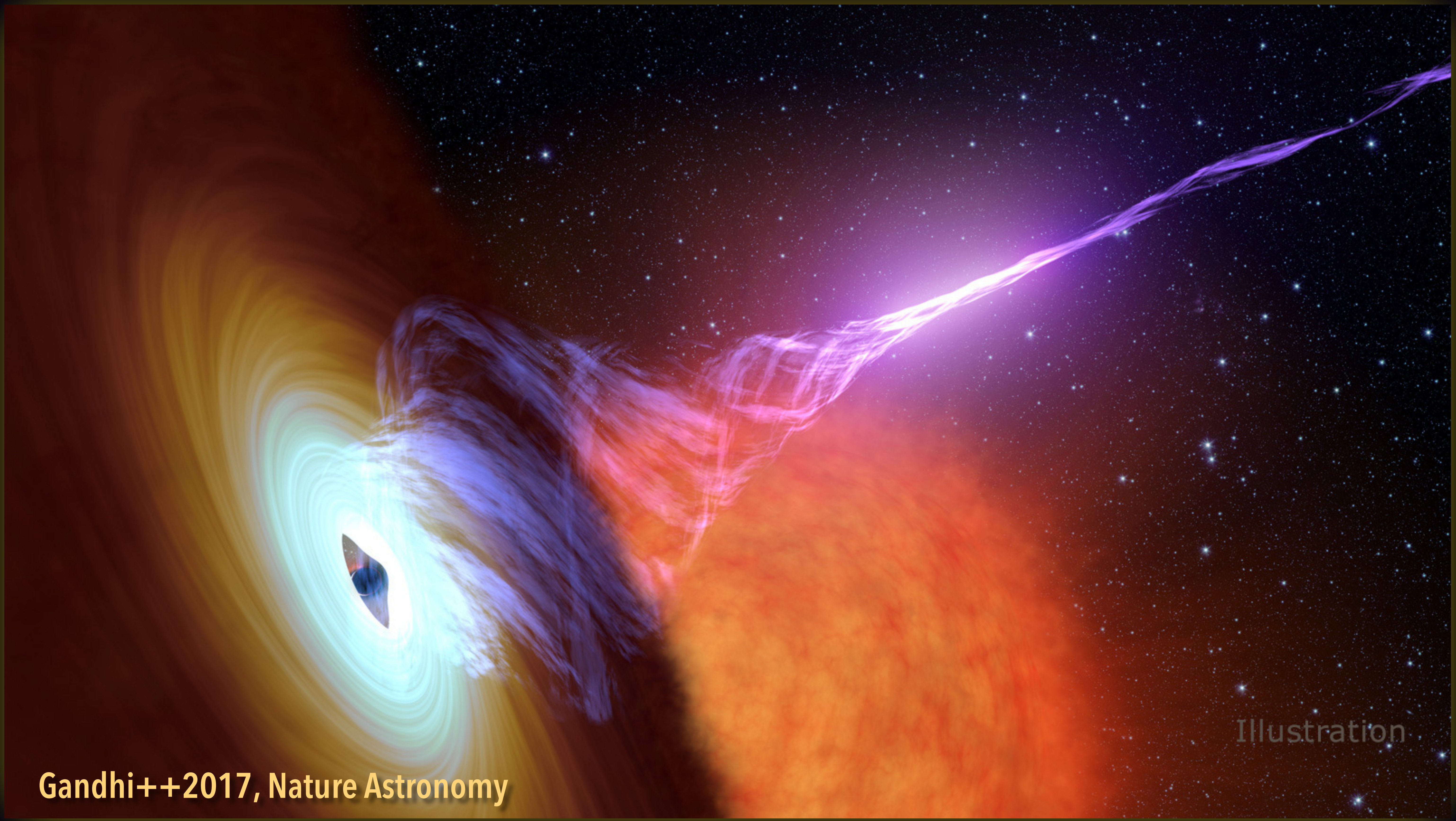
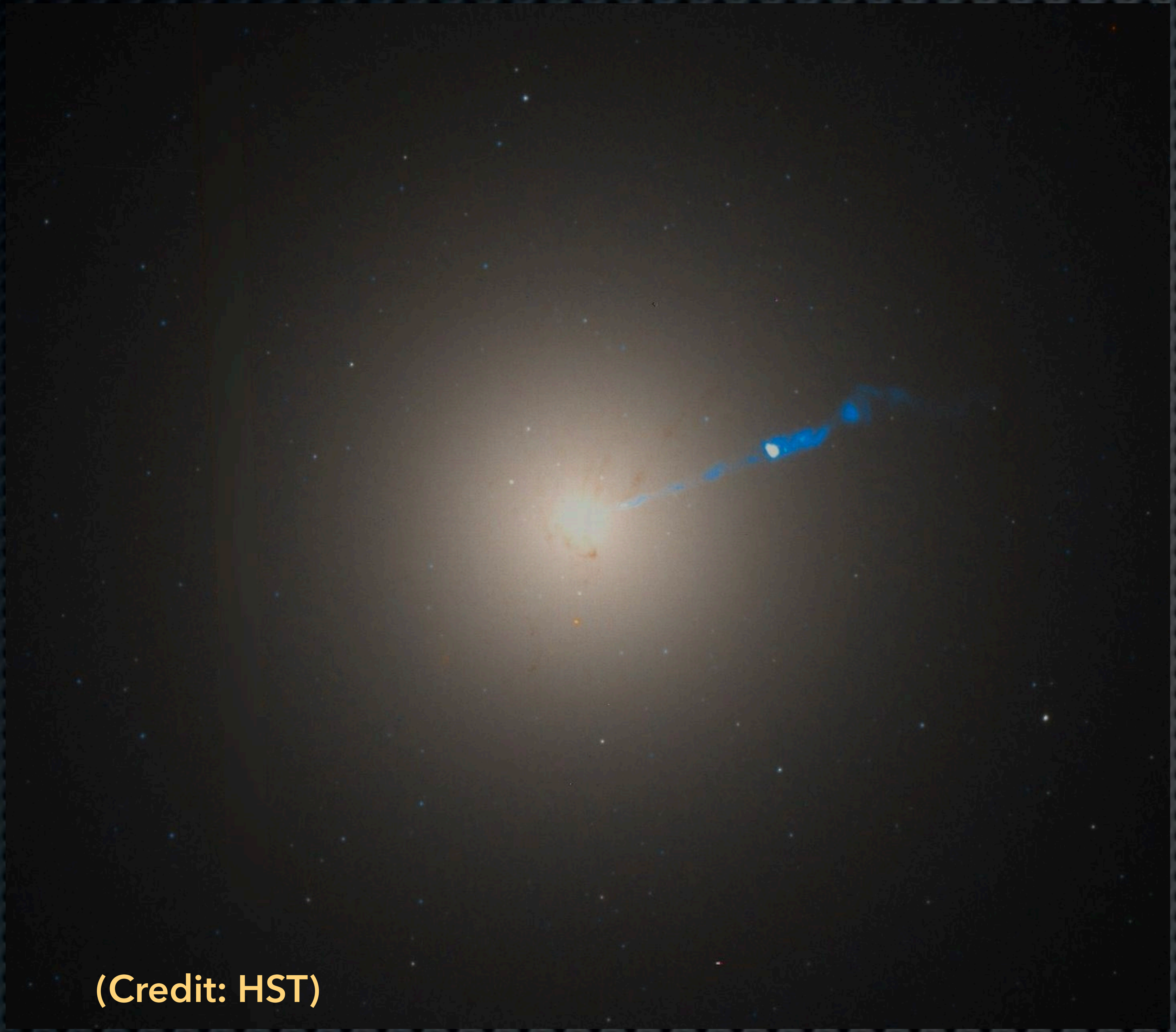
And then there was light:
What makes astrophysical jets radiate?

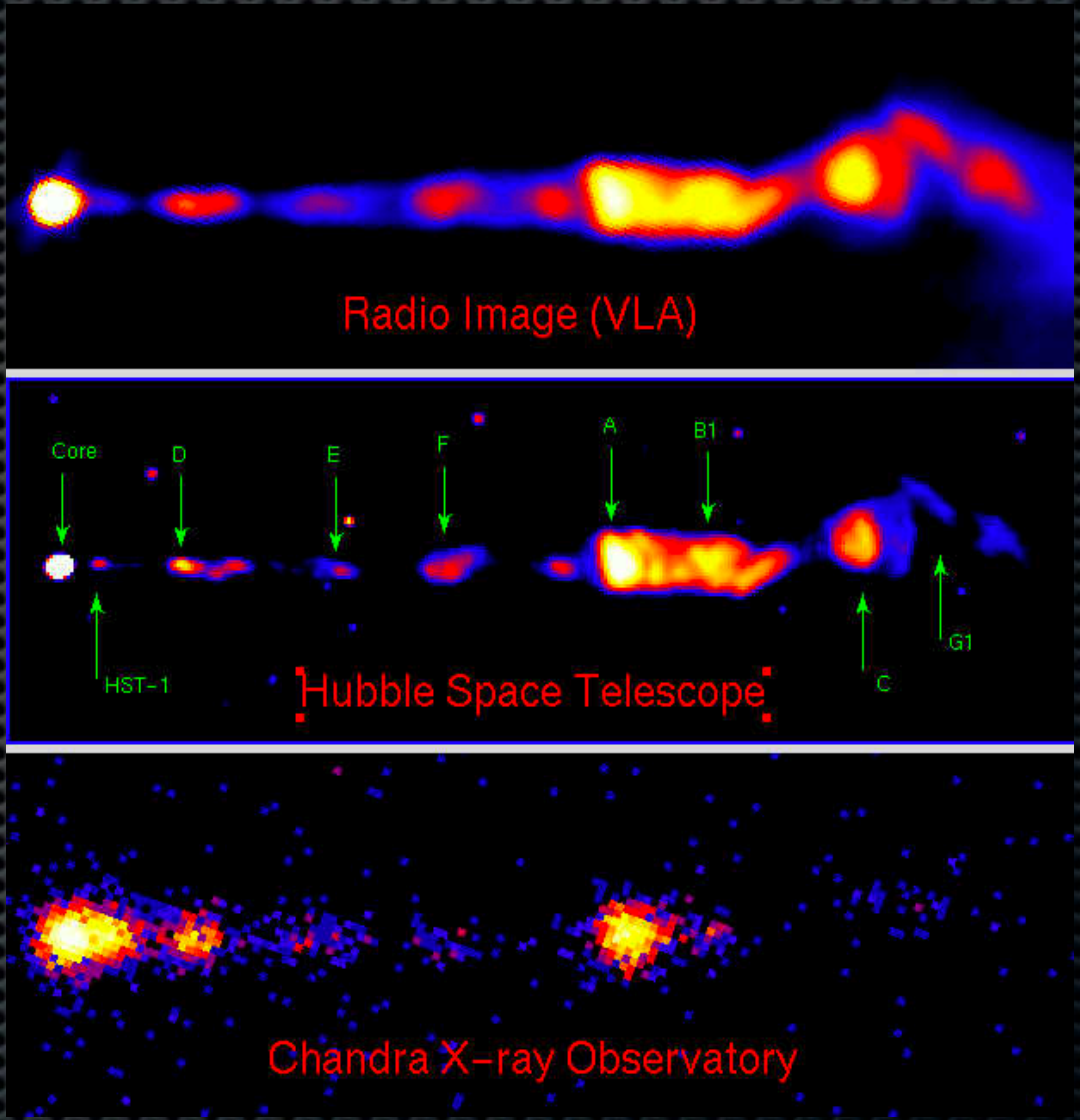


Gandhi++2017, Nature Astronomy

Sera Markoff (API/GRAPPA, University of Amsterdam) C.Ceccobello, K.Chatterjee, A.Chhotray, R.Connors, P. Crumley, D.v.Eijnatten, P.Gandhi, C.Hesp, F.Krauss, M.Liska, M.Lucchini, D.Russell, T.Russell, D.Meier, P.Polko, A.Tchekhovskoy, Z.Younsi + JACPOT, EHT]

100 years since M87's jet discovered by Curtis++1918

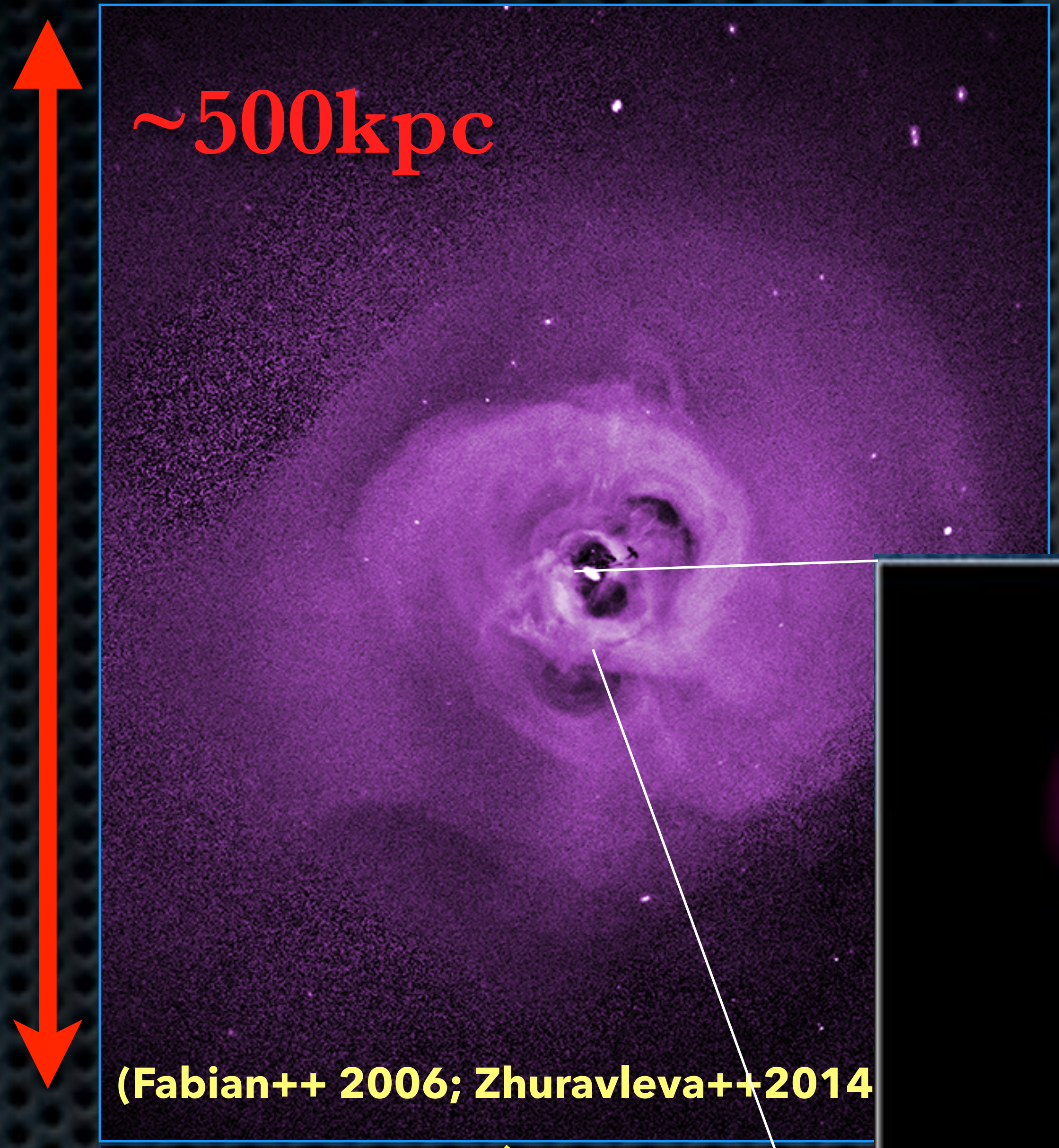




- ★ Same questions: How are jets launched and collimated, what are they made of, what is their total power? We still do not have a *predictive* model for jets and their radiation!

Black holes play an outsized role in the Universe

GALAXY EVOLUTION/ AGN FEEDBACK



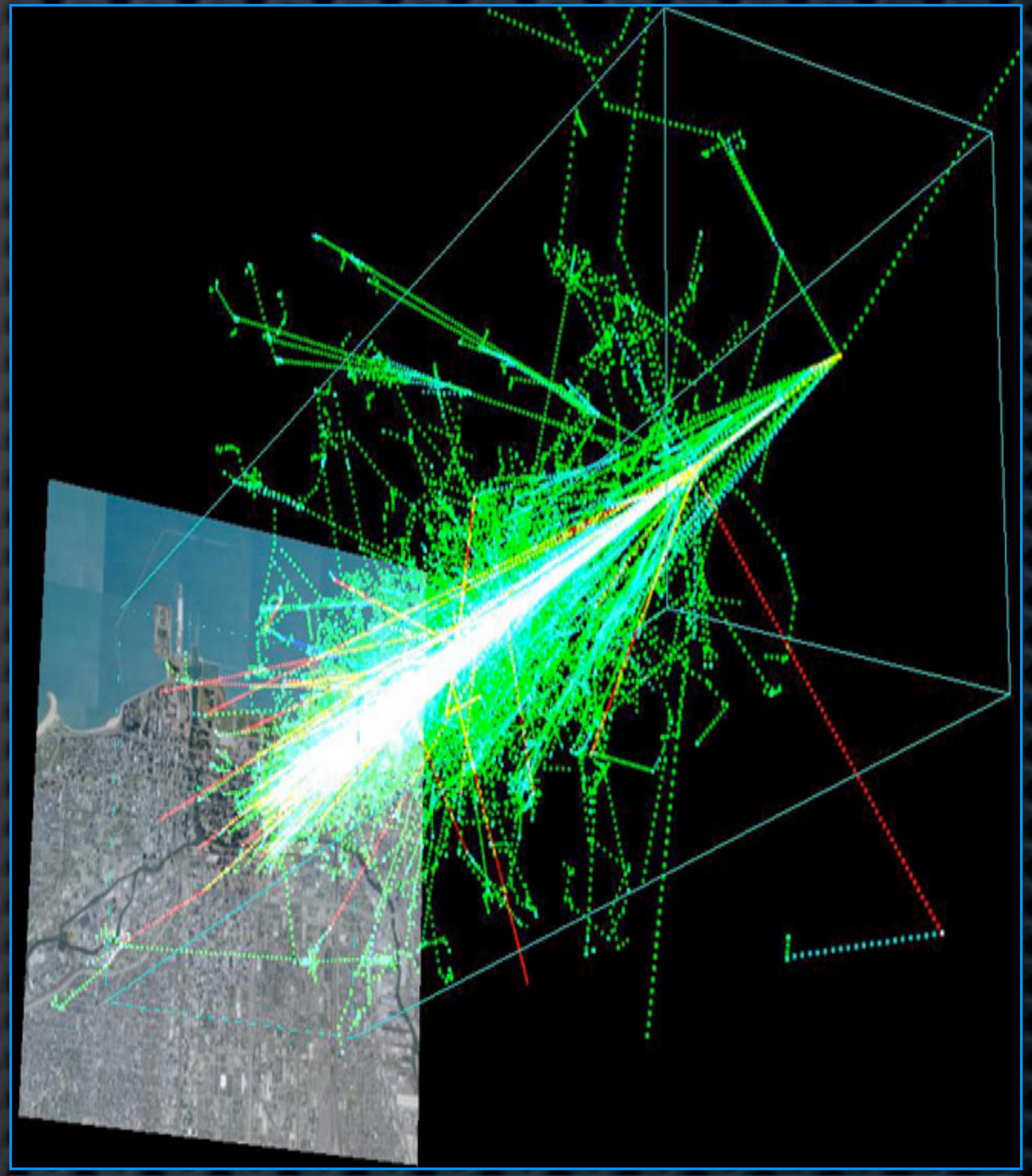
(Fabian++ 2006; Zhuravleva++2014)

VLA radio image

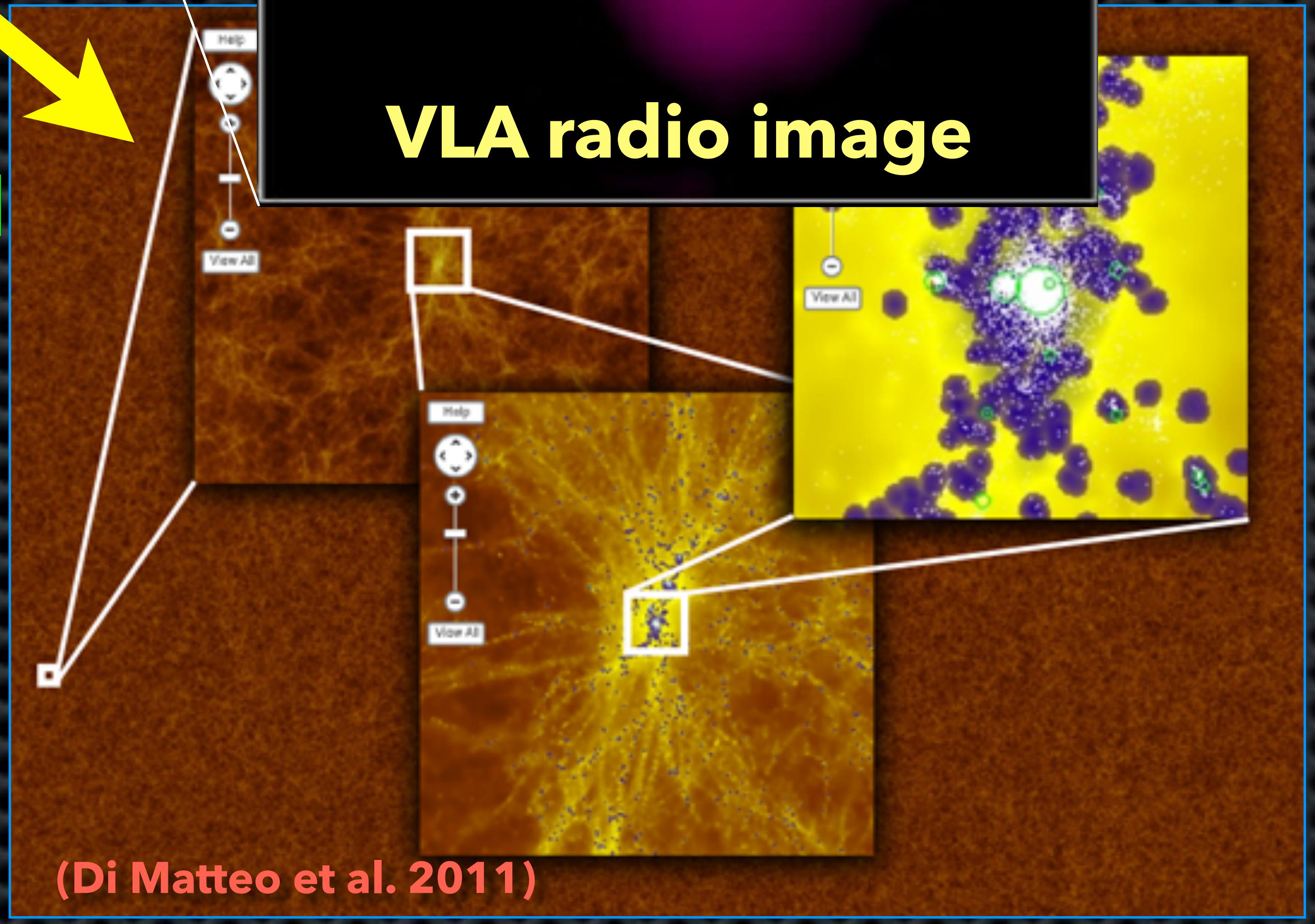
IONIZATION OF SURROUNDING GAS

ull et al. 2010)

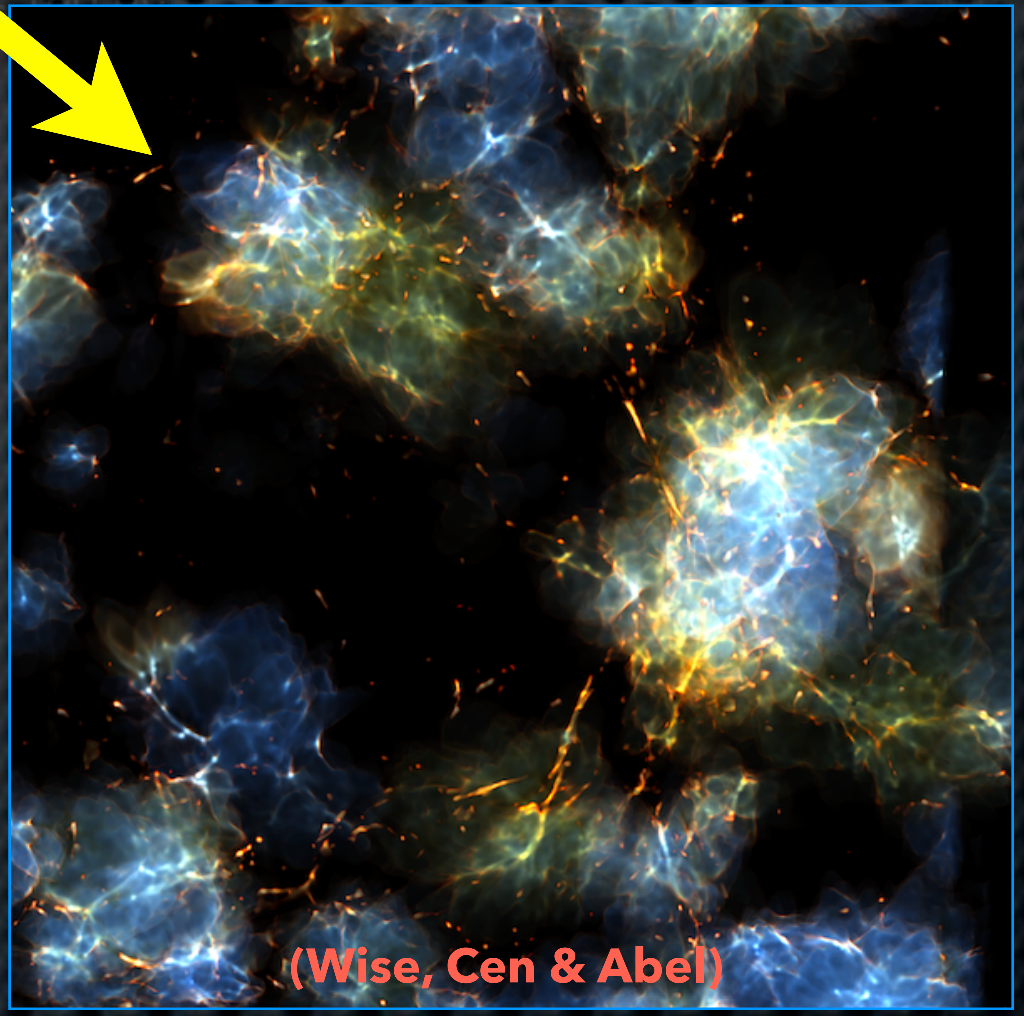
HIGH-ENERGY PARTICLE ACCELERATION



Cosmological Simulations:



(Di Matteo et al. 2011)



(Wise, Cen & Abel)

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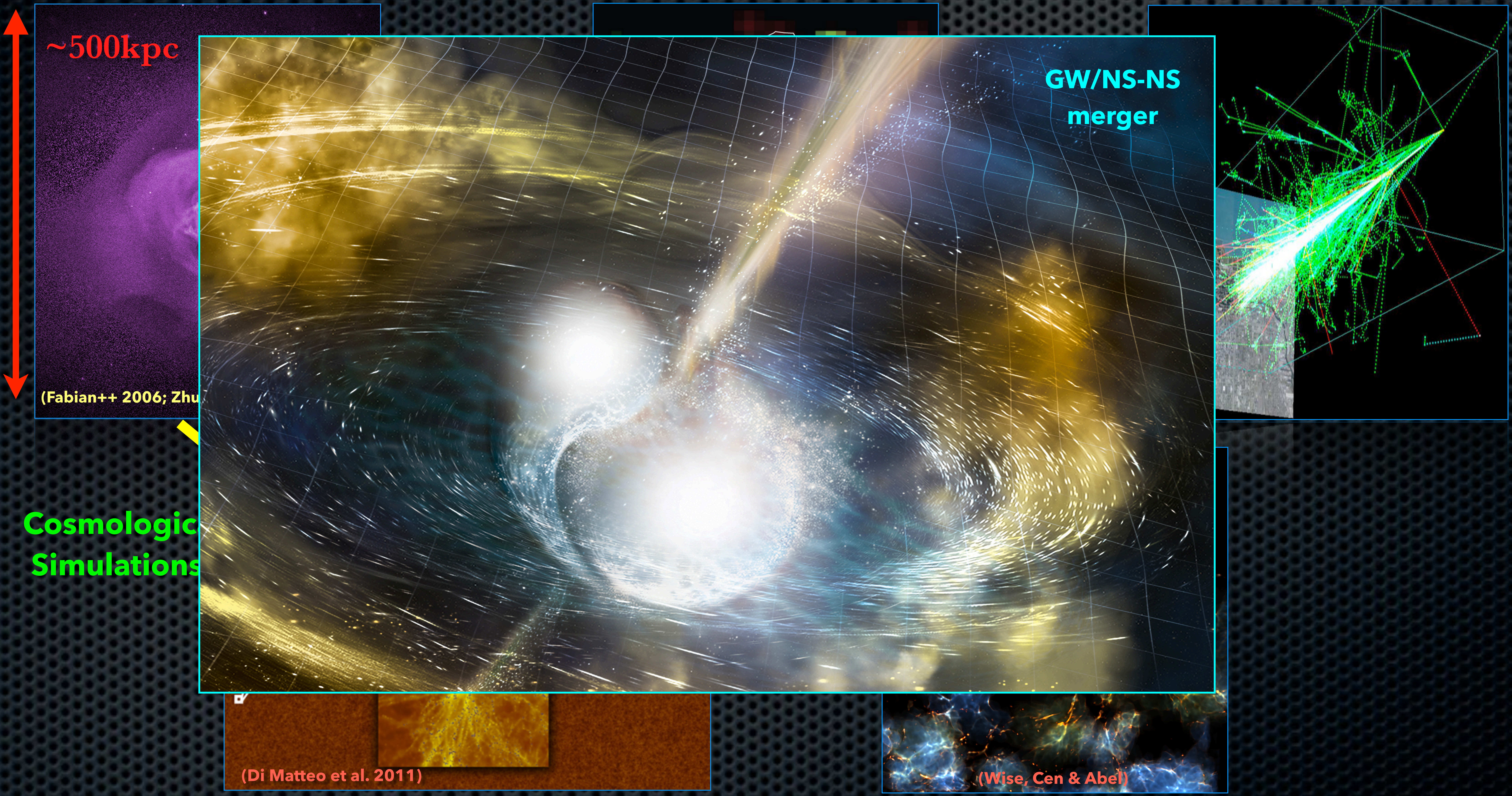
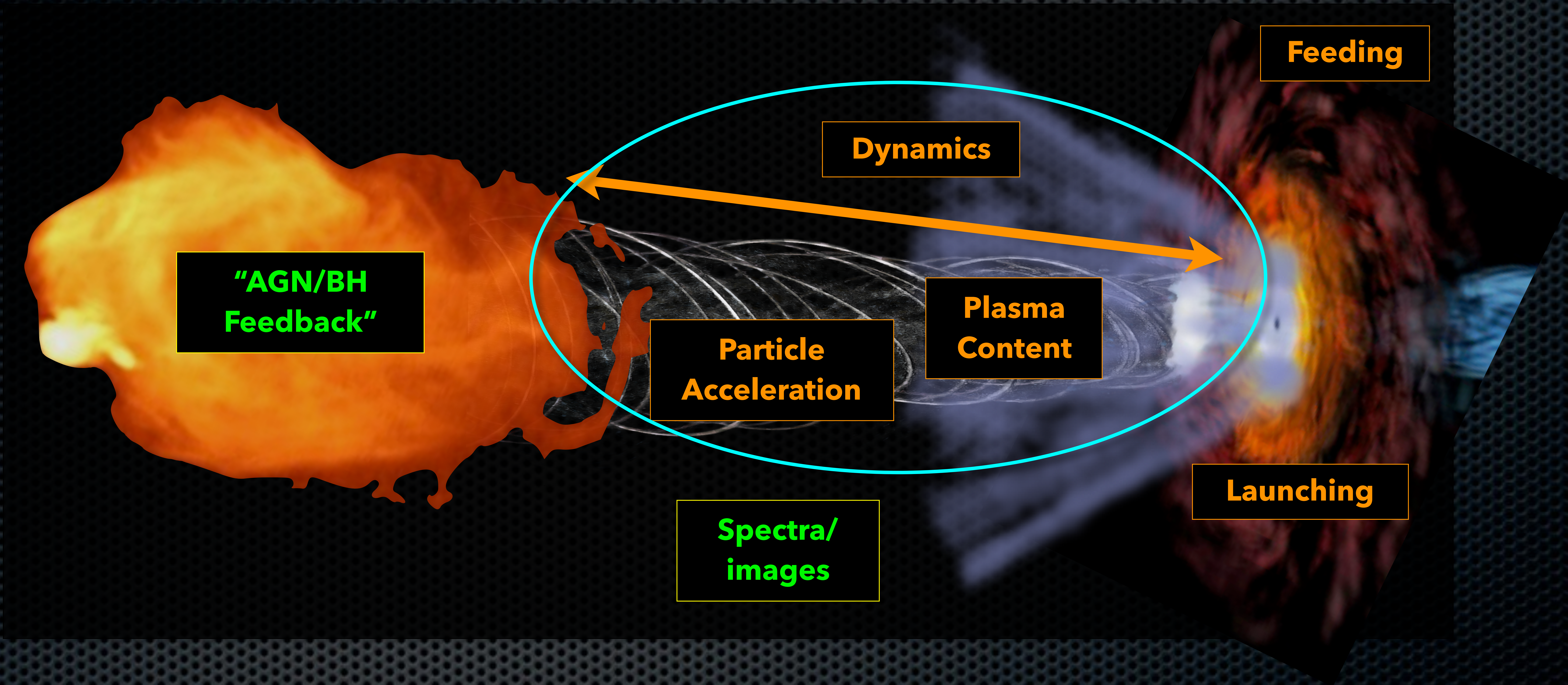


Key aspect of the problem: macro-microphysics link



From 10^5 r_g to 10 cm or less, dynamic range of $\gtrsim 10^{17}$ for 10^8 $M_\odot$ BH

Outline

(sorting out the micro-micro-microphysics connection)

- ★ Observational perspective from AGN/Sgr A* & XRBs
- ★ Phenomenological and semi-analytical approaches
- ★ Cutting edge/work in progress: numerical approach
- ★ Summary/Outlook

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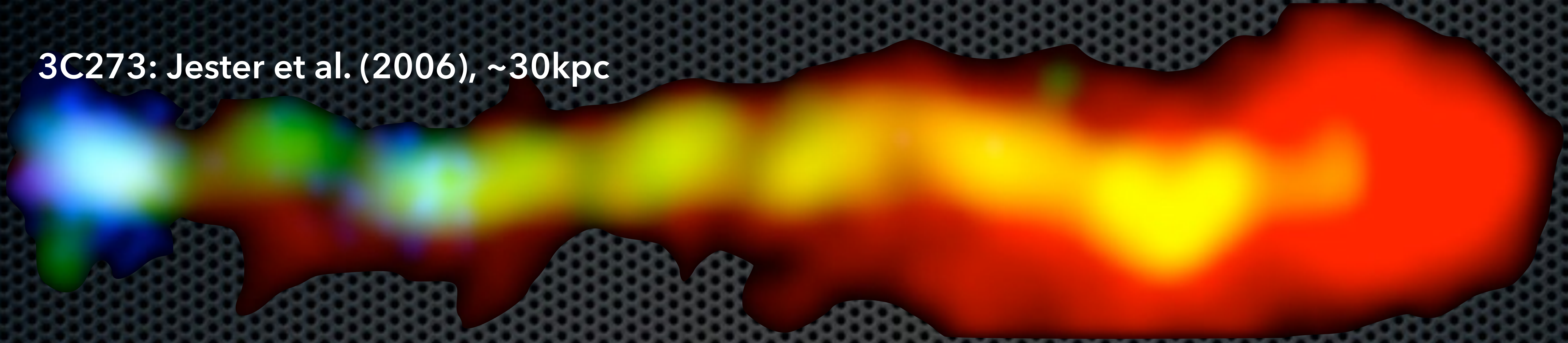
How do we recognize particle acceleration?

3C273: Jester et al. (2006), ~30kpc



Blue: X-rays (Chandra), Green: Optical (Hubble Space Telescope) , Yellow: Optical & Peak Radio, Red: Radio (Very Large Array)

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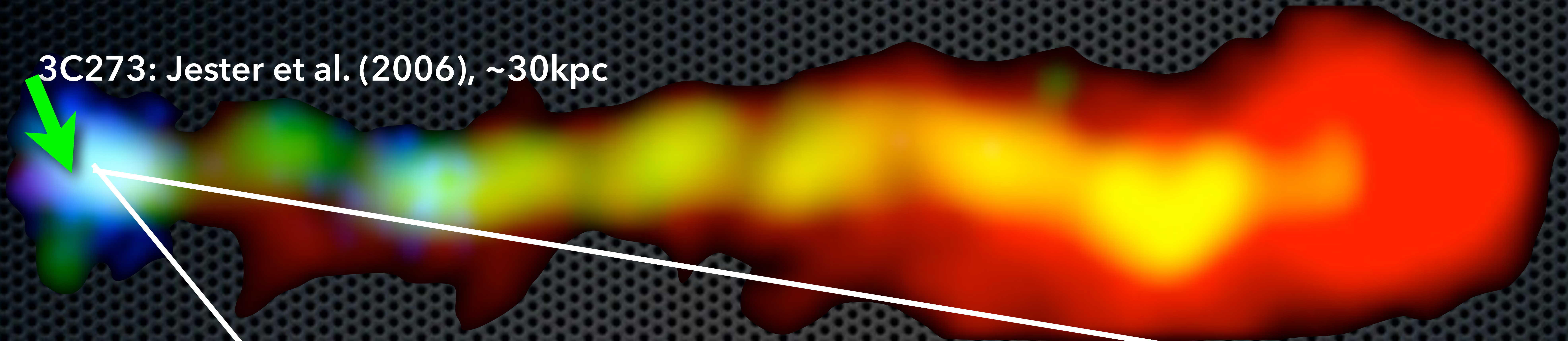
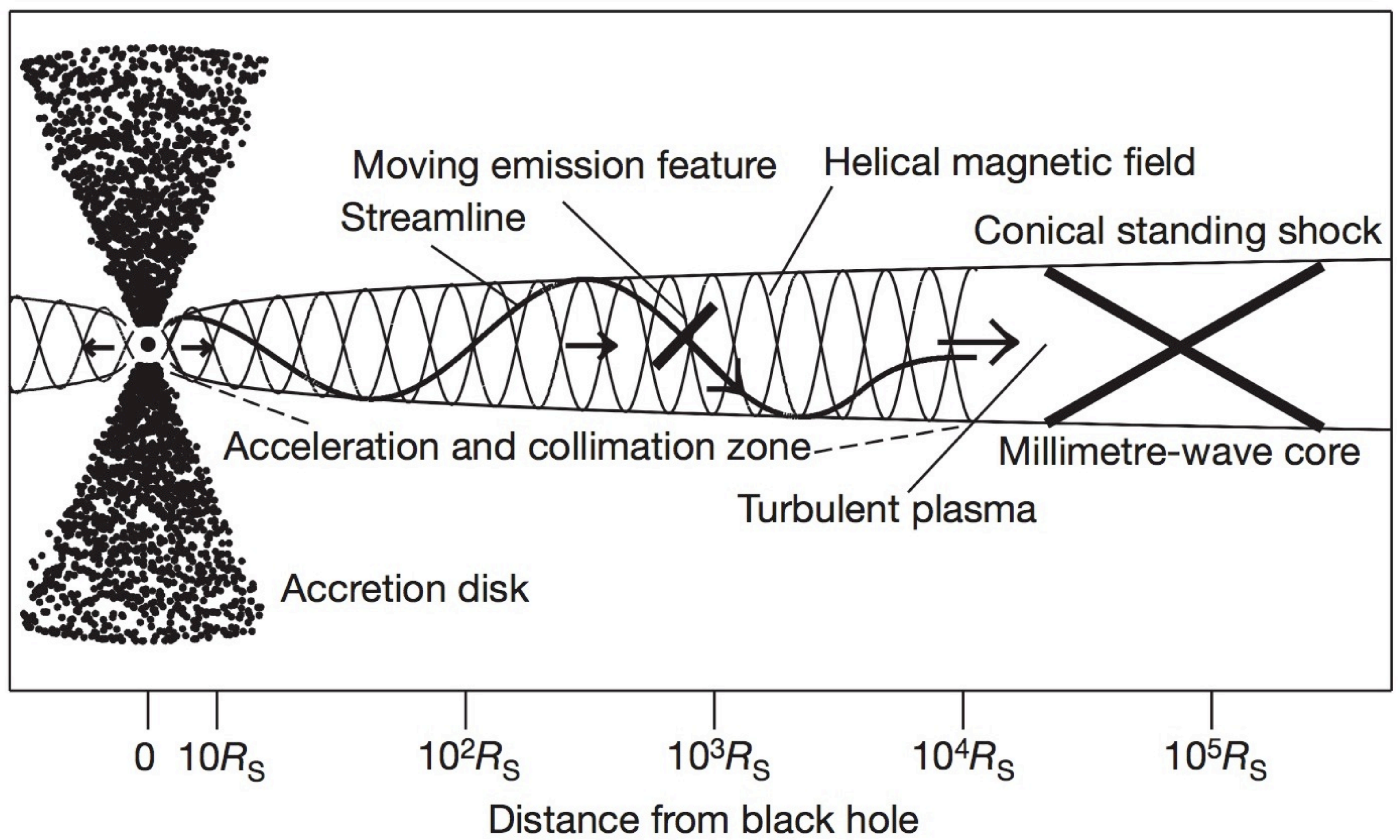
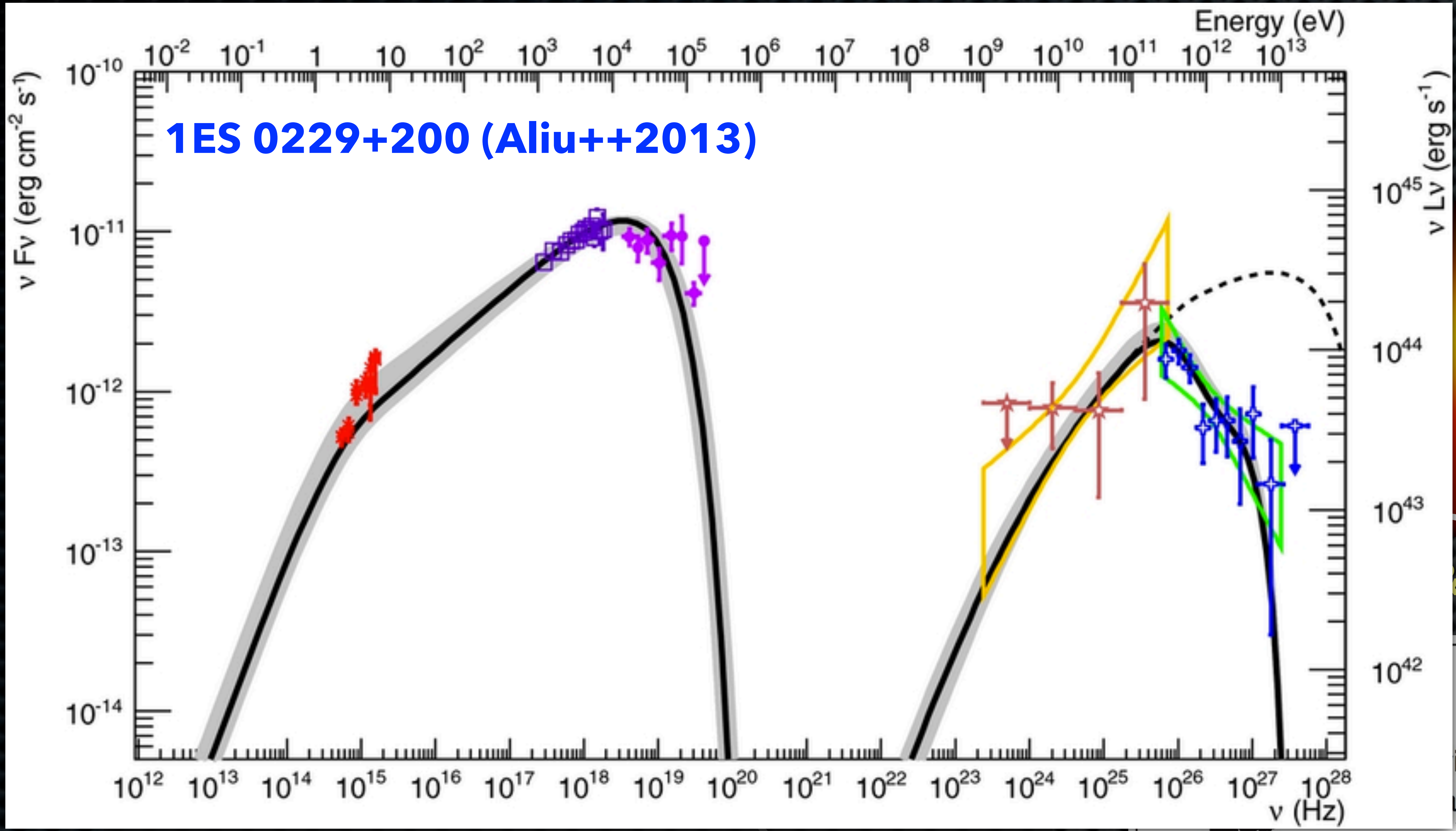


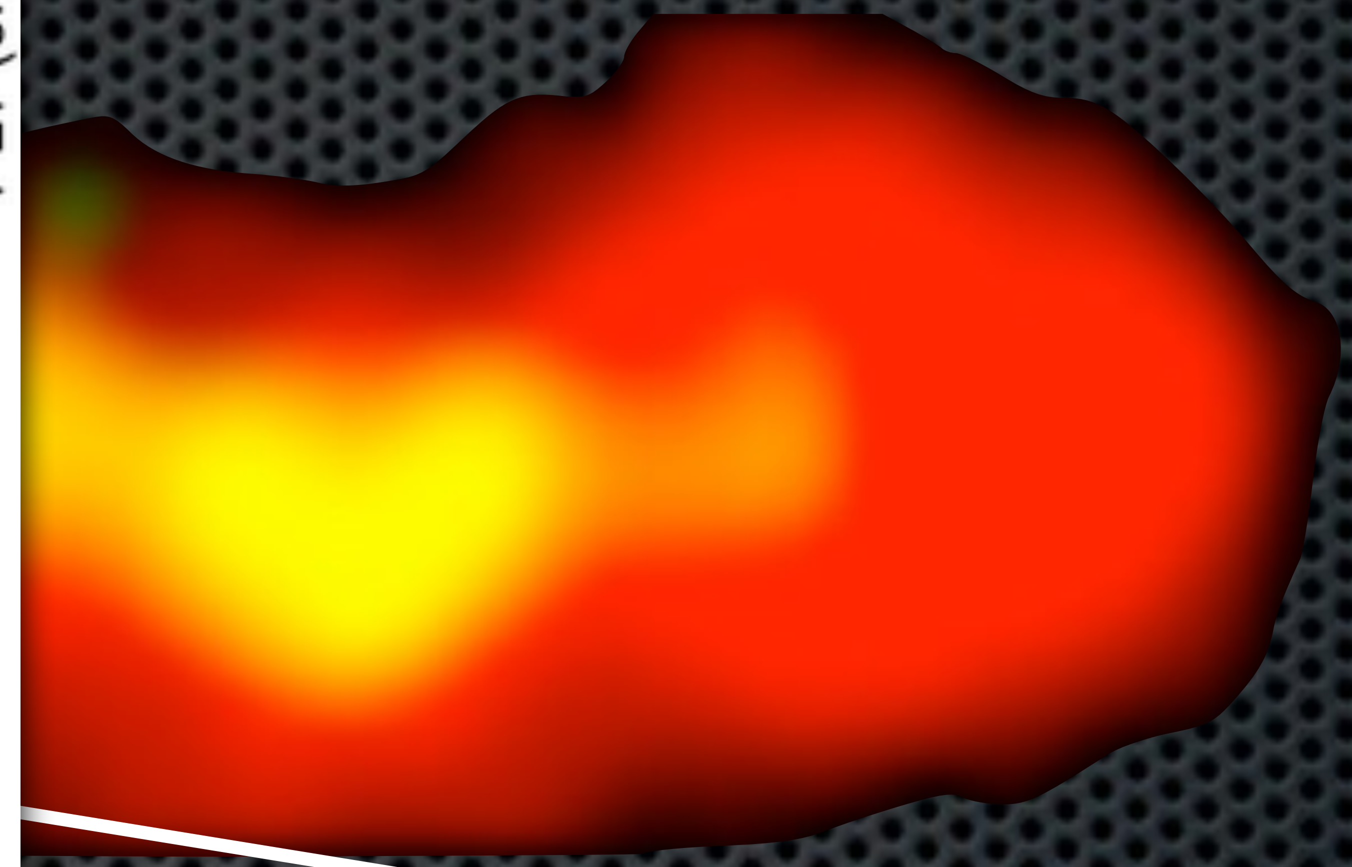
Blue: X-rays (Chandra), Green: Optical (Hubble Space Telescope) , Yellow: Optical & Peak Radio, Red: Radio (Very Large Array)

Marscher++2008, 2014; Cohen+ +2014/MOJAVE (VLBI) picture:
Standing/recollimation shock where most of the "action" takes place, 10^3-10^5 r_g from the black hole

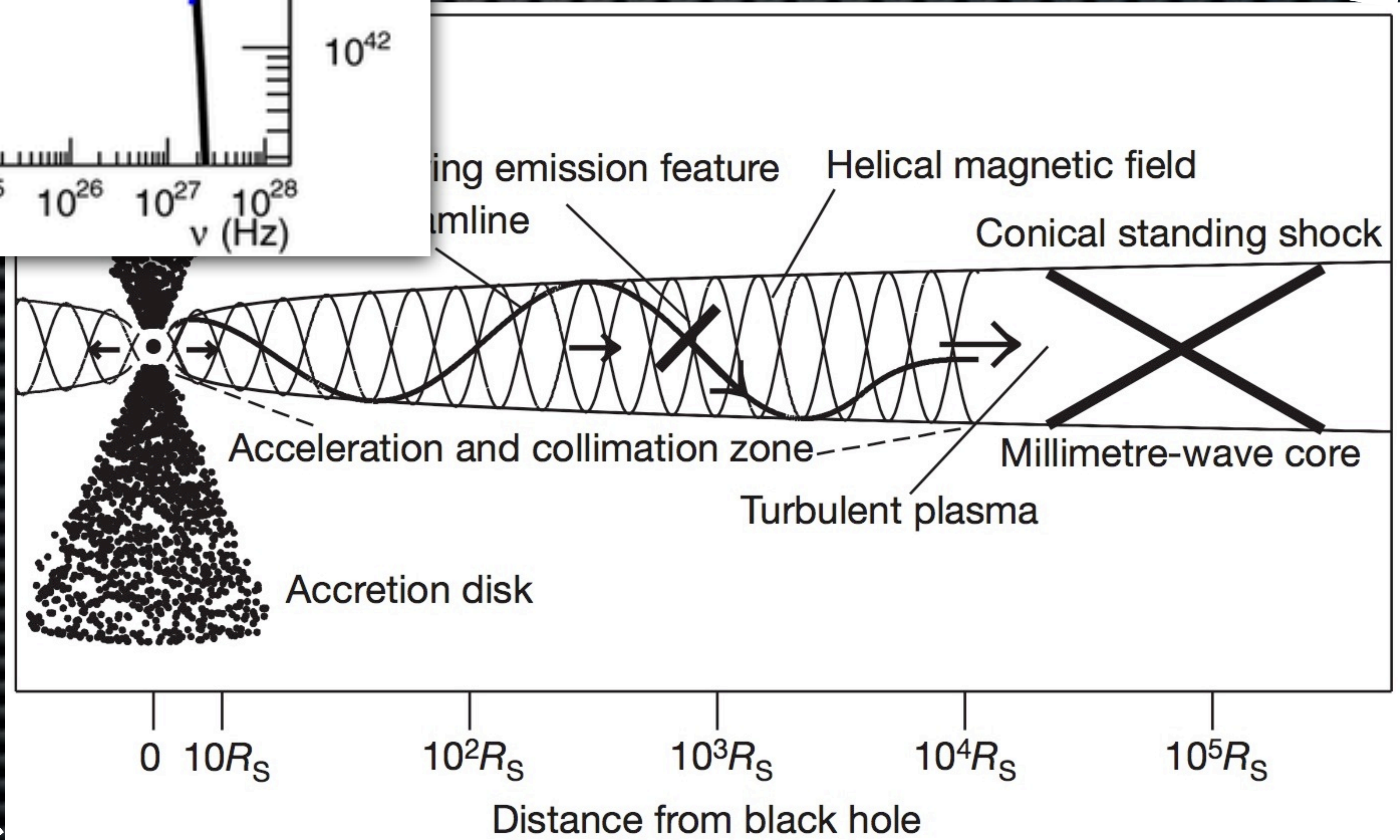


acceleration?





Peak Radio, Red: Radio (Very Large Array)



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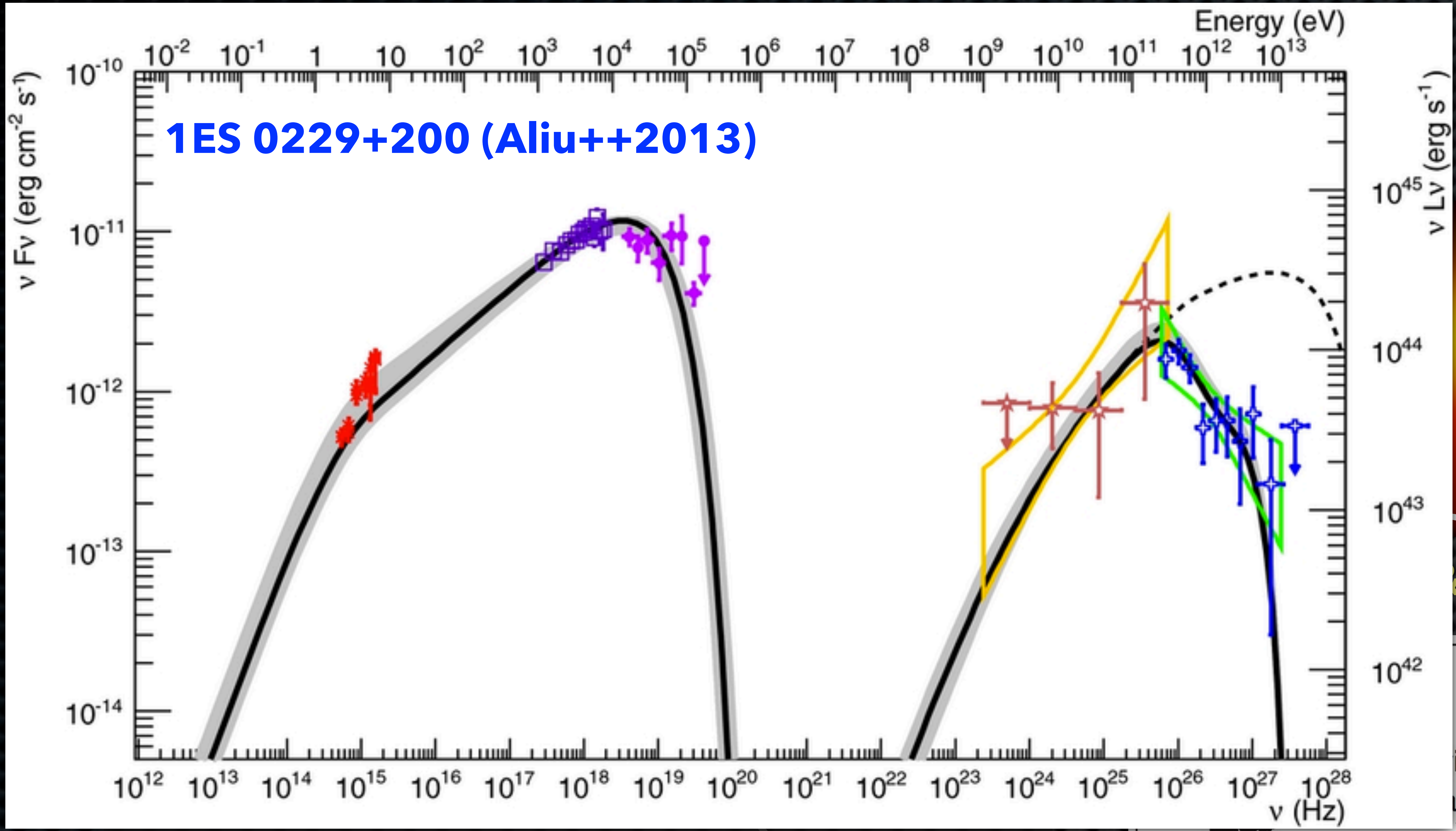

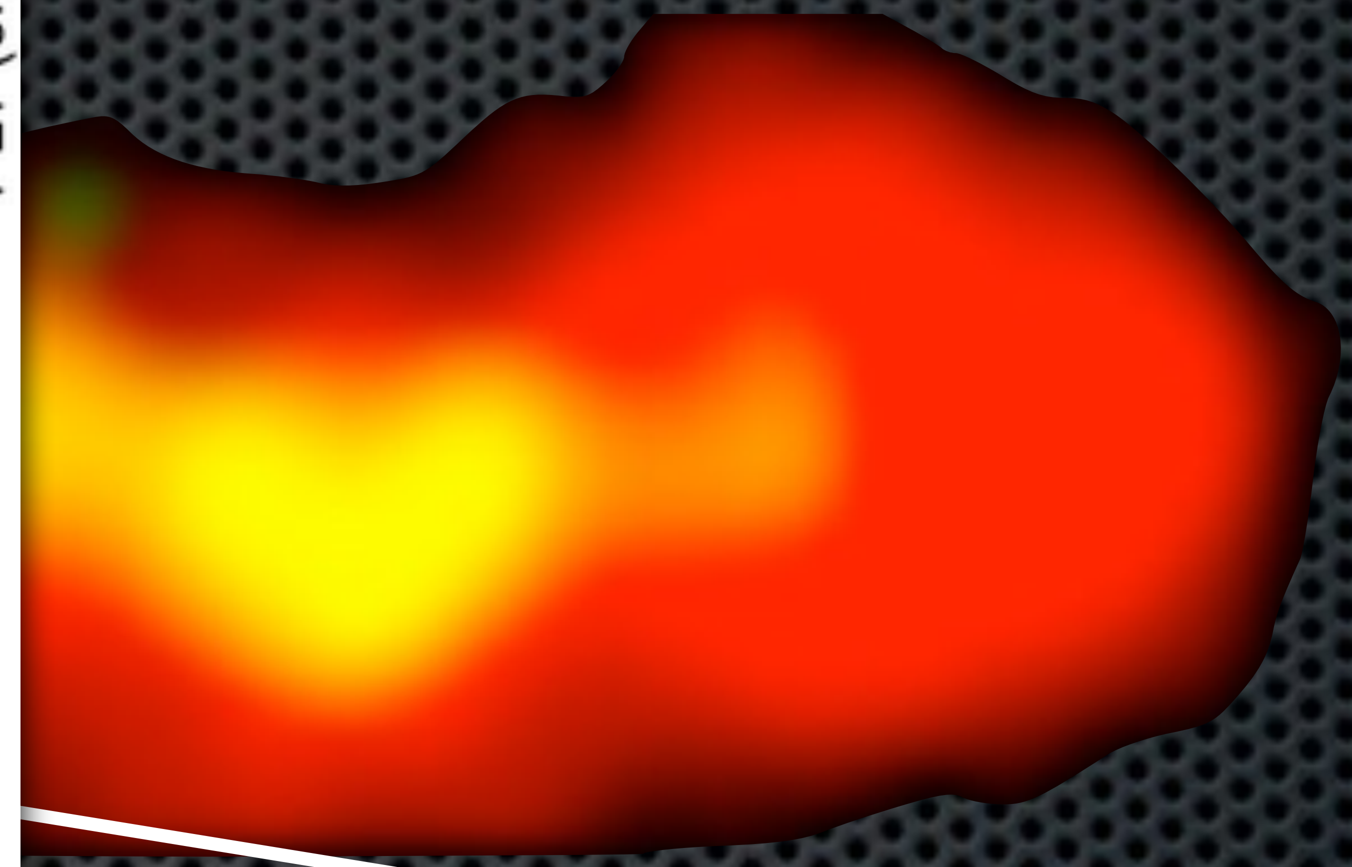

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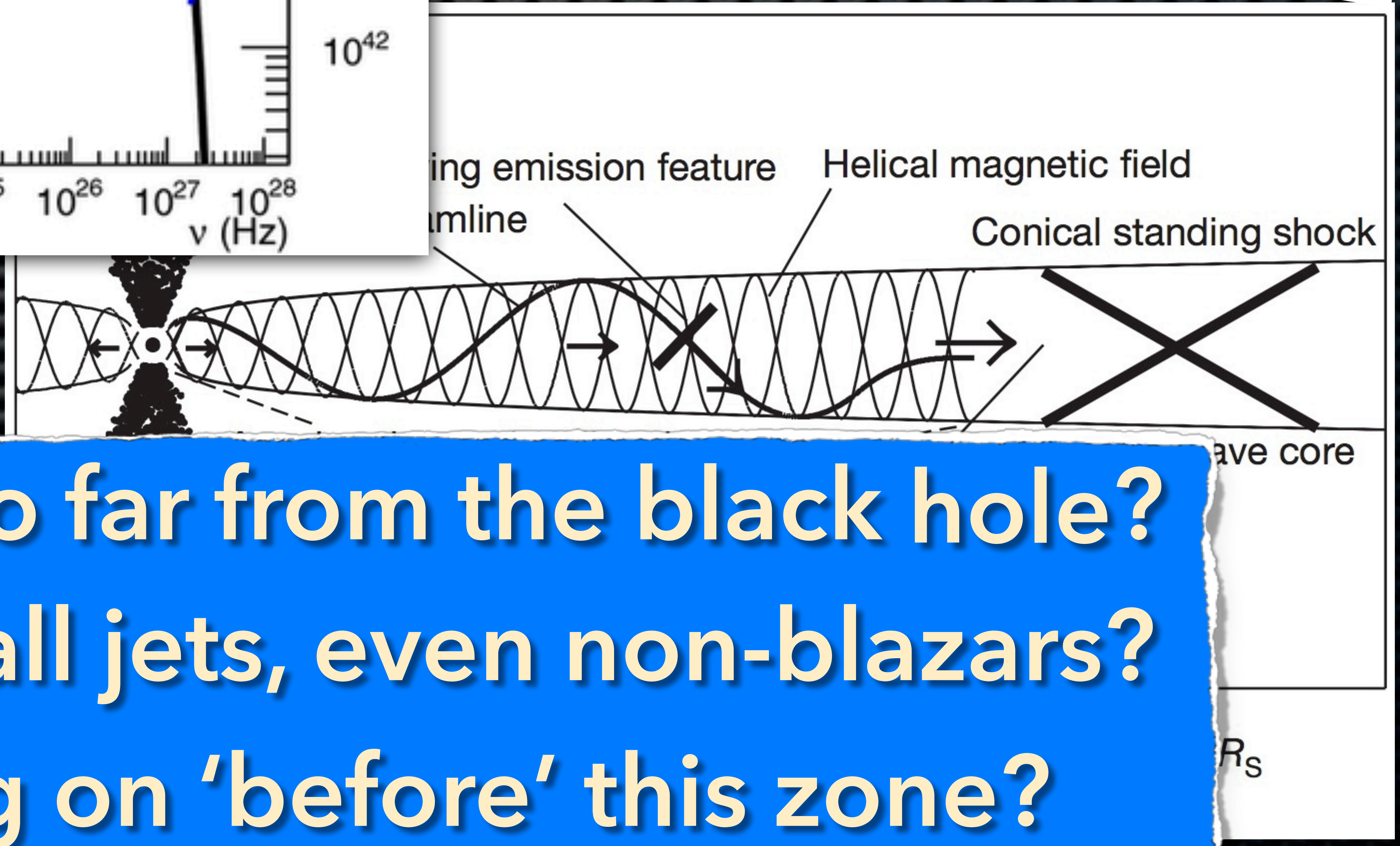


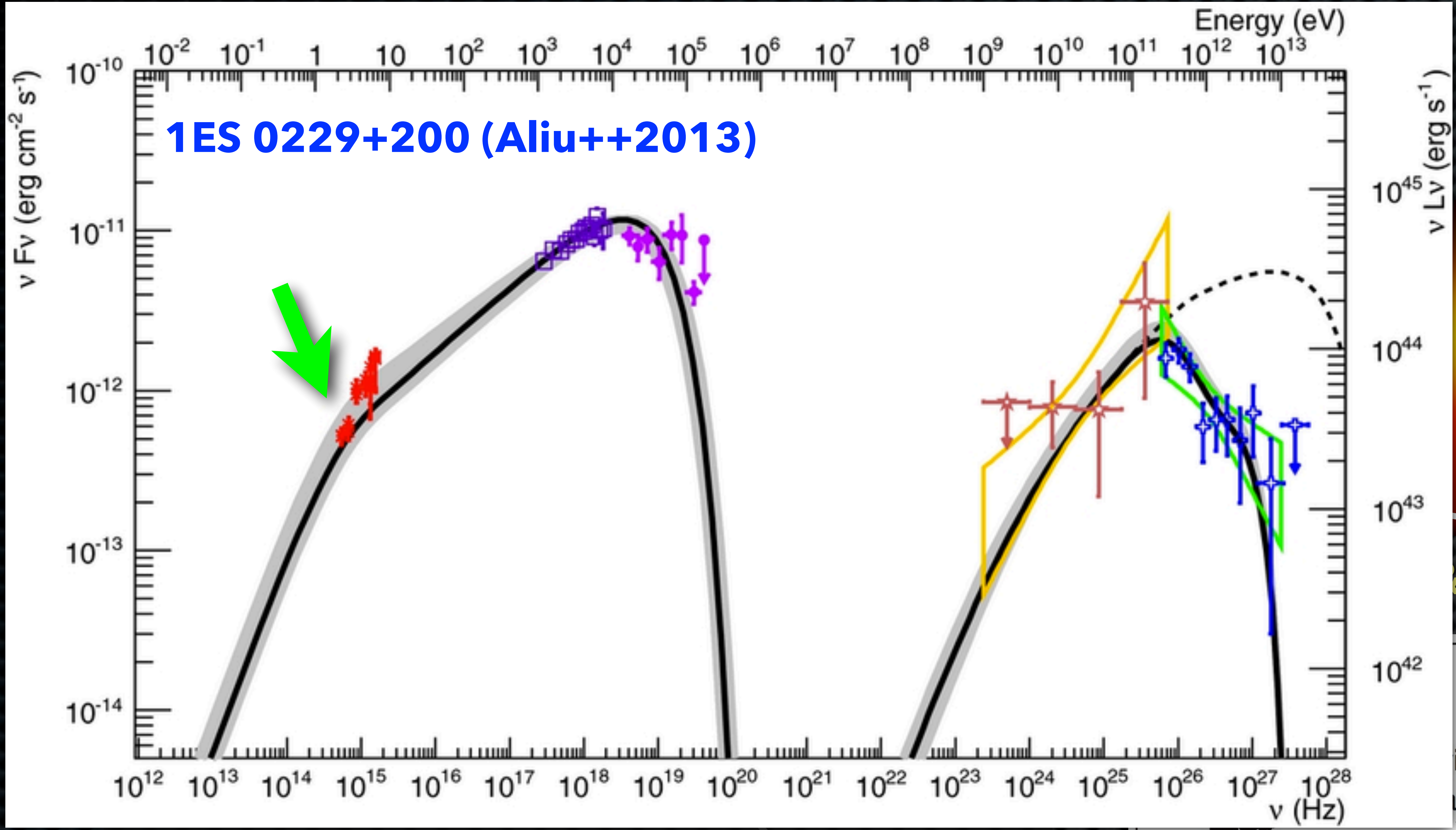
Standing/recollimation shock where most of the "action" takes place, 10^3-10^5 r_g

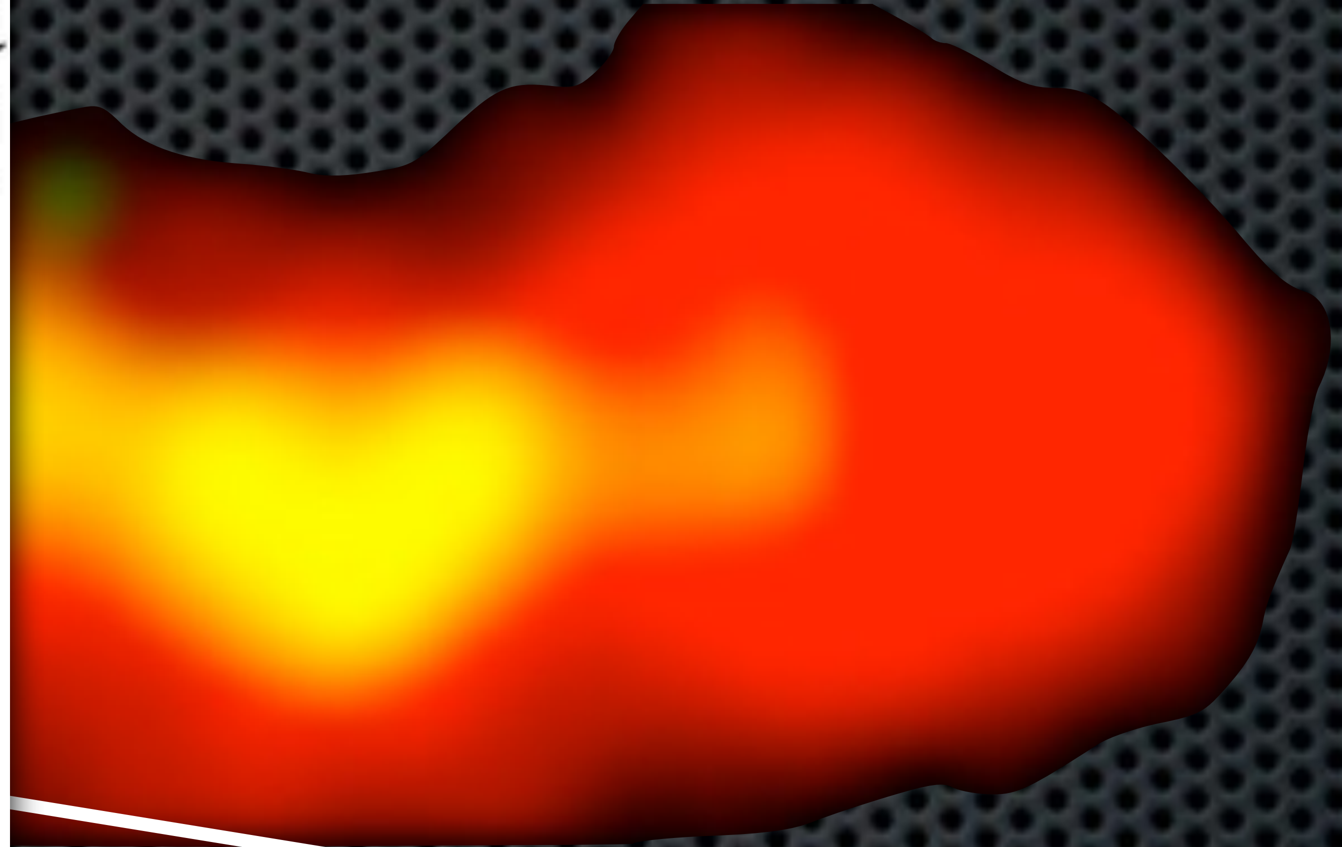
But why the offset so far from the black hole?

Is this universal for all jets, even non-blazars?

And what is going on 'before' this zone?

acceleration?





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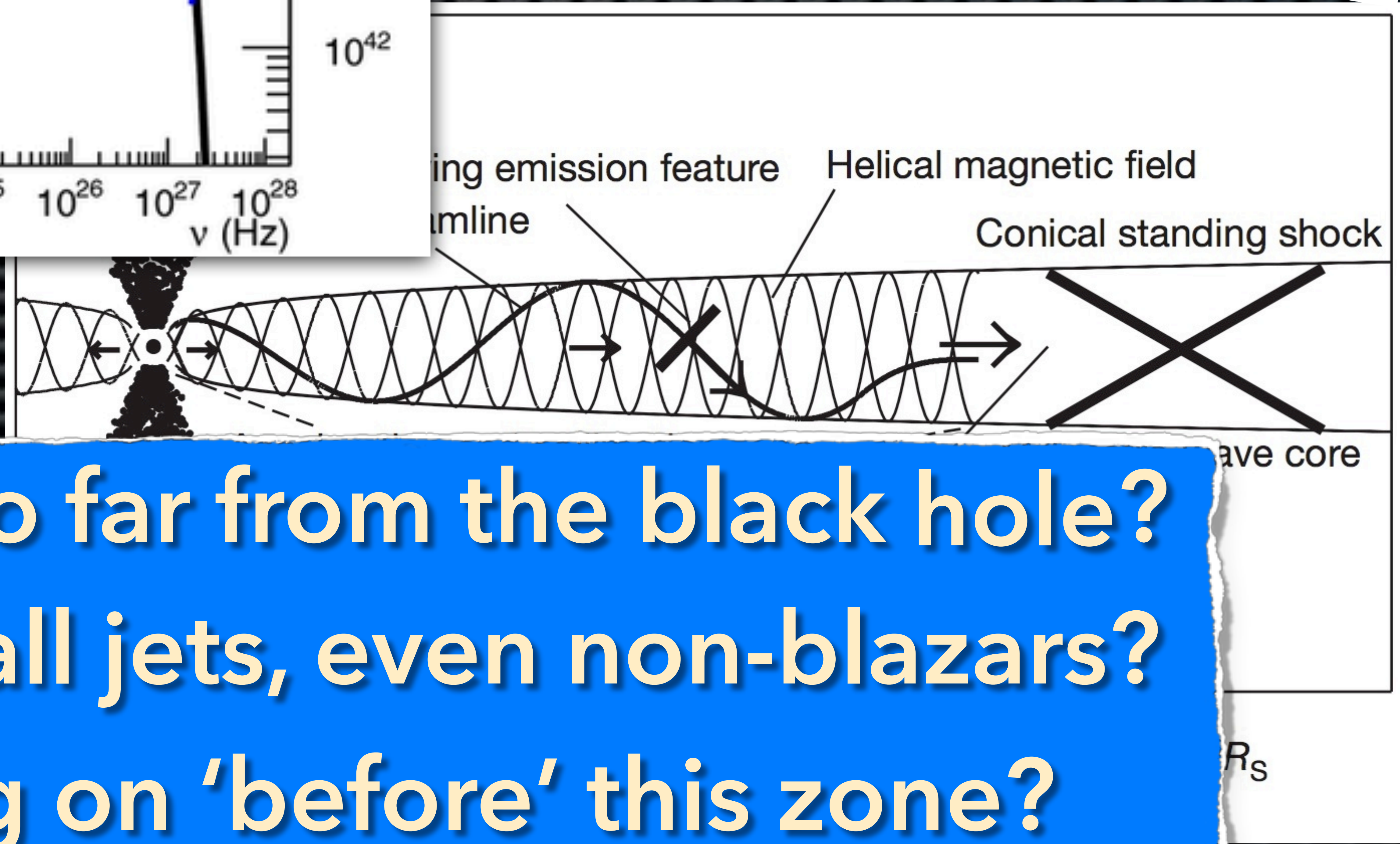

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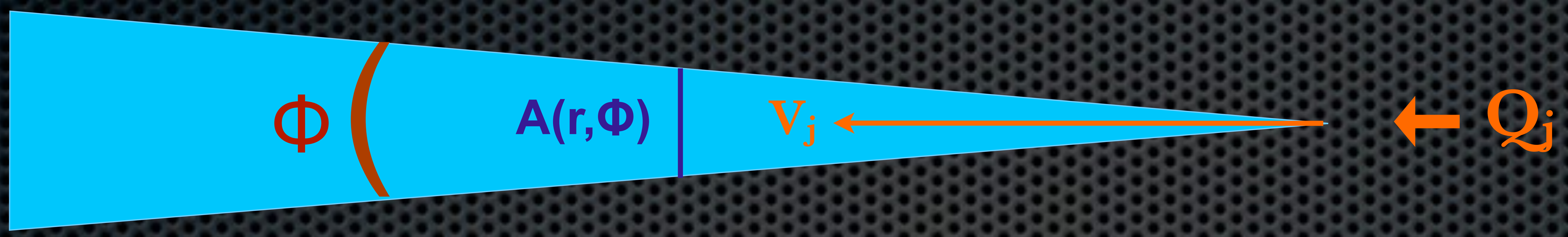
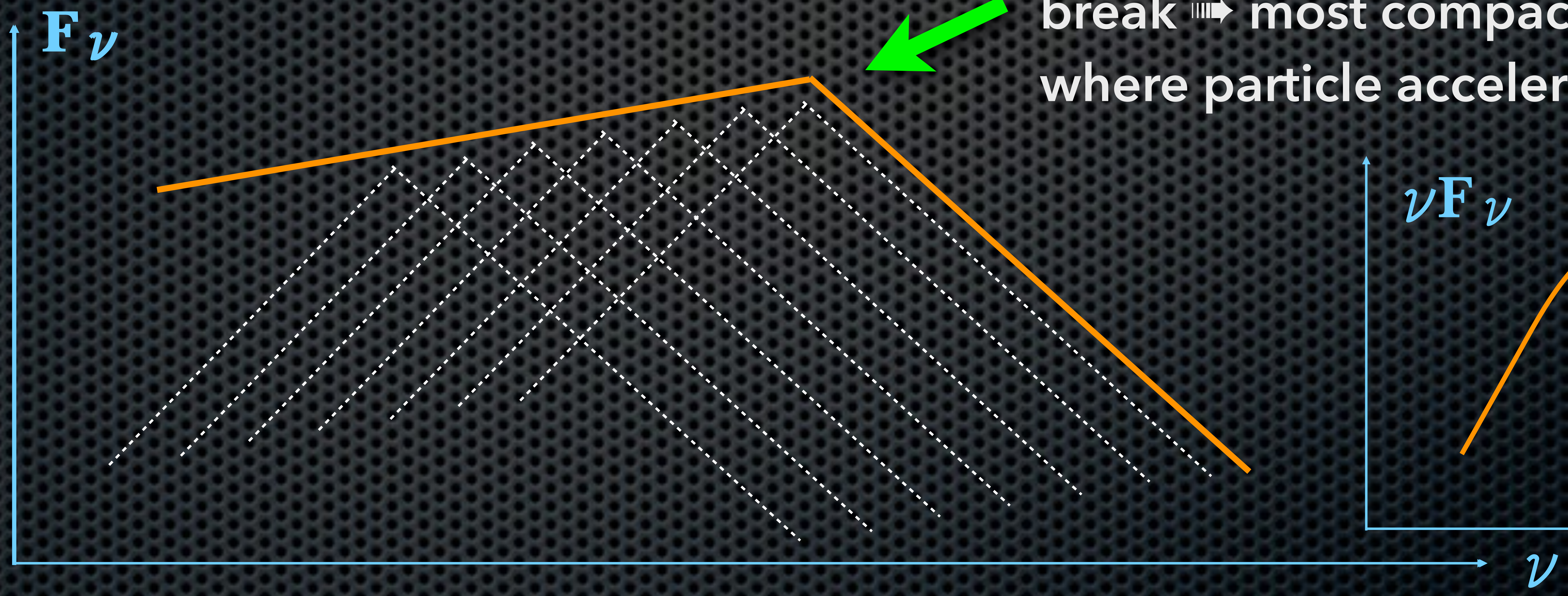
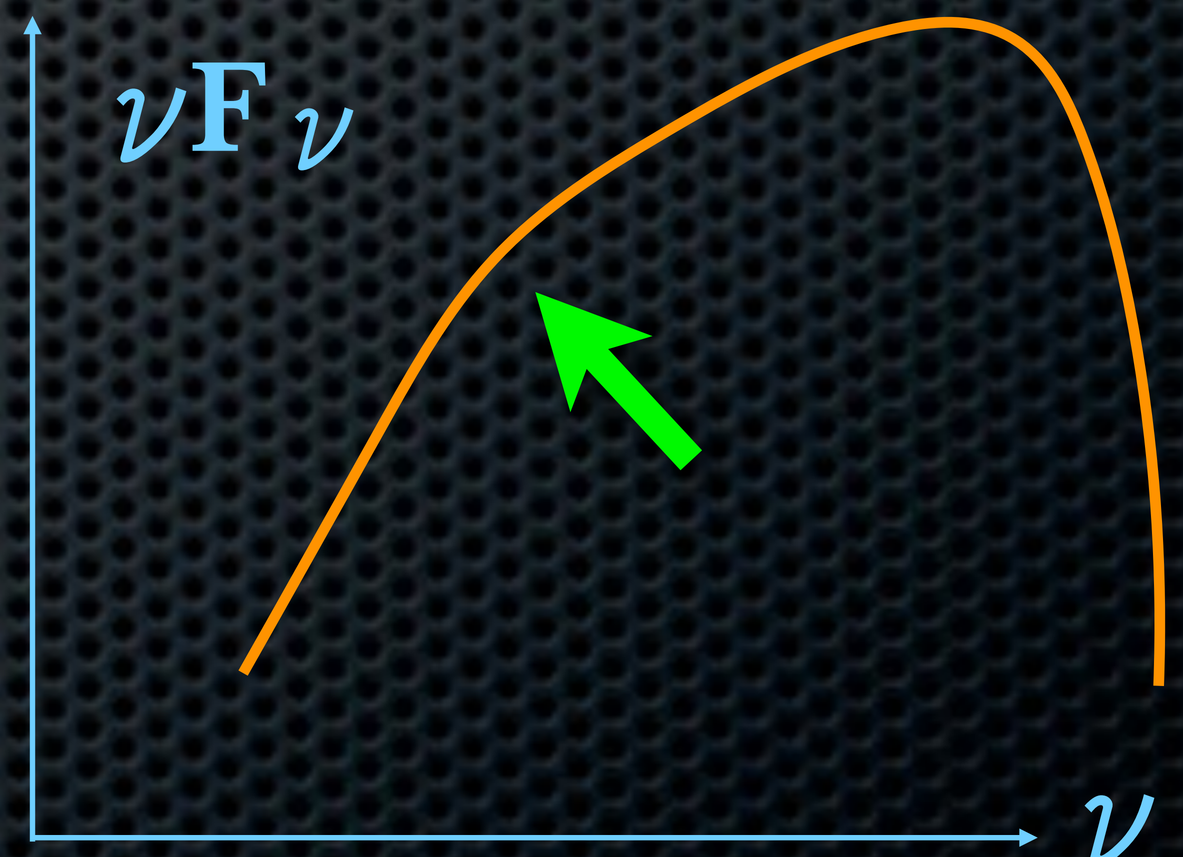
Blandford & Königl 1979: flat jet spectra → synchrotron self-absorption



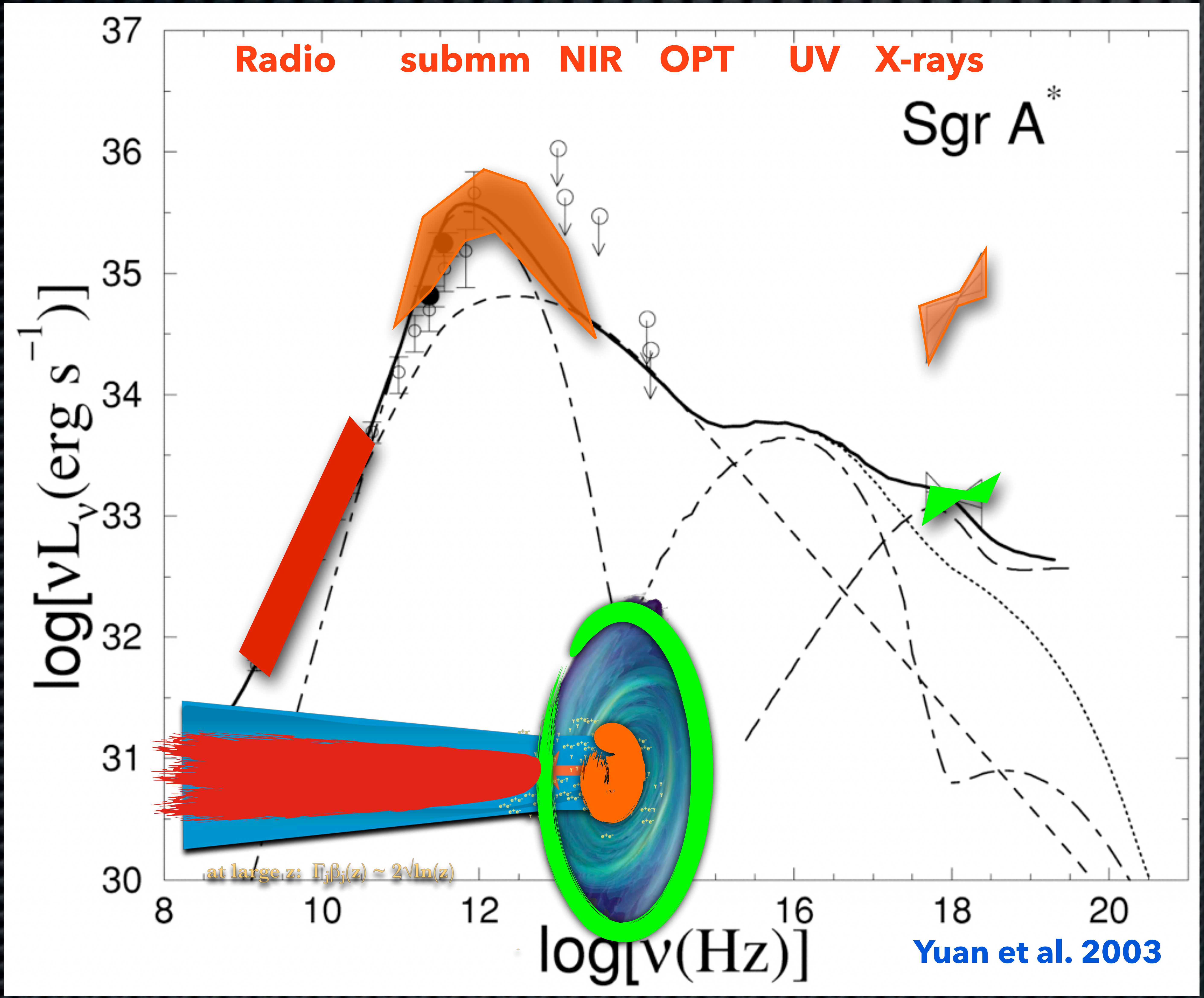
$$r \propto \nu^{-1}$$

Maximum synchrotron self-absorption break ➠ most compact part of jet where particle acceleration occurs





Before the acceleration zone: Sgr A* – thermal (relativistic!) corona



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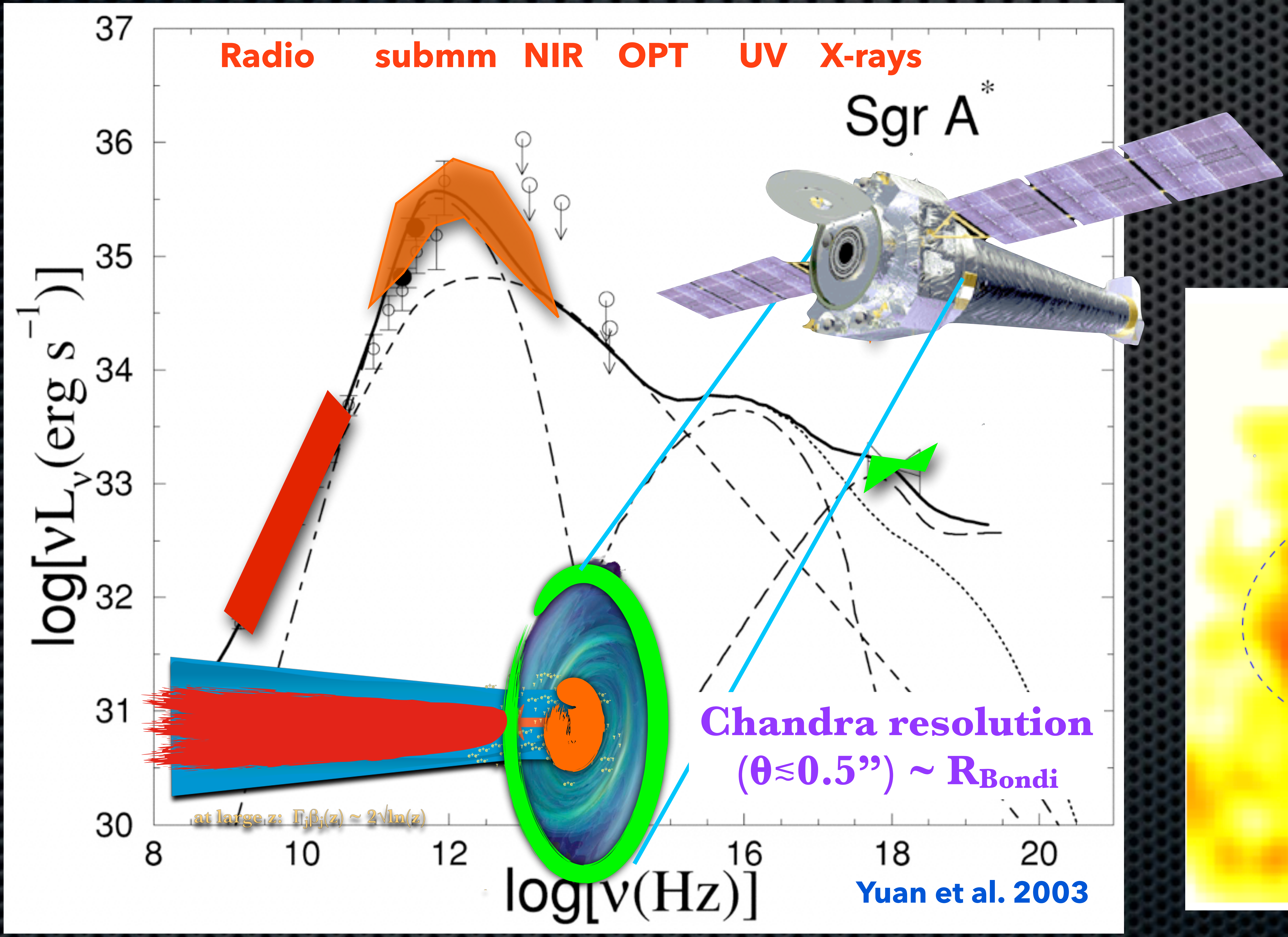

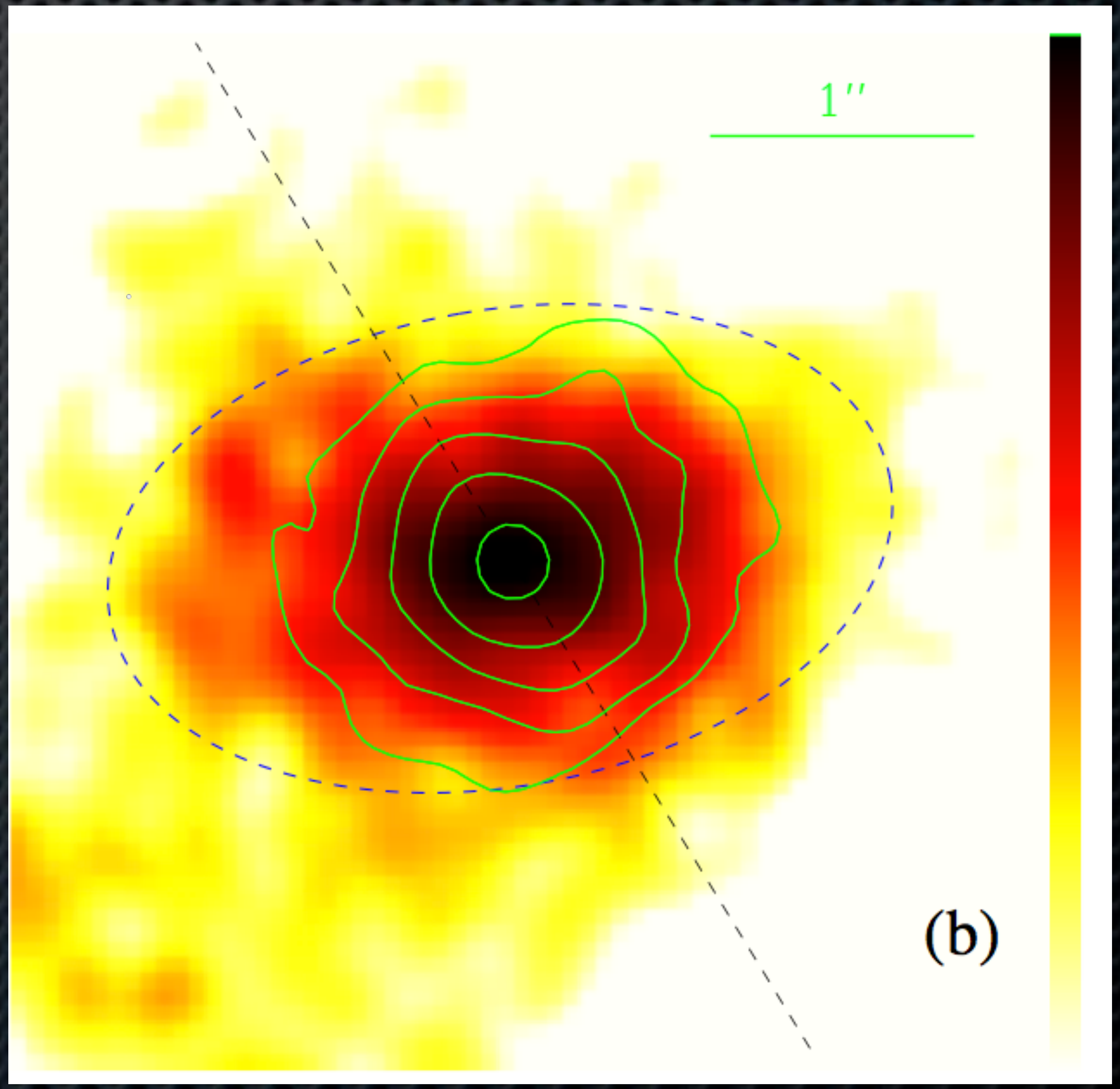

(Wang, Nowak, SM++, Science, 2013)

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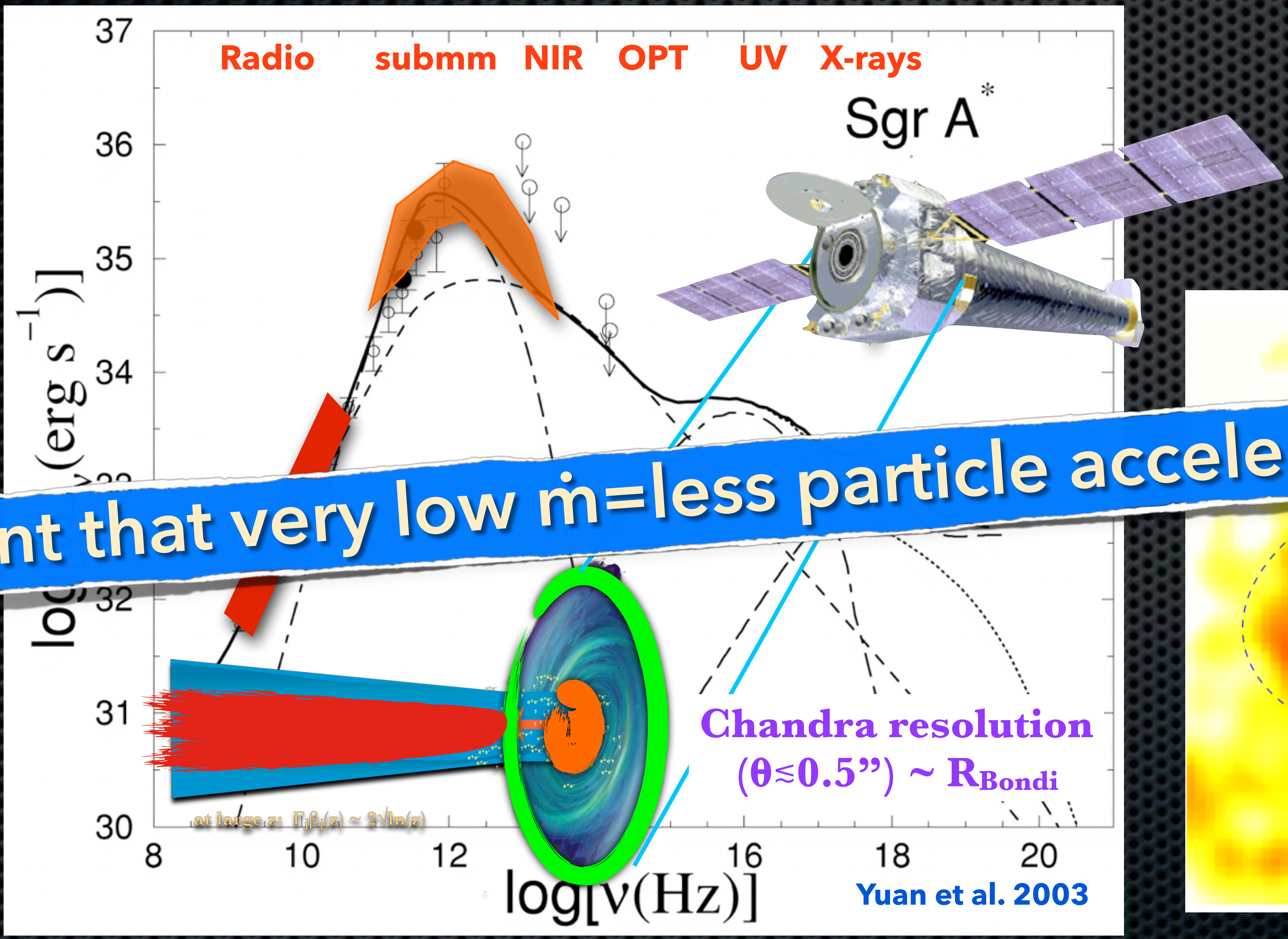
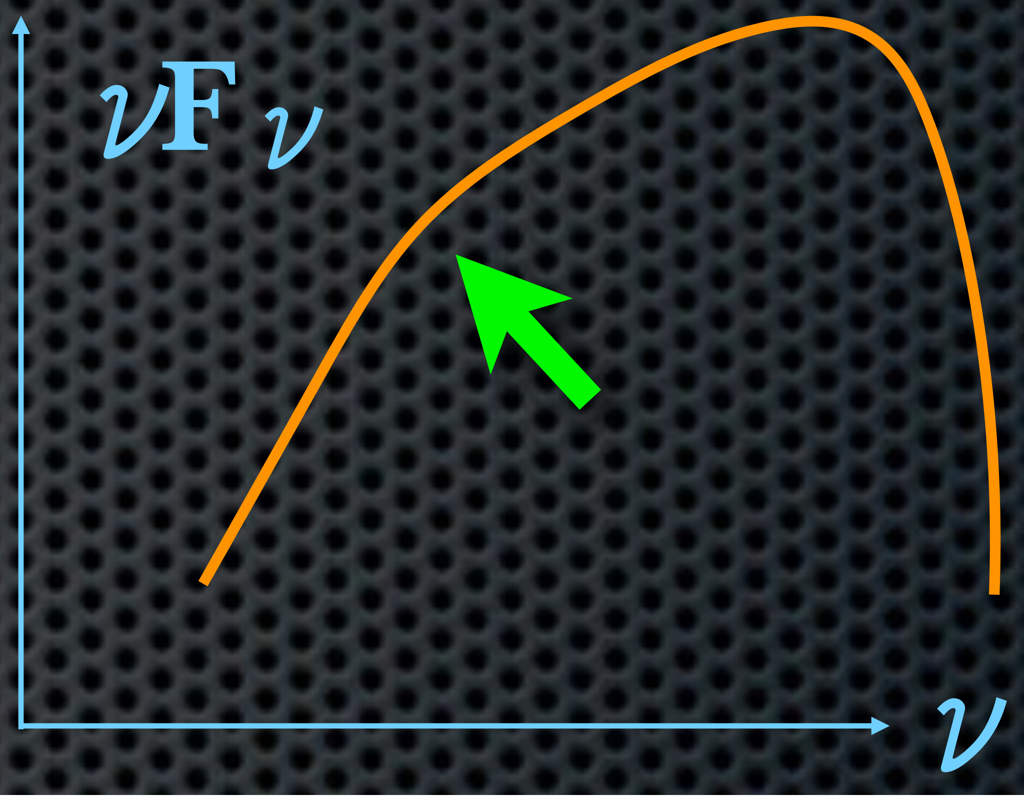
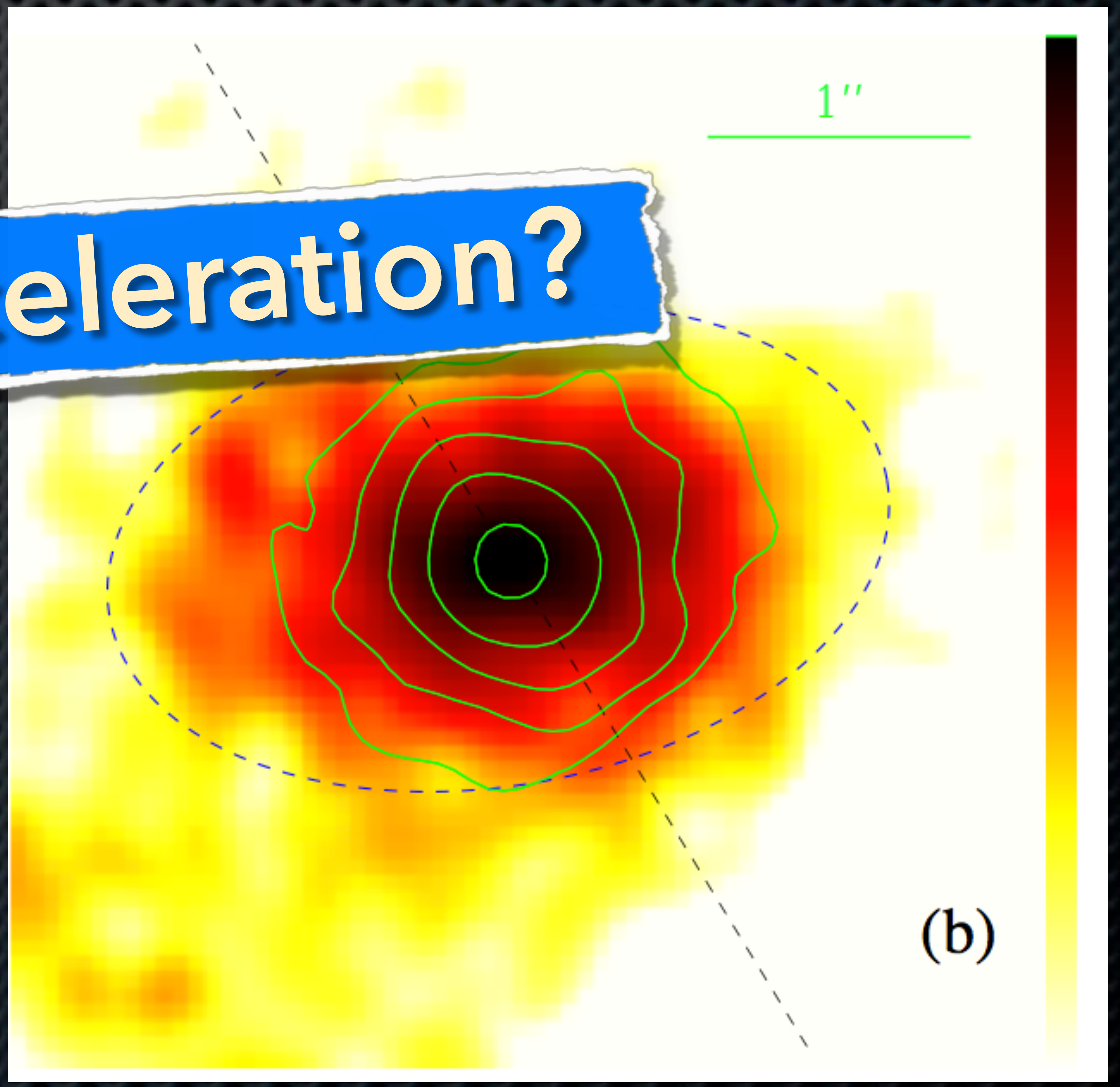


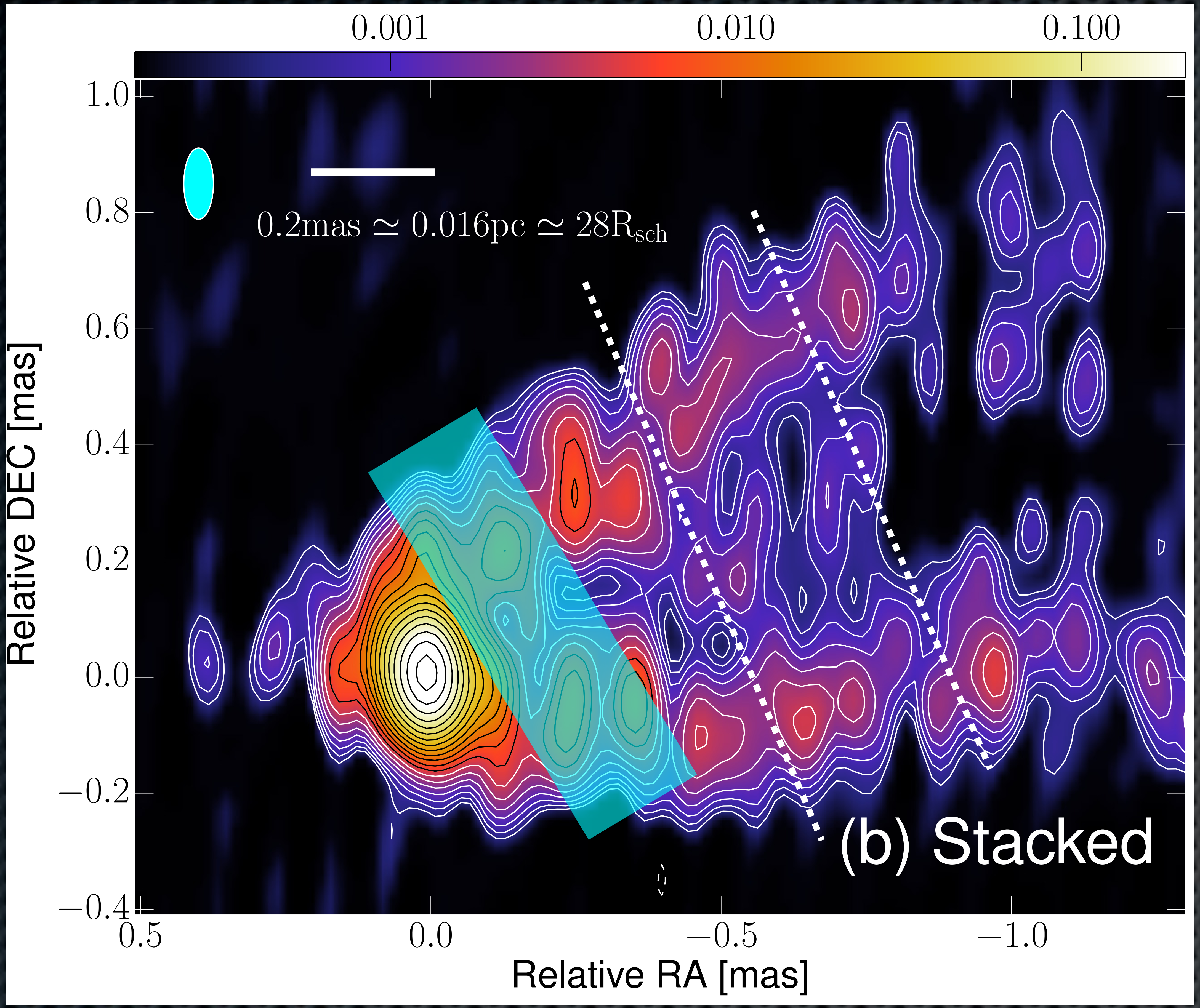


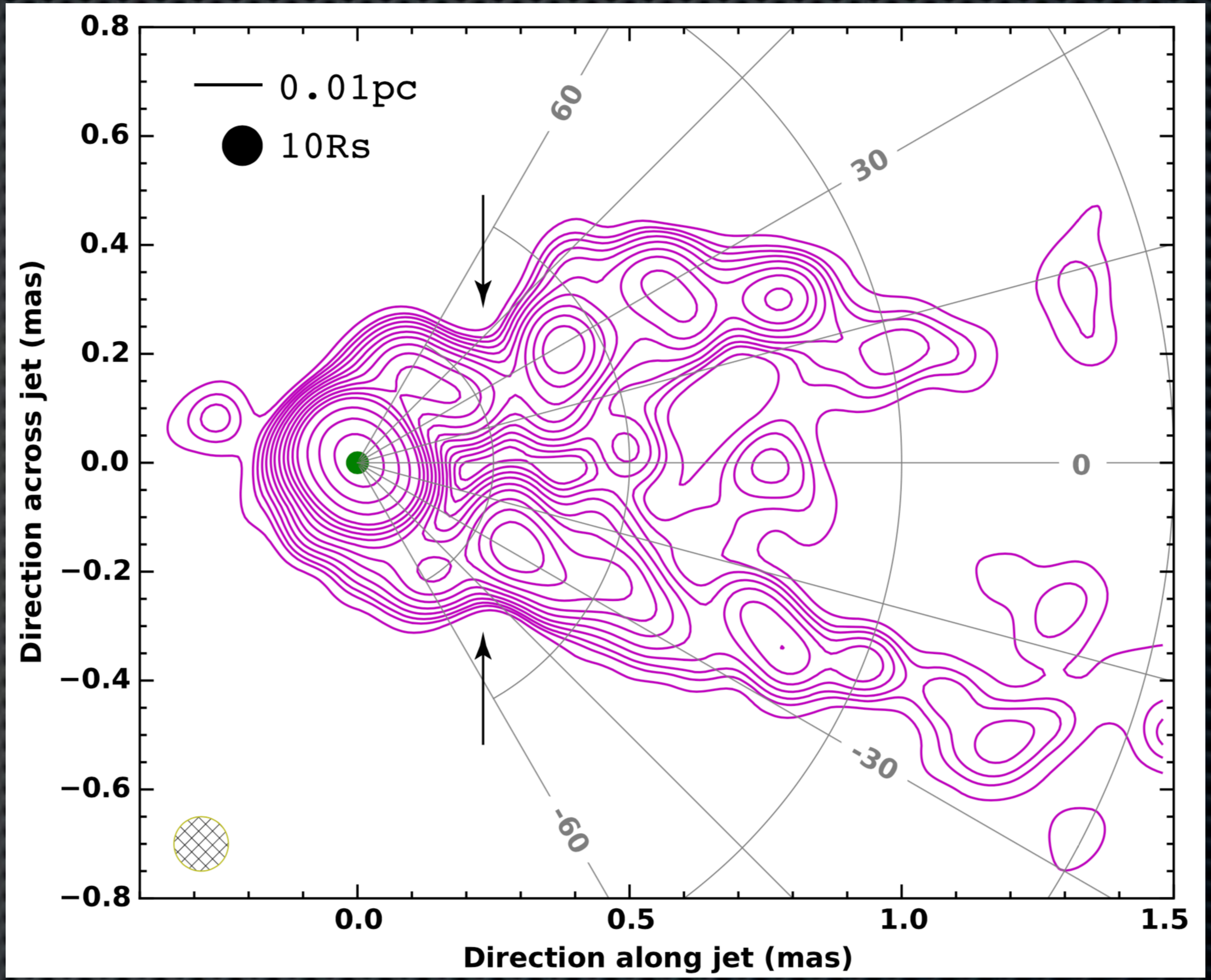


Hint that very low ṁ=less particle acceleration?

(Wang, Nowak, SM++, Science, 2013)

VLBI: very high-resolution view of inner jets of M87

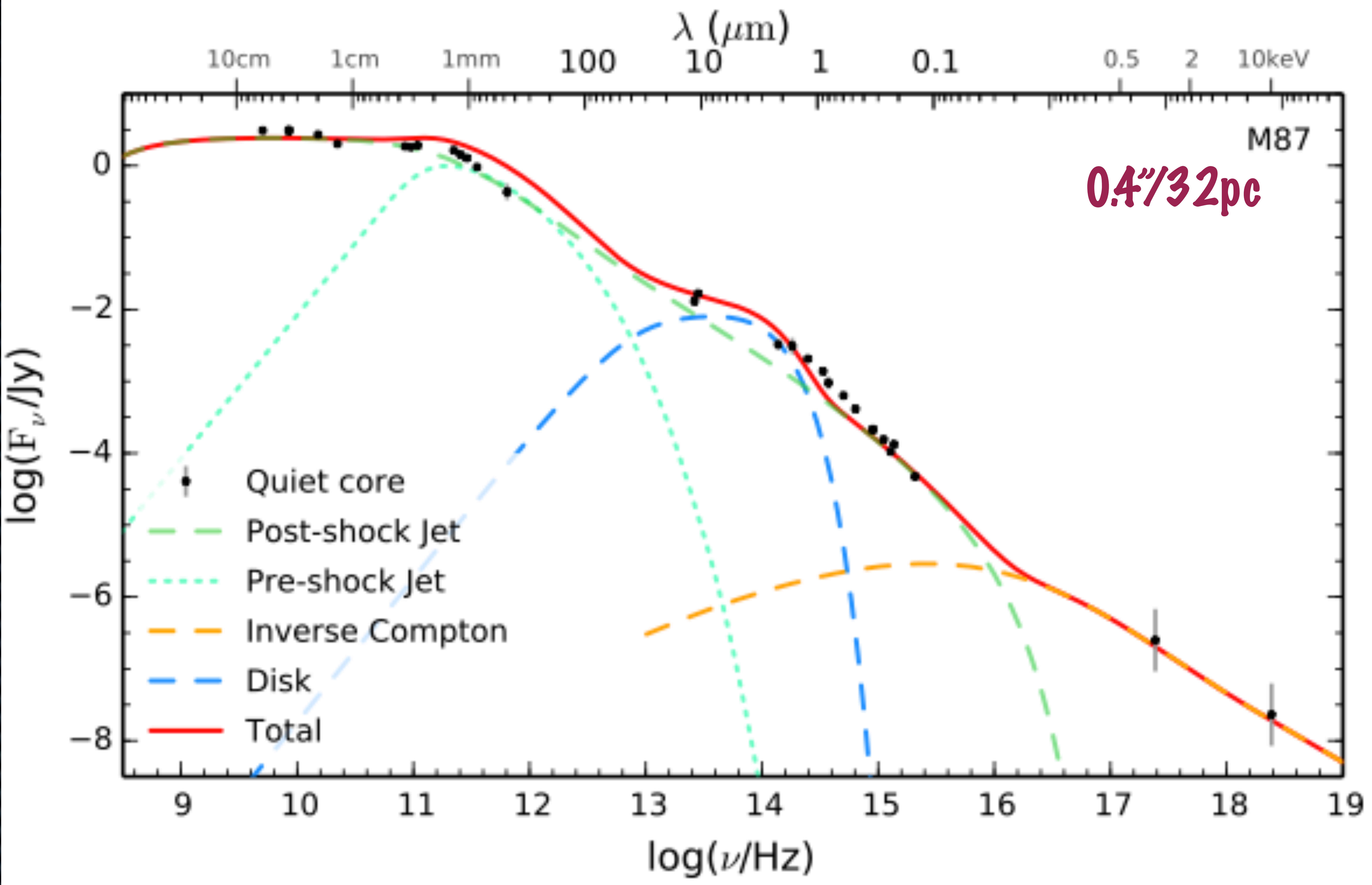


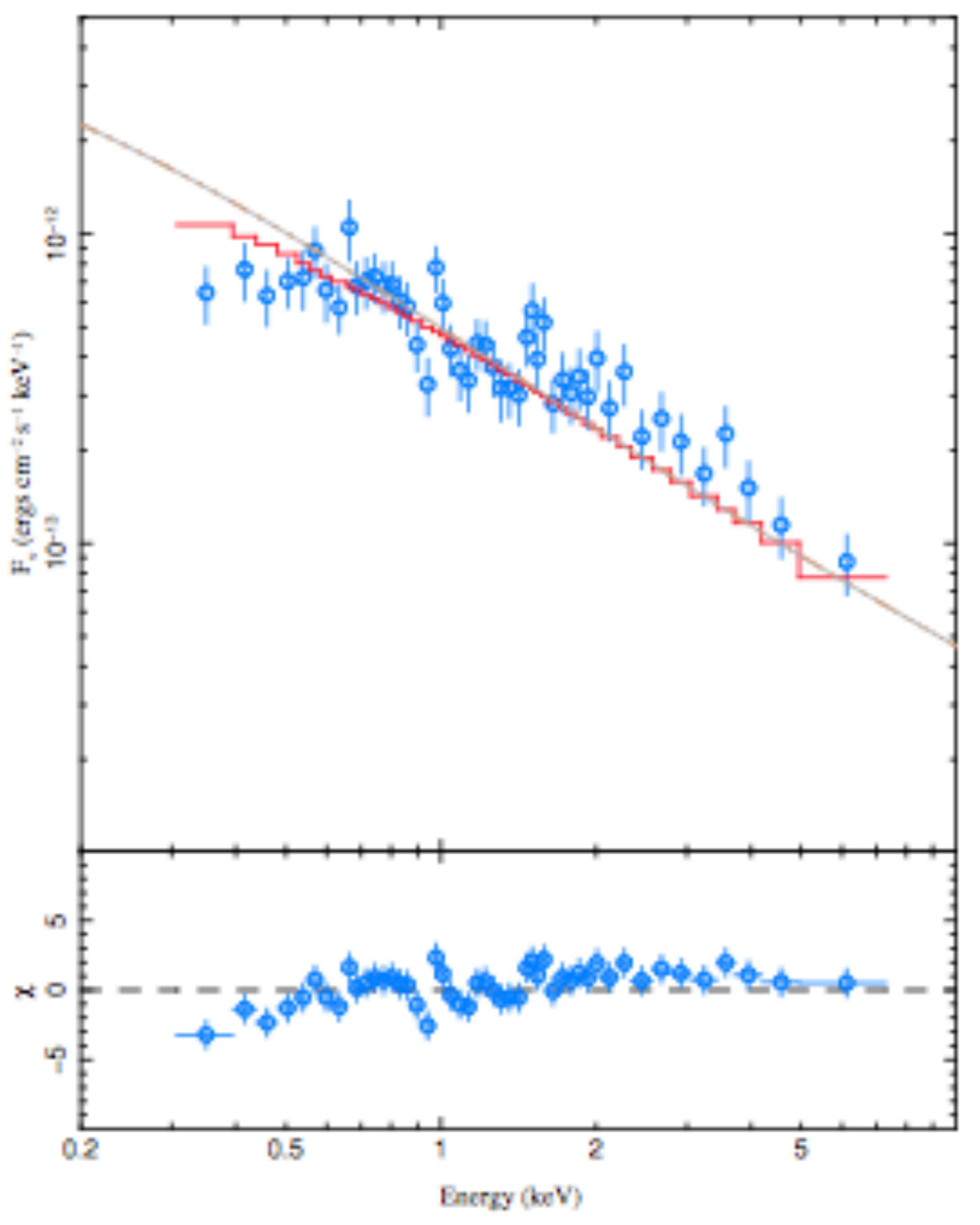


Jets near core seem to also be dominated by thermal particles (1000:1). Is particle acceleration associated with "pinch" at ~100 r_g ?

(Kim++2018; Walker++2018; Hada++14,16,18; Acciari++10; Abramowski++12, etc.)

First high-resolution multiwavelength spectrum of M87's core: consistent with offset

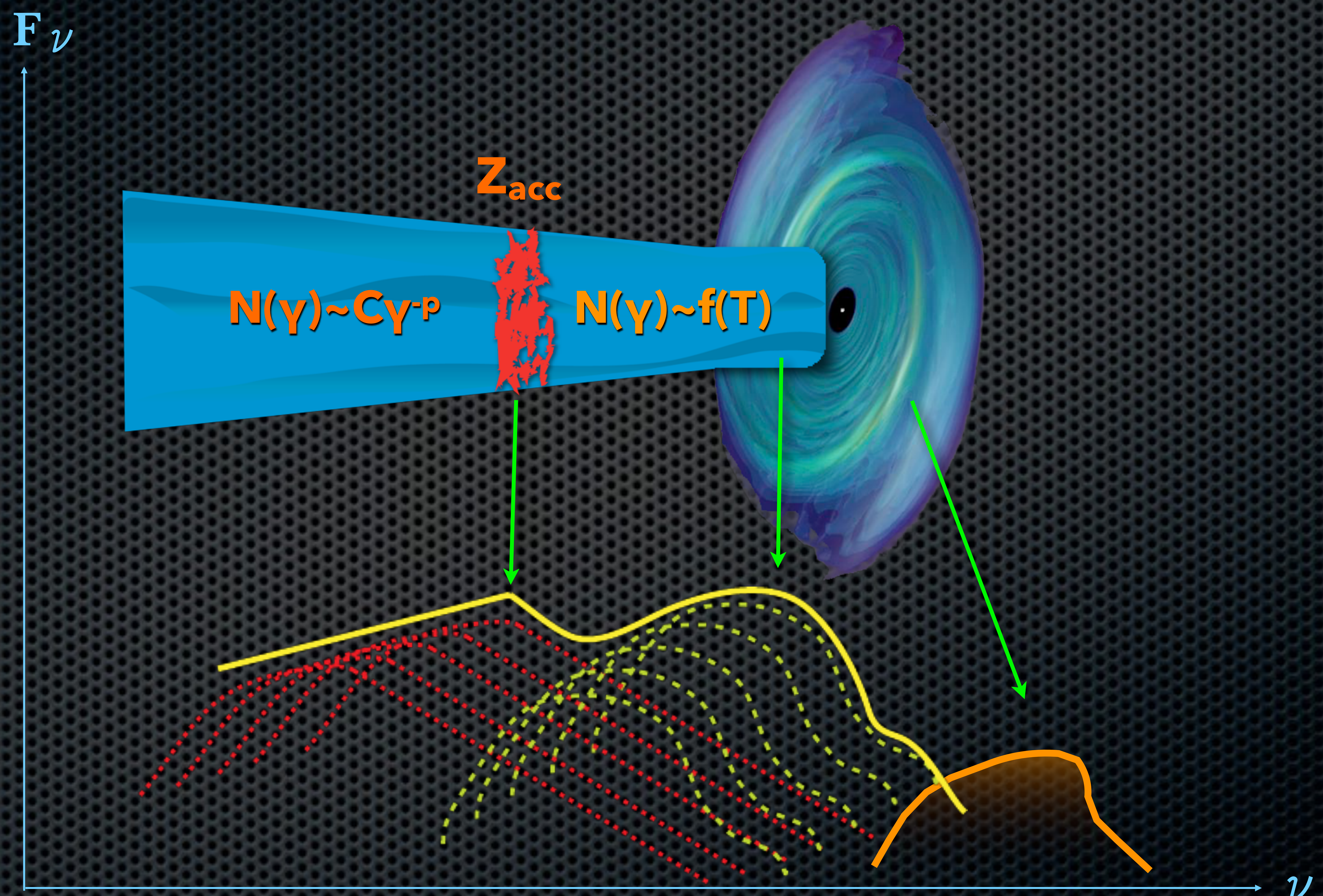




Much lower $\dot{m}$~10^{-5} $M_\odot$/yr than typical blazars, where the "dissipation zone" is 100-1000x further out along the jets. Is this trend meaningful?

(Prieto, Fernandez-Ontiveros, SM & Espada 2016)

Schematic of thermal/nonthermal jet spectrum



(SM, Falcke & Fender 2001; SM, Nowak & Wilms 2005)

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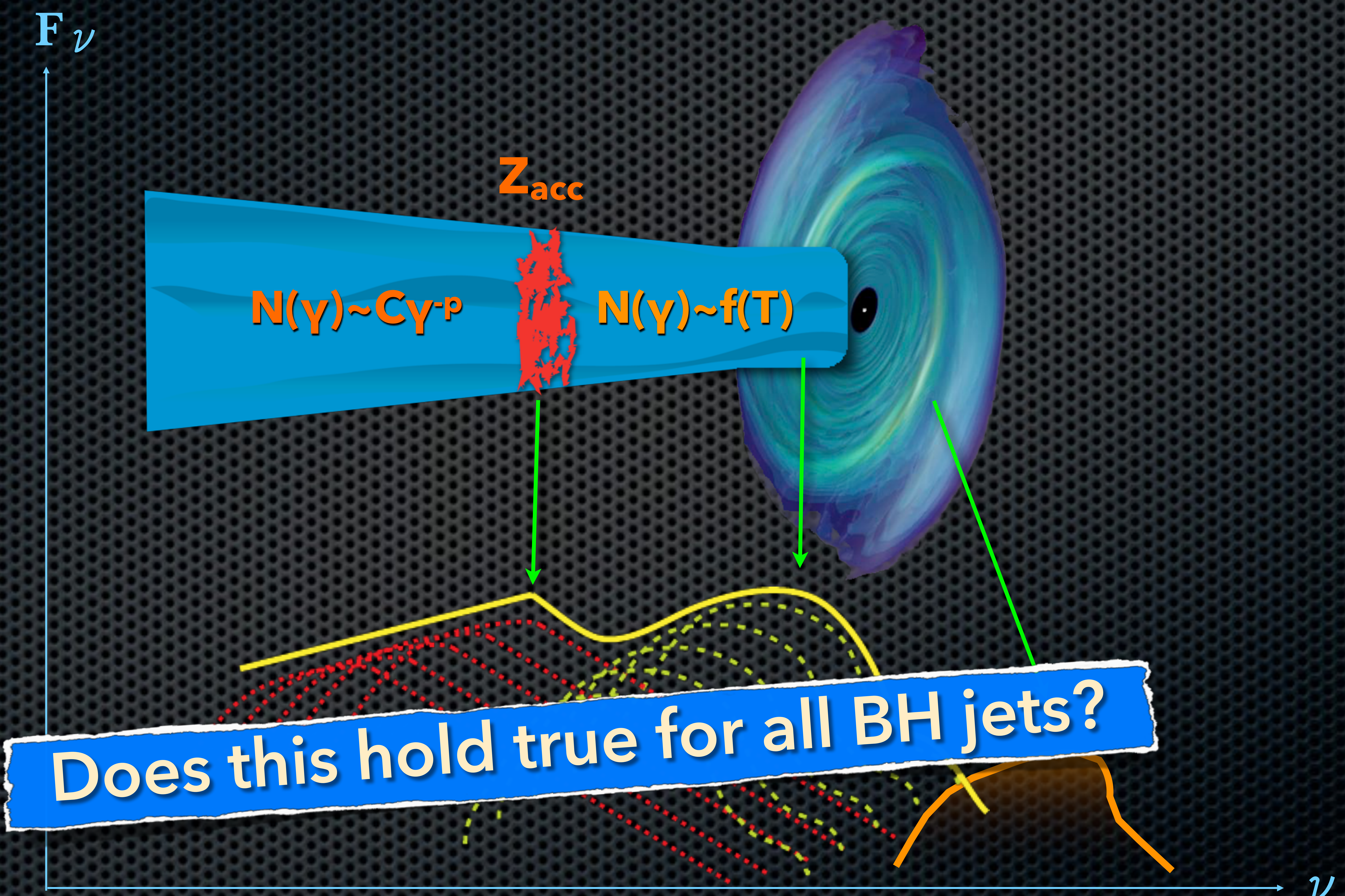
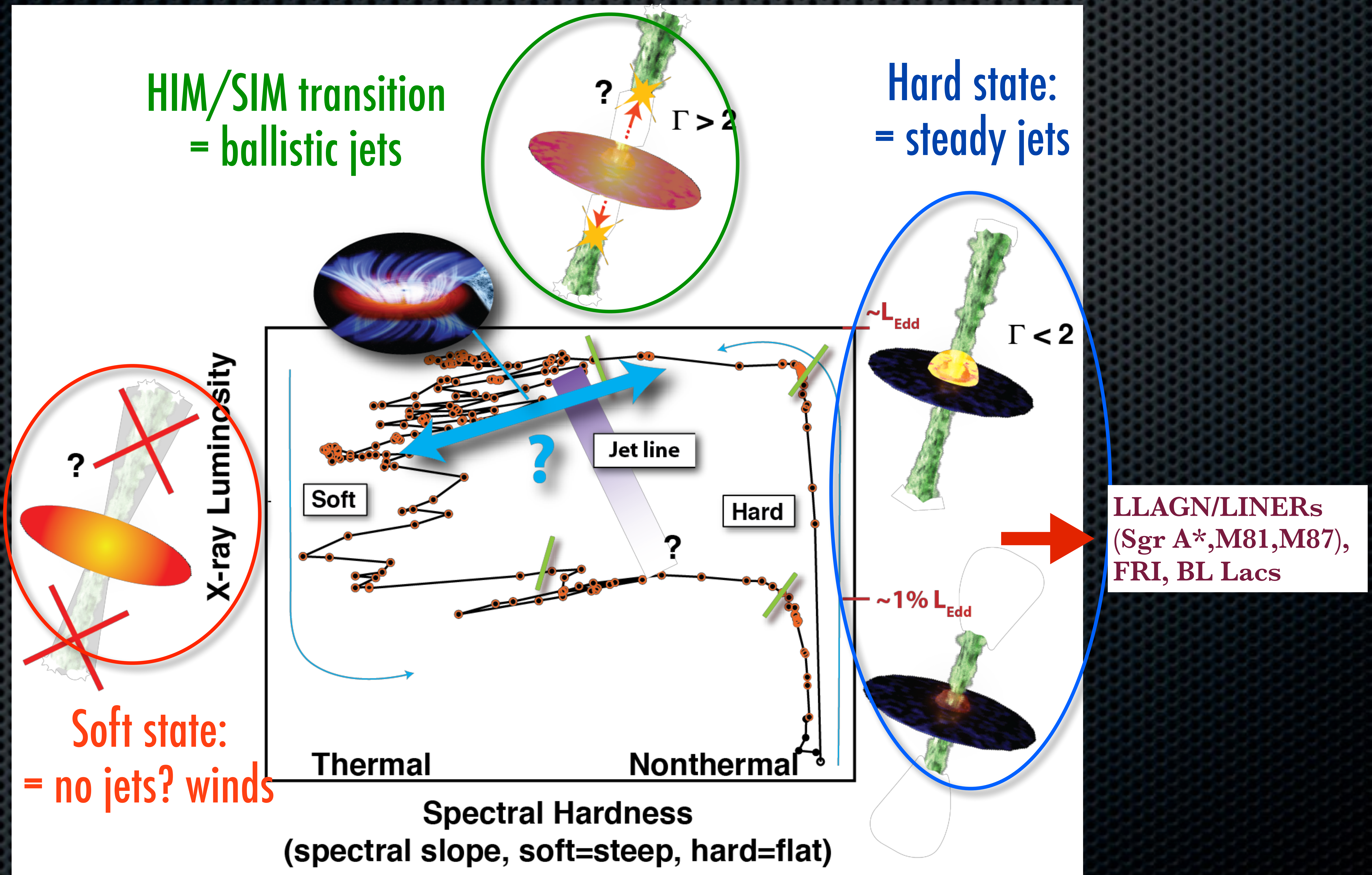
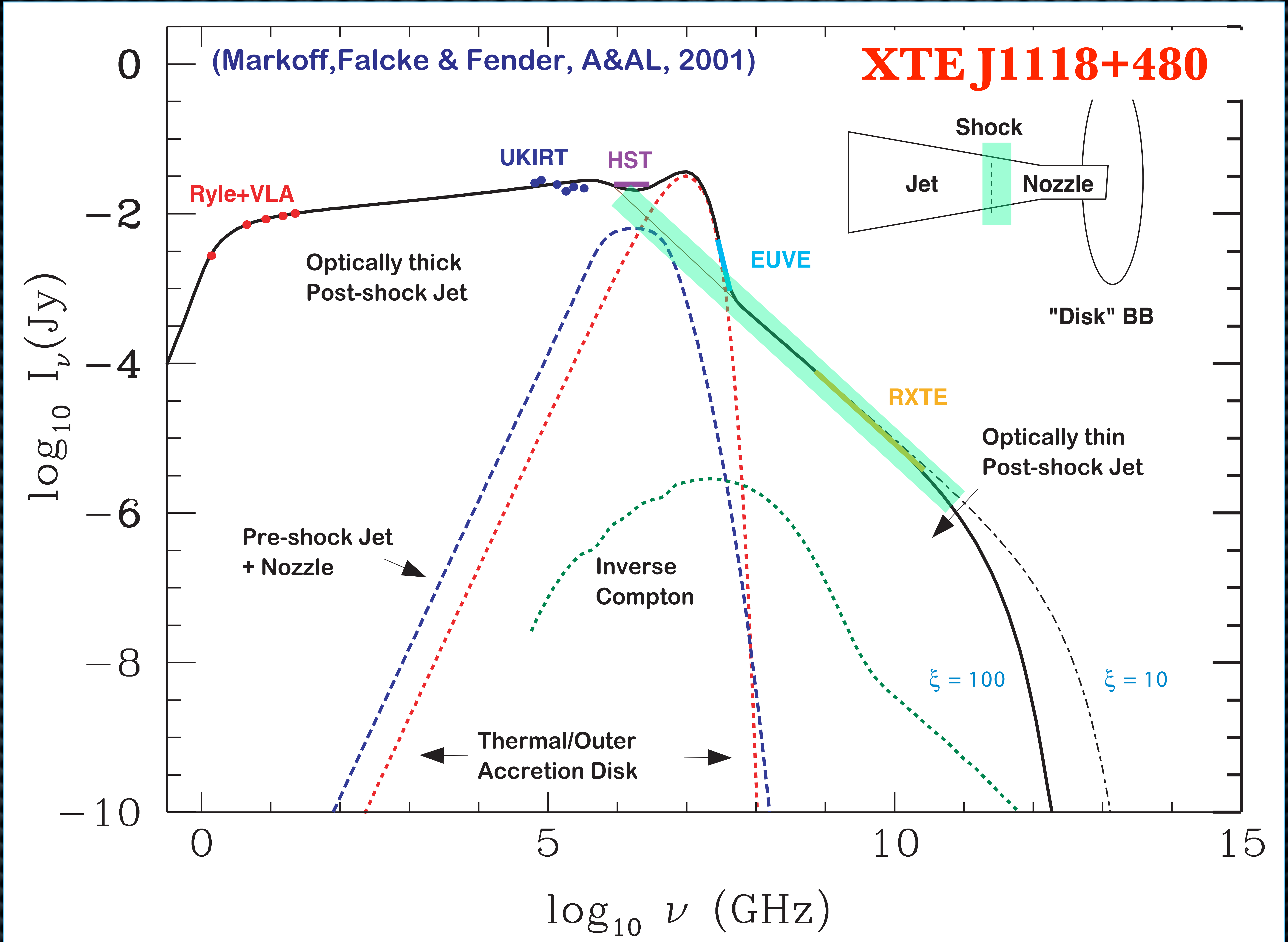


(SM, Falcke & Fender 2001; SM, Nowak & Wilms 2005)

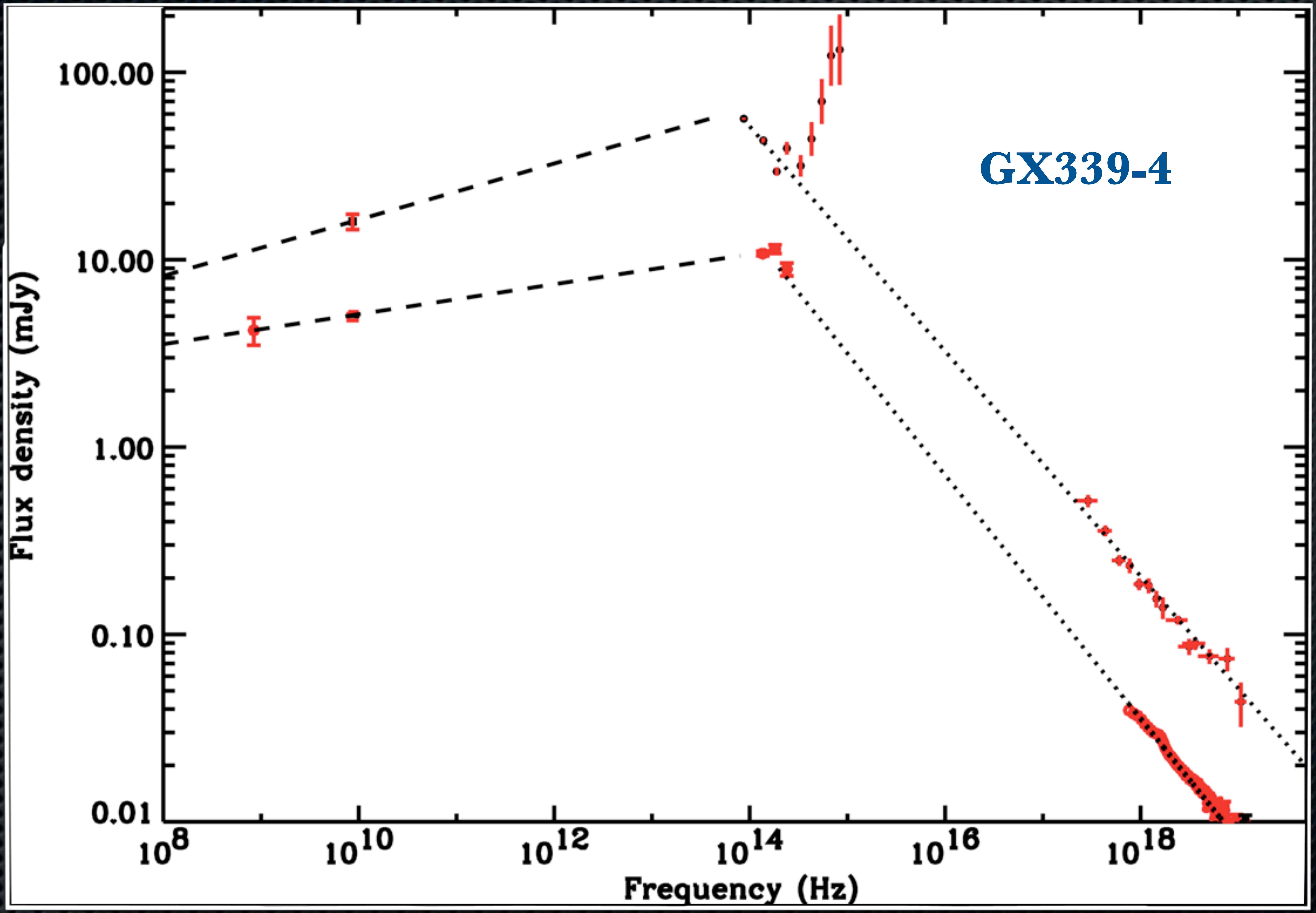
XRBs and AGN share a similar central "engine"



Simultaneous MWL data from XRBs: particle acceleration



(Quasi)-simultaneous XRB spectra: spectral breaks



(Corbel & Fender 02; SM++ 01, 03, 05; Gallo++07; Maitra, SM++ 09; Gandhi++ 11; DRussell++13)

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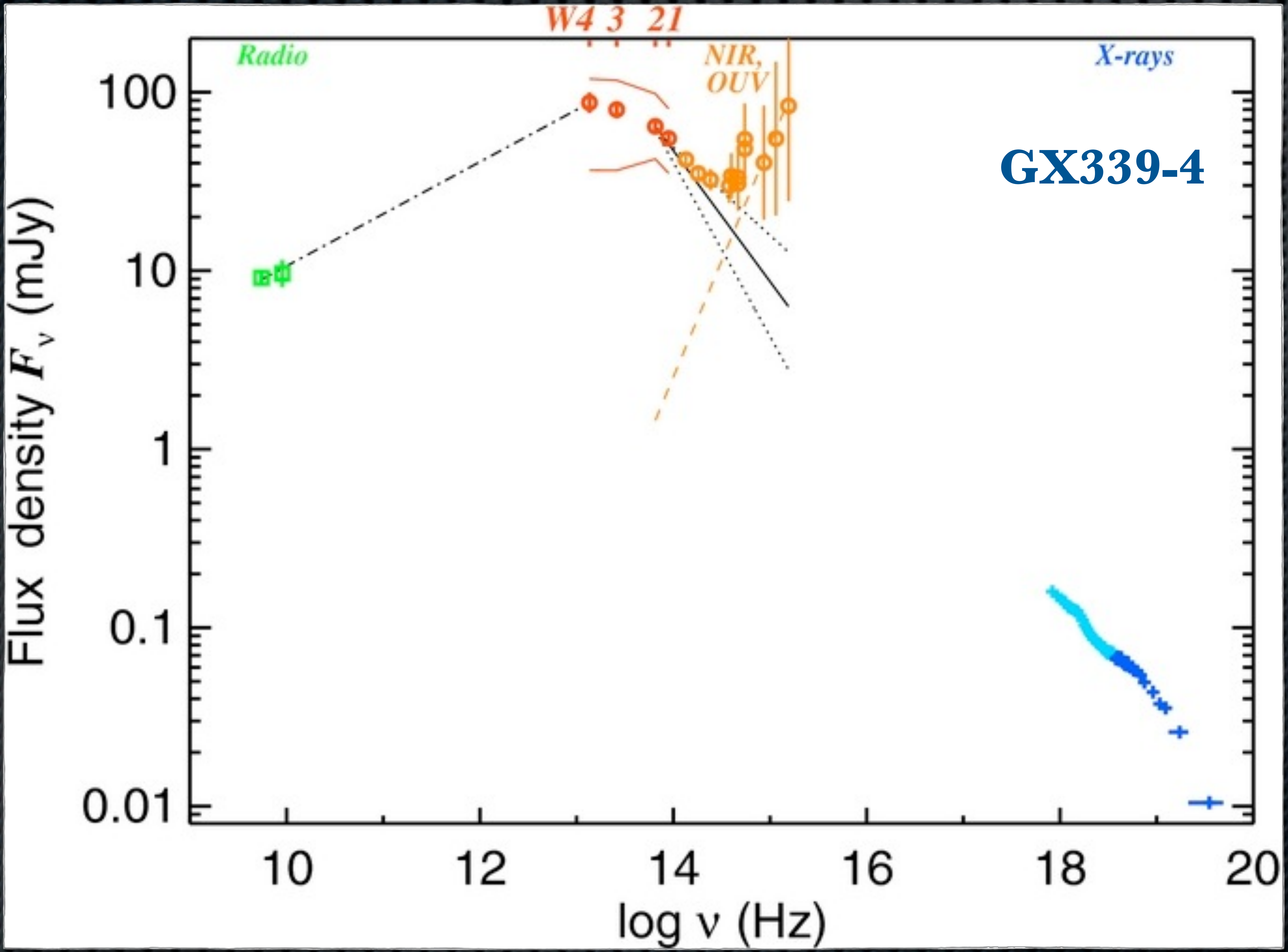

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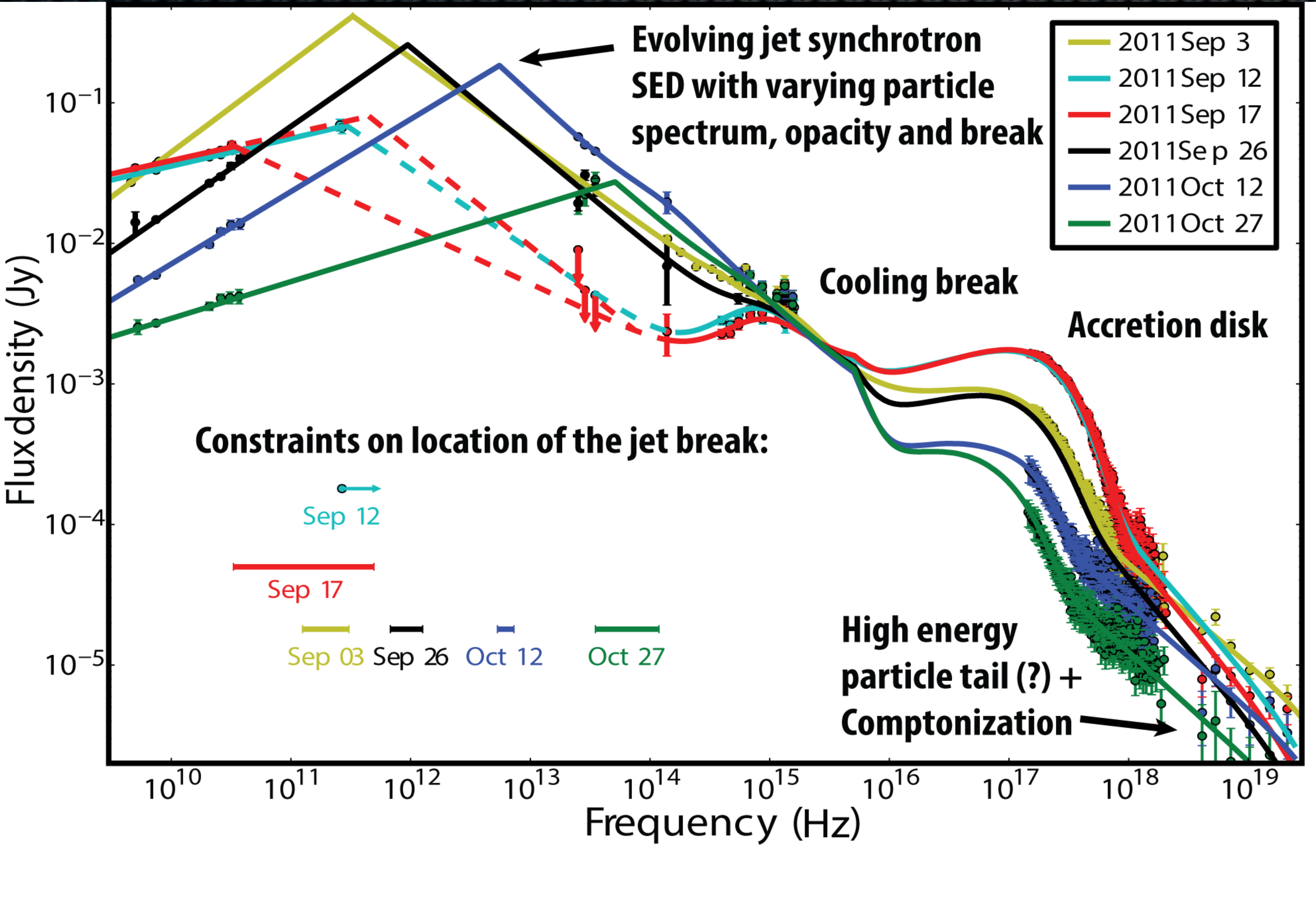
“Next gen” XRB monitoring campaigns: MAXI J1836-194



(TRussell, Miller-Jones,++ 2014; TRussell ++ in prep.; see also DRussell++13; Koljonen++ 2015)

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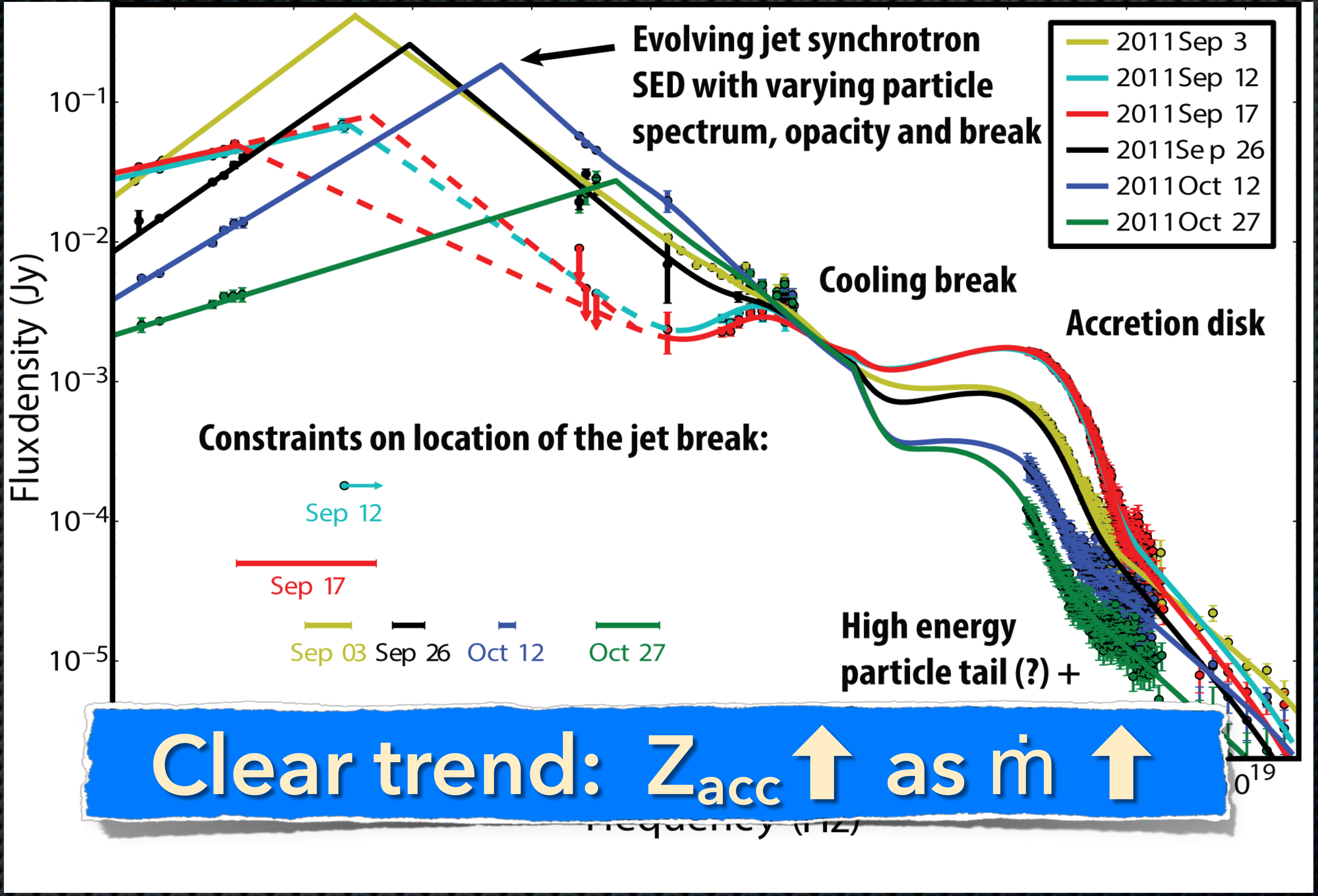
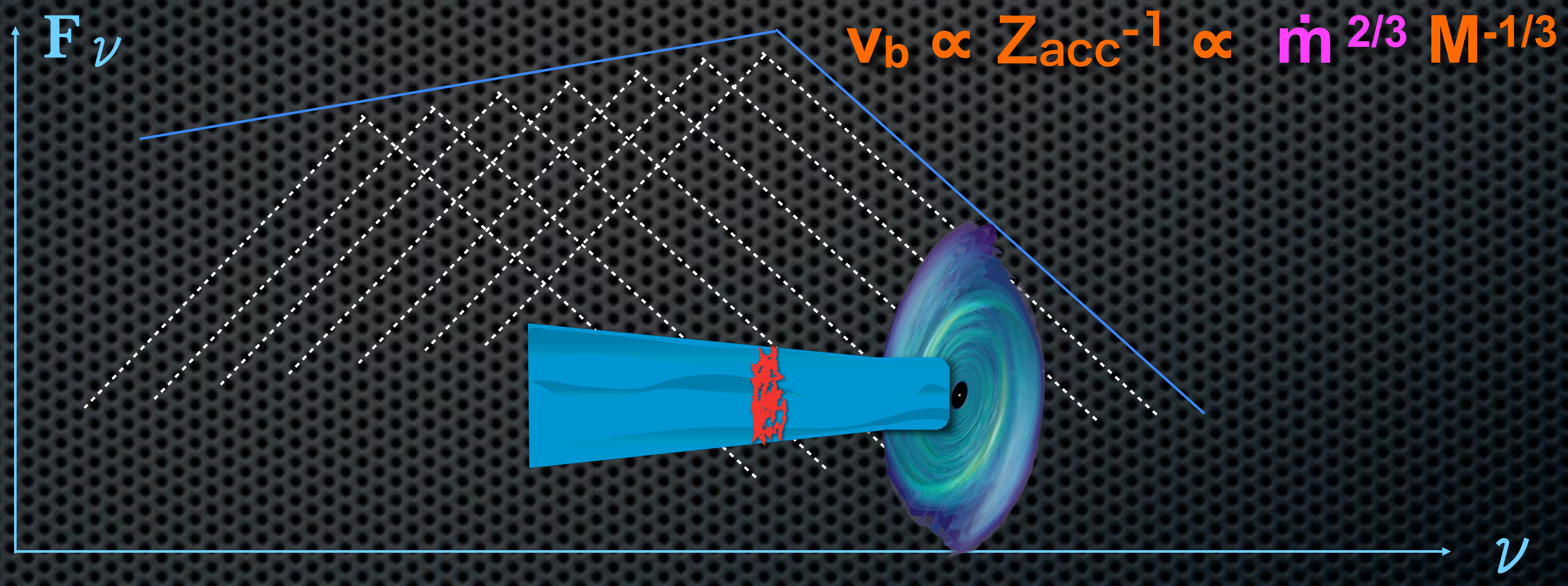


(TRussell, Miller-Jones,++ 2014; TRussell ++ in prep.; see also DRussell++13; Koljonen++ 2015)

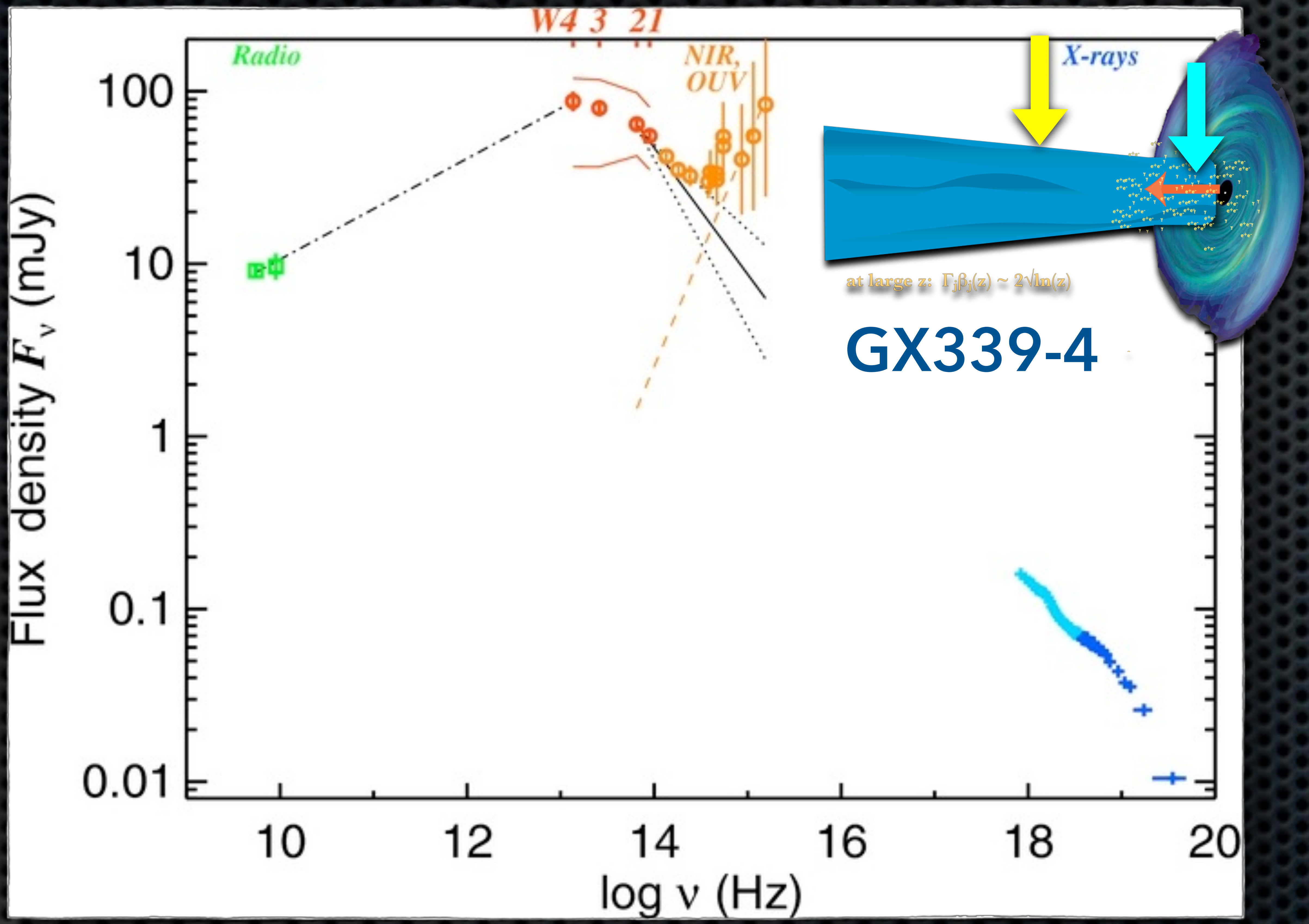
Evolution opposite that expected for optical depth effects alone

- Break always predicted to scale *positively* with ṁ if acceleration always starts at the same offset in jet
- Opposite behaviour hints at dynamical/structural changes
- Speed of evolution suggests internal/MHD driven



(Blandford & Königl 1979; Falcke & Biermann 1995; SM++ 2003; Heinz & Sunyaev 2003; Romero, Böttcher, SM, Tavecchio 2017)

Independent determination of Z_{acc}!



- Broadband noise: IR lags X-ray by ~110ms ➠ largest scale ~ 2×10^9cm (few 10^3 r_g), consistent with spectral fitting.

(Kalamkar++2016; Gandhi++ 2017; Paice, Gandhi++, in prep.)

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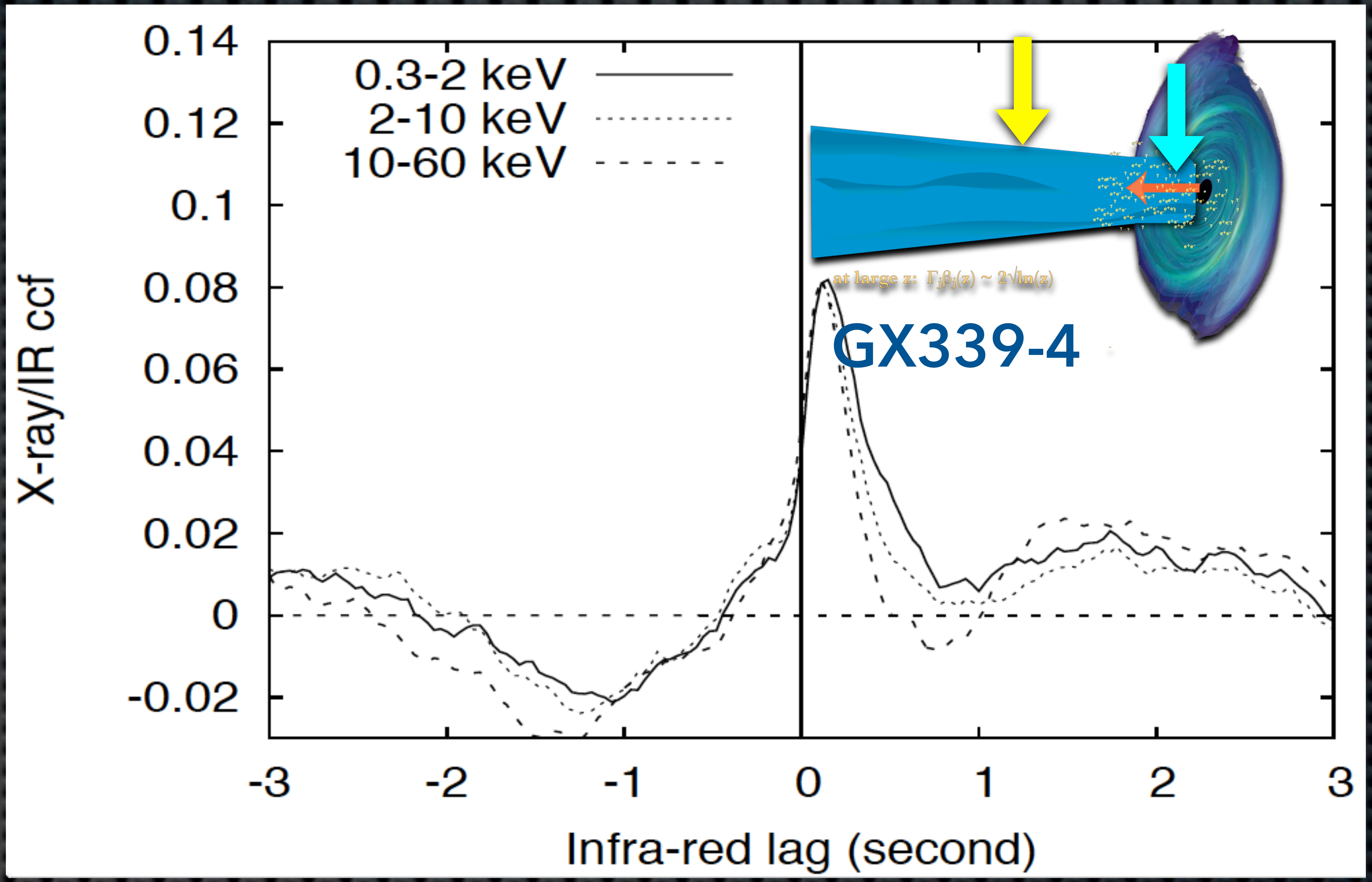

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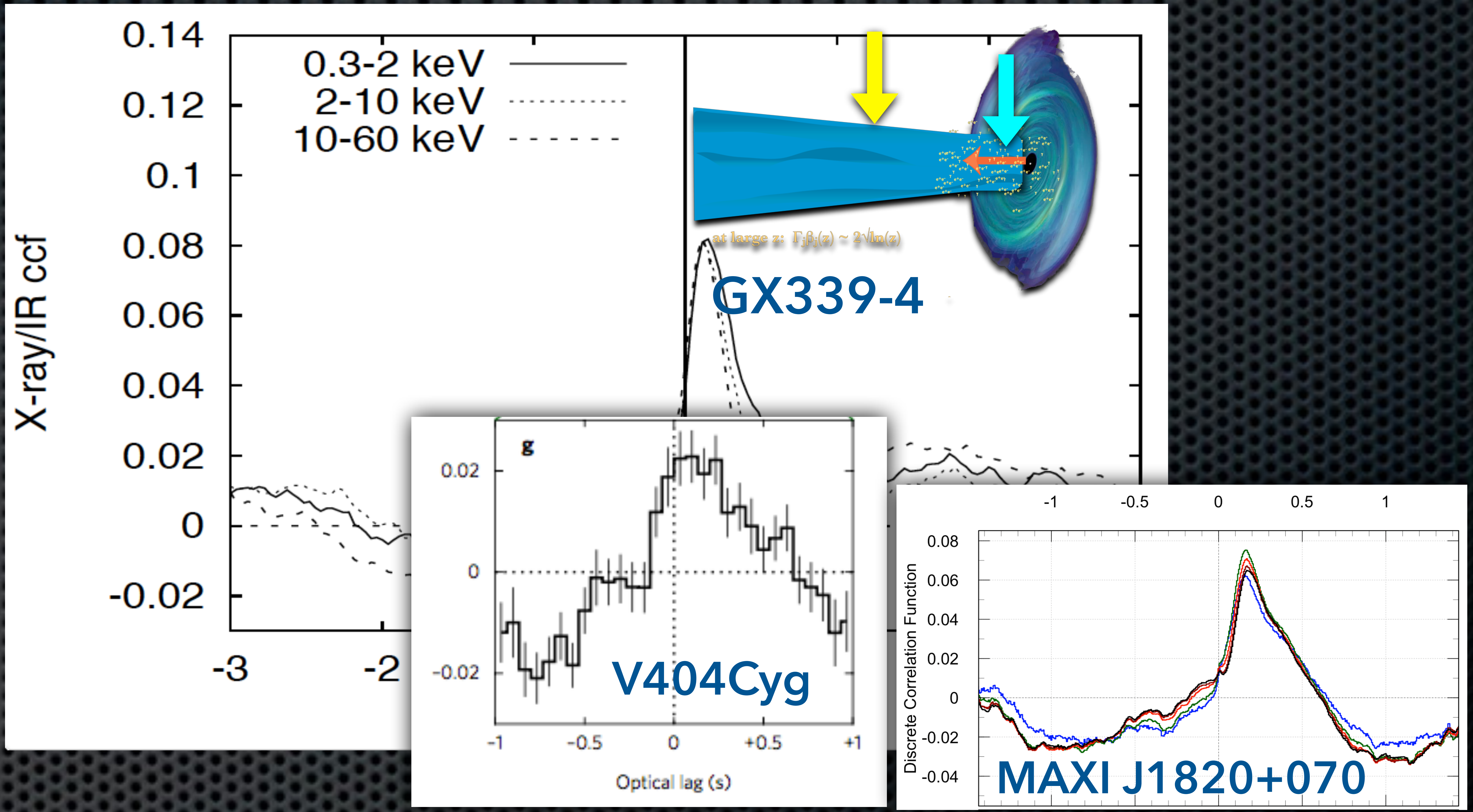

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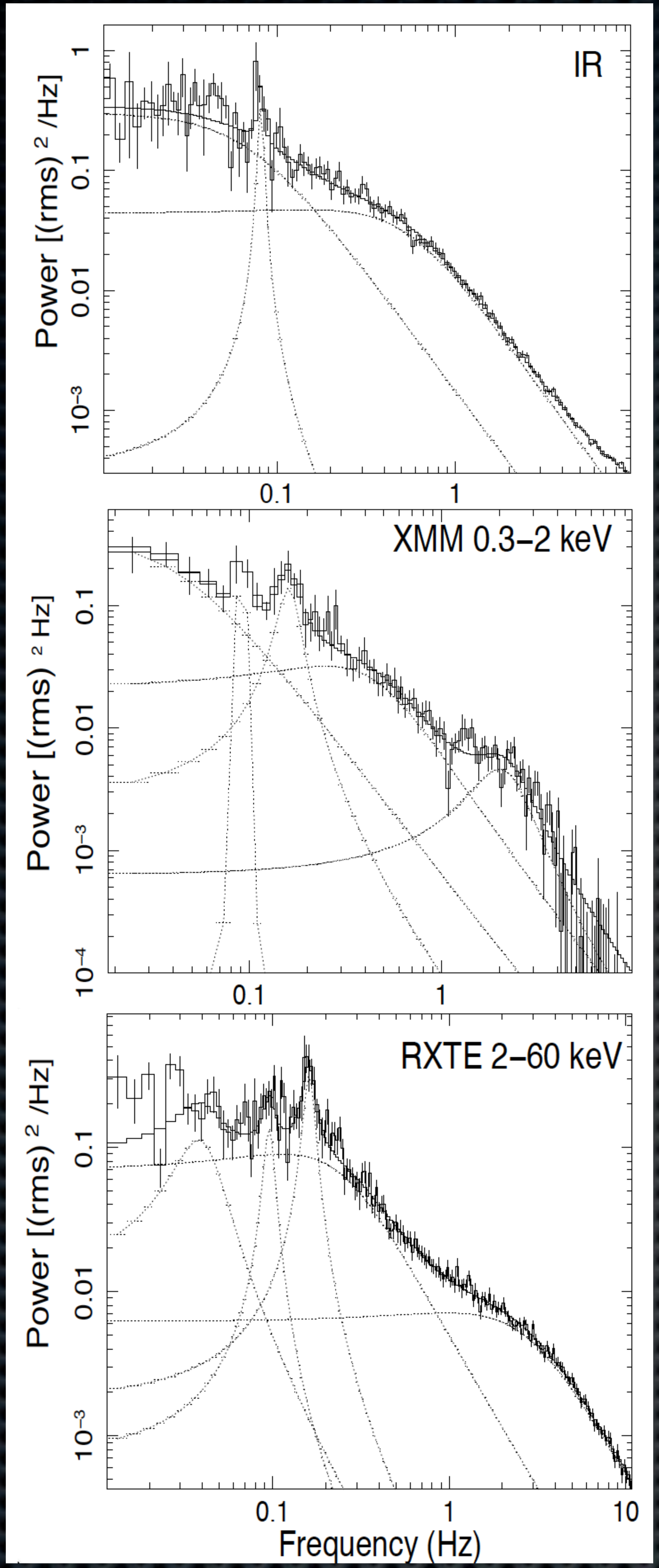

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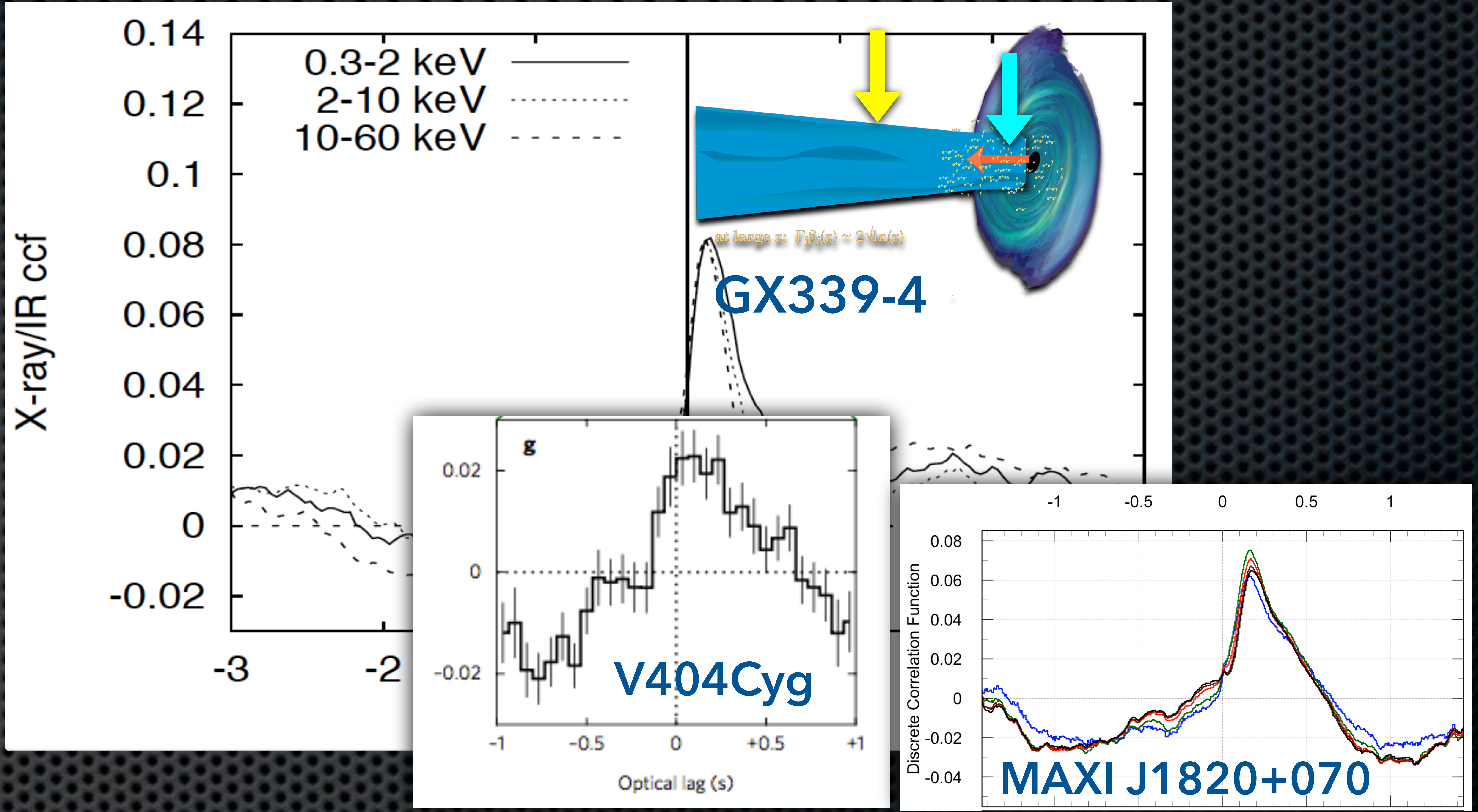
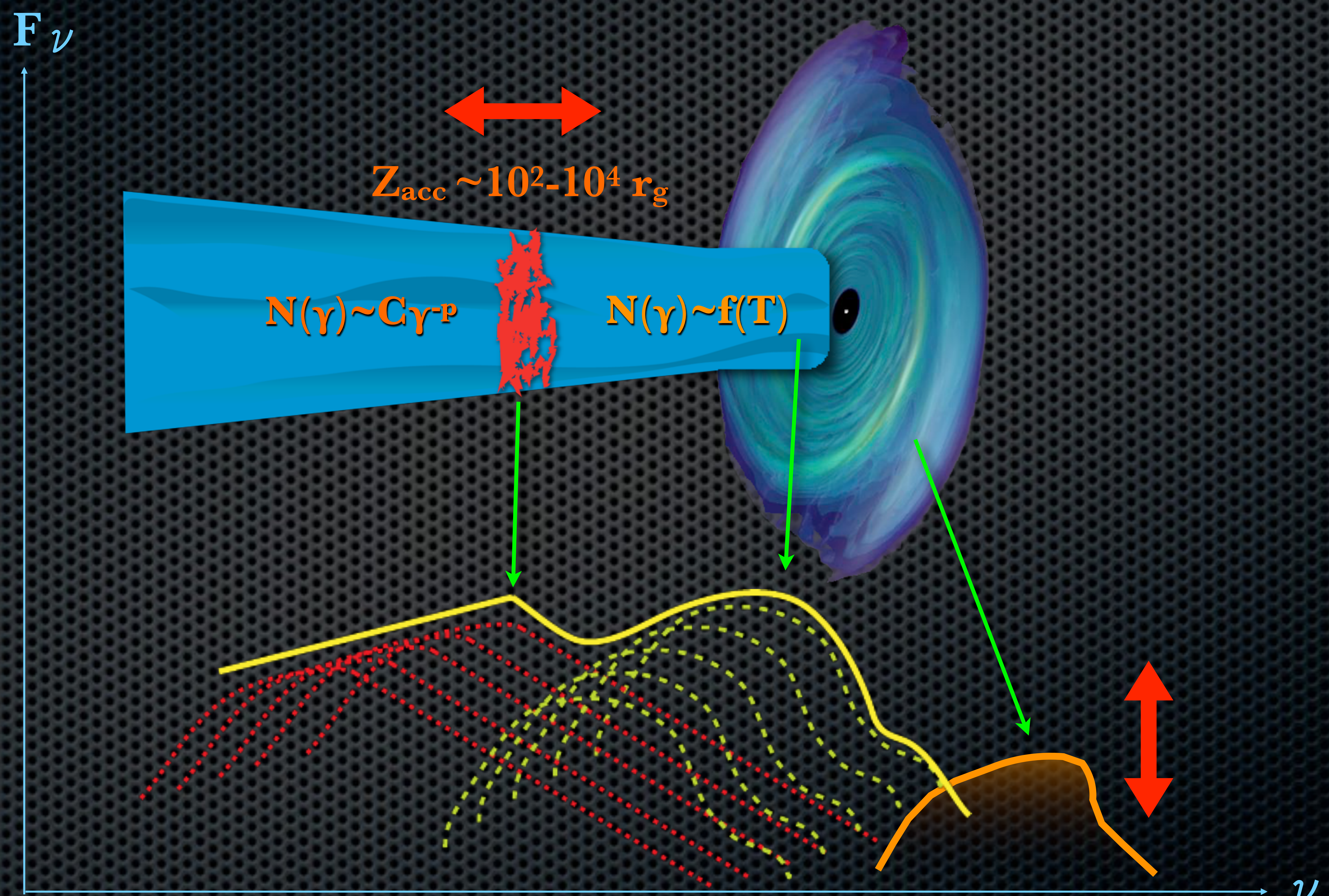


- Broadband noise: IR lags X-ray by ~110ms ➠ largest scale ~ 2×10^9 cm (few 10^3 r_g), consistent with spectral fitting.
- Now found in three sources, all 0.1-0.3ms!
- First IR LFQPO's! Half the Xray frequency

(Kalamkar++2016; Gandhi++ 2017; Paice, Gandhi++, in prep.)

Offset confirmed for both AGN/XRBs, responds to changes in the accretion flow



(SM, Falcke & Fender 2001; SM, Nowak & Wilms 2005)

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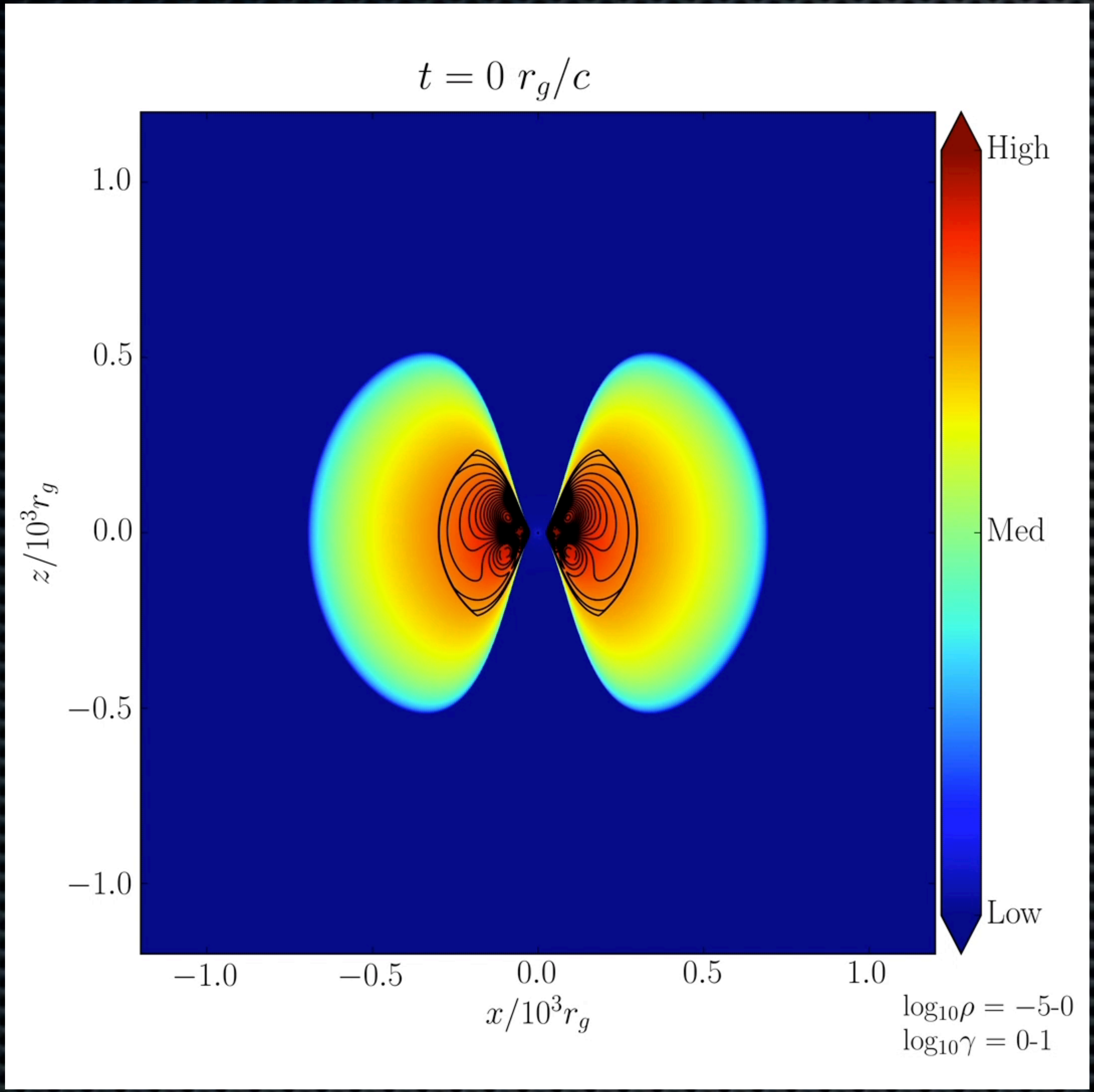
Theoretical advances: we can model jets to physical scales!



(Chatterjee, Liska, Tchekhovskoy & SM, in prep.)

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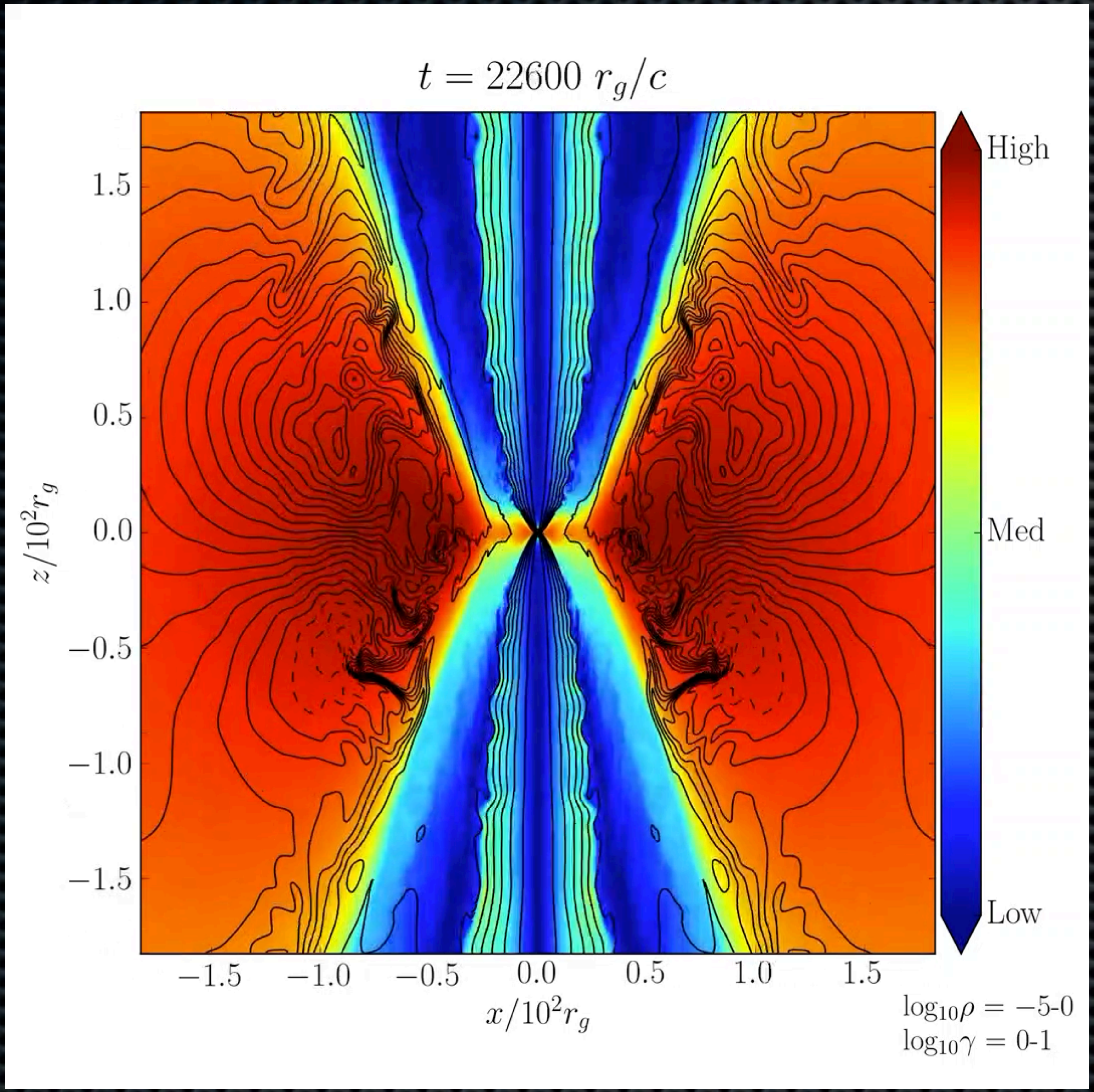

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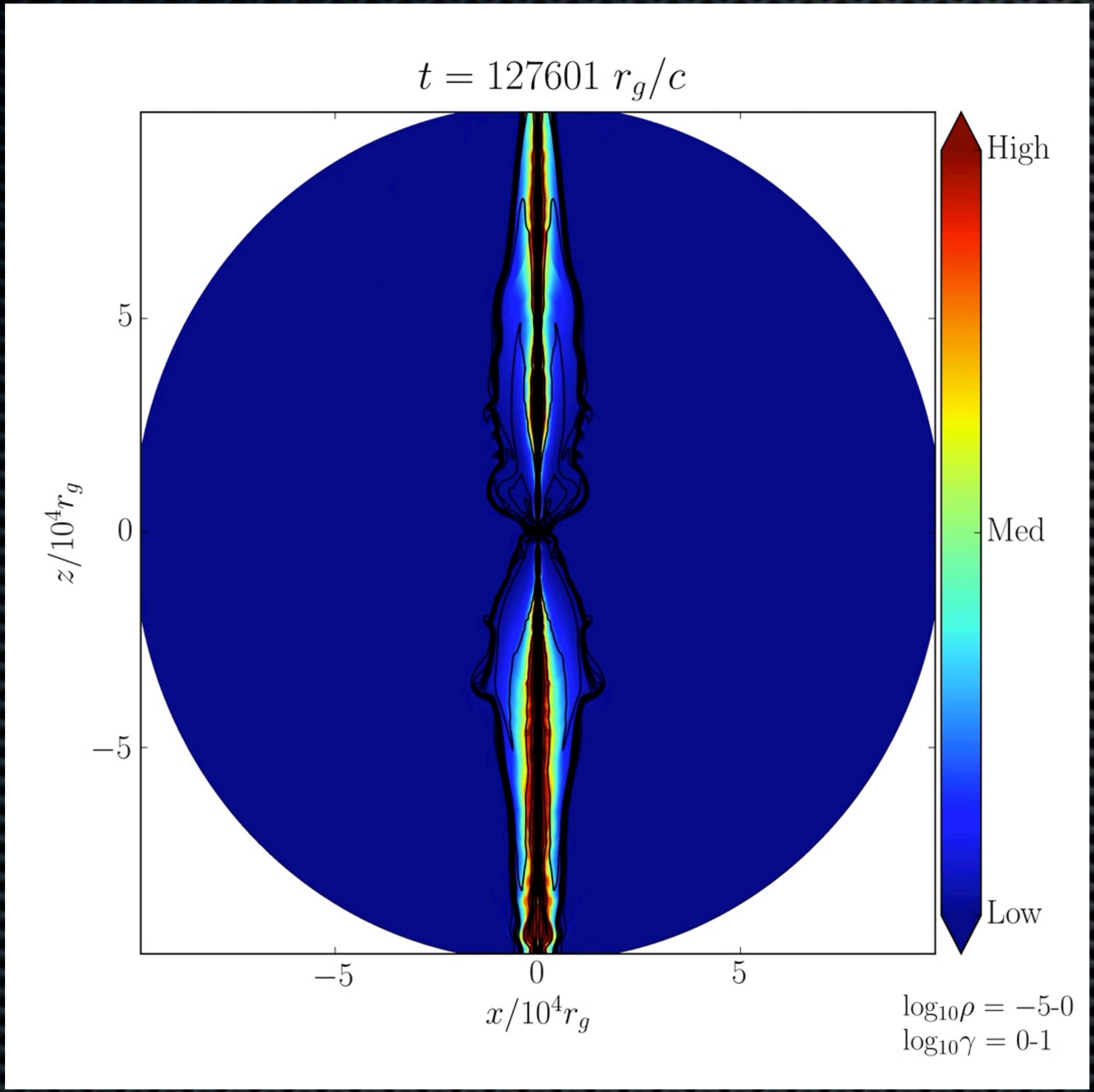

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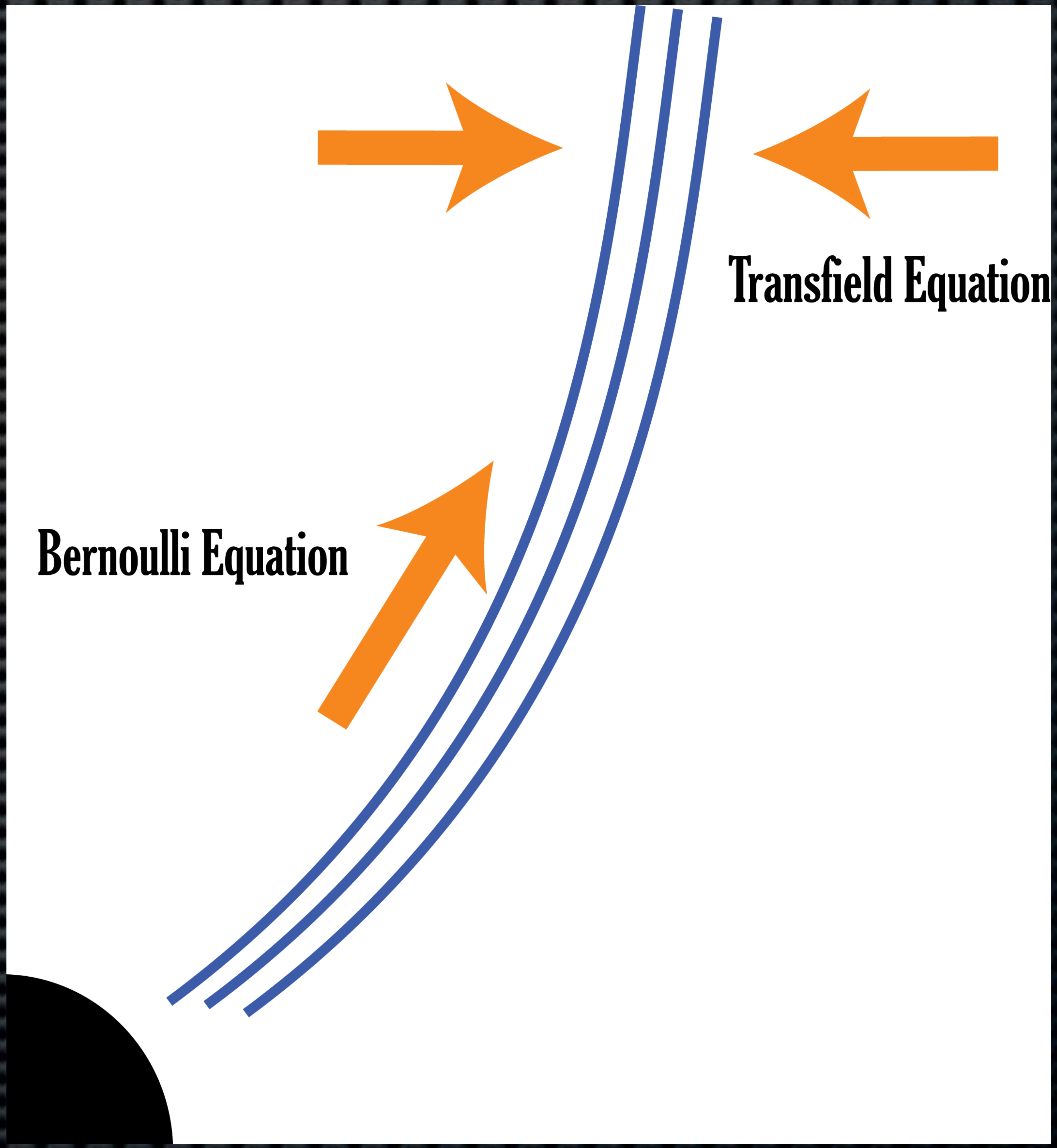


(Vlahakis++2000; Vlahakis & Königl 2003; Polko, Meier & SM 2010, 2013, 2014; Ceccobello, Cavecchi, Heemskerk, SM+ 2017; Chhotray, SM, Ceccobello++ in prep.)

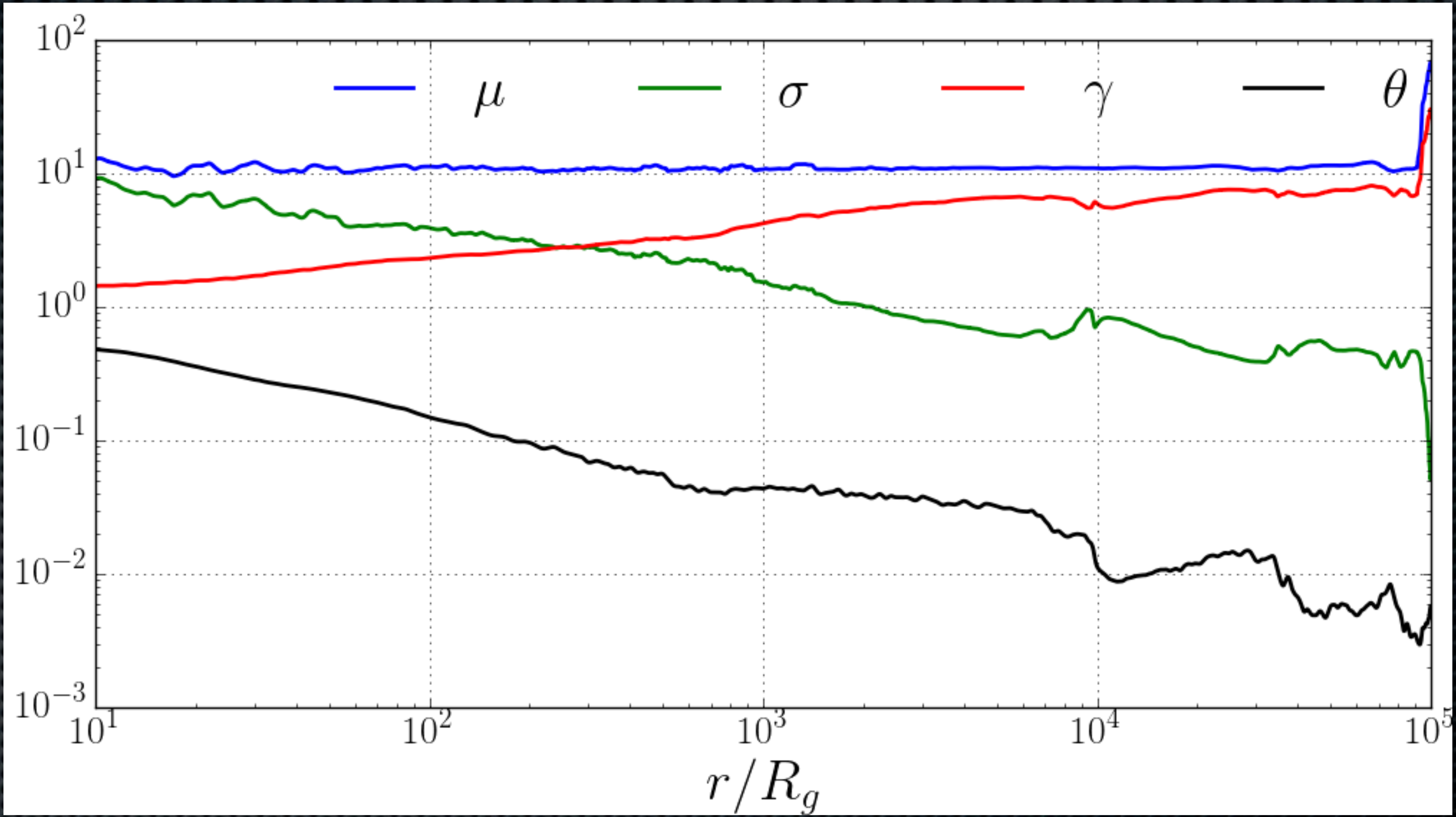
Evolution of dynamical properties from GRMHD simulations

specific energy flux

magnetisation

Bulk Lorentz factor

Jet opening angle



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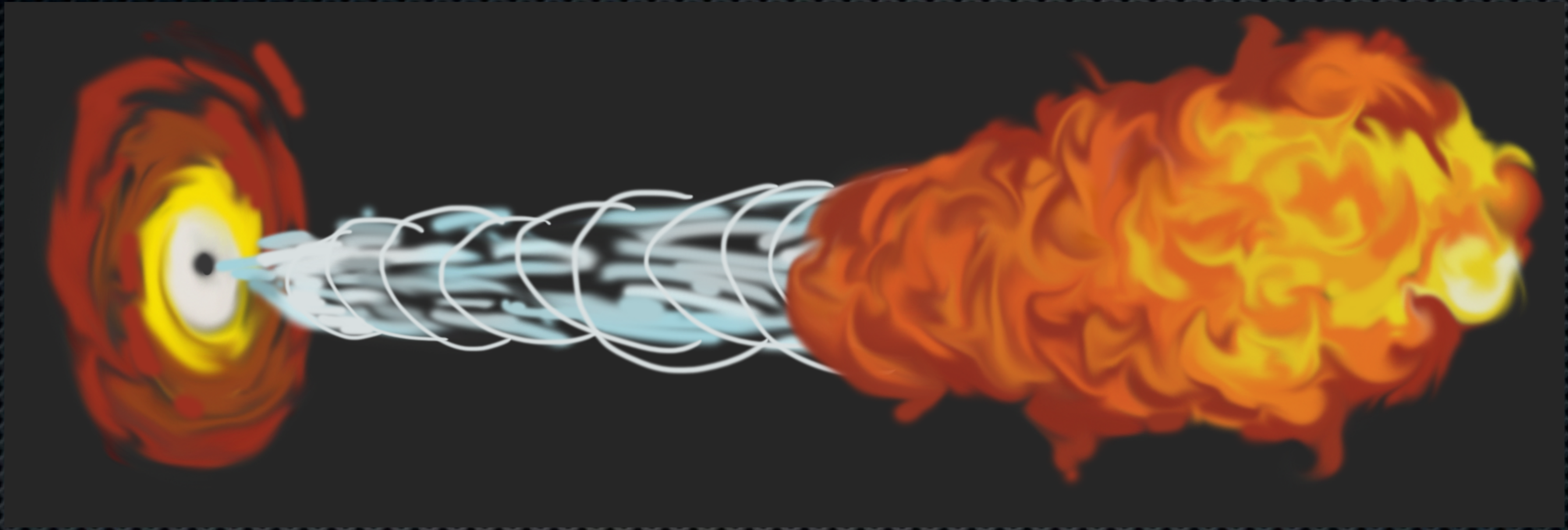
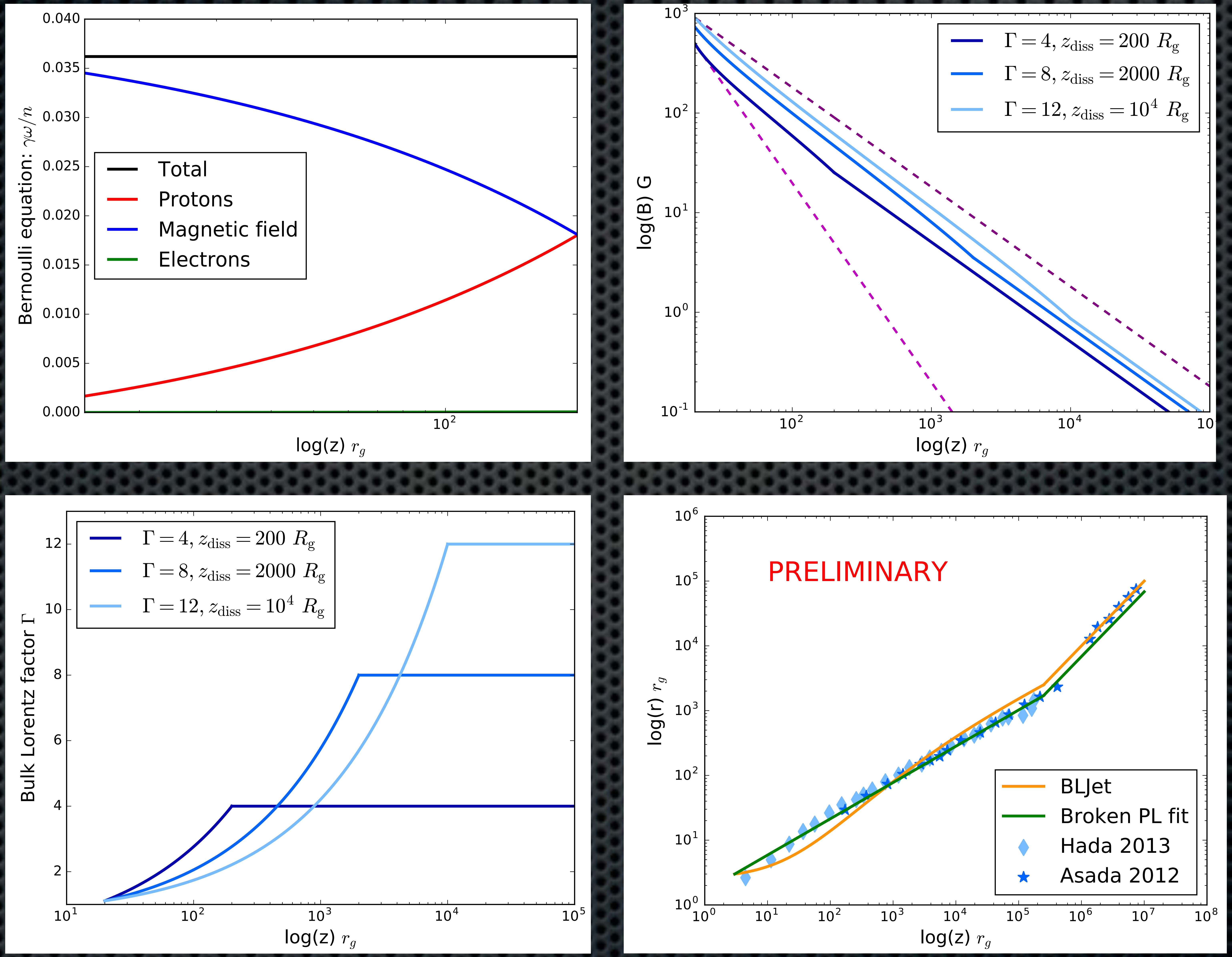
Modeling w/simplified (from RMHD) dynamics



★ Bernoulli equation: $\gamma_j(z)\dfrac{\omega(z)}{n(z)} = \text{constant}$

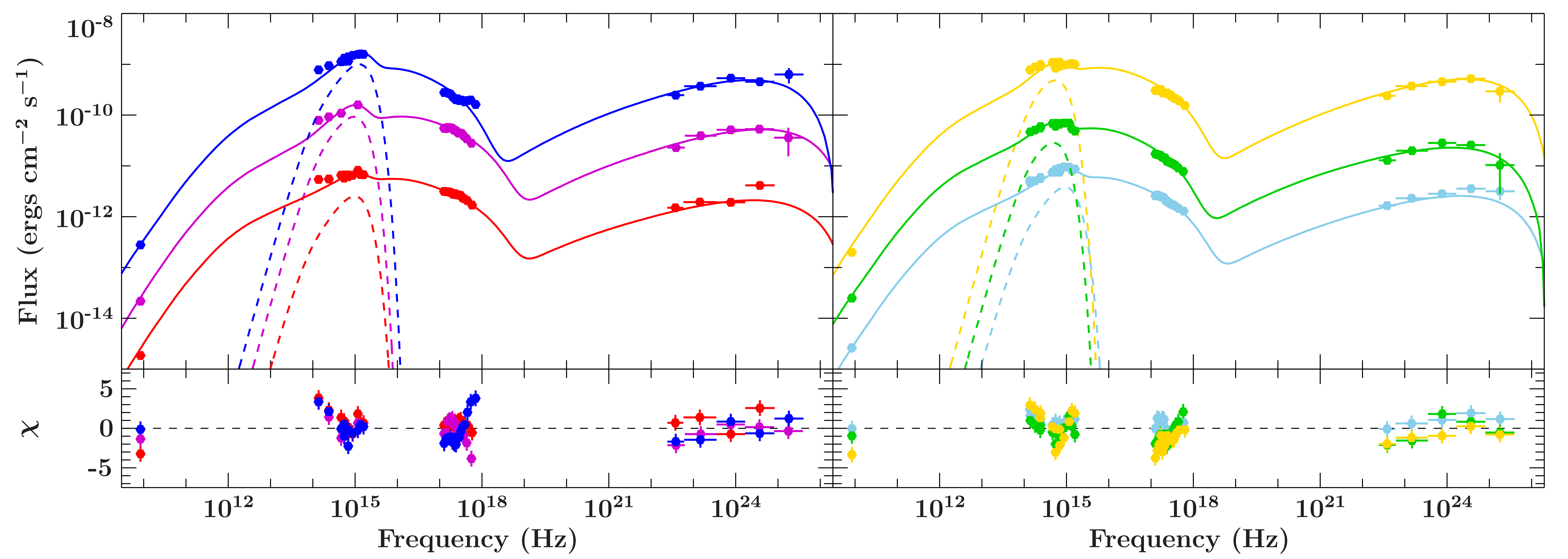
(Lucchini, SM, Crumley, Krauss & Connors 2018)

Modeling w/simplified (from RMHD) dynamics



(Lucchini, SM, Crumley, Krauss & Connors 2018)

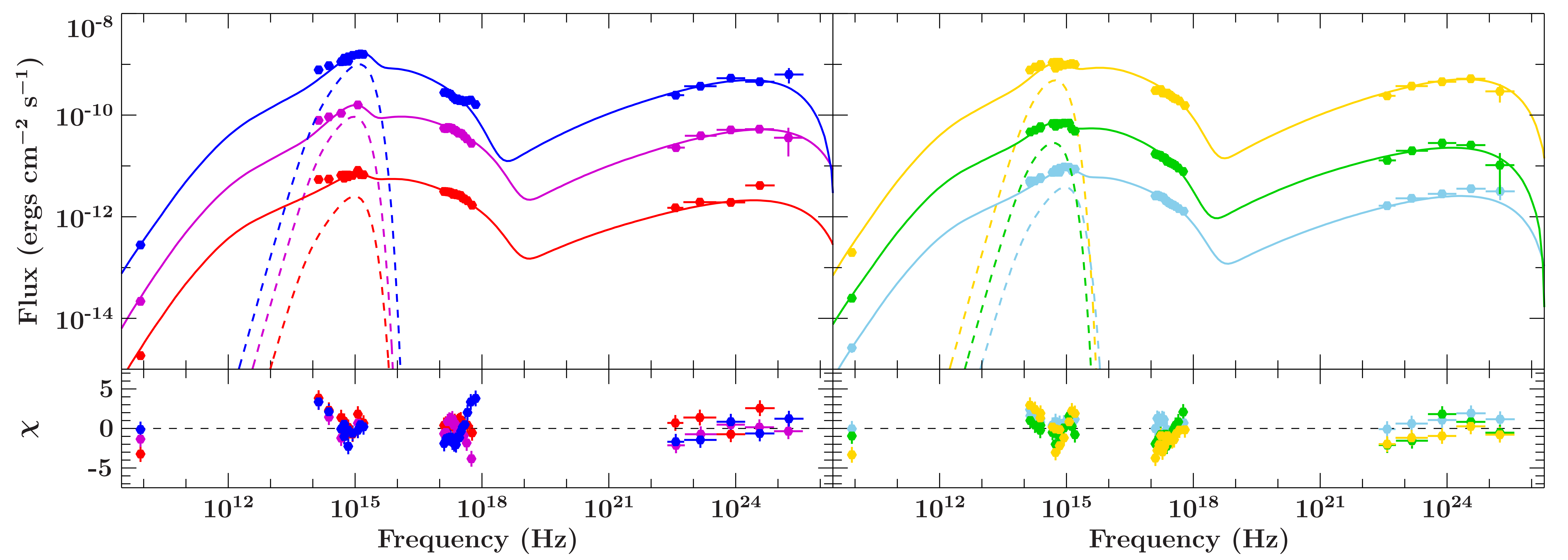
Application: Blazar PKS2155-304 (joint fitting)



	$\dot{M}_{disc}$ [$\dot{M}_{Edd}$] 10^{-2}	R_{in} [R_g]	N_j [L_{Edd}] 10^{-2}	r_0 [R_g]	z_{diss} [R_g]	p	f_{heat}	f_b	f_{sc} 10^{-6}	σ_{diss} 10^{-2}	B [G]	$n(e)$ [cm^{-3}]	γ_{min}	γ_{brk} 10^2	γ_{max} 10^5	χ^2/dof
α	2.9	22	1.0	29	510	1.9	20	40	2.7	2.0	0.24	52.6	133	11	3.2	59.33/22
β	1.6	30	1.0	75	1360	1.8	10	22	2.5	3.2	0.30	17.3	63	7.1	2.7	38.51/15
γ	/	/	0.9	23	1700	1.9	11	30	2.0	5.6	0.37	56.6	72	7.1	2.4	58.3/21
δ	1.4	100	0.9	10	1170	1.6	8	86	1.2	2.0	0.23	97.3	51	7.3	1.8	66.05/24
ϵ	0.7	79	1.5	15	960	1.8	6	50	1.2	1.4	0.23	130	43	8.2	1.8	29.87/24
ζ	0.9	18	1.6	26	1720	1.9	8	43	1.6	1.6	0.28	90.1	55	8.1	2.3	33.72/25

(Lucchini, SM, Crumley, Krauss & Connors 2018; data from Krauss++2006)

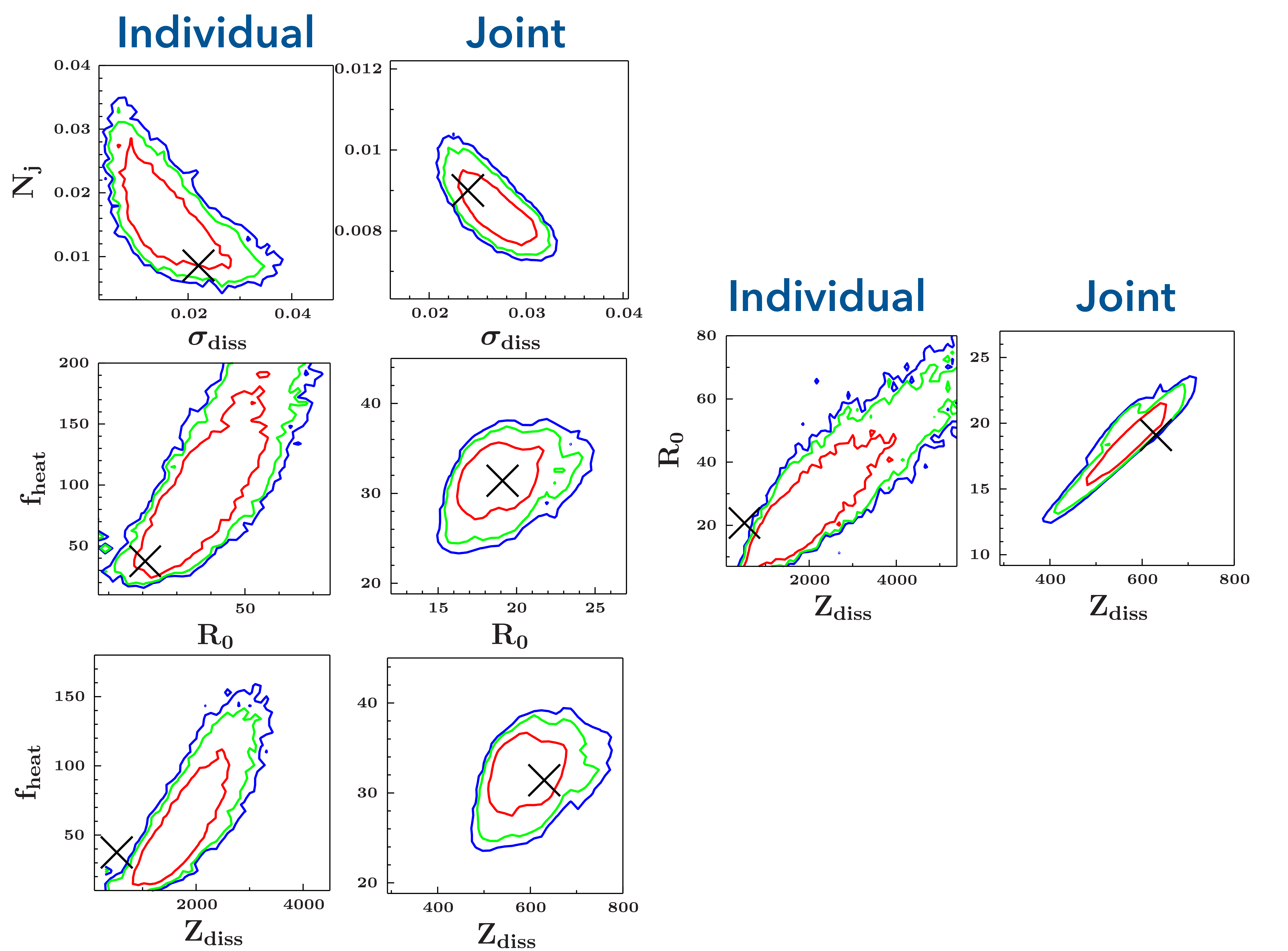
Application: Blazar PKS2155-304 (joint fitting)



	$\dot{M}_{disc}$	R_{in}	N_j	r_0	z_{diss}	p	f_{heat}	f_b	f_{sc}	σ_{diss}	γ_{brk}	γ_{max}	χ^2/dof
	$[\dot{M}_{Edd}]$ 10^{-2}	$[R_g]$	$[L_{Edd}]$ 10^{-2}	$[R_g]$	$[R_g]$				10^{-6}	10^{-2}	10^2	10^5	
Joint			$0.90^{+0.06}_{-0.07}$	18^{+3}_{-2}	600^{+62}_{-65}		$10.4^{+0.8}_{-0.6}$			$2.5^{+0.1}_{-0.2}$			265.54/156
α	$2.6^{+0.3}_{-0.2}$	20^{+3}_{-2}				$1.74^{+0.05}_{-0.04}$		48^{+12}_{-4}	$1.4^{+0.1}_{-0.2}$		8	2.0	
β	$2.6^{+0.3}_{-0.3}$	46^{+8}_{-7}				$2.01^{+0.04}_{-0.03}$		8^{+2}_{-1}	$4.2^{+0.8}_{-0.7}$		52	3.3	
γ	$0.8^{+0.1}_{-0.1}$	23^{+4}_{-3}				$1.99^{+0.04}_{-0.03}$		17^{+3}_{-3}	$5.1^{+0.6}_{-0.4}$		24	3.8	
δ	$1.4^{+0.1}_{-0.1}$	110^{+20}_{-20}				$1.90^{+0.03}_{-0.03}$		17^{+3}_{-1}	$1.9^{+0.1}_{-0.1}$		23	2.3	
ϵ	$0.8^{+0.1}_{-0.1}$	79^{+10}_{-11}				$1.98^{+0.03}_{-0.03}$		17^{+3}_{-2}	$1.3^{+0.1}_{-0.1}$		22	1.9	
ζ	$1.2^{+0.1}_{-0.1}$	31^{+5}_{-4}				$1.94^{+0.03}_{-0.03}$		20^{+4}_{-3}	$2.2^{+0.2}_{-0.1}$		20	2.5	

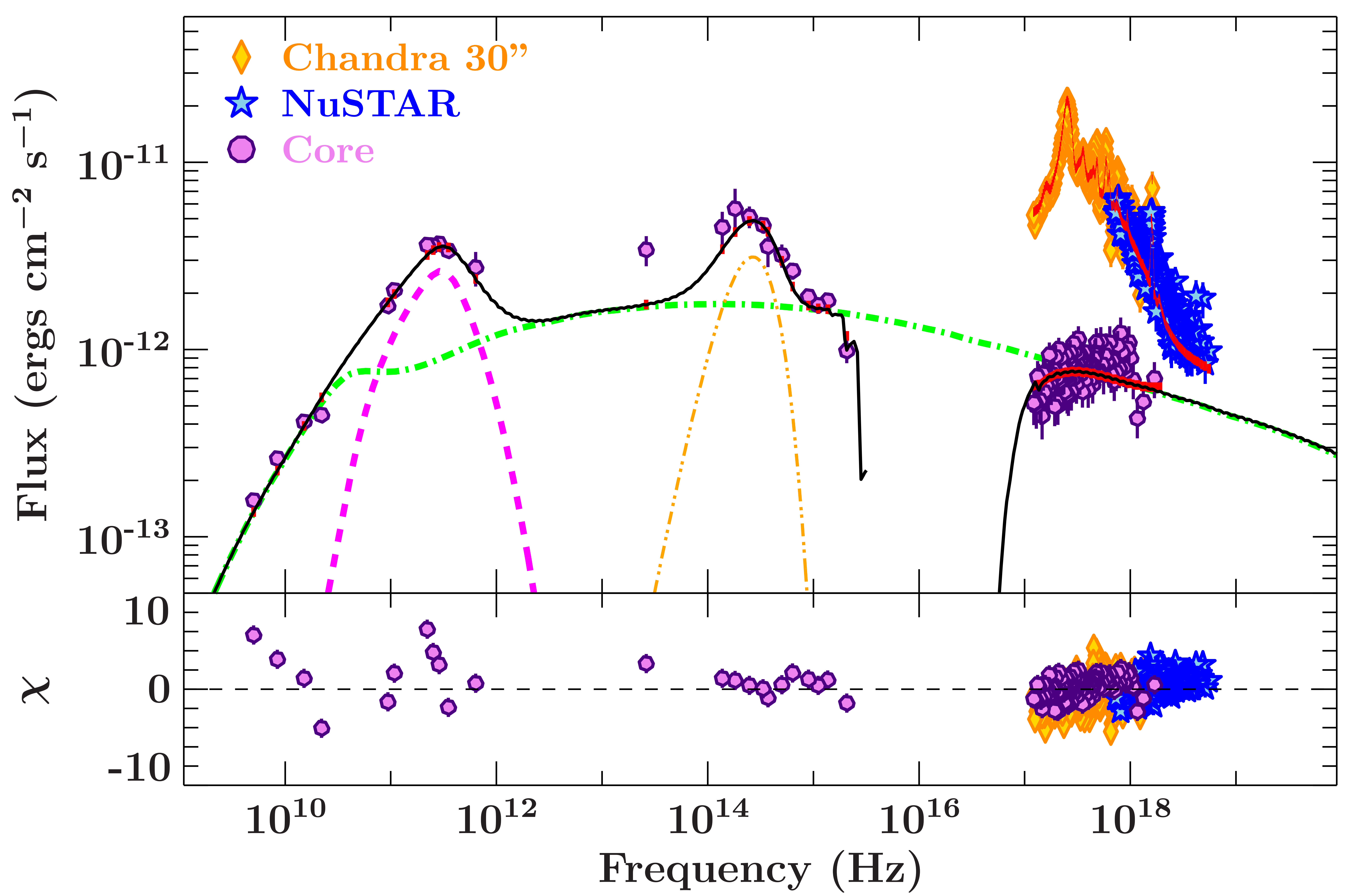
(Lucchini, SM, Crumley, Krauss & Connors 2018; data from Krauss++2006)

Application: Blazar PKS2155-304 (joint fitting)



(Lucchini, SM, Crumley, Krauss & Connors 2018; data from Krauss++2006)

Application: M87



$M_{bh} = 6 \cdot 10^9 M_\odot$

$\theta = 15^\circ$

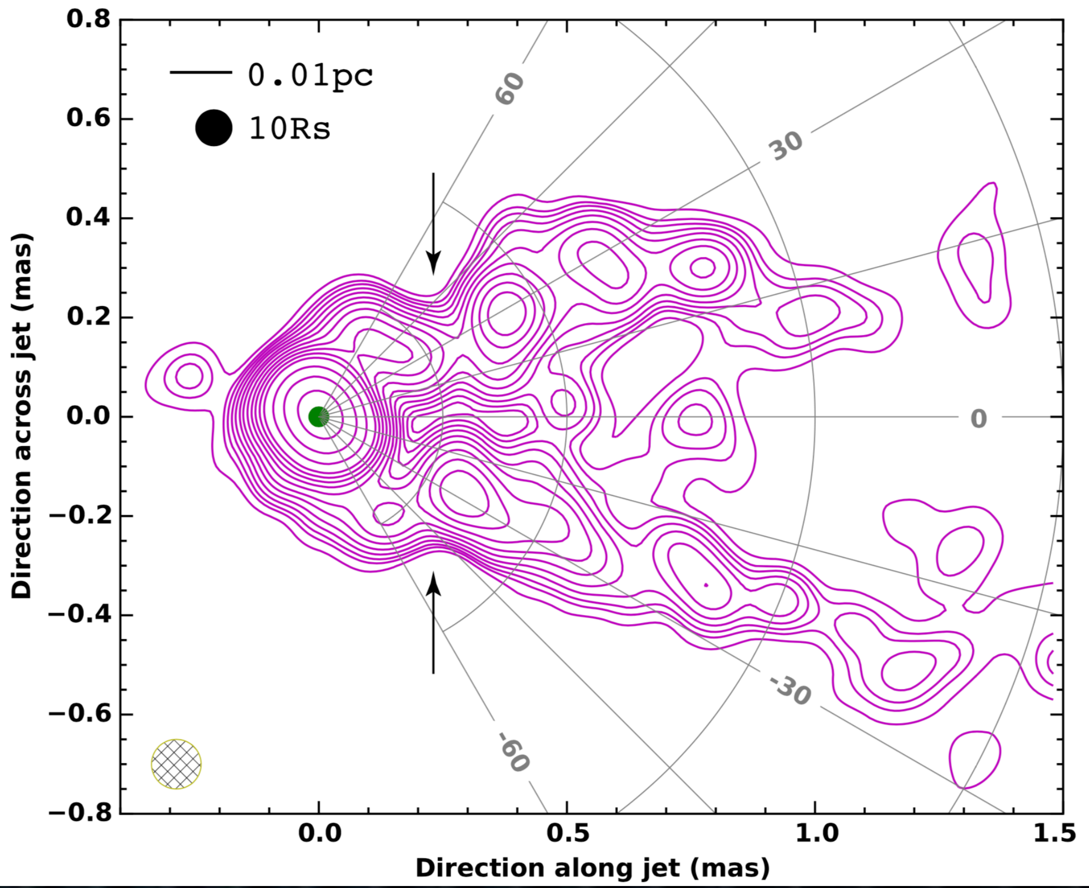
$N_j = 2.5 \cdot 10^{-5} L_{Edd}$

$z_{acc} = 110 R_g$

$T_e = 6.5 \cdot 10^{10} K$

$p = 2.34$

$\gamma_{max} = 10^7$



(Lucchini, Krauss & SM, in prep.)

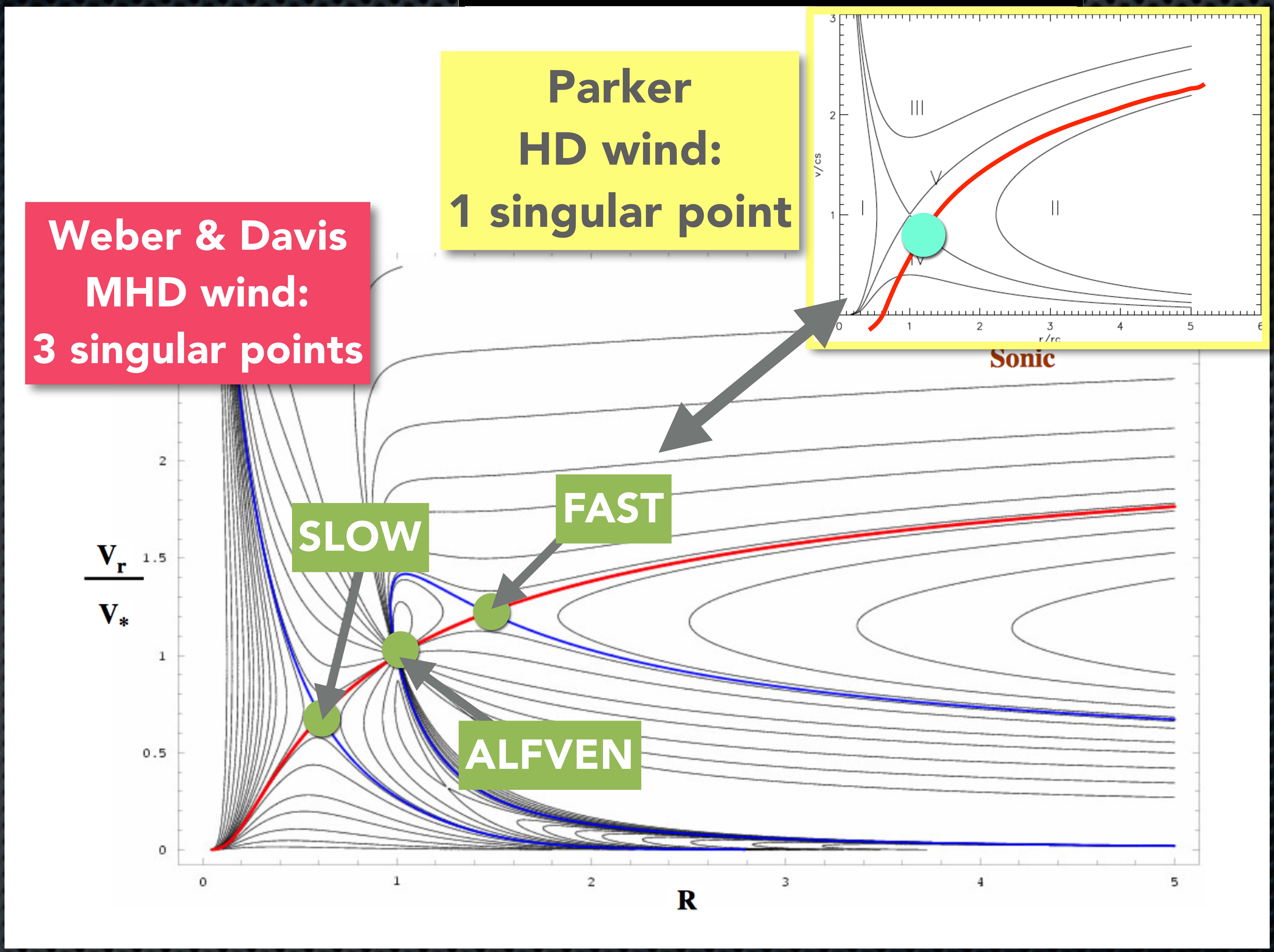
New relativistic MHD + PN gravity model

AIM: we want to describe

- a relativistic, hot, accelerating flow
- with a strong magnetic field
- close to a BH (non-negligible gravity)

(Vlahakis et al. 2000, Vlahakis & Königl 2003, Polko, Meier & SM 2010, 2013, 2014; Ceccobello, Cavecchi, Heemskerk, SM+ 2017)

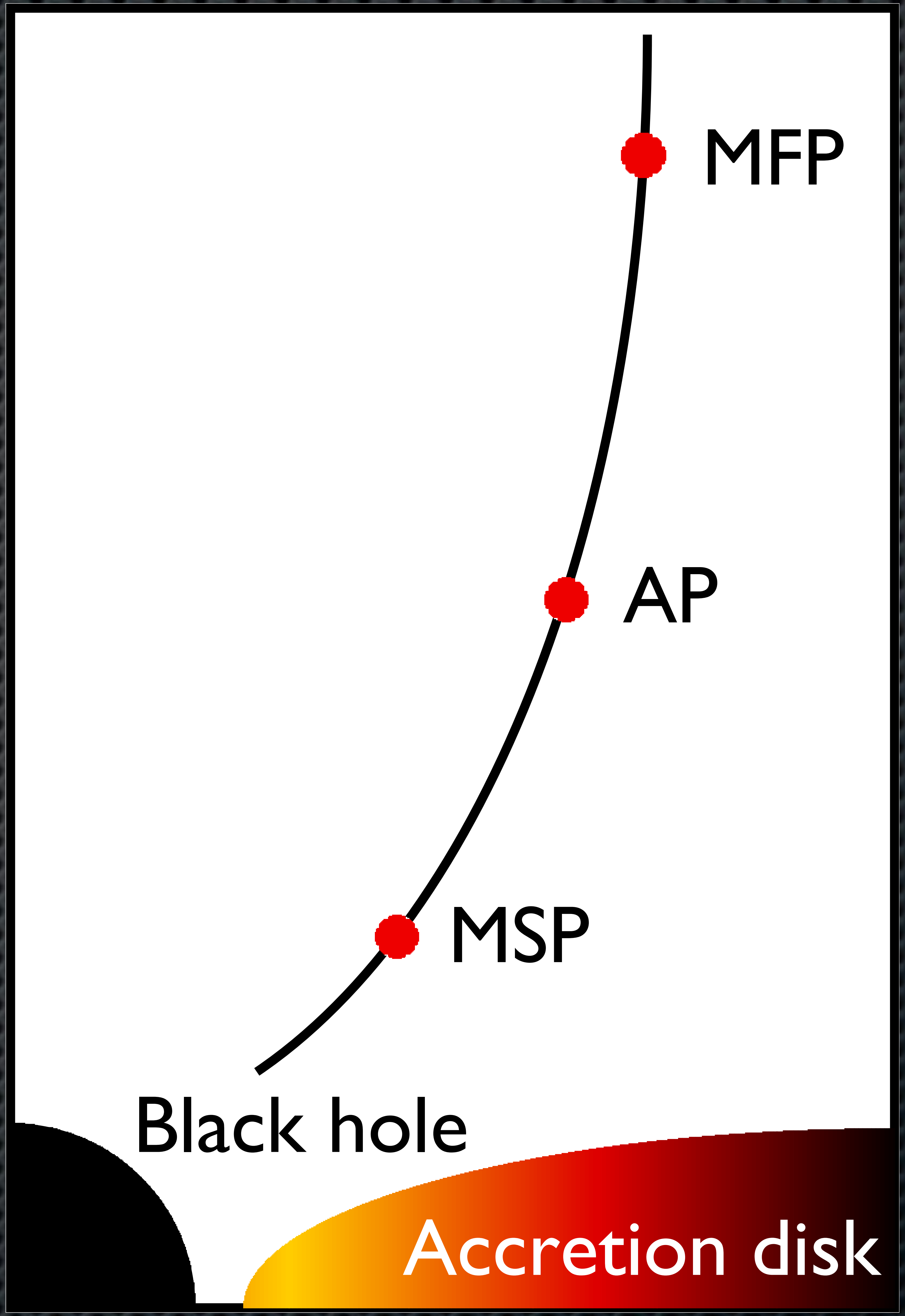
New relativistic MHD + PN gravity model



(Vlahakis et al. 2000, Vlahakis & Königl 2003, Polko, Meier & SM 2010, 2013, 2014; Ceccobello, Cavecchi, Heemskerk, SM+ 2017)

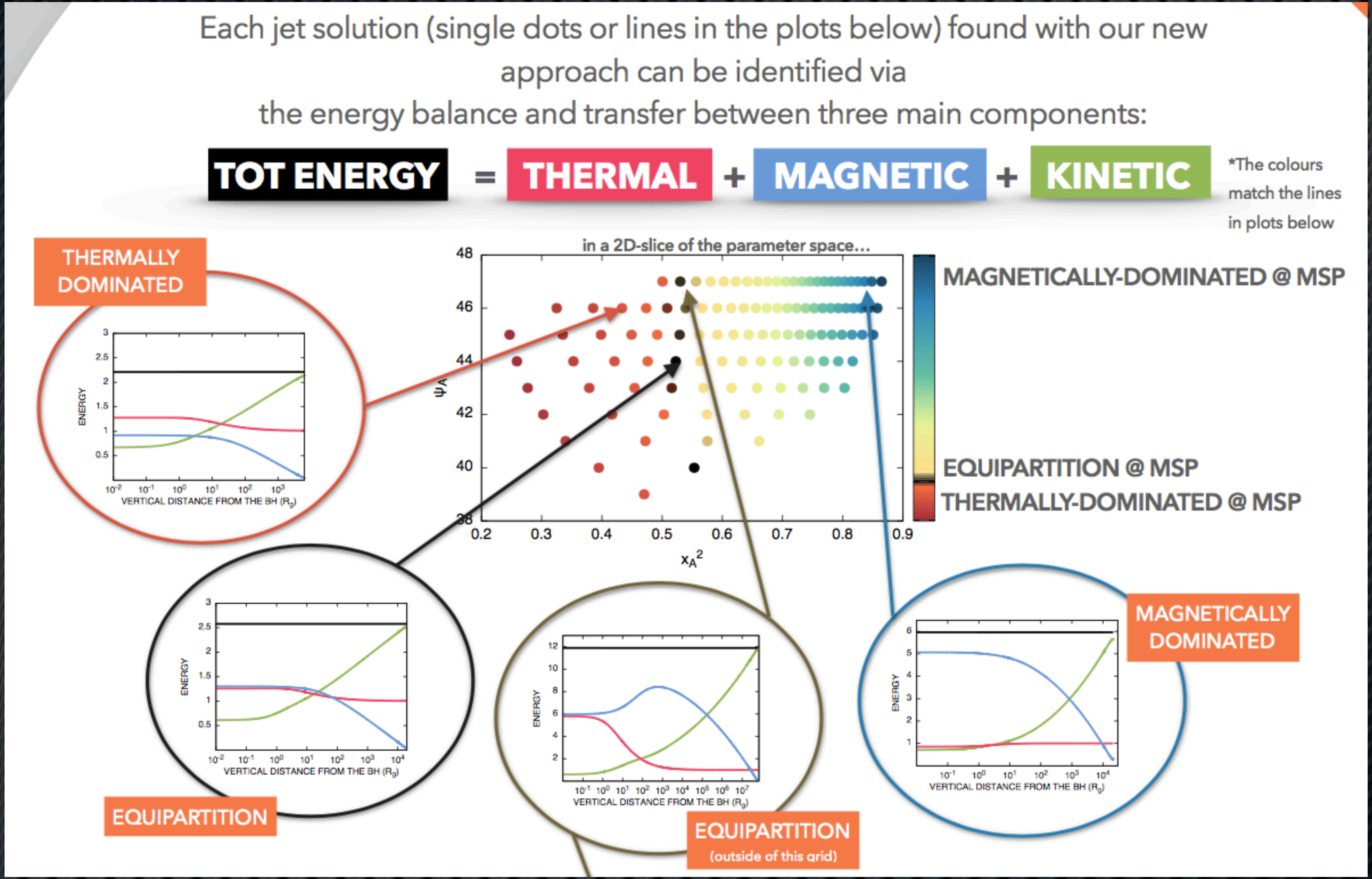
New relativistic MHD + PN gravity model

- Ideal MHD: solve for jet properties as function of conditions at launch point
- When $\Gamma_j > V_{FMS}$, flow out of causal contact with the black hole: instabilities can lead to pile-up/shocks
  ☛ dissipation zone??



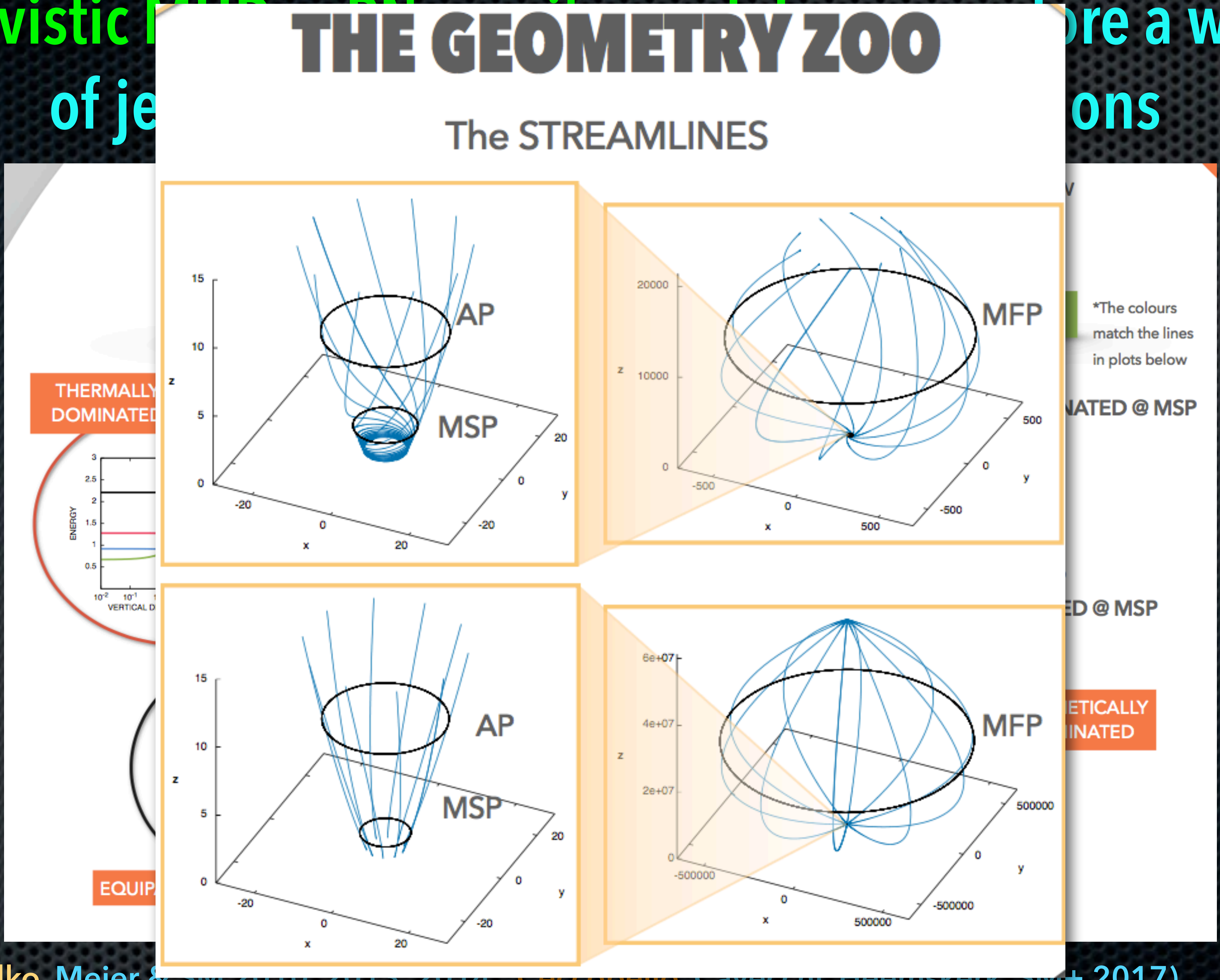
(Vlahakis et al. 2000, Vlahakis & Königl 2003, Polko, Meier & SM 2010, 2013, 2014; Ceccobello, Cavecchi, Heemskerk, SM+ 2017)

New relativistic MHD + PN gravity model: can explore a wide range of jet solutions and compare to simulations



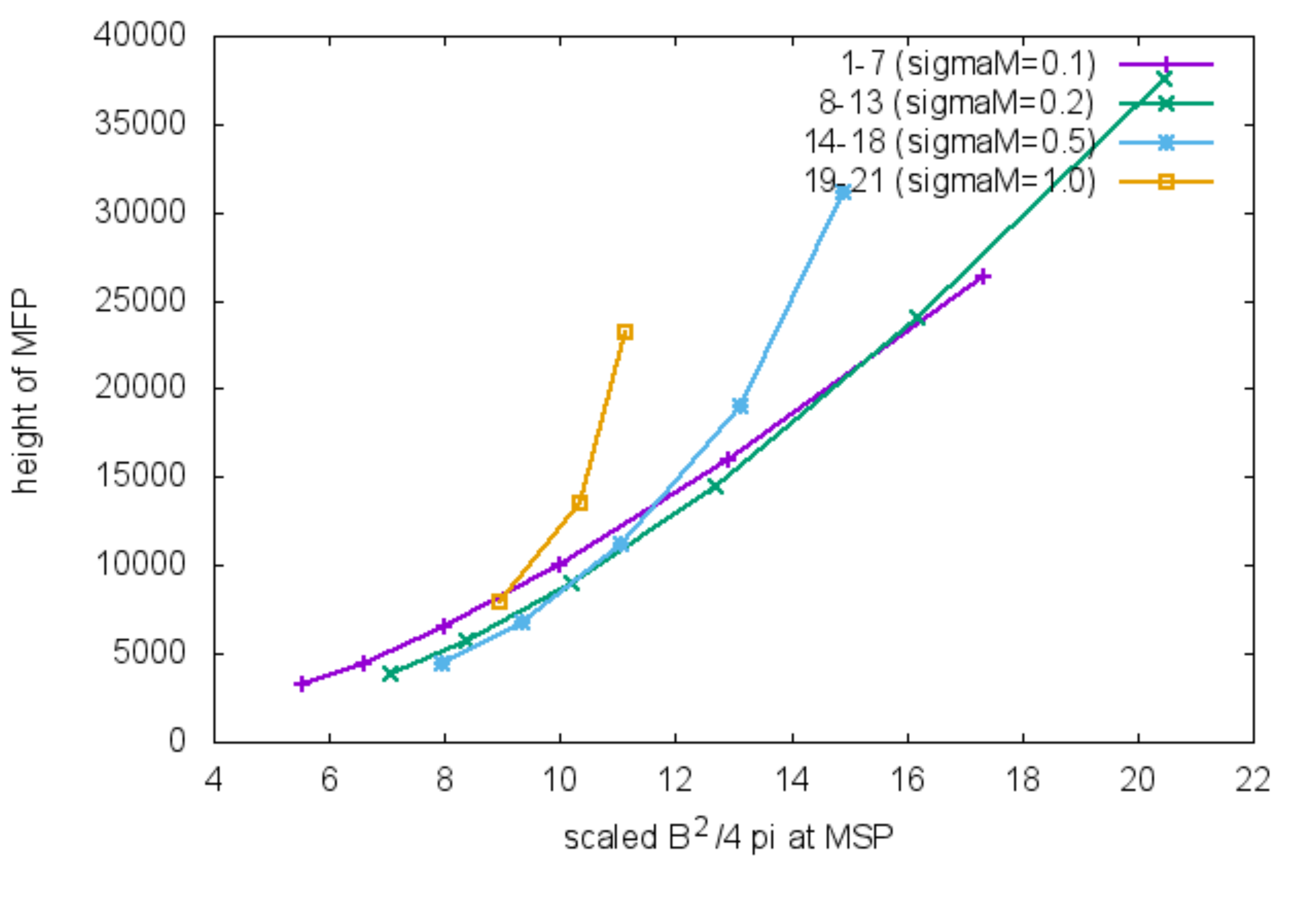
(Polko, Meier & SM 2010, 2013, 2014; Ceccobello, Cavecchi, Heemskerk, SM+ 2017)

New relativistic ... ore a wide range of je... ons



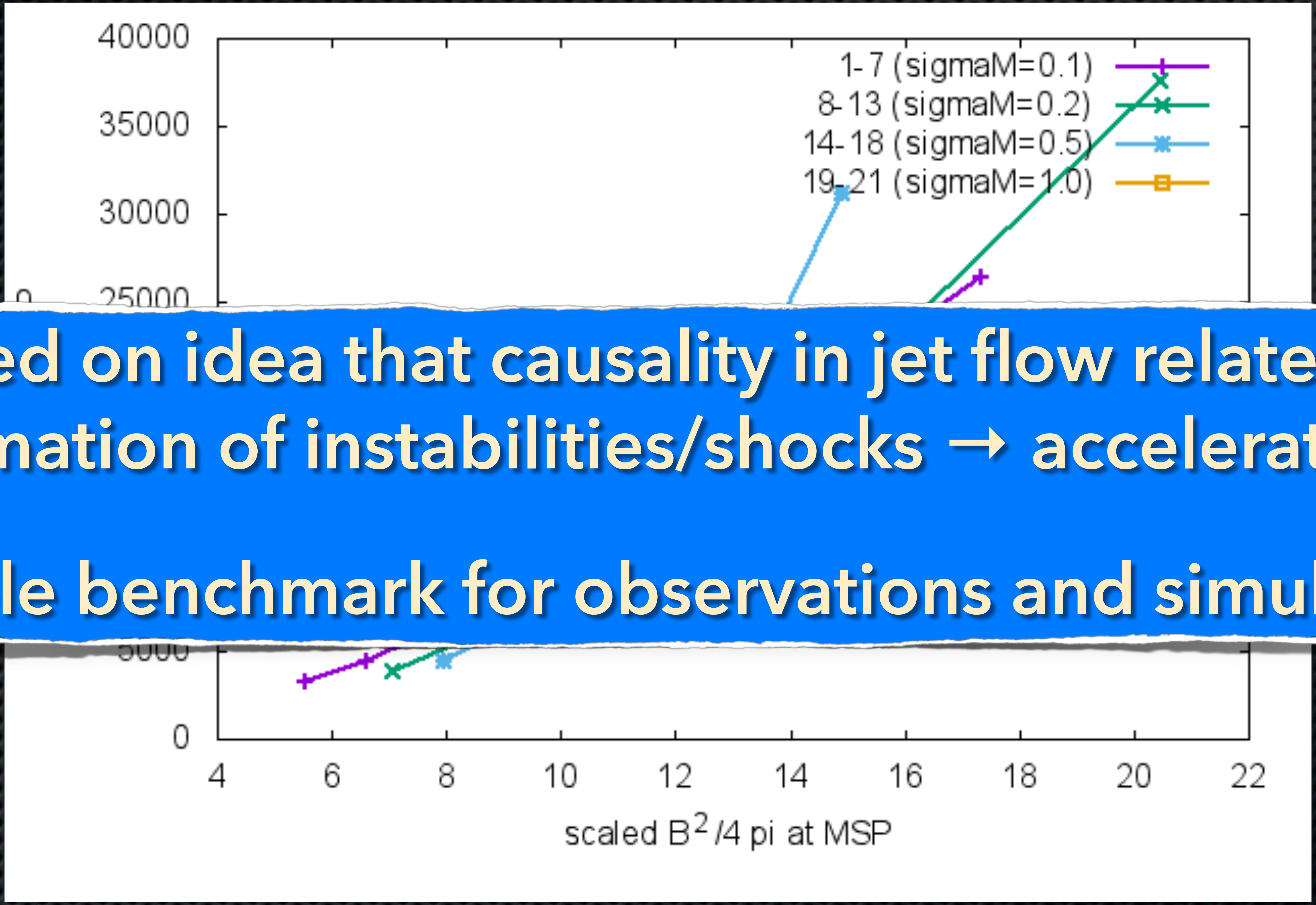
(Polko, Meier ... SM+ 2017)

New relativistic MHD + PN gravity model: reproduce correct trend and physical location of Z_{acc}



(Ceccobello, Cavecchi, Heemskerk, SM, Polko, Meier 2017)

New relativistic MHD + PN gravity model: reproduce correct trend and physical location of Z_{acc}



Based on idea that causality in jet flow related to formation of instabilities/shocks → acceleration

Testable benchmark for observations and simulations

(Ceccobello, Cavecchi, Heemskerk, SM, Polko, Meier 2017)

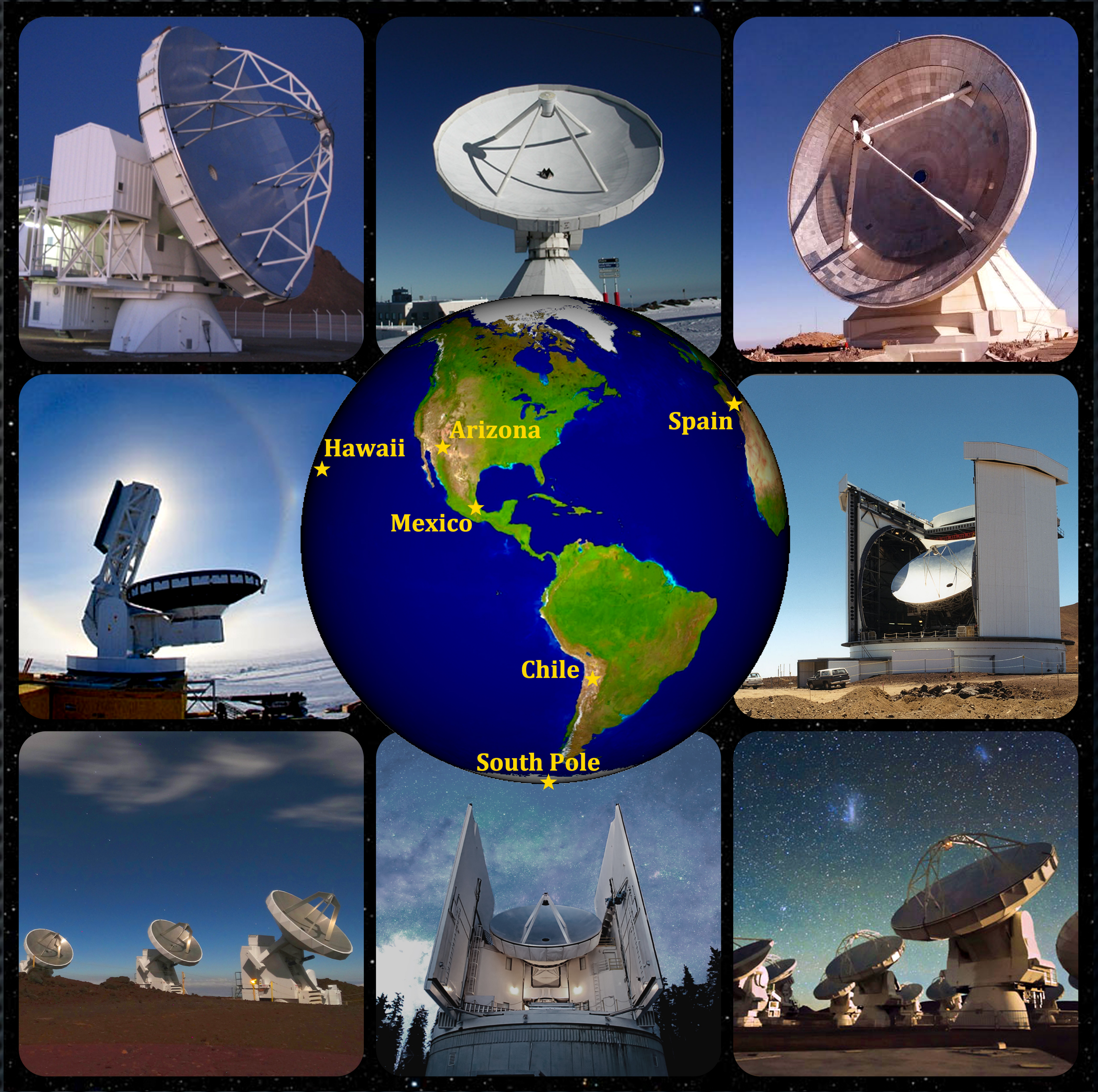
Outline

(sorting out the micro-micro-microphysics connection)

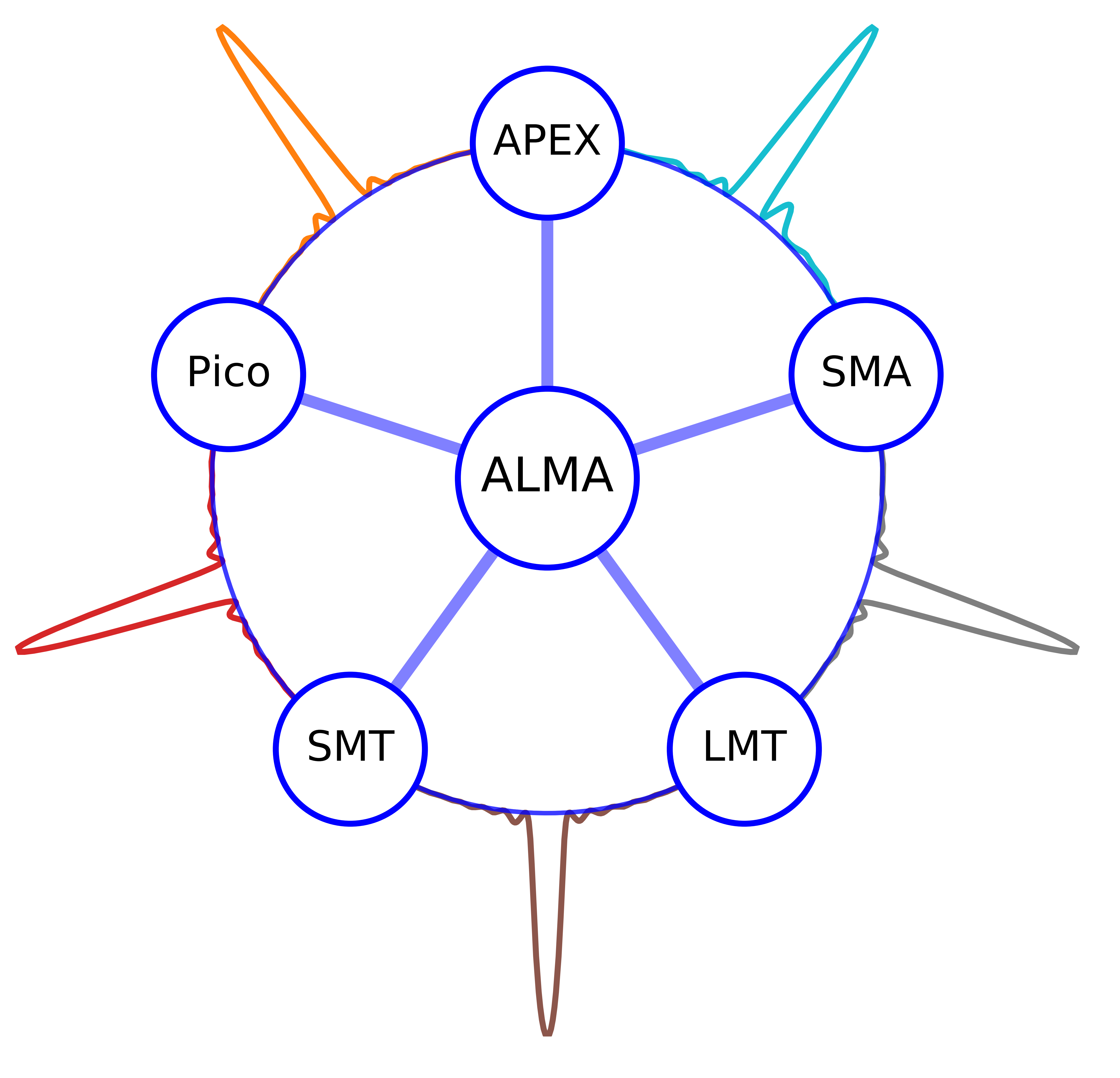
- ★ Observational perspective from AGN/Sgr A* & XRBs
- ★ Phenomenological and semi-analytical approaches
- ★ Cutting edge/work in progress: numerical approach
- ★ Summary/Outlook

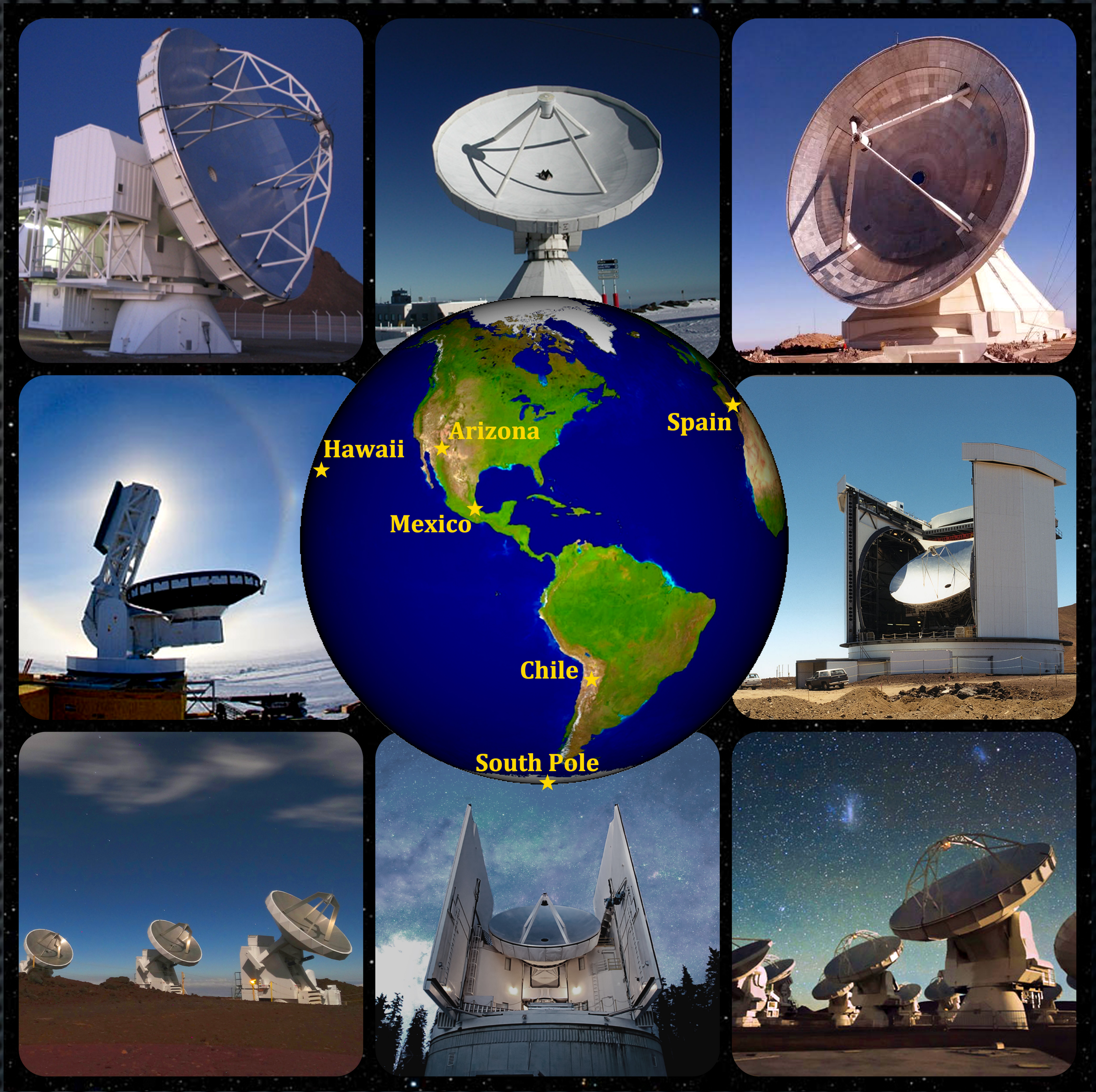
EHT 2017 campaign (Sgr A*, M87, 3C279, OJ287, Cen A, ++)

- Atacama Large Millimeter Array (ALMA), Chile
- ALMA Pathfinder Experiment (APEX), Chile
- James Clerk Maxwell Telescope (JCMT), Hawaii
- Large Millimeter Telescope (LMT), Mexico
- IRAM 30-meter Telescope, Spain
- South Pole Telescope (SPT), South Pole
- Submillimeter Array (SMA), Hawaii
- Submillimeter Telescope (SMT), Arizona



EHT 2017 campaign (Sgr A*, M87, 3C279, OJ287, Cen A, ++)





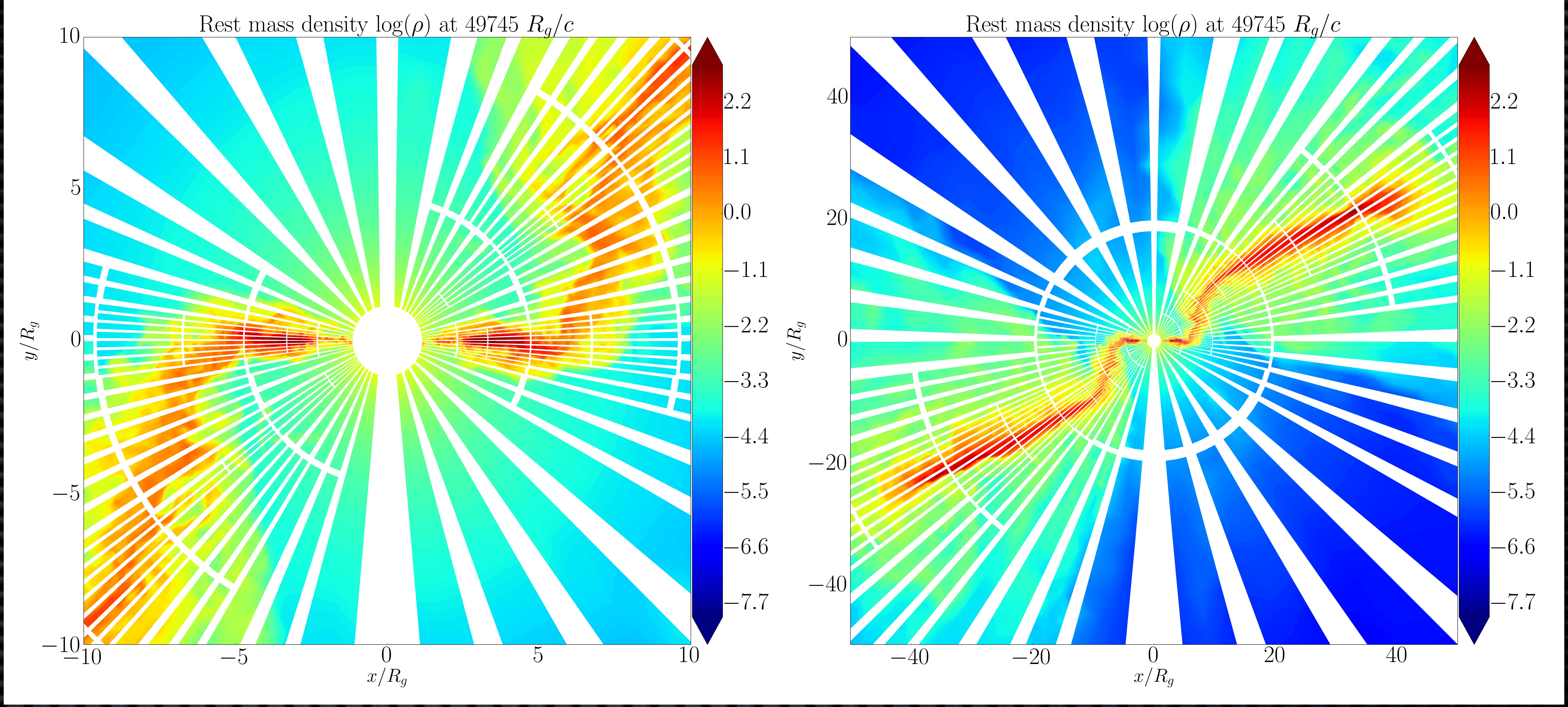
Theory & Simulations WG: code comparison

Simulations with many different algorithms and models of the microphysics show broadly consistent images that are asymmetric with clear black-hole shadows

H-AMR: GPU-accelerated update of HARM with AMR

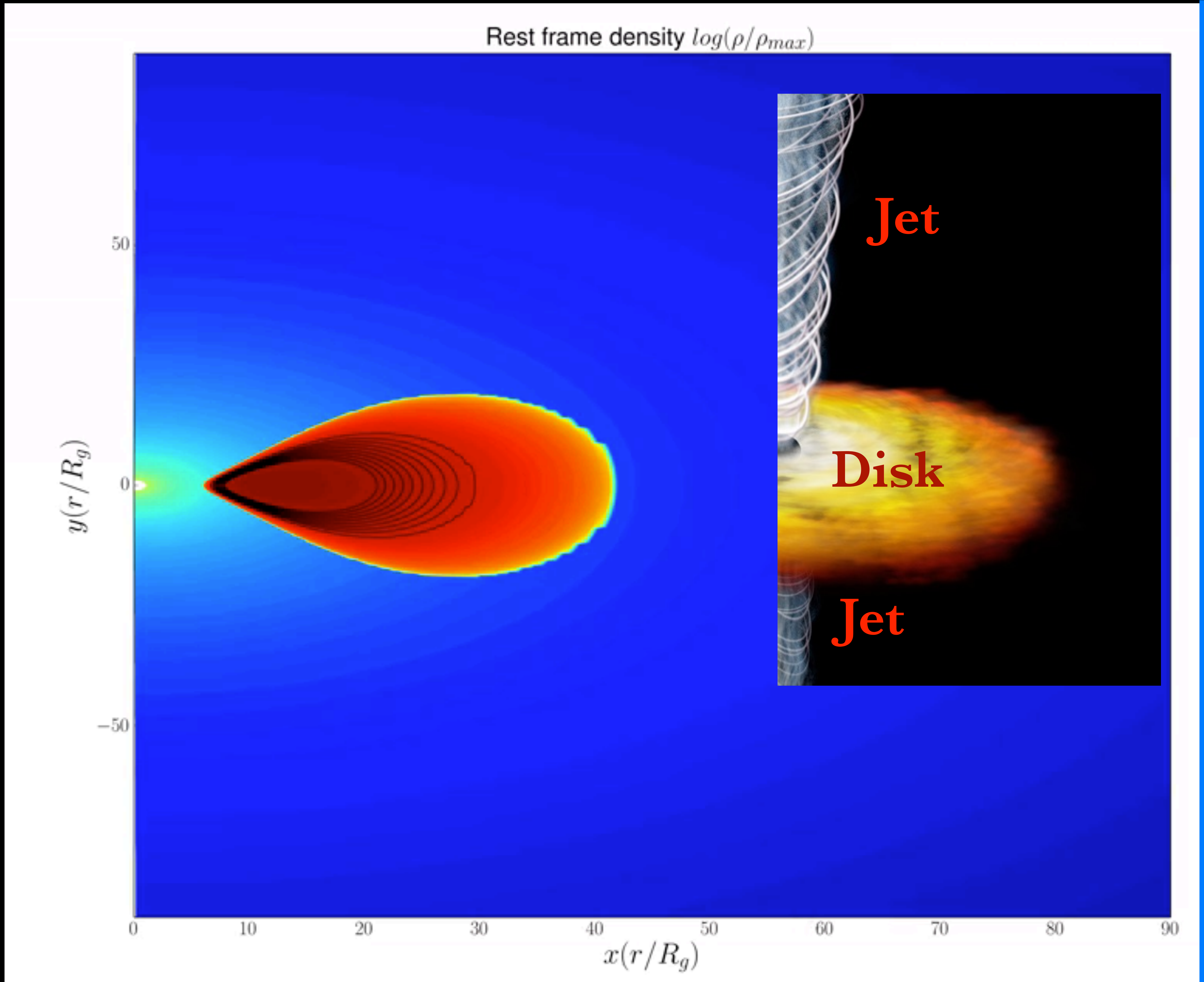
(developed by MSc/PhD student M. Liska)

Visualization of AMR (each block has 180x18x30 cells):



(Liska, Hesp, Tchekhovskoy, Ingram, vd Klis, SM++ 2018)

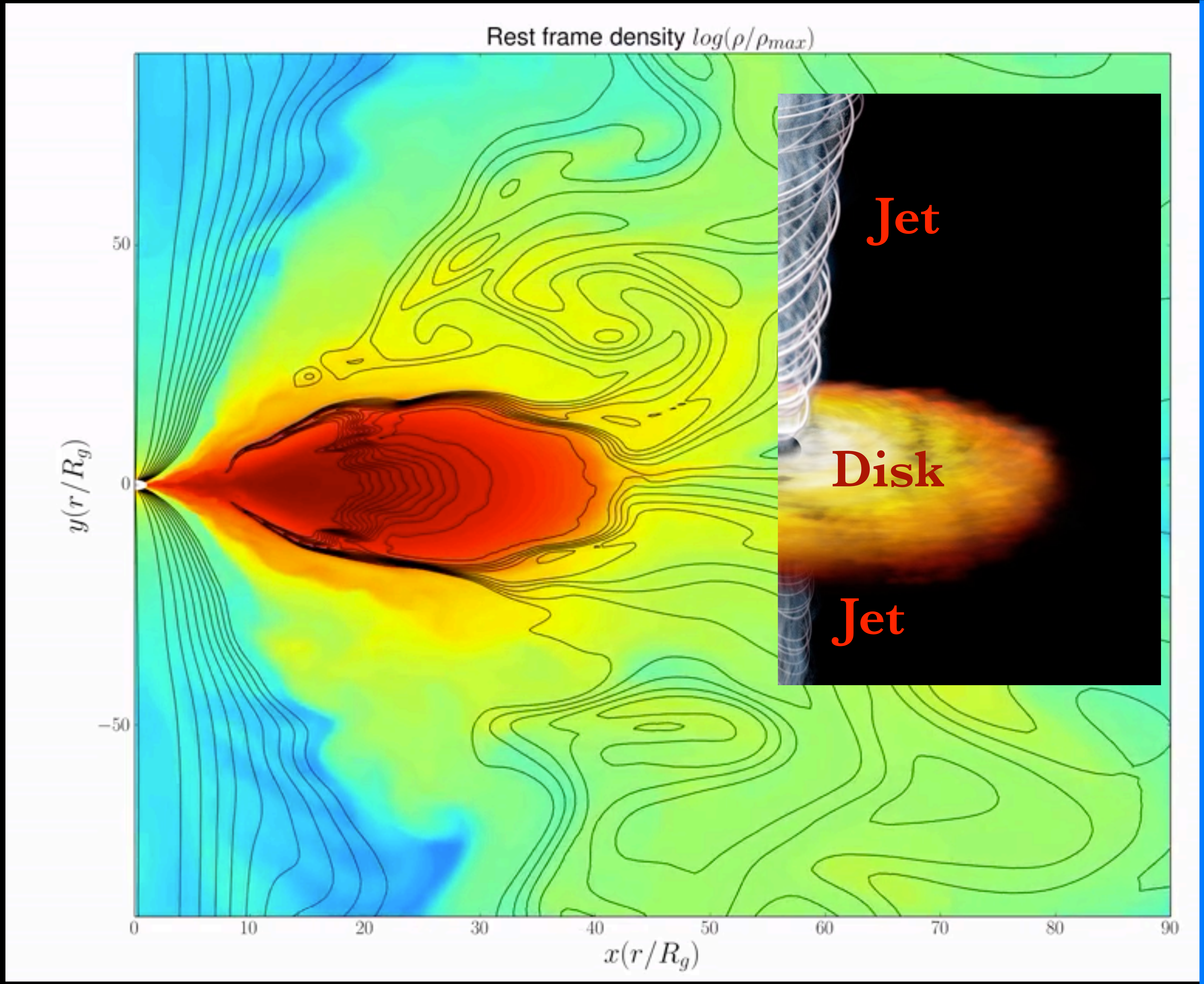
Simulations: time-dependent dynamics but missing microphysics



- ⭐ Unrealistic/limited geometry, resolution
- ⭐ Degeneracy in plasma initial conditions ($\dot{m}$, β, σ, μ, B field config.)
- ⭐ Ideal MHD: Empty jets (*=density floors*), no dissipation
- ⭐ 1-fluid (no e^--ion TD)
- ⭐ no microphysics = no light!

(Dibi, Drappeau, Fragile, SM & Dexter 2012; Drappeau, Dibi, Dexter, SM & Fragile 2013; Li
Chatterjee, Liska, Tchekhovskoy & SM 2018, ...plus many other groups!)

Simulations: time-dependent dynamics but missing microphysics



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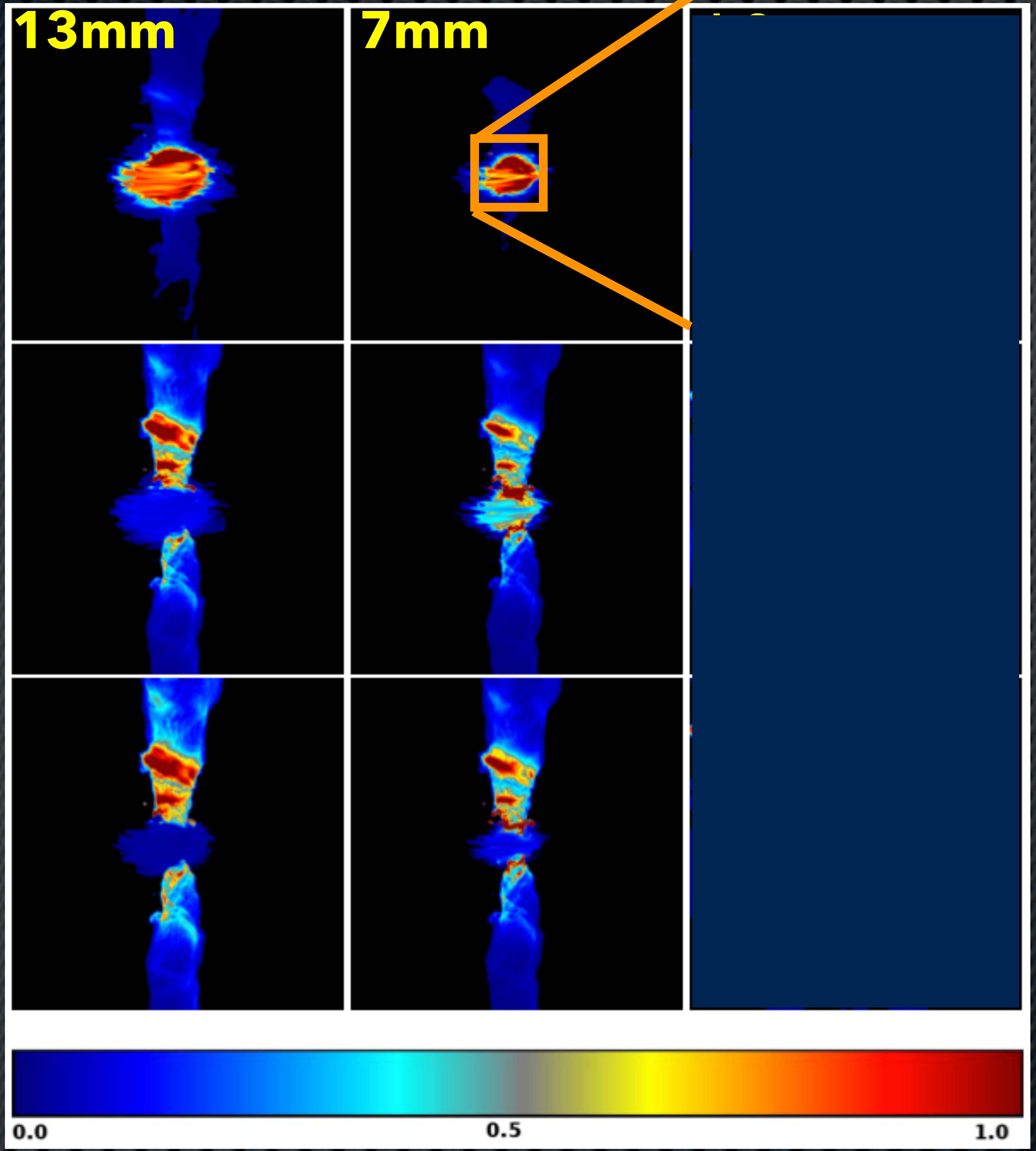
(**Dibi, Drappeau,** Fragile, SM & Dexter 2012; **Drappeau, Dibi**, Dexter, SM & Fragile 2013; **Li** **Chatterjee, Liska**, Tchekhovskoy & SM 2018, ...plus many other groups!)

Illustration of “macro/microphysics problem” for EHT

$T_p/T_e=5$

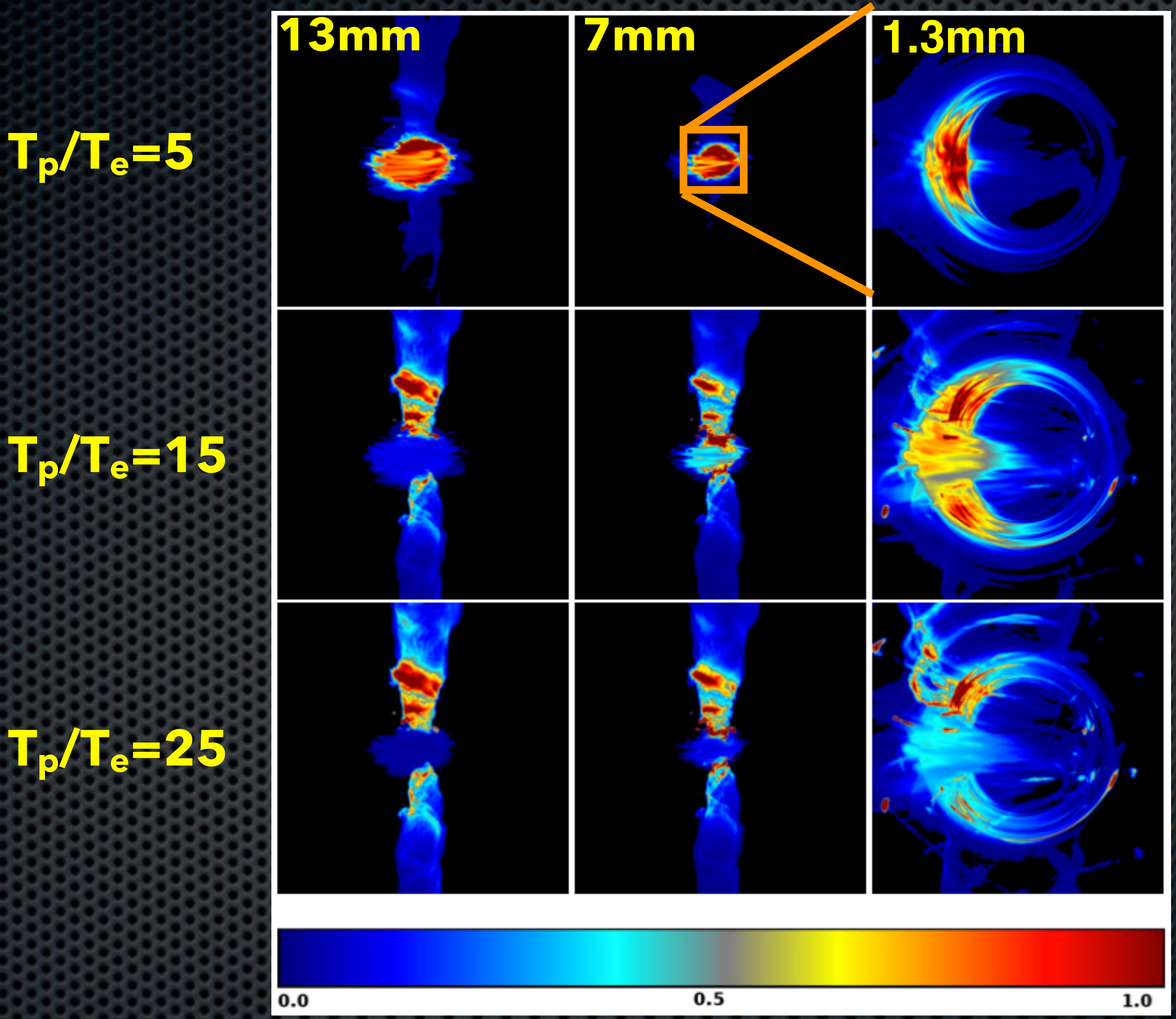
$T_p/T_e=15$

$T_p/T_e=25$



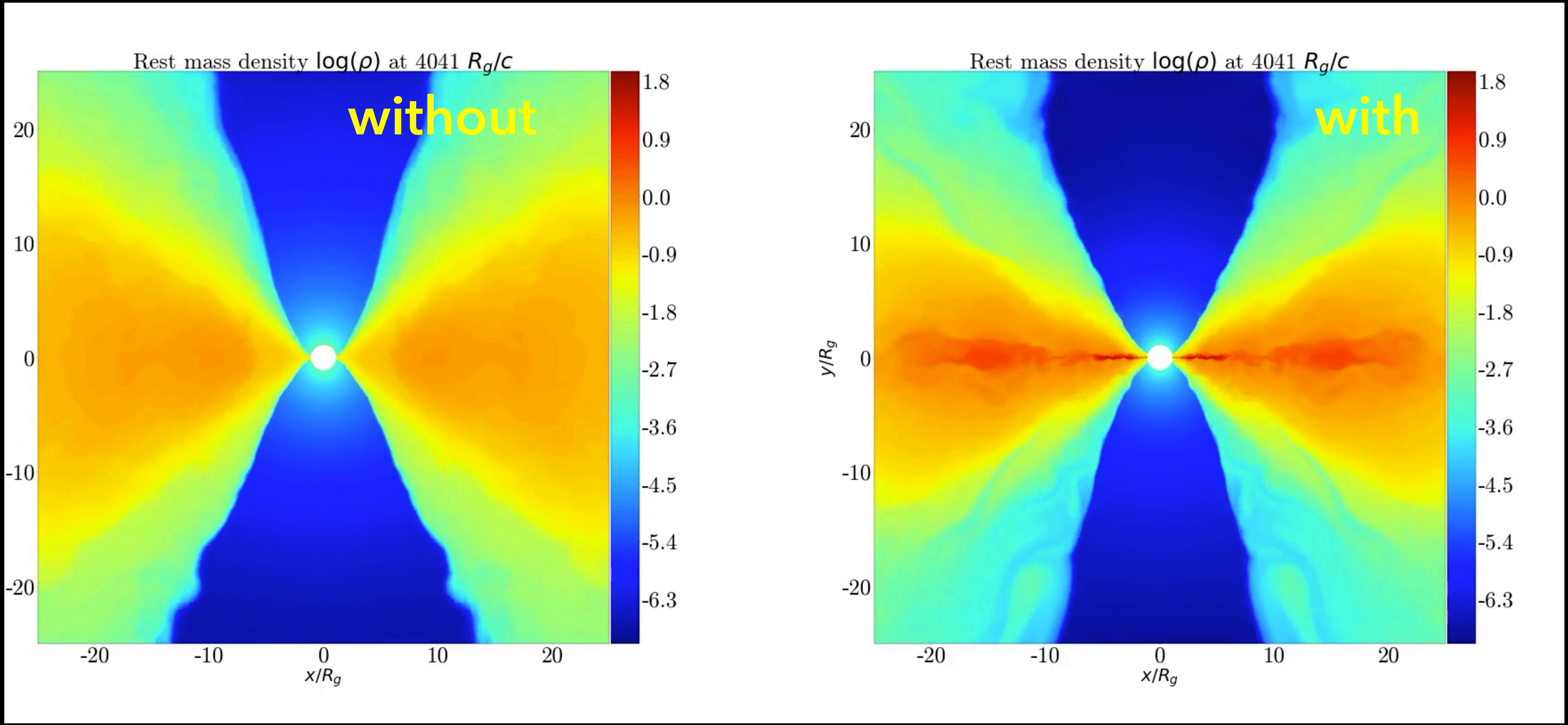
(Moscibrodzka, Falcke, Shiokawa & Gammie 2014; see also Ressler++15,17; Chael++18; Ryan++18)

Illustration of "macro/microphysics problem" for EHT



(Moscibrodzka, Falcke, Shiokawa & Gammie 2014; see also Ressler++15,17; Chael++18; Ryan++18)

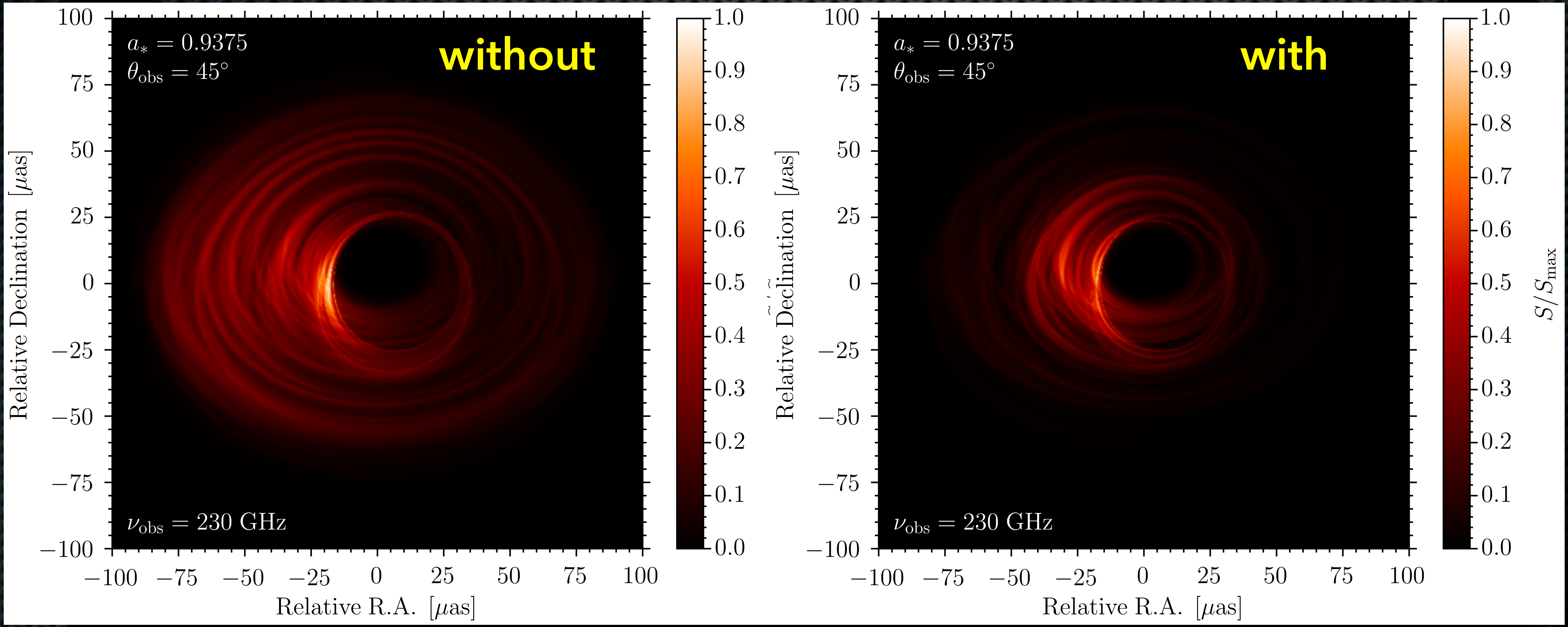
Simulations including radiative cooling (optically thin)



(Dibi, Drappeau, Fragile, SM & Dexter 2012; Drappeau, Dibi, Dexter, SM & Fragile 2013; Chatterjee, van Eijnatten, SM, Younsi, ++ in prep.

Simulations including radiative cooling (optically thin)

Comparison of 1.3mm images for maximally spinning Sgr A*, 10^{-8} $M_\odot$/yr, GR raytracing using BHOSS (Younsi++16)

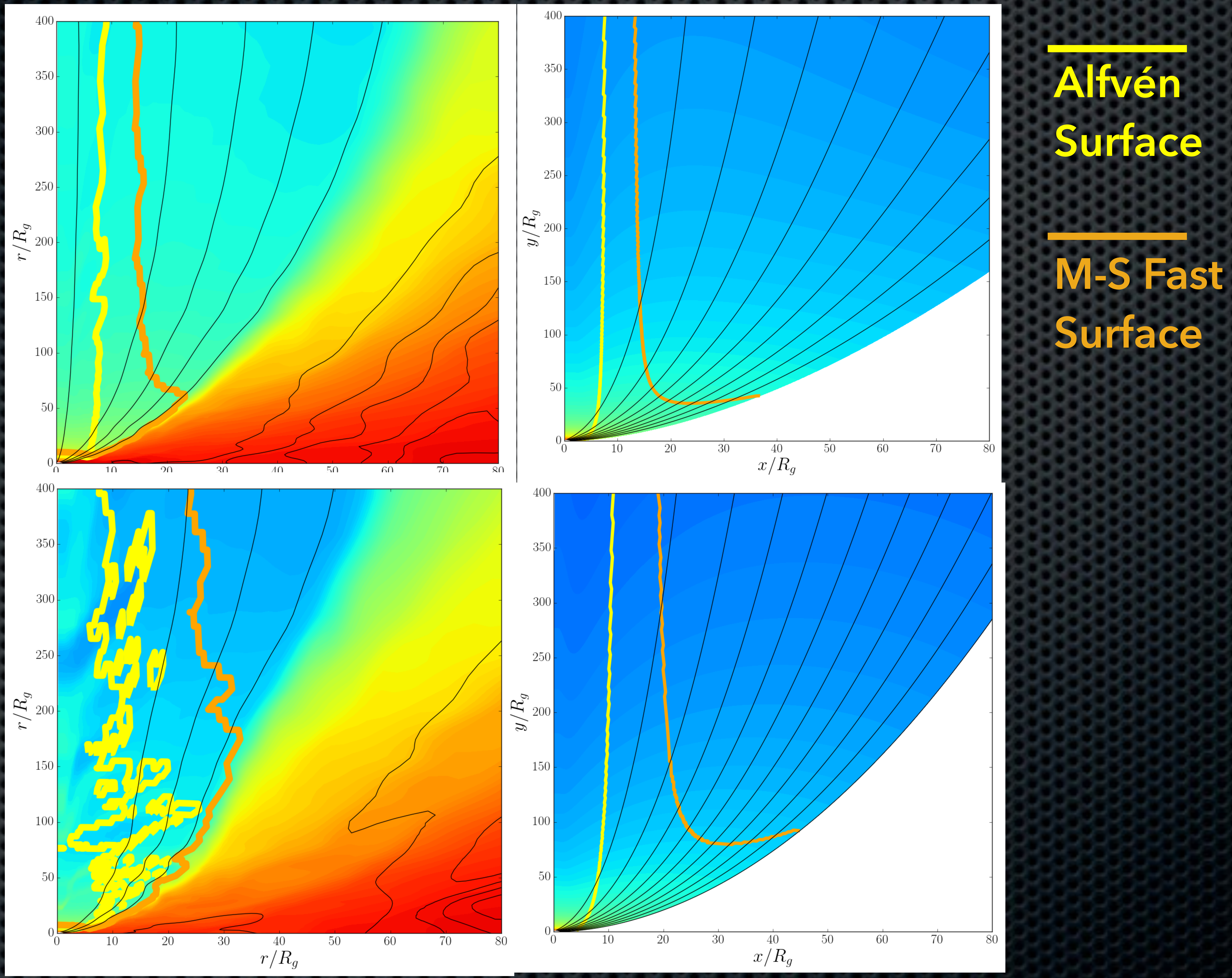


(Dibi, Drappeau, Fragile, SM & Dexter 2012; Drappeau, Dibi, Dexter, SM & Fragile 2013; Chatterjee, van Eijnatten, SM, Younsi, ++ in prep.

Studying causality in GRMHD to explain Z_{acc}

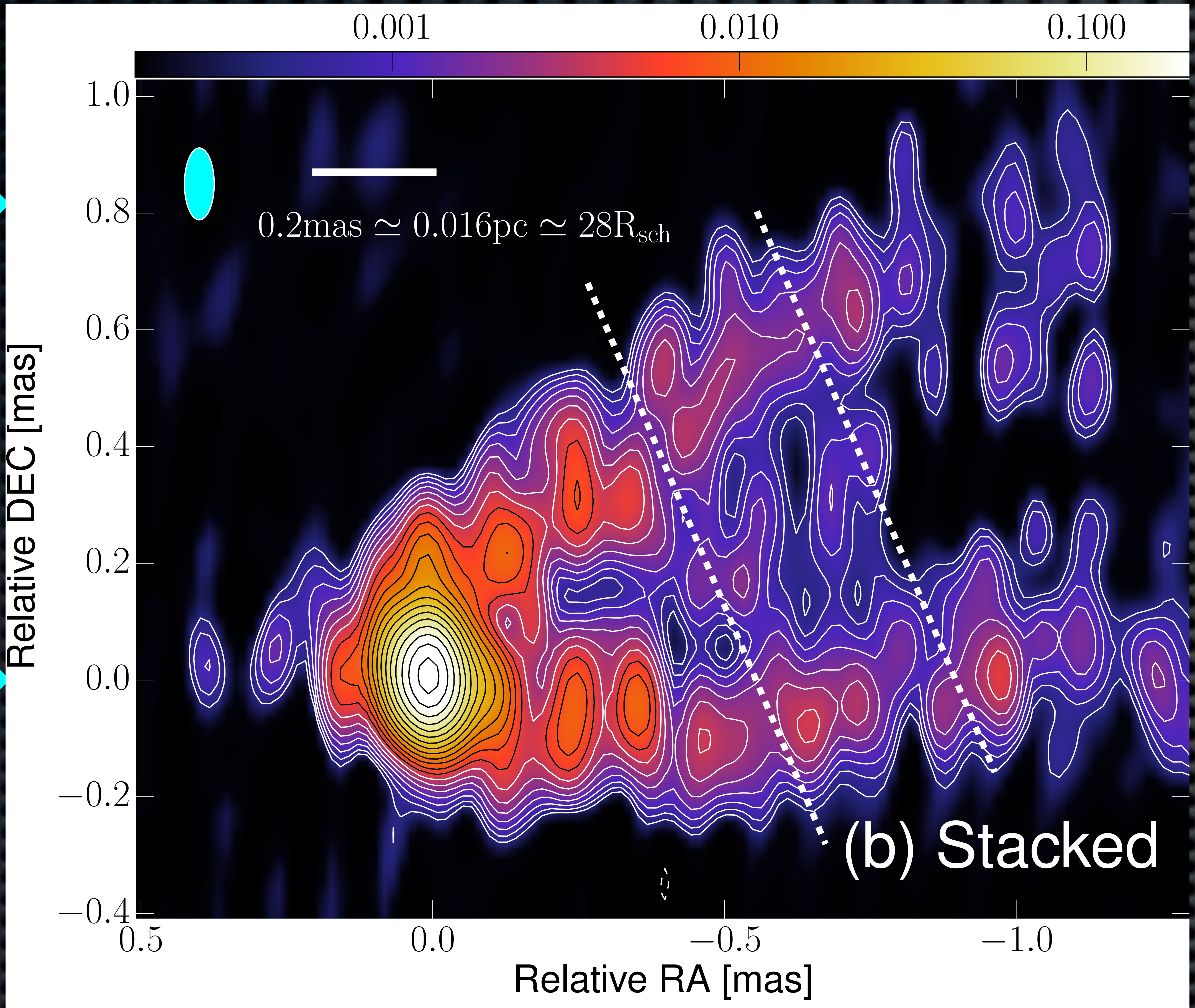
σ_0=10

σ_0=60

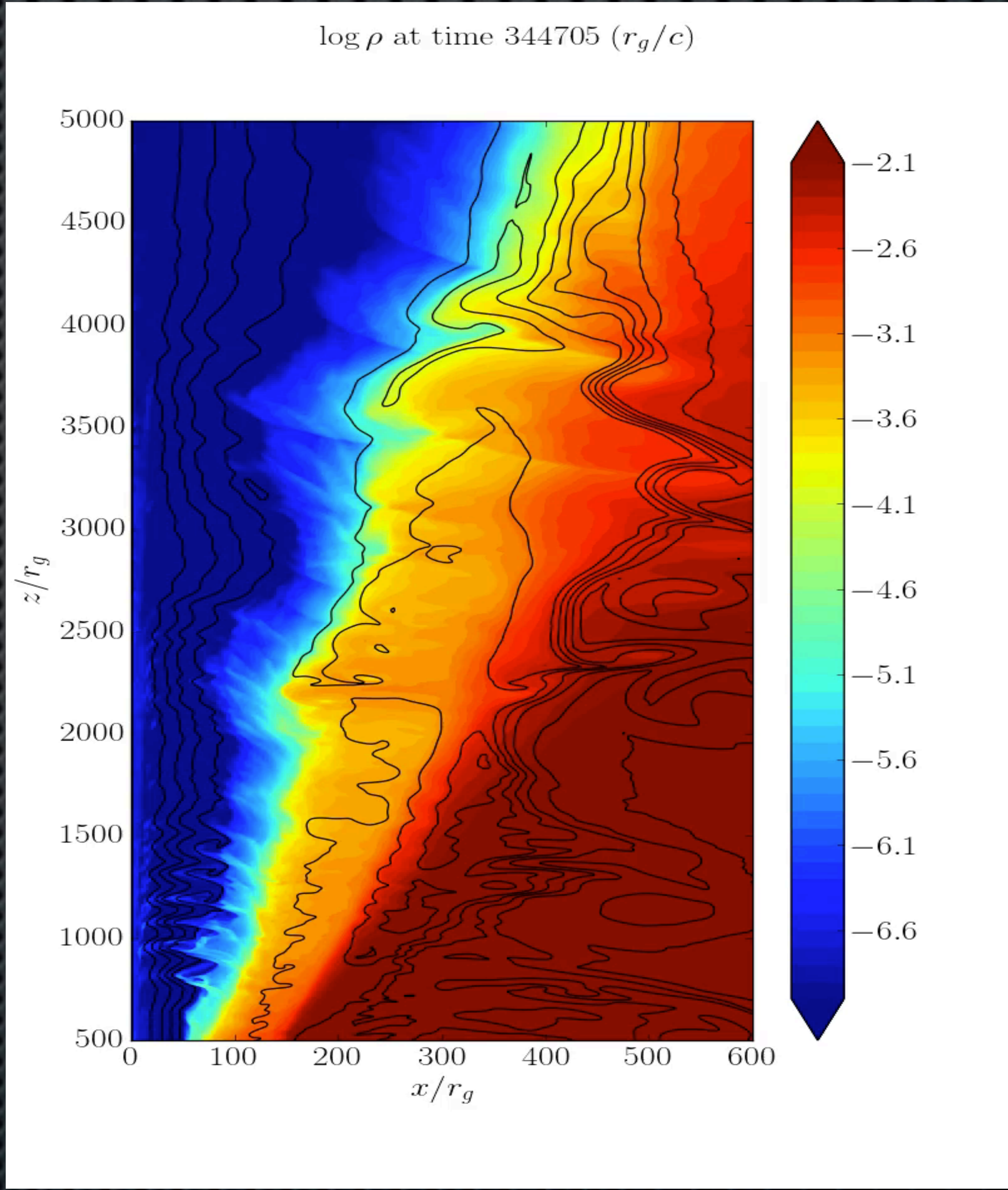


(Chatterjee, Liska, Tchekhovskoy, SM, ++, in prep.)

Theory is catching up to the dynamical range of MWL timing constraints



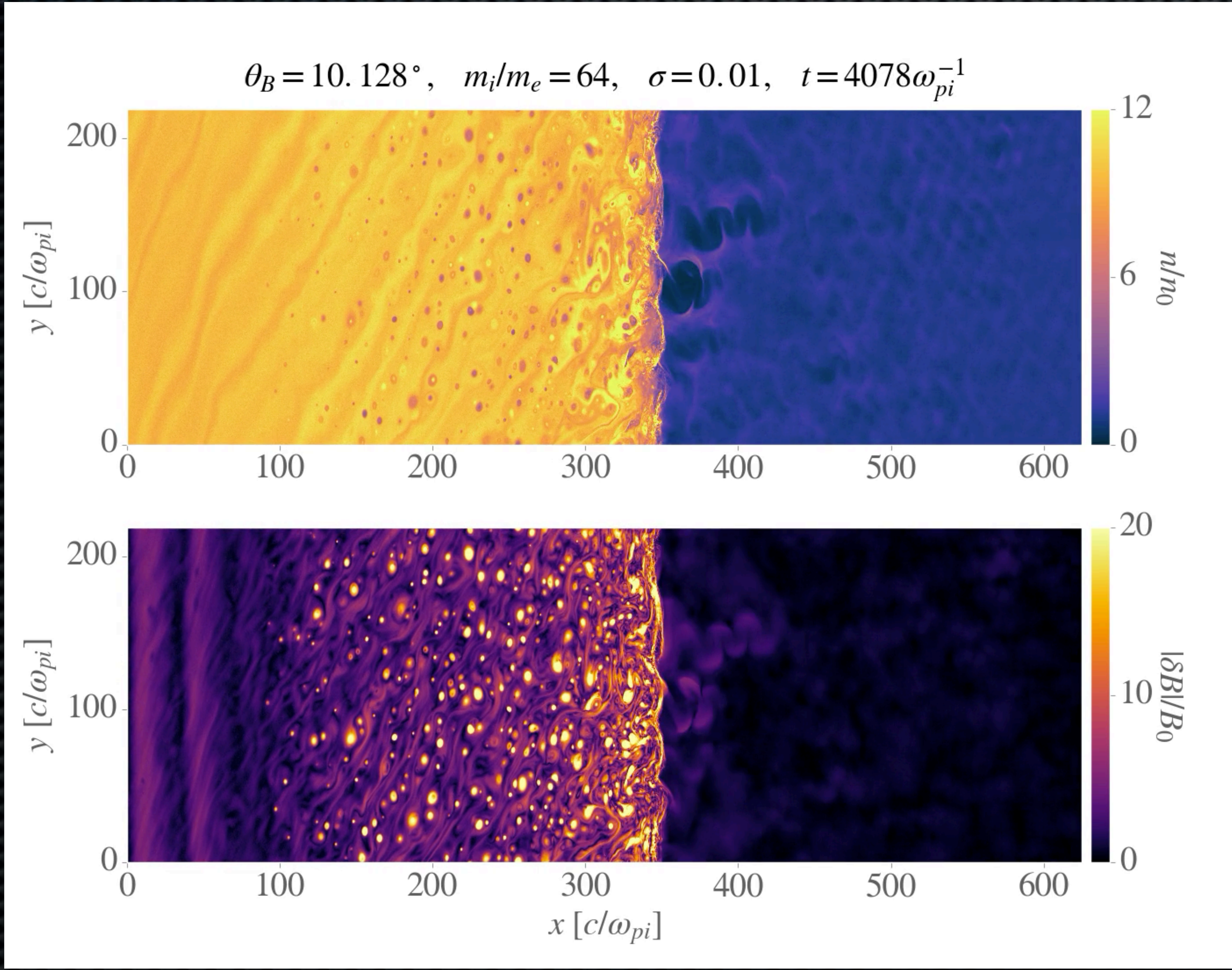
(Kim++2018; Walker++2018; Hada++14,16,18; Acciari++10; Abramowski++12, etc.)



(Chatterjee, Liska, Tchekhovskoy, SM++, in prep.; see also spine/sheath ideas eg. Ghisselini++)

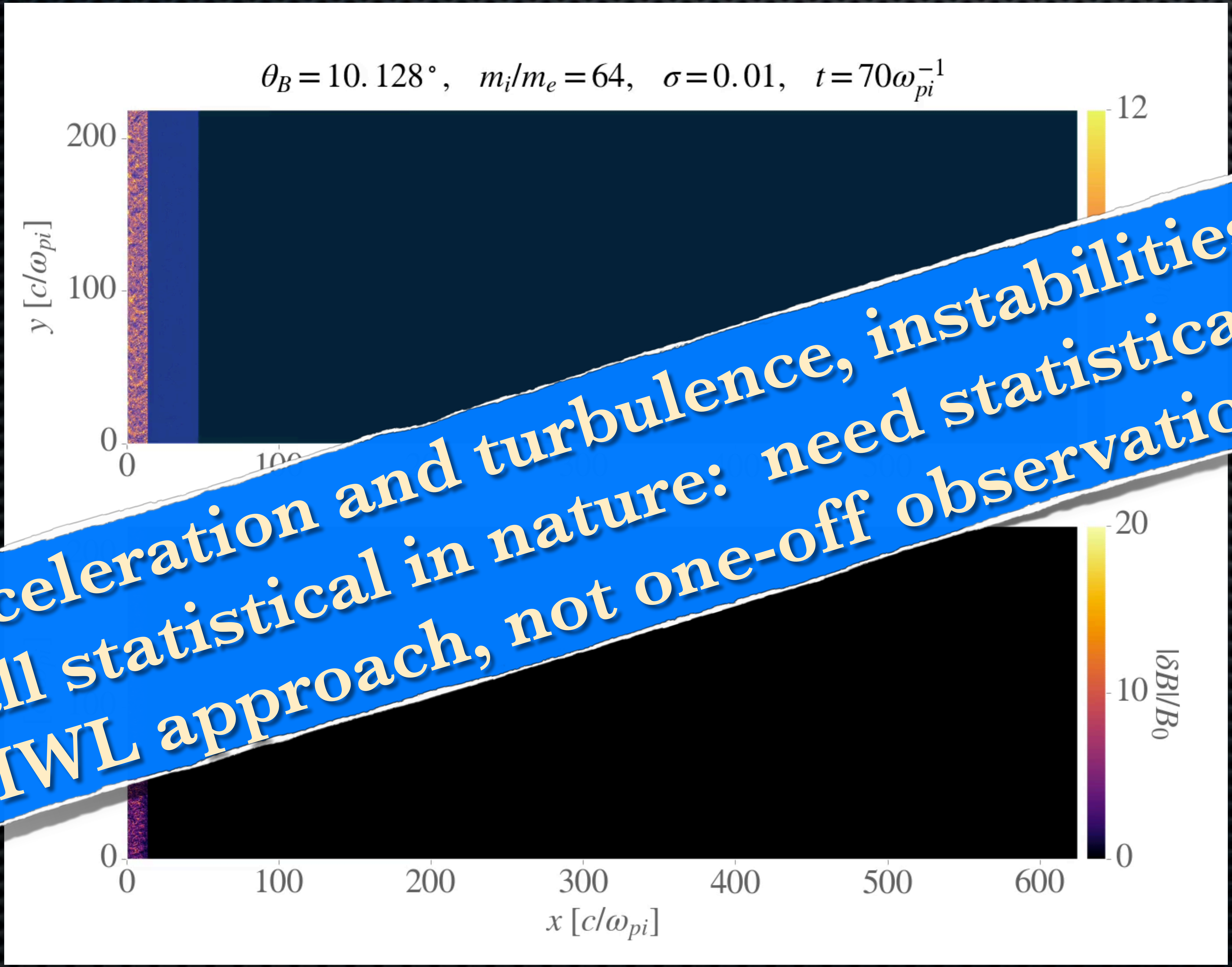
Theory is catching up to the dynamical range of MWL timing constraints

(6000x800



(Crumley, Caprioli, SM, Spitkovsky, subm.; plus work of many other groups: Spitkovsky++, Sironi++, Phillipov++etc.)

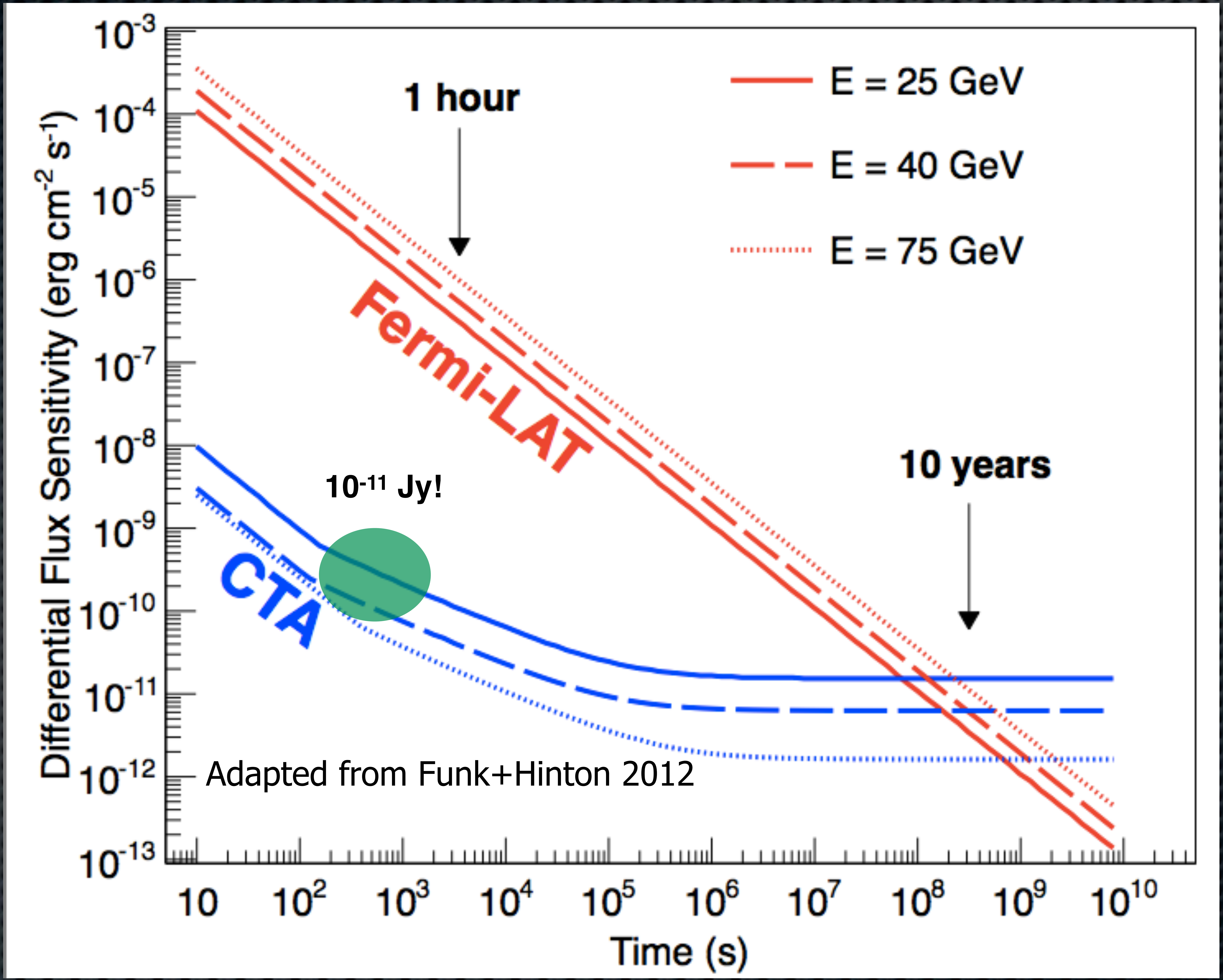
Theory is catching up to the dynamical range of MWL timing constraints



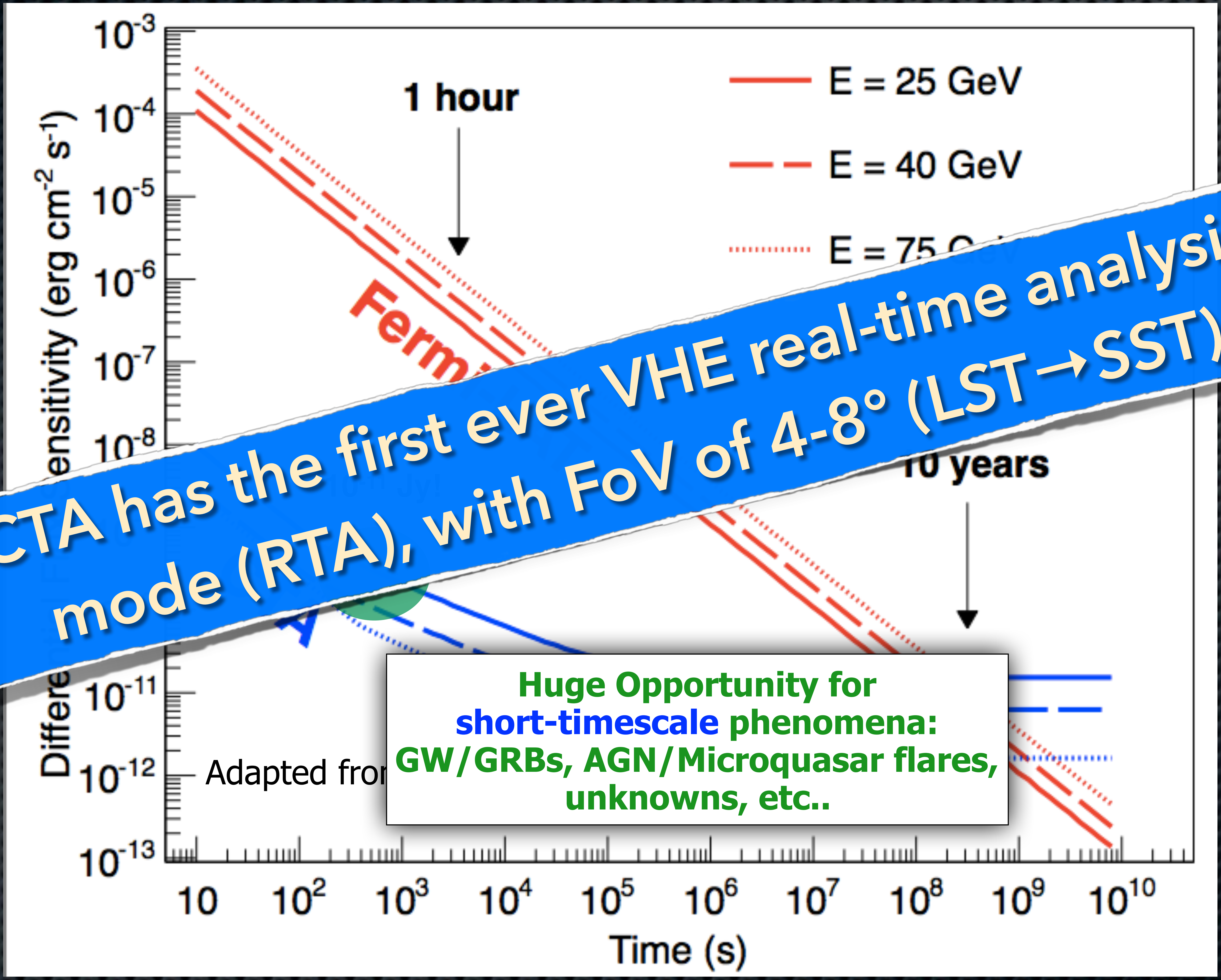
Acceleration and turbulence, instabilities, all statistical in nature: need statistical MWL approach, not one-off observations

(Crumley, Caprioli, SM, Spitkovsky, subm.; plus work of many other groups: Spitkovsky++, Sironi++, Phillipov++etc.)

Upcoming new window: CTA!



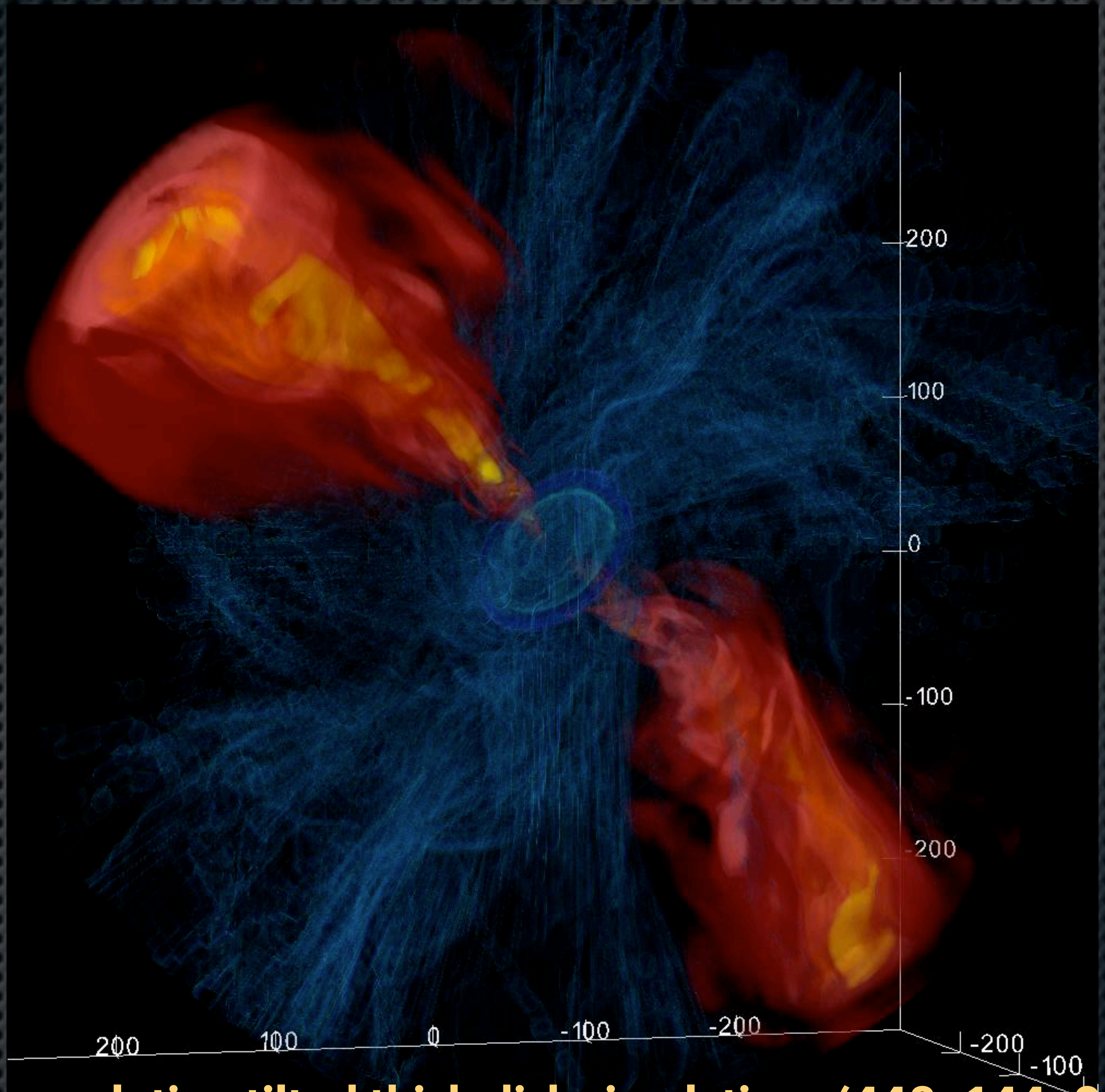
Upcoming new window: CTA!



CTA has the first ever VHE real-time analysis mode (RTA), with FoV of 4-8° (LST→SST)

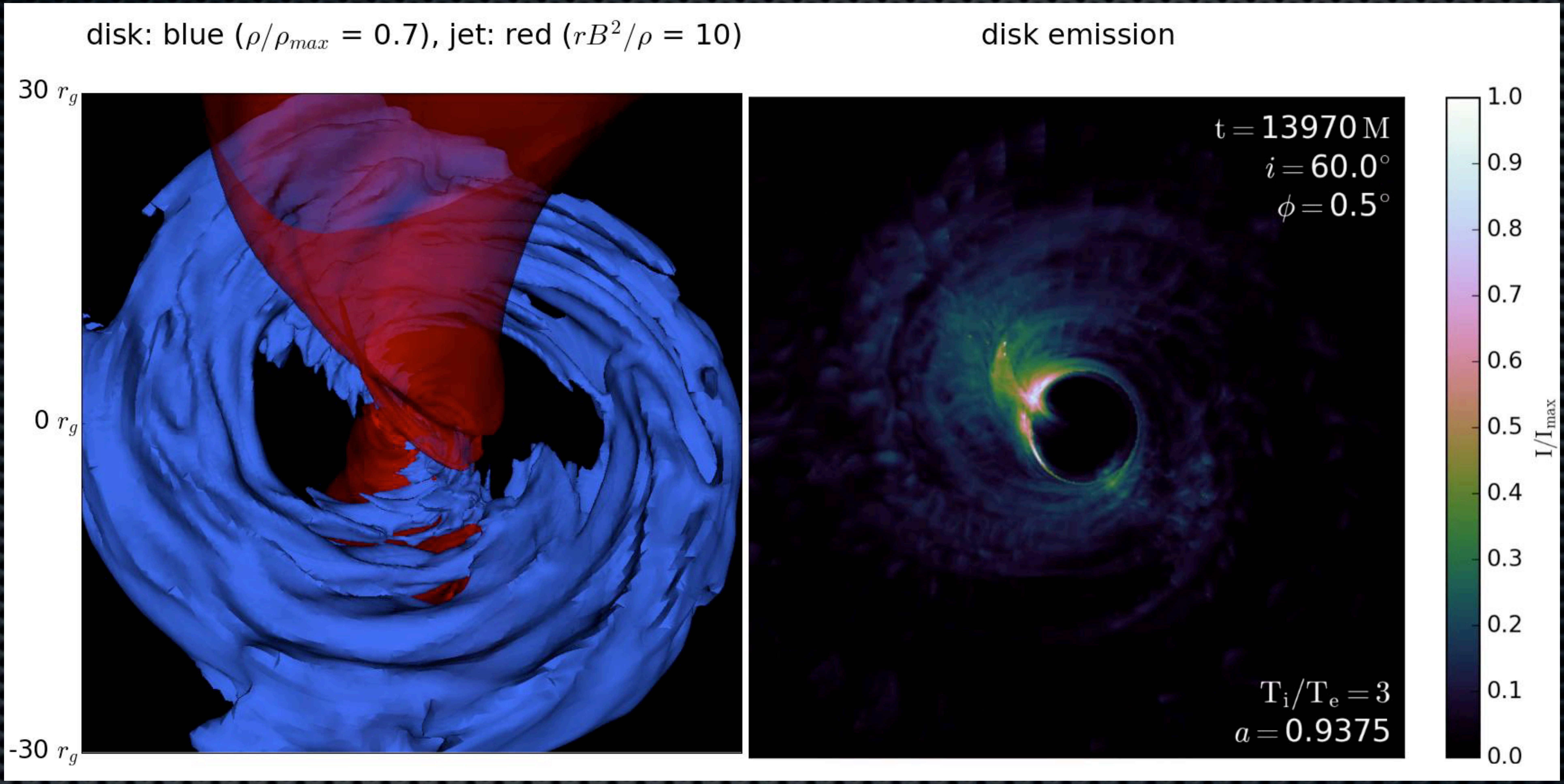
Huge Opportunity for short-timescale phenomena: GW/GRBs, AGN/Microquasar flares, unknowns, etc..

High resolution, 3D tilted disk simulations (H/R~1)



Highest ever resolution tilted thick disk simulations (448x144x240). Led by MSc/PhD students: M. Liska, visualisation by C. Hesp

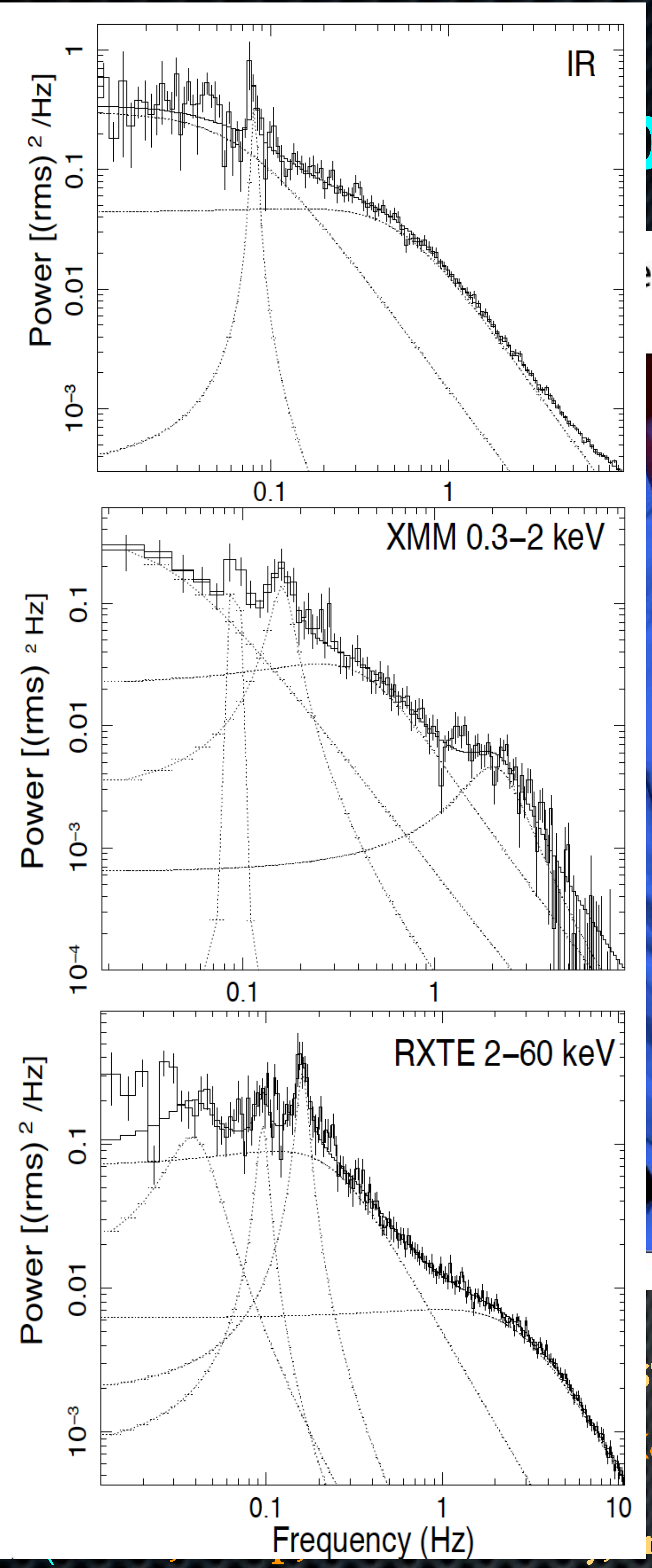
Variability in high-resolution 3D-GRMHD simulations

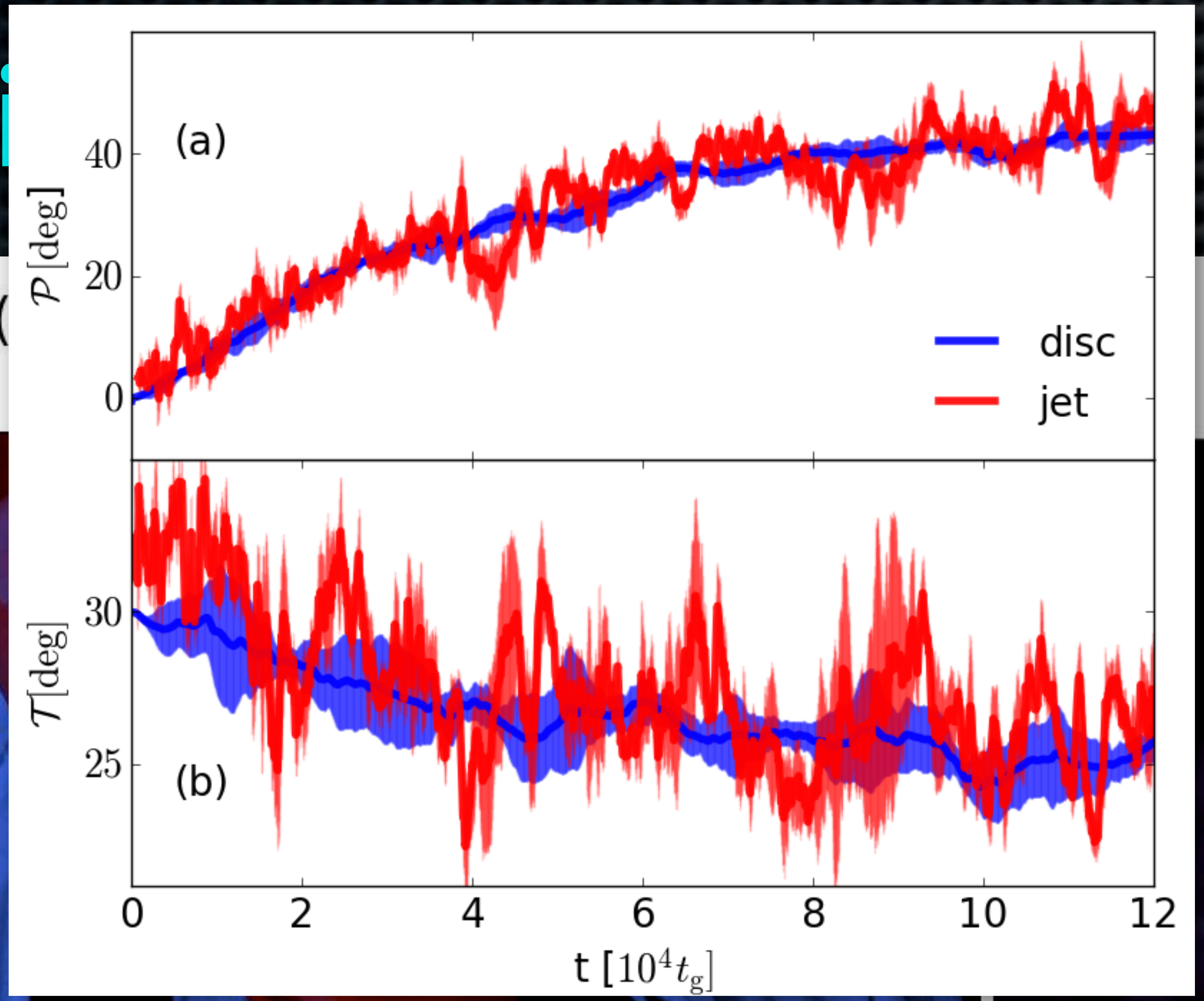


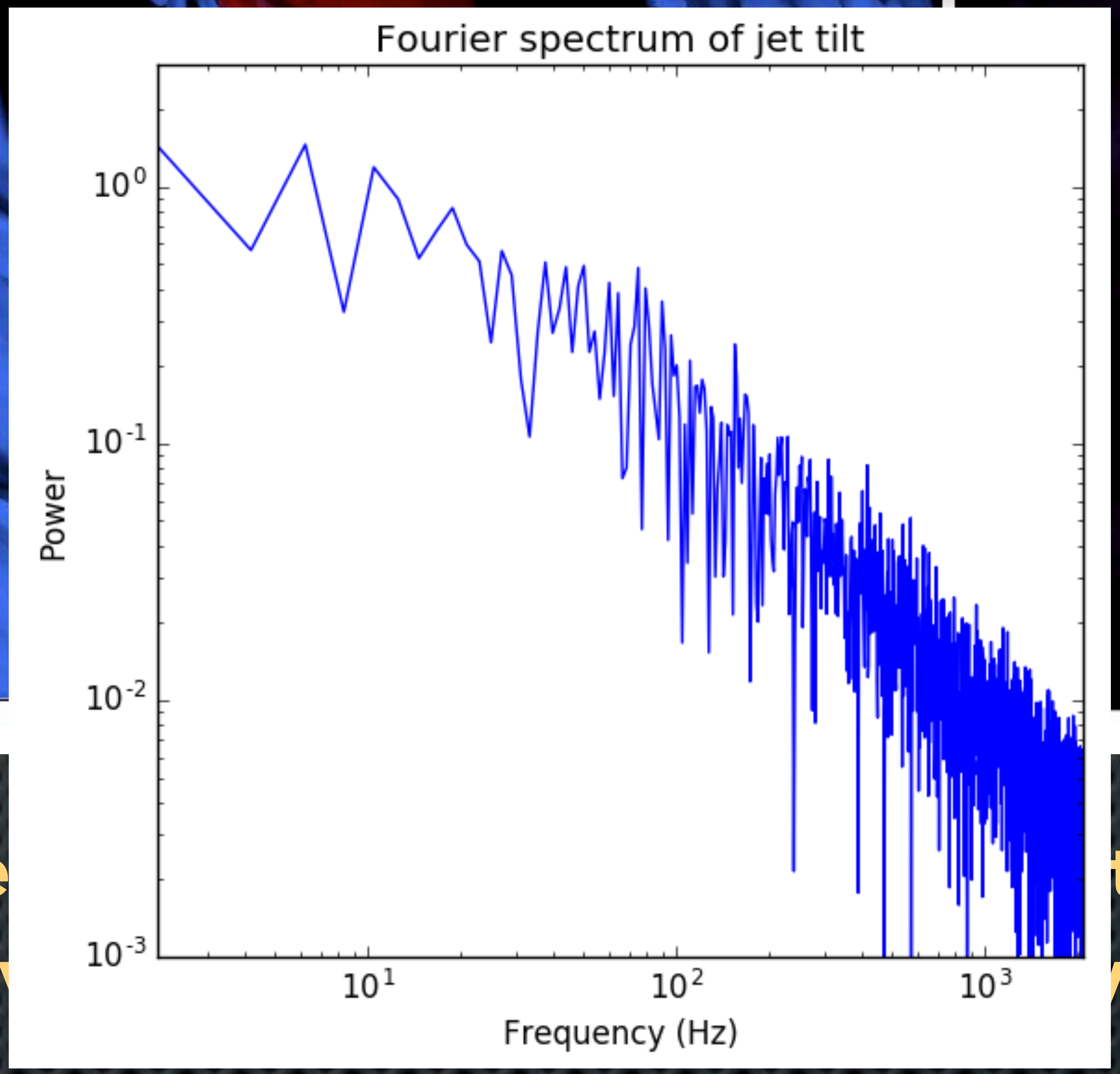
Highest ever resolution tilted disk simulations. Led by MSc/PhD students:
M. Liska, visualisation by C. Hesp with ray tracing by Dr. Ziri Younsi

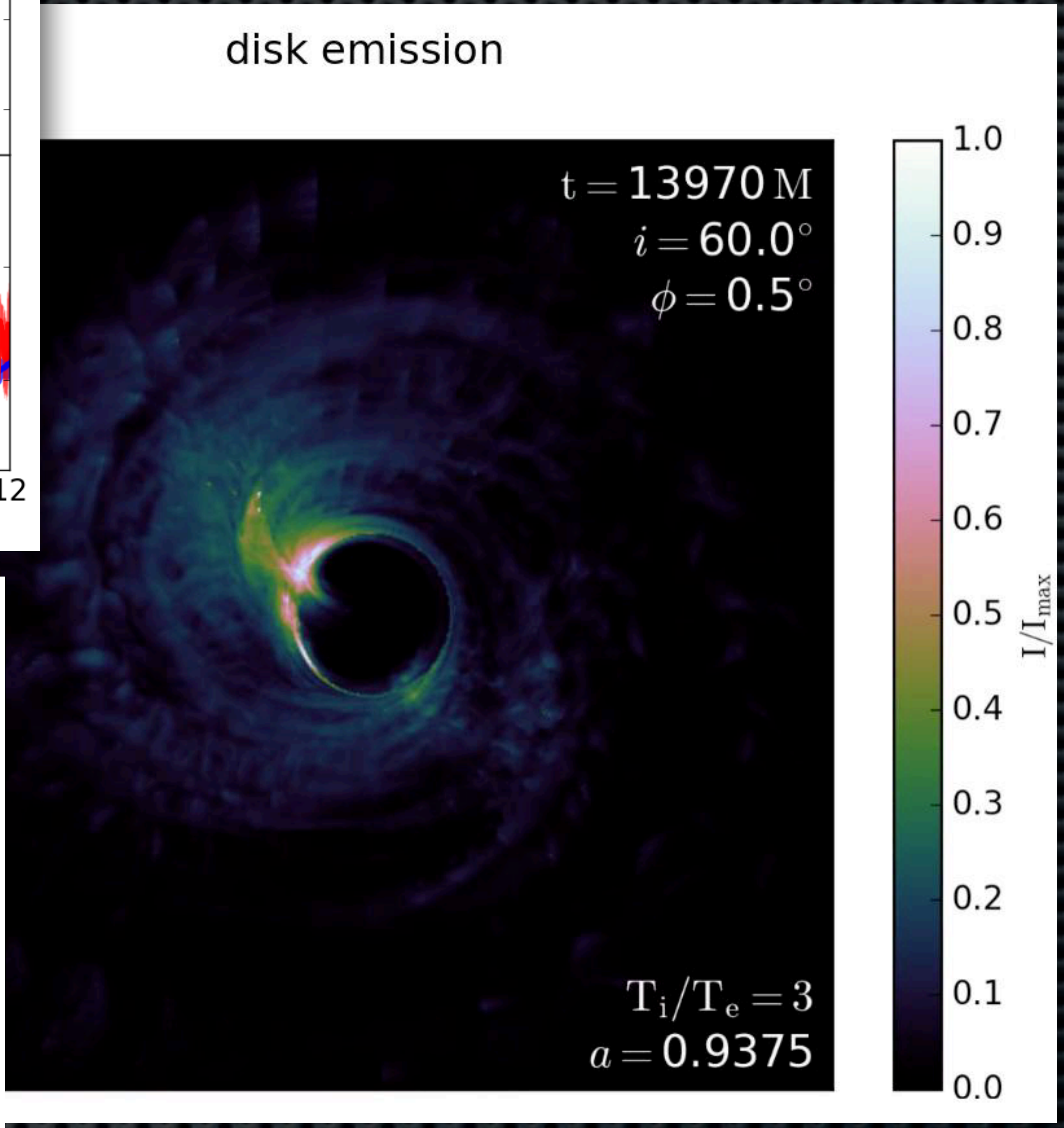
(Liska, Hesp, Tchekhovskoy, Ingram, vd Klis, SM++ 2018; Chatterjee, van Eijnatten, SM, Hesp, Liska, Younsi, Tchekhovskoy++ in prep.

…3D-GRMHD simulations









…t e… …tions. Led by MSc/PhD students:

…a, … …tracing by Dr. Ziri Younsi

…ngram, vd Klis, SM++ 2018; Chatterjee, van Eijnatten, SM, Hesp, Liska, Younsi, Tchekhovskoy++ in prep.

Summary

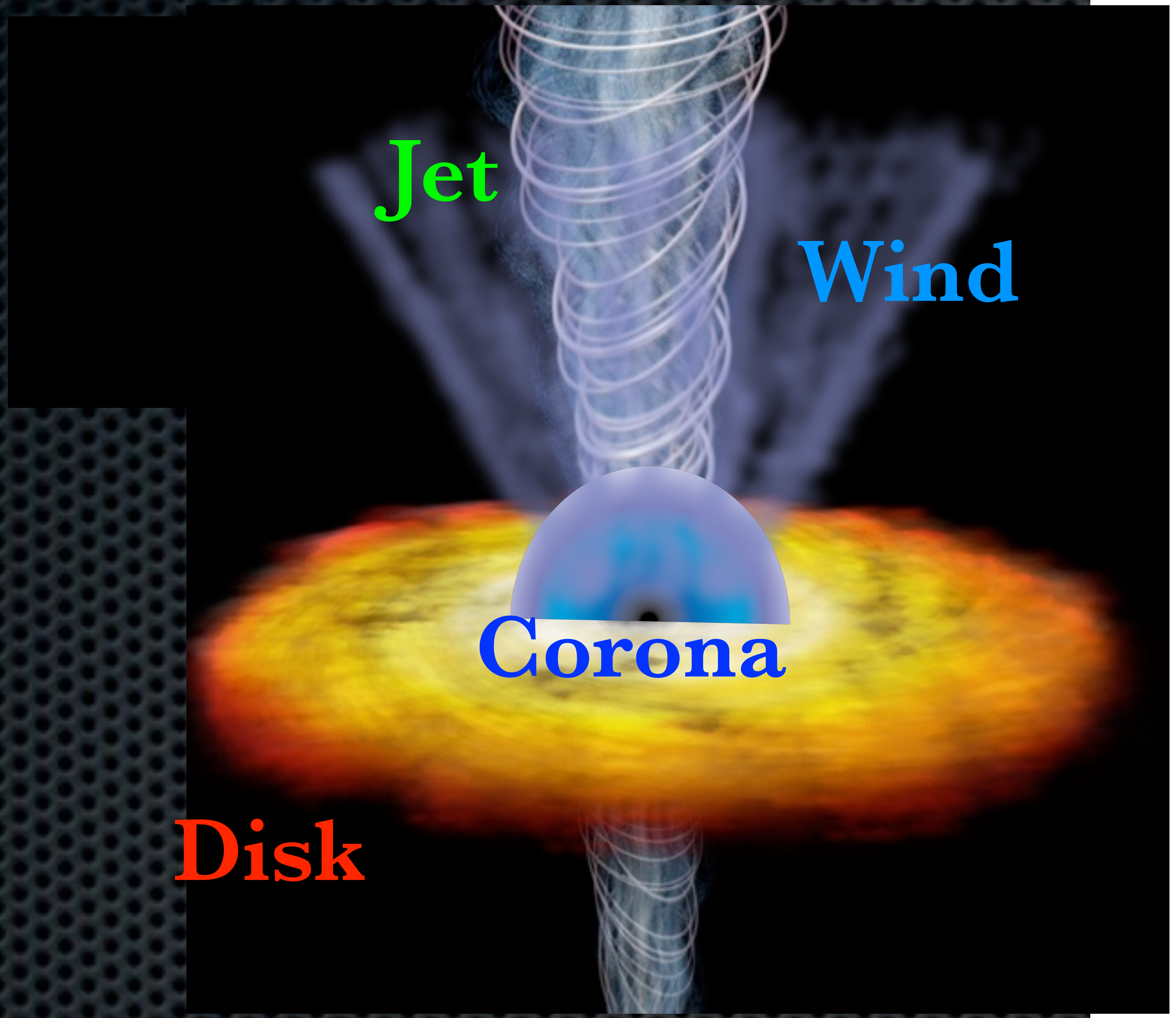
- It's complicated, but we cannot separate dynamics from microphysics
- Observational trends, like evolution in acceleration zone offset from BH with $\dot{m}$, can be exploited to "anchor" physics in theoretical models/simulations
- EHT will help us understand more details of micro/macro connection, CTA will help pinpoint and track particle acceleration in response to dynamics
- Outlook: radiation (GR)MHD, non-ideal effects, particle physics
  ➠ working our way towards the "end goal" of predictive models
- Stay tuned for EHT 2017 results in early 2019 and CTA early science in ~2023!

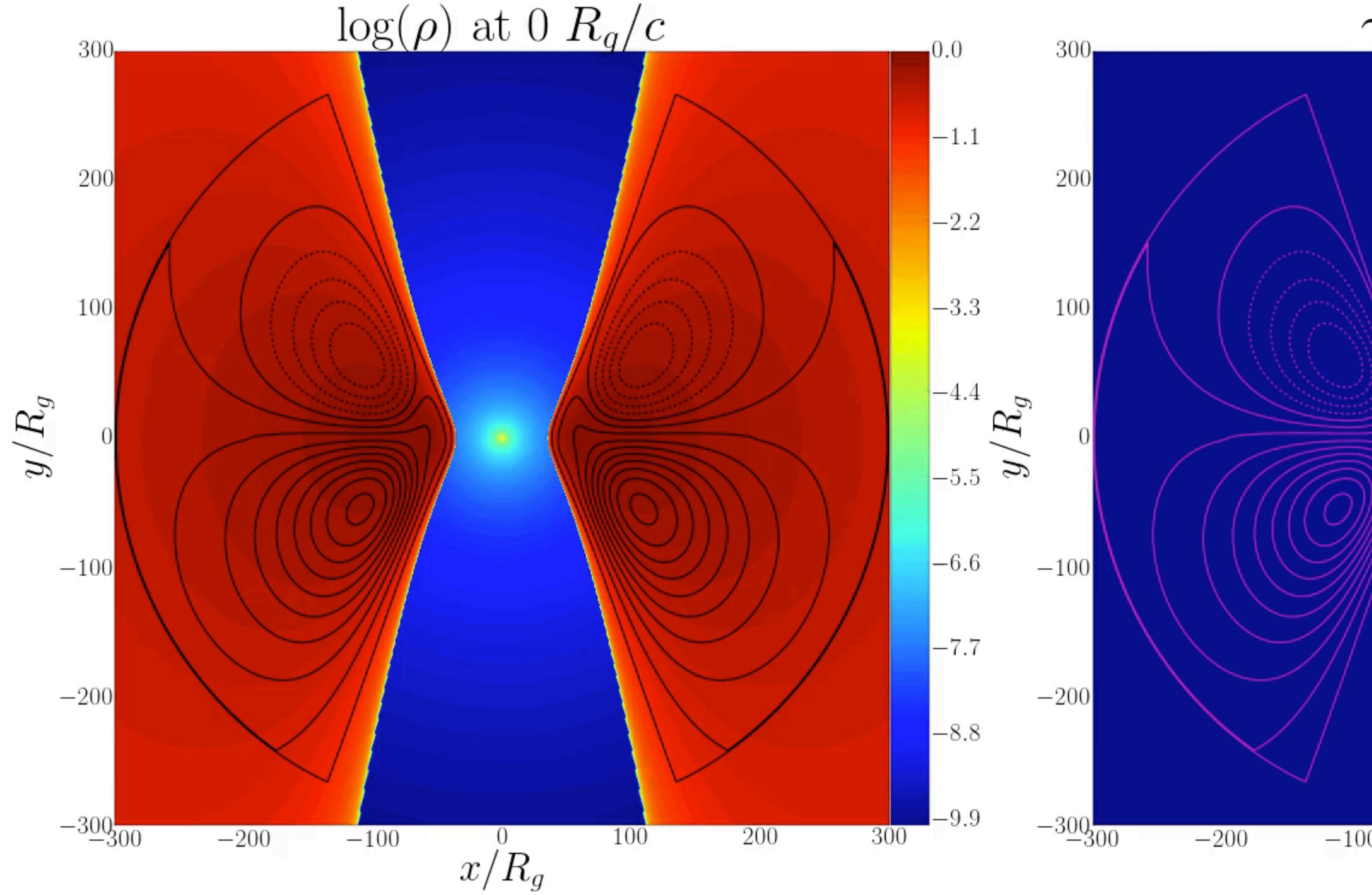
Other things to talk with me about while I'm here!

- Mass scaling physics between XRBs and AGN
- EHT and CTA + slaved optical telescope
- Semi-analytical models of jets
- MWL campaigns on transient XRBs
- Spectral fitting, joint fitting with your own models using ISIS
- Reflection modeling from jets

Extra Slides

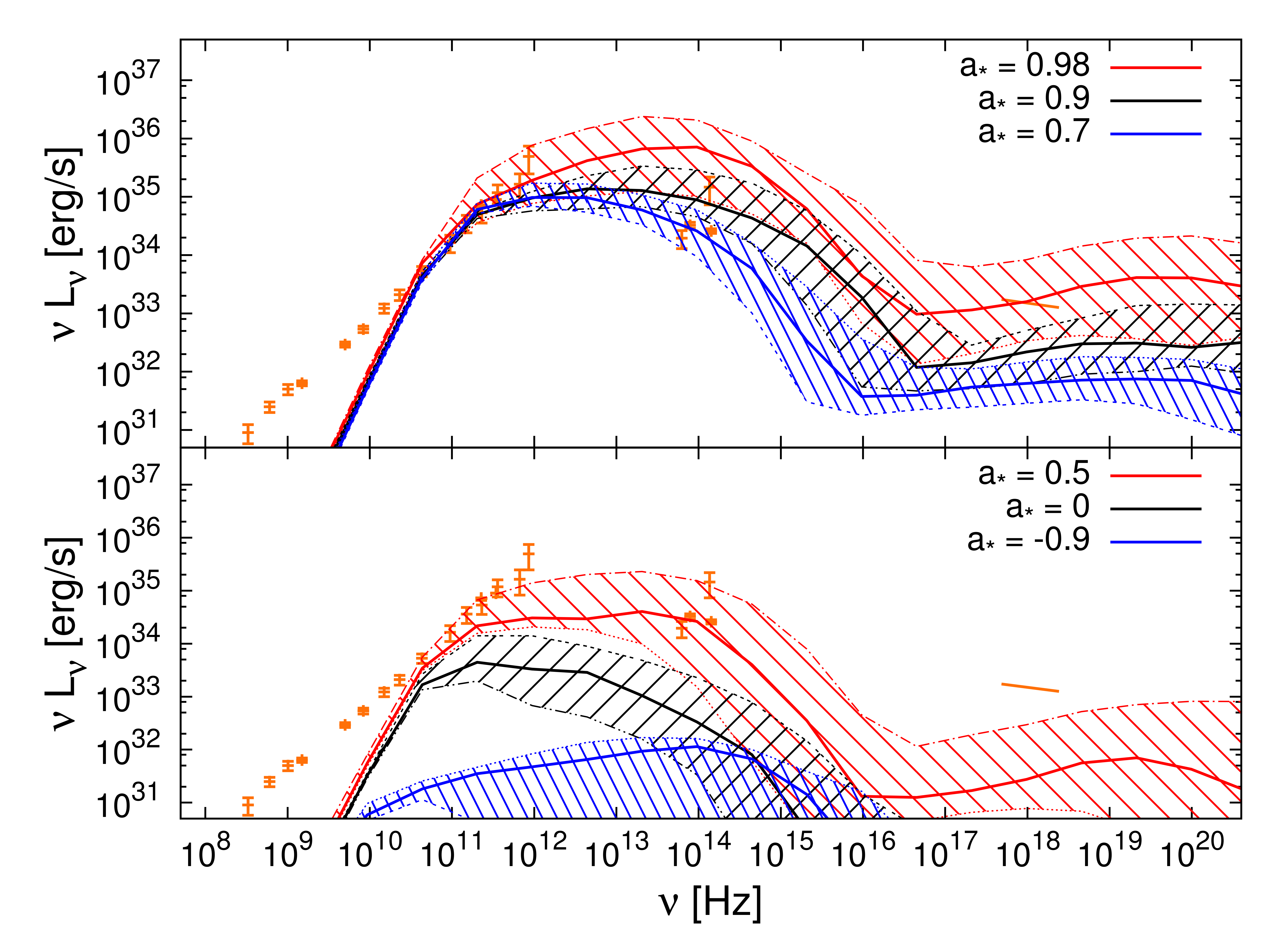
Dynamical MHD simulations challenge old concepts





Chatterjee, Liska, SM, Tchekhovskoy++ in prep.

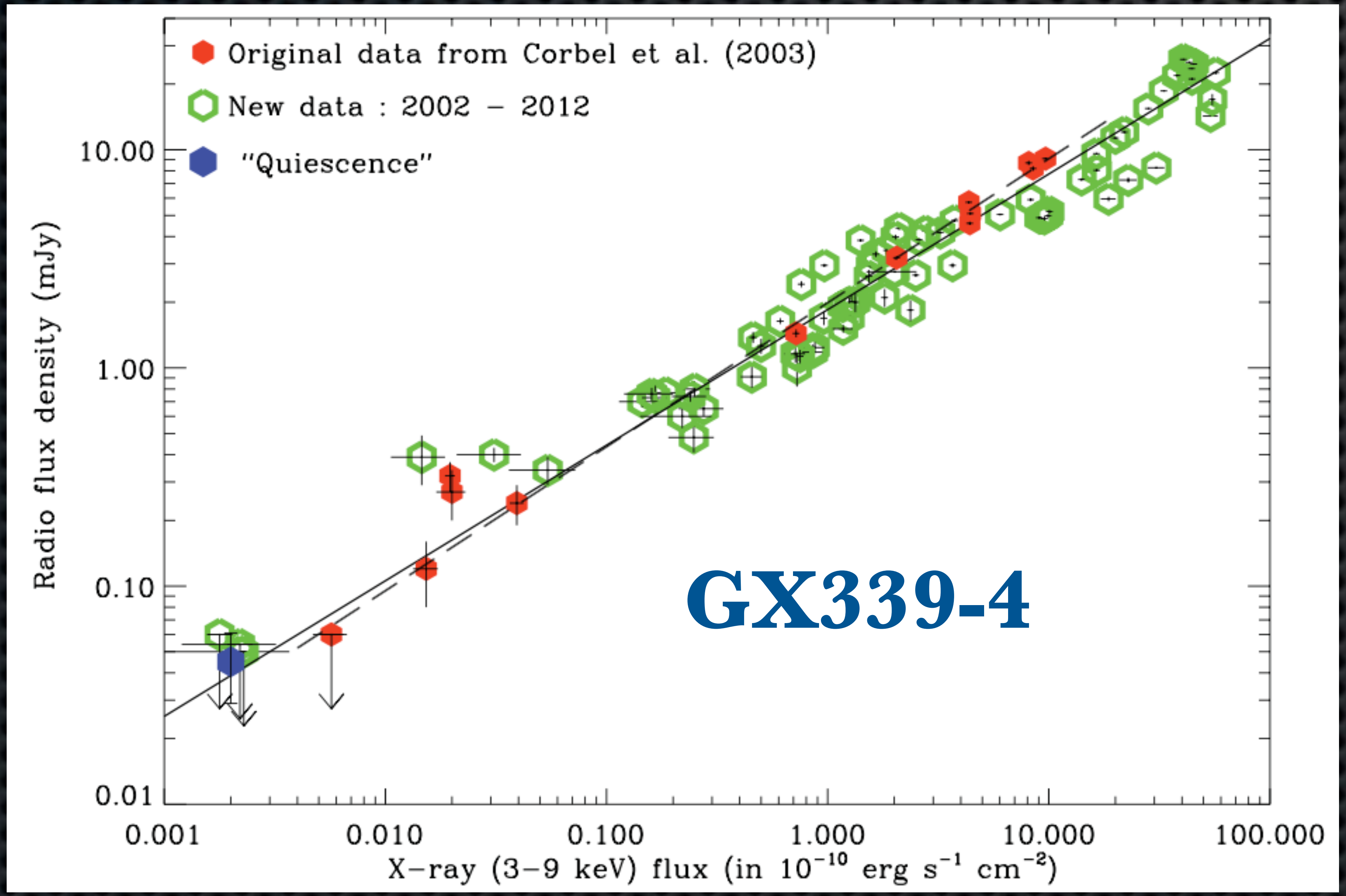
Next step: predictions of spectra to compare to MWL data

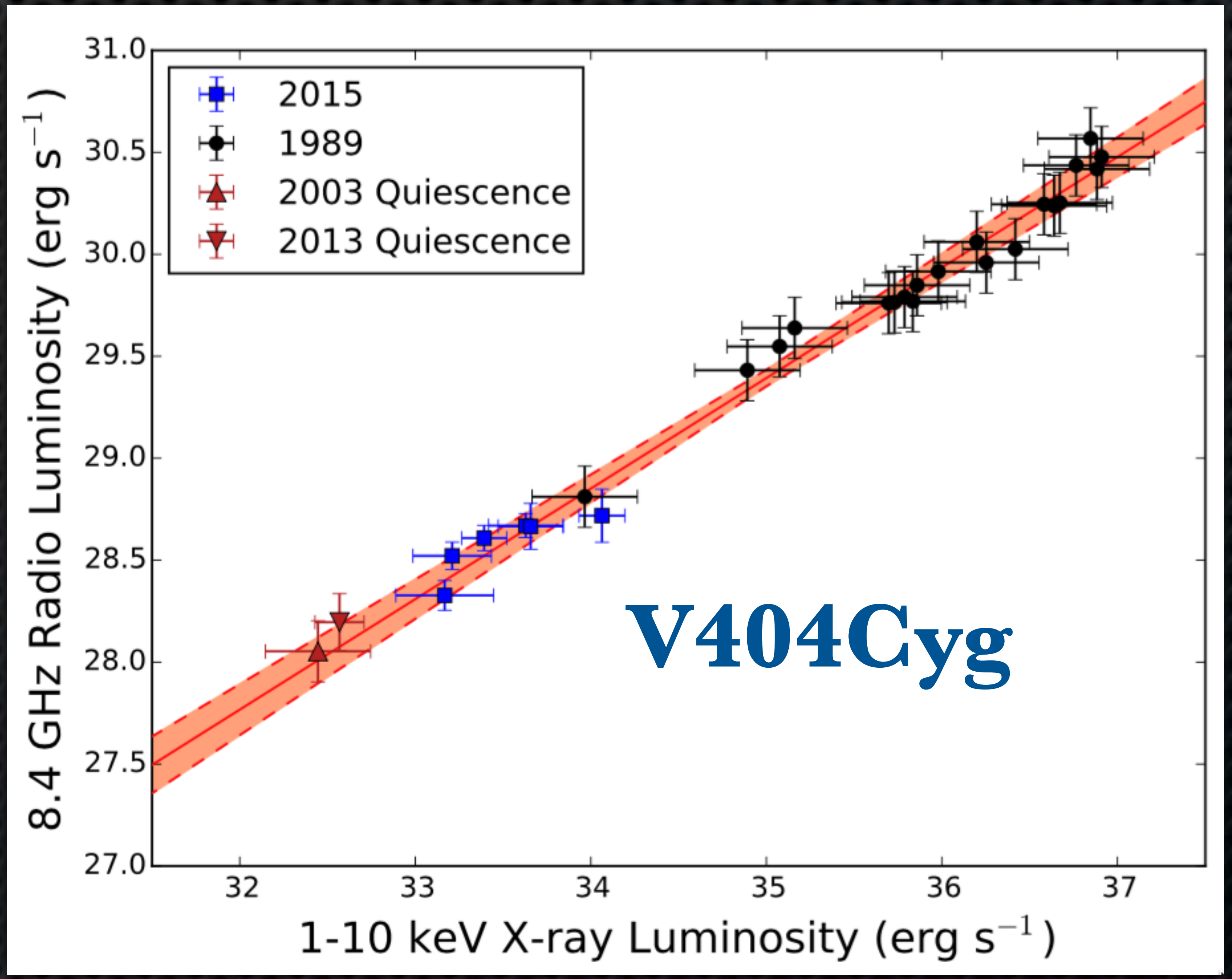


(Drappeau, Dibi, Dexter, SM & Fragile 2013)

XRBs and AGN share a similar central "engine"

- Four independent types of observations find clear scaling of the physics across the mass scale:
  - — "Fundamental Plane" (e.g., Merloni++03, Falcke, Körding & SM 04, Plotkin, SM++12)





XRBs and AGN share a similar central "engine"

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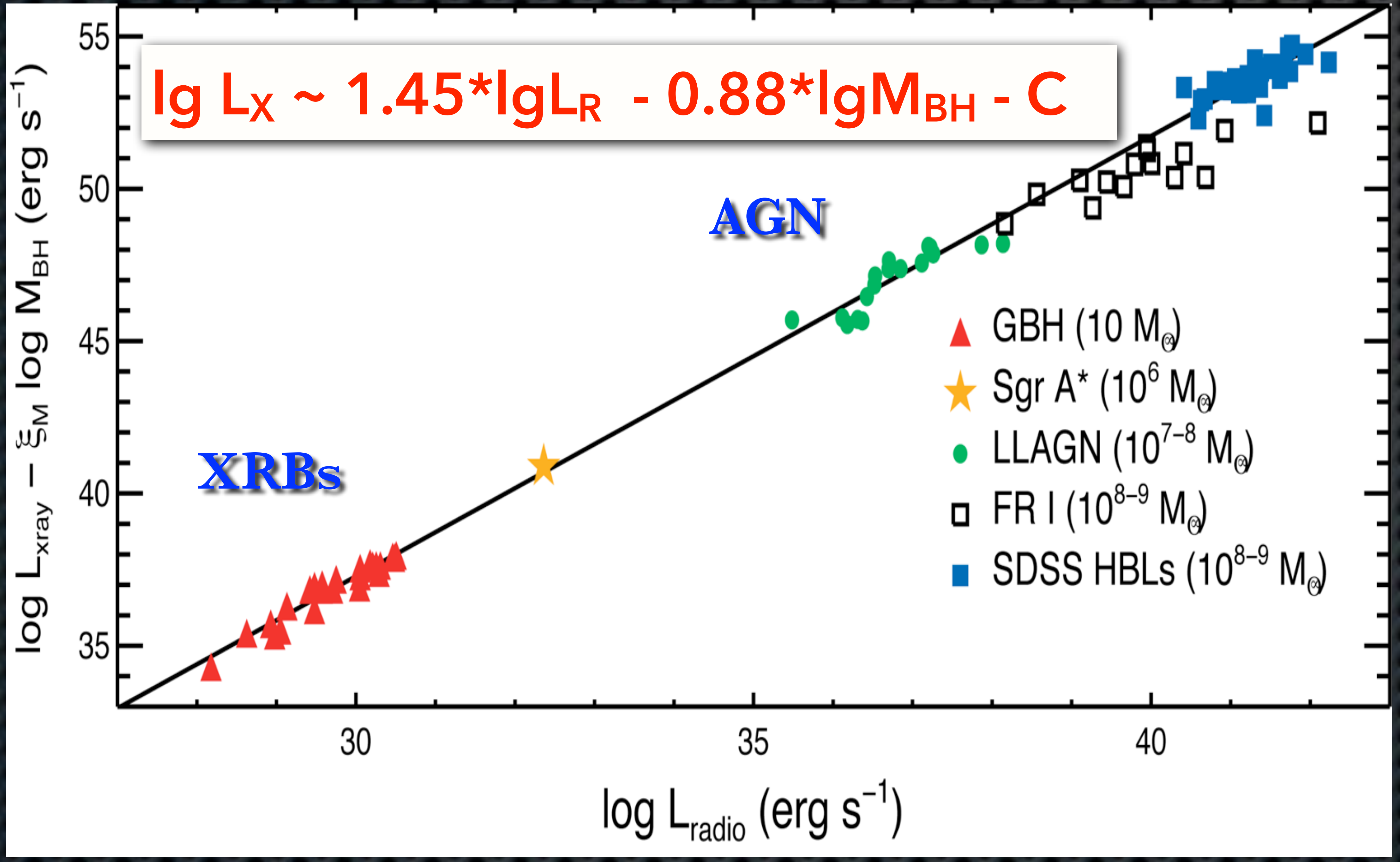

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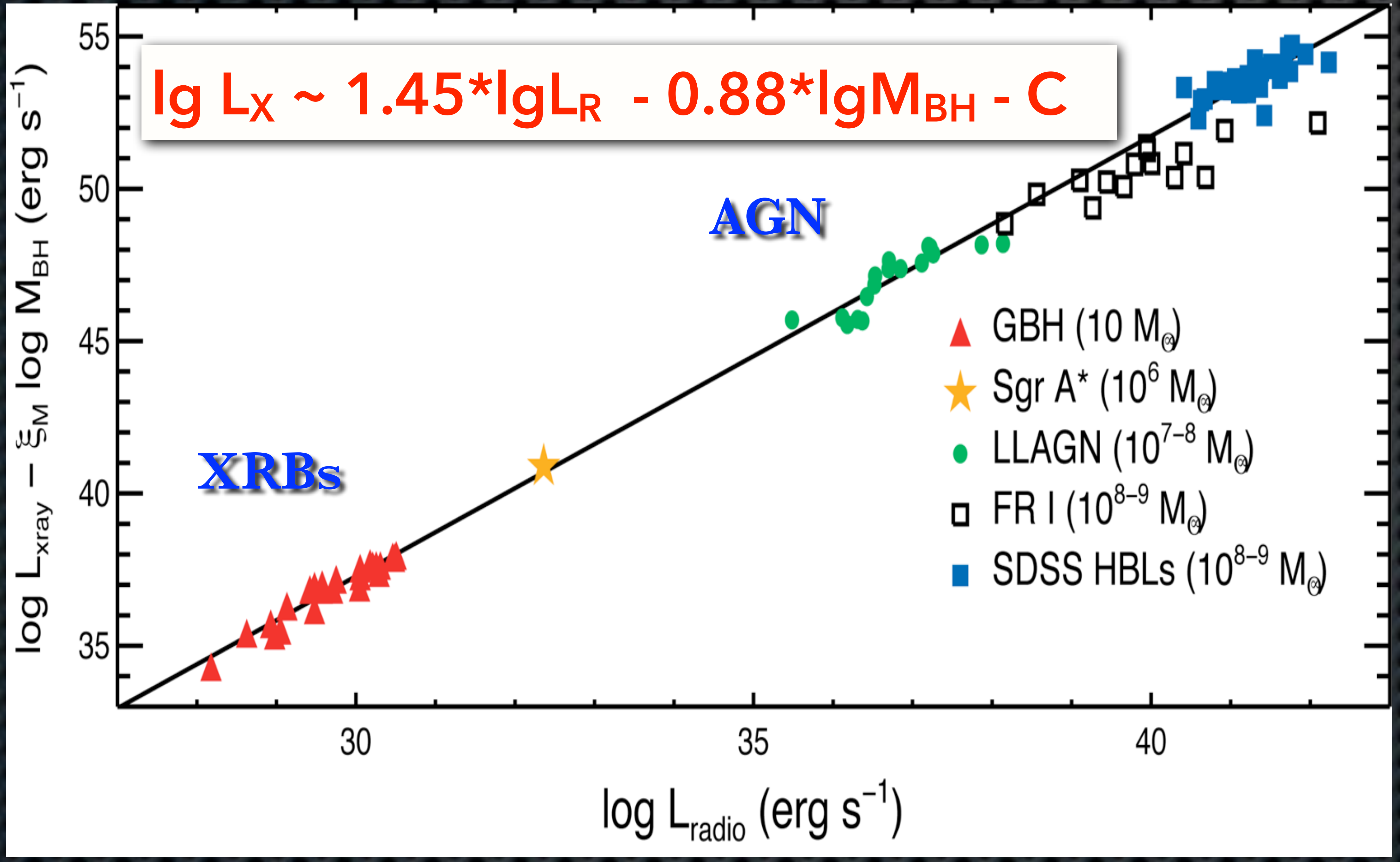

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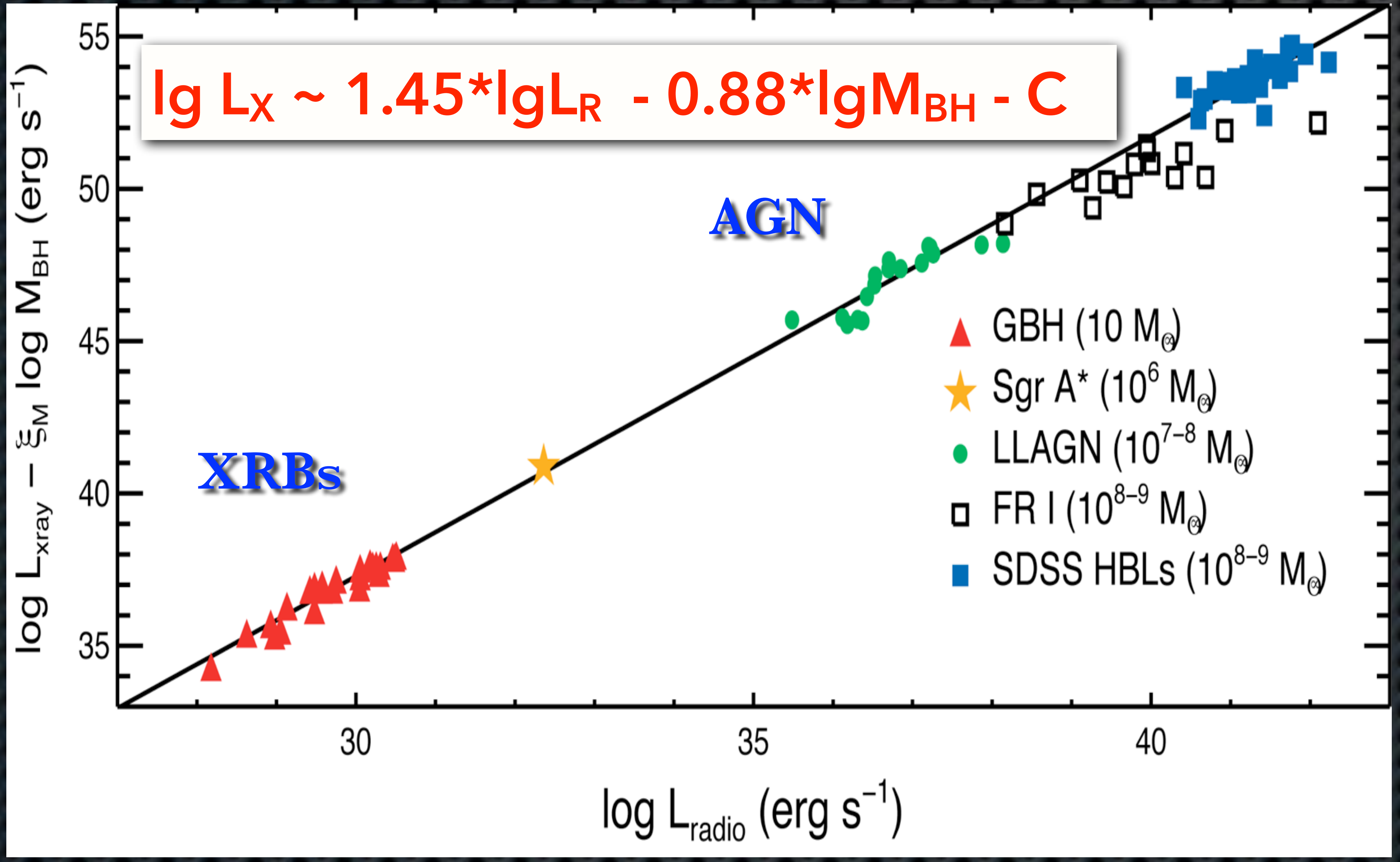

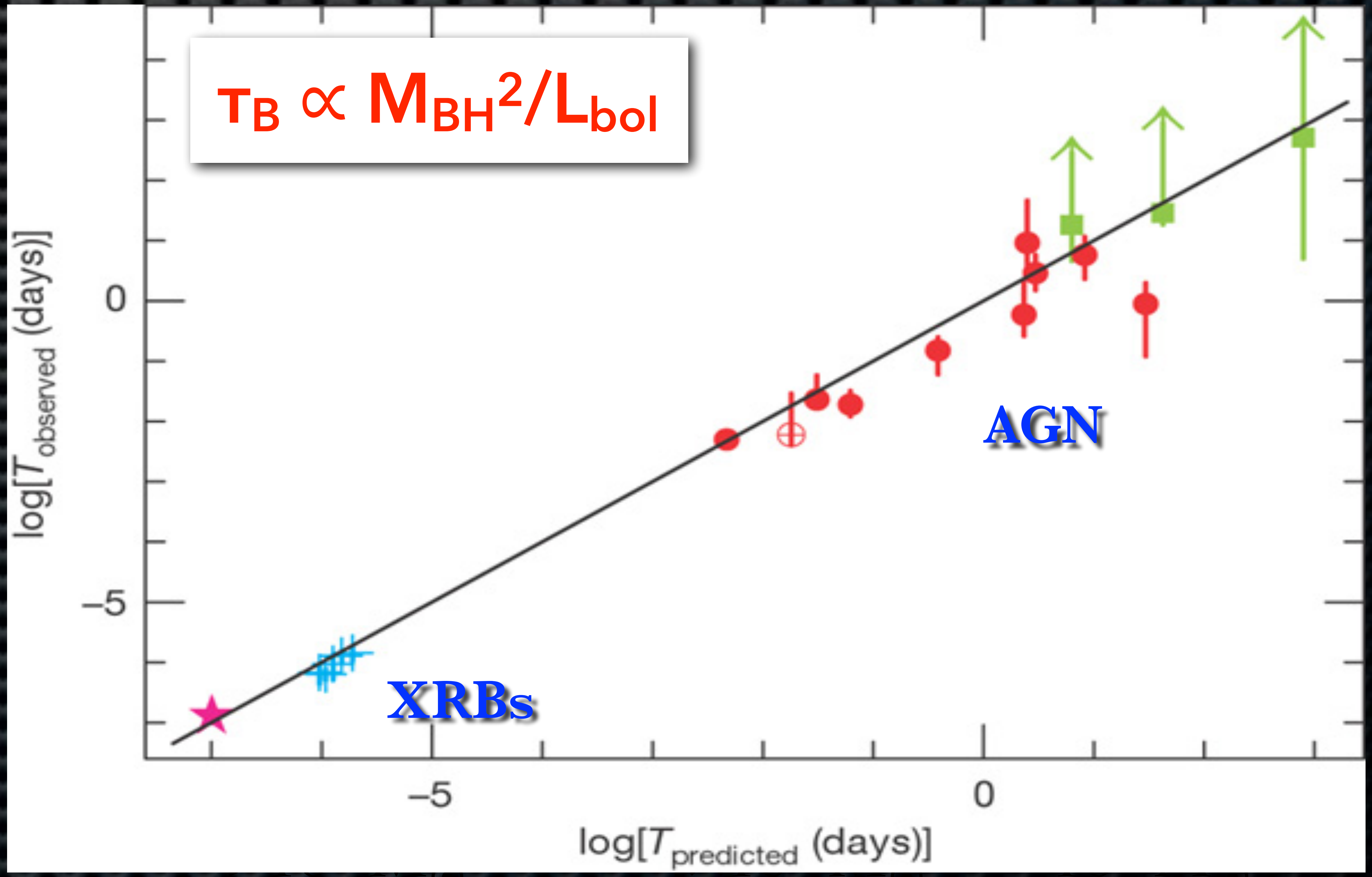

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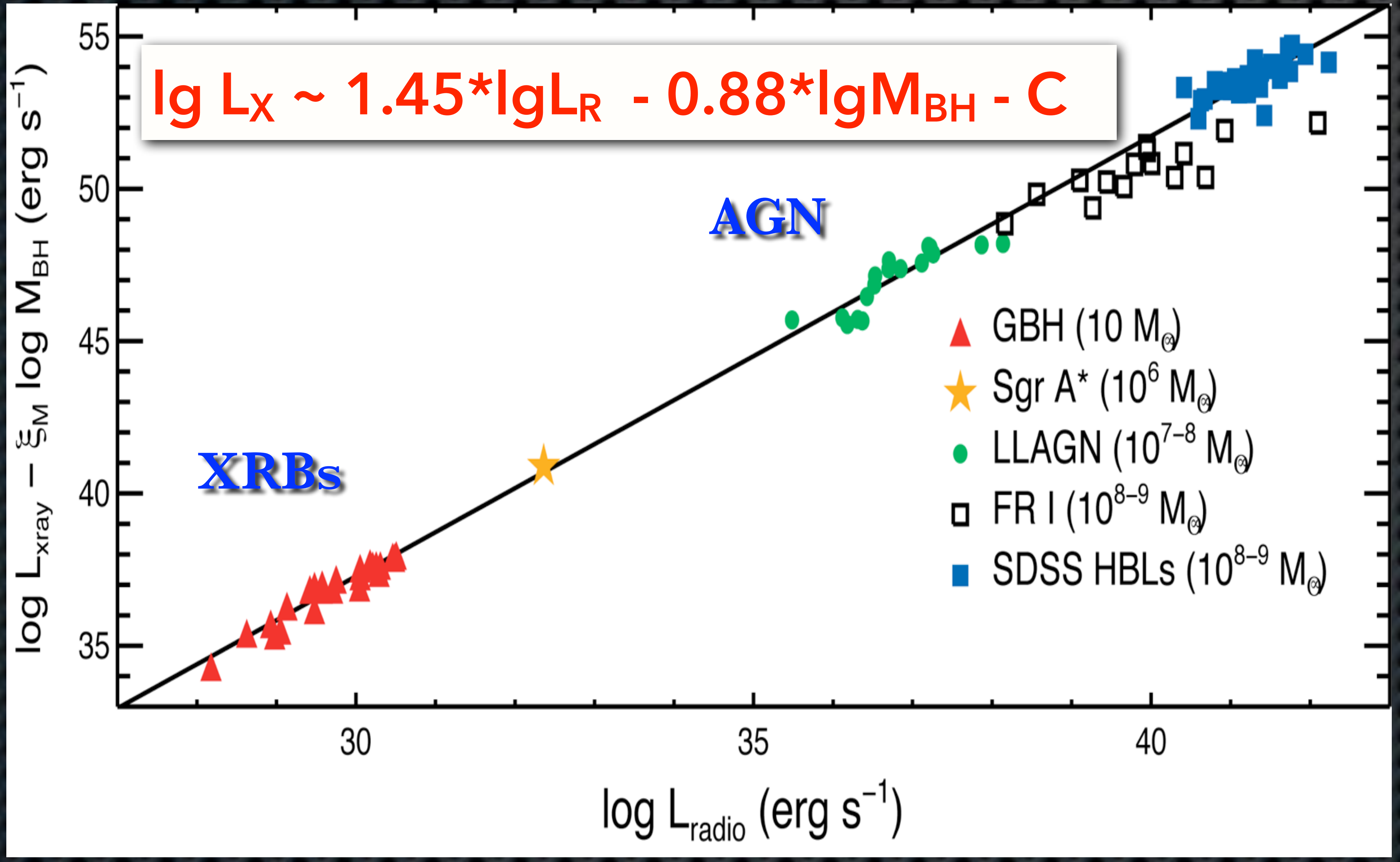
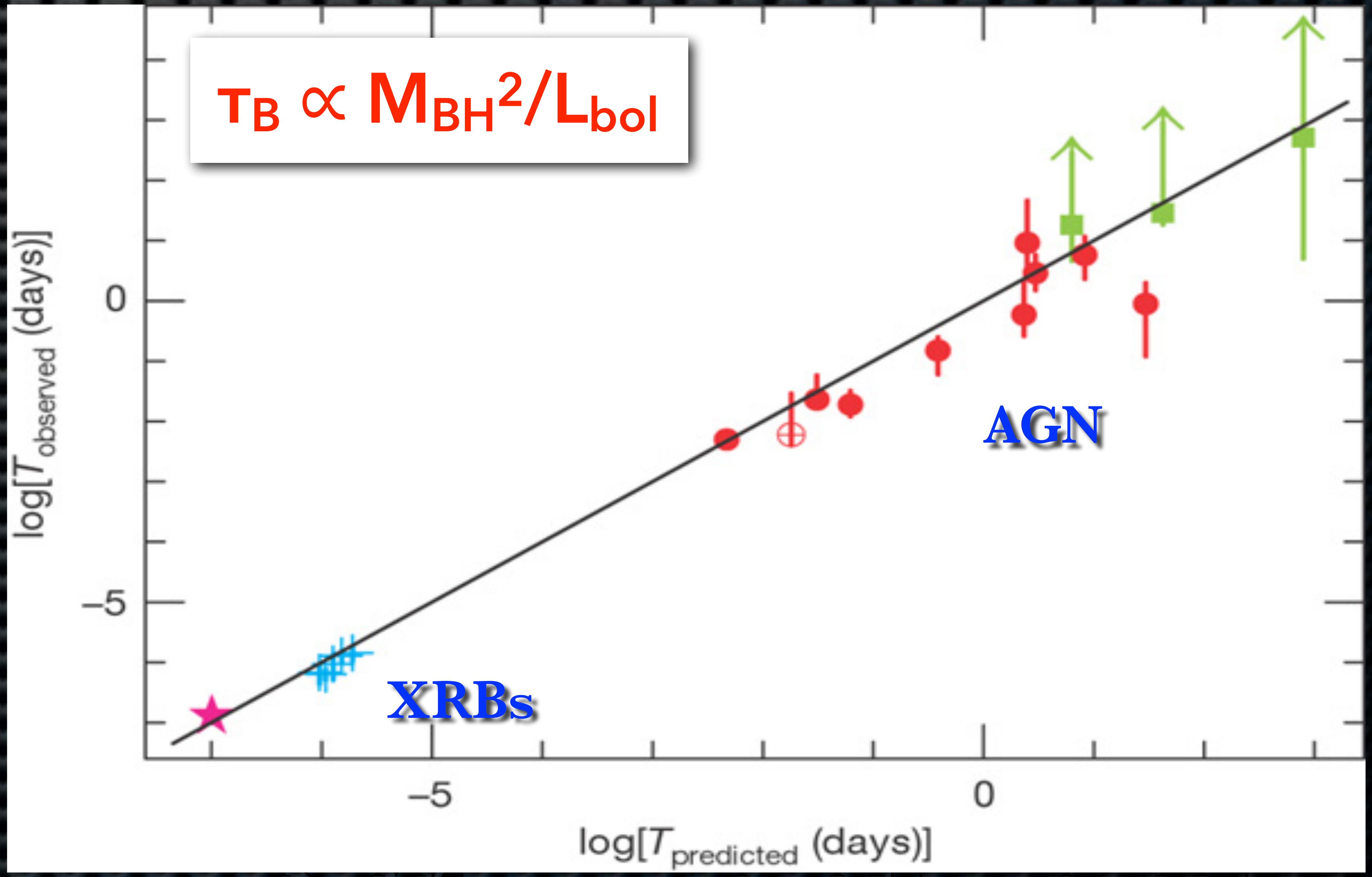
  - Reflection "reverberation" mapping (e.g., Fabian++, Dauser++13, van Eijnatten, Connors, Garcia, SM++ in prep.)





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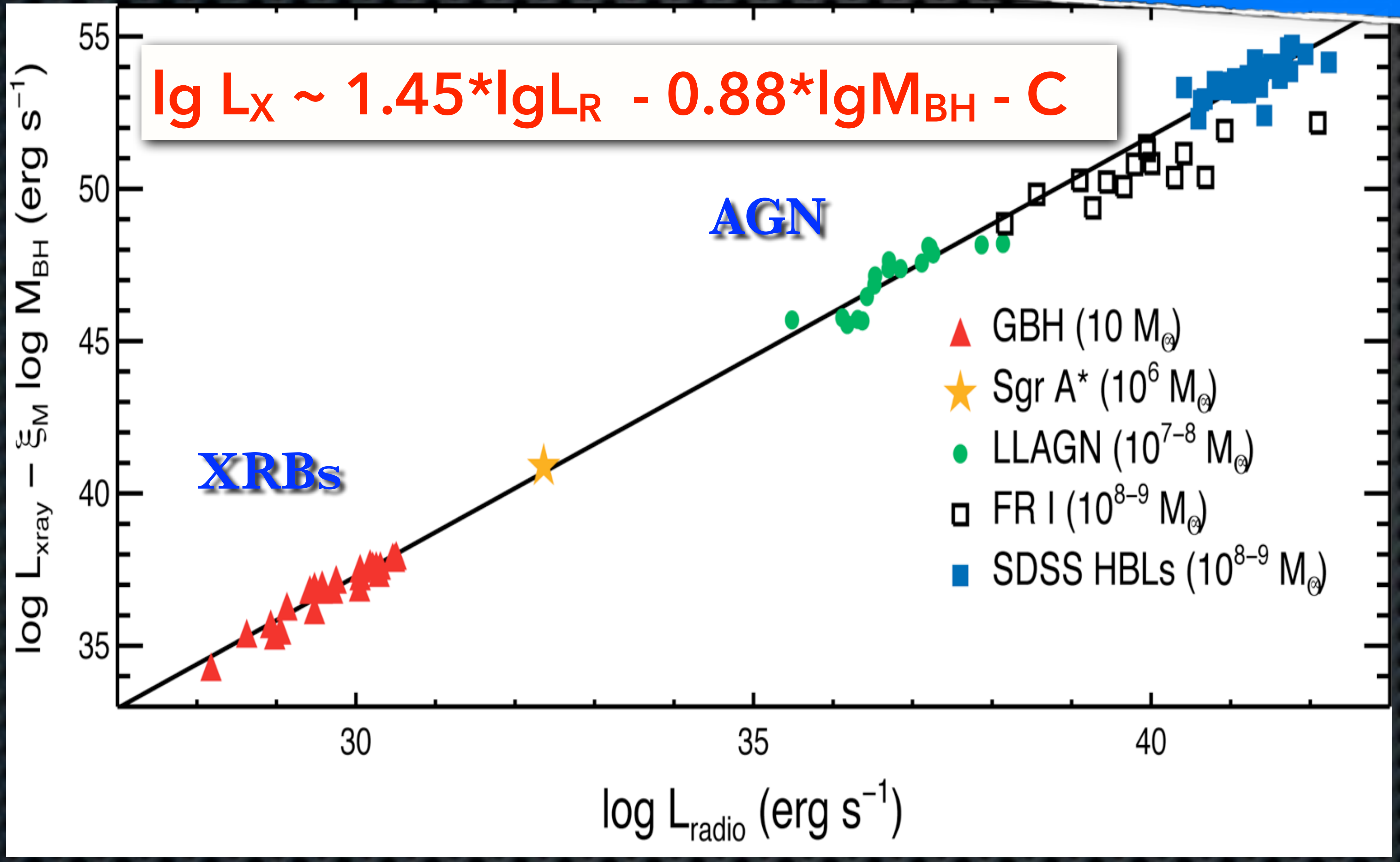
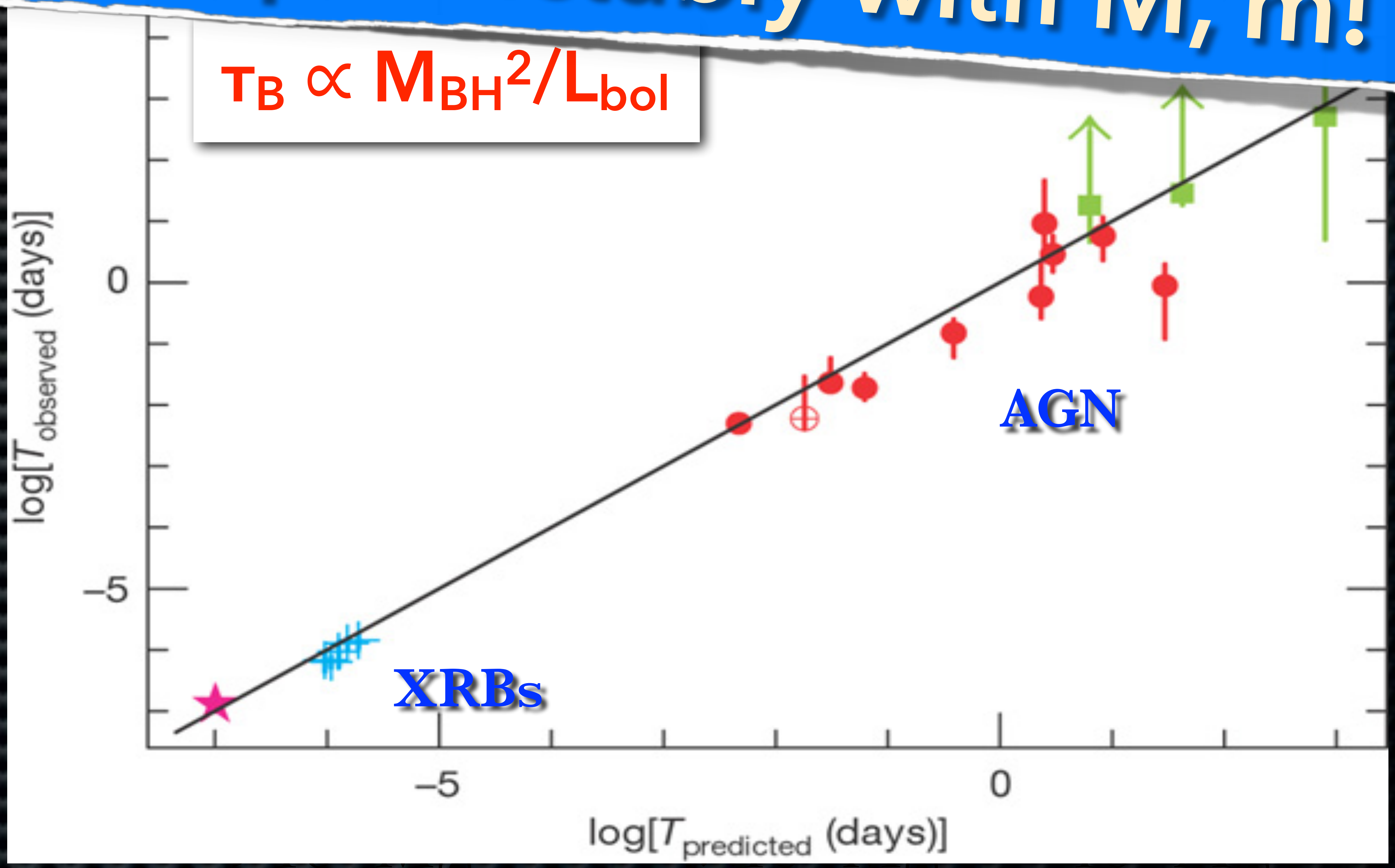
  - — ... ping (e.g., Fabian++, Dauser++13, van Eijnatten, Connors, García, SM++ ...

Bulk properties of AGN/XRBs scale predictably with M, ṁ!



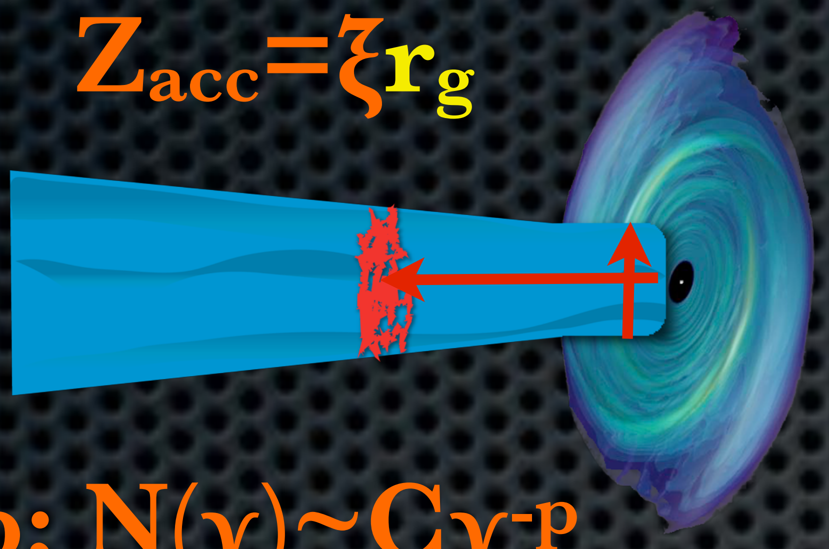


Jet breaks

Mass/power scaling models (synchrotron example)

$(R_d, R_0) = (\zeta_d, \zeta_0) r_g$

$Z_{acc} = \xi r_g$



$Q_j = \eta \dot{M} c^2 = \eta \dot{m} M c^2$

$U_B/U_e = k$

p; $N(\gamma) \sim C\gamma^{-p}$

- You can also do similar analysis for direct feeding from various known accretion flow
- This assumption is equivalent also to coronae (if radiatively inefficient)

- $C \propto B^2$ (fixed partition of energy), in disk launching $P, \rho \propto Q_j/(R^2 c) \propto \dot{M}/M^2 \propto \dot{m}/M$, $B^2 \sim P, \rho \propto \dot{m}/M$
- Synchrotron self absorption:

$$\alpha_\nu \propto C B^{(p+2)/2} \nu^{-(p+4)/2}$$

$$j_\nu \propto C B^{(p+1)/2} \nu^{-(p-1)/2}$$

$$\tau = R_j \alpha_\nu \qquad R_j \propto M \qquad S_\nu \propto \xi(\theta) j_\nu (1 - e^{-\tau_\nu})/\alpha_\nu$$

- Consider (self-absorbed) flux from contributing τ=1 surfaces at some ν:

$$F_\nu = \int_{r_g}^{\infty} dr R_r S_\nu(r) = F_\nu(M, \dot{m}, a, \nu, \theta)$$

- Derive expected scalings i.e.,

$$\nu_{SSA} \propto \left(M \phi_c \phi_B^{(p+2)/2}\right)^{2/(p+4)}$$

$$\frac{\partial \ln F_\nu}{\partial \ln \dot{m}} \equiv \xi_{\dot{m}} = \frac{2p + (p+6)\alpha_{RIR} + 13}{2(p+4)} \sim \frac{17}{12} + \frac{2}{3}\alpha_{RIR}$$

$$\sim \dot{m}^{2/3} M^{-1} = \dot{M}^{2/3} M^{-1}$$

(Falcke & Biermann 1995; SM++ 2003; Merloni, Heinz & diMatteo 2003; Falcke, Körding, SM 2004; Heinz & Sunyaev 2003)