Max-Planck-Institut
für Radioastronomie

Recollimation Shocks in Blazar Jets

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05.12.2012

Collaborators:
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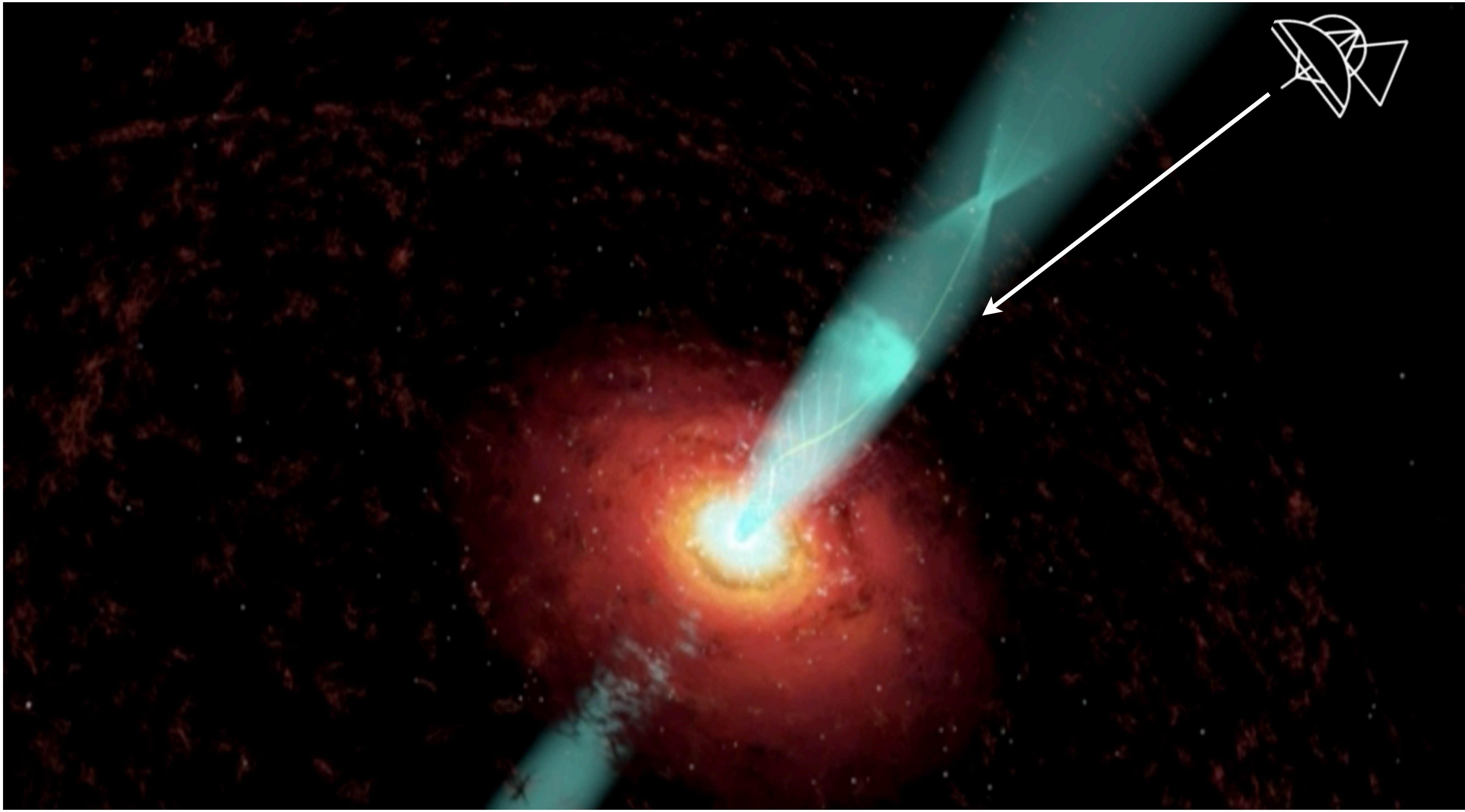
IMPRS astronomy & astrophysics Bonn and Cologne

Outline

- **Introduction to Blazars**
- **Observation of the Blazar CTA 102**
- **Simulation of Blazars**
- **Summary and Outlook**

Introduction to Blazars



Ref: Cosmovision, W. Steffen, Chang et al. (2011)

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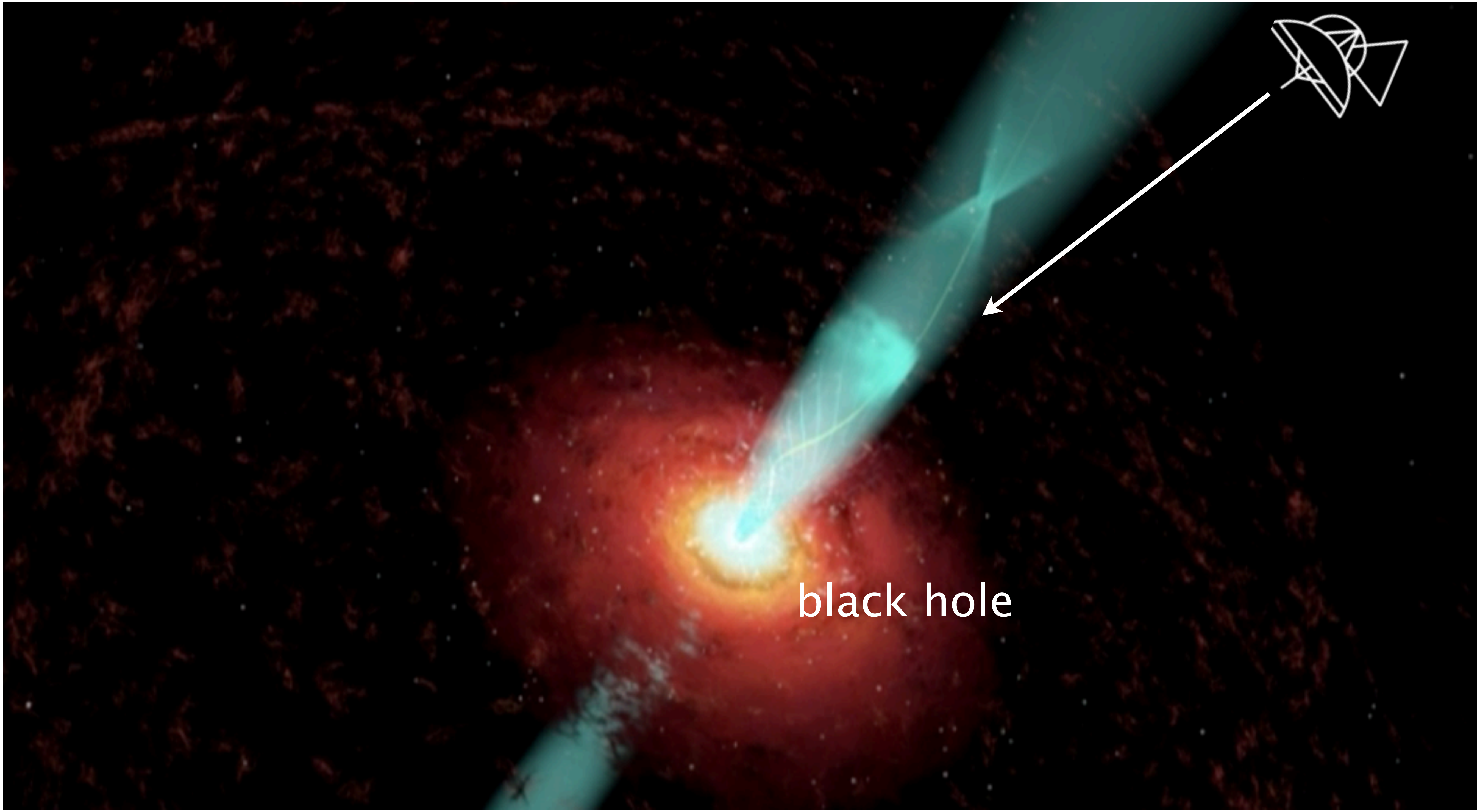

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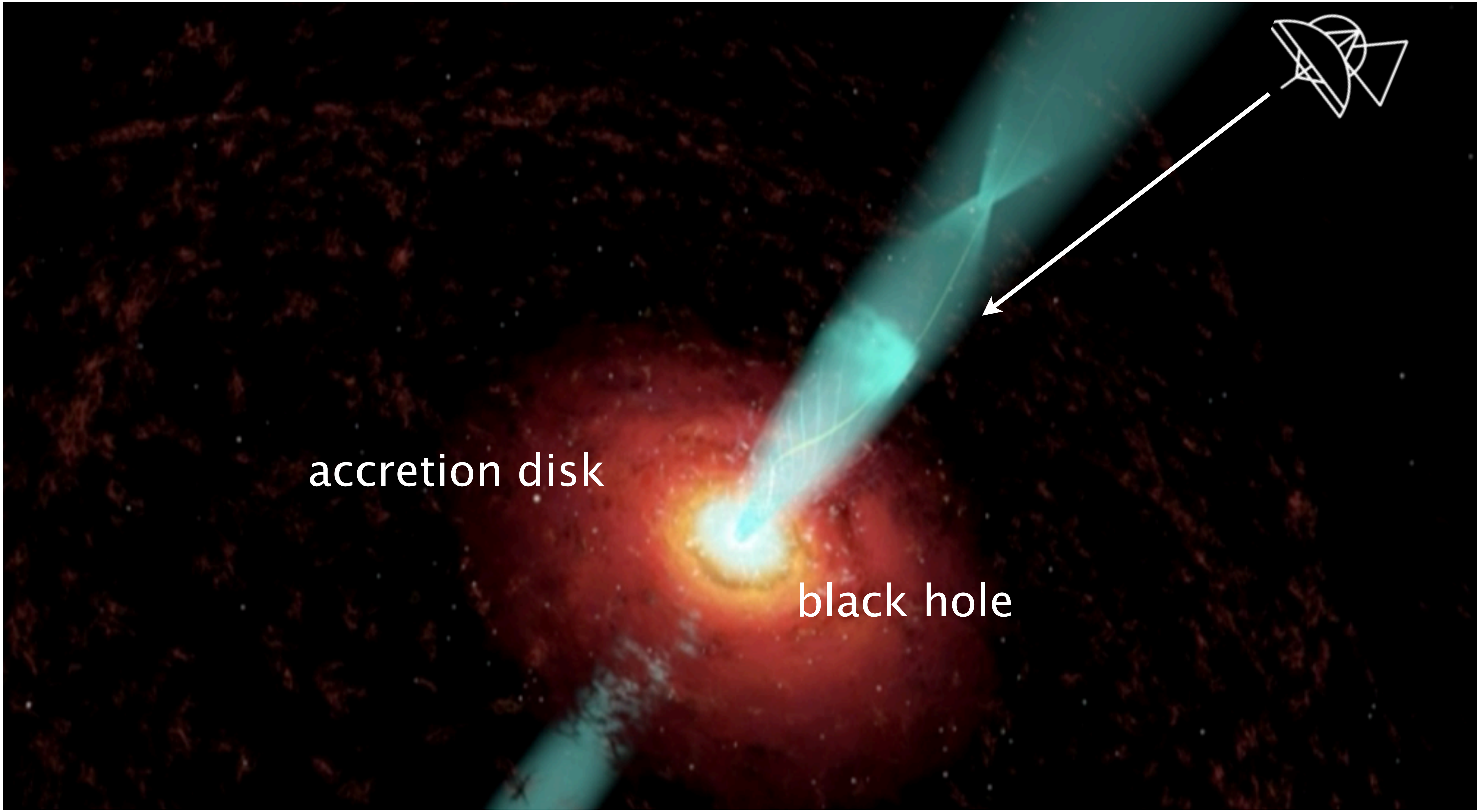

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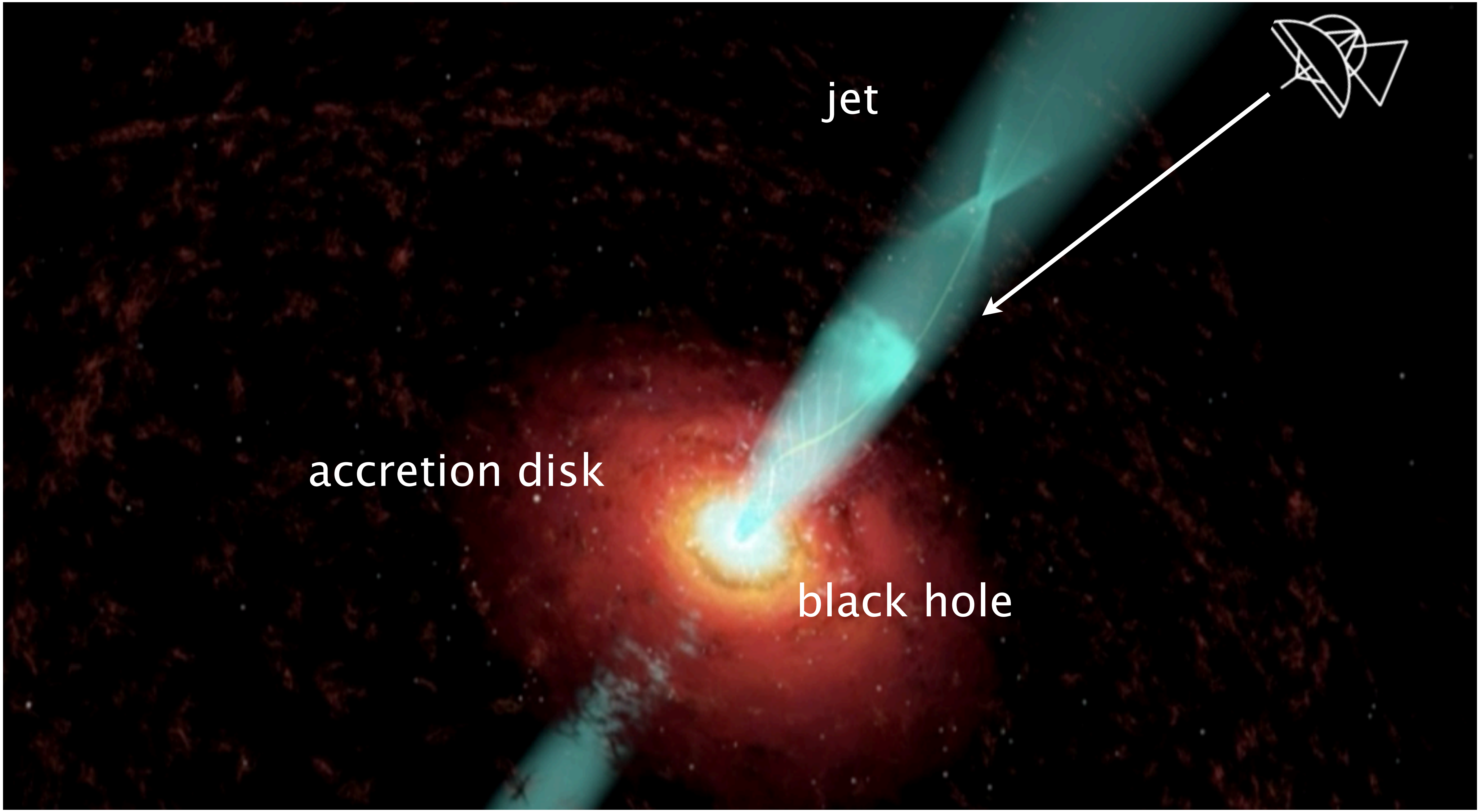

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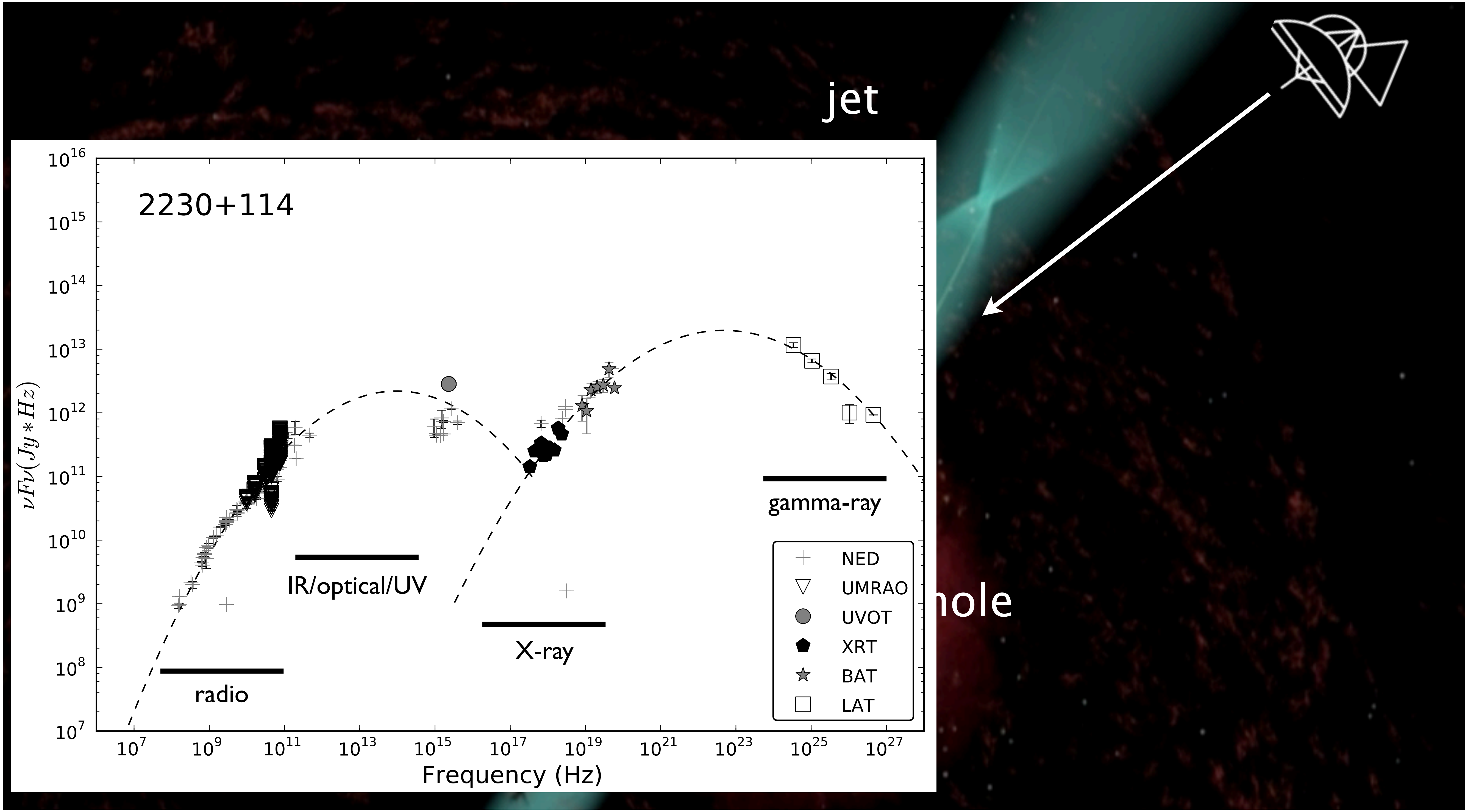

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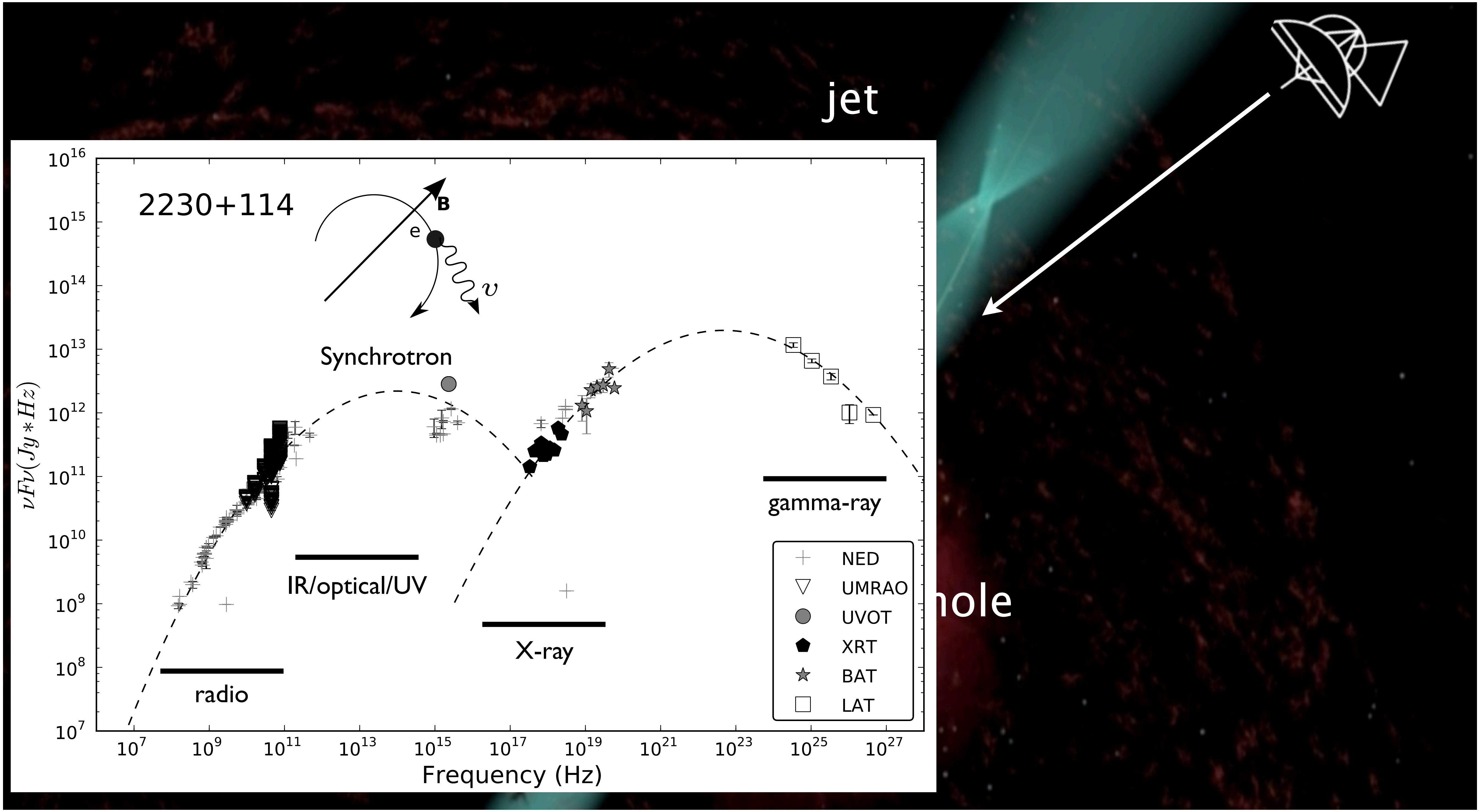

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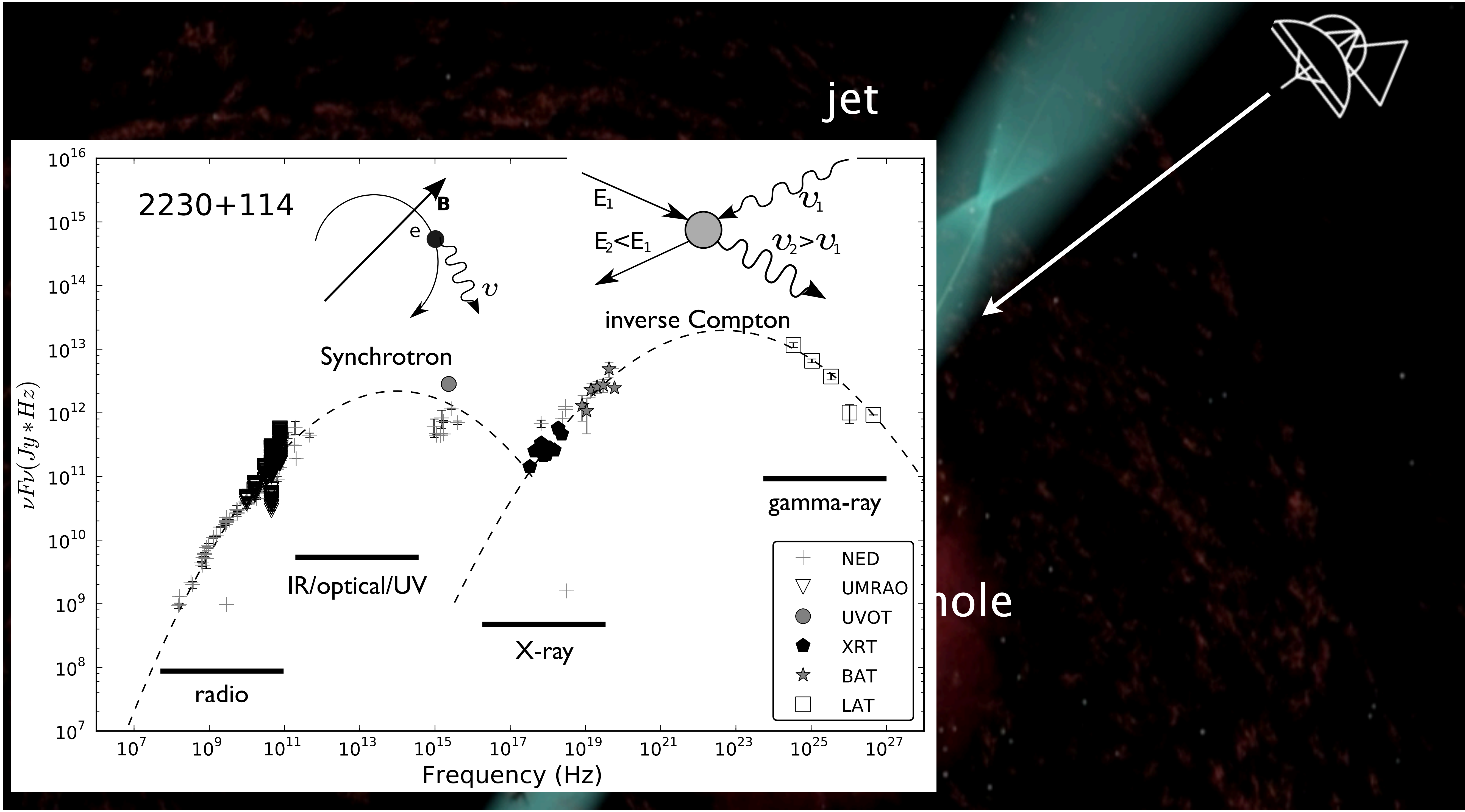

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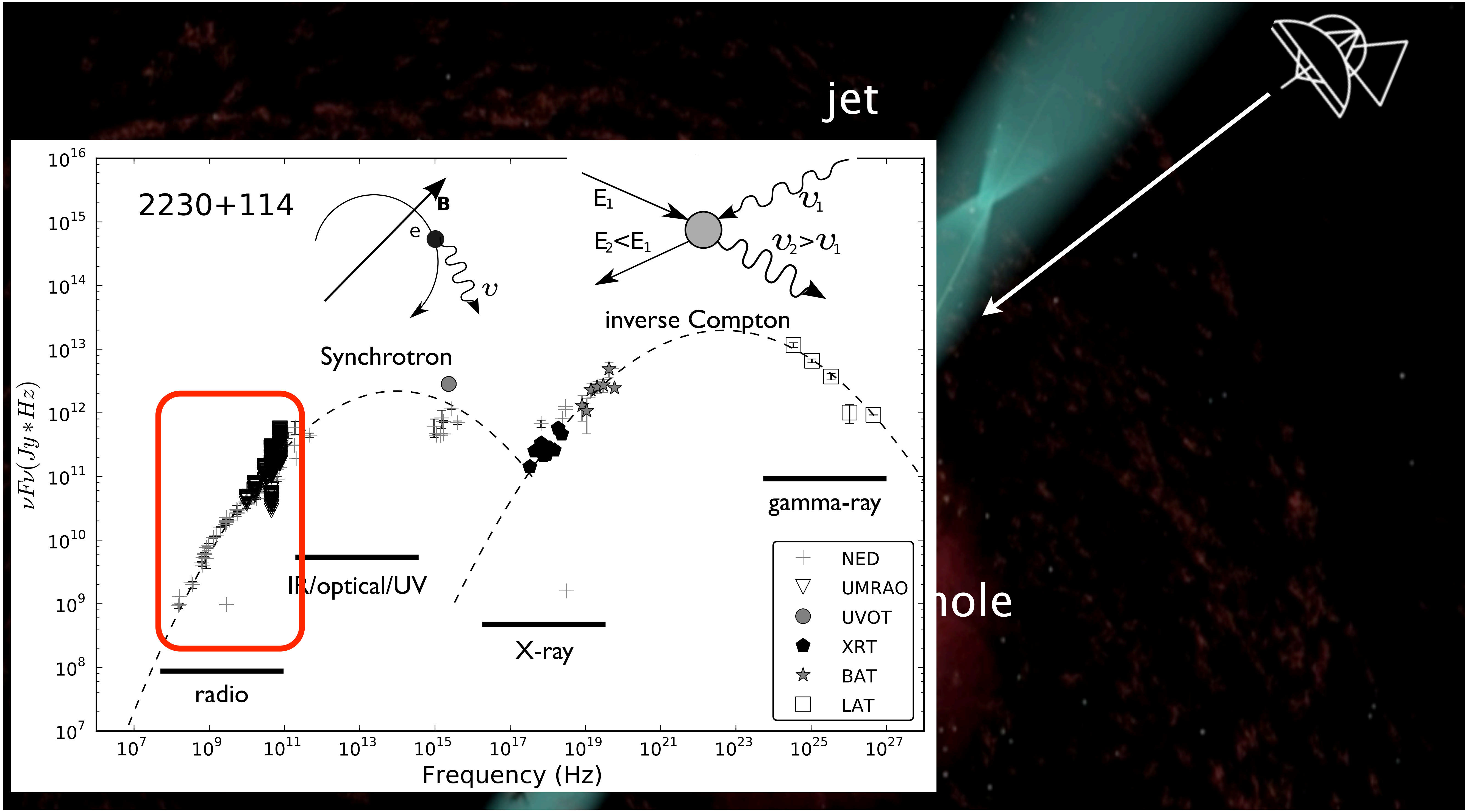

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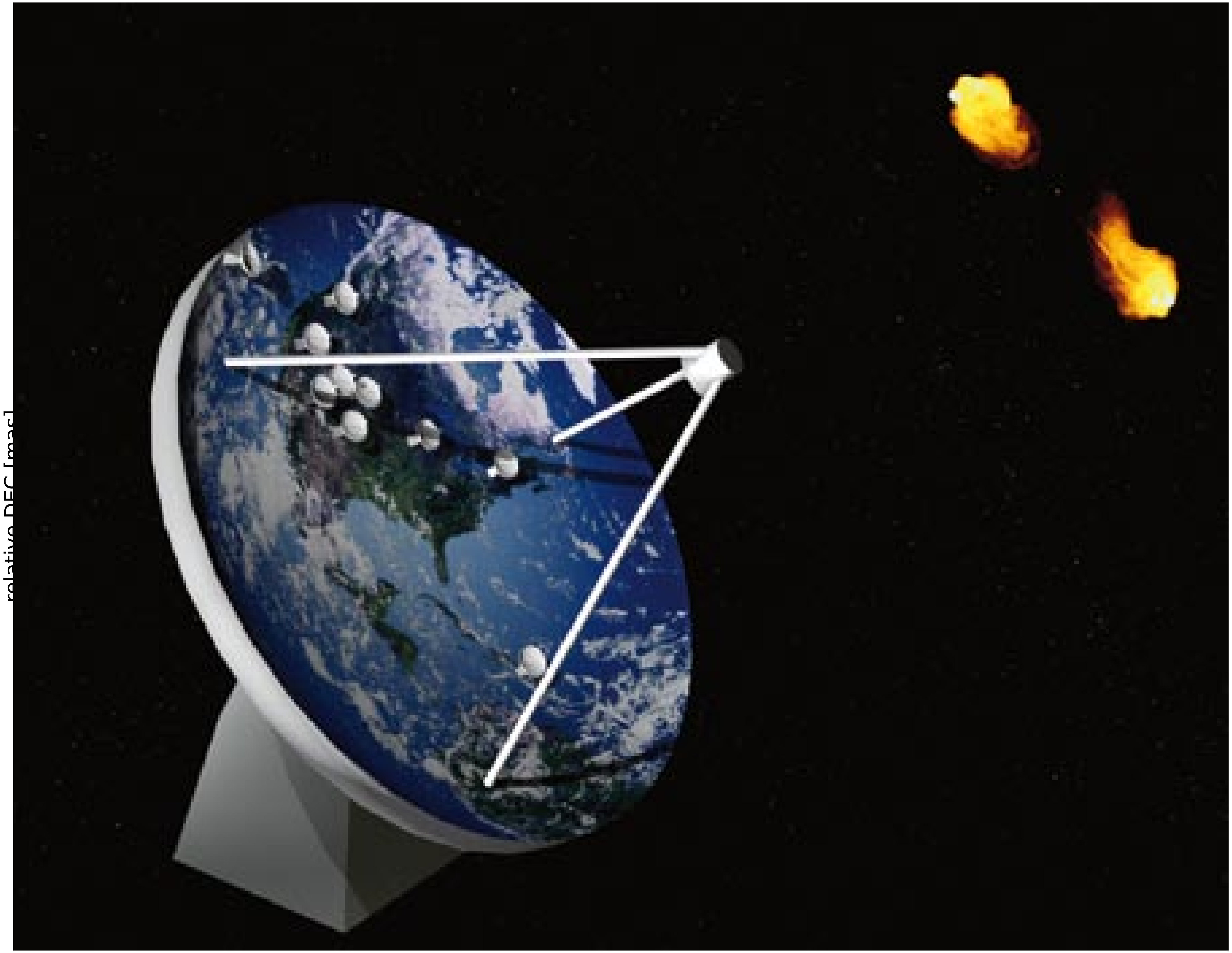
VLBI Observations of Blazars



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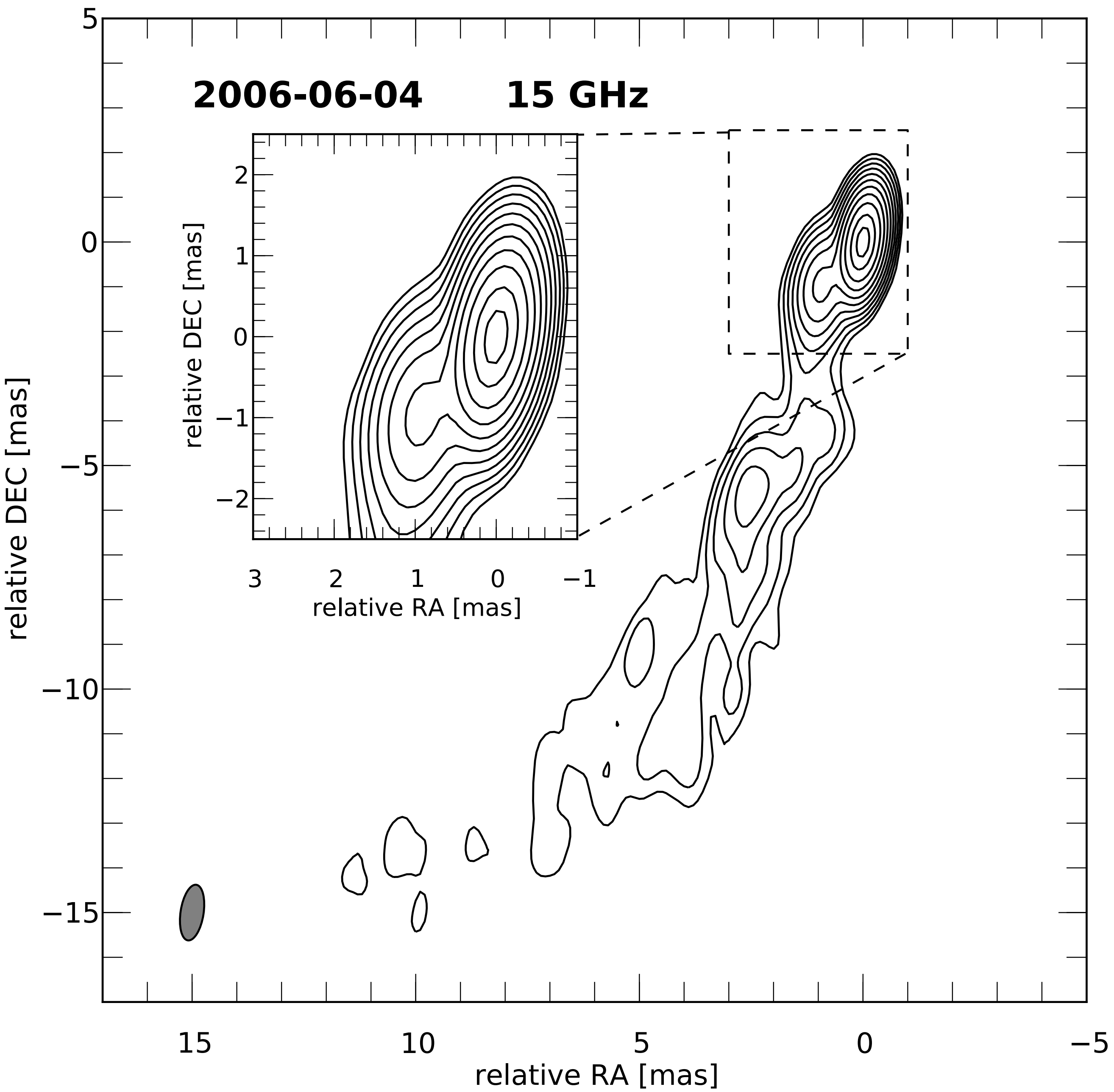
VLBI Observations of Blazars

CTA 102 (z=1.037)



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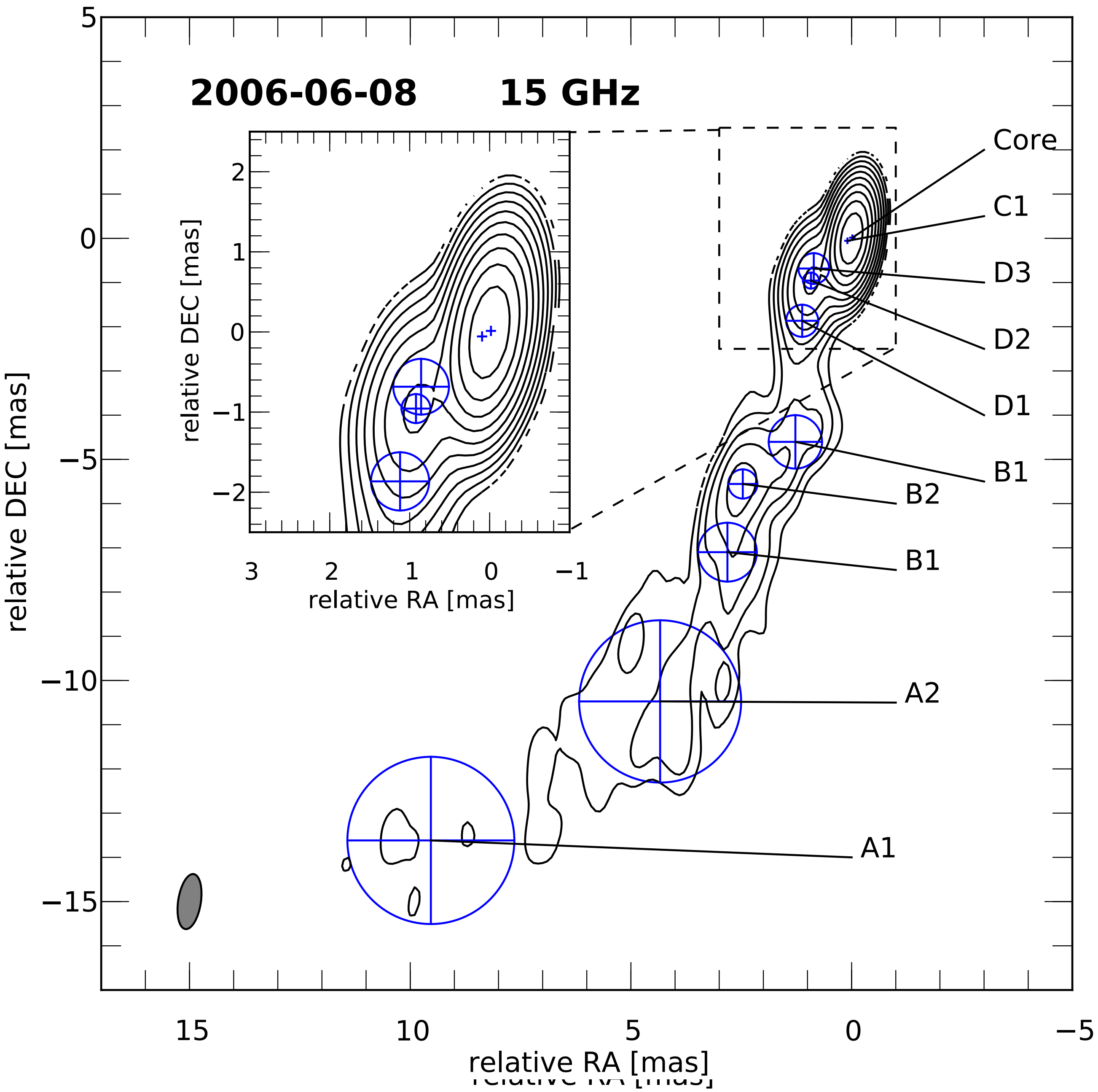

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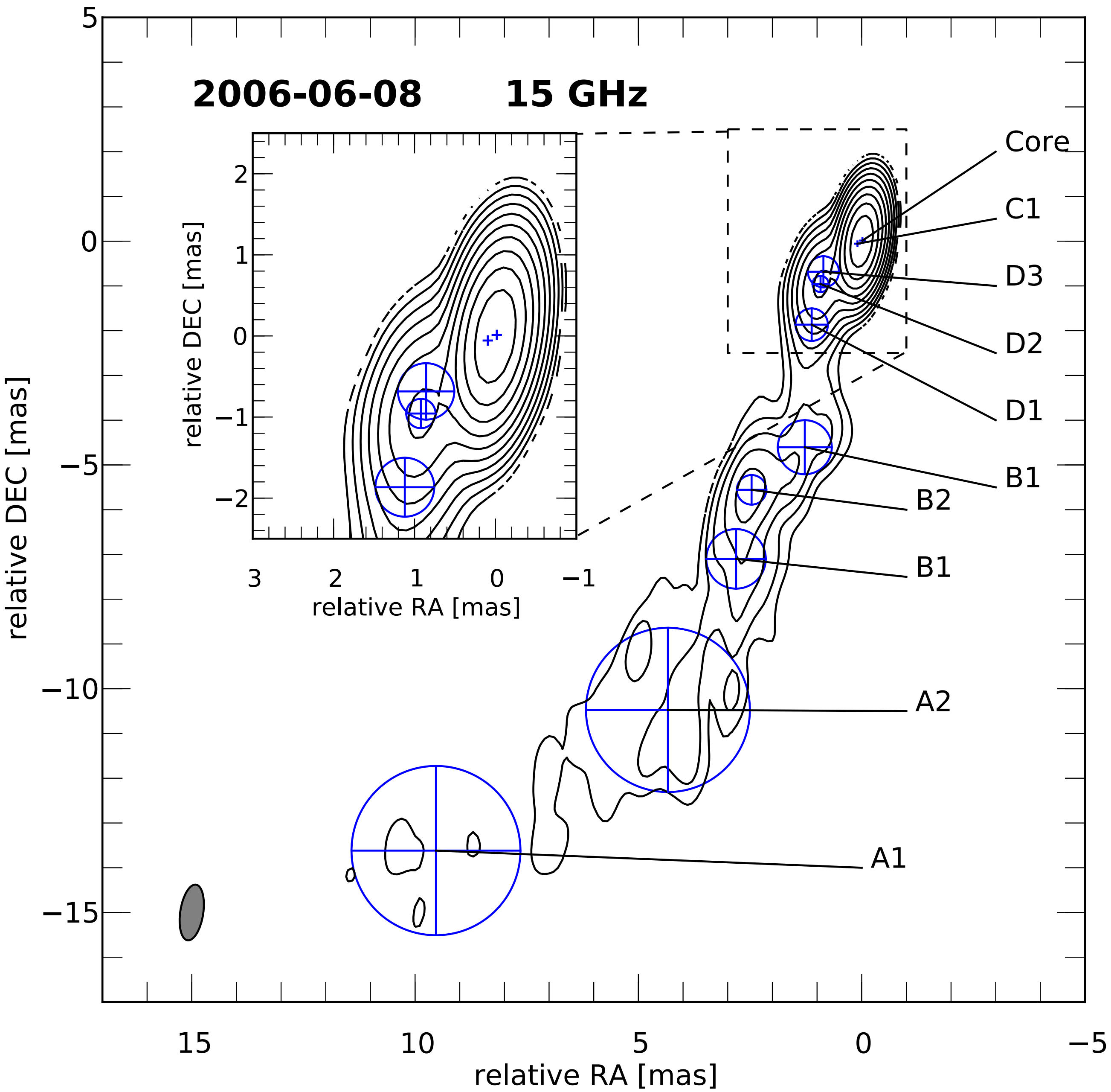

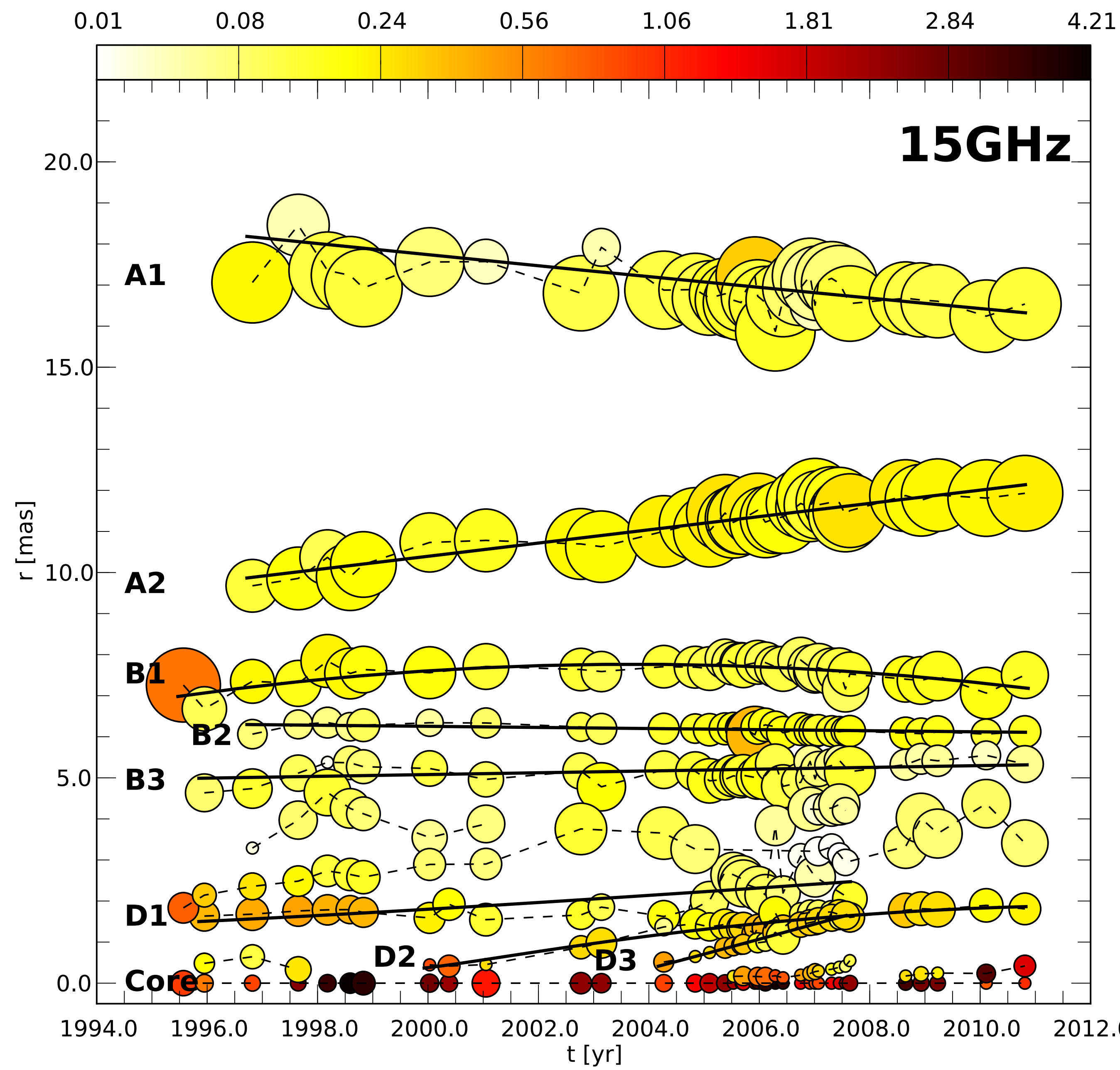

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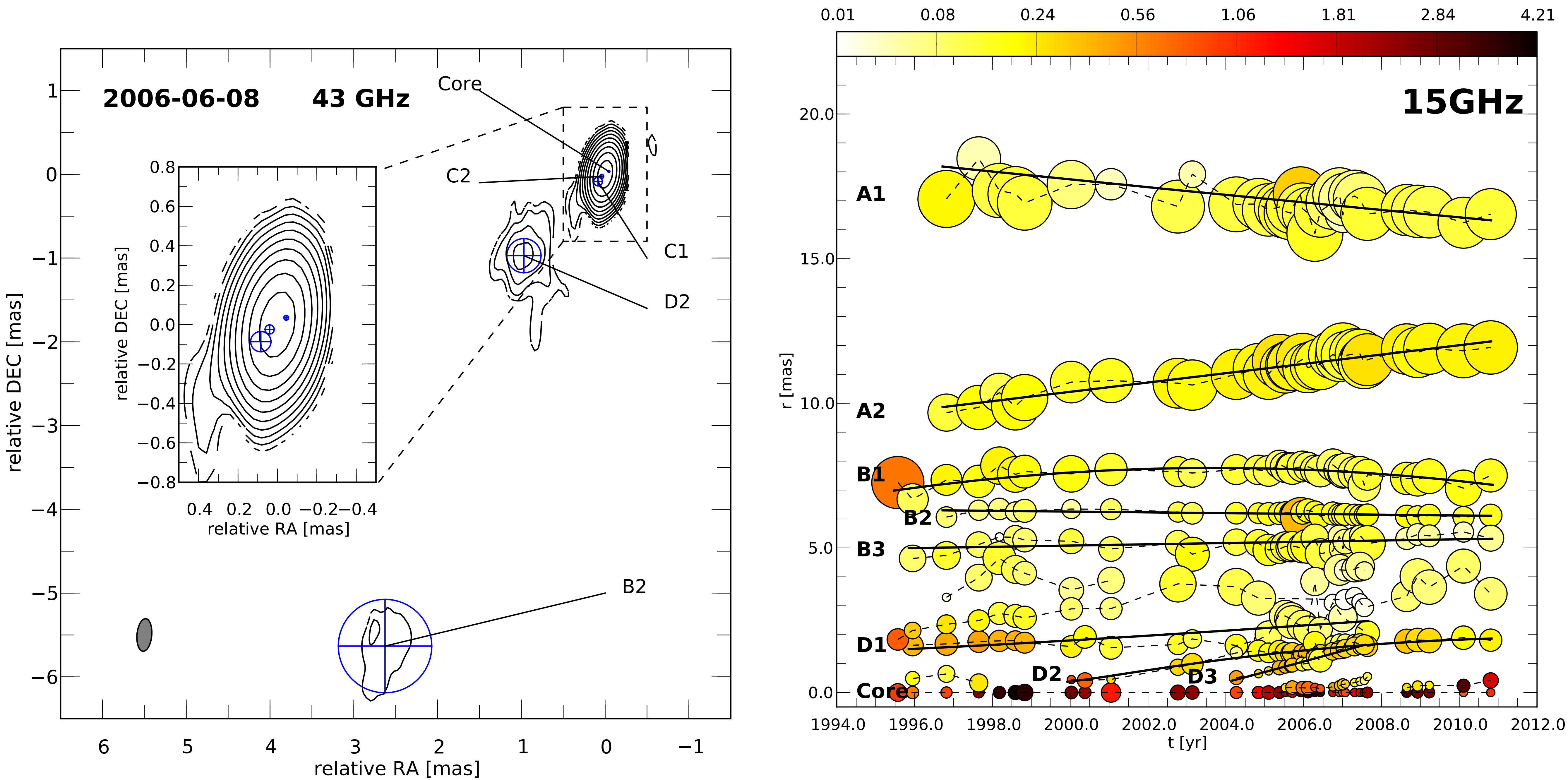

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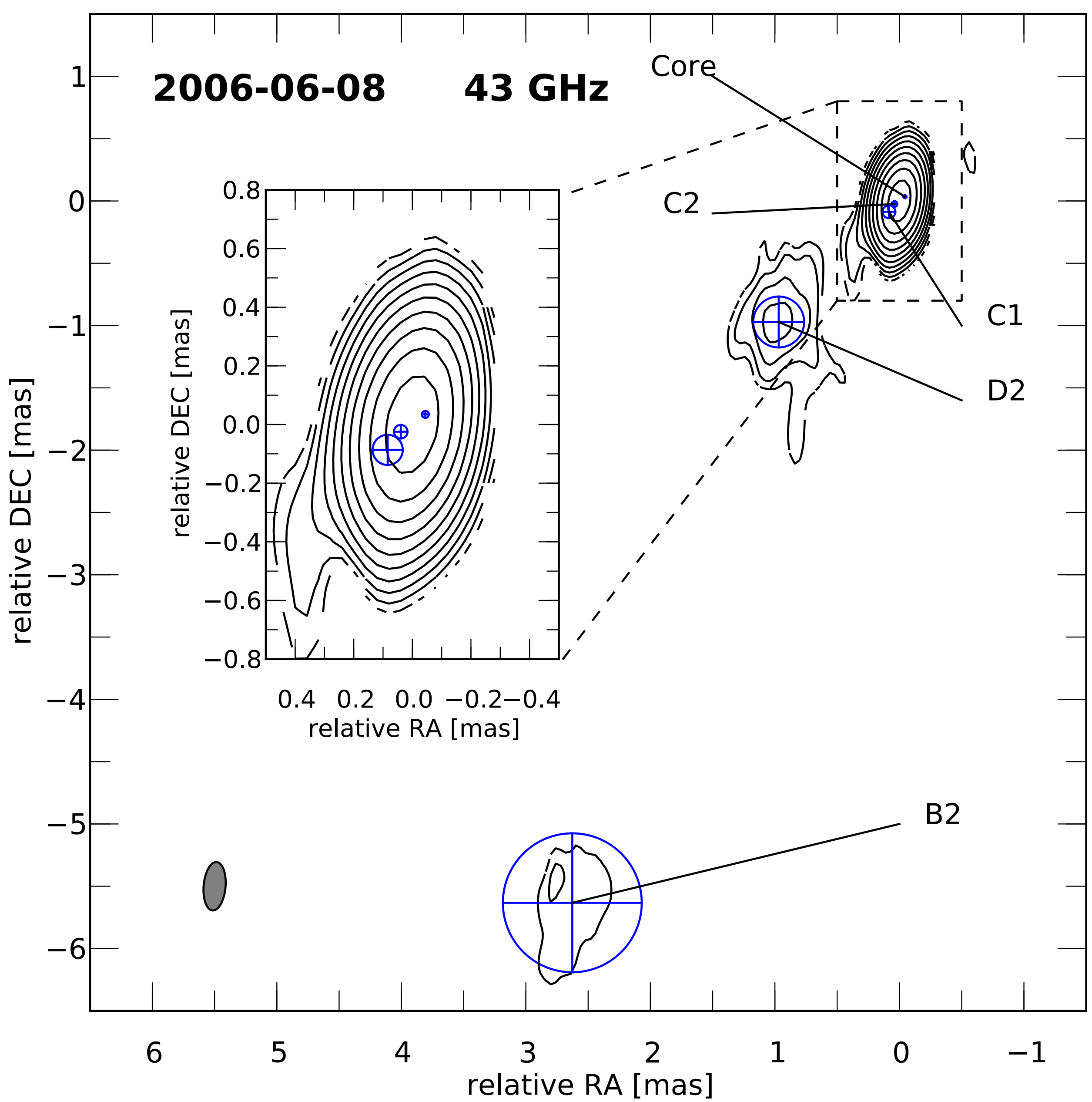

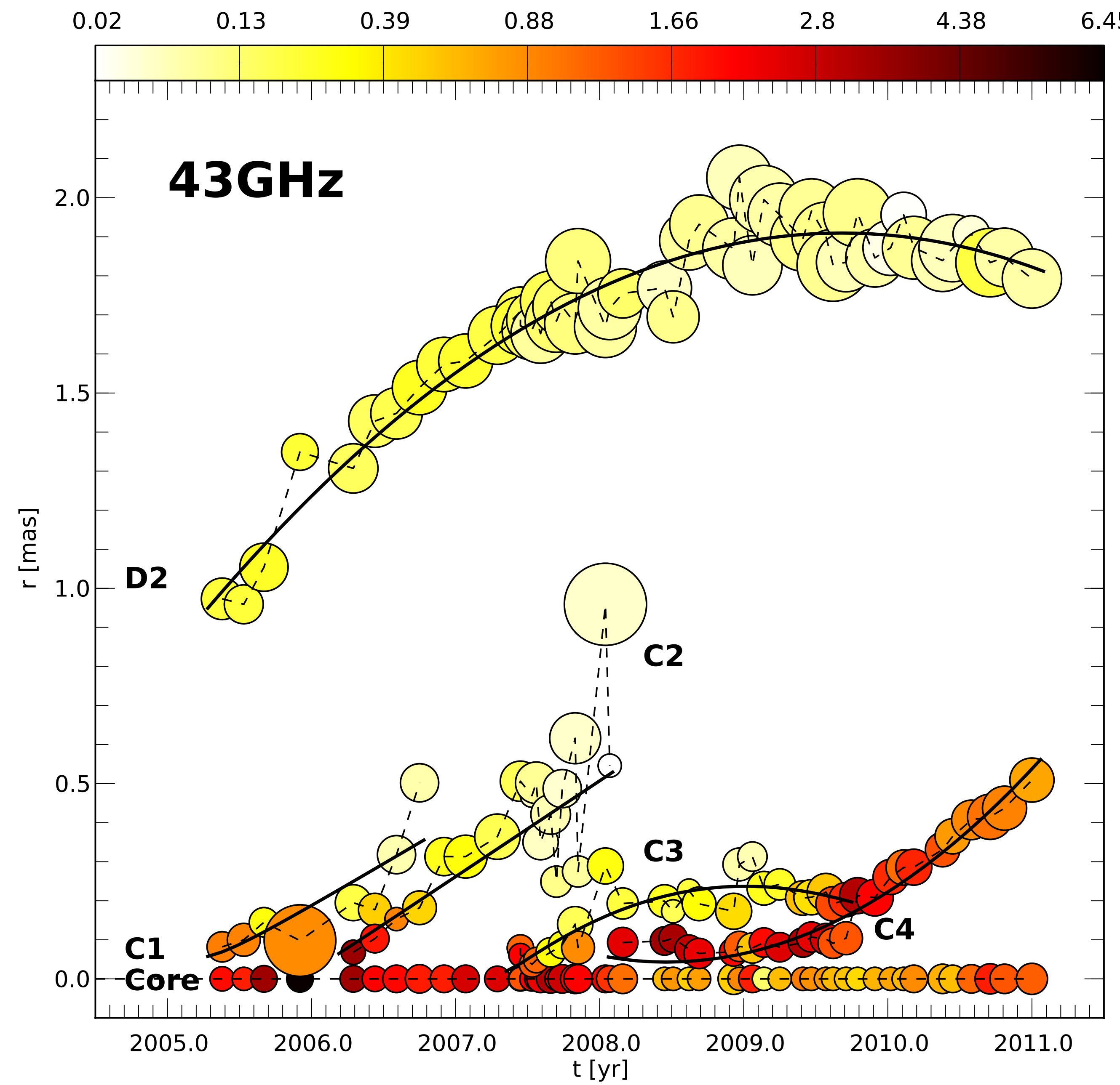

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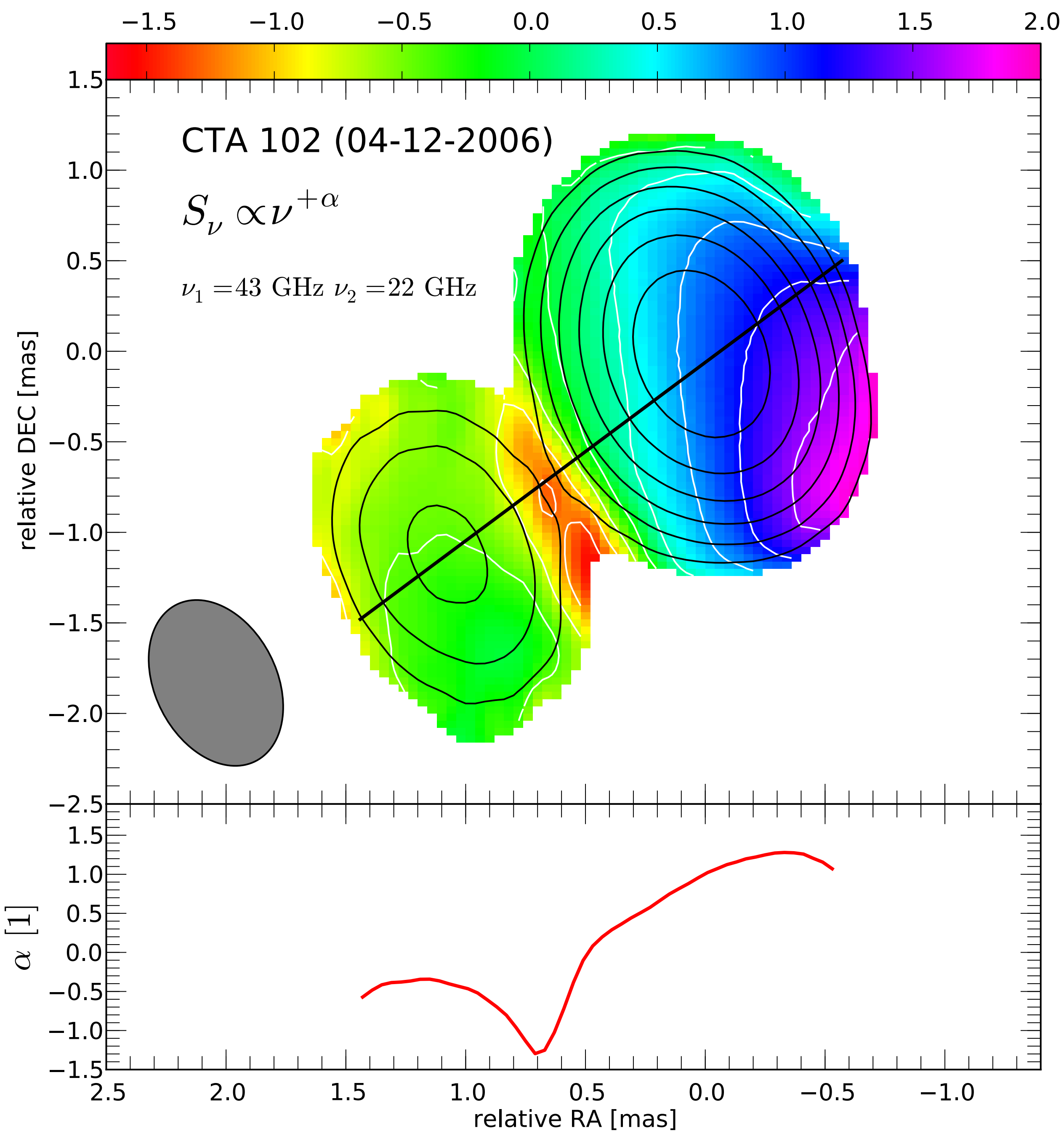

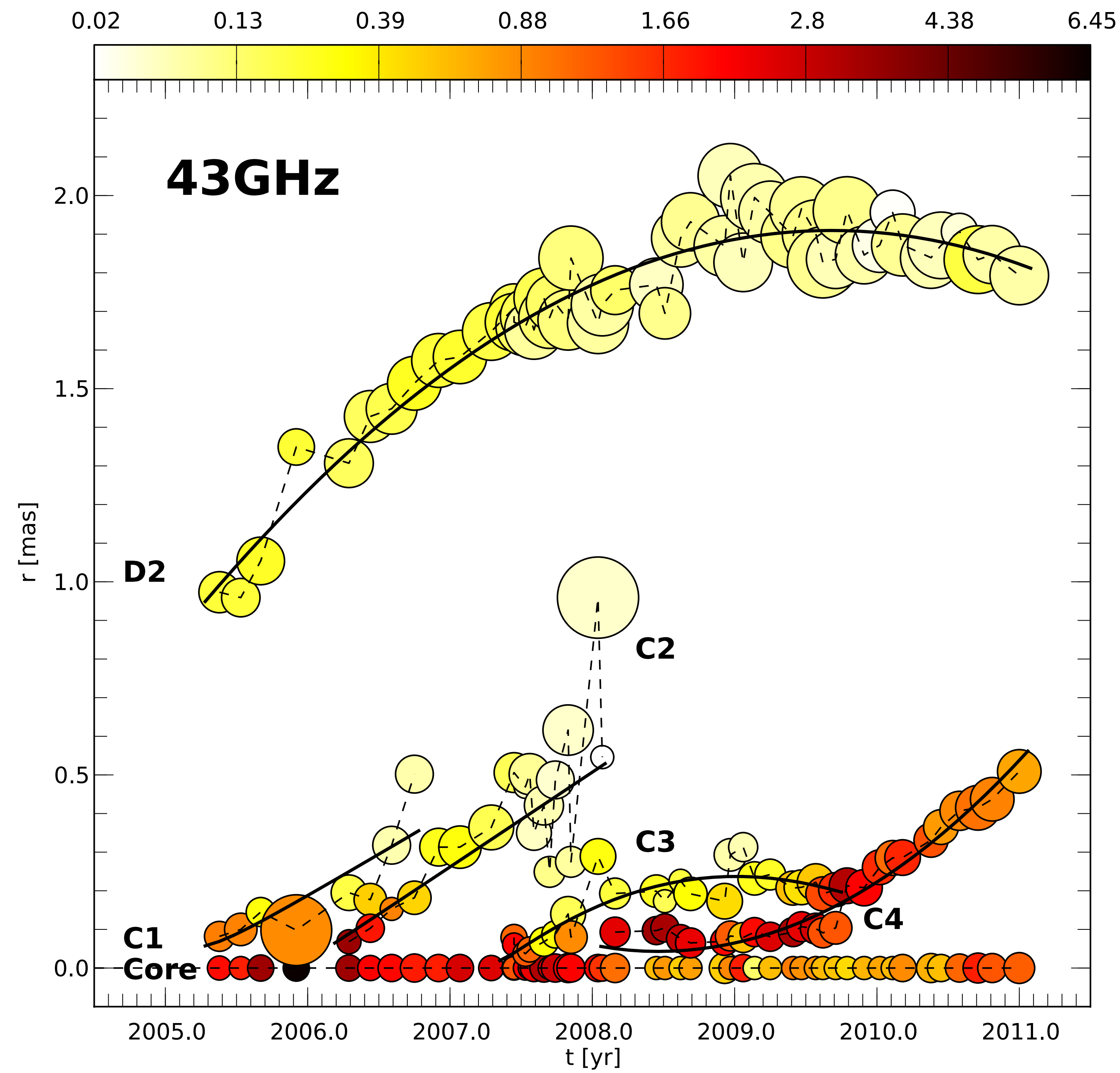

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Physical parameters from observations

steady state

speed of the components

Doppler factor

viewing angle

size of the jet/emission region

magnetic field and its evolution

particle density and its evolution

magnetization

$$\begin{aligned} \beta_{\rm app} &= 4 - 16 \\ \delta_{\rm max} &= 8 - 21 \\ \vartheta_{\rm max} &= 2.6^\circ - 3.6^\circ \\ R &= 0.4 - 40\,{\rm pc} \\ B_{\rm core} &= 100\,{\rm mG} \\ N_{\rm core} &= 40\,{\rm cm}^{-3} \\ \sigma &\sim 0.1 \end{aligned}$$

during 2006 flare

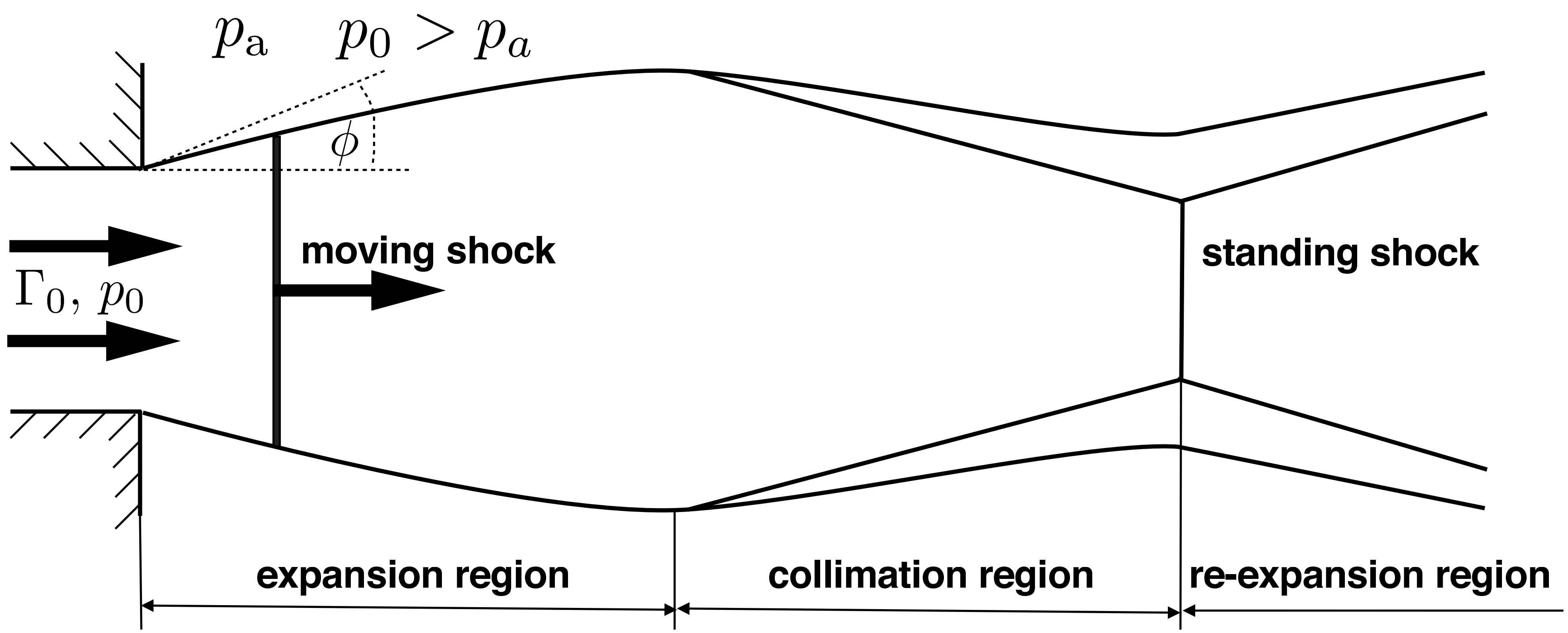
variation of the magnetic field

variation of the particle density

$$\begin{aligned} B_{\rm core} &= 100\,{\rm mG} \\ N_{\rm core} &= 100\,{\rm cm}^{-3} \end{aligned}$$

Ref: Fromm et al (in prep.)

Recollimation Shocks



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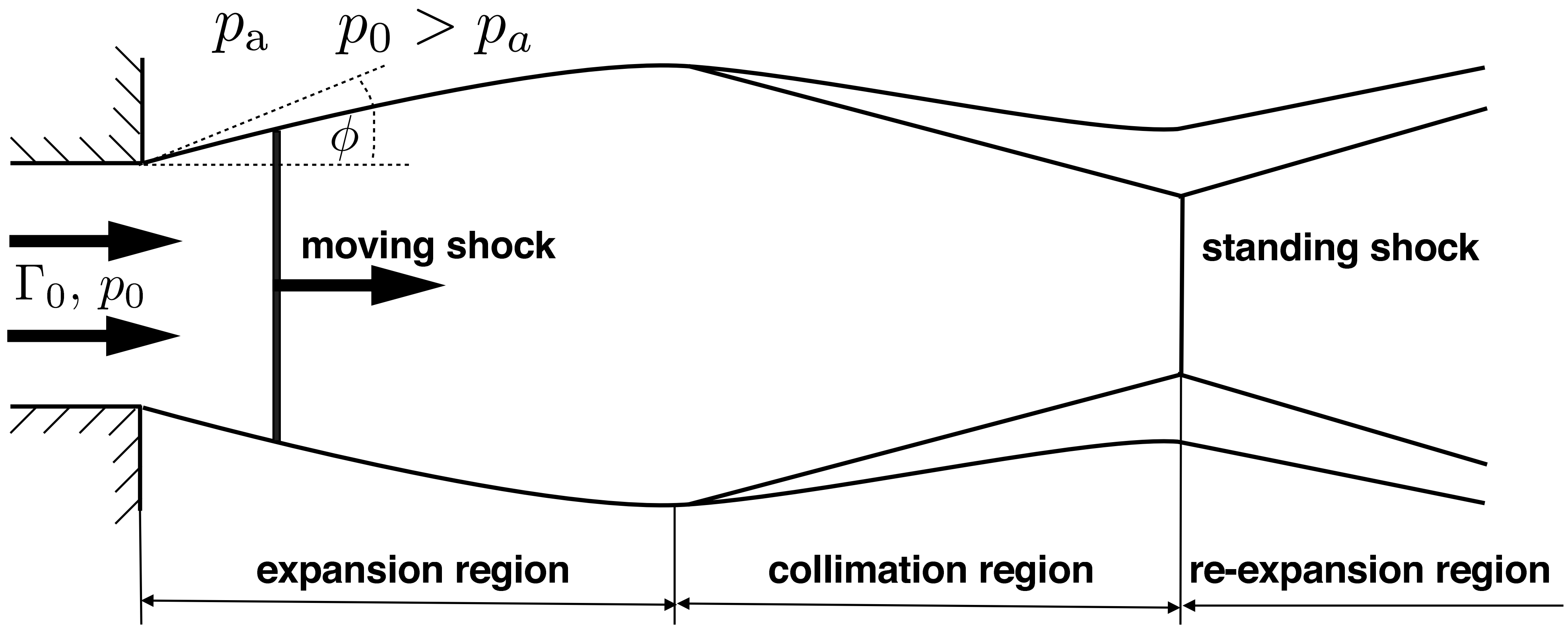

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RHD & emission Simulation

Relate observed emission structure to radiation microphysics and macroscopic dynamics

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RHD code RATPENAT (Perucho et al. 2010)

$R_{j,0}$	d_k	Γ	ρ_j	p_j	M	$\hat{\gamma}$
[pc]	[1]	[1]	[g/cm^3]	[dyne/cm^2]	[1]	[1]
0.15	3	12	$3.4 \cdot 10^{-26}$	$6.0 \cdot 10^{-8}$	3.0	13/9

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Emission code LUXS (Fromm et al. 2012)

$$n(\gamma) = n_0(\gamma_{\min}) \left(\frac{\gamma}{\gamma_{\min}} \right)^{-p} \qquad \gamma_{\min} < \gamma < \gamma_{\max}$$

including adiabatic and radiative losses

ϵ_b	ϵ_e	ϵ_a	p	z
[1]	[1]	[1]	[1]	[1]
0.3	0.005	10^6	2.2	1.037

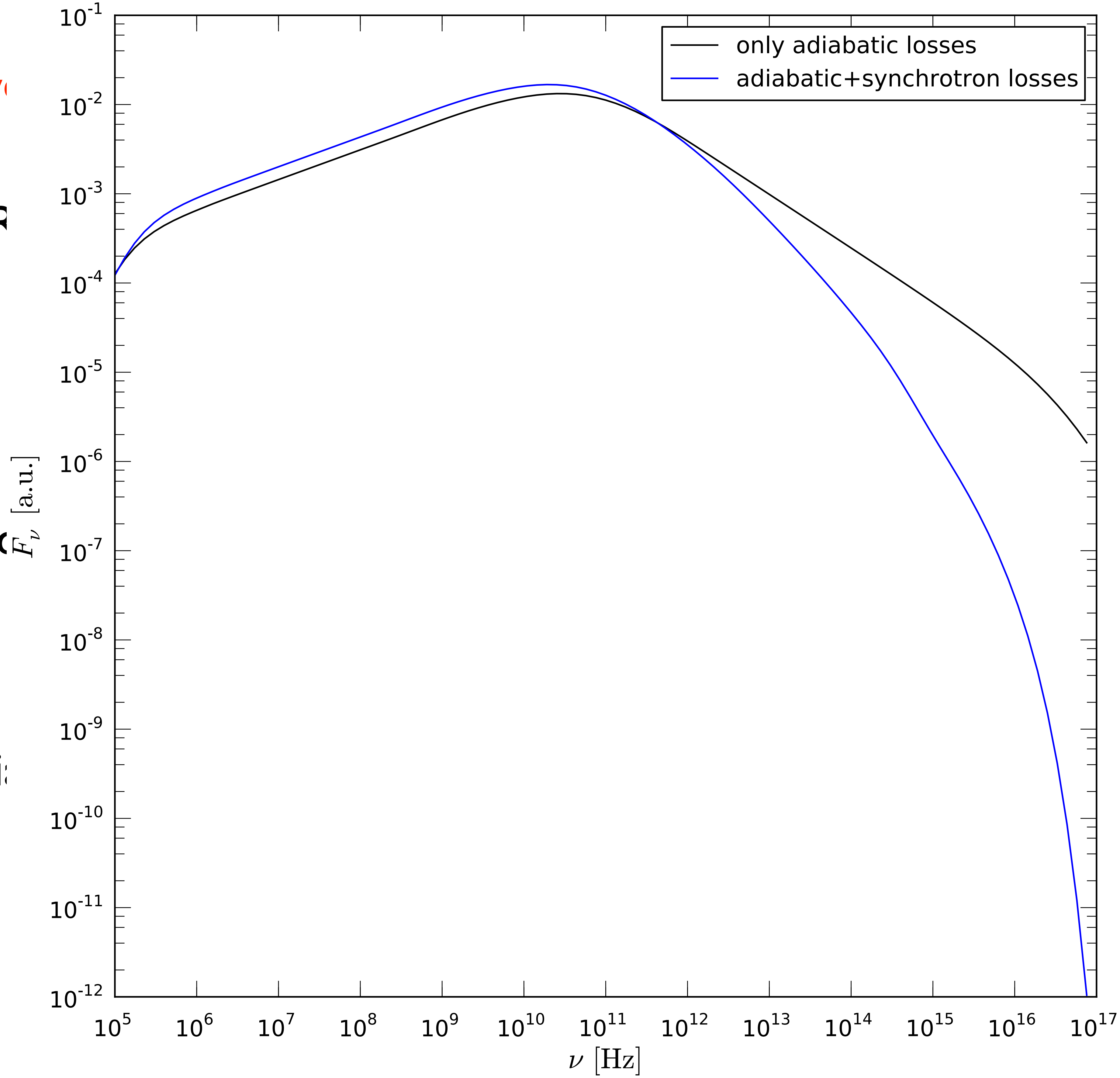
RHD & emission Simulation

Relate observ… …: dynamics

RHD code R…

Emission coo…

including adi…



RHD Simulation (thermal particles)

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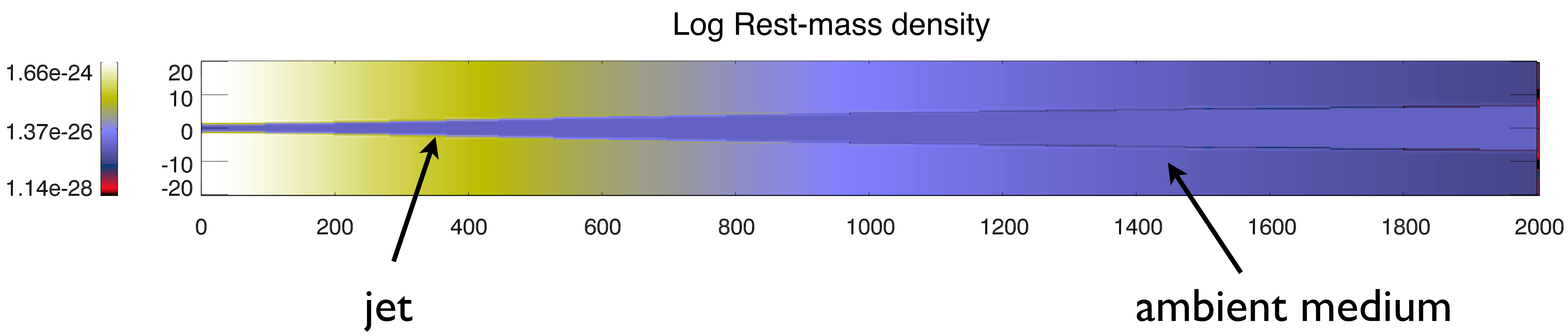

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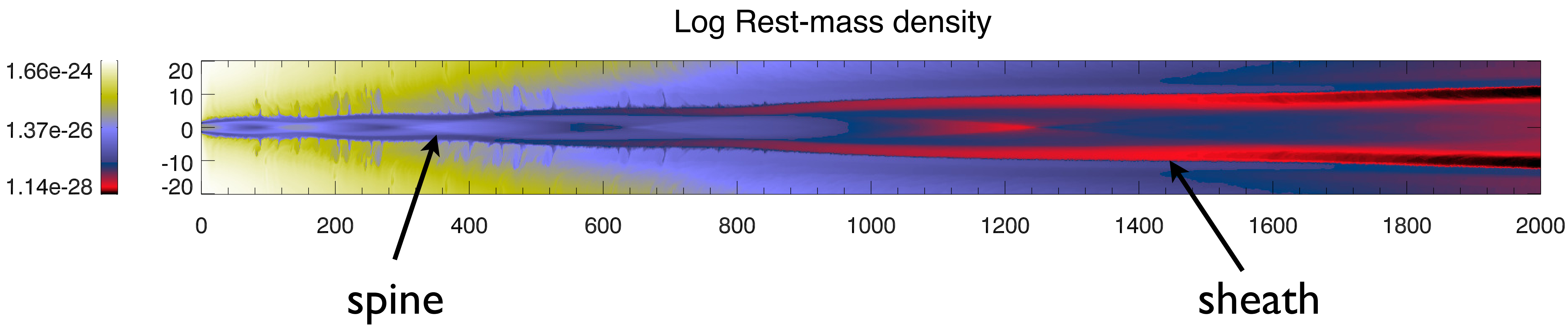

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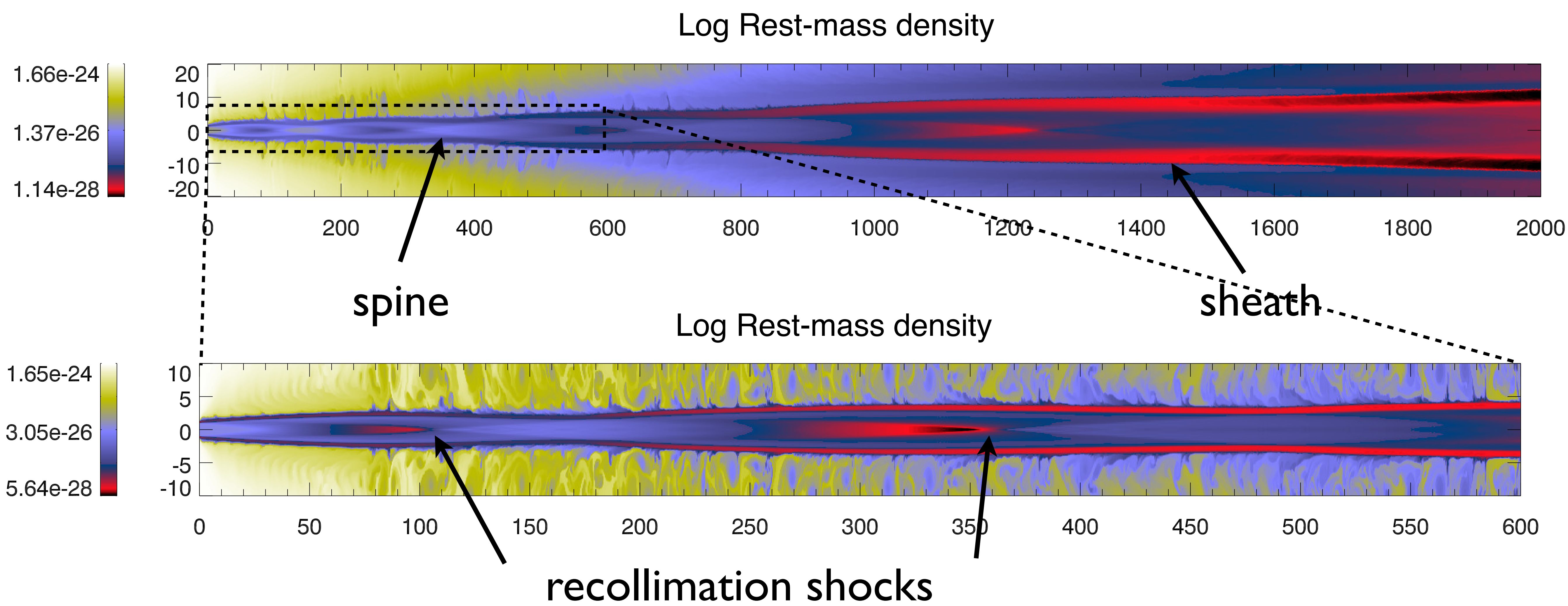

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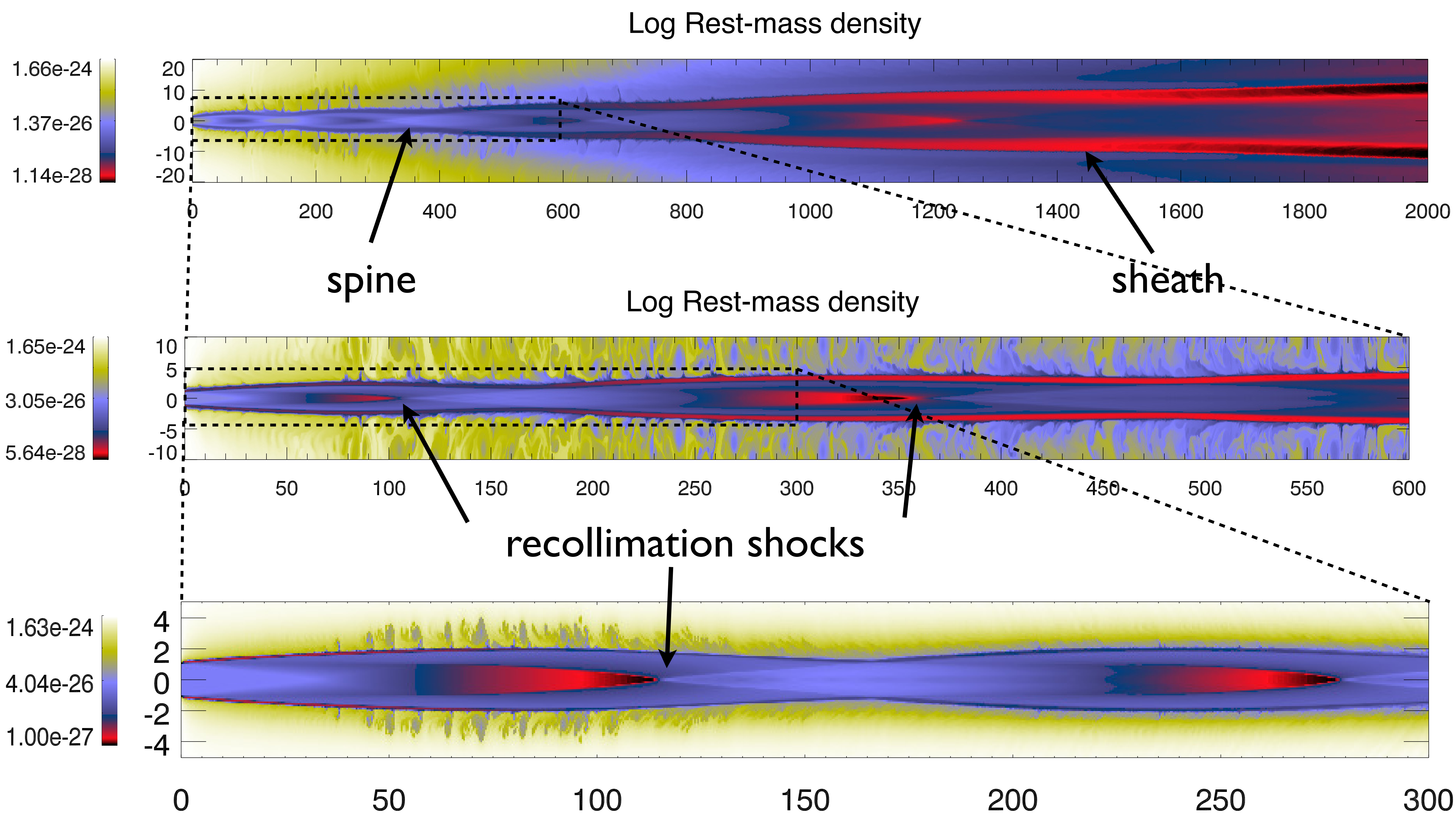

Emission Simulations (non-thermal)

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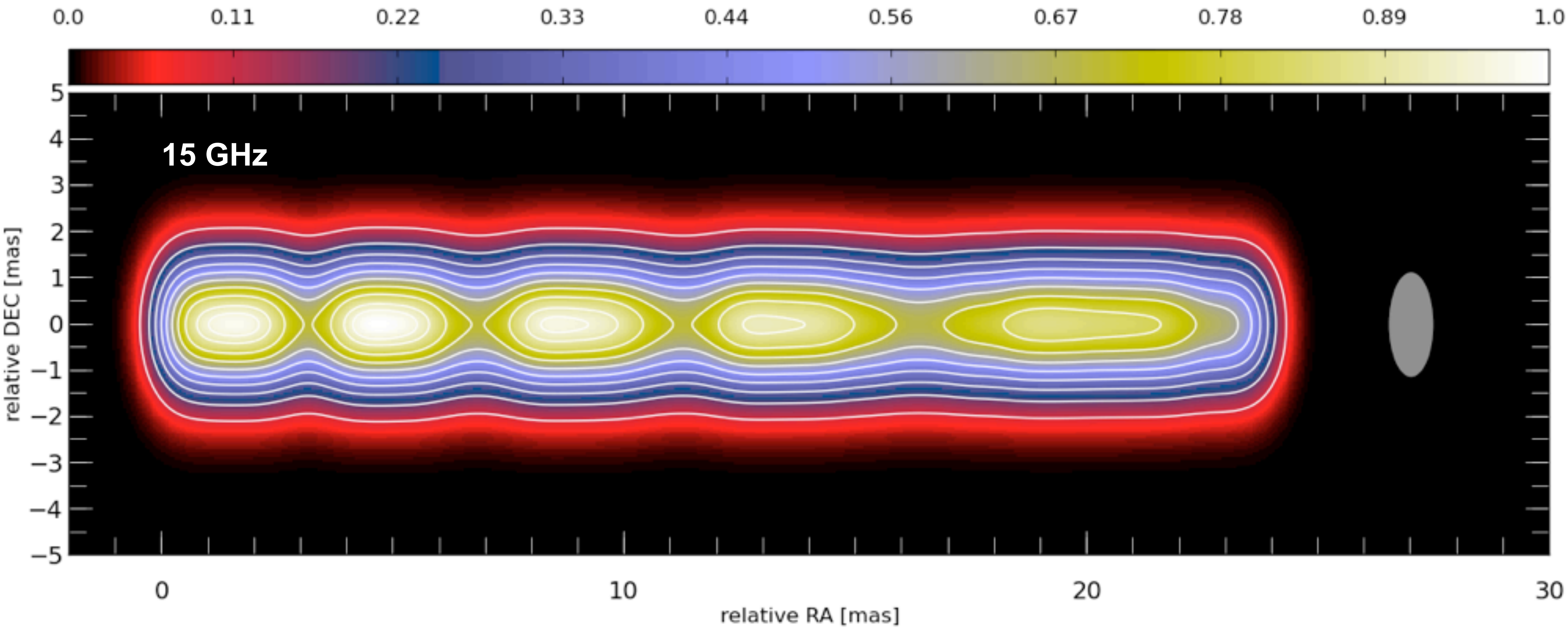

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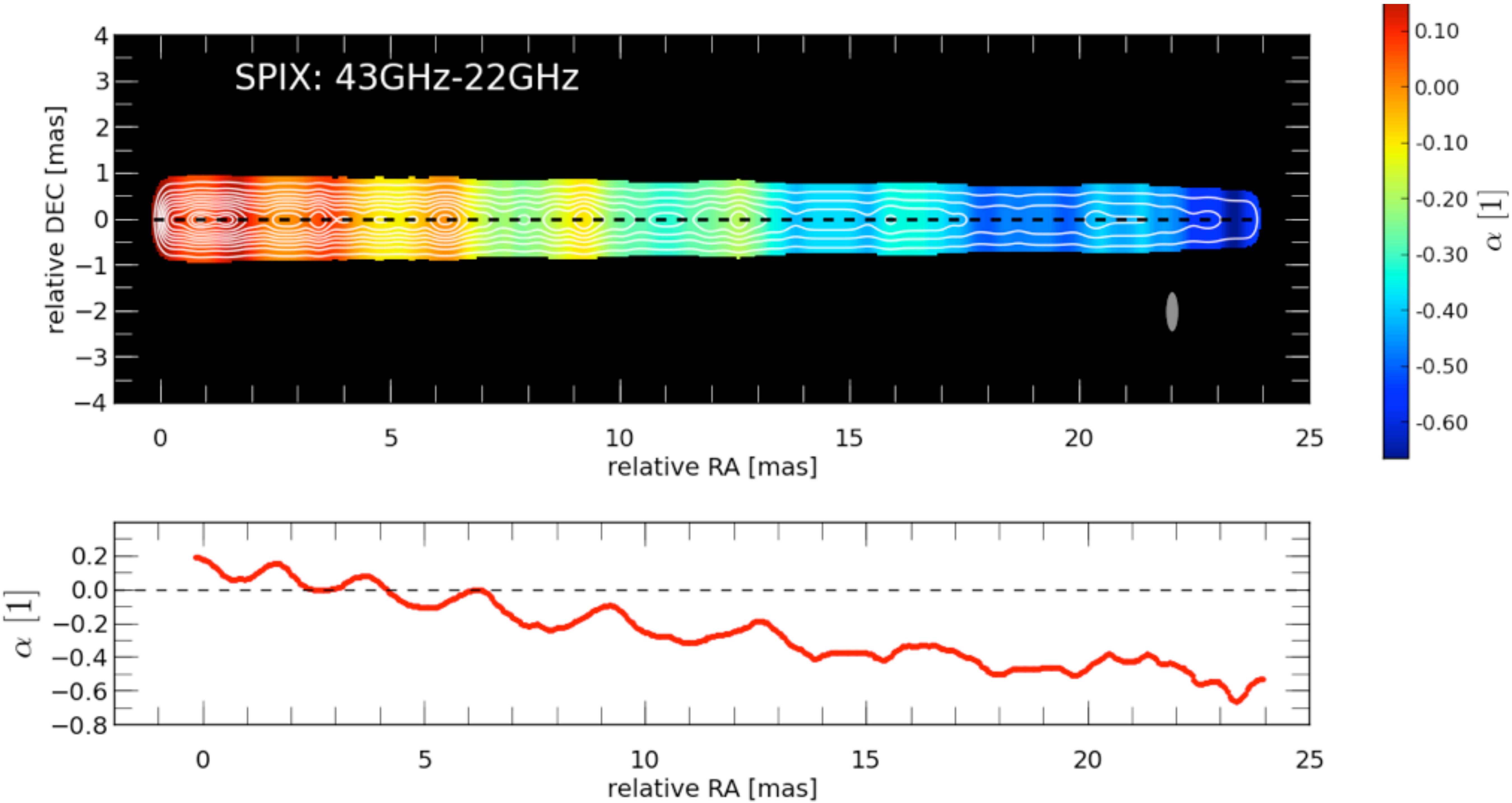
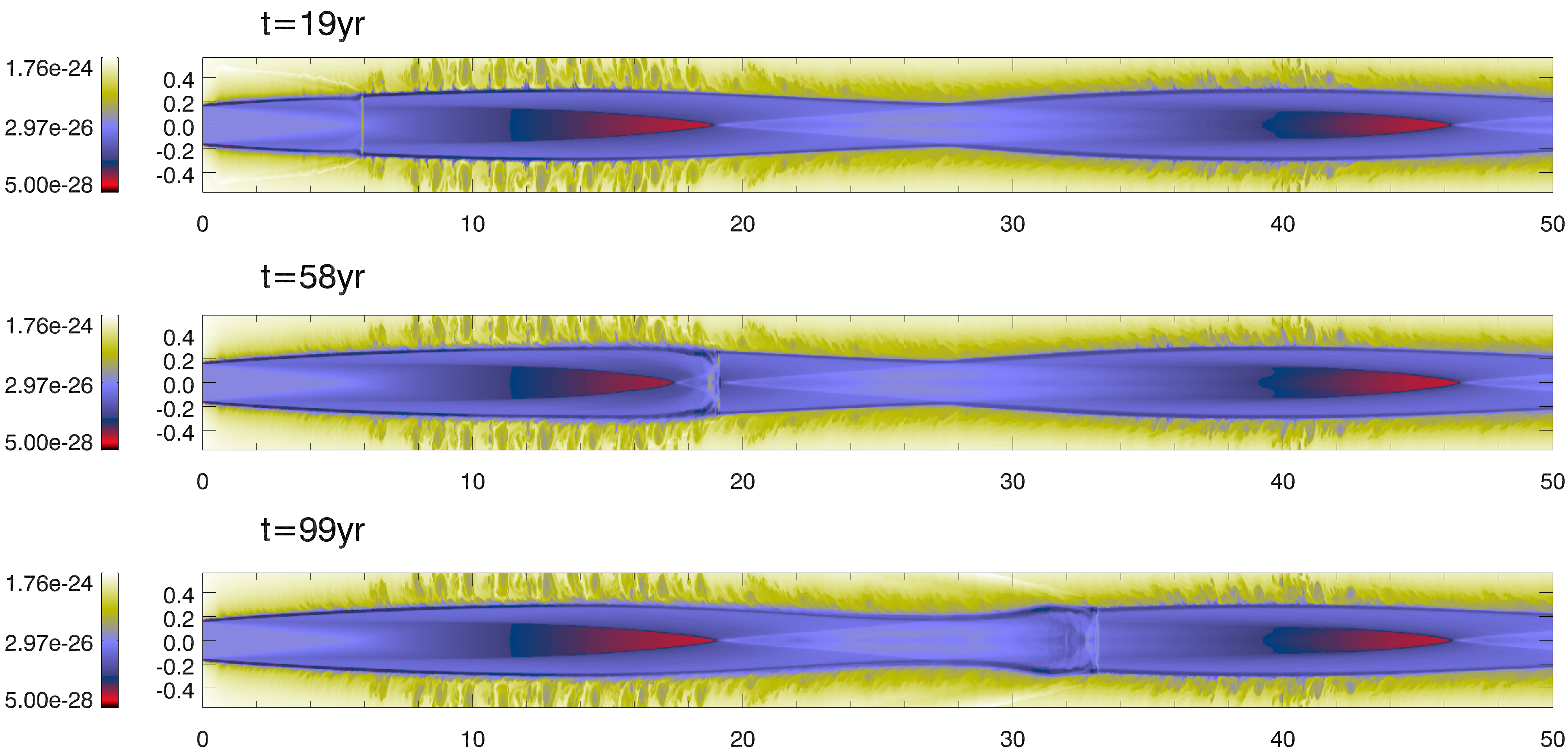
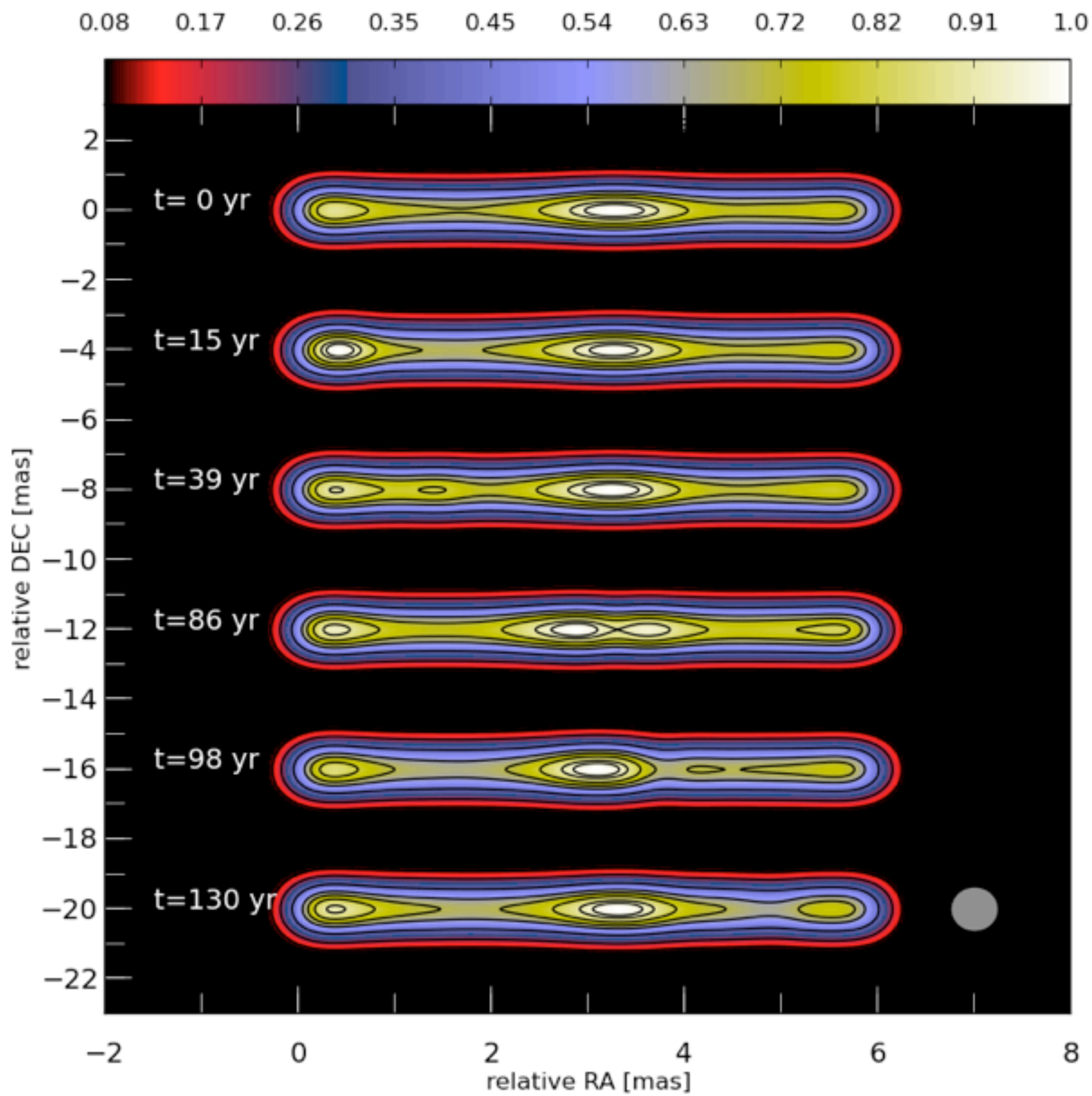


Shock-Shock interaction (thermal)



see also Gomez et al. (1997), Mimica et al. (2009)

Shock-Shock interaction (non-thermal)



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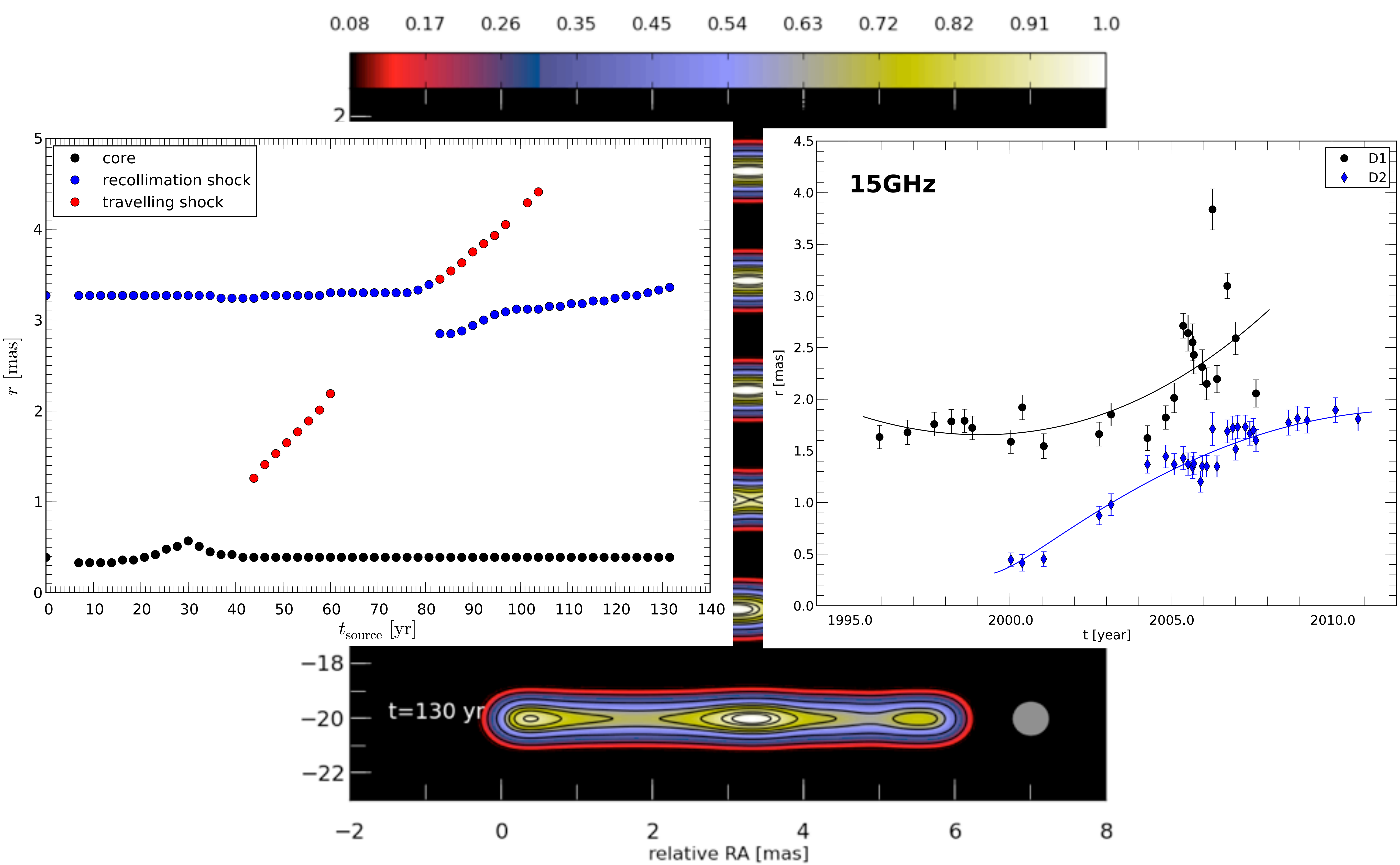

Summary & Outlook

- intrinsic parameters from observations
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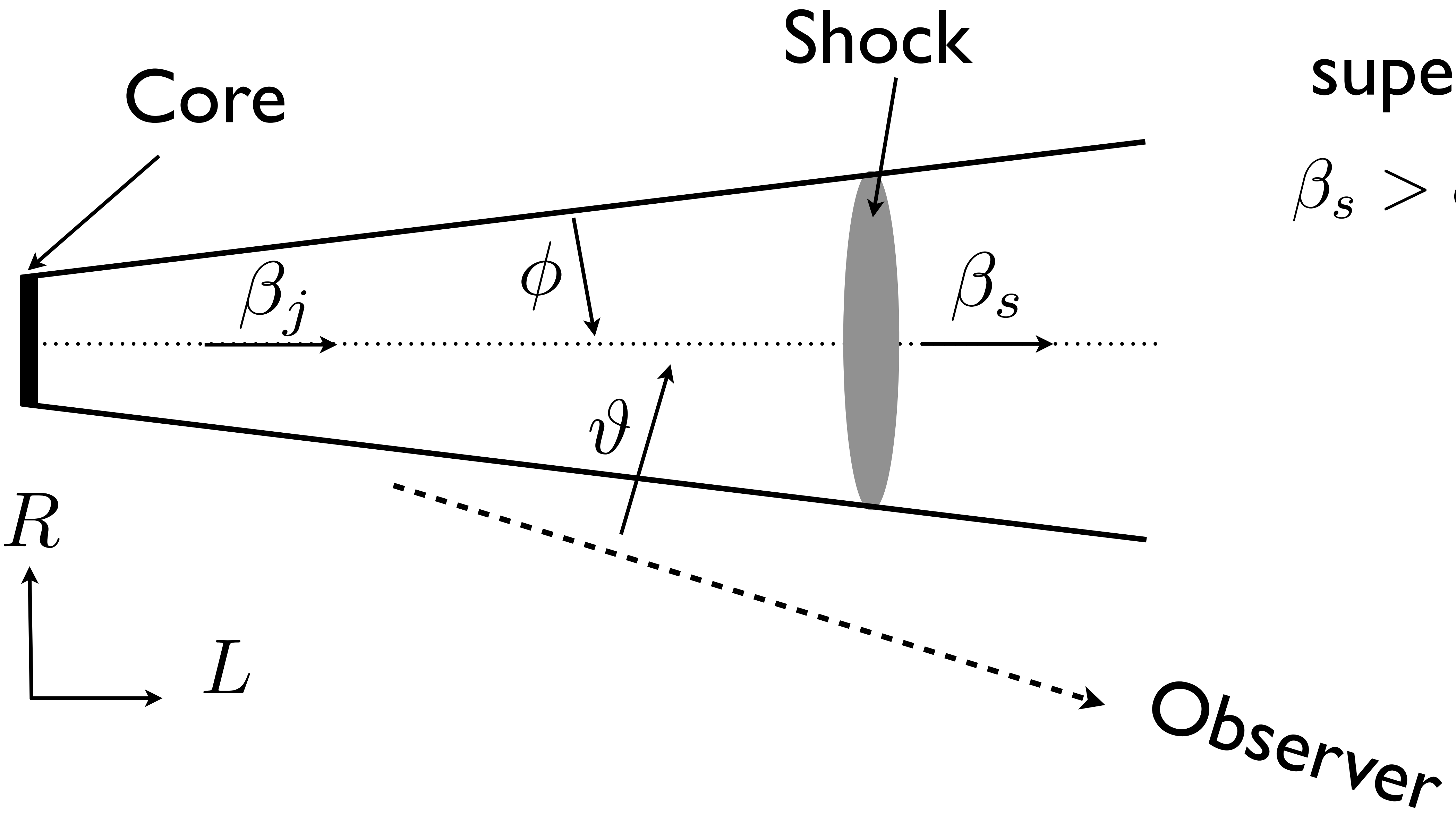
Thank you

BackUp Slides

- Energy Loss Stages
- Equations Shock-in-Jet Model
- Turnover freq. & turnover flux density 2D map
- Core-Shift & Equations
- eRHD Equations and Assumptions
- Shock-Shock spectrum
- Simulated Single Dish Spectrum
- K-H Instabilities

Shock-in-Jet Model



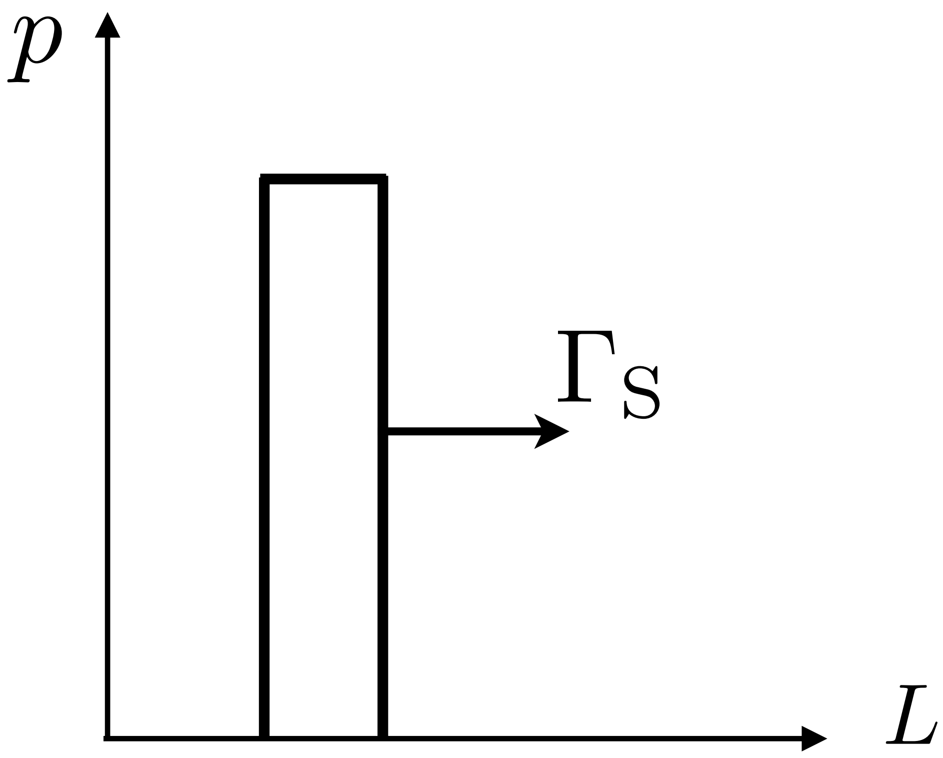
$\beta_s > \beta_j$

supersonic

$\beta_s > c_s$

Ref: Marscher & Gear (1985), Tuerler et al. (2000)

Shock-in-Jet Model



Relativistic gas: $\gamma_{\rm s} = 4/3$

Compression ratio: $\eta \approx \dfrac{\gamma_s \Gamma_s + 1}{\gamma_s - 1}$

Particle Energy gain: $\xi = \eta^{1/3}$

Ref: Marscher & Gear (1985), Daly & Marscher (1988)

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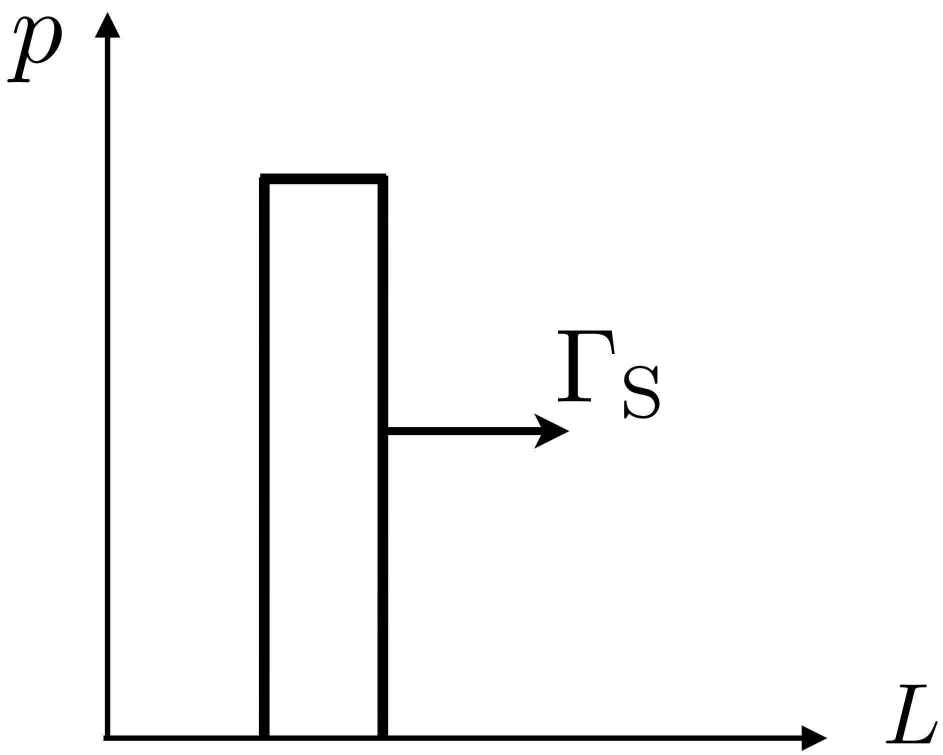

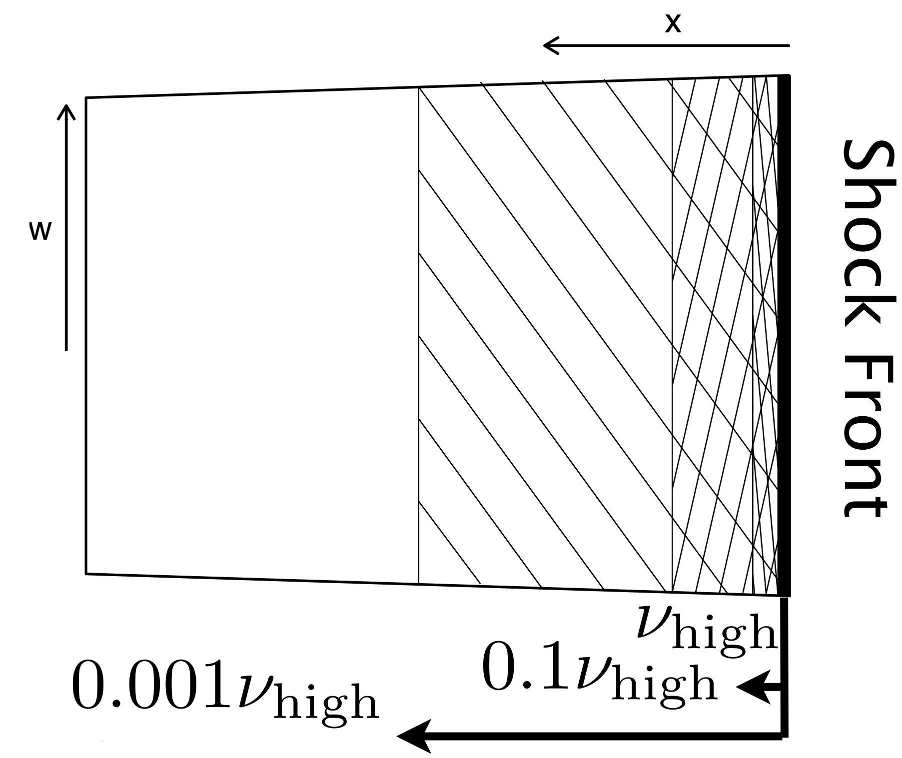

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Compression ratio: $\eta \approx \dfrac{\gamma_s \Gamma_s + 1}{\gamma_s - 1}$

Particle Energy gain: $\xi = \eta^{1/3}$

Compton: $x \sim c t_{cool,comp}$

$t_{cool,compt} \propto U_{ph}^{-1}$

Synchrotron: $x \sim c t_{cool,synch}$

$t_{cool,synch} \propto U_B^{-1}$

Adiabatic: $x \sim R$

Ref: Marscher & Gear (1985), Daly & Marscher (1988)

Shock-in-Jet Model

Assumptio $N(\gamma) = K\gamma^{-s} \quad \gamma_{\min} < \gamma < \gamma_{\max}$

$$K \propto R^{-k} \quad B \propto R^{-b} \quad D \propto R^{-d}$$

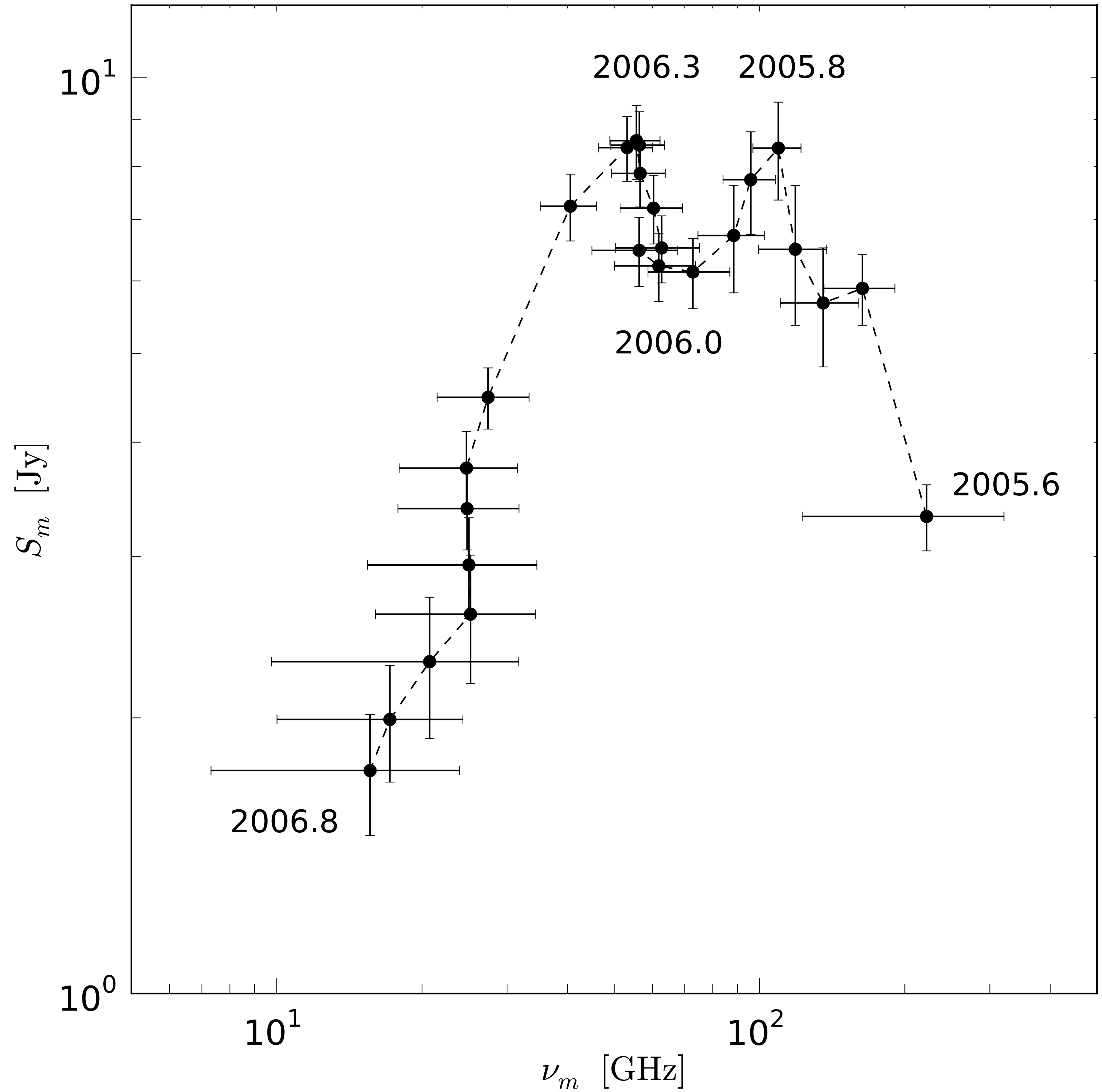
$$\begin{aligned}
n_1 &= -(b+1)/4 - d(s+3)/(s+5) \\
n_2 &= -[2k + b(s-1) + d(s+3)]/(s+5) \\
n_3 &= -[2(k-1) + (b+d)(s+2)]/(s+4) \\
f_1 &= (11-b)/8 - d(3s+10)/(s+5) \\
f_2 &= 2 - [5k + b(2s-5) + d(3s+10)]/(s+5) \\
f_3 &= [2s + 13 - 5k - b(2s+3) - d(3s+7)]/(s+4)
\end{aligned}$$

i=1: Compton
i=2: Synchrotron

$$S_m \propto \nu_m^{f_i/n_i}$$

Ref: Marscher & Gear (1985)

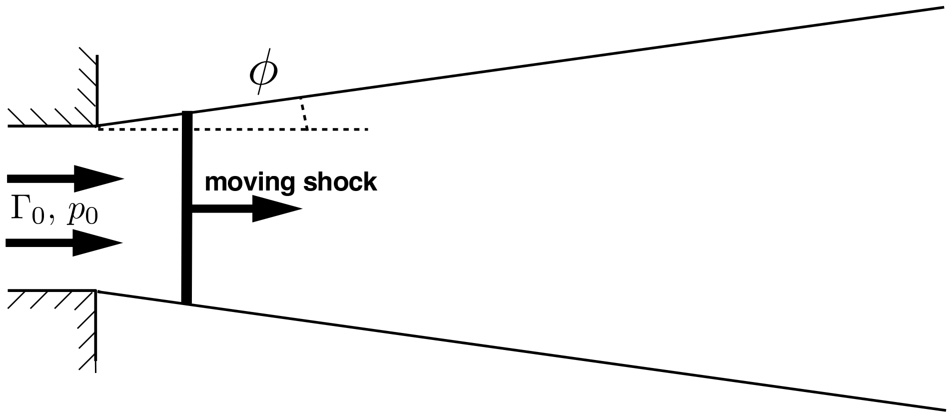
Modified Shock-in-Jet Model

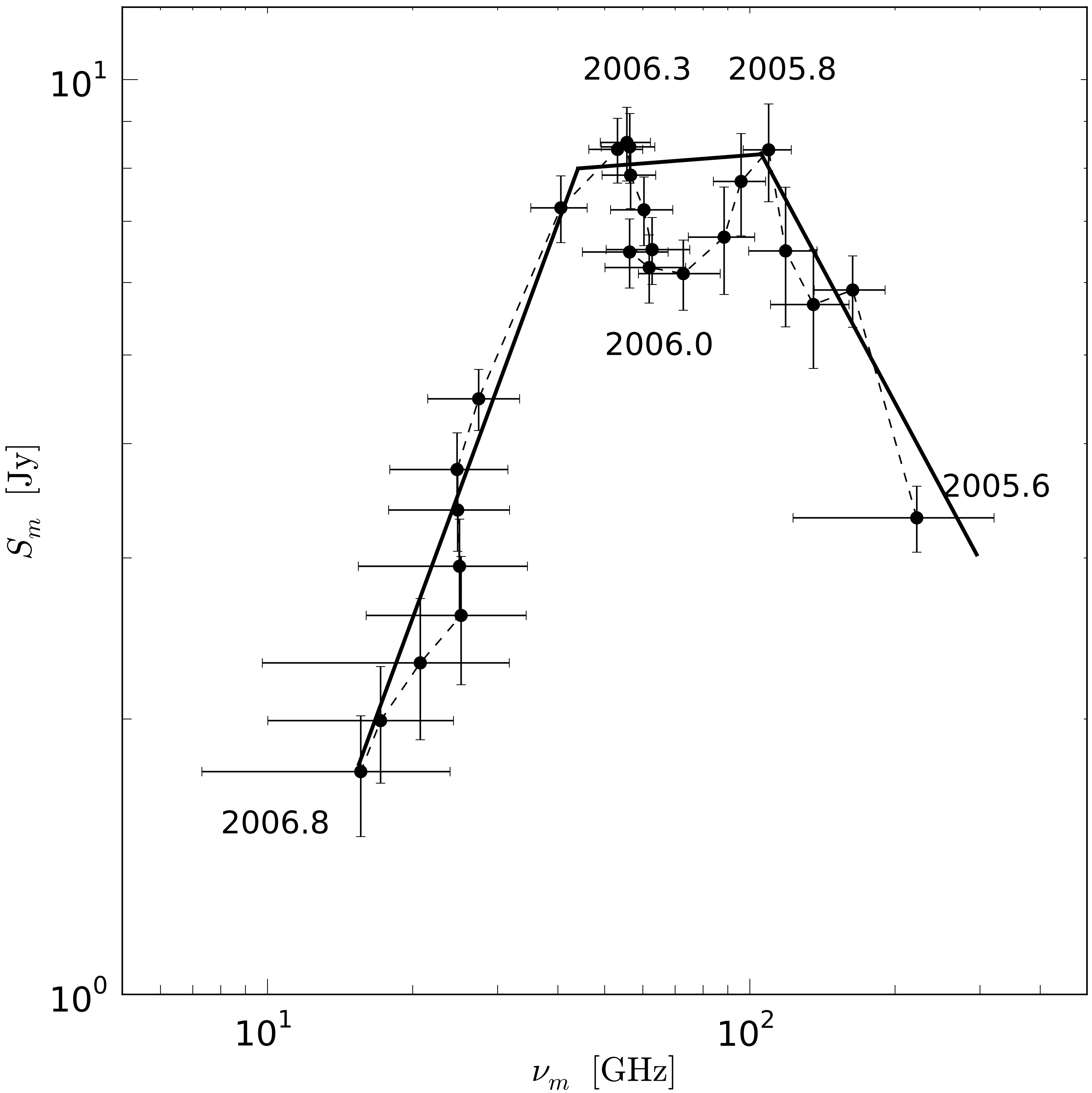


Ref: (Paper I)

Modified Shock-in-Jet Model

conical jet





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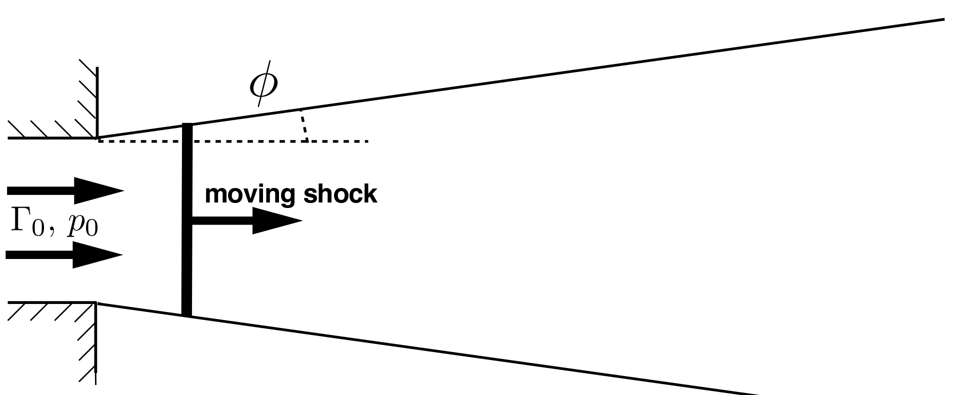
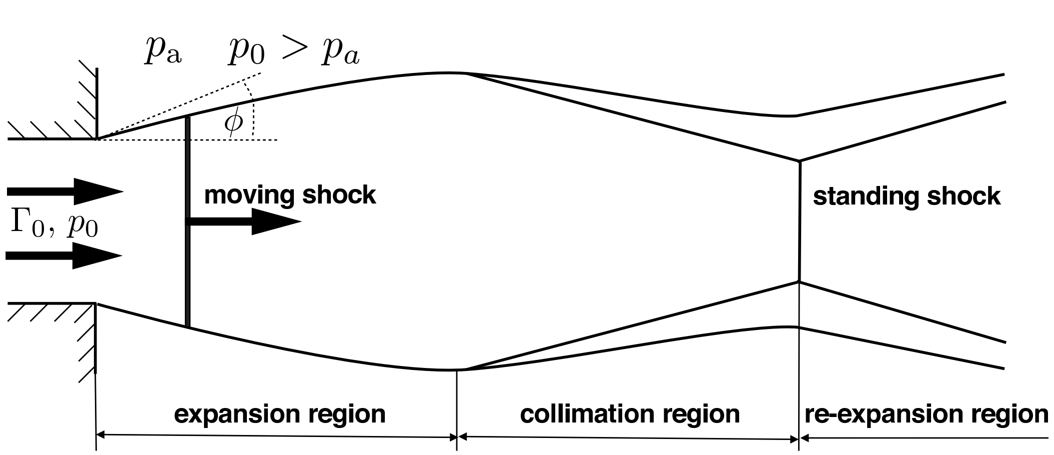
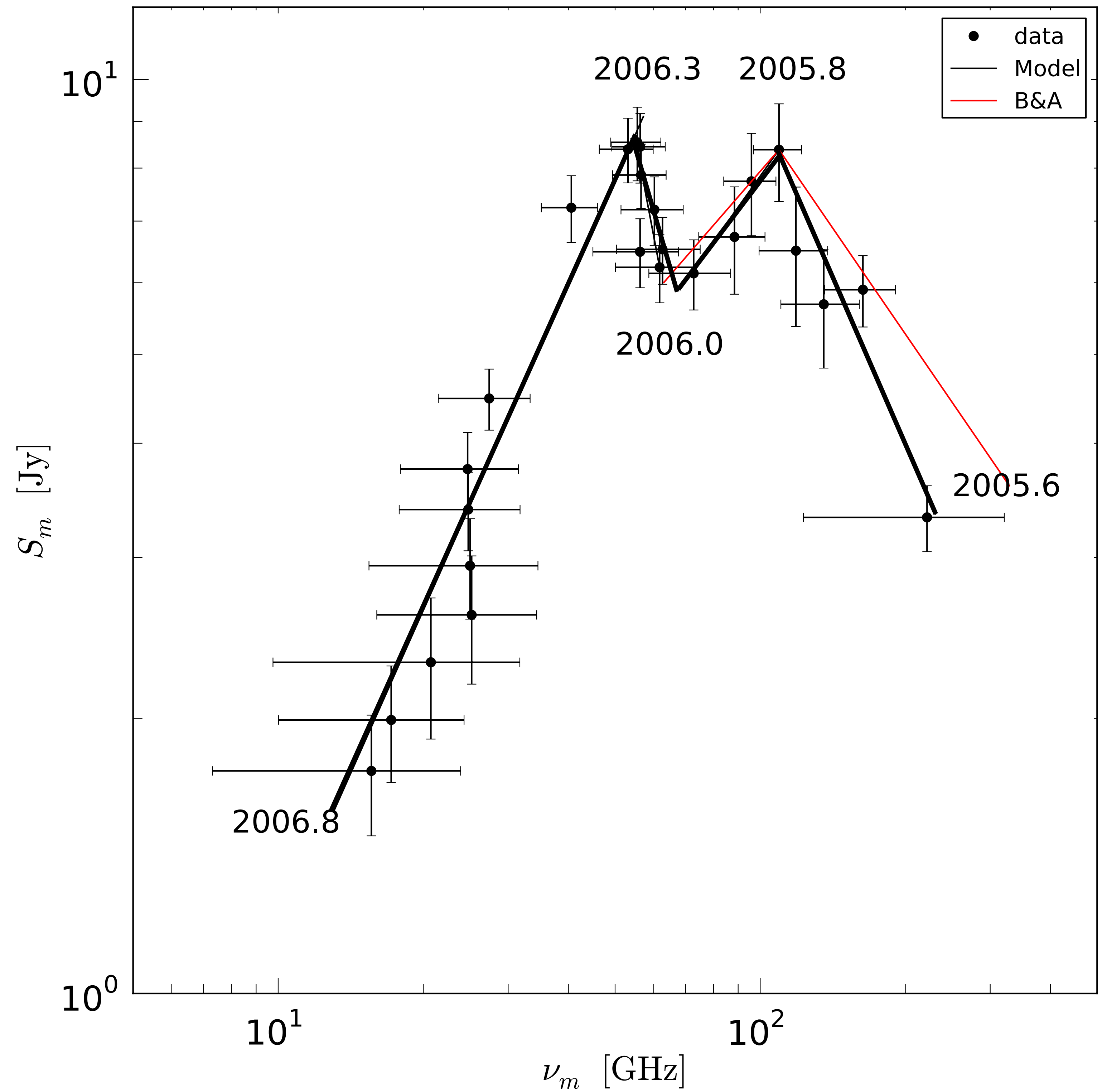


over-pressured jet

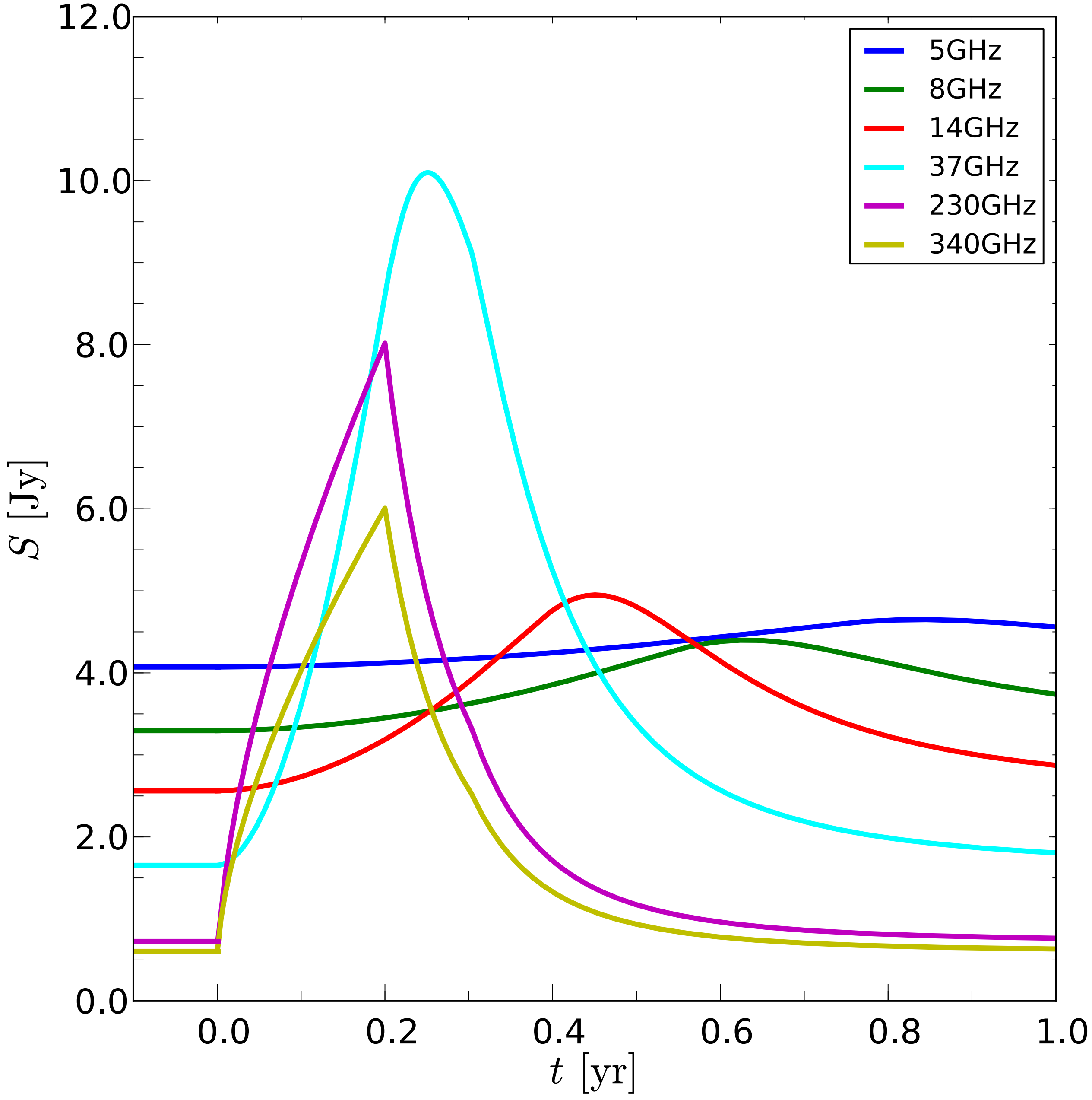




Ref: (Paper I)

Single Dish analysis

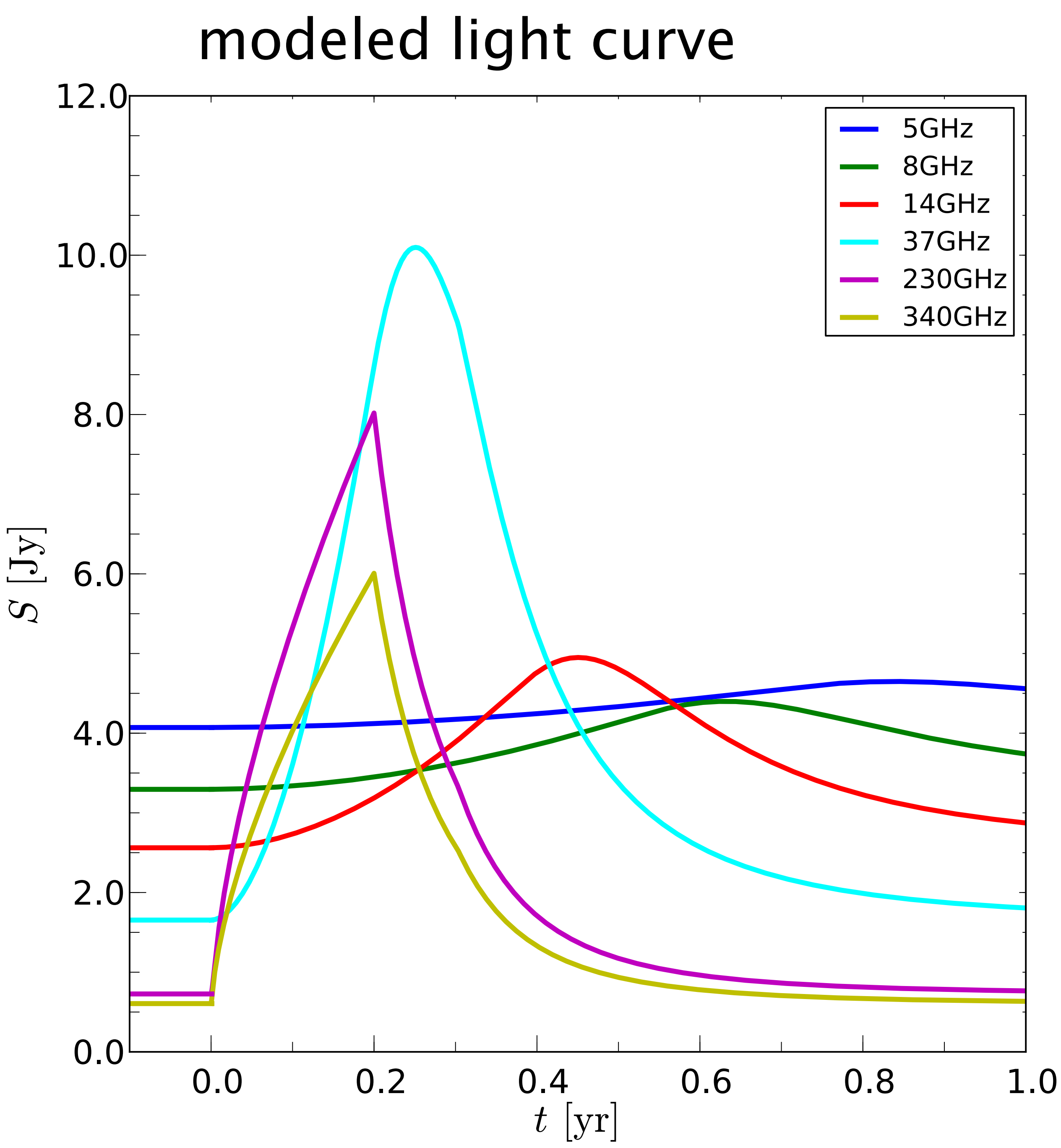
modeled light curve

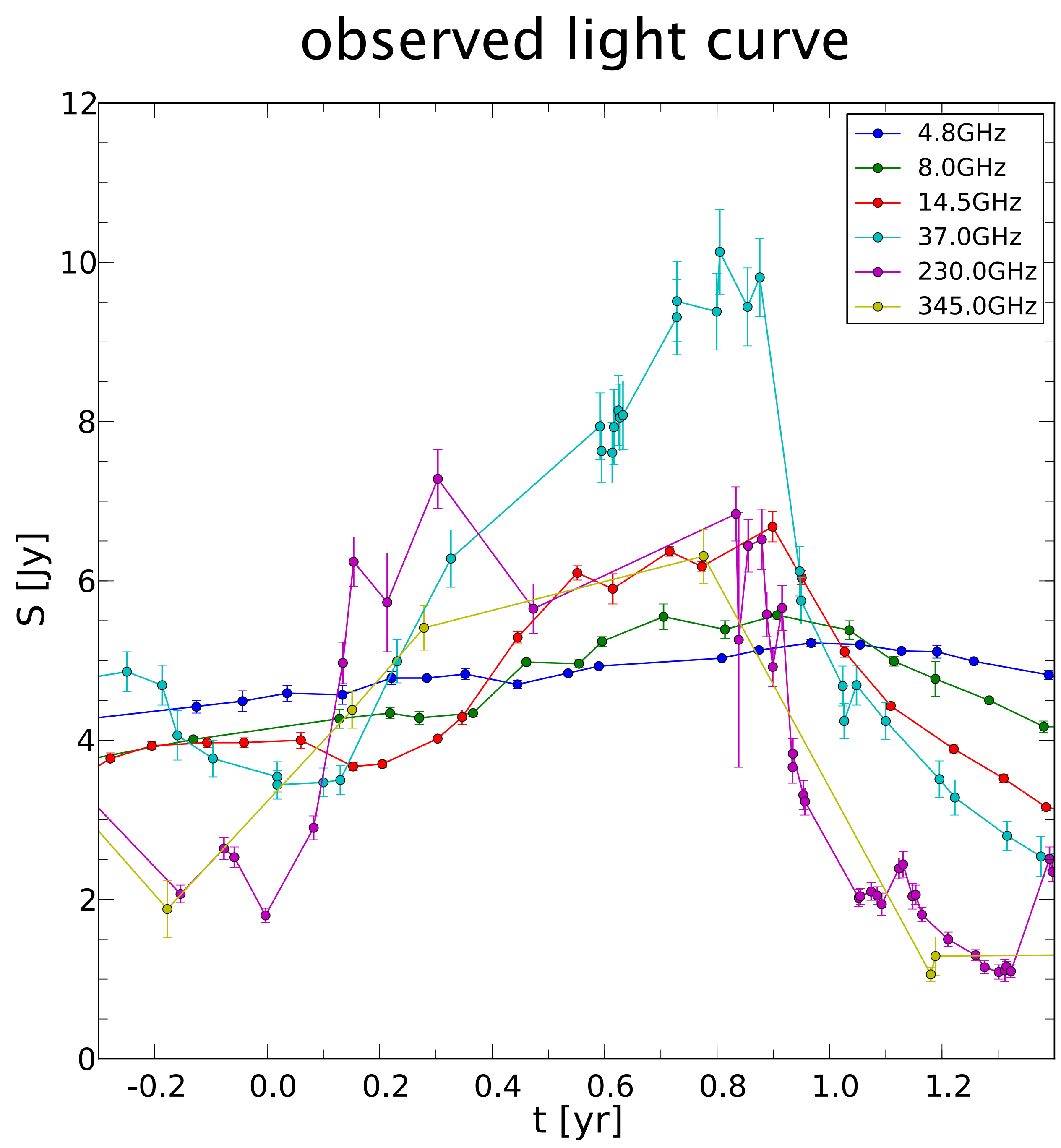


observed light curve

Ref: Fromm et al. 2011 (Paper I)

Single Dish analysis





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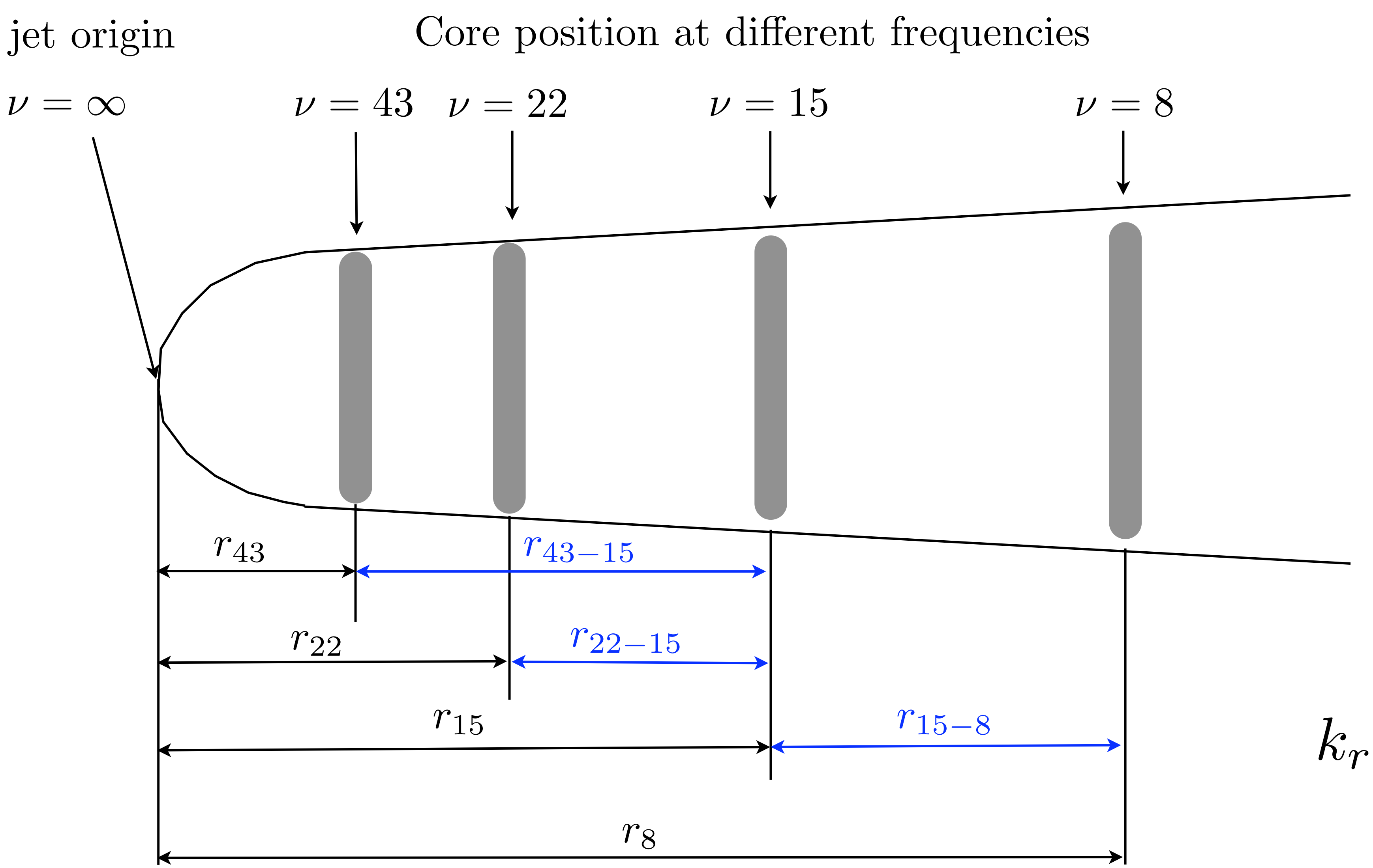
Opacity variation in the core



$$N = K\gamma^{-s}$$

$$N \propto R^{-n}$$

$$B \propto R^{-b}$$

$$\alpha = -(s-1)/2$$

$$\Delta r \propto \nu^{-1/k_r}$$

$$k_r = \frac{(3-2\alpha)b + 2n - 2}{5 - 2\alpha}$$

→ 2D cross-correlation of VLBI maps

Ref: Marcaide & Shapiro (1984), Lobanov A. P. (1998)

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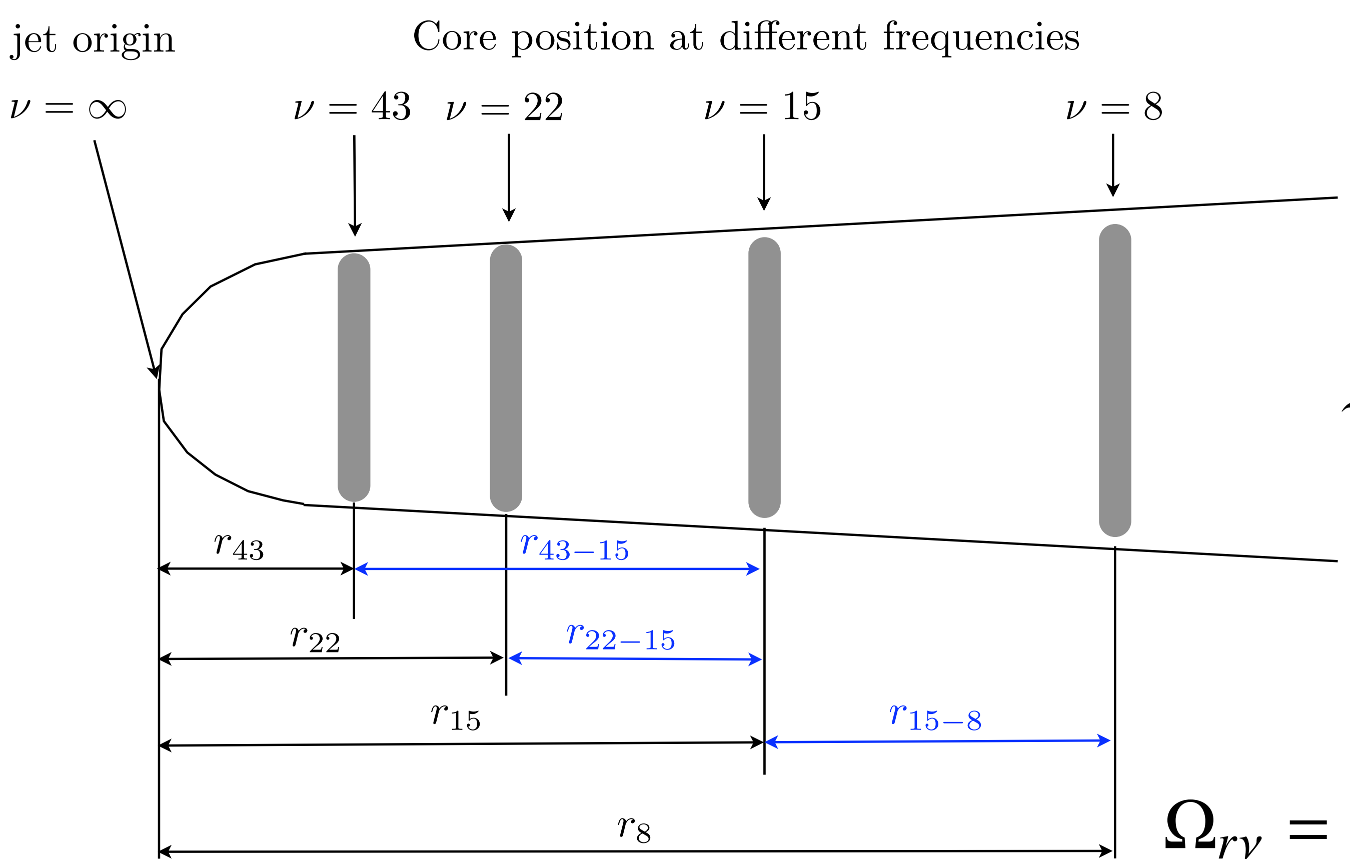


$$r_{\rm core}(\nu) \approx \Omega_{r\nu}\left(1+\beta_{\rm app}^2\right)^{1/2}\nu^{-1}\ [\mathrm{pc}]$$

$$B_{\rm core} = B_1 r_{\rm core}^{-1}$$

$$\tau'_{\nu'} = c_\kappa(s)c_{\kappa,b}(s)(1+z)^{-\frac{s-4}{2}}R\delta^{\frac{s+4}{2}}KB^{\frac{s+2}{2}}\nu'^{-\frac{s+4}{2}}$$

$$\Omega_{r\nu} = 4.85\cdot 10^{-9}\frac{\Delta r_{\nu_1,\nu_2}D_L\nu_1^{1/k_r}\nu_2^{1/k_r}}{(1+z)^2\left(\nu_2^{1/k_r}-\nu_1^{1/k_r}\right)}\ [\mathrm{pc}\cdot\mathrm{GHz}],$$

$$B_1 \approx 0.042\,\Omega_{r\nu}^{3/4}(1+z)^{1/2}\frac{\left(1+\beta_{\rm app}^2\right)^{3/8}}{\beta_{\rm app}^{1/2}}\ [\mathrm{G}]$$

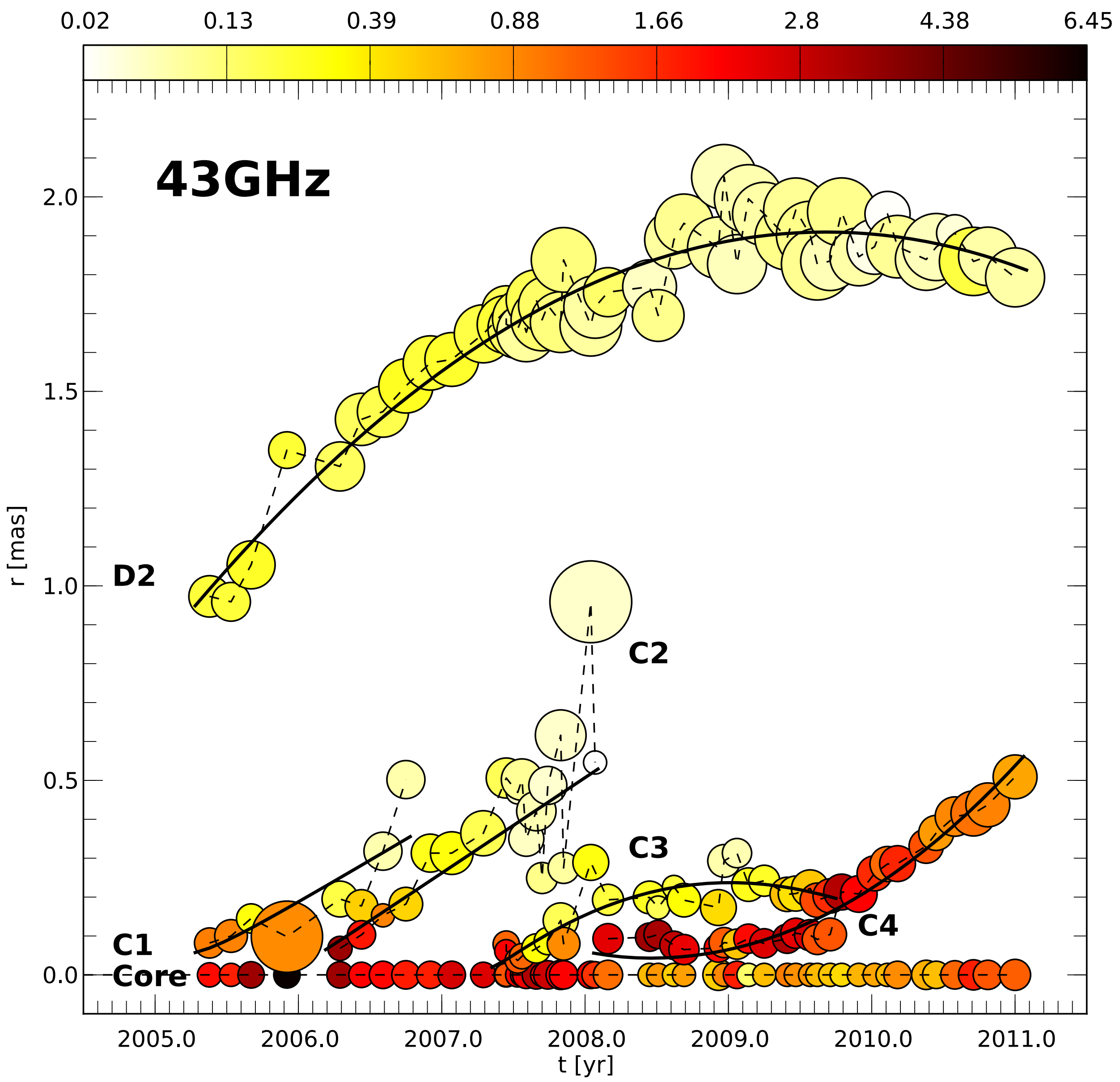
$$N_1 = 0.47\cdot 10^6\gamma_{\min}^{-1}B_1^2.$$

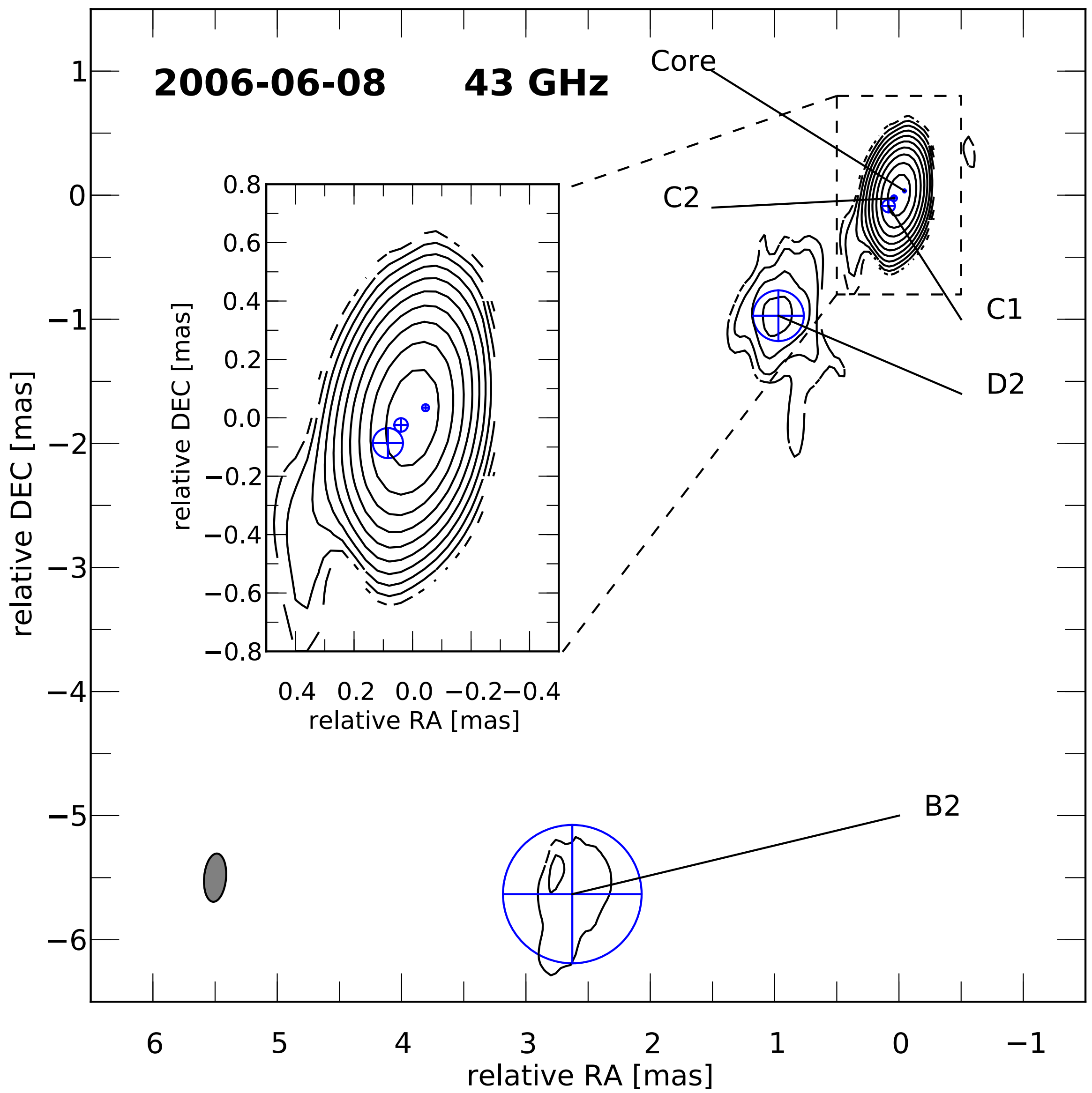
Ref: Marcaide & Shapiro (1984), Lobanov A. P. (1998)

VLBI Kinematics

2D Gaussian Modeling: Position (x,y), Flux Density, (S) and Size (FWHM)

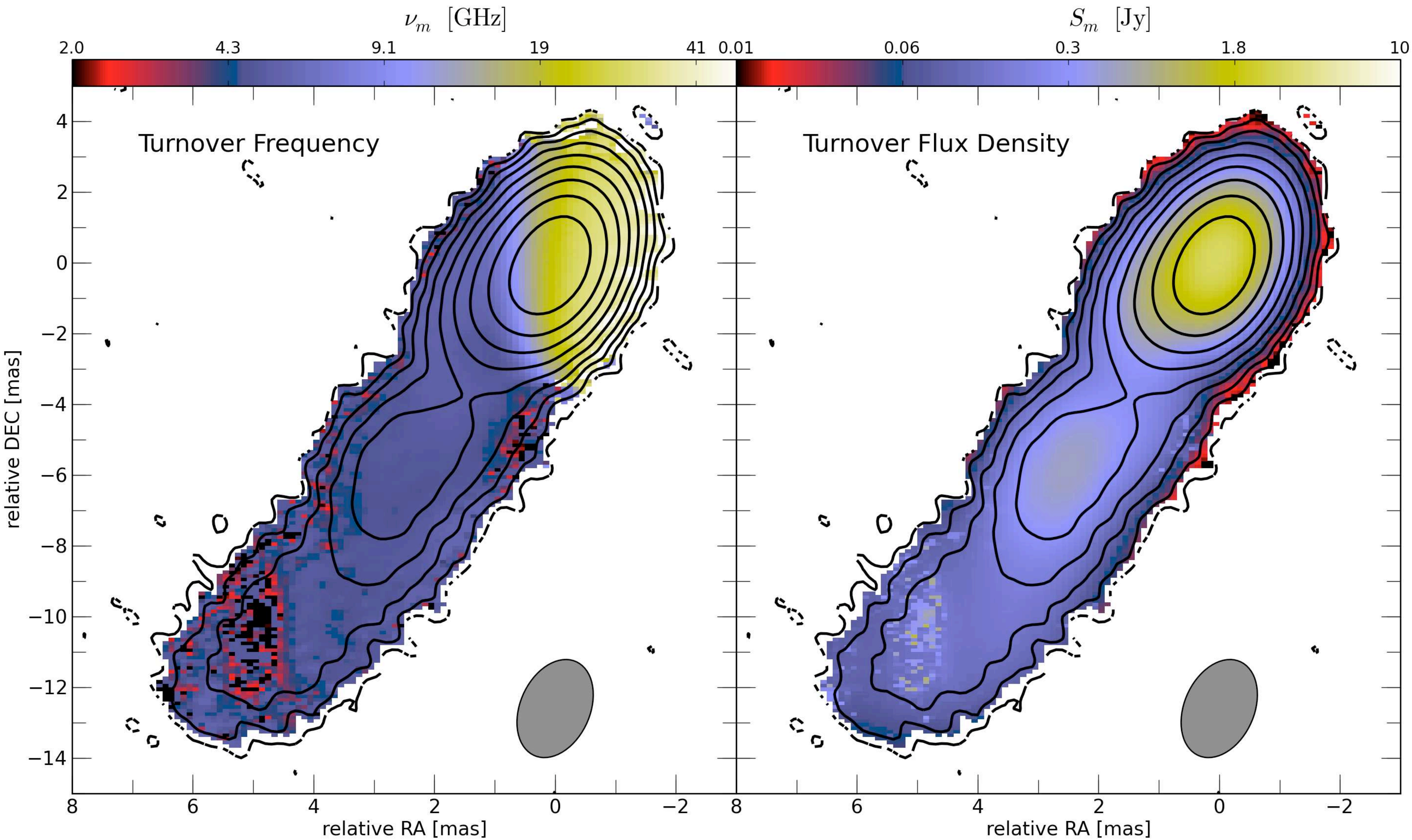
identify and trace features with time and frequency





Ref: Fromm et al. 2012 (Paper II)

VLBI Modeling



Ref: Fromm et al in prep. (Paper III)

Simulation of Blazar Jets

Relate observed emission structure to radiation microphysics and macroscopic dynamics

$$r_{B,p^+} = 10^{-12}\gamma B^{-1}[\mathrm{pc}] \ll L_j[\mathrm{pc}]$$

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Relativistic Hydrodynamics + emission calculations

$$\frac{\partial D}{\partial t} + \sum_{j=1}^{3} \frac{\partial}{\partial x^j}\left(Dv^j\right) = 0$$

$$\frac{\partial S^i}{\partial t} + \sum_{j=1}^{3} \frac{\partial}{\partial x^j}\left(S^i v^j + \delta^{ij} p\right) = 0 \;\; (i = 1, 2, 3)$$

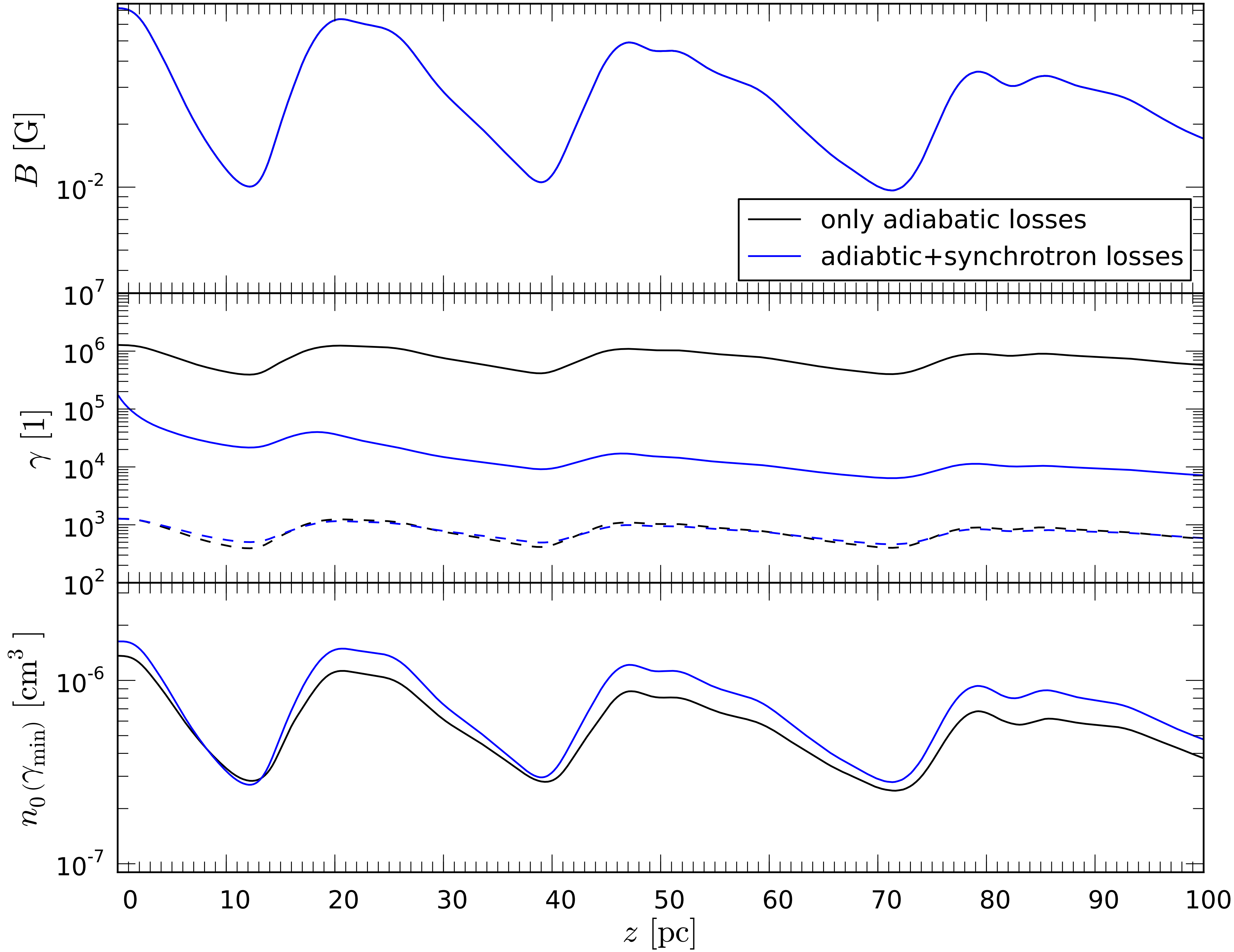
$$\frac{\partial \tau}{\partial t} + \sum_{j=1}^{3} \frac{\partial}{\partial x^j}\left(S^j - Dv^j\right) = 0$$

$$p = (\hat{\gamma} - 1)\,\varepsilon\rho$$

$$D = \rho W \quad \mathbf{S} = \rho h W^2 \mathbf{v} \quad \tau = \rho h W^2 - p - \rho W \quad W = \left(1 - v^2\right)^{-1/2}$$

Emission Simulation

$n(\gamma) =$ ... on



(Mimica et al. 2010, Dermer & Boettcher 2010)

Emission Simulation

$$n(\gamma) = n(\gamma_{\min}) \left(\frac{\gamma}{\gamma_{\min}} \right)^{-p} \qquad \gamma_{\min} < \gamma < \gamma_{\max}$$

e- distribution

$$B = \left(\epsilon_b \frac{8\pi p_{th}}{\widehat{\gamma} - 1} \right)^{1/2}$$

magnetic field [G]

(Mimica et al. 2010, Dermer & Boettcher 2010)

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$$\gamma_{\max} = \left(\frac{9 m_e^2 c^4}{8\pi e^3 \epsilon_a B}\right)^{1/2}$$

max e- Lorentz factor

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$$n(\gamma_{\min}) = \frac{\epsilon_e p_{th} (p-2)}{(\widehat{\gamma} - 1) \gamma_{\min}^2 m_e c^2} \left[1 - \left(\frac{\gamma_{\max}}{\gamma_{\min}} \right)^{2-p} \right]^{-1}$$

coeff. e- distribution

(Mimica et al. 2010, Dermer & Boettcher 2010)

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max e- Lorentz factor

$$\boxed{\begin{array}{c} 0 < \epsilon_e < 1 \\ 0 < \epsilon_b < 1 \\ 1e3 < \epsilon_a < 1e6 \end{array}}$$

$$\gamma_{\min} = \frac{\boxed{\epsilon_e} p_{th} m_p (p-2)}{\rho_{th} (\widehat{y} - 1) m_e c^2 (p-1)}$$

min e- Lorentz factor

$$n(\gamma_{\min}) = \frac{\boxed{\epsilon_e} p_{th} (p-2)}{(\widehat{\gamma} - 1) \gamma_{\min}^2 m_e c^2} \left[1 - \left(\frac{\gamma_{\max}}{\gamma_{\min}} \right)^{2-p} \right]^{-1}$$

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Emission Simulation

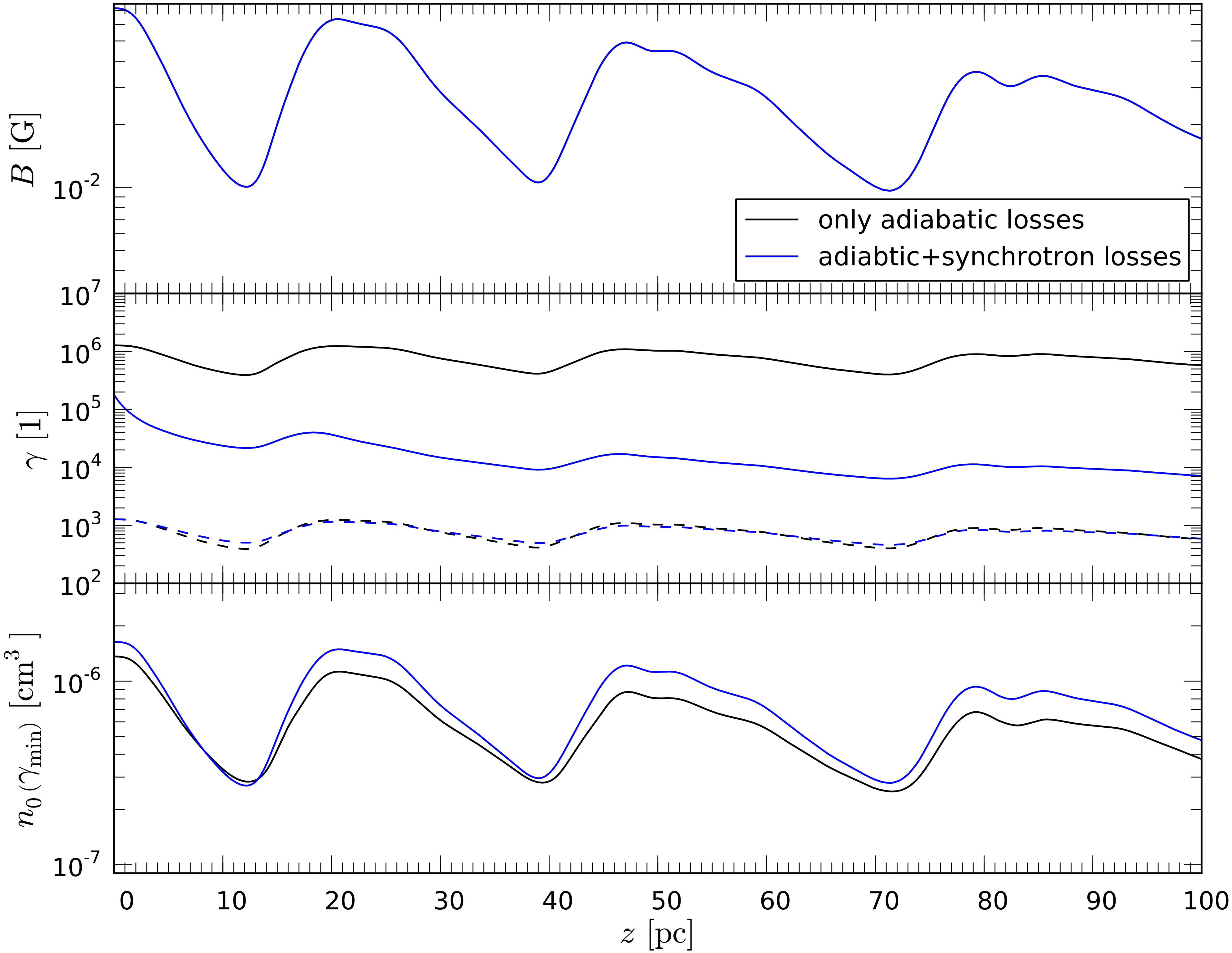
$n(\gamma) =$ … on

$B = \Big(\boxed{\epsilon_b}$ … d [G]

$\gamma_{\max} =$ … tz factor

$\gamma_{\min} =$ … tz factor

$n(\gamma_{\min})$ … ribution



(Mimica et al. 2010, Dermer & Boettcher 2010)

Emission Simulation

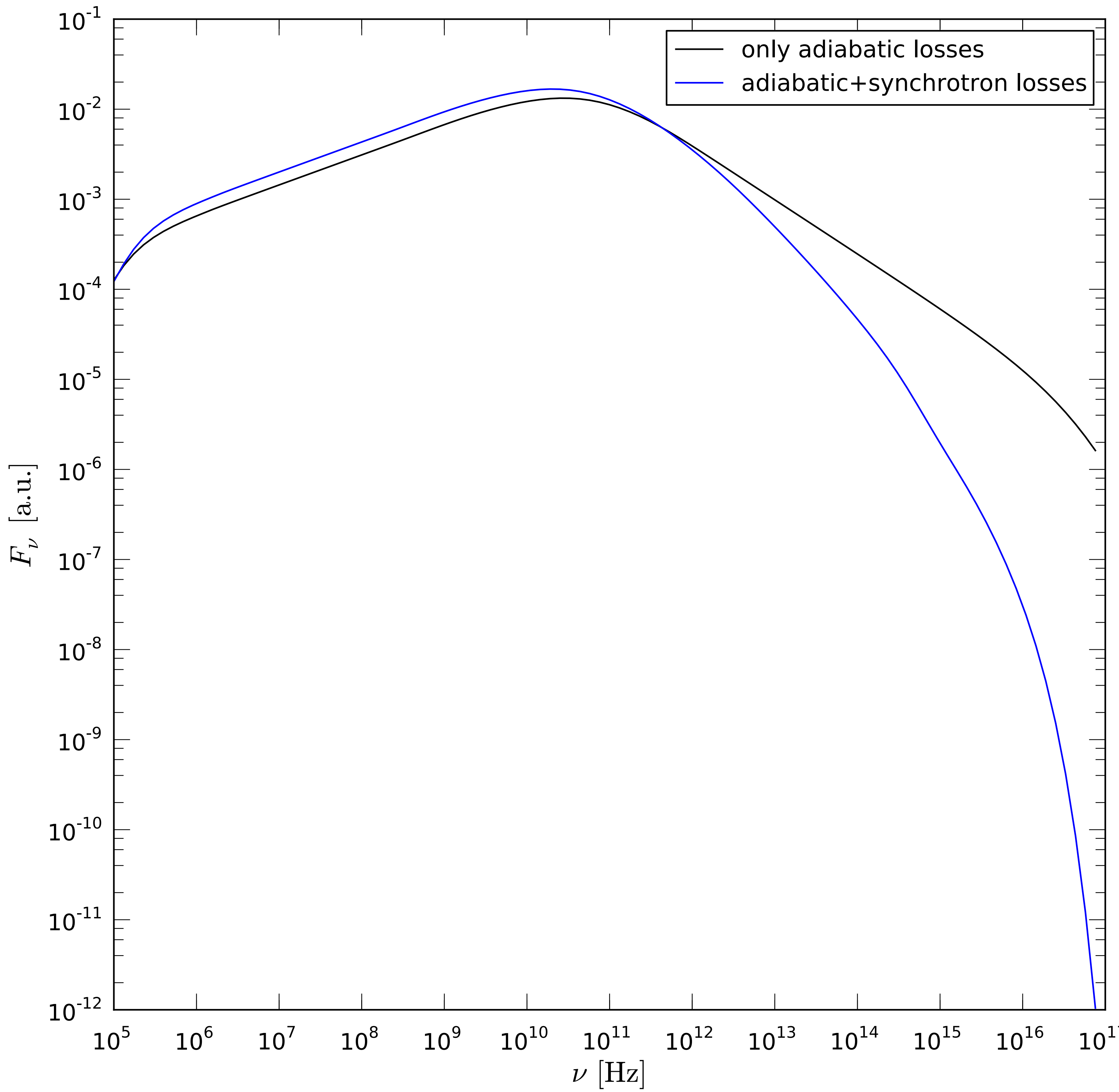
$n(\gamma) = n(\gamma_{\mathrm{n}}$ … stribution

$B = \Bigg(\boxed{\epsilon_b} \frac{8\pi p_t}{\widehat{\gamma} -}$ … etic field [G]

$\gamma_{\max} = \Bigg(\frac{9}{8\pi}$ … e- Lorentz factor

$\gamma_{\min} = \frac{\boxed{\epsilon}}{\rho_{th}(}$ … - Lorentz factor

$n(\gamma_{\min}) = \frac{}{(}$ … e- distribution



(Mimica et al. 2010, Dermer & Boettcher 2010)

Synchrotron Emission

$$n(\gamma) = n(\gamma_{\min}) \left(\frac{\gamma}{\gamma_{\min}} \right)^{-p}$$

e- distribution

$$j_{\rm syn}(\nu) = \frac{\sqrt{3} q^3 B \sin(\theta)}{4\pi m c^2} n(\gamma_{\min}) \gamma_{\min} H \left(\frac{\nu}{\nu_0 \gamma_{\min}^2}, p, \eta \right) ,$$

emission coeff

$$\alpha_{\rm syn}(\nu) = \frac{\sqrt{3} q^3 B \sin(\theta)}{8\pi m^2 c^2} n(\gamma_{\min}) \frac{p+2}{\nu^2} H \left(\frac{\nu}{\nu_0 \gamma_{\min}^2}, p+1, \eta \right)$$

absorption coeff

$$H(x, p, \eta) = \frac{1}{2} x^{(1-p)/2} \int\limits_{x/\eta^2}^{x} \mathrm{d}\xi \, \xi^{(p-3)/2} \, F(\xi)$$

$$F(x) = x \int_x^\infty d\xi K_{5/3}(\xi)$$

ordered mag. field:

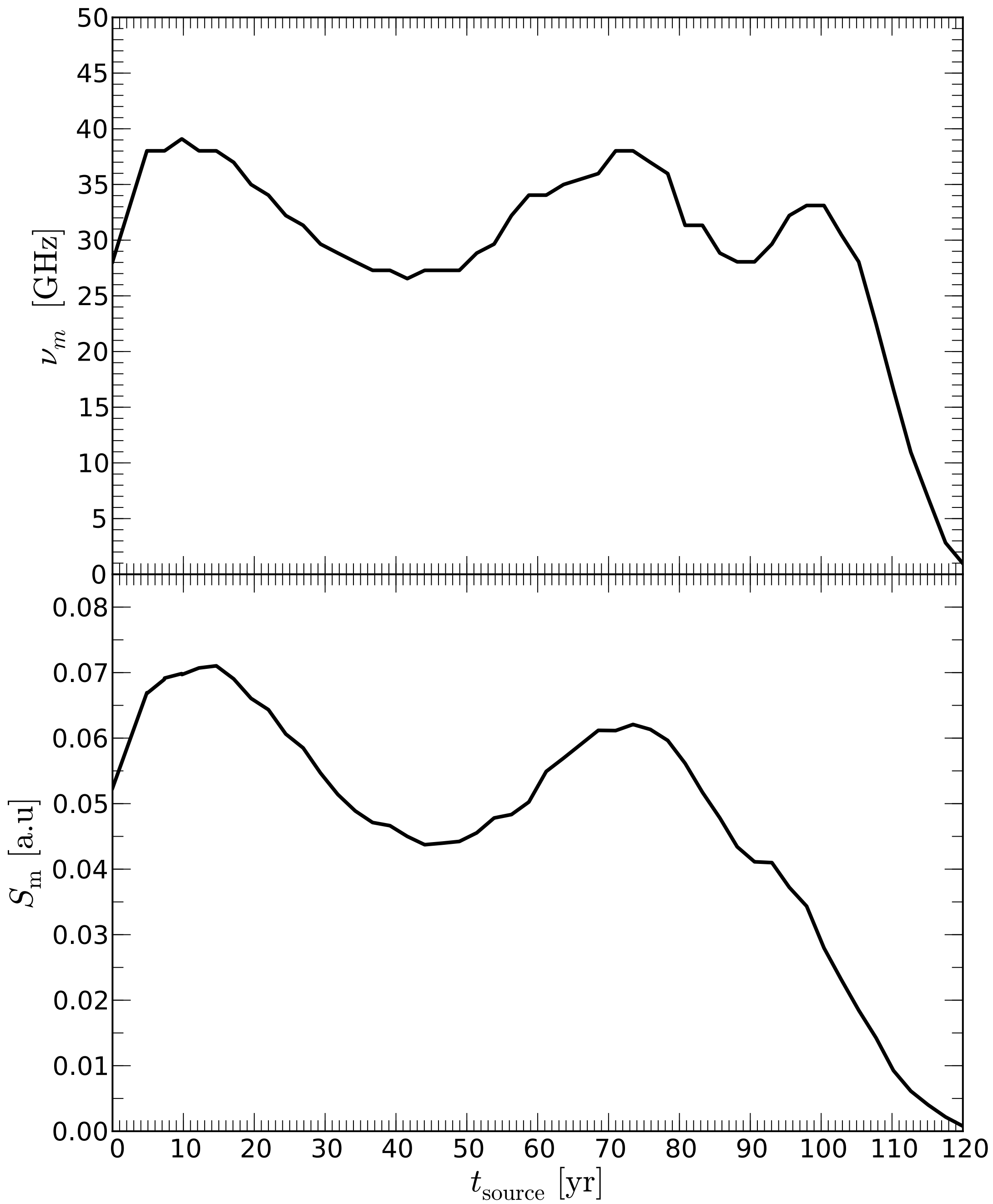
$$R(x) = \frac{1}{2} \int_0^\pi d\alpha \sin^2 \alpha F \left(\frac{x}{\sin \alpha} \right)$$

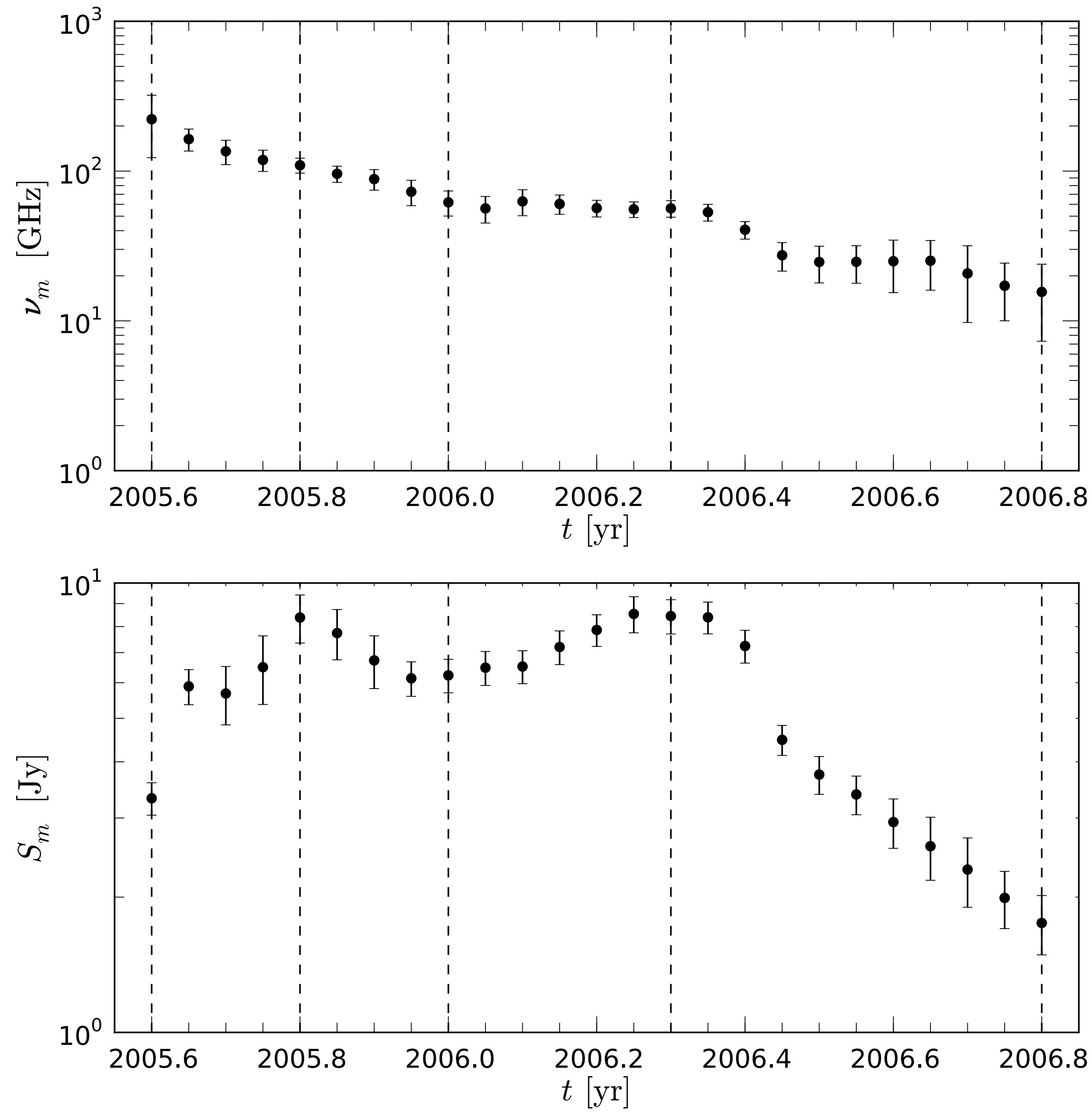
random mag. field:

(Mimica et al. 2009)

Shock-Shock interaction

Single Dish spectral evolution





Ref: Fromm et al. 2011, Fromm in prep.

Kelvin-Helmholtz Instabilities