MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Radioastronomie

Recollimation Shocks in parsec-scale Jets

-observations and simulations-

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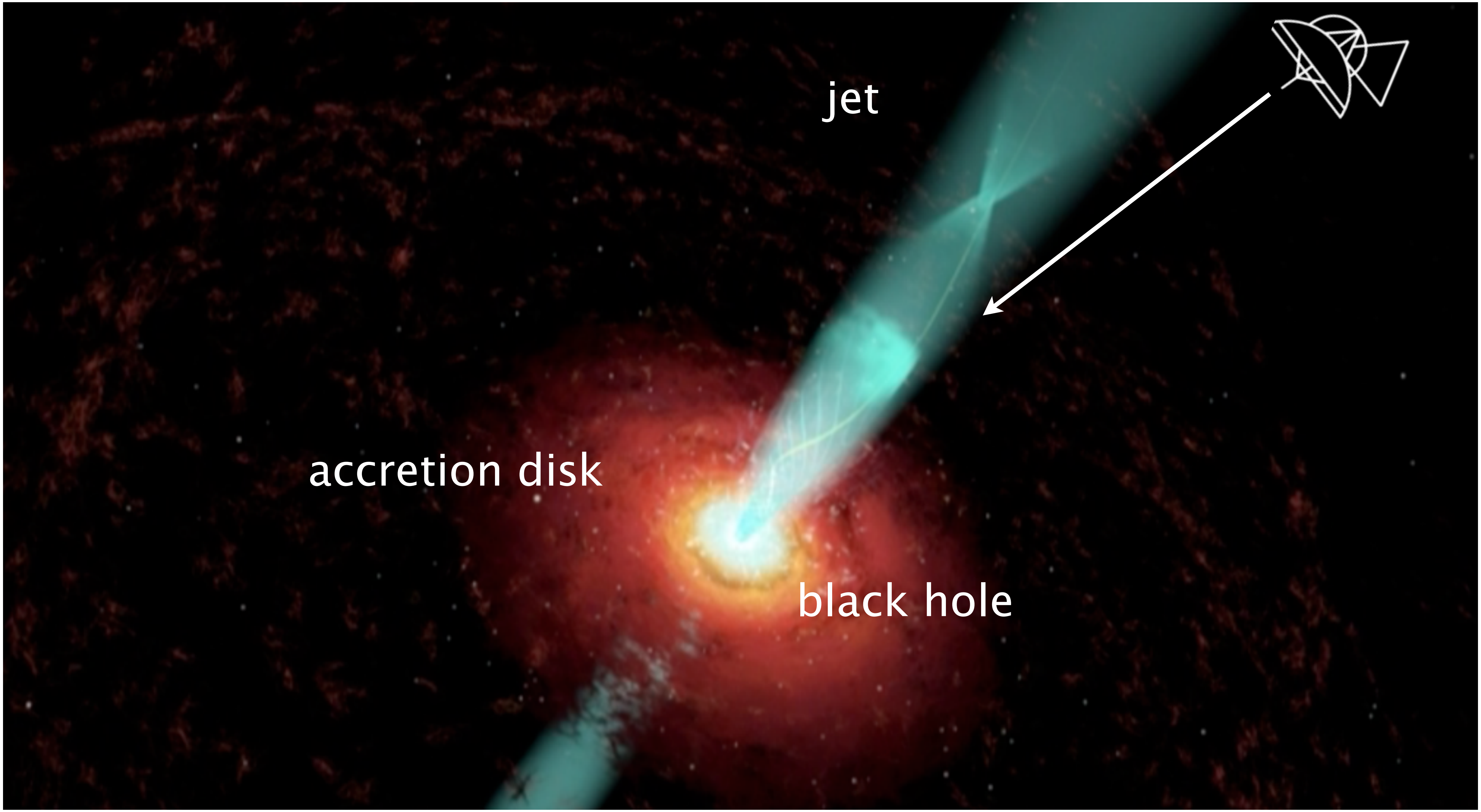
IMPRS astronomy & astrophysics Bonn and Cologne

Outline

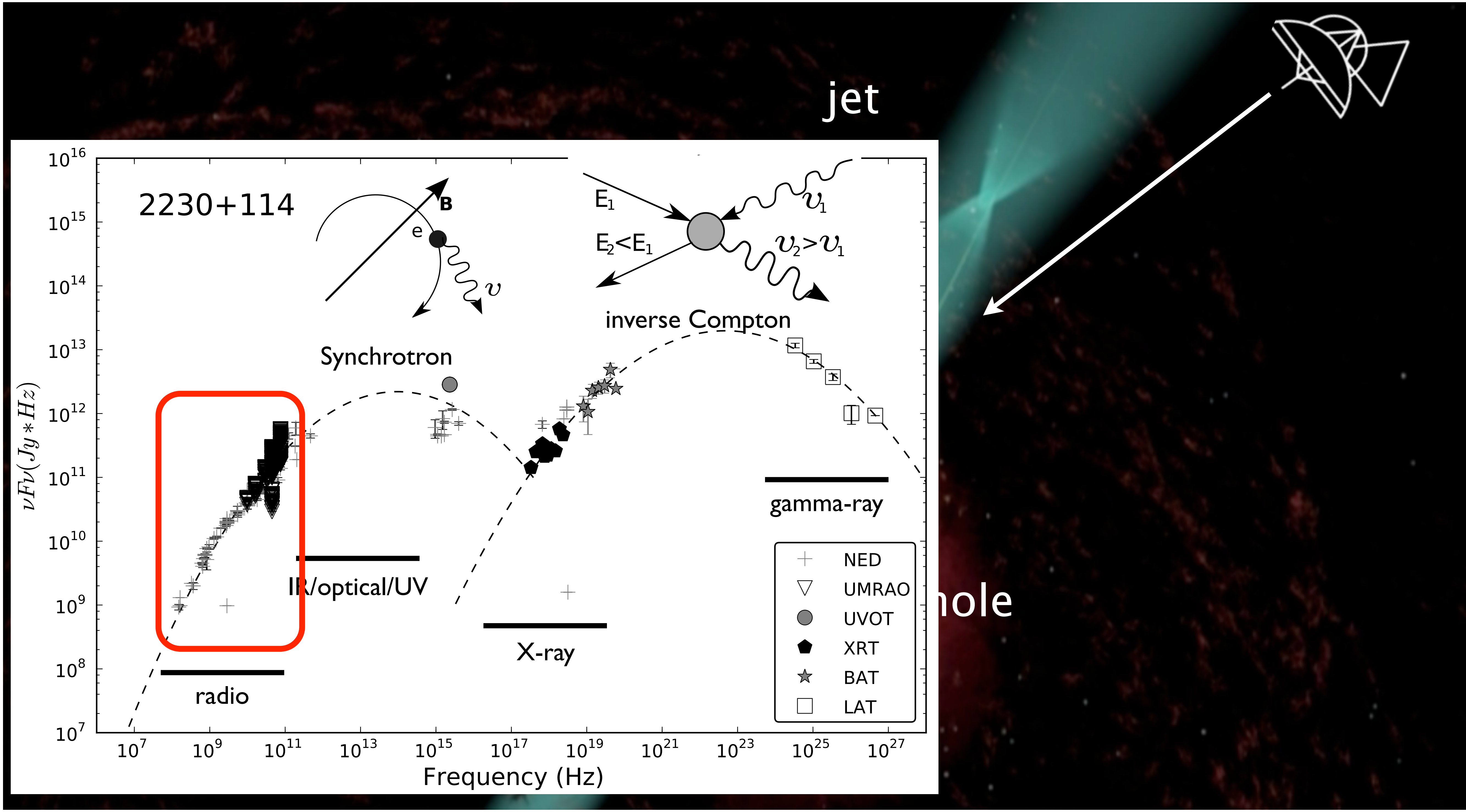
- Introduction
- Observations
- Simulations
- Summary and Outlook

Introduction



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

Introduction

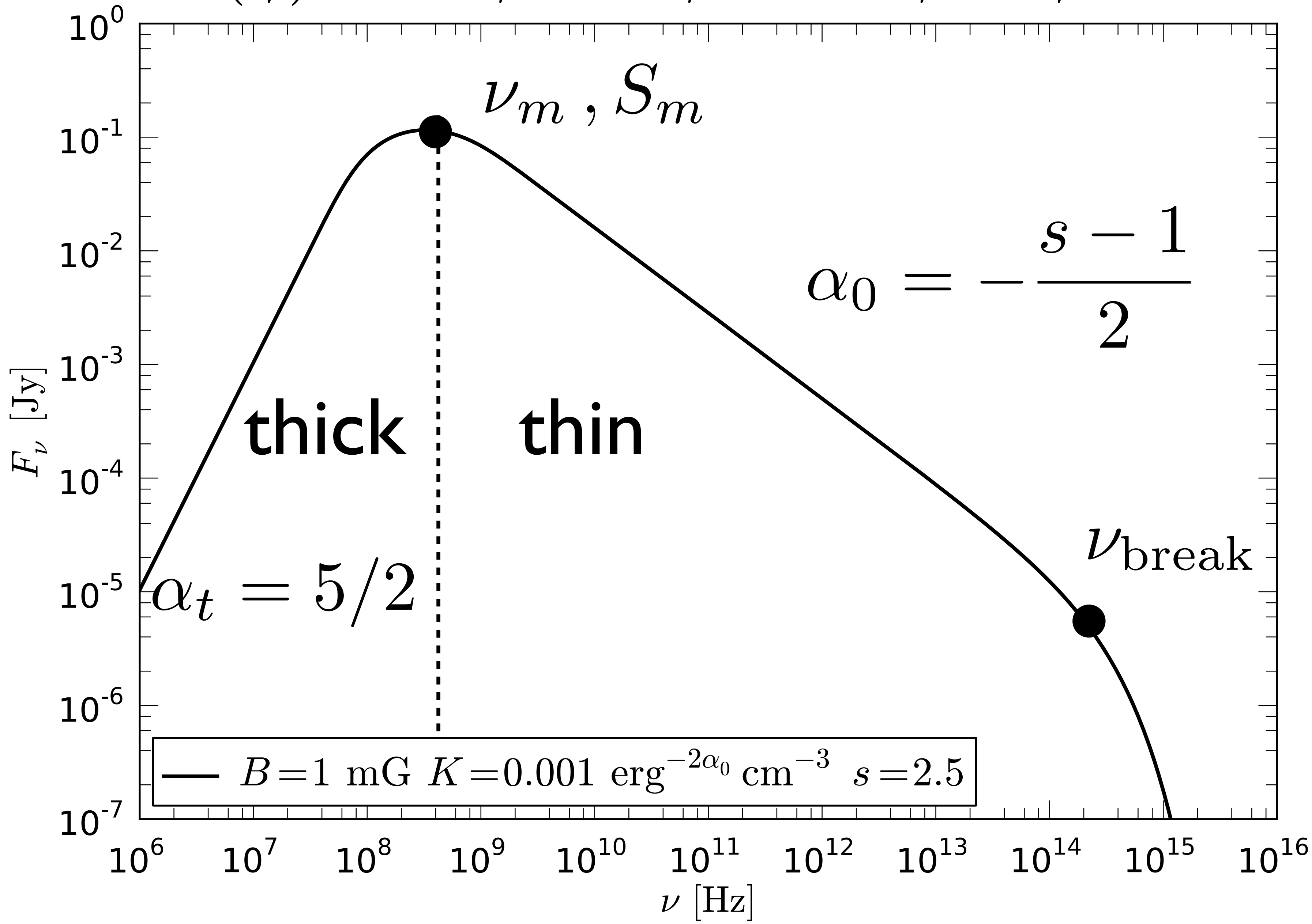


Ref: Cosmovision, W. Steffen, Chang et al. 2011

Synchrotron Radiation

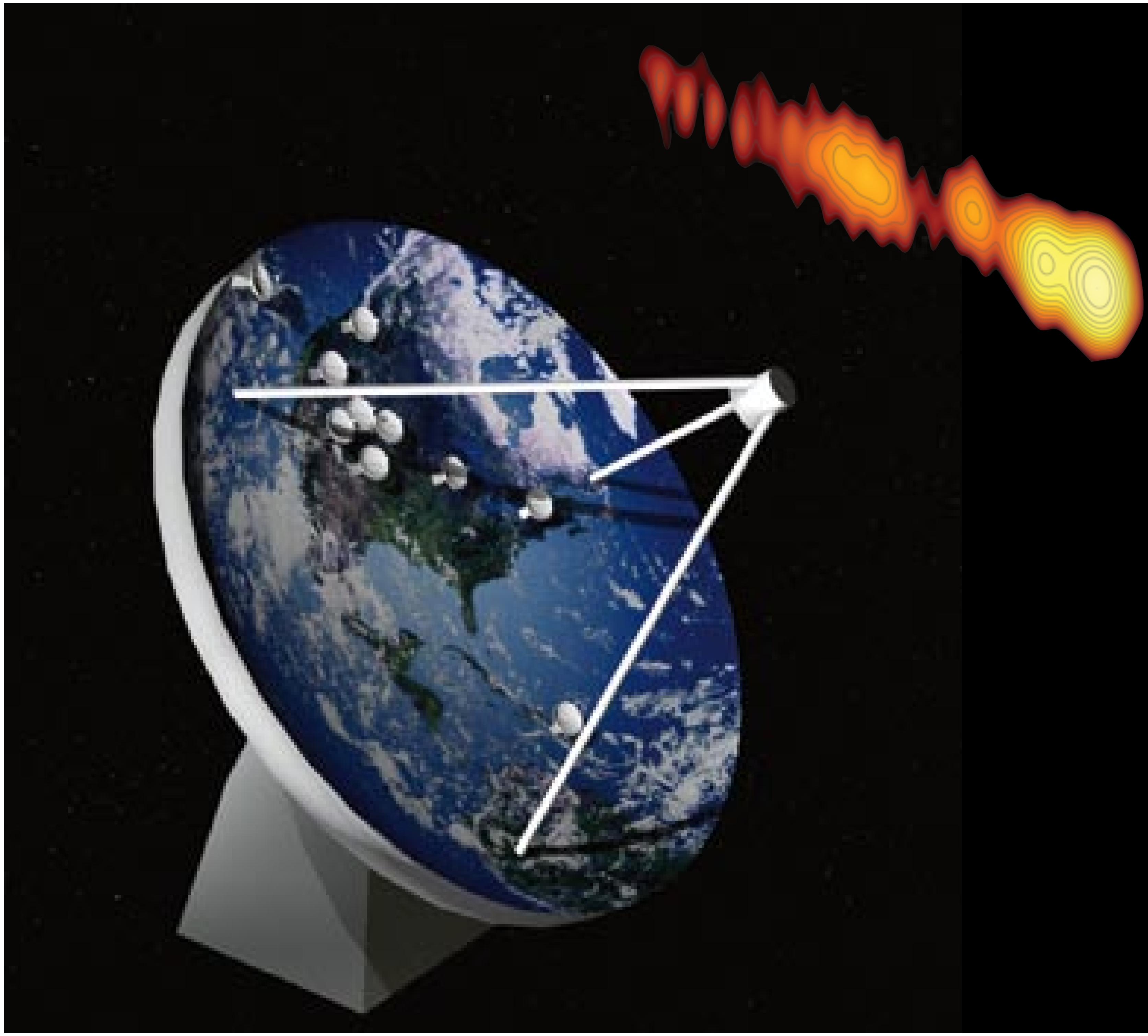
rel. electrons + mag. field => Synchrotron radiation

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



→ extract $B \propto \nu_m^5 S_m^{-2}$ and $K \propto \nu_m^{-(2s+3)} S_m^{s+2}$

VLBI Observations



MOJAVE:

VLBA@15GHz
>100 sources
since 1994
bi-monthly

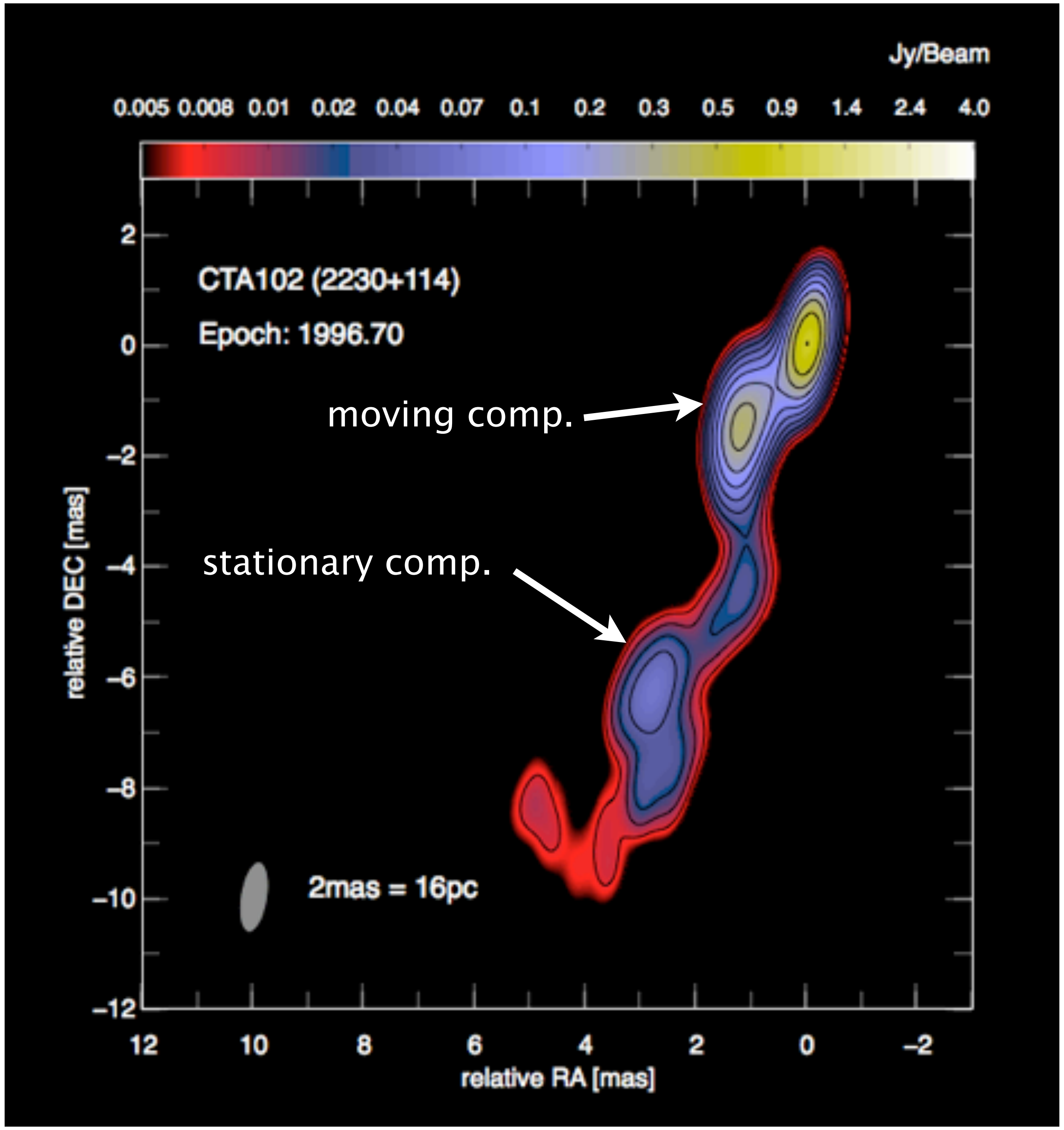
BU Blazar:

VLBA@43GHz
>30 sources
since 2007
monthly

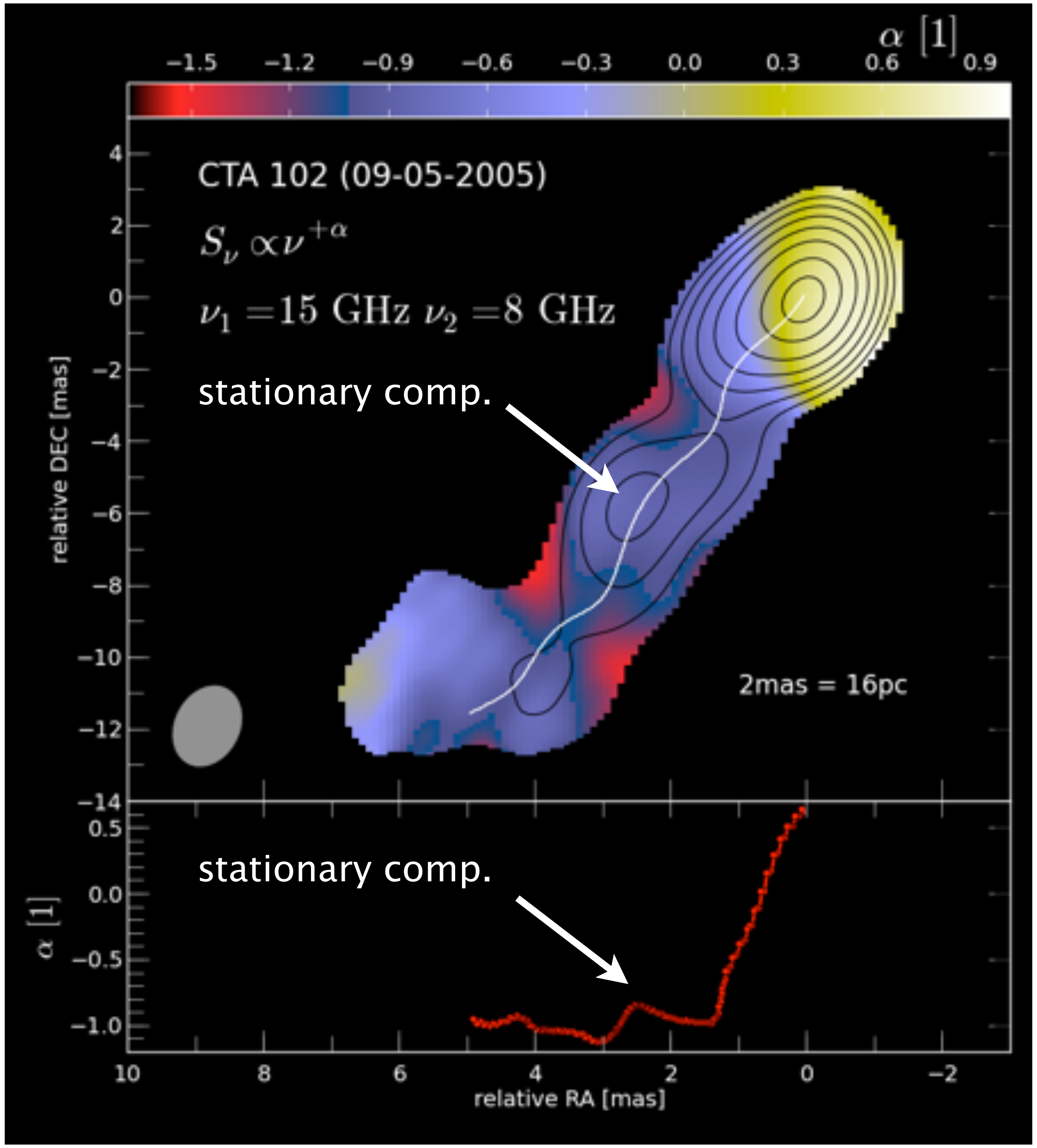
Ref: Gomez et al. 2009, Fromm et al. 2009, Lister et al. 2009, Marscher et al. 2010

VLBI observations

15GHz Monitoring
(macro-physics)

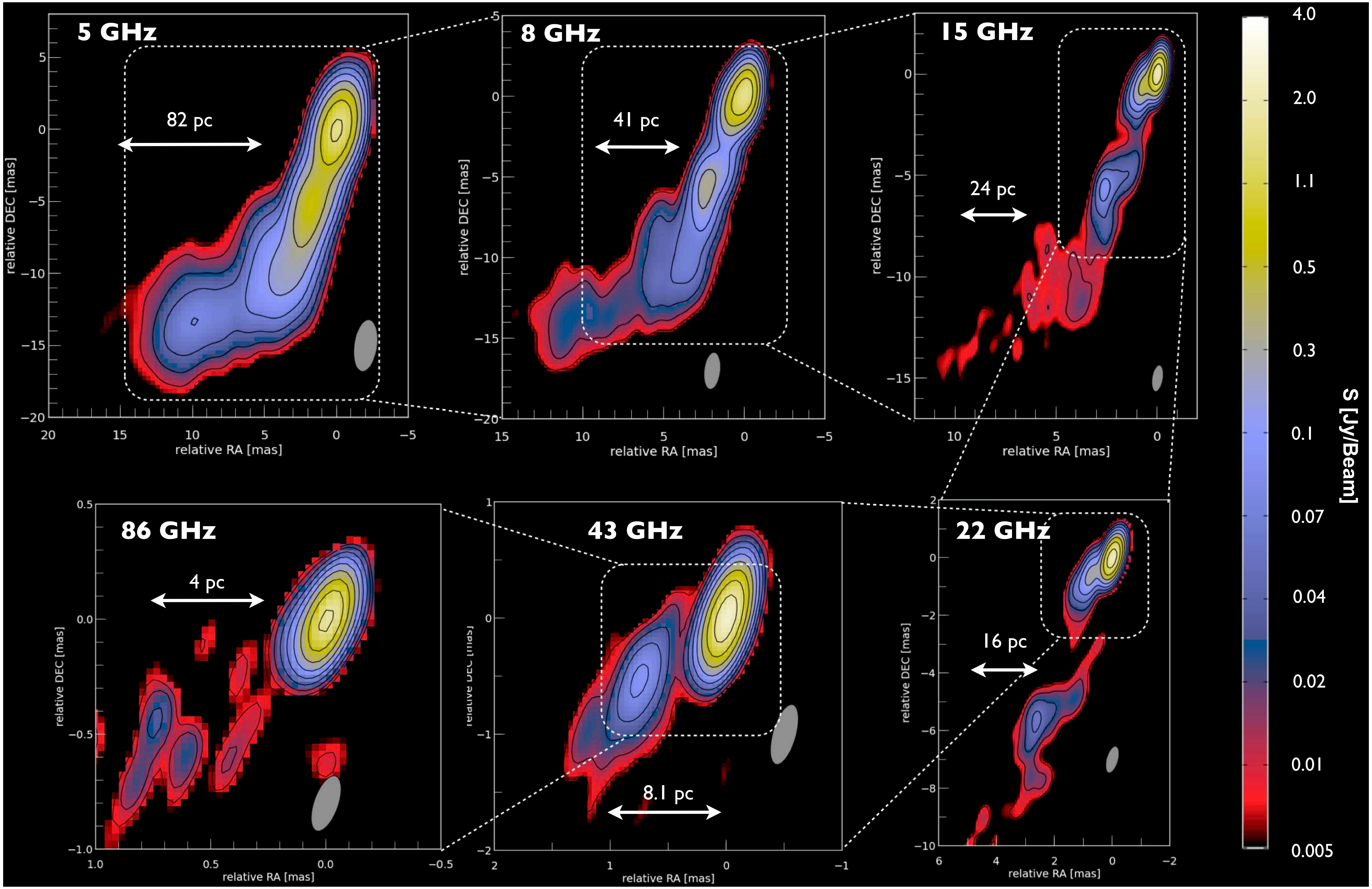


Multi-frequency
(micro-physics)



Ref: Lister et al. 2009, Fromm et al. 2013a, 2013b

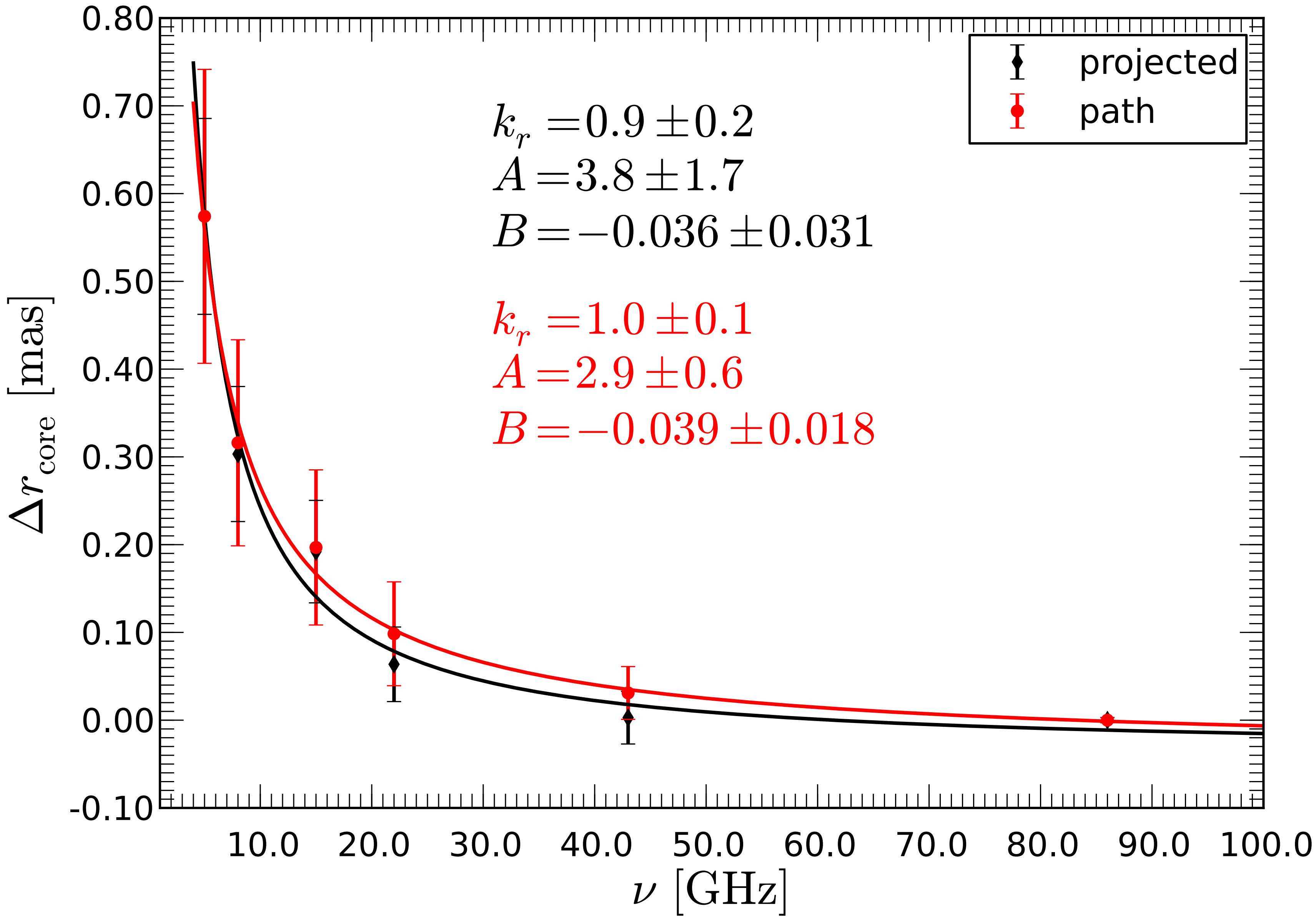
VLBI observations



Ref: Fromm et al. 2014

VLBI observations

estimate for the distance to the black hole

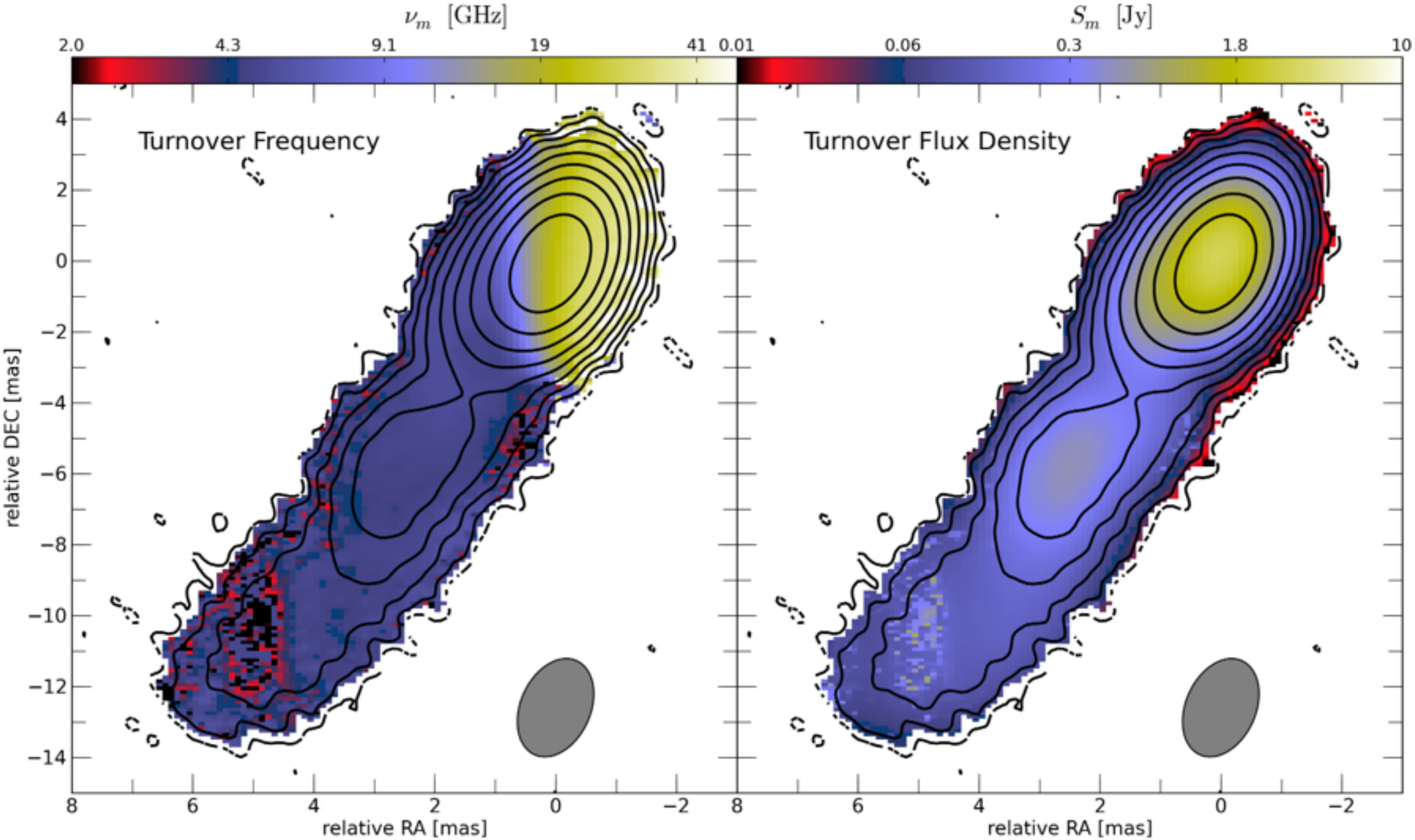


$$r_{\rm BH} \sim 7\,{\rm pc}\,\left(8.5 \times 10^5 R_s \text{ for } M_{\rm BH} = 10^{8.93} M_\odot\right)$$

Ref: Fromm et al. 2014

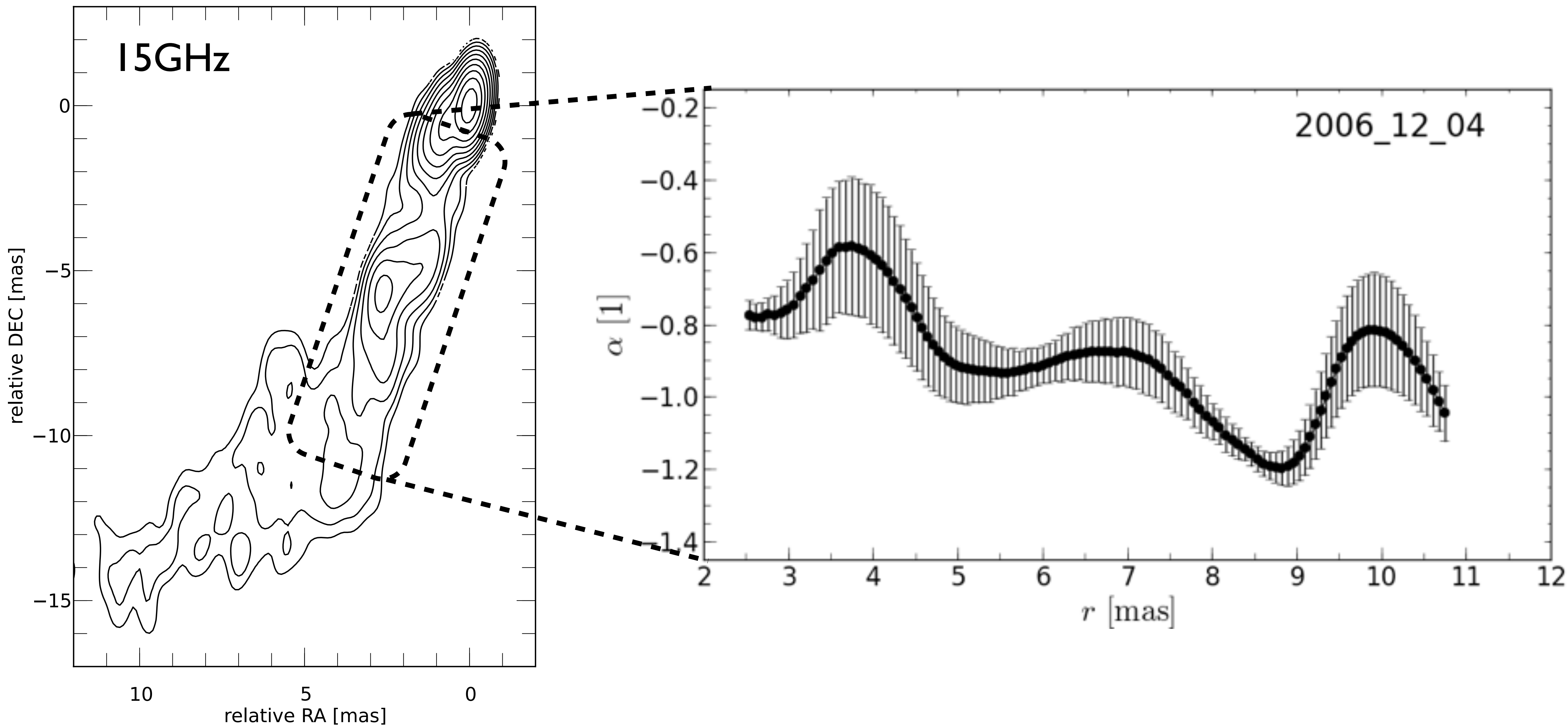
VLBI observations

$$S_\nu \approx S_m \left(\frac{\nu}{\nu_m}\right)^{\alpha_t} \frac{1-\exp\left(-\tau_m \left(\nu/\nu_m\right)^{\alpha_0-\alpha_t}\right)}{1-\exp\left(-\tau_m\right)}$$



Ref: Fromm et al. 2013b

VLBI observations



$$B \propto \nu_m^5 S_m^{-2}$$

$$K \propto \nu_m^{-(2s+3)} S_m^{s+2}$$

+ energy losses ➡ $N_{\rm tot}$, $U_{\rm re}$, $\sigma = B^2/(8\pi U_{\rm re})$

Ref: Fromm et al. 2013b

Physical parameters from observations

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 $\gamma_{\mathrm{min}} = 1$ $\gamma_{\mathrm{max}} = 1 \times 10^5$

distance to black hole

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

$$r_{\mathrm{BH}} \sim 7\,\mathrm{pc}\,\left(8.5 \times 10^5 R_s\right)$$

Ref: Fromm et al. 2013a, 2013b

Simulation of parsec-scale Jets

Relate observed emission structure to **radiation microphysics** and **macroscopic dynamics**

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

→

relativistic hydrodynamics

(Perucho & Marti 2004)

+

emission calculations

(Fromm 2013)

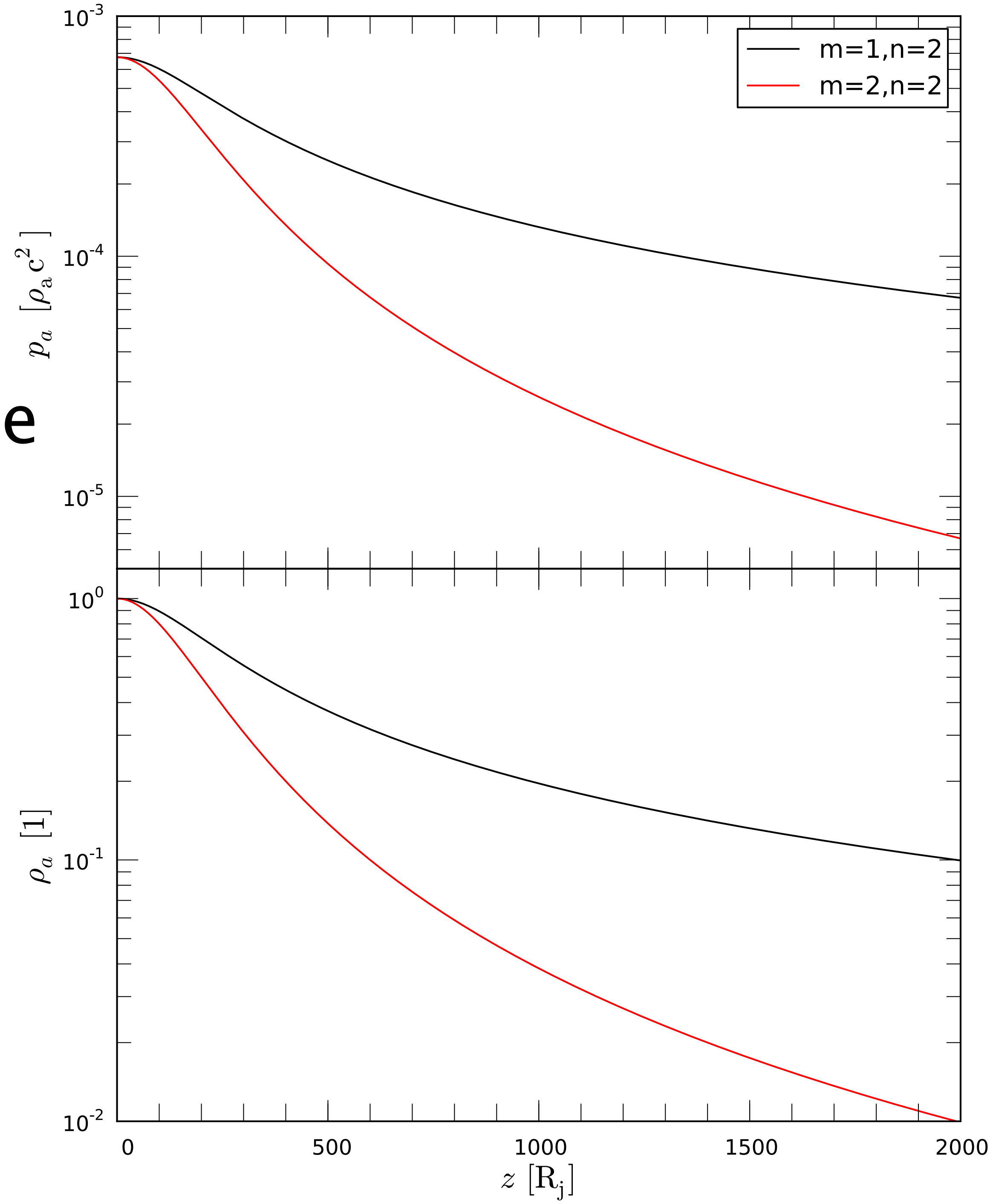
Simulation of parsec-scale Jets

initial parameters

grid: 100×8000 cells (low res.)

640×12800 cells (high res.)

ambient medium: decreasing pressure

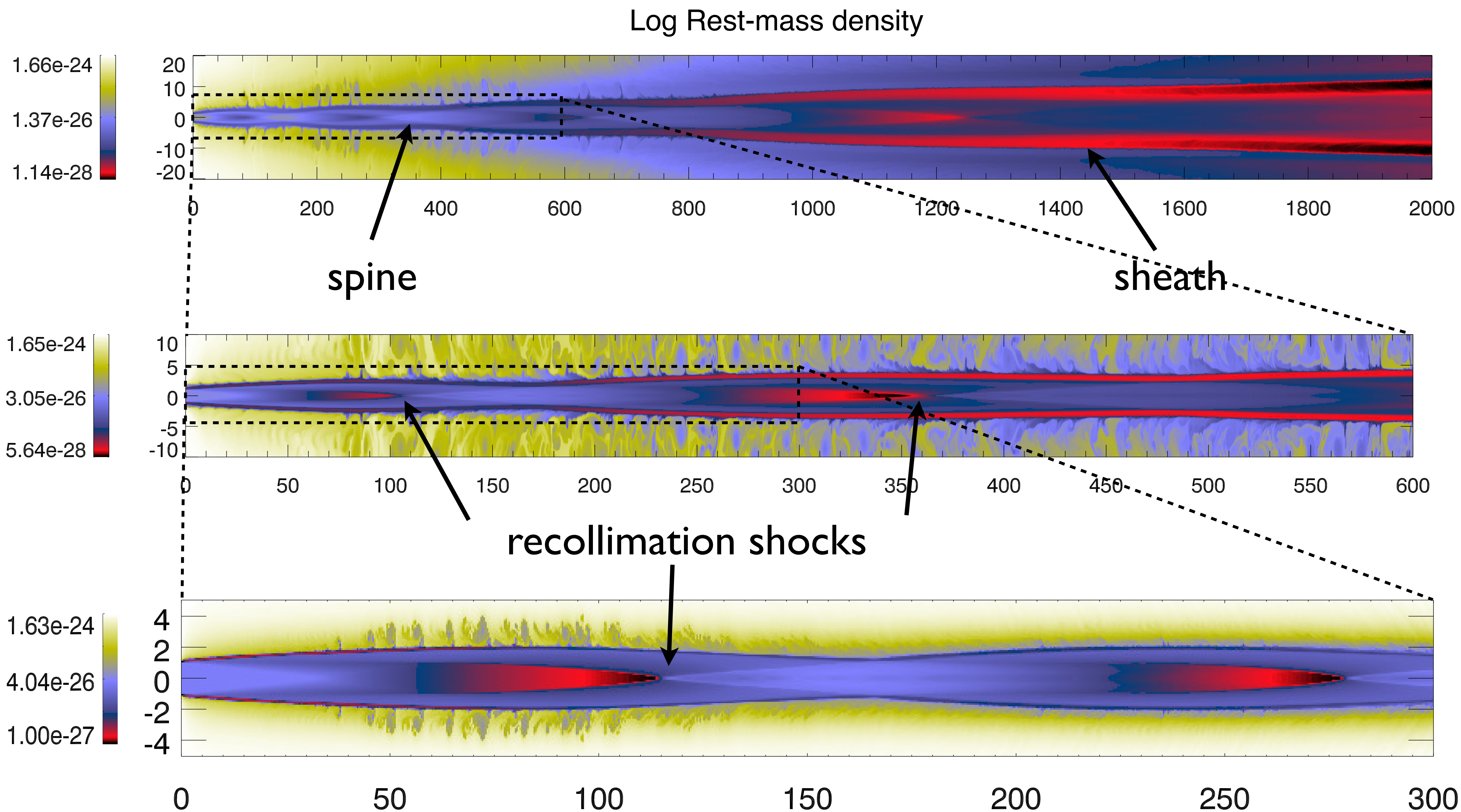


Kings' profile: $$p_a(z) = \frac{p_j}{d_k}\left[1 + \left(\frac{z}{z_c}\right)^n\right]^{\frac{m}{n}}$$

jet:

d_k	Γ	ρ_j	p_j	M	$\hat{\gamma}$
3	12	0.02	0.002	3.0	13/9

RHD Simulation (thermal particles)



Ref: Fromm PhD, Fromm in prep.

Emission Simulation

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

e- distribution

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

magnetic field [G]

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

max e- Lorentz factor

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

min e- Lorentz factor

Ref: Mimica et al. (2009, 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]

$$0 < \epsilon_e < 1$$
$$0 < \epsilon_b < 1$$
$$1e3 < \epsilon_a < 1e6$$

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

max e- Lorentz factor

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

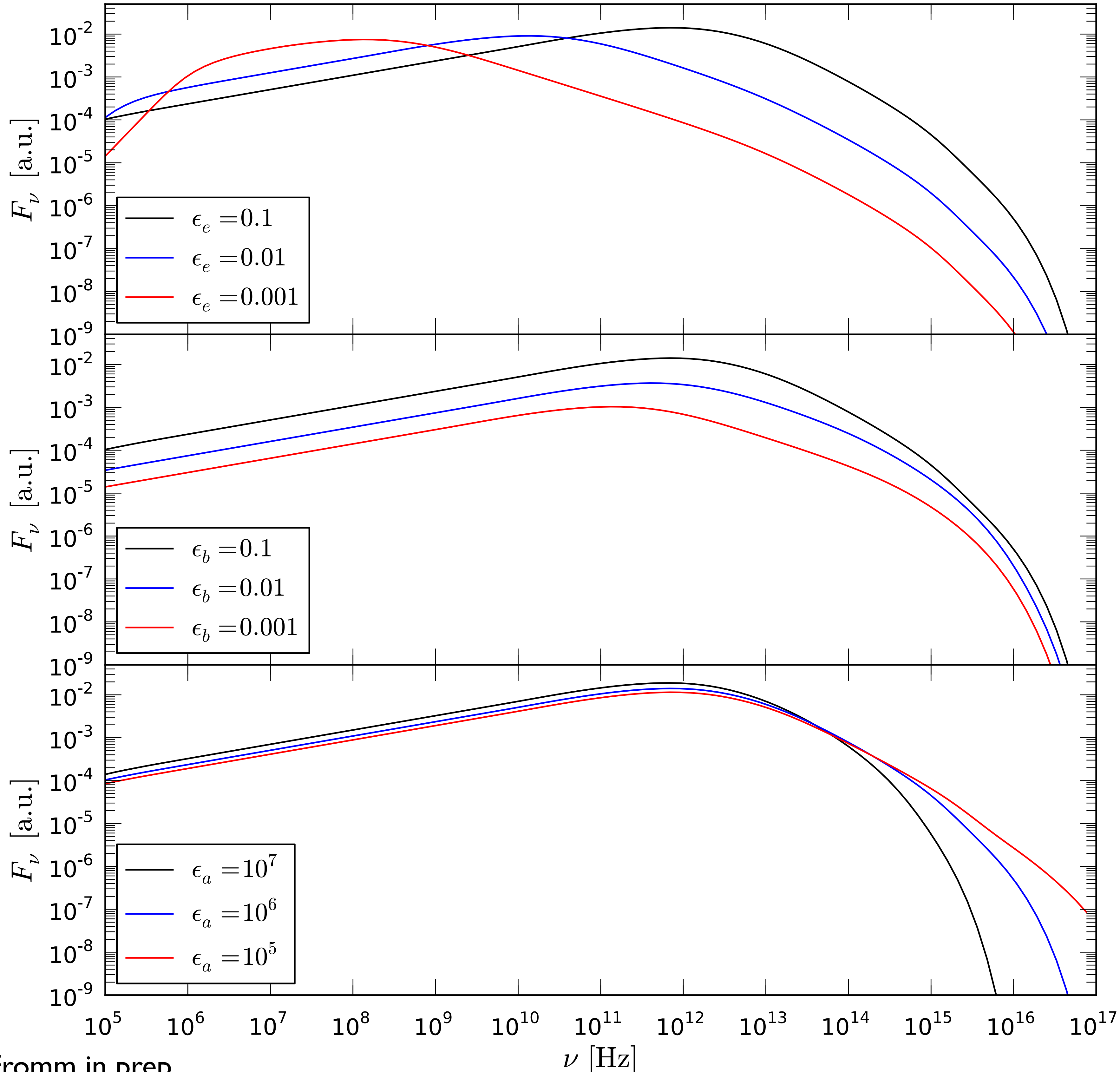
min e- Lorentz factor

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

coeff. e- distribution

Ref: Mimica et al. (2009, 2010), Dermer & Boettcher (2010)

Emission Simulation



Ref: Fromm PhD 2013, Fromm in prep.

Emission Simulation

evolution of e– Lorentz factor (see Mimica et al. 2009)

$$\frac{d\gamma}{d\sigma} = k_a\gamma - k_s\gamma^2$$

adiabatic losses radiative losses

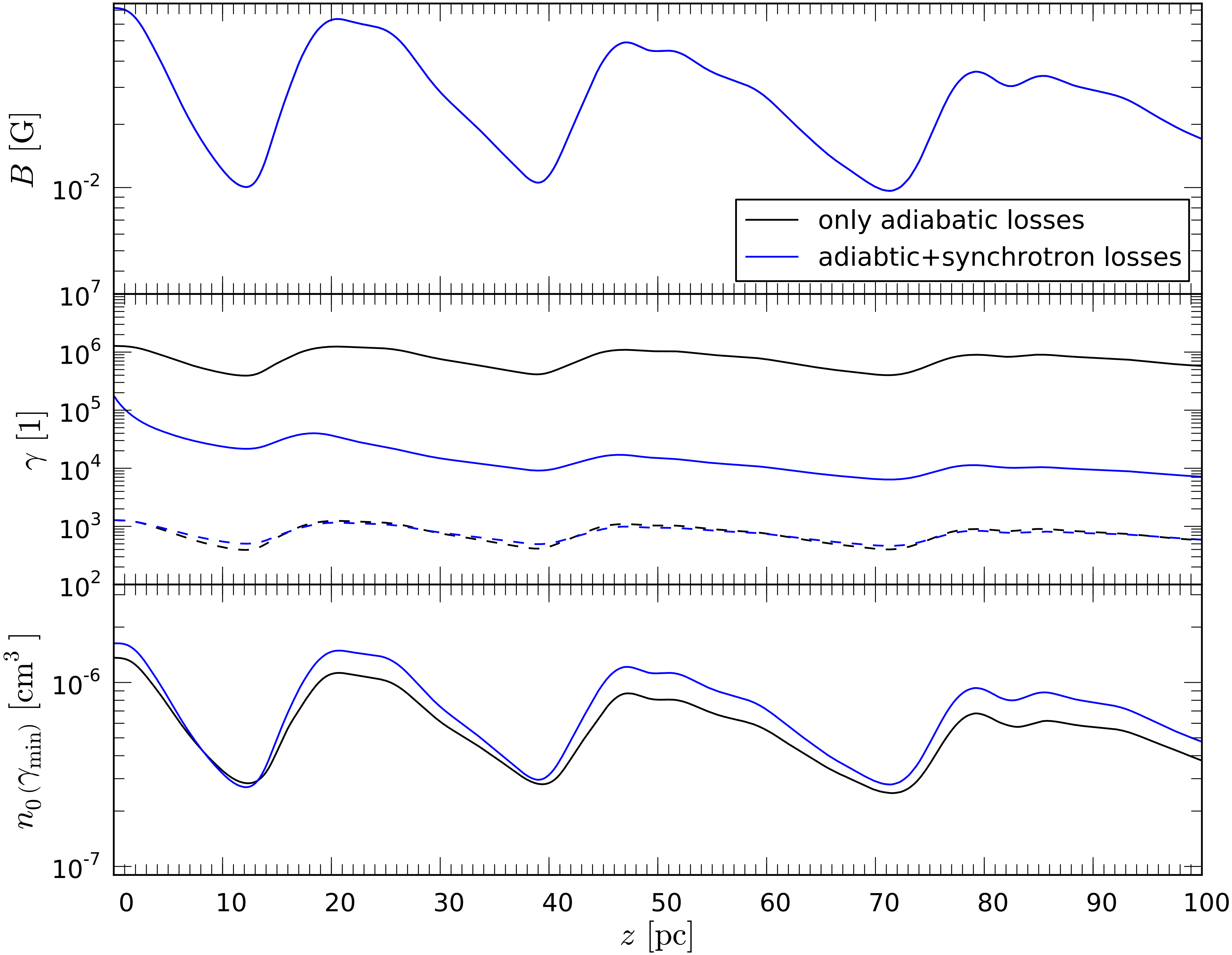
$$k_a = \frac{1}{3}\frac{dln\rho_j}{d\sigma} \qquad k_s = \frac{2}{3}\frac{e^4}{8\pi m_e^3 c^5}B^2$$

e–Lorentz factor: $$\gamma(\sigma) = \gamma_0 \frac{k_a e^{k_a \Delta\sigma}}{k_a + \gamma_0 k_s \left(e^{k_a\Delta\sigma} - 1\right)}$$

coeff. e– distr. $$n_0(\gamma(\sigma)) = n_0\left(\gamma_0\right)\left[e^{k_a\Delta_\sigma}\left(1 + \gamma_0\frac{k_s}{k_a}\left(e^{k_a\Delta\sigma} - 1\right)\right)\right]^2$$

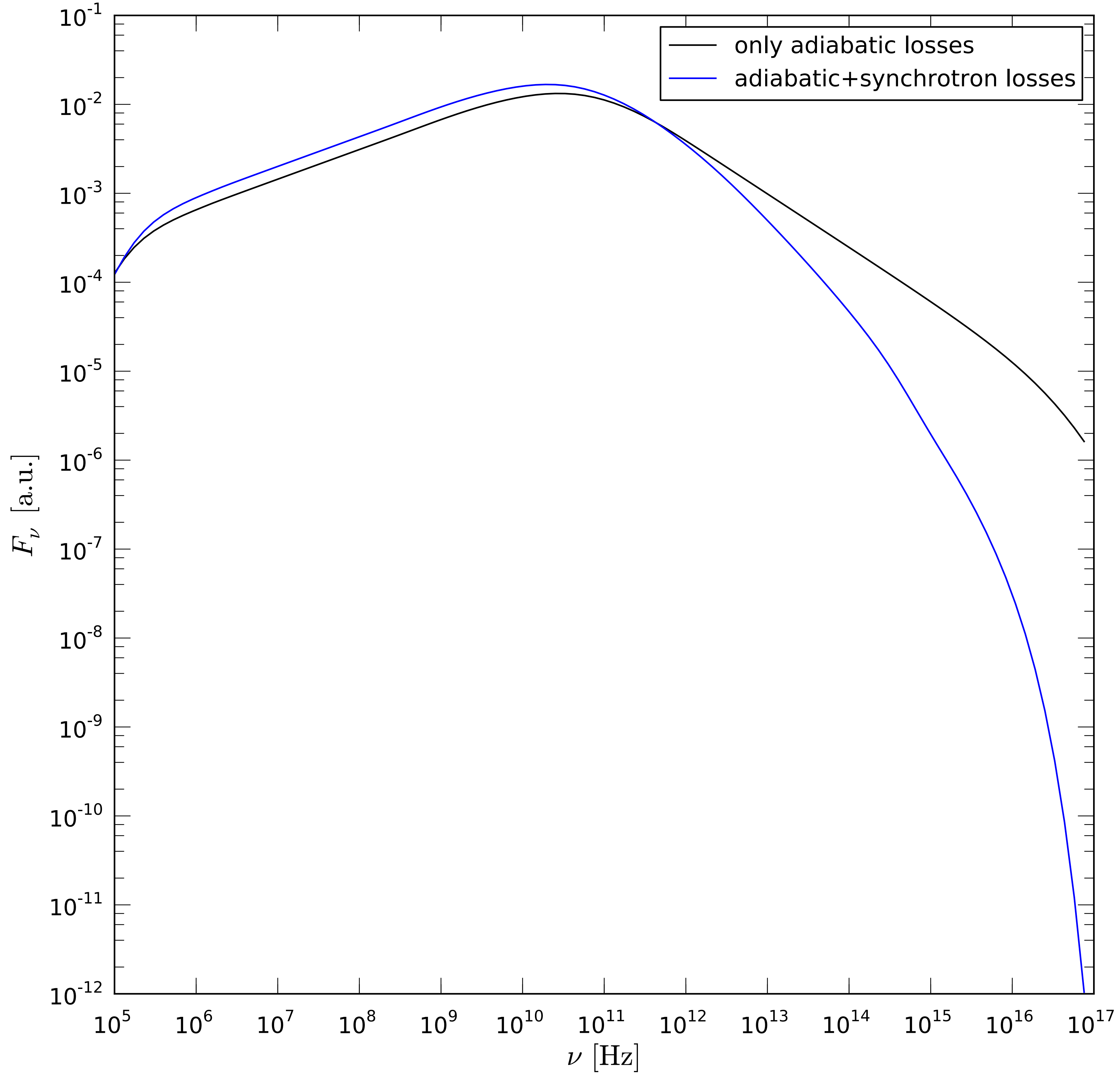
Ref: Mimica et al. (2009, 2010)

Emission Simulation



Ref: Mimica et al. (2009, 2010), Fromm PhD 2013

Emission Simulation

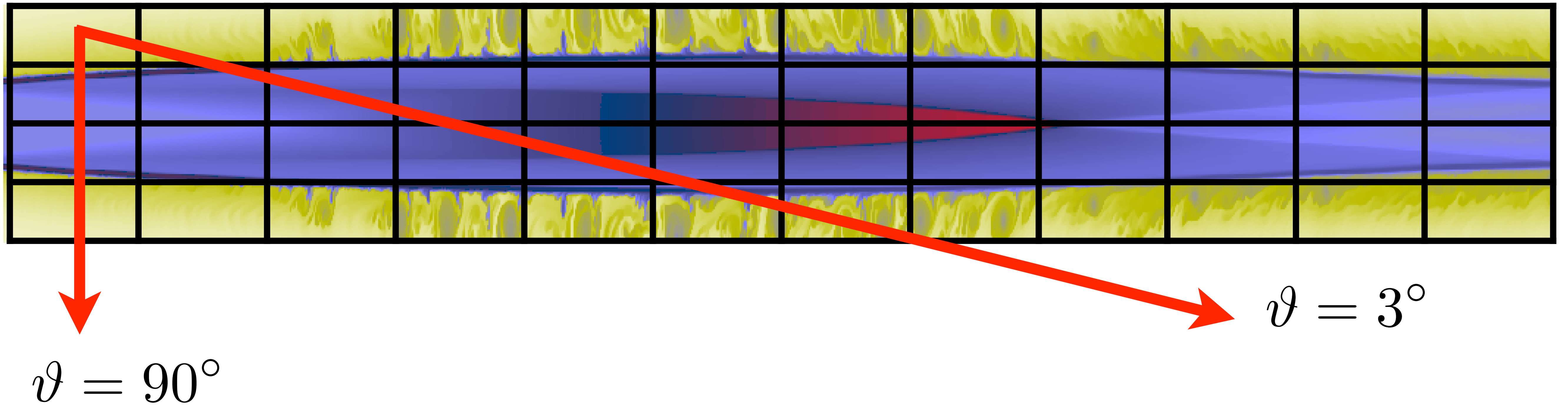


Ref: Mimica et al. (2009, 2010), Fromm PhD 2013

Radiative transfer (ray tracing)

include Micro-physics: absorption, emission and losses

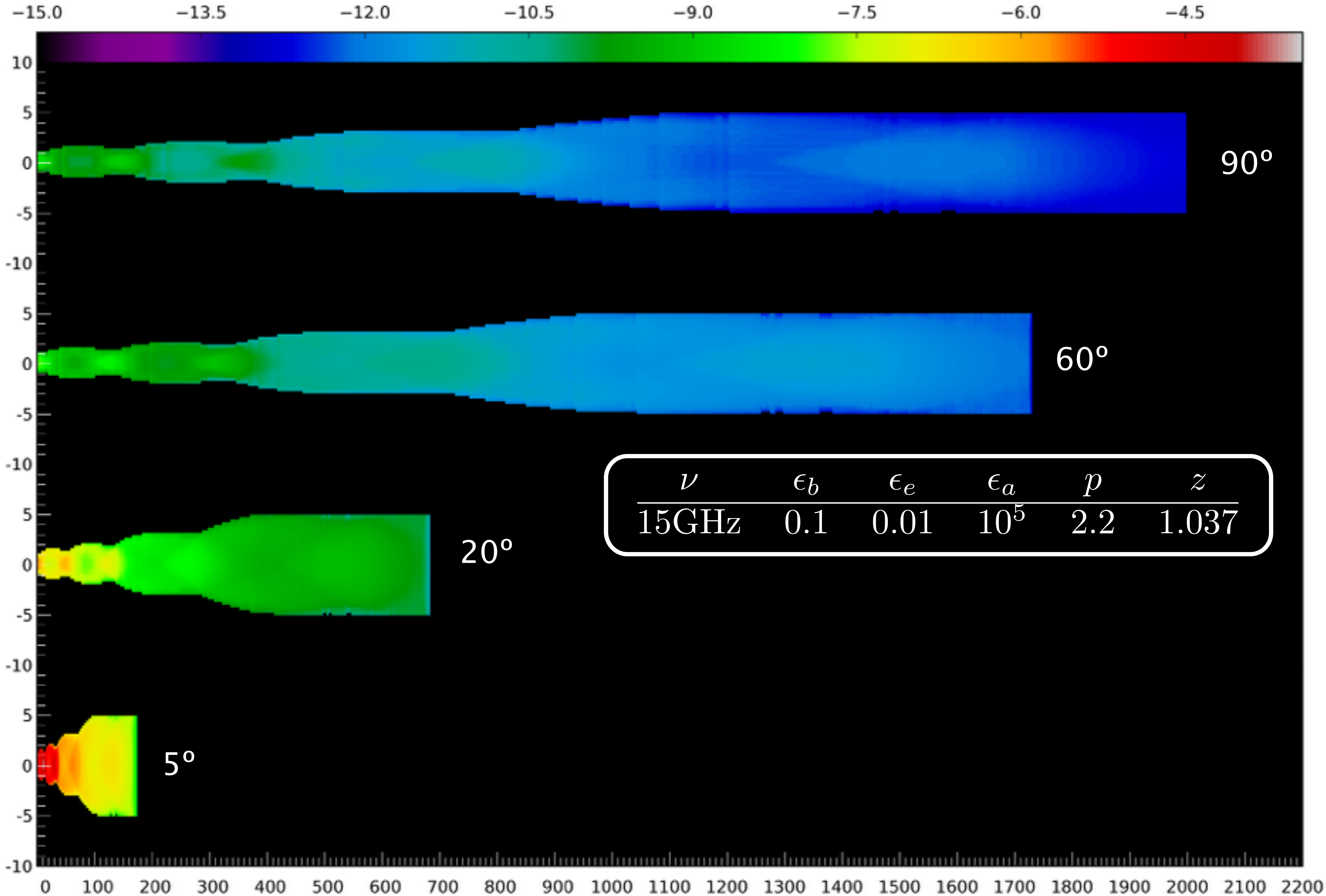
using 3D ray-tracing technique and large frequency range



→ entire synchrotron spectrum at each pixel

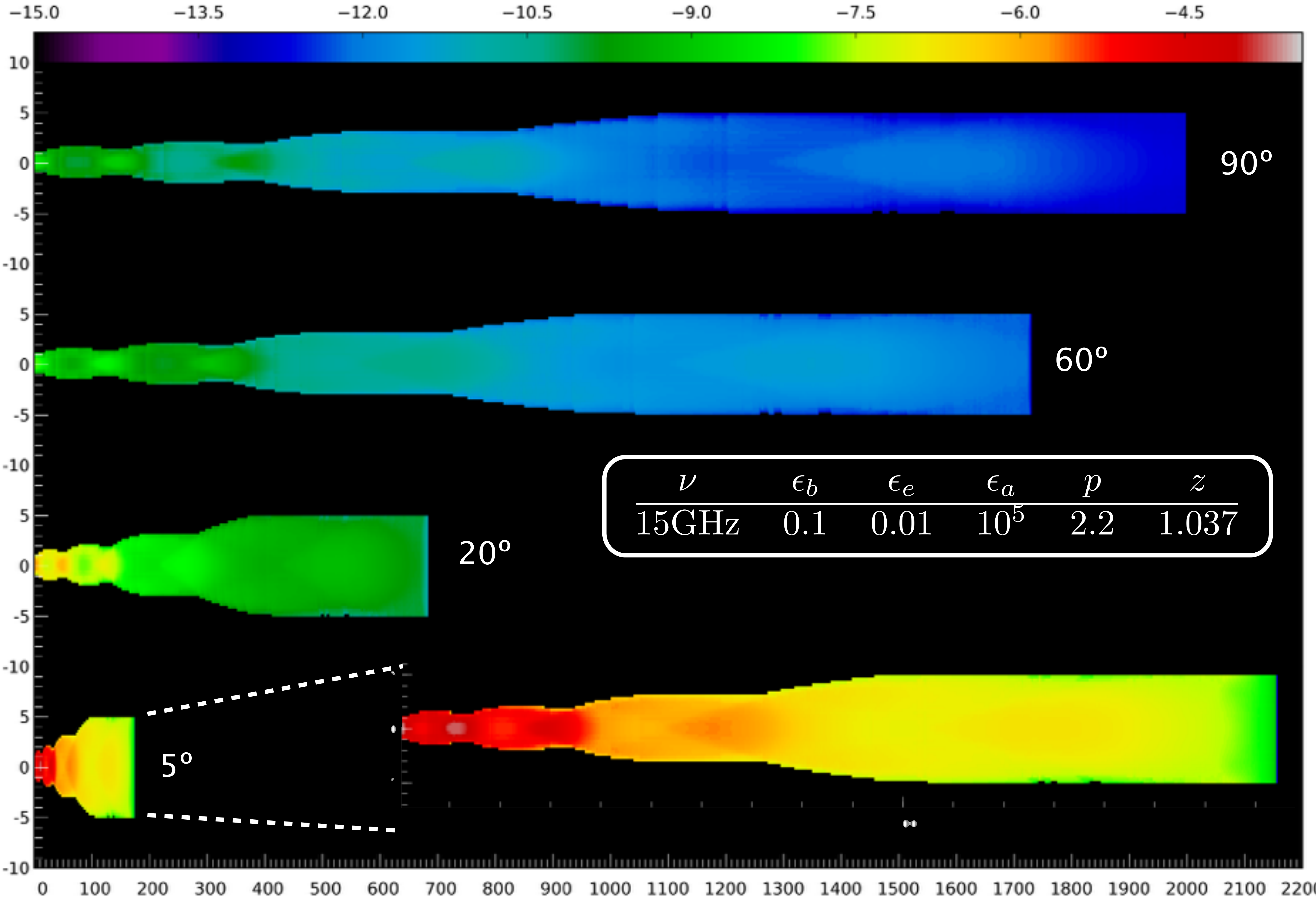
Ref: Mimica et al. 2009, Fromm et al. 2013, 2014

Emission Simulation



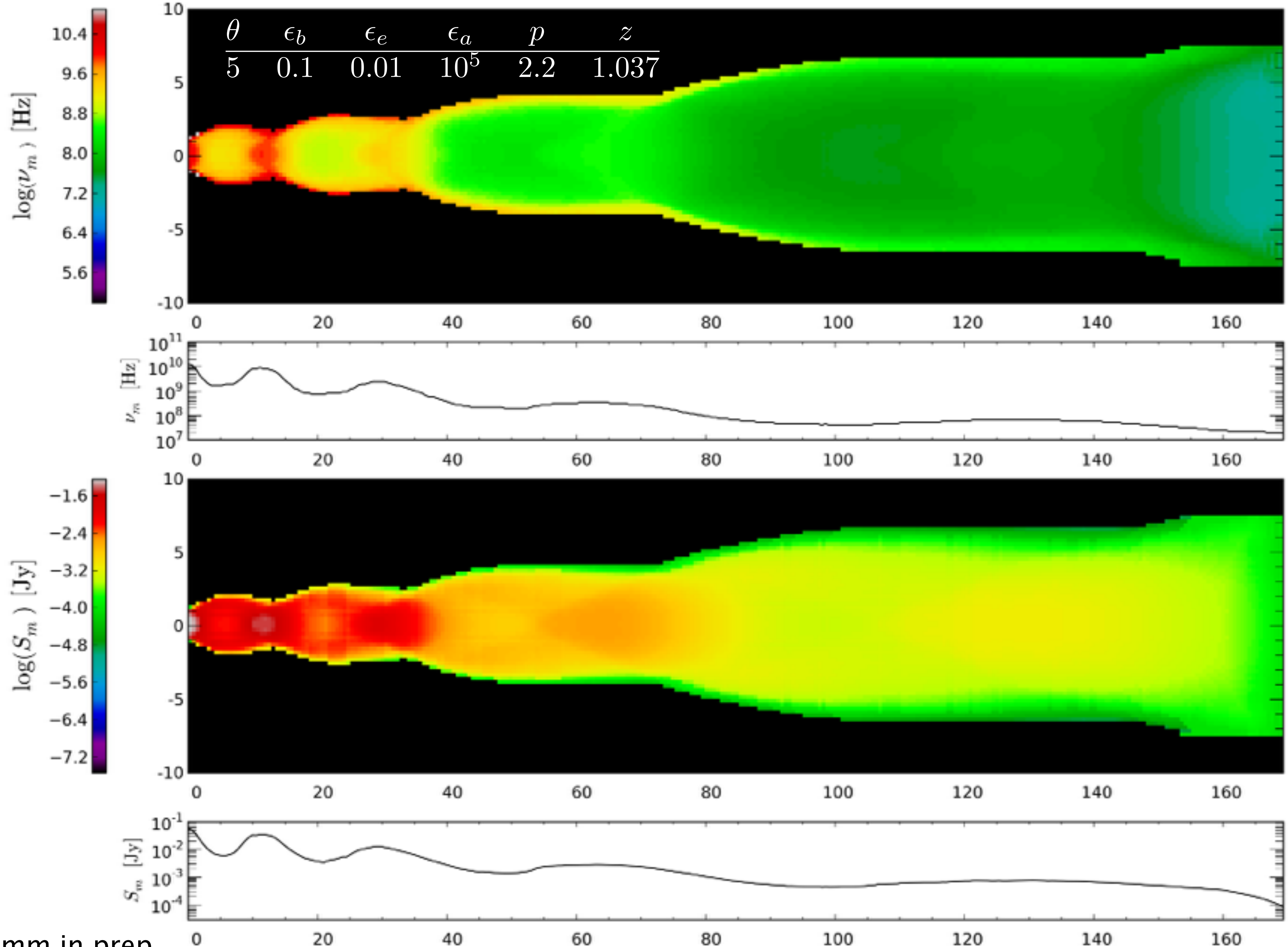
ν	ϵ_b	ϵ_e	ϵ_a	p	z
15GHz	0.1	0.01	10^5	2.2	1.037

Emission Simulation



ν	ϵ_b	ϵ_e	ϵ_a	p	z
15GHz	0.1	0.01	10^5	2.2	1.037

Emission Simulation

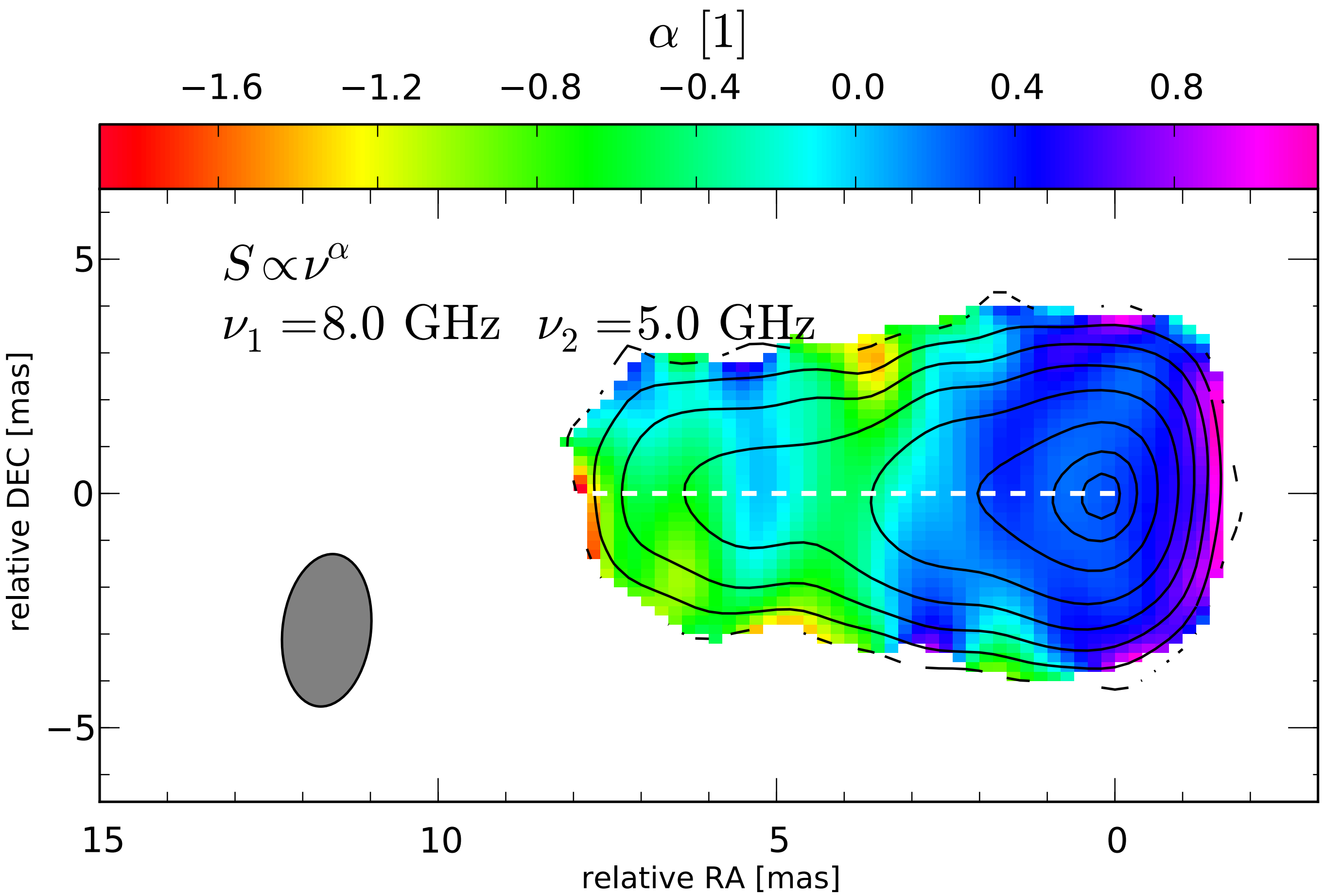


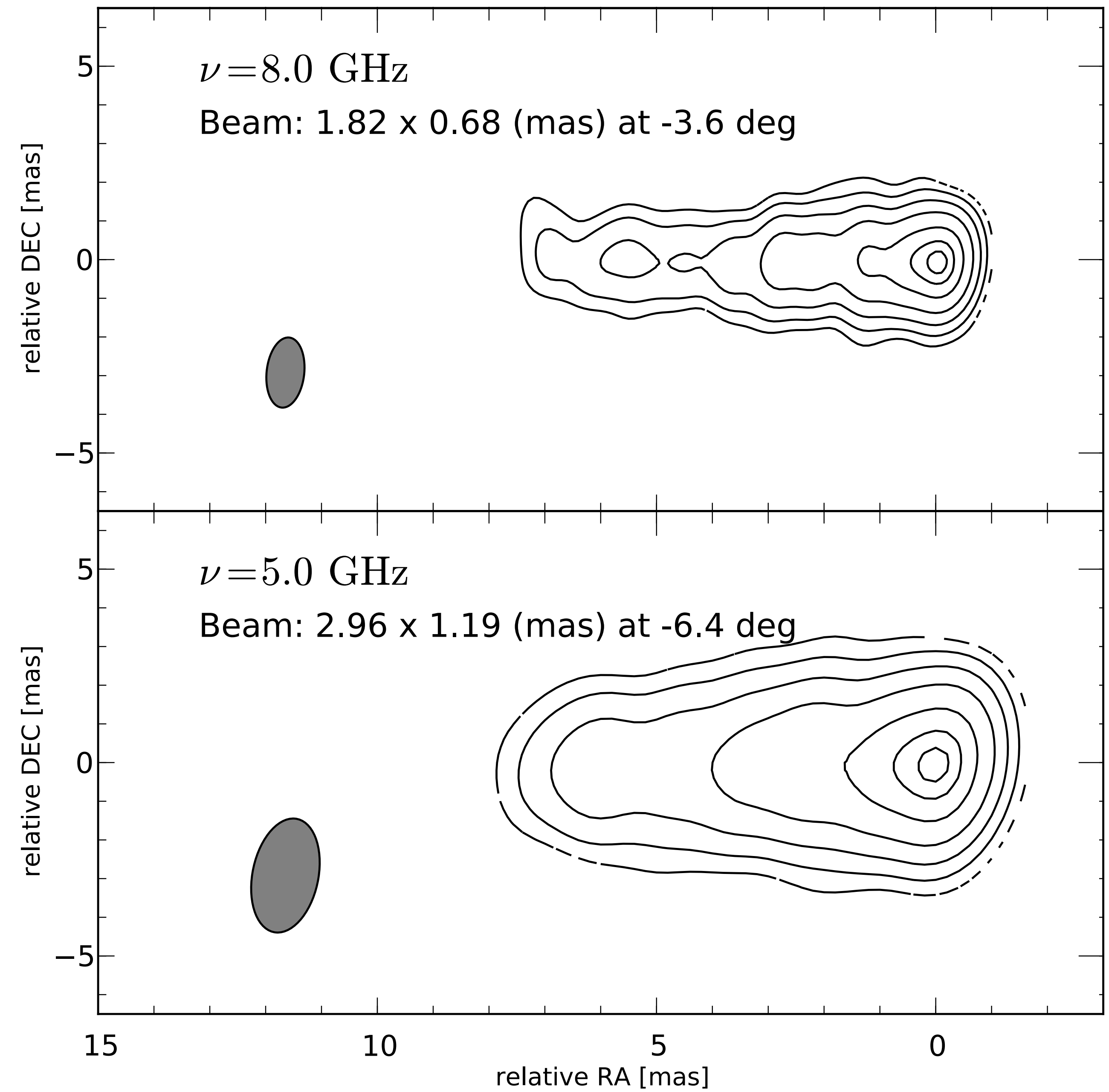
Ref: Fromm in prep.

Emission Simulation

using VLBA properties
and observation settings

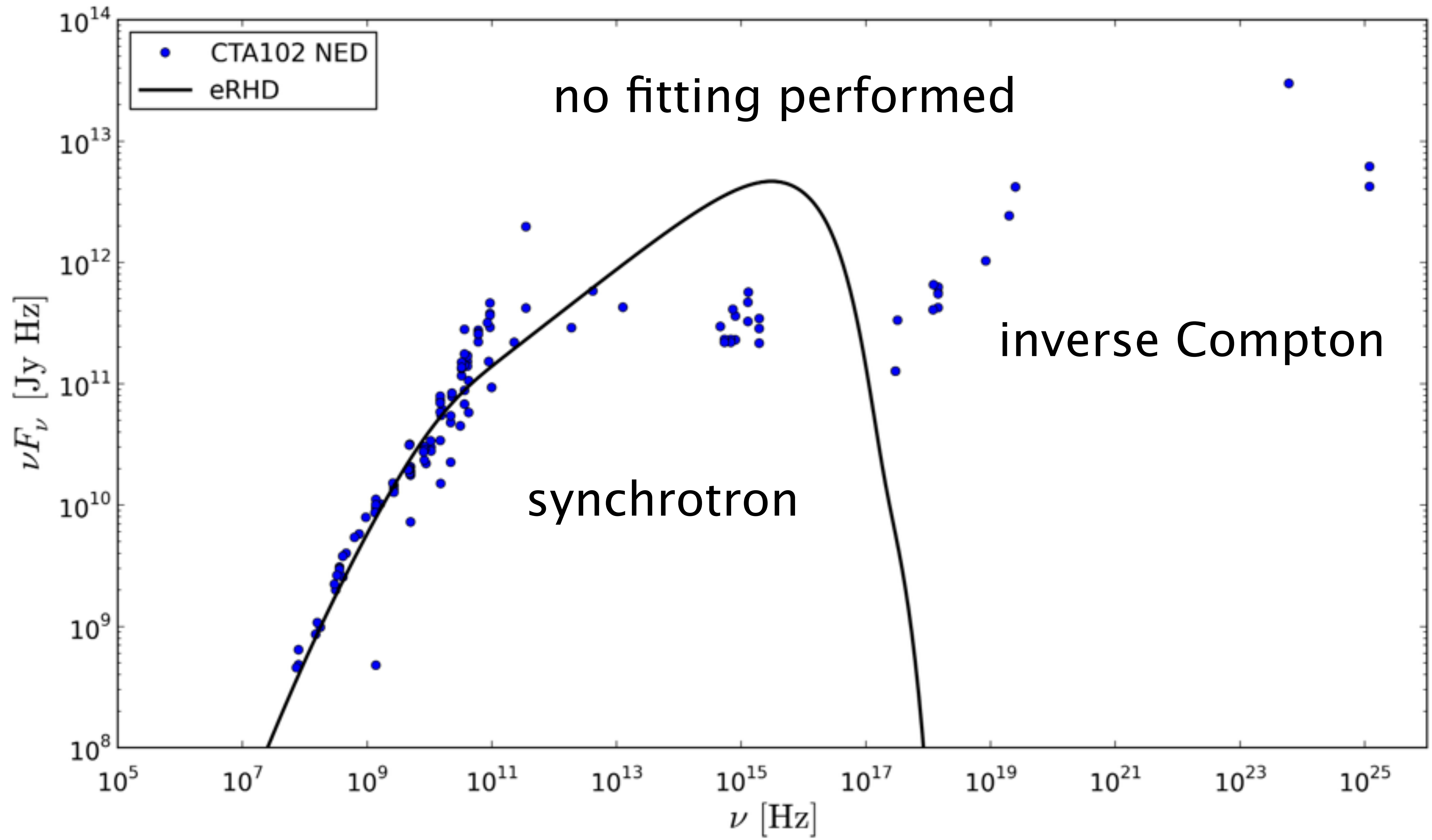
θ	ϵ_b	ϵ_e	ϵ_a	p	z
5	0.1	0.01	10^5	2.2	1.037





Ref: Fromm in prep.

Emission Simulation

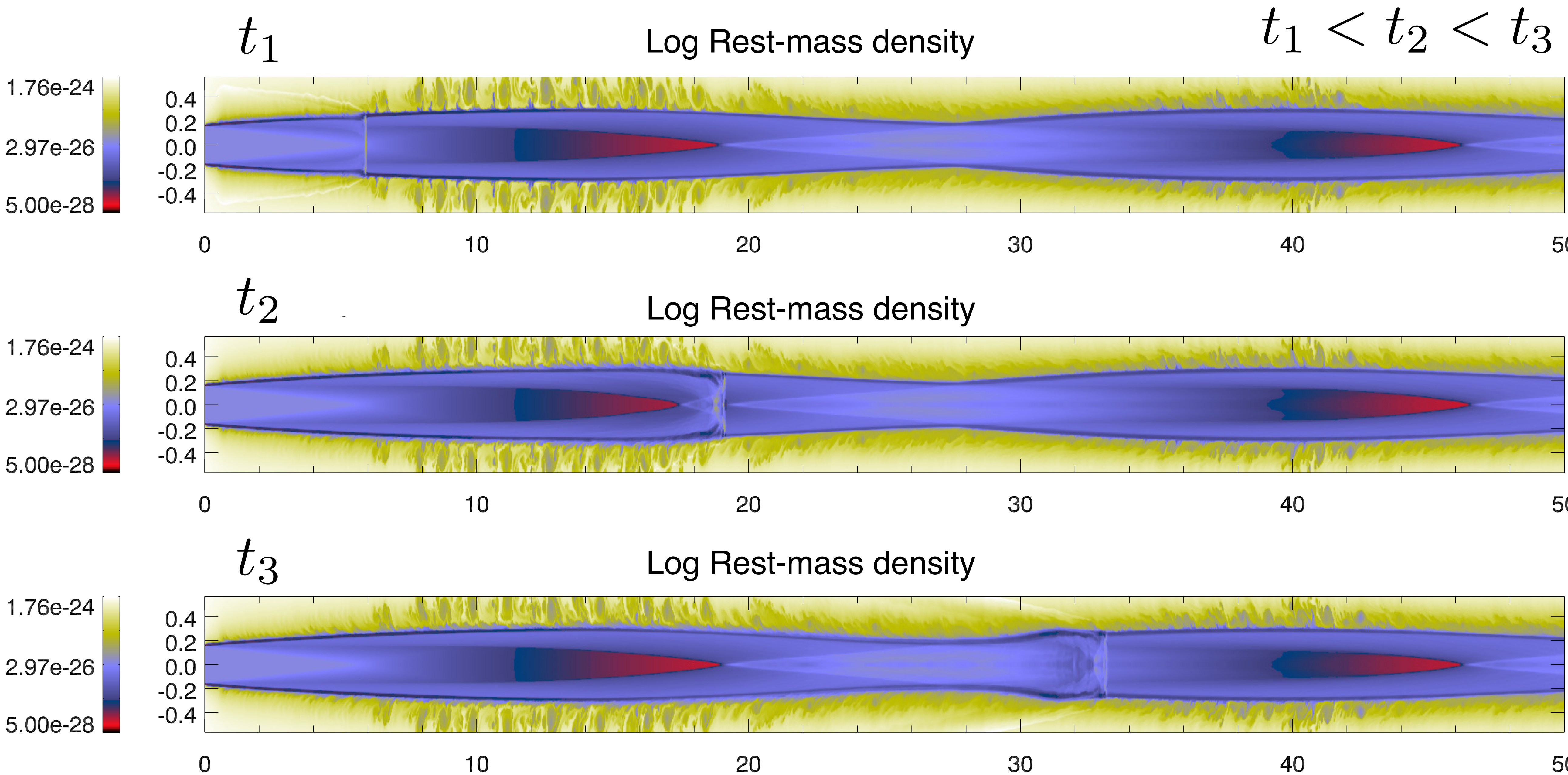


→ improve by modification of emission parameters

Ref: Fromm in prep.

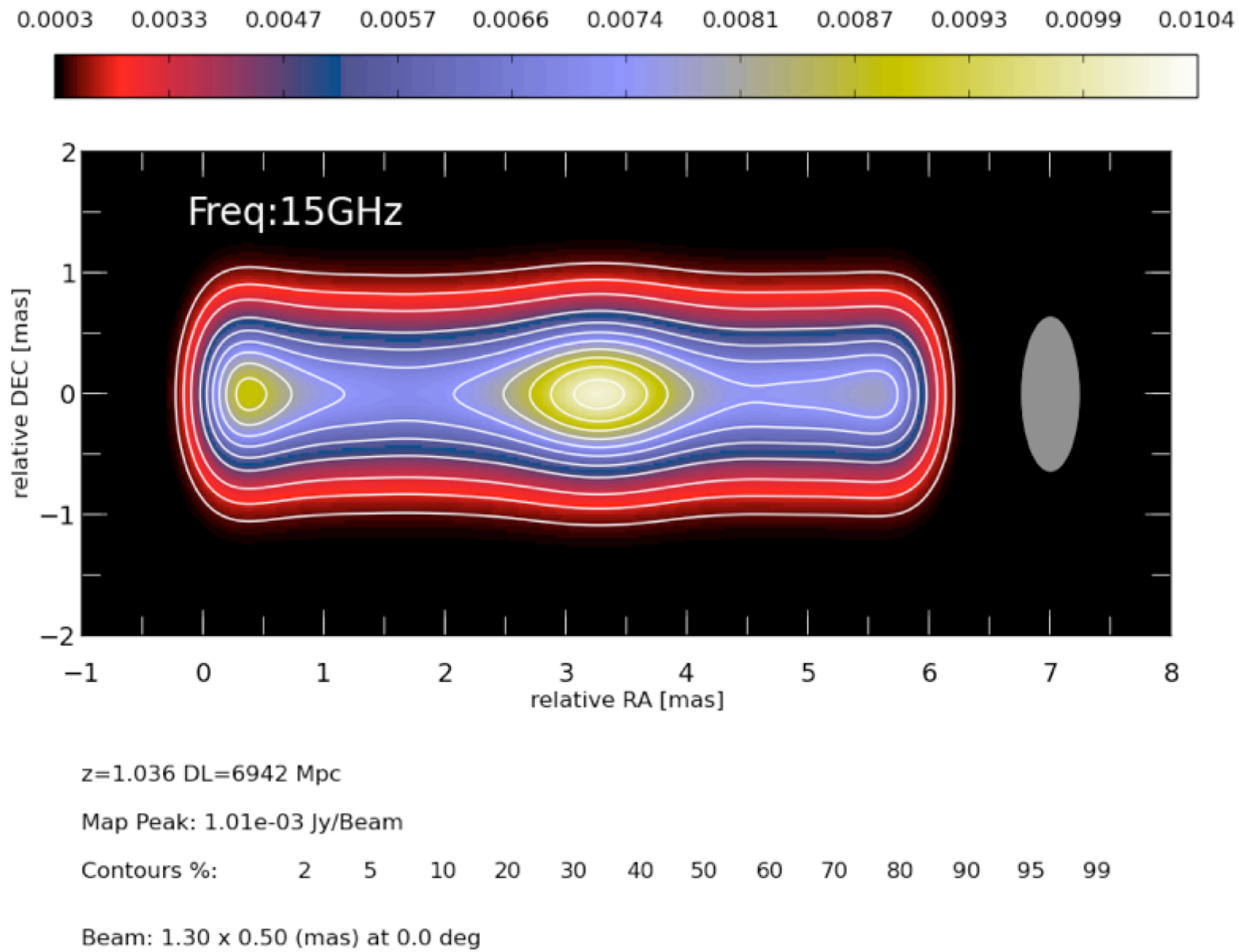
Shock–Shock interaction

perturbation: $\rho_{\rm p} = 4 \cdot \rho_{\rm j,0} \quad p_{\rm p} = 4 \cdot p_{\rm j,0} \quad \Gamma_{\rm p} = \Gamma_{\rm j,0}$



Ref: Fromm in prep., Gomez et al. 1997, Mimica et al. 2009

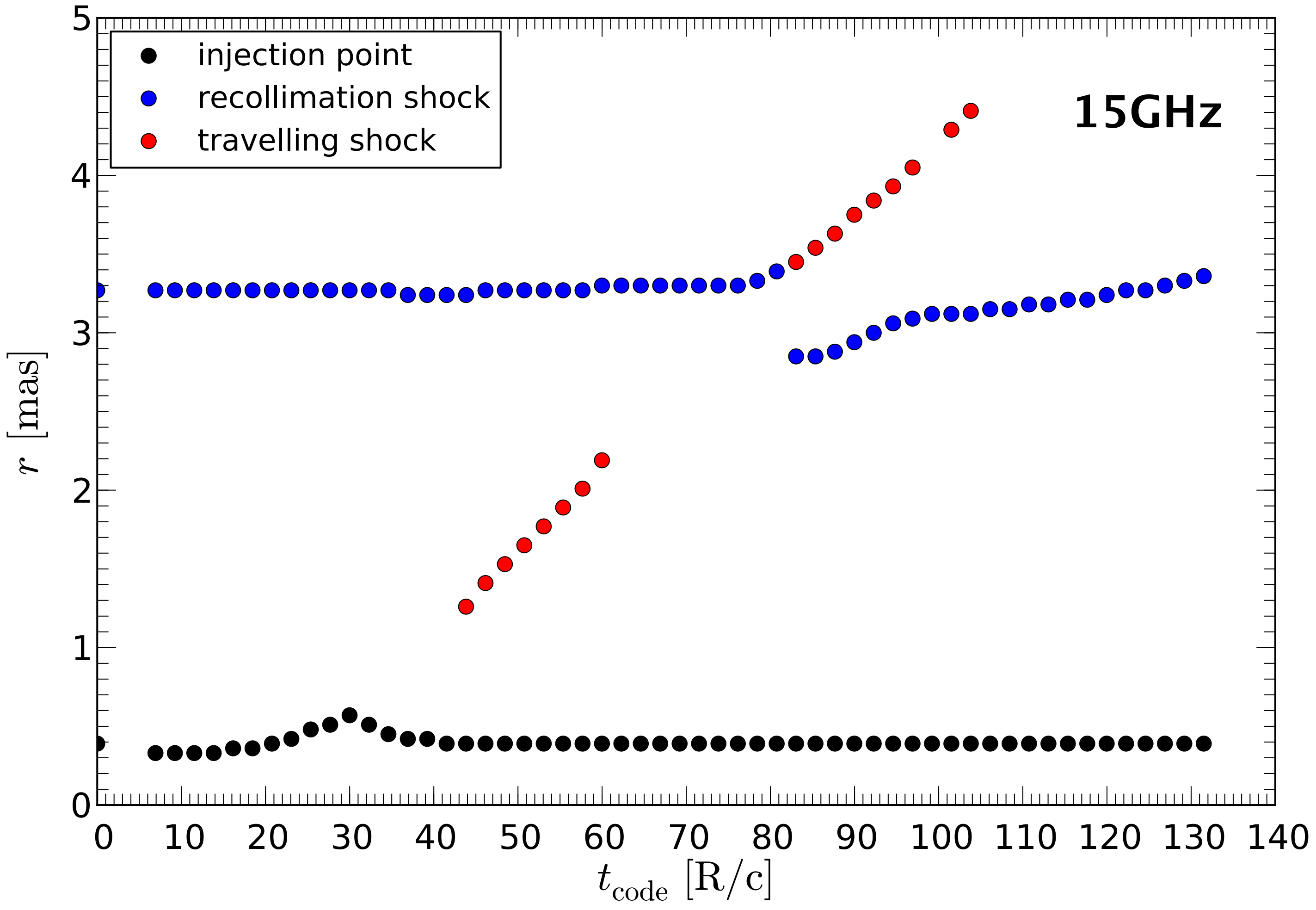
Shock-Shock interaction



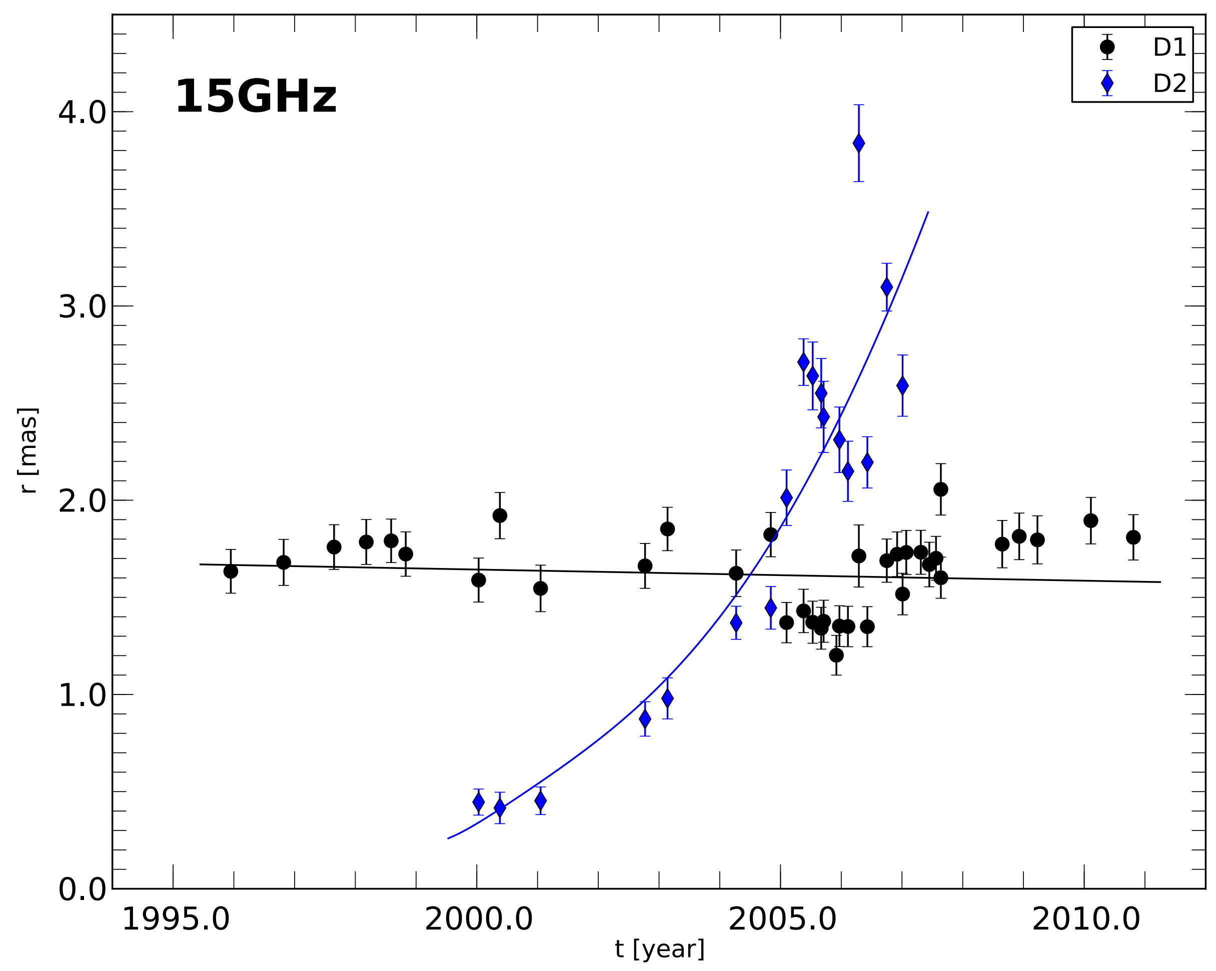
Ref: Fromm in prep.

Shock–Shock interaction

eRHD simulations



VLBI observations



→ signature of shock–shock interaction

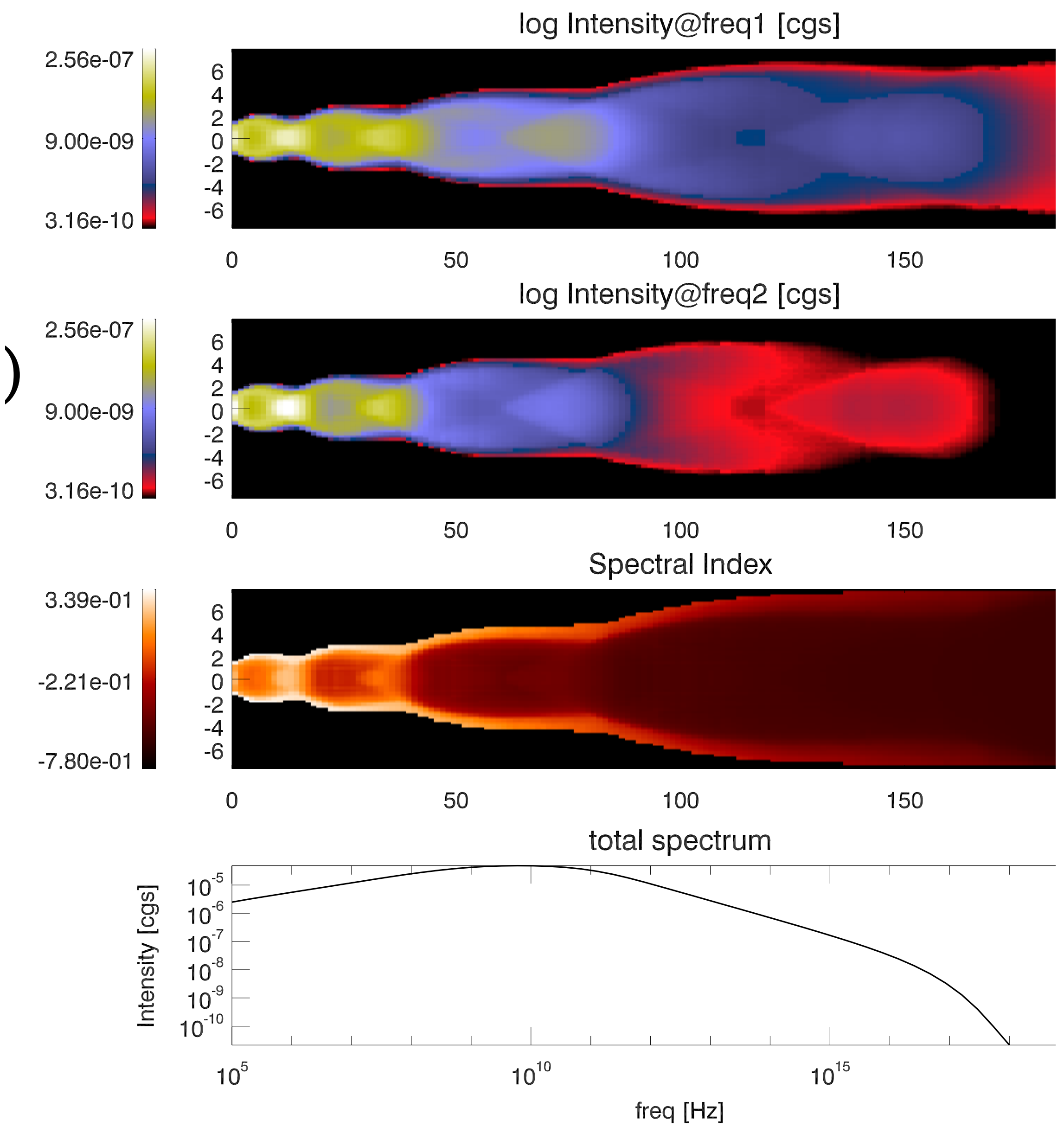
Ref: Fromm in prep.

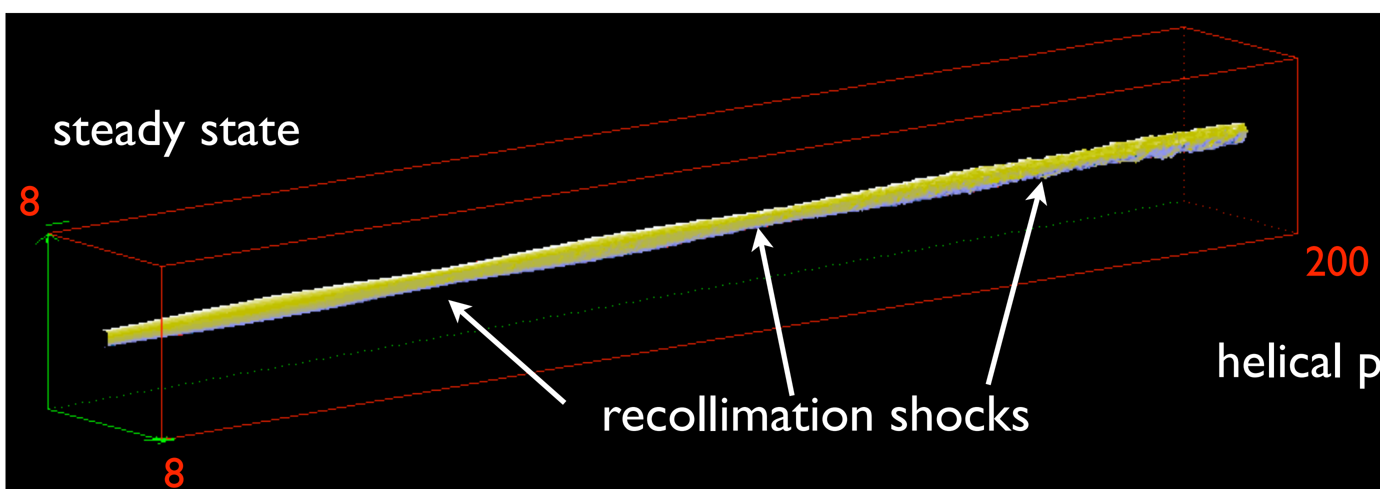
Summary

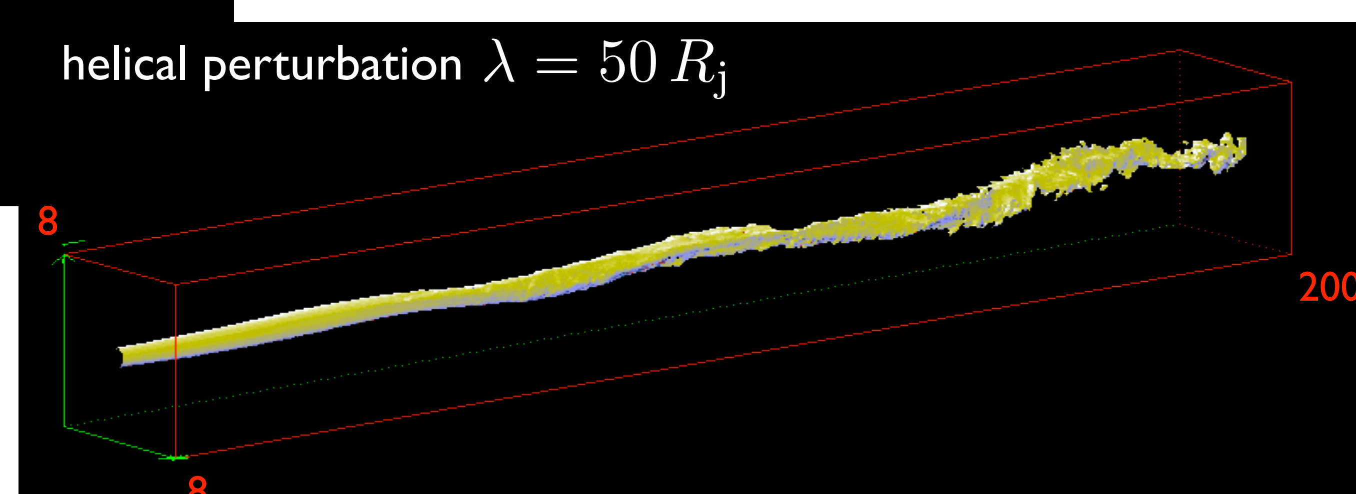
- extraction of physical parameters from multi-freq. VLBI observations
- observational signature of recollimation shocks
- RHD simulation of jets
- Emission simulation of jets
- Fake radio maps using real array properties
- model steady state and shock-shock interaction

Outlook

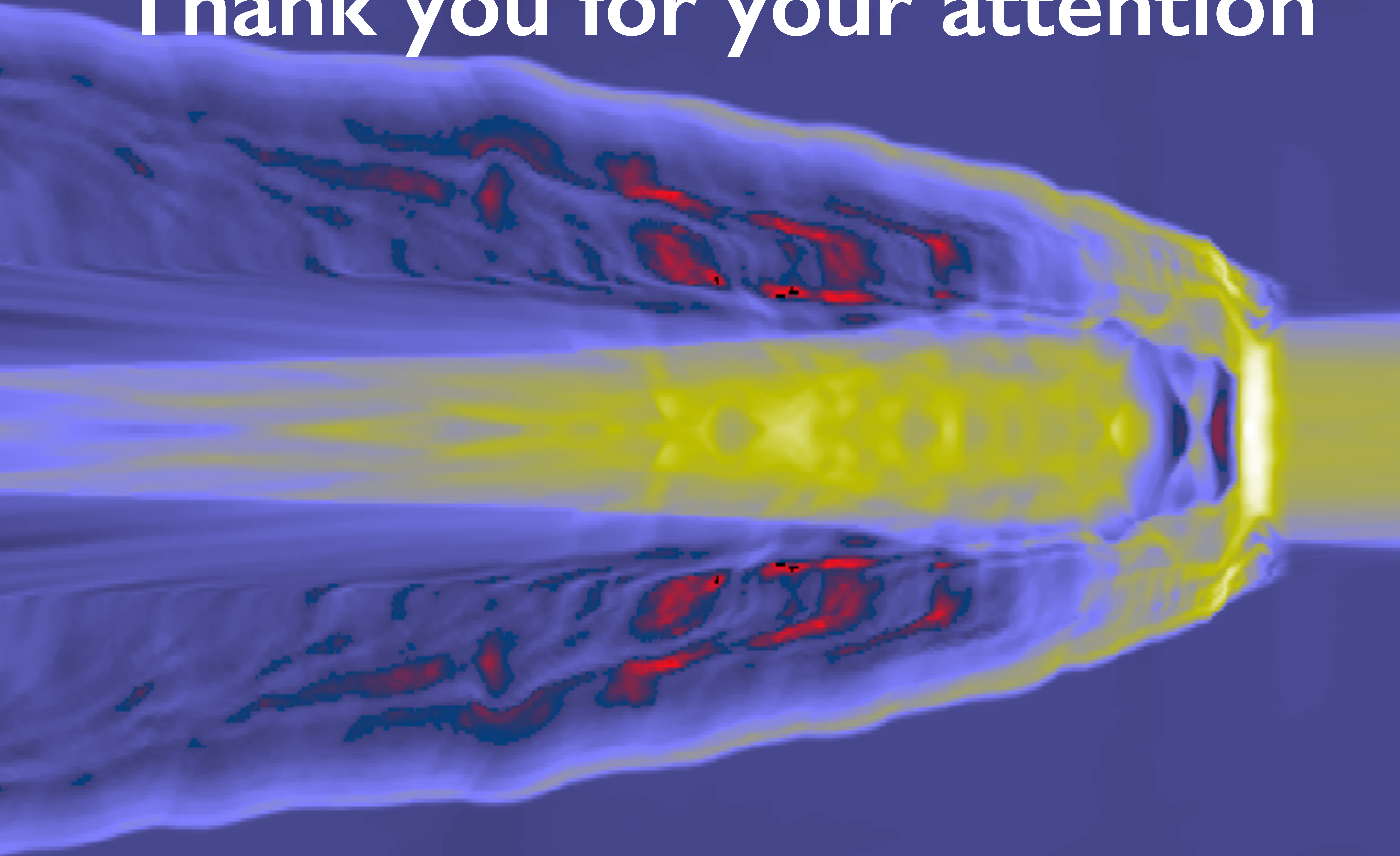
- modify the radiative transfer code (3D ray tracing + inverse Compton)
- polarized radiative transfer
- 3D RHD simulations (test stability of jets)
- RMHD simulations of jets
- values from jet launching simulation
- connection to high energy
- application to M87 and other jet







Thank you for your attention



snapshot of high-res shock-shock interaction

Outlook

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