Blazar Variability with Magnetic Reconnection

Marc Klinger, Philipp Mertsch

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TTK Institut für Theoretische Teilchenphysik und Kosmologie | RWTH AACHEN UNIVERSITY

Active Galactic Nuclei (AGN)

- black hole

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- accretion disk

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- black hole
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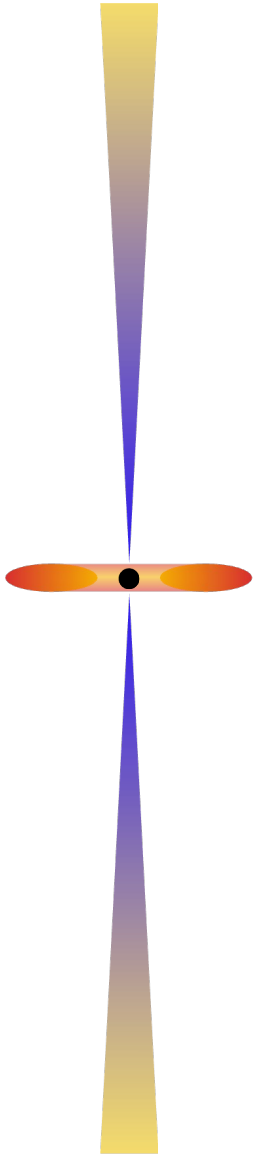
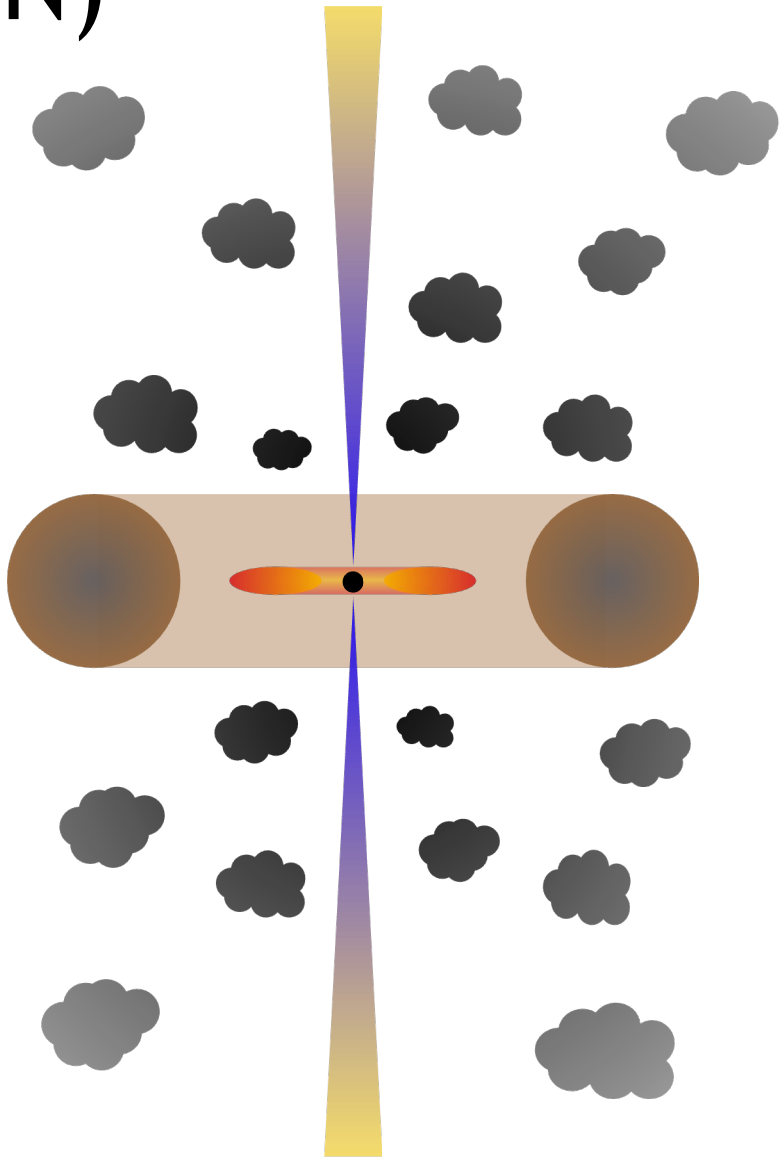
- jet: collimated outflow of relativistic plasma and twisted magnetic fields



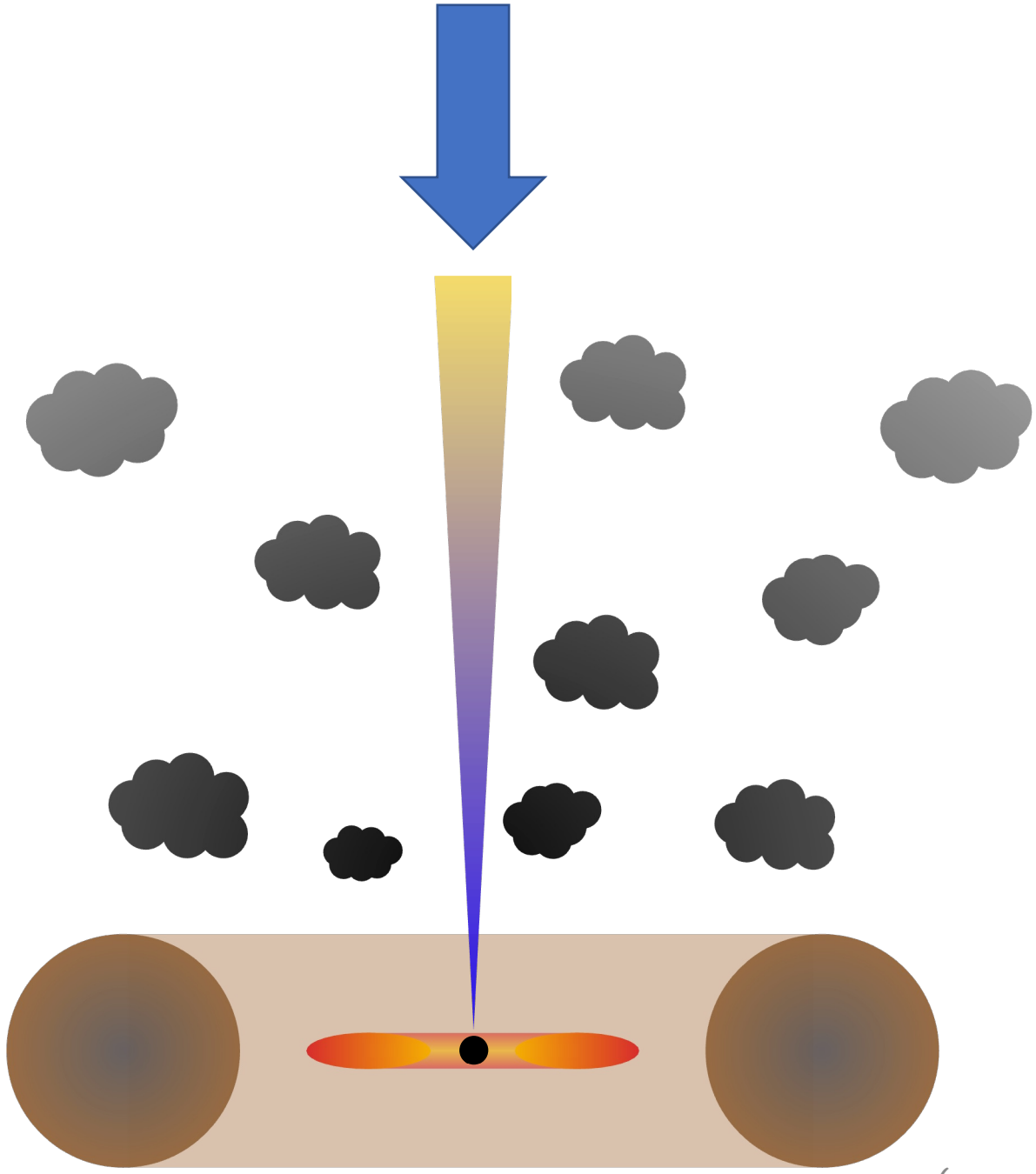
Active Galactic Nuclei (AGN)

- black hole
- accretion disk
- jet: collimated outflow of relativistic plasma, twisted magnetic fields
- dust torus
- broad line region (BLR)
- narrow line region (NLR)



Blazars

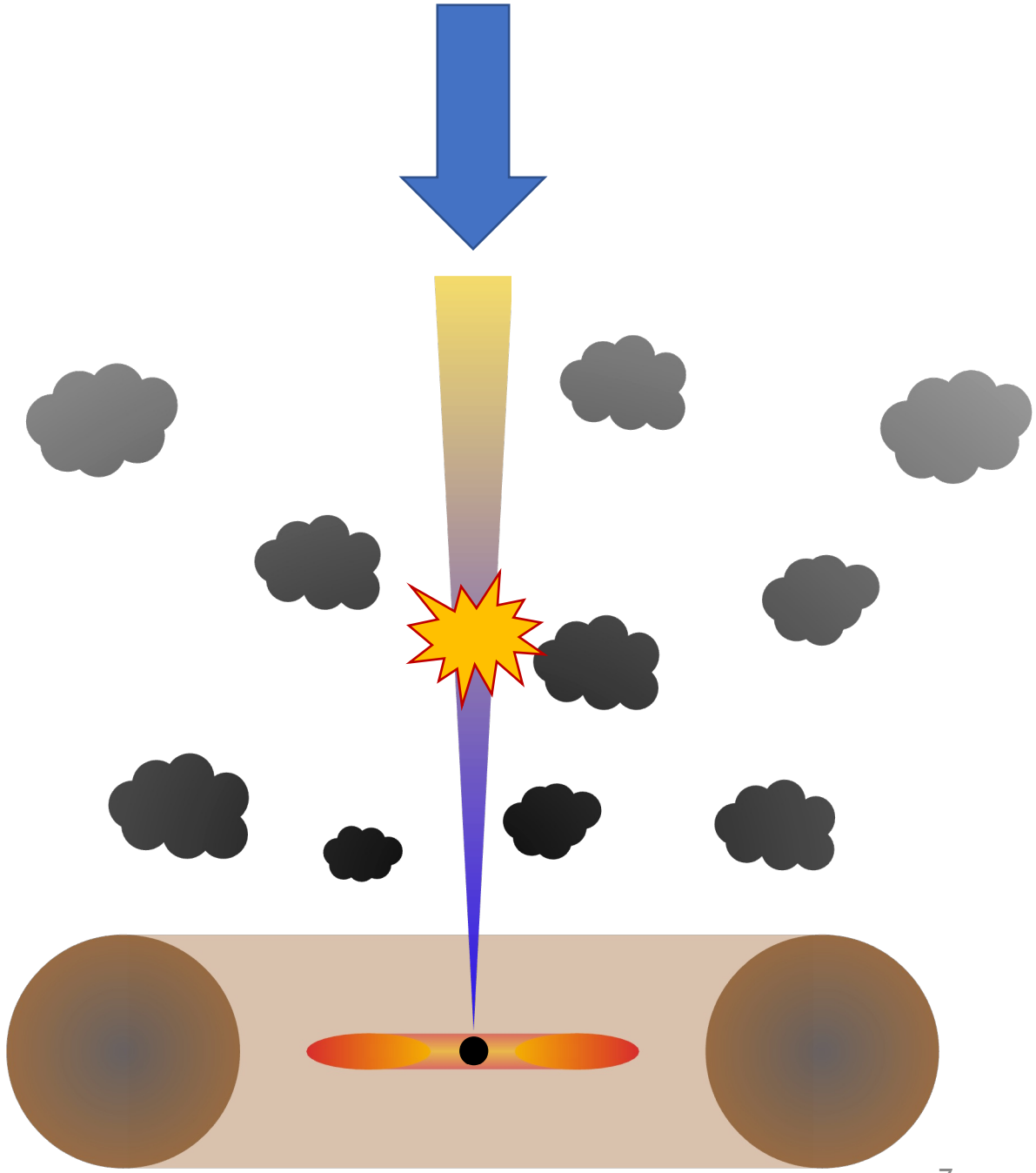
- jet points towards earth



Blazars

- jet points towards earth
- gamma-ray variability down to minutes observed

→ energy dissipation confined to small emission regions

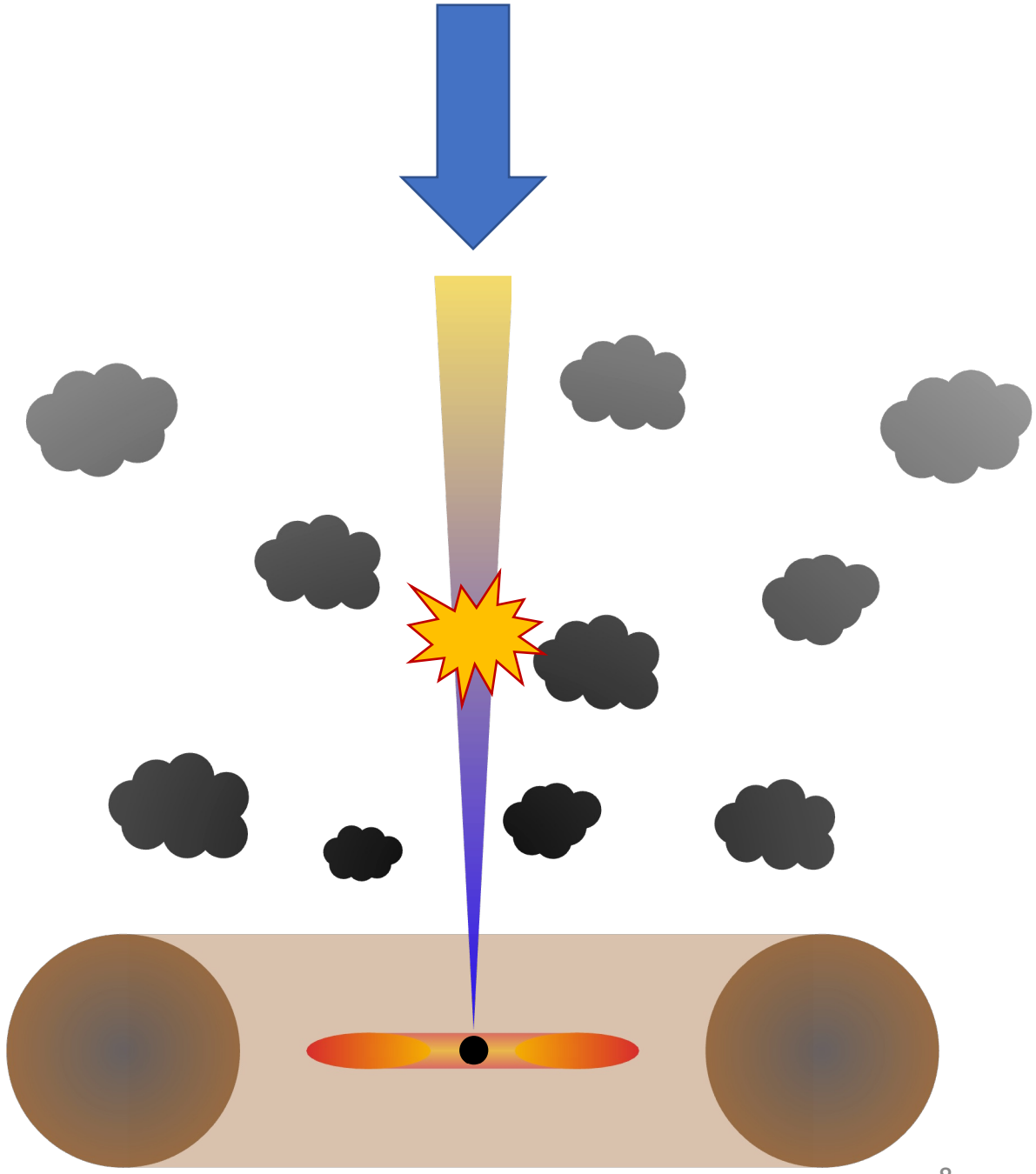


Blazars

- jet points towards earth
- gamma-ray variability down to minutes observed

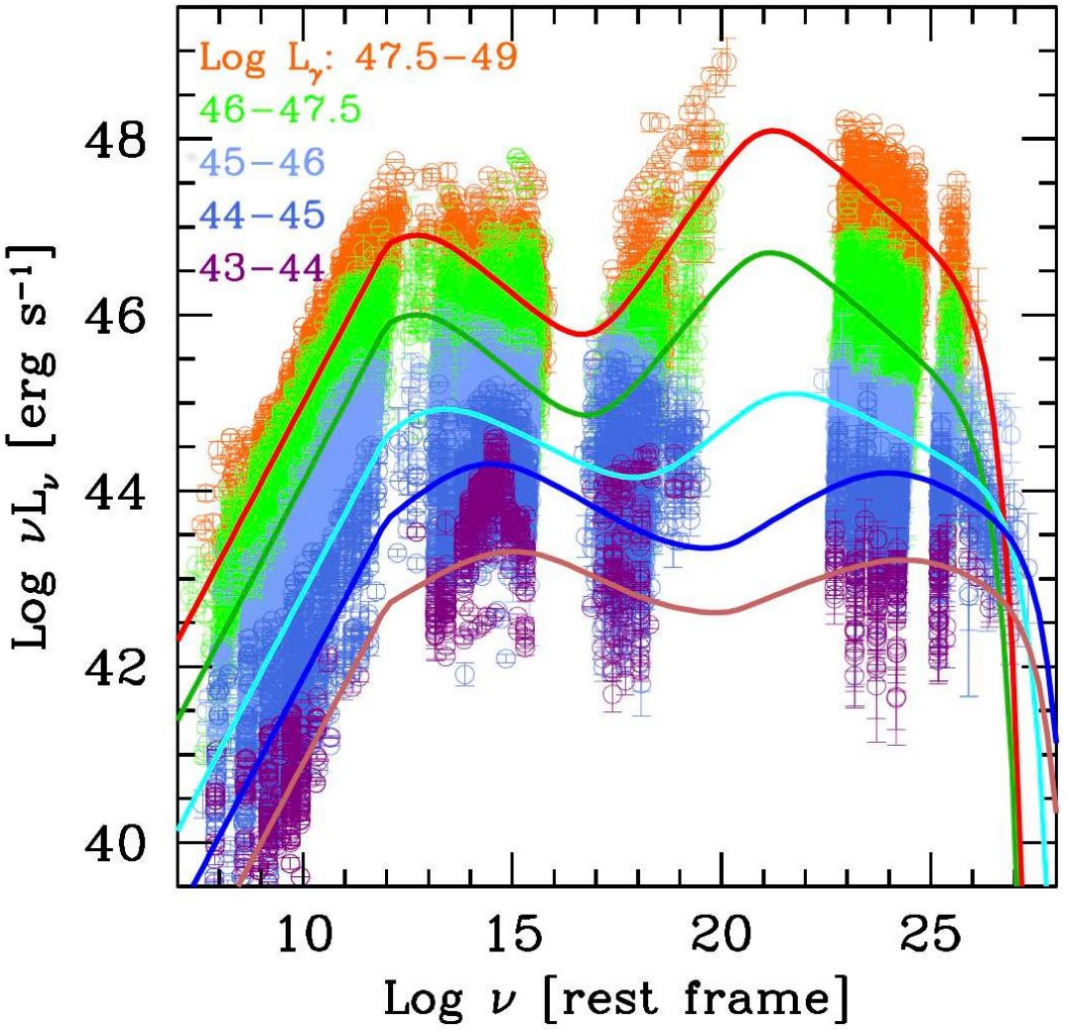
→ energy dissipation confined to small emission regions

- **where?**



Blazar Sequence from Observations

Ghisellini (2016) [arXiv:1609.08606] , Ghisellini et al. (2017) [arXiv:1702.02571]

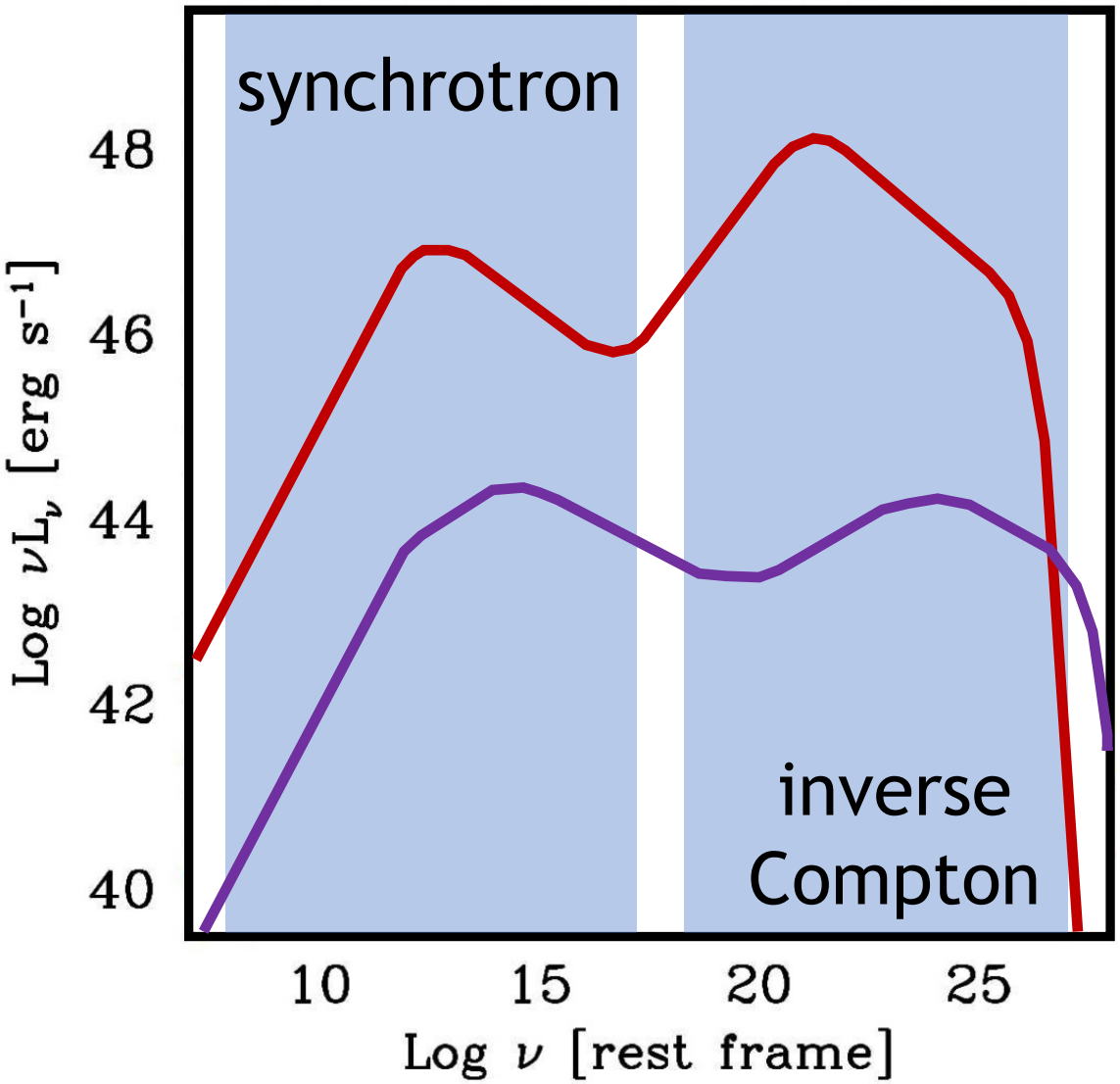


→ bin spectra of blazars in gamma-ray luminosity

Flat Spectrum Radio Quasars (FSRQ)

BL Lacertae (BL Lac)

Idealised Picture



FSRQ

BL Lac

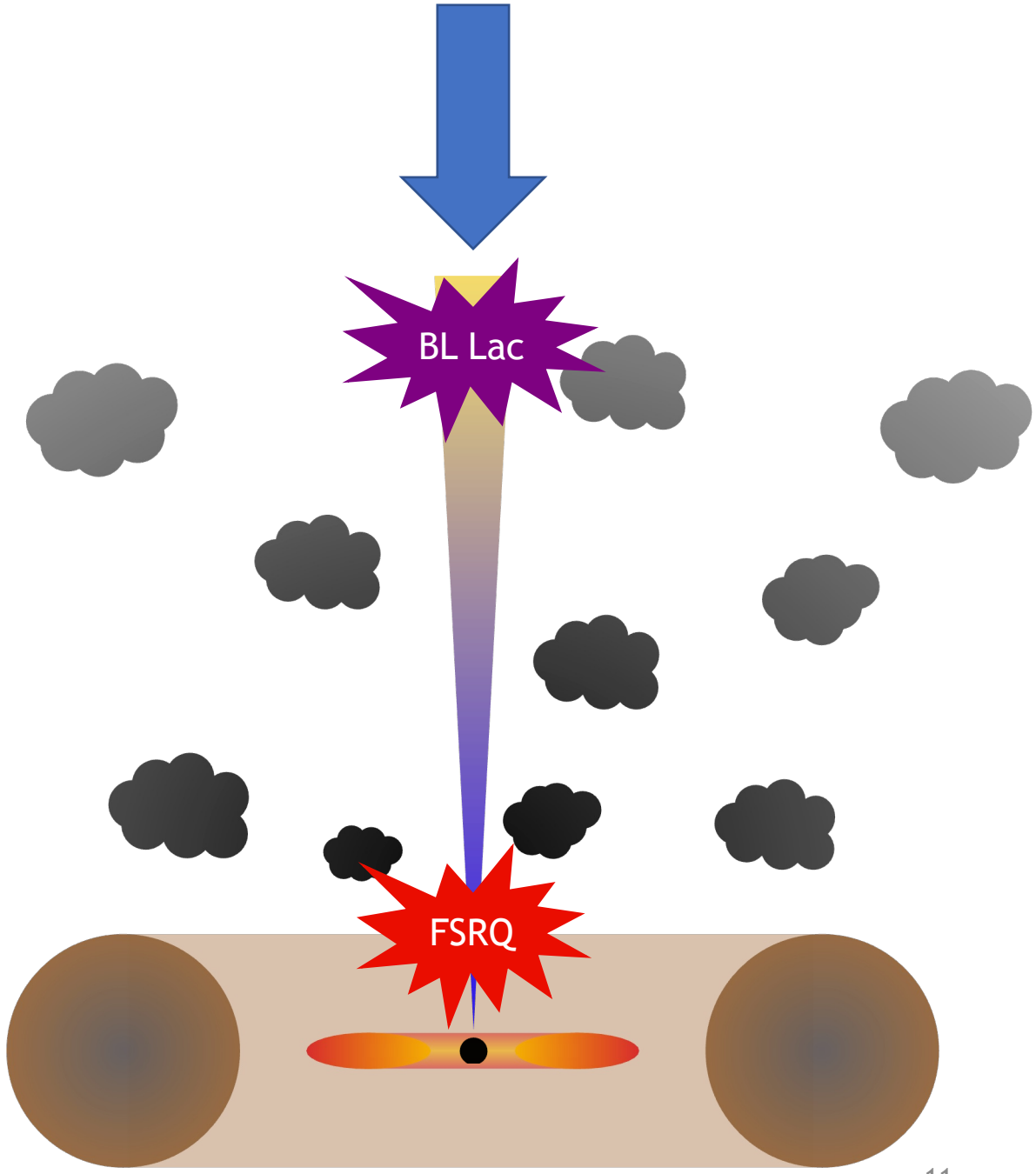
Blazars

- jet points towards earth
- gamma-ray variability down to minutes

→ energy dissipation confined to small emission regions

- where?

→ **FSRQ vs. BL Lac**



Blazars

- jet points towards earth
- gamma-ray variability down to minutes

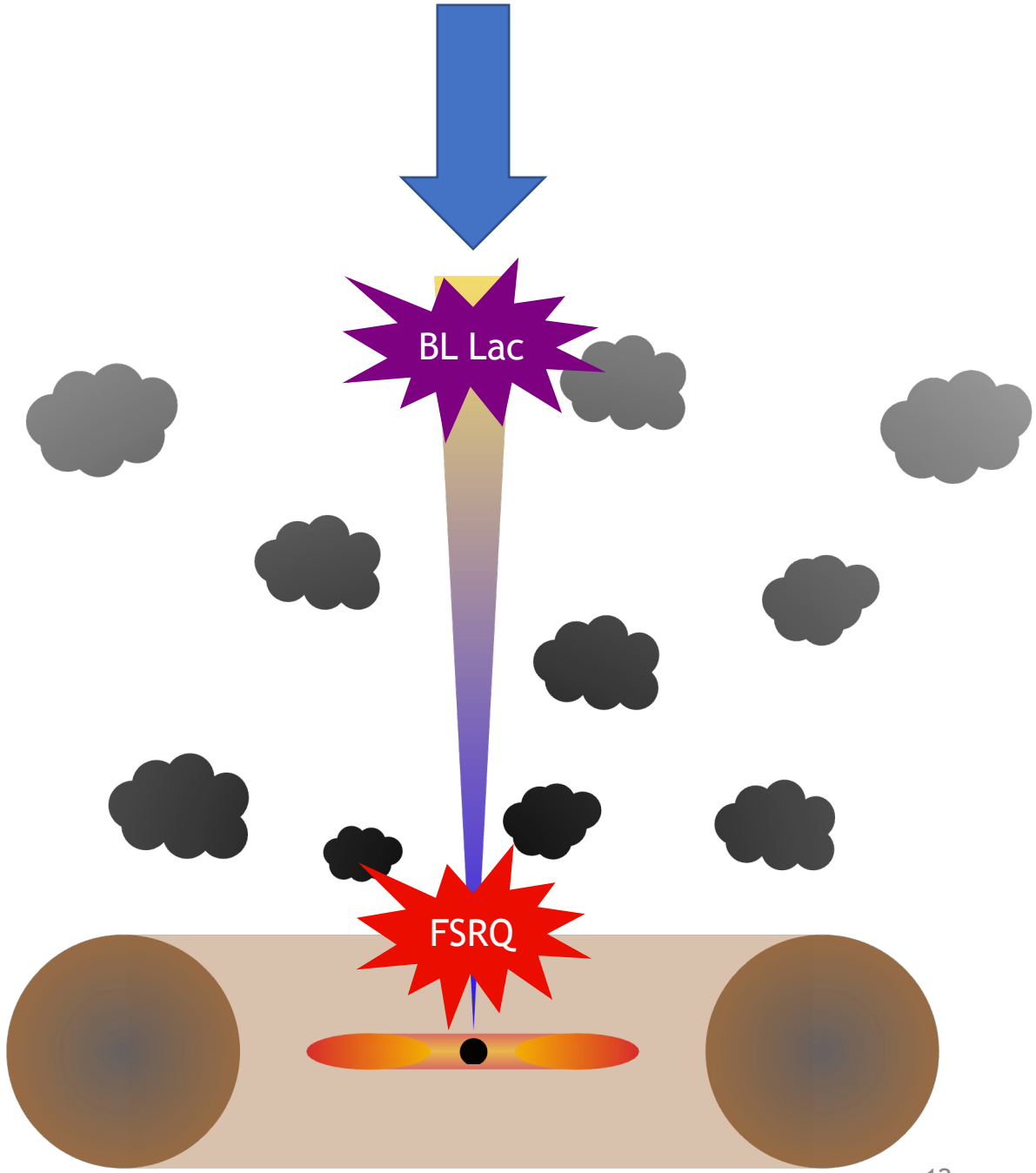
→ energy dissipation confined to small emission regions

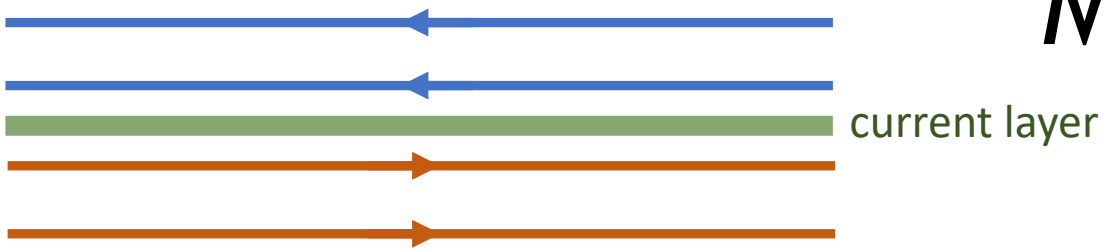
- where?

→ FSRQ vs. BL Lac

- **how?**

→ **relativistic magnetic reconnection offers natural explanation**

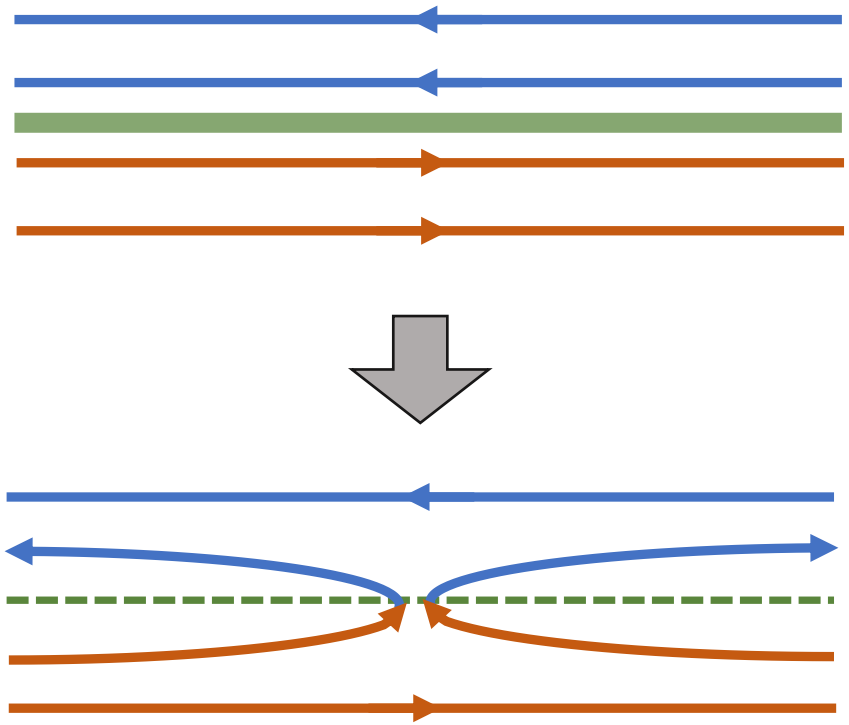




Magnetic Reconnection

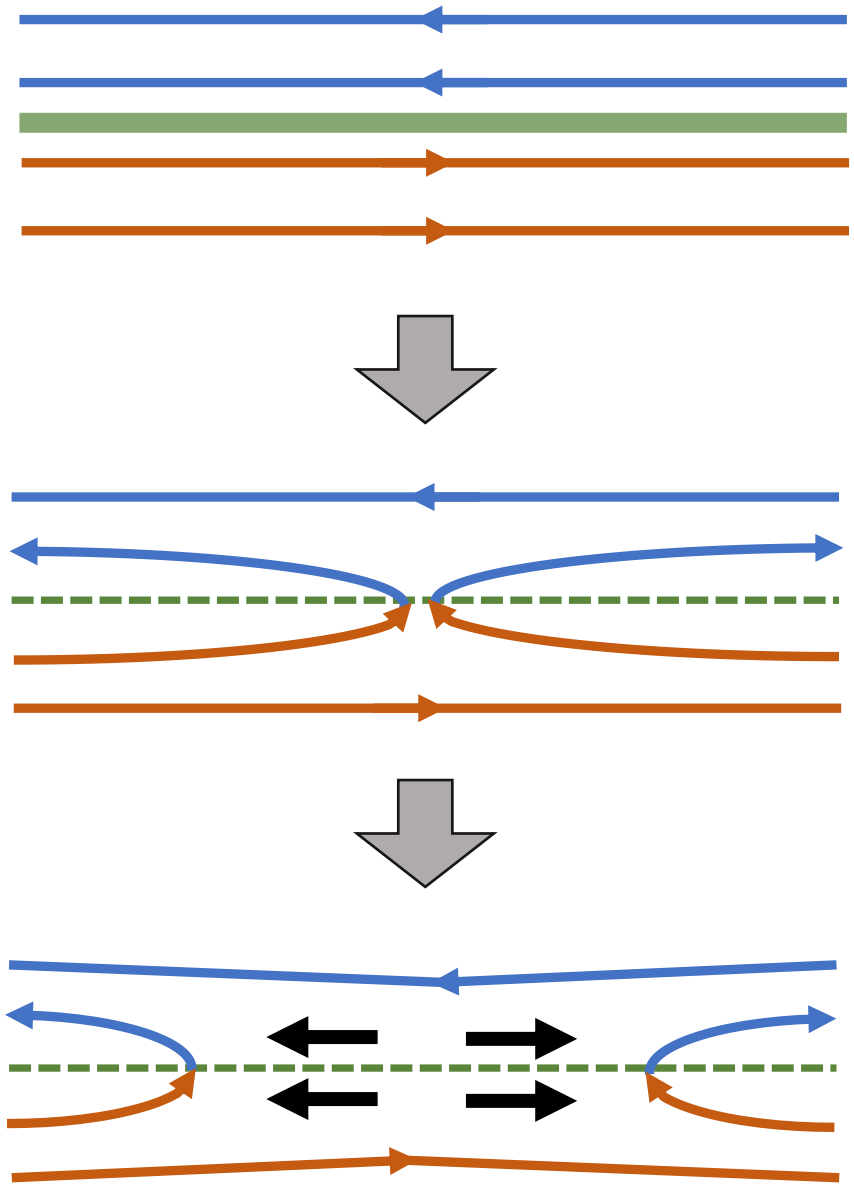
- antiparallel magnetic fields in the plasma
- strong currents in boundary layer cause resistive fluctuations

Magnetic Reconnection



- topological rearrangement of field lines

Magnetic Reconnection

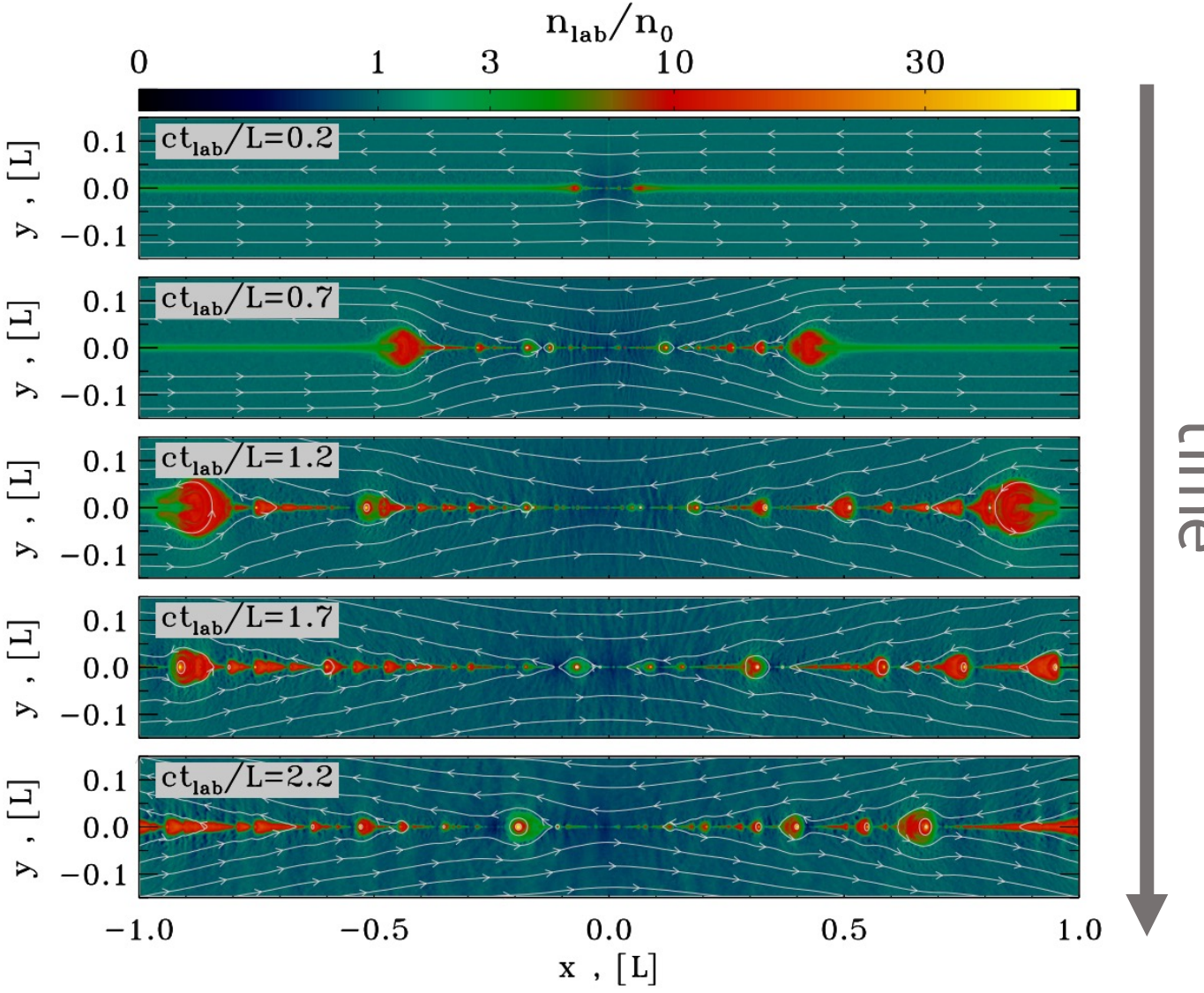


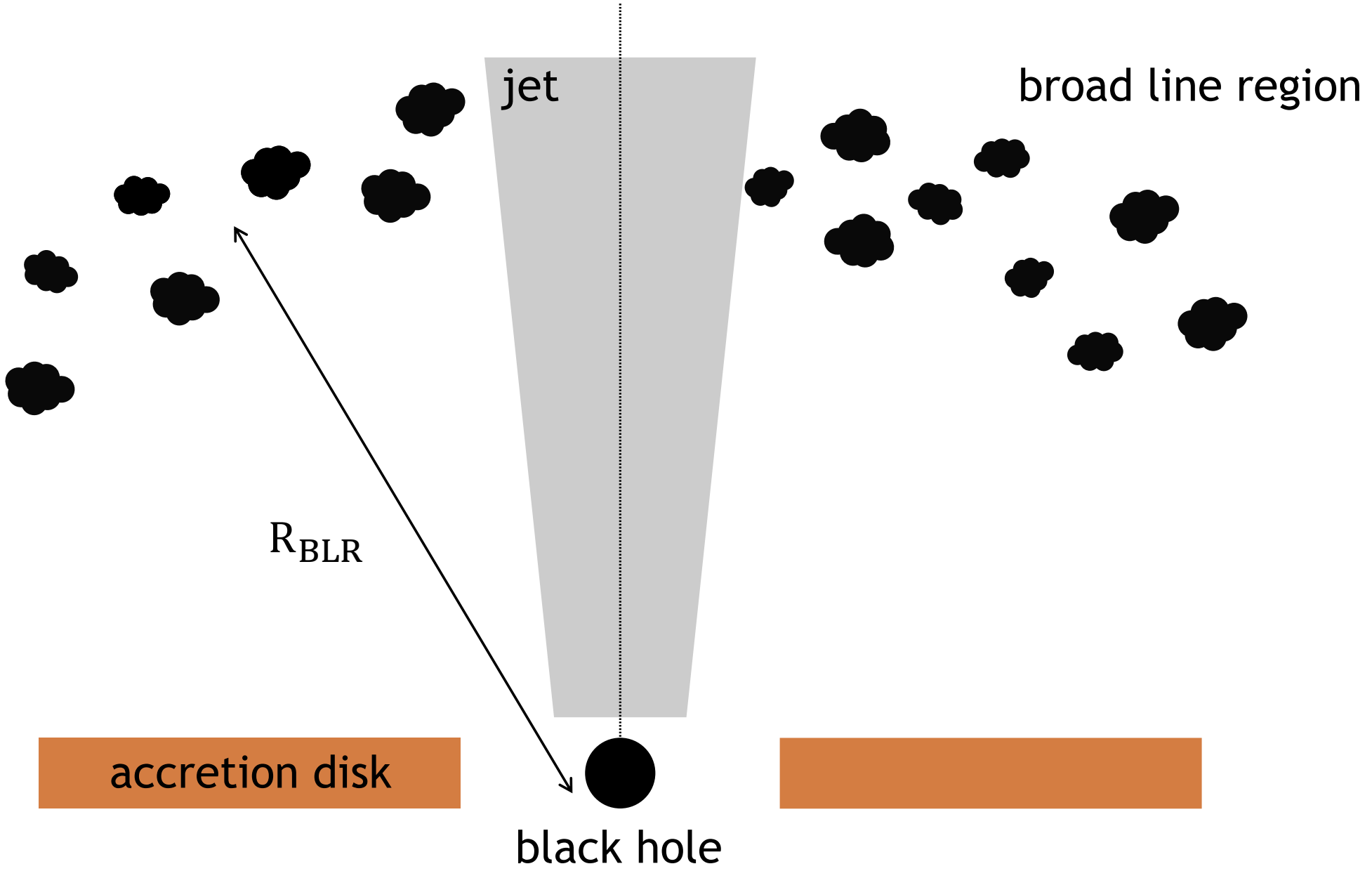
- magnetic tension causes plasma outflow

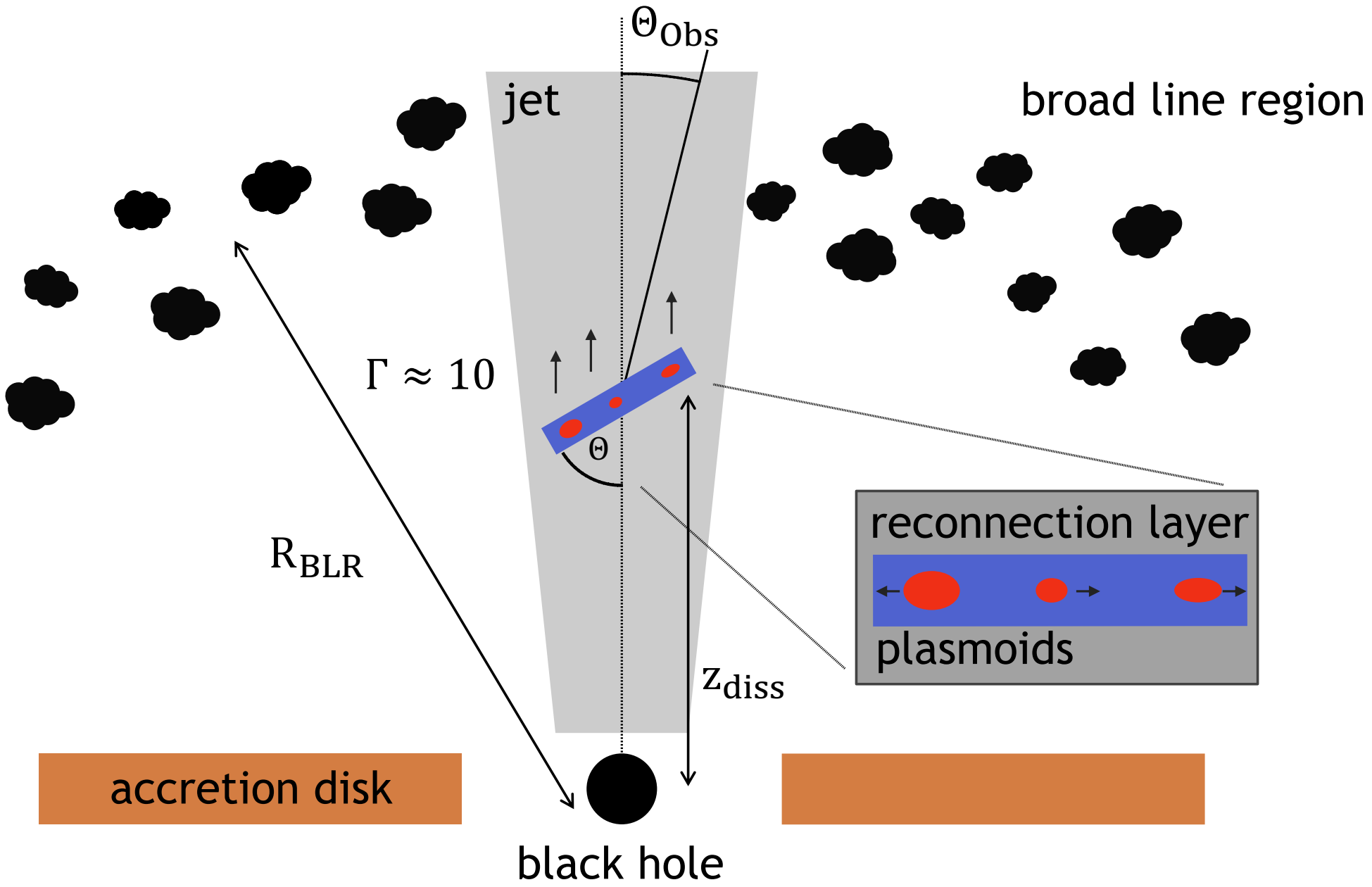
Plasmoids in PIC Simulations

Sironi, Giannios, Petropoulou (2016) [arXiv: 1605.02071]

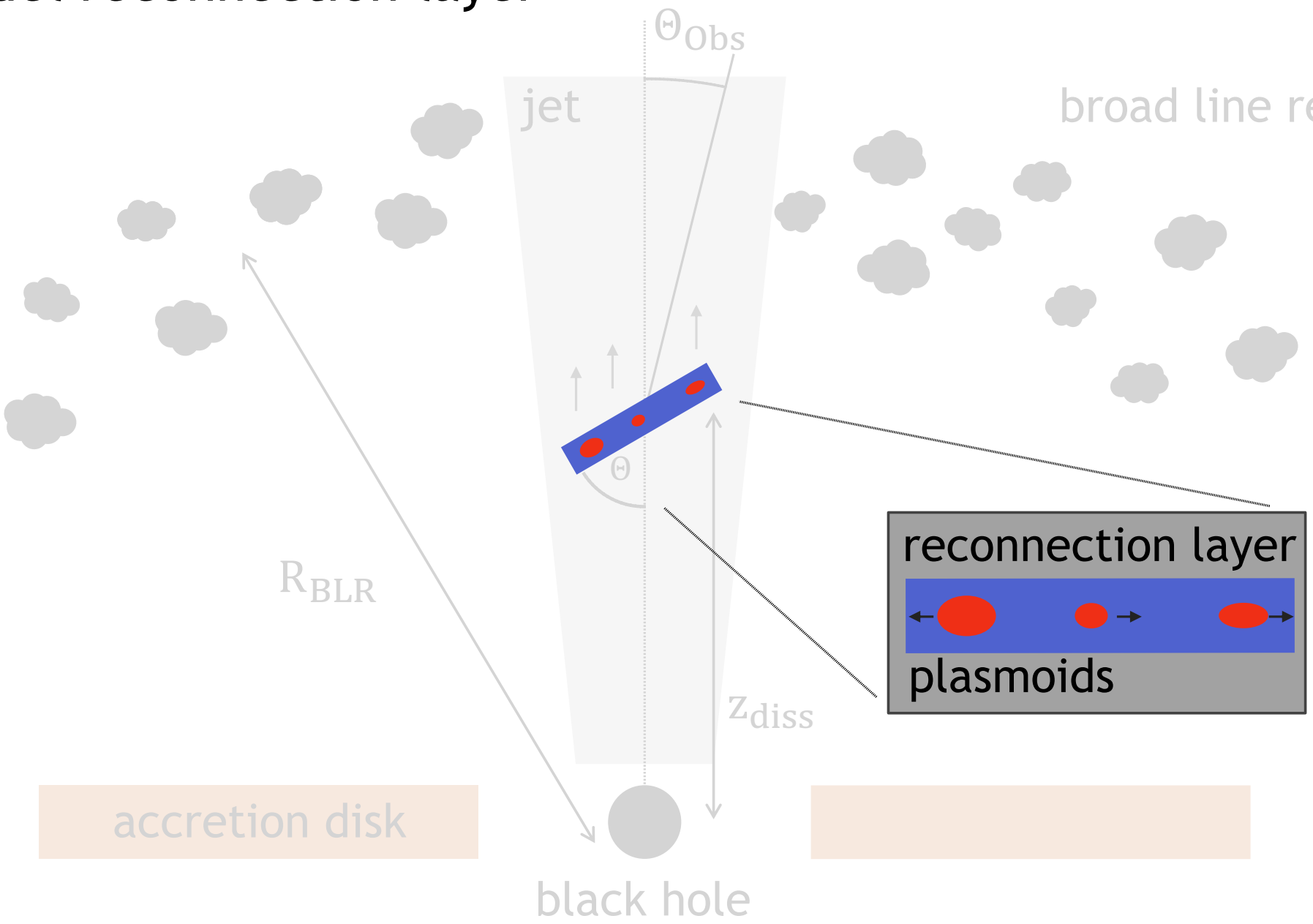
- Particle-In-Cell (PIC)
- stable structures of high plasma density: **plasmoids**
- acceleration outwards (magnetic tension)
- growth, birth, mergers
- reconnection layer allows for steady state



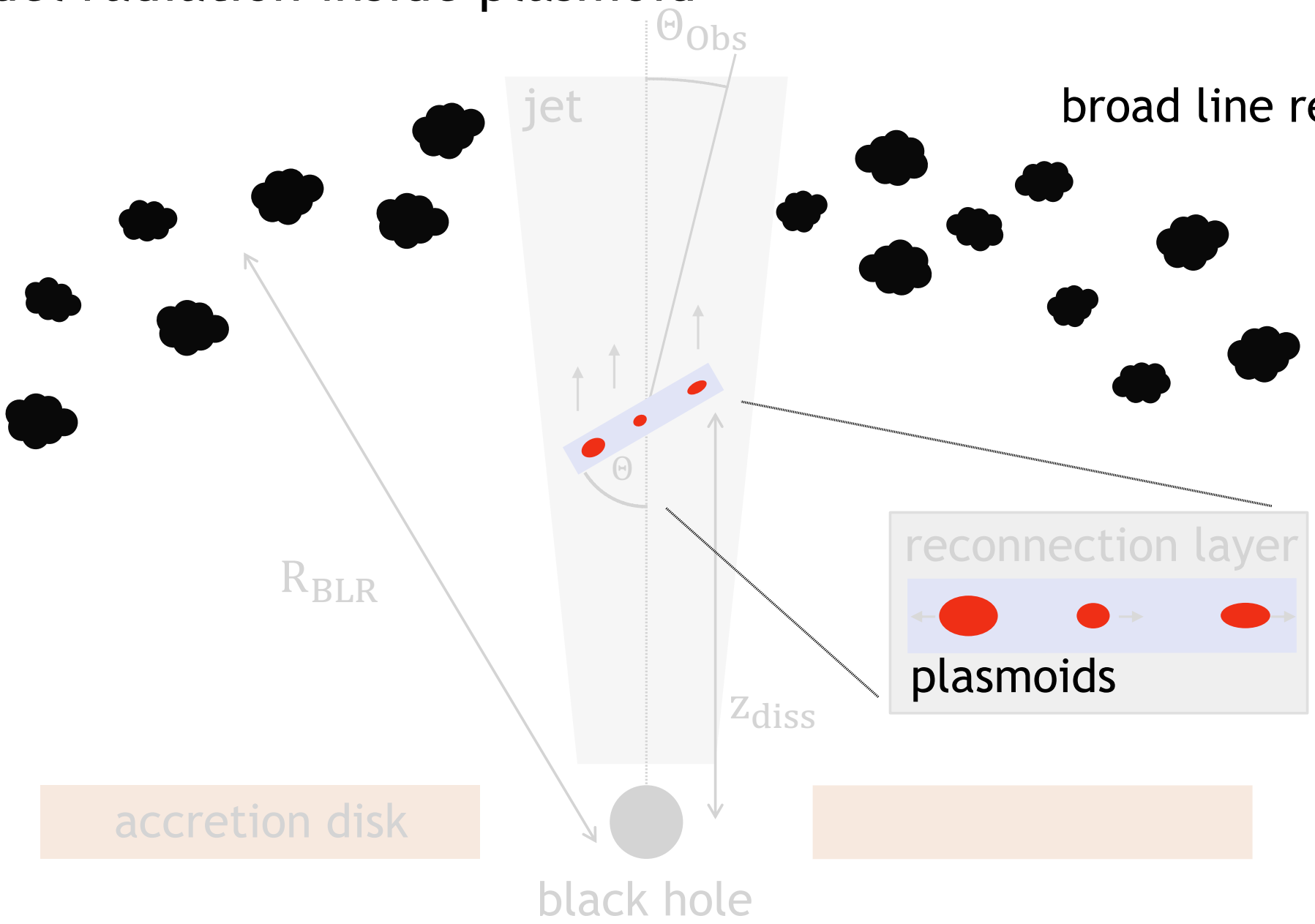

jet
broad line region
R_{BLR}
accretion disk
black hole


Θ_{Obs}
jet
broad line region
$\Gamma \approx 10$
Θ
R_{BLR}
reconnection layer
plasmoids
z_{diss}
accretion disk
black hole

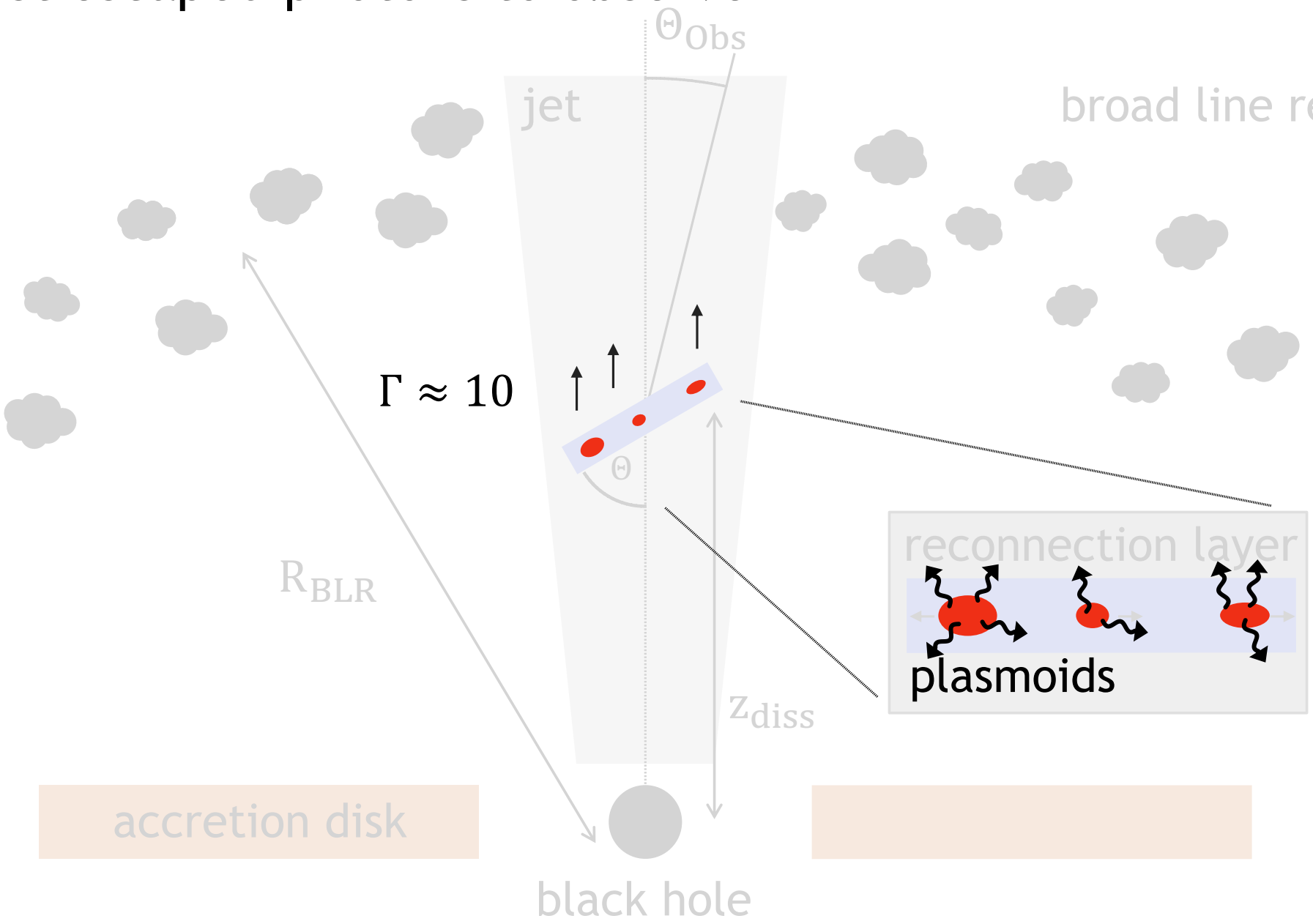
Step 1: Model reconnection layer



Step 2: Model radiation inside plasmoid



Step 3: Boost escaped photons to observer



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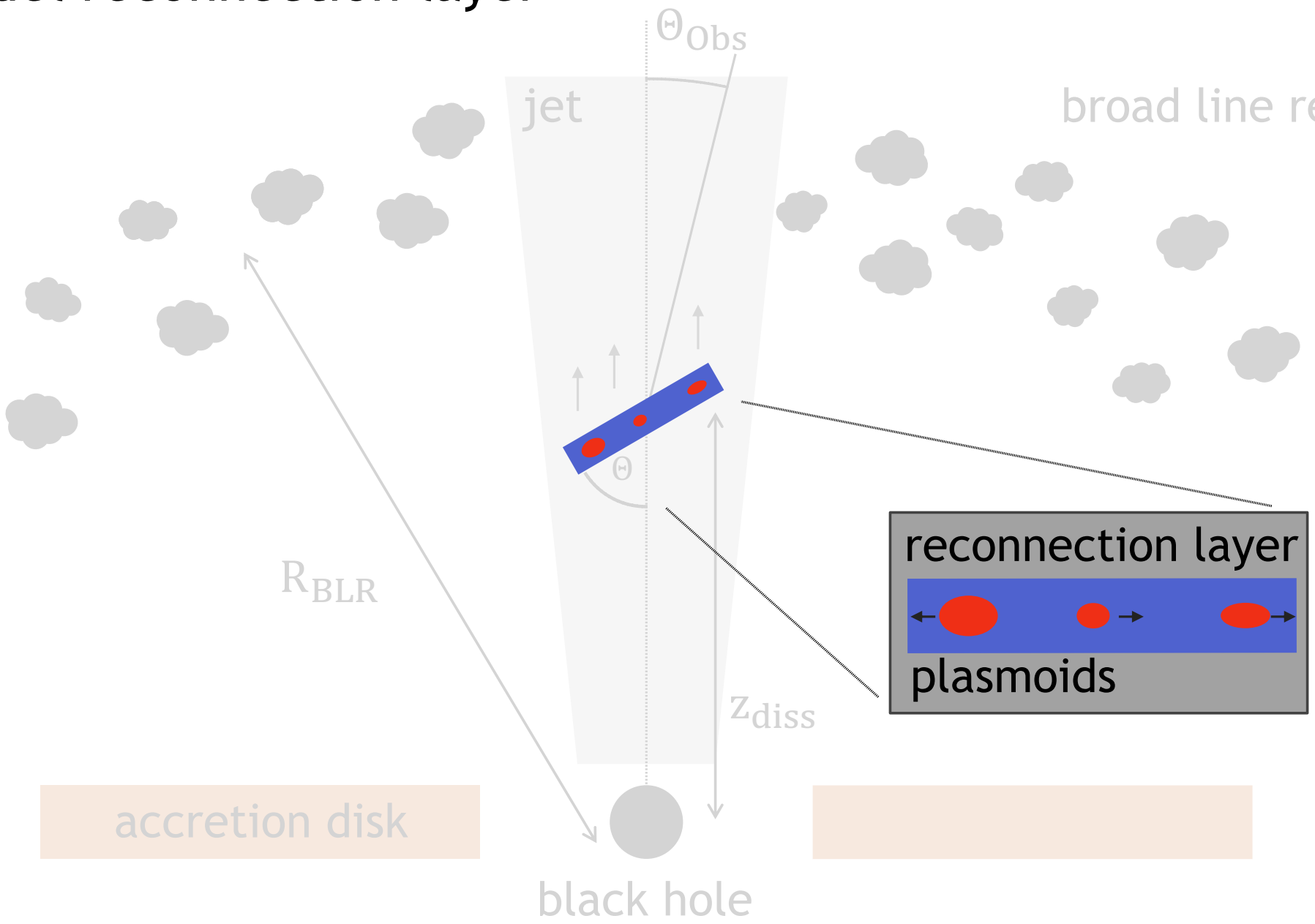
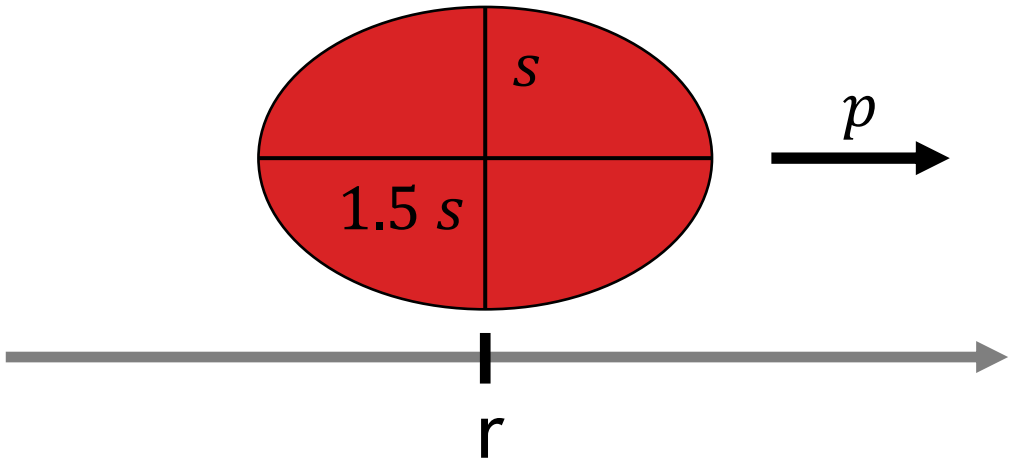


Monte Carlo Approach

Petropoulou, Christie, Sironi, Giannios (2017) [arXiv: 1710.00724]

- resemble PIC simulations
  - computationally cheaper, faster
- treat plasmoids as ellipsoids with **width s** and **position r**
- momentum as function $p(r, s)$



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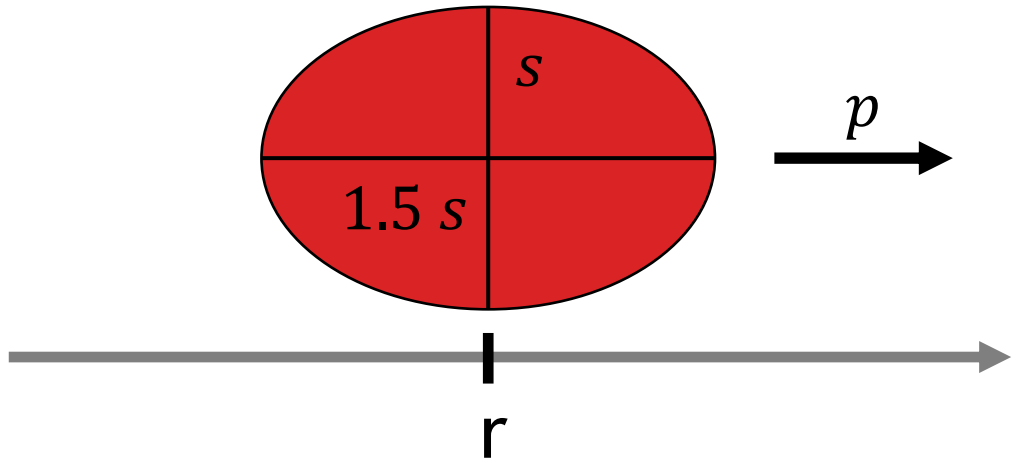
  1. **eqs. of motion and growth**



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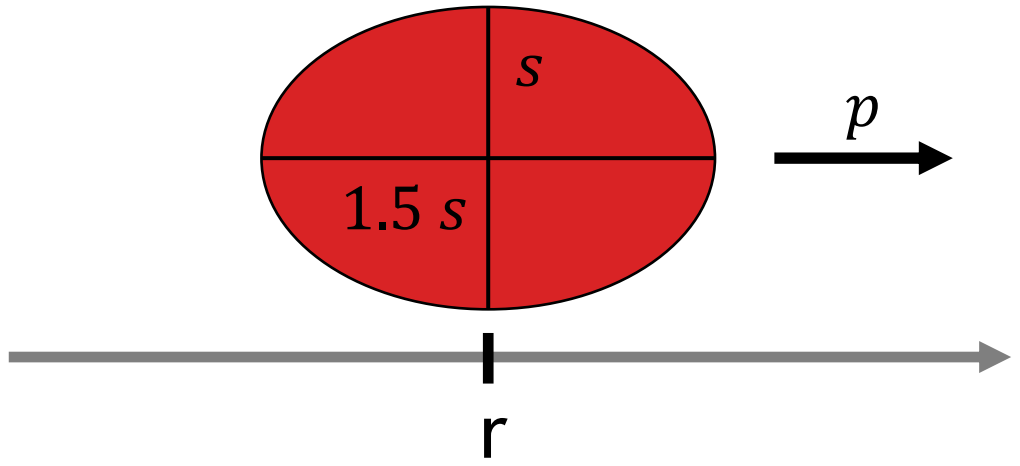
  2. **mergers and exit at boundaries**



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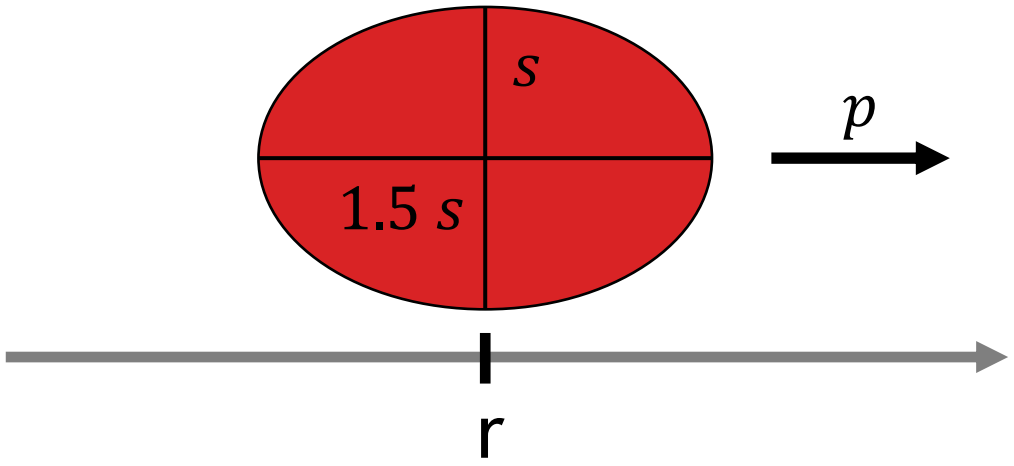
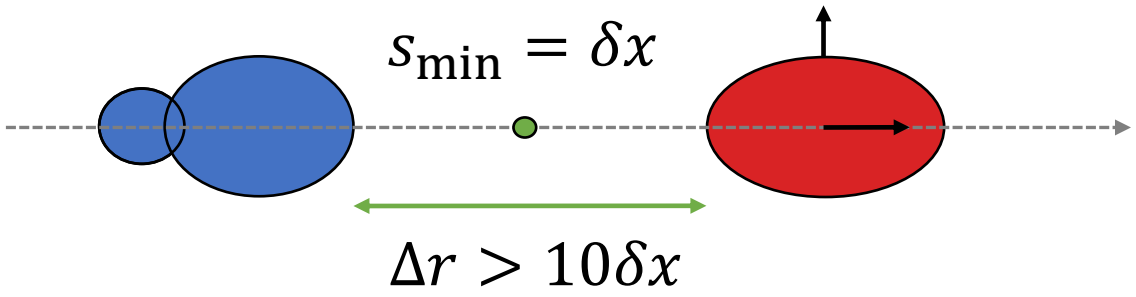
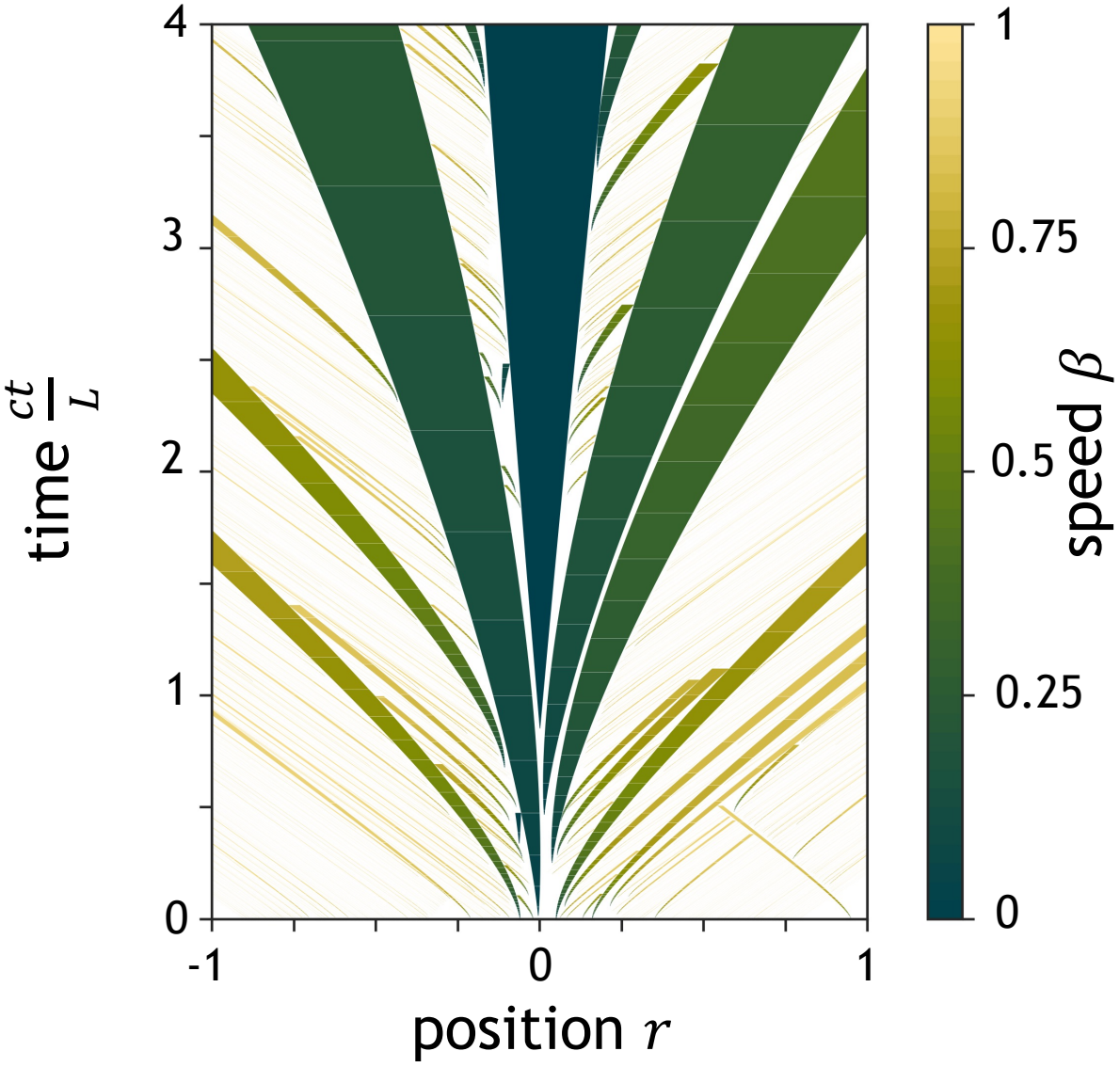
- momentum as function $p(r, s)$
- handle
  1. eqs. of motion and growth
  2. mergers and exit at boundaries
  3. **birth of new plasmoids in free space**

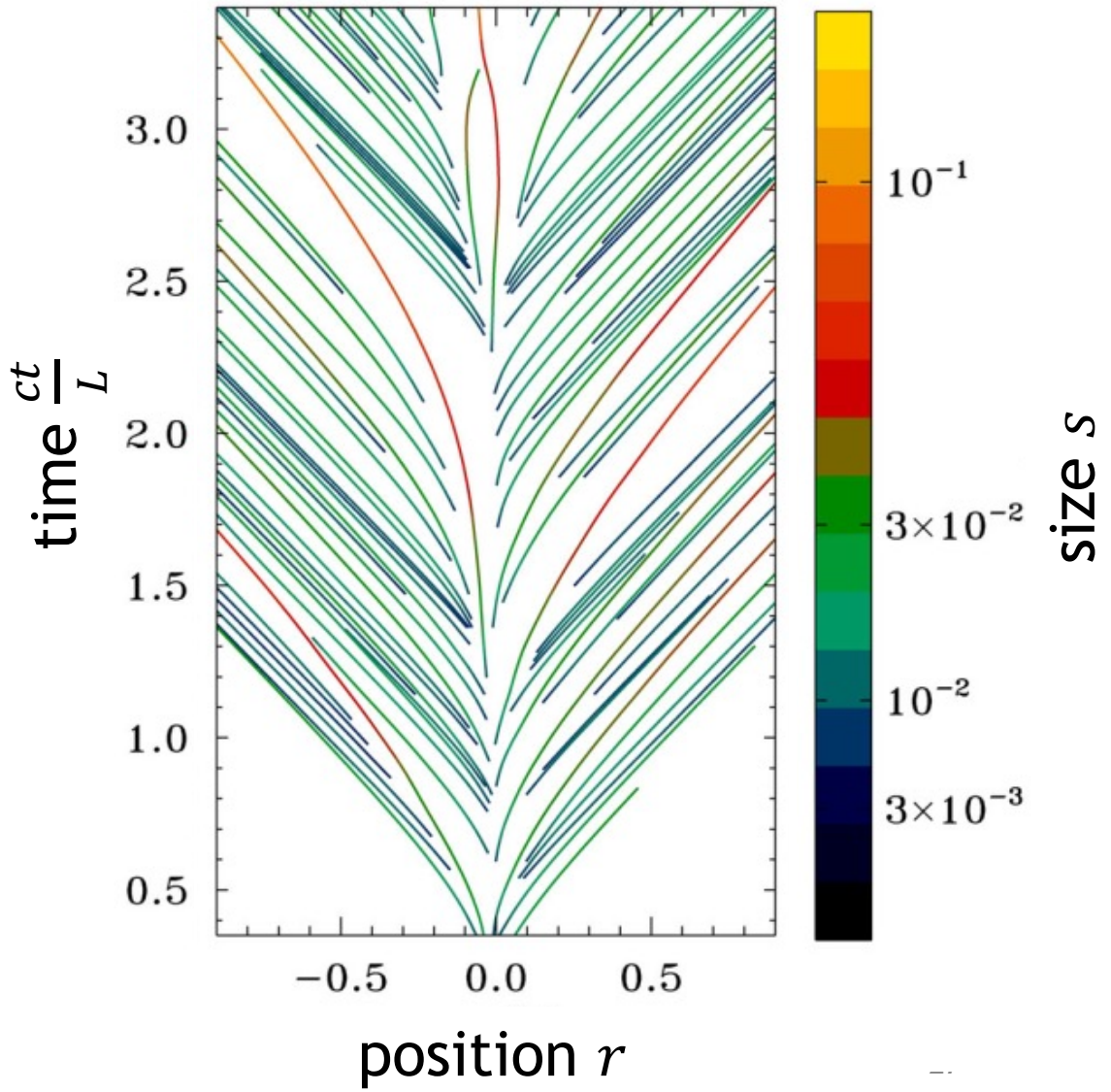




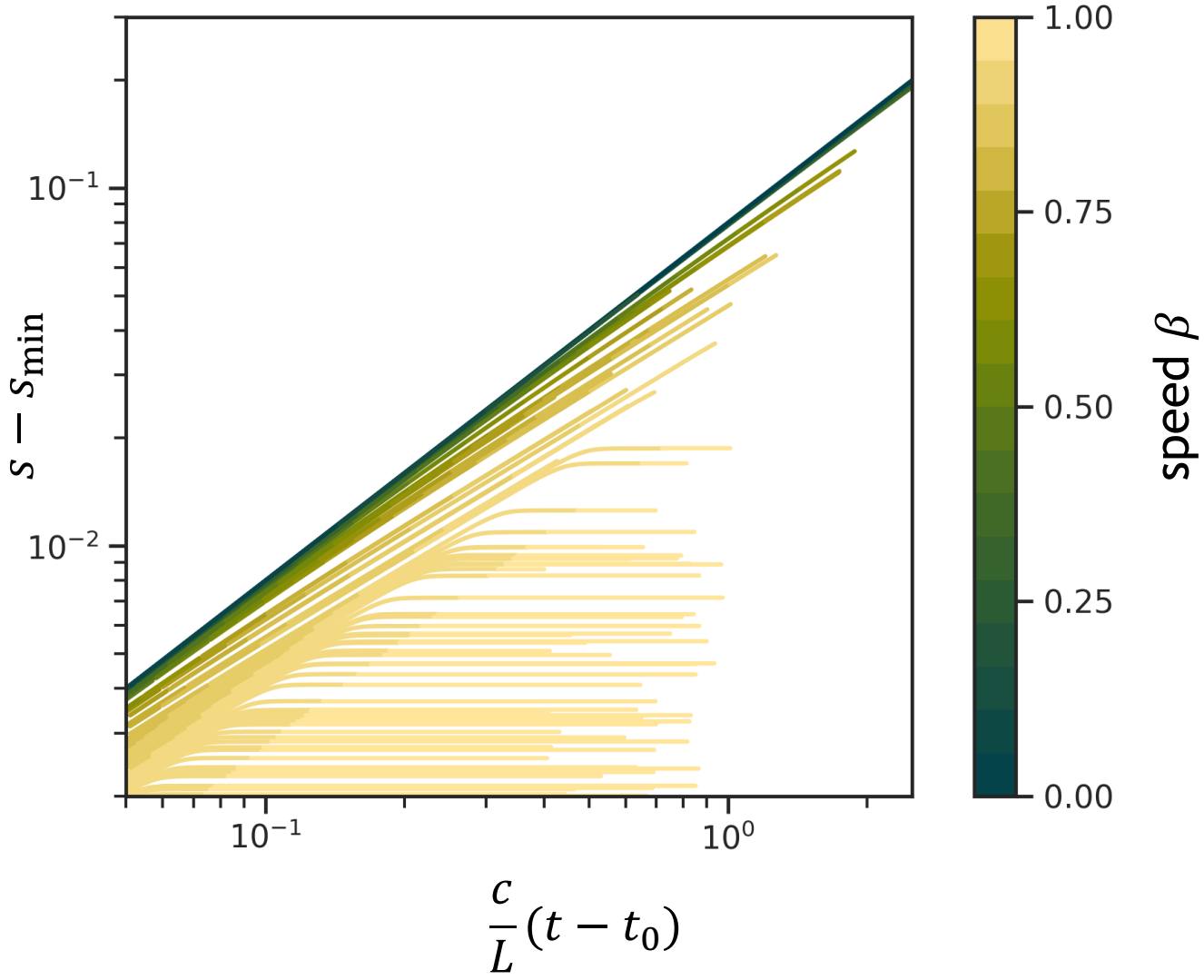
Evolution of a Layer

Sironi, Giannios, Petropoulou (2016) [arXiv: 1605.02071]



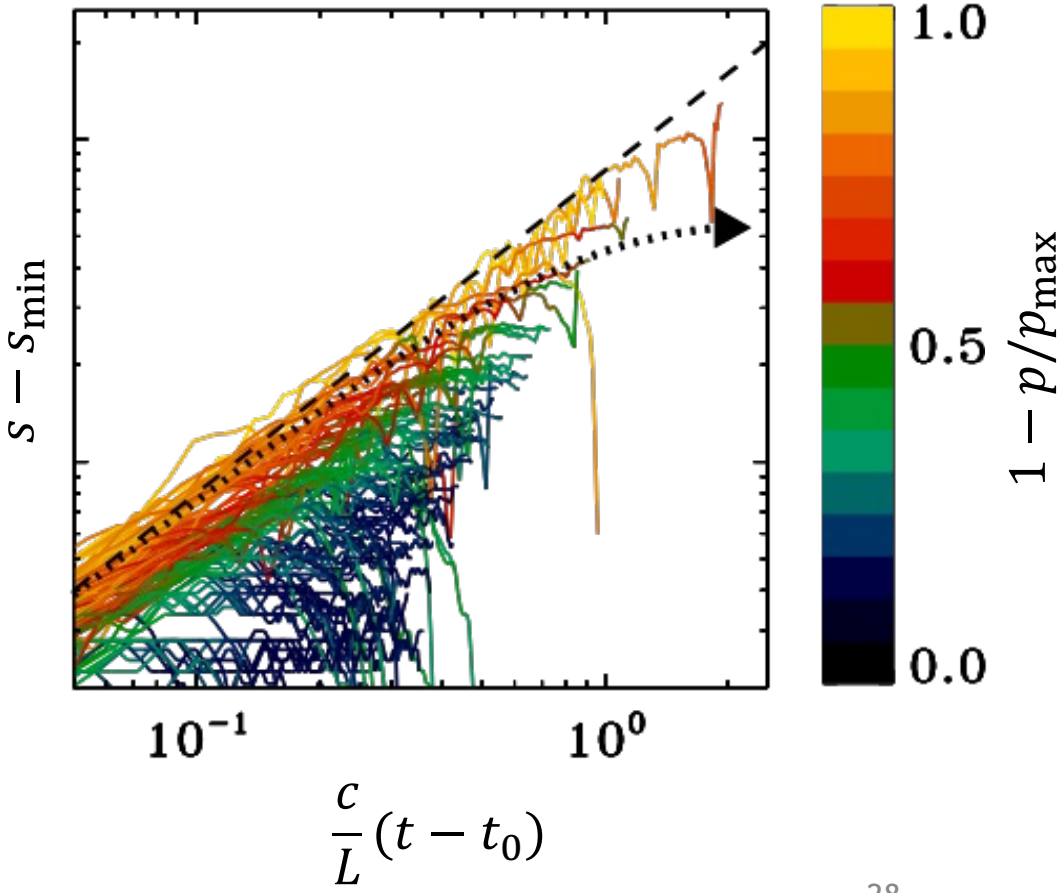


Plasmoid Growth

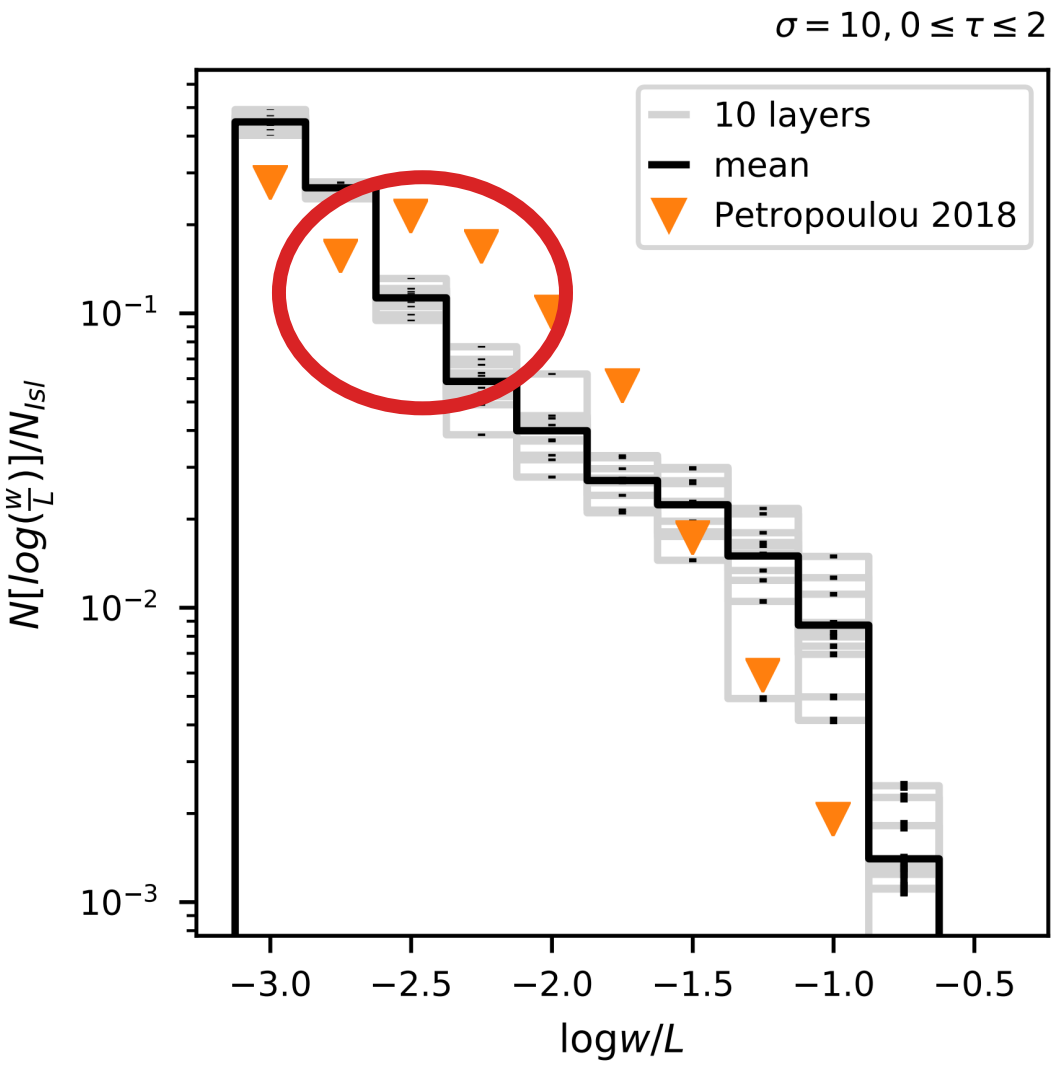


$$\frac{\mathrm{d}s}{\mathrm{d}\tau} = \frac{\beta_g}{\Gamma f_{\mathrm{sup}}(\hat{p})}$$

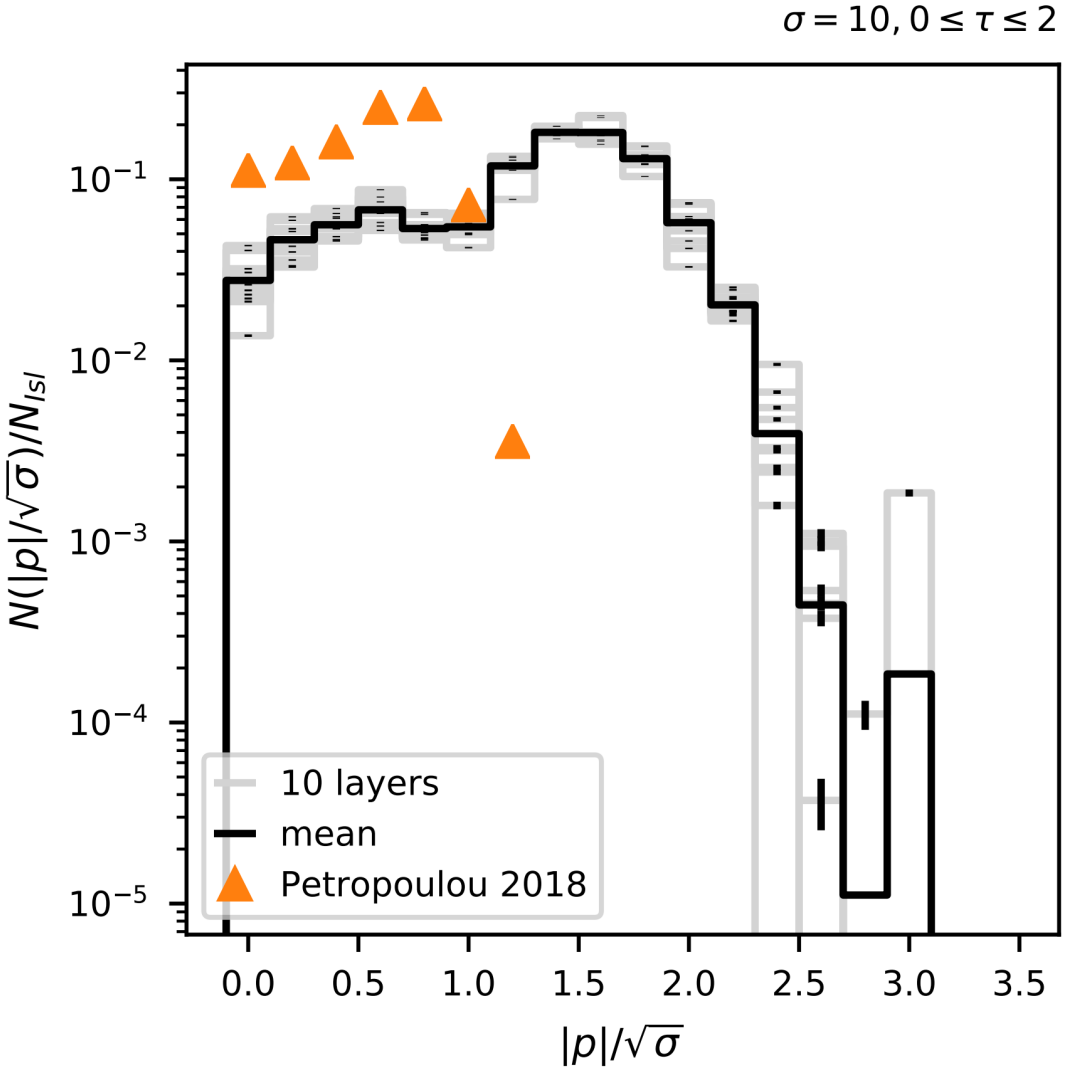
Sironi, Giannios, Petropoulou (2016) [arXiv: 1605.02071]



Size

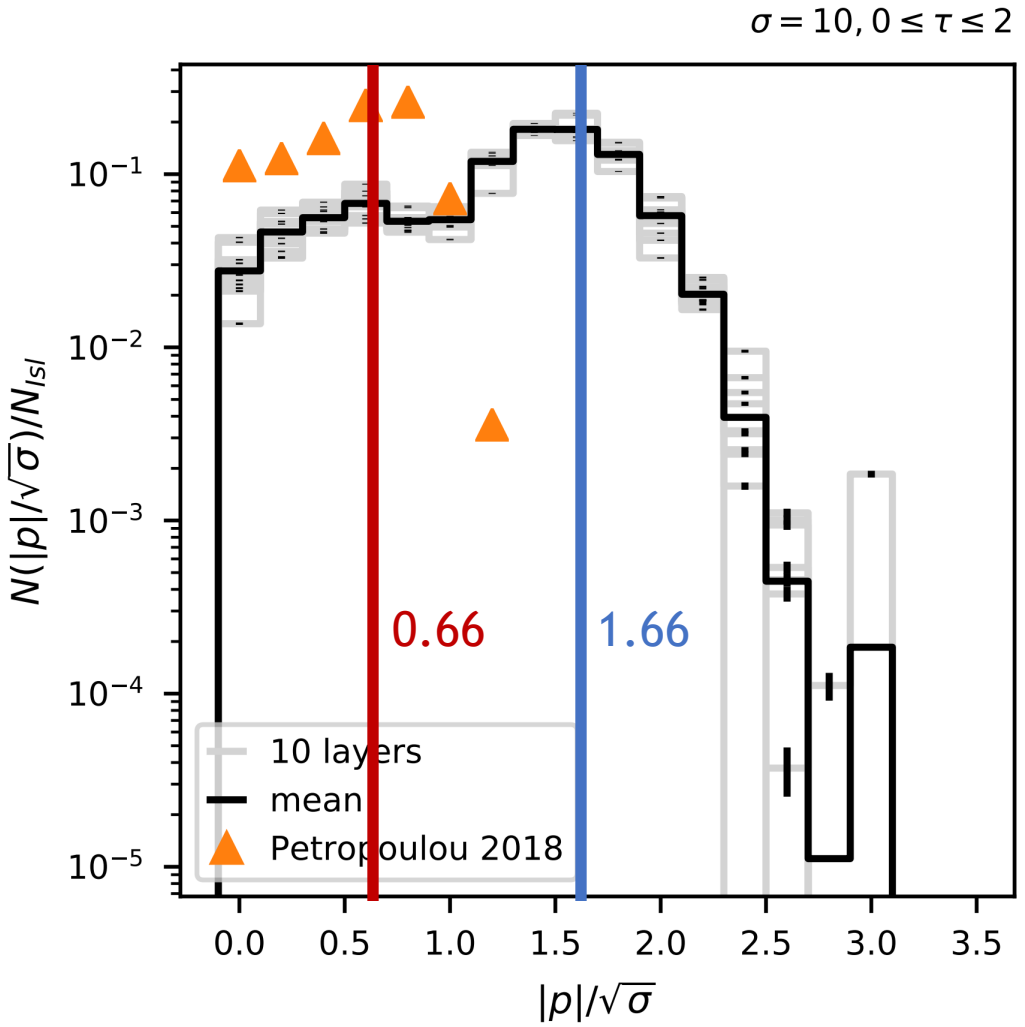


Momentum

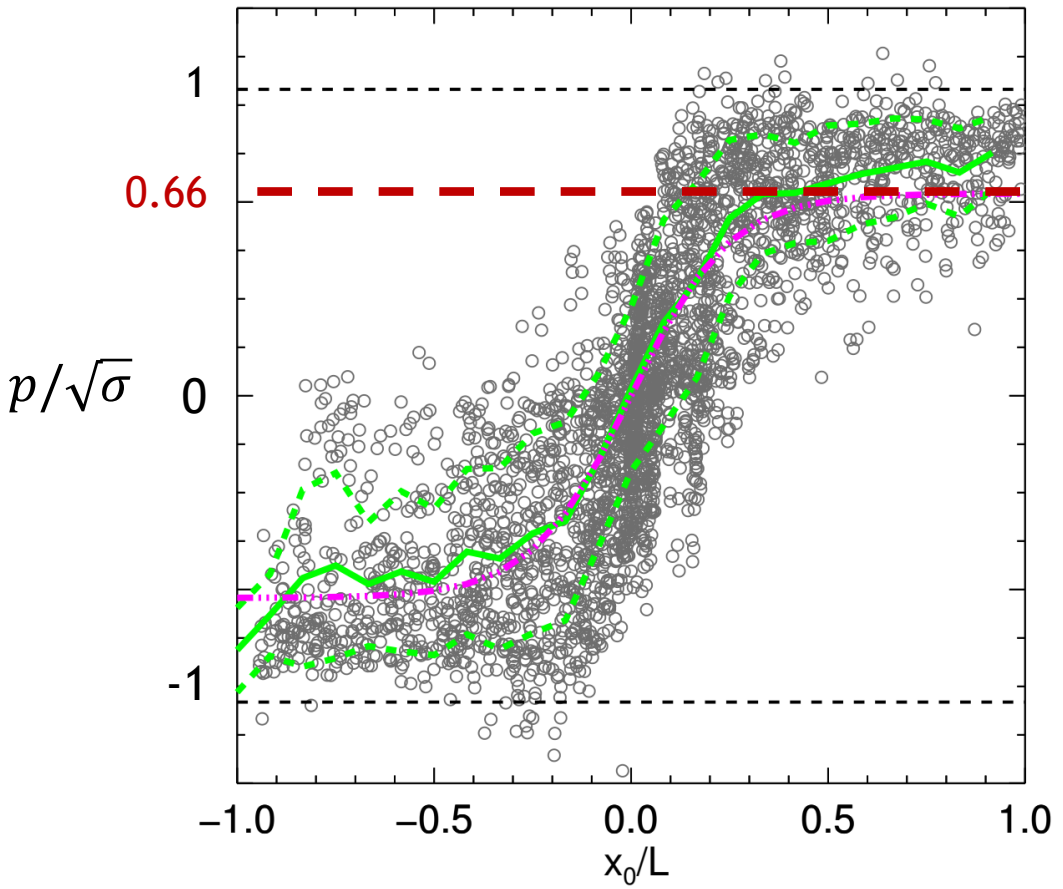


with $s = w/L$

Discrepancy in Momentum Distribution



$$\hat{p}(r(\tau), s(\tau)) = \sqrt{\sigma}\tanh\left(\frac{\beta_a}{\sqrt{\sigma}}\frac{r - r_0}{s}\right) + \hat{p}_0$$

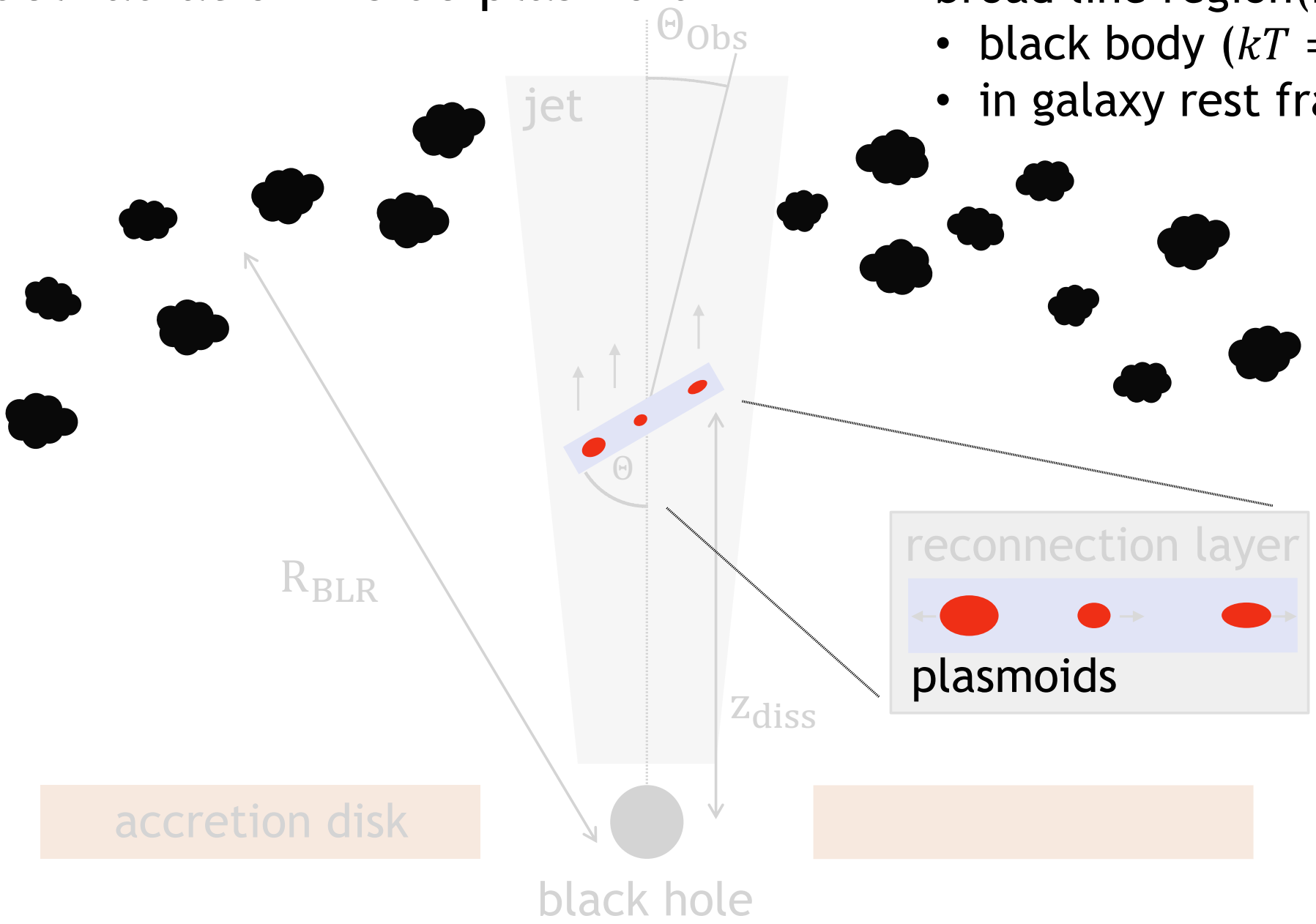


Petropoulou, Christie, Sironi, Giannios (2018) [arXiv: 1710.00724]

Step 2: Model radiation inside plasmoid

broad line region(BLR):

- black body ($kT = 10^{-5} m_e c^2$)
- in galaxy rest frame

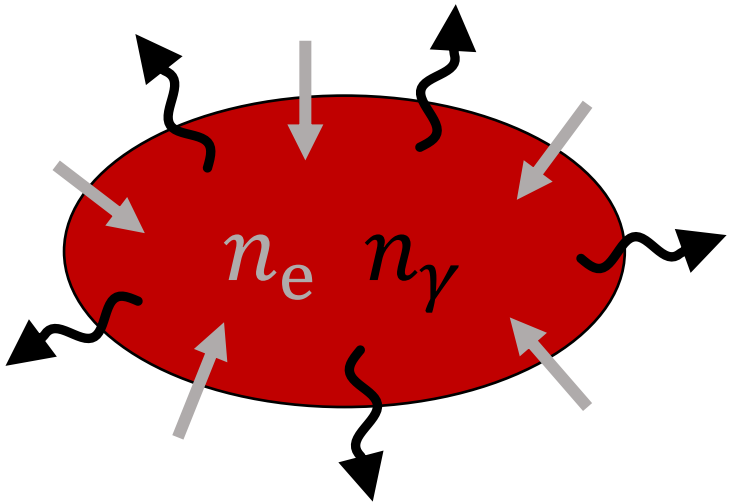


Radiation Modelling

following Christie, Petropoulou, Sironi, Giannios (2018) [arXiv: 1807.08041]

$$\frac{\partial n_e}{\partial \tau} = Q^e_{inj} + Q^e_{\gamma\gamma} - L^e_{syn} - L^e_{IC}$$

$$\frac{\partial n_\gamma}{\partial \tau} = -\frac{n_\gamma}{\tau_{esc}} + Q^\gamma_{syn} + Q^\gamma_{IC} - L^\gamma_{\gamma\gamma} - L^\gamma_{ssa}$$



electron injection:

- from PIC:
  - power law in energy
  - constant number density
  - equipartition of magnetic fields and relativistic particles
- size evolution from Plasmoid Monte Carlos

Radiation Modelling

following Mastichiadis and Kirk (1995) [arXiv:astro-ph/9408077]

$$\frac{\partial n_e}{\partial \tau} = Q^e_{inj} + Q^e_{\gamma\gamma} - L^e_{syn} - L^e_{IC}$$

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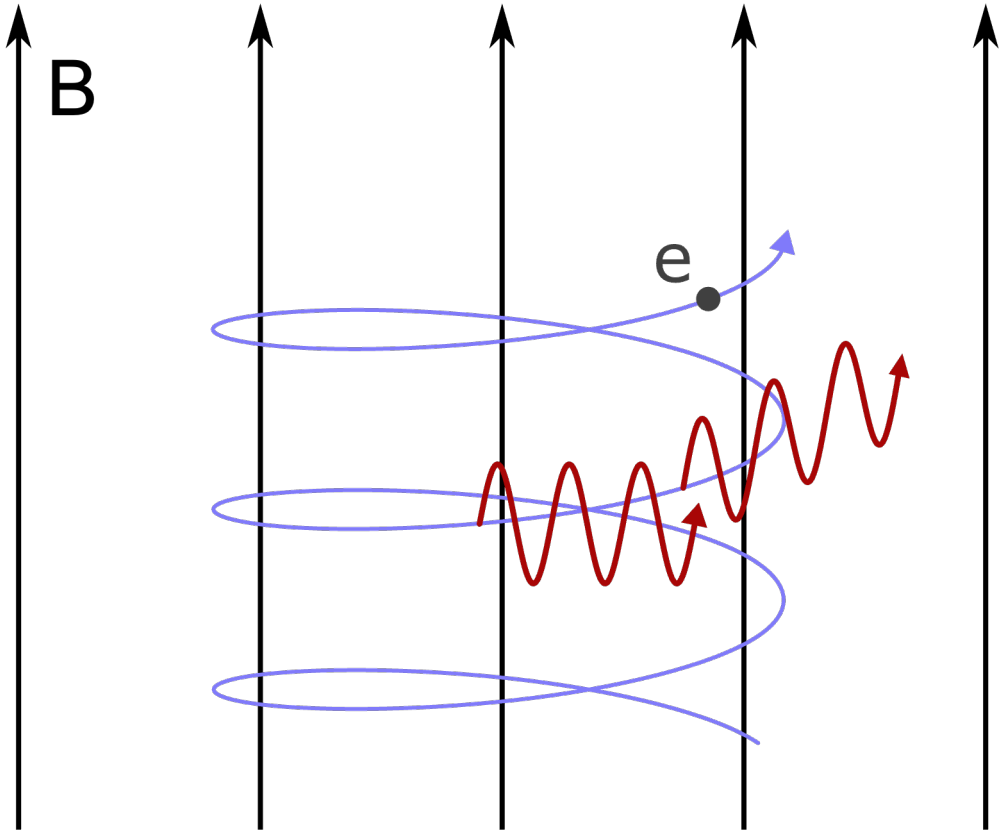
synchrotron radiation

- optical thin
- optical thick
  (synchrotron self-absorption)



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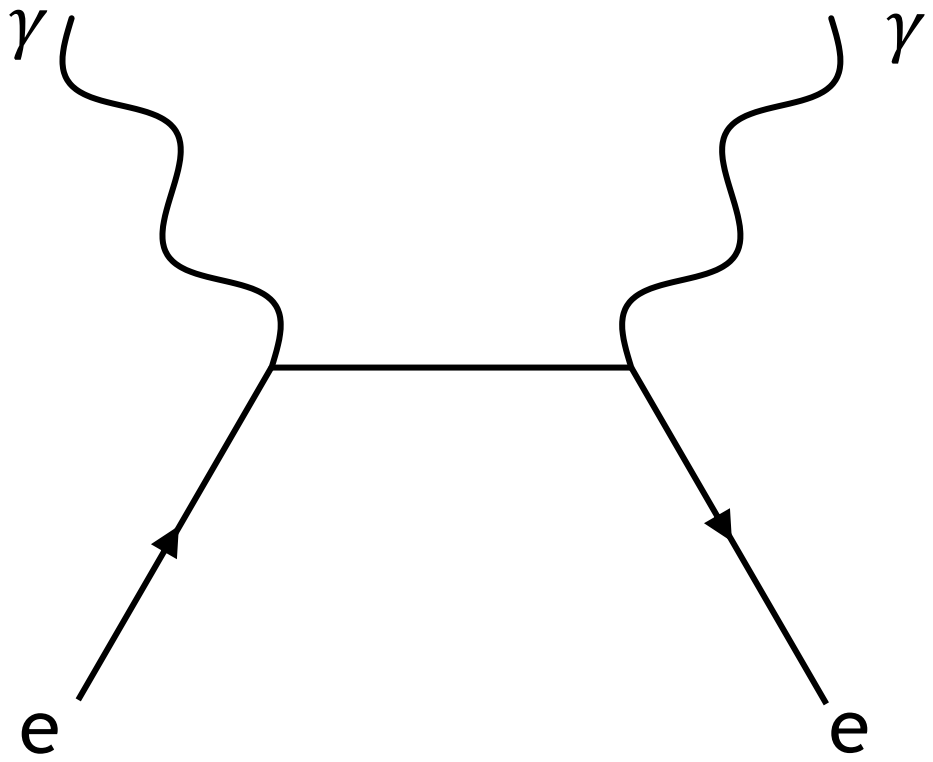
inverse Compton scattering

- Thomson regime ($\gamma\epsilon \ll m_\mathrm{e}c^2$)
- Klein-Nishina regime ($\gamma\epsilon > m_\mathrm{e}c^2$)
- incoming radiation field:
  - synchrotron self-Compton (SSC)
  - external Compton (EC) → black body



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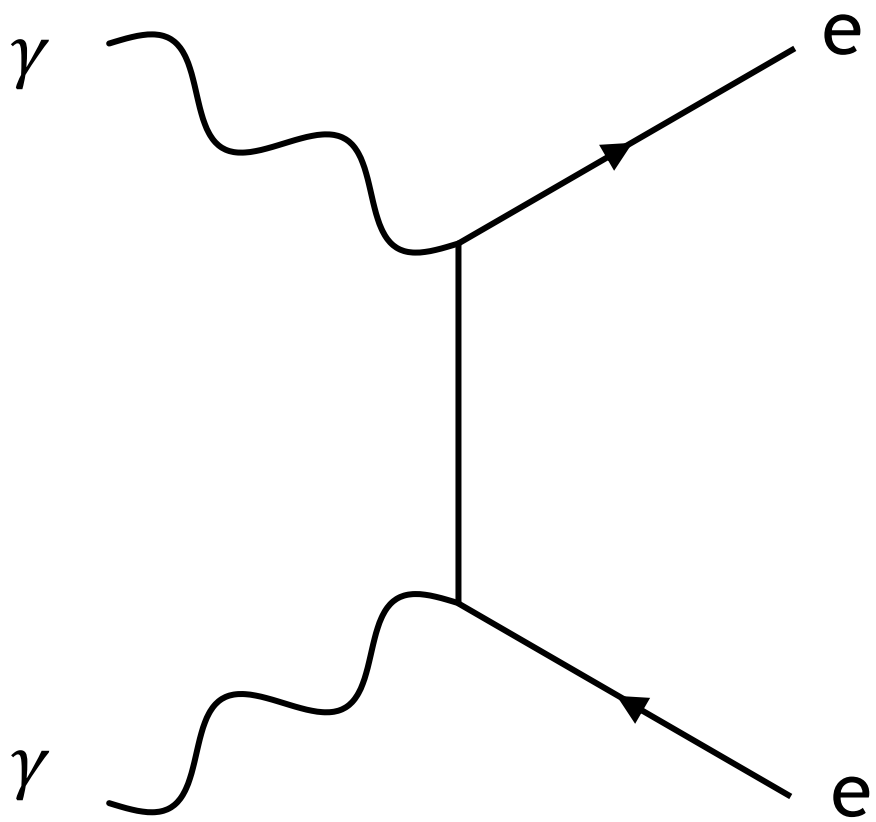
pair production ($\gamma + \gamma \rightarrow e^+ + e^-$)



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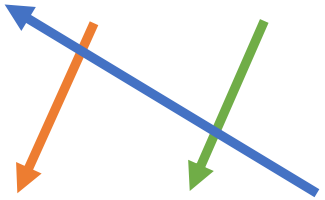
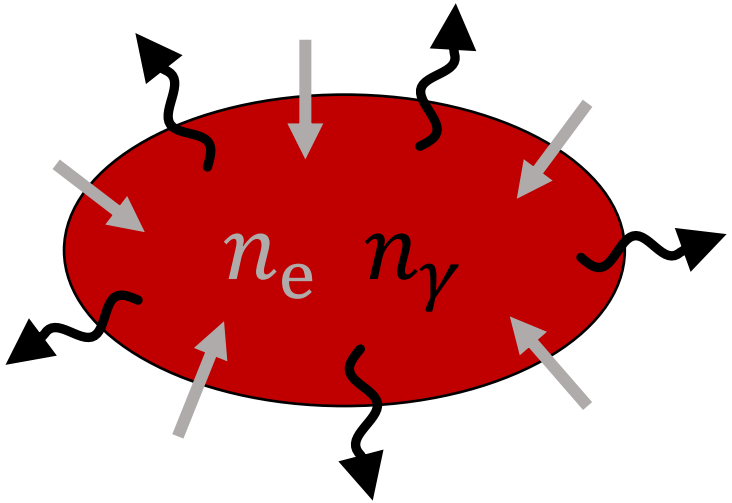


$$\frac{\partial n_\gamma}{\partial \tau} = -\frac{n_\gamma}{\tau_{esc}} + Q^\gamma_{syn} + Q^\gamma_{IC} - L^\gamma_{\gamma\gamma} - L^\gamma_{ssa}$$

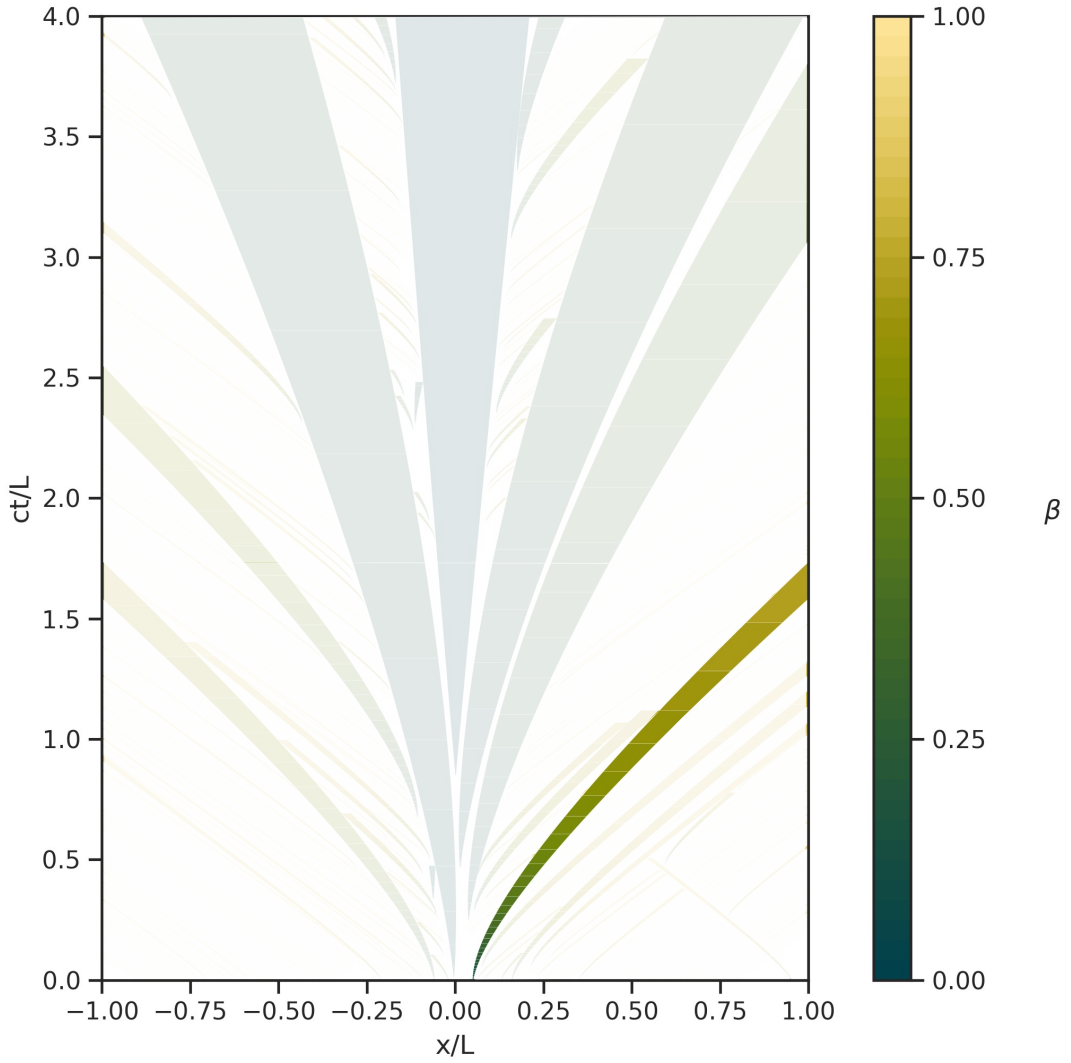


photon escape:

- rescale to plasmoid volume V
- number of emitted photons per $\mathrm{d}x = \frac{h\mathrm{d}\nu}{m_e c^2}$:

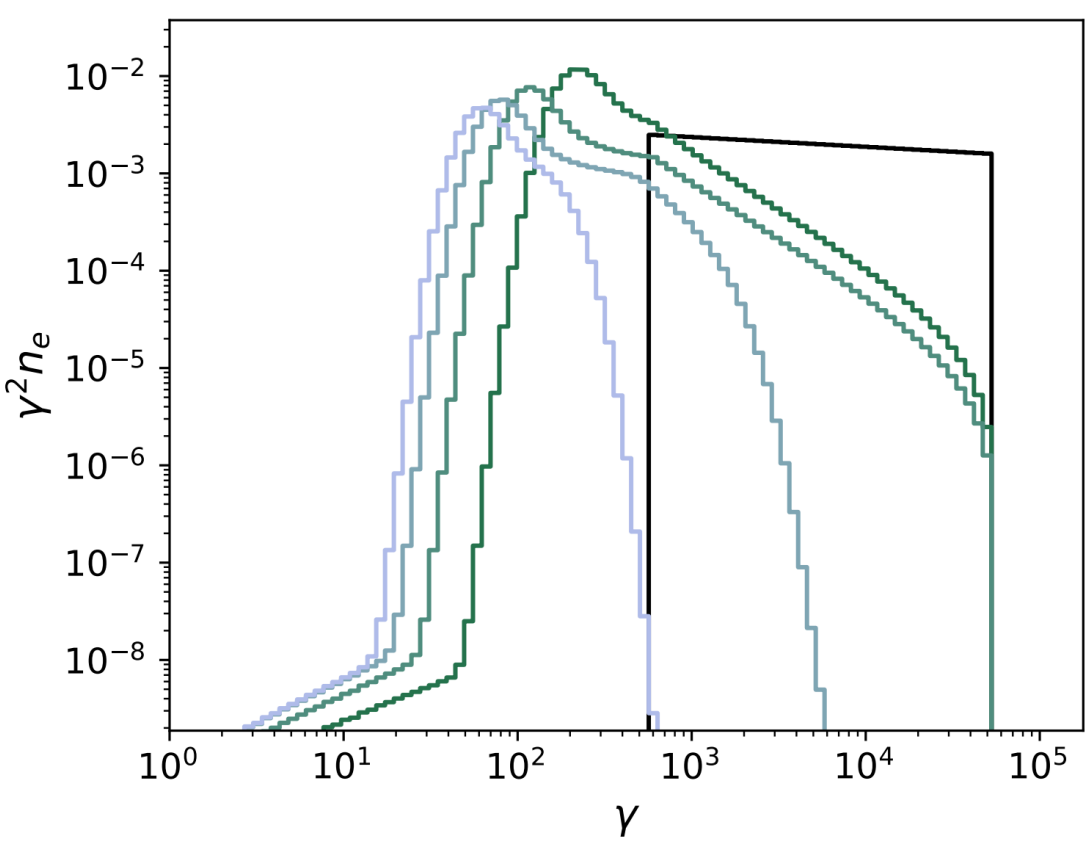
$$\frac{\mathrm{d}N(x,t)}{\mathrm{d}x} \sim V \frac{n_\gamma(x,t)}{\tau_{esc}}$$

Results for Exemplary Plasmoid

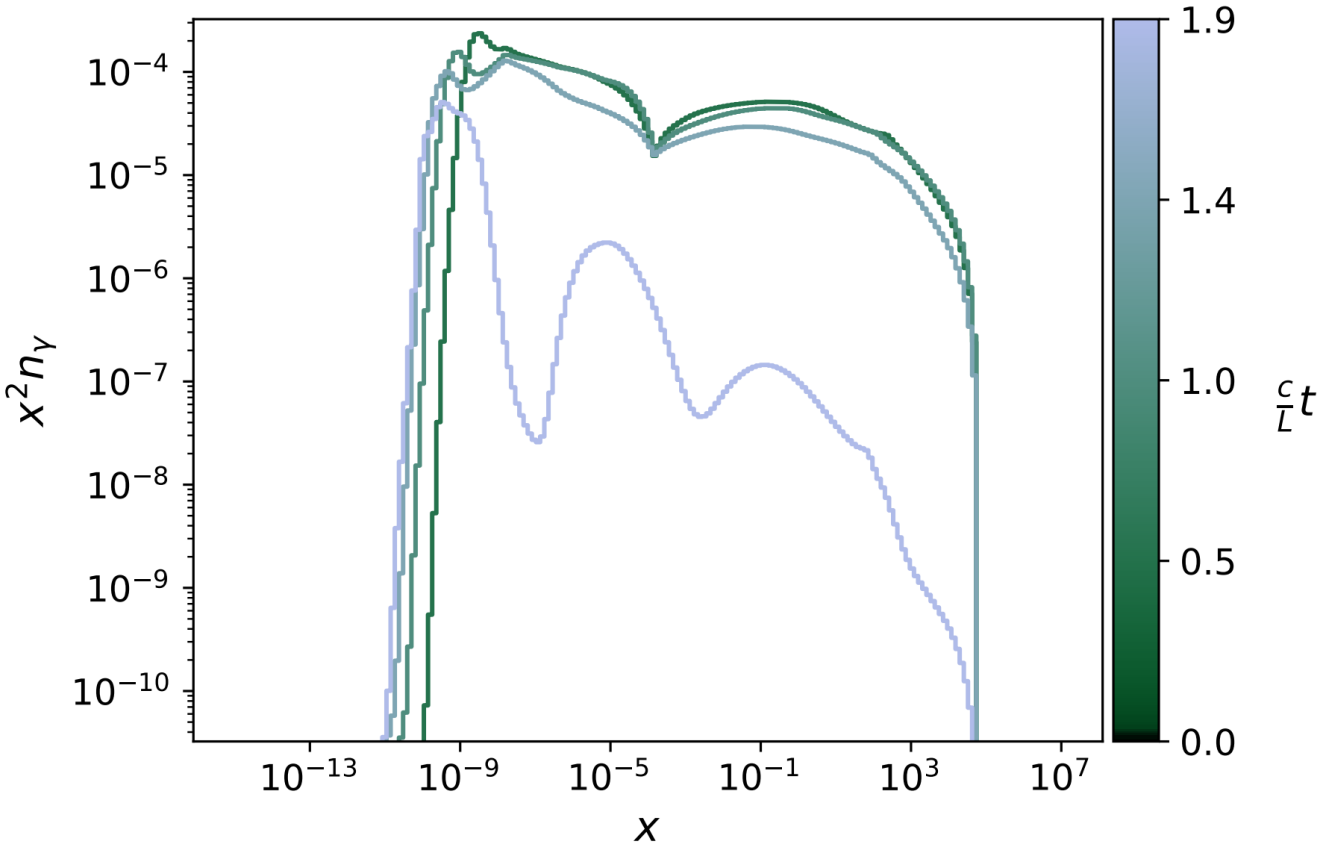


Rest Frame: BL Lac

electrons

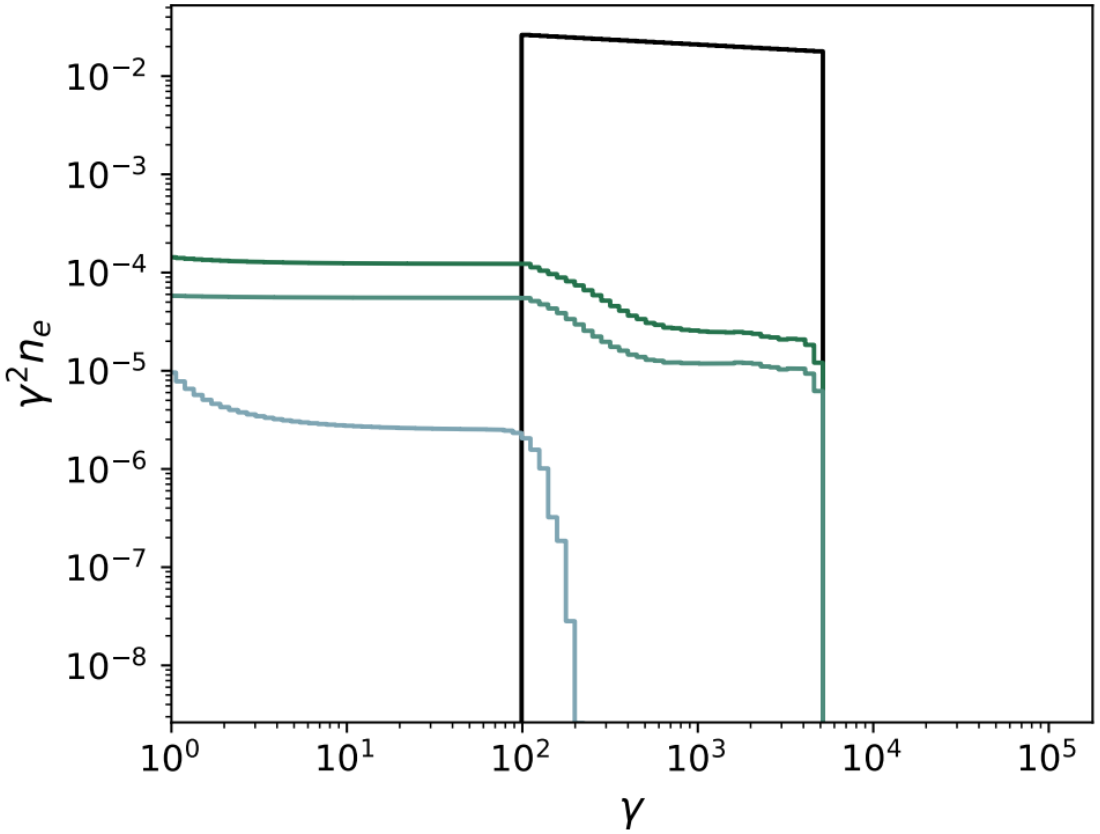


photons



Rest Frame: FSRQ

electrons



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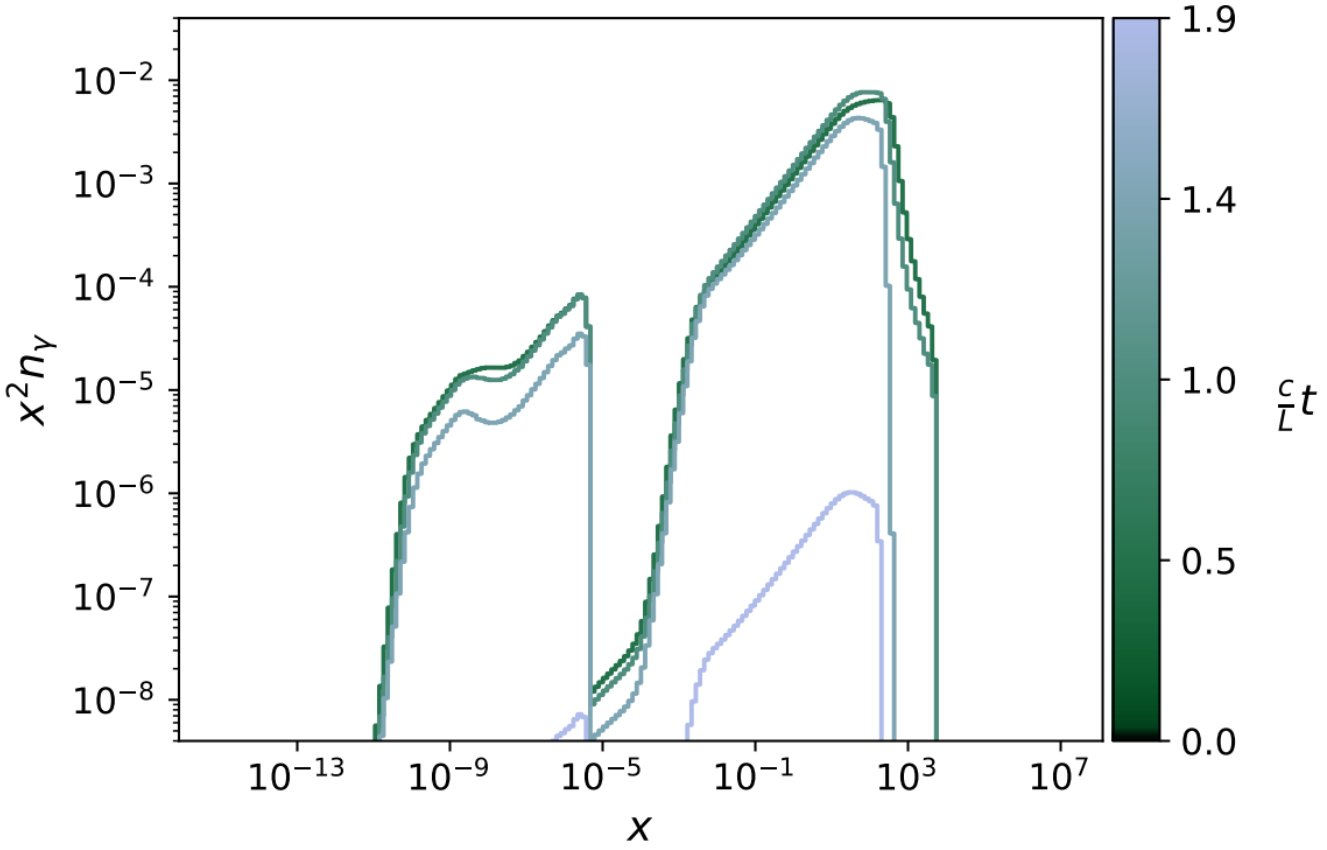
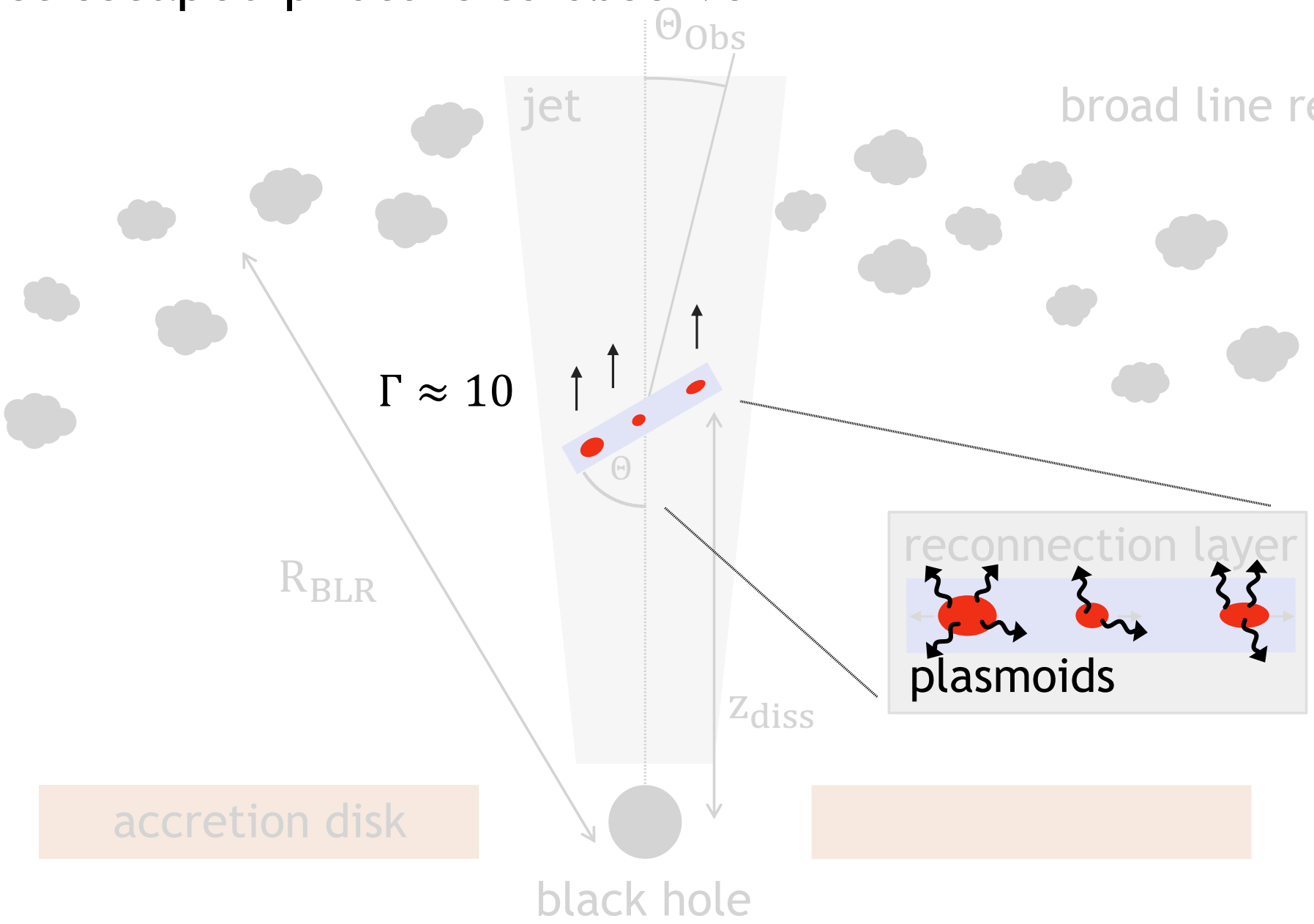


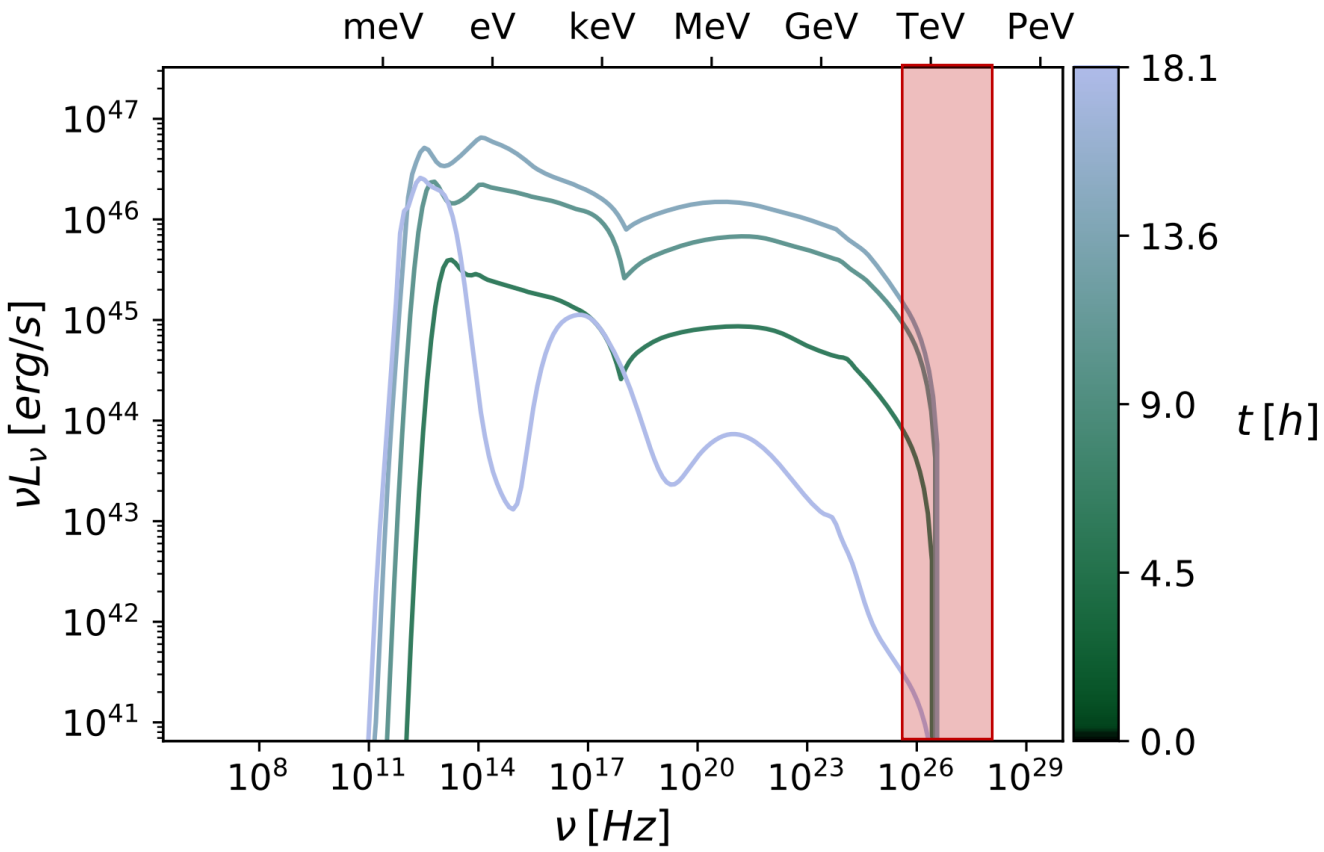
Step 3: Boost escaped photons to observer

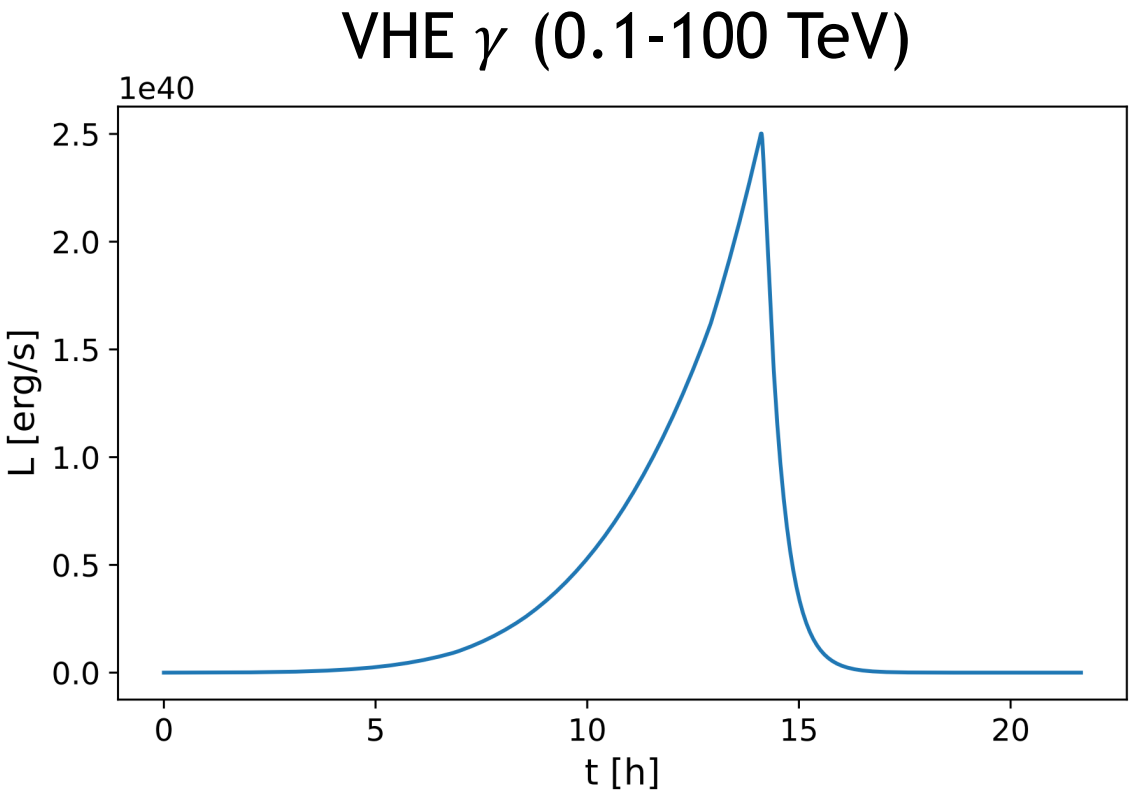


Processing of Photon Escape

- special relativity: relativistic Doppler effect
- 3 frames:
  - plasmoid
  - reconnection layer
  - observer / BLR
- spectrum (binned in energy): $\delta^4 \, x^2 \, \frac{\mathrm{d}N(x,t)}{\mathrm{d}x}$
- light curve (binned in time) : $\delta^4 \int \mathrm{d}x \, x \, \frac{\mathrm{d}N(x,t)}{\mathrm{d}x}$

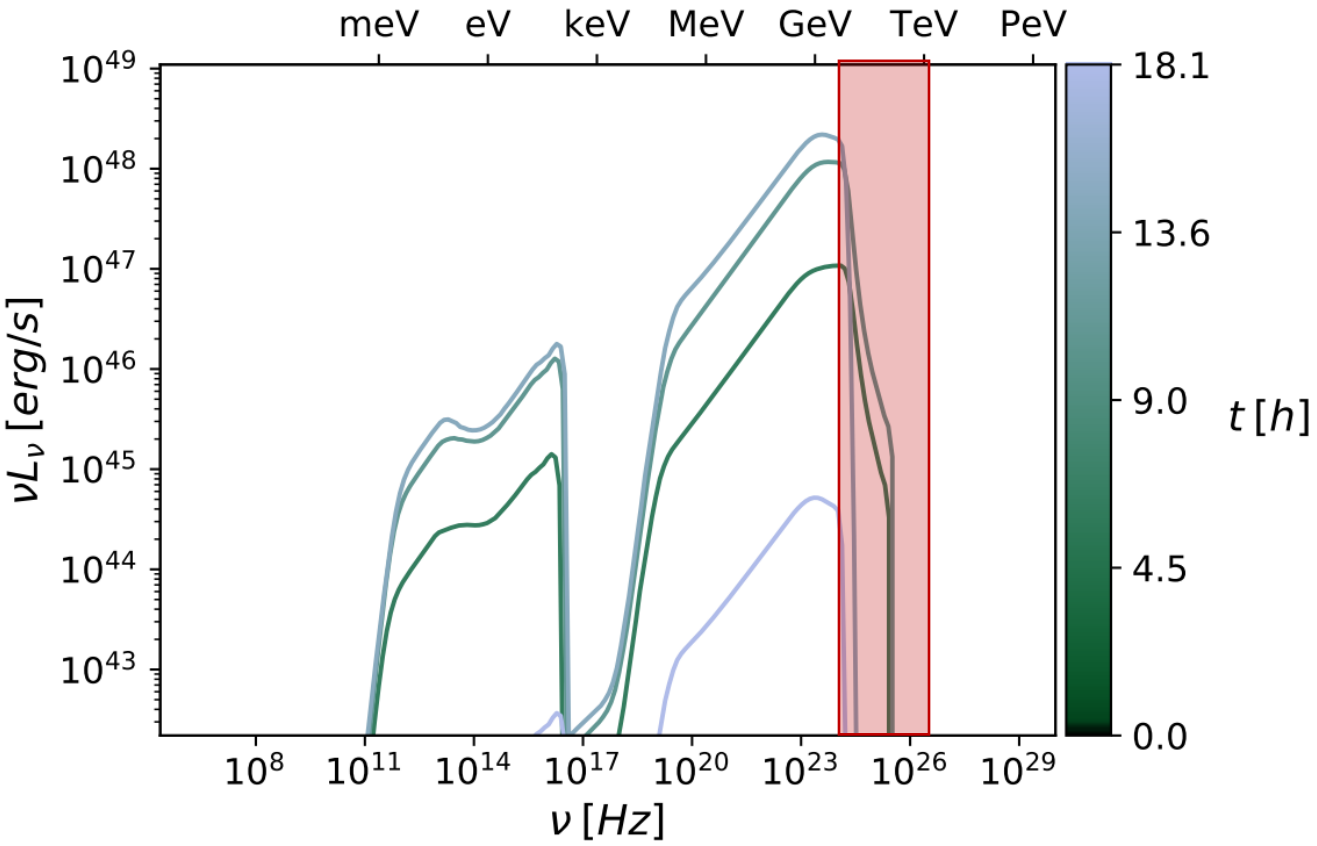
BL Lac in Observer Frame



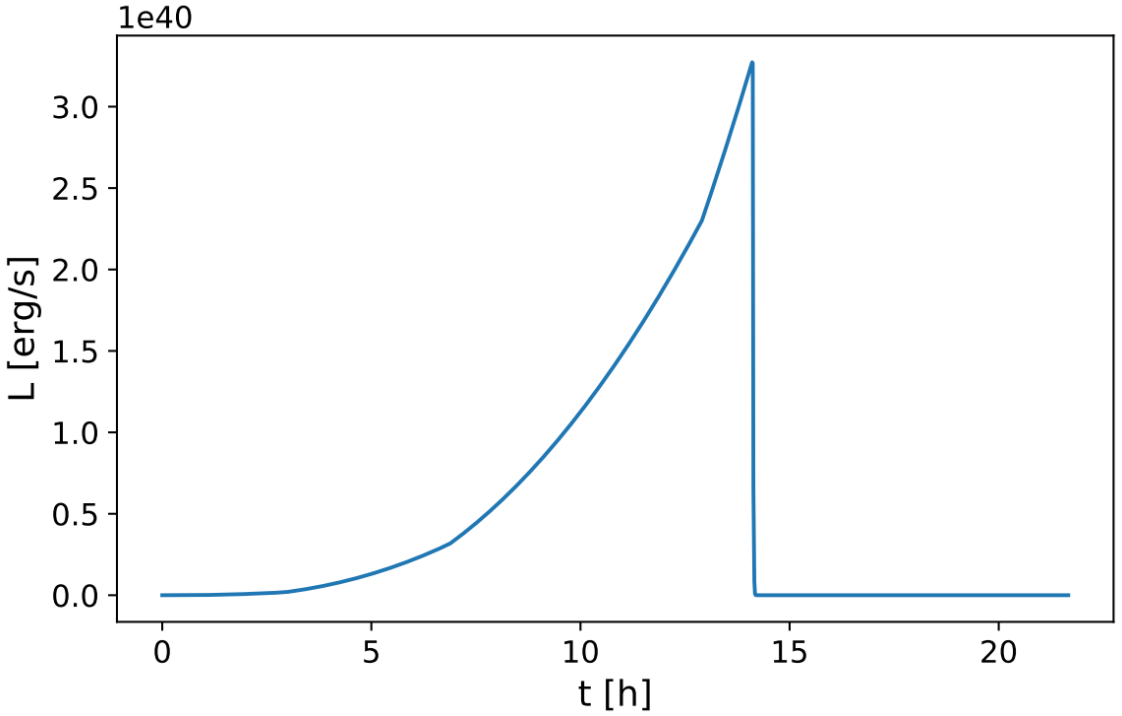


→ flux doubling time ~4h

FSRQ in Observer Frame

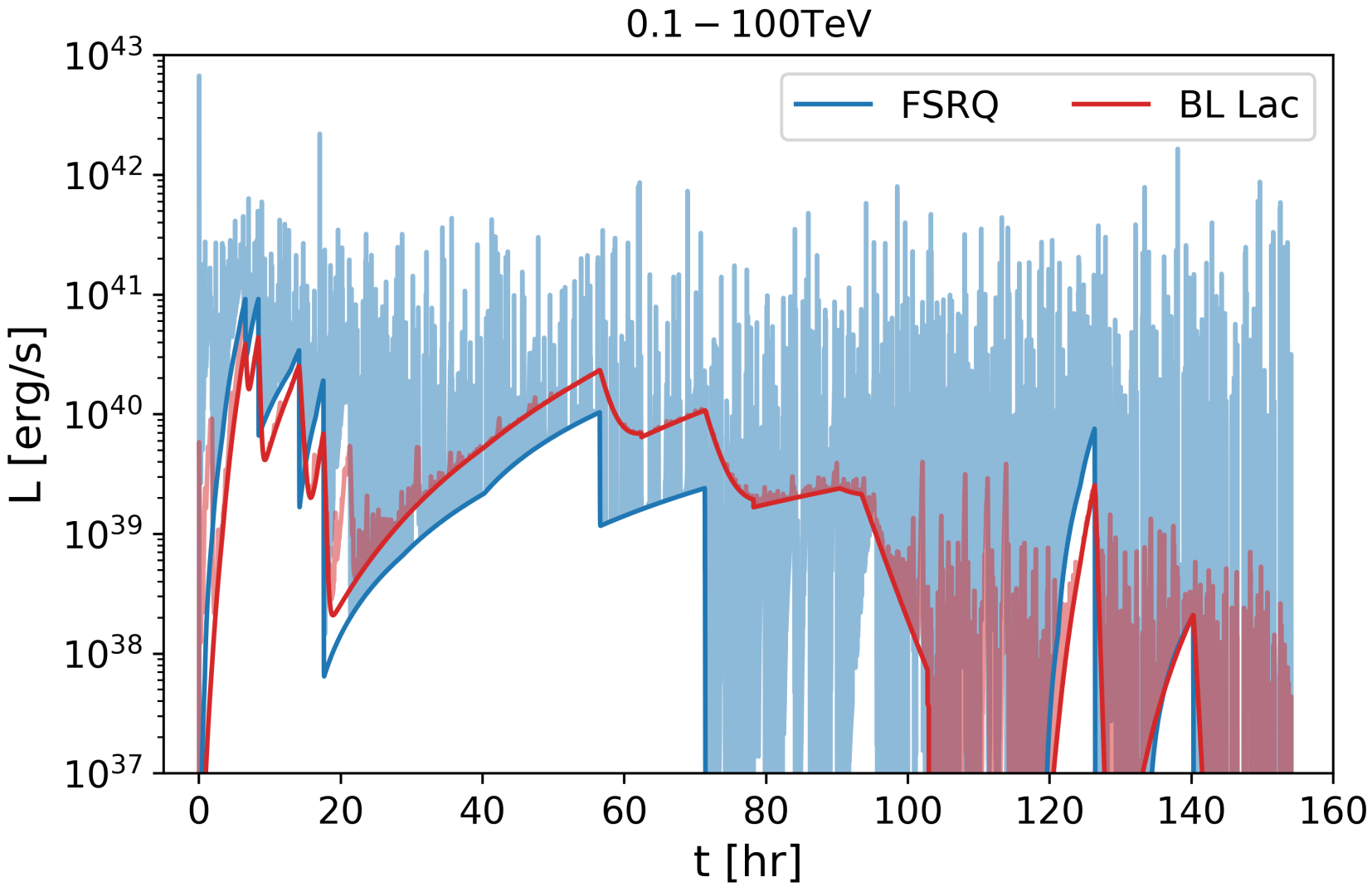


VHE γ (0.1-100 TeV)

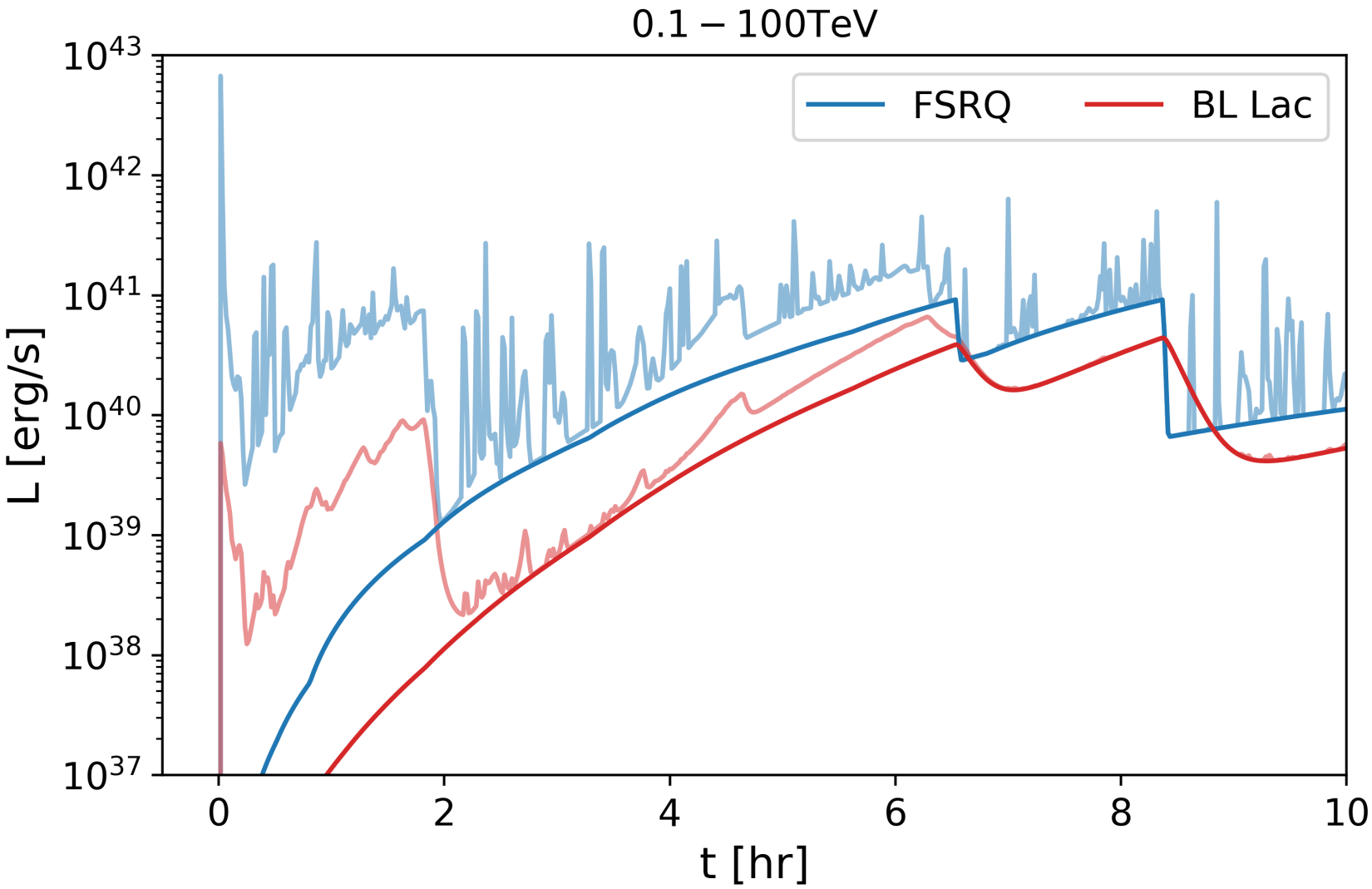


→ flux doubling time ~3h

Complete Layer

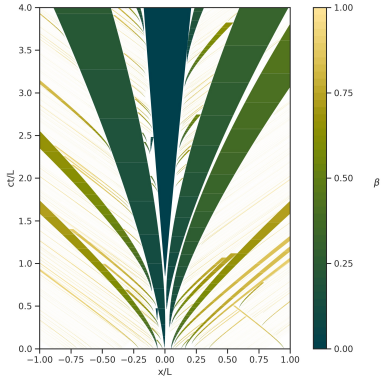


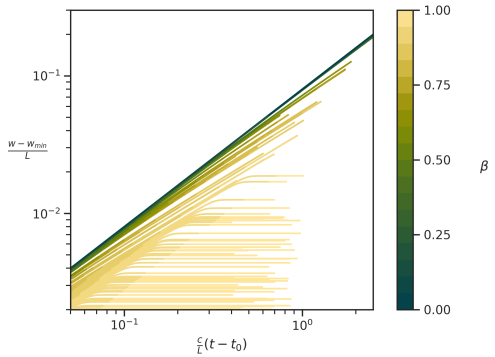
Complete Layer

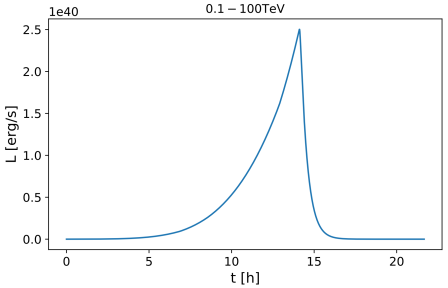


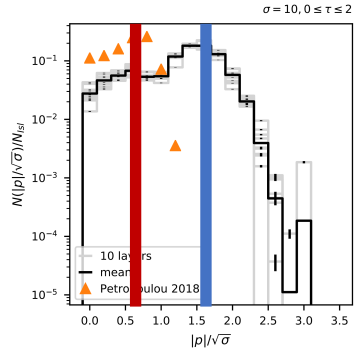
Summary

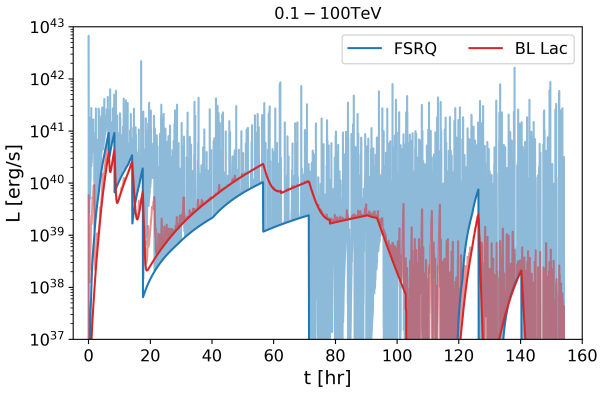
- simulated reconnection layer with MC approach and compared it to PIC simulations
- modelled radiation inside plasmoid and boosted results to observers frame
- presented spectra and VHE light curves for exemplary plasmoid
- presented a lightcurve of the complete layer

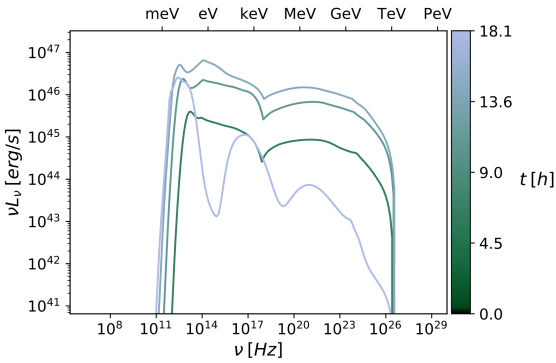












Conclusions and Outlook

Can blazar variability be explained by magnetic reconnection?

Conclusions and Outlook

Can blazar variability be explained by magnetic reconnection?

probably…

- Discrepancy of MC distributions?
- long term evolution of layer?
- more than one layer?
- effect of pair production and SSC?
- interplay of plasmoids?

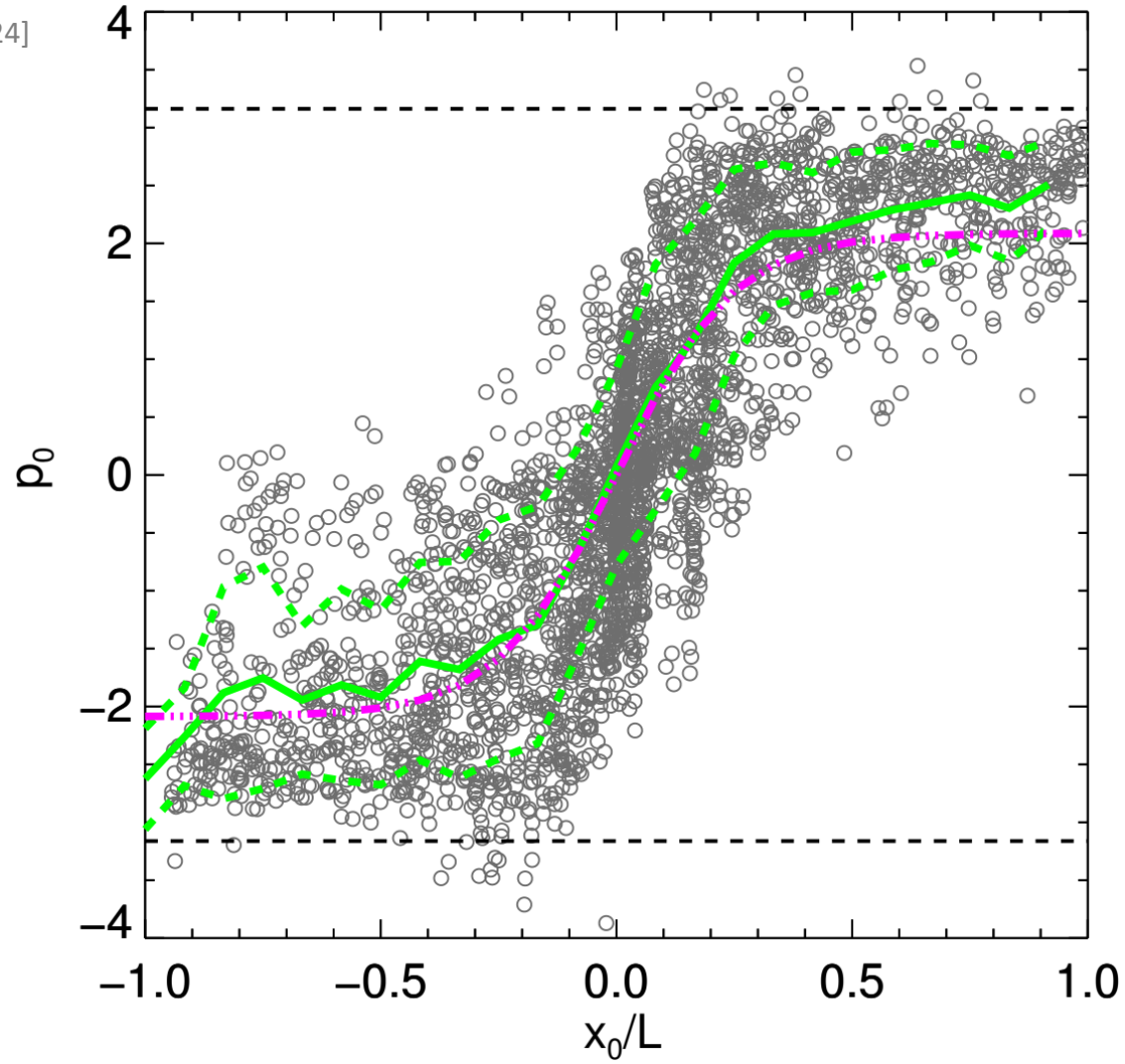
- explore parameter space for realistic solutions
- correlation of different wavelengths
- compare to multiwavelength data

Backup

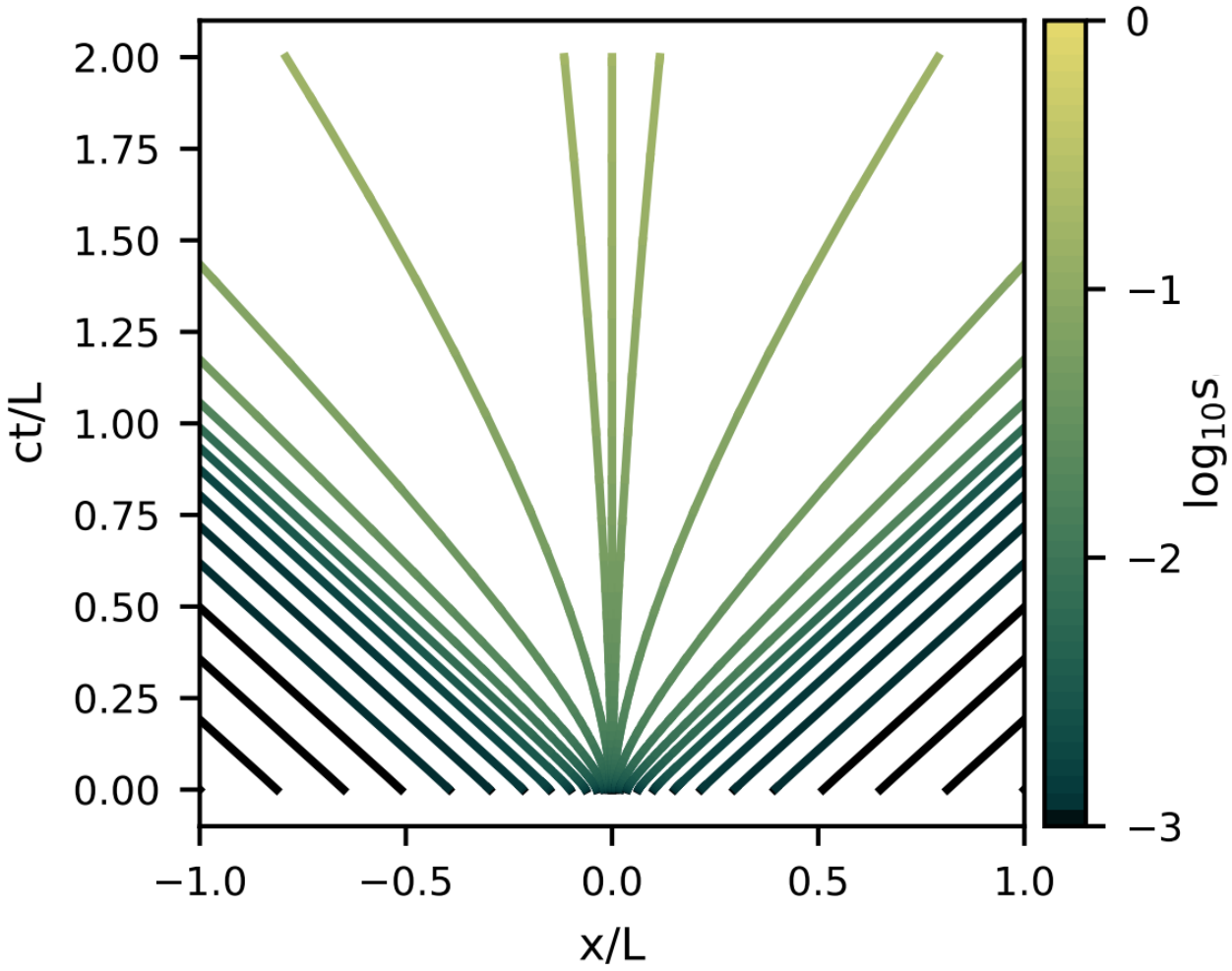
Initial Momentum

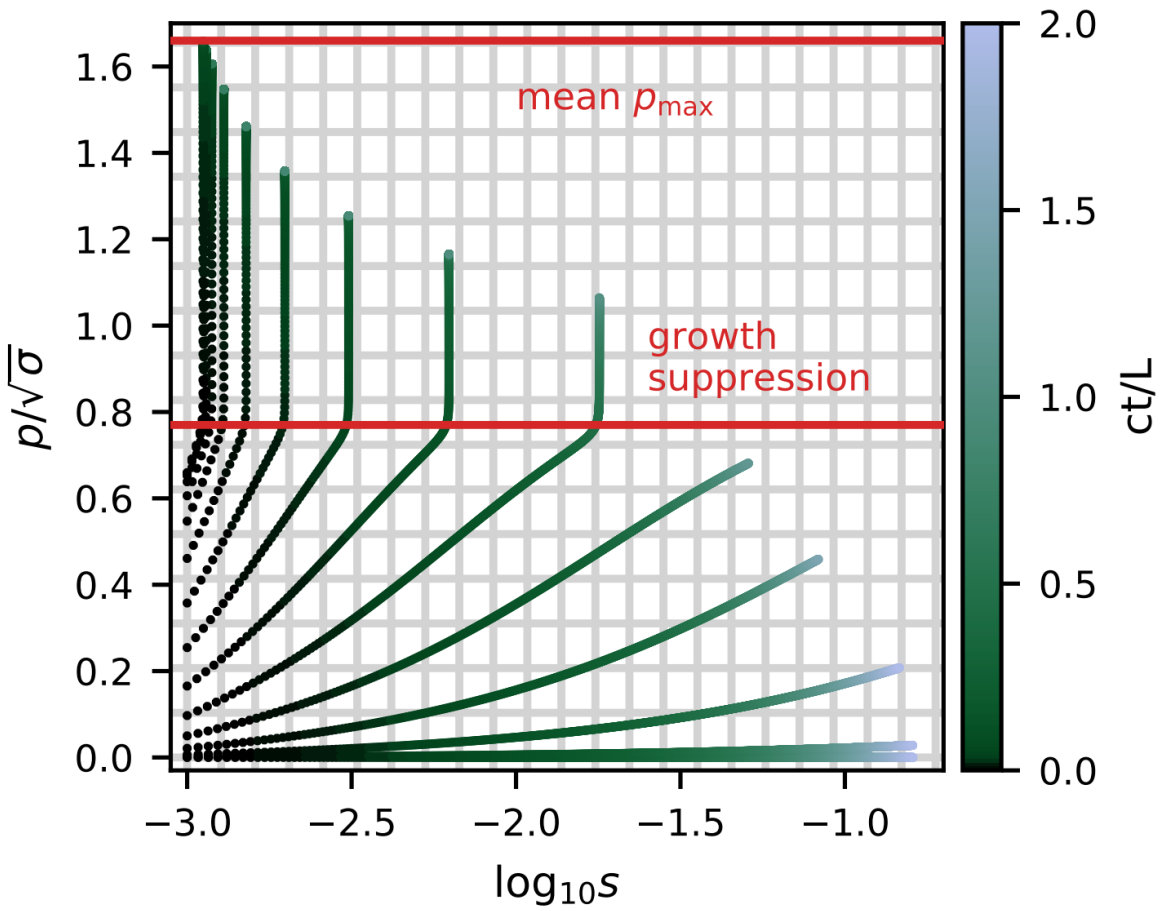
Petropoulou, Christie, Sironi, Giannios (2017) [arXiv: 1710.00724]

- initial momentum correlated to initial position:
  - normal distribution
  - $\langle p_0 \rangle = 0.66\,\sqrt{\sigma}\,\tanh\left(\frac{x_0}{l_0}\right)$
  - std. deviation: $0.3\,\sqrt{\sigma}$



Growth and Motion only

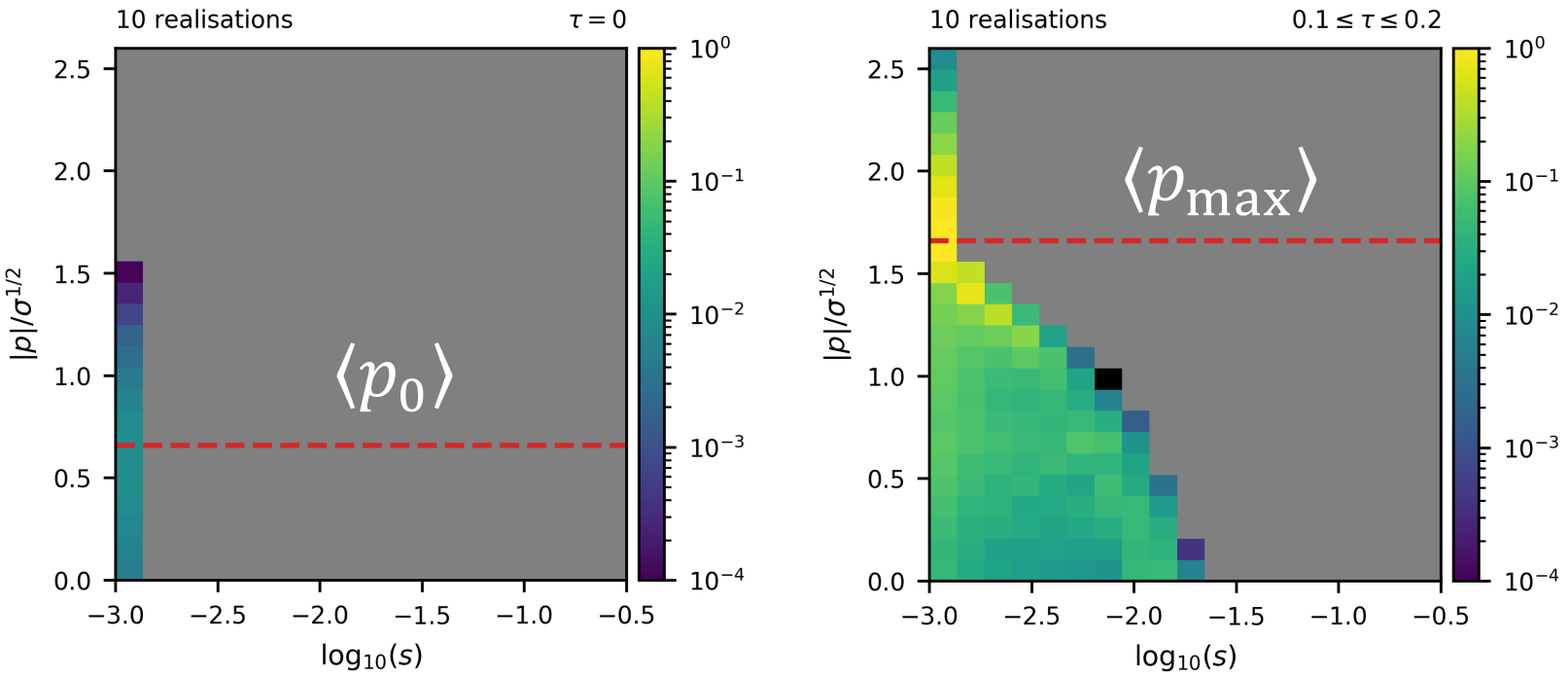




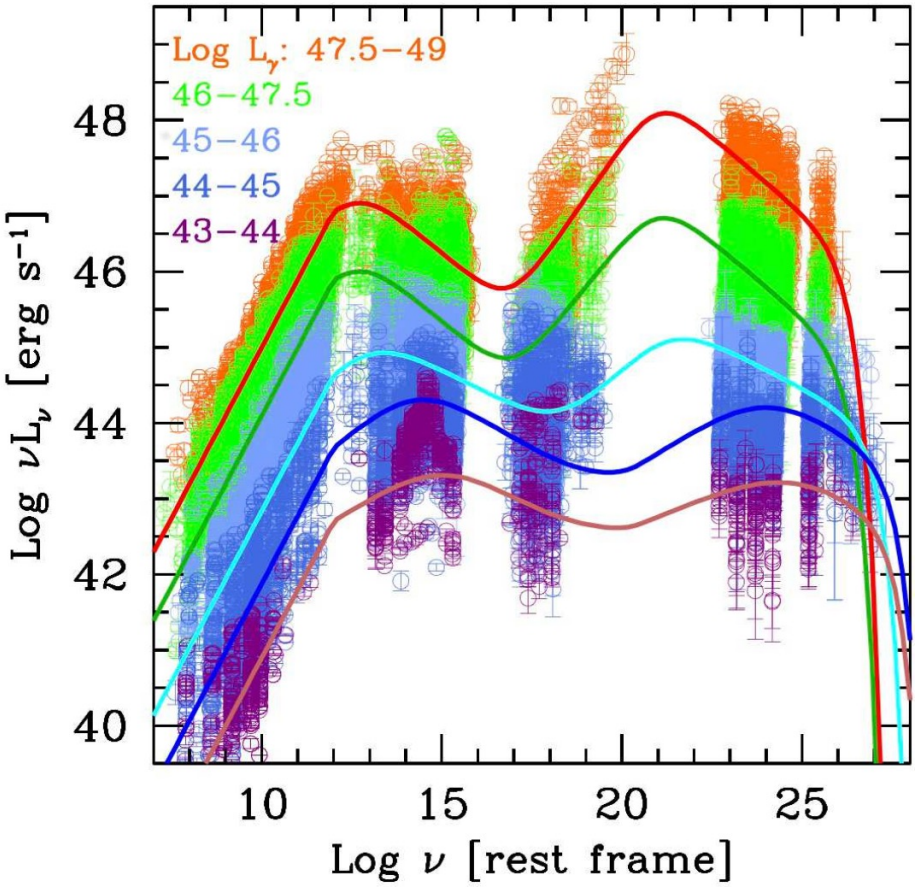
Temporal Evolution

$$\hat{p}(r(\tau), s(\tau)) = \sqrt{\sigma}\tanh\left(\frac{\beta_a}{\sqrt{\sigma}}\frac{r - r_0}{s}\right) + \hat{p}_0$$

$$\sim \mathcal{N}\left(0.66\sqrt{\sigma}\tanh\left(\frac{x_0}{l_0}\right), 0.3\sqrt{\sigma}\right)$$



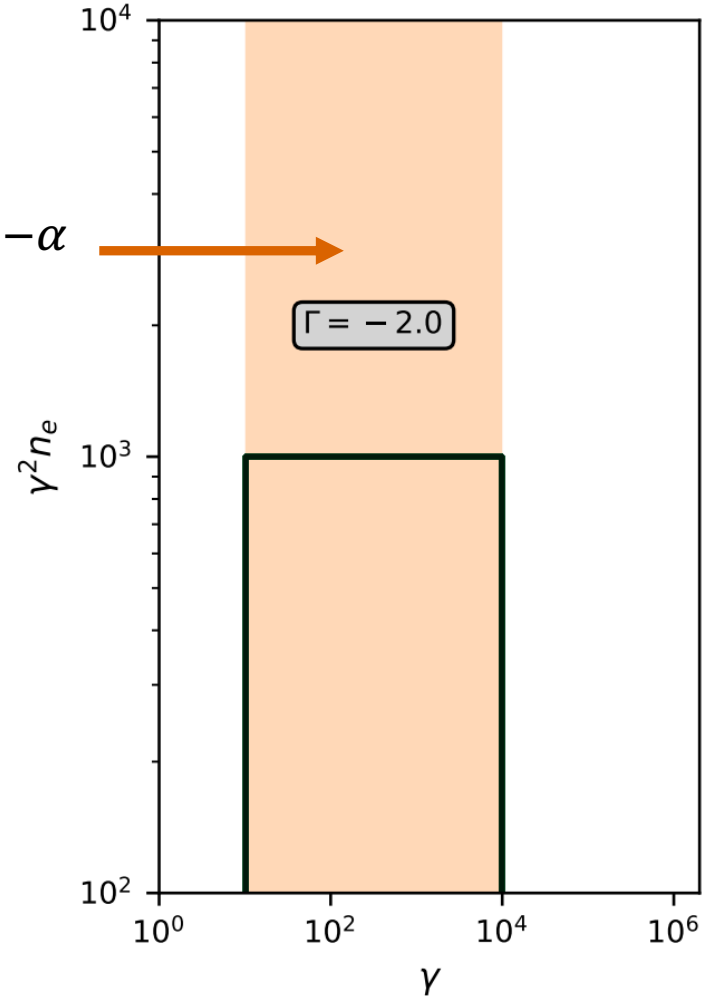
Parameter

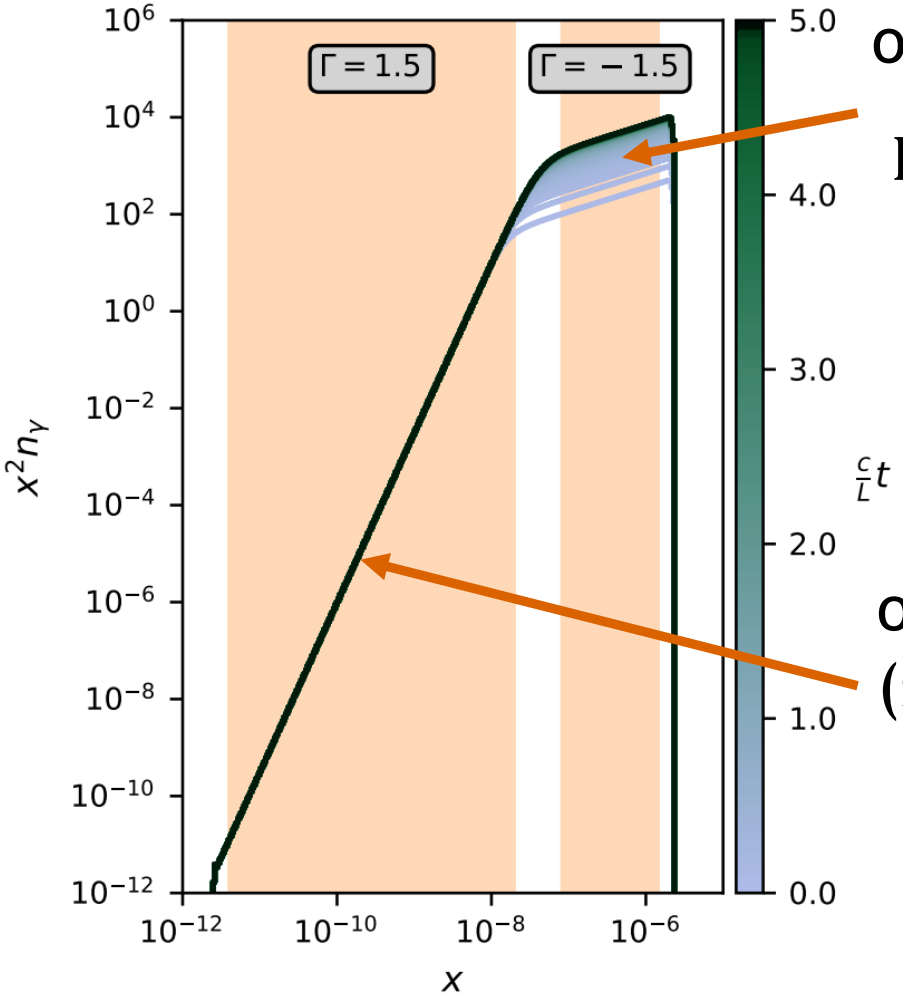


FSRQ	BL Lac
$B = 7$	$B = 2$
$z_{\mathrm{diss}} < R_{\mathrm{BLR}}$ $z_{\mathrm{diss}} = 10^{17}\mathrm{cm}$ $R_{\mathrm{BLR}} = 5 \cdot 10^{17}\mathrm{cm}$	$z_{\mathrm{diss}} > R_{\mathrm{BLR}}$ $z_{\mathrm{diss}} = 10^{18}\mathrm{cm}$ $R_{\mathrm{BLR}} = 5 \cdot 10^{17}\mathrm{cm}$
$94 \leq \gamma \leq 5\,000$	$560 \leq \gamma \leq 50\,000$
$L_{\mathrm{BLR}} = 1.2 \cdot 10^{46}\mathrm{erg/s}$	$L_{\mathrm{BLR}} = 5 \cdot 10^{41}\mathrm{erg/s}$

Synchrotron from Power Law

$$n_e(\gamma, t) = K\gamma^{-\alpha}$$





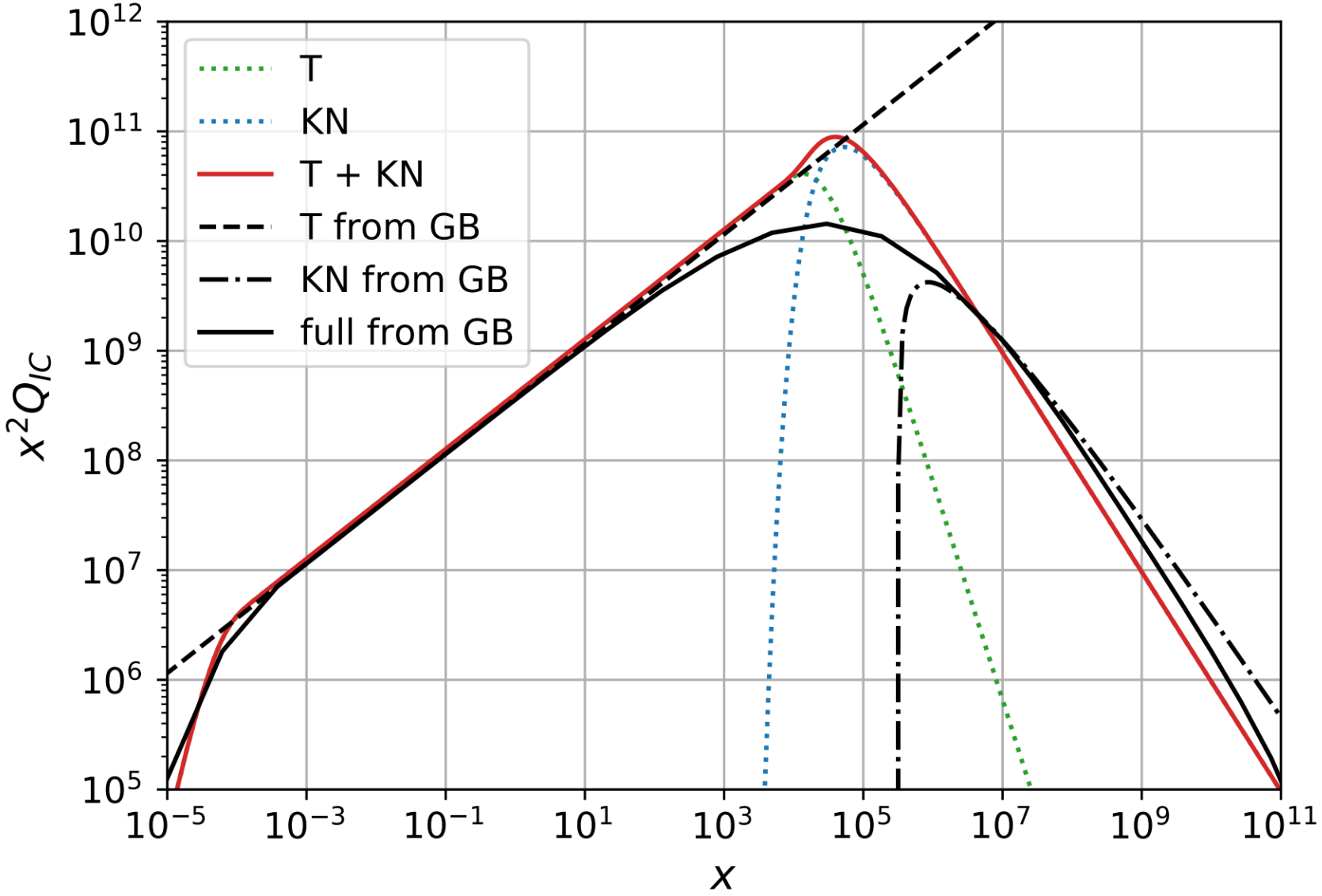
optically thin

$$\Gamma = -\frac{\alpha + 1}{2} = -1.5$$

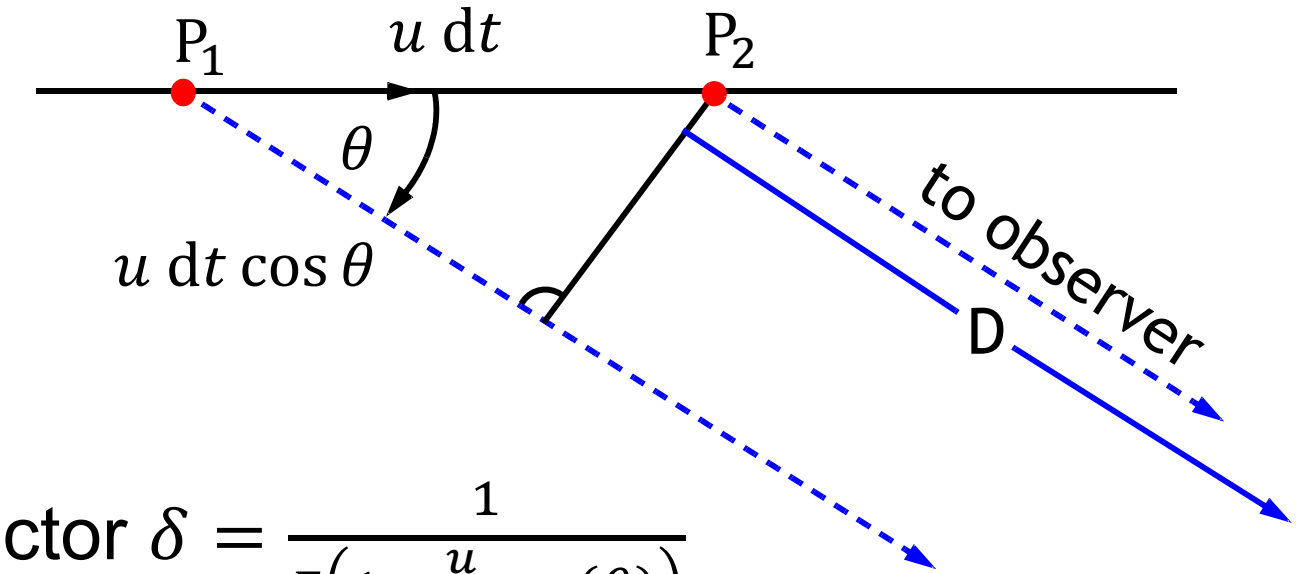
optically thick
(synch. self-abs.)

$$\Gamma = 1.5$$

Inverse Compton from Power Law



Effects of Special Relativity



- 3 frames:
  - plasmoid
  - reconnection layer
  - observer / BLR
- Doppler effect → Doppler factor $\delta = \frac{1}{\Gamma\left(1 - \frac{u}{c}\cos(\theta)\right)}$
- combine motion of plasmoid ($\beta_{\mathrm{P}}{}'$) and layer in jet (β_{jet}):
  - $\delta = [\Gamma_{\mathrm{P}}''(1 - \beta_{\mathrm{P}}'\cos(\theta'' - \theta_{\mathrm{Obs}}''))]^{-1}$
- spectral number density scales with δ^4 (BLR, emission)
- interpolation in time (3 grids)