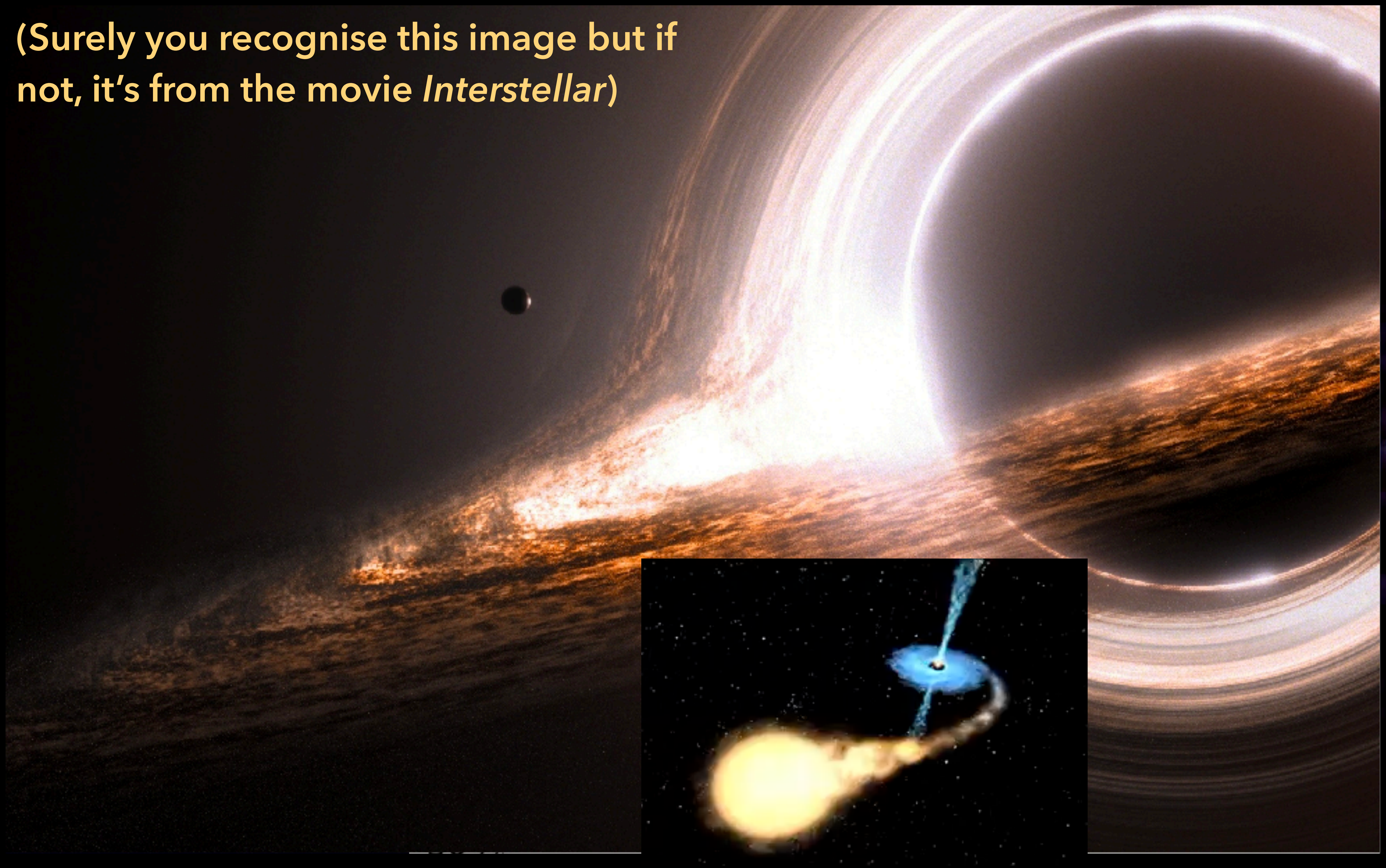
Tomorrow: How 2 Apply 4 Stuff*

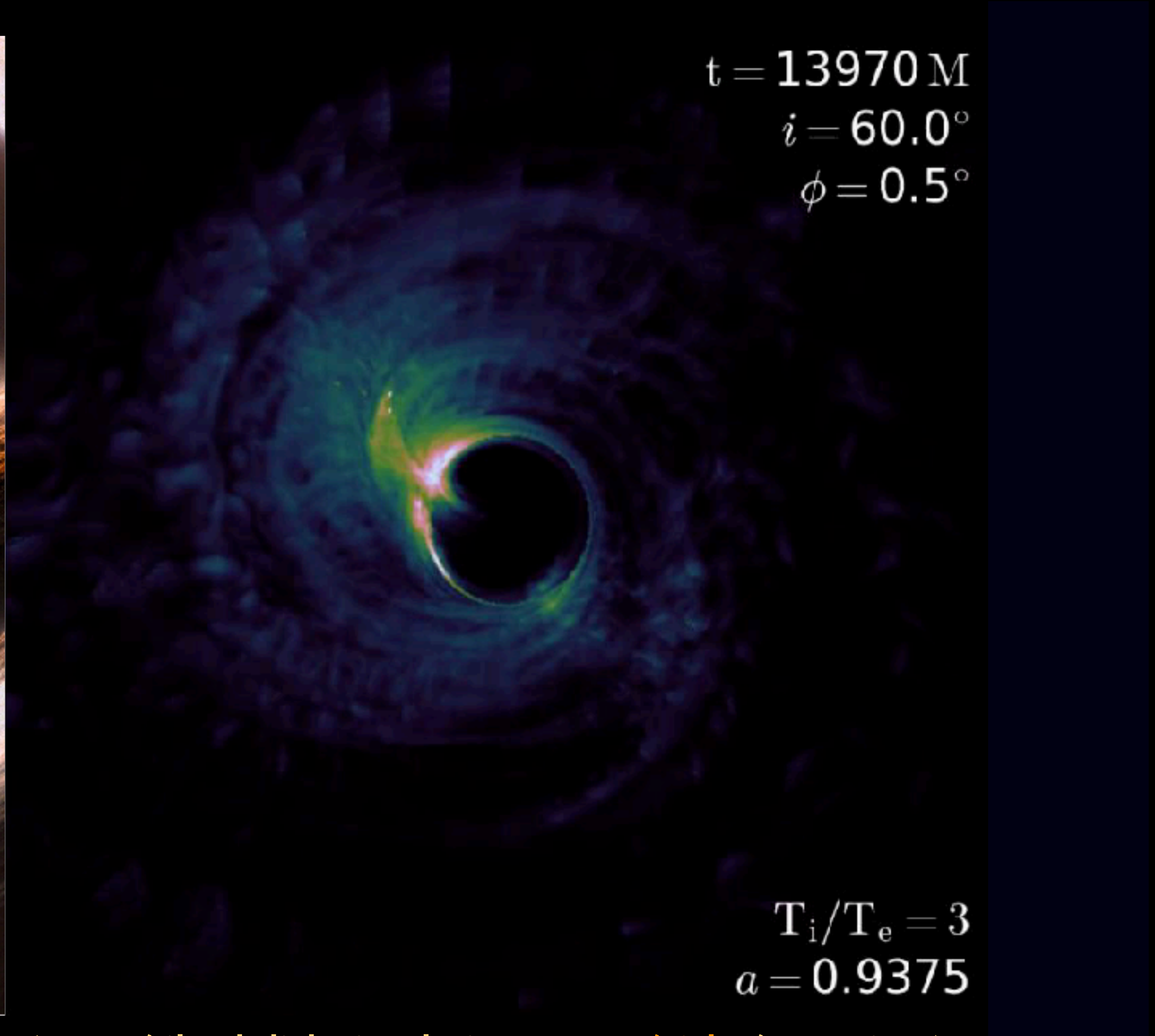
(Strategic thinking and tips for academic job applications and career planning)

Please look at the (soon to be?) posted slides and email or tell me the topics you are most keen to discuss!   s.b.markoff@uva.nl

Three hour primer on black holes of all sizes



(Surely you recognise this image but if not, it's from the movie *Interstellar*)



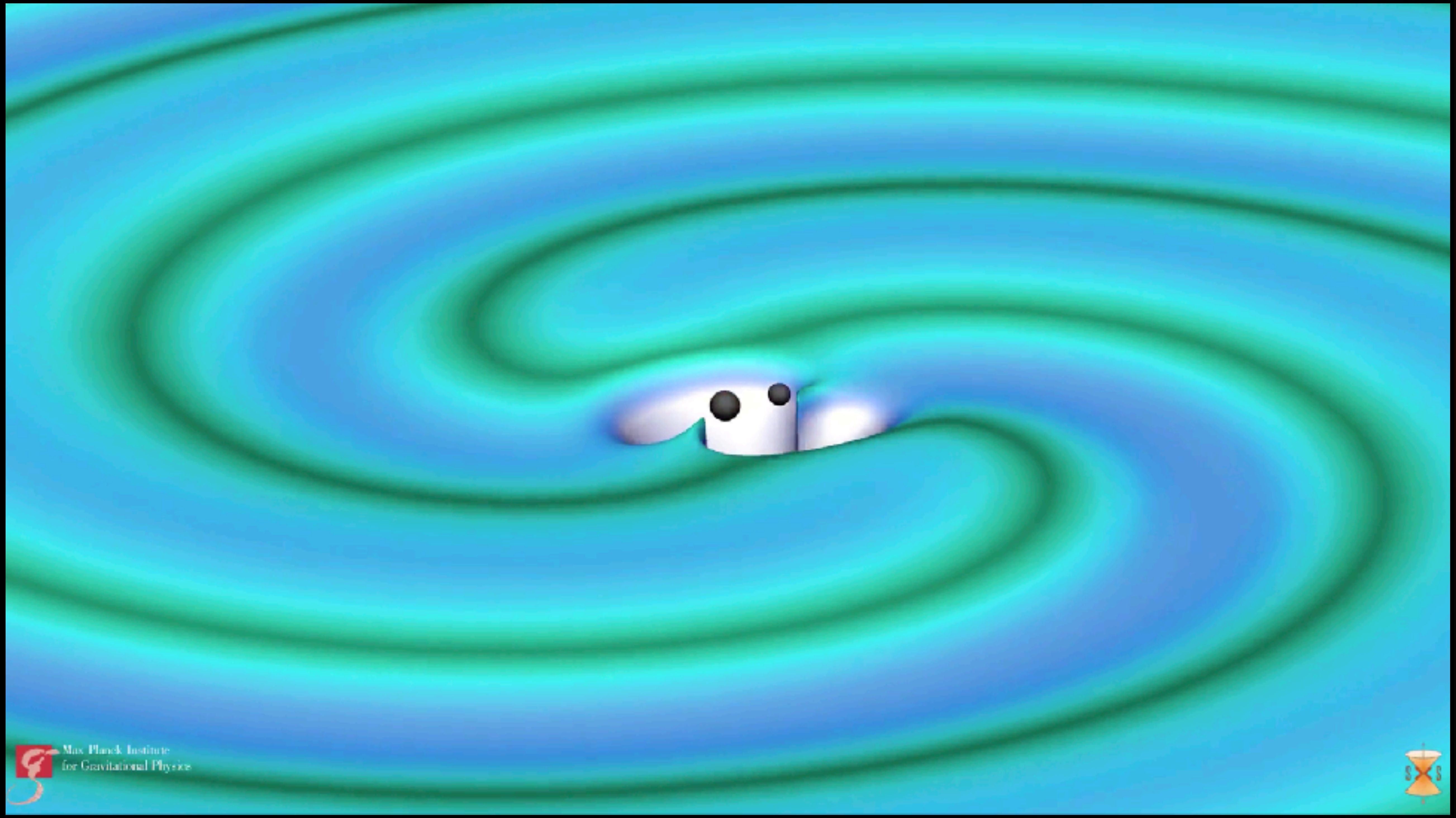
(BH w/tilted disk simulation; Hesp/Liska/Younsi++)

Sera Markoff (API/GRAPPA, University of Amsterdam)

C.Ceccobello, A.Chhotray, A.Cooper, K.Chatterjee, R.Connors, P.Crumley, J.Dexter, S.Dibi, S. Drappeau, D.v.Eijnatten, C.Fragile, F.Krauss, M.Lucchini, D.Russell, T.Russell, C.Hesp, M.Liska, P.Gandhi, D.Meier, P.Polko, A.Tchekhovskoy, D.Yoon, Z.Younsi + EHT collaboration]

The new revolution in (astro)physics: "seeing" black holes

2015: discovery of gravitational waves from merging black holes (*2017 Physics Nobel Prize*)



LIGO/VIRGO collaboration

4/2019: first image of a supermassive black hole in the heart of a galaxy

Event Horizon Telescope Collaboration

New multimessenger "laboratories" for understanding extreme matter and particle processes in strongly curved spacetime

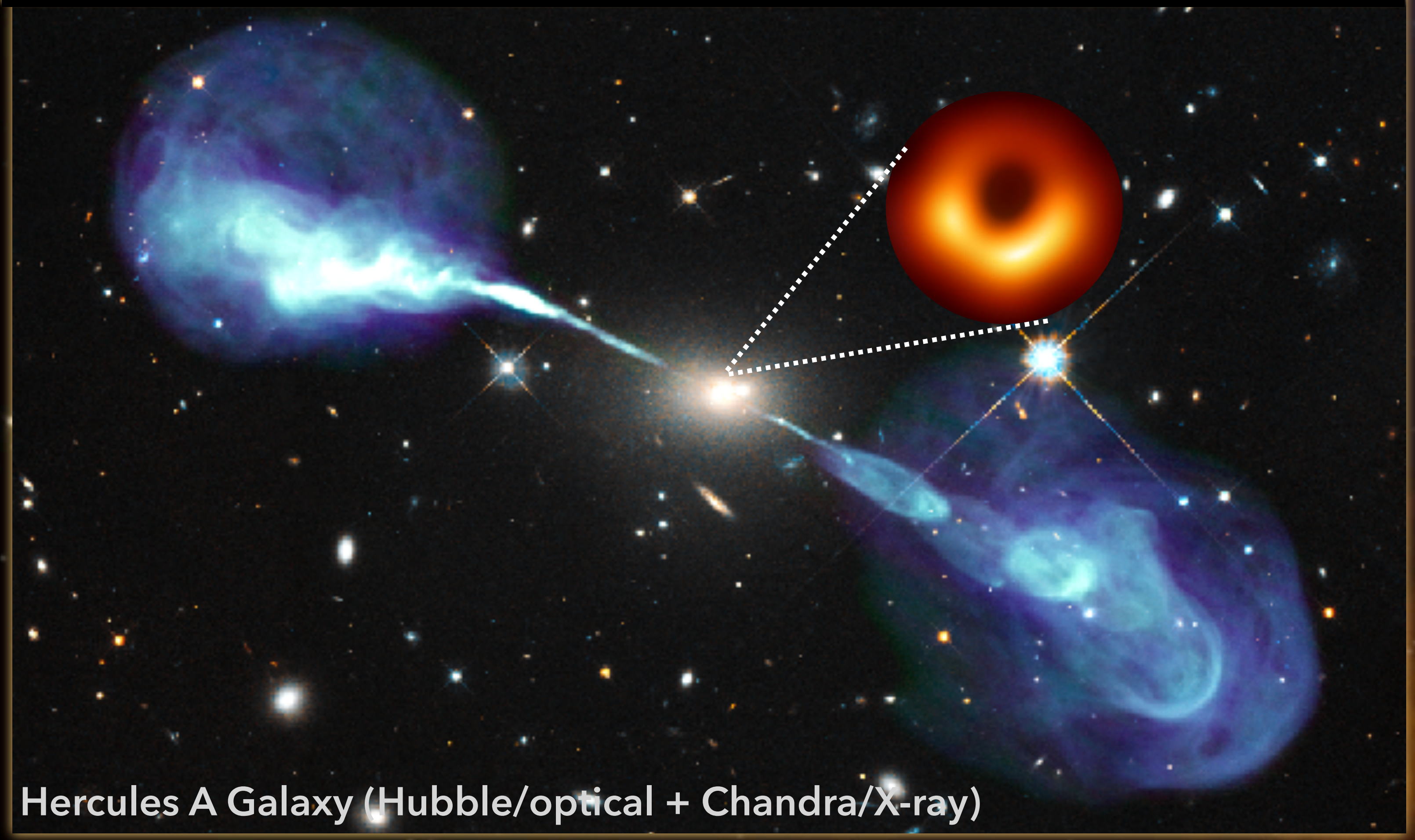
2017: first merging pair of neutron stars

LIGO/VIRGO collaboration

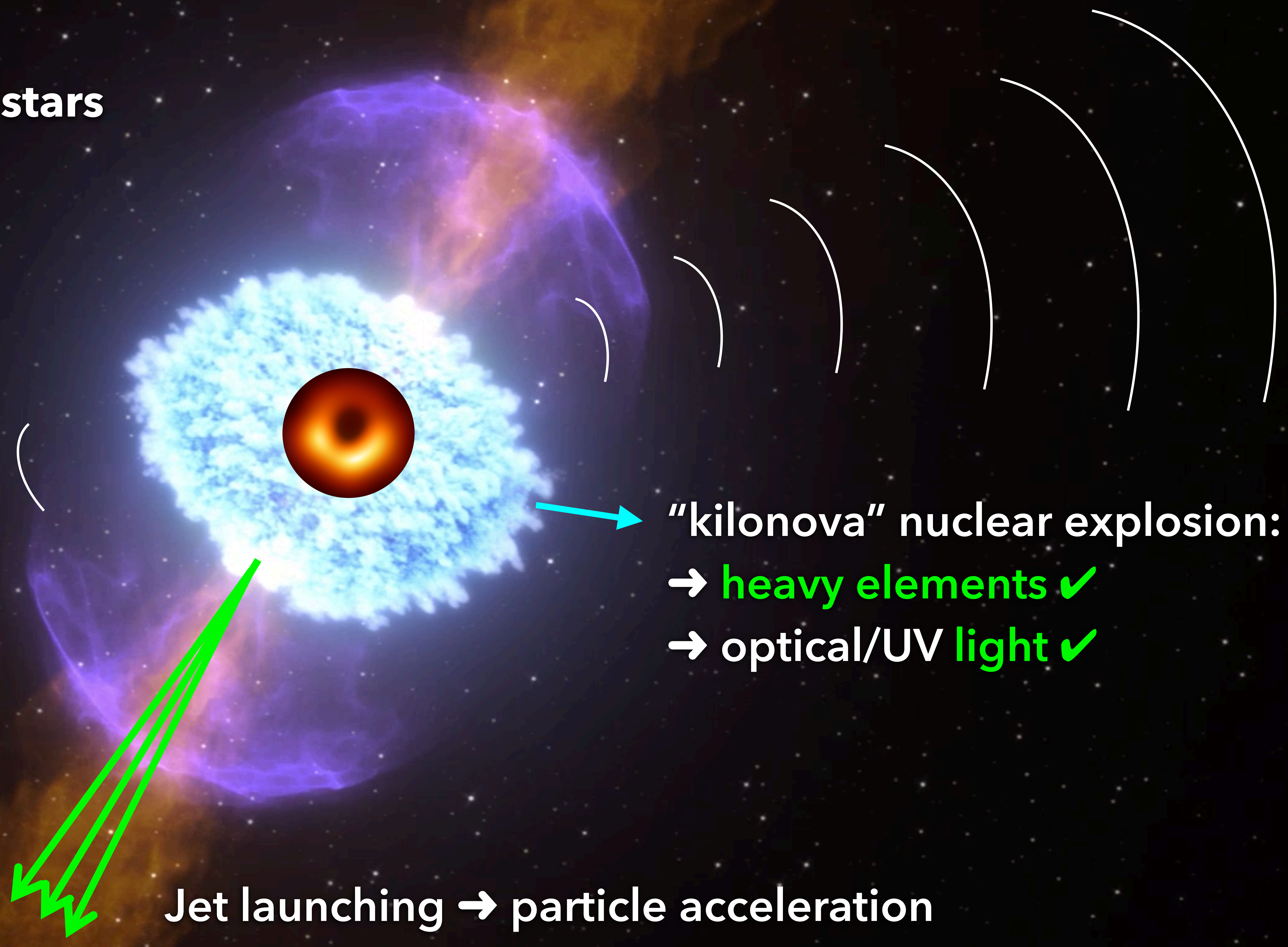
New multimessenger "laboratories" for understanding extreme matter and particle processes in strongly curved spacetime

2017: first merging pair of neutron stars
➜ Gravitational waves ✔

2018: first neutrino (✔) detected from supermassive black hole jets



Hercules A Galaxy (Hubble/optical + Chandra/X-ray)



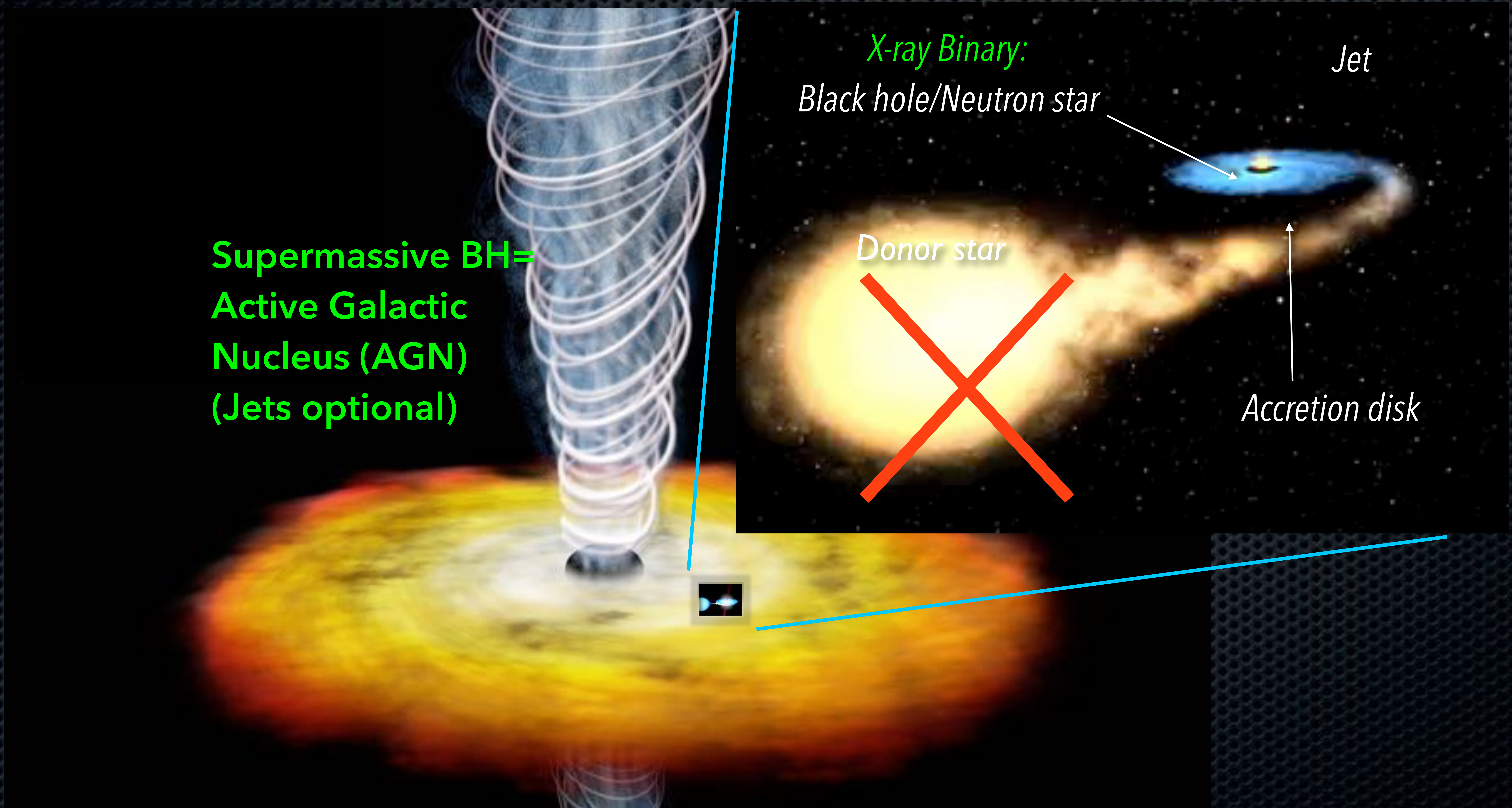
"kilonova" nuclear explosion:
➜ heavy elements ✔
➜ optical/UV light ✔

Jet launching ➜ particle acceleration
➜ cosmic rays ➜ neutrinos, gamma-rays + radio to X-ray light
? ? ✔ ✔

LIGO/VIRGO collaboration


Chance to move from 'reactive' to 'predictive' models
Number Events
1000
100
10
1
1/wk
2/wk
1/day
1/hour!!
Black Hole Mergers
Neutron Stars Mergers
New era
1 April
1 May
Surprises?
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
LIGO/Virgo
KAGRA
LIGO-India Einstein Telescope Construction
Grav. waves
AUGER
AUGER PRIME
Cosmic rays
ICECUBE
KM3NeT construction
ICECUBE + KM3NeT
Neutrinos
H.E.S.S. + Magic + Veritas
CTA construction
CTA
Gamma-rays

Start with static/symmetric spacetime:
Supermassive BHs in galaxies, and stellar BHs in X-ray binaries



Outline

- ★ Role of black holes in the universe and major questions
- ★ Influence of spacetime geometry on accretion
- ★ Event Horizon Telescope: context, results, upcoming
- ★ Black holes across the mass scale: XRBs as ‘mini’ AGN?
- ★ Cutting edge (if time…)

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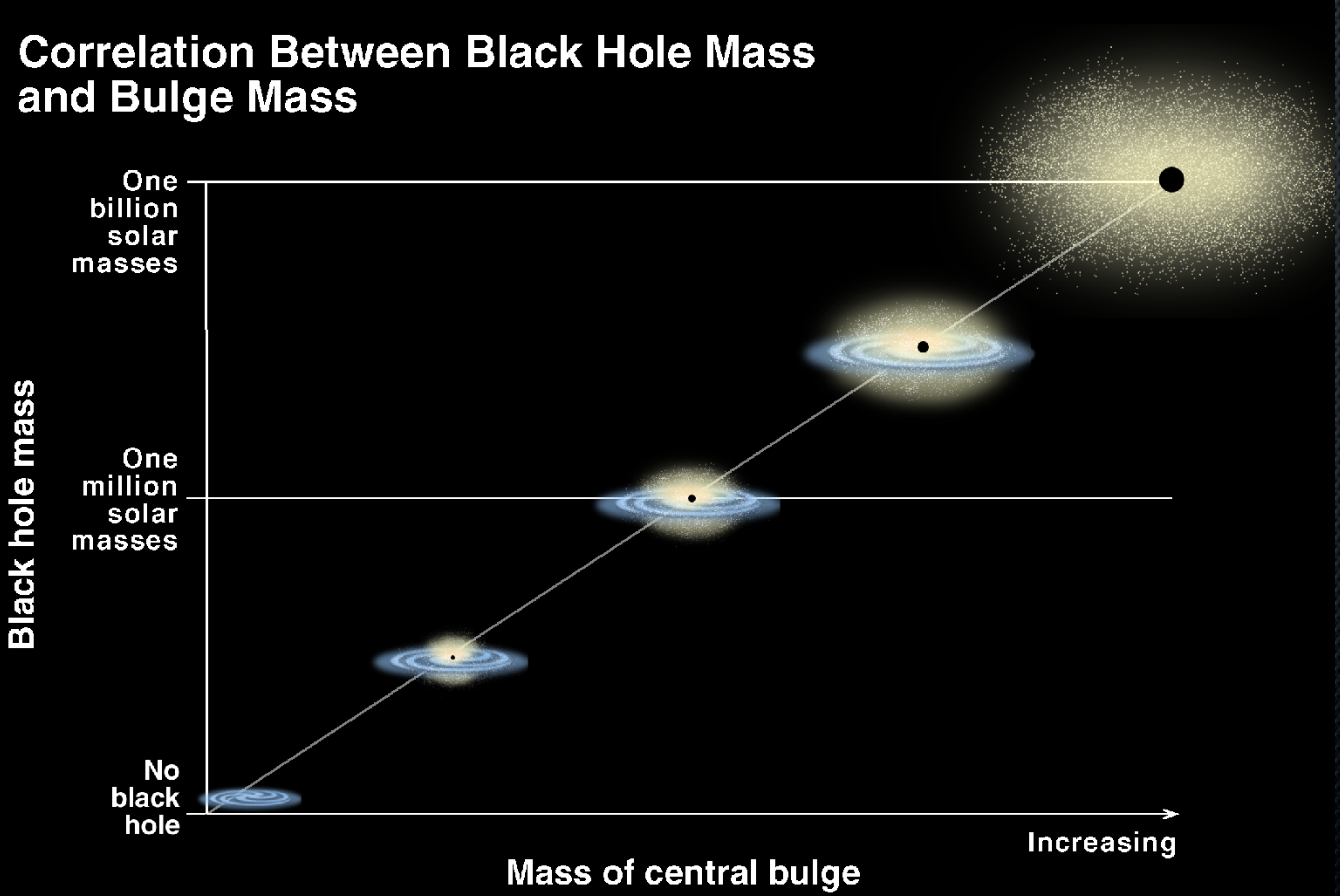
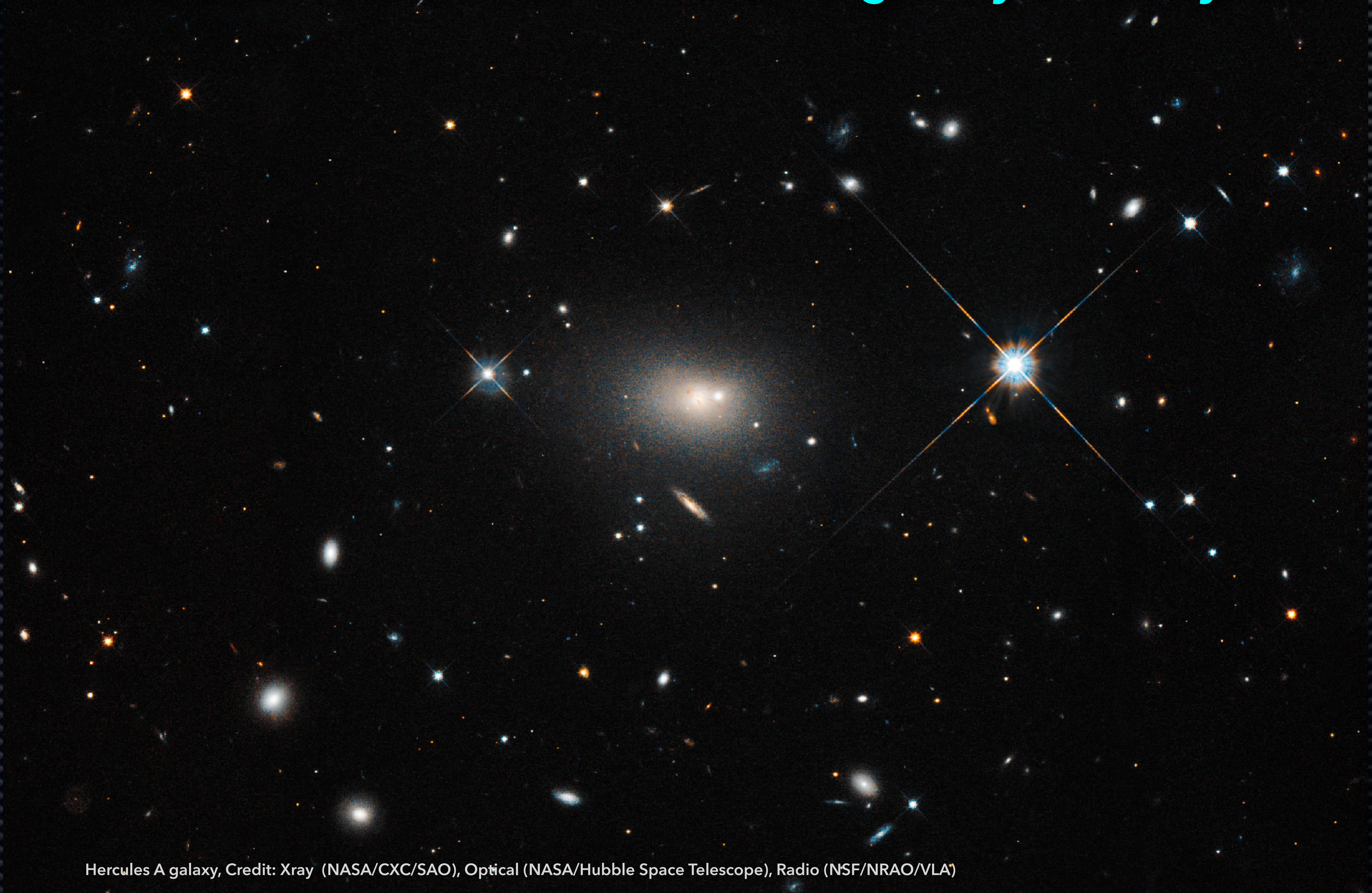
Correlation Between Black Hole Mass and Bulge Mass



Credit: K. Cordes & S. Brown (STScI)

Even a huge black hole is tiny compared to its host galaxy

How does a black hole “talk” to its galaxy and beyond?



Hercules A galaxy, Credit: Xray (NASA/CXC/SAO), Optical (NASA/Hubble Space Telescope), Radio (NSF/NRAO/VLA)

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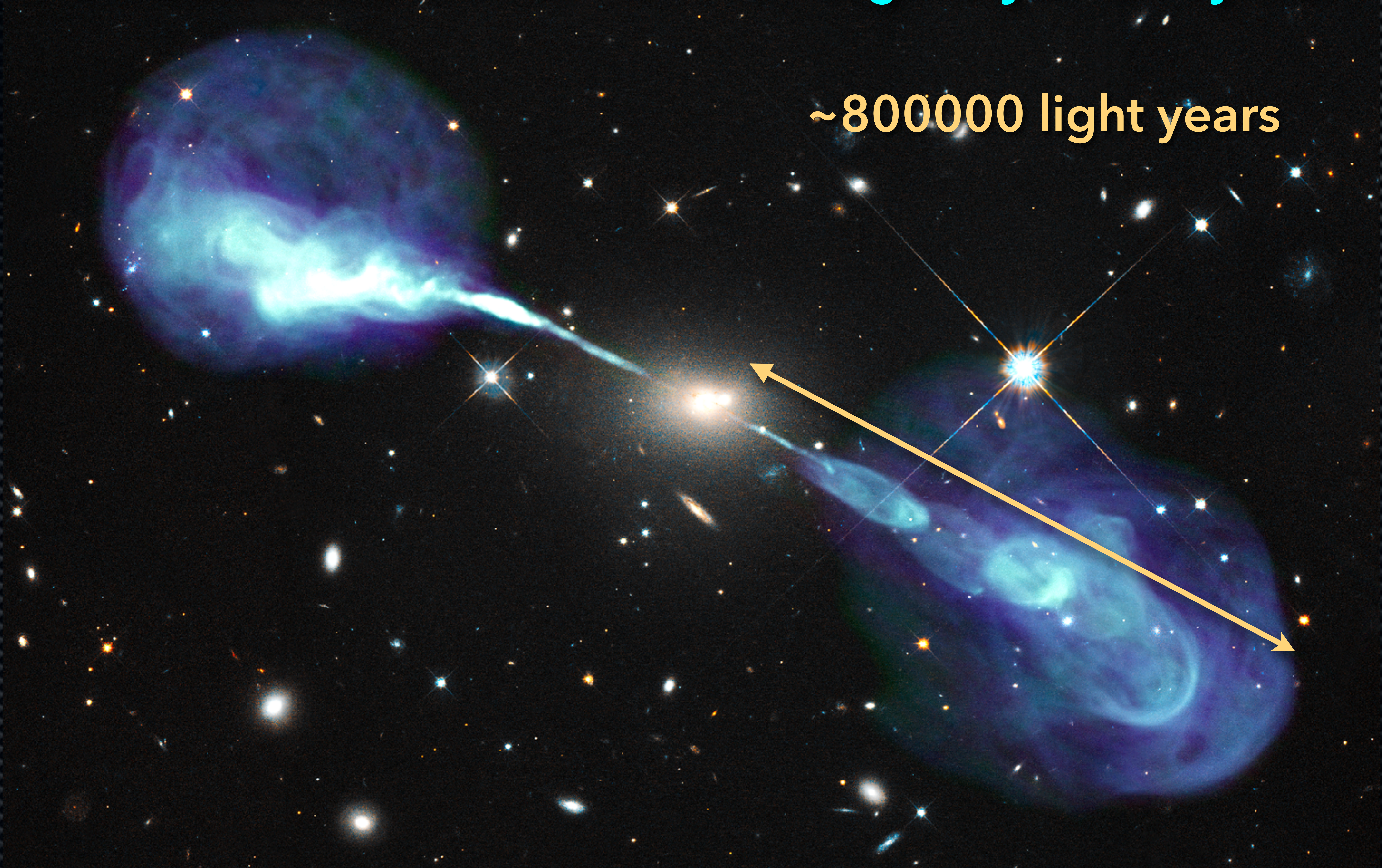

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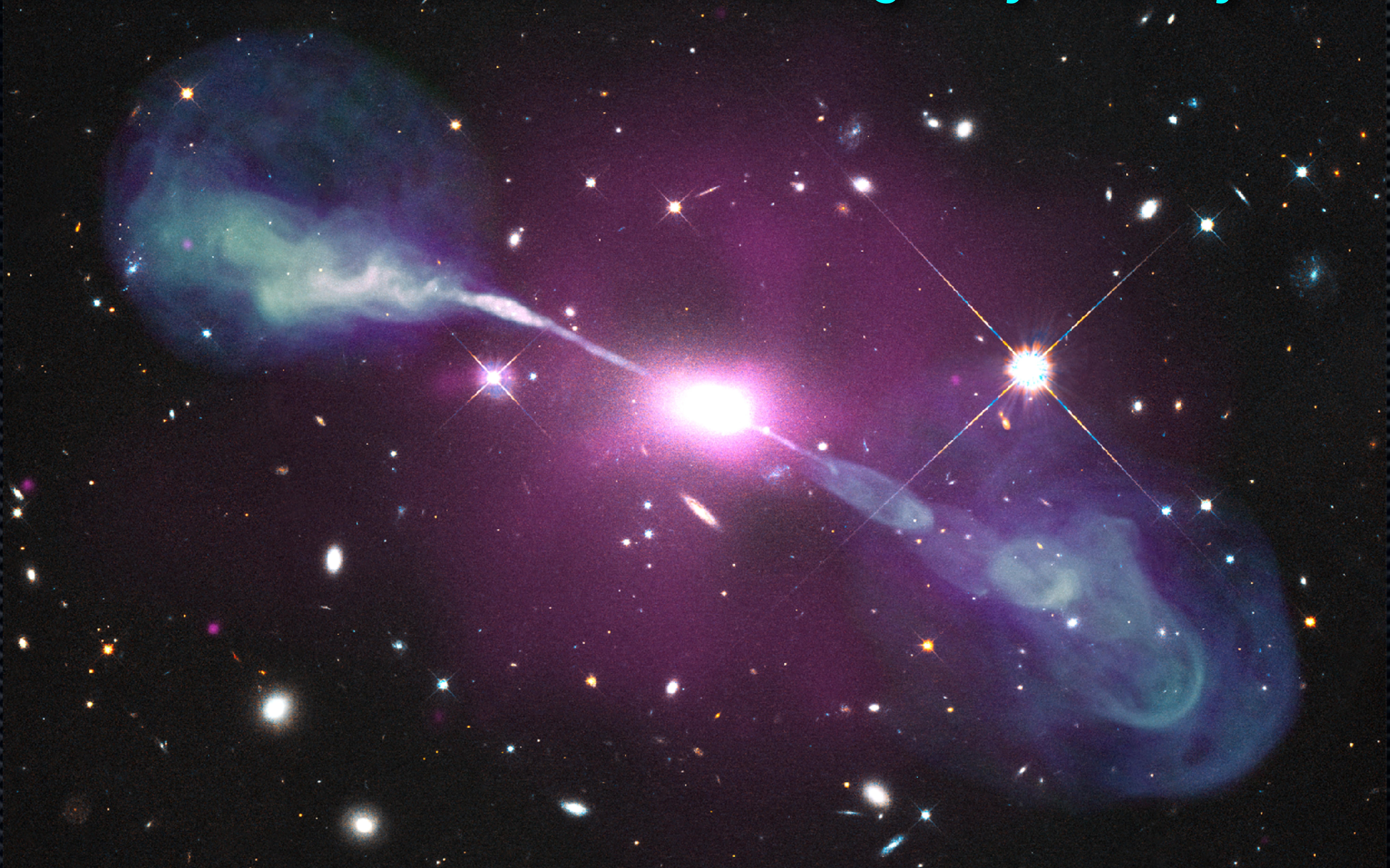
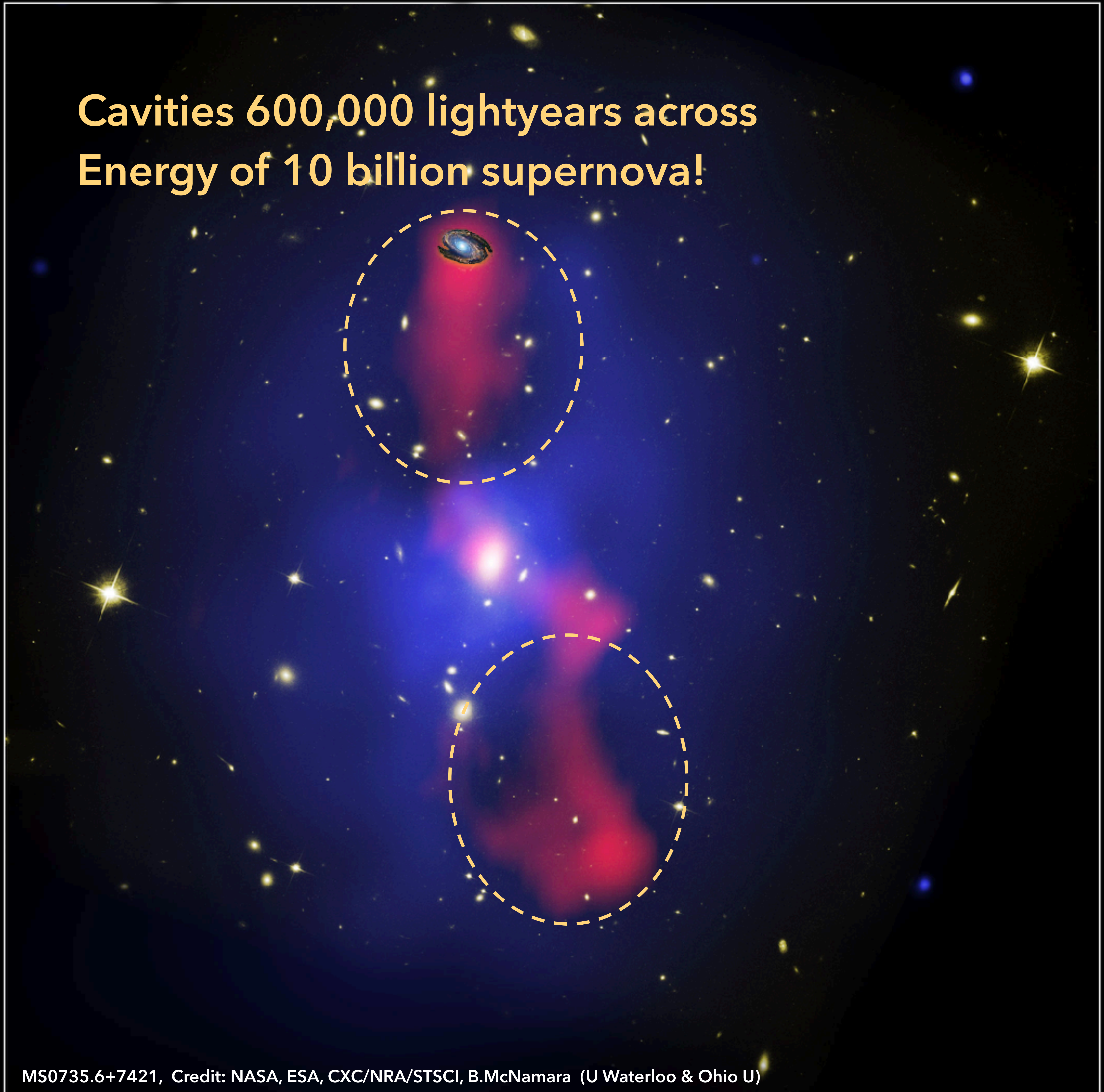
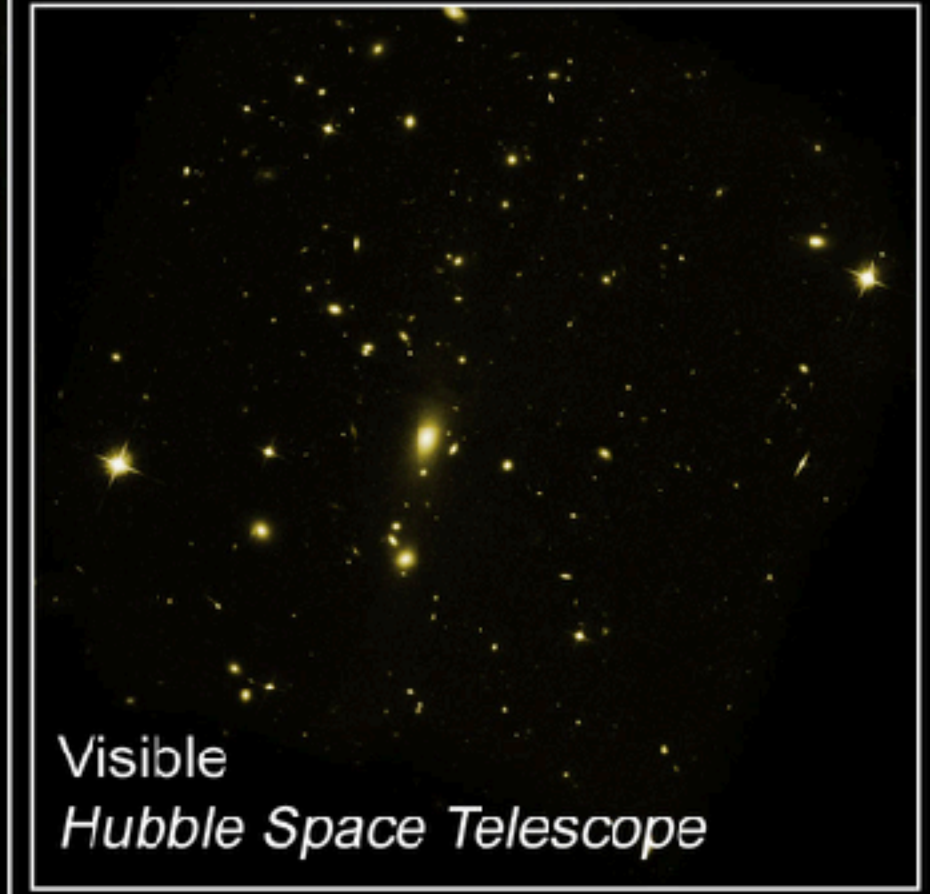
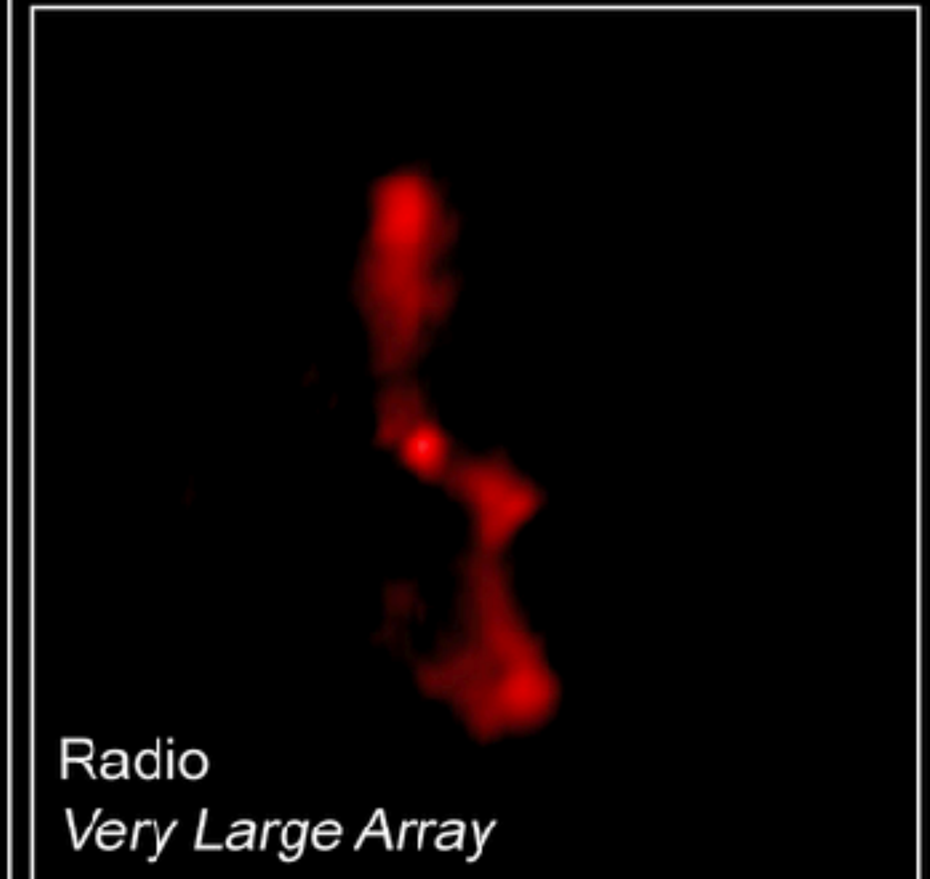


Hercules A galaxy, Credit: Xray (NASA/CXC/SAO), Optical (NASA/Hubble Space Telescope), Radio (NSF/NRAO/VLA)

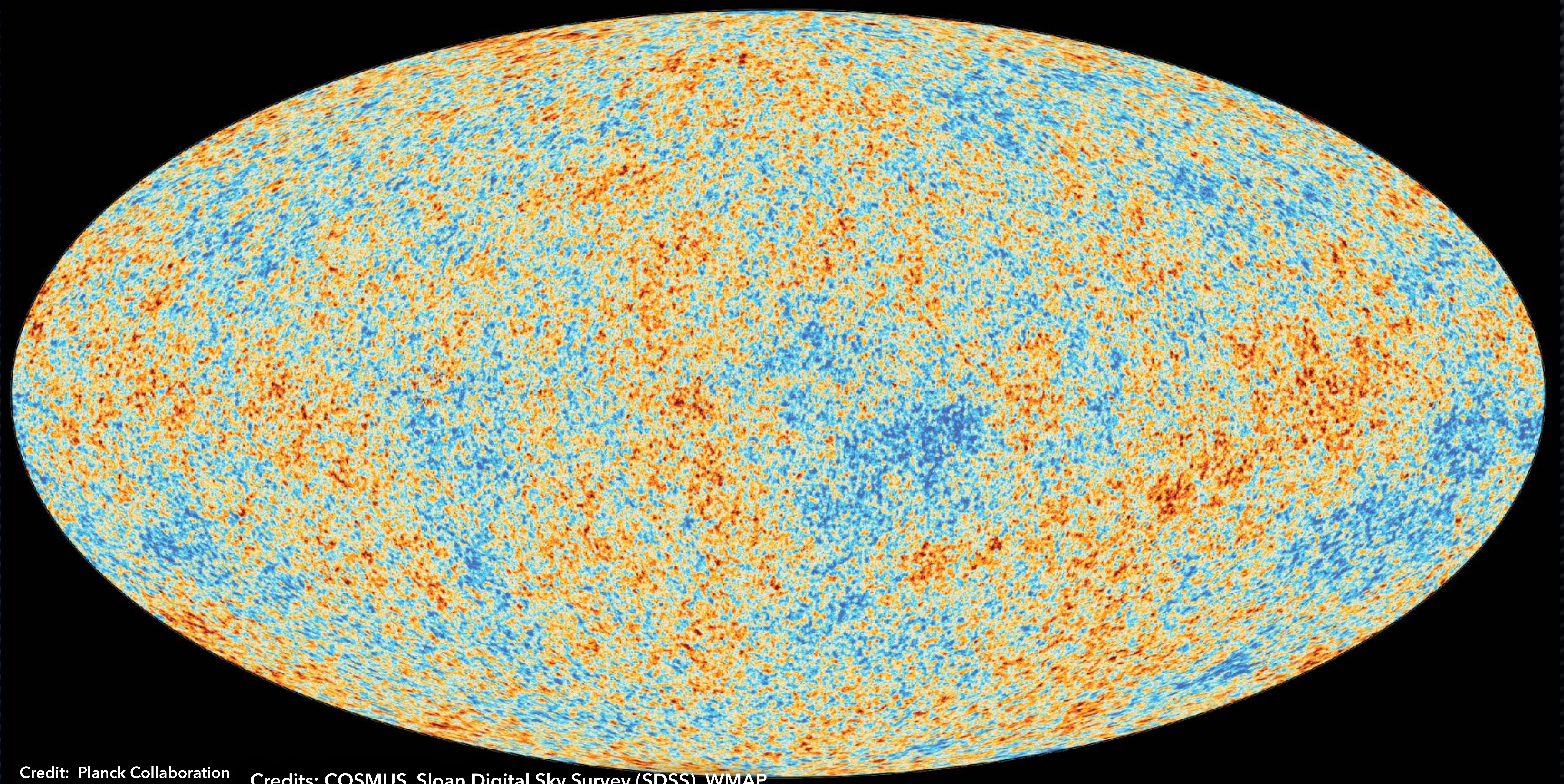
Black holes profoundly impact their environments via outflows!







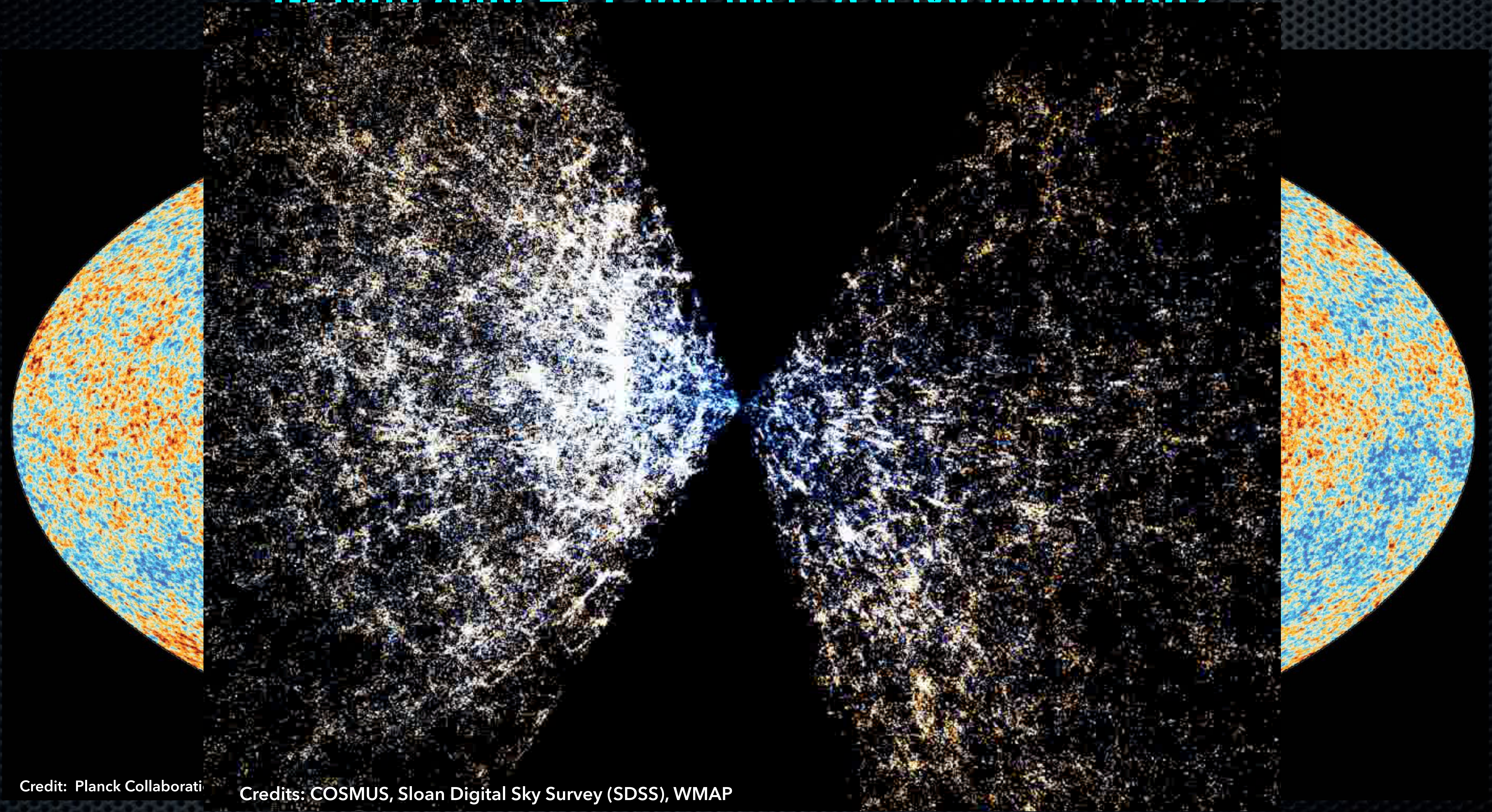
Gravity only = "Capitalist" galaxy formation?



Credit: Planck Collaboration

Credits: COSMUS, Sloan Digital Sky Survey (SDSS), WMAP

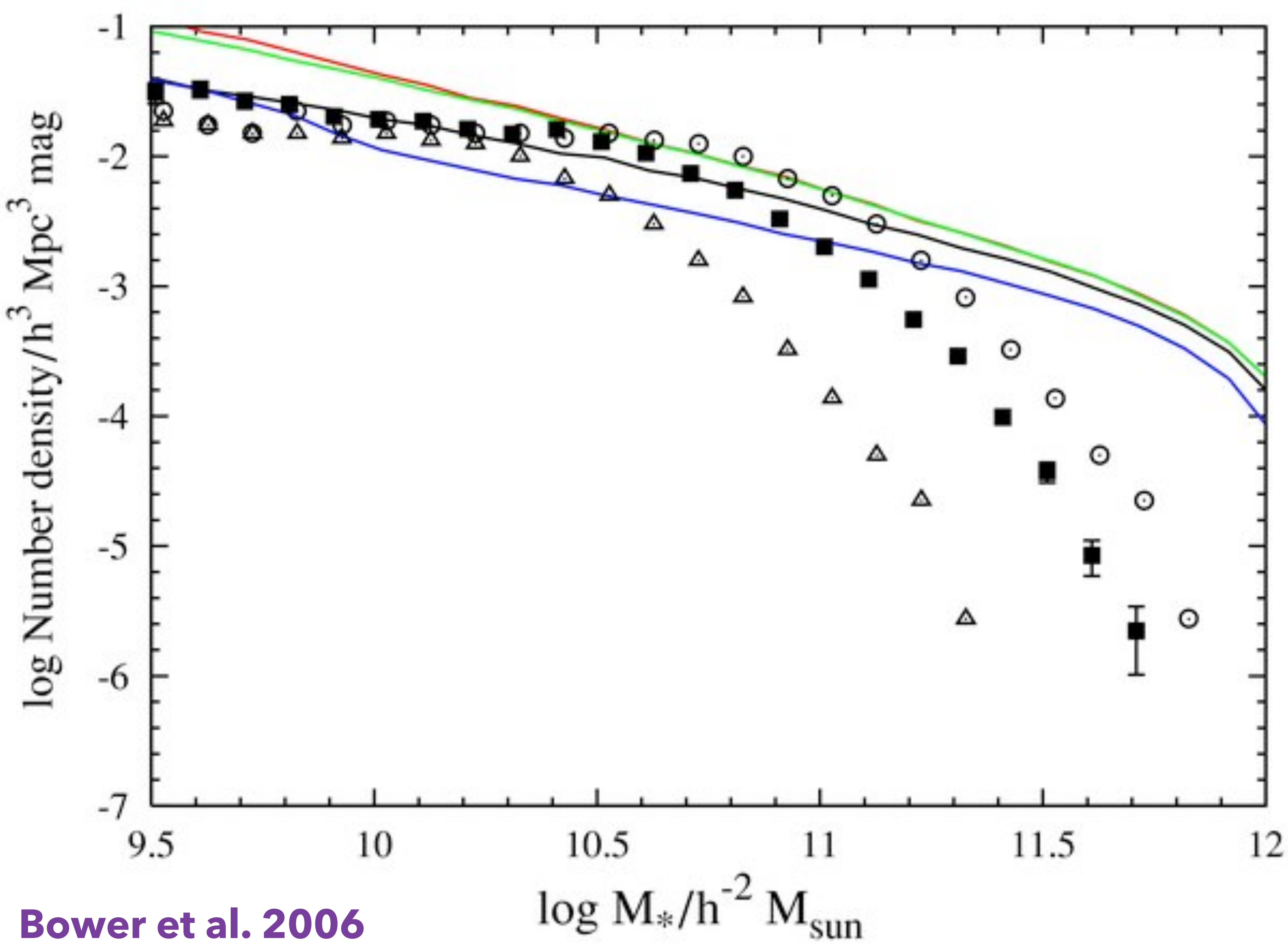
Gravity only — "Capitalist" galaxy formation?



Credit: Planck Collaborati

Credits: COSMUS, Sloan Digital Sky Survey (SDSS), WMAP

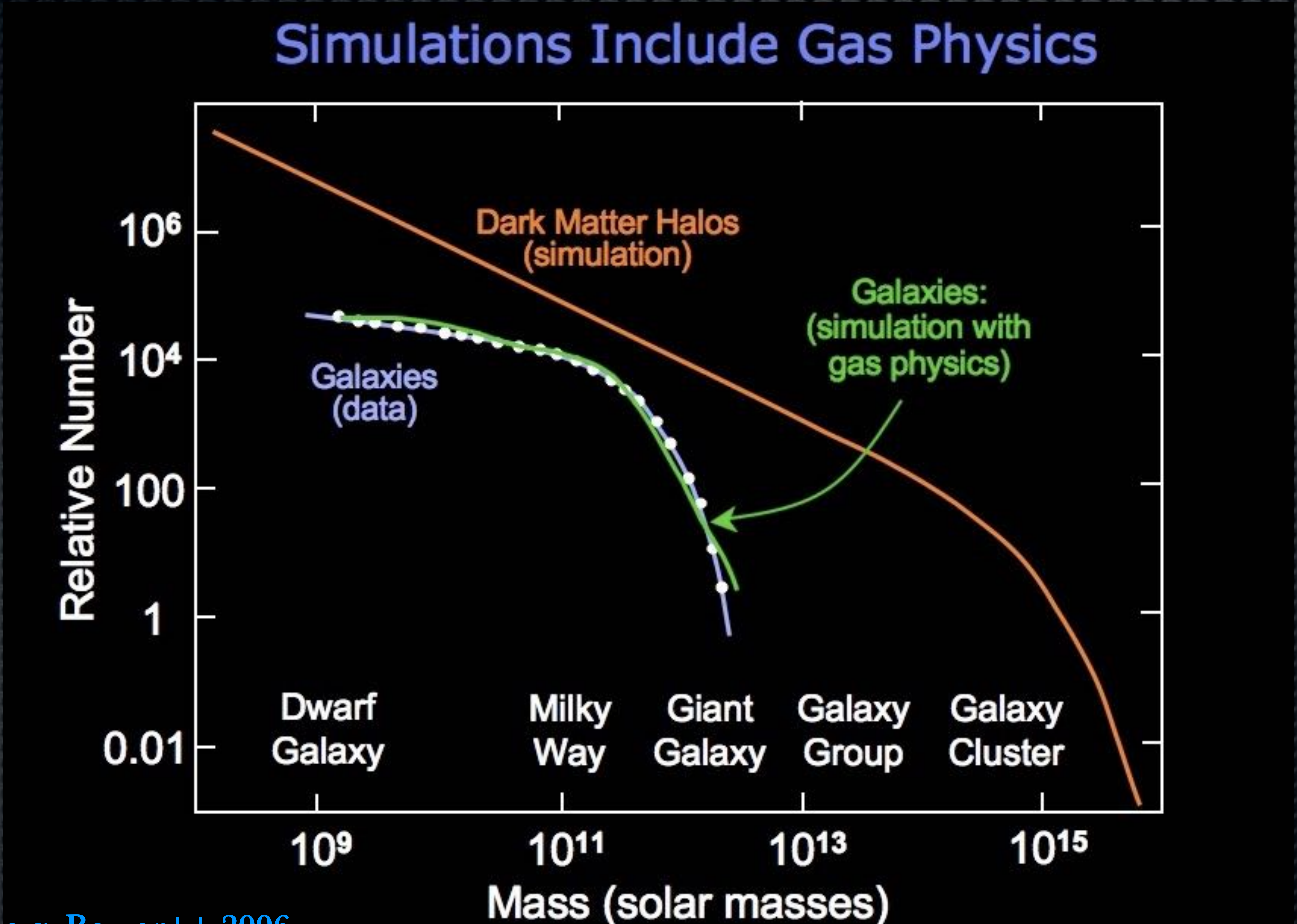
Simulations predicted too many massive galaxies



Bower et al. 2006

Black holes "redistribute the wealth", suppressing the largest galaxies

BH feedback "fixes" over-predictions of massive galaxies



e.g. Bower++ 2006

What proxy is used for black holes??

- Usual assume $\dot{M}_{\text{Bondi-Hoyle}}$ (Bondi & Hoyle 1944), originally for gas cloud moving past a star

$$\frac{mv^2}{2} = \frac{GM_{\rm bh}m}{r} \Longrightarrow r_a = \frac{2GM_{\rm bh}}{v^2}$$

$$\dot{M}_{\rm BondiHoyle} = \pi r_a^2 \rho v = \frac{4\pi G^2 M_{\rm bh}^2 \rho}{v^3}$$

- Gas streams past, gravity bends ➠ collisions cancel angular momentum ➠ quasi-spherical inflow, $r_a \sim 10^5\ r_g$

- Typical proxy: assume some fixed fraction (~$0.1\dot{M}_{\text{Bondi-Hoyle}}\, c^2$) fed back into simulation as heat/mechanical energy

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$$\frac{mv^2}{2} = \frac{GM_{\rm bh}m}{r} \Longrightarrow r \ldots 2GM\ldots$$

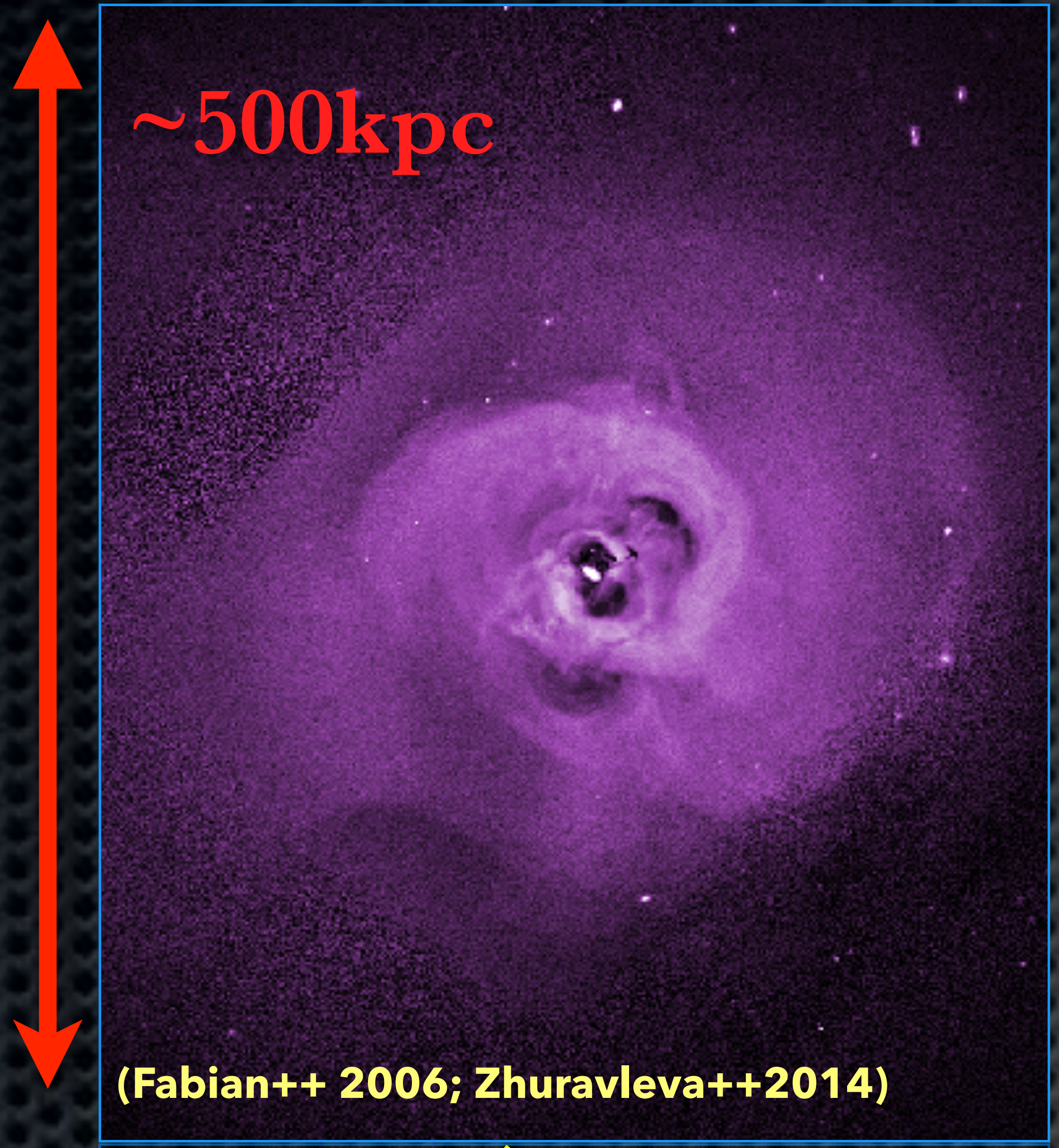
Problem is that this proxy is extremely simplistic, and may be skewing results particularly on smaller (galaxy cluster/group) scales

- …ds ➠ collisions cancel angular momentum … quasi-spherical inflow, $r_a \sim 10^5\ r_g$

- Typical proxy: assume some fixed fraction $(\sim 0.1\dot{M}_{\text{Bondi-Hoyle}}\, c^2)$ fed back into simulation as heat/mechanical energy

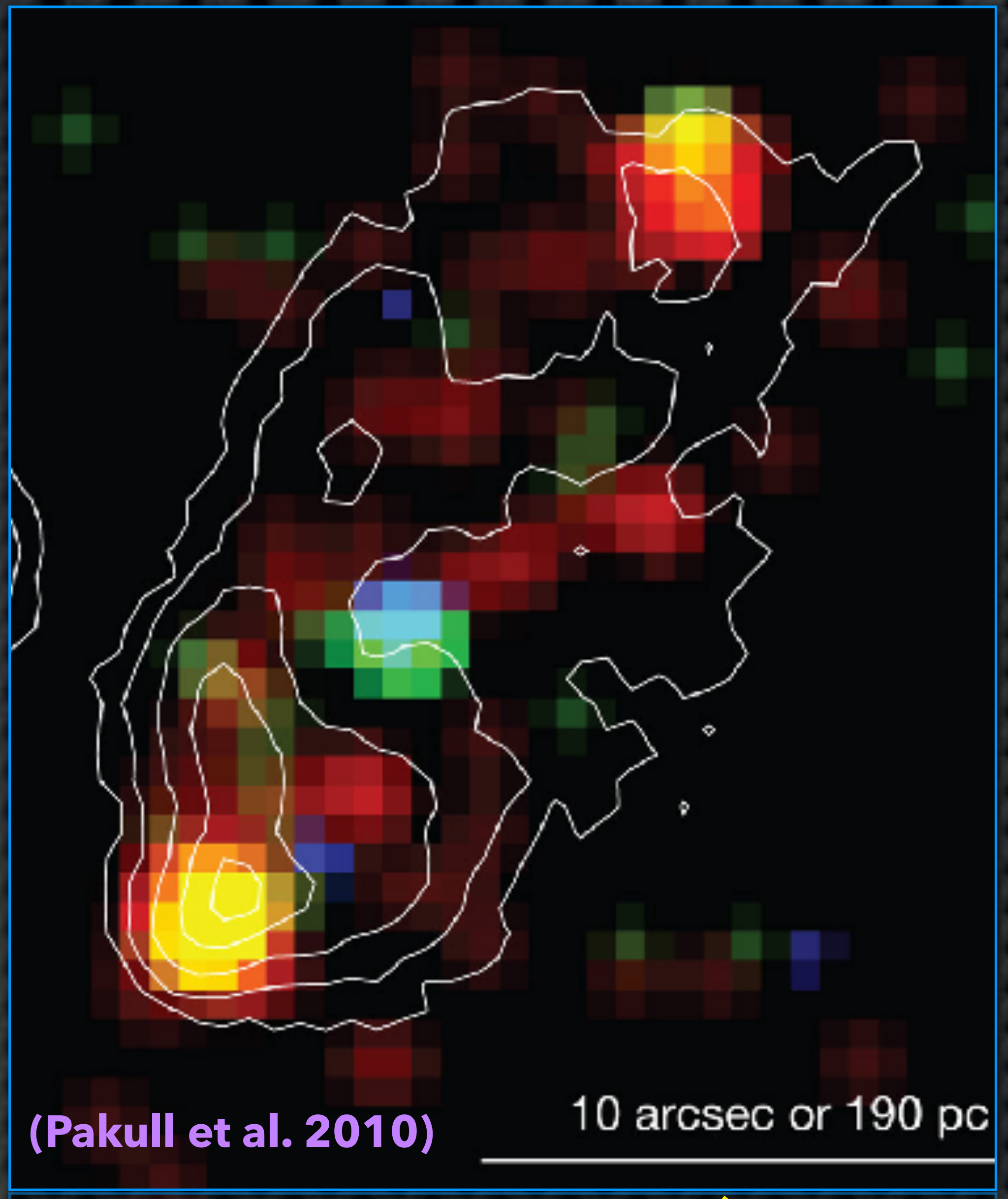
Black holes play an outsized role in the Universe

GALAXY EVOLUTION/ AGN FEEDBACK



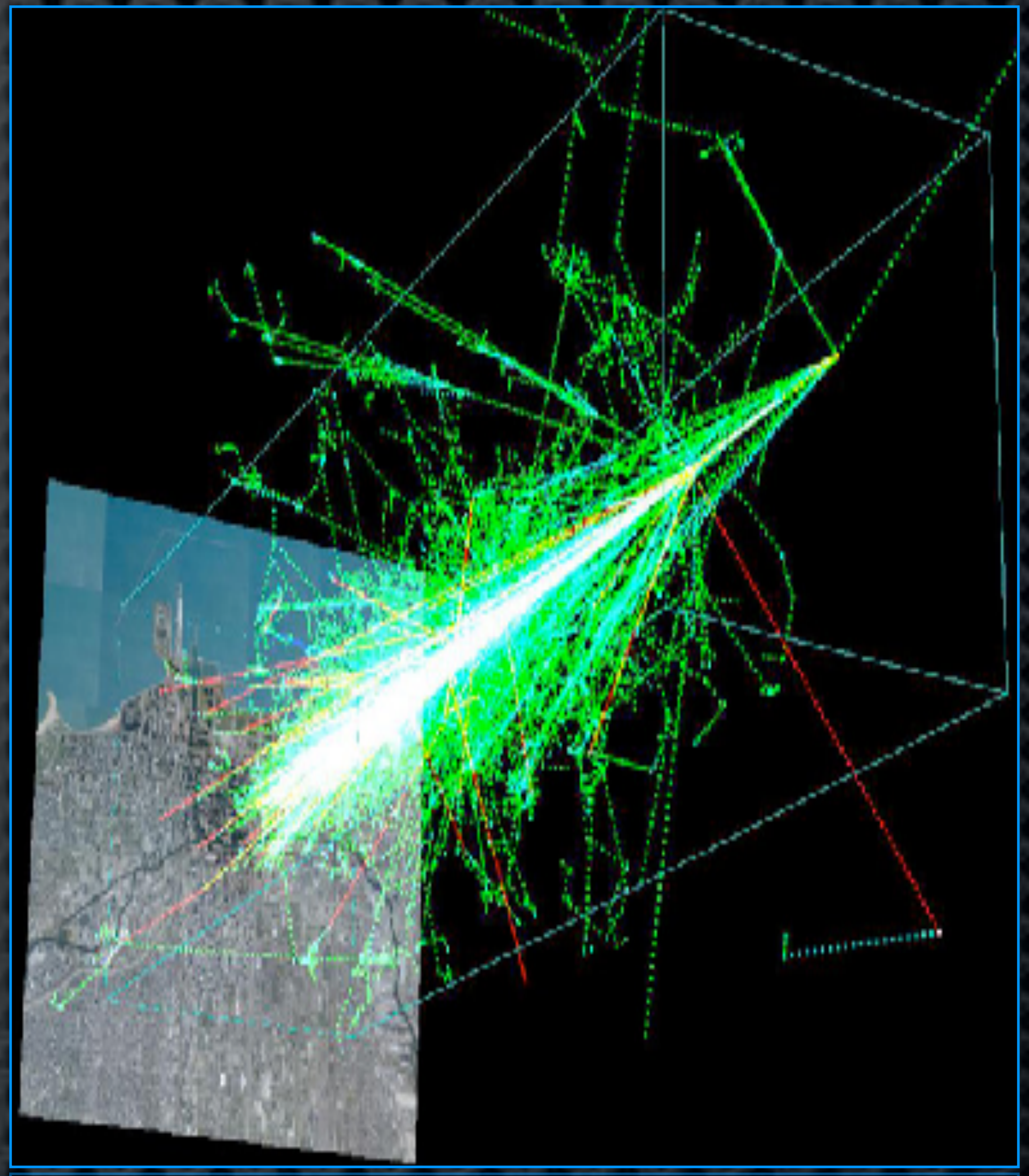
(Fabian++ 2006; Zhuravleva++2014)

IONIZATION OF SURROUNDING GAS

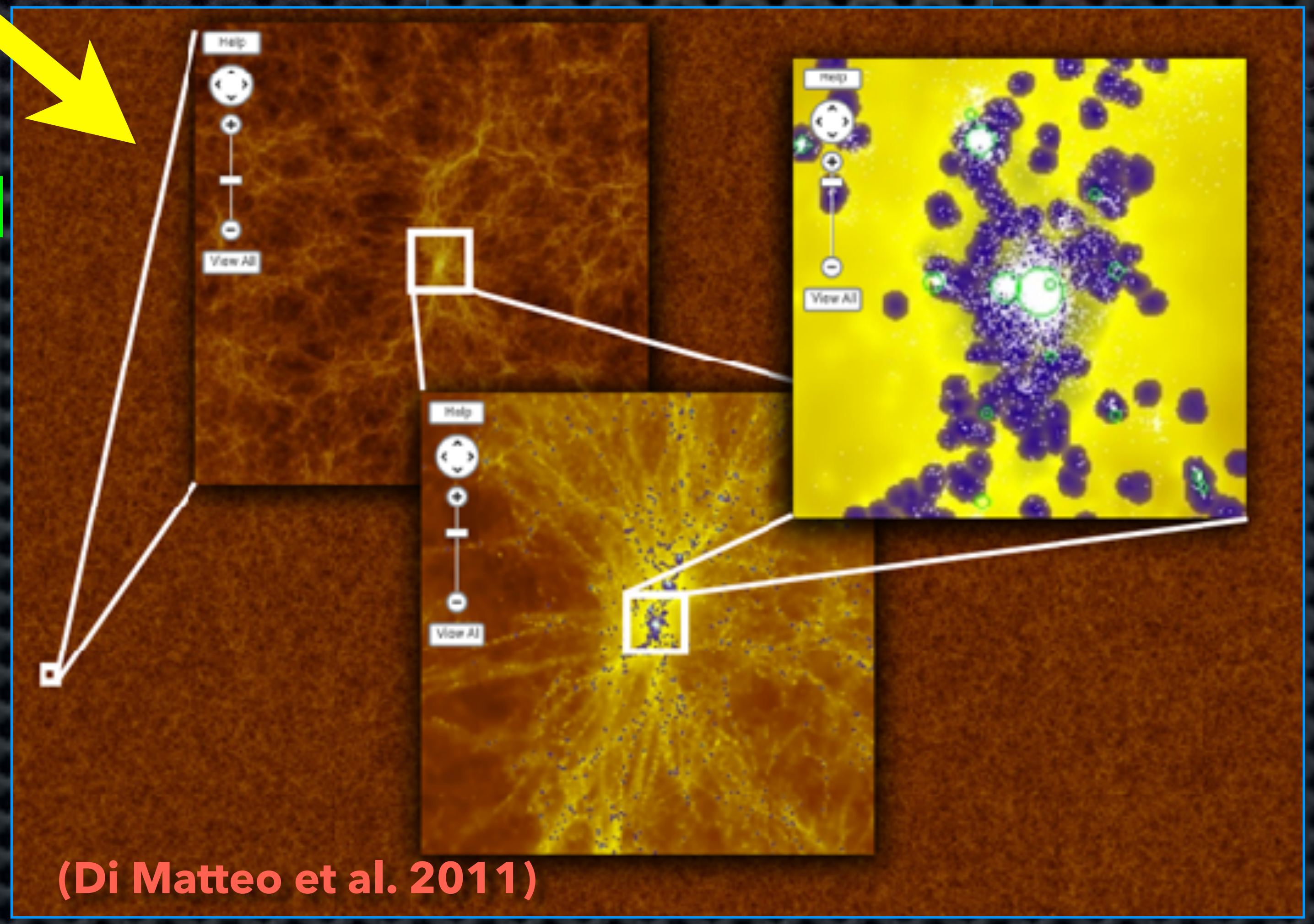


(Pakull et al. 2010)

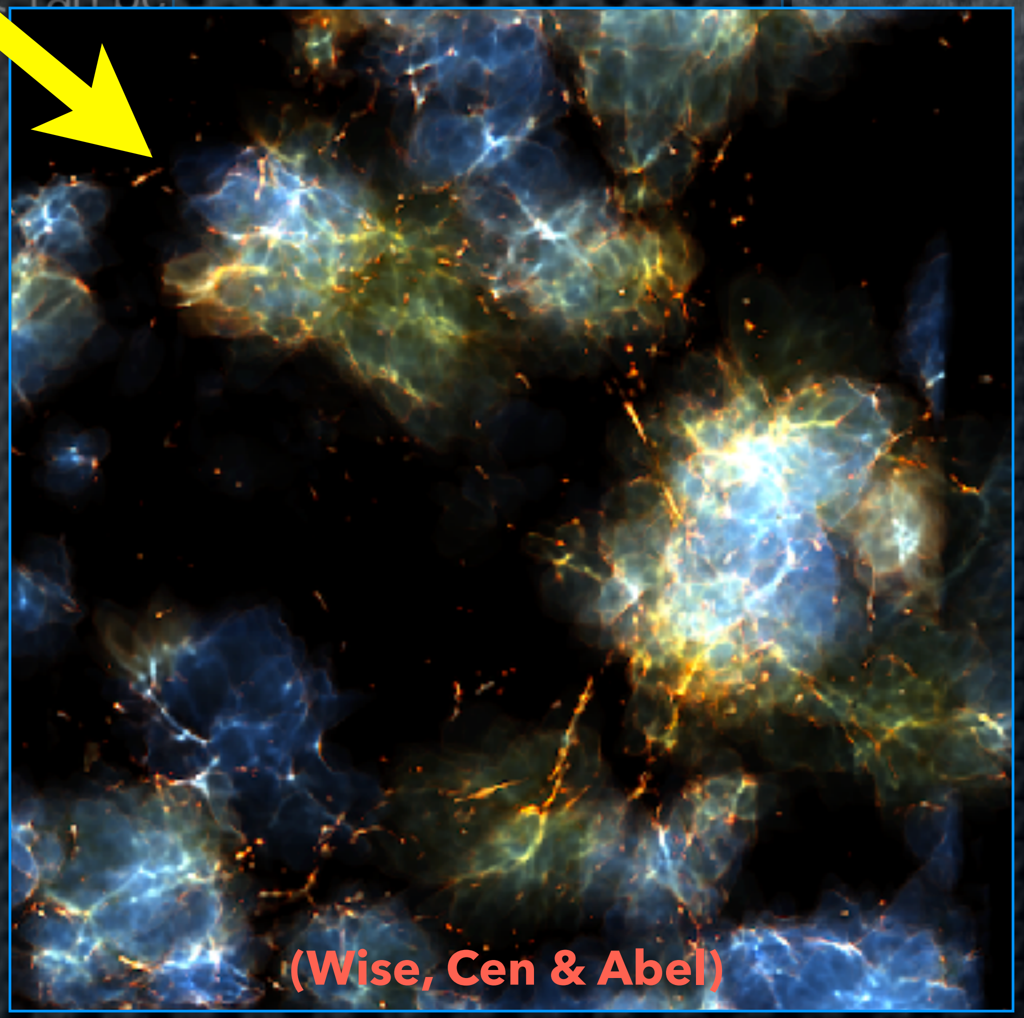
HIGH-ENERGY PARTICLE ACCELERATION



Cosmological Simulations:



(Di Matteo et al. 2011)



(Wise, Cen & Abel)

Key outstanding questions

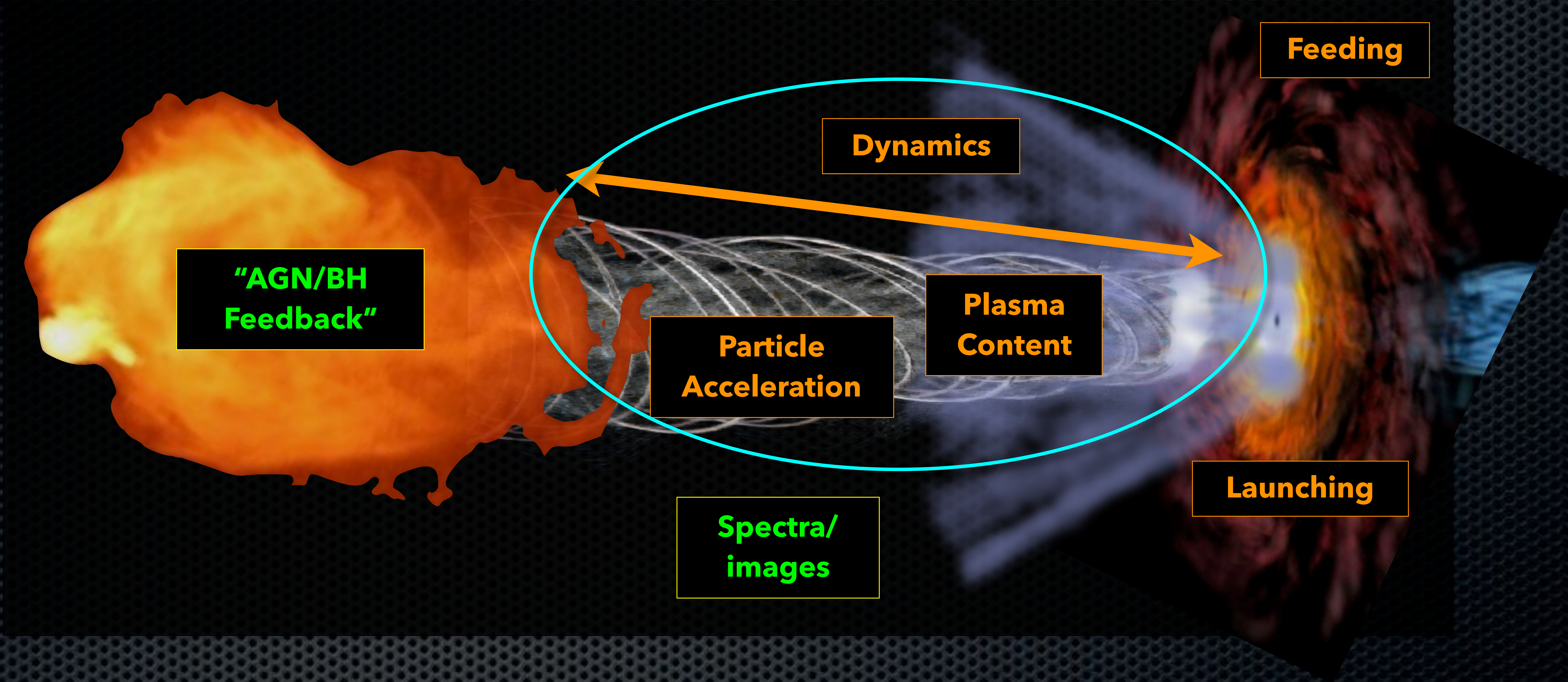
- How are jets and winds launched/accelerated/collimated?

- Relationship between disk/jet/wind bulk properties ("macro") and particle heating/acceleration ("micro)?

- Relationship between $\dot{M}_{disk}$, black hole spin and jet/wind power? Which dominates feedback?

- What sets timescales for accretion espisodes?

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

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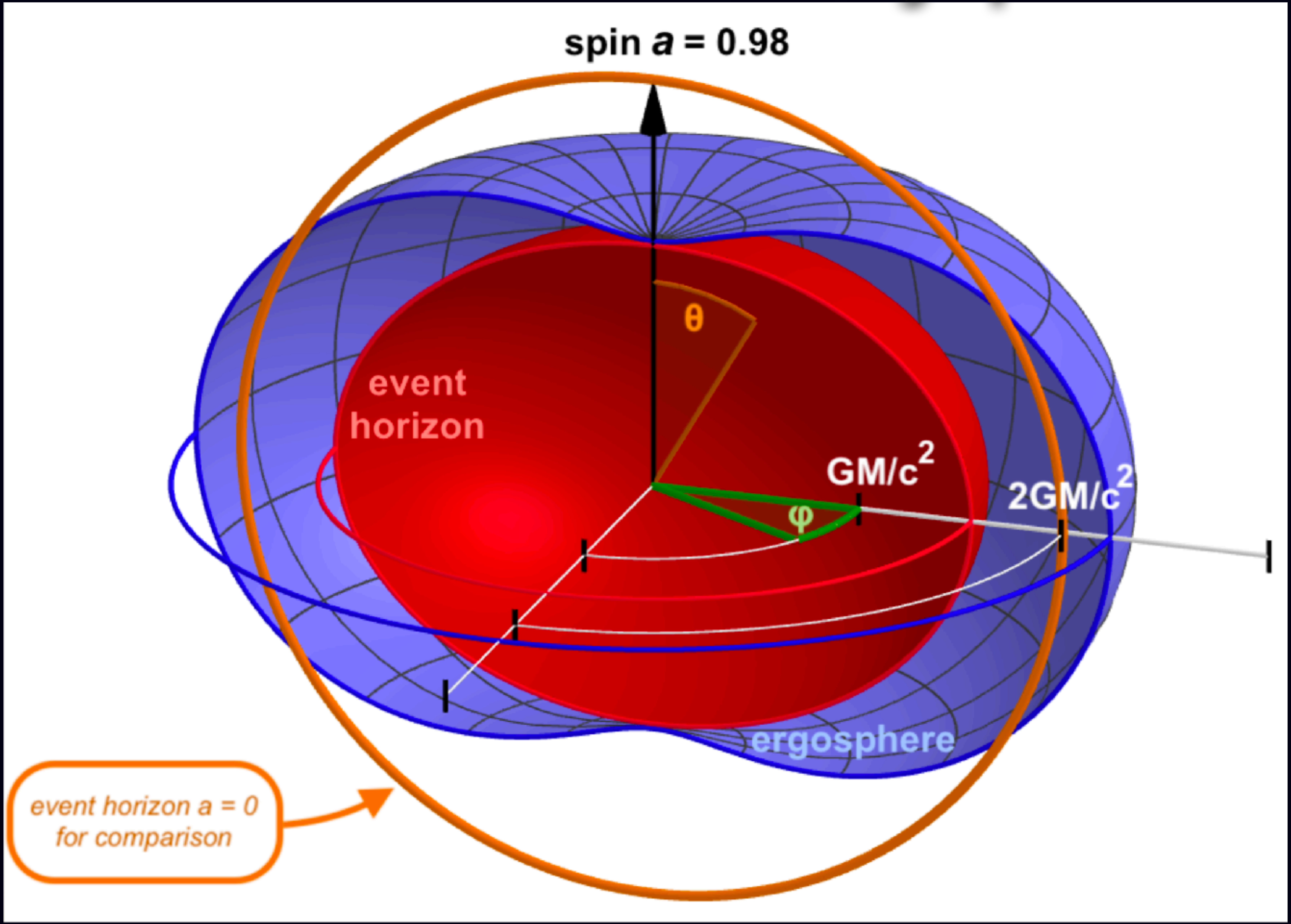
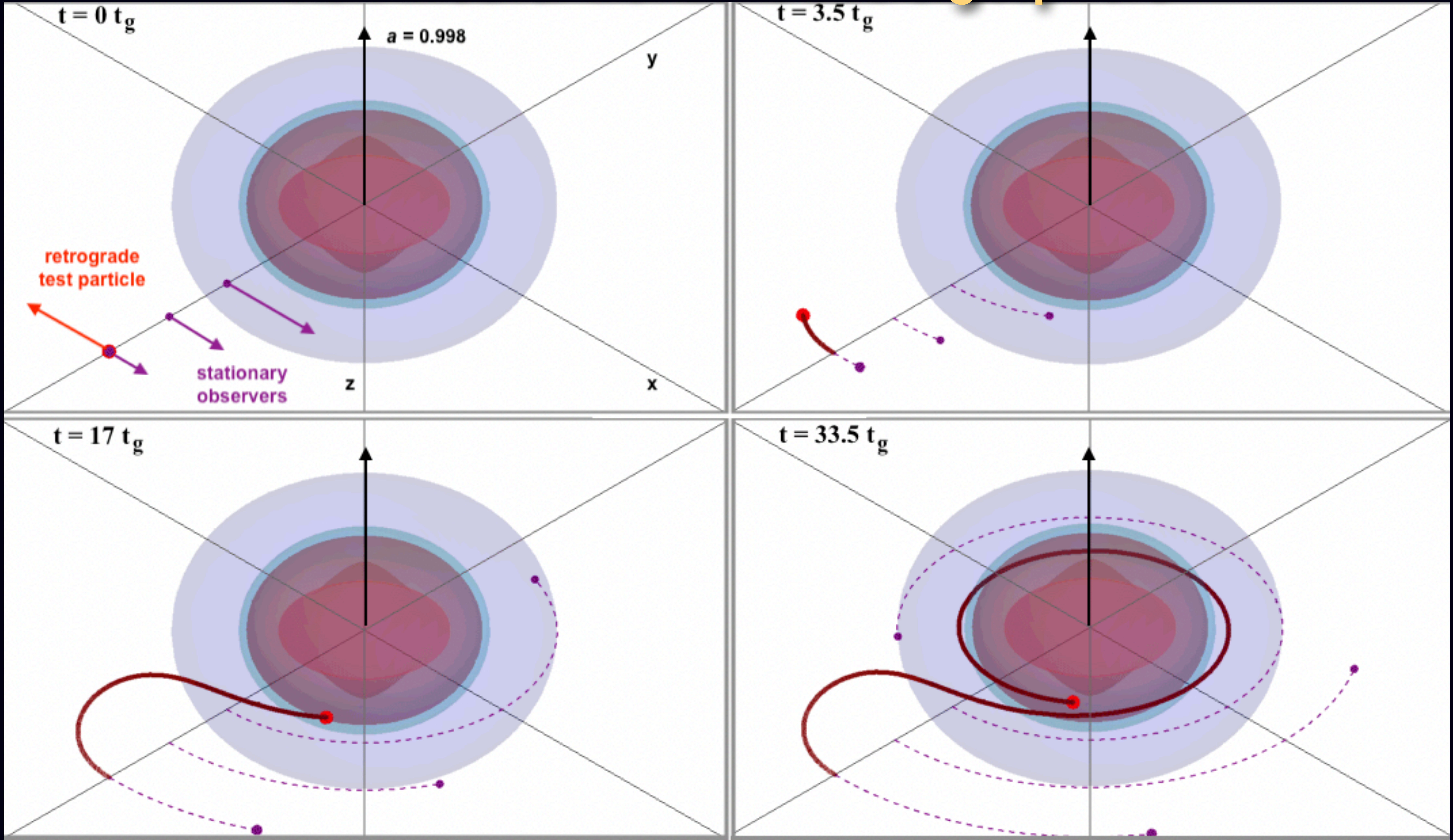
Kerr metric: horizons and ergosphere



Casper Hesp (MSc thesis)

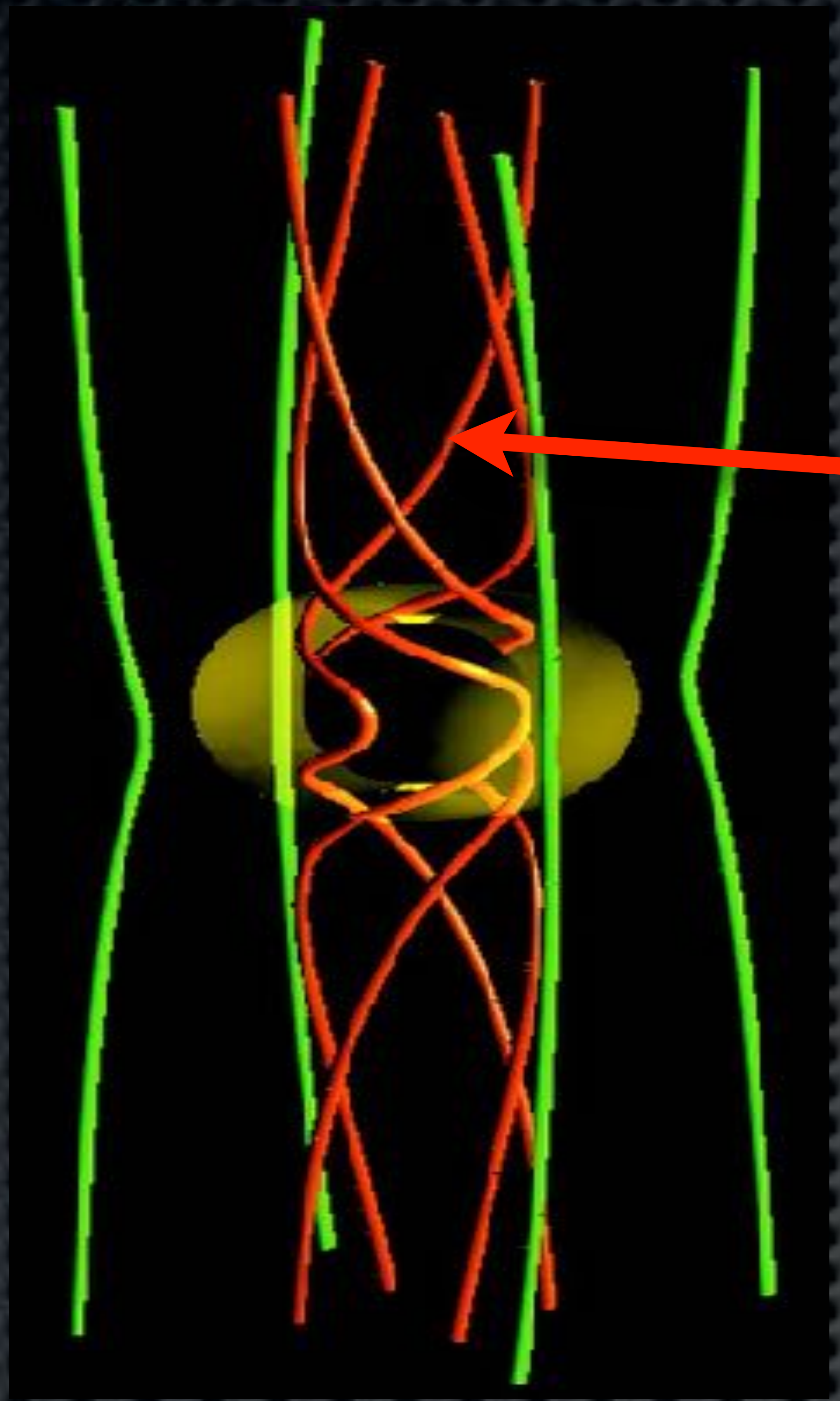
Kerr metric: horizons and ergosphere

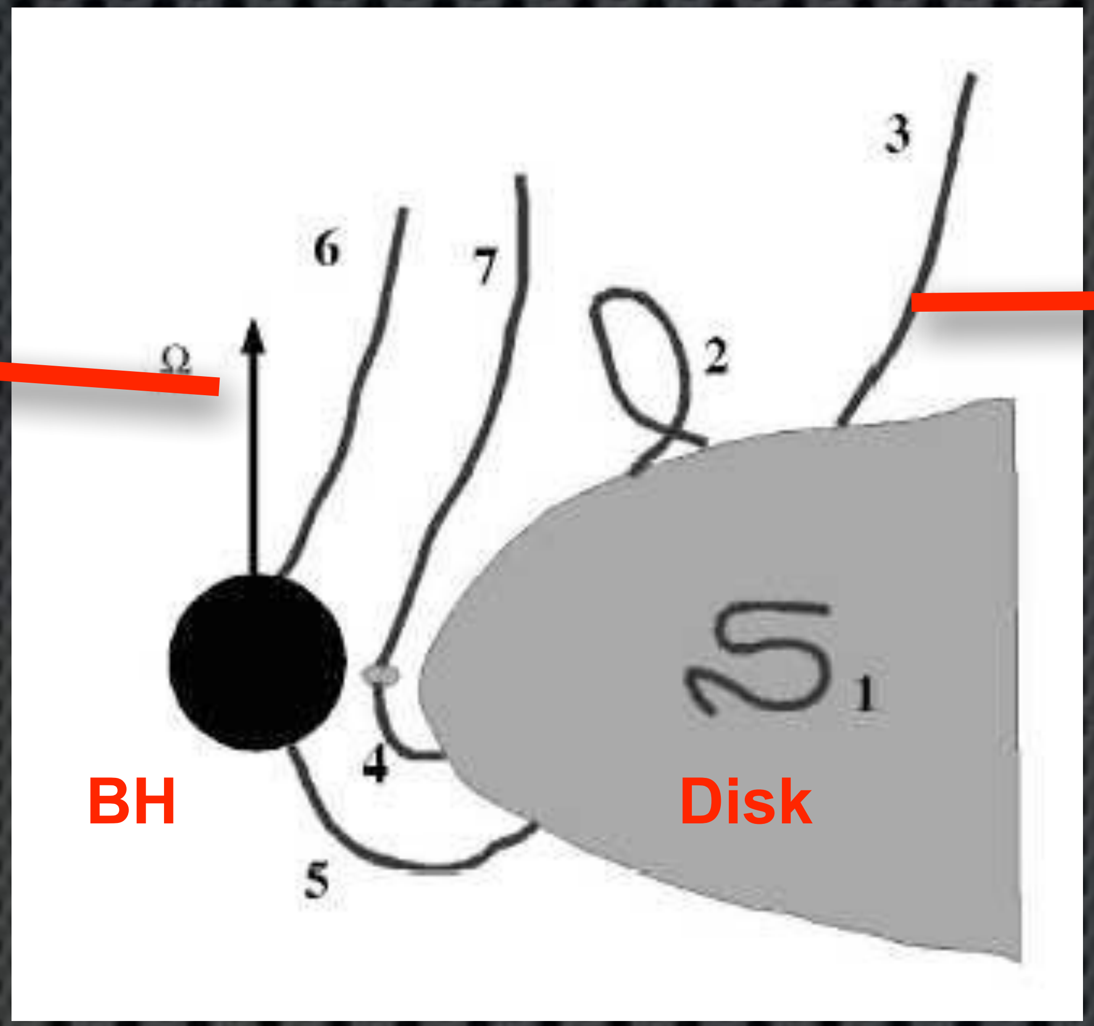


Adapted from Simon Tyran by Casper Hesp (MSc thesis)

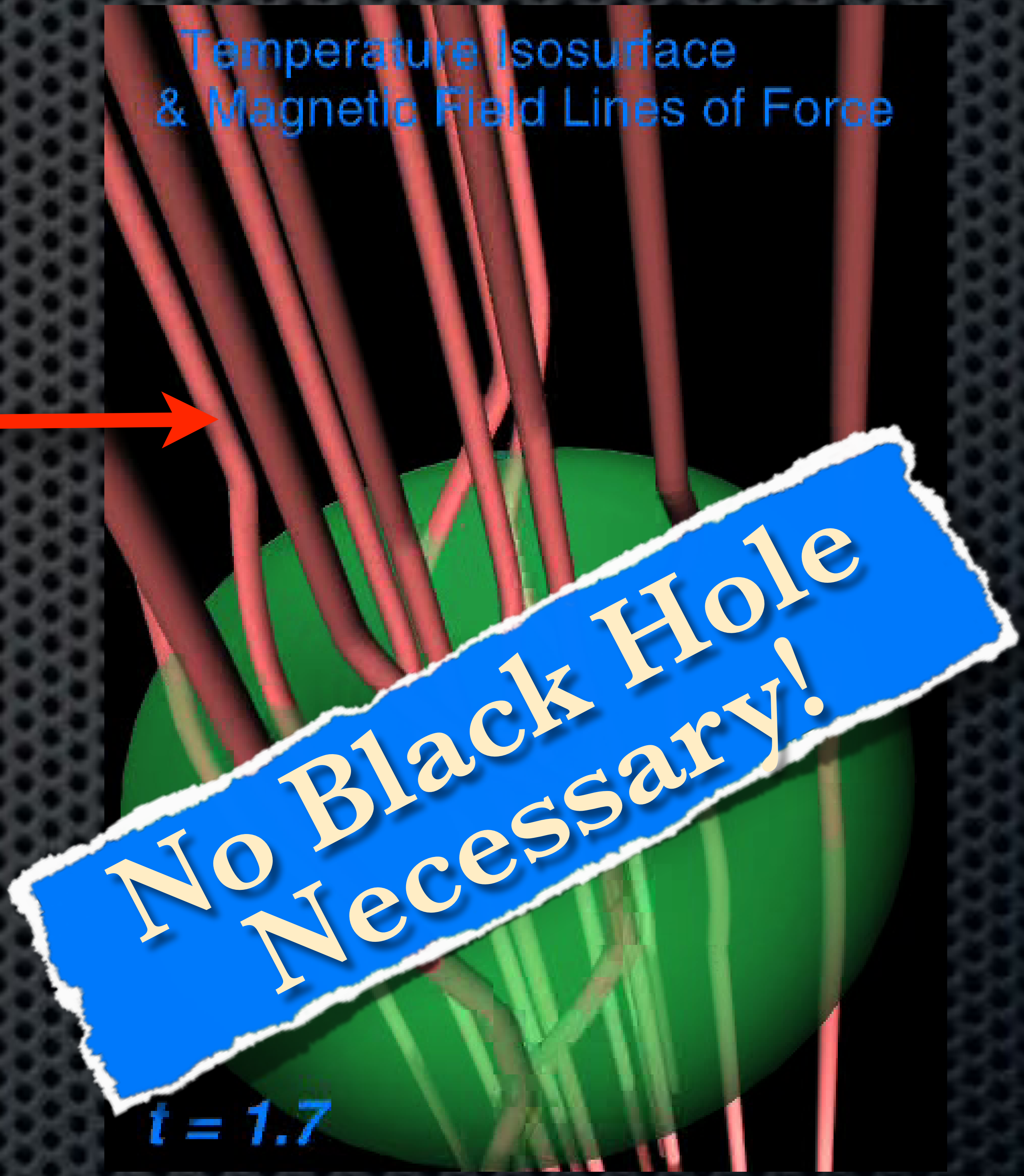
Jet power: two primary theoretical scenarios

Blandford-Znajek





Blandford-Payne



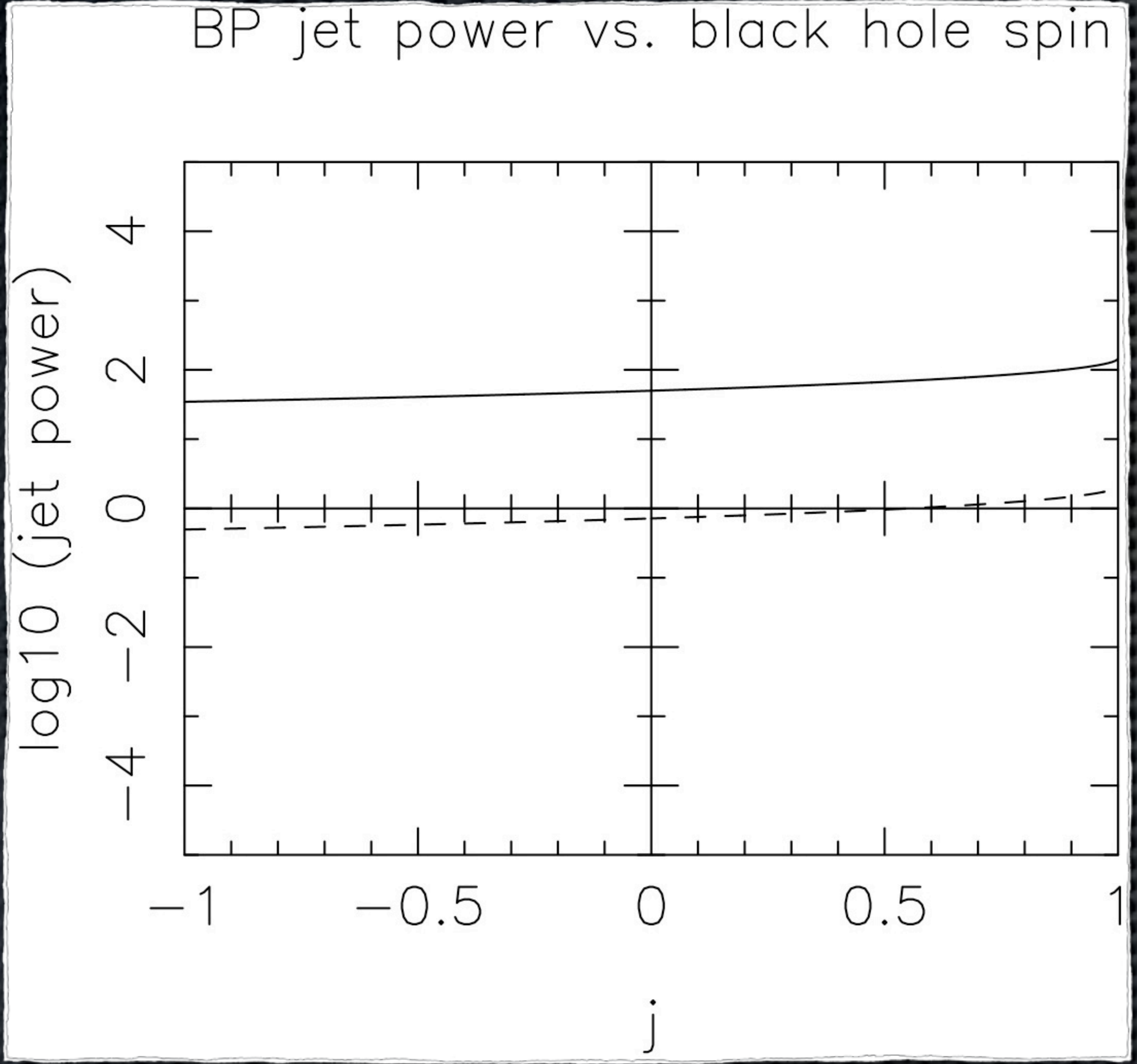
- Spin energy extracted from BH via magnetic fields
- Jets initiated as e^+e^- pairs, Poynting flux dominated

- Plasma accelerated up field lines from disk ("bead on wire")
- Jets loaded with neutral matter (ions, e^-s) from disk

(Blandford & Znajek 1977, Blandford & Payne 1982)

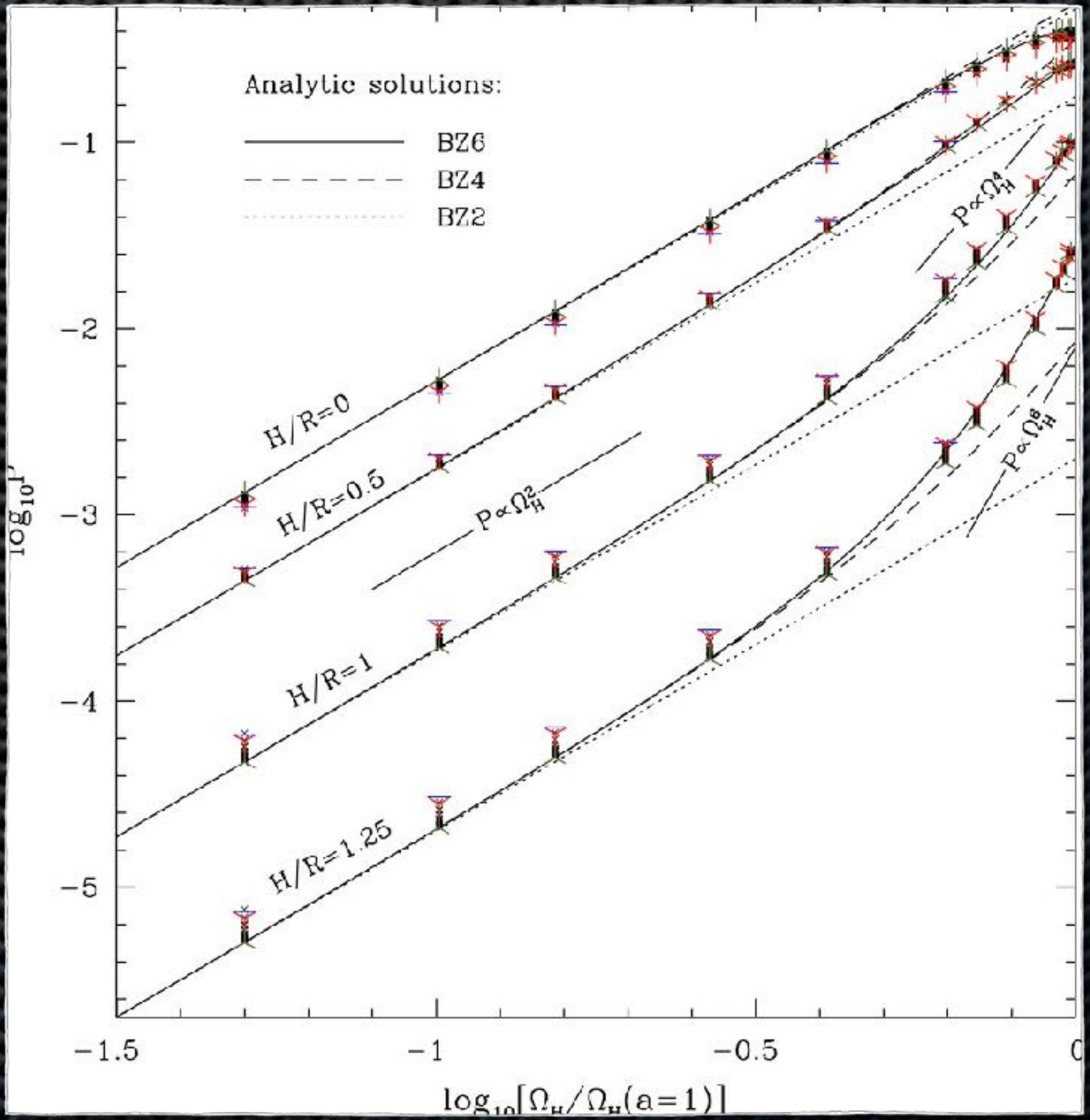
Jet power dependence on spin

Blandford-Payne like



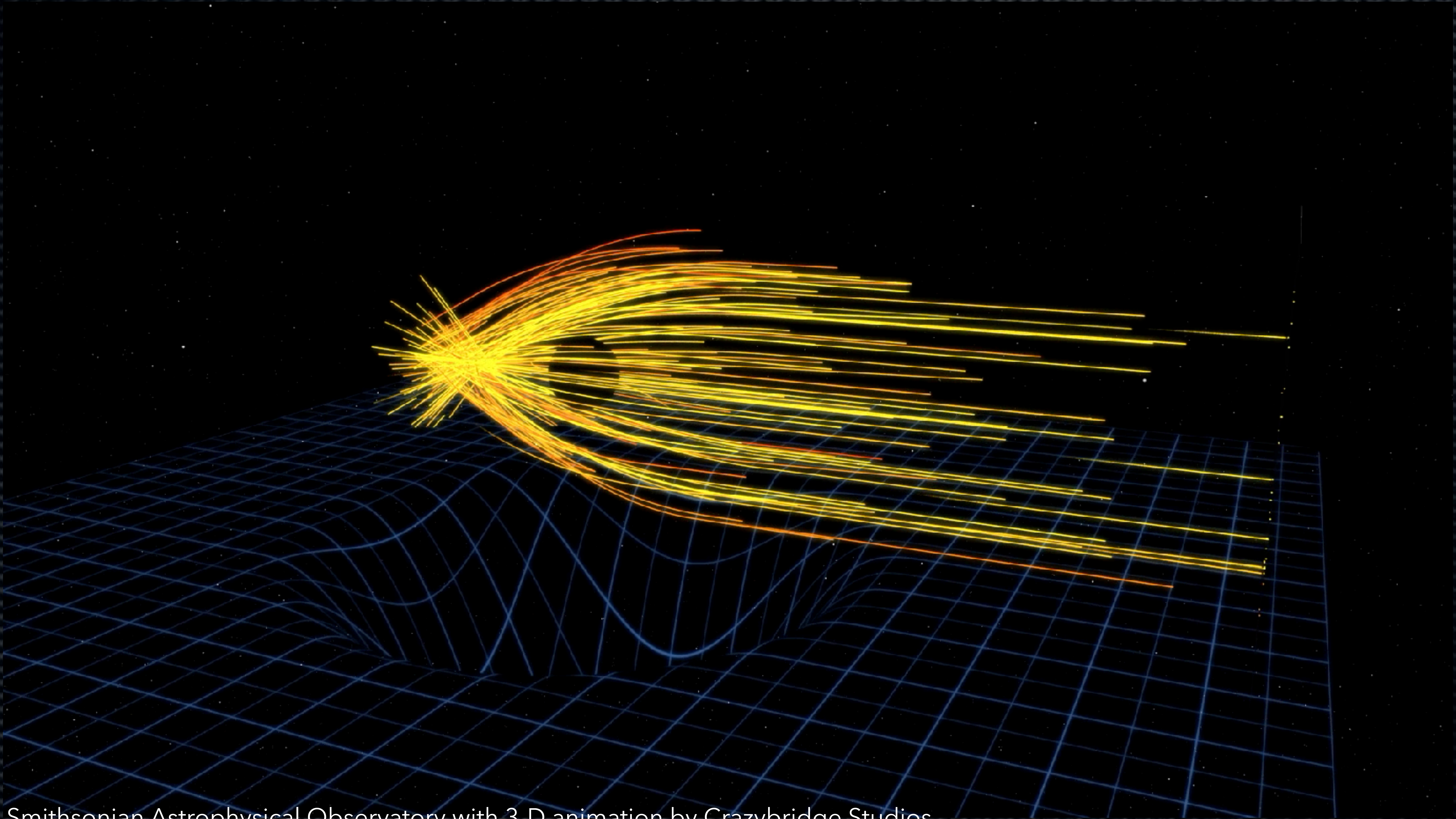
(Meier 2001, Meier 2012)

Blandford-Znajek like



(Tchekhovskoy, Narayan & McKinney 2010)

Spacetime effects dominate close to the black hole



Smithsonian Astrophysical Observatory with 3-D animation by Crazybridge Studios

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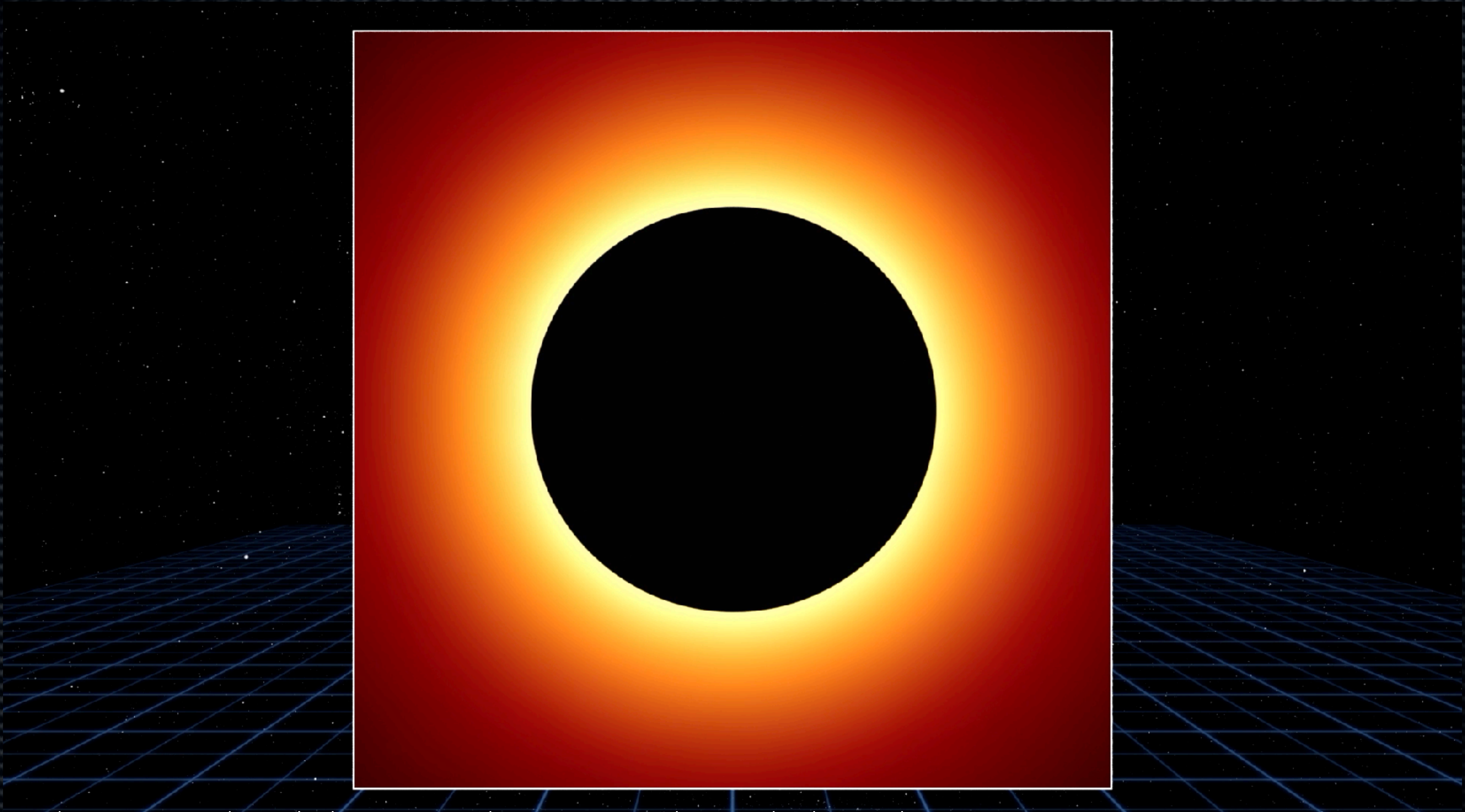
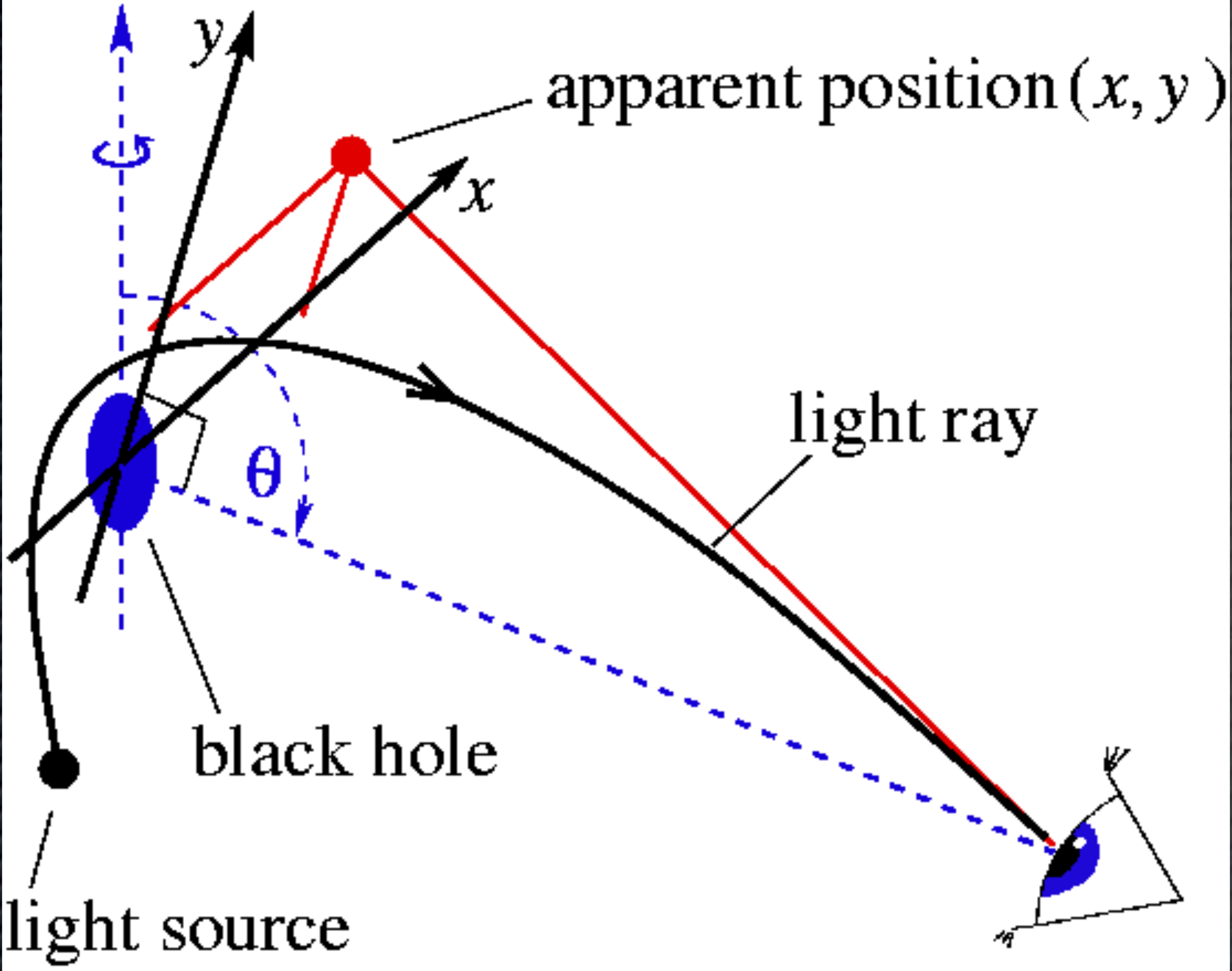


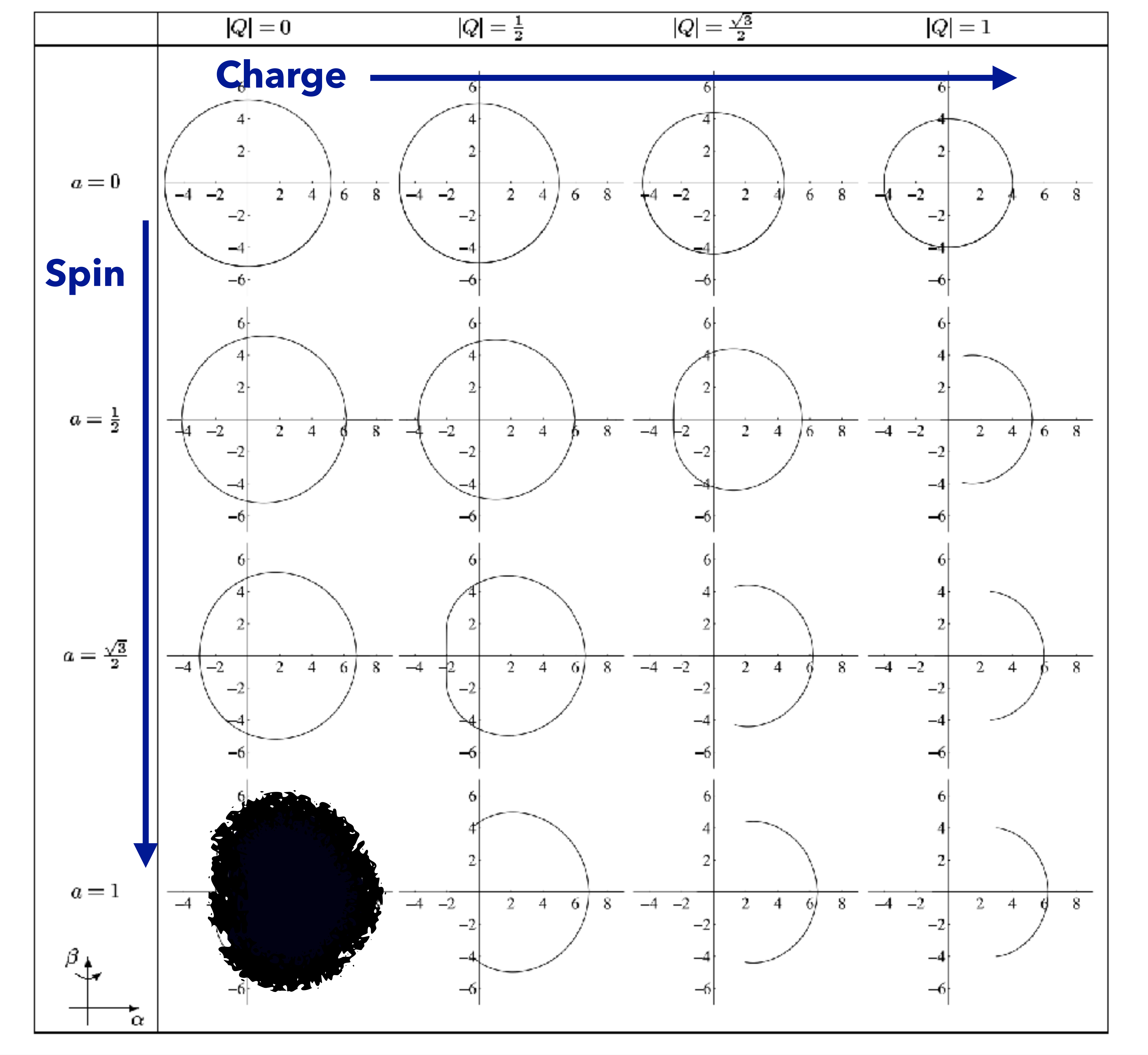
Smithsonian Astrophysical Observatory with 3-D animation by Crazybridge Studios

What is the size of a black hole shadow?

Impact parameter for nonspinning BH:

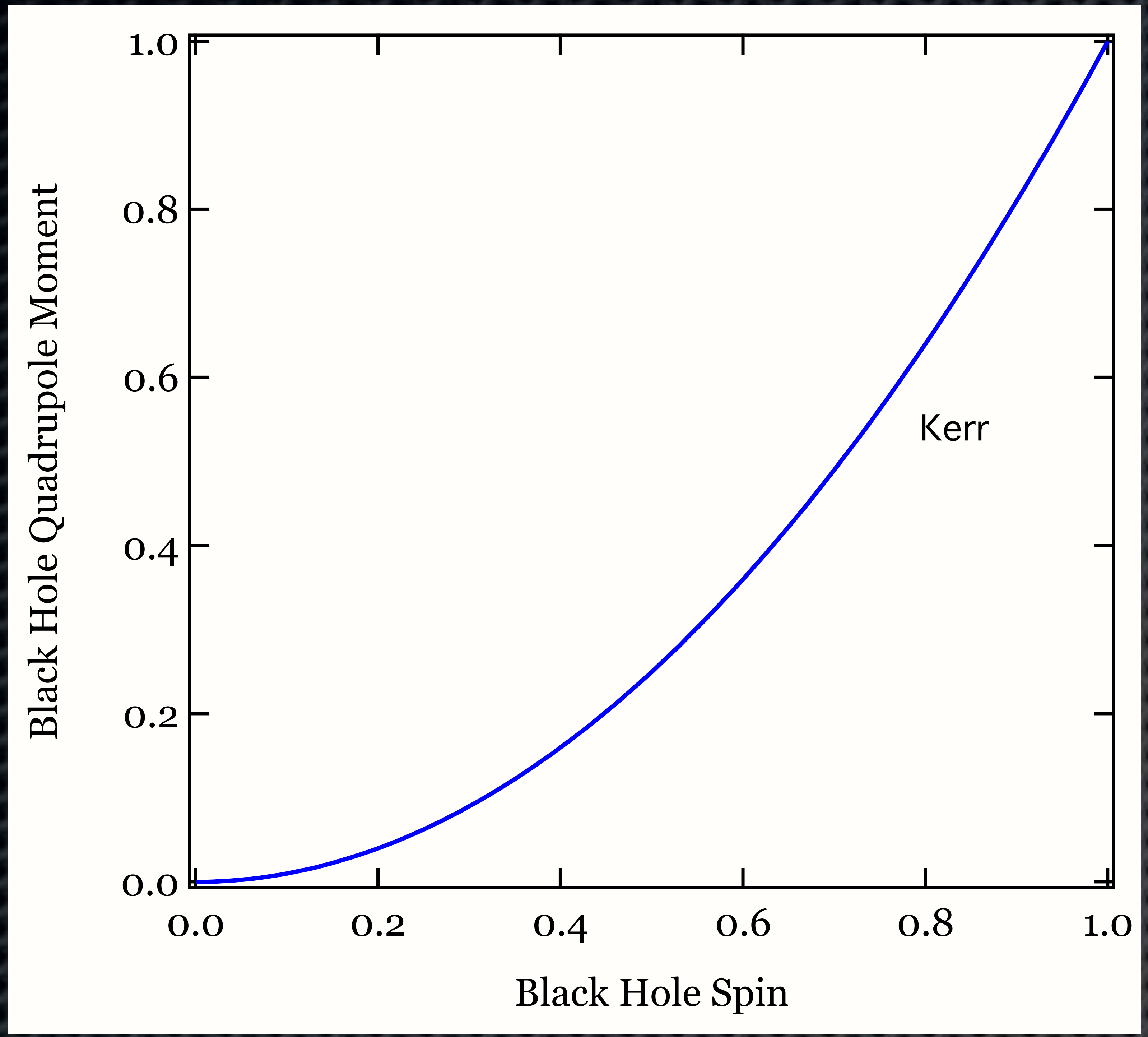
$b_{min} = \sqrt{27}\, r_g \sim 5r_g = 5M$ in natural units

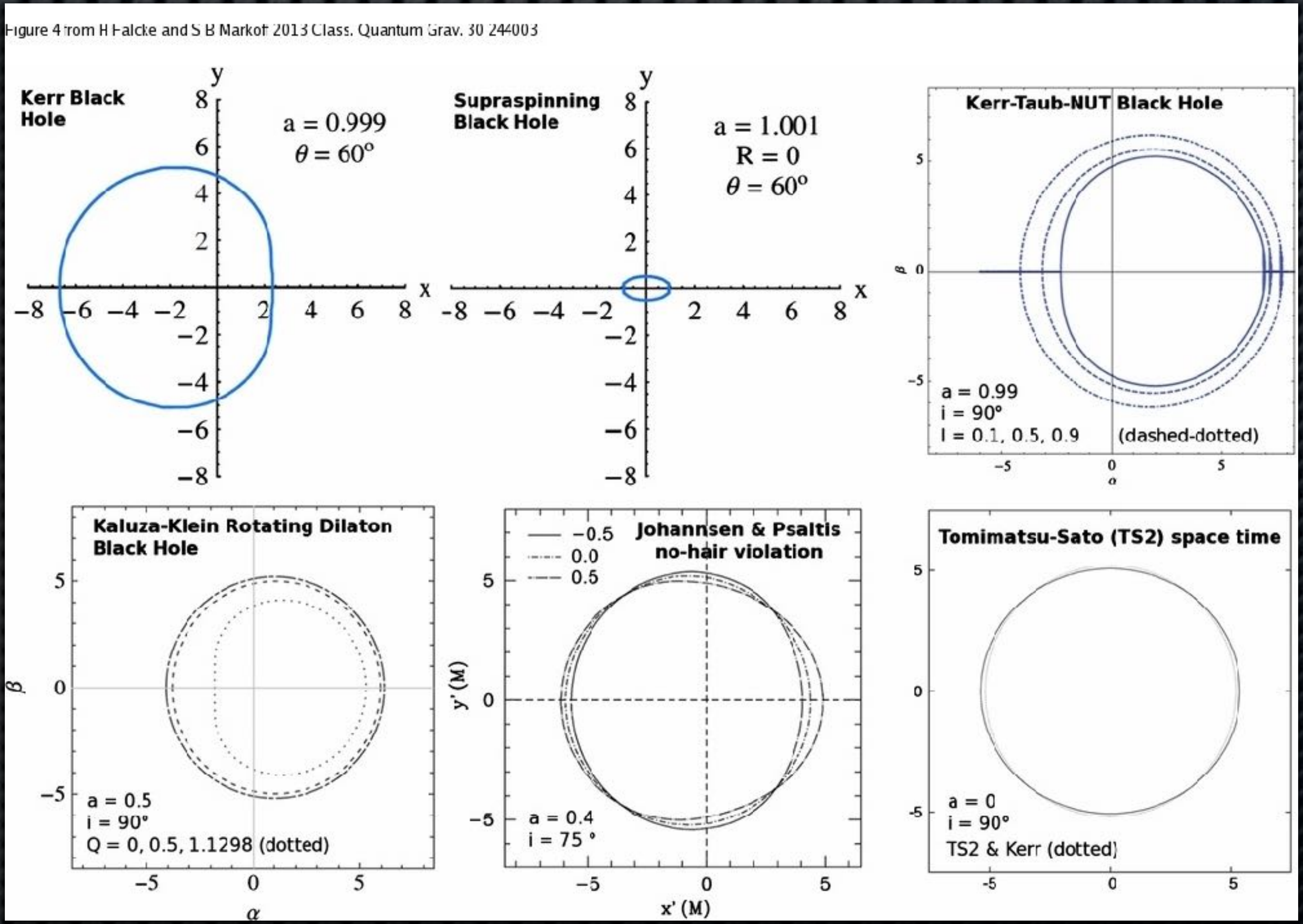




(e.g., Bardeen 1973; de Vries 2000)

We can test GR (or not) via shape of shadow

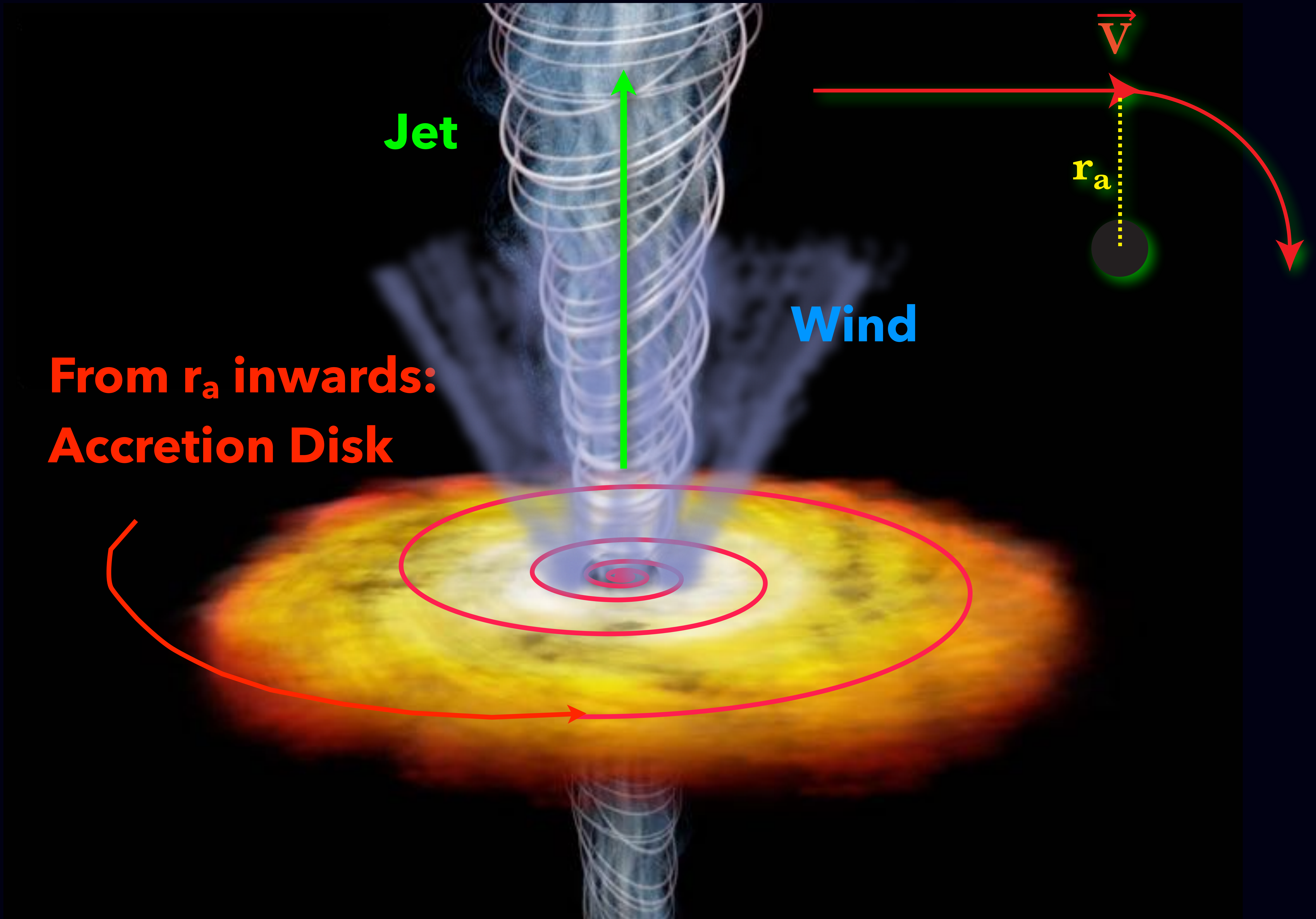




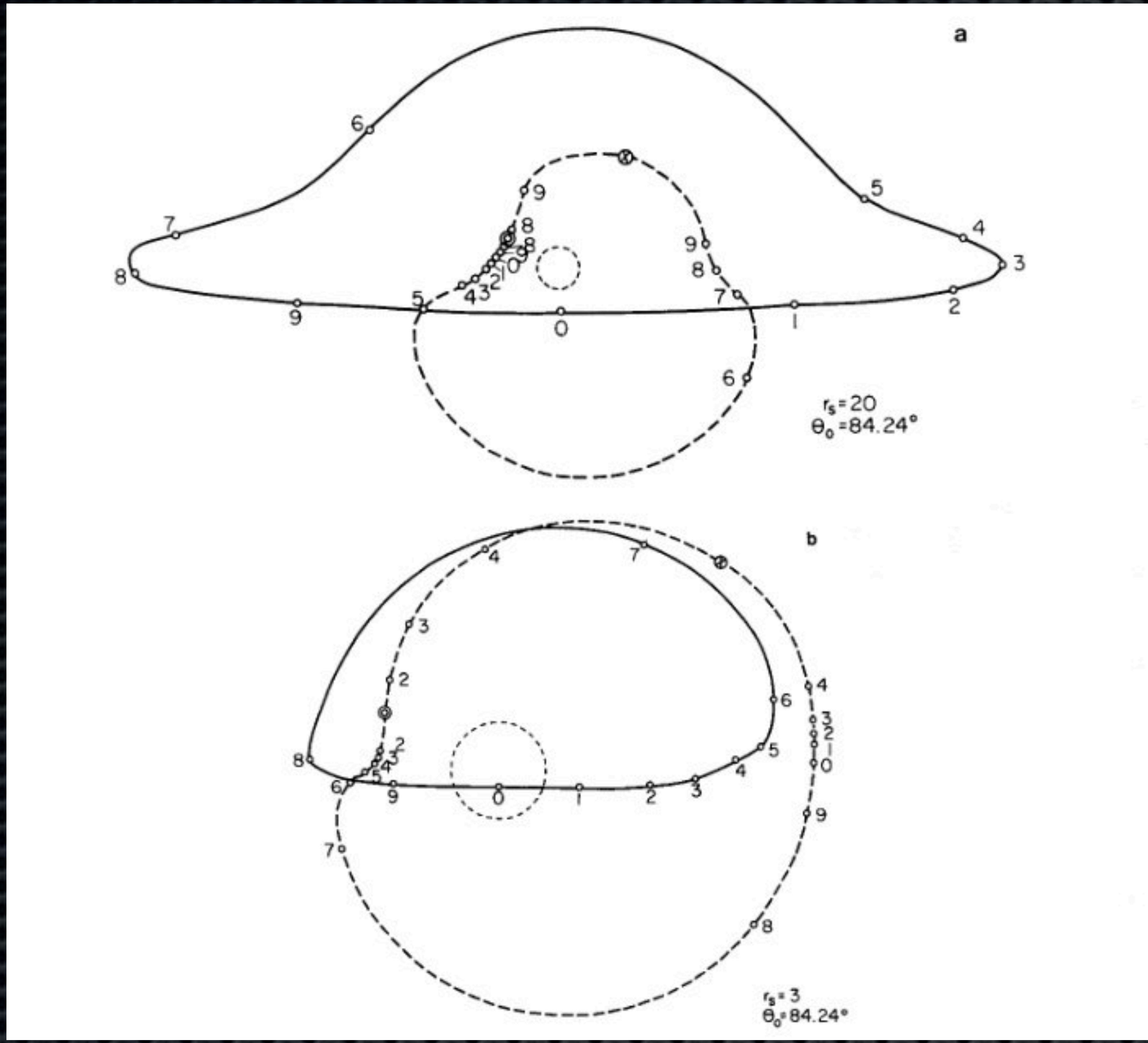
- ★ Multipole expansion of vacuum metric: monopole = M, dipole = a/M, quadrupole $=Q/M^3 \propto a^2$

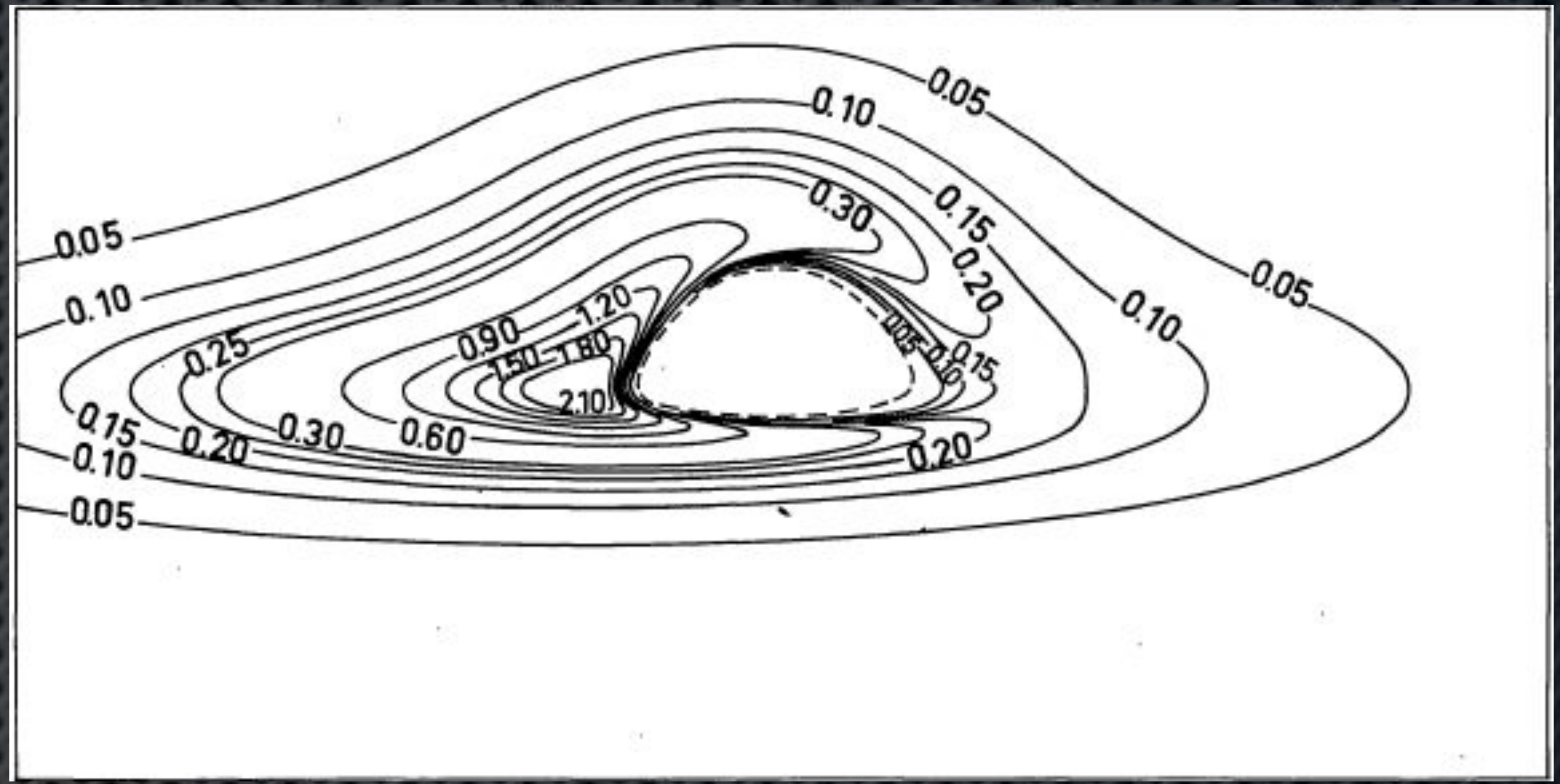
(e.g., Ryan 1995; Wex & Kopeikin 1999; Collins & Hughes 2004; Glampedakis & Babak 2006; Will 2008; Brink 2008; Gair et al. 2008; Apostolatos et al. 2009; Vigeland & Hughes 2010; Lukes-Gerakopoylos et al. 2010; Vigeland 2010; Vigeland, Stein, & Yunes 2011; Johannsen & Psaltis 2011; Johannsen 2013; Falcke & Markoff 2013; Psaltis et al. 2015)

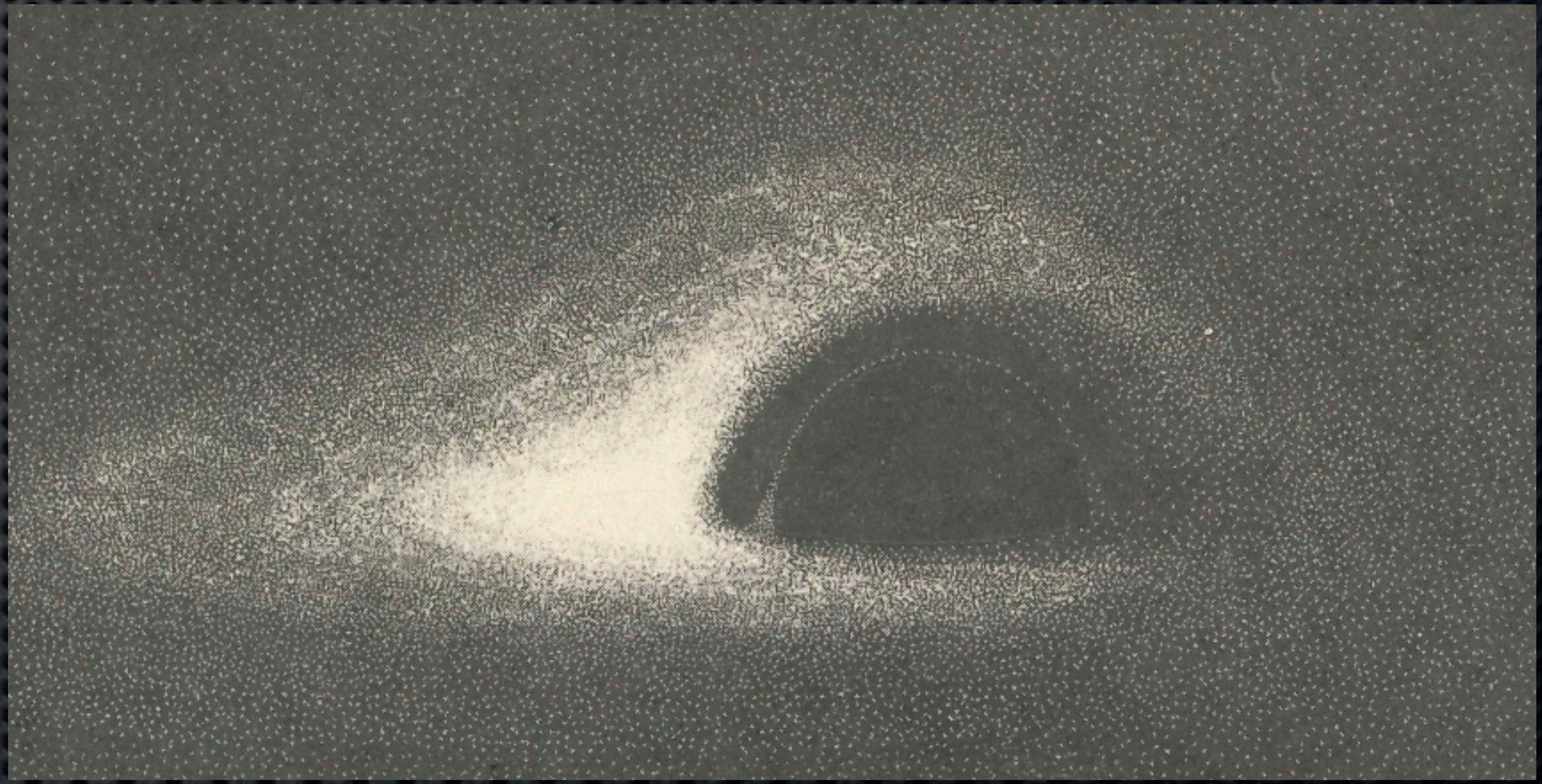
What are we actually looking at then?



What will a black hole with a star/disk look like?





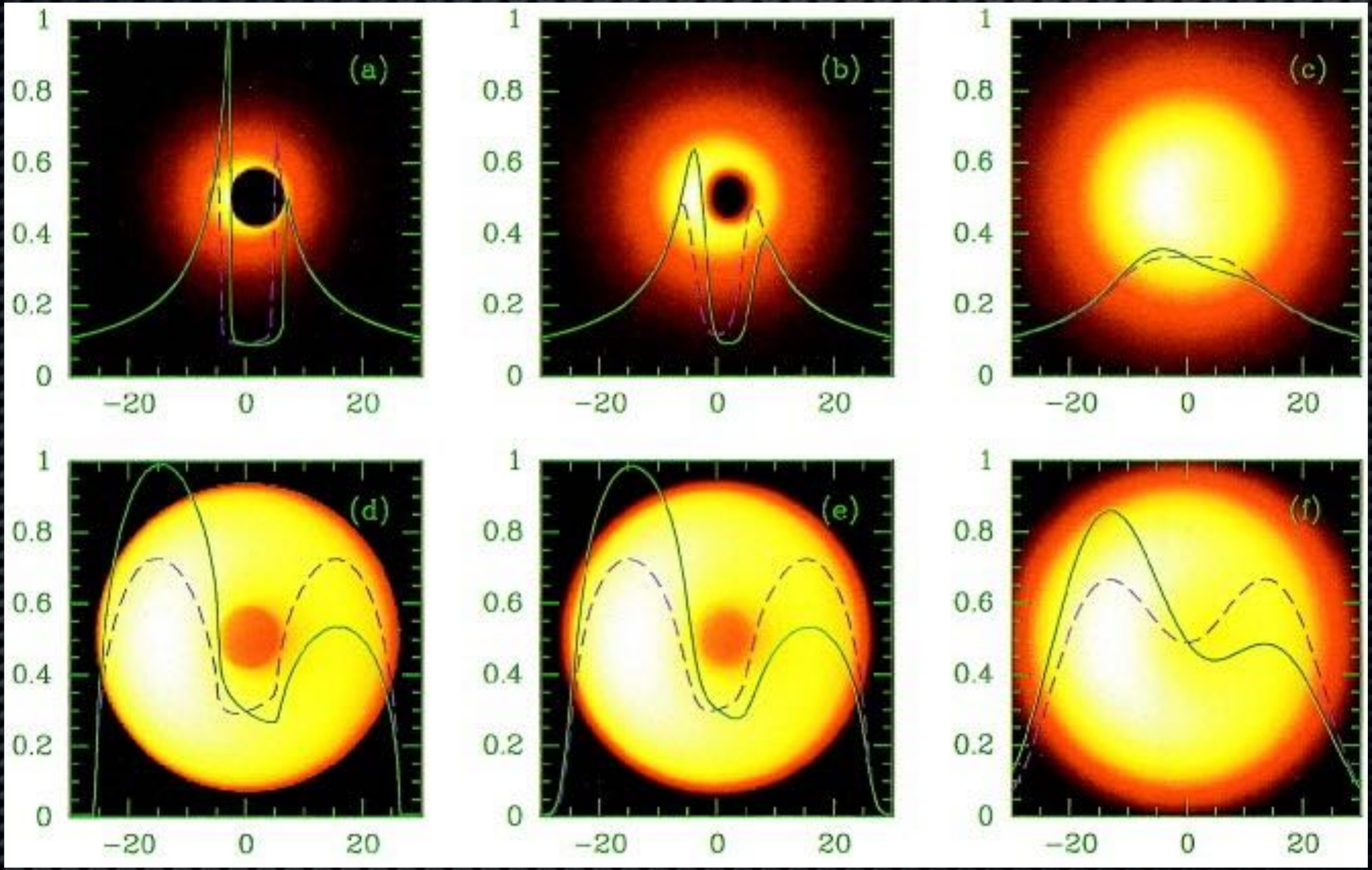


(e.g., Cunningham & Luminet 1979; Luminet 1979)

What will a black hole with a disk look like …with mm-VLBI?

Maximally spinning

Not spinning



(Falcke, Melia & Agol 2000)

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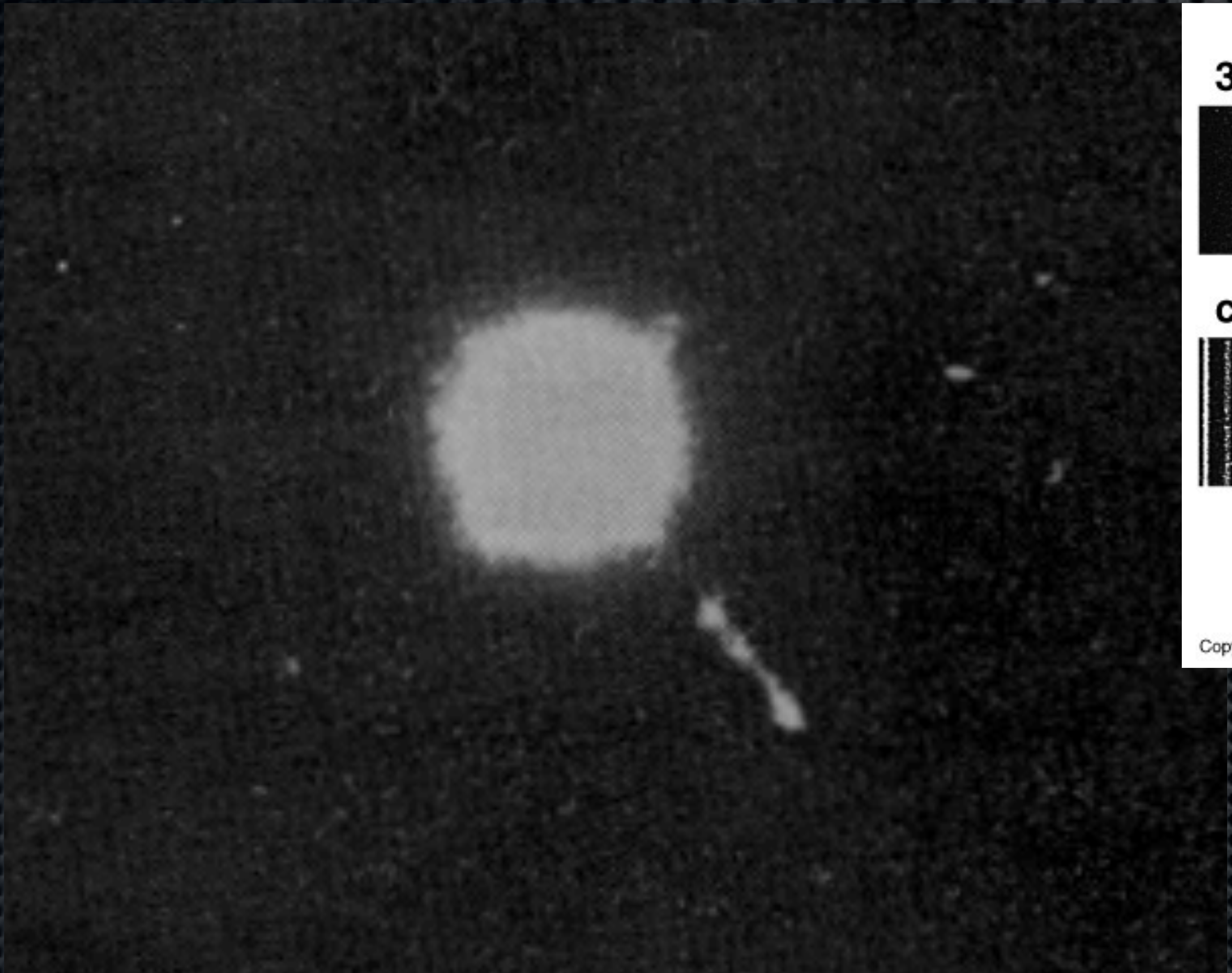
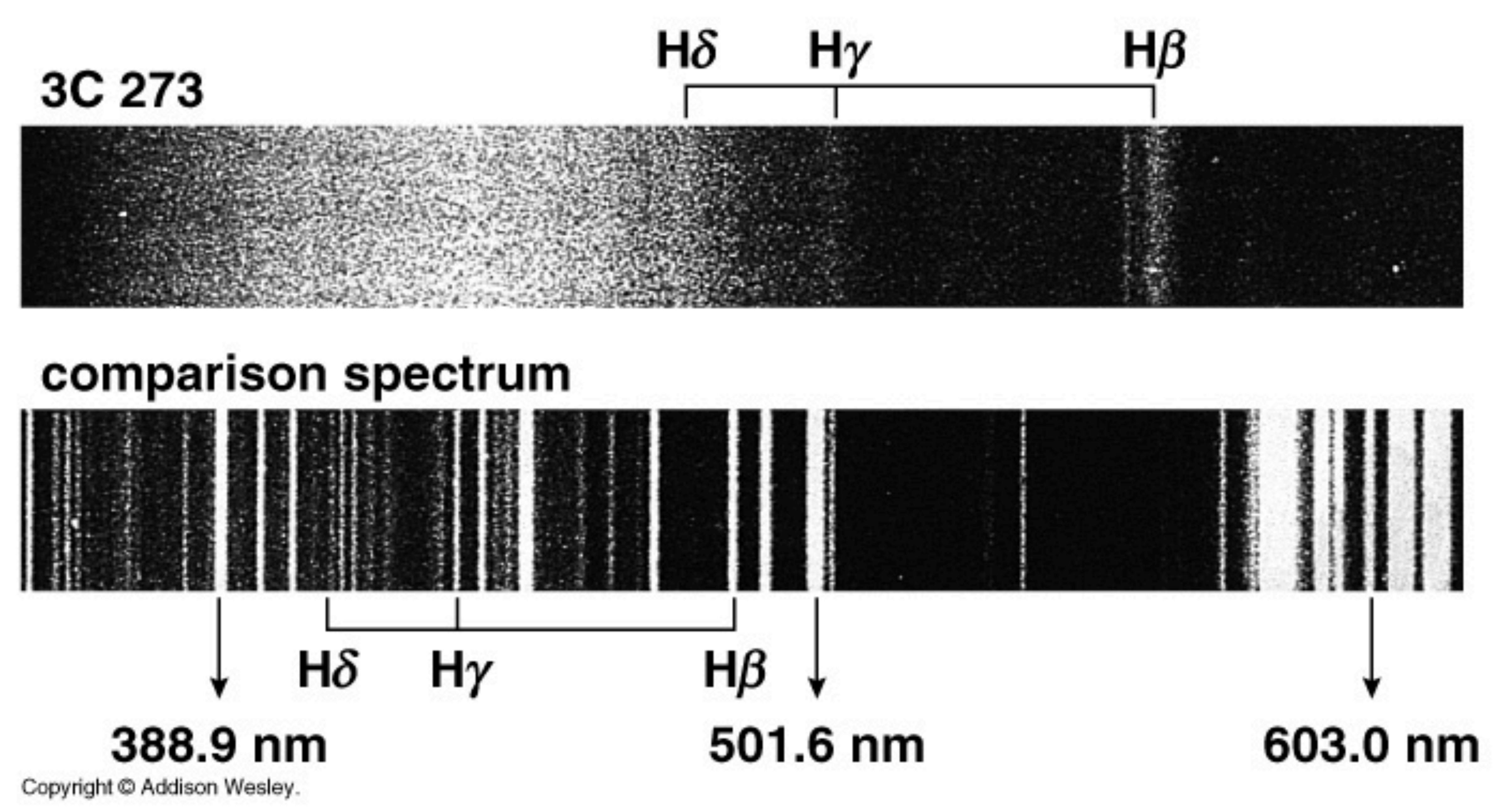
How did the idea of imaging a black hole originate?? (1918-1963)



(3C 273 in old optical plate image. Credit: Narlikar 1993)



(Schmidt++1963)

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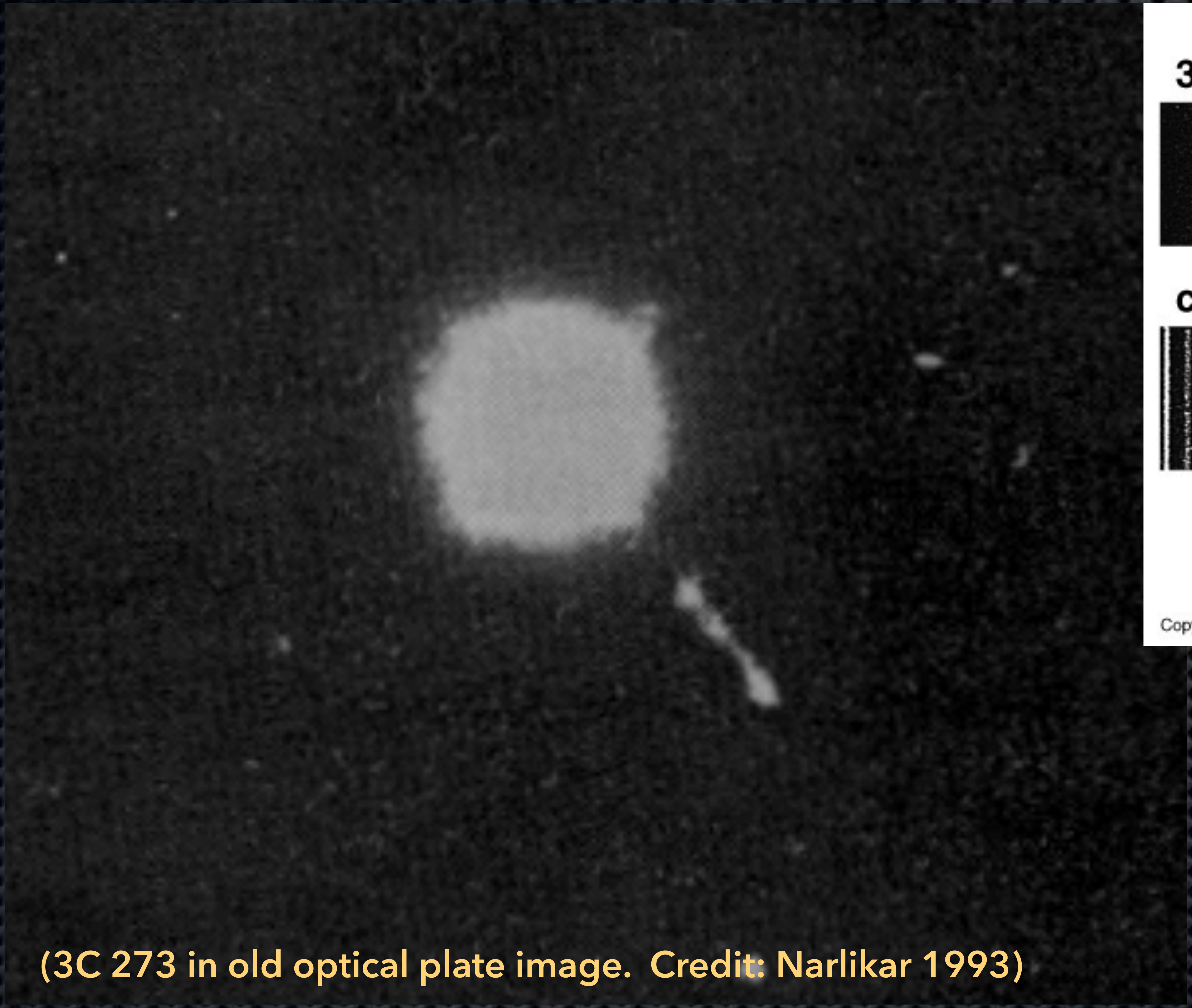


(3C 273 in old optical plate image. Credit: Narlikar 1993)

How did the idea of imaging a black hole originate?? ('60s-'70s)

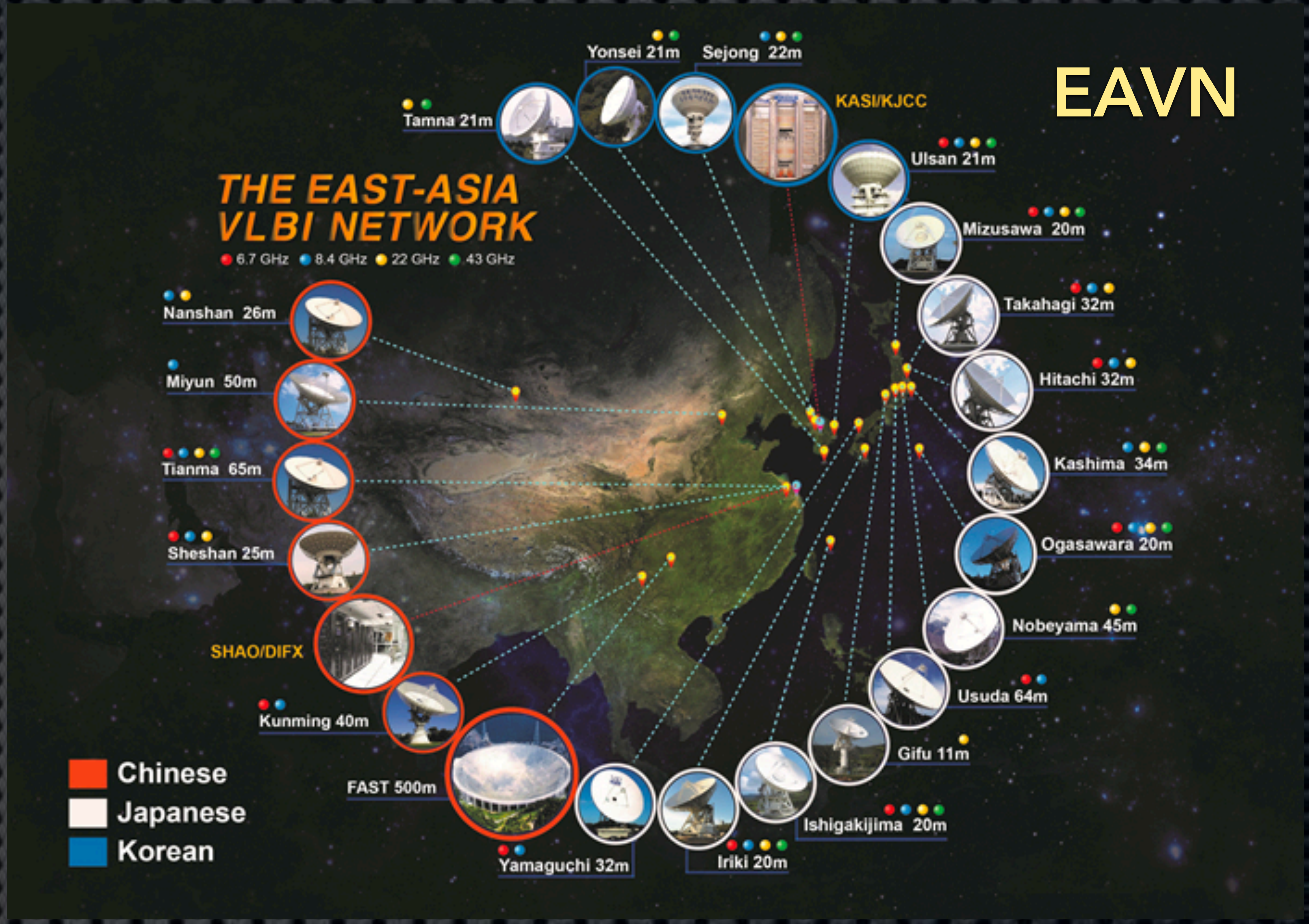
- ★ Spatial resolution of a telescope $\theta \sim \lambda/D_{telescope} \sim \lambda/D_{baseline}$
- ★ 1967: first very long baseline interferometry (VLBI) w/3074km baseline [DRAO and Algonquin Radio Observatory, Canada]
- ★ 1971: American Academy of Arts and Sciences awards Rumford Prize to three pioneering VLBI research groups
- ★ Lynden-Bell & Rees 1971:

> 2. Very long baseline interferometry may soon be possible with a broad enough bandwidth to measure sources as weak as 0·5 f.u. to diameters of 10^{-3}″. If so, it may be possible to determine the size of any central black hole that there may be in our galaxy. However H II may render the central source opaque with a greater angular size.

- ★ Ballick & Brown 1974: identify compact radio core w/black hole

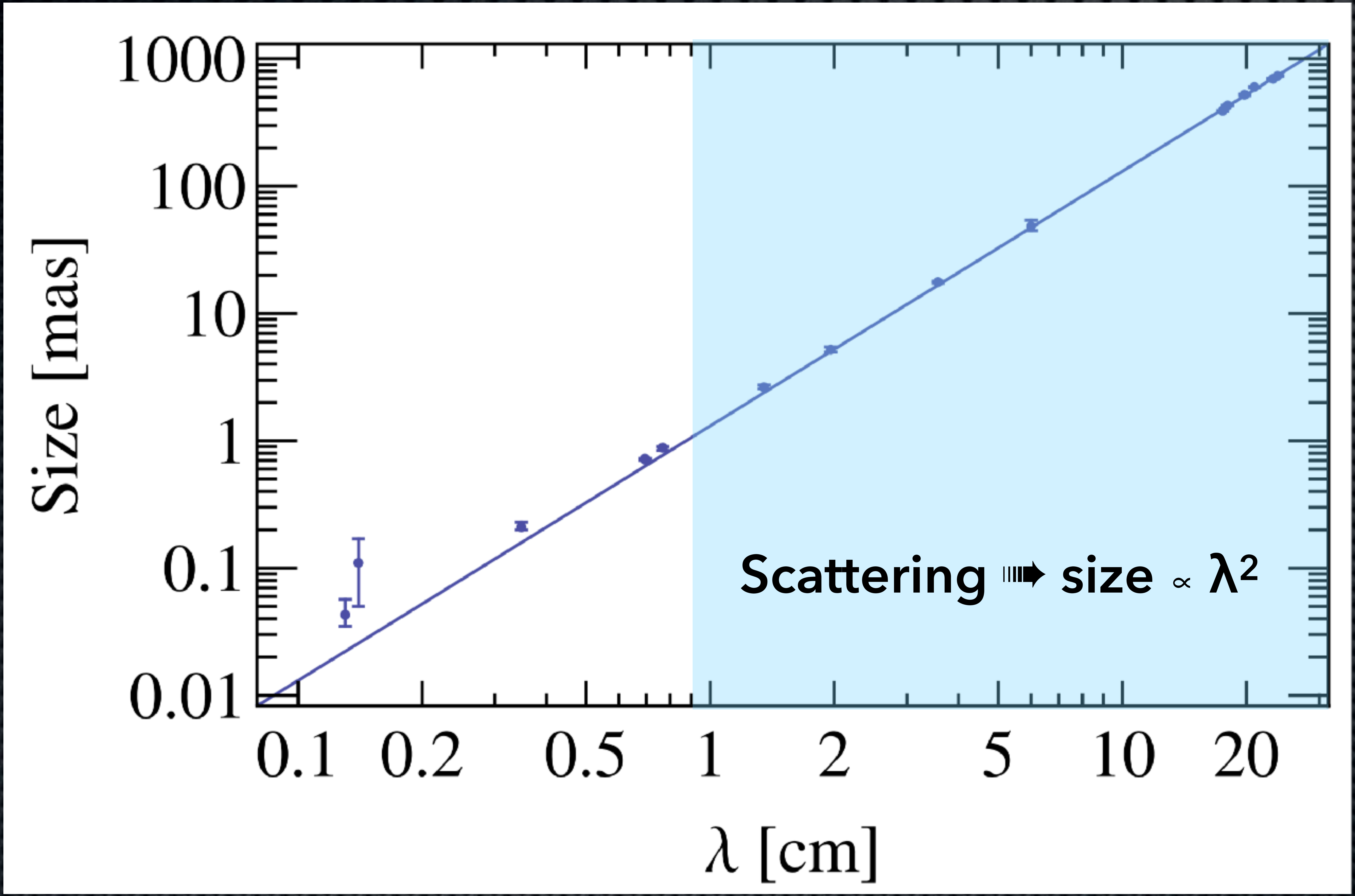
A promising black hole candidate: Sgr A*

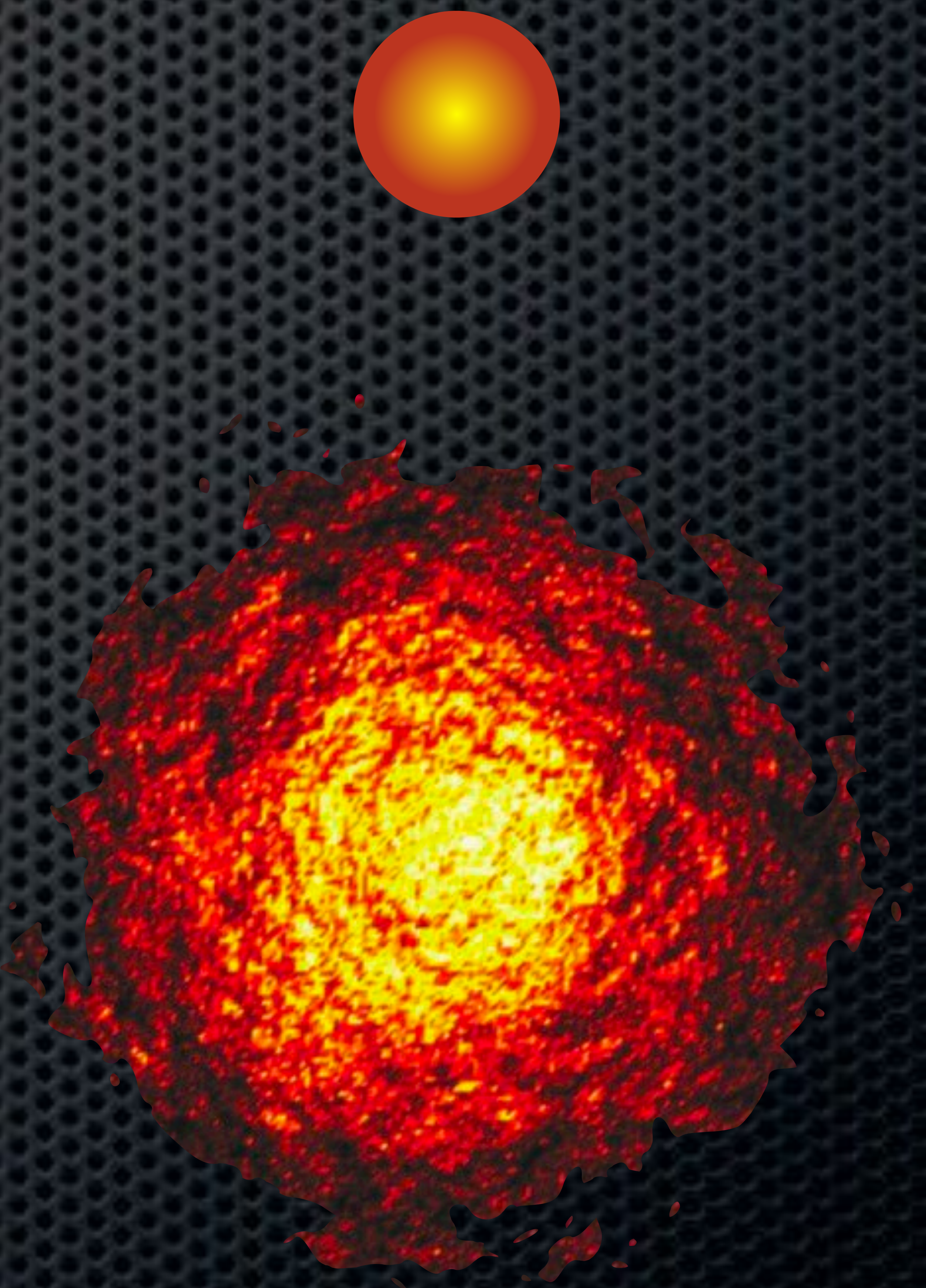
Current cm-wave radio VLBI arrays



- ★ EVN (10000 km), VLBA (8600km), EAVN (5000 km)
- ★ typically 0.1-few mas resolution
- ★ Hubble has ~50 mas for comparison

Sgr A*: the conspiracy of scattering vs. optical depth

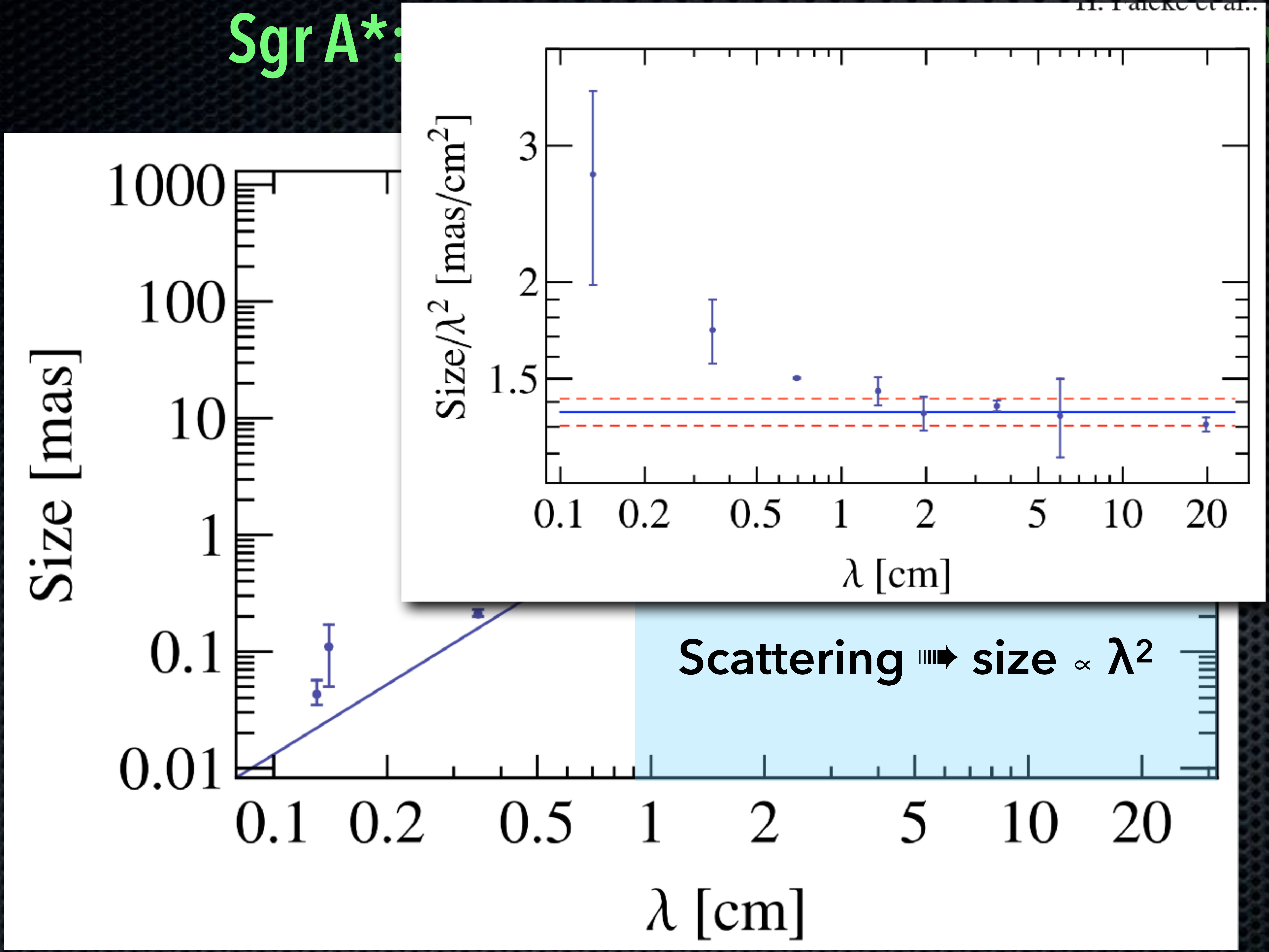




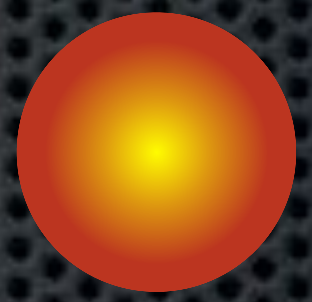
(M.Johnson/SAO)

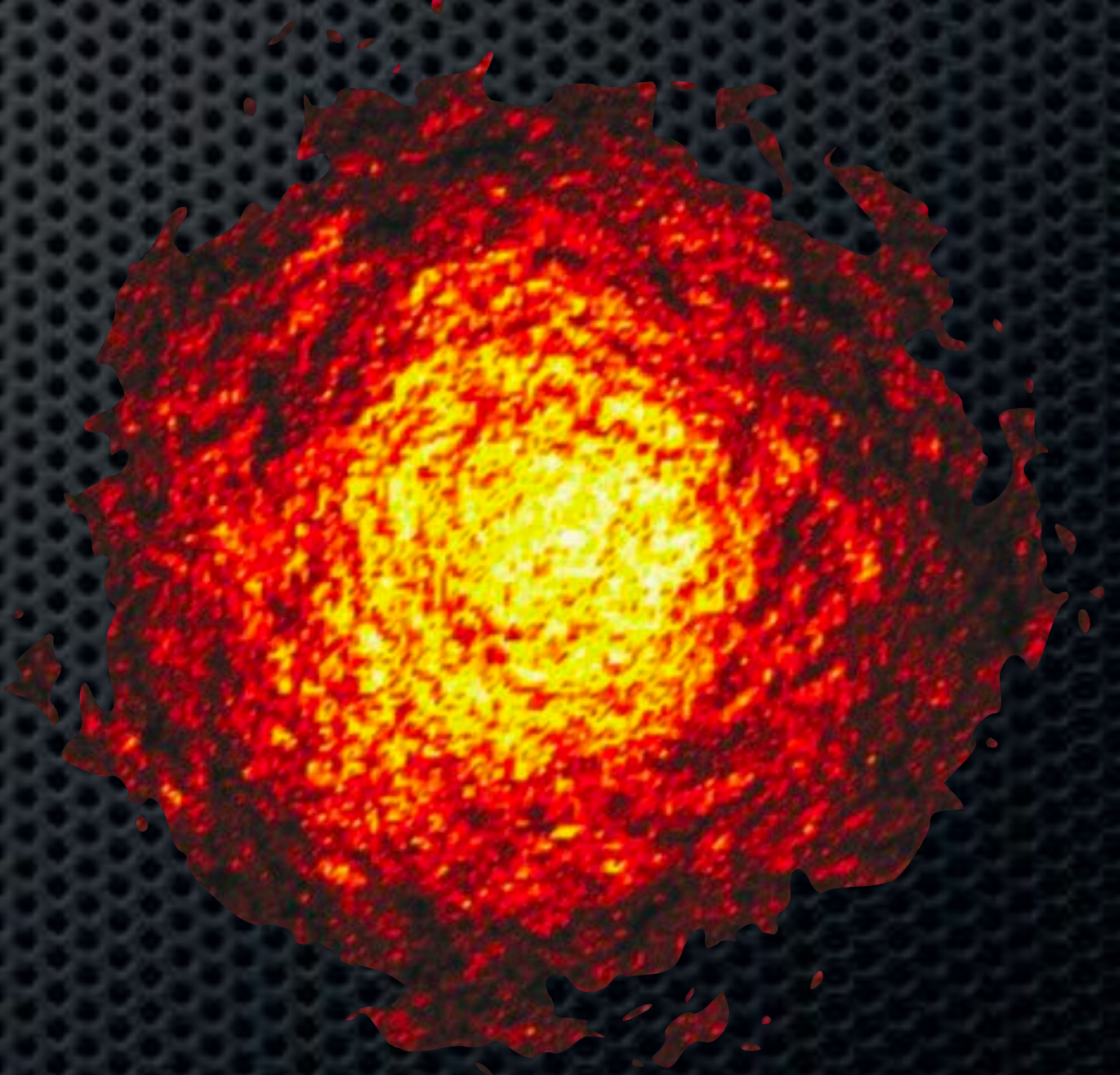
(Lo 1993; Bower et al. 2006,2008; Falcke, SM, Bower 2009, and references therein)

Sgr A*: tical depth



Scattering ➠ size $\propto \lambda^2$

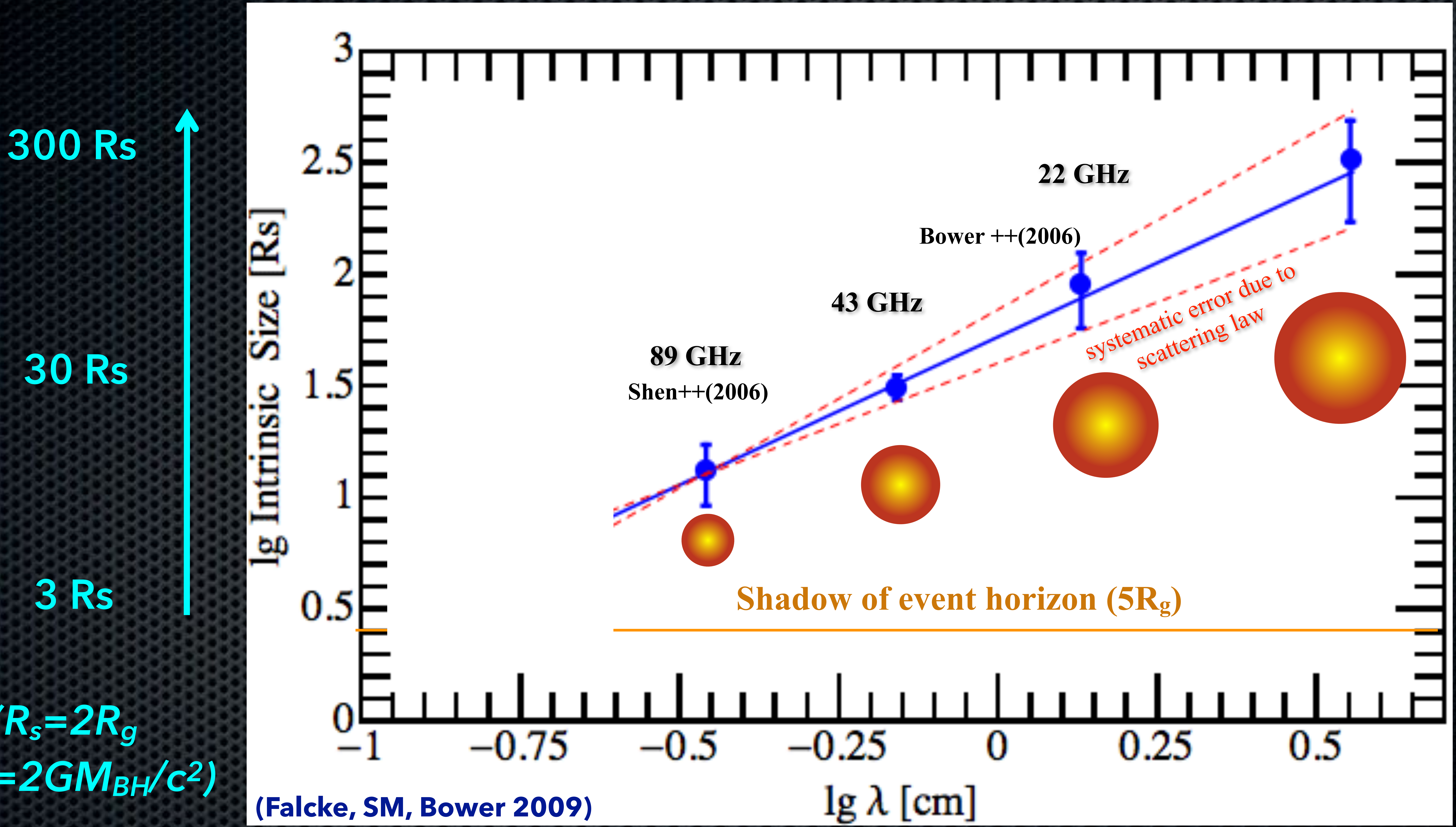




(M.Johnson/SAO)

(Lo 1993; Bower et al. 2006,2008; Falcke, SM, Bower 2009, and references therein)

Sgr A*: the conspiracy of scattering vs. optical depth



$(R_s = 2R_g = 2GM_{BH}/c^2)$

(Falcke, SM, Bower 2009)

What size telescope do you need @ 1mm?

Resolution of a telescope $\theta \sim \lambda/D \Rightarrow D_{40\mu as} > 5000\text{km}$, >20000km for 10µas!

$r_{shadow} = \sqrt{27}\, r_g \sim 5GM_{BH}/c^2$

$$\theta_{BH} = \frac{2\sqrt{27}GM}{c^2 D} = \left(\frac{M}{10^8 M_\odot}\right)\left(\frac{D}{10\text{Mpc}}\right)^{-1} \mu as$$

Equivalent to seeing the head of a pin (~1.5mm) in NYC from Marseille (~6300km)!!!

Sgr A* (GC)
Mass = $4 \times 10^6\ M_\odot$
D = 8.3 kpc
shadow ~ 50 µas*

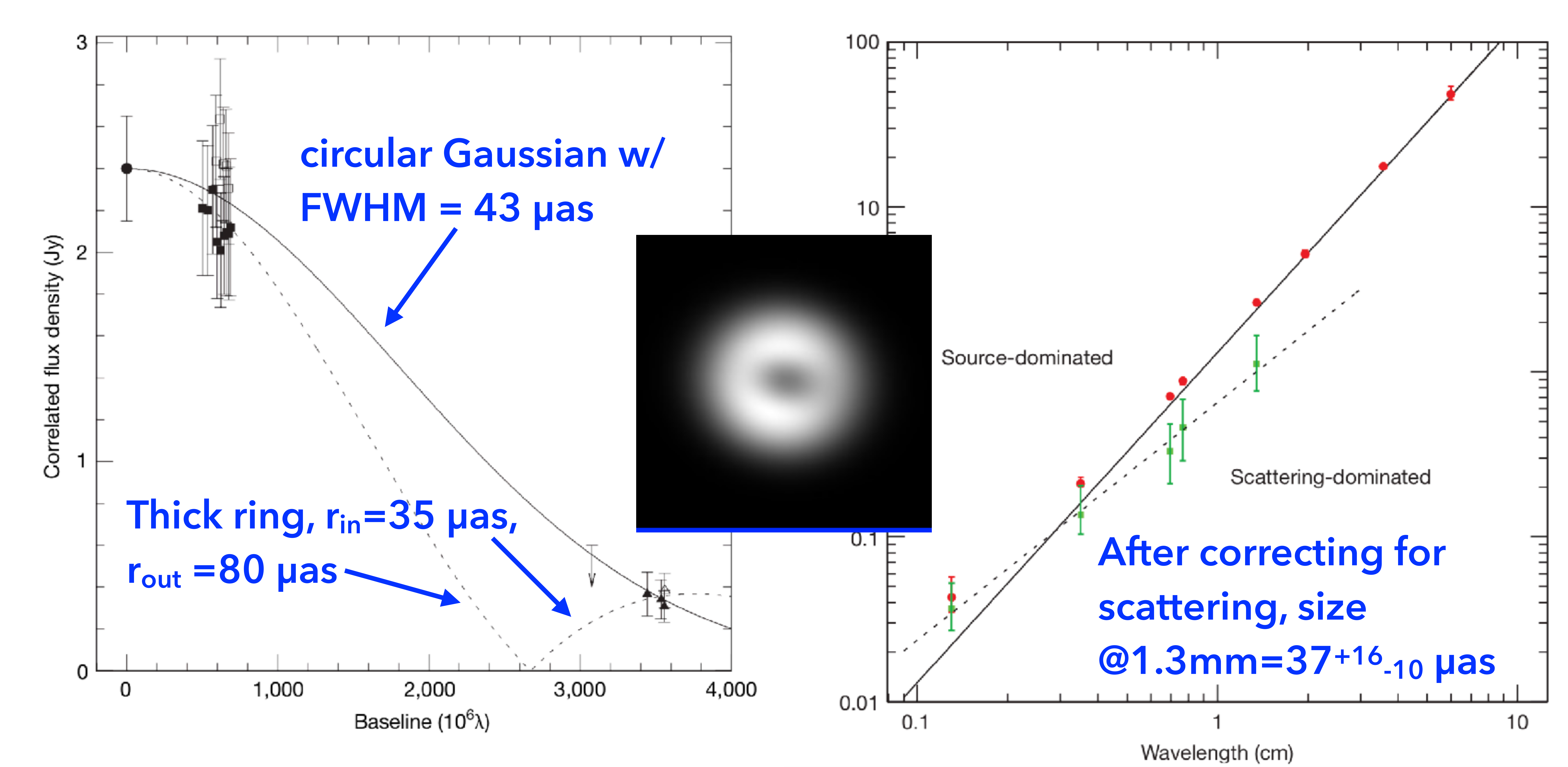
M87*
Mass = $6.7 \times 10^9\ M_\odot$
D = 16.4 Mpc
shadow ~ 40 µas

*1000x smaller than HST

First 'proof-of-concept' with 3 stations (SMT, CARMA, JCMT)

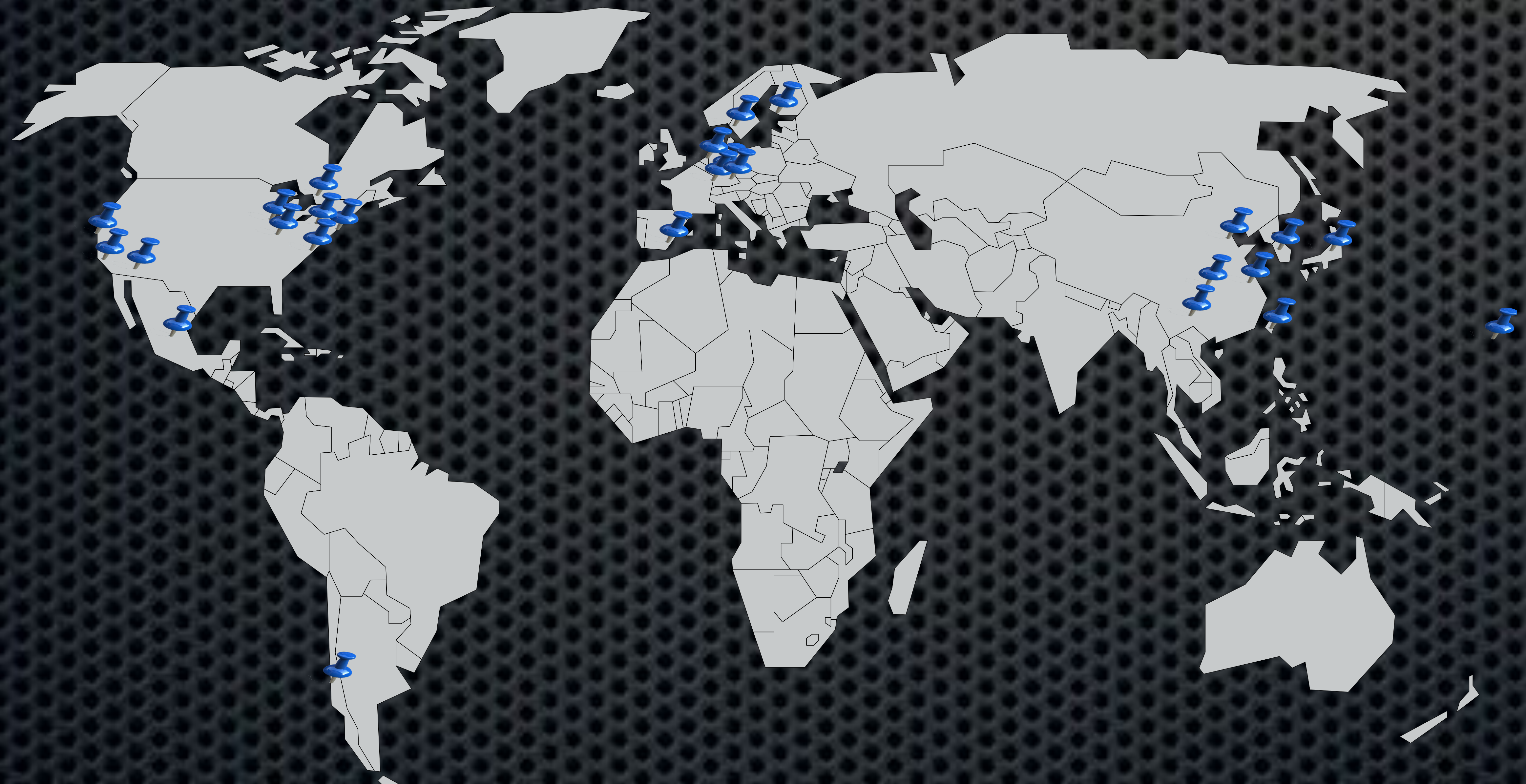
Doeleman++08, Nature

First 'proof-of-concept' with 3 stations (SMT, CARMA, JCMT)



Doeleman++08, Nature

Now EHT is a global project: ~40 institutes, ~300 members



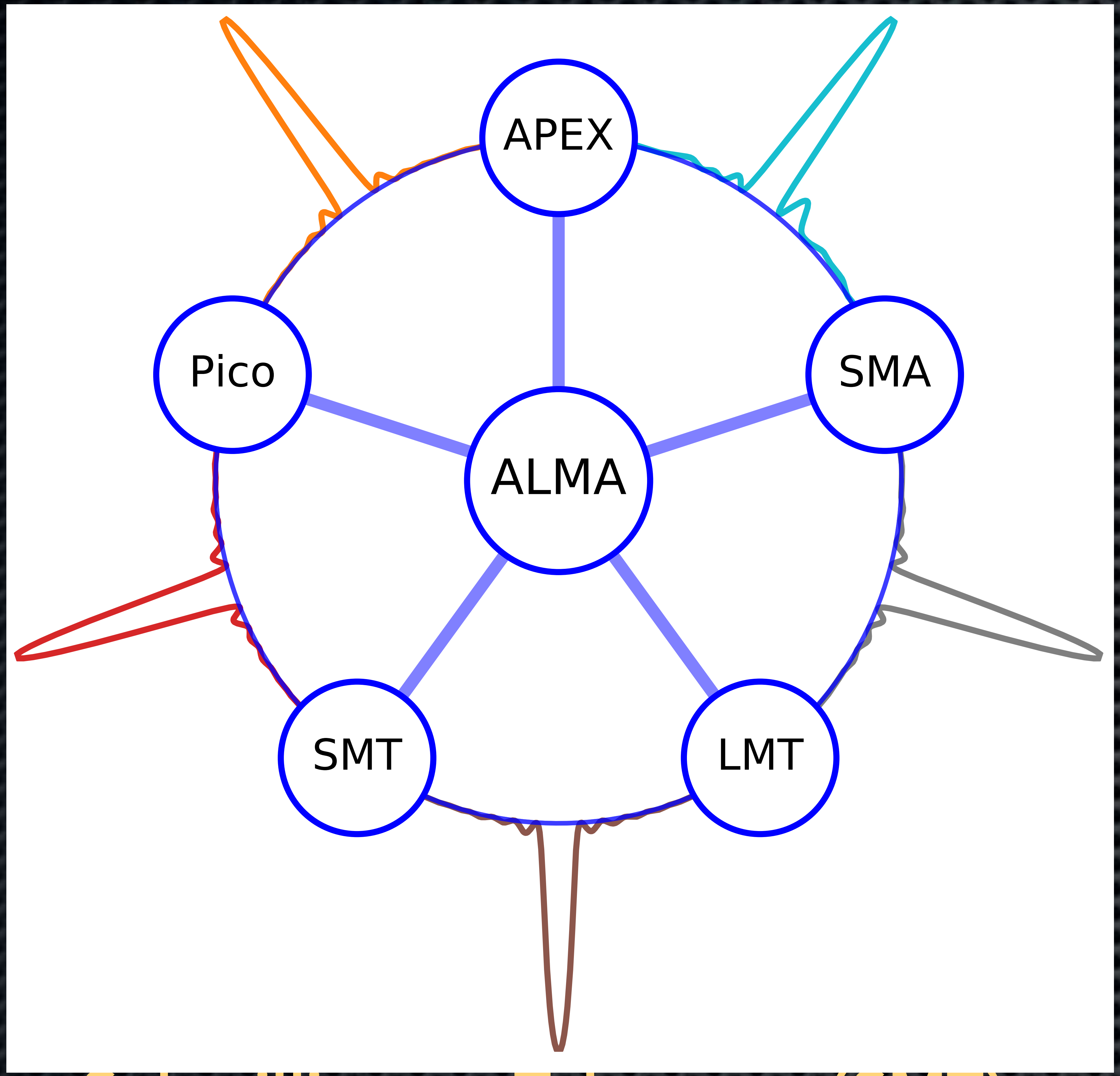
Aalto University
Universiteit van Amsterdam
Arizona Radio Observatory
Instituto de Astrofísica de Andalucía
Instituto Nacional de Astrofísica, Óptica y Electrónica
Institute for Astrophysical Research
Boston University
Brandeis University
University of California, Berkeley
California Institute of Technology
Chinese Academy of Sciences
Cologne University
Universidad de Concepción
Cornell University
Institute of High Energy Physics
Huazhong University of Science & Technology
University of Illinois
Joint Institute for VLBI ERIC
Kavli Institute for Astronomy and Astrophysics
Korea Astronomy and Space Science Institute
Leiden University
University of Maryland
University of Massachusetts Amherst
Max Planck Institute for Extraterrestrial Physics
Nanjing University
National Astronomical Observatories of China
Onsala Space Observatory
Peking University
Purple Mountain Observatory
University of Science and Technology
University of Science and Technology of China
Seoul National University
Shanghai Astronomical Observatory
Institute of Statistical Mathematics
University of Waterloo
Yunnan Observatory

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

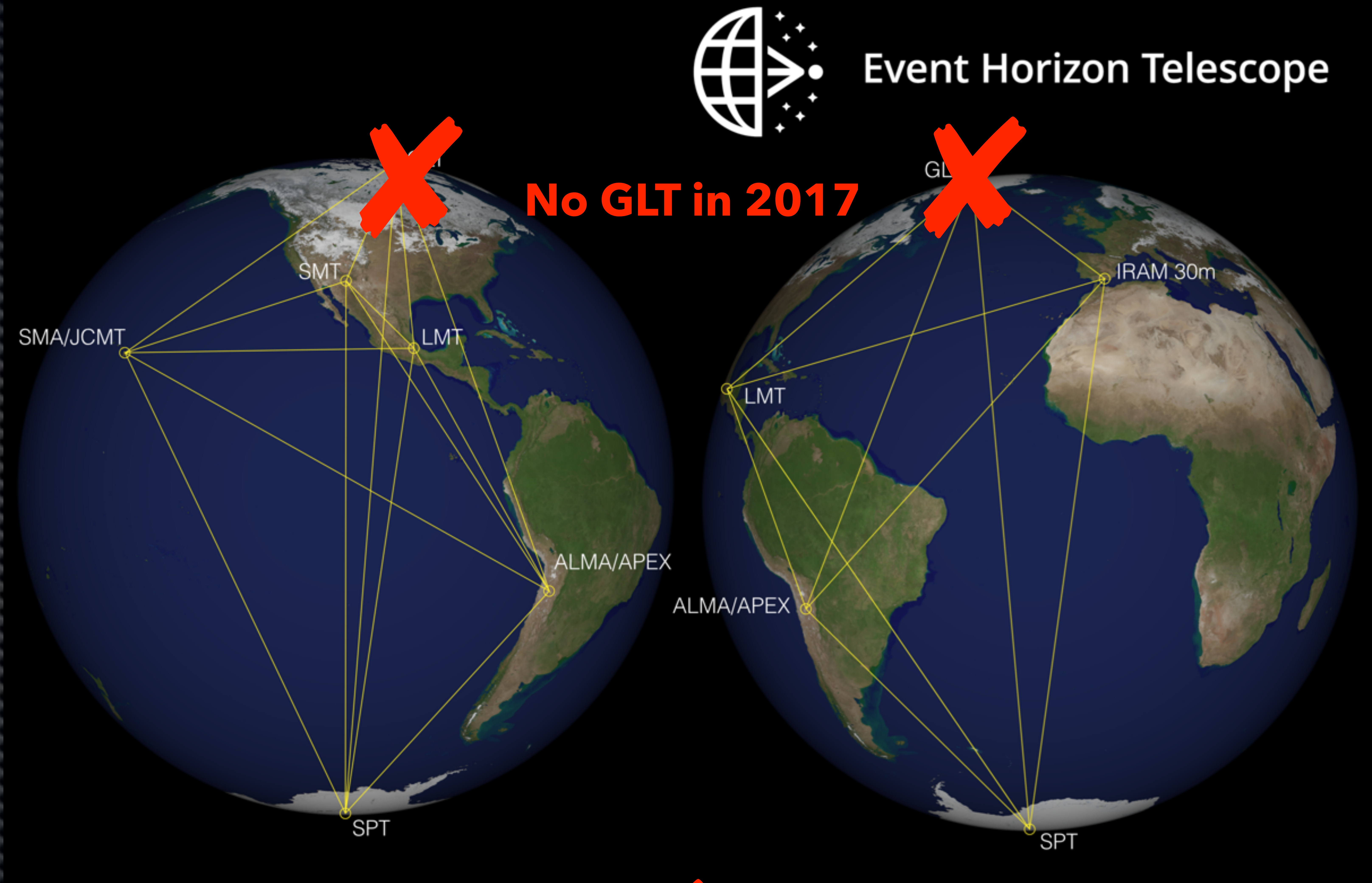
- Atacama Large Millimeter Array (ALMA), Chile
- ALMA Pathfinder Experiment (APEX), Chile
- James Clerk Maxwell Telescope (JCMT), Hawaii
- Large Millimeter Telescope (LMT), Mexico
- IRAM 30-meter Telescope, Spain
- South Pole Telescope (SPT), South Pole
- Submillimeter Array (SMA), Hawaii
- Submillimeter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

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

- Atacama Large Millimeter Array (ALMA), Chile

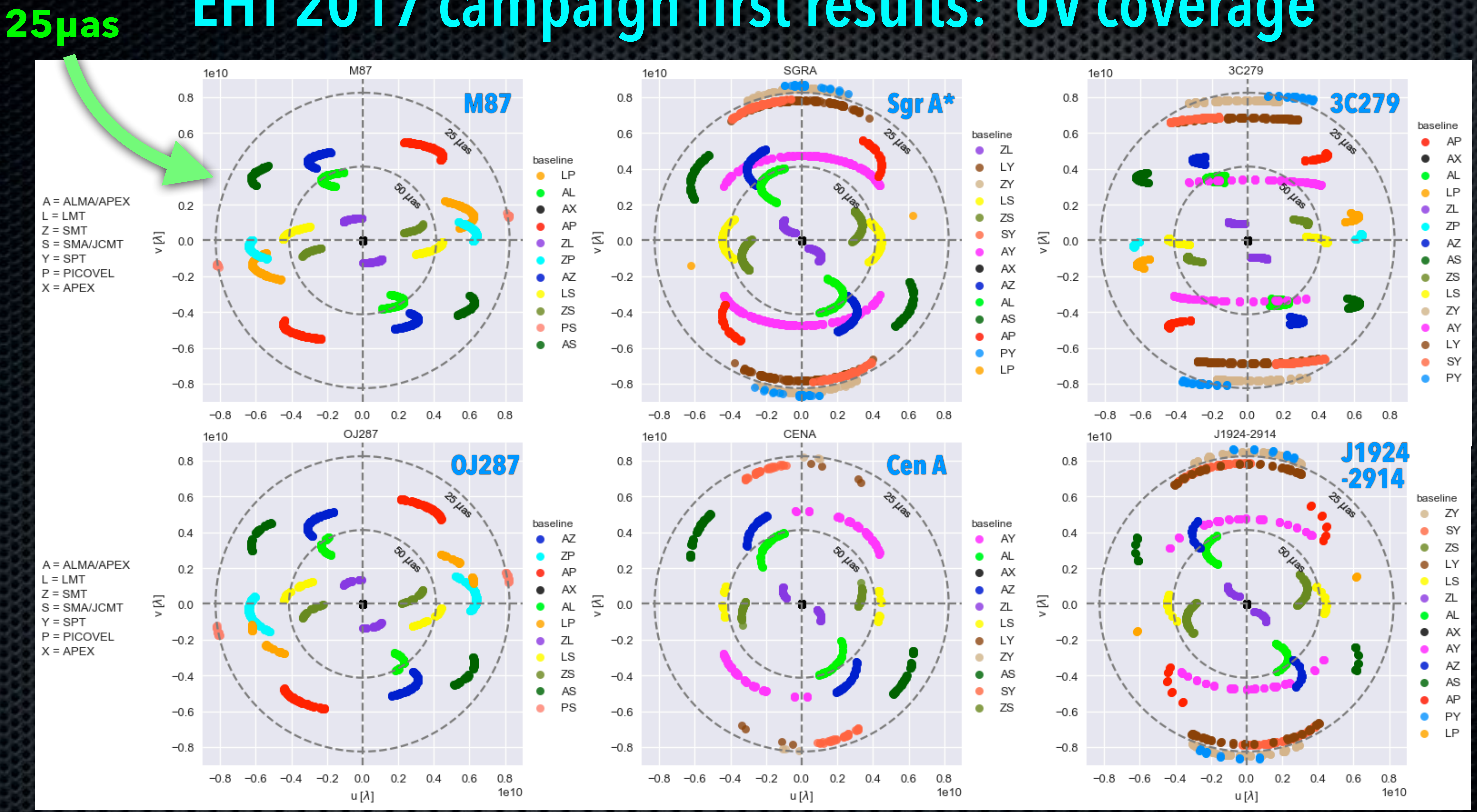


- Submillimeter Telescope (SMT), Arizona



How EHT works in practice

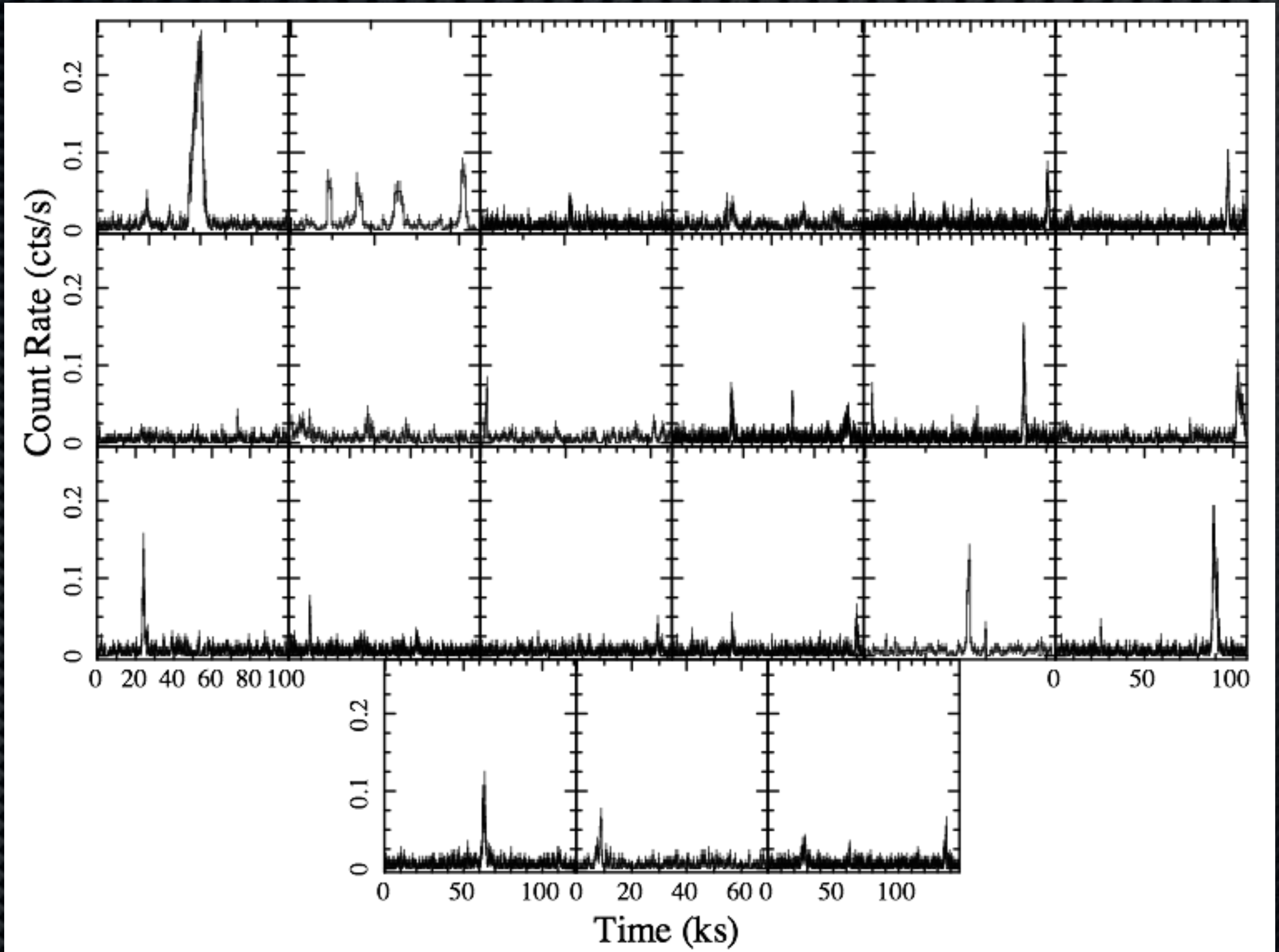
EHT 2017 campaign first results: UV coverage



~ 7 PB of data @ 32GB/s recording rate!

Why did we do M87 first??

Sgr A* variability: Roughly daily nonthermal IR/Xray flares

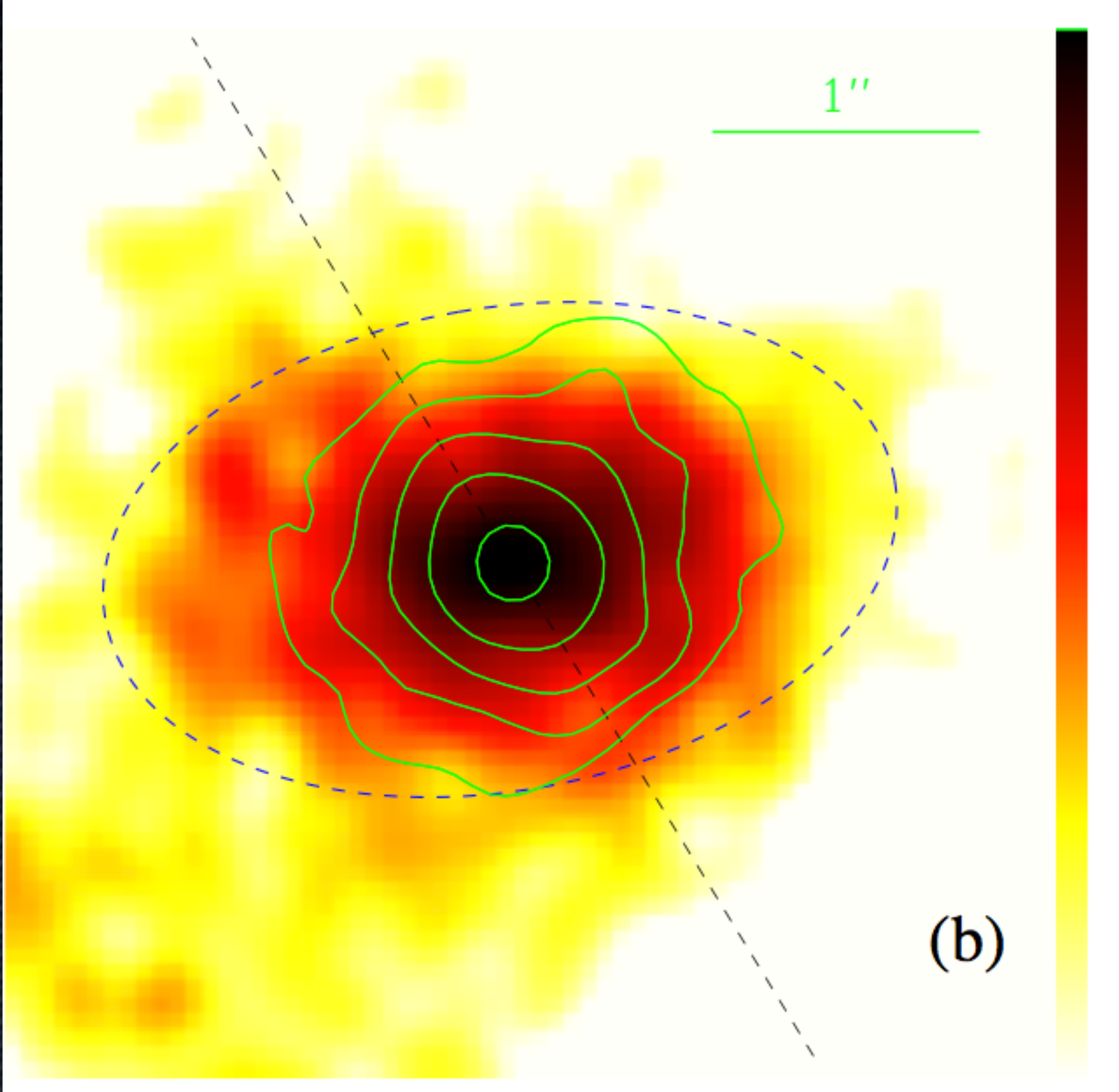


(Dodds-Eden 2009; Witzel++ 2012; 18; Nielsen++ 2013, Nielsen, SM++ 2015; Dibi, SM++2014; Dibi, SM, Nielsen++2016)

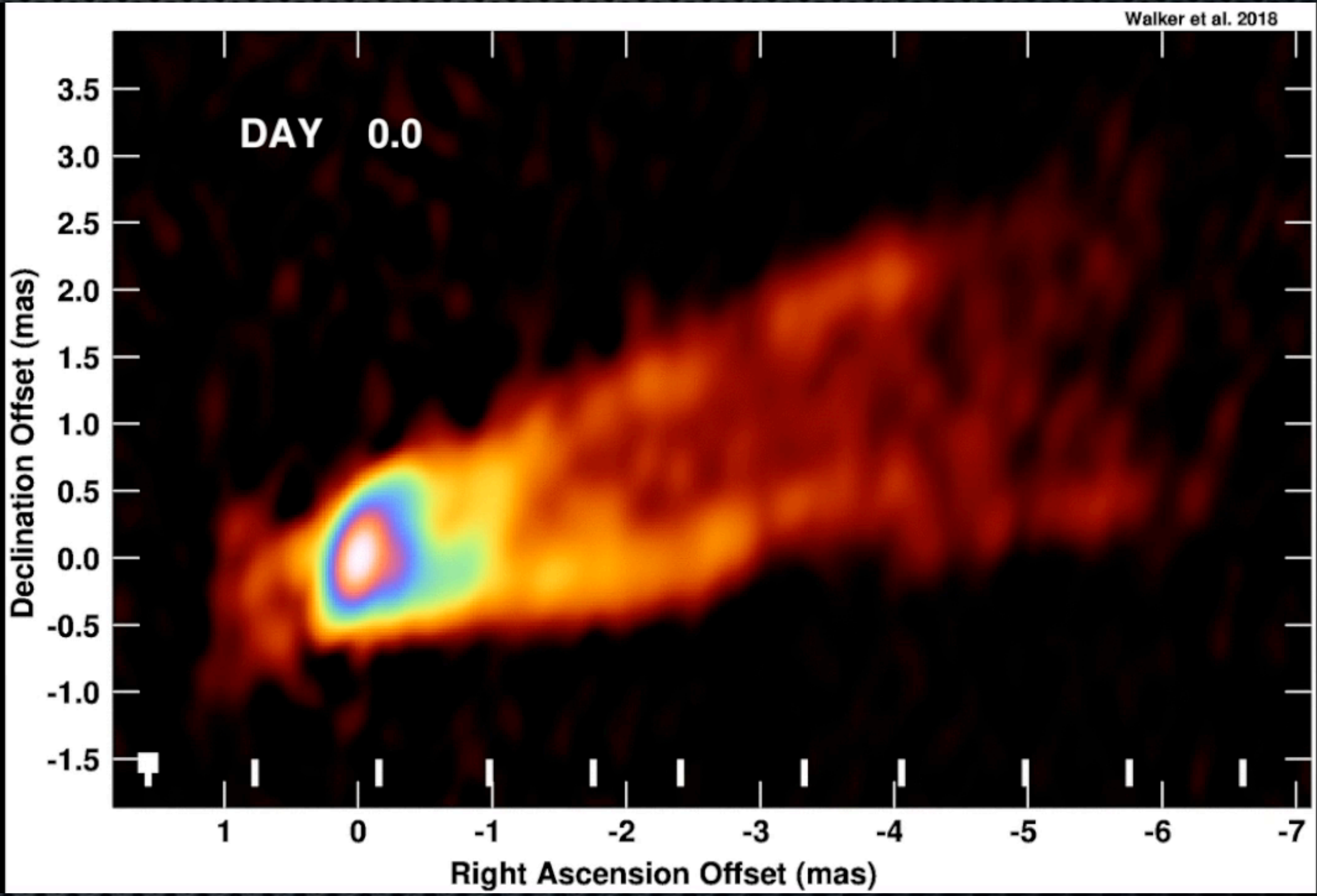
Understanding black hole duty cycles: Sgr A* vs M87

Sgr A* @ 10^{-9} L_{Edd}
Xray image of inflow but no jets!

M87 @ 10^{-5} L_{Edd}
VLBI + EHT image of jets, but no disk info

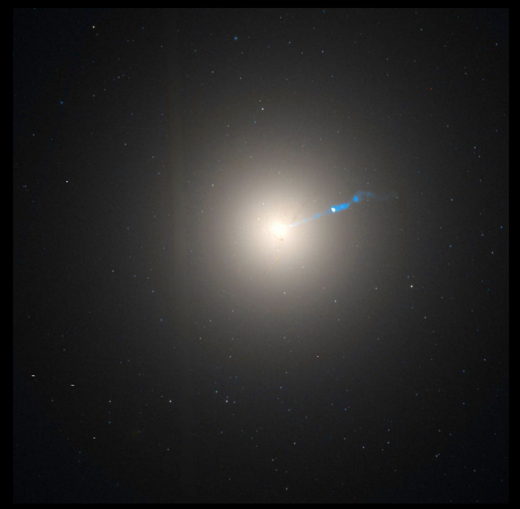


(Wang, Nowak, SM++, Science, 2013)

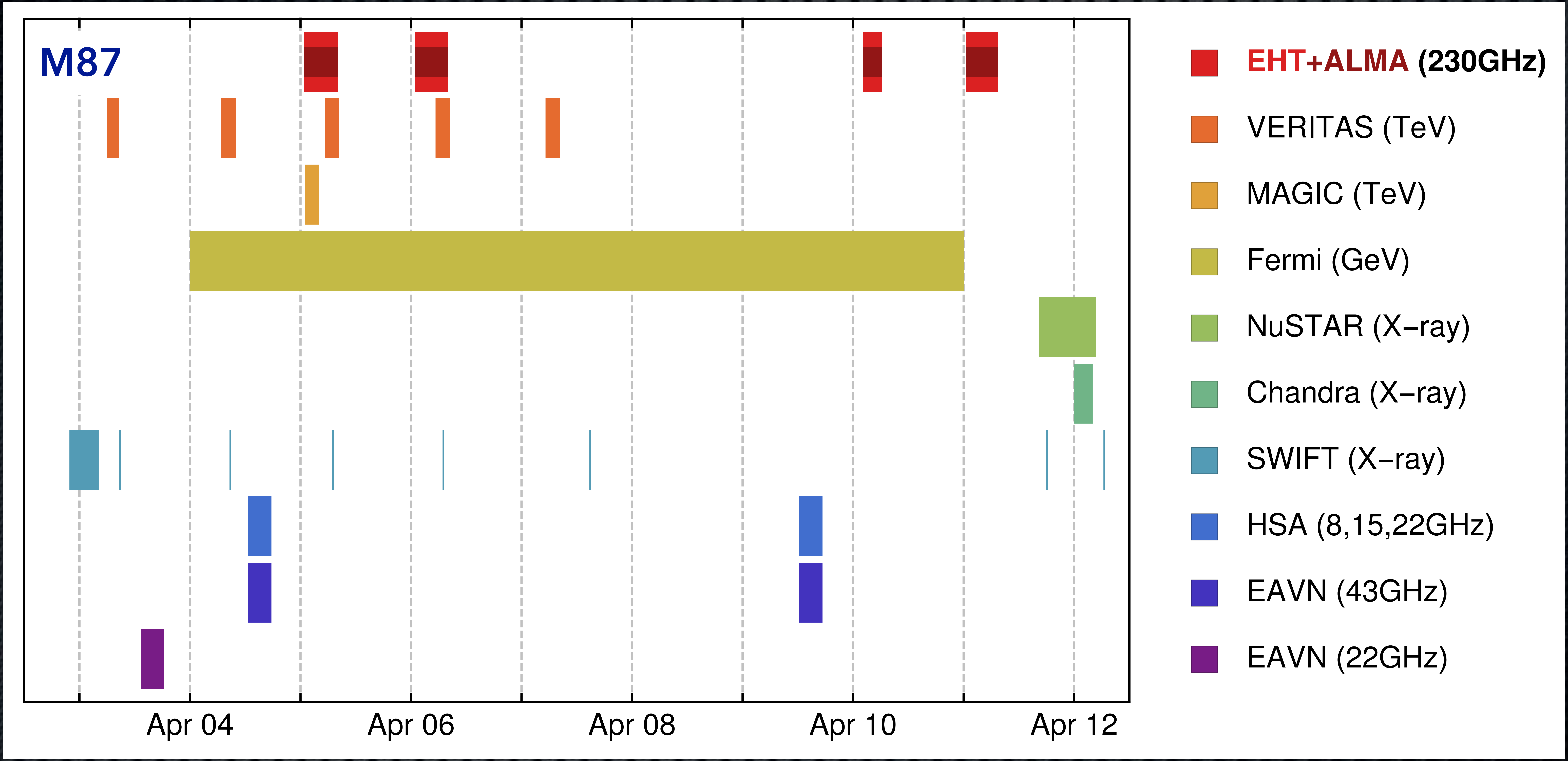


(Kim++2018; Walker++2007;2018; Hada++14,16,18; Acciari++10; Abramowski++12, etc.)


Chandra X-Ray
VLA Radio
HST Optical



Multiwavelength WG (coordinators: SM, Kazuhiro Hada)



(M. Johnson, J. Farah/UMass, for EHT MWL WG)

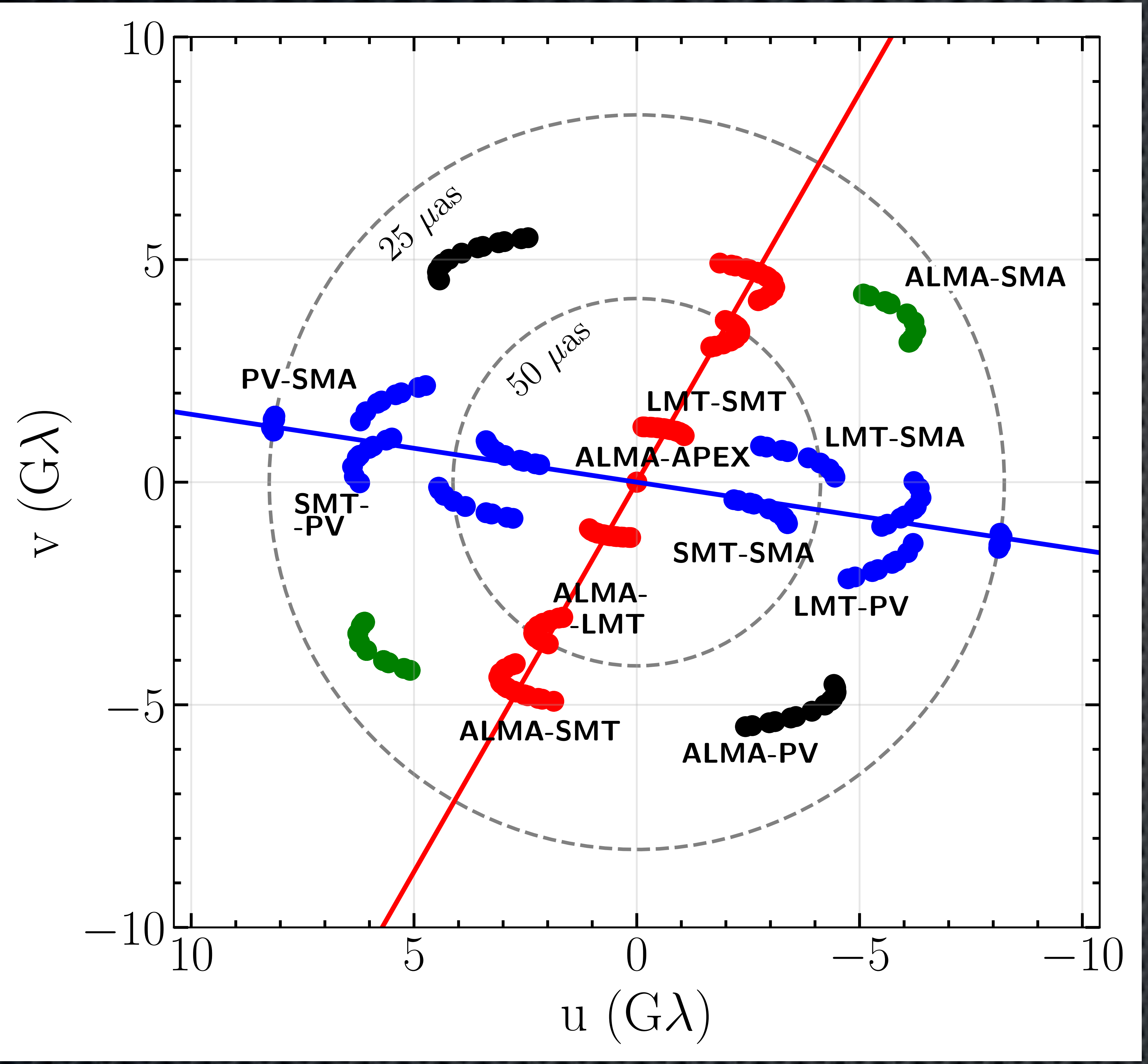
First EHT Results!

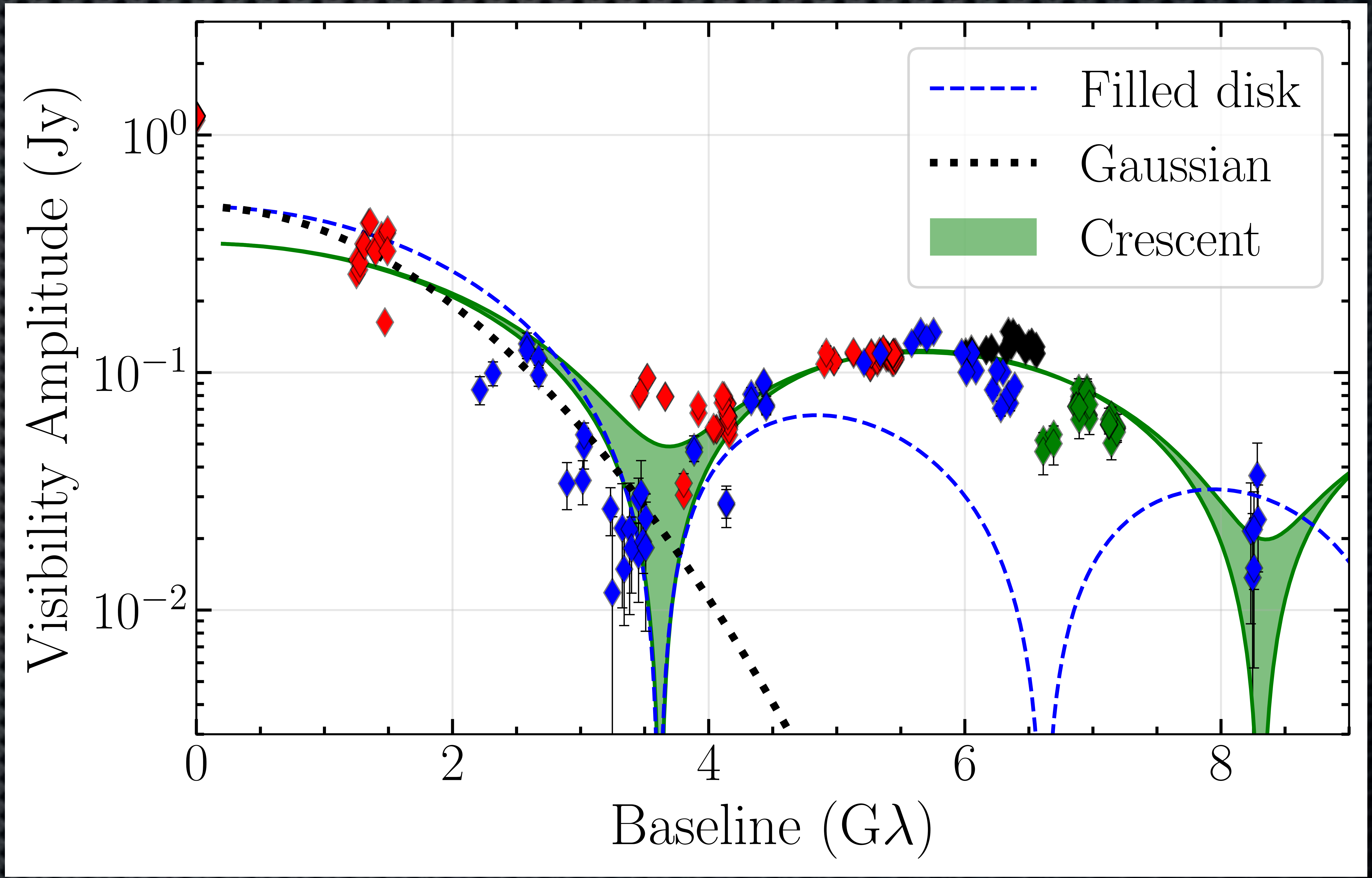
Paper VI: quantify M87 source properties

Writing team:
K. Asada, G. Bower, A. Broderick, A. Chael,
J. Dexter, B. Georgiev, B. Jeter, S. Markoff, C. Ni,
F. Özel, D. Pesce, D. Psaltis, P. Tiede, T. Trent

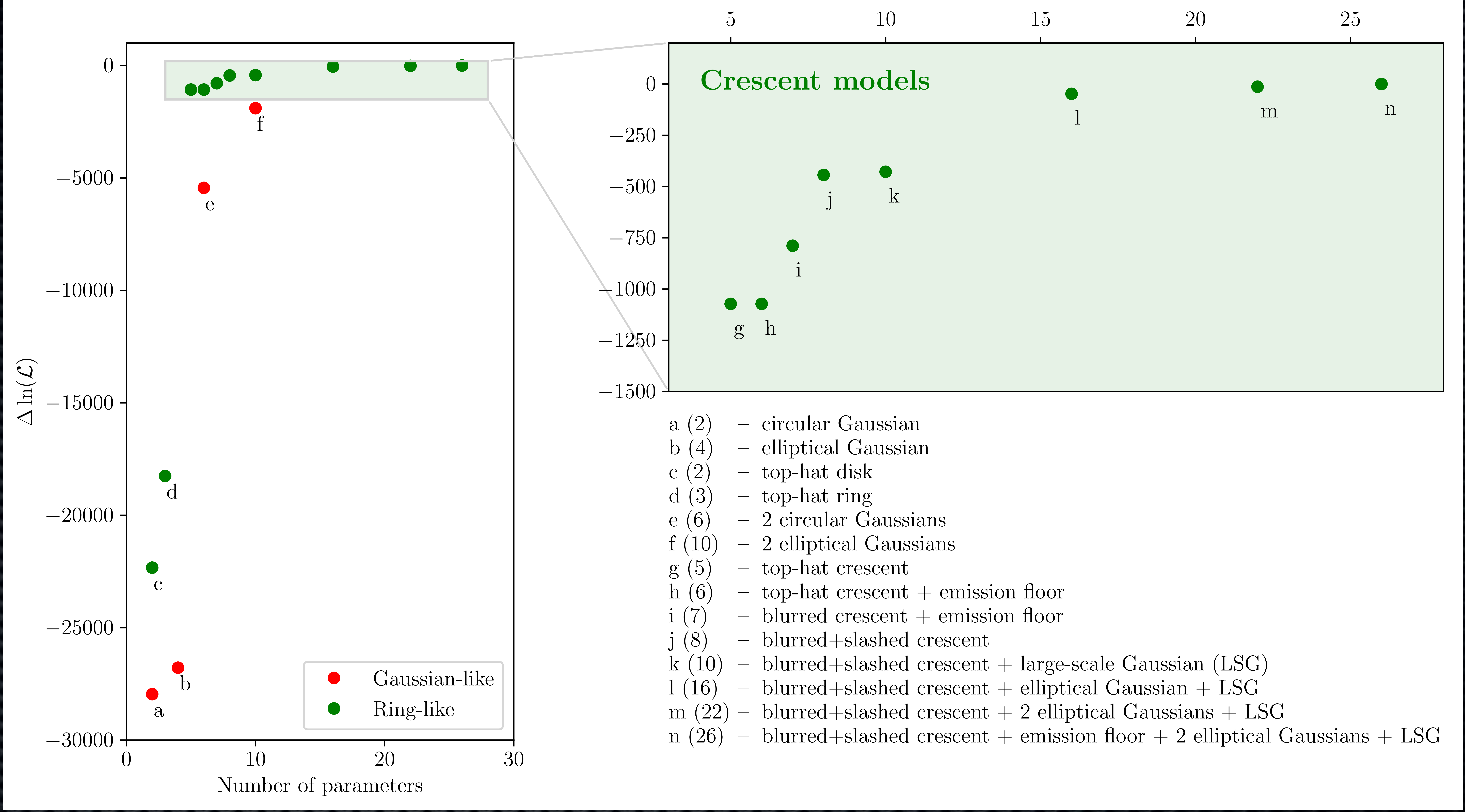
小红书
淘宝
Trending in Beijing: Black Hole Memes, SOHO's Ba
theyhadsomuchpotential
Schooley
@Rschooley
Second picture of black hole.
WHAT BREXIT LOOKS LIKE FROM SPACE
DEAL APPEARS AS FAR, FAR AWAY AS THIS BLACK
HELPLESS MAY SUCKED INTO THE BRUSSELS VO
×400%
×300%
×200%
×100%

Visibility data consistent with an asymmetric ring ("crescent")

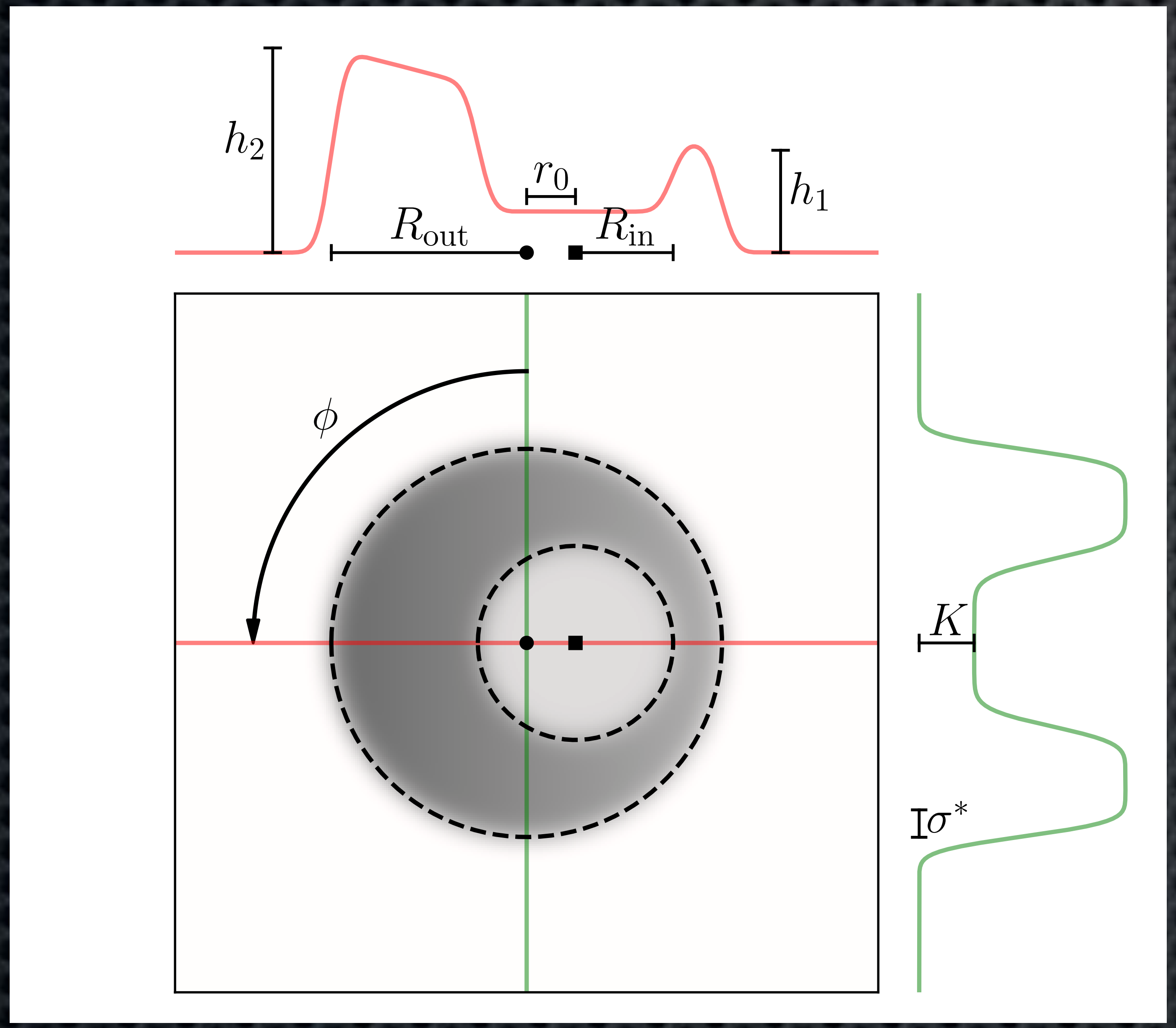


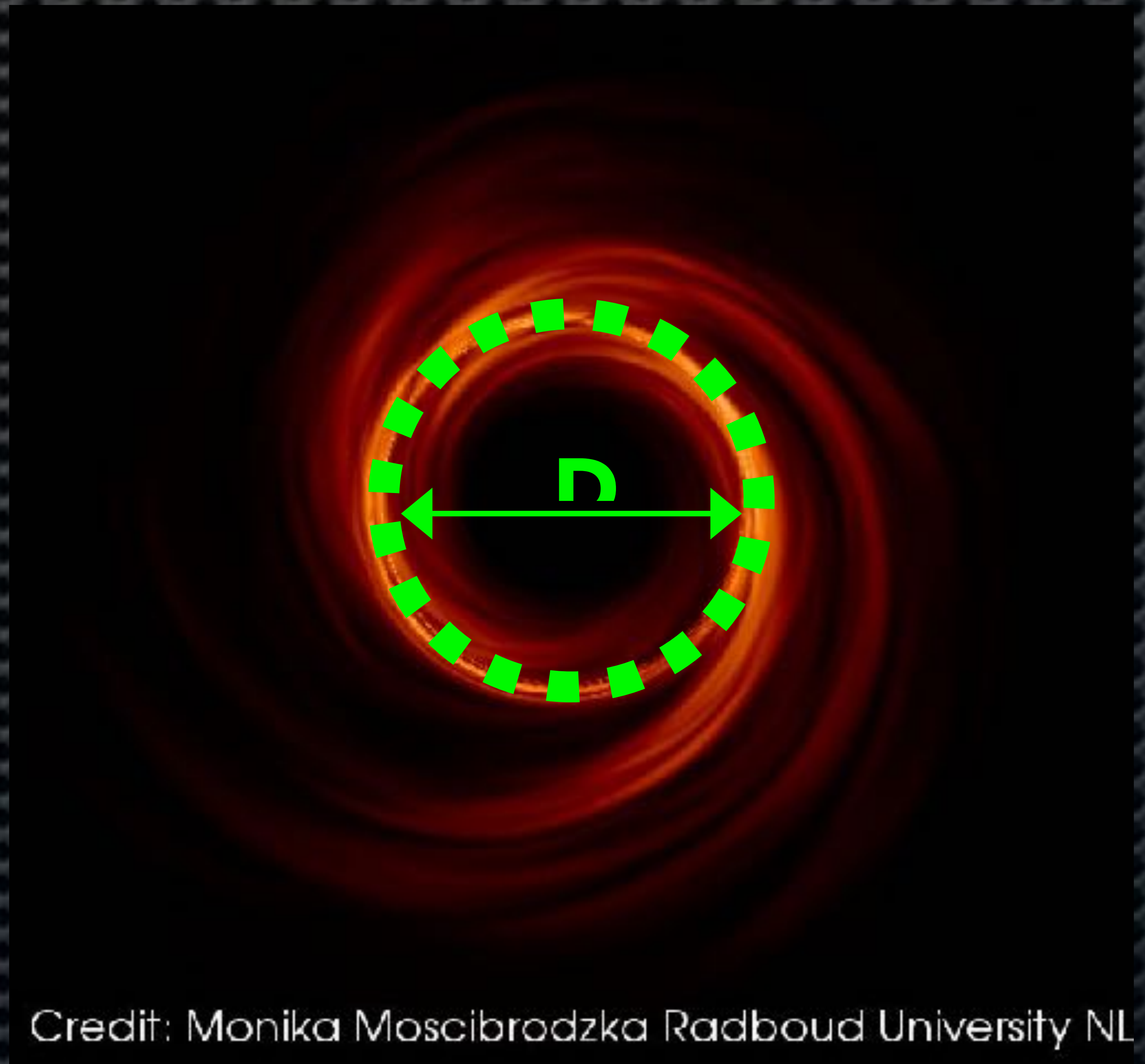


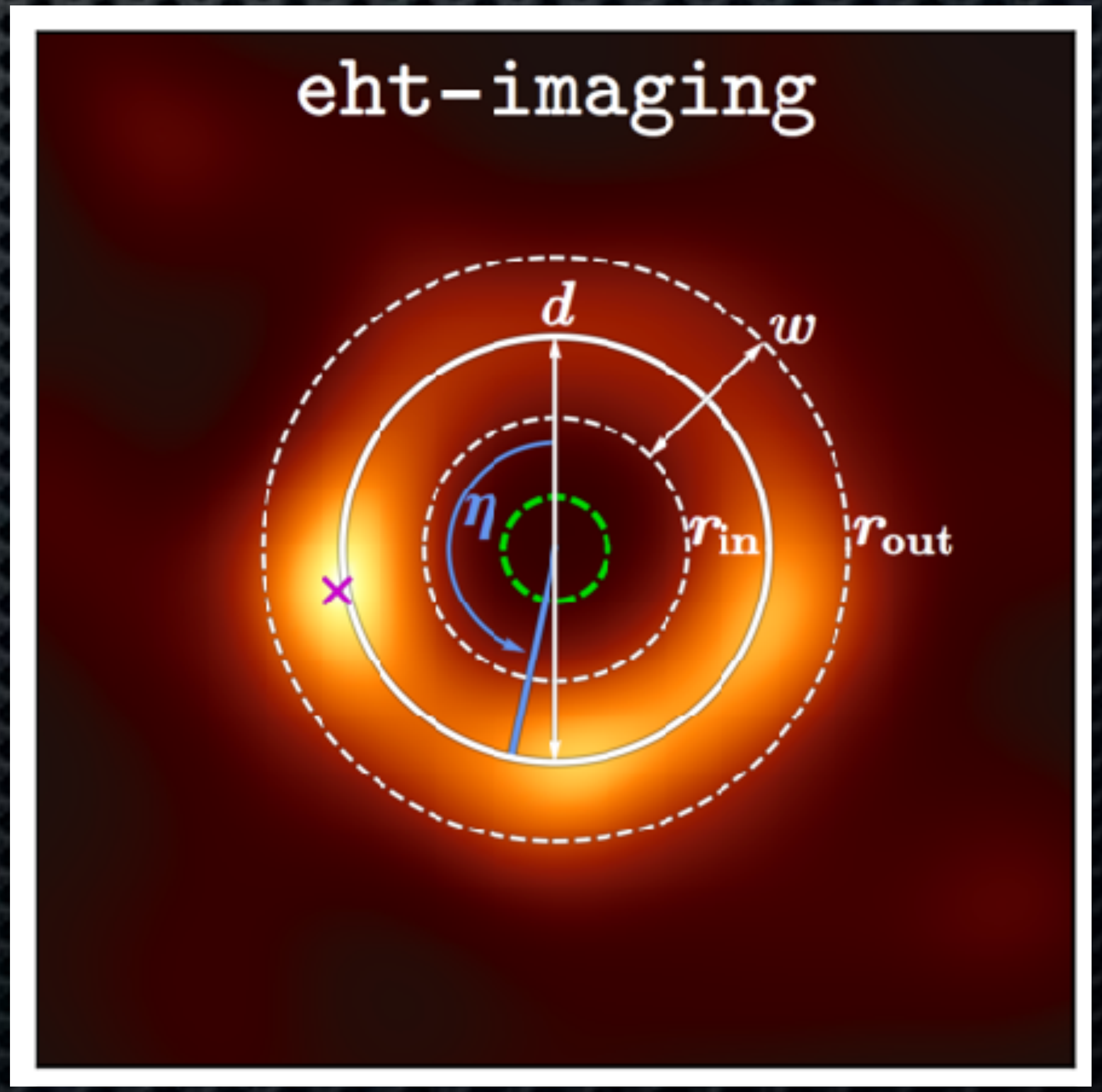
Geometric model fitting: crescents overwhelmingly preferred



Three methods to extract the black hole mass in M87



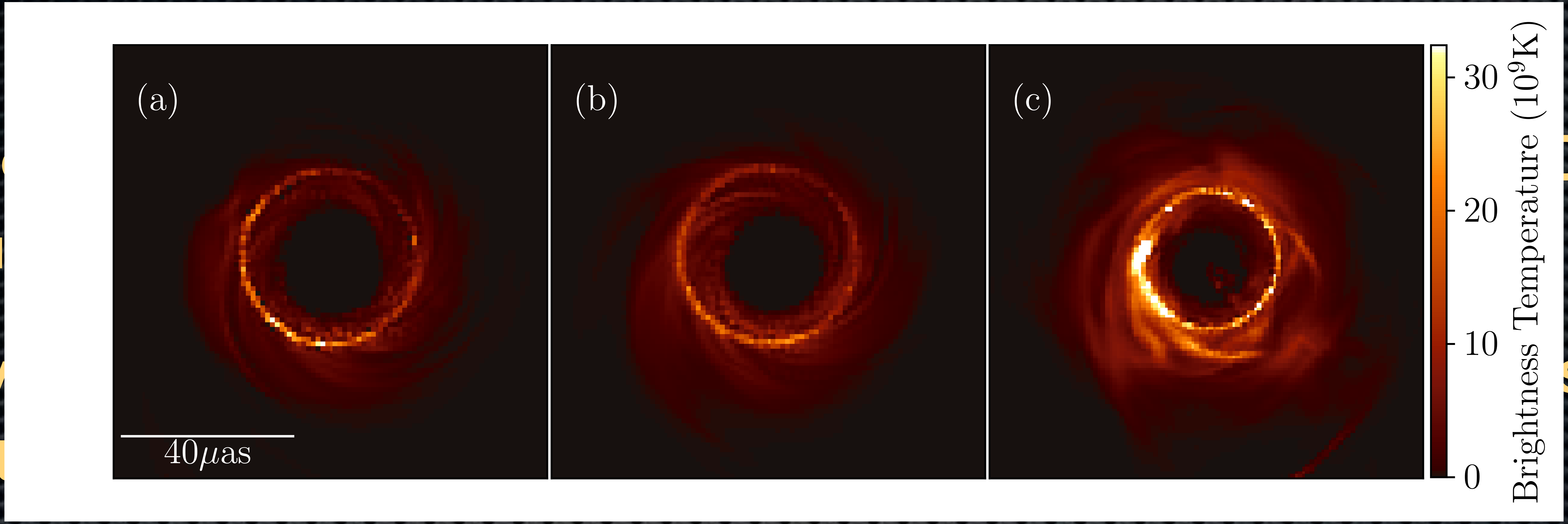




From diameter to black hole mass

- Observed diameter should scale with $\theta_g = GM/Dc^2$ (=M/D in natural units!) ➠ $d = \alpha\theta_g$
- Naive approach: assume measured diameter corresponds to photon ring, α = 9.6-10.4 (Johannsen & Psaltis 2010)
- GRMHD models show bright photon ring, but also extra emission
- Calibrate α by fitting geometric models to a set of GRMHD models where θ_g is known: α = 11.5 +/- 10%

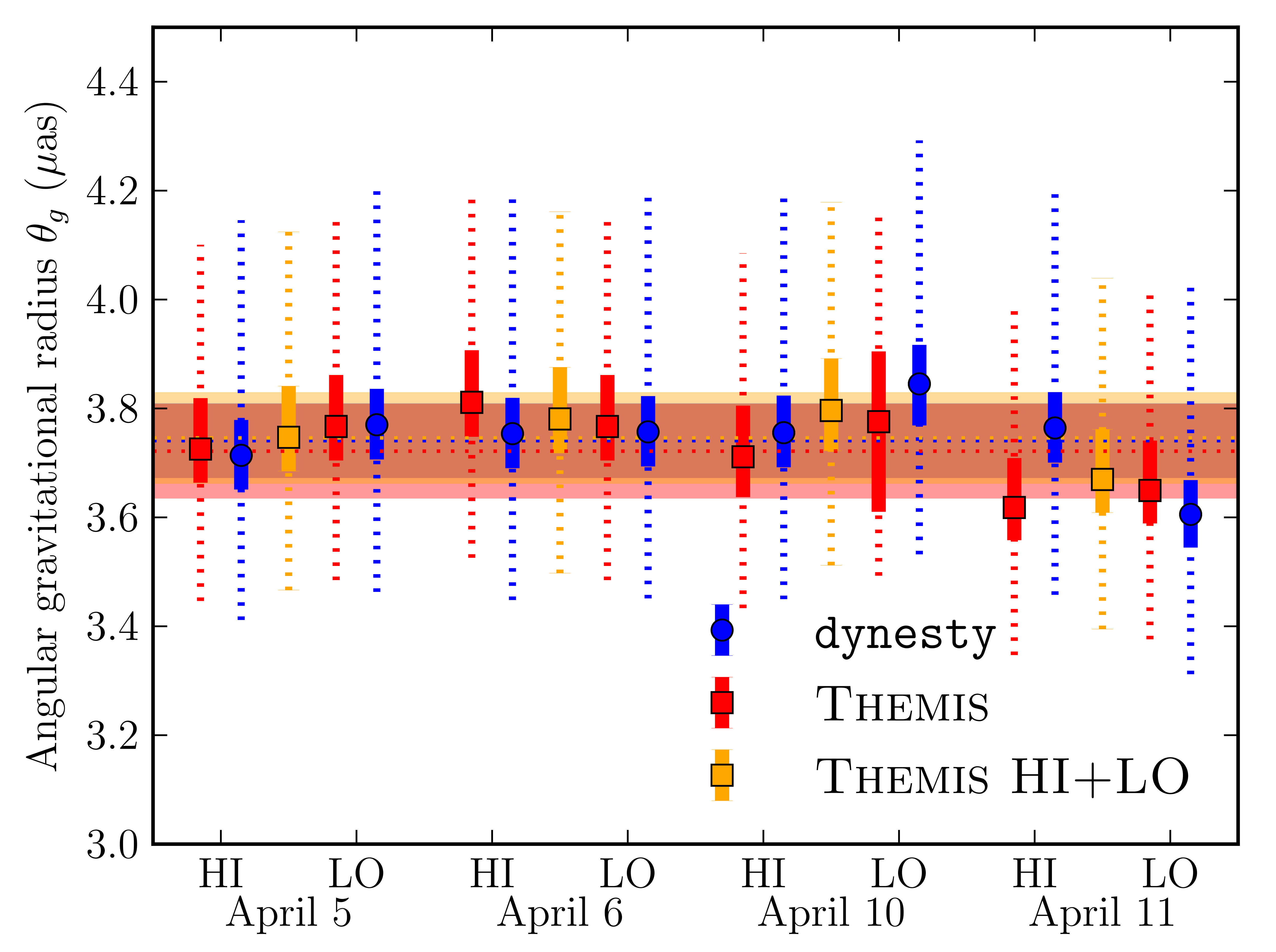
From diameter to black hole mass



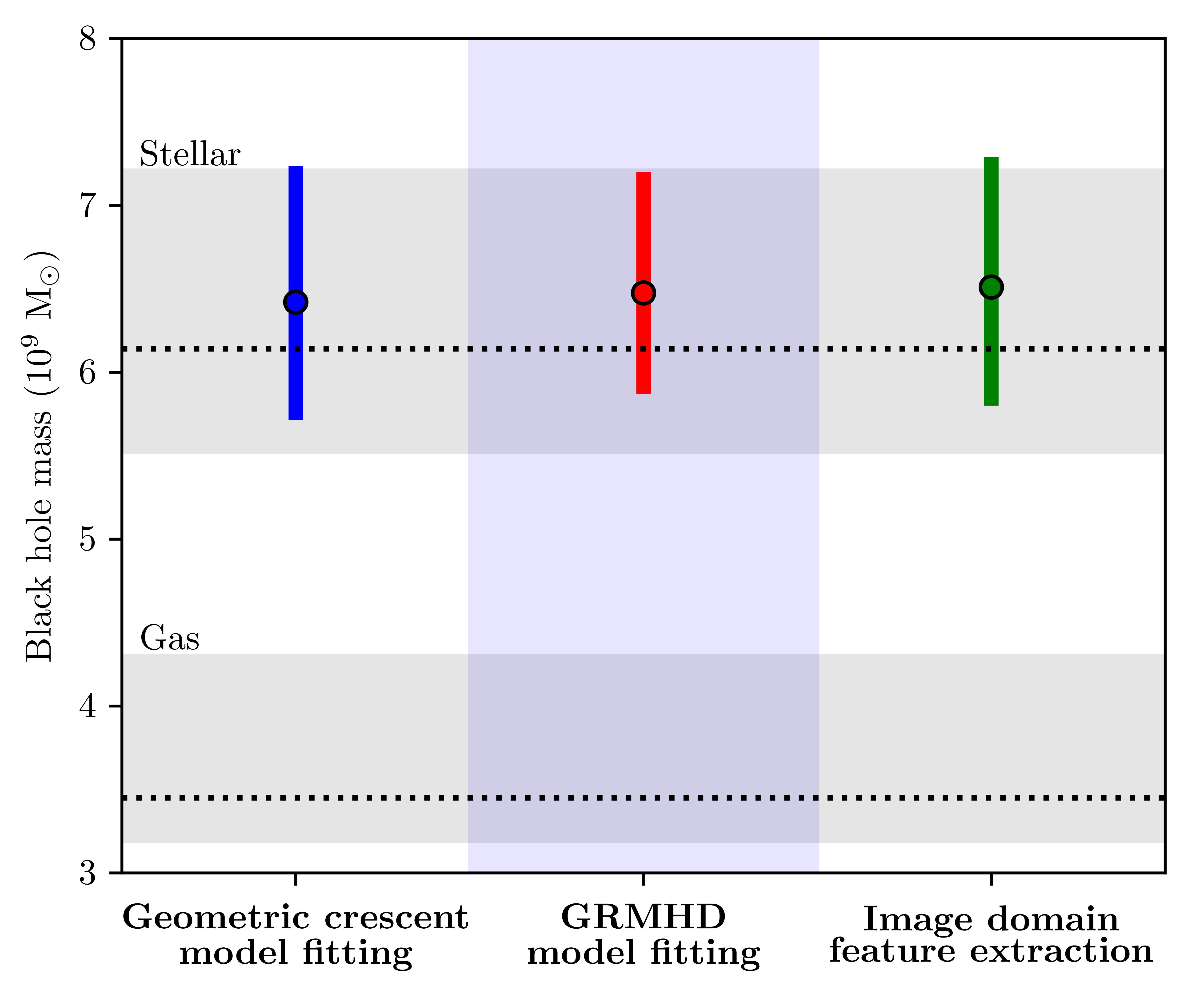
- Obs… D in natu…
- Naiv… s to phot…
- GRMHD models show bright photon ring, but also extra emission
- Calibrate α by fitting geometric models to a set of GRMHD models where θ_g is known: α = 11.5 +/- 10%

From diameter to black hole mass

- Using α, D = 16.8 ± 0.7 Mpc, convert constraints on d ⇒ θ_g
- Systematic "theory" error (~10%) dominates over distance error

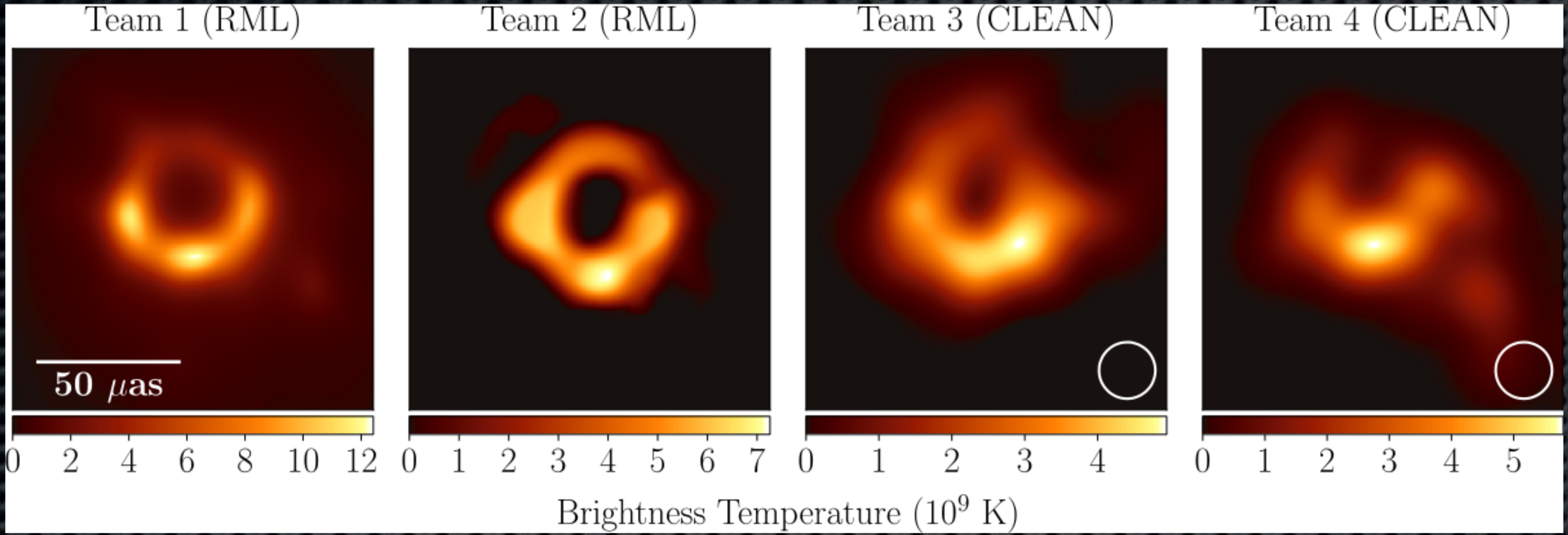


All three methods agree for M87's black hole



$(6.5 \pm 0.7) \times 10^9\ M_\odot$

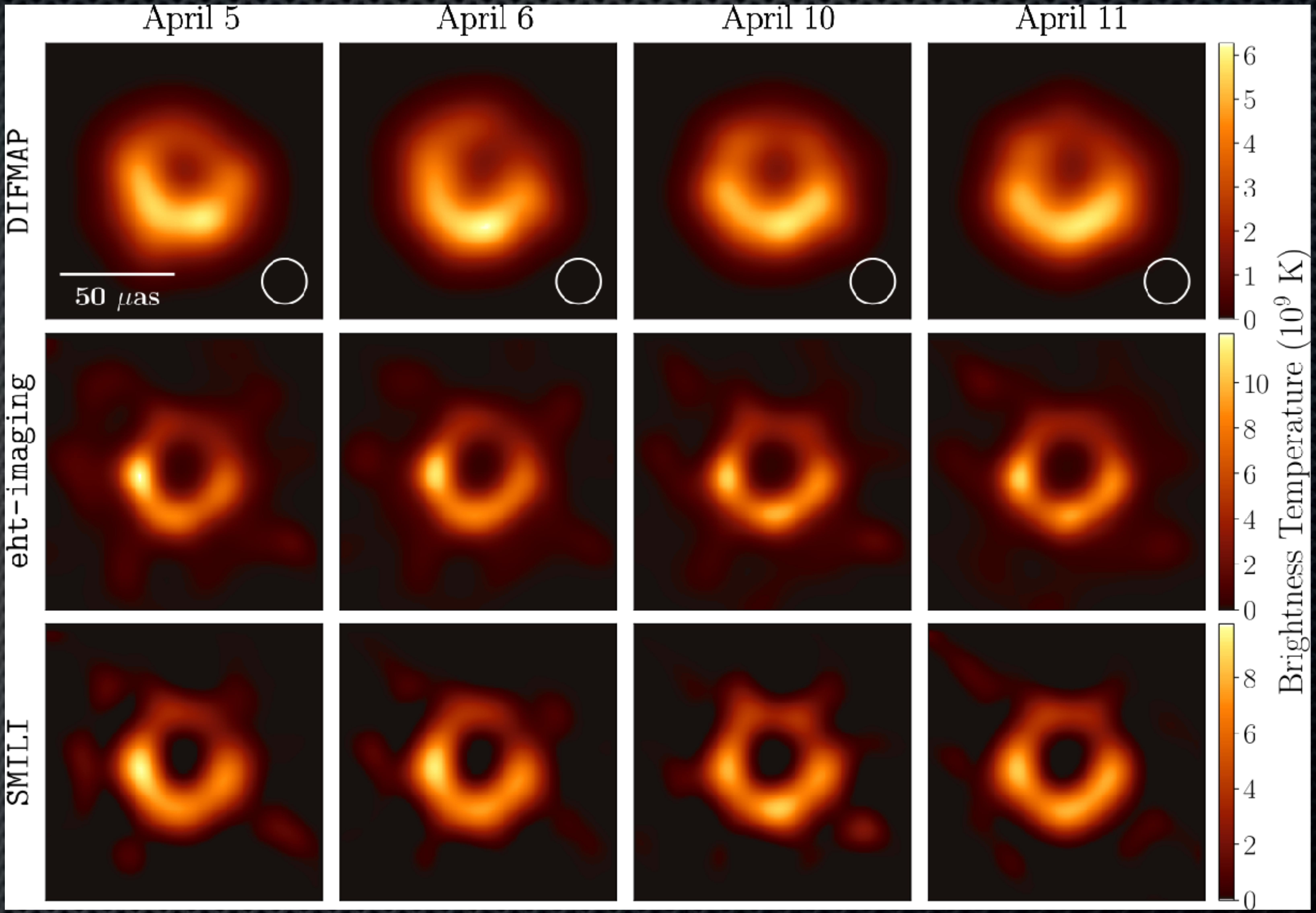
Post lunch added slides I: blind imaging



- Use early engineering release of data from Apr 11 observations and imaged both M87 and calibrators.
- April 11 was chosen because of best coverage of the M87/3C279 pair and most stable a priori calibration.
- All images show the asymmetric ~40-45 μas ring with brighter emission in the south.
- Differences in the images result from different assumptions regarding the total compact flux density and because a restoring beam (20 μas) is only used in the CLEAN images.

Post lunch added slides II: final images

- Next step: average across imaging methods after smoothing RML methods to DIFMAP resolution.



Post lunch added slides II: final images

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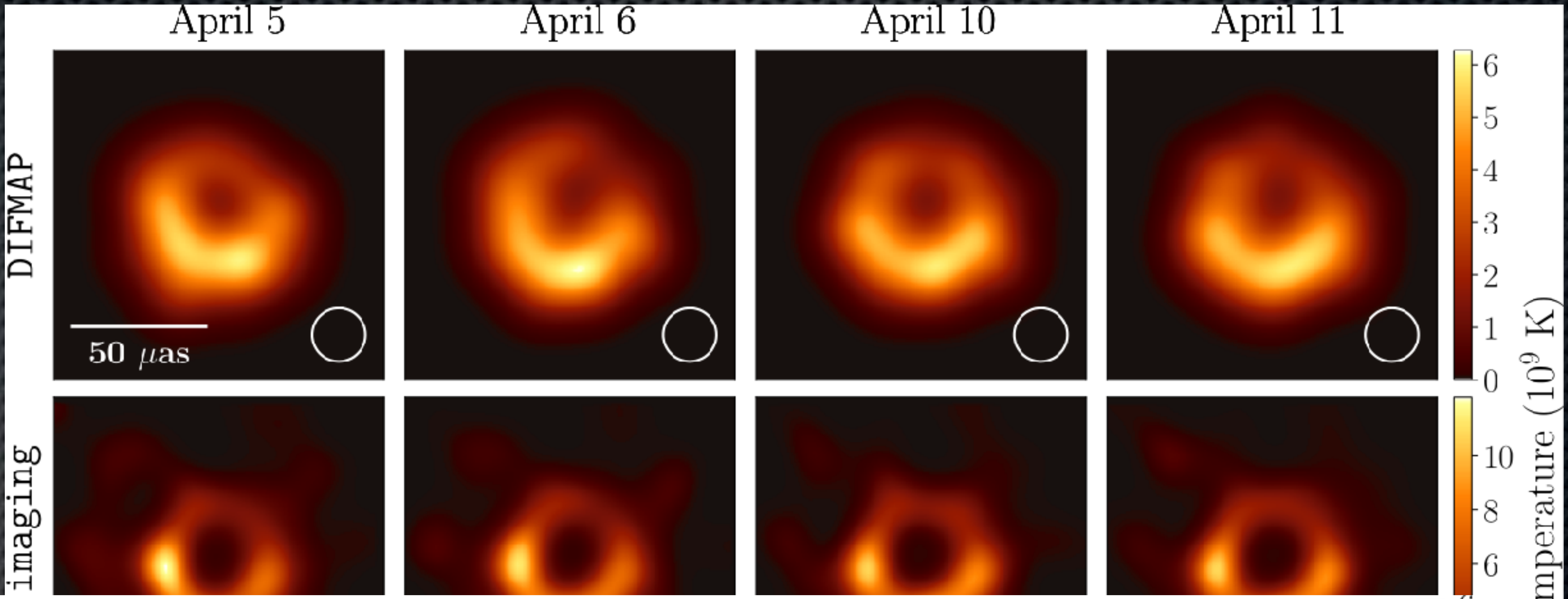
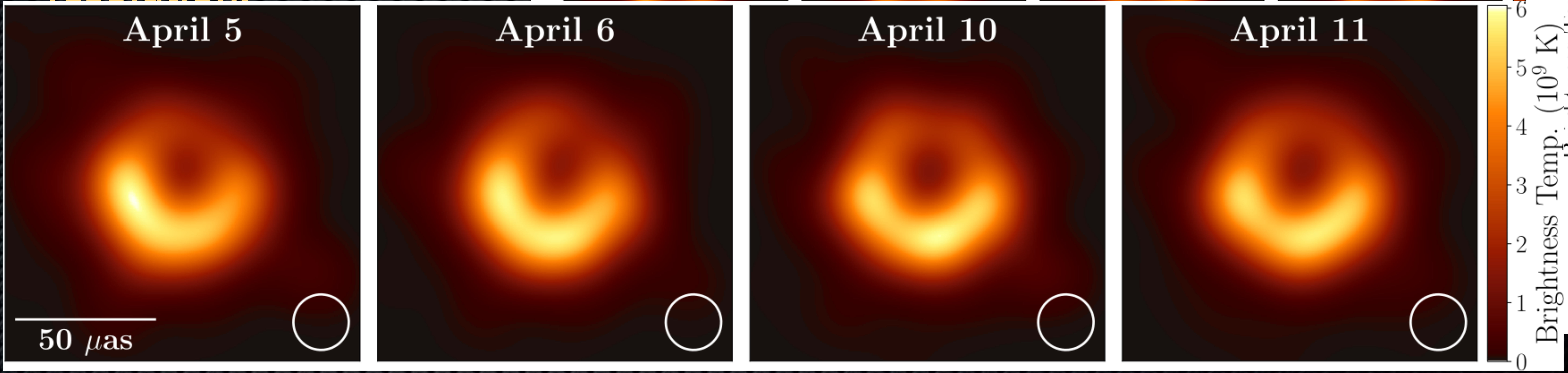




Post lunch added slides III: weather

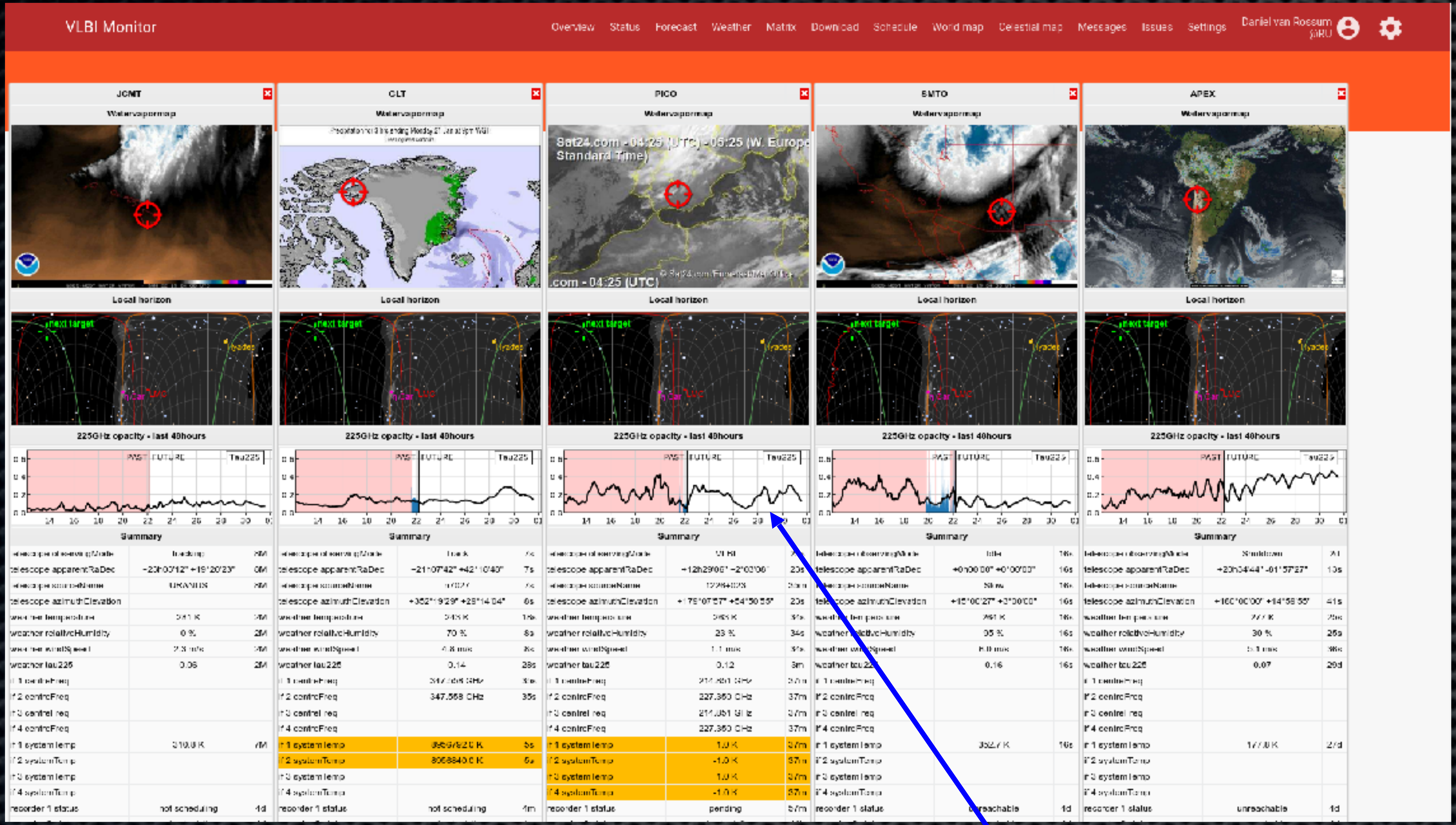
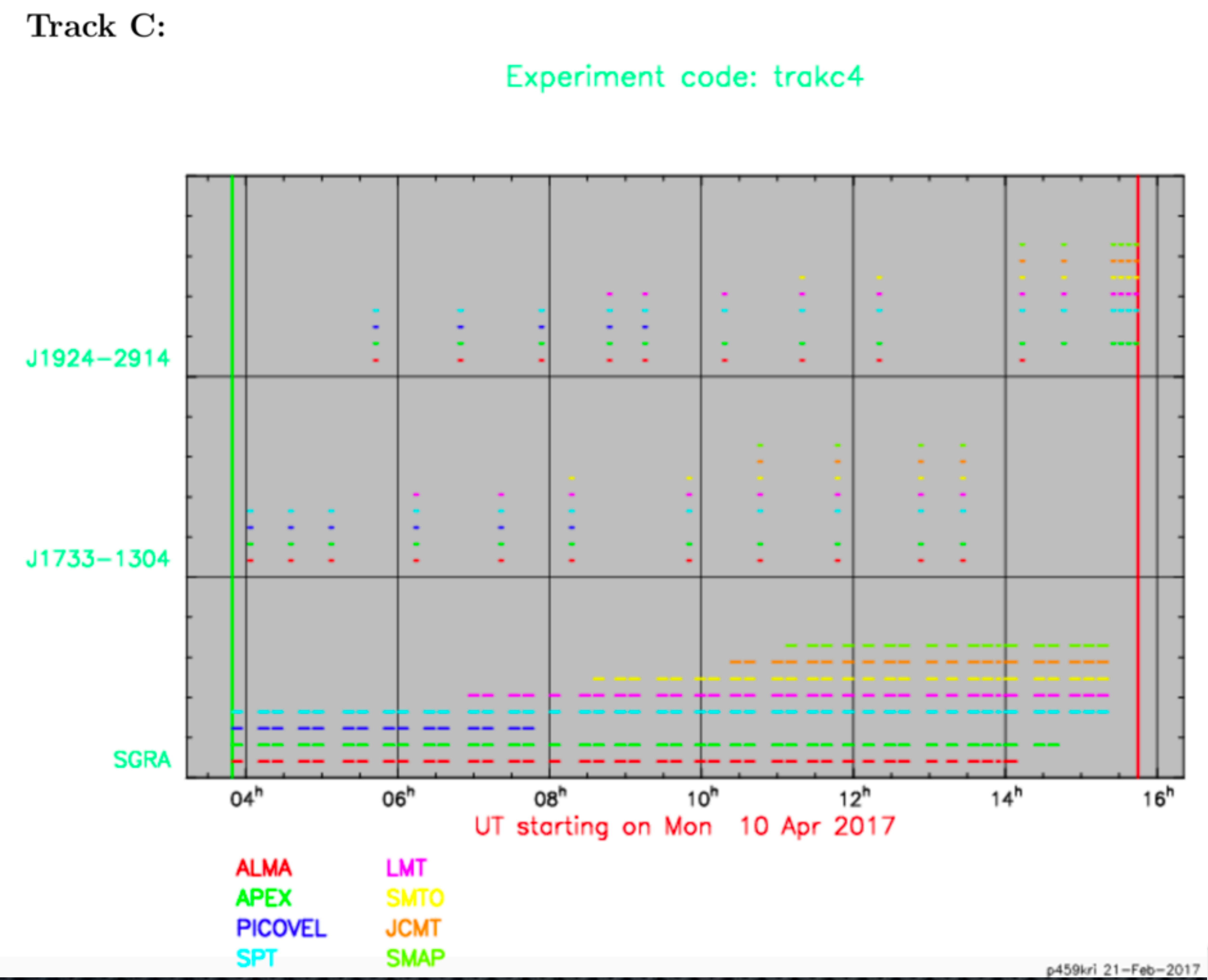


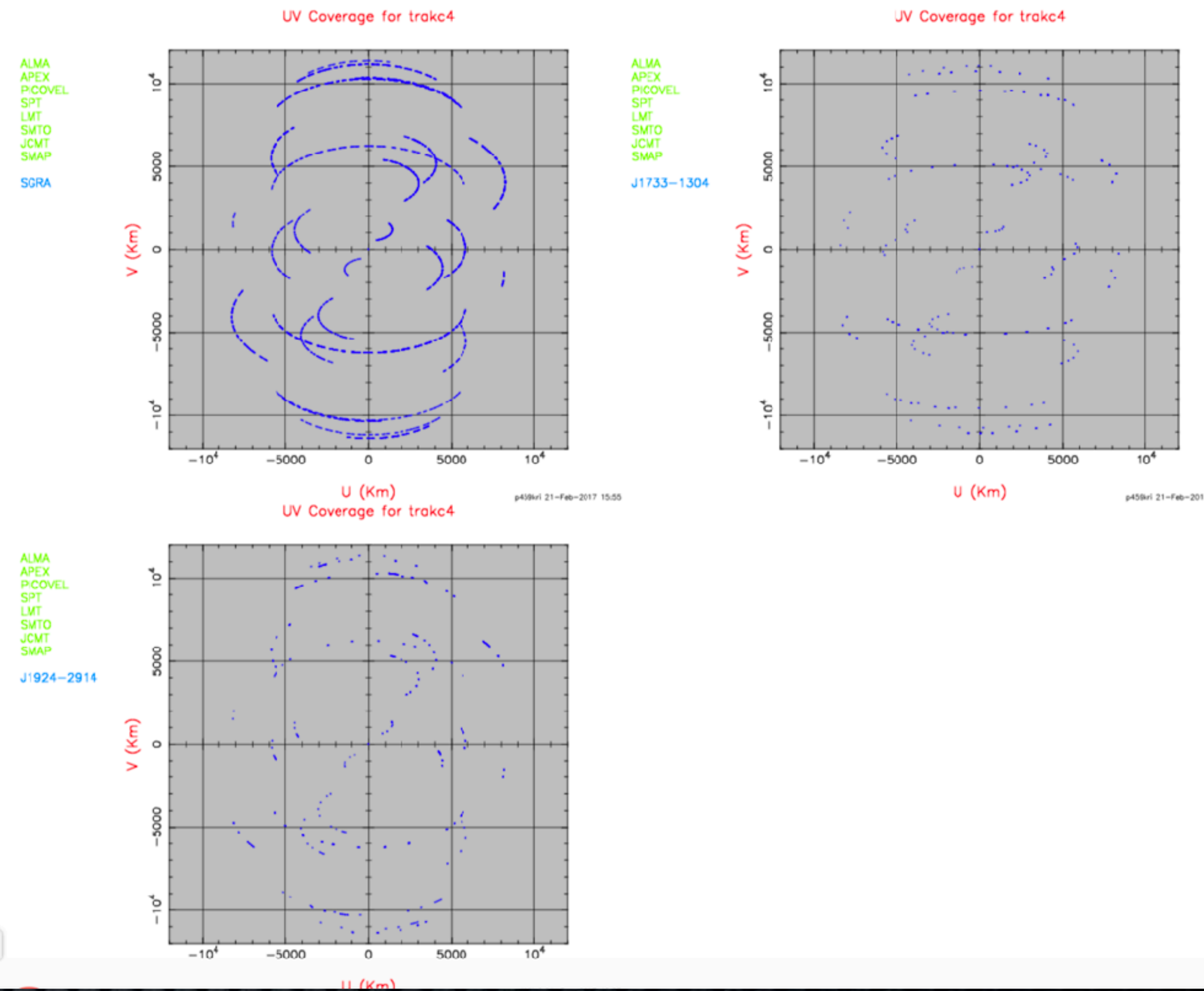
Table 1
Median Zenith Sky Opacities (1.3 mm) at EHT Sites during the 2017 April Observations

Station	Median Zenith $\tau_{1.3\ \mathrm{mm}}$				
	Apr 5	Apr 6	Apr 7	Apr 10	Apr 11
ALMA/APEX	0.06	0.04	0.05	0.03	0.06
SMA/JCMT	0.10	0.07	0.09	0.05	0.08
PV	0.18	0.13	0.14	0.10	0.15
LMT	0.13	0.16	0.21	0.26	0.24
SMT	0.21	0.28	0.23	0.19	0.16
SPT	0.04	0.05	0.07	0.08	0.07

Central observing desk developed by Radboud VLBI group with dedicated, real-time 10-day forecast of water vapor levels and wind speeds by KNMI for all EHT stations based on EU forecast model.

Post lunch added slides IV: scheduling sudoku





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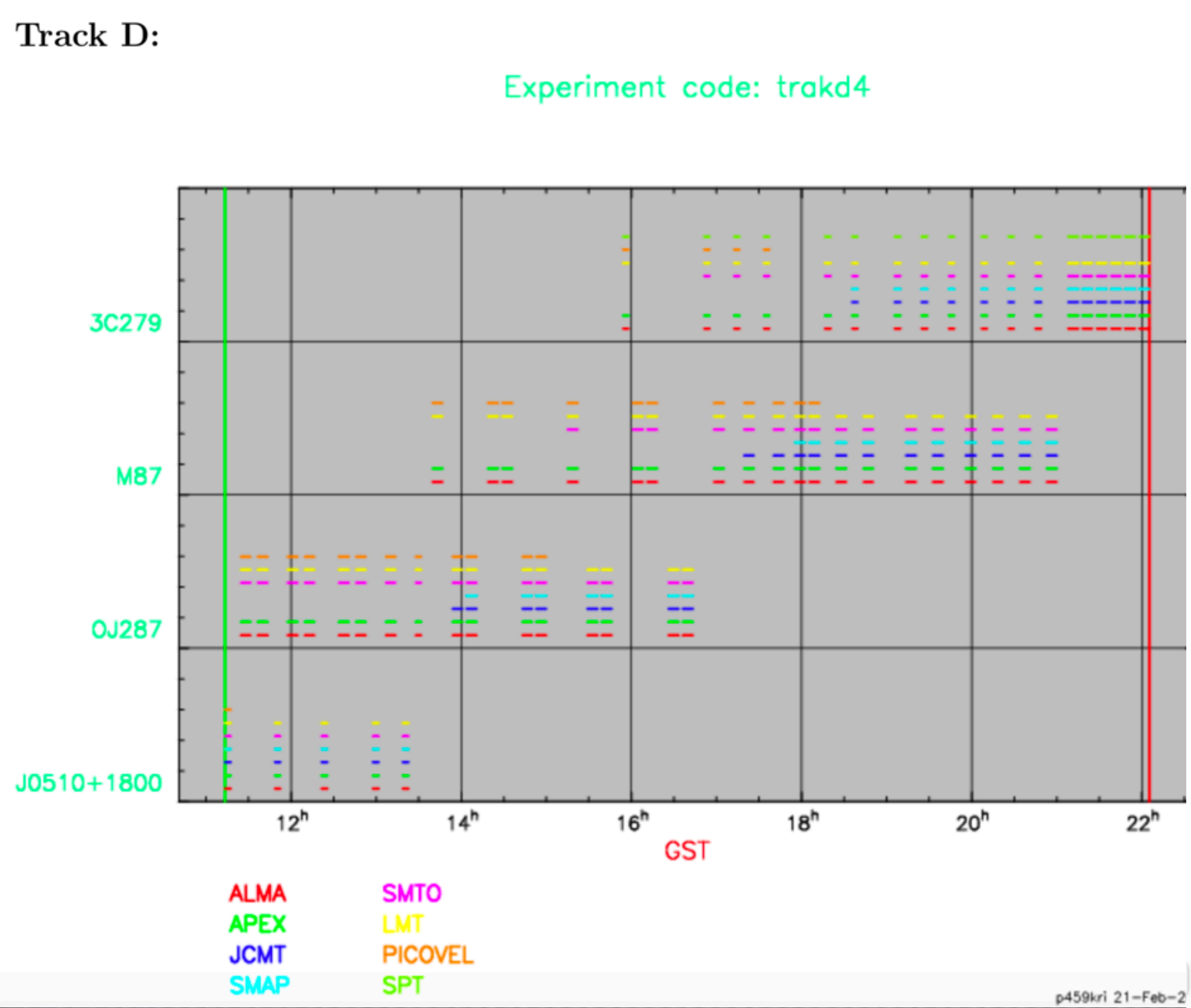
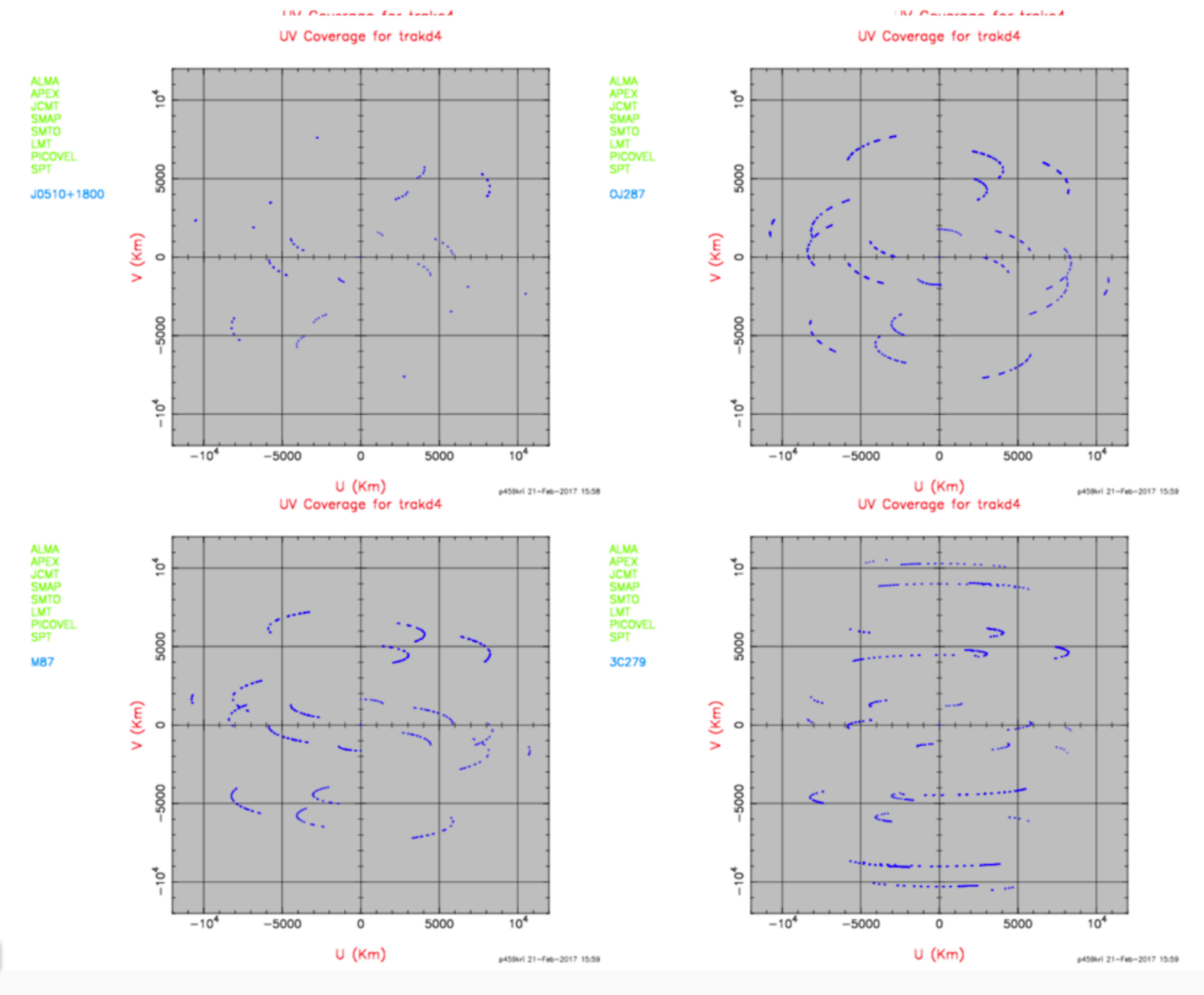
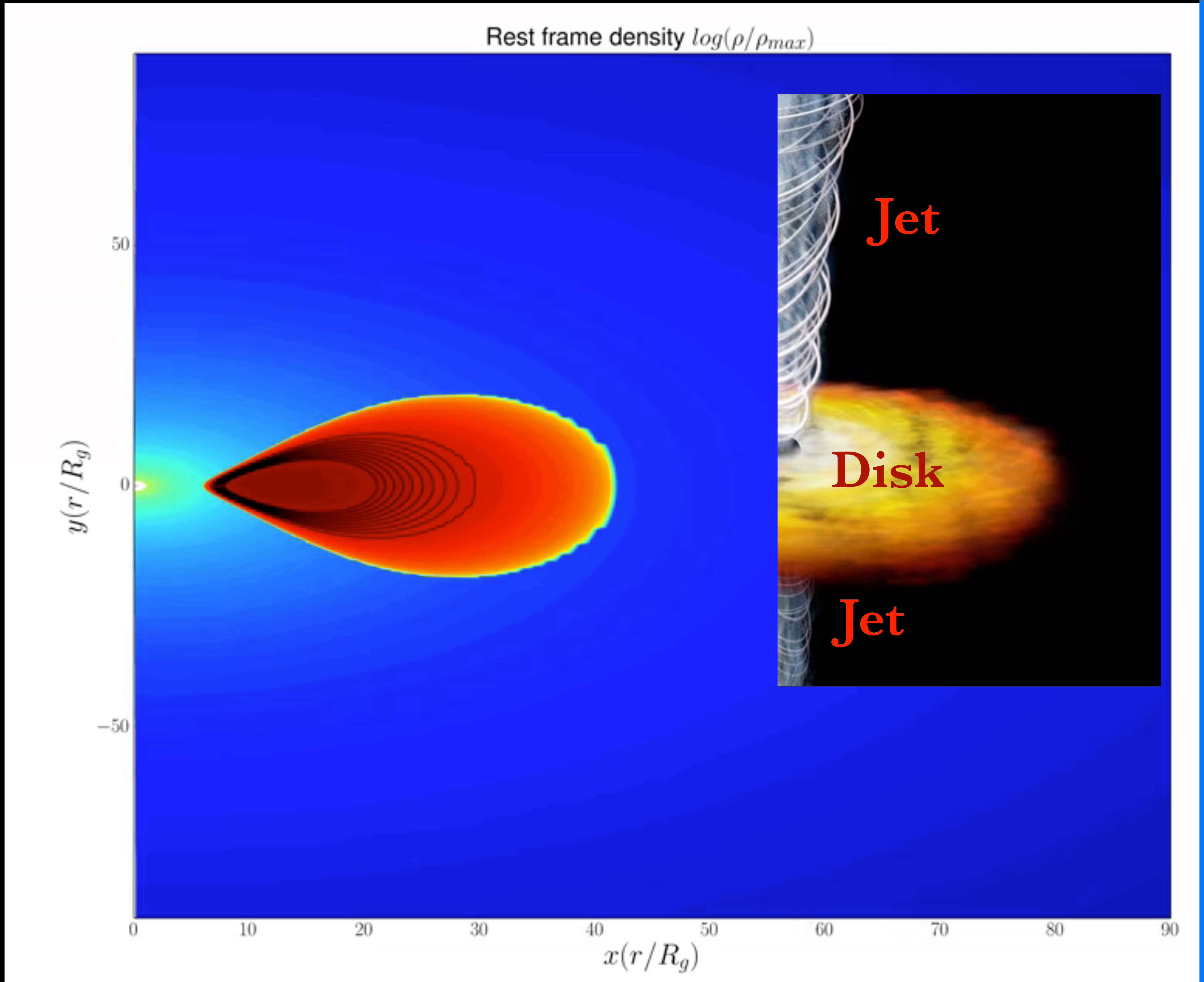




Limitations of current tools

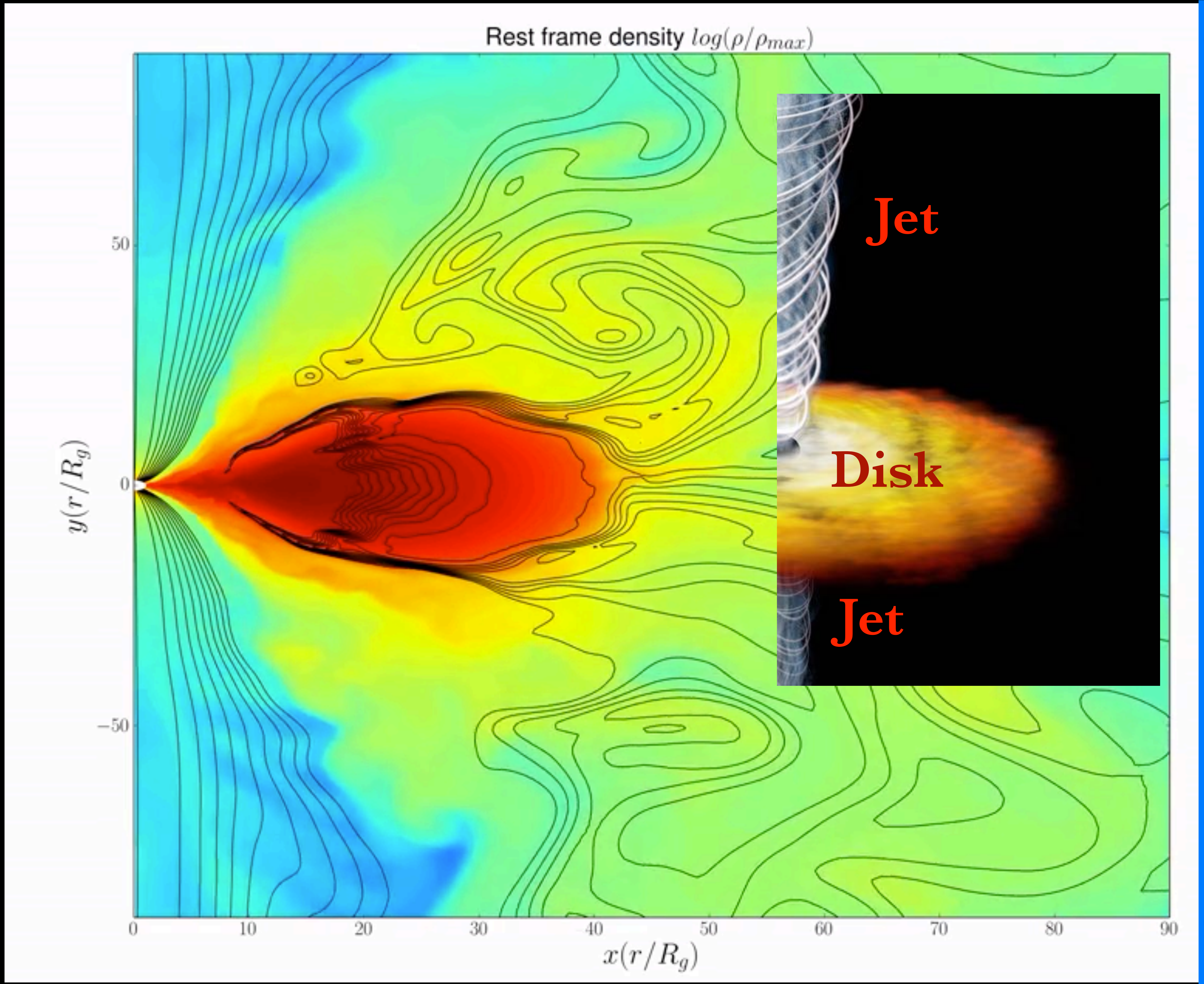
Simulations: time-dependent dynamics but missing microphysics



- ⭐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 subm., ...plus many other papers and groups!)

Simulations: time-dependent dynamics but missing microphysics



- ★Unrealistic/limited geometry, resolution
- ★Degeneracy in plasma initial conditions ($\dot{m}$, β, σ, μ, B field config.)
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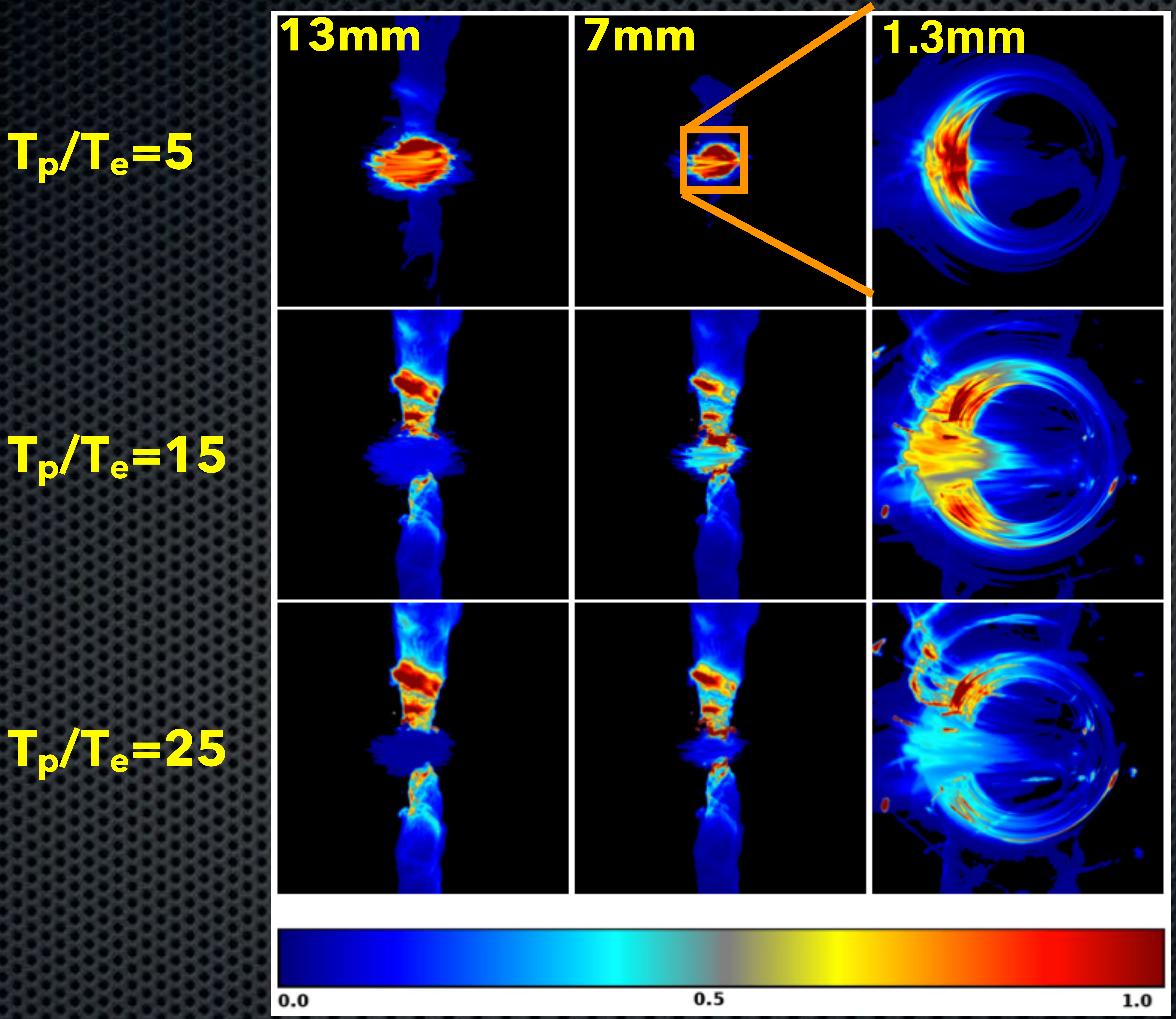
(**Dibi, Drappeau,** Fragile, SM & Dexter 2012; **Drappeau, Dibi**, Dexter, SM & Fragile 2013; **Li** ... **Chatterjee, Liska**, Tchekhovskoy & SM subm., ...plus many other papers and groups!)

Illustration of "macro/microphysics problem" for EHT

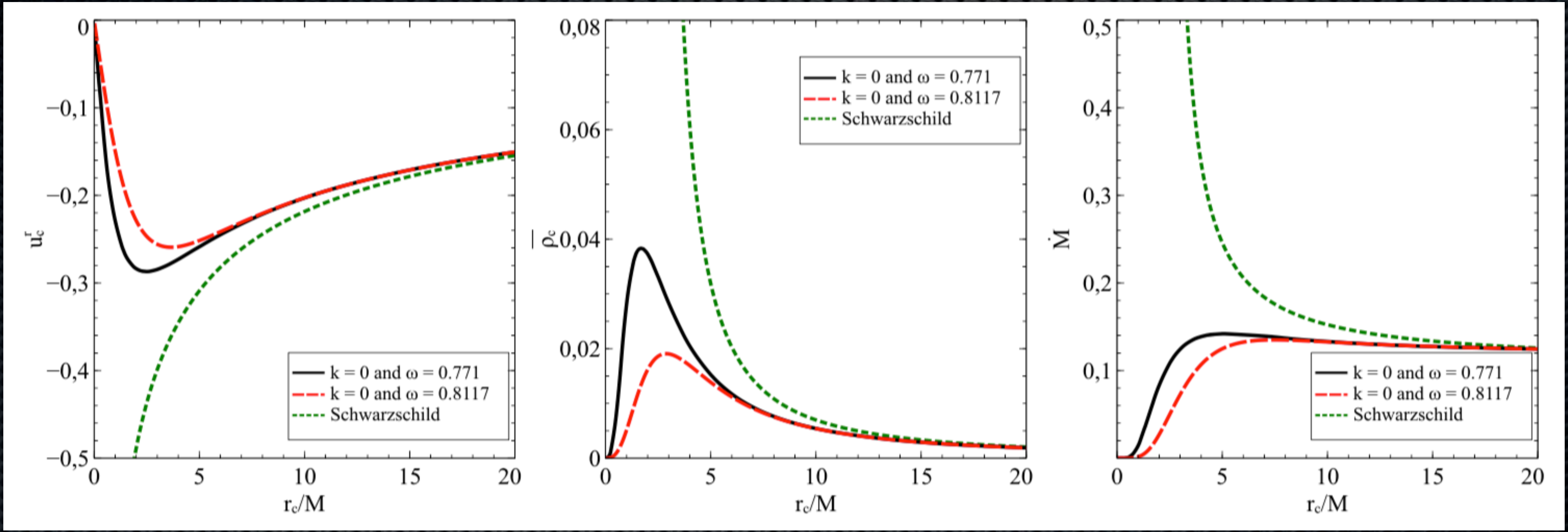


(Moscibrodzka, Falcke, Shiokawa & Gammie 2014; see also Ressler++15,17; Chael++18; Ryan++18)

Theory & Simulations WG: code comparison (Porth, Chatterjee++2018)

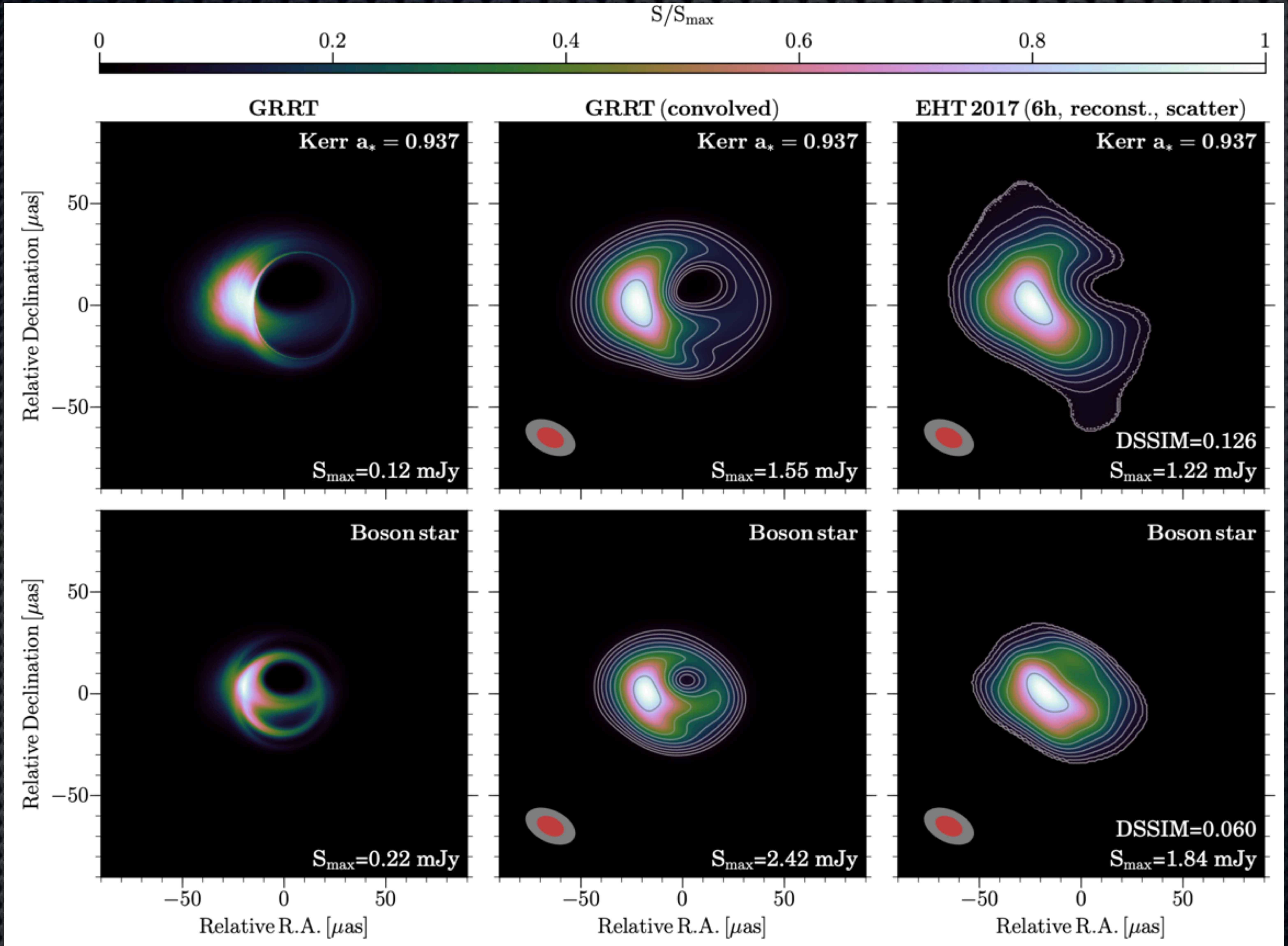
Simulations with many different algorithms and models of the microphysics show broadly consistent images that are asymmetric with clear black-hole shadows

Can you rule out weird stuff like boson stars?



(Meliani, Grandclément, Casse et al. 2016)

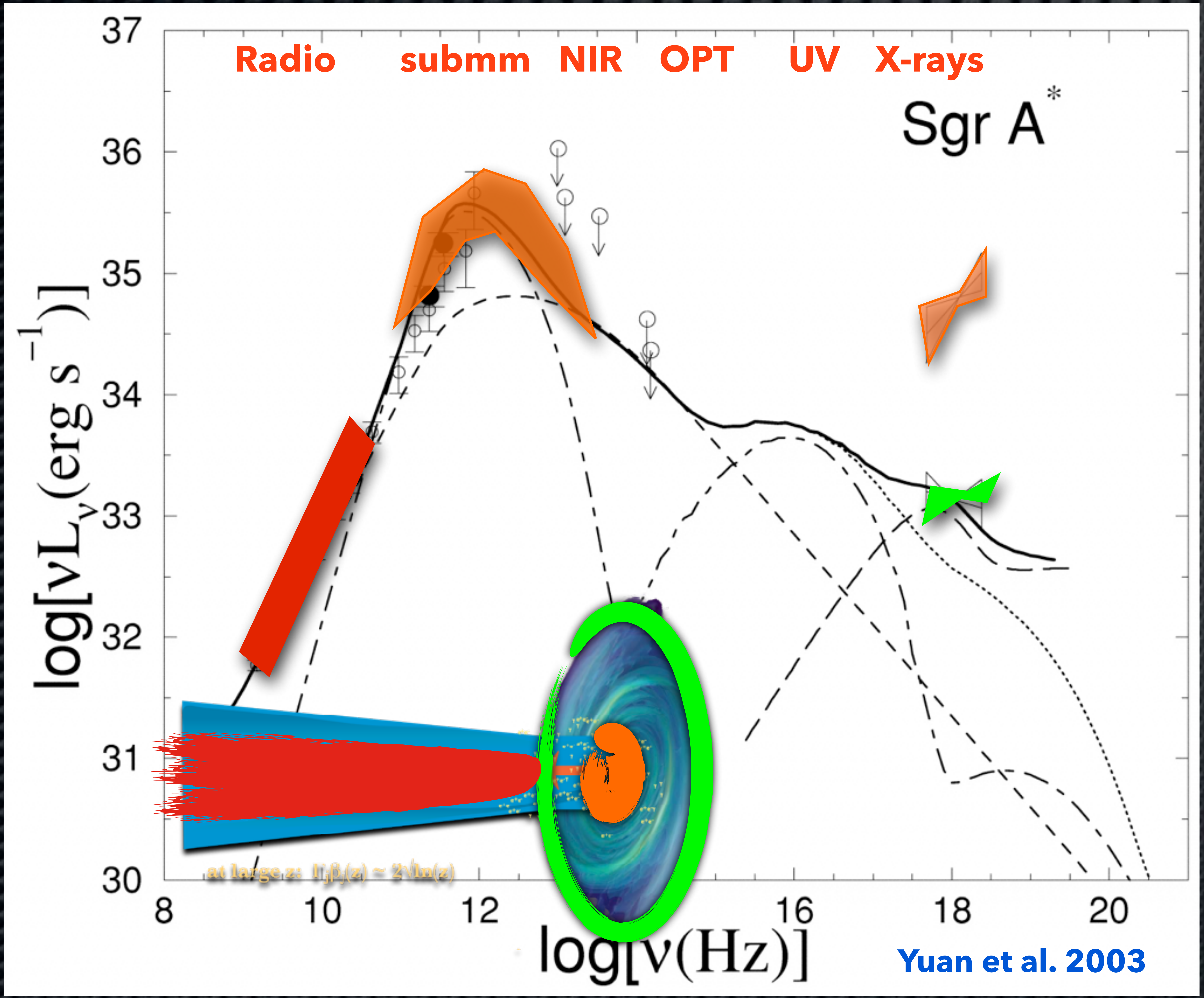
Can you rule out weird stuff like boson stars?



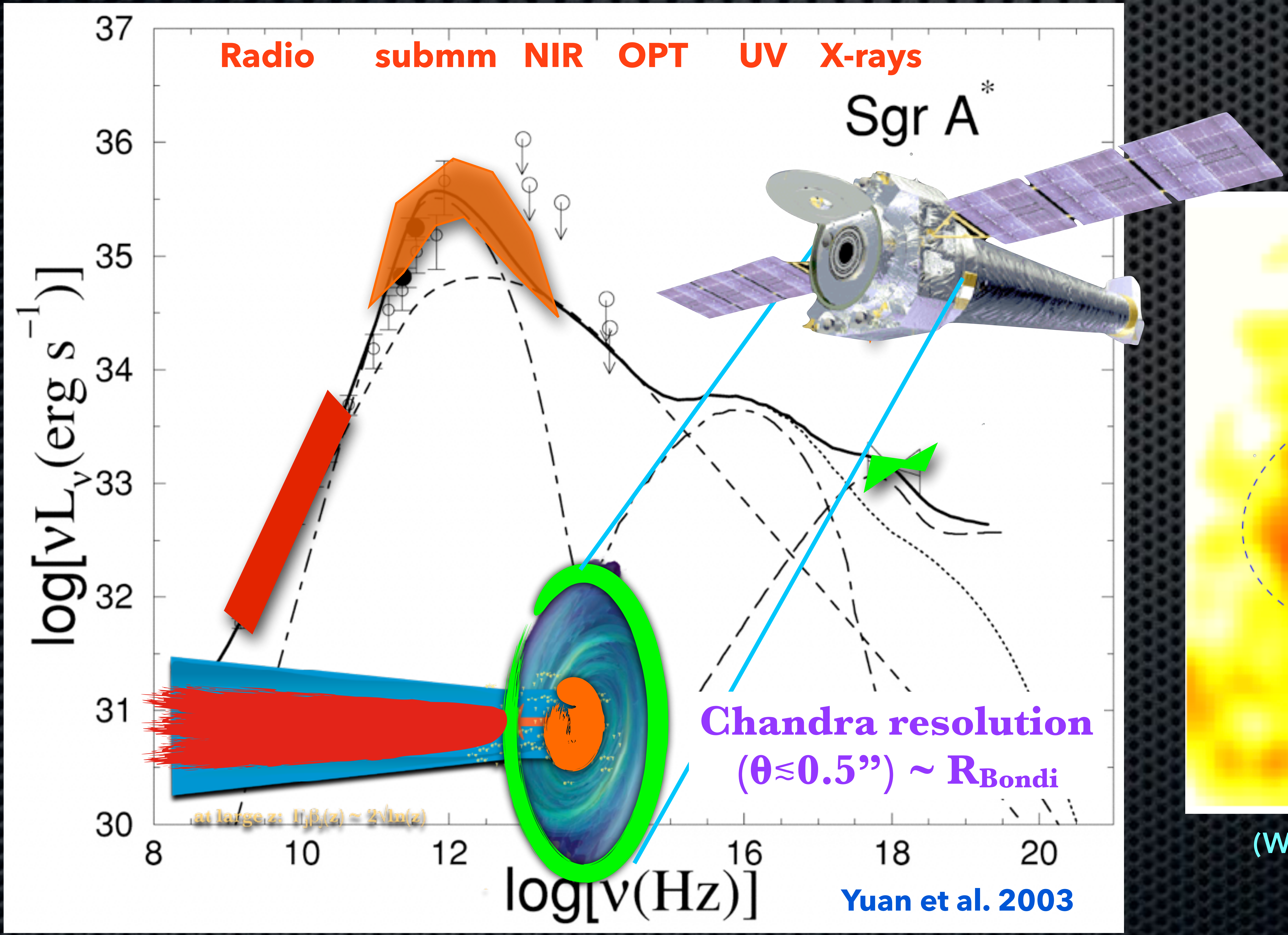
(Olivares, Younsi, Fromm++ 2018)

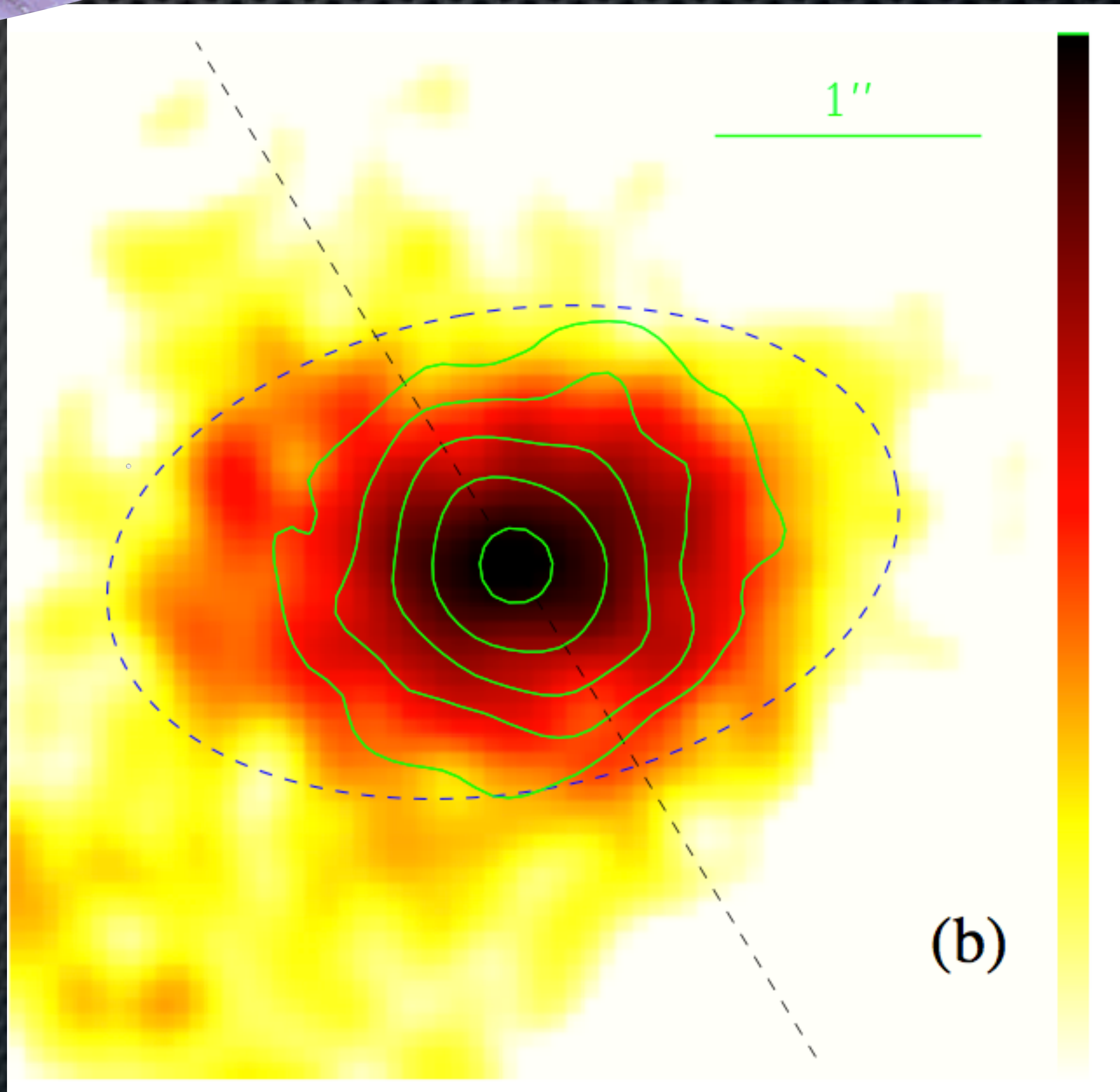
Next for EHT: Sgr A*

Sgr A* – Best constrained black hole we know!



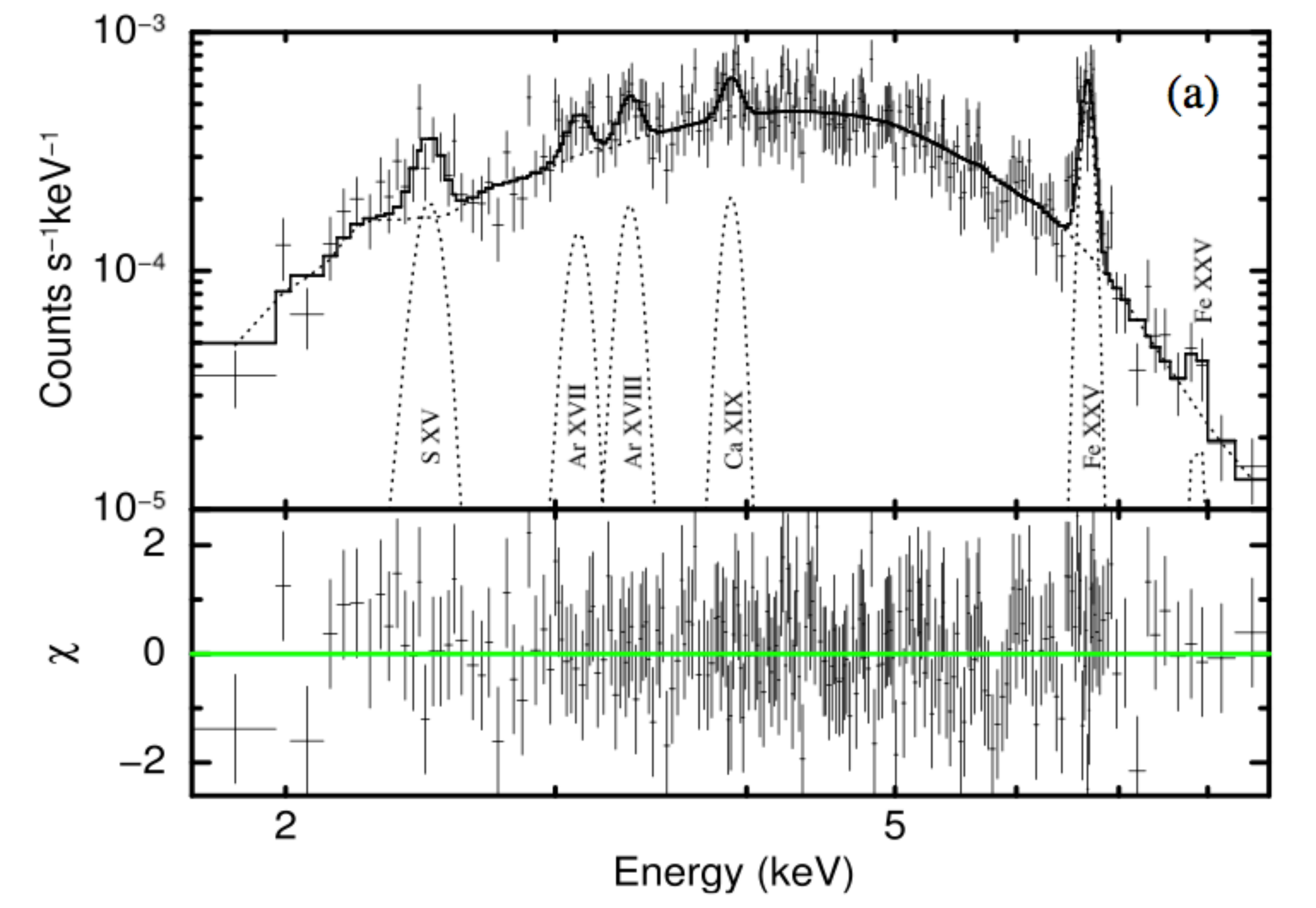
Sgr A* – Best constrained black hole we know!





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

3Ms (!!) XVP Chandra-HETG observations of Sgr A*:
First detailed plasma diagnostics



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

3Ms (!!) XVP Chandra-HETG observations of Sgr A*:
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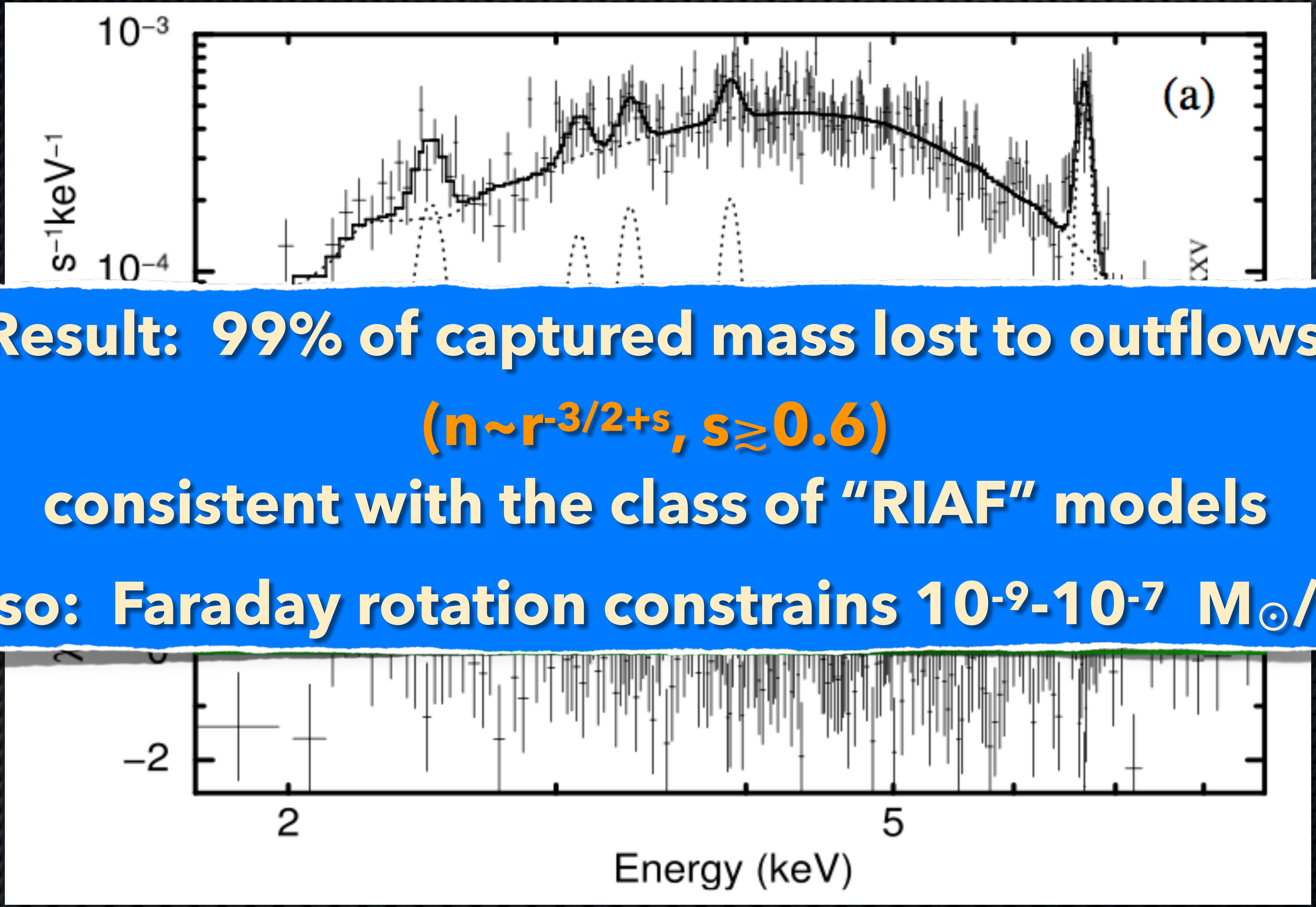


Result: 99% of captured mass lost to outflows!

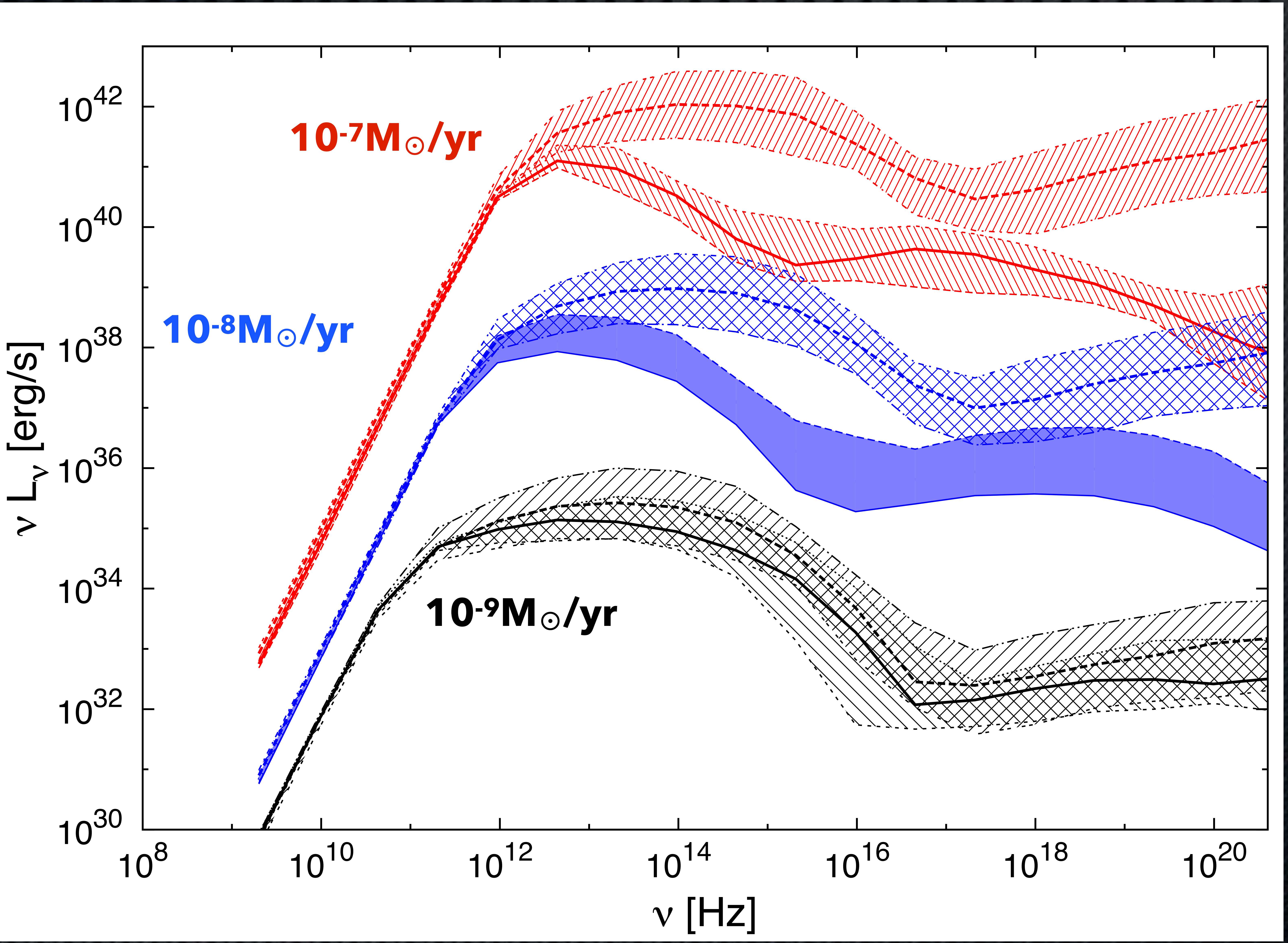
($n \sim r^{-3/2+s}$, $s \gtrsim 0.6$)

consistent with the class of "RIAF" models

Also: Faraday rotation constrains 10^{-9}-10^{-7} $M_\odot$/yr

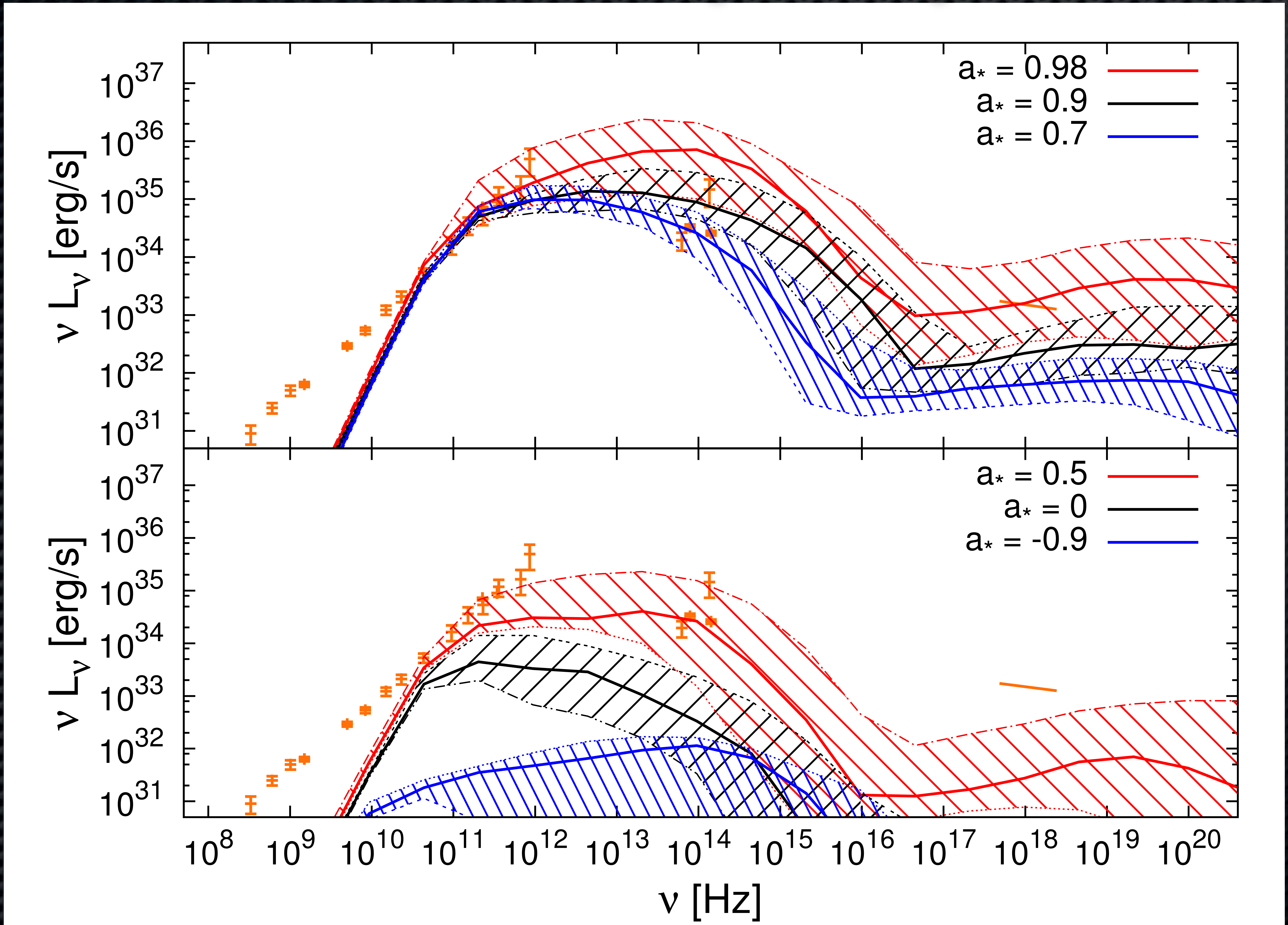
(Wang, Nowak, SM++, Science, 2013)

First GRMHD simulations of Sgr A* with (τ<1) cooling using Cosmos++



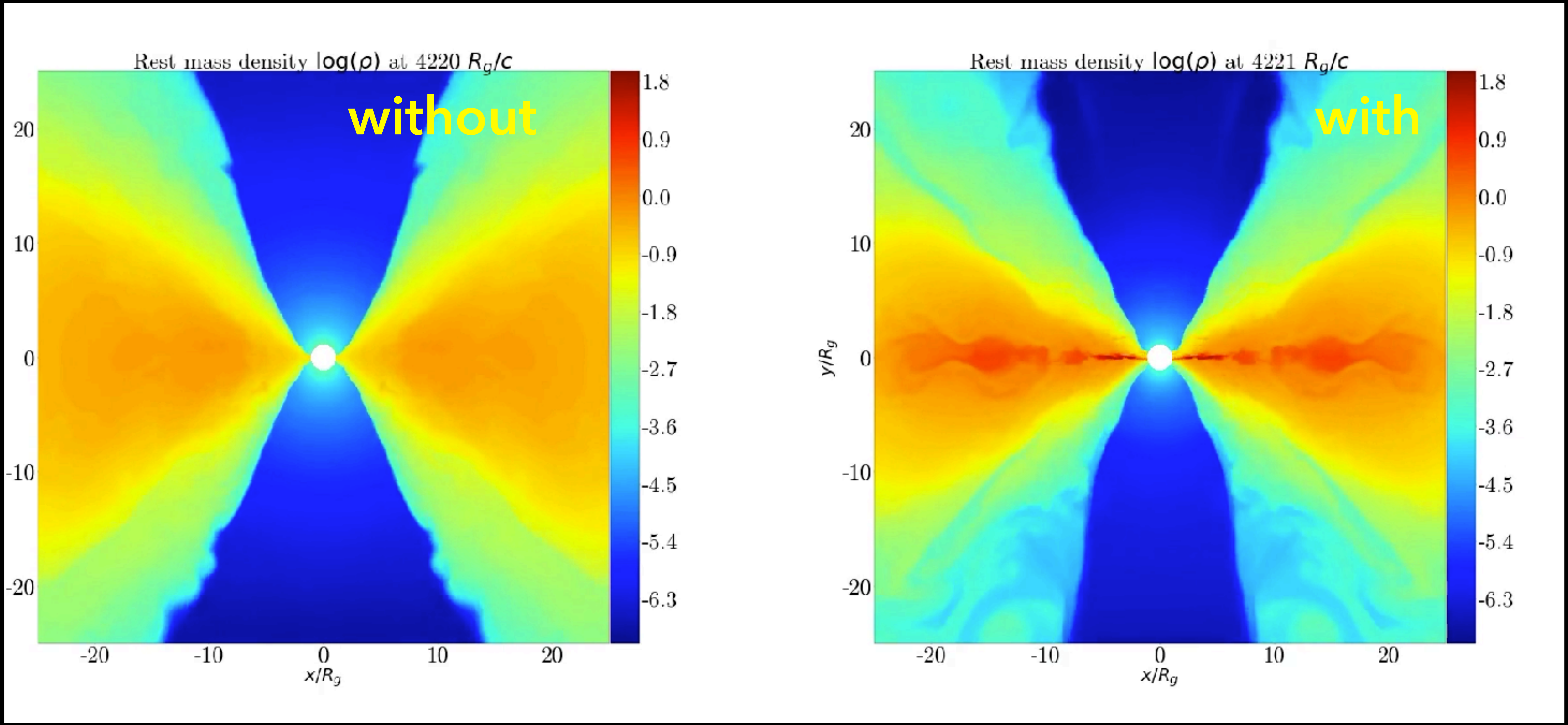
(Dibi, Drappeau, Fragile, SM, Dexter 2012; Drappeau, Dibi, Dexter, SM & Fragile 2013)

Effect of black hole spin on spectrum



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

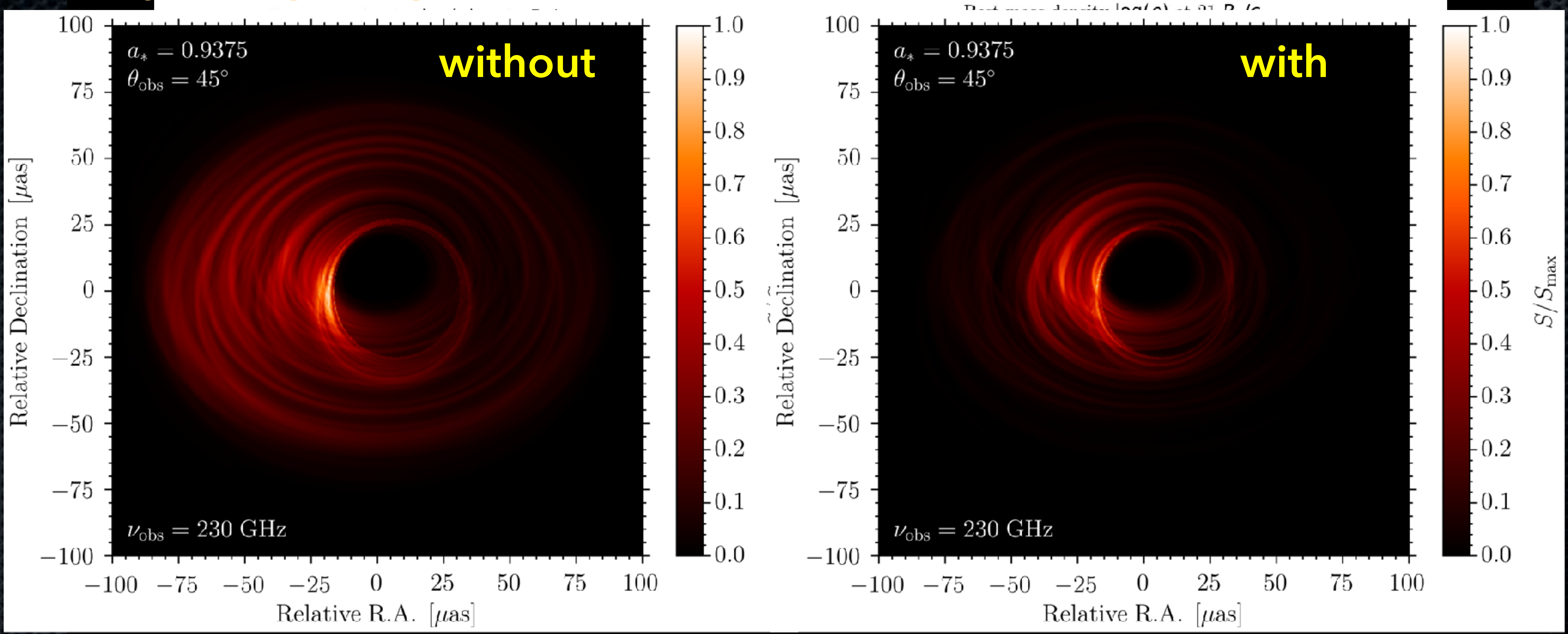
Simulations including radiative cooling with H-AMR



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

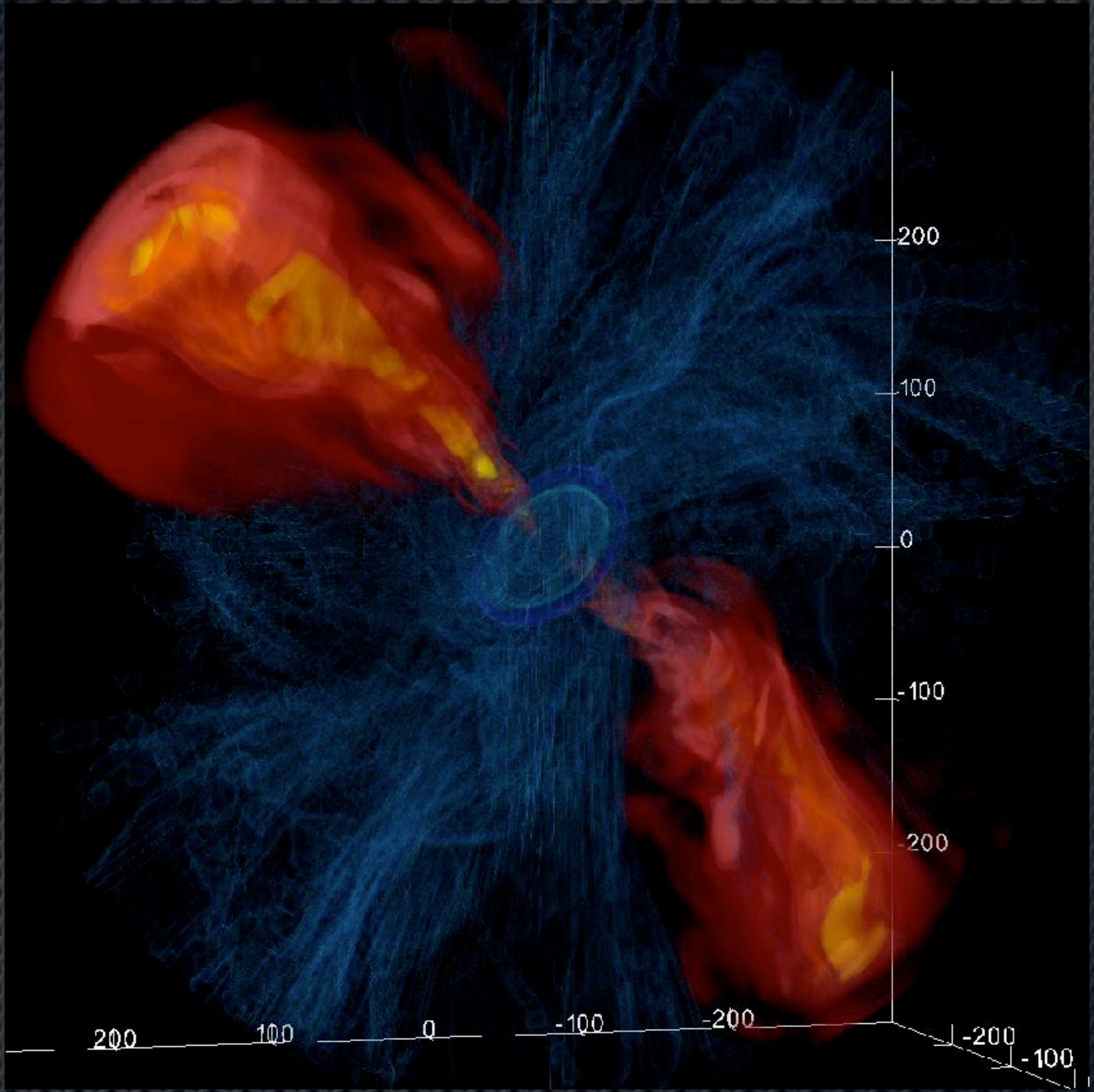
Simulations including radiative cooling with H-AMR

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, Yoon, SM, Younsi, ++ in prep.)

First hi-res tilted disks (black hole spin not aligned with disk)



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

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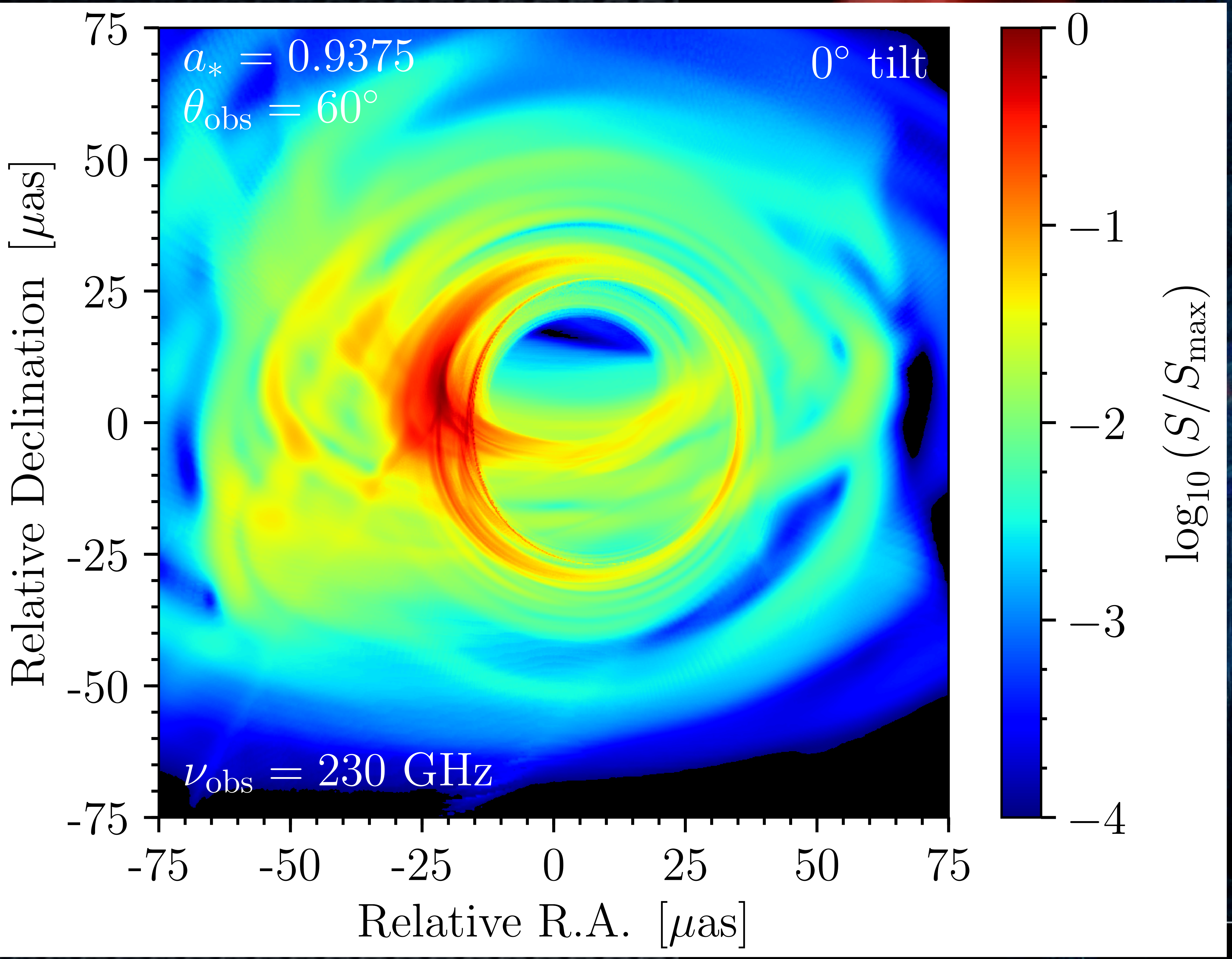
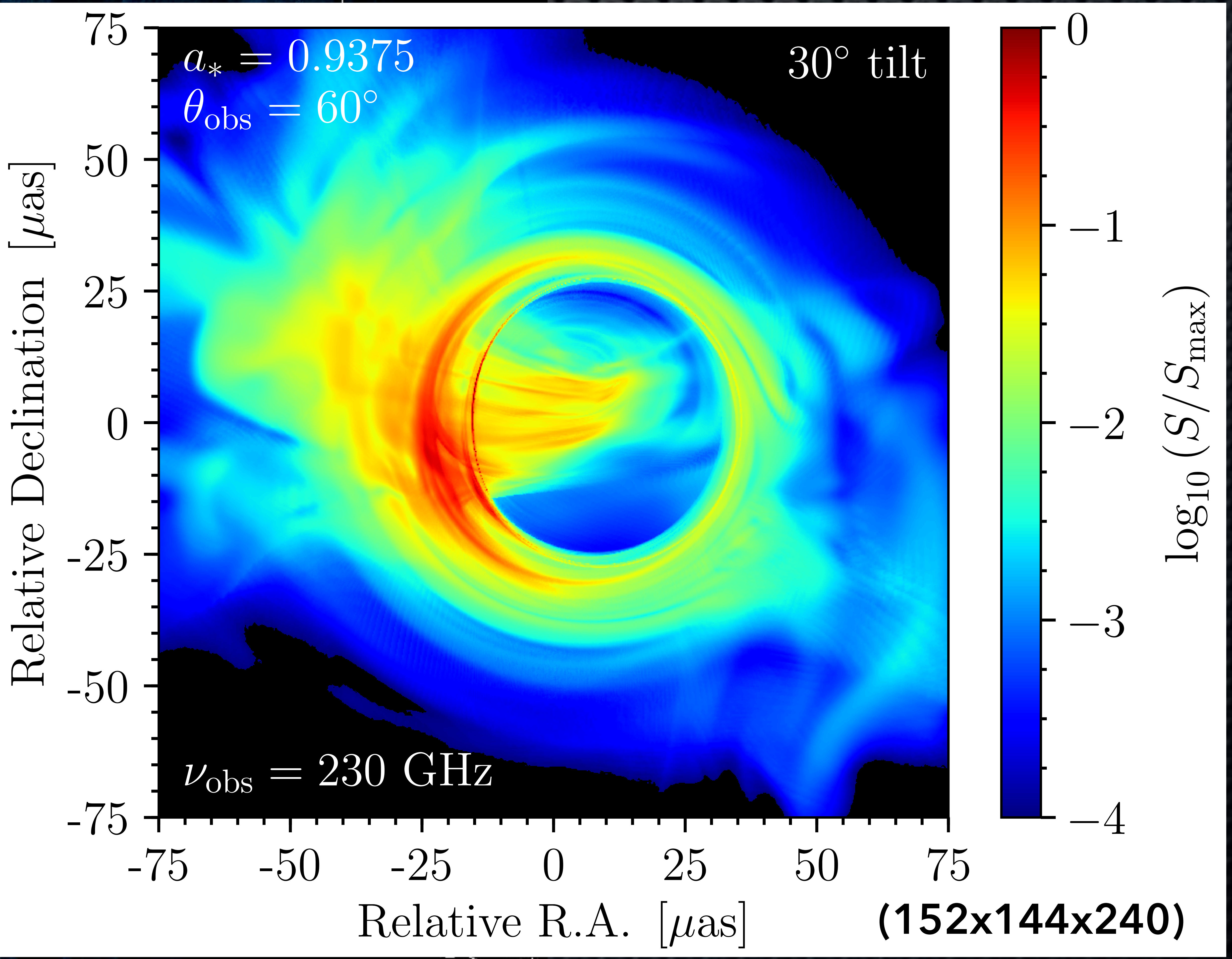
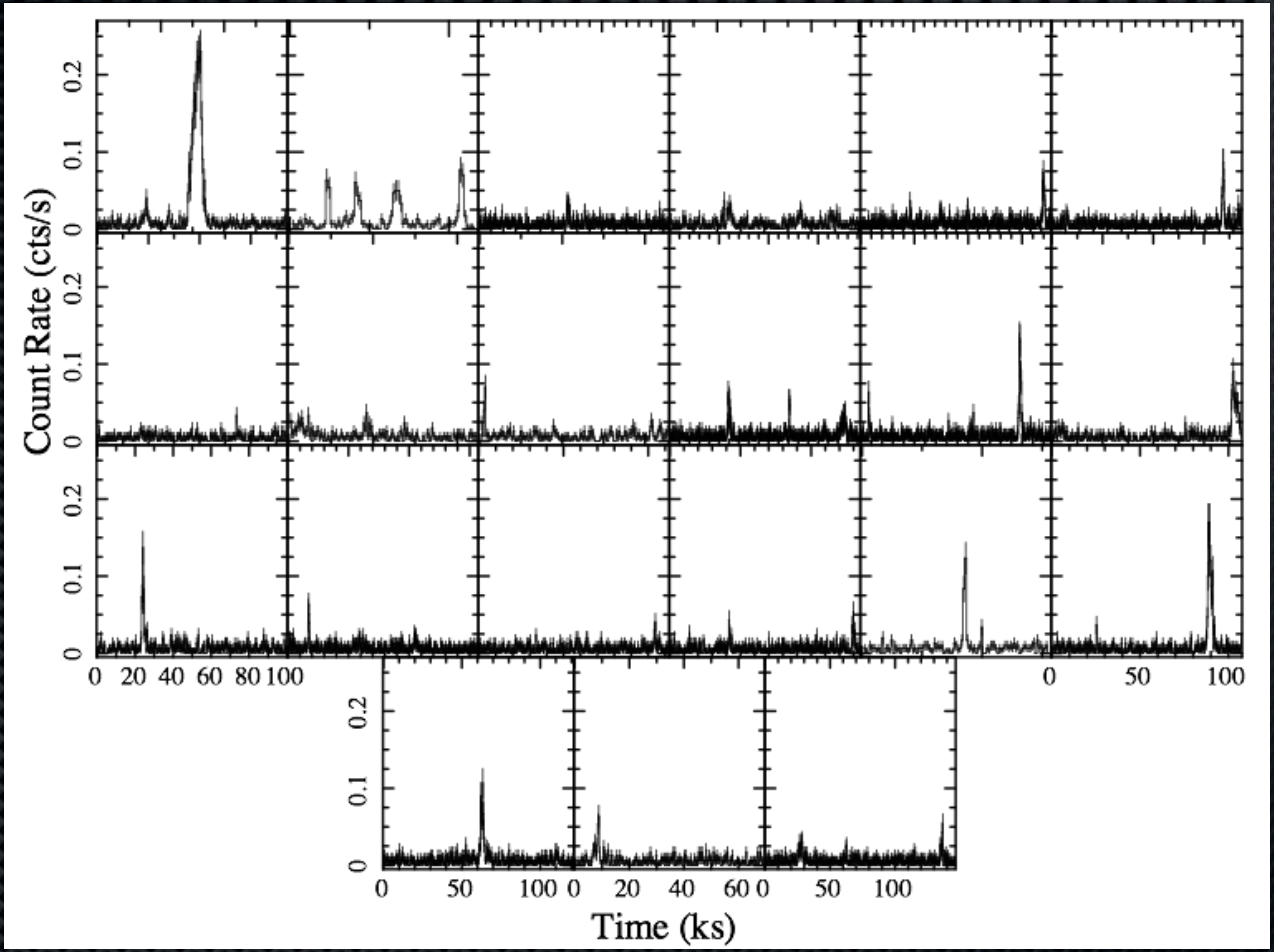




(152x144x240)

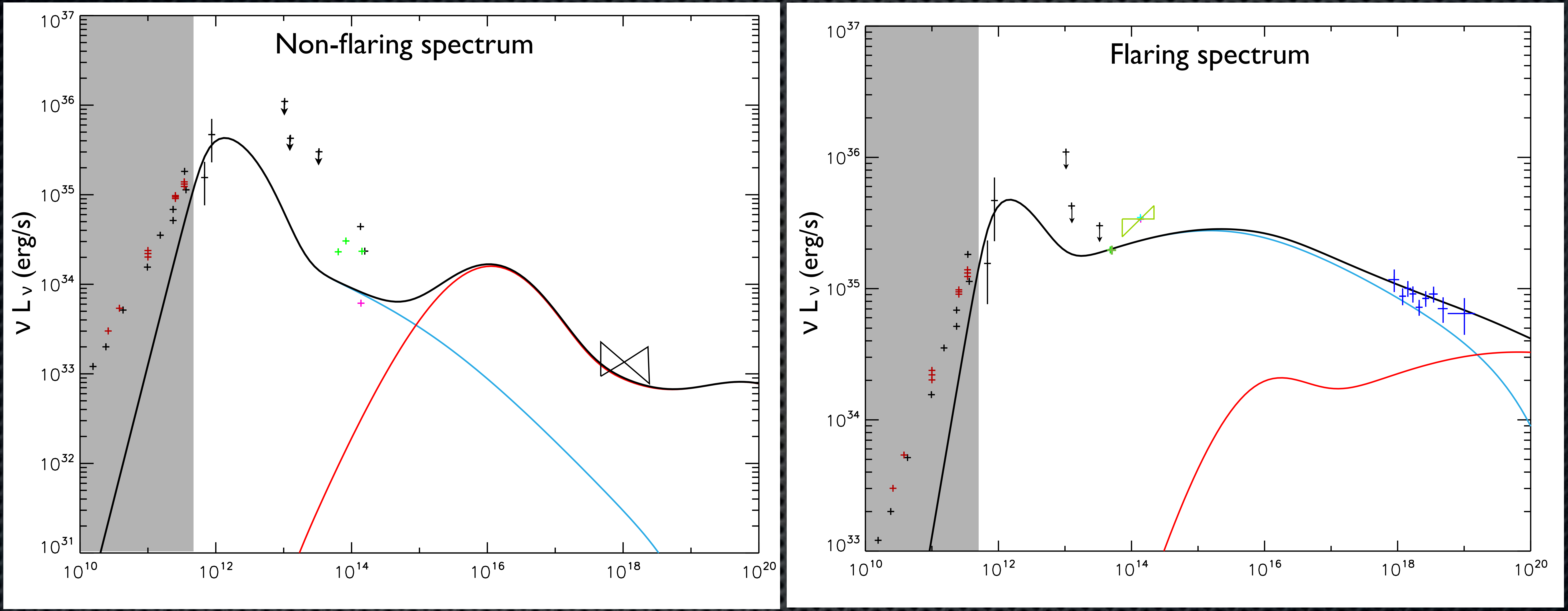
(Liska, Hesp, Tchekhovskoy, Ingram, vd Klis, SM++ 2018; Chatterjee, Yoon, van Eijnatten, Hesp, Liska, Younsi, SM, Tchekhovskoy++ in prep.

Sgr A* variability: Statistical benchmark for microphysics



(Dodds-Eden 2009; Witzel++ 2012; 18; Nielsen++ 2013, Nielsen, SM++ 2015; Dibi, SM++2014; Dibi, SM, Nielsen++2016)

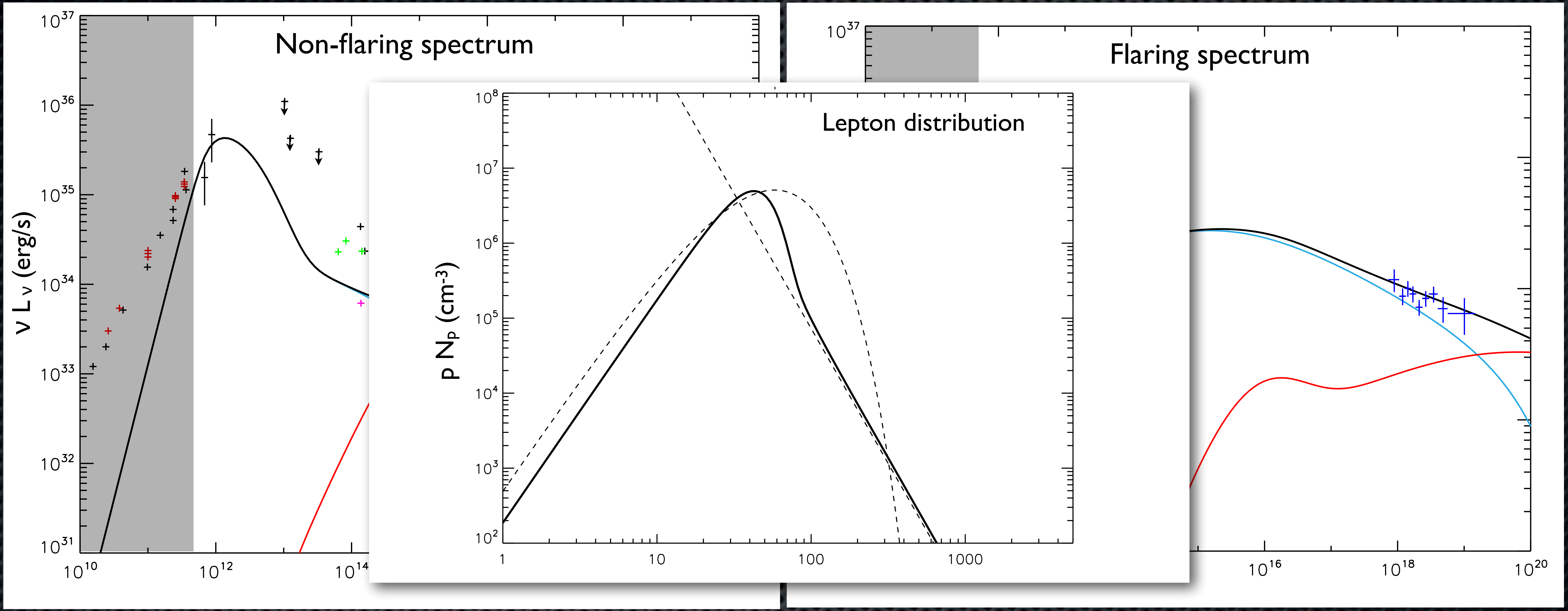
Modeling flares: microphysical approach



- ★ Magnetic injection: in the above, the transition from quiescence to flaring is due to transfer of magnetic to particle energy (e.g., reconnection in turbulent eddies?)

(Dibi, SM, Belmont & Malzac 2014)

Modeling flares: microphysical approach



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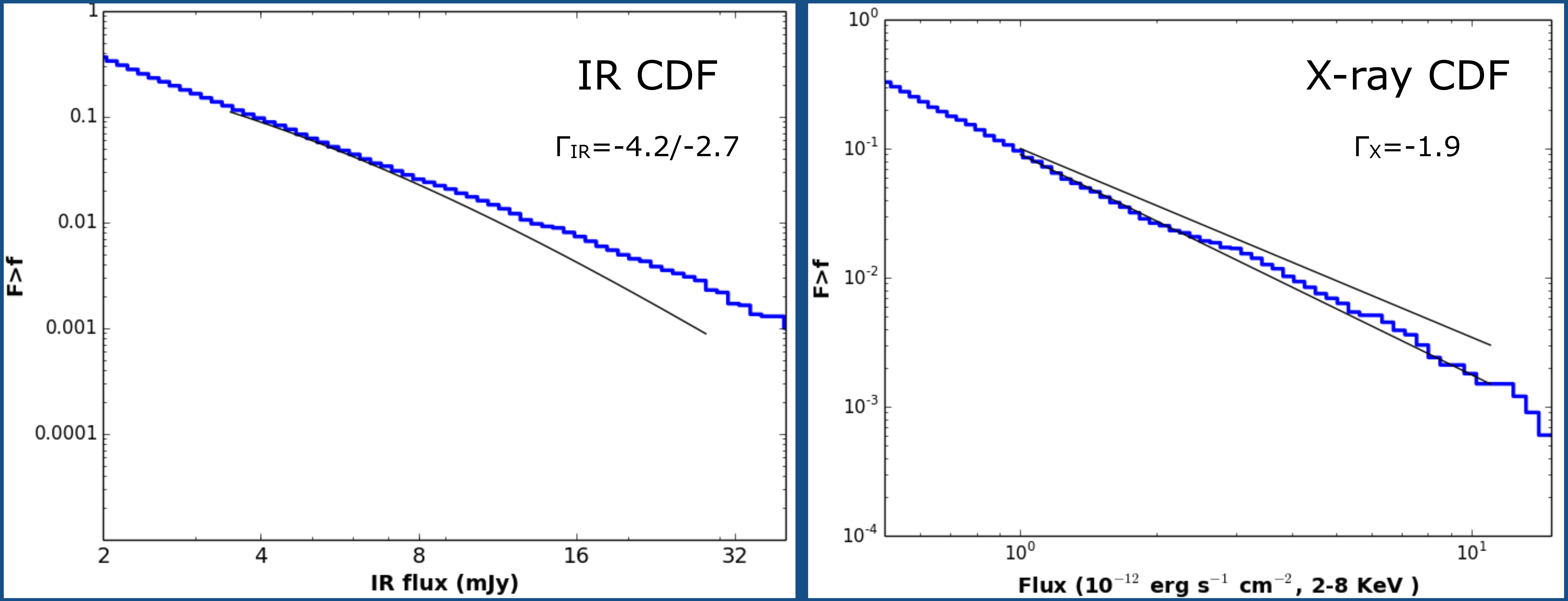
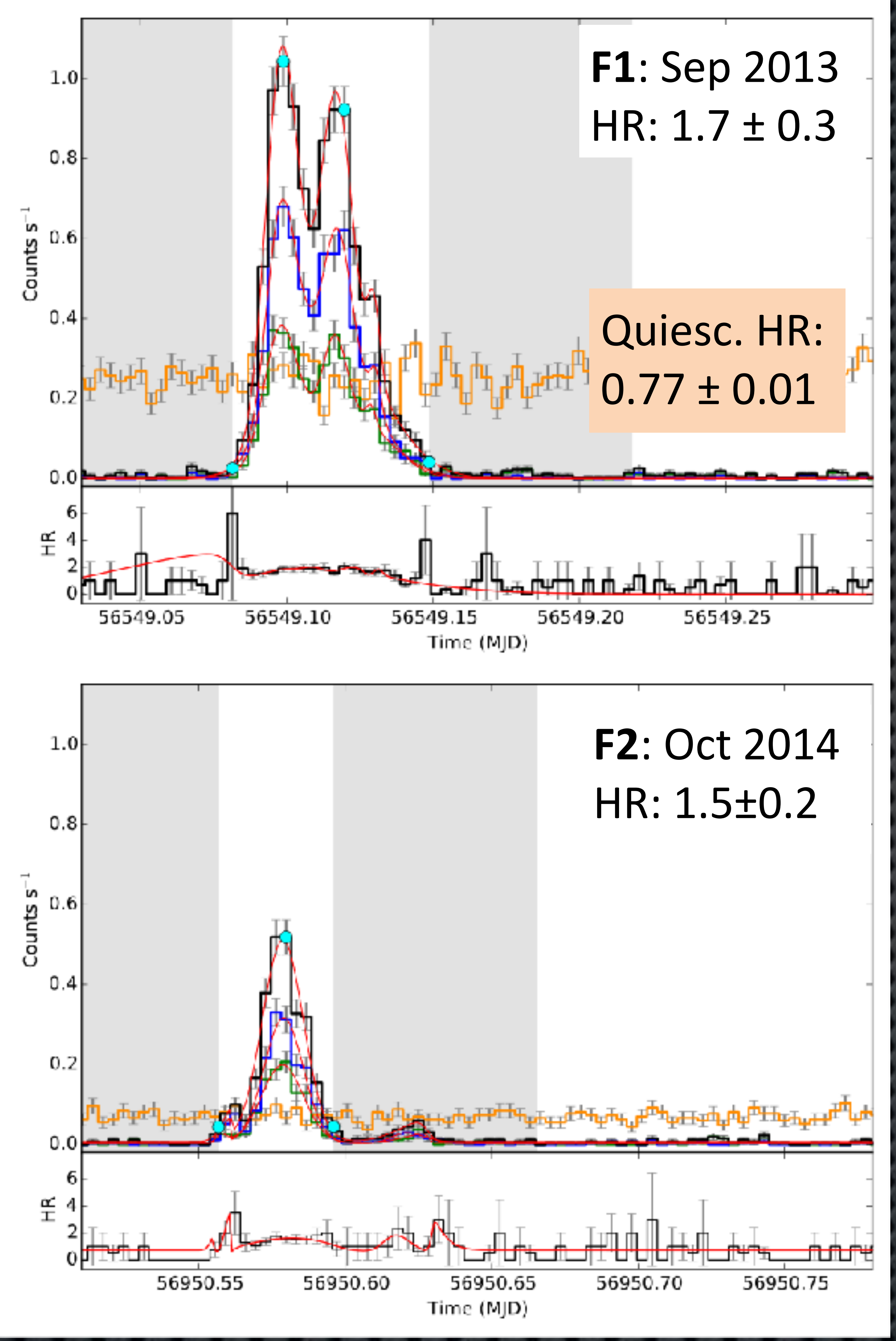


The simplest synchrotron scenario with non-thermal acceleration cannot recover both CDFs!

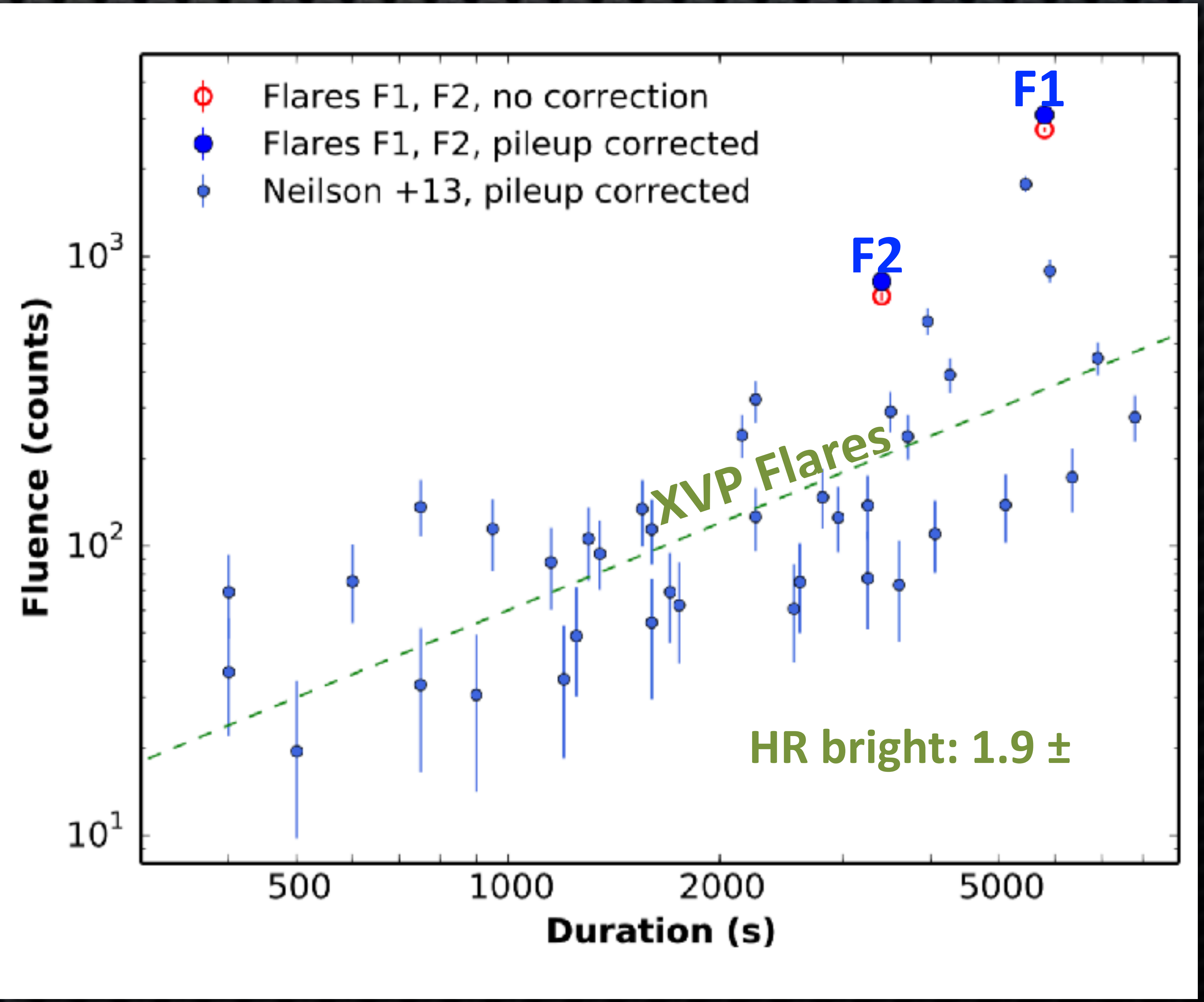
(Dodds-Eden 2009; Witzel++ 2012; 18; Nielsen++ 2013, Nielsen, SM++ 2015; Dibi, SM++2014; Dibi, SM, Nielsen++2016)

Sgr A* variability: precision clues about microphysics & geometry

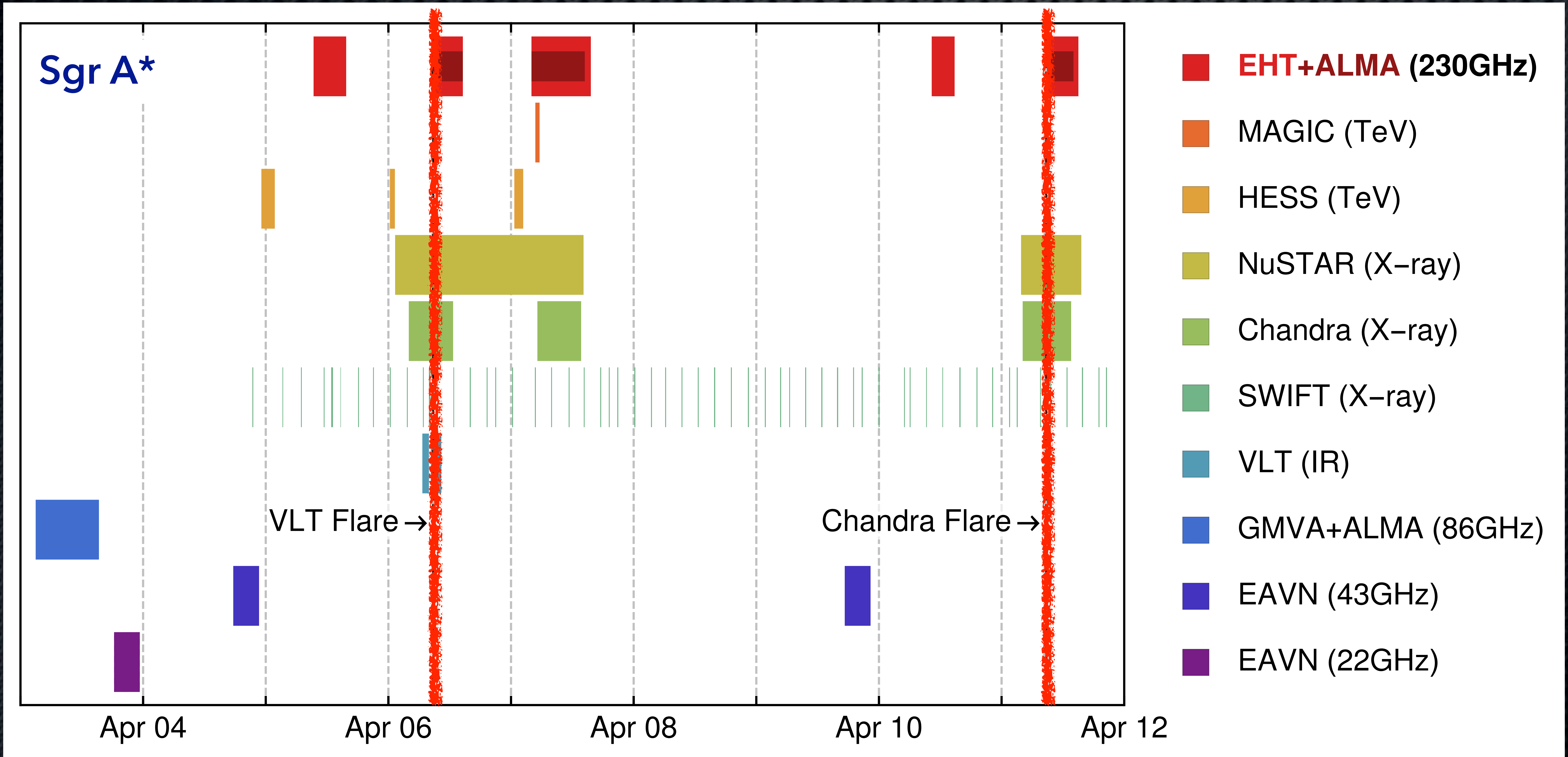


(Haggard, Nynke++, subm.)

- F1 double-peaked morphology
- Durations: 5.8 ks (1.6 hrs) & 3.4 ks
- F1 energy (2-10 keV): ~3×10^{39} erg!!

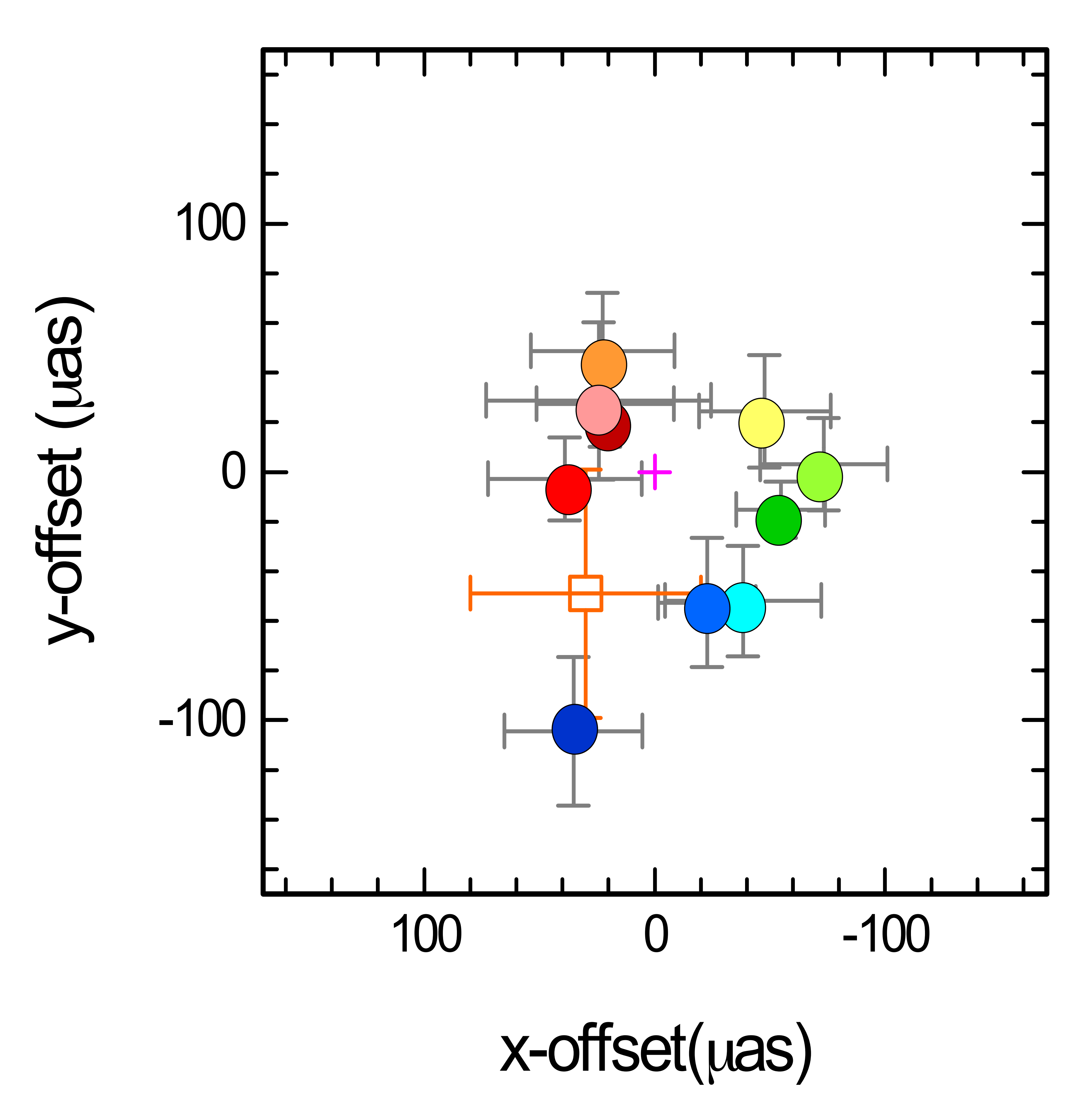


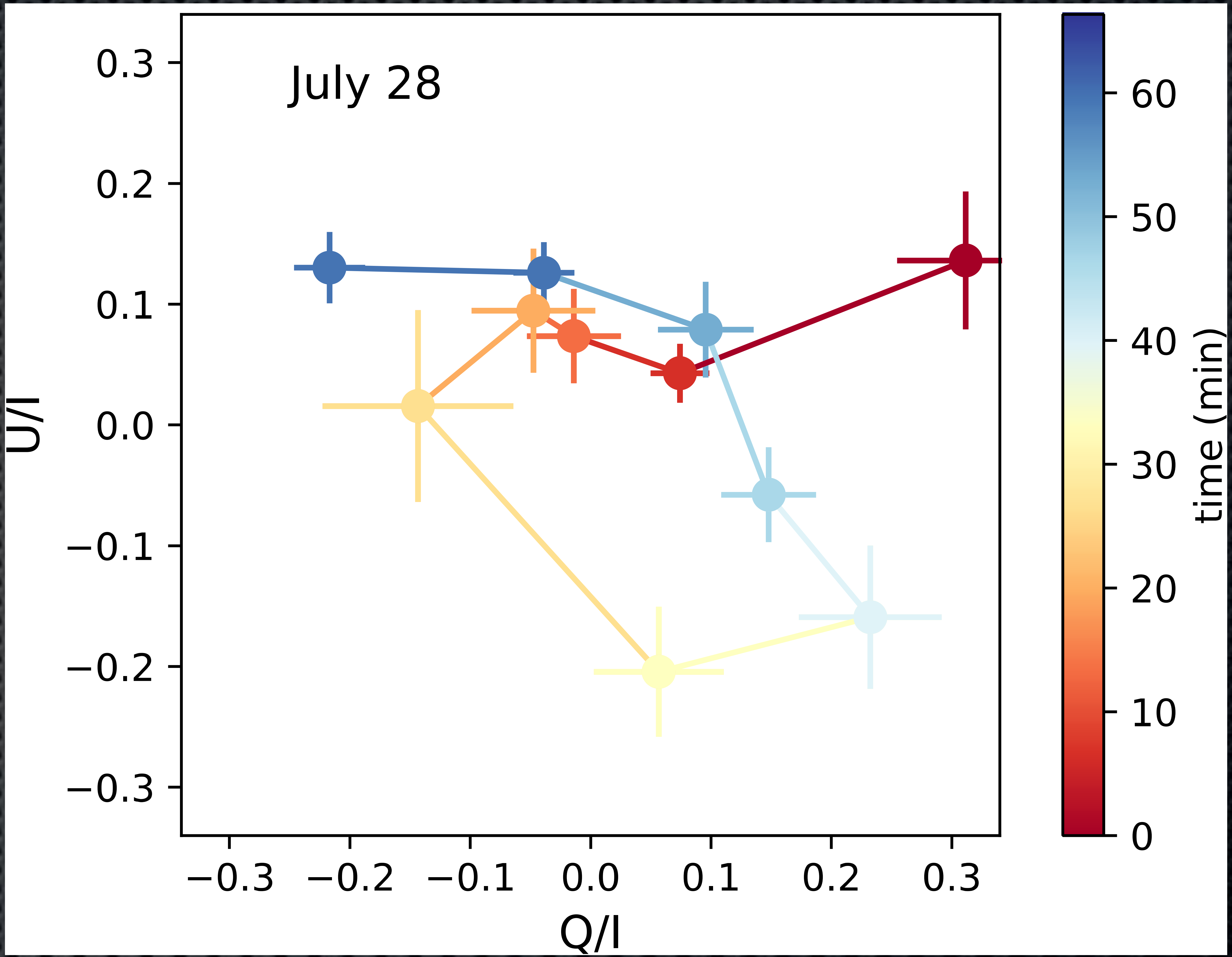
Multiwavelength WG (coordinators: SM, Kazuhiro Hada)



(M. Johnson, J. Farah/UMass, for EHT MWL WG)

Flares in context: new VLTI results with GRAVITY!!

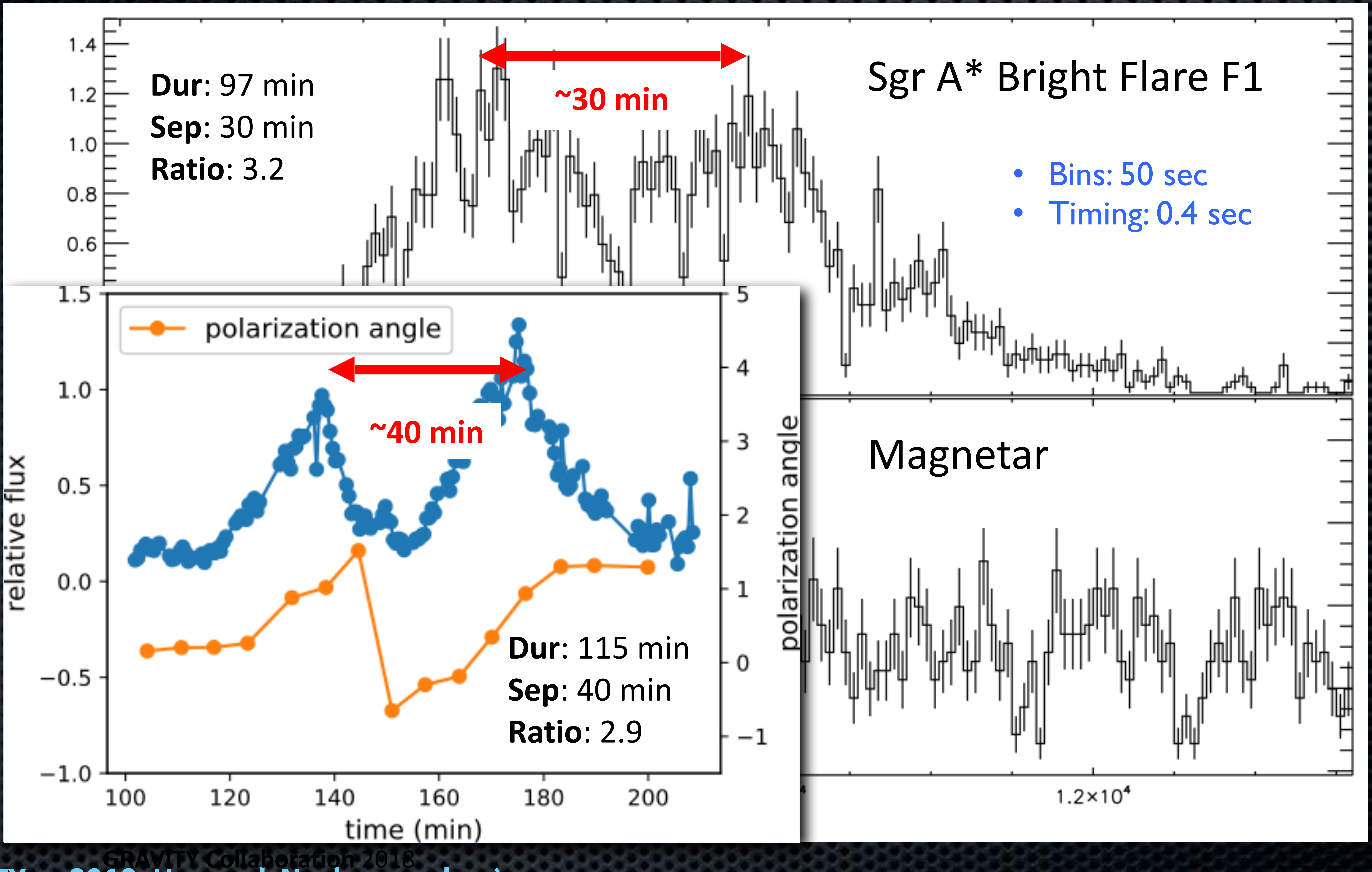




- ★ Near-horizon orbital motion in Sgr A* IR flares on same scale/timescale as the Xray flares!
- ★ Polarization angle rotation "Q/U" loop

(GRAVITY++2018)

EHT 2020: planning to co-observe with GRAVITY! (low odds of success but…)



(GRAVITY++ 2018; Haggard, Nynke++, subm.)

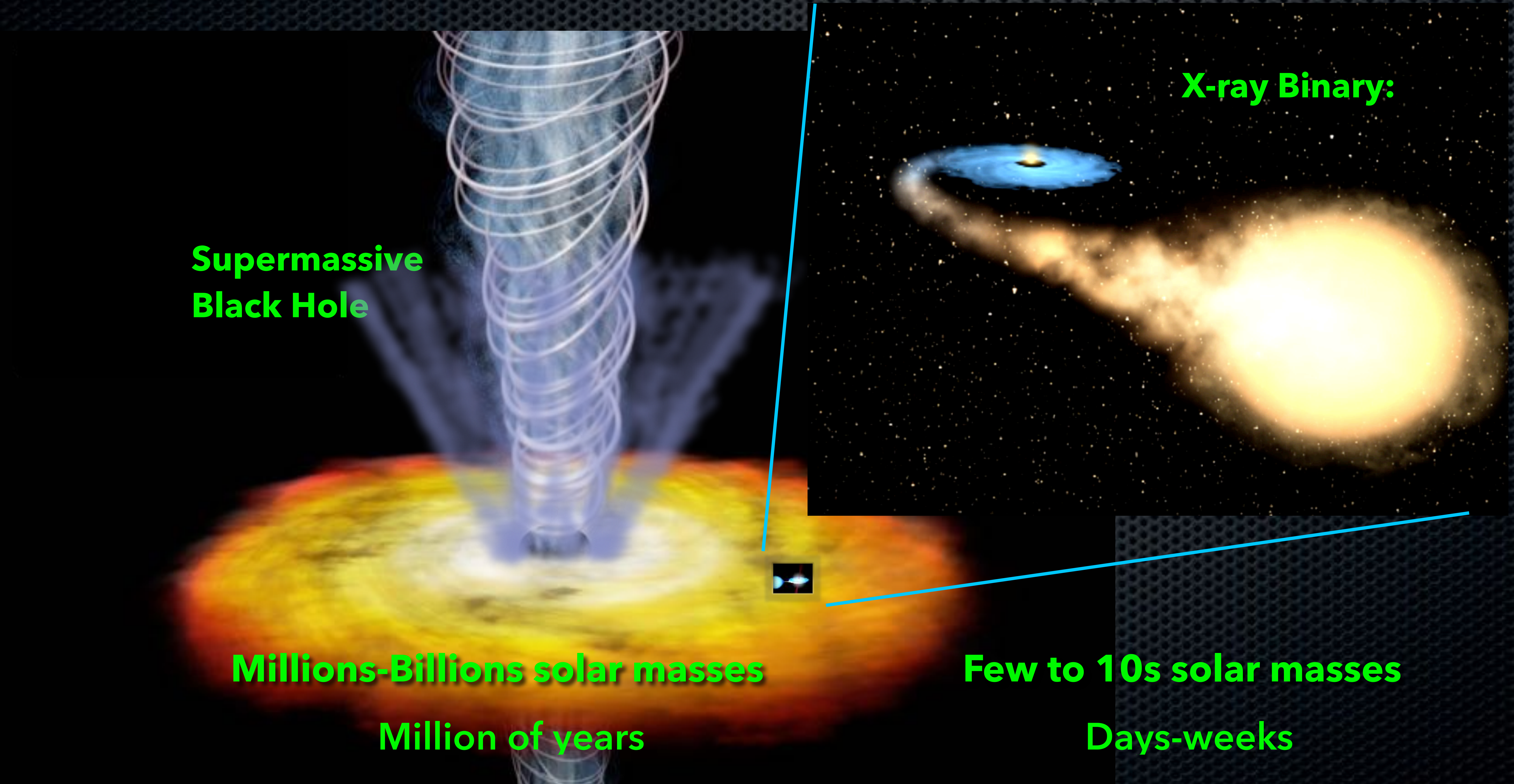
Theoretical aspect: how to identify plasmoids: potential sites for flaring?

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

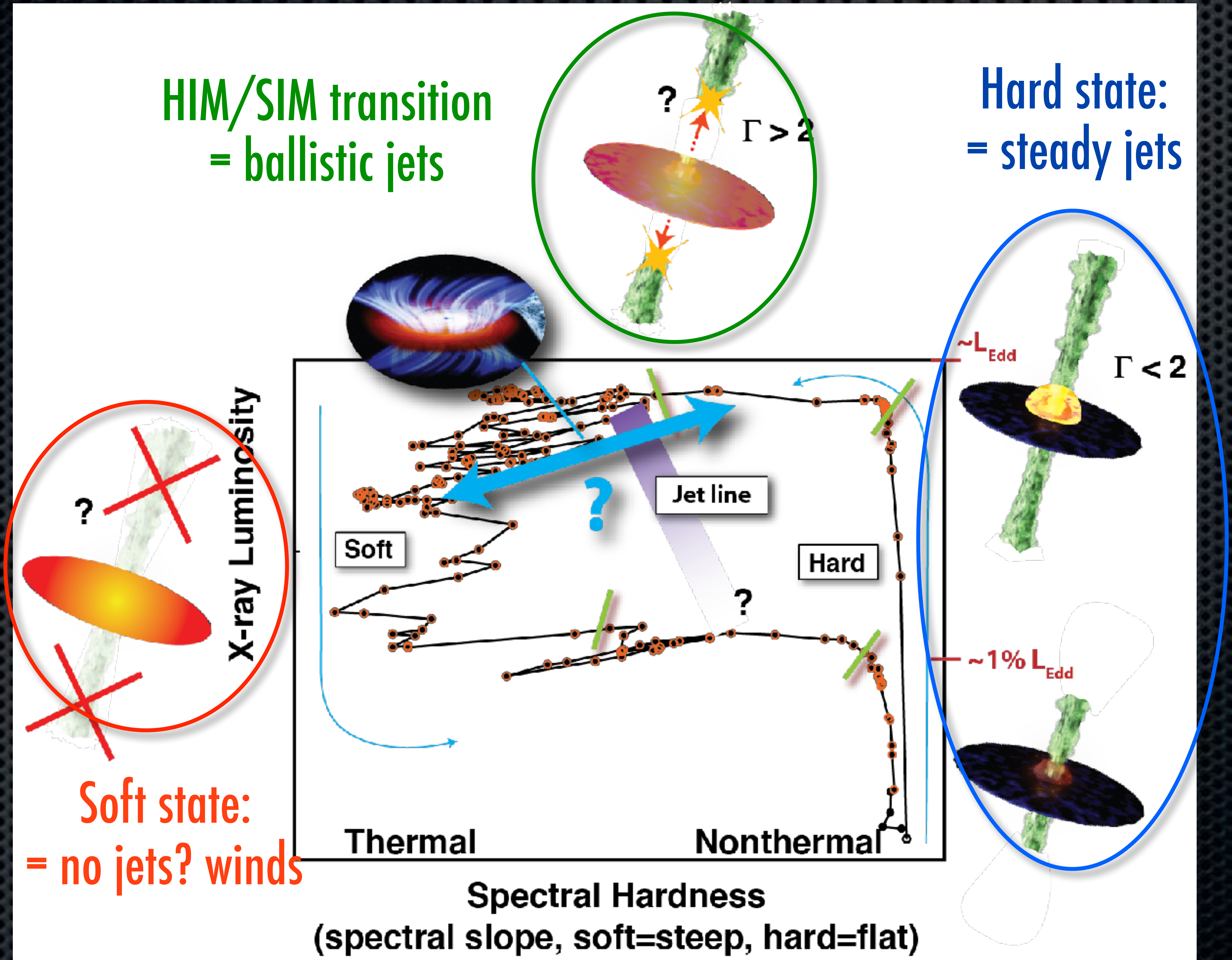
Outline

- ★ Role of black holes in the universe and major questions
- ★ Influence of spacetime geometry on accretion
- ★ Event Horizon Telescope: context, results, upcoming
- ★ Black holes across the mass scale: XRBs as 'mini' AGN?
- ★ Cutting edge (if time…)

Are black holes “self-similar”? I.e. does GR dominate over environment?

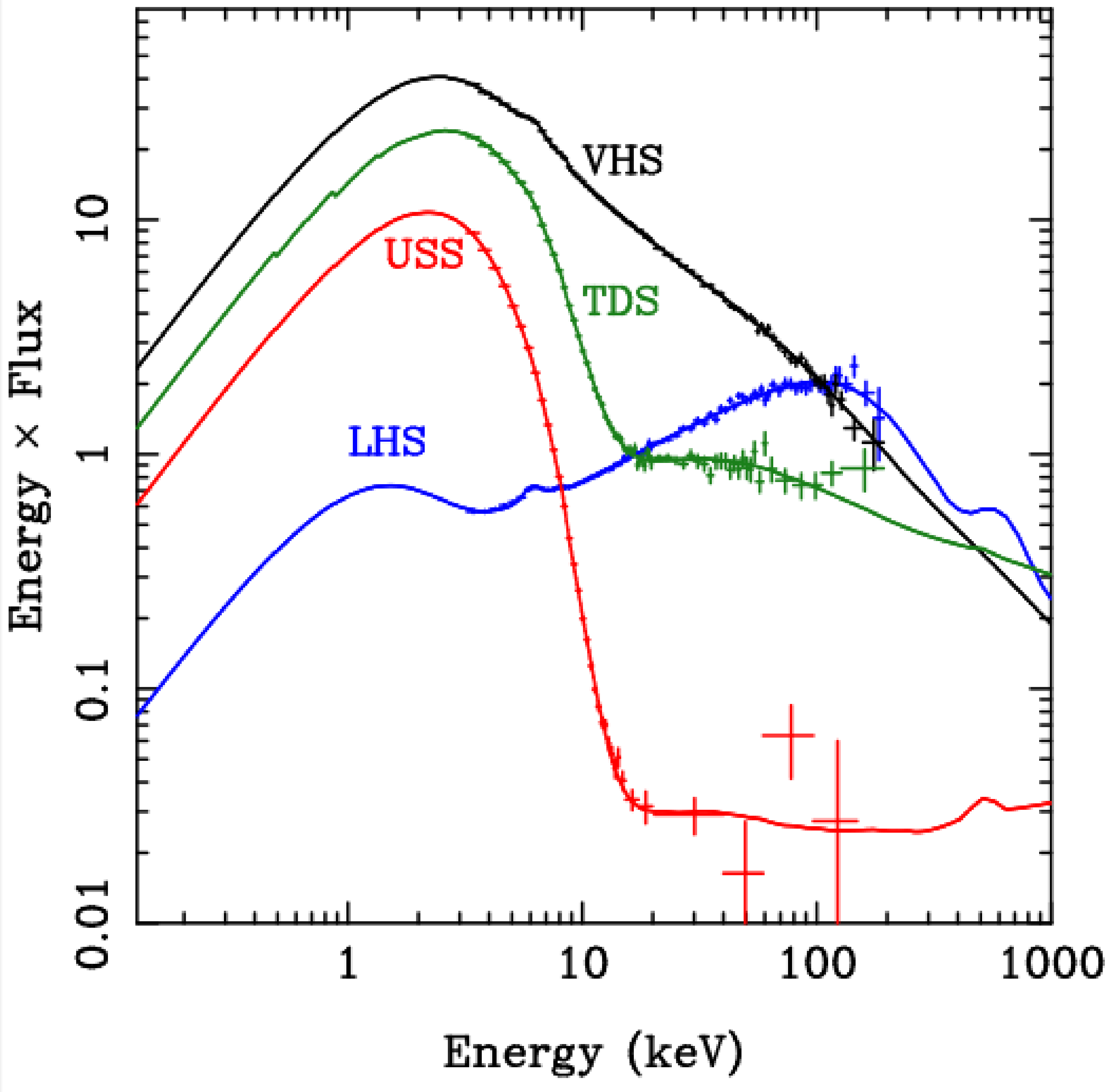


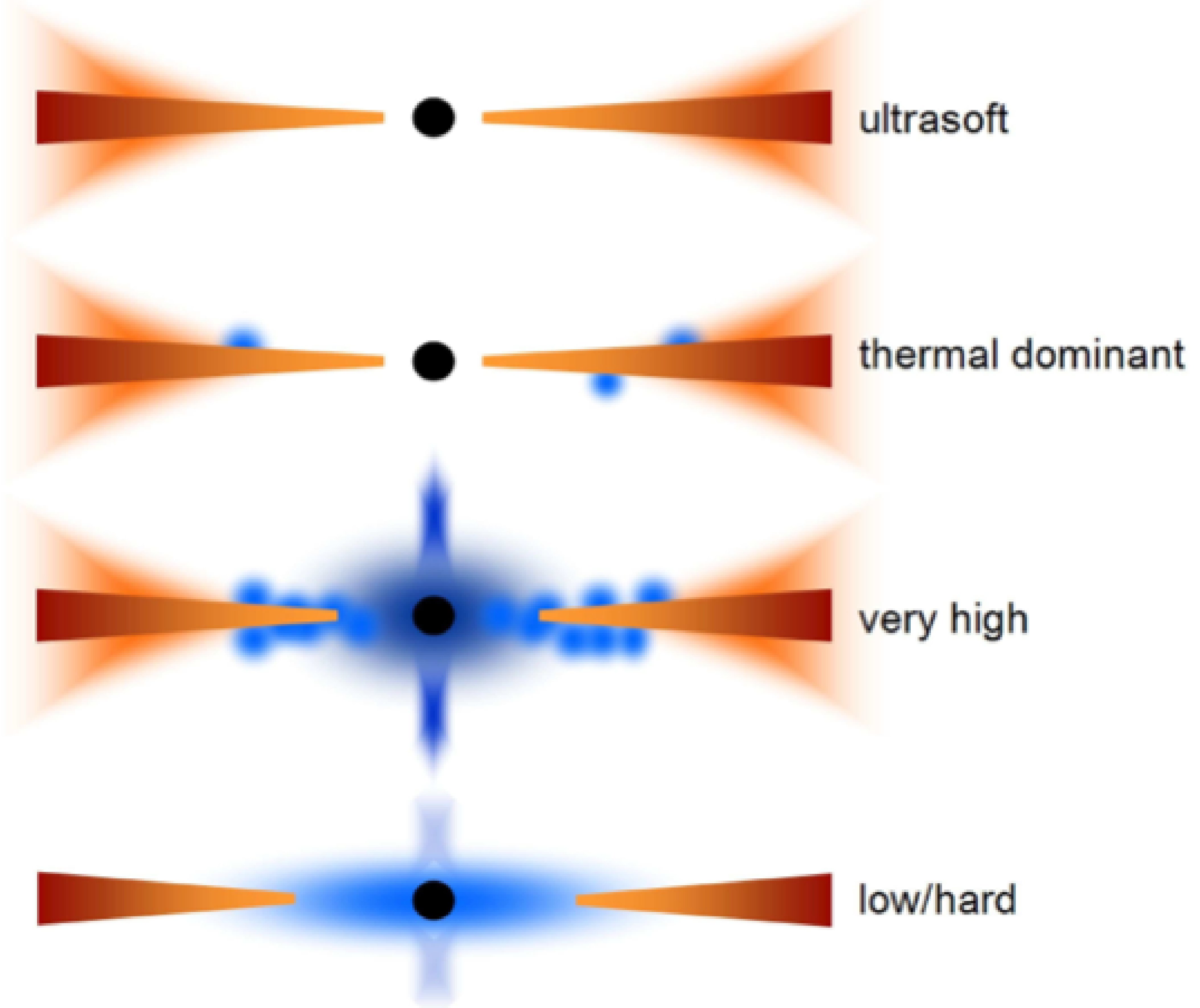
XRBs show a complex phenomenology of "states"



Time variable XRB behavior: The HID

Spectra and Interpretation

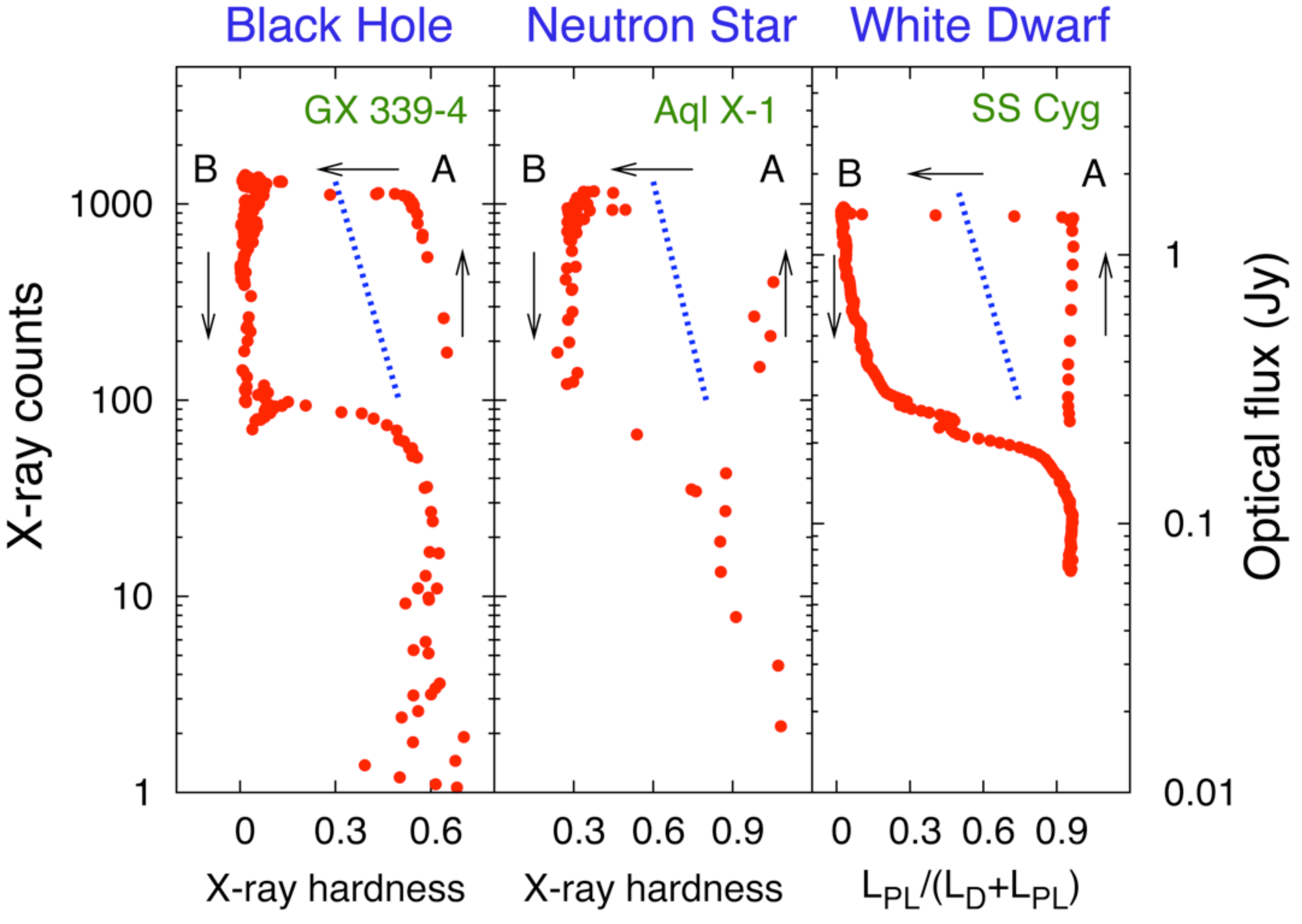




(Esin et al. 1997; Done, Gierlinski & Kubota 2007)

Why might these states be applicable to AGN?

- Neutron stars and white dwarfs show a similar outburst evolution as BHXRBs:



(Körding et al. 2008, Science)

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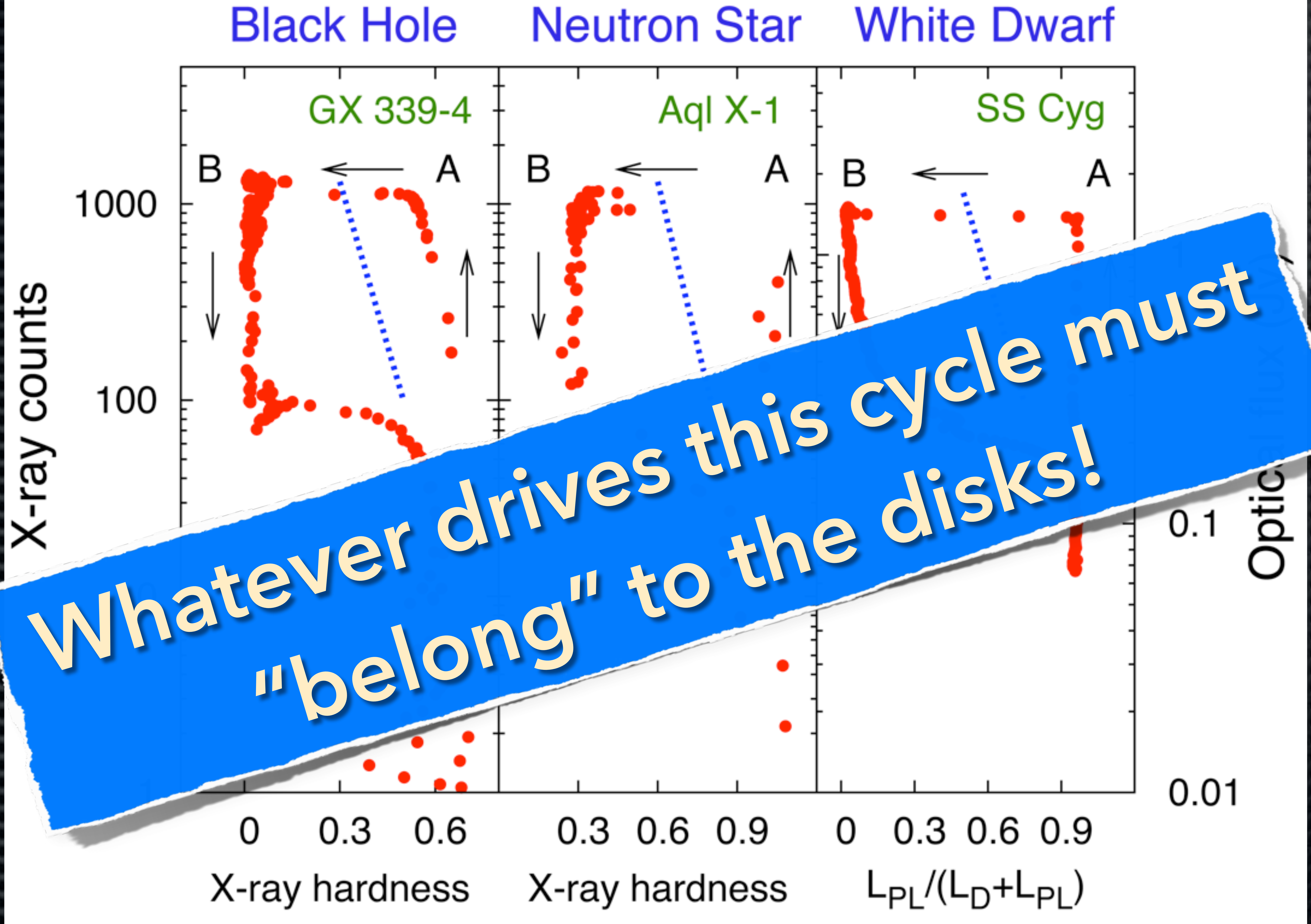
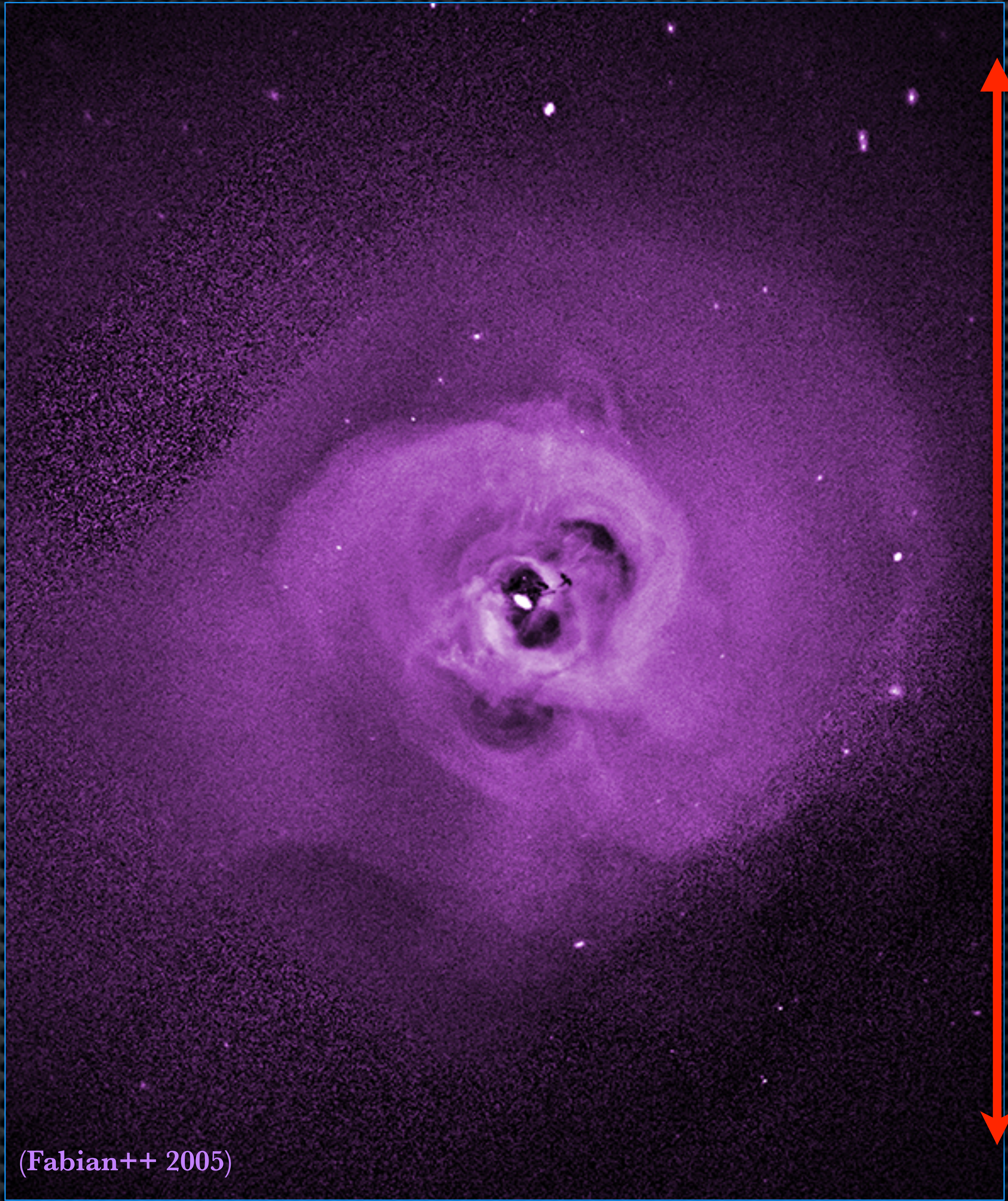


Whatever drives this cycle must "belong" to the disks!

(Körding et al. 2008, Science)

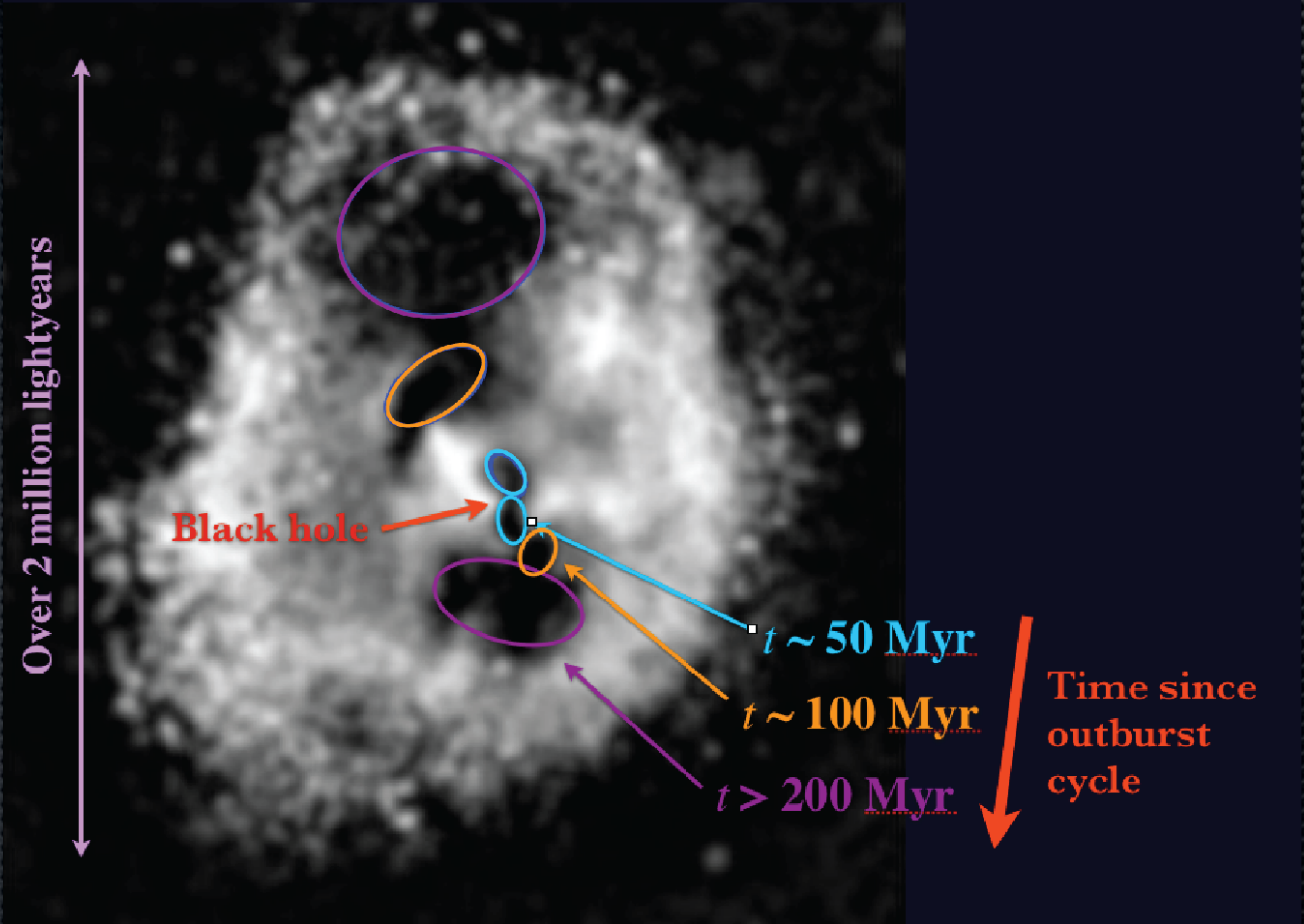
Black holes experience cyclic outbursts of activity



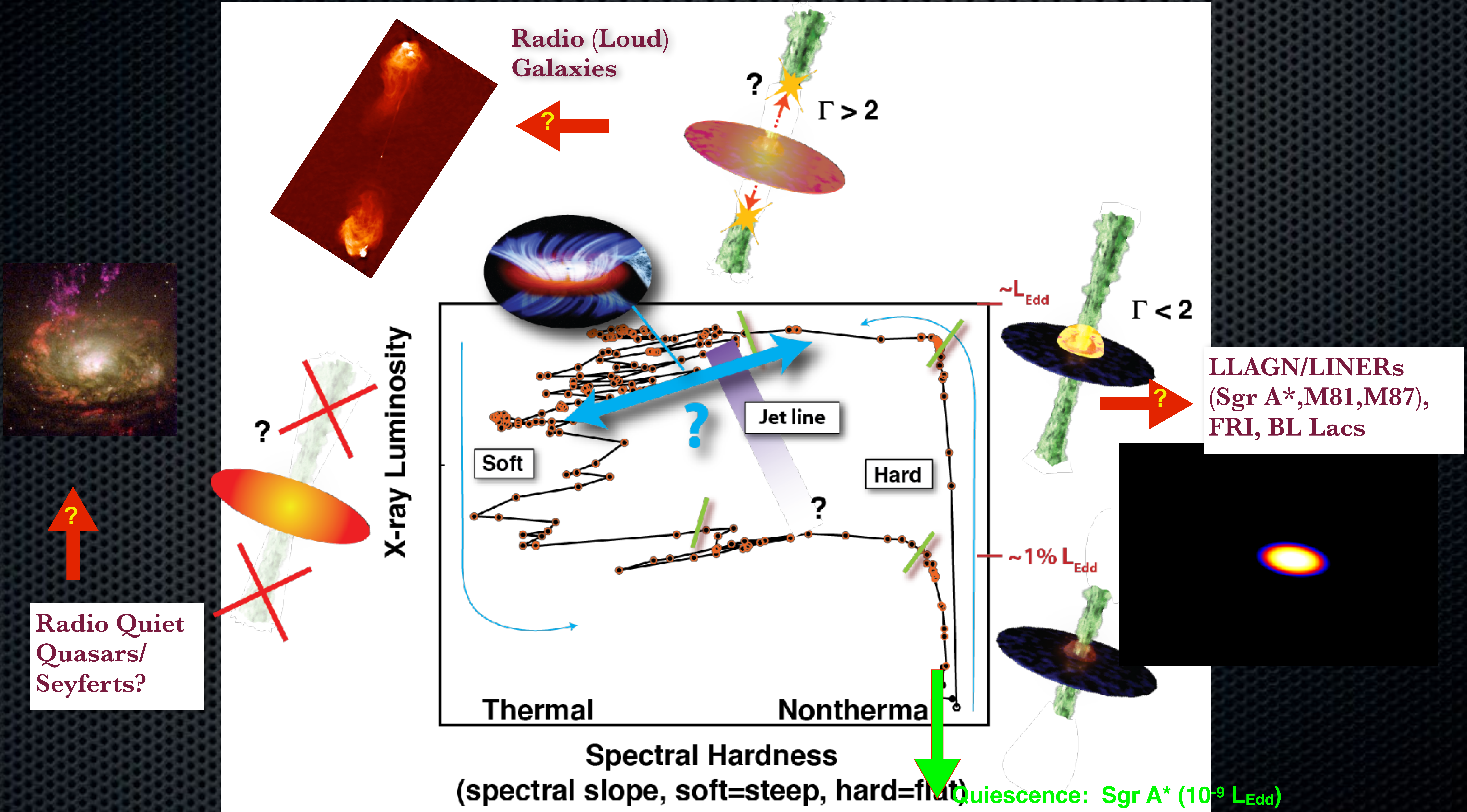
>few million light yrs

~10^{20} km

Black holes experience cyclic outbursts of activity

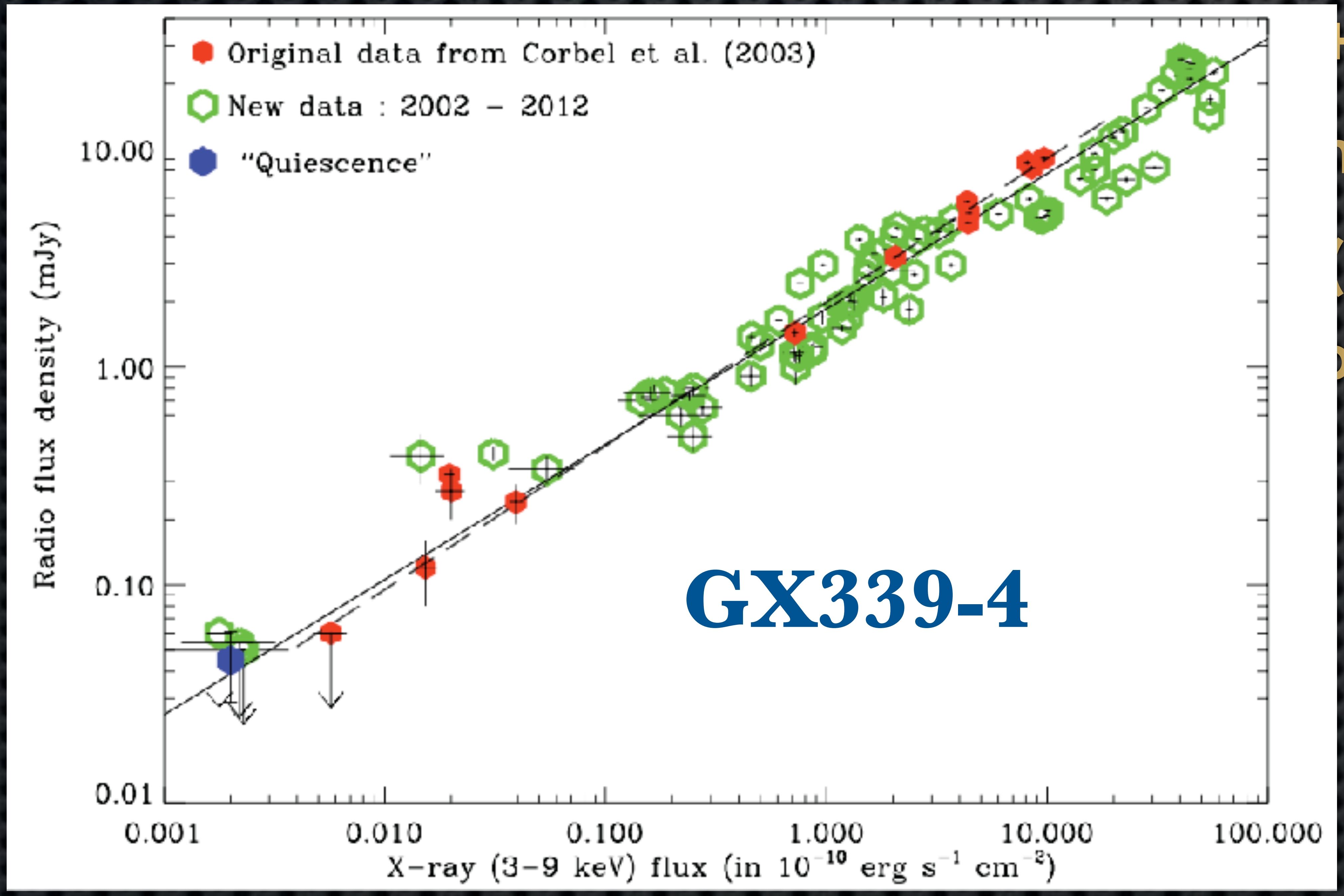


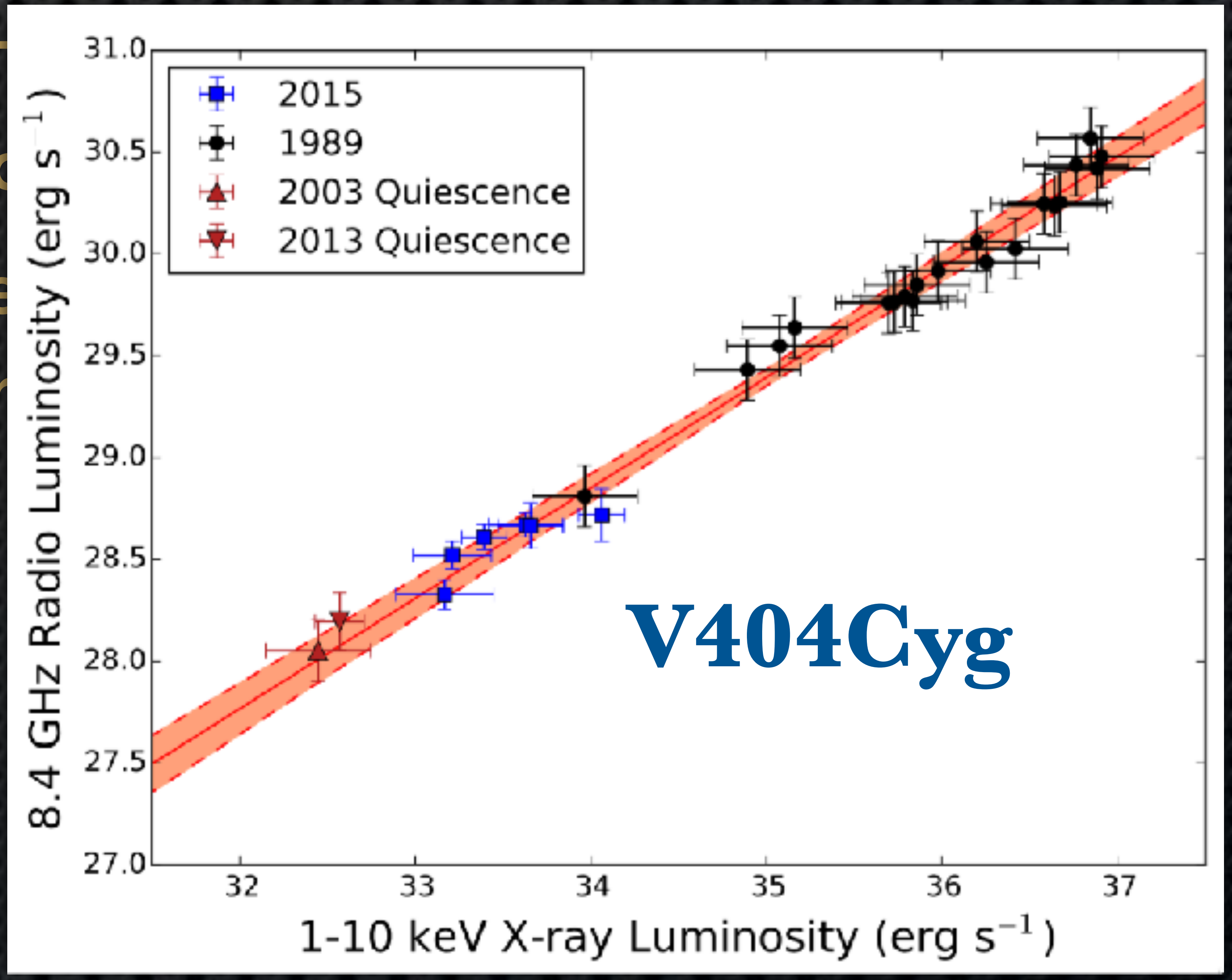
Do these states correspond to classes of AGN?



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)





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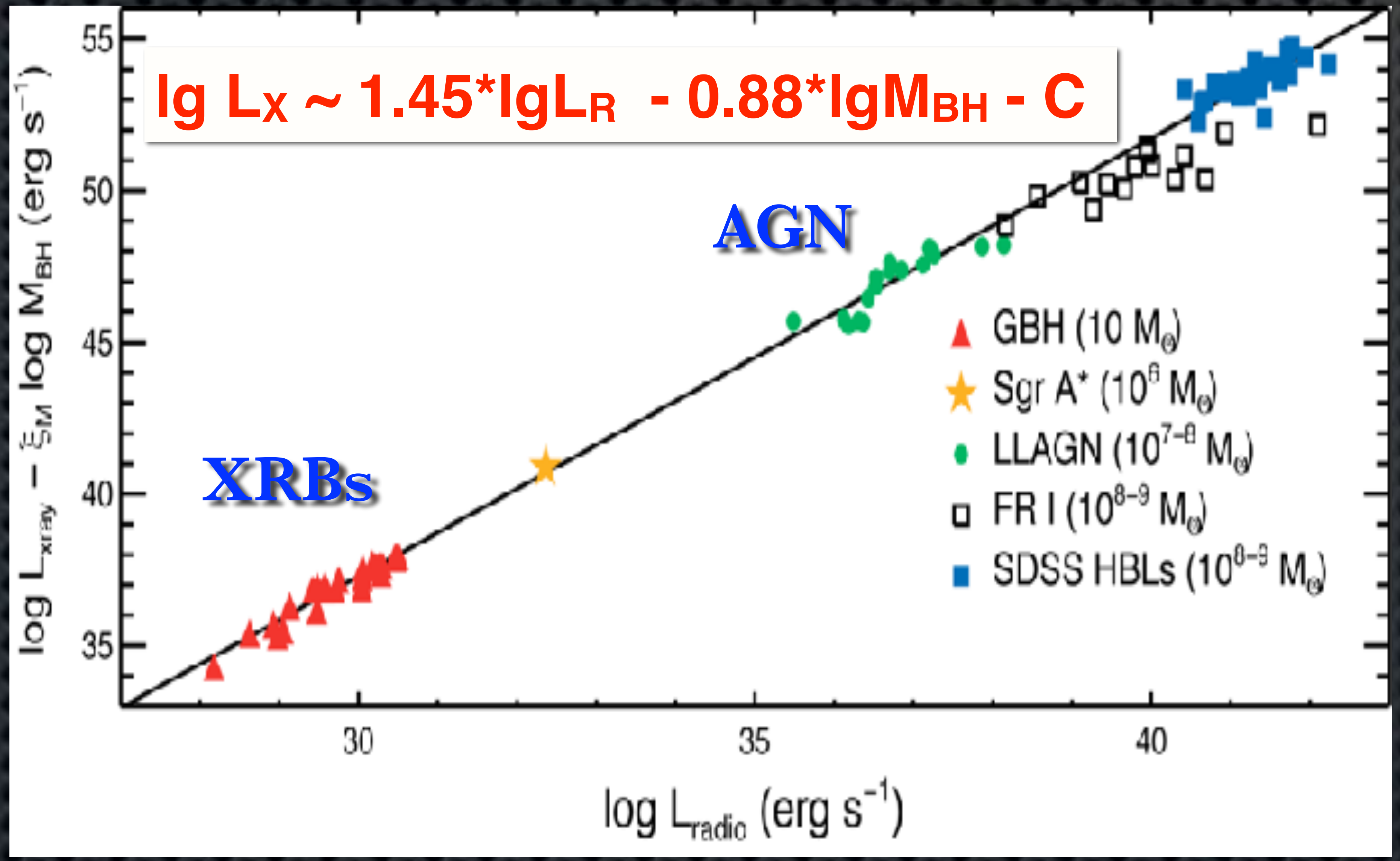
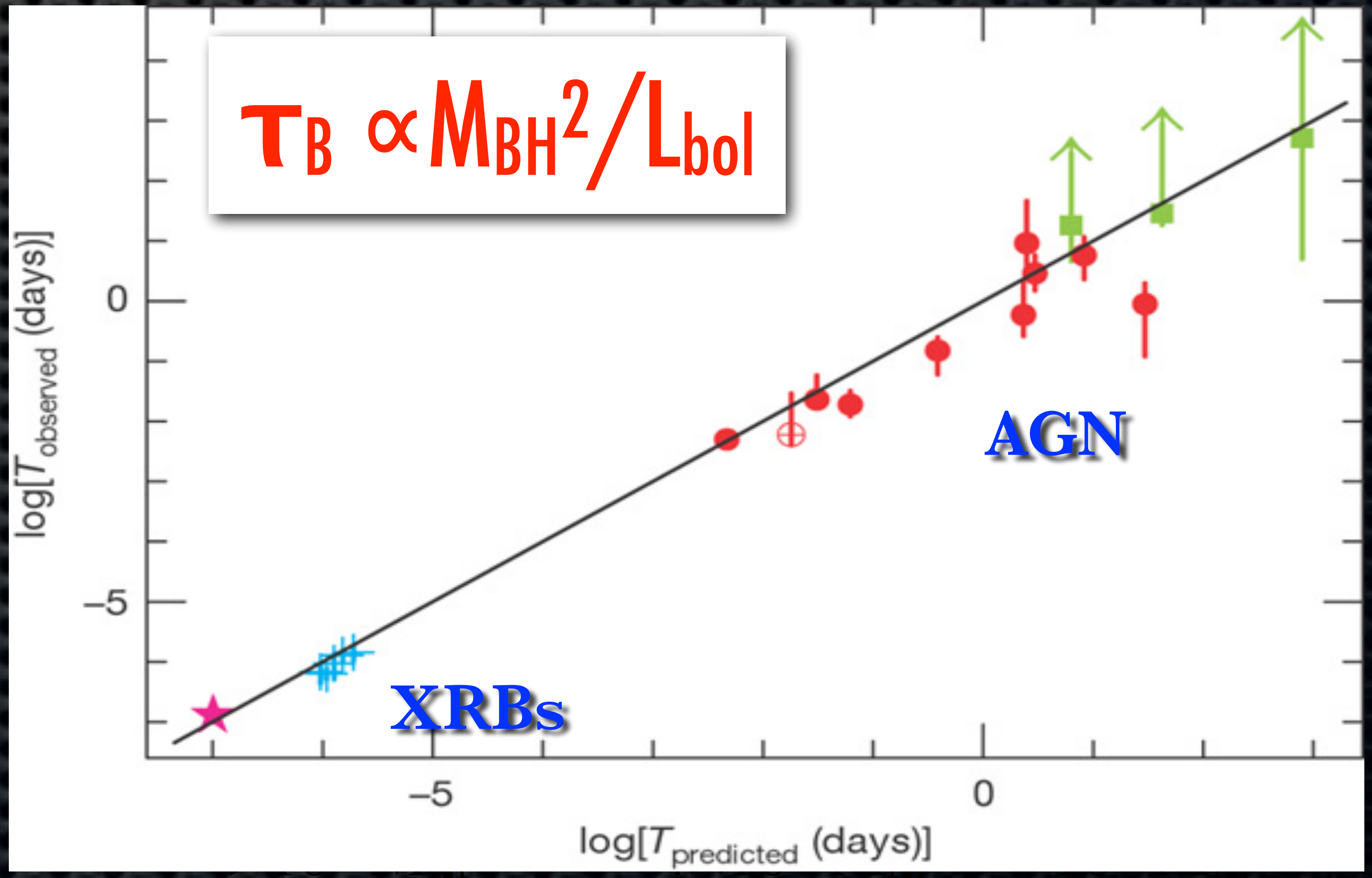
  - MWL joint fits with same model (SM++15, Connors, SM++17)
  - X-ray RMS variability "break" frequency (e.g., McHardy, Uttley++06)
  - Reflection "reverberation" mapping (e.g., Fabian++, Dauser++13, van Eijnatten, Connors, Garcia, SM++ in prep.)





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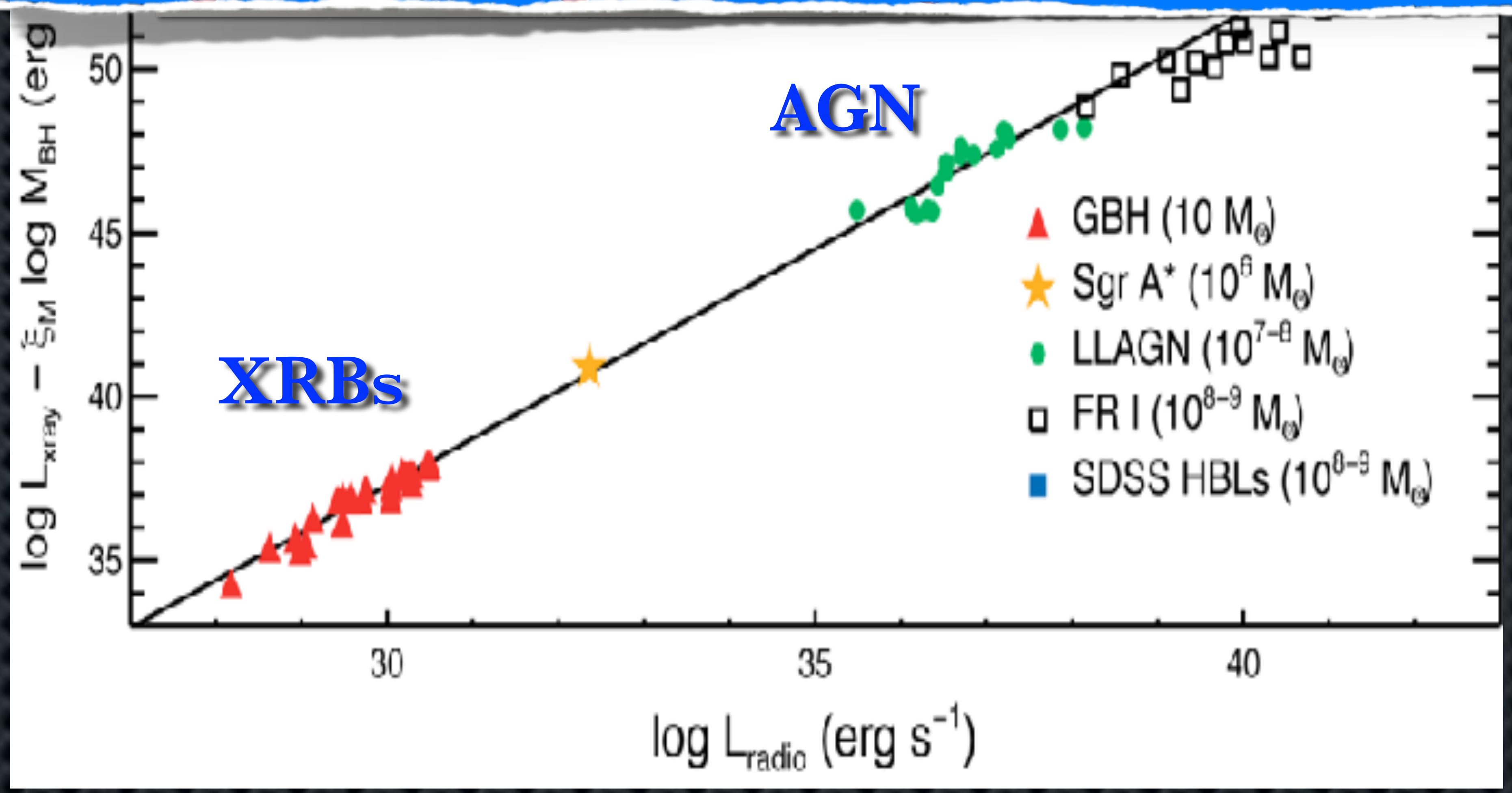
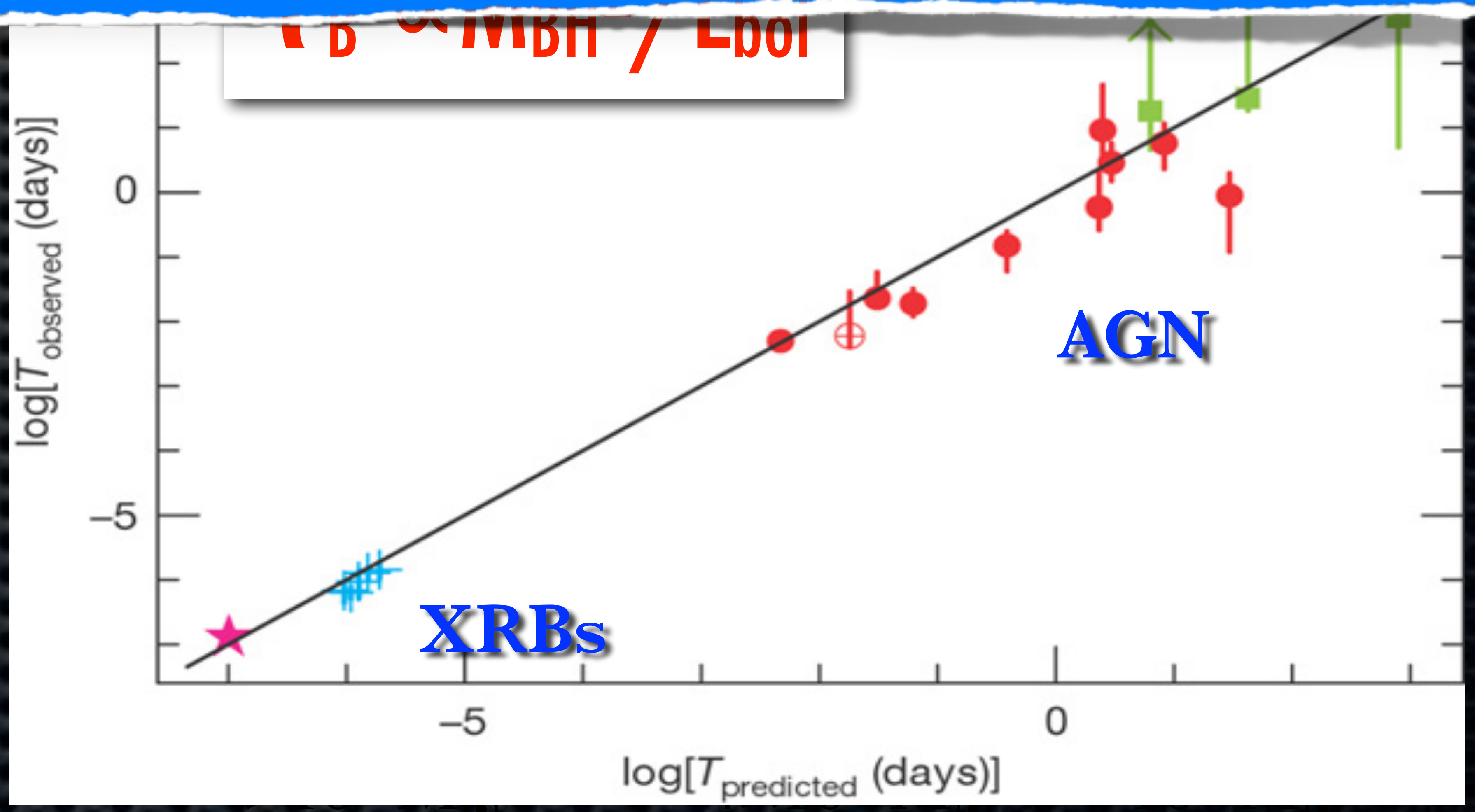
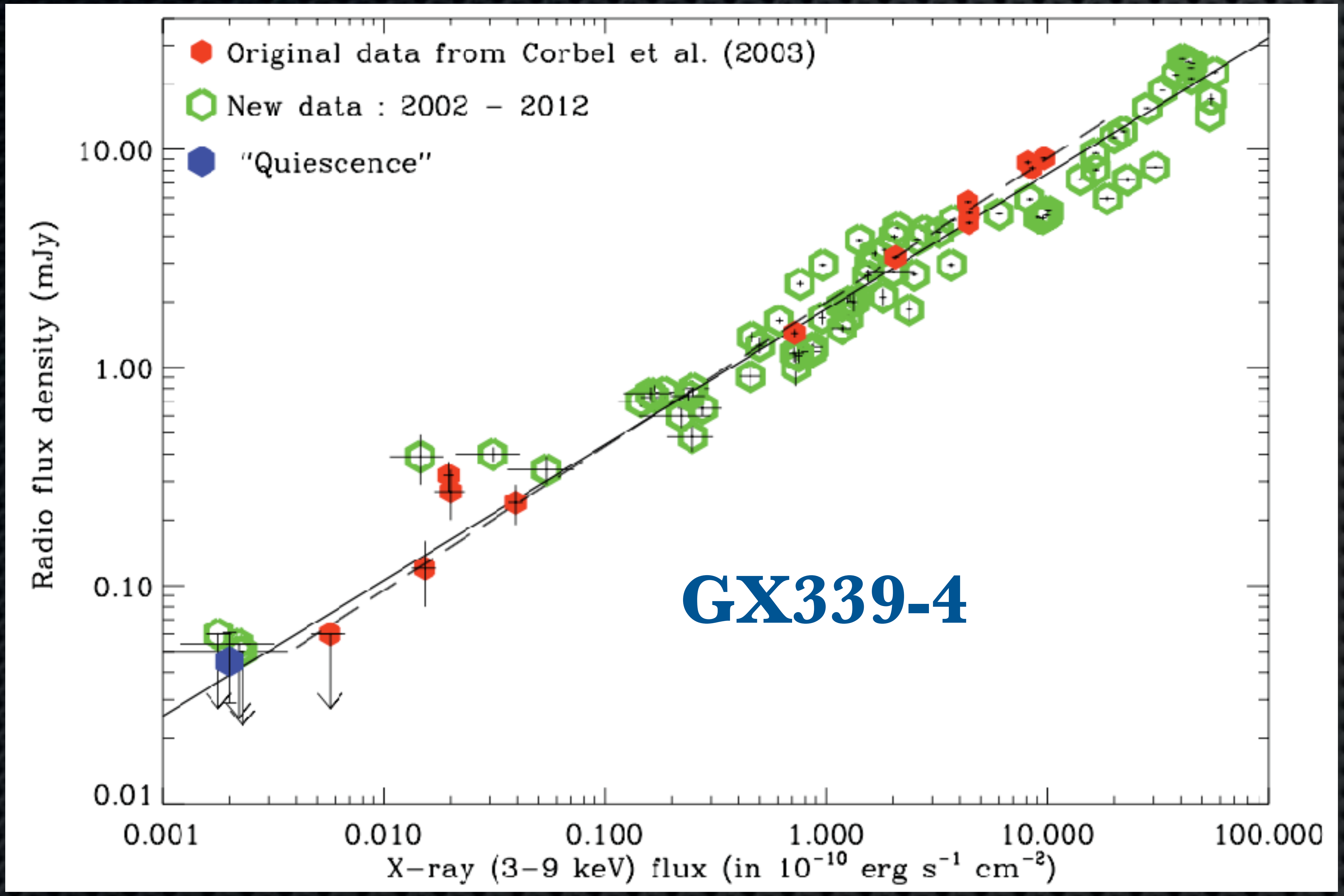
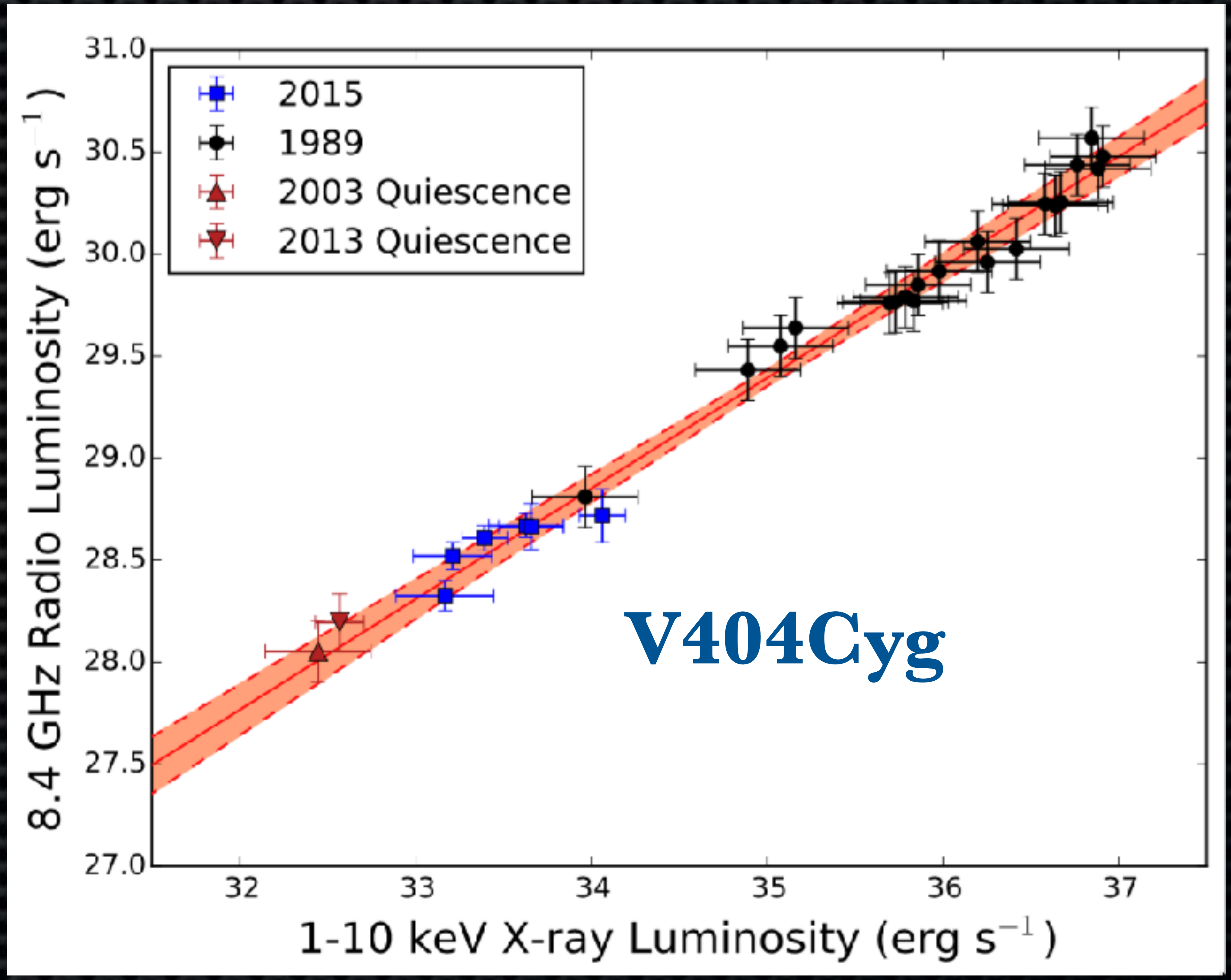
Bulk properties of AGN/XRBs scale predictably with M, ṁ!





What XRBs can teach us about "disk/jet coupling"

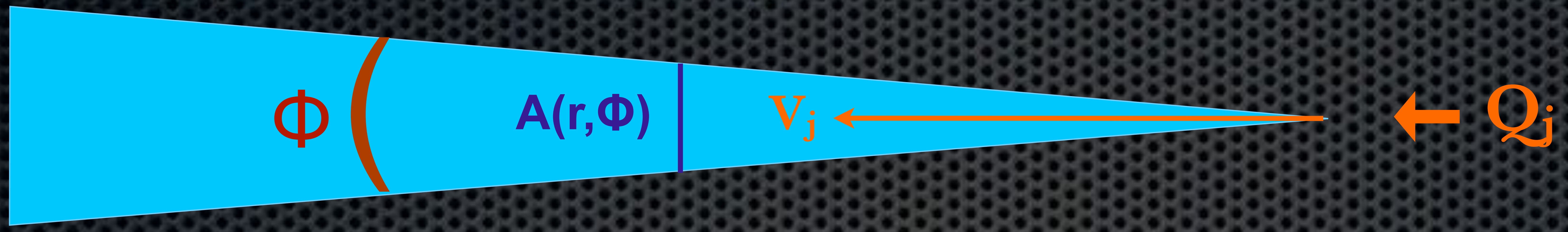




$$L_R \propto L_X^{0.55-0.7}$$

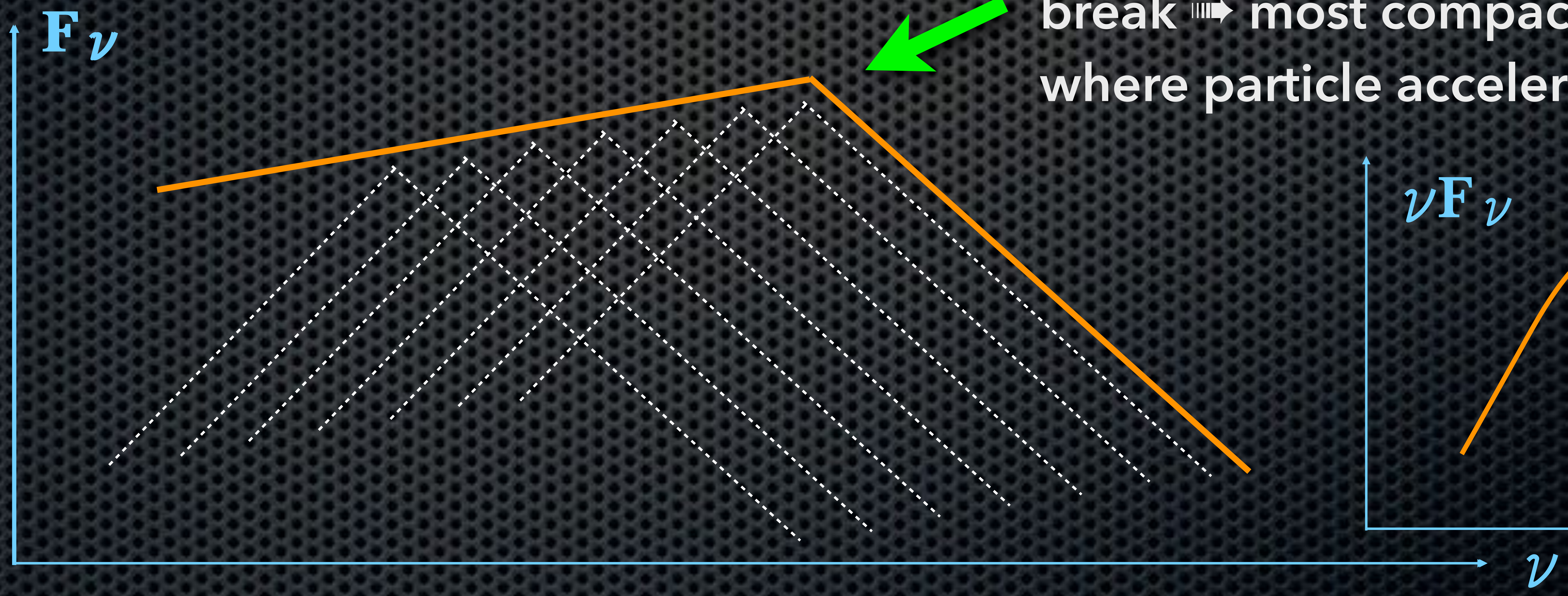
(SM++01,03,05; Corbel++2008; Hynes++2009; Corbel++2013; Gallo++2014; Rana++2016; Plotkin++2016)

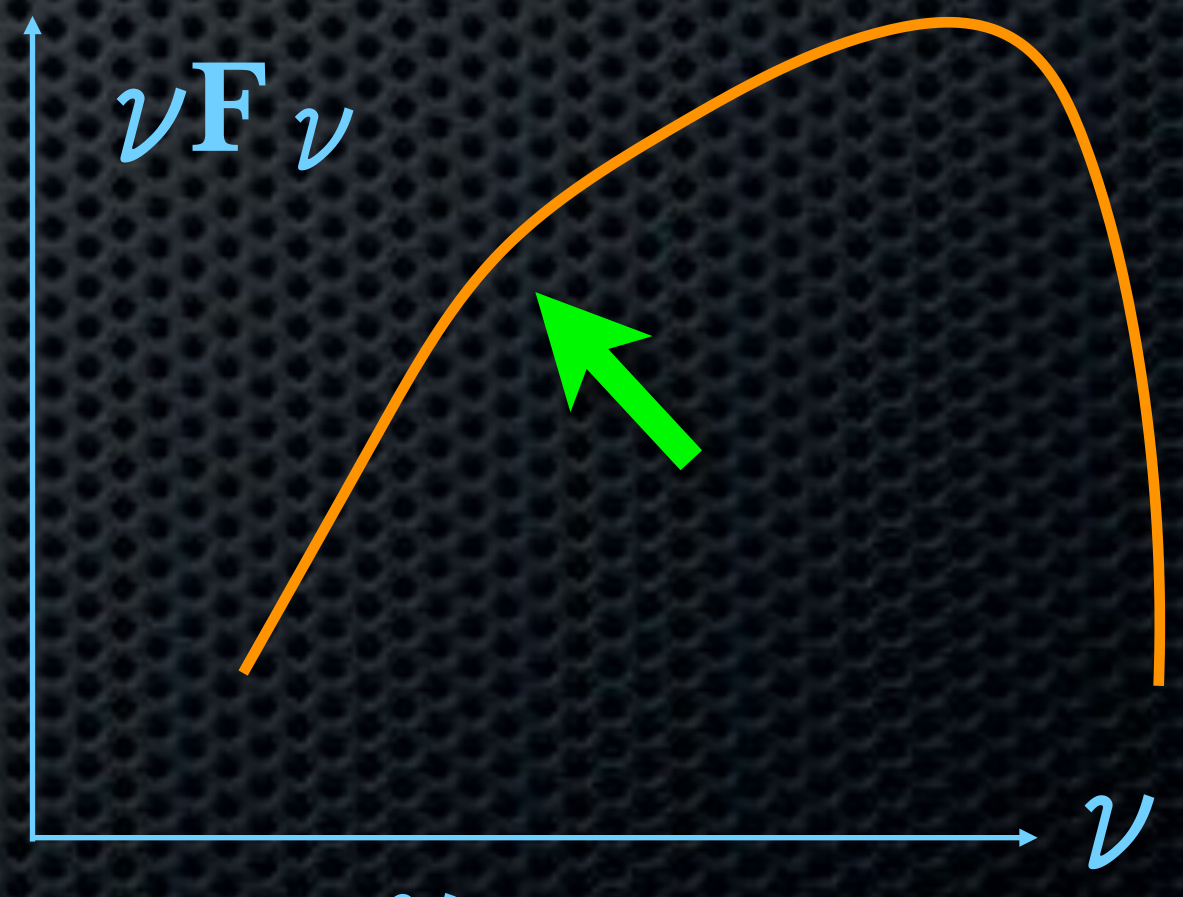
Blandford & Königl 1979: flat jet spectra → synchrotron self-absorption



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

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

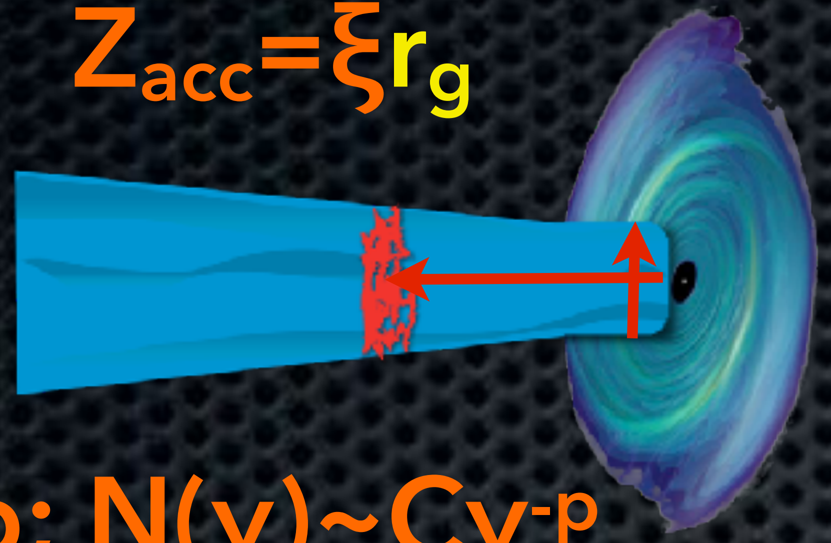




Mass/power scaling models (synchrotron example)

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

$Z_{acc} = \xi r_g$



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

$U_B / U_e = k$

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:

$$\alpha_\nu \propto C B^{(p+2)/2} \nu^{-(p+4)/2} \qquad j_\nu \propto C B^{(p+1)/2} \nu^{-(p-1)/2}$$

$$S_\nu \propto \xi(\theta) j_\nu (1 - e^{-\tau_\nu})/\alpha_\nu$$

$$\tau = R_j \alpha_\nu \qquad R_j \propto M$$

★ 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 useful 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)

Radio/Xray correlation: ratio of efficiencies

For objects with the *same* mass, like XRBs:

$$L_R \propto L_X^{0.55-0.7}$$ (**observed*: e.g., Gallo++2014, Plotkin++2016)*

$$L_R \propto \dot{m}^{17/12+2/3\alpha_R}$$

$$\Longrightarrow 0.55 - 0.7 = \frac{\frac{17}{12} + \frac{2}{3}\alpha_R}{q}$$

$$L_X \propto \dot{m}^q$$

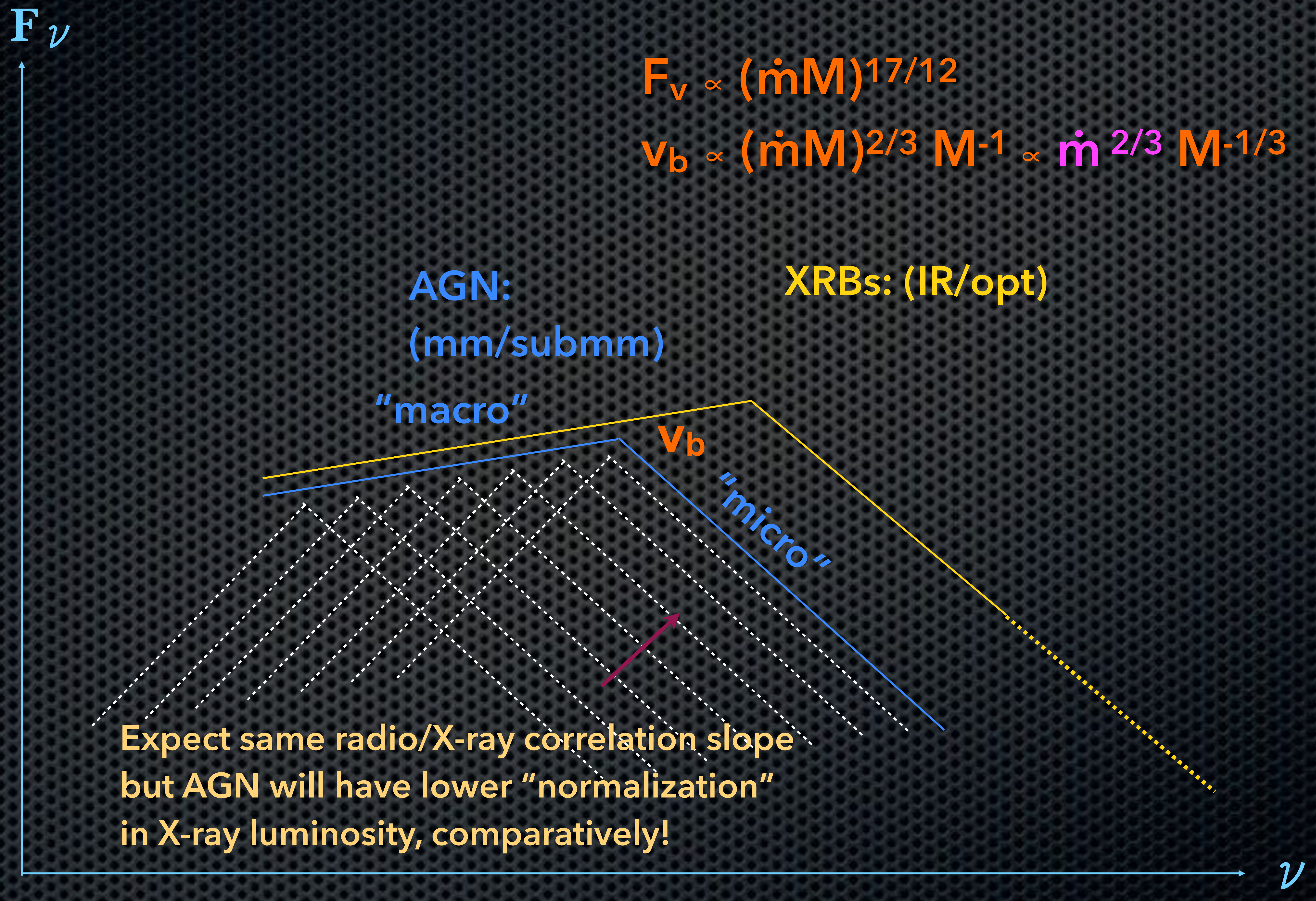
- For the observed range in α_R~0.0-0.3, q~2-3 ➠ ***radiatively efficient (∝ ṁ) X-ray emission processes ruled out!***
- $L_X \propto \dot{m}^2$ consistent with synchrotron, bremsstrahlung, optically thin (single scattering) inverse Comptonization of disk photons, $L_X \propto \dot{m}^3$ consistent with optically thin SSC
- Cooled synchrotron gives q~[p+2 - 3/2Γ_X], closer to $L_X \propto \dot{m}$
- 2 < q < 3 consistent with either mixed contributions or optically depth effects (still degenerate) ➠ broadband SEDs modeling!!

(Blandford & König 1979; Falcke & Biermann 1995; SM++2003; Heinz & Sunyaev 2003; Merloni, Heinz & diMatteo 2003; Falcke, Körding & SM 2004; Heinz 2004, Plotkin, SM++2012)

Compact jets: optical depth and mass scaling

$$F_\nu \propto (\dot{m}M)^{17/12}$$

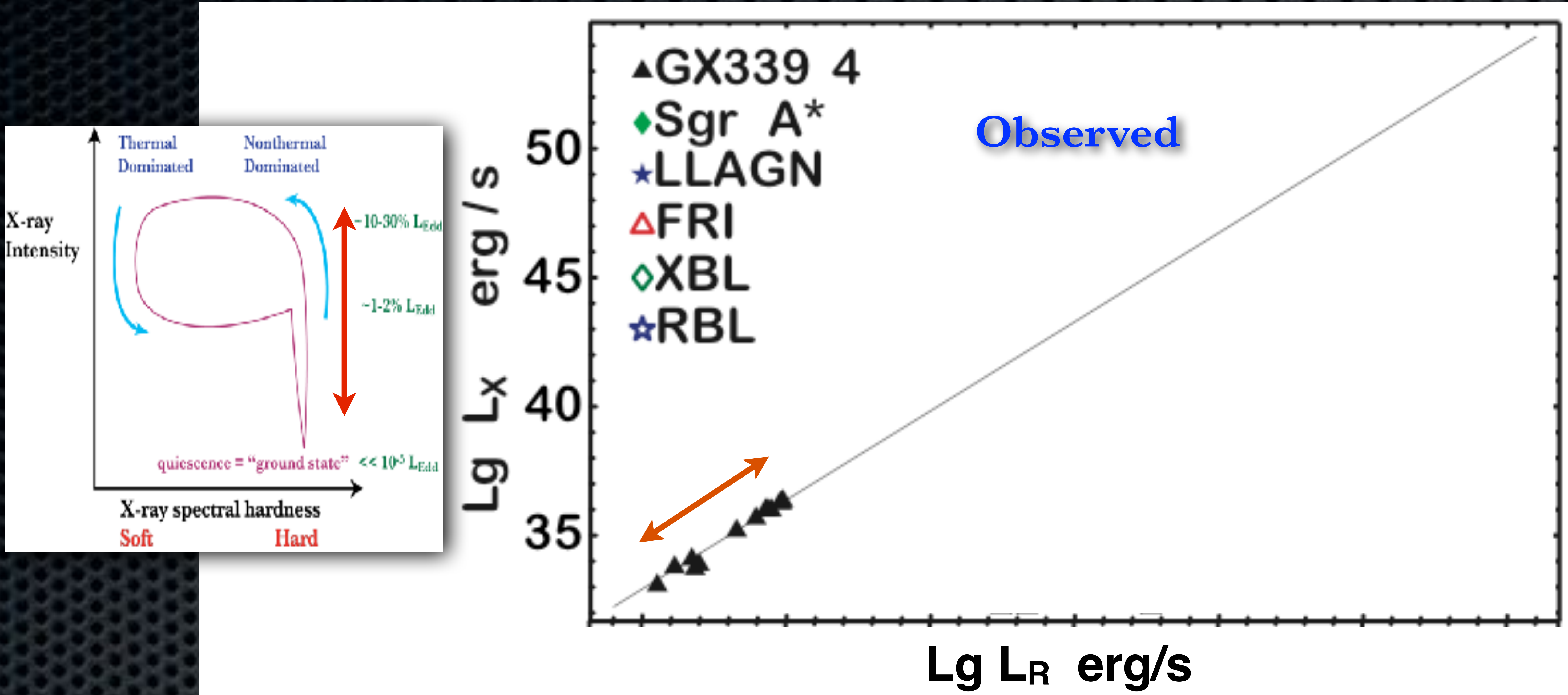
$$\nu_b \propto (\dot{m}M)^{2/3}\, M^{-1} \propto \dot{m}^{2/3}\, M^{-1/3}$$



Expect same radio/X-ray correlation slope but AGN will have lower "normalization" in X-ray luminosity, comparatively!

(Blandford & Königl 1979; Falcke & Biermann 1995; SM++ 2003, Heinz & Sunyaev 2003; Plotkin, SM++ 2012)

Fundamental Plane of Black Hole Accretion



(SM et al. 2003, Merloni,Heinz & diMatteo 2003, Falcke, Körding & SM 2004, SM 2005, Merloni et al. 2006, Kording et al. 2006)

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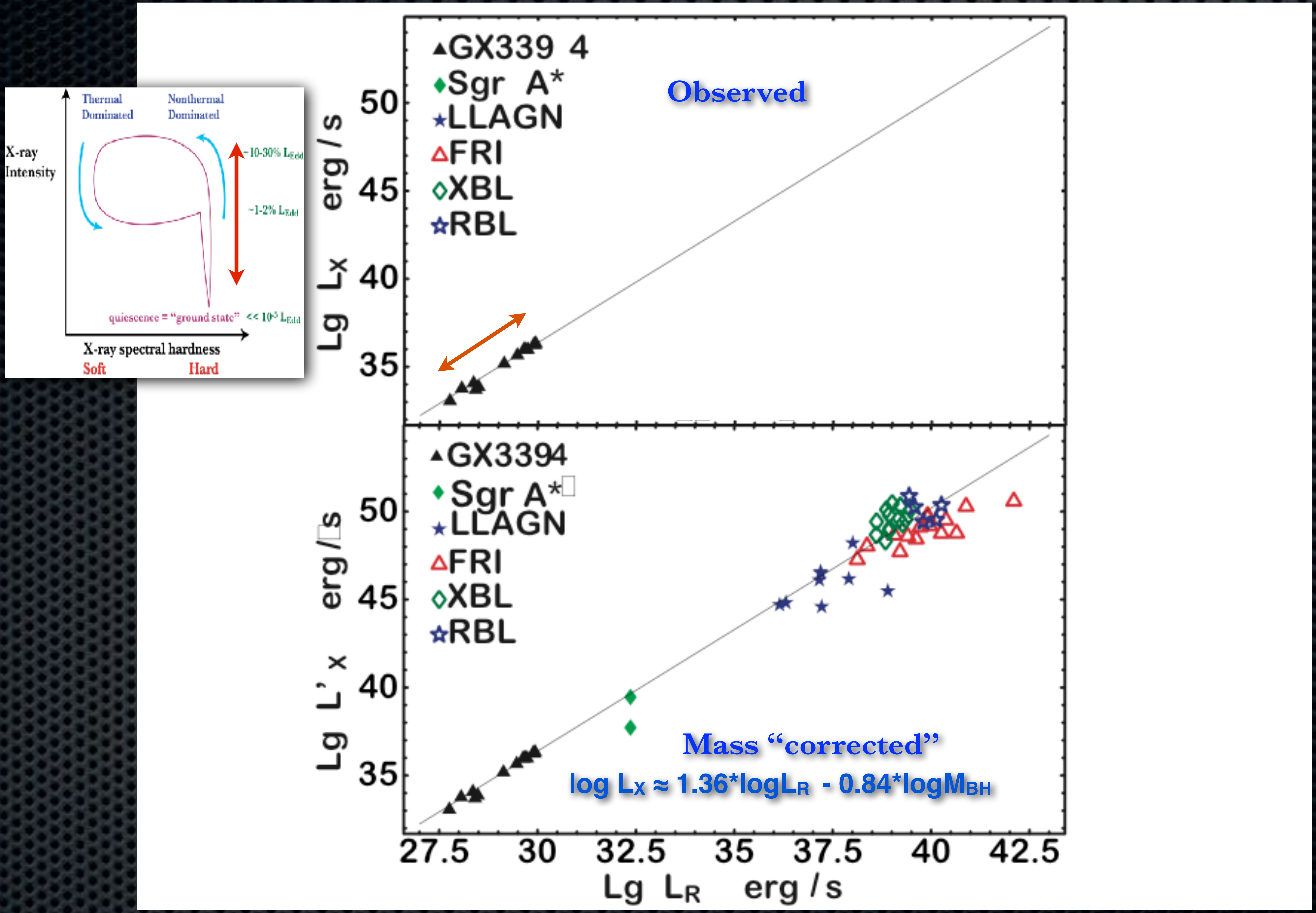
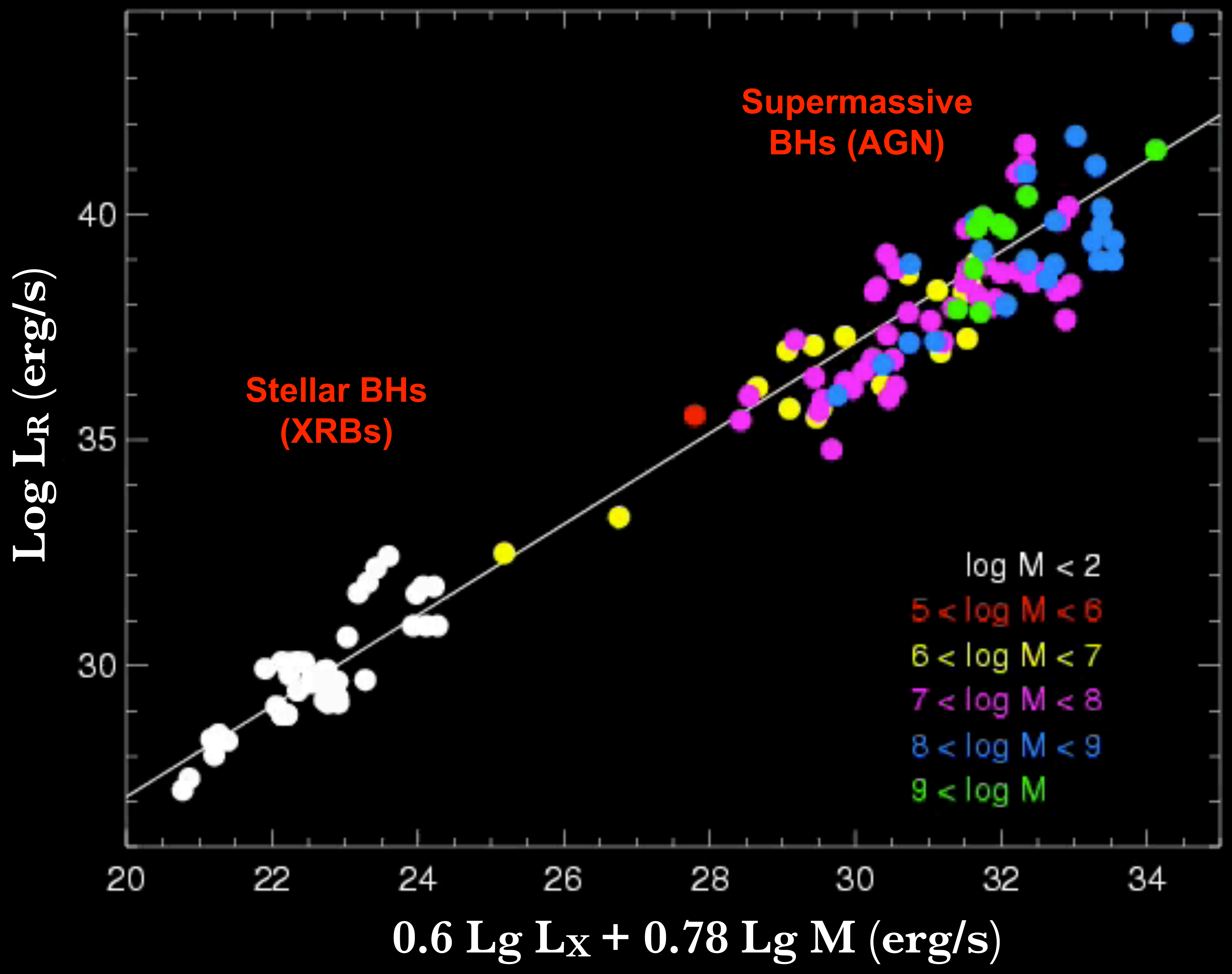


(SM et al. 2003, Merloni, Heinz & diMatteo 2003, Falcke, Körding & SM 2004, SM 2005, Merloni et al. 2006, Kording et al. 2006)

Fundamental Plane of Black Hole Accretion: connecting (low $\dot{M}$) black holes of all masses



(SM et al. 2003; Merloni,Heinz & diMatteo 2003; Falcke, Körding & SM 2004; SM 2005; Merloni et al. 2006; Körding et al. 2006; Gültekin et al. 2009; Plotkin, SM et al. 2011)

(movie courtesy of S. Heinz)

Fundamental Plane of Black Hole Accretion:

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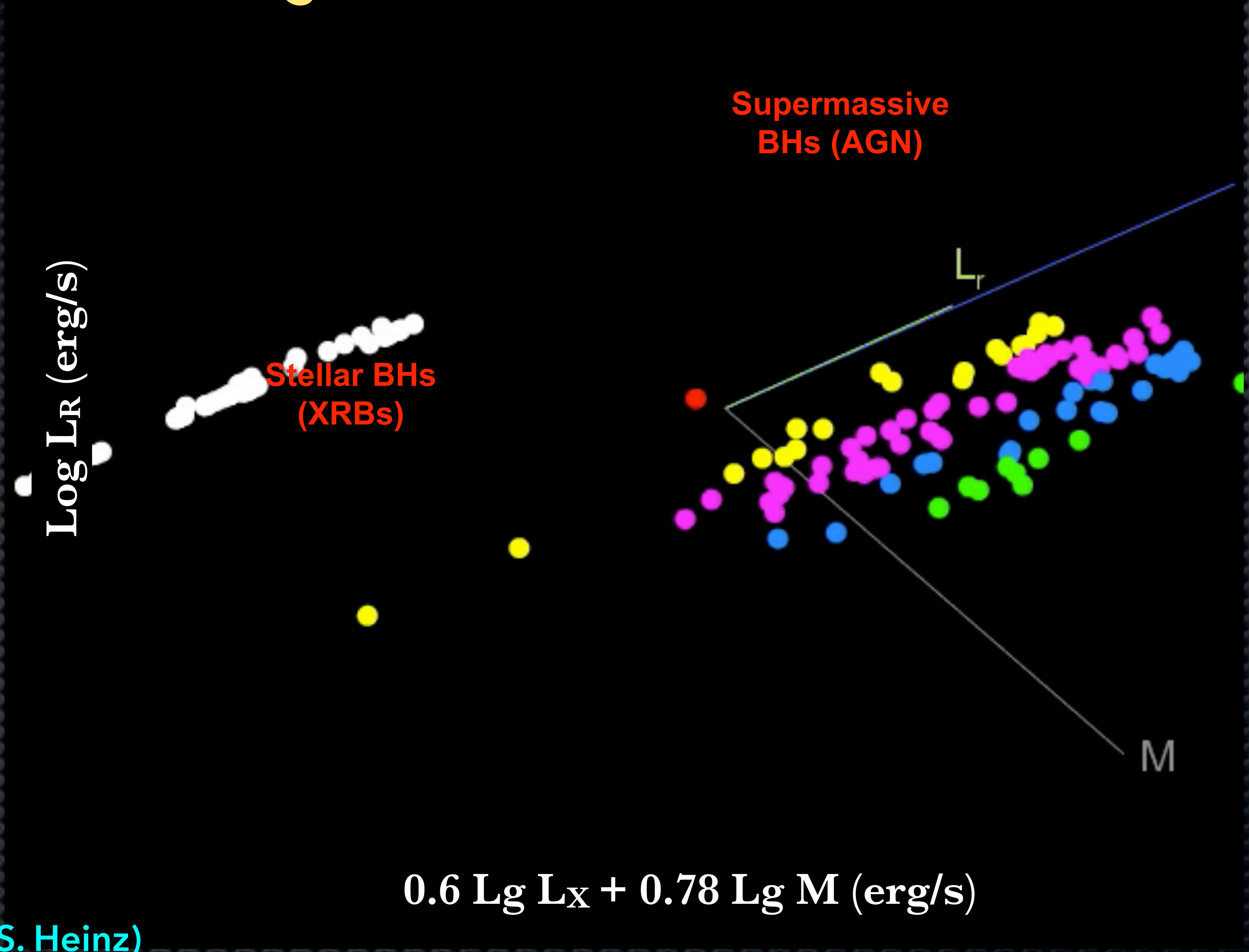
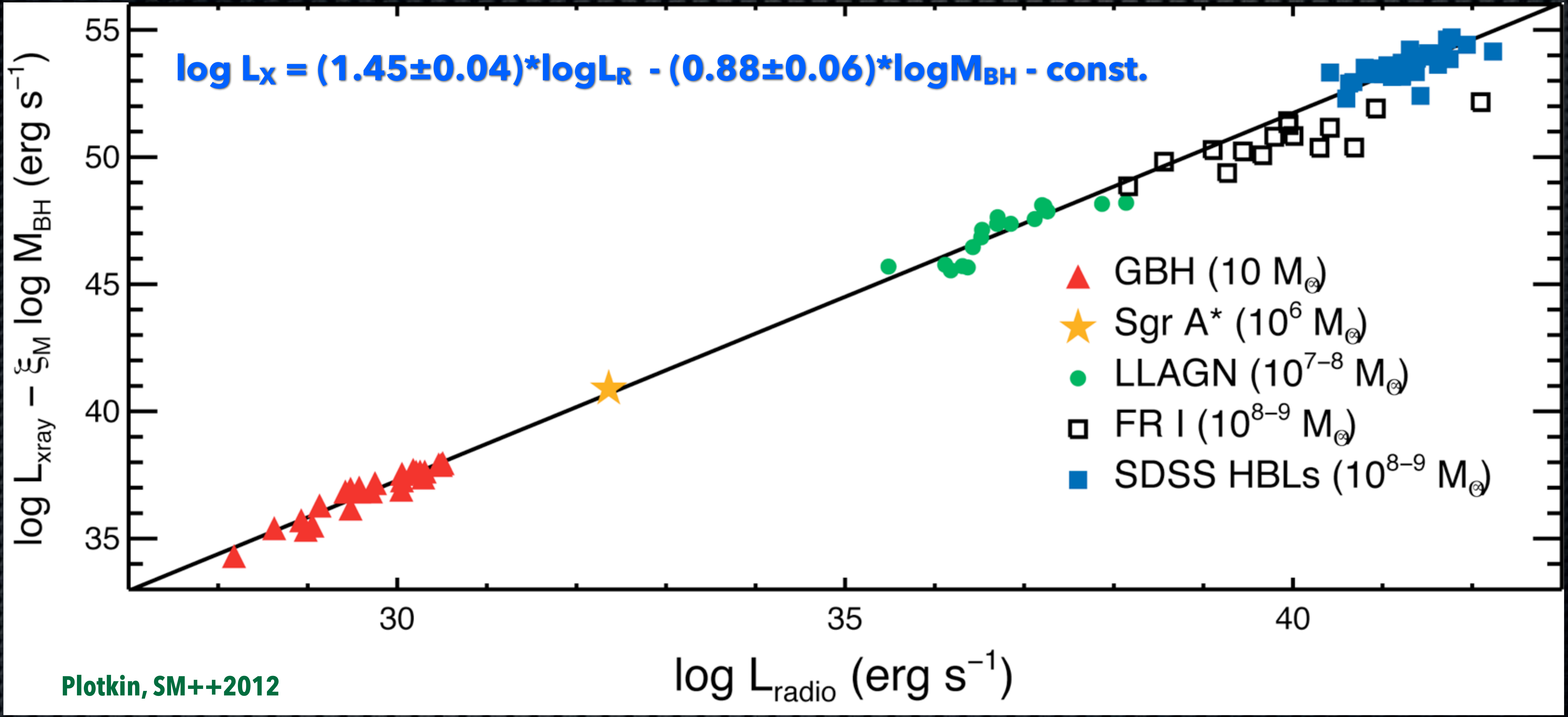


(SM et al. 2003; Merloni,Heinz & diMatteo 2003; Falcke, Körding & SM 2004; SM 2005; Merloni et al. 2006; Körding et al. 2006; Gültekin et al. 2009; Plotkin, SM et al. 2011)

(movie courtesy of S. Heinz)

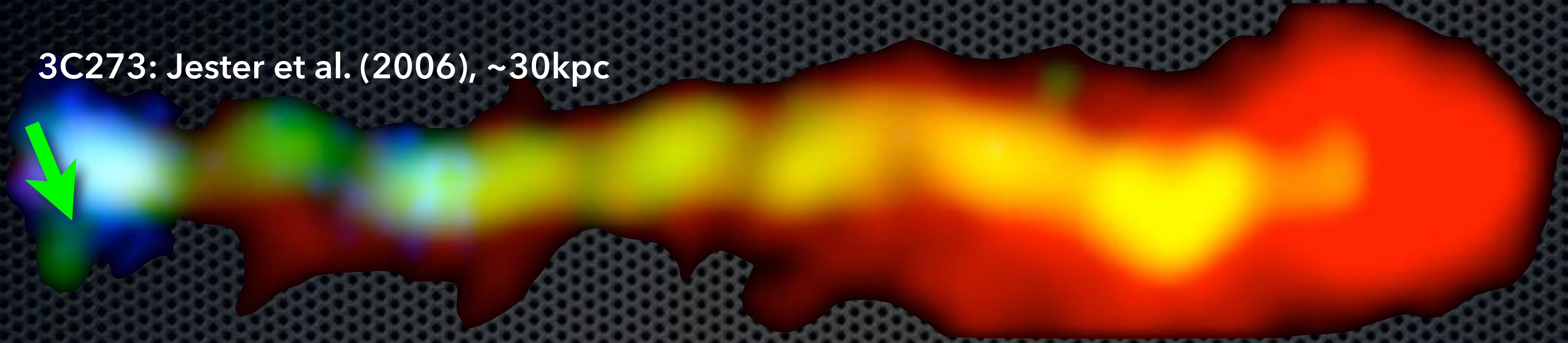
Jet-dominated states: 'hard-coded' output efficiencies



(SM++01,03,05; Corbel++2008; Hynes++2009; Corbel++2013; Gallo++2014; Rana++2016; Plotkin++2016)

Macro/micro connection

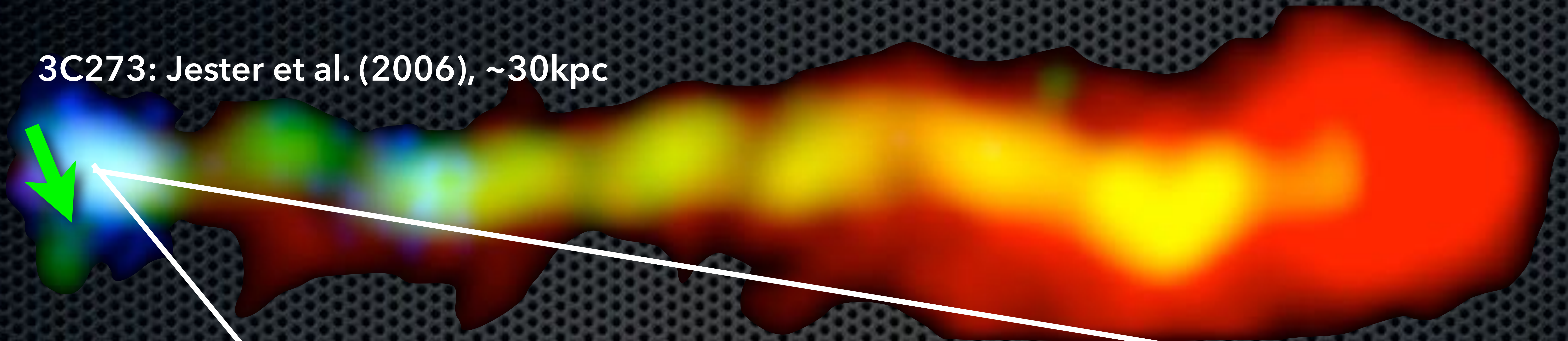
How do we recognize particle acceleration?



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

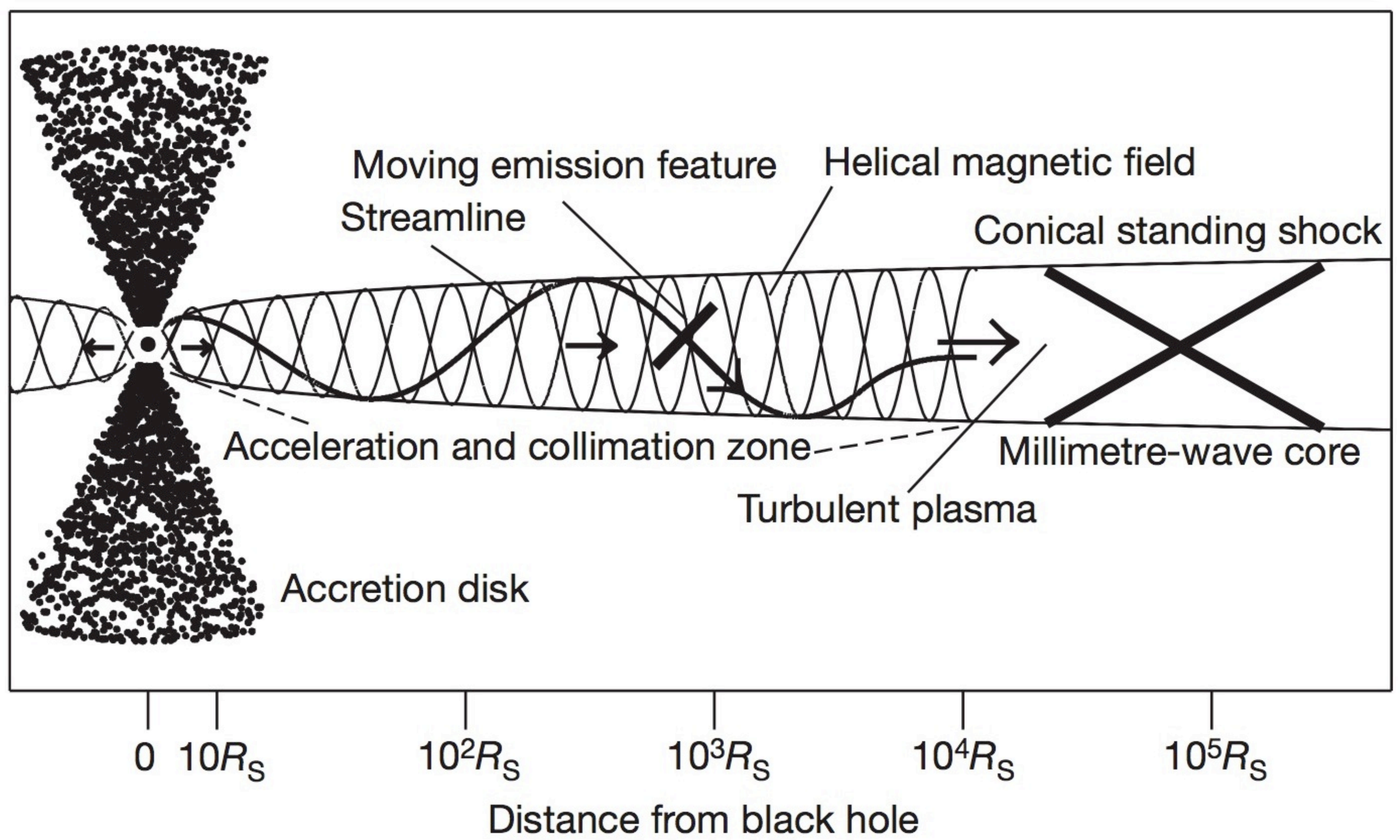
How do we recognize particle acceleration?

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

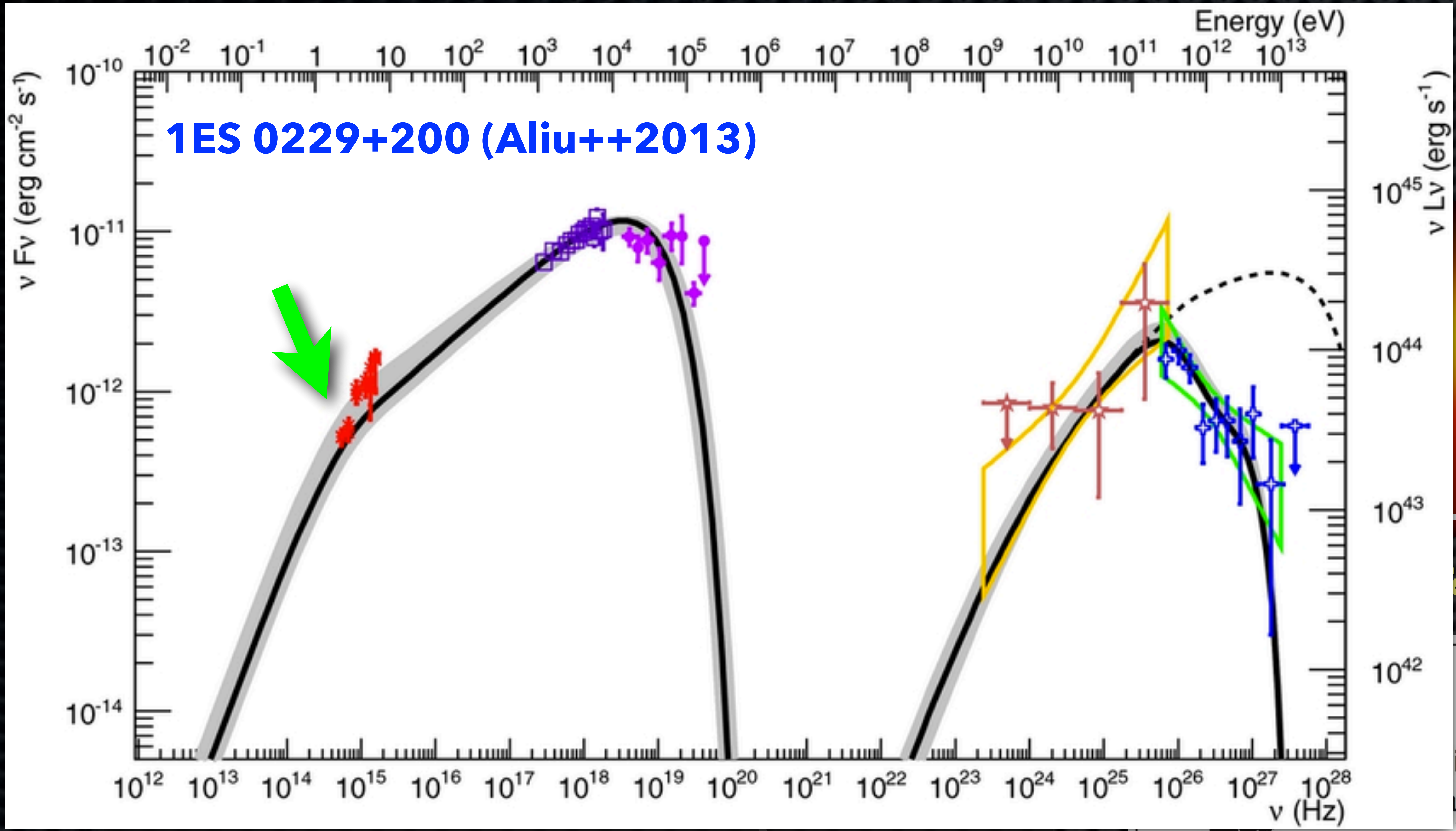


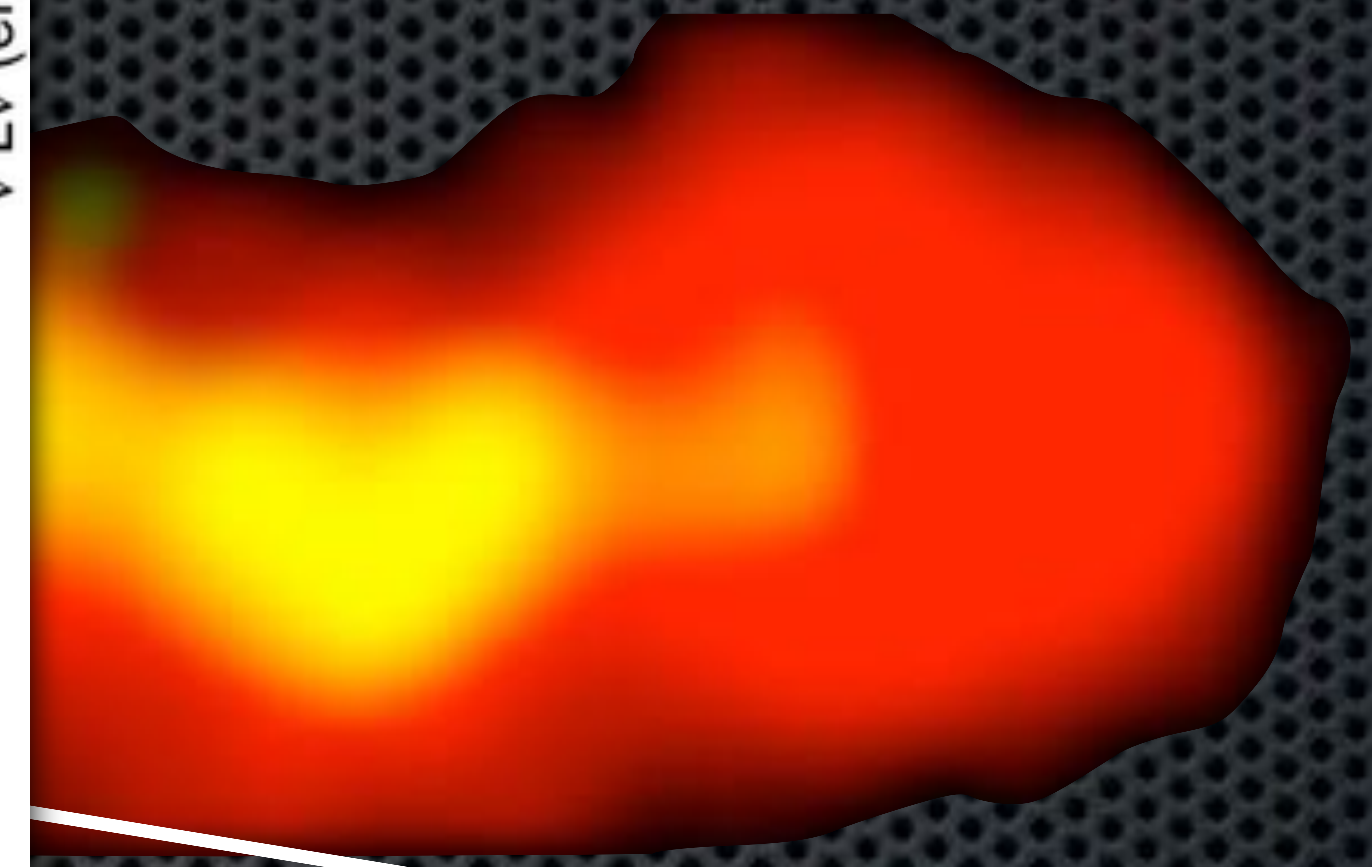
Blue: X-rays (Chandra), Green: Optical (Hubble Space Telescope) , Yellow: Optical & Peak Radio, Red: Radio (Very Large Array)

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

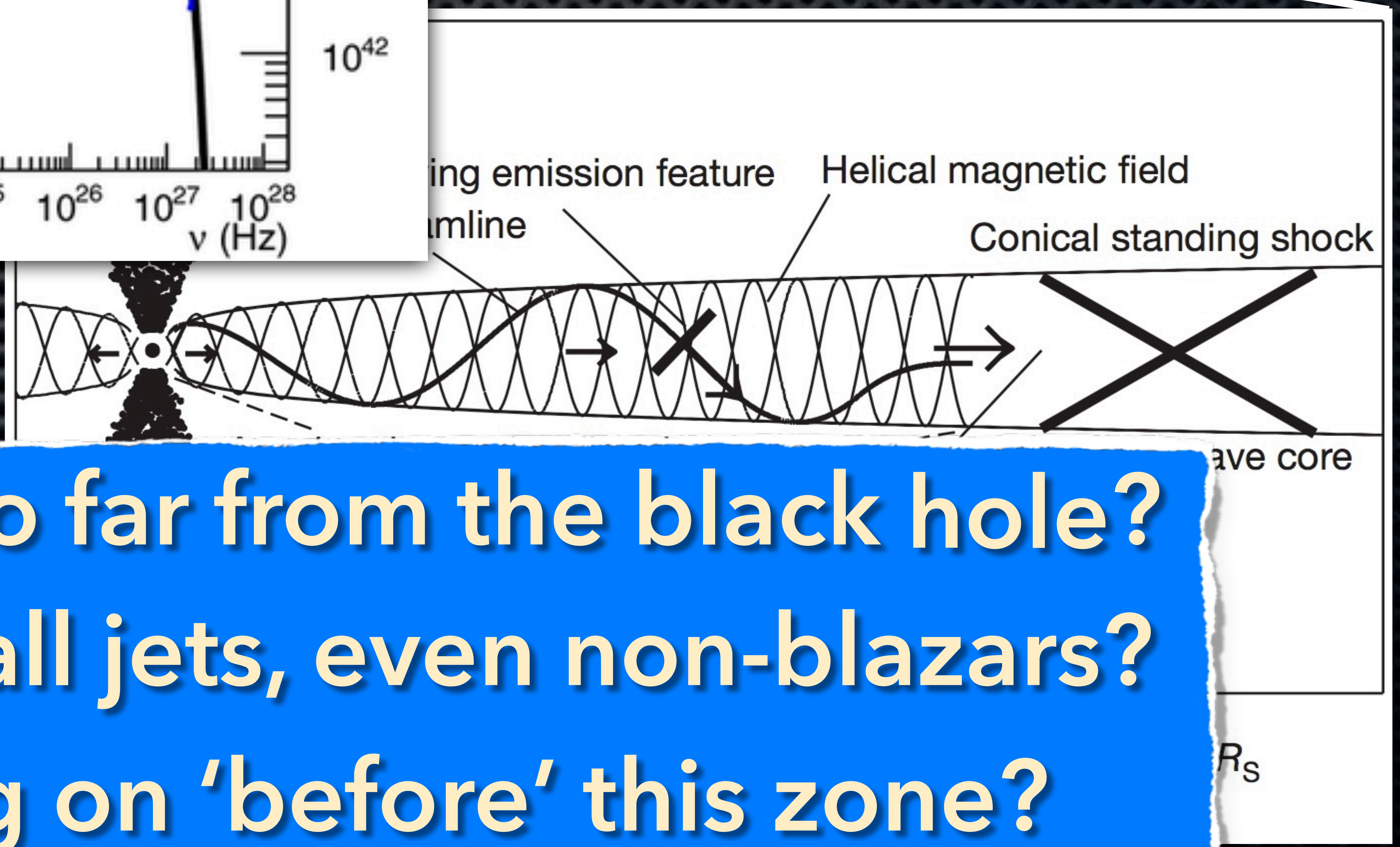


acceleration?





Peak Radio, Red: Radio (Very Large Array)



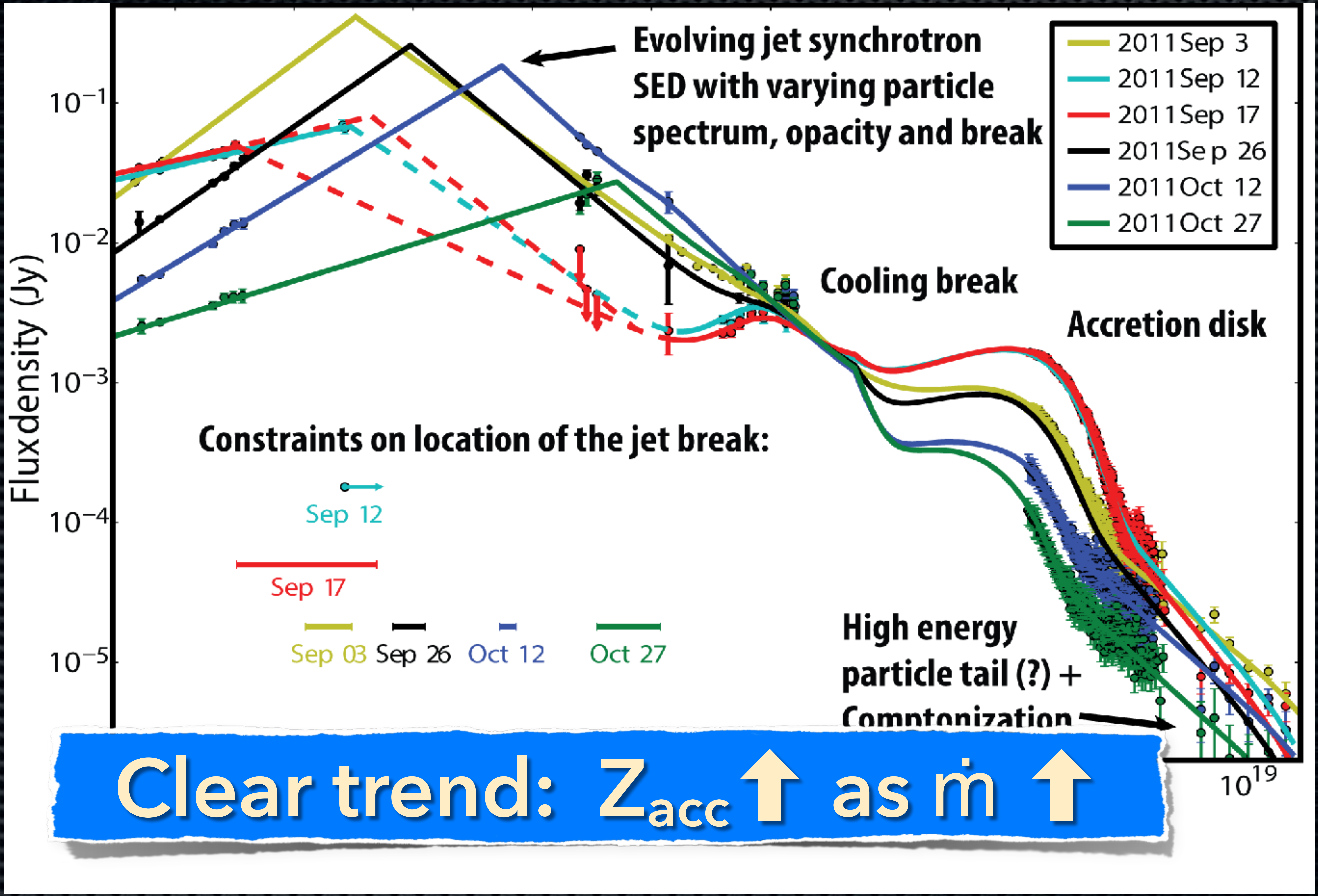
Standing/recollimation shock where most of the "action" takes place, 10^3-10^5 r_g

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?

"Next gen" XRB monitoring campaigns: MAXI J1836-194

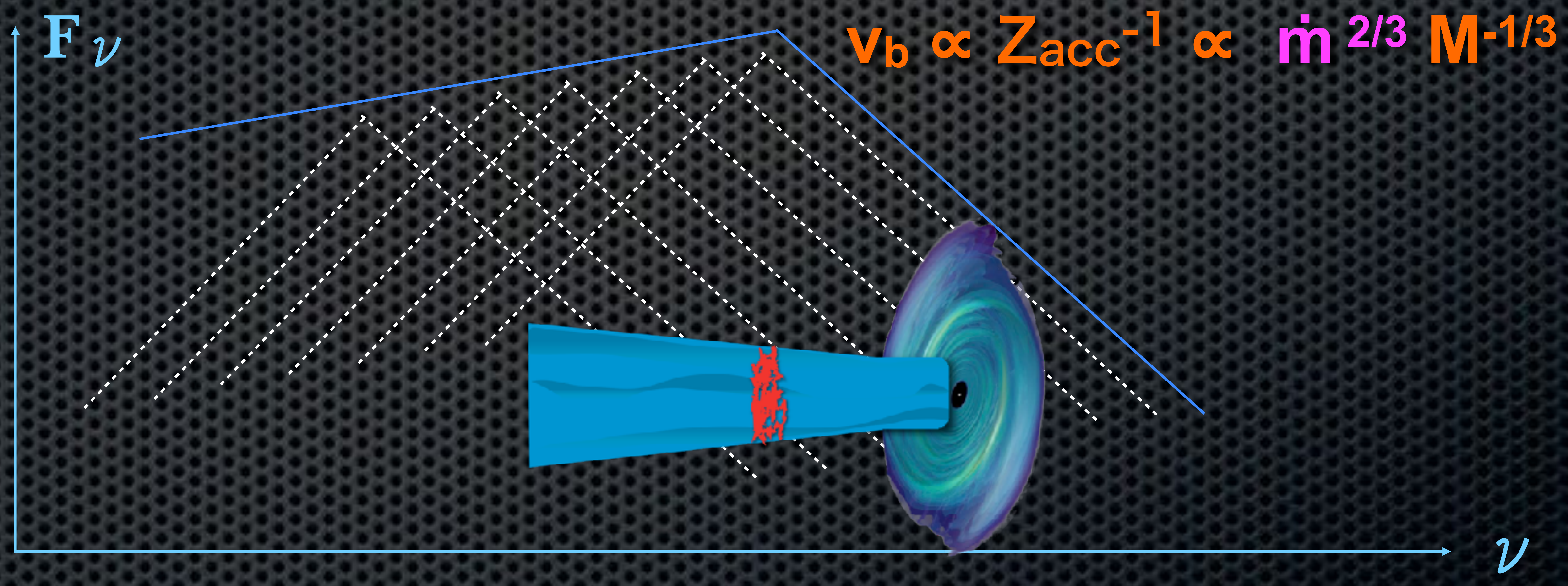


Clear trend: Z_{acc} ⬆ as $\dot{m}$ ⬆

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

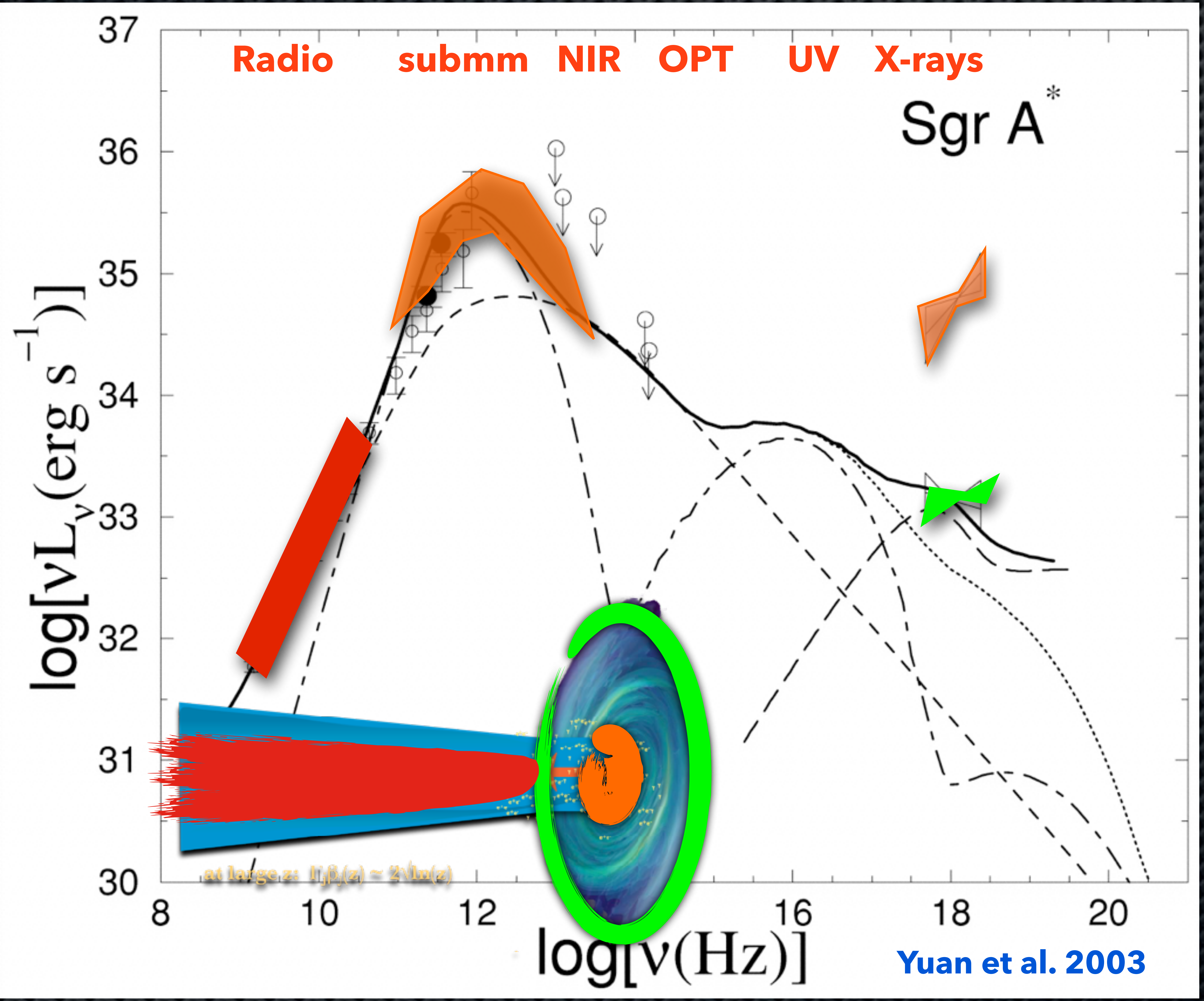
Evolution opposite the expectations for optical depth effects alone

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

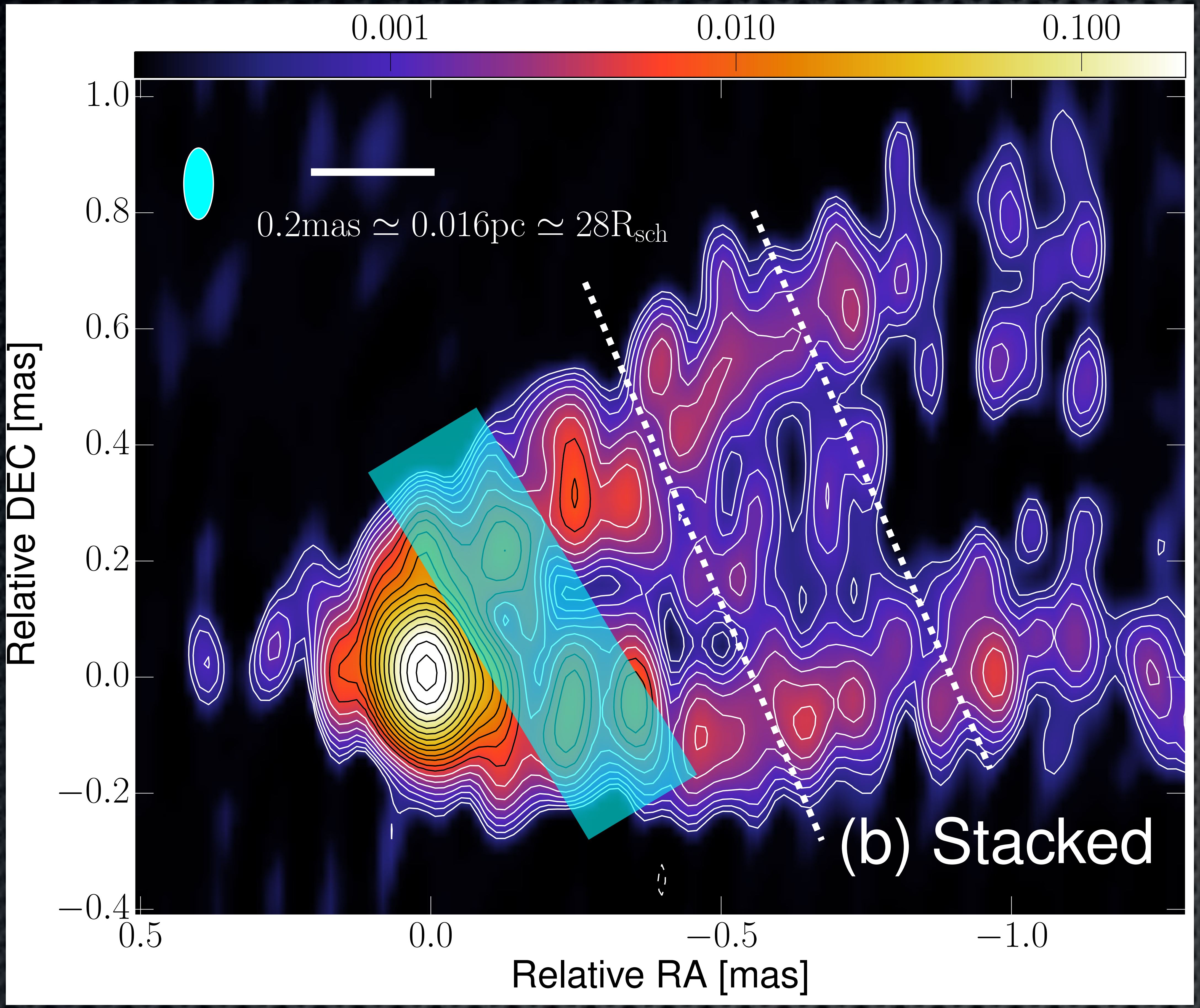


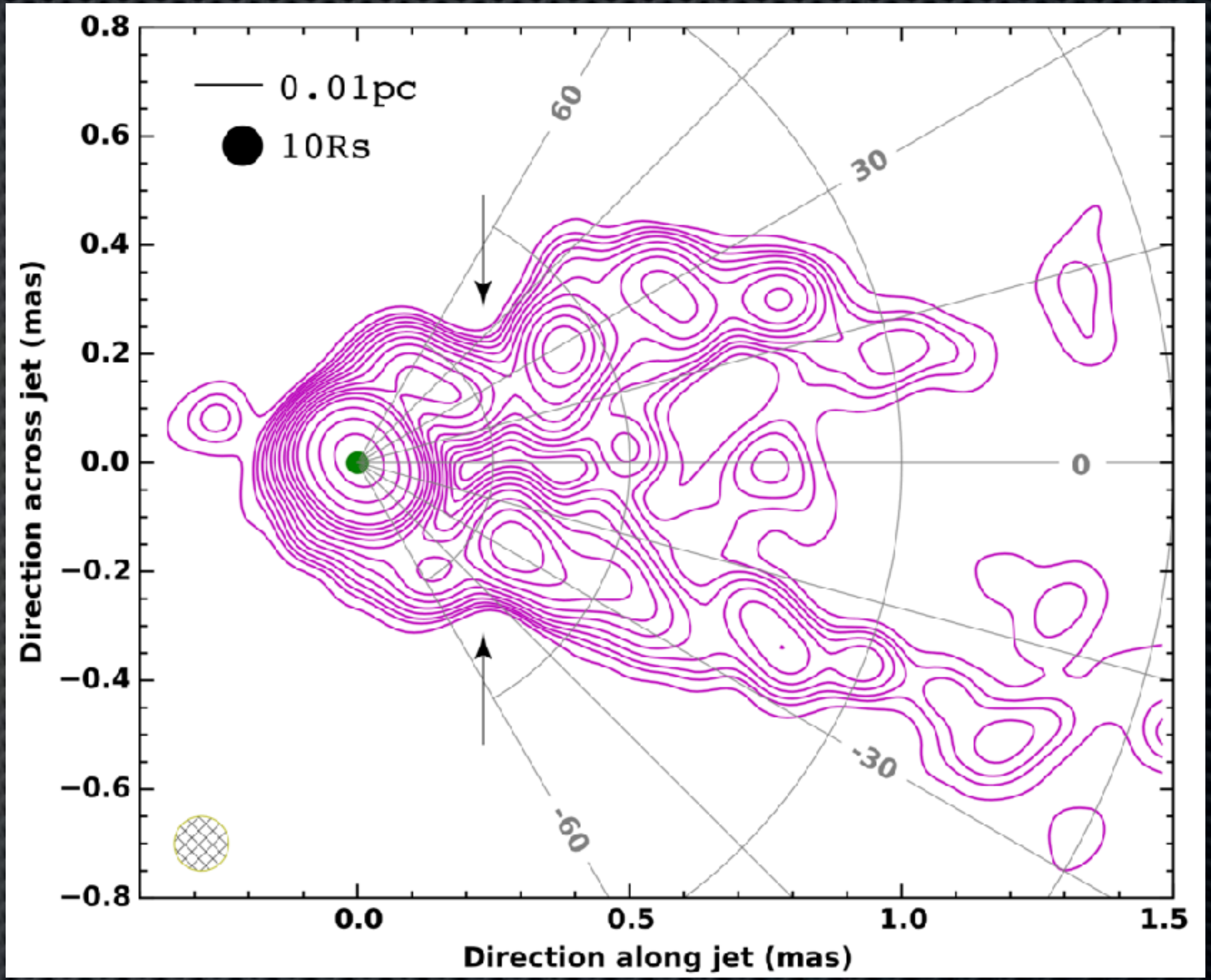
(Blandford & Königl 1979; Falcke & Biermann 1995; SM++ 2003; Heinz & Sunyaev 2003; Romero, Böttcher, SM, Tavecchio 2017)

Sgr A* – Thermal dominated jet?



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

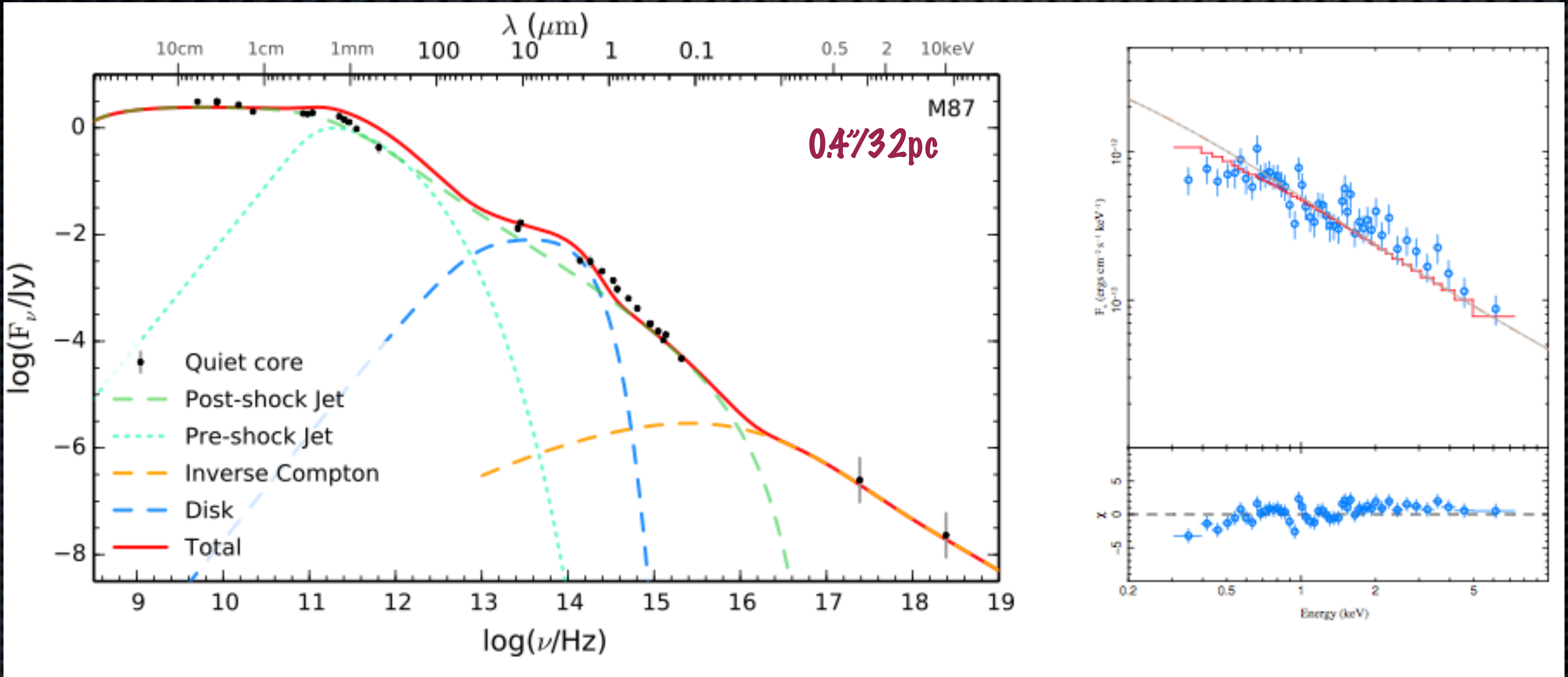




Jets near core seem to also be dominated by thermal particles (1000:1). Is particle acceleration associated with "pinch" at ~100 r_g ?

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

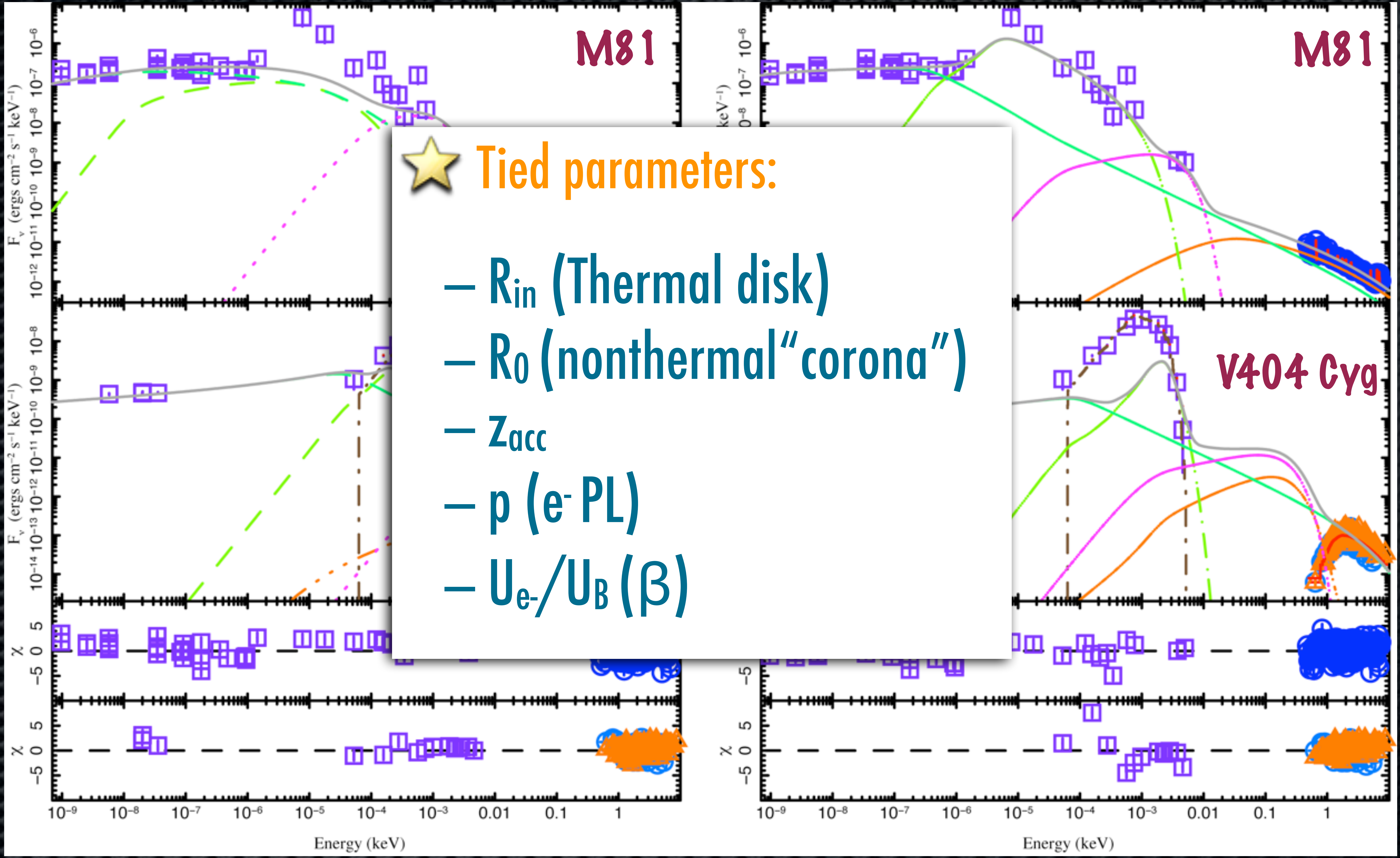
First high-resolution multiwavelength spectrum of M87's core: consistent with offset



Z_{acc}~10-100r_g, while for blazars seems to be further out (~$10^5 r_g$). But M87 is much less luminous than blazars. Seems to support same trend seen in XRBs.

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

Joint fits of similar ṁ sources: M81⇔V404 Cyg (L_X~10^{-6} L_{Edd})

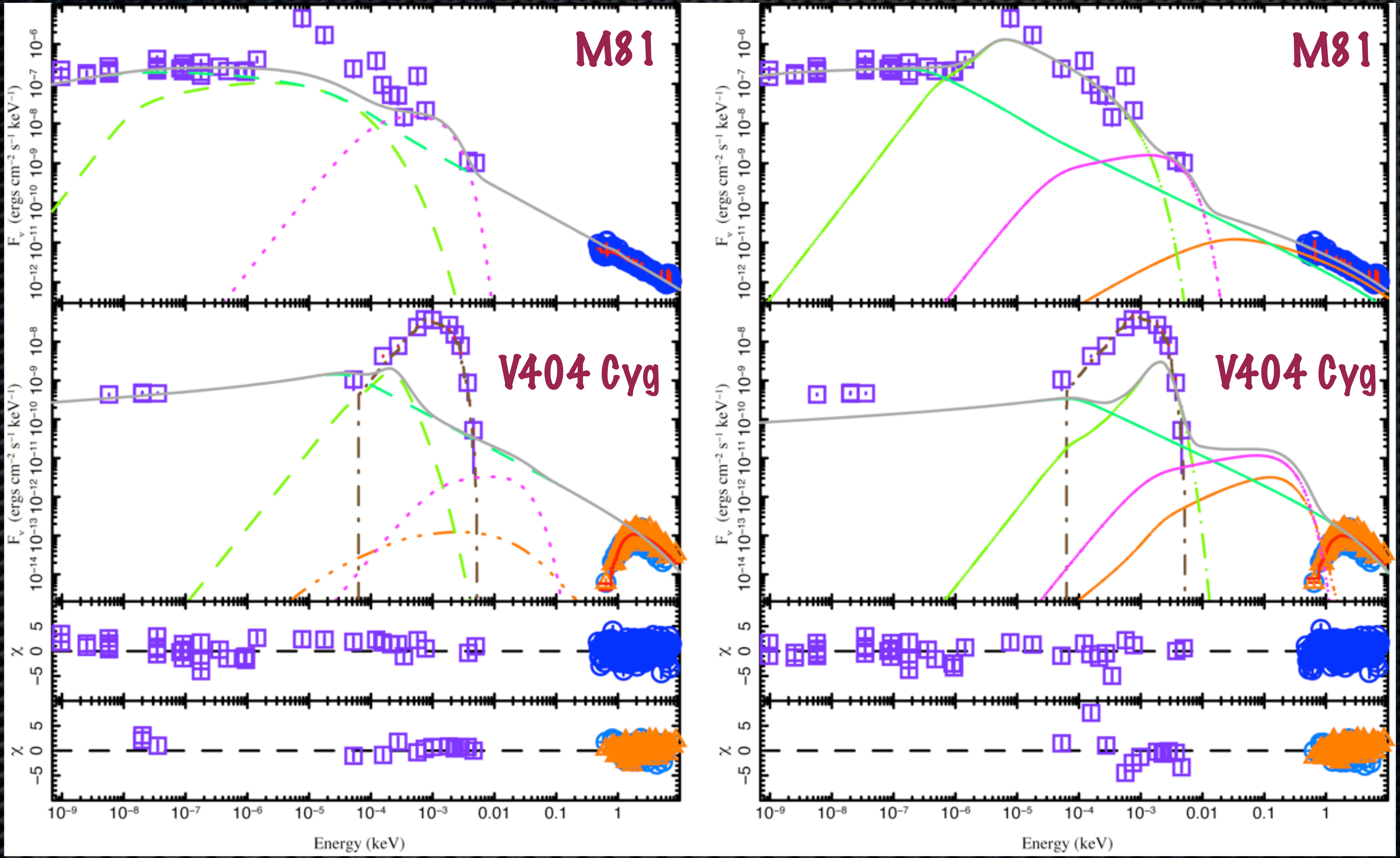


☆ Tied parameters:

- R_{in} (Thermal disk)
- R_0 (nonthermal "corona")
- z_{acc}
- p (e^- PL)
- U_{e-}/U_B (β)

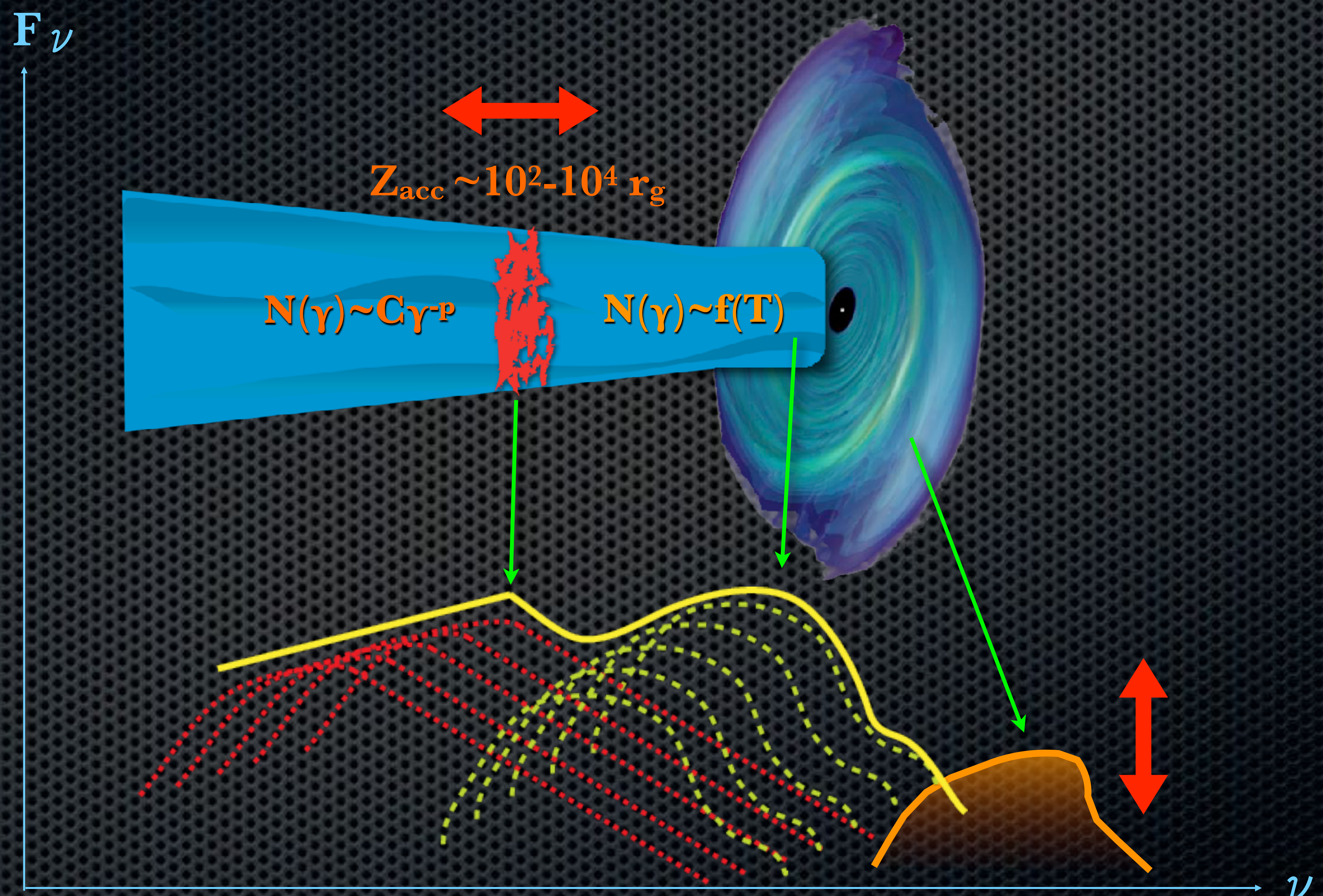
(SM, Nowak++ 2015; *simultaneous VLA/HST/Chandra V404 data from Hynes++2009, OIR archival*)

Joint fits of similar ṁ sources: M81⇔V404 Cyg ($L_X \sim 10^{-6} L_{Edd}$)



(SM, Nowak++ 2015; *simultaneous VLA/HST/Chandra V404 data from Hynes++2009, OIR archival*)

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

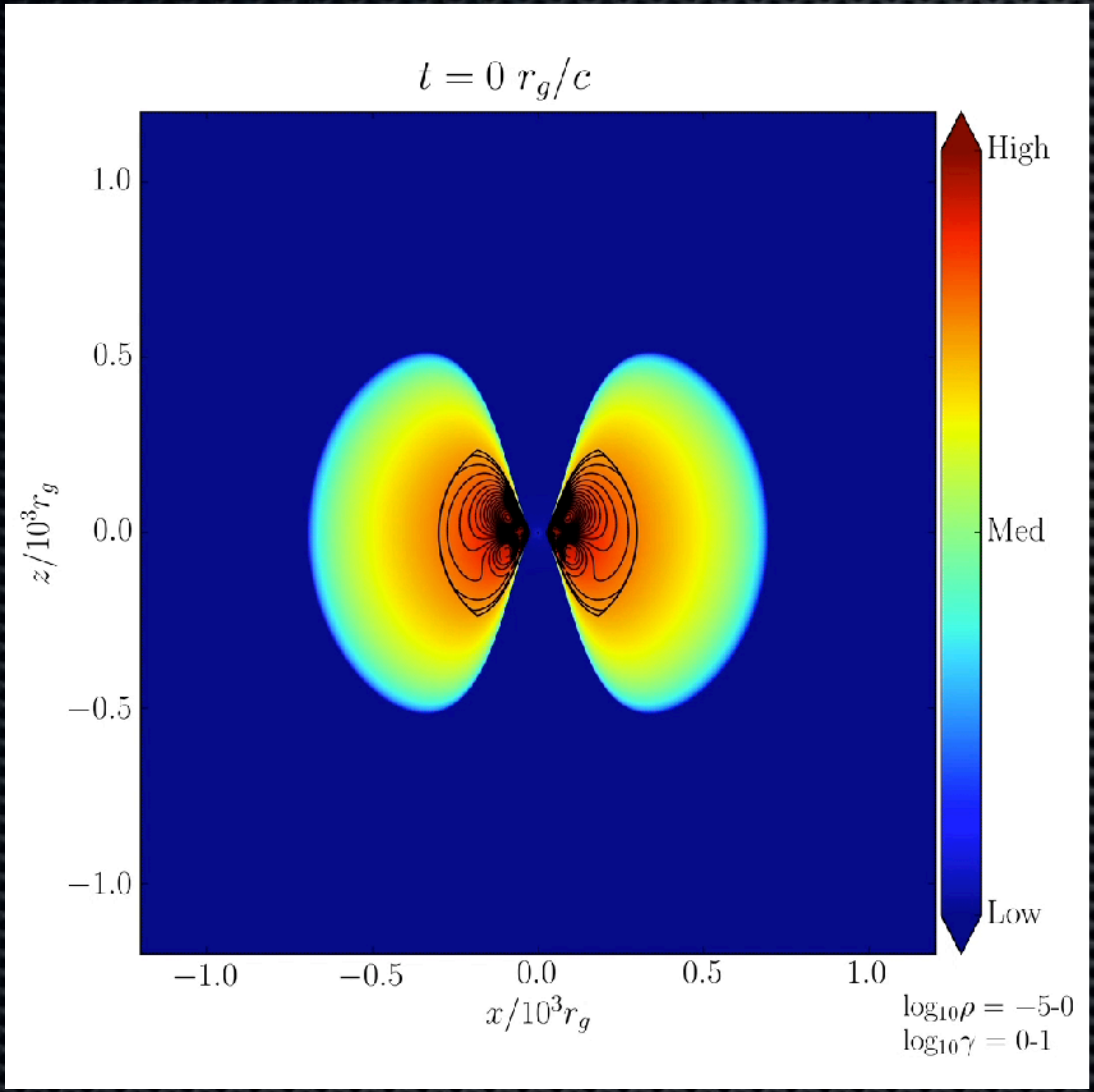


(SM, Falcke & Fender 2001; SM, Nowak & Wilms 2005)

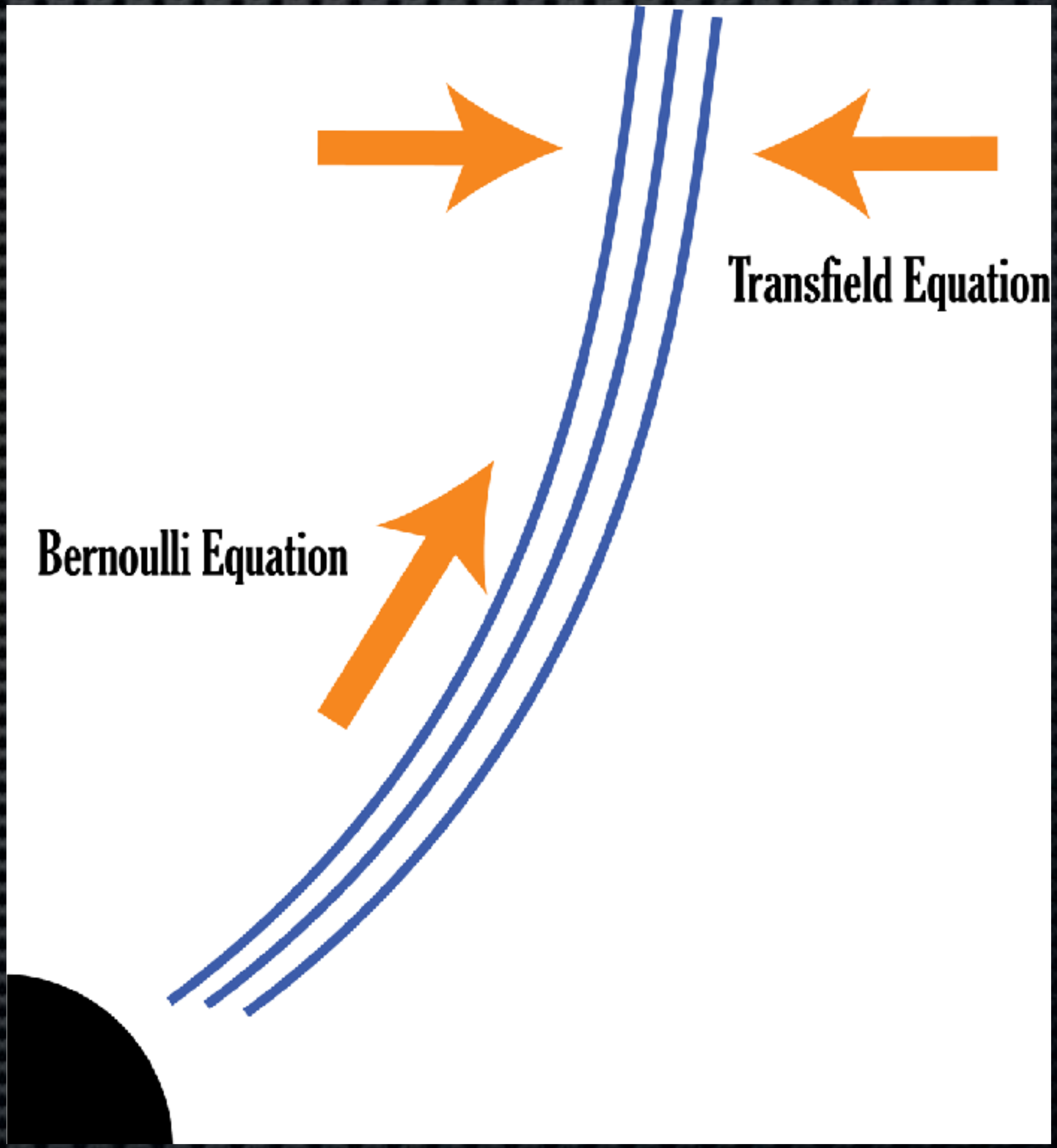
Outline

- ★ Role of black holes in the universe and major questions
- ★ Influence of spacetime geometry on accretion
- ★ Event Horizon Telescope: context, results, upcoming
- ★ Black holes across the mass scale: XRBs as 'mini' AGN?
- ★ Cutting edge (if time...)

Theoretical advances: we can model jets to physical scales!

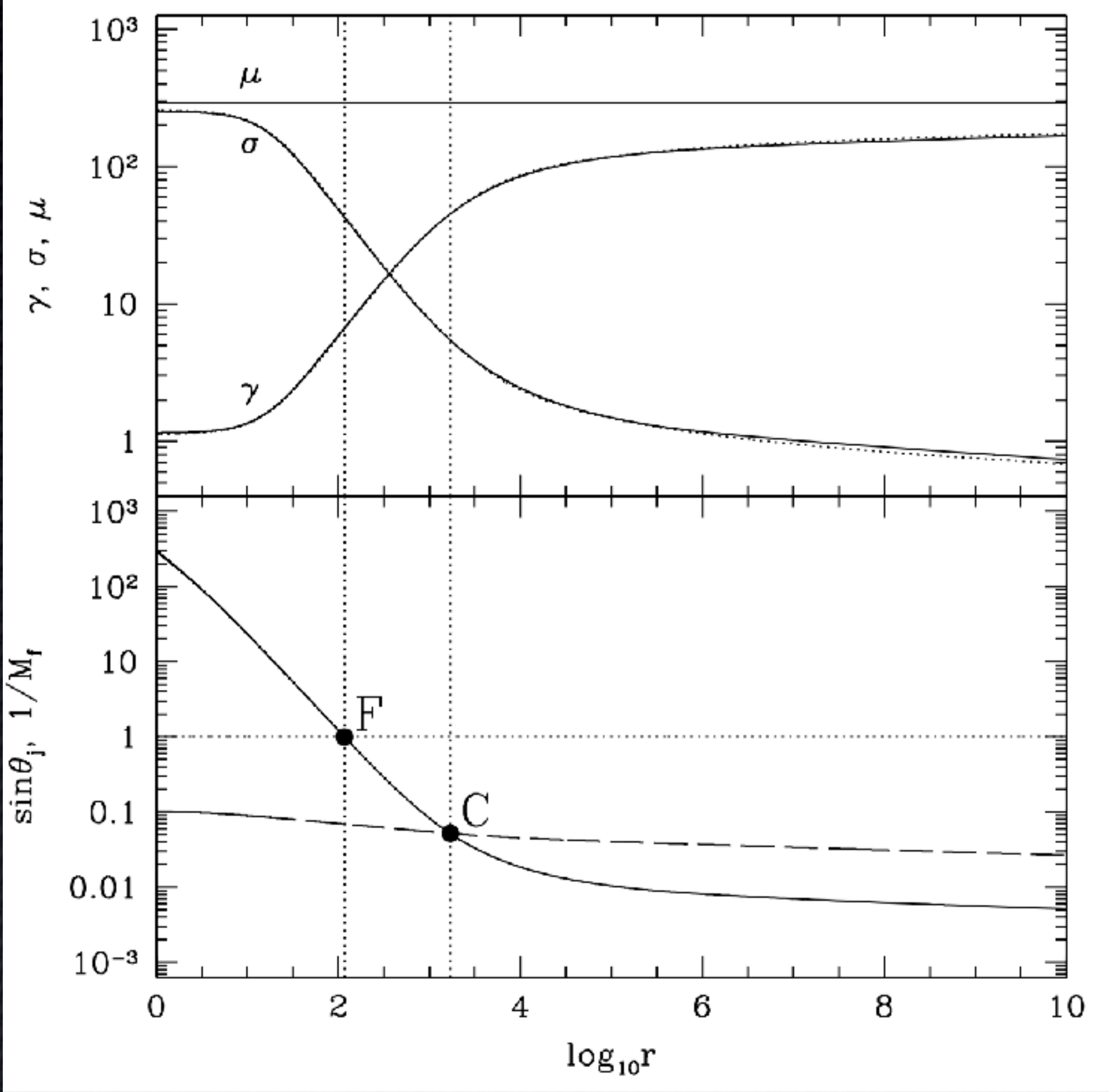


(Chatterjee, Liska, Tchekhovskoy & SM, subm.)

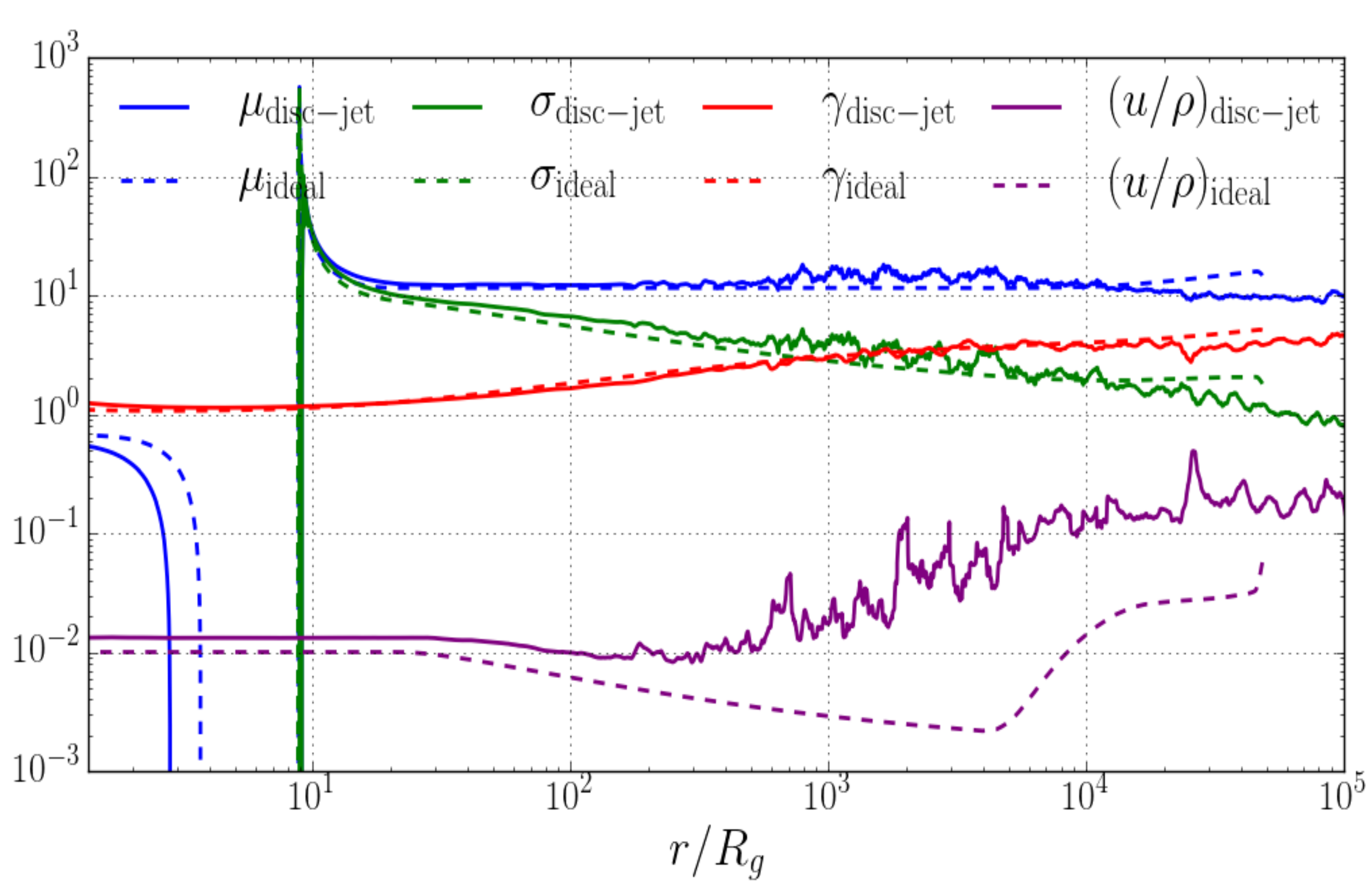


(Vlahakis++2000; Vlahakis & Königl 2003; Polko, Meier & SM 2010, 2013, 2014; Ceccobello, Cavecchi, Heemskerk, SM+ 2017; Chhotray, Ceccobello, SM++ in prep.)

Understanding jet dynamics and link to microphysics

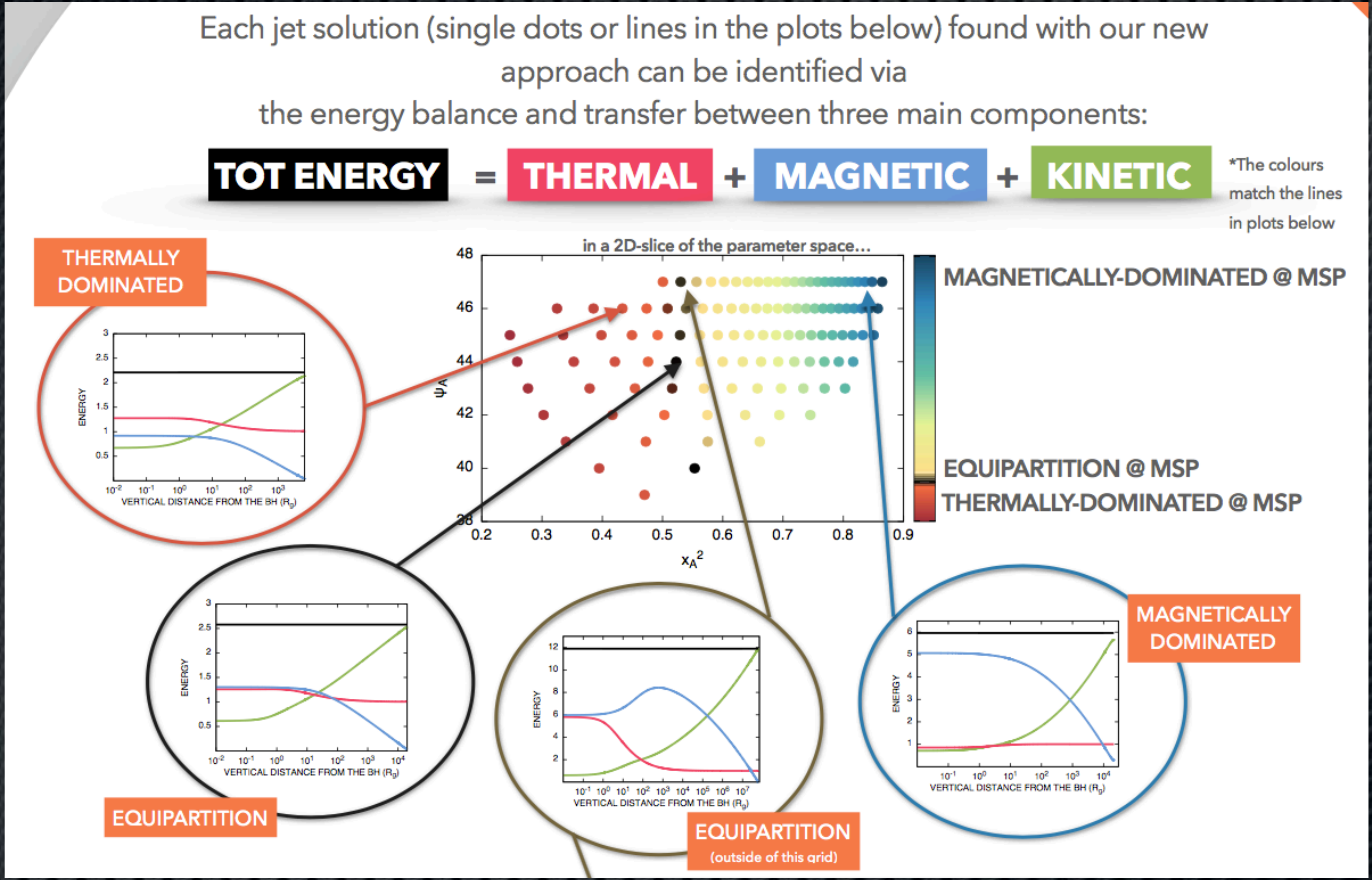


(Tchekhovskoy, McKinney & Narayan 2009)



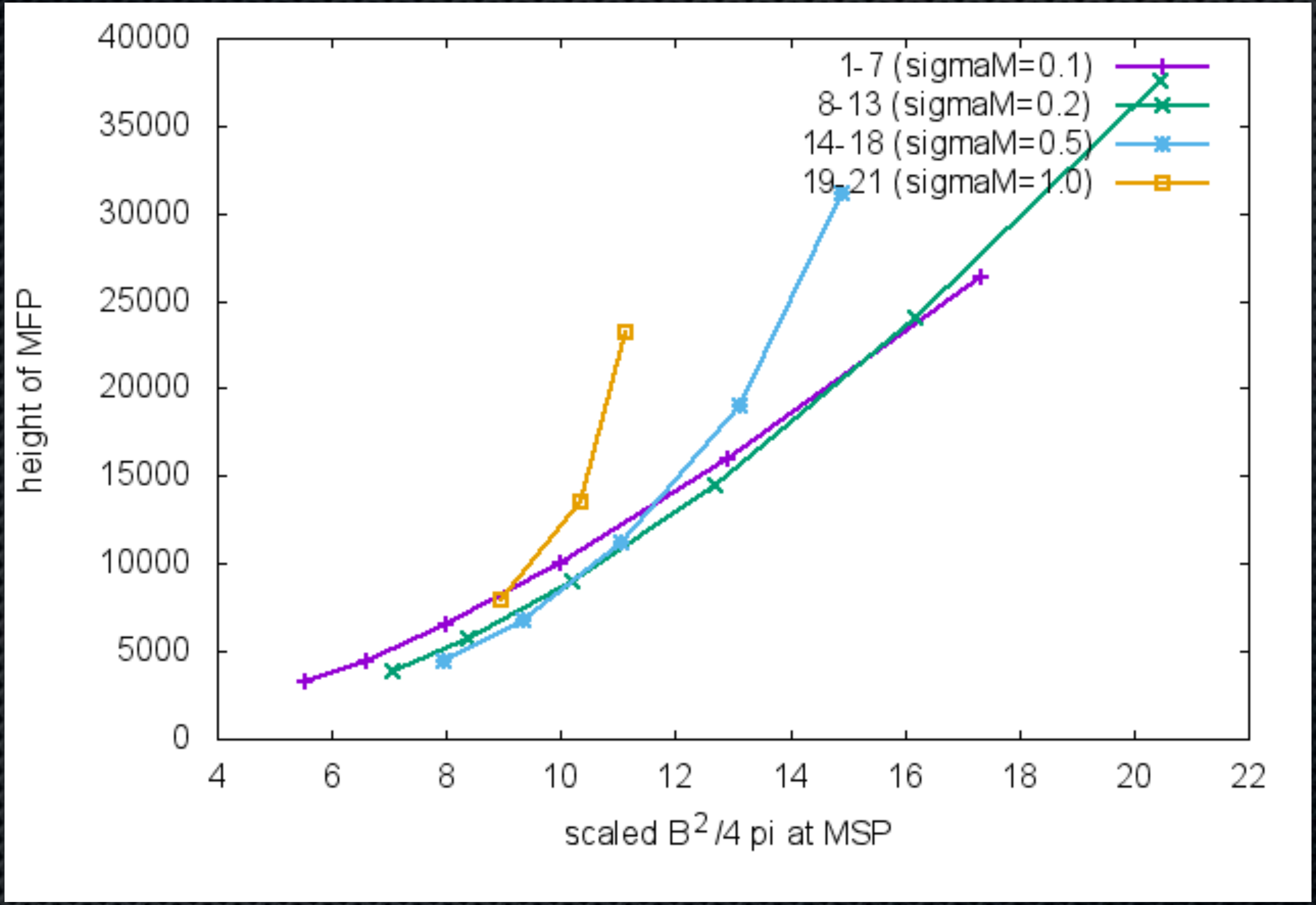
(Chatterjee, Liska, Tchekhovskoy & SM subm.)

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, Chhotray, Ceccobello, SM++ in prep.)

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



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

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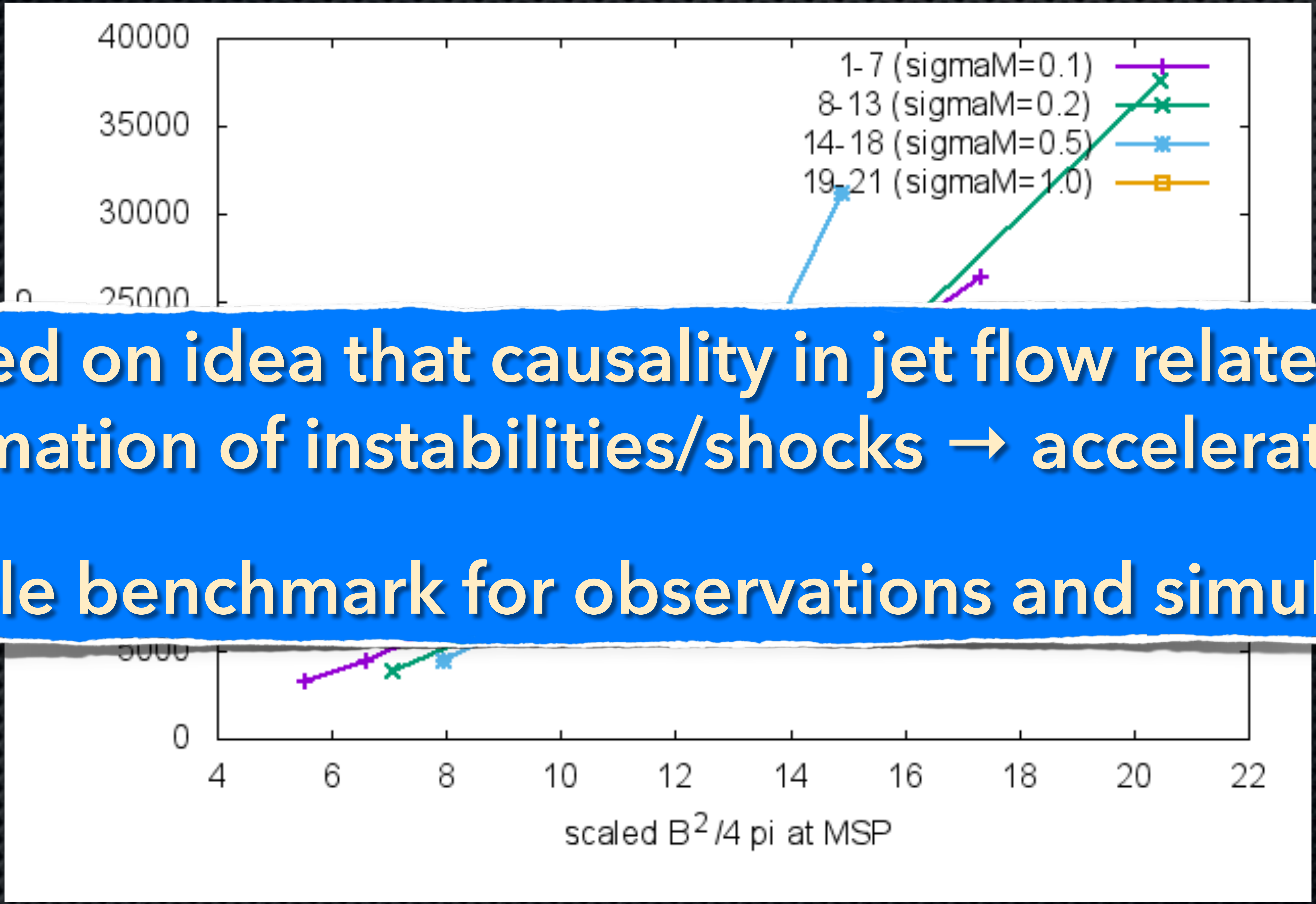
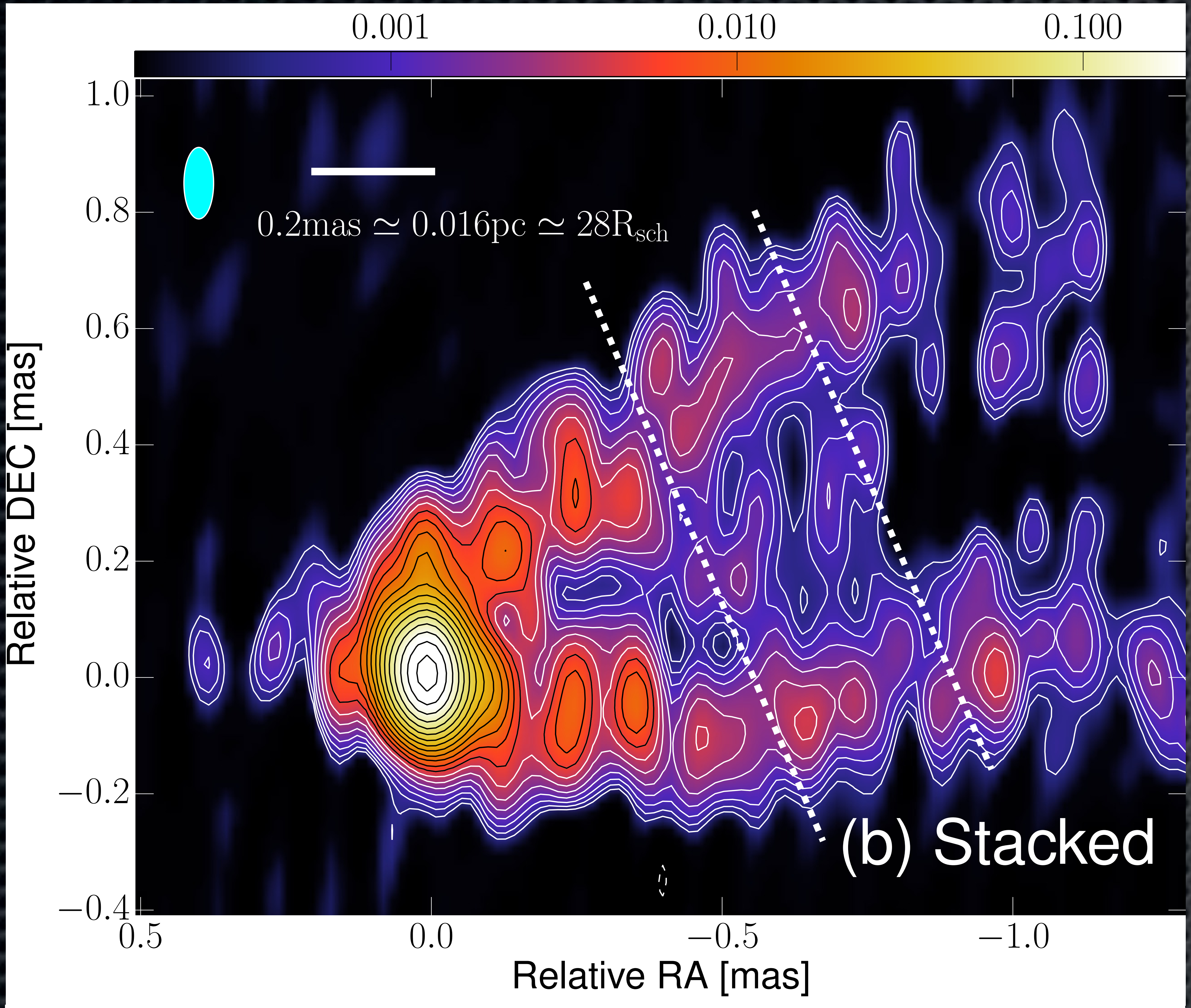


Based on idea that causality in jet flow related to formation of instabilities/shocks → acceleration

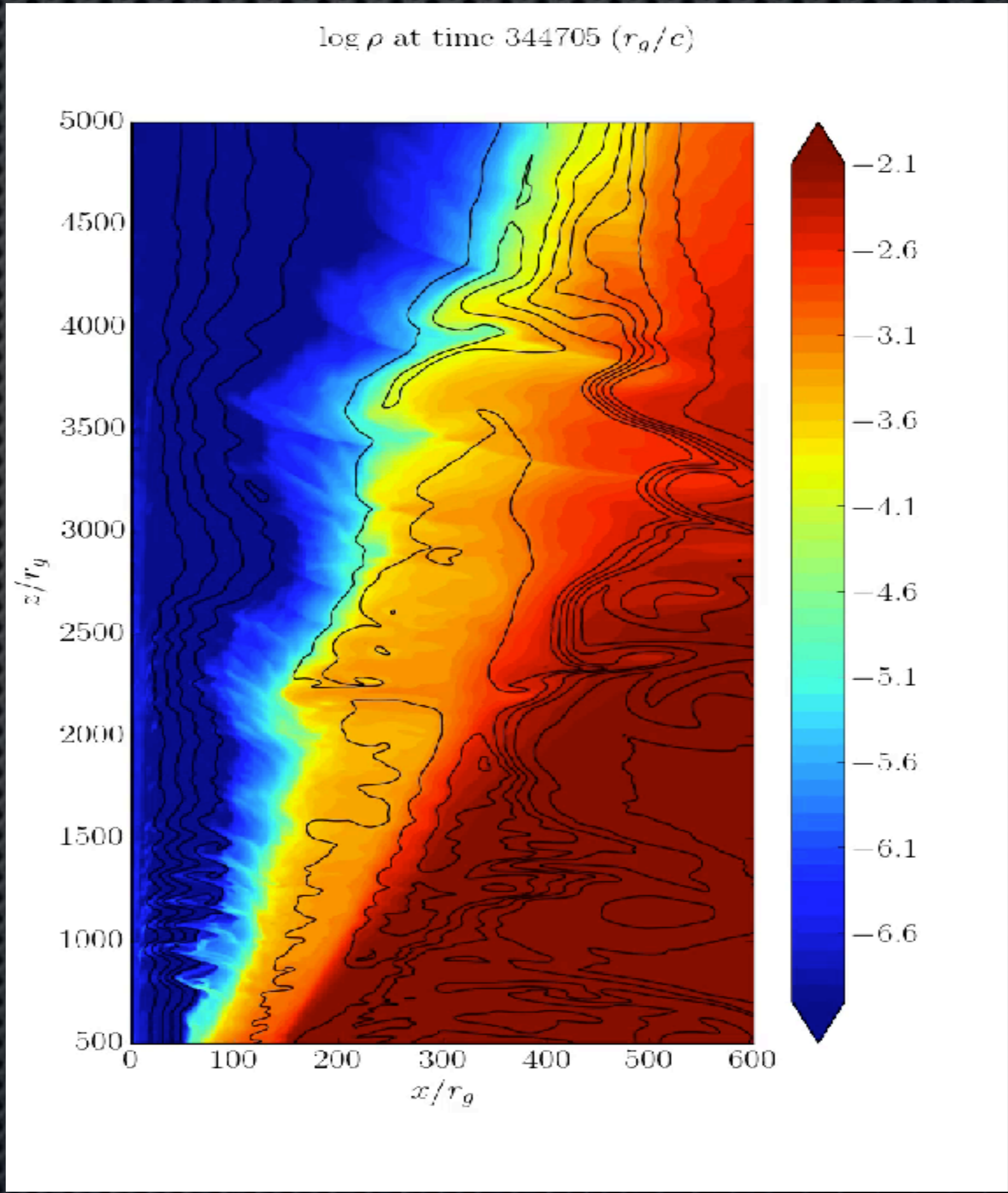
Testable benchmark for observations and simulations

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

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

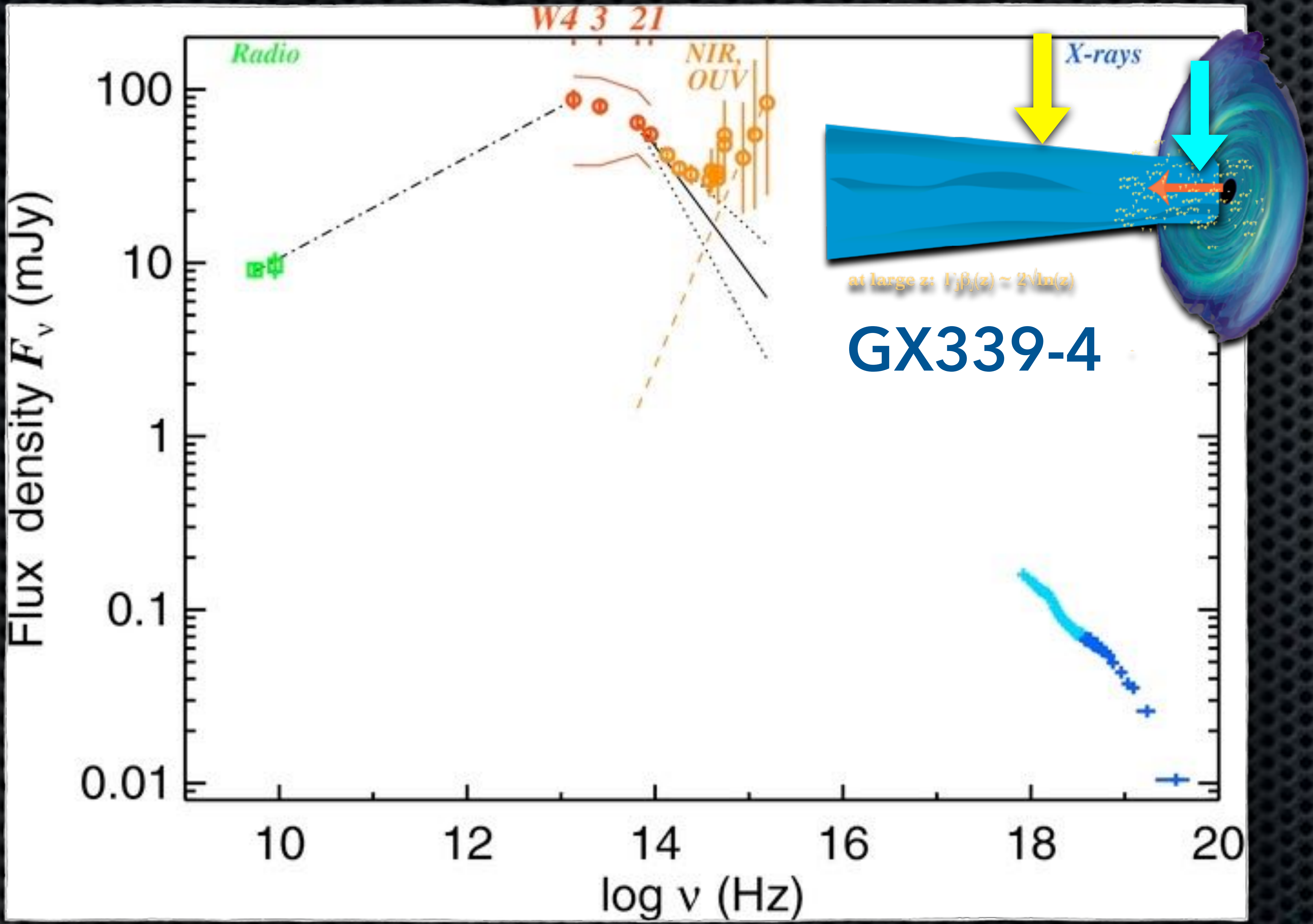


(Kim++2018; Walker++2018; Hada++14,16,18; Acciari++10; Abramowski++12, etc.)



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

Independent determination of Z_{acc}!



- Broadband noise: IR lags X-ray by ~110ms ➠ largest scale ~ 2x10^9cm (few 10^3 r_g), consistent with spectral fitting.

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

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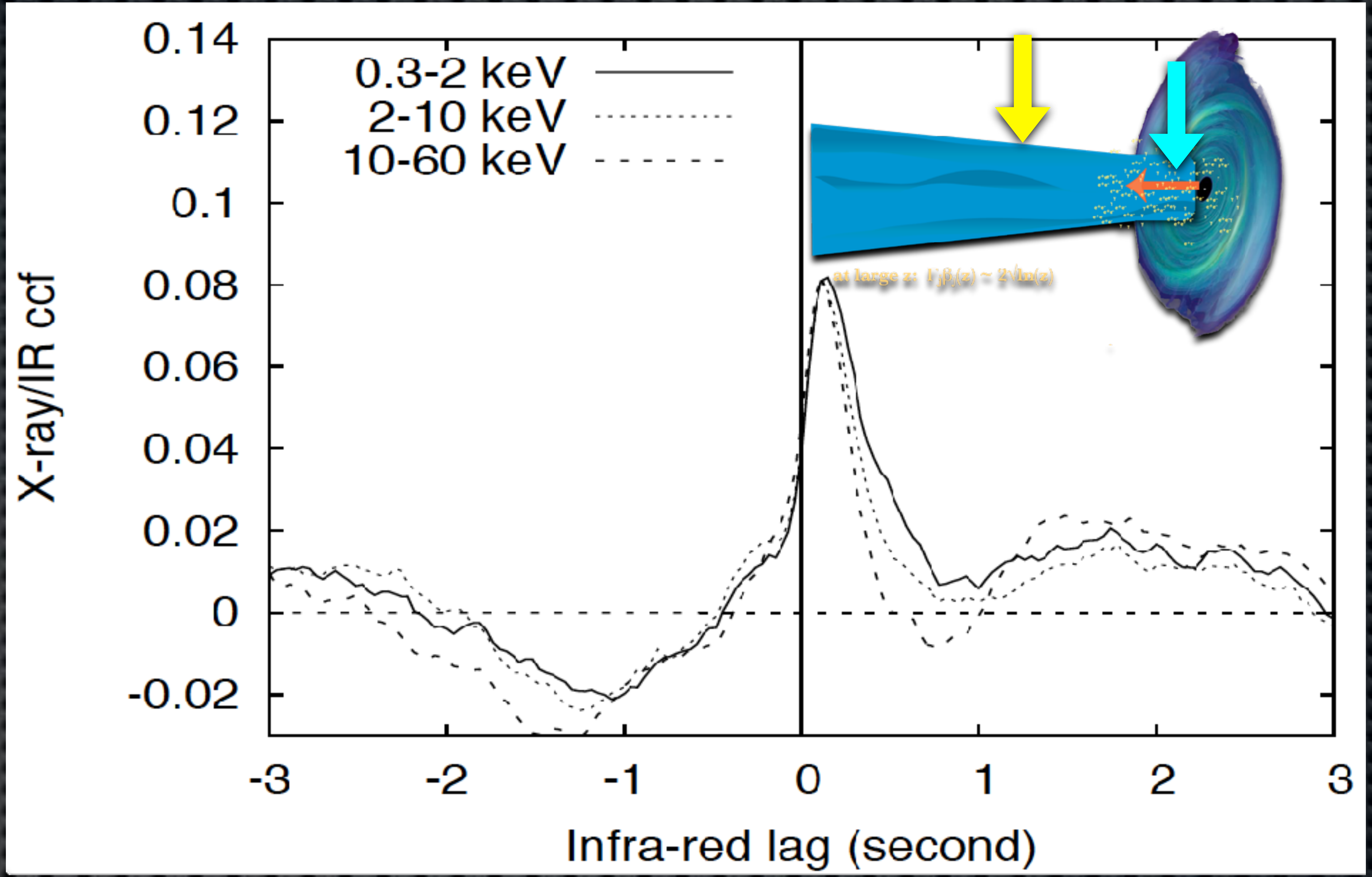

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- First IR LFQPO's! Half the Xray frequency

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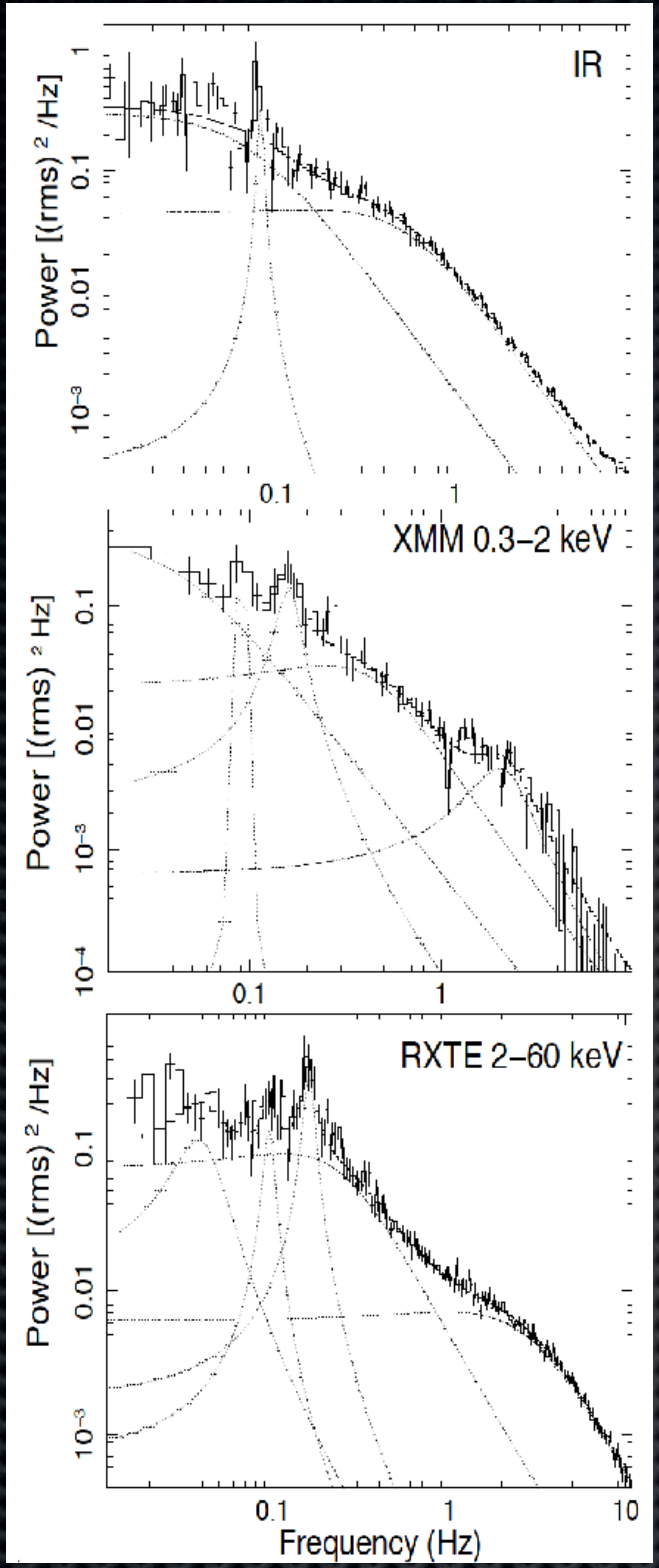

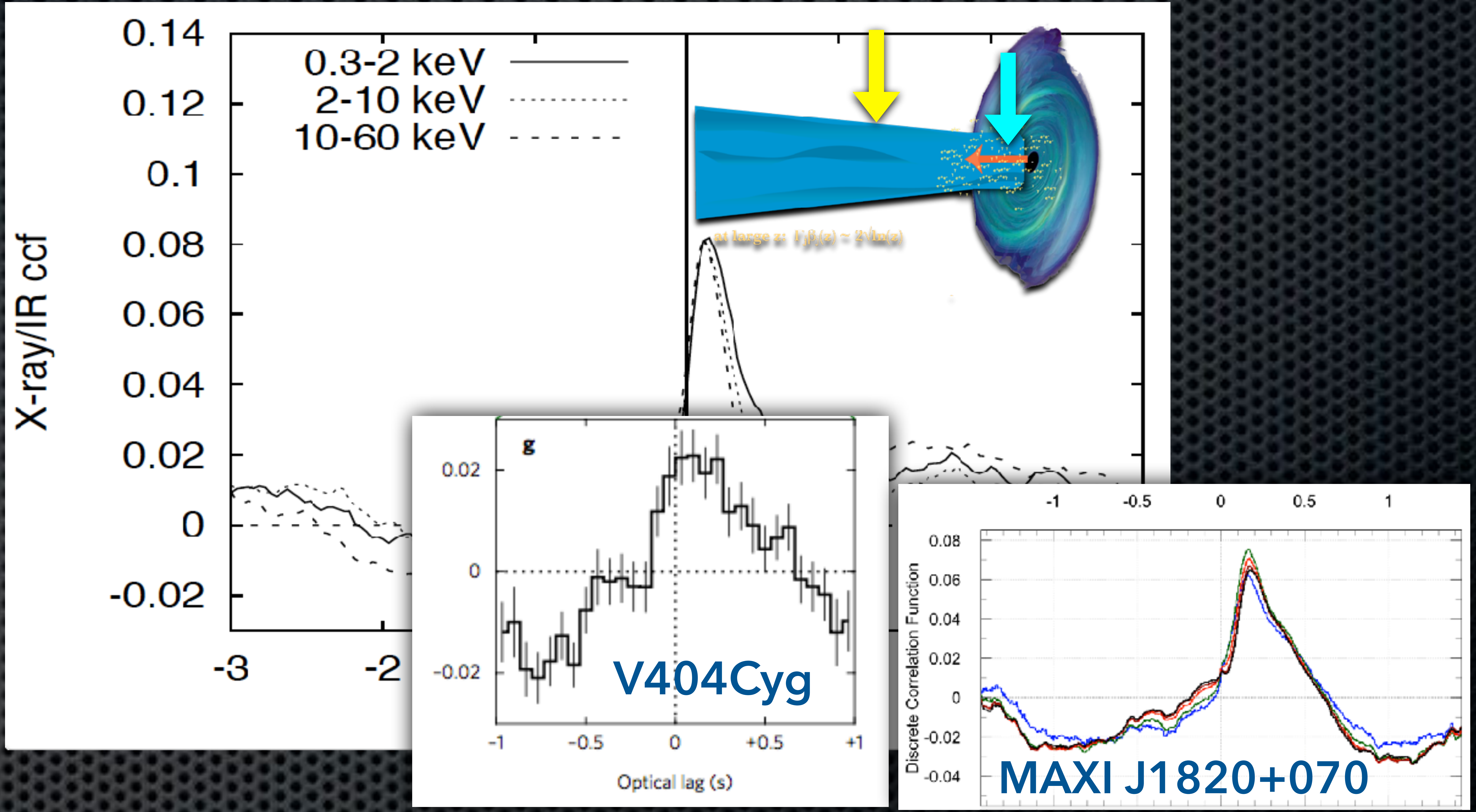

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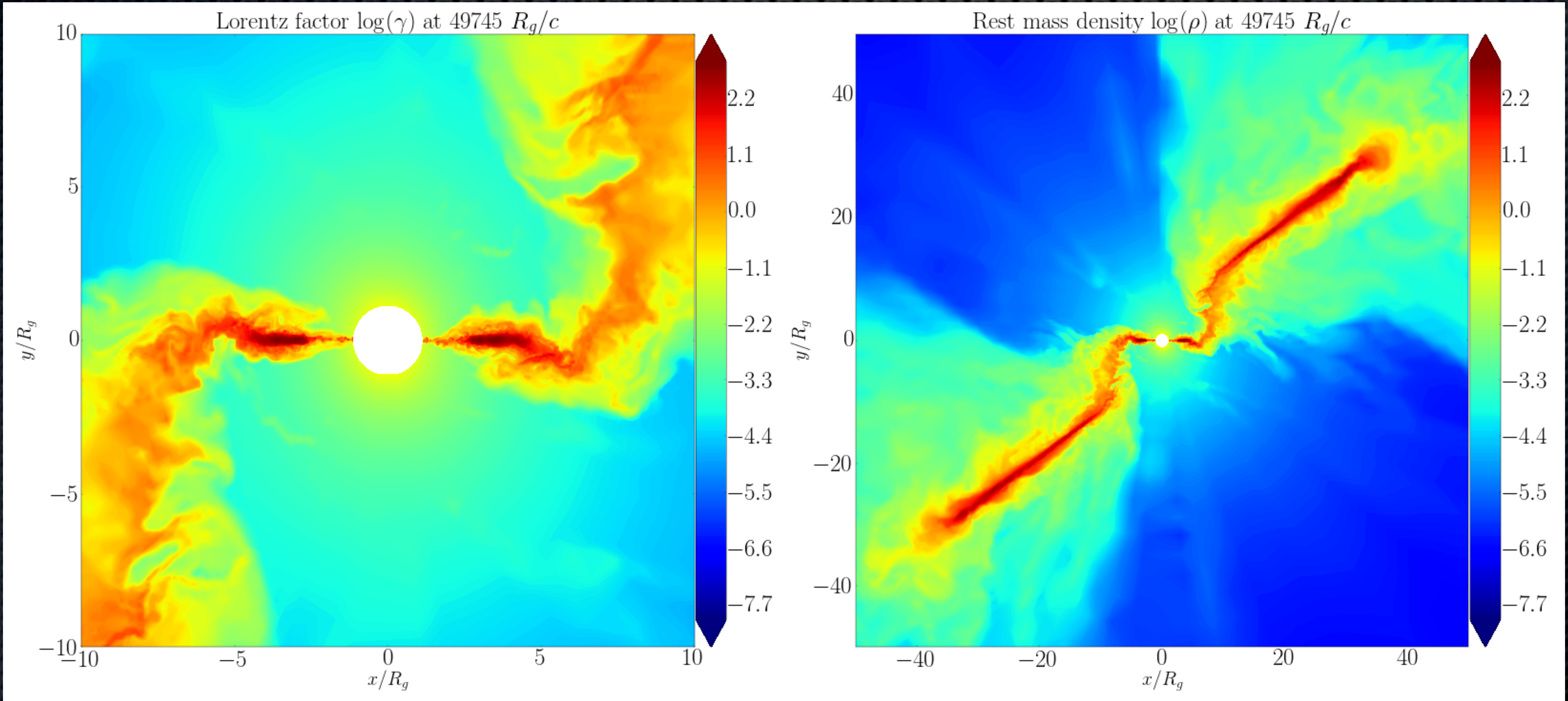
Very high resolution 3D GRMHD simulation of tilted thin disk: Lense-Thirring precession

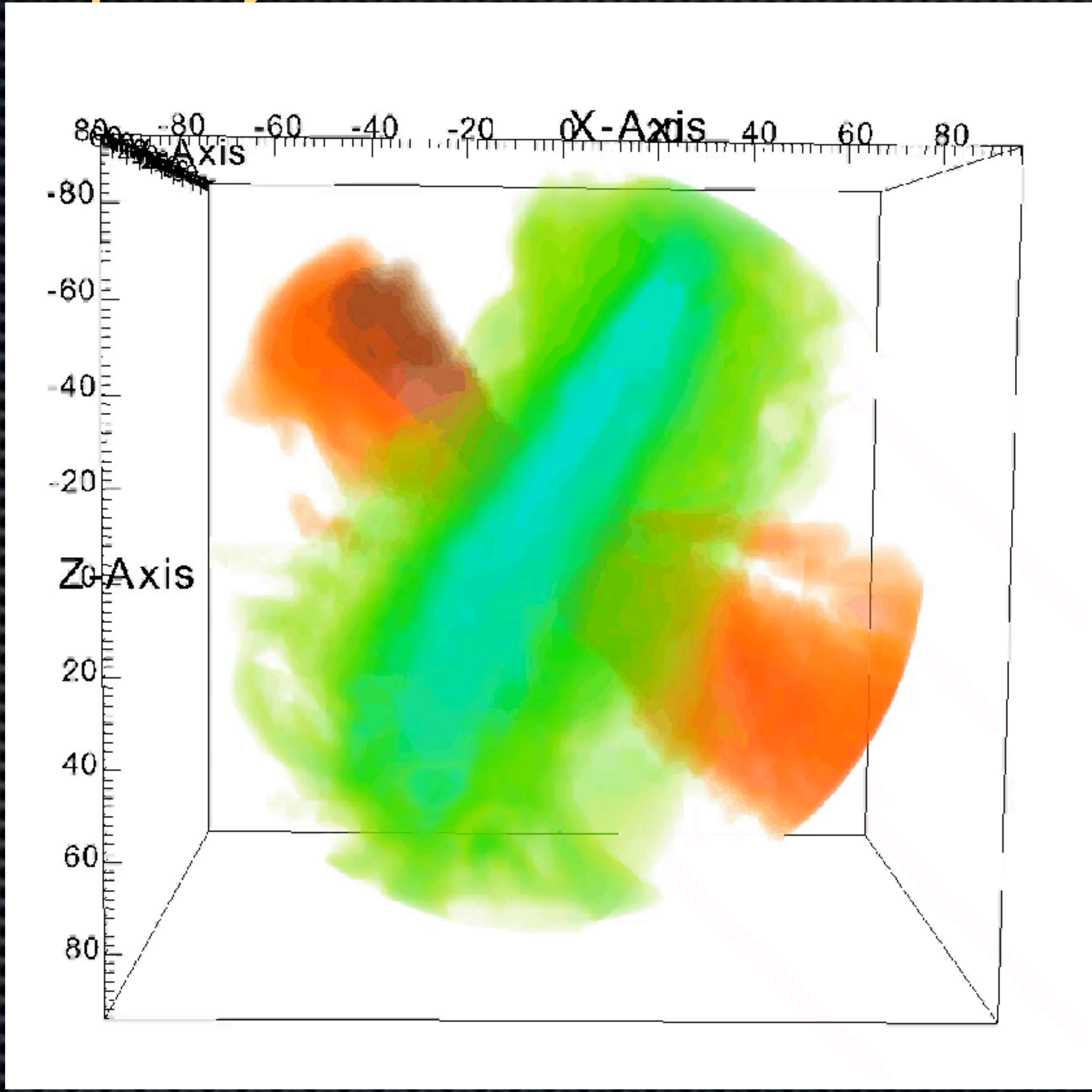
H/R=0.03, 40° tilt, resolution in disk= (5480x1720x2400)



(Liska, Tchekhovskoy, Ingram, vd Klis, SM++, in prep.)

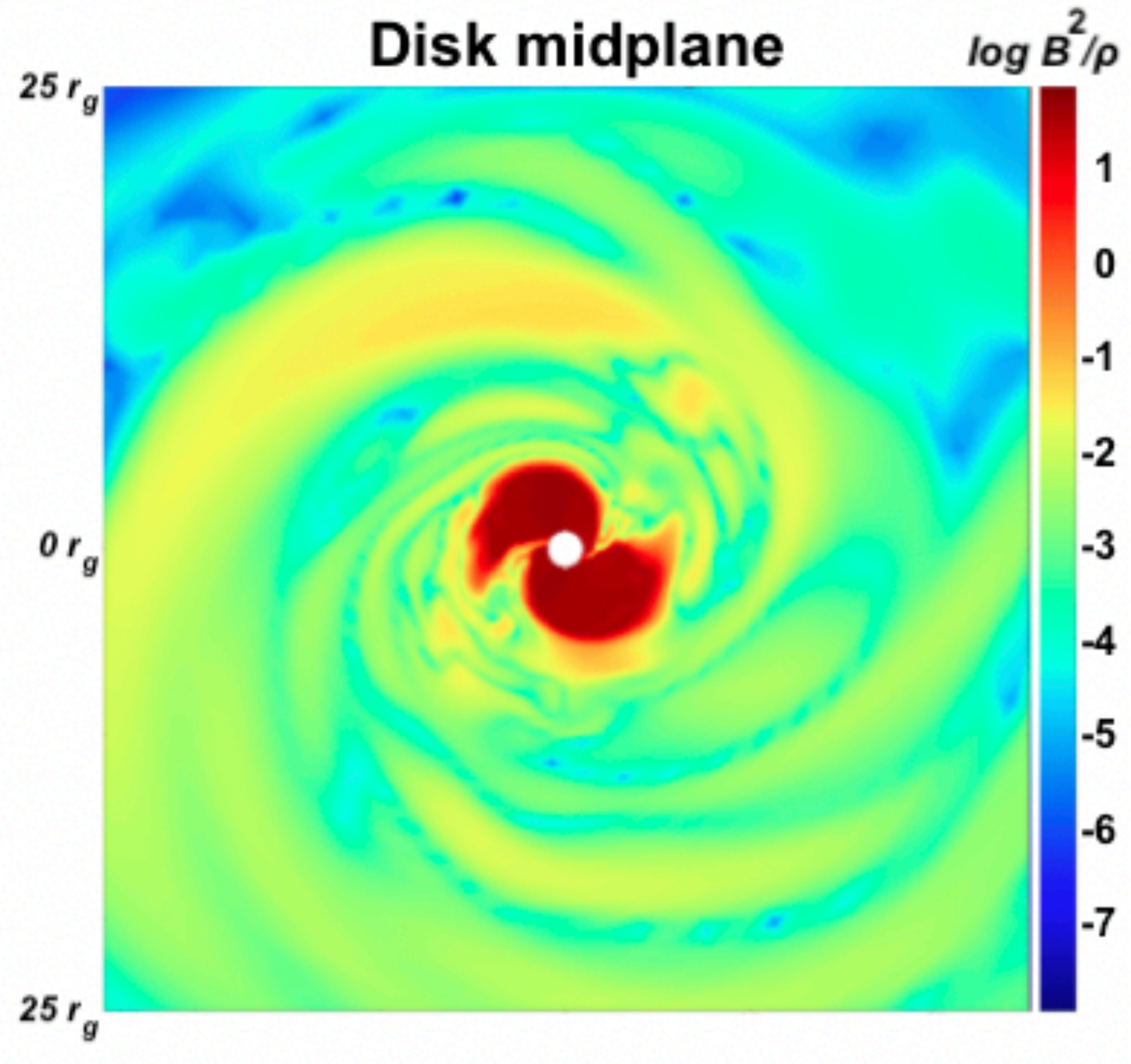
H-AMR: GPU-accelerated update of HARM with AMR

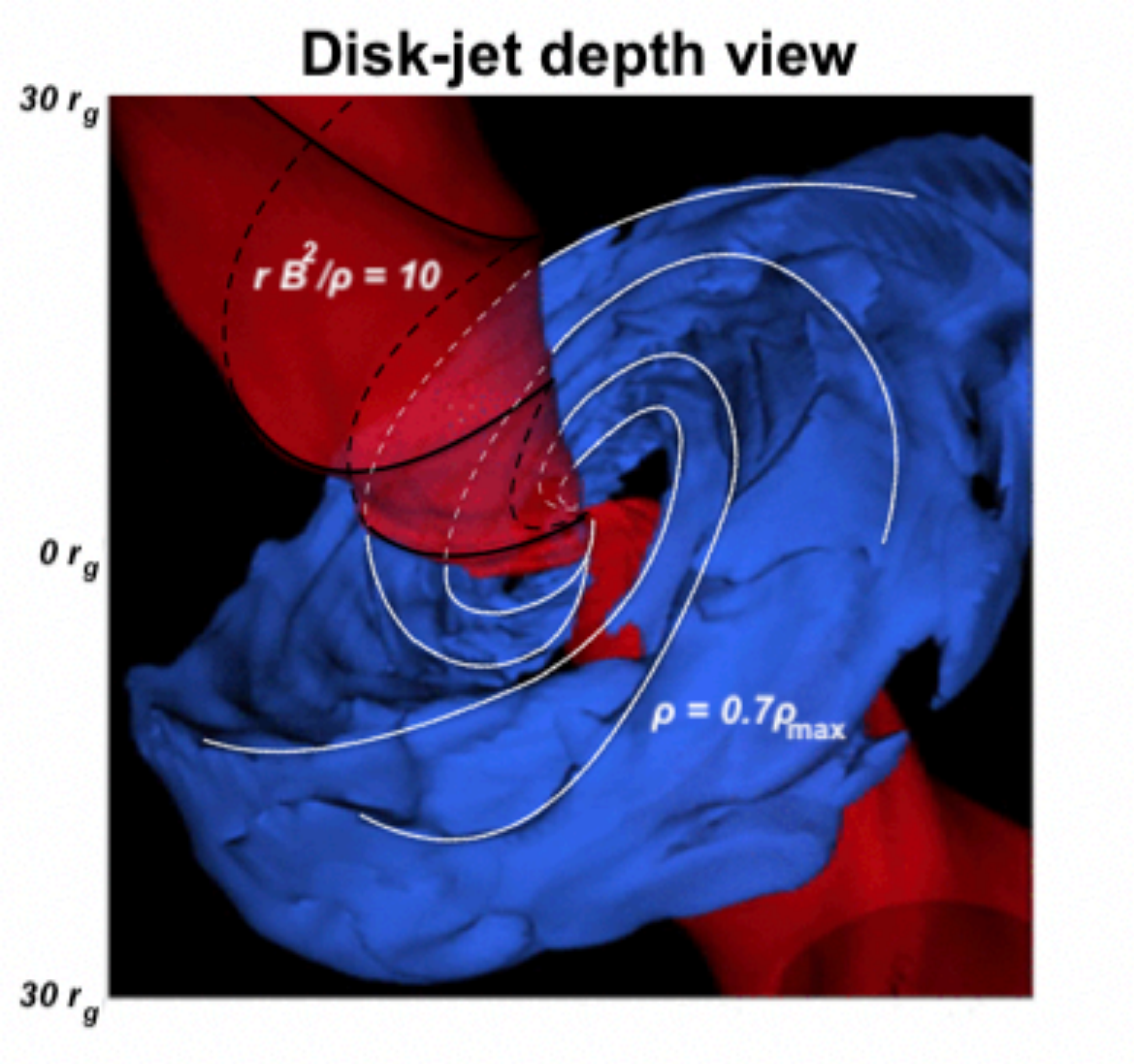
(developed by UvA MSc → PhD student M. Liska)



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

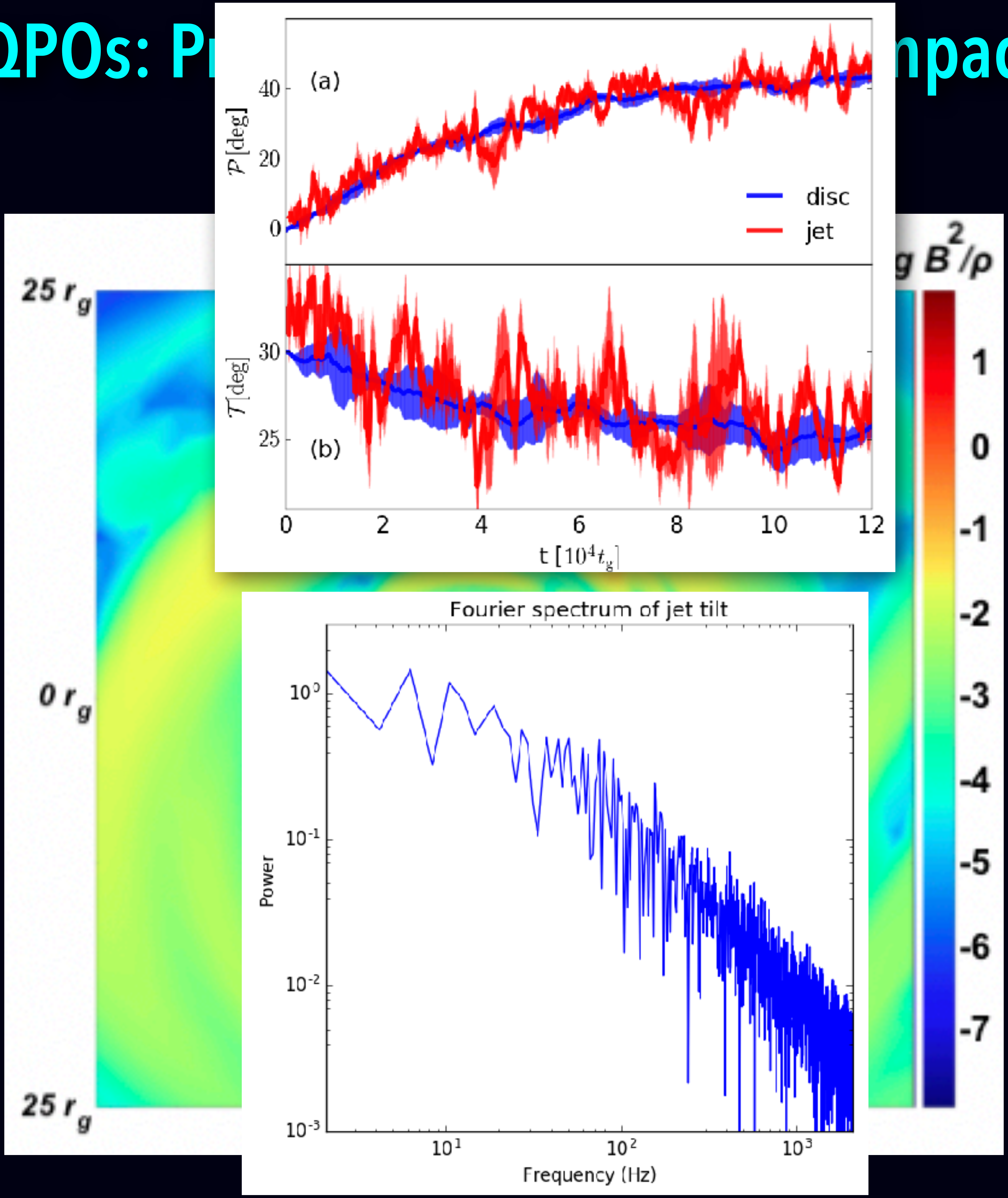
QPOs: Precessing jet structure impacted by "plunge streams" in tilted disk?

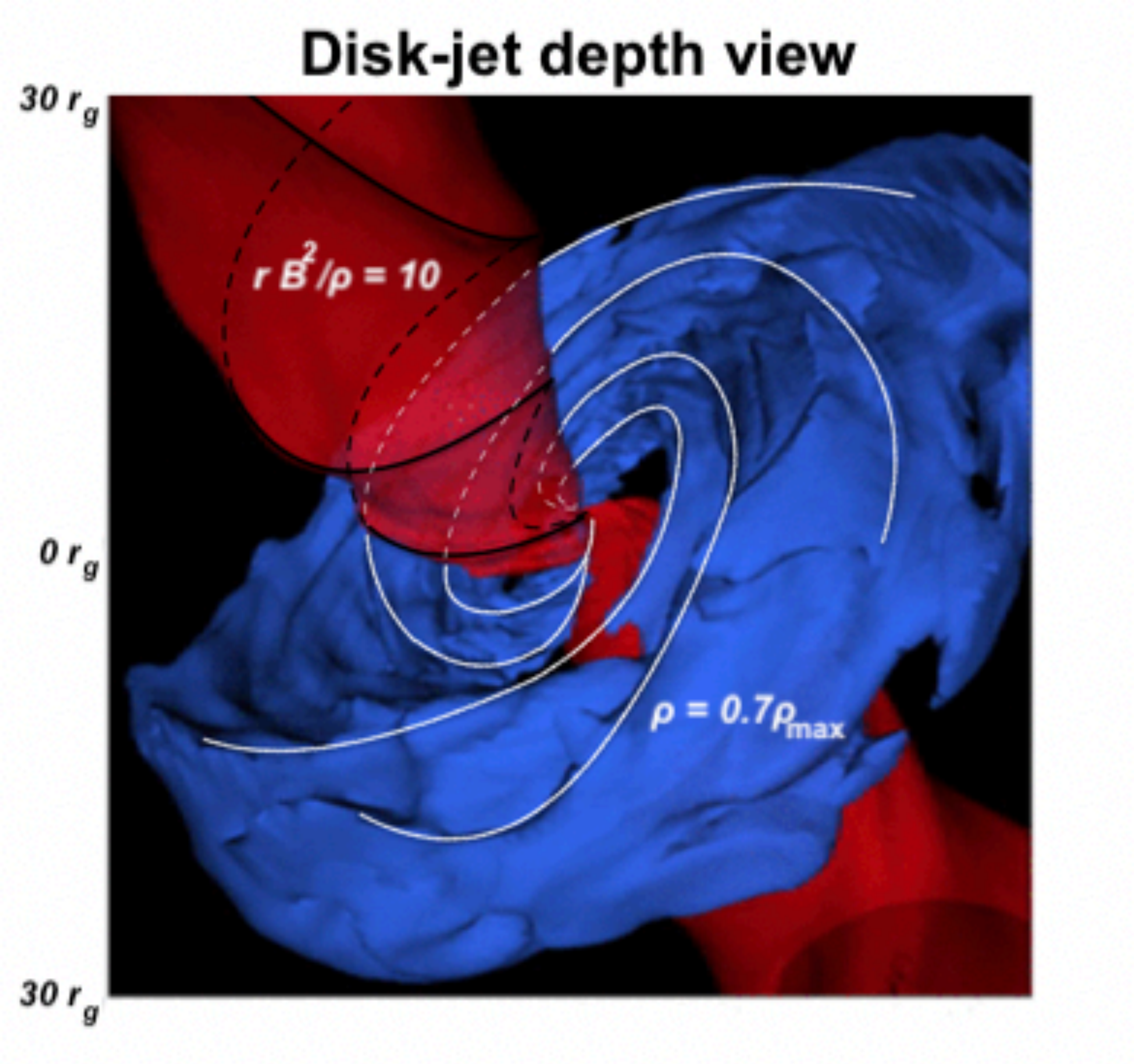




Casper Hesp (MSc thesis) + Liska, Hesp, Tchekhovskoy, SM++, in prep.)

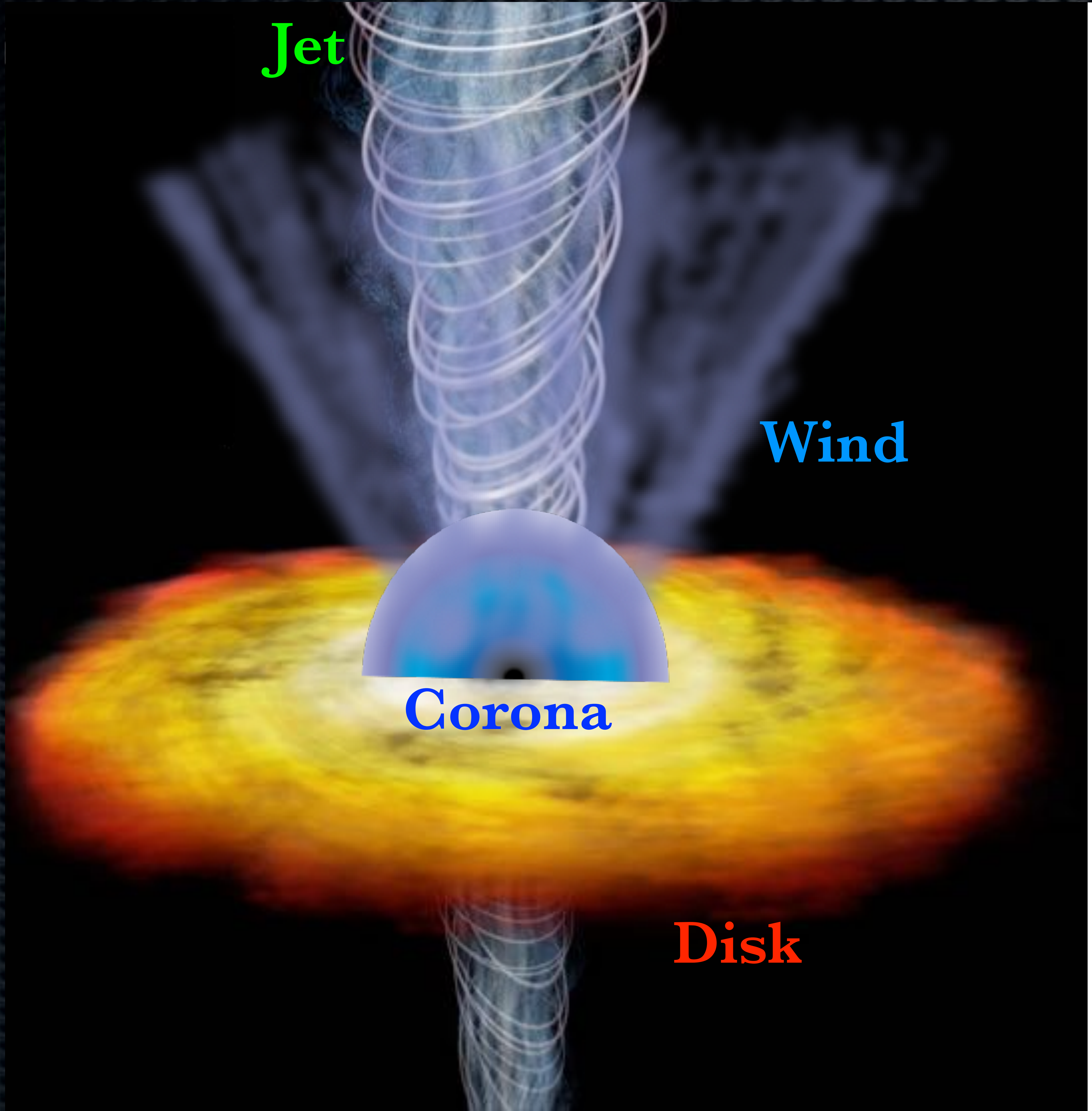
QPOs: Pr npacted by “plunge streams” in tilted disk?

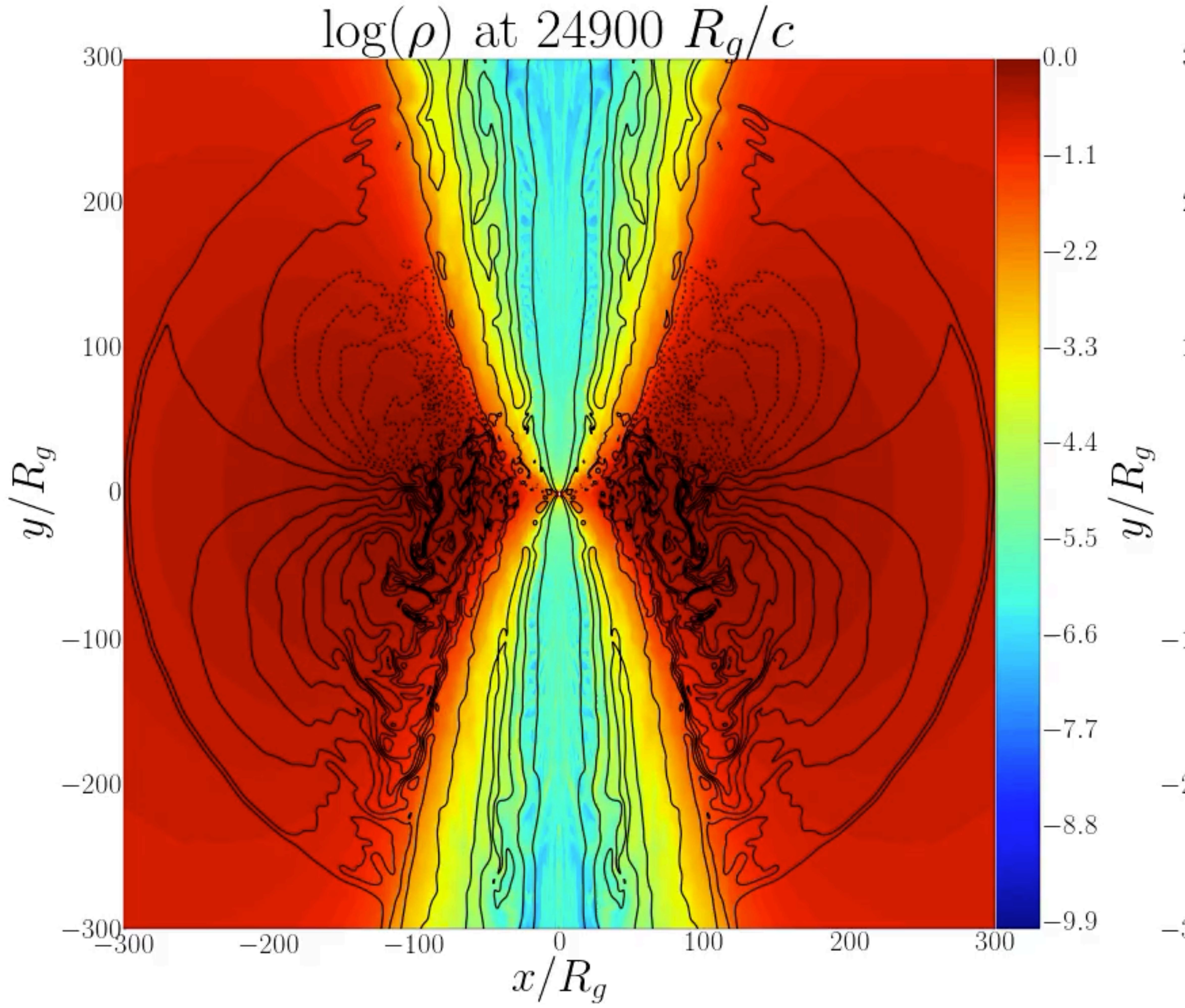




Casper Hesp (MSc thesis) + Liska, Hesp, Tchekhovskoy, SM++, in prep.)

Dynamical MHD simulations challenge old concepts





Chatterjee, Liska, SM, Tchekhovskoy++, subm.

Summary

- Holy ****, we can actually "see" black holes!
- EHT will further test GR and exotic physics, but also shine light on many key problems involving black hole "engines"
- Challenge for modelling particularly at the microphysical/plasma level, how to handle the full dynamical range of physics?
- XRBs offer direct probes of "macro/micro coupling", a complementary view to what AGN/EHT give
- All this physics needs to be understood to properly model black hole astrophysics and account for their role in the Universe