	59.784%	91.229%







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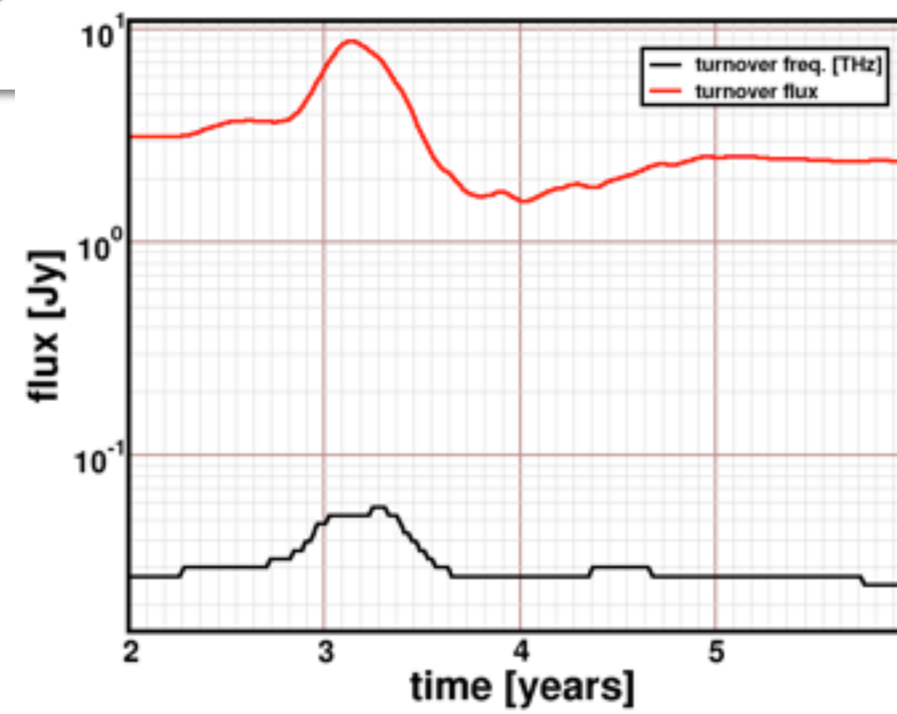

Fromm *et al.* 2014 (in preparation)

Summary, to do list, wish list, distant goals

- relativistic jet simulations: ability to study many jet aspects
- consistent emission calculations: expensive, but enable direct simulation-observation comparisons
- modelling of individual sources starts to become feasible
- **to-do list** (some tasks partially complete):
  - improve shock acceleration models: input from PIC simulations (energy distr.)
  - add non-ideal effects: resistivity (RRMHD), reconnection
  - improve radiation transfer: polarisation, in full GR, more processes
  - improve methods: realistic EOS, higher-order schemes
- **wish list**:
  - improved parallelism (easier switching shared <->distributed memory)
  - improved I/O performance (improve parallel read/write performance)
  - multidimensional shock-front reconstruction (identification of particle acceleration sites)
  - hydro + emission code comparisons
- **distant goals**:
  - 3D GRRMHD + 3D non-thermal particle transport
  - time dependent radiative transfer in GR
  - angle dependent synchrotron + SSC (nonlinear cooling) + EC (realistic seed photons) + pair production + γ-hadron interaction + EM-cascades