Using our Galactic supermassive black hole Sgr A* as a testbed for theories of accretion and cosmic evolution

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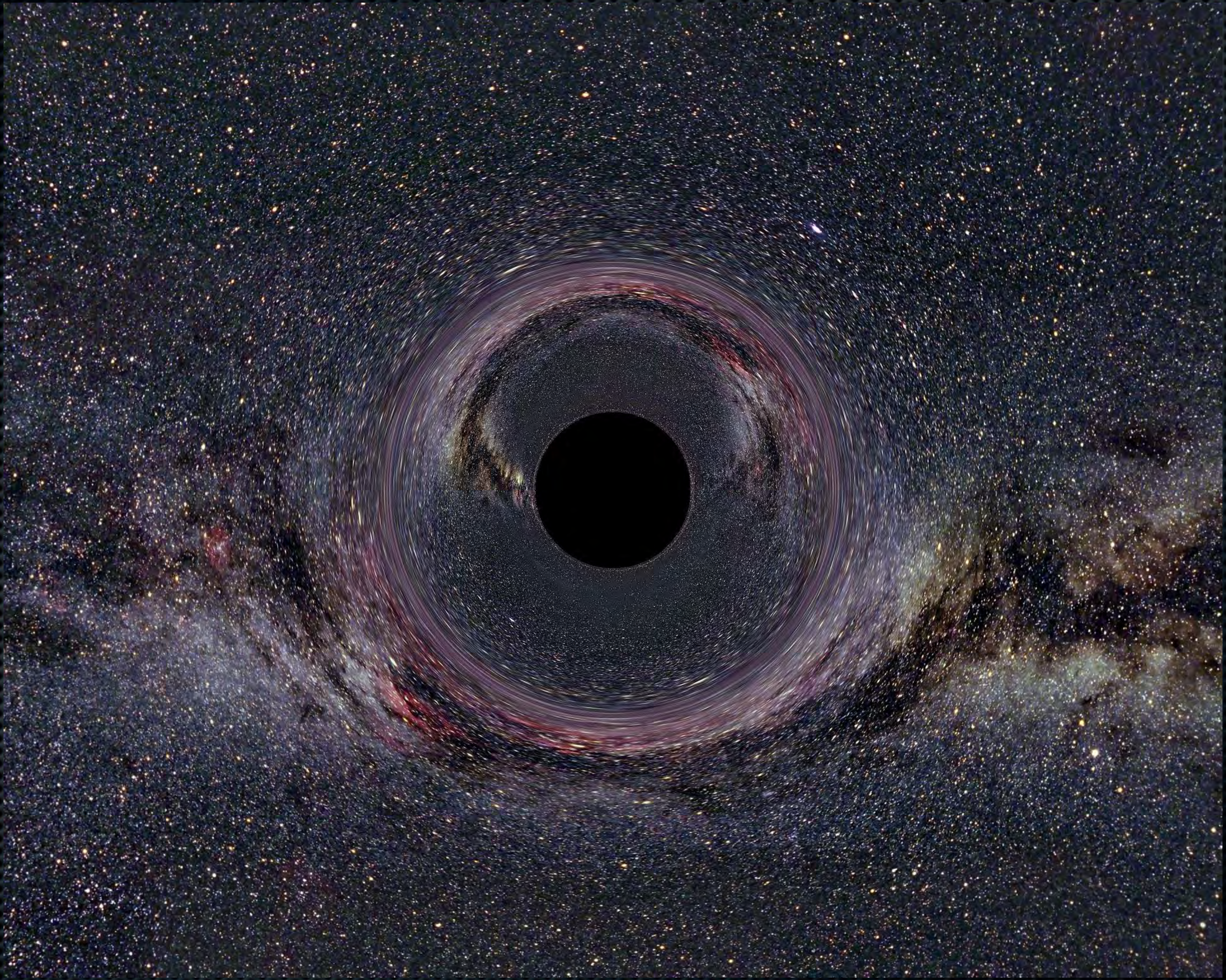
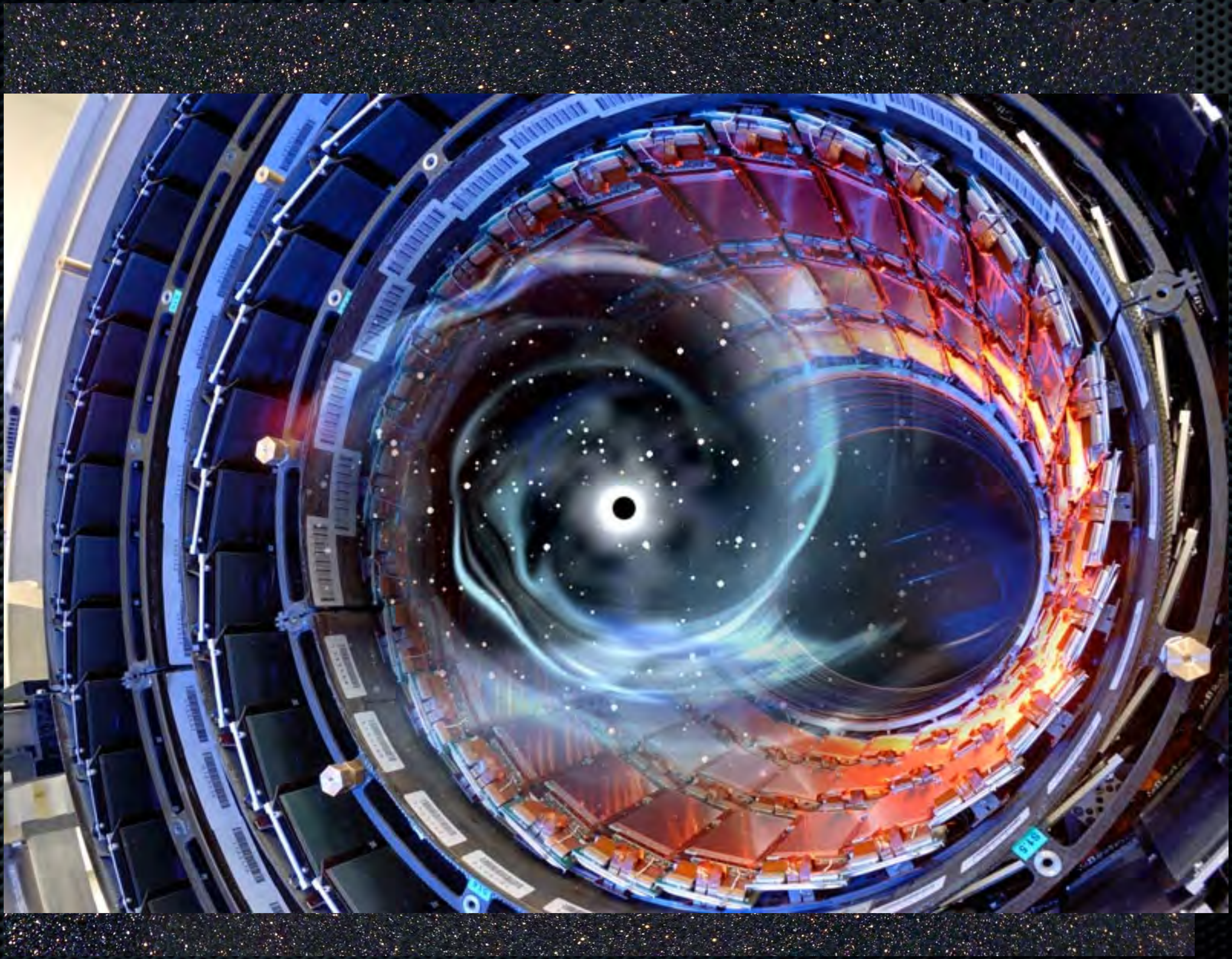
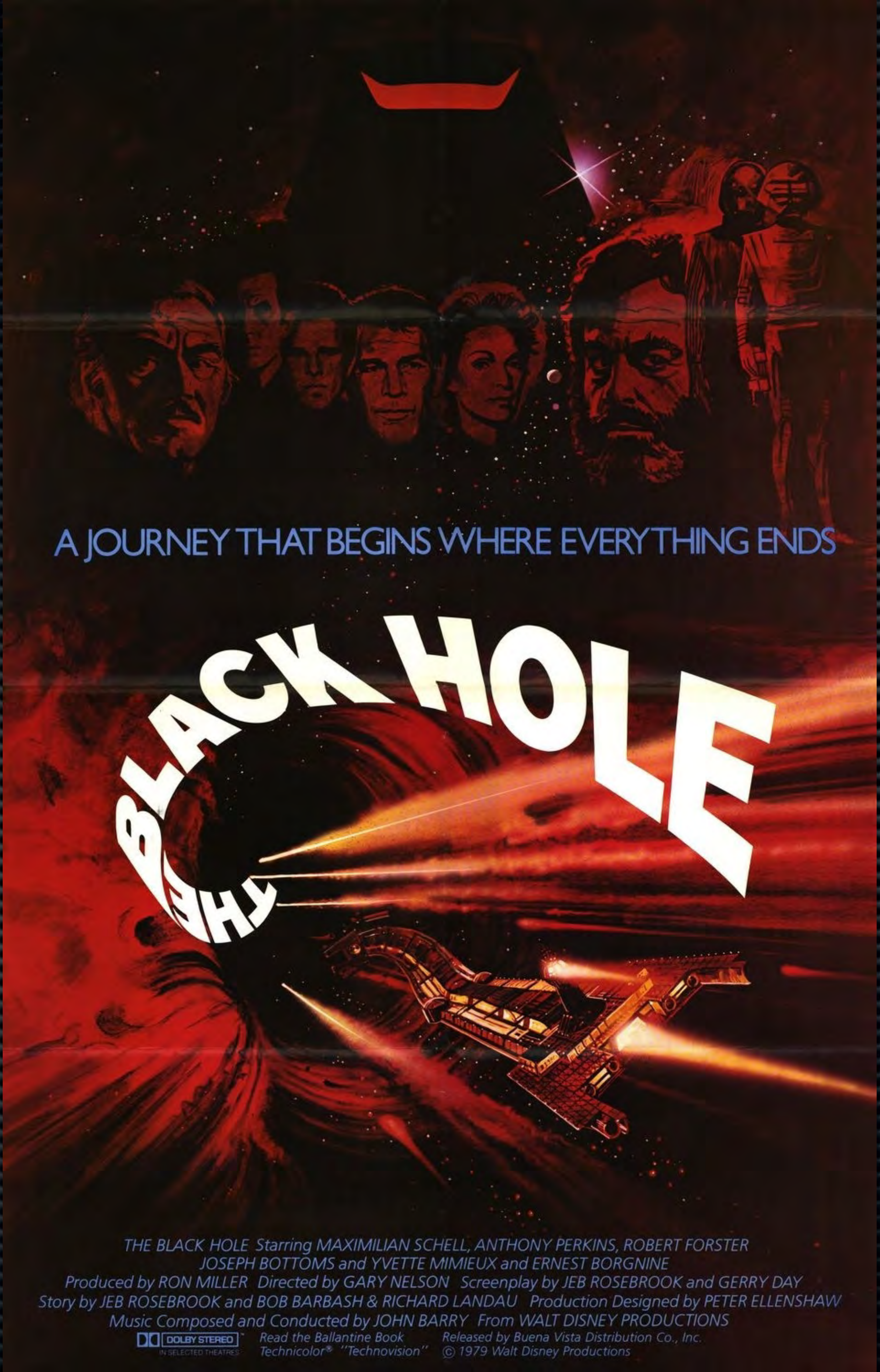
(Bkgd: A new view of the minispiral at 105 GHz with ALMA: Rushton, Brinkerink, Falcke et al.)

Black Holes



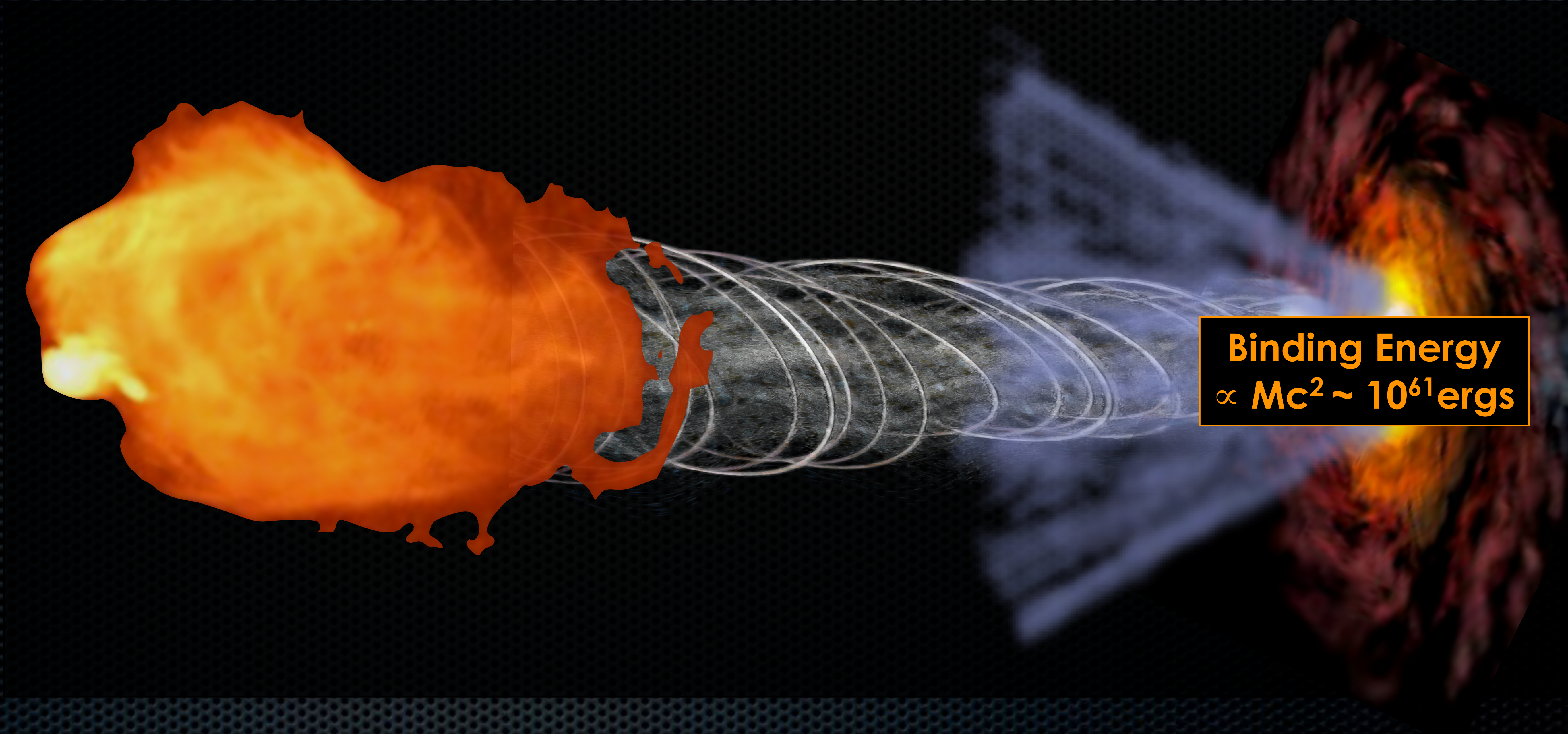
Black Holes



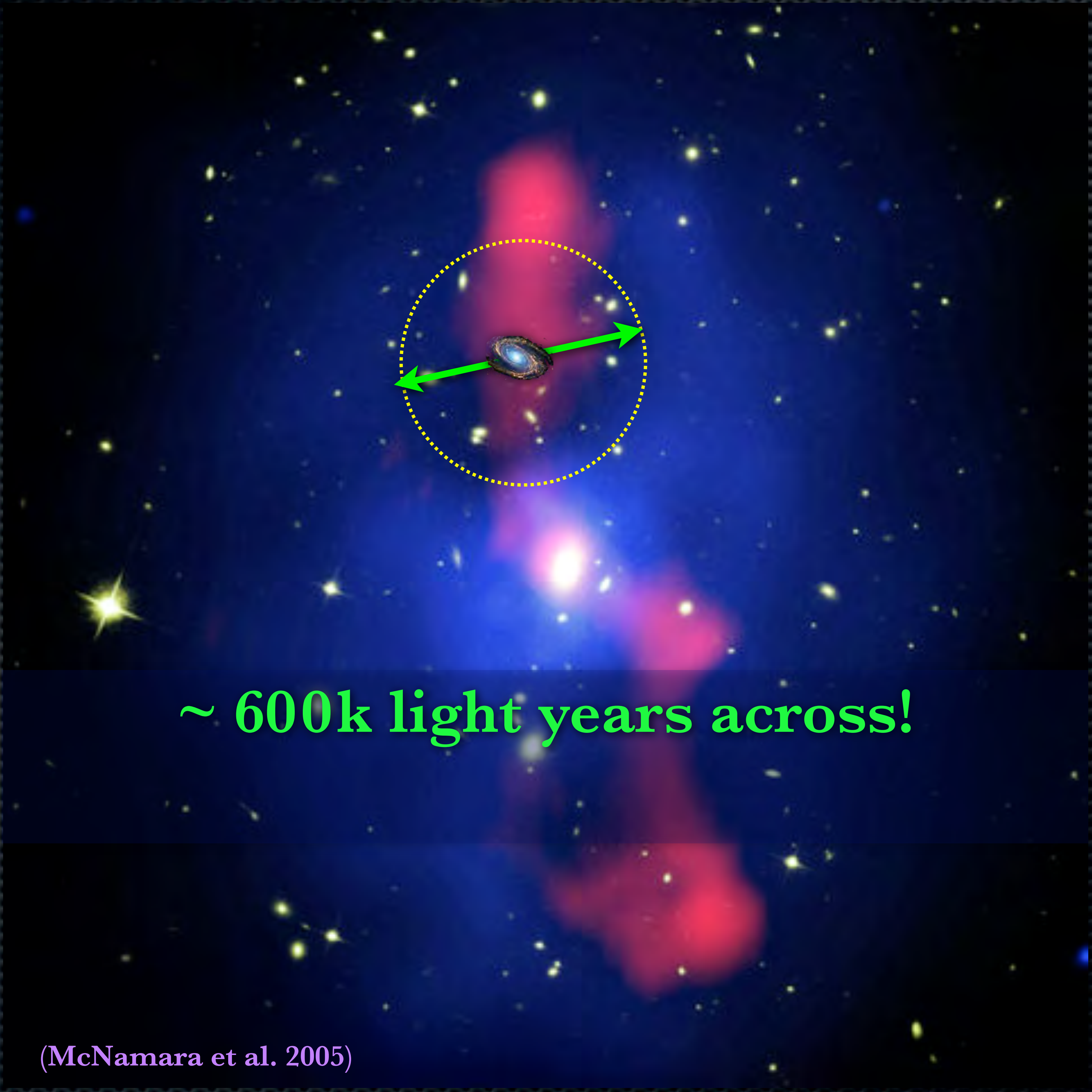

A JOURNEY THAT BEGINS WHERE EVERYTHING ENDS
THE BLACK HOLE
THE BLACK HOLE Starring MAXIMILIAN SCHELL, ANTHONY PERKINS, ROBERT FORSTER
JOSEPH BOTTOMS and YVETTE MIMIEUX and ERNEST BORGNINE
Produced by RON MILLER Directed by GARY NELSON Screenplay by JEB ROSEBROOK and GERRY DAY
Story by JEB ROSEBROOK and BOB BARBASH & RICHARD LANDAU Production Designed by PETER ELLENSHAW
Music Composed and Conducted by JOHN BARRY From WALT DISNEY PRODUCTIONS
DOLBY STEREO
IN SELECTED THEATRES
Read the Ballantine Book
Technicolor® "Technovision"
Released by Buena Vista Distribution Co., Inc.
© 1979 Walt Disney Productions

Extremely efficient "engines" (releasing ≳40% $\dot{m}c^2$)

☛ **Output channels: radiation, winds, jets**



Jets seem to provide means to halt massive galaxy growth



>few 10^6 lt yrs

~10^{20} km

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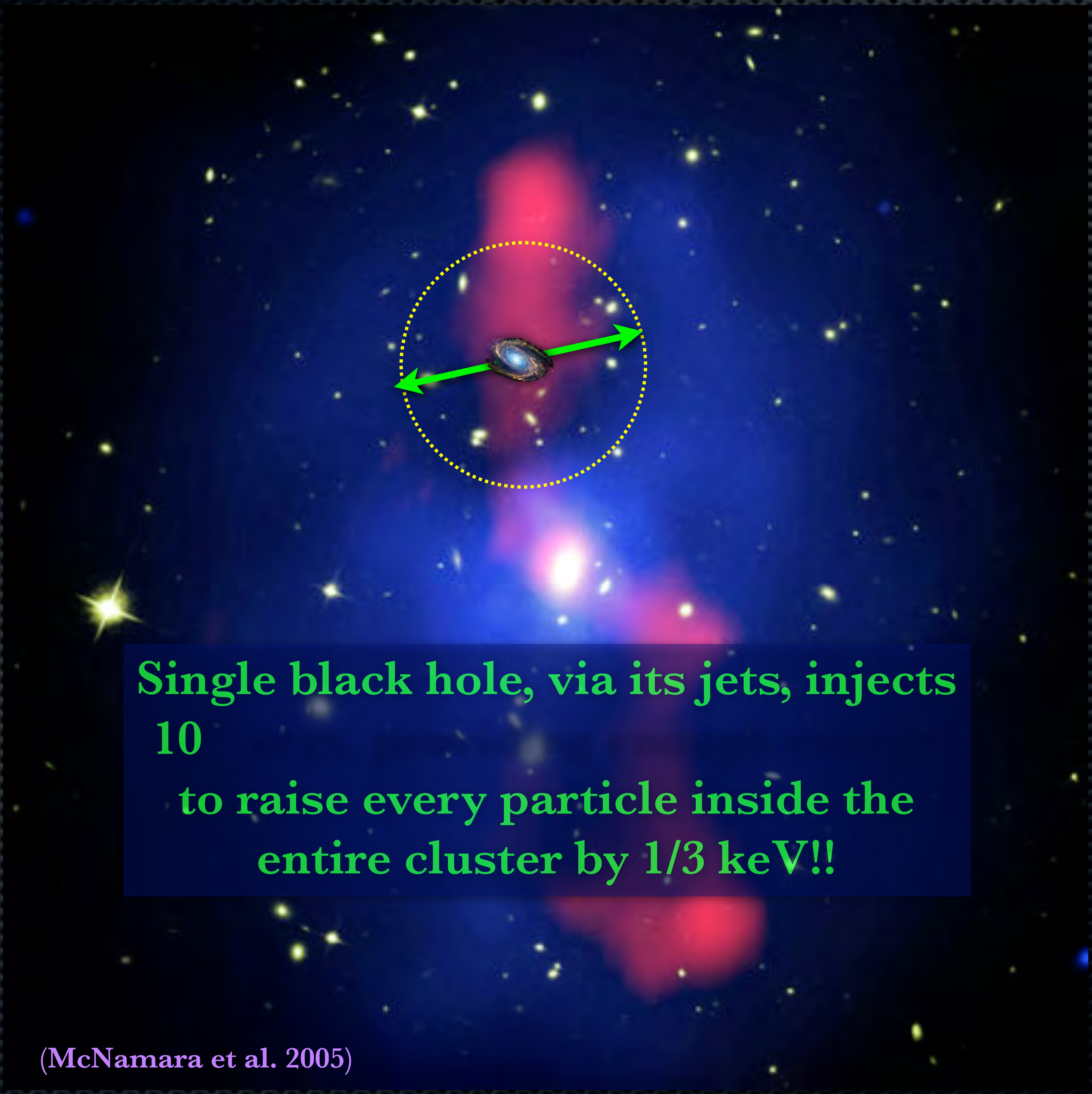

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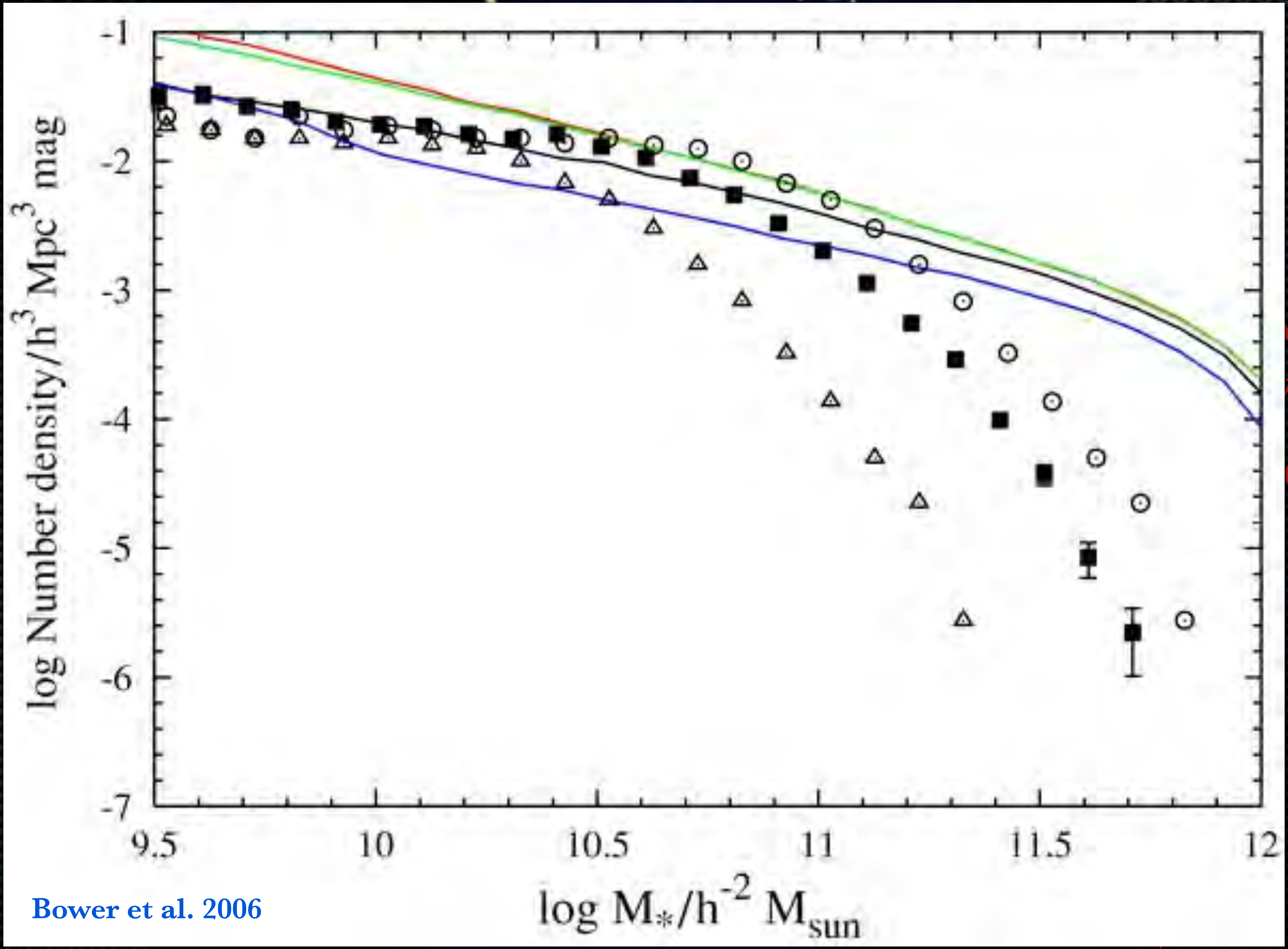
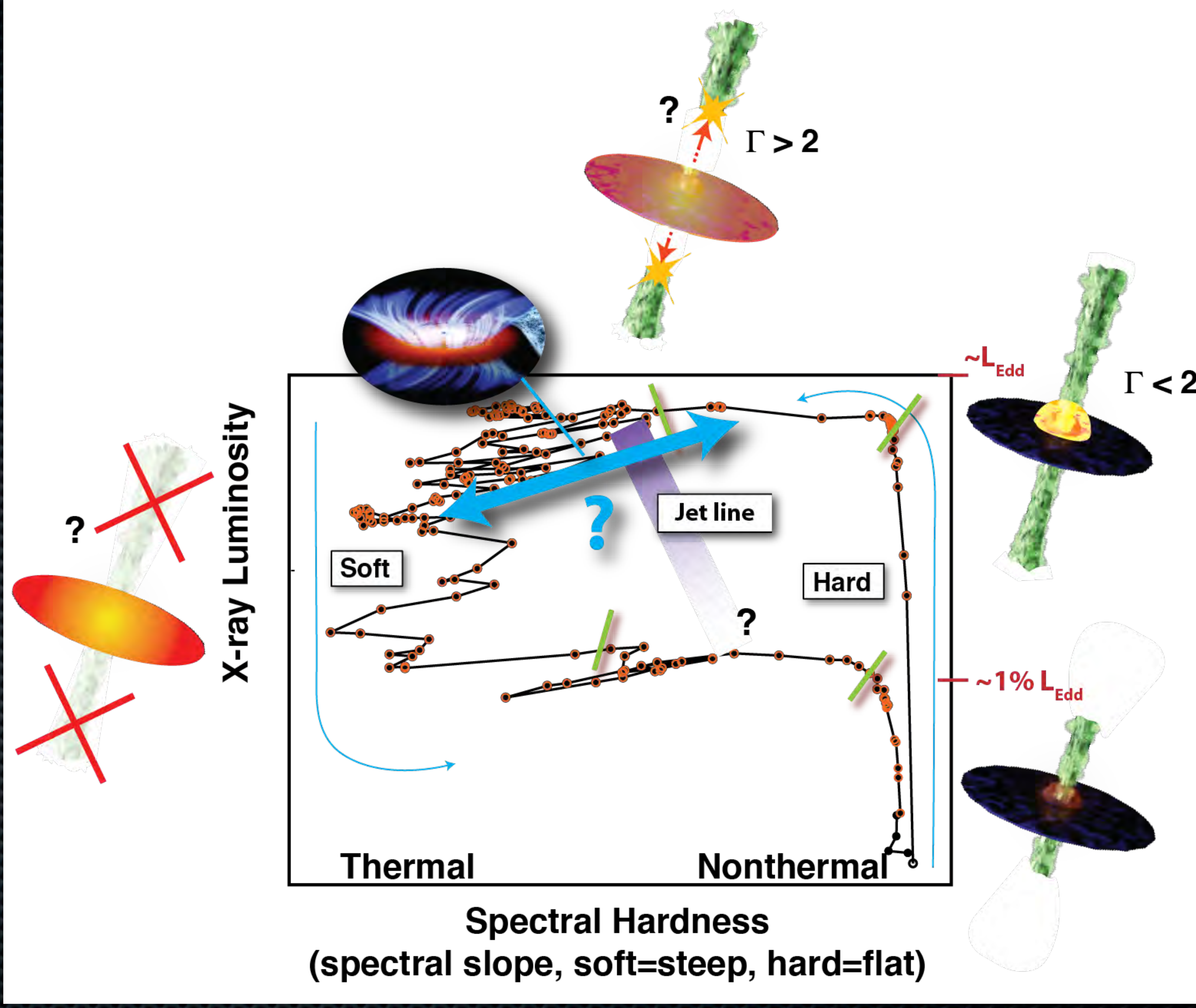
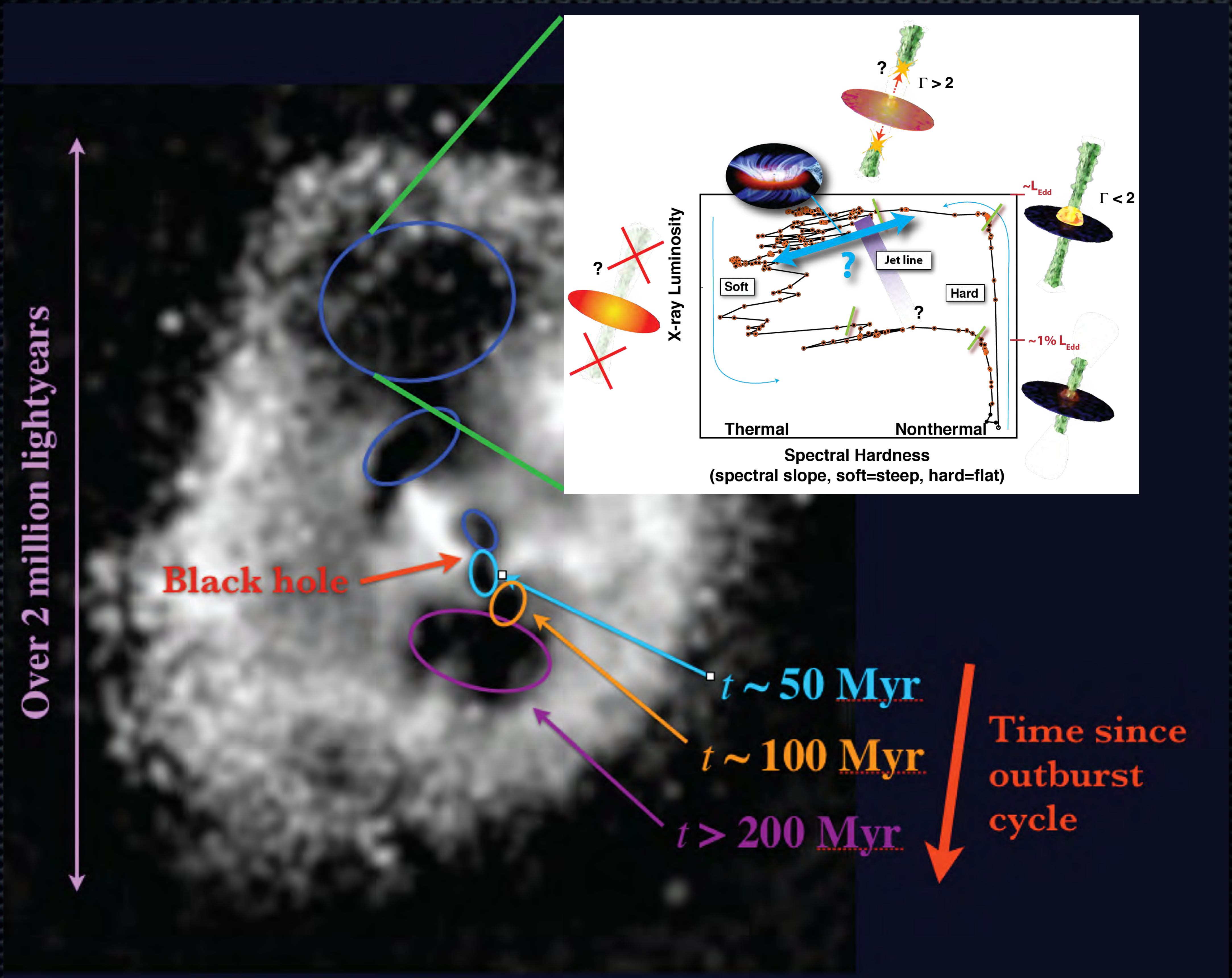


Stellar-mass BHs in X-ray Binaries:
Different power channels: jets, winds or disk/radiation



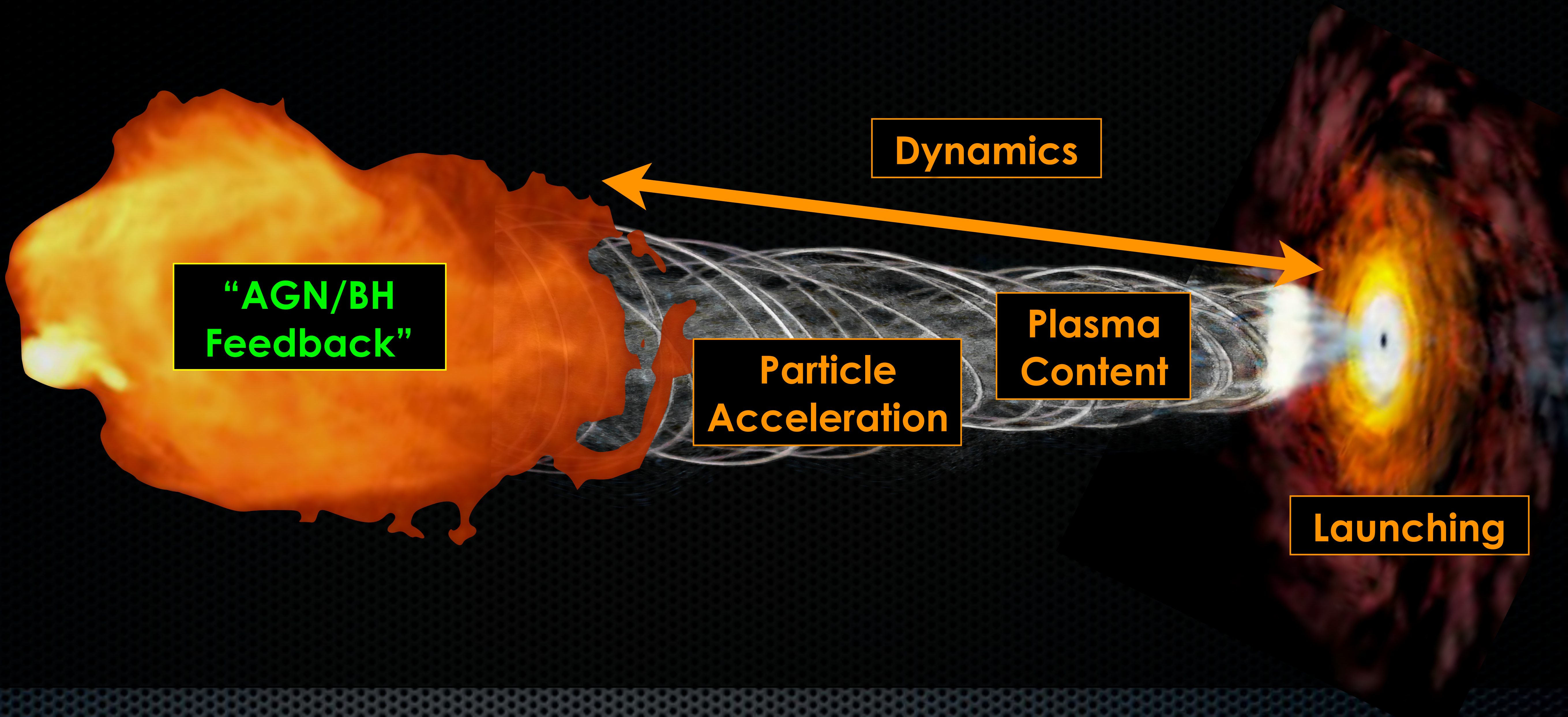
Evidence of AGN outburst cycles:
Do these cycles also involve "channel" switching??



Some "overarching" questions

- **"Fueling"** ➠ *What determines SMBH activity? What drives duty cycles, and can they be compared to XRBs?*
- **"Power output channel"** ➠ *What determines how the gravitational potential energy is unleashed on environment?*
- **"Inflow/outflow problem"** ➠ *How are outflows launched, what are their physical properties, and what determines them?*
- **"Particle acceleration"** ➠ *How (and which) particles get accelerated to high energy (e.g., ultra-high energy cosmic rays, neutrinos, etc.)*

Too many unknowns = degeneracy in the theories

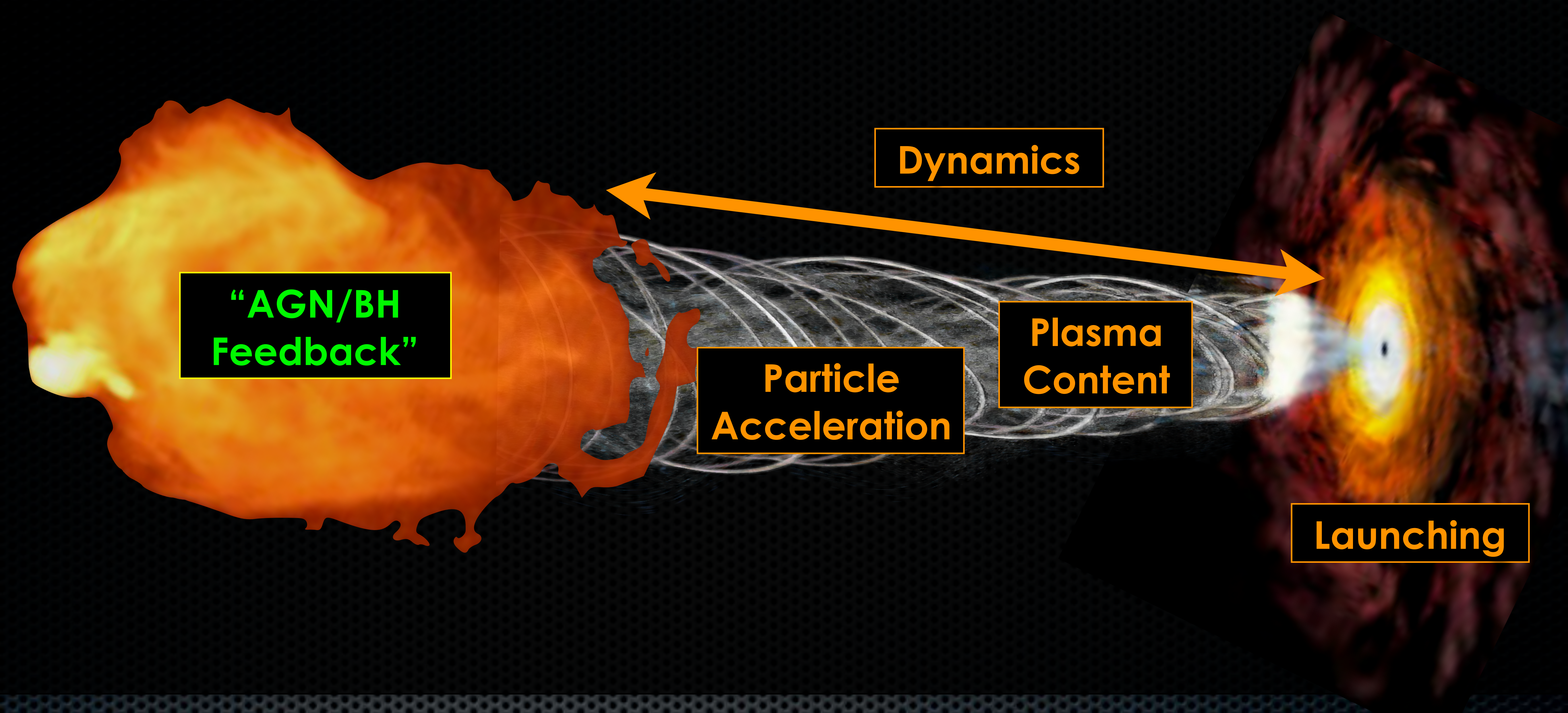


How and why are outflows launched and (for jets) confined? What's inside them? For jets, how and where are particles accelerated?

Requires more information about conditions near the black hole:

Accretion flow properties and structure, magnetic field strength and configuration

Too many unknowns = degeneracy in the theories



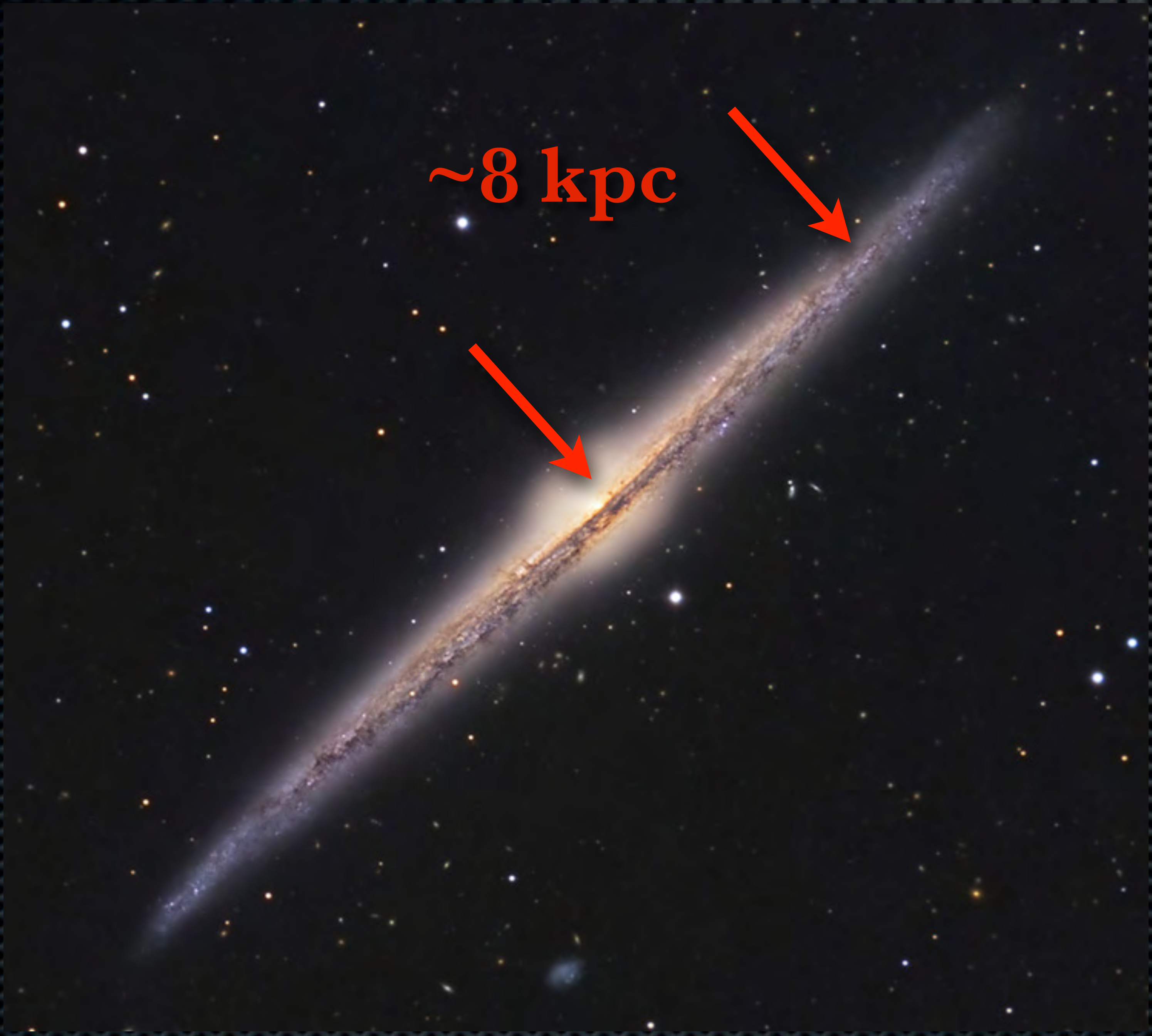
We need a source that can give us access to near-event horizon, + "micro/macro", physics

Introducing: Sagittarius (Sgr) A*!!

Outline for rest of talk

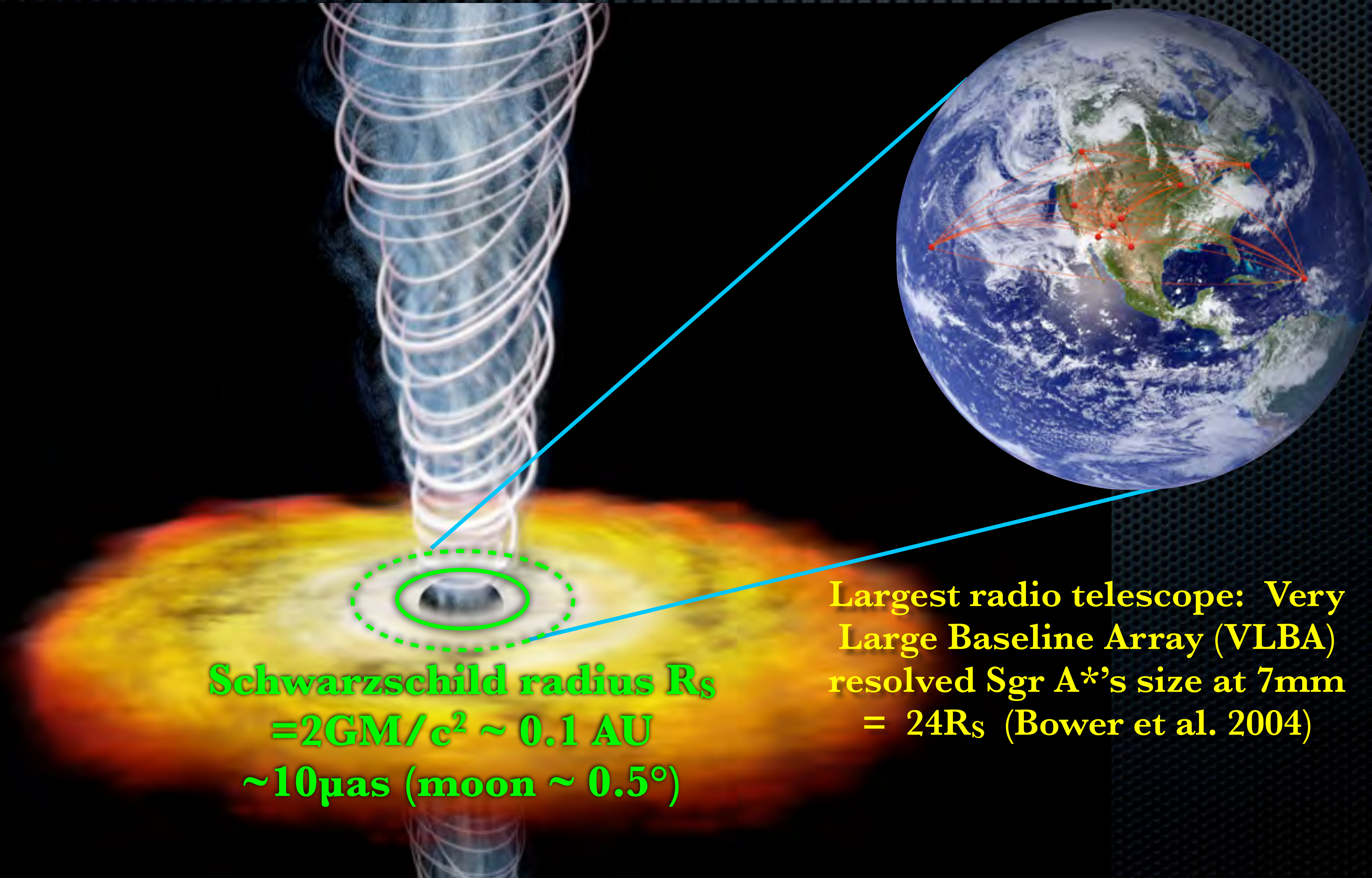
- Quick and dirty introduction to Sgr A* (the past ~30 years)
- Current state of the art for Sgr A* (past few years)
- How does what we are learning for Sgr A* connect back to the bigger picture?

Sgr A*: What can we actually see?



- Staring through the plane of the Galaxy creates some problems:
  - extreme absorption in optical/UV
  - limited to radio, sub(mm), NIR, X-ray
  - scattering $\sim\lambda^2$, smears out radio images

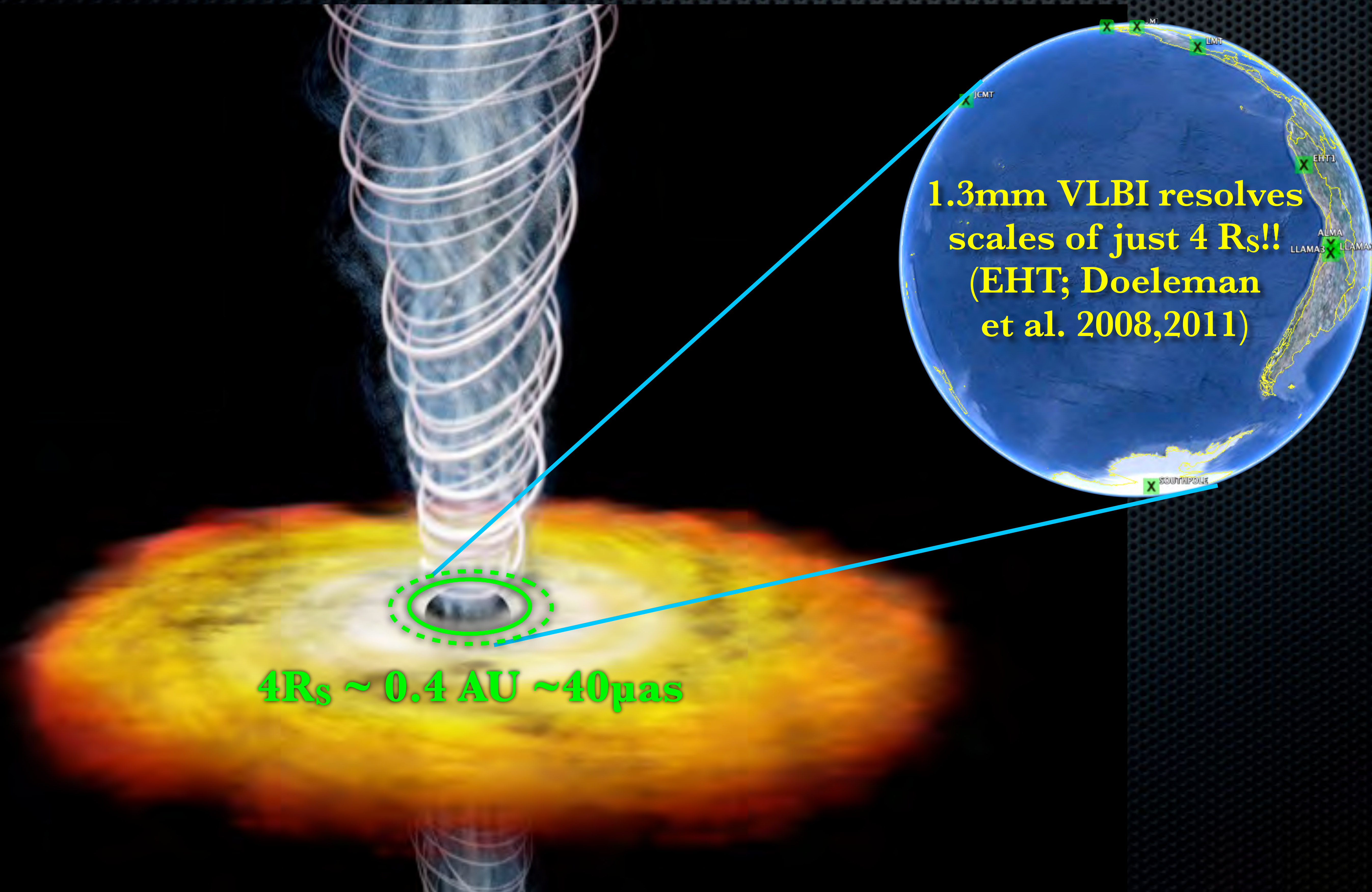
Plumbing the depths: Sgr A*'s event horizon



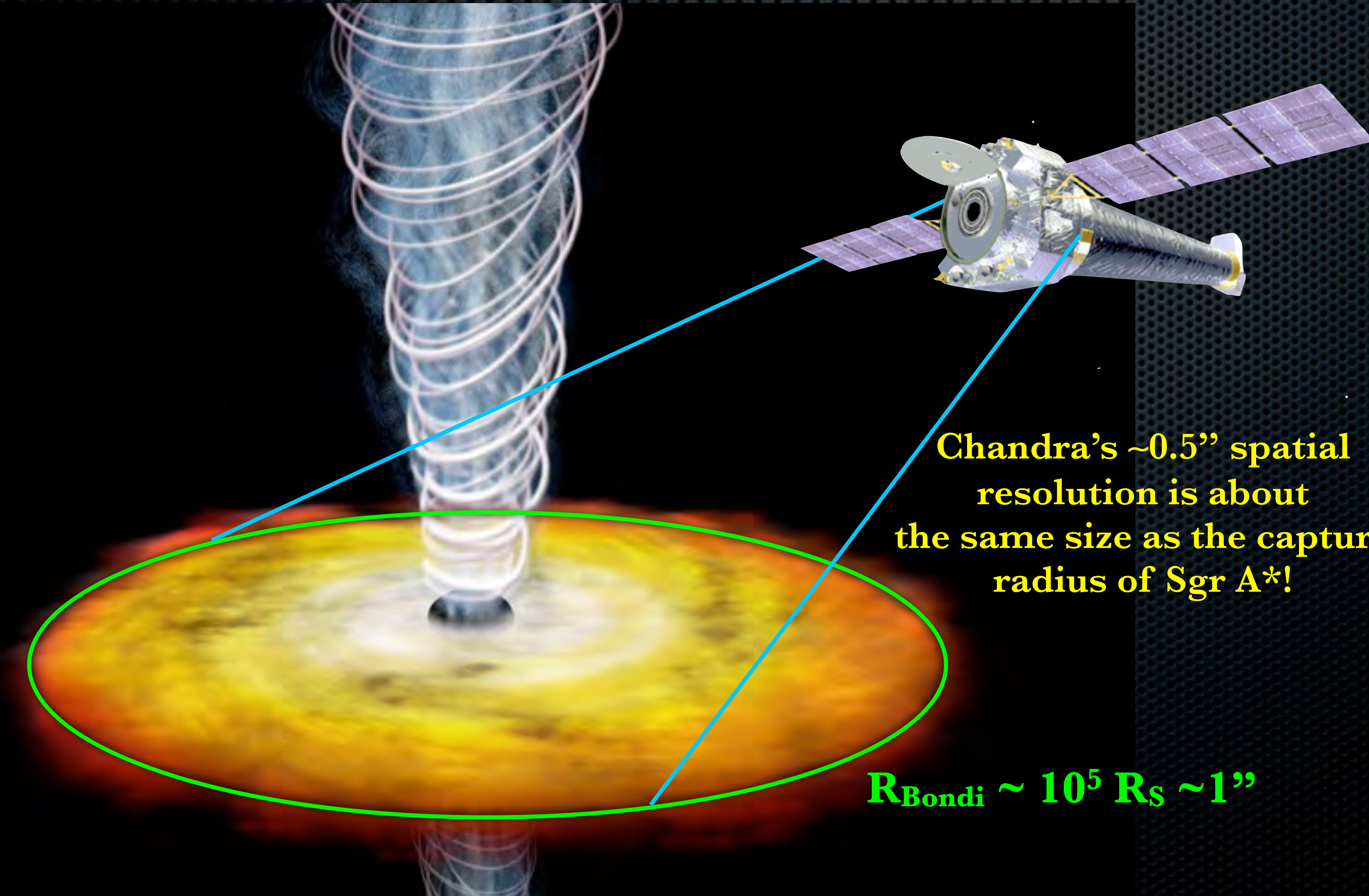
Schwarzschild radius R_S
$=2GM/c^2 \sim 0.1$ AU
~10μas (moon ~ 0.5°)

Largest radio telescope: Very Large Baseline Array (VLBA) resolved Sgr A*'s size at 7mm = $24R_S$ (Bower et al. 2004)

Plumbing the depths: Sgr A*'s event horizon



Constraining the food supply: Sgr A*'s accretion disk



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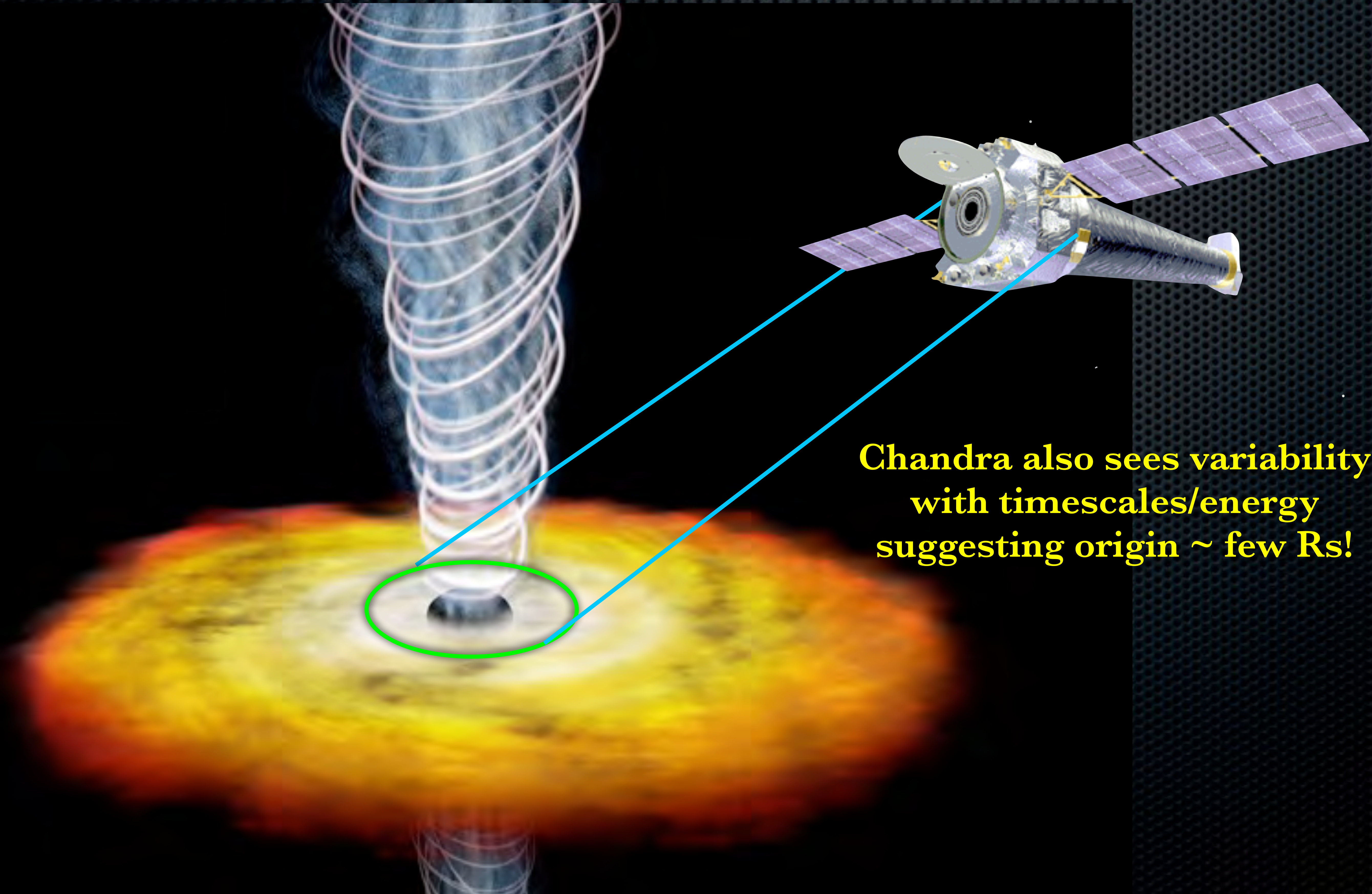
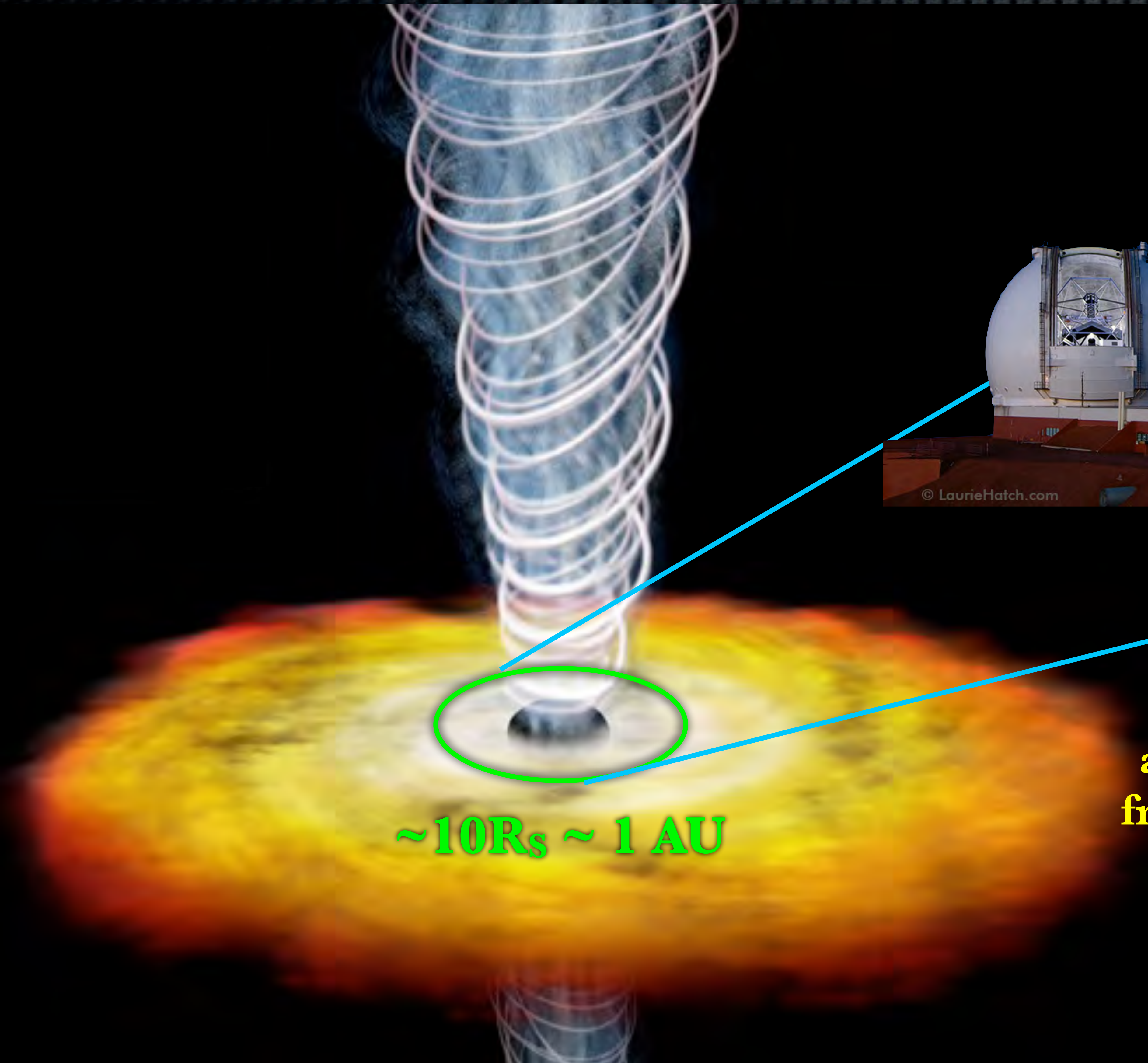
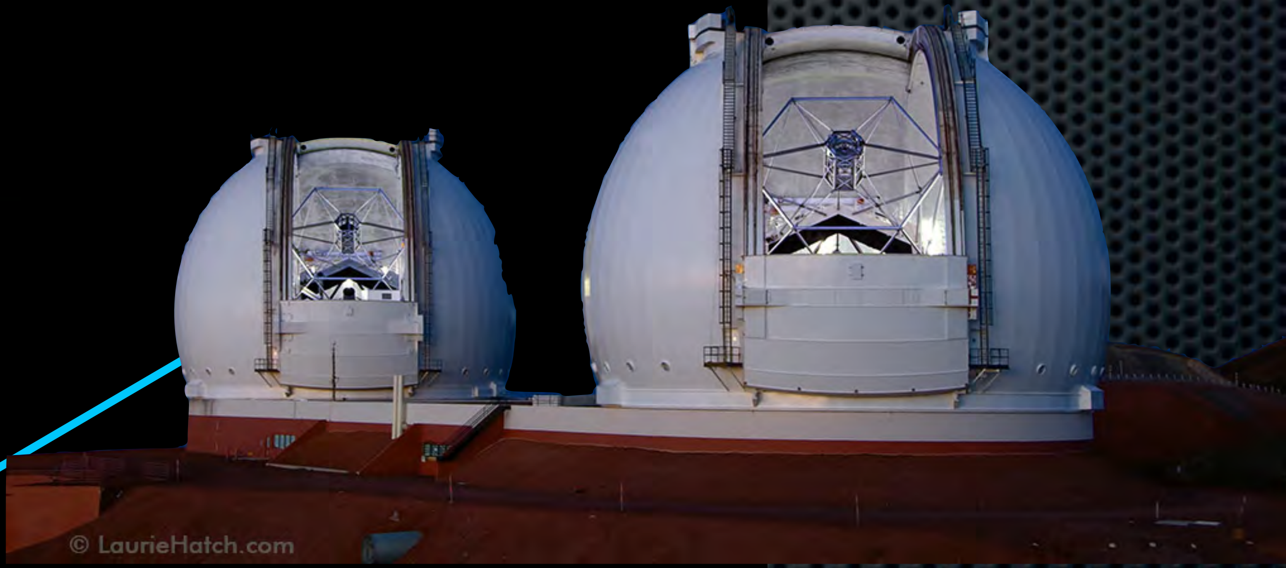


Chandra also sees variability with timescales/energy suggesting origin ~ few Rs!

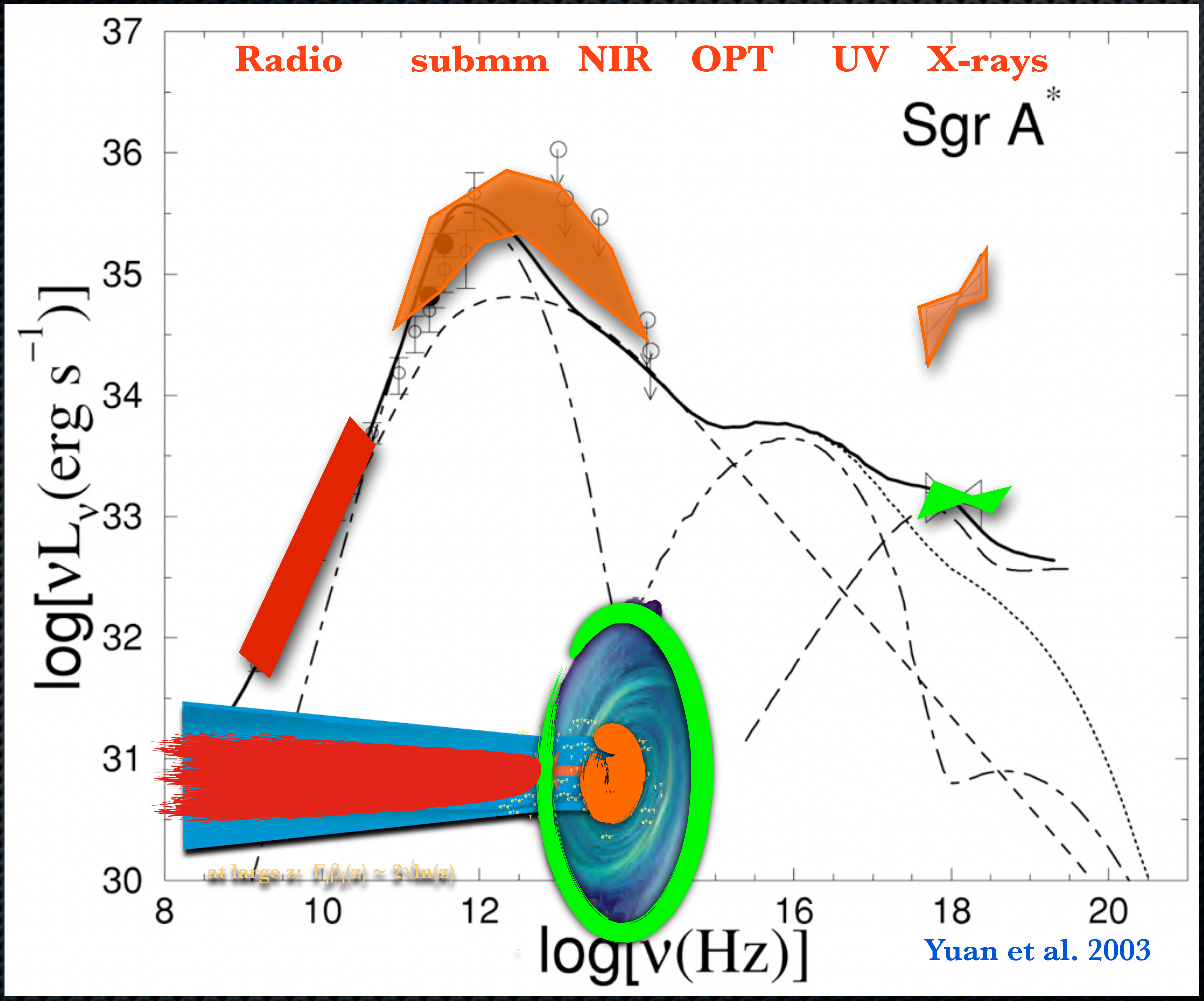
Plumbing the depths: Sgr A*'s event horizon

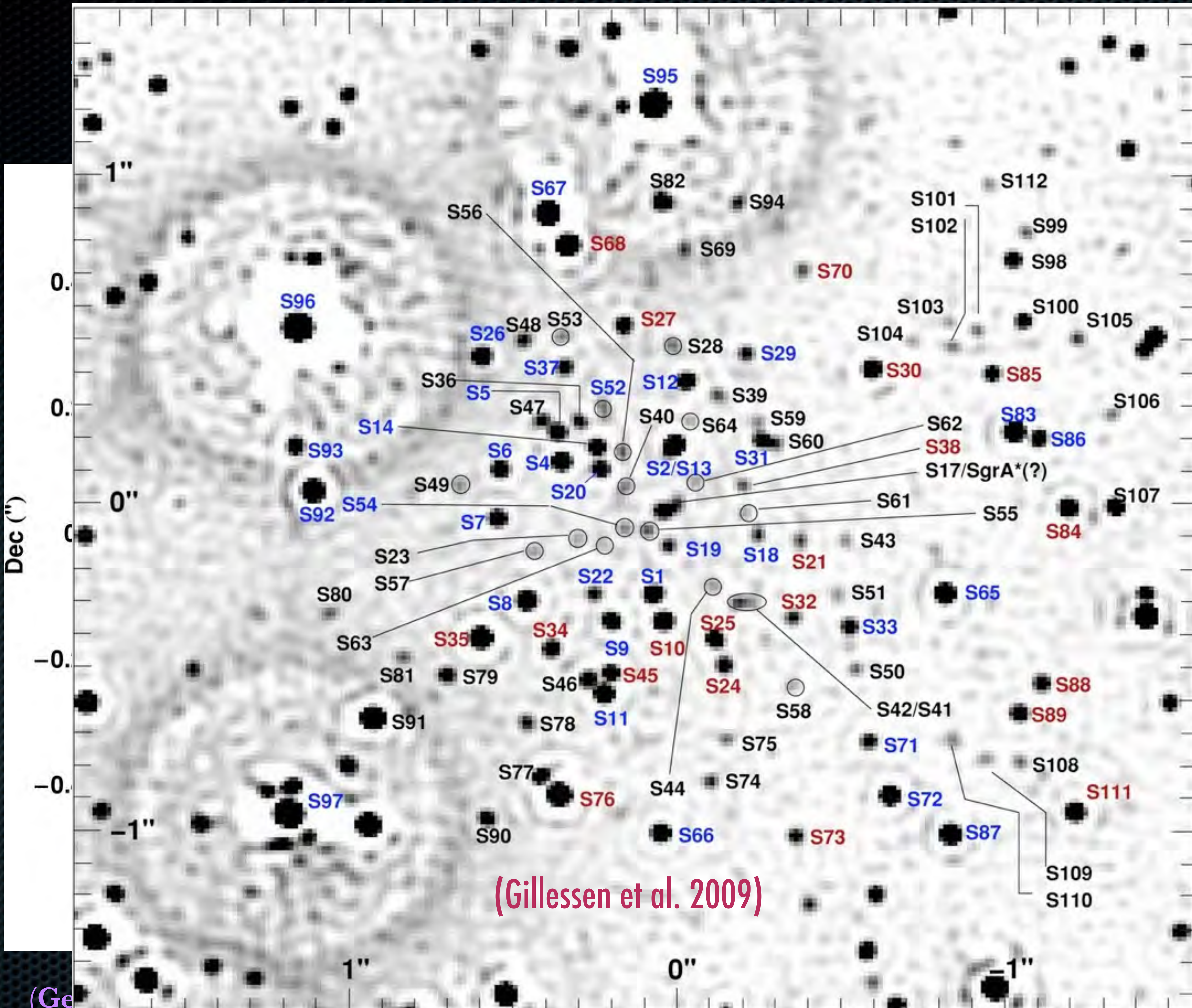




Keck and VLT (IR) also detect variability from scales of ~few R_S!

Sgr A* spectrum – probing accretion scales





sity

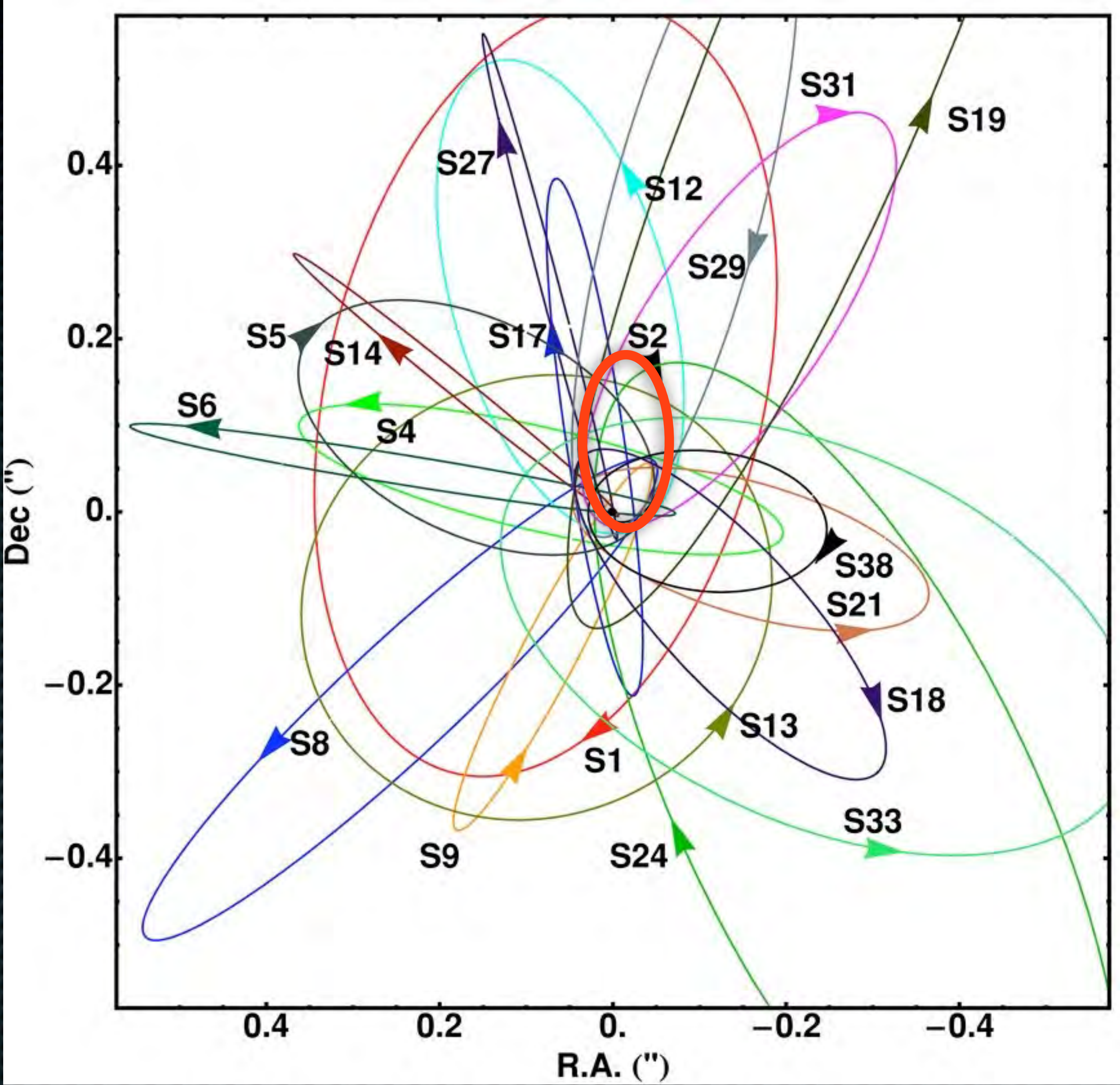
Edd !

M

$erg\ s^{-1}$

(Ge

Weighing a black hole: stellar orbits



- **Orbits:**
  $M_{BH}=4\times10^6\ M_\odot$
- **Lowest luminosity black hole we know!**

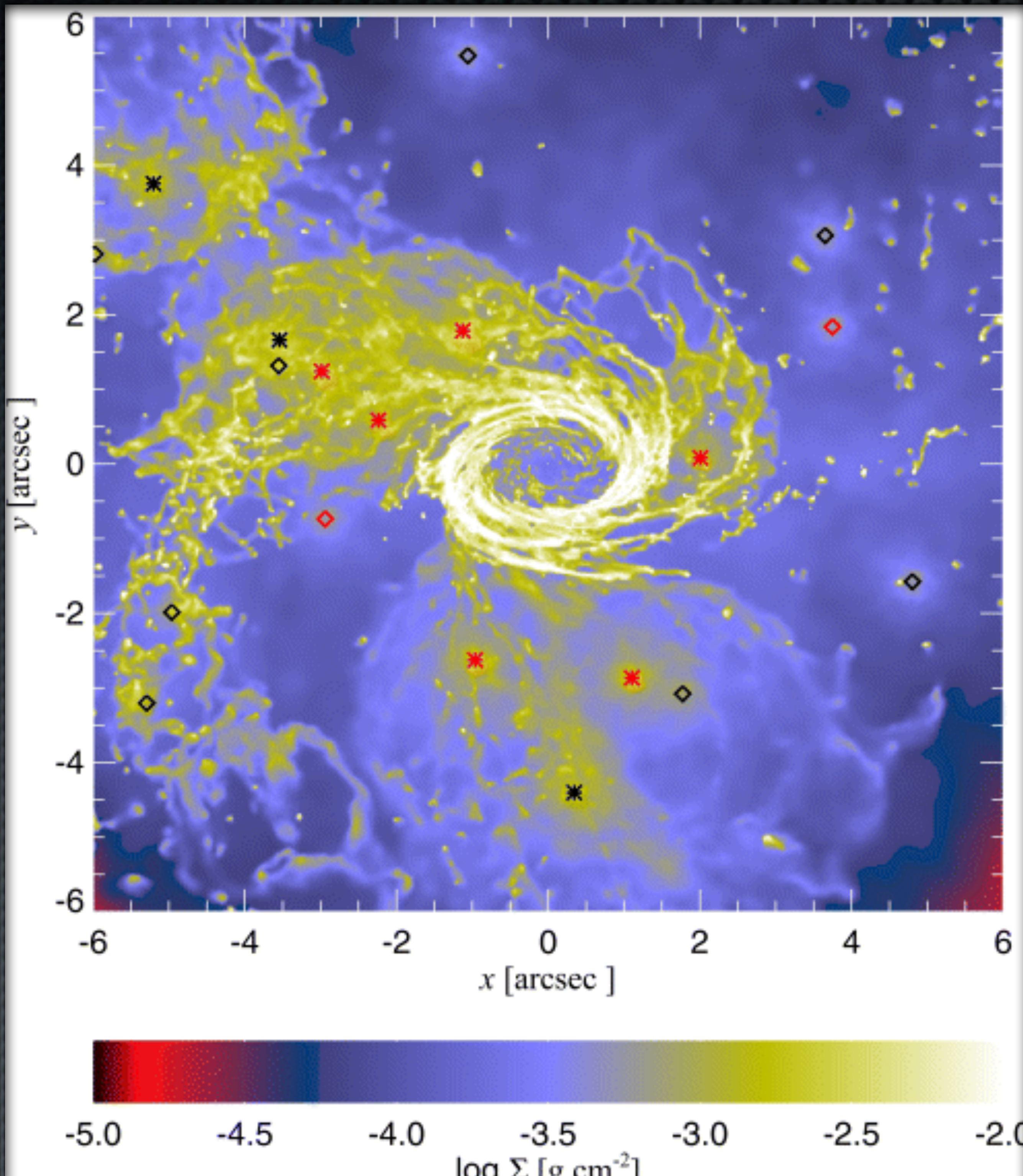
☛ $L_{BOL} = 10^{-9}\ L_{Edd}$!

$$L_{\rm Edd} = \left(\frac{4\pi G m_p c}{\sigma_T}\right) M$$

$$= 1.3\times10^{38}\left(\frac{M}{M_\odot}\right) erg\ s^{-1}$$

(Genzel et al. ++, Ghez et al. ++)

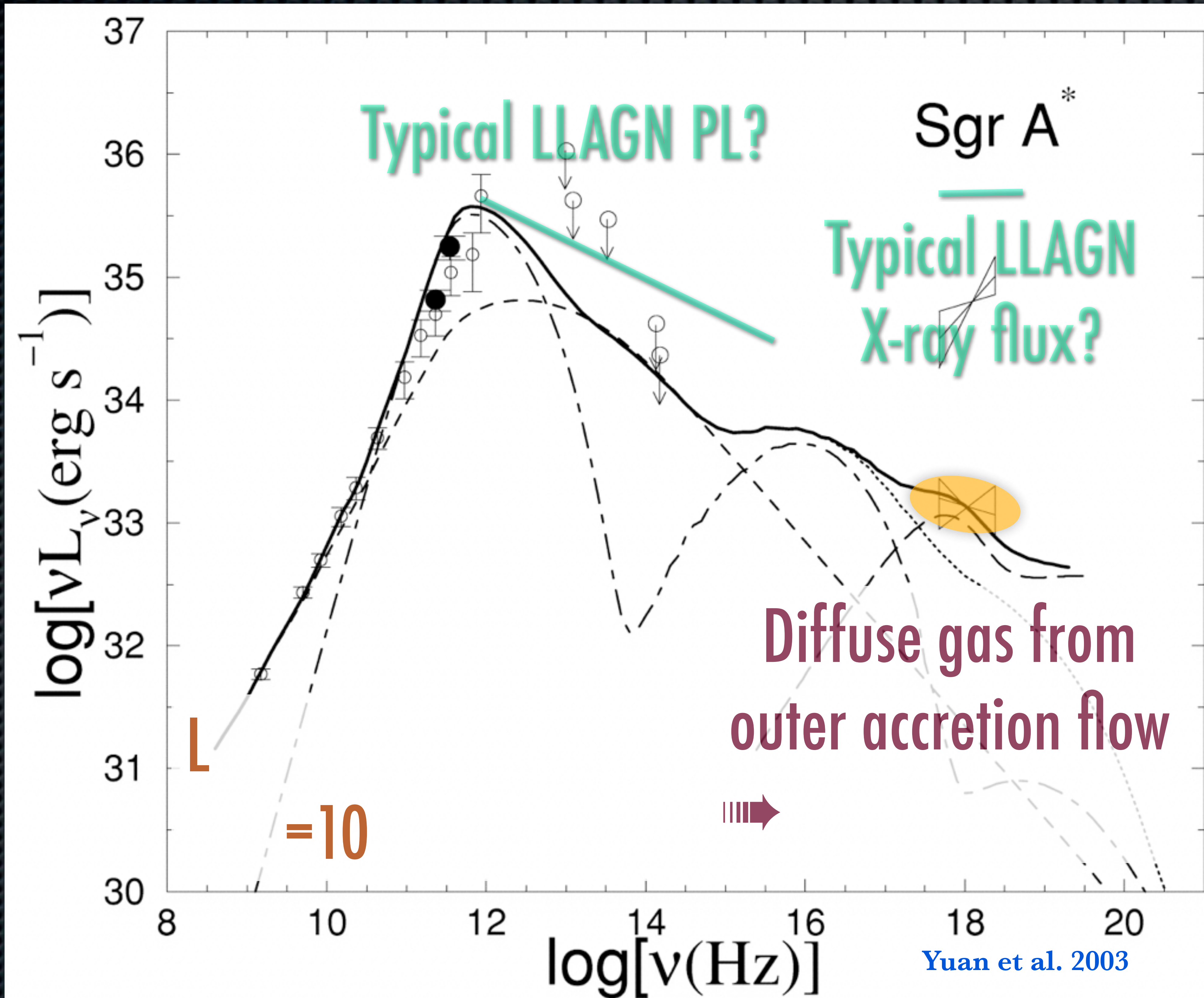
Stellar orbits and types measured – Can estimate available "fuel" supply for SMBH



- Estimates based on stellar winds and simulations thereof: $10^{-5} - 10^{-3}\ M_{\odot}/yr$
- At 10% efficiency would expect $L_{Bol} \sim 10^{-4} - 10^{-2}\ L_{Edd}$

(Coker & Melia 97, 00, Cuadra ea. 05)

Sgr A* quiescent spectrum – Very weak!



(Baganoff++2000,2003; Bower++; Marrone ea. 2007; Dibi, Drappeau ea. 2012, 2013)

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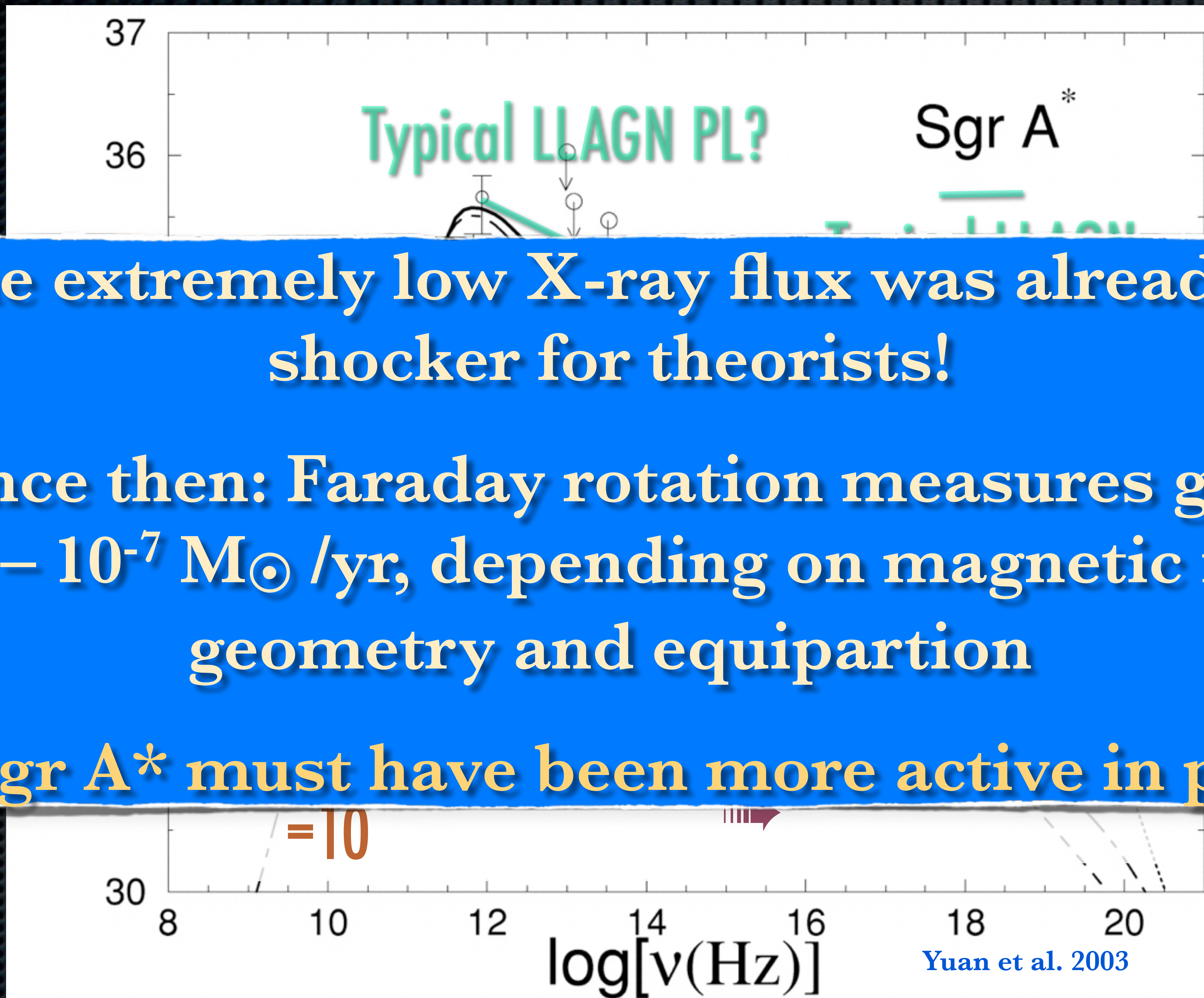


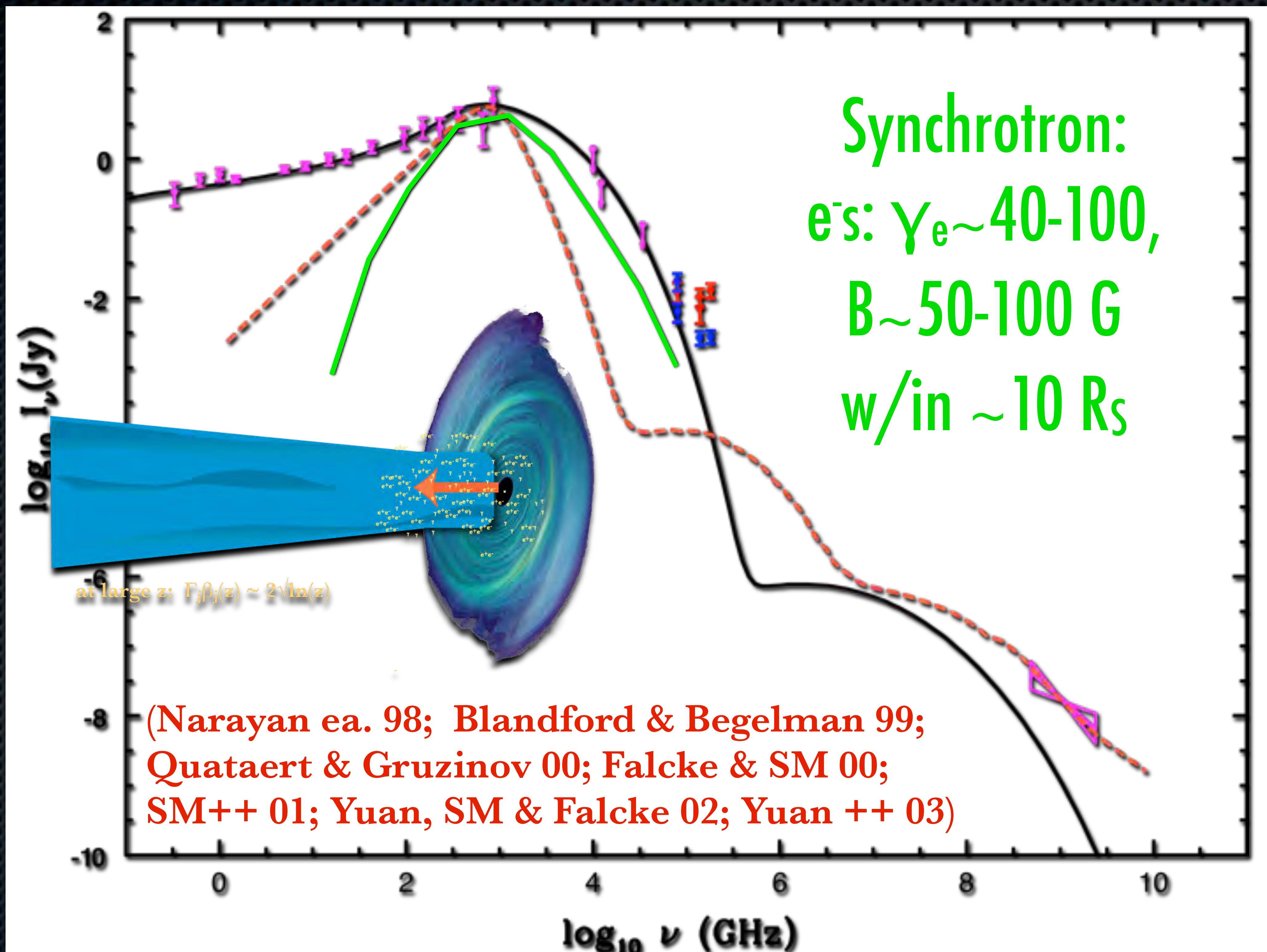
The extremely low X-ray flux was already a shocker for theorists!

Since then: Faraday rotation measures give $10^{-9} – 10^{-7}$ M⊙ /yr, depending on magnetic field geometry and equipartion

➠ Sgr A* must have been more active in past!

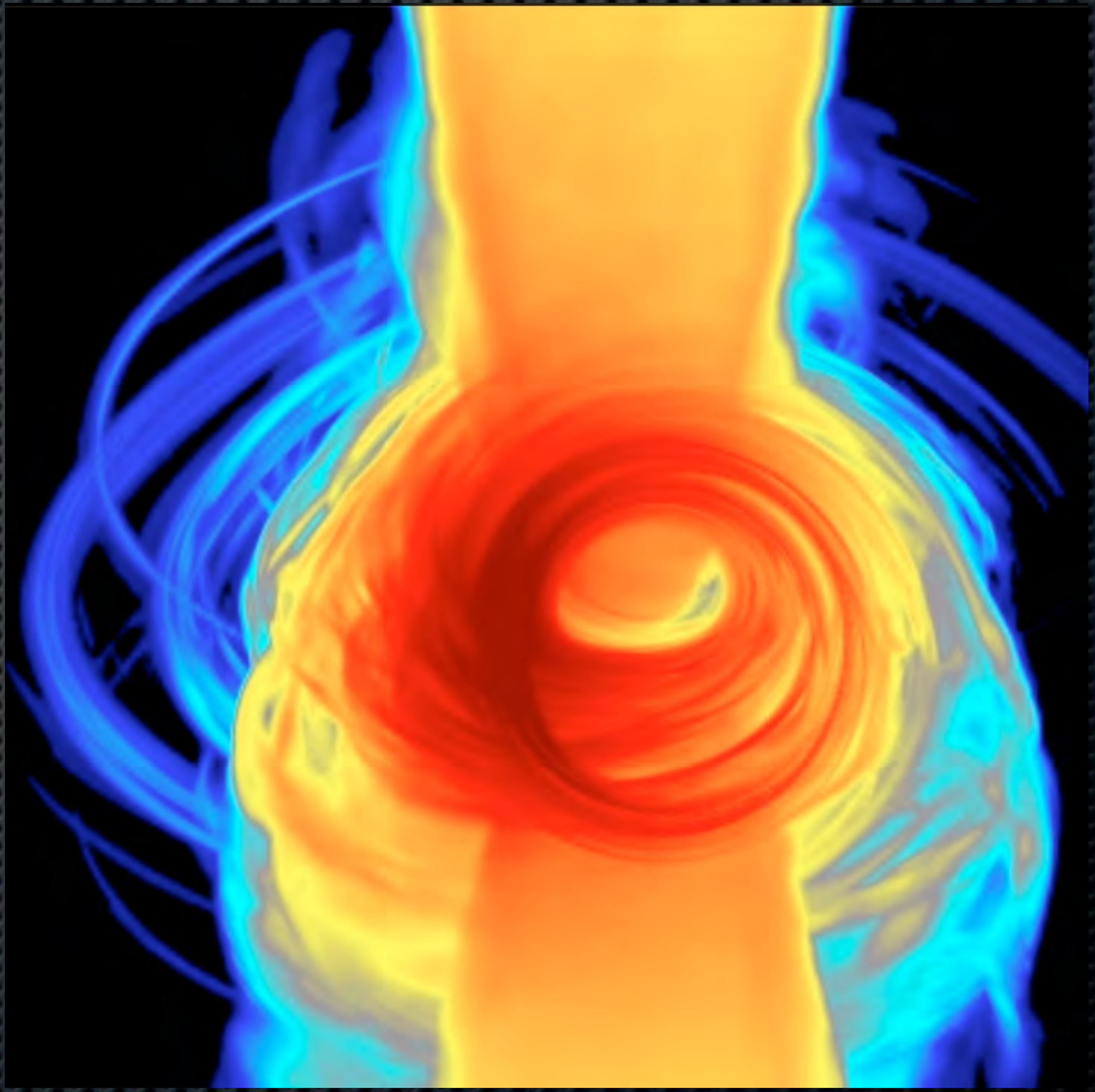
(Baganoff++2000,2003; Bower++; Marrone ea. 2007; Dibi, Drappeau ea. 2012, 2013)

Sgr A* in quiescence – physical models (very good constraints on <10R_S conditions)



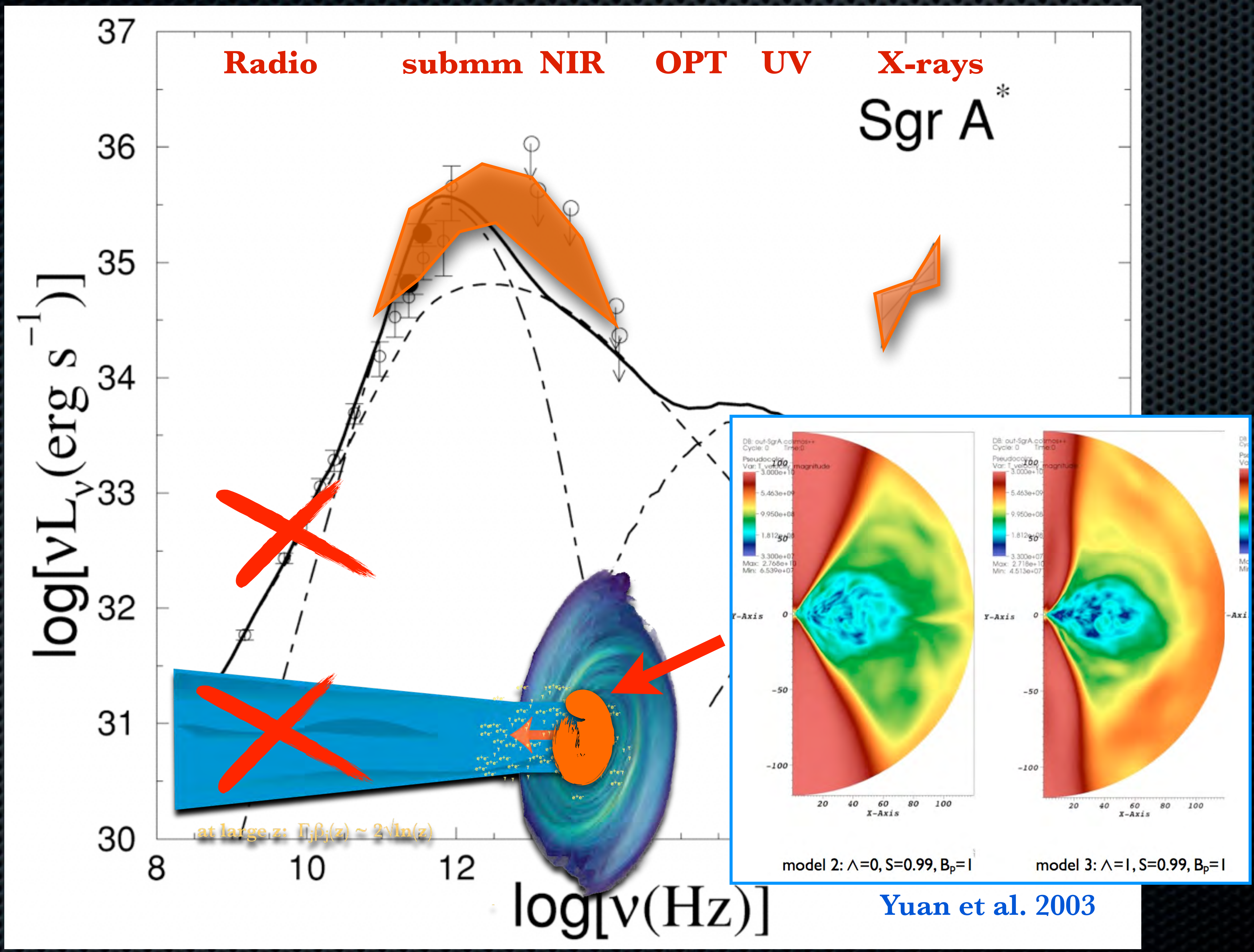
Advancing the Astrophysical Model

- 2.5-3D (ideal) Magnetohydrodynamics
- General Relativity
- Inflow: Accretion
- Outflow: Jets
- BH – MHD interface (ISCO)
- Microphysics: Heating & cooling of particles
- Radiation Transport
- Can we reproduce basic parameters, spectrum, size, and variability of Sgr A*?



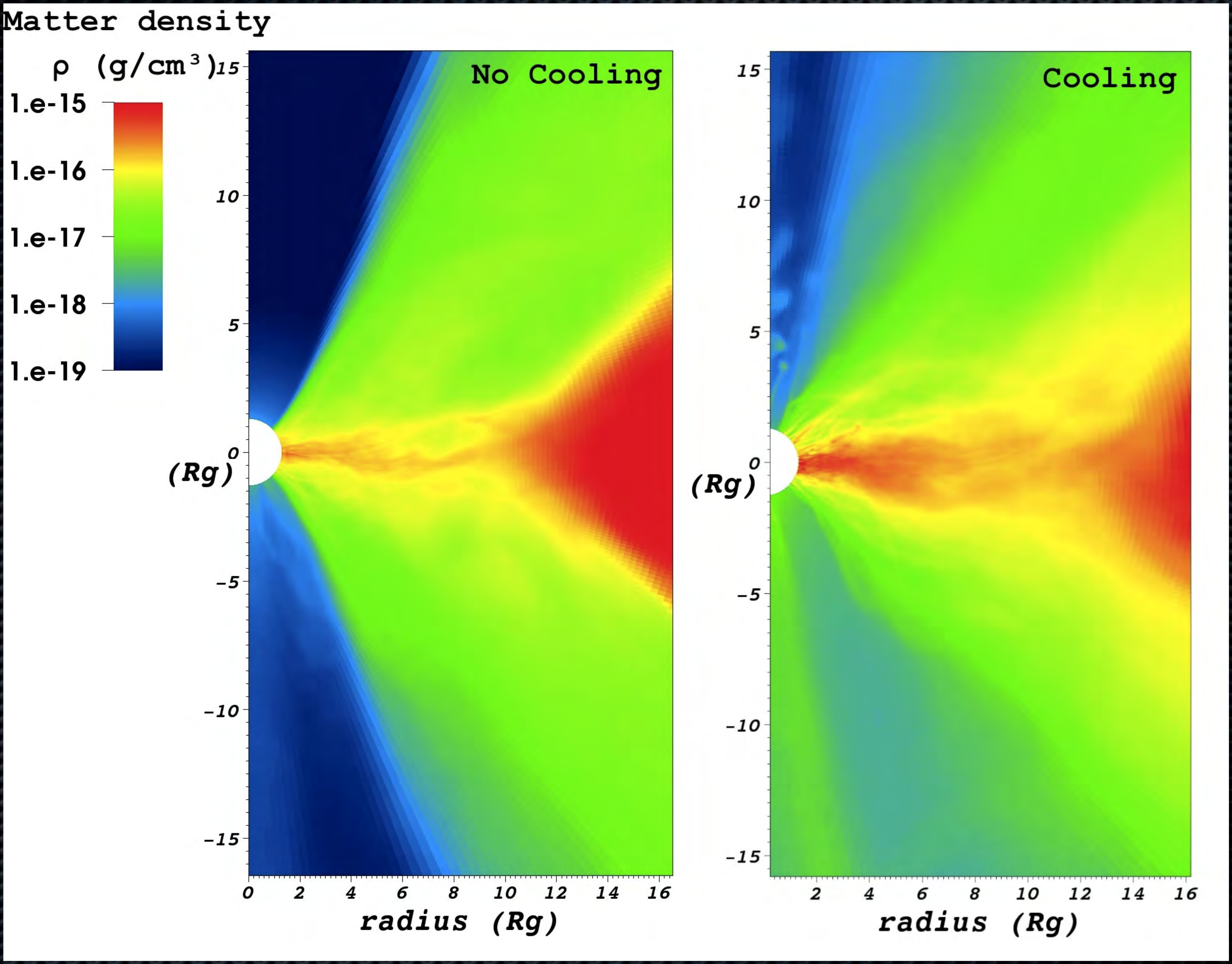
(Gammie et al.)

Sgr A* spectrum – GRMHD simulations



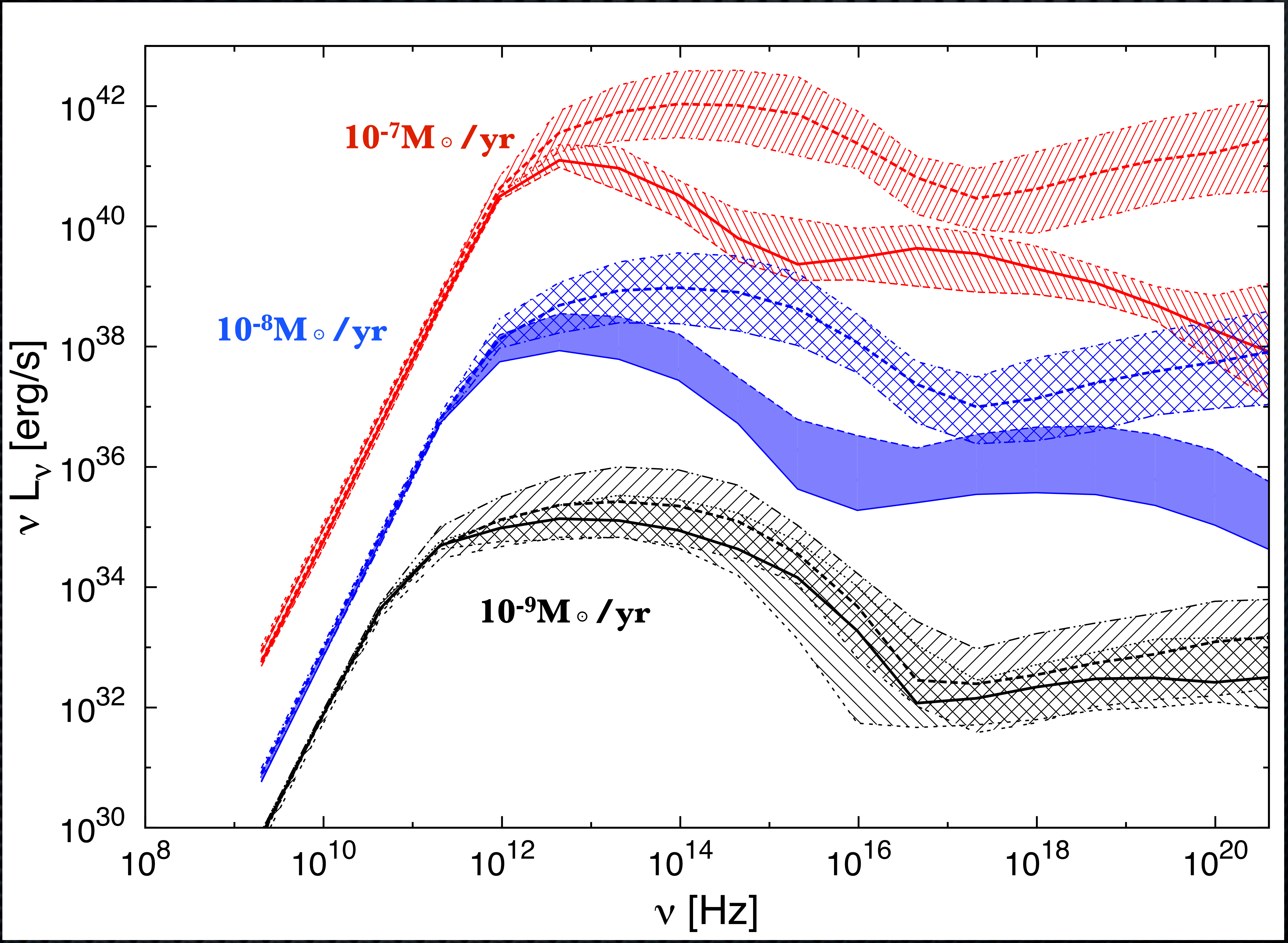
(Dibi, Drappeau, Fragile, SM & Dexter 2012; Drappeau, Dibi, Dexter, SM & Fragile 2013)

Effect of cooling on temperature and structure



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

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



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

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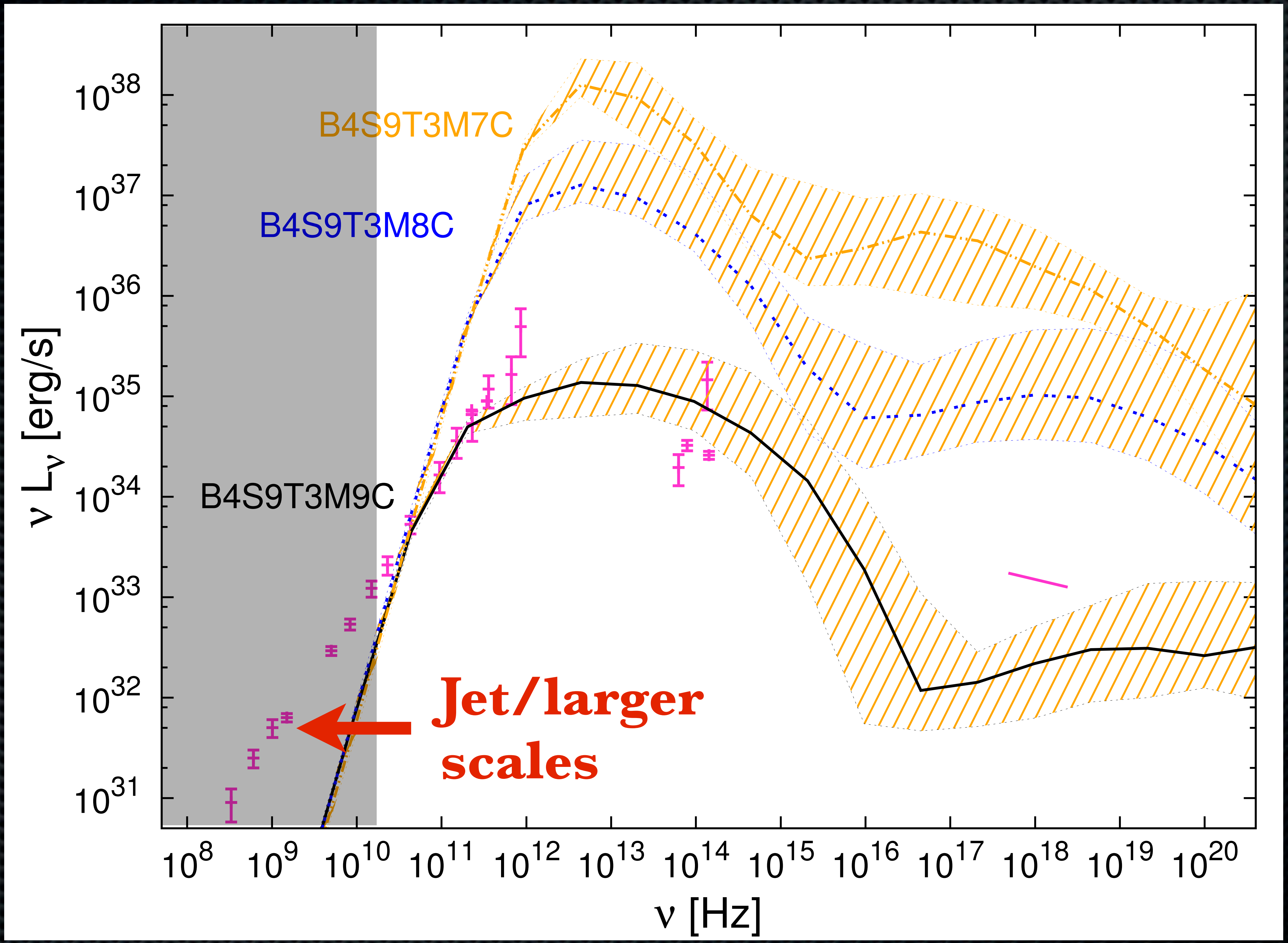
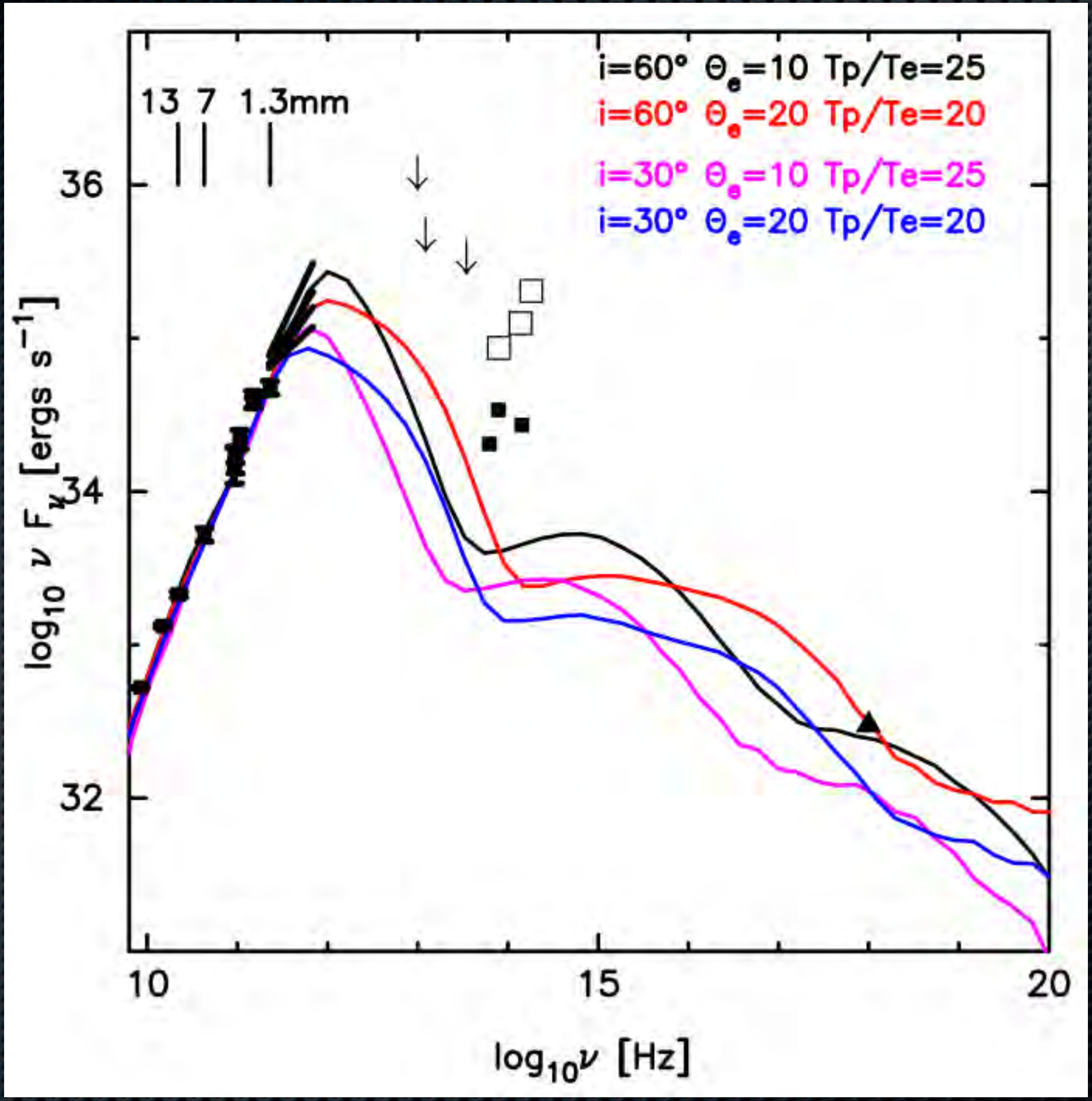


(**Dibi, Drappeau,** Fragile, SM & Dexter 2012; **Drappeau, Dibi**, Dexter, SM & Fragile 2013)

Another method: “Painting” simulations with particles



(Moscibrodzka, Falcke, Shiokawa & Gammie 2014)

Current outstanding questions

- **Can we understand black hole feeding from outer boundary to the Event Horizon?** ➠ ***How is Sgr A* powered, and where does the energy go?***
- **What's driving the flares?** ➠ ***Can we connect bulk plasma properties with particle acceleration?***
- **Is there a jet?** ➠ ***What is the dominant output channel at low luminosity?***
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Chandra-HETG observations of Sgr A*:
an "X-ray Visionary Project" in 2012
(PIs: Baganoff, SM, Nowak)

- 3Msec (35 days!) exposure of Galactic Center, 20 observations
- Doubled the photon/flare counts for Sgr A* within a year compared to the last decade, much higher cadence for flare detections
- First ever high resolution X-ray spectra of Sgr A* and GC diffuse emission (+ point sources)
  - Spatially and spectrally resolve accretion flow (1-2")
  - Constrain energy and width of known Fe complex around 6.6 keV ➠ key plasma diagnostics
  - Detect optically thin He- and H-like emission lines (Si, S, Ar) predicted by radiatively inefficient accretion models
  - Avoid (~40%) pileup ➠ constrain flare spectrum!

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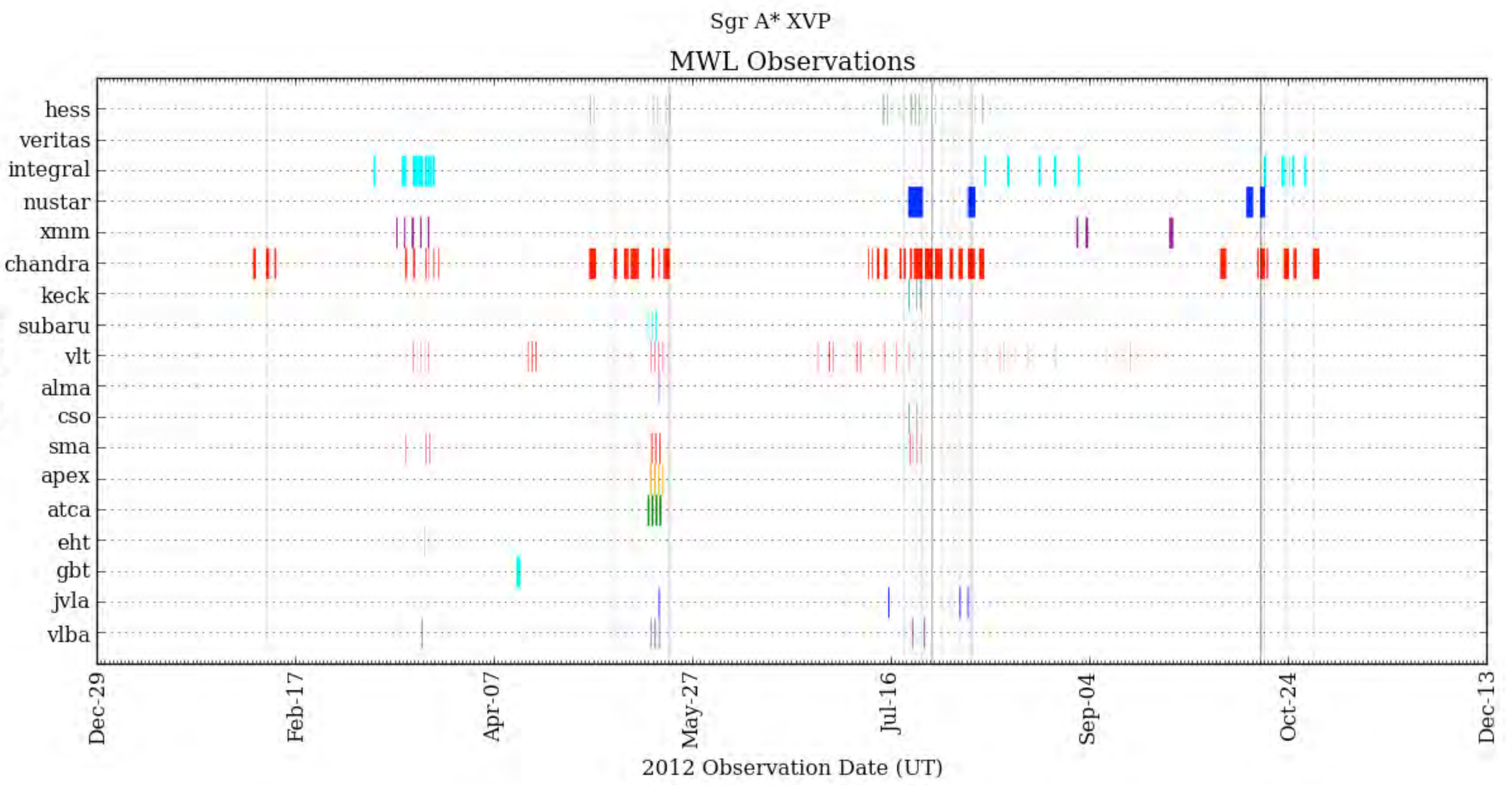

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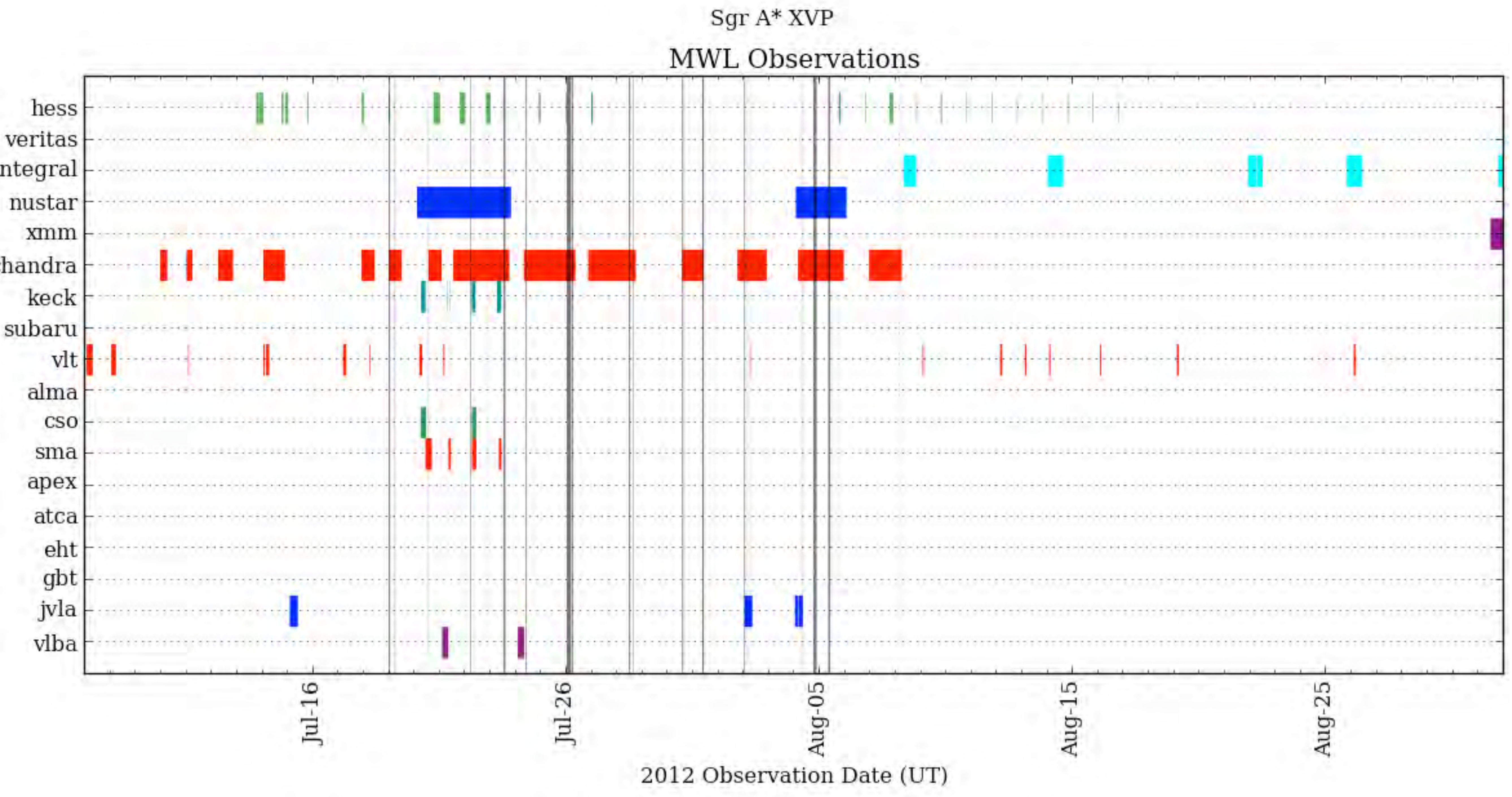
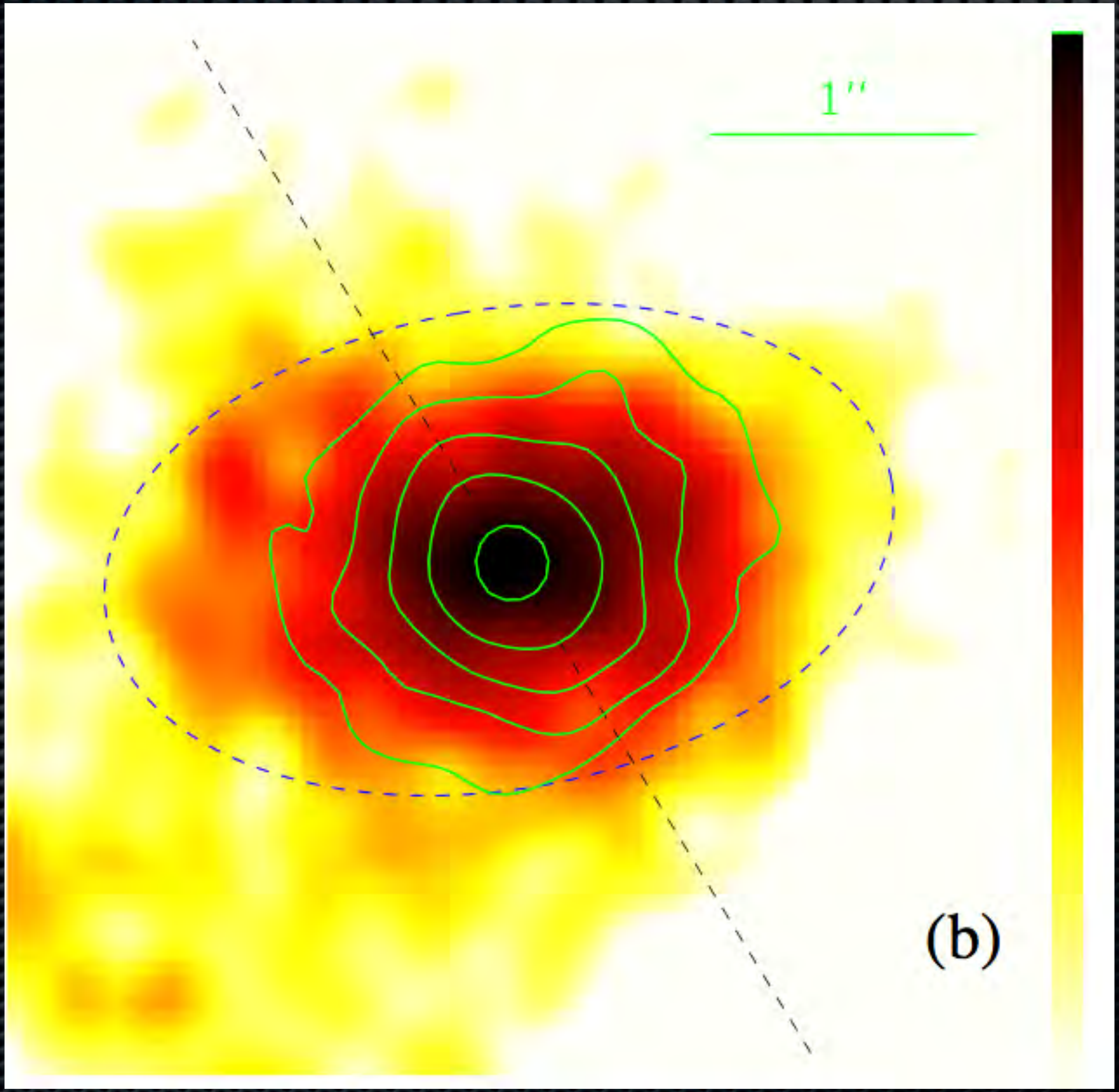
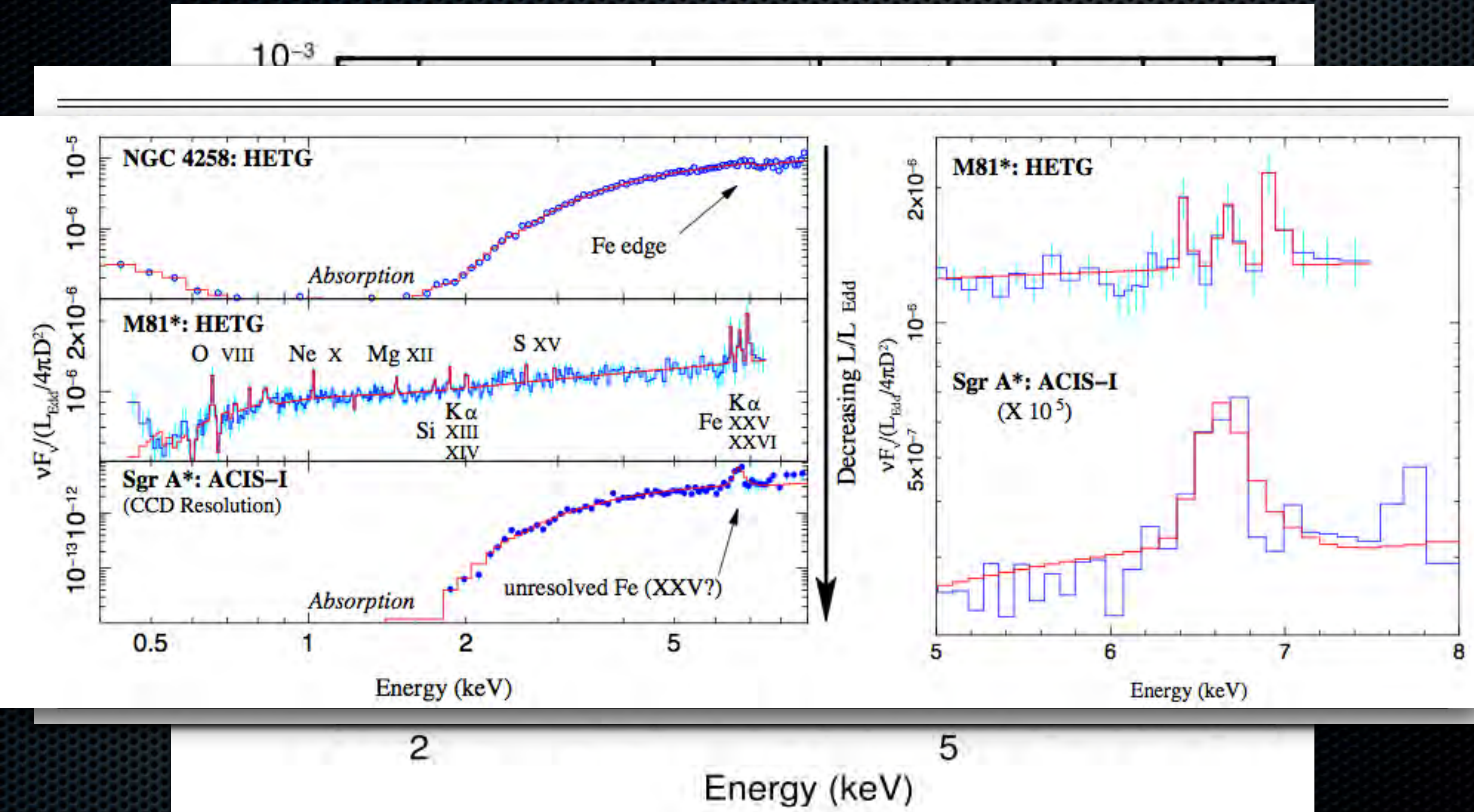


First (and deepest) Chandra-HETG observations of Sgr A*:
Evidence for elongation of quiescent emission



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

Chandra-HETG observations of Sgr A*:
First detailed plasma diagnostics



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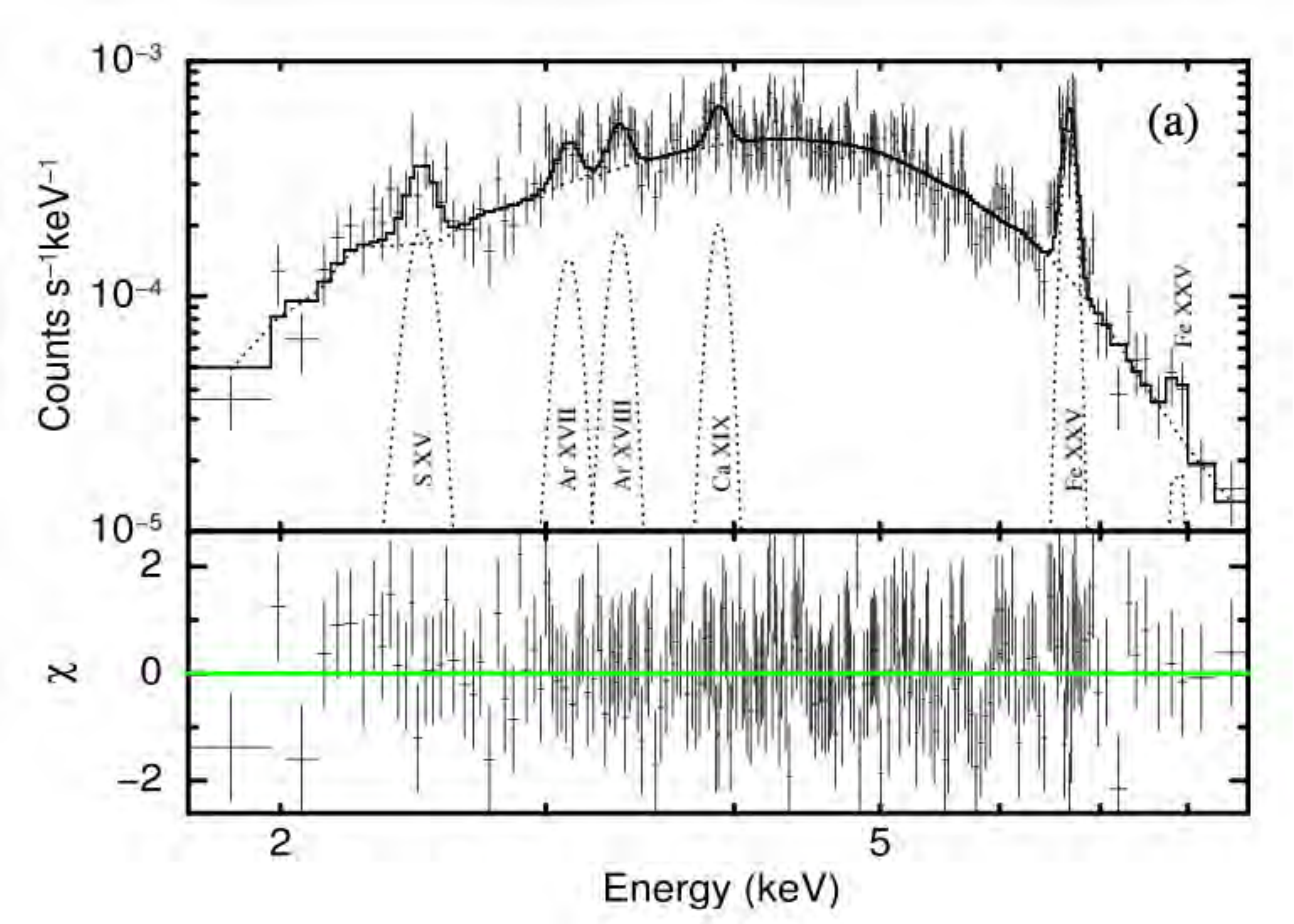

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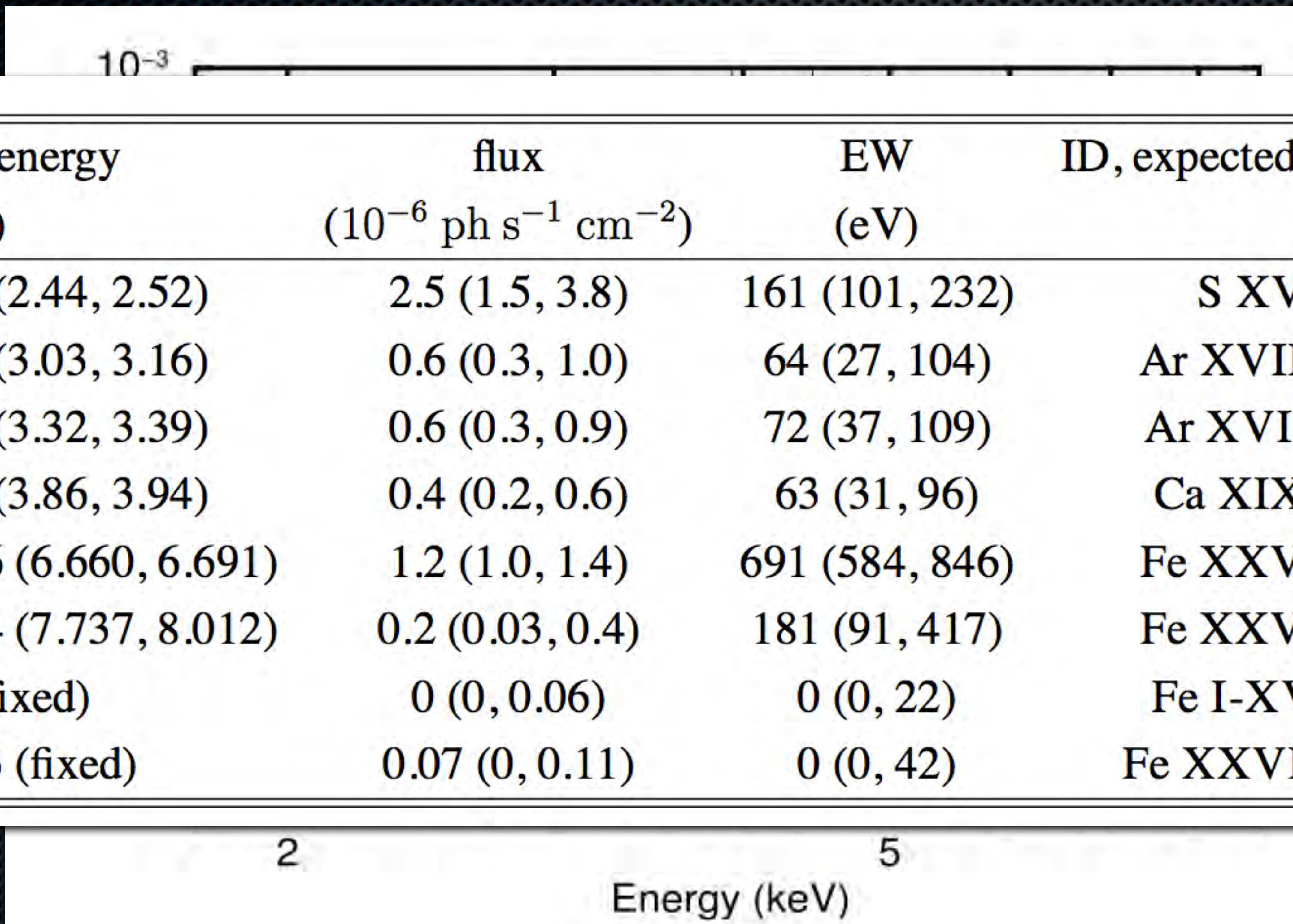

Line energy (keV)	flux (10^{-6} ph s^{-1} cm^{-2})	EW (eV)	ID, expected energy (keV)
2.48 (2.44, 2.52)	2.5 (1.5, 3.8)	161 (101, 232)	S XV, 2.461
3.10 (3.03, 3.16)	0.6 (0.3, 1.0)	64 (27, 104)	Ar XVII, 3.140
3.35 (3.32, 3.39)	0.6 (0.3, 0.9)	72 (37, 109)	Ar XVIII, 3.32
3.91 (3.86, 3.94)	0.4 (0.2, 0.6)	63 (31, 96)	Ca XIX, 3.861
6.676 (6.660, 6.691)	1.2 (1.0, 1.4)	691 (584, 846)	Fe XXV, 6.675
7.874 (7.737, 8.012)	0.2 (0.03, 0.4)	181 (91, 417)	Fe XXV, 7.881
6.4 (fixed)	0 (0, 0.06)	0 (0, 22)	Fe I-XVII, 6.4
6.973 (fixed)	0.07 (0, 0.11)	0 (0, 42)	Fe XXVI, 6.973

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

Chandra-HETG observations of Sgr A*:
Best fit ➠ 99% mass lost to outflows!

- **$n \sim r^{-3/2+s}$** ➠ *s=0 is "no outflow" solution (steep gradient, whatever is captured falls in and piles up in the center)*
- **Our fits constrain s>0.6** ➠ *s~1 is consistent with the class of radiatively inefficient accretion models (flatter density distribution means outflow roughly balances inflow)*
- **How?** *s=0 substantially overpredicts the H-like Fe Ka line (Fe XXVI) while other lines are not fully accounted for. Predicted spectrum also too flat in the X-ray band*

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

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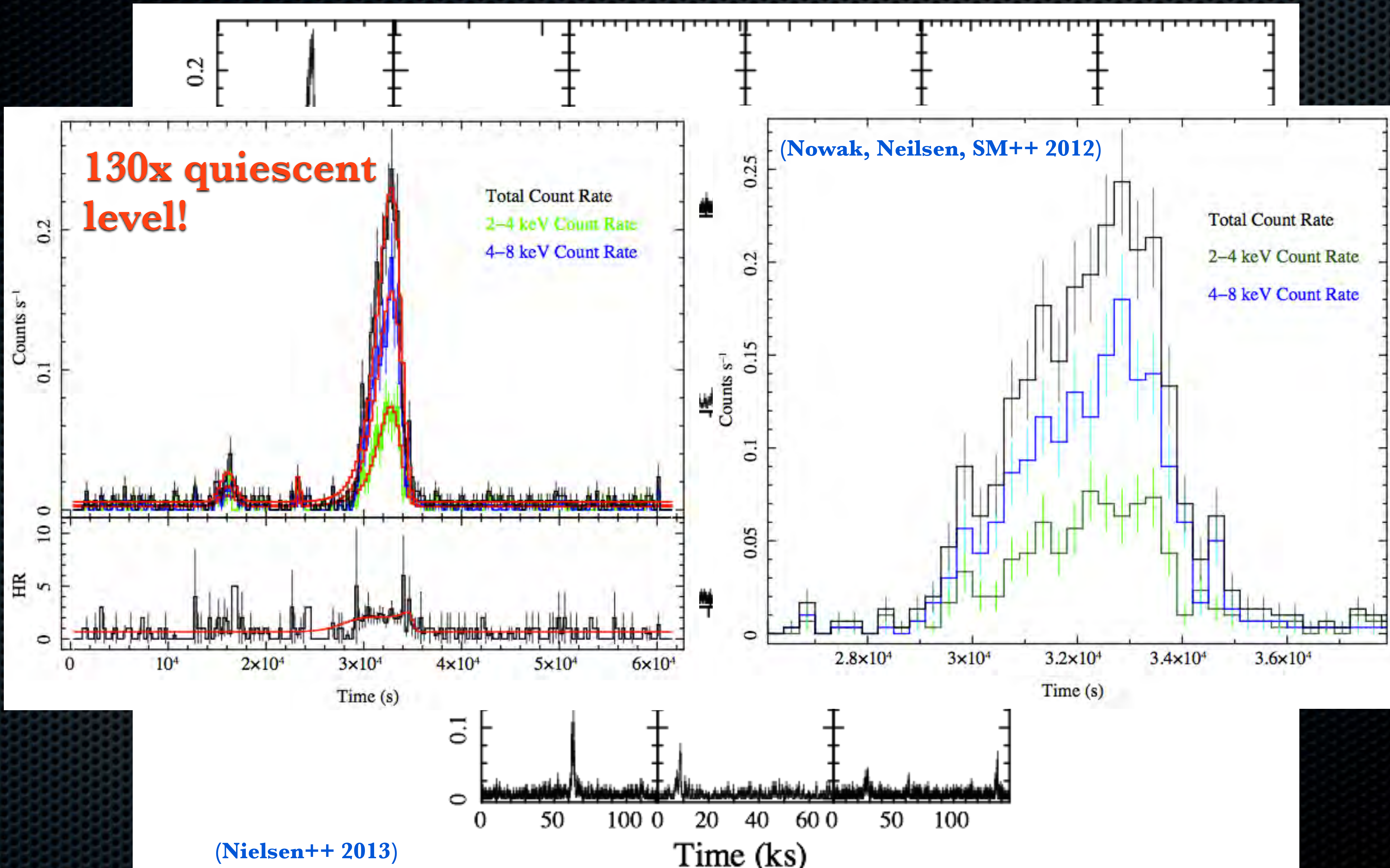
Chandra-HETG observations of Sgr A*:

Tripled the number of flares (~20 ➠ ~65)



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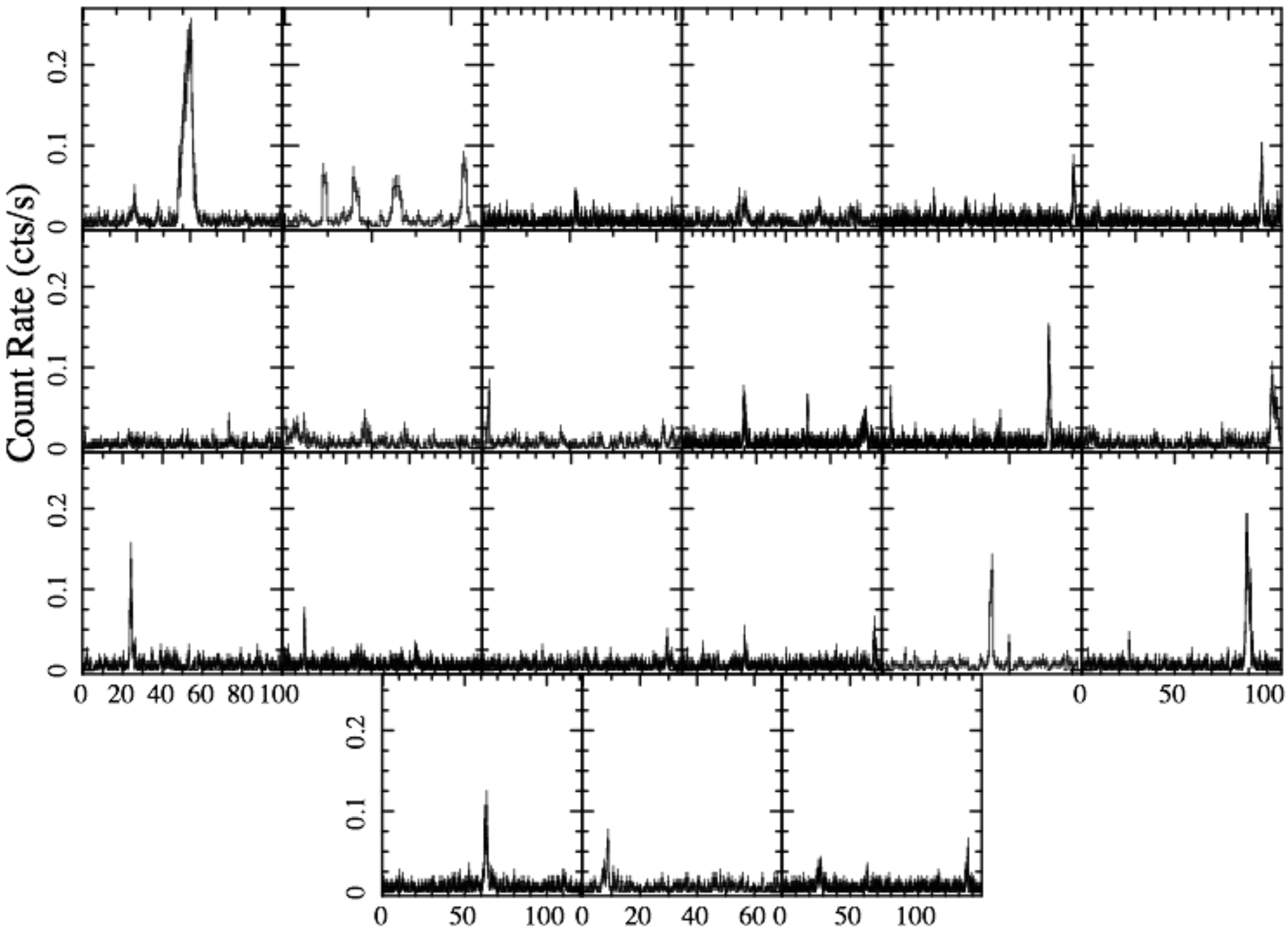
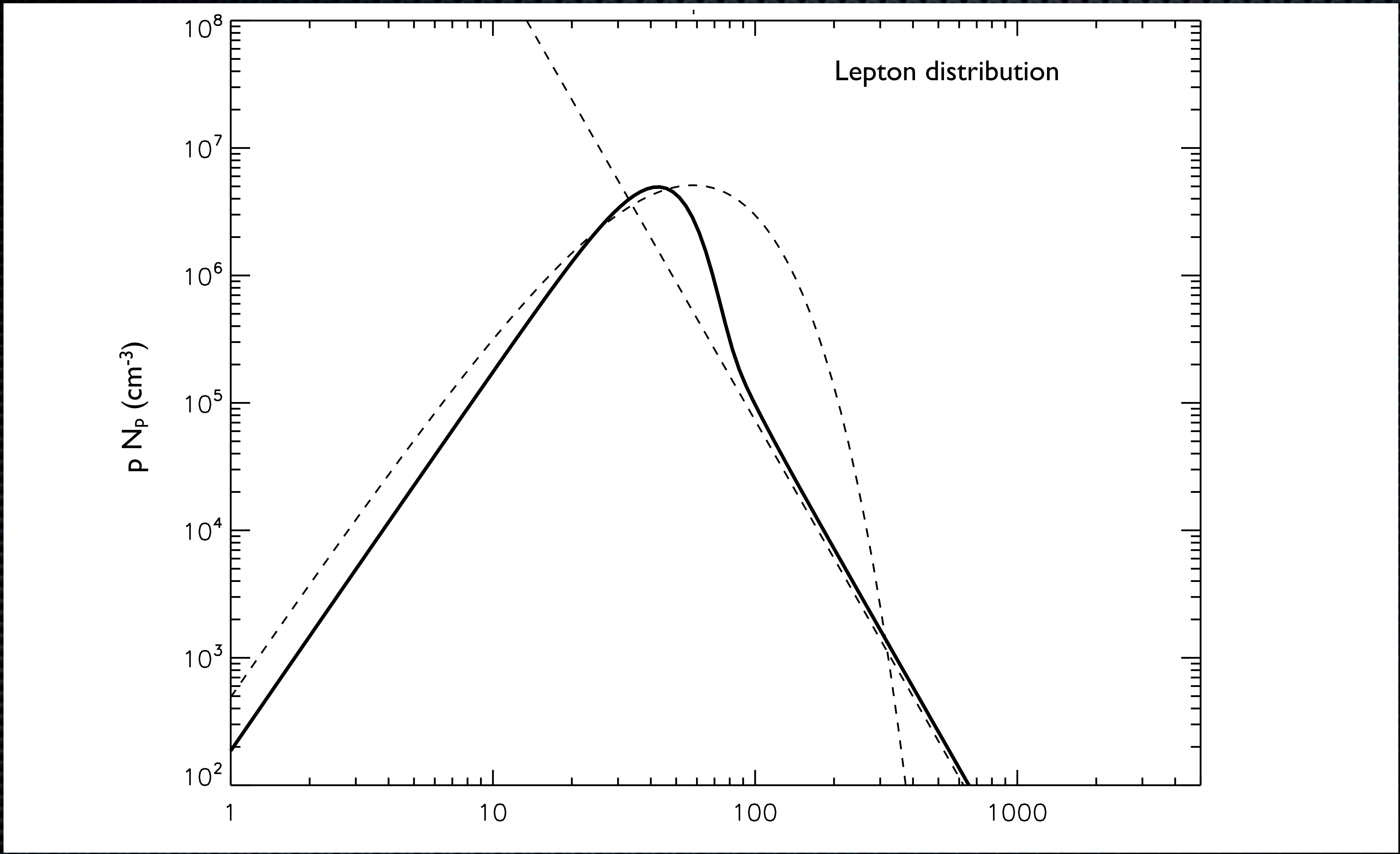


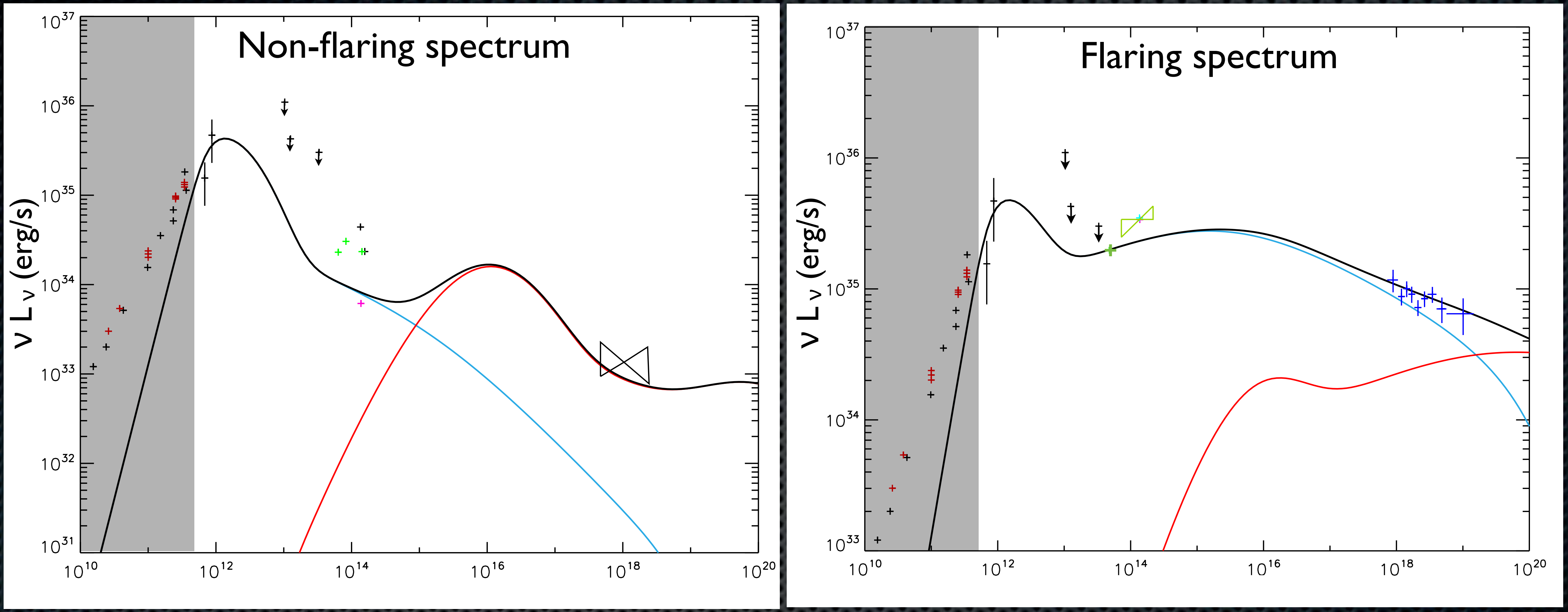
(Nielsen++ 2013)

Modeling the plasma: microphysical approach



(Dibi, SM, Belmont & Malzac 2014)

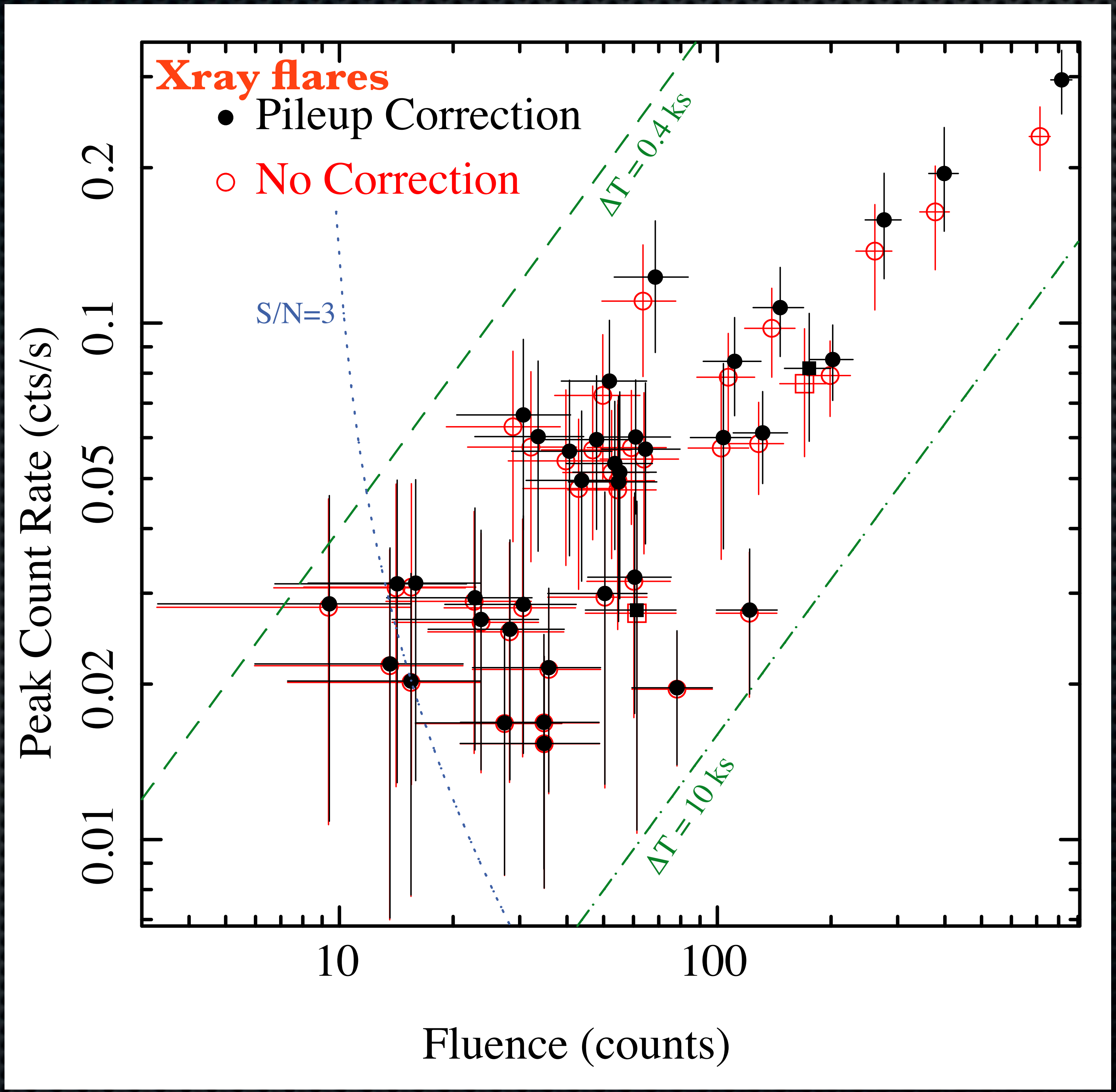
Modeling plasma: quiescence ➟ flares



- **Magnetic injection:** in the above example, the transition from quiescence to flaring is achieved by transferring magnetic energy to particle energy (reconnection in turbulent eddies?)

(Dibi, SM, Belmont & Malzac 2014)

Chandra-HETG observations of Sgr A*:
Able to perform statistics for the first time!



(Dodds-Eden 2009; Witzel++ 2012; Nielsen++ 2013; Dibi, SM, Nielsen++, in prep.)

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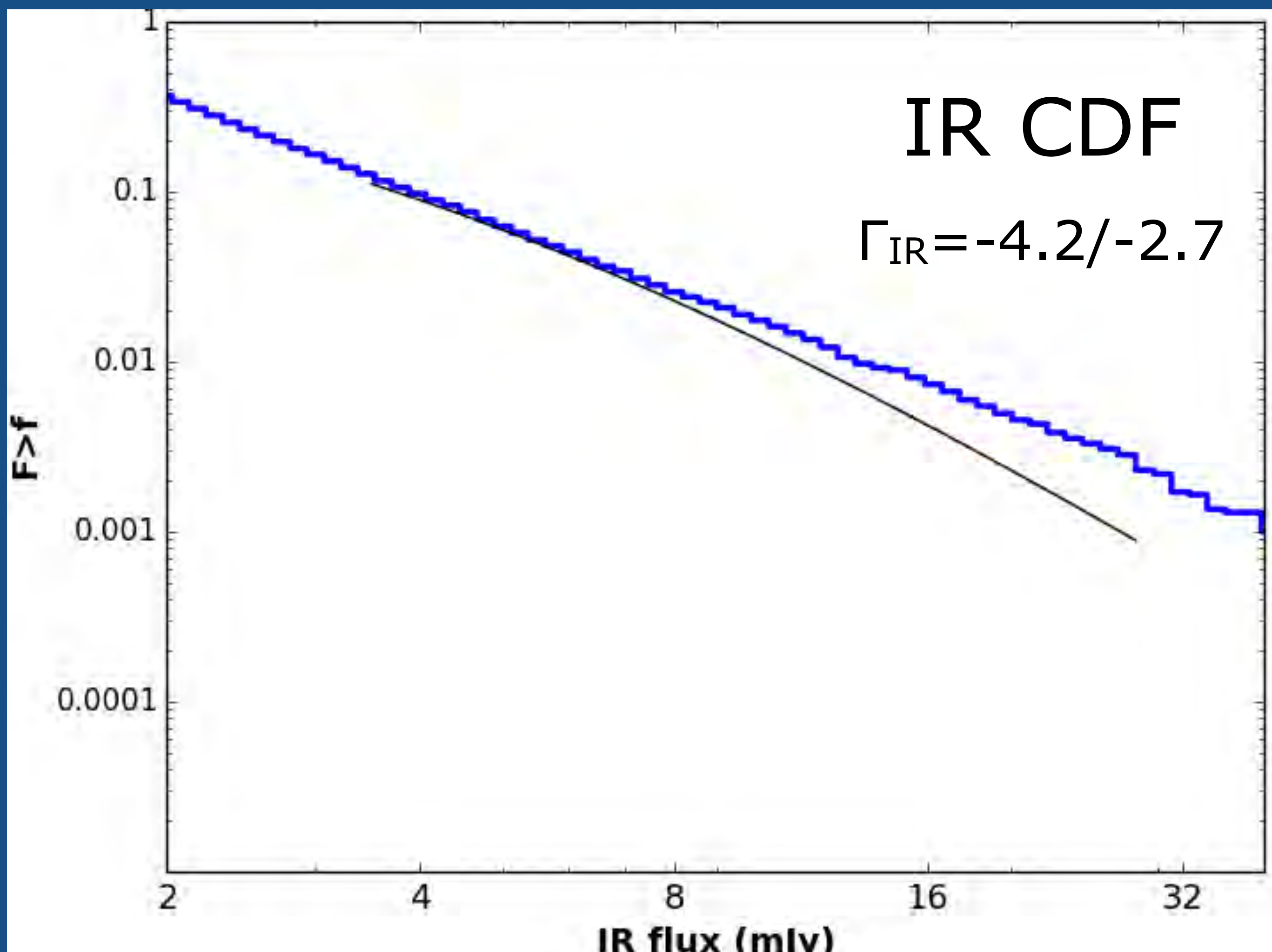

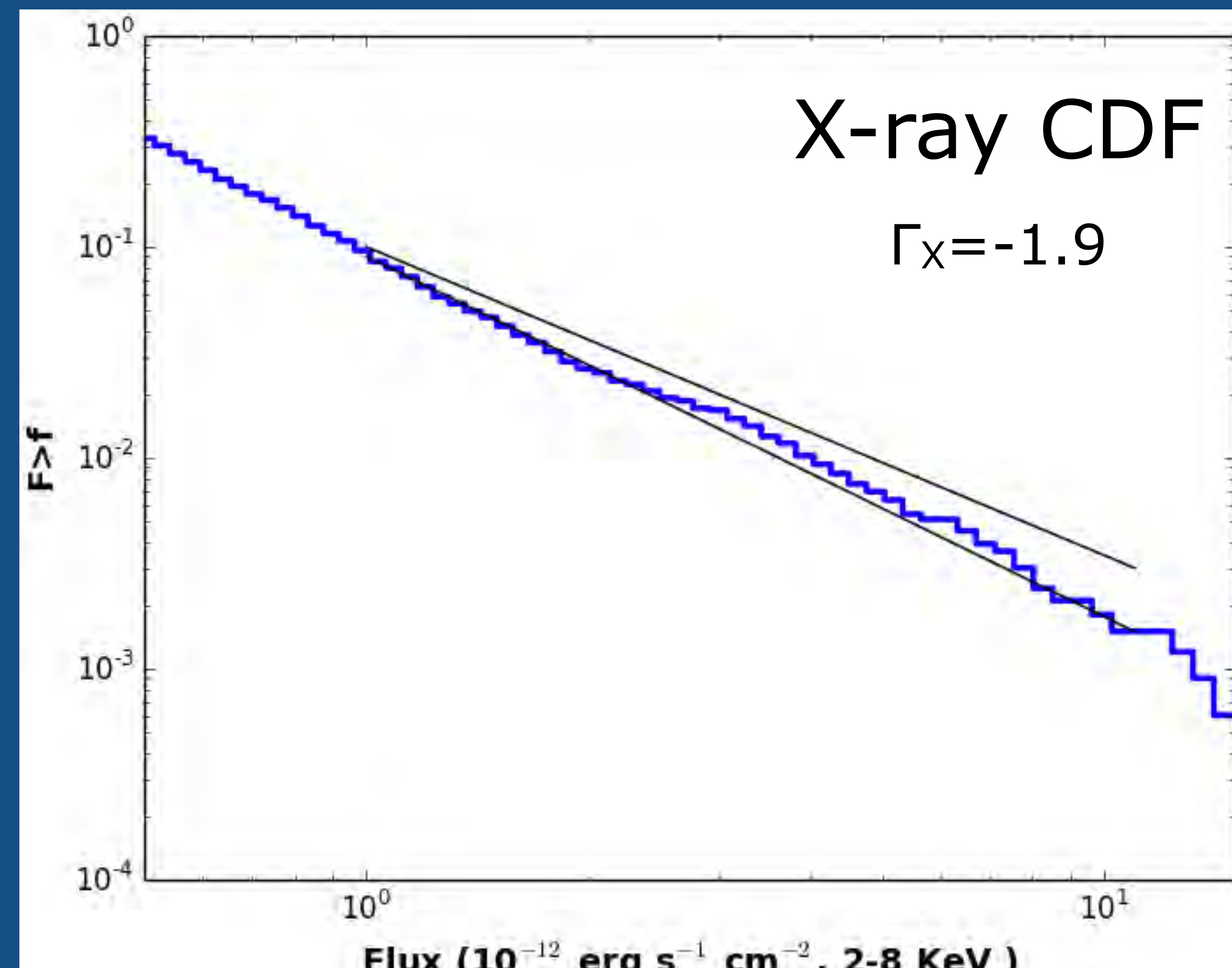

The simplest synchrotron scenario with non-thermal acceleration cannot recover both CDFs

(Dodds-Eden 2009; Witzel++ 2012; Nielsen++ 2013; Dibi, SM, Nielsen++, in prep.)

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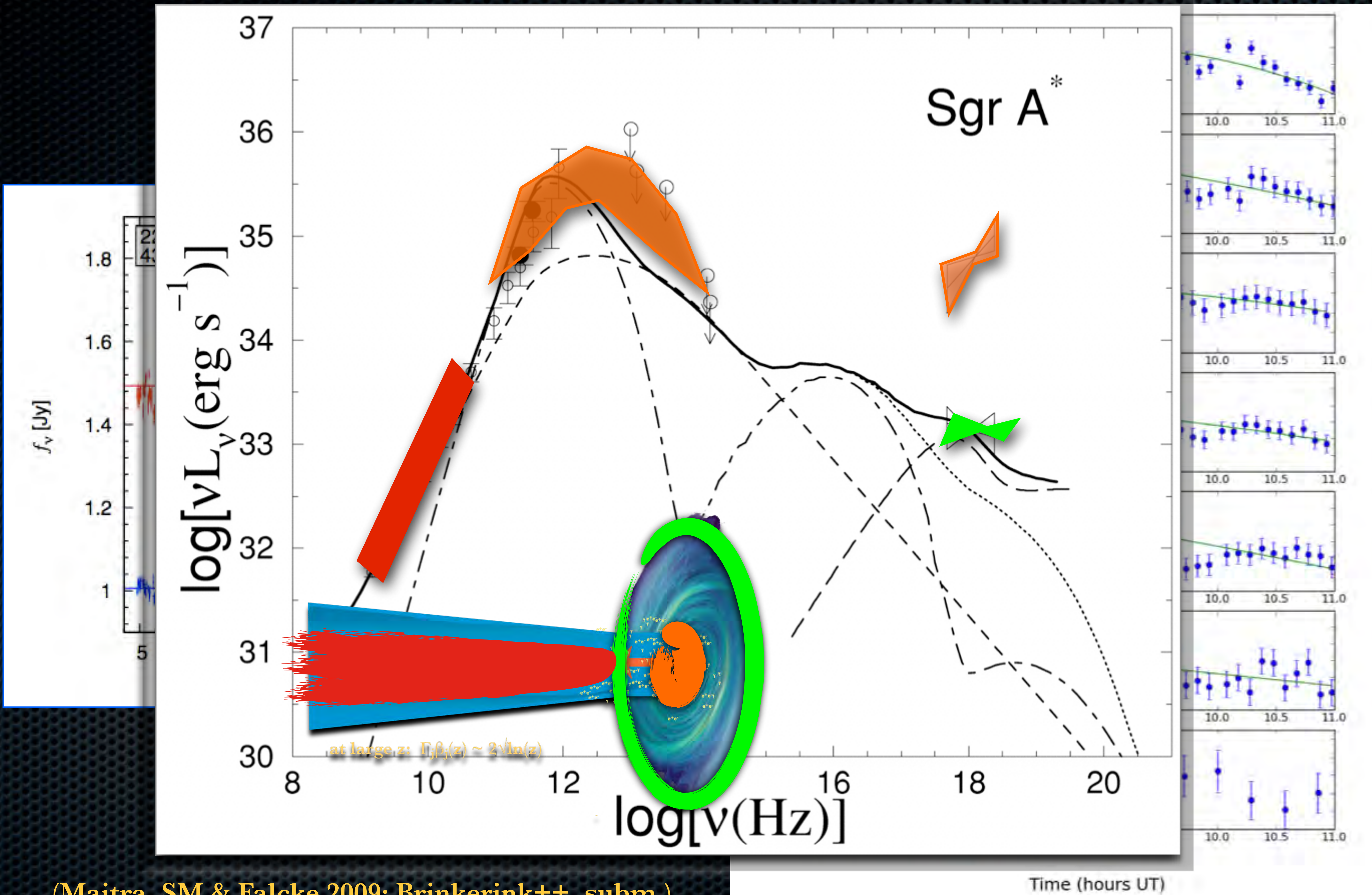
Indirect evidence for jets: "classic" expanding plasmons



(Maitra, SM & Falcke 2009; Brinkerink++, subm.)

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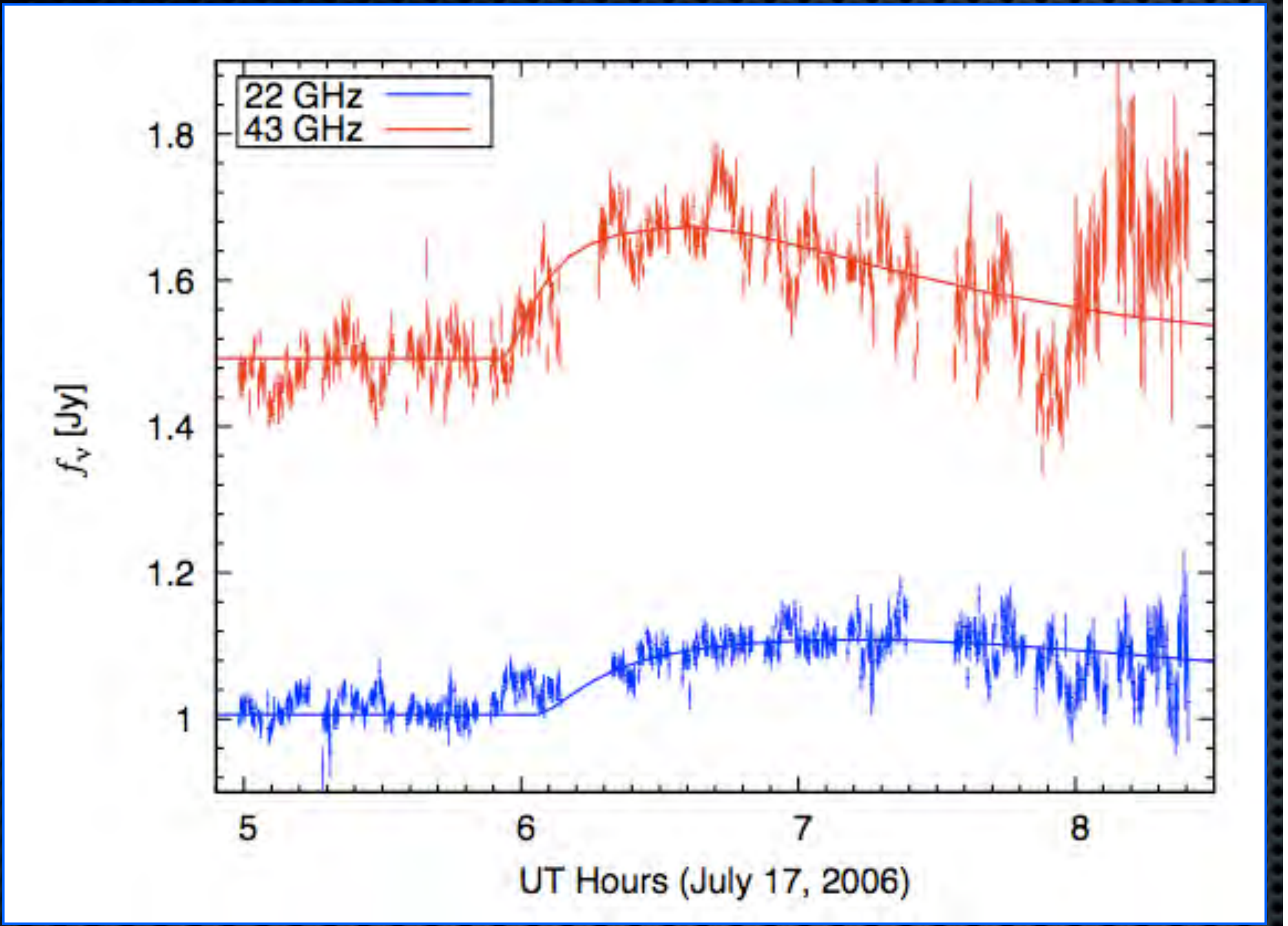

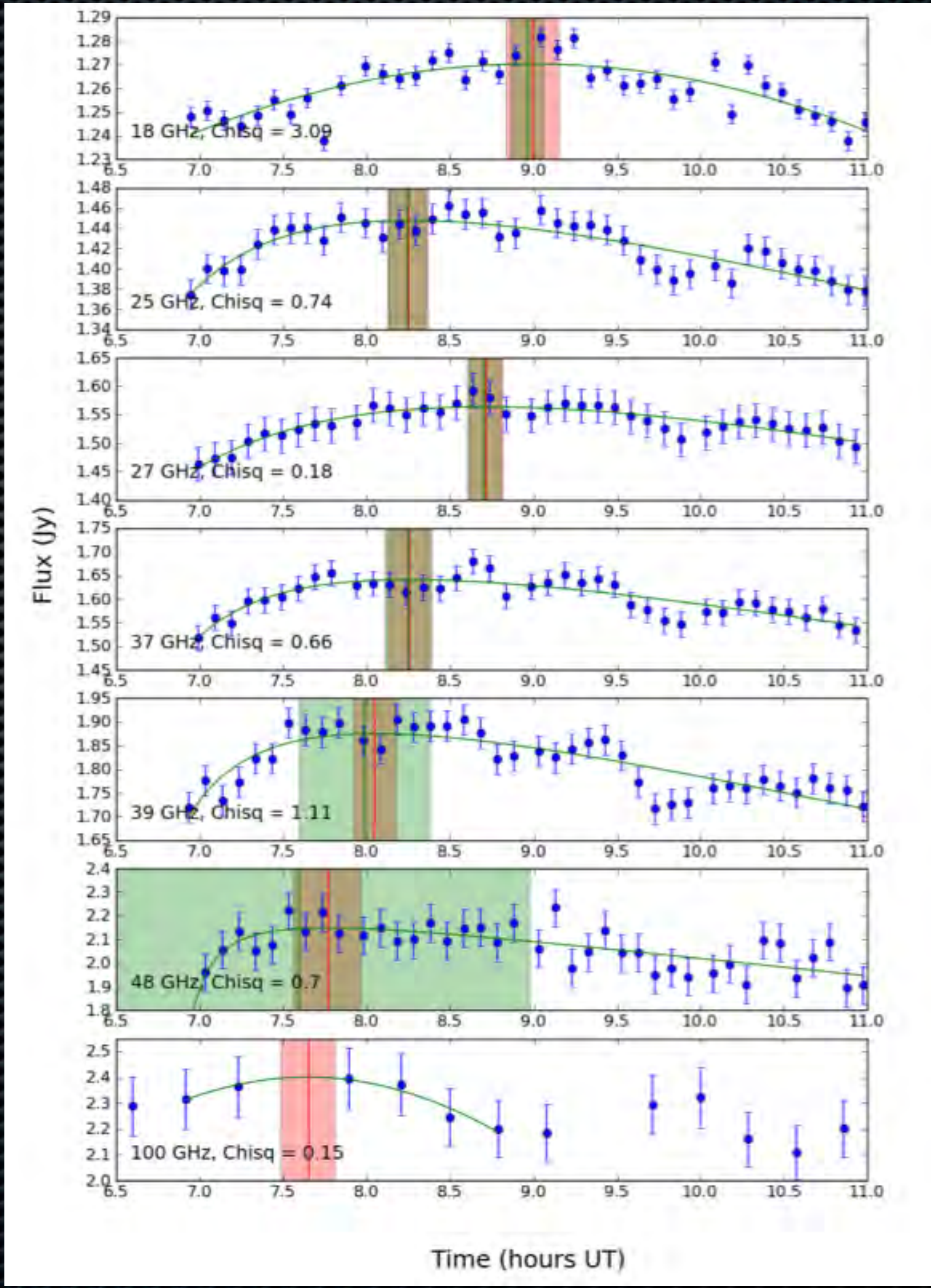

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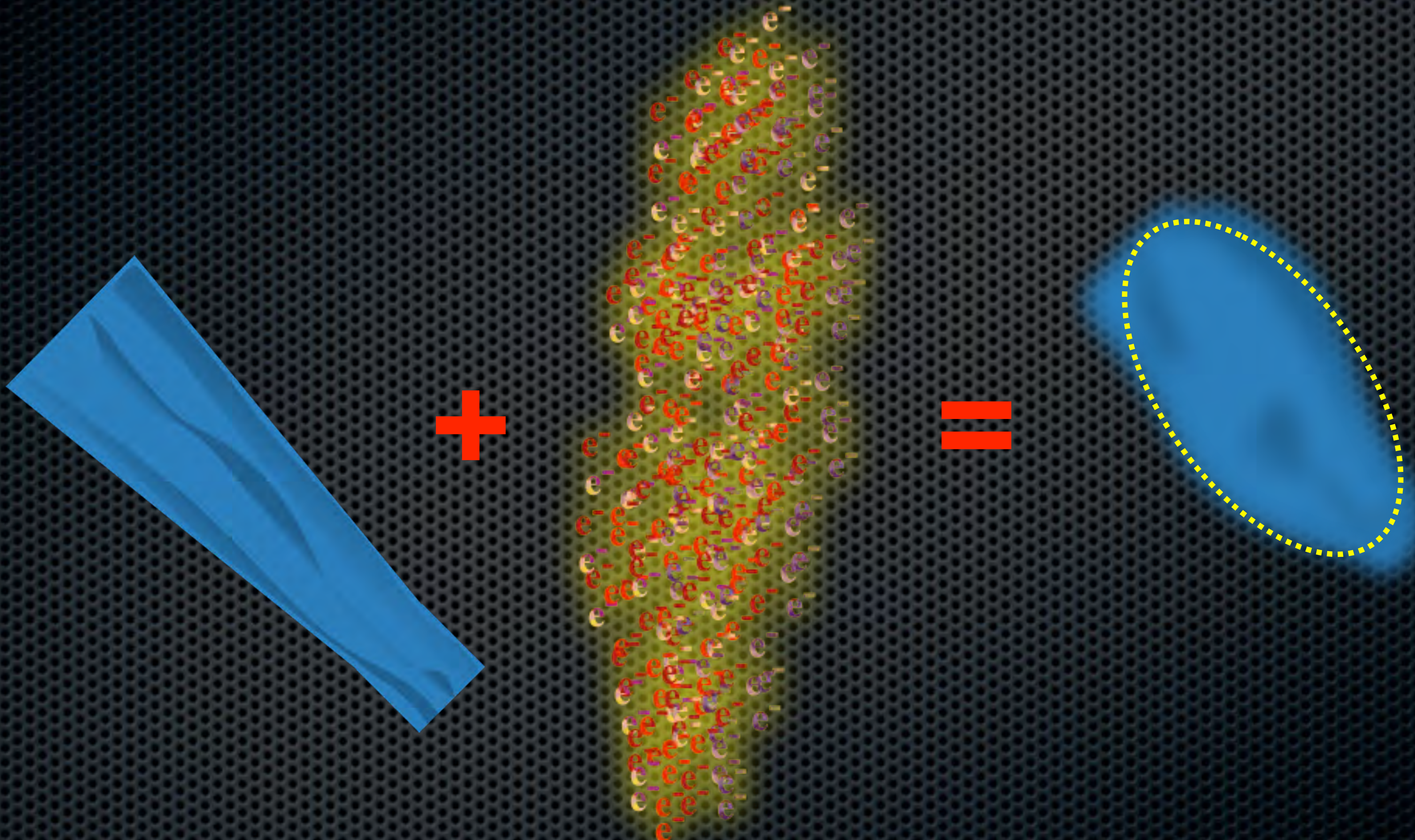
Scattering by intervening e-'s can hide Sgr A*'s jets!



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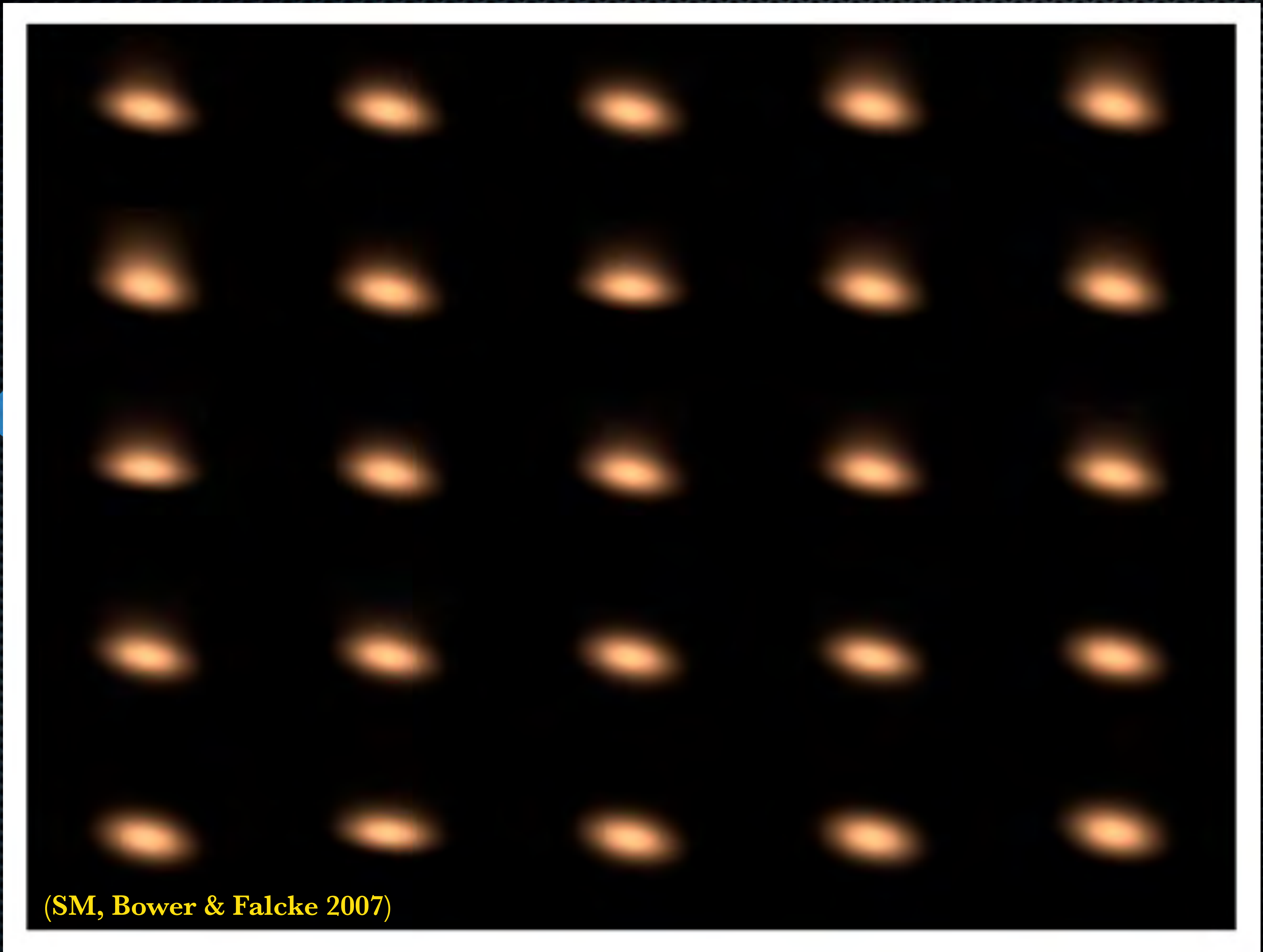

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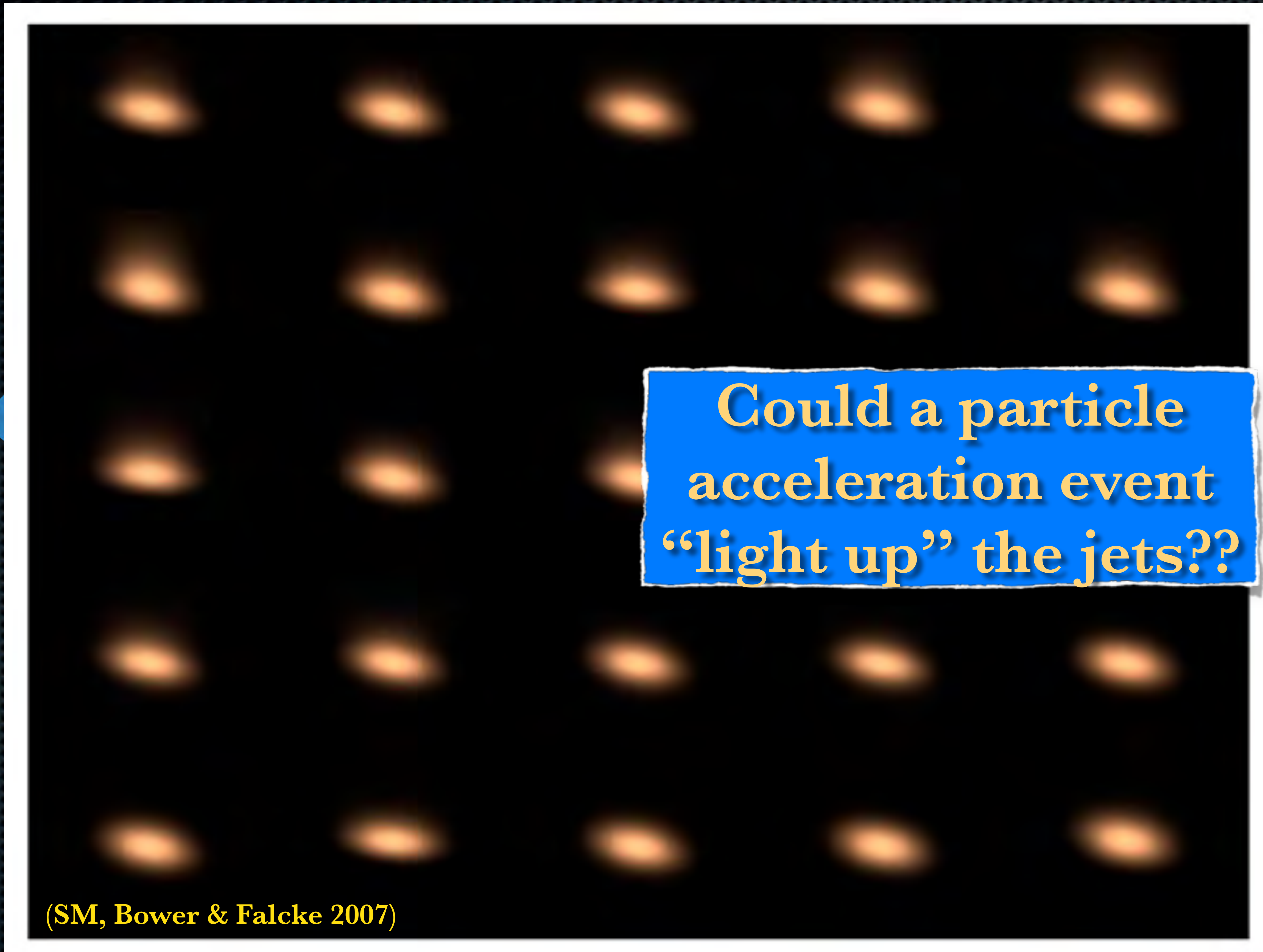

Could a particle acceleration event "light up" the jets??

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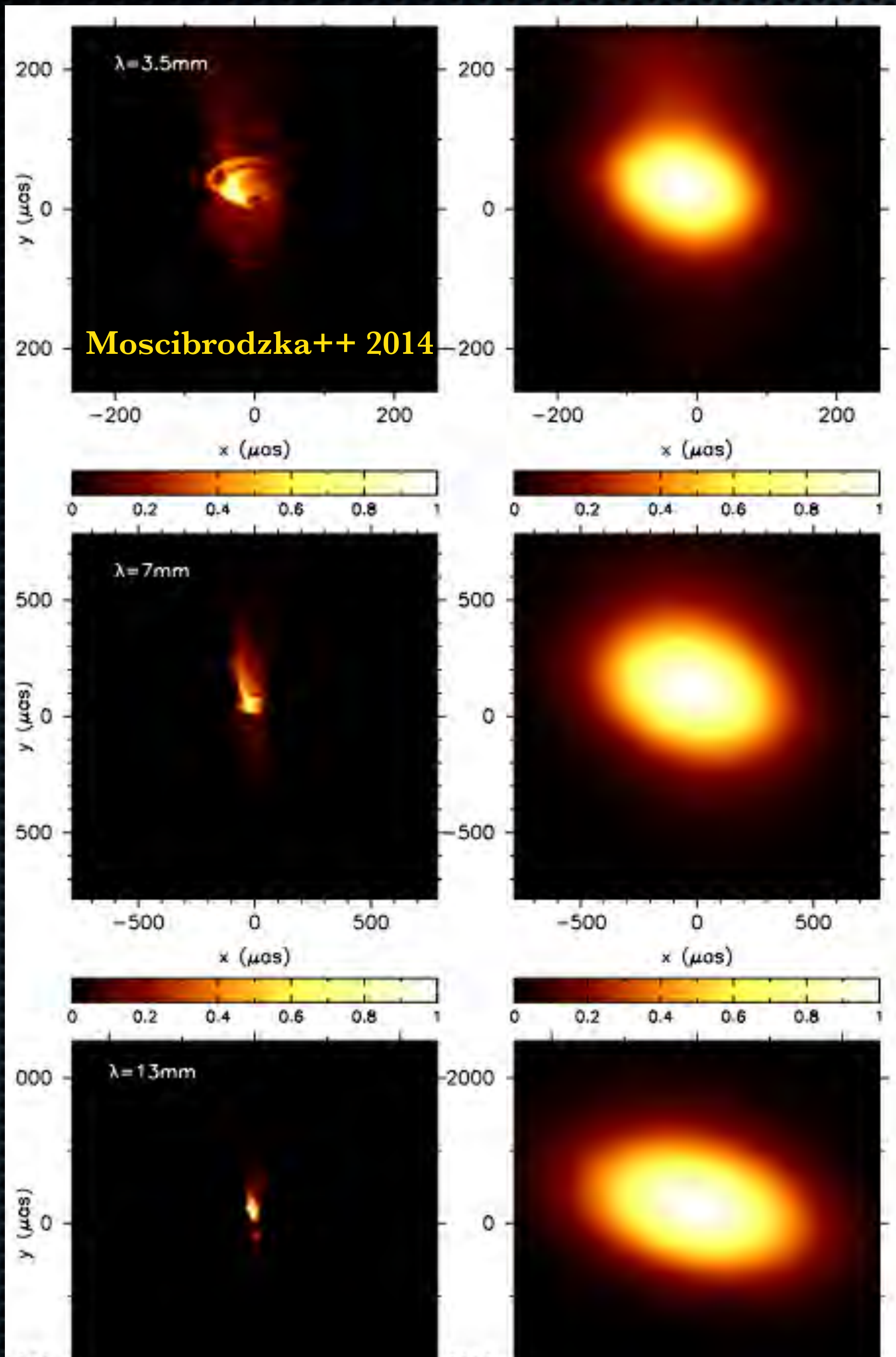
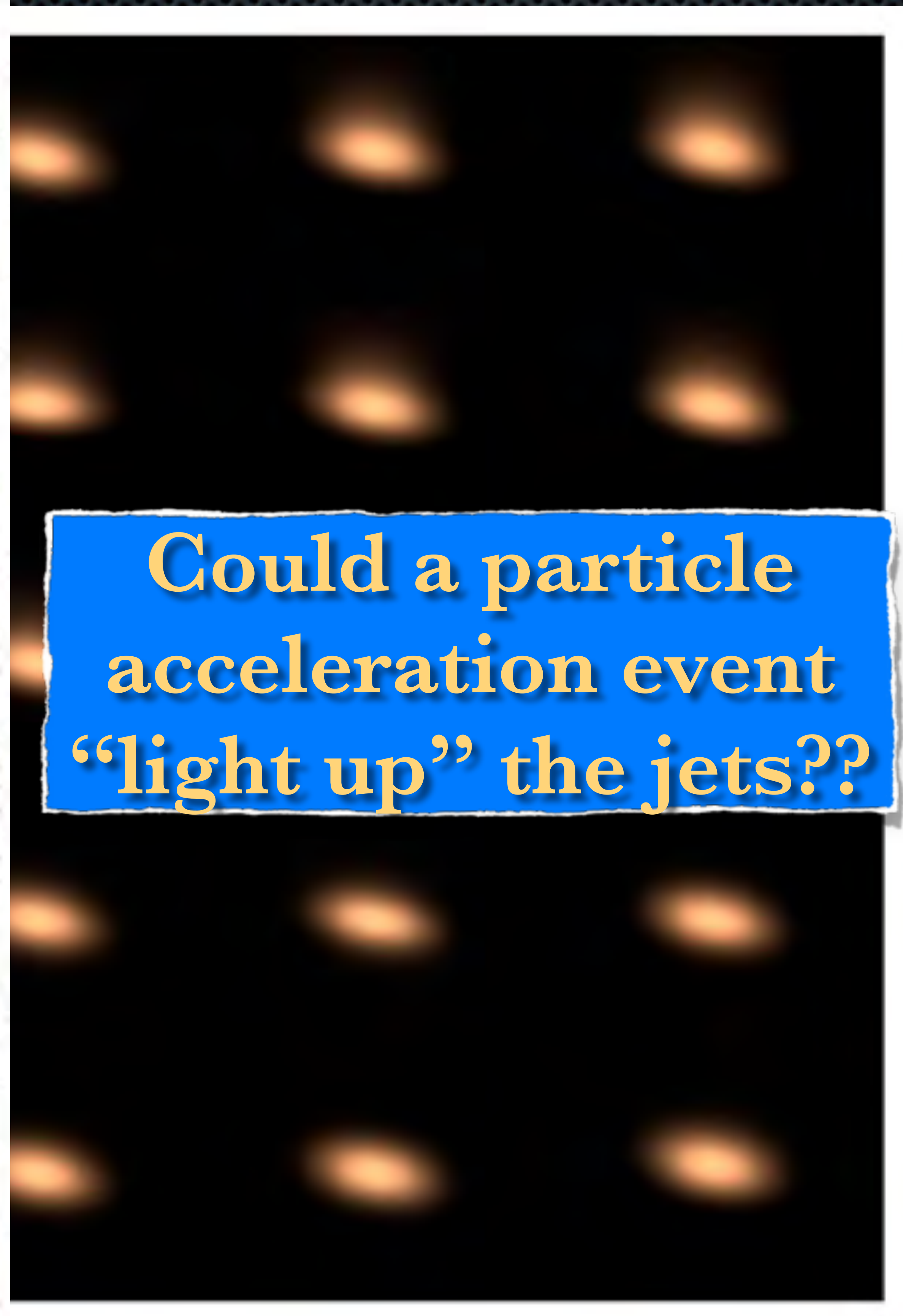
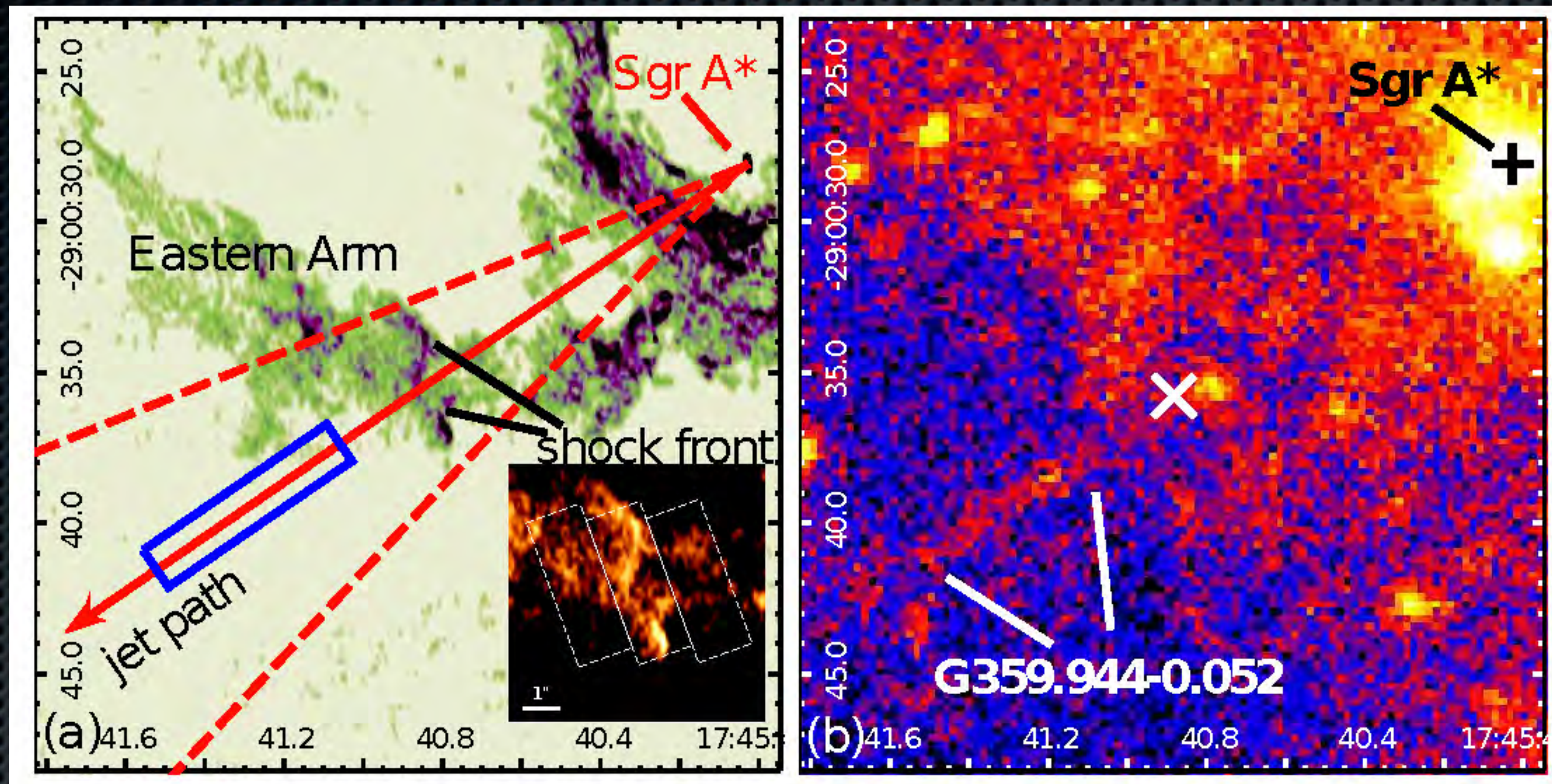
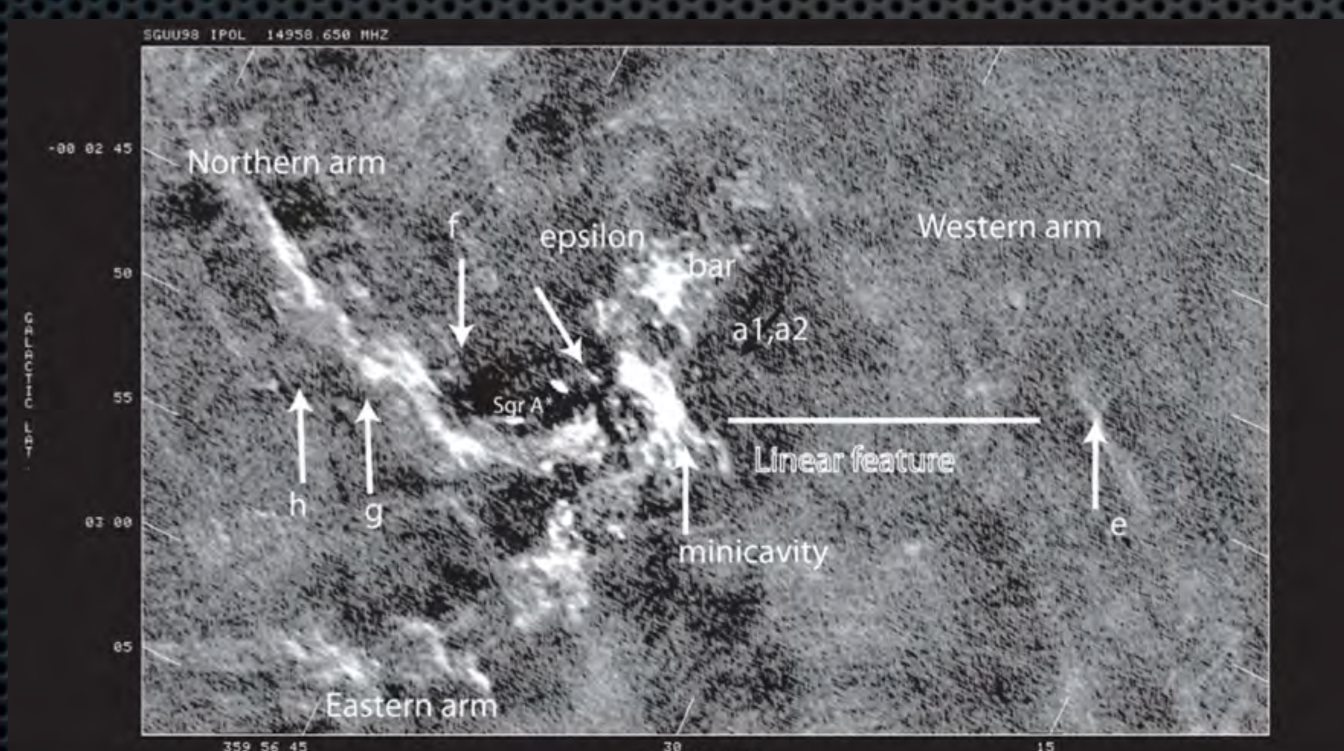


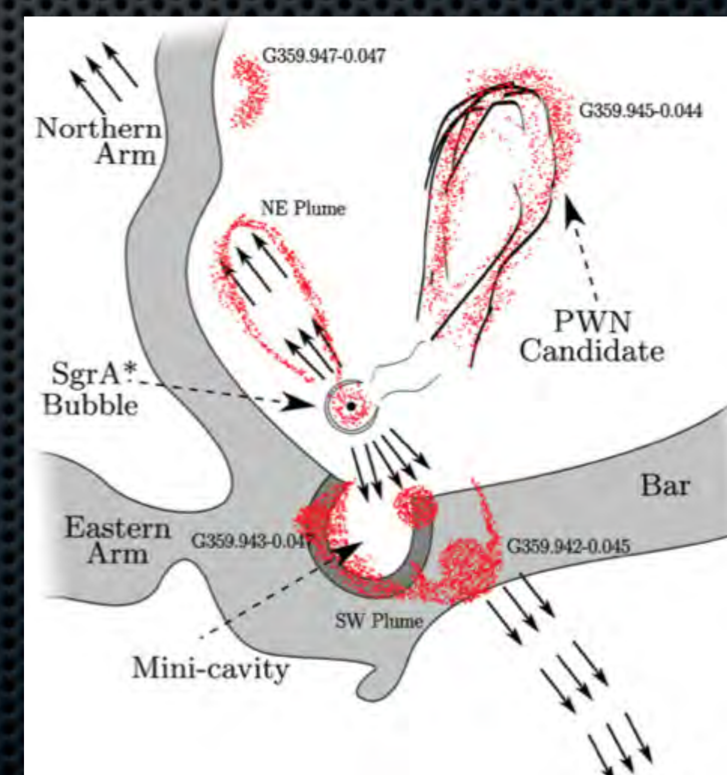


Could a particle acceleration event "light up" the jets??

G2 “encounter”: Illuminate “passive" jets?







(Yusef-Zadeh ea. 2012; Li, Morris & Baganoff 2013; Yusef-Zadeh & Wardle 2013; Walg, SM, Achterberg ++, in prep)

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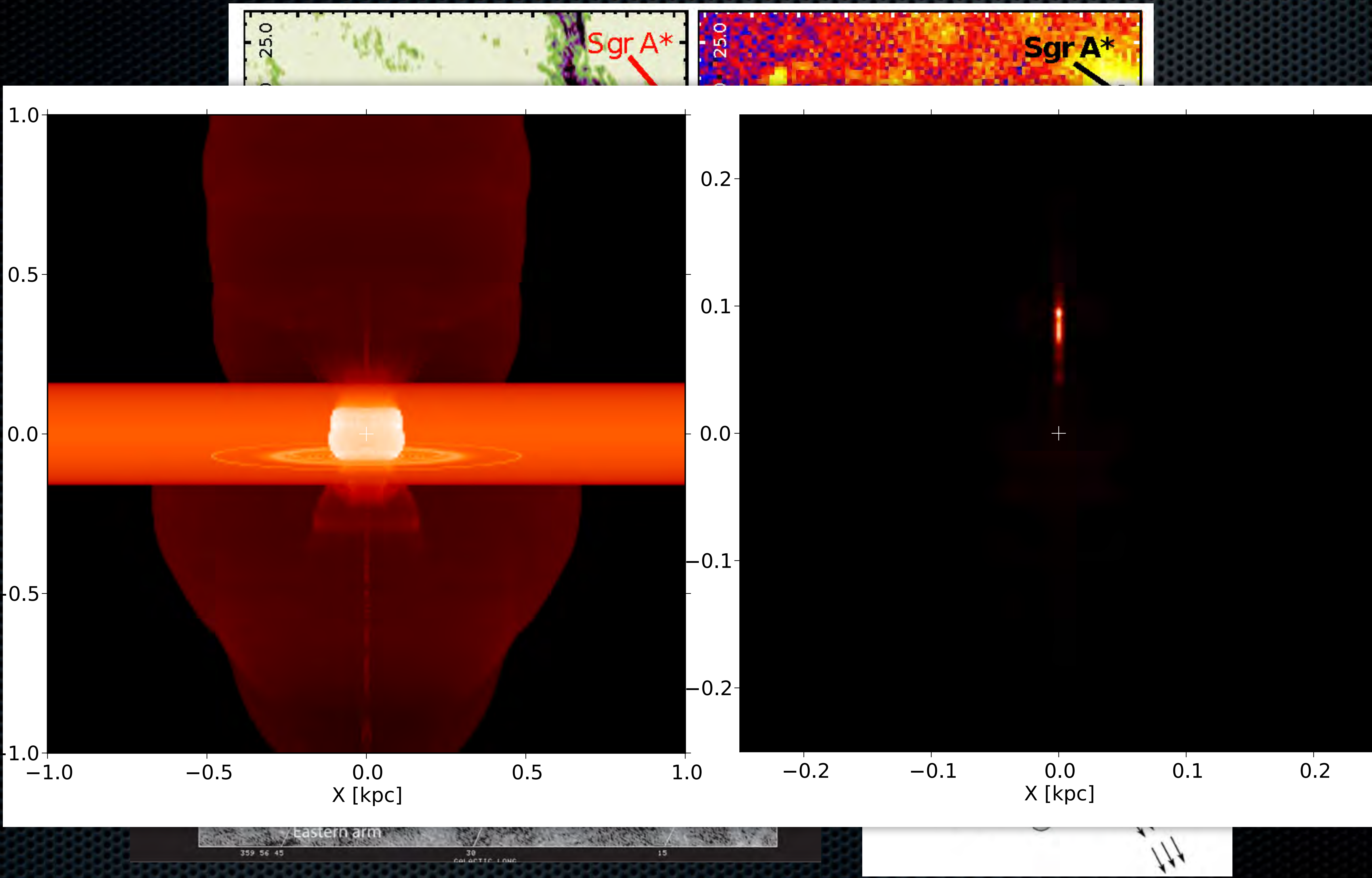

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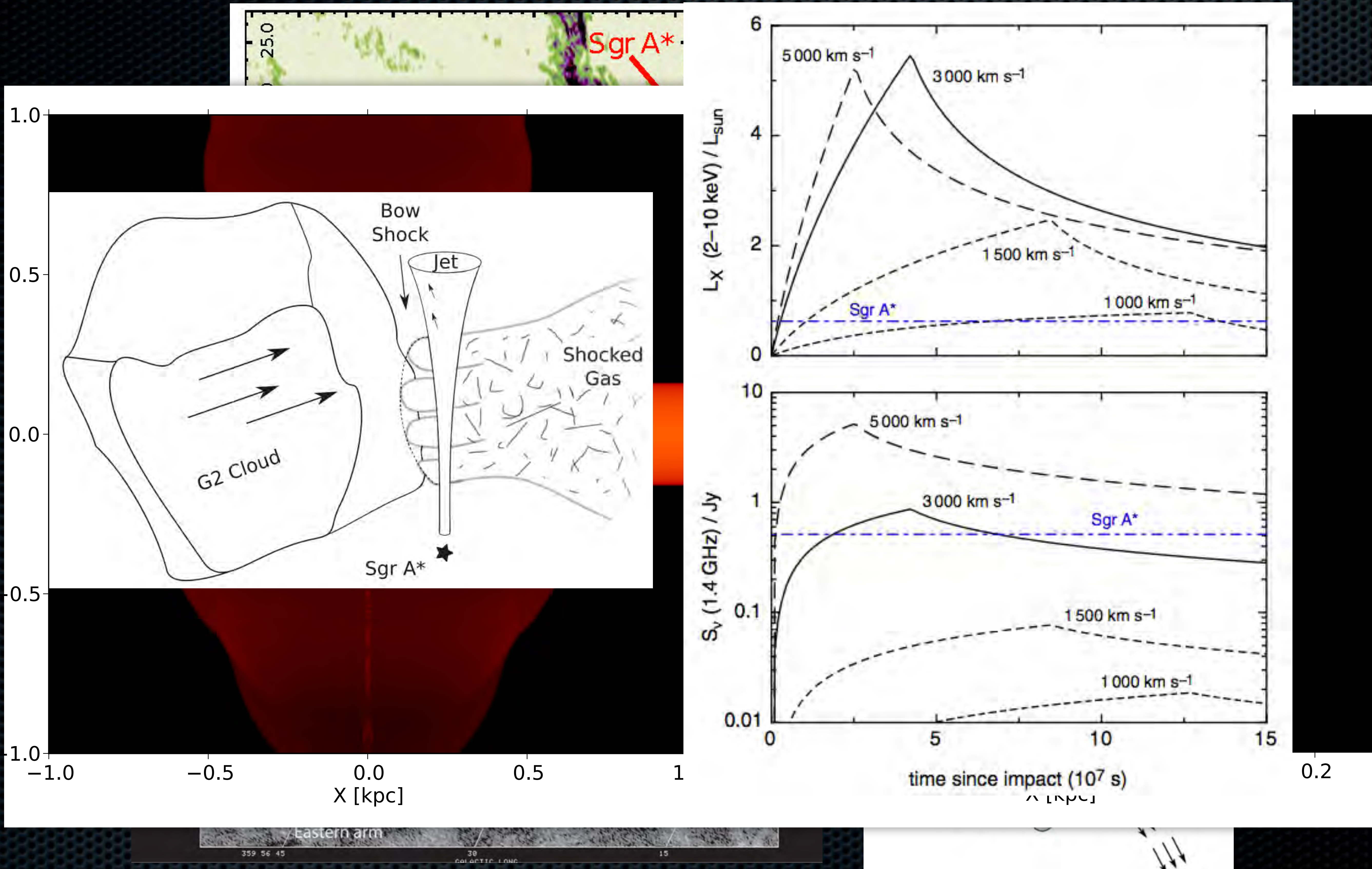

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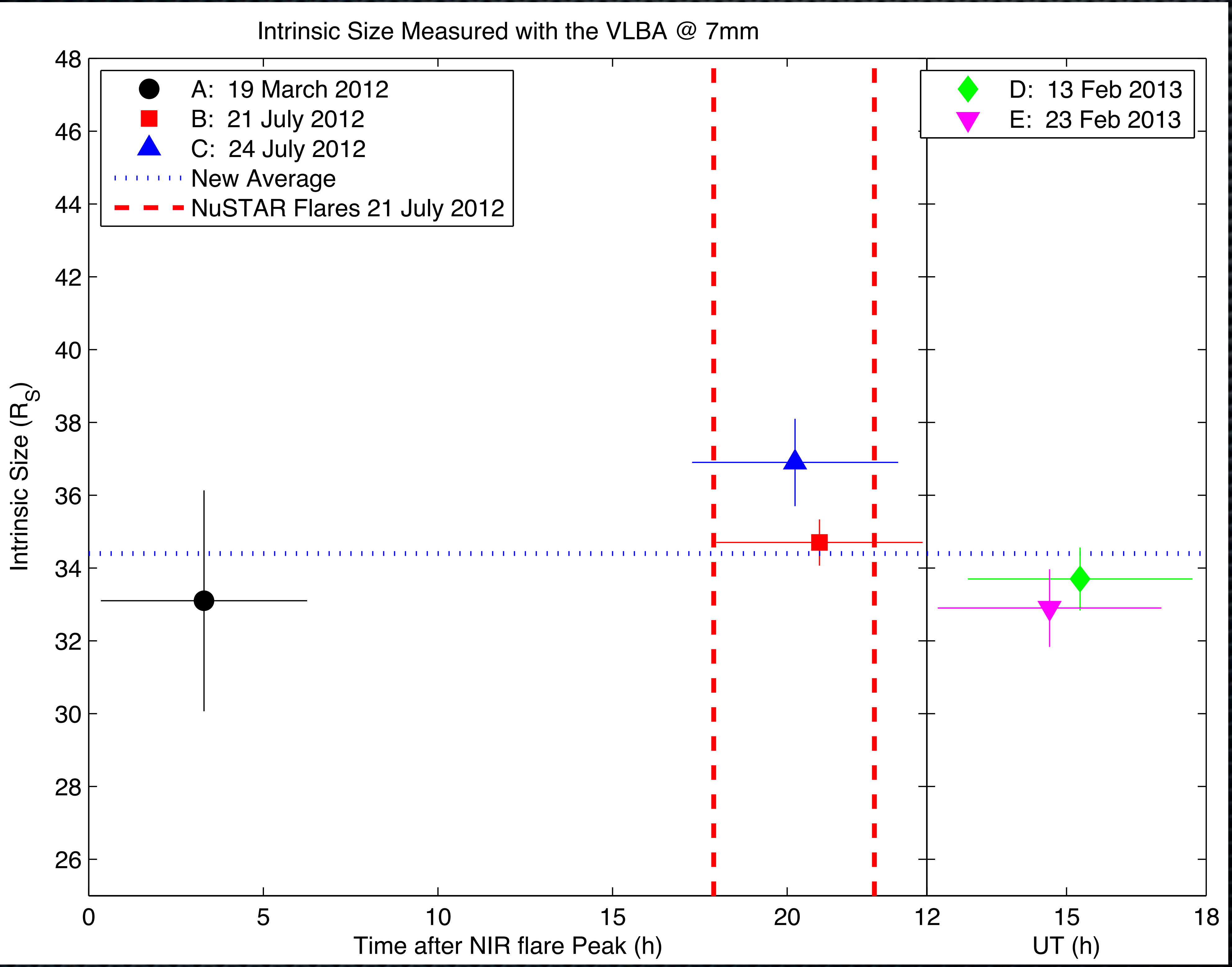
Could G2/flares light up jets?

VLA/VLBA observations triggered from IR



(Bower, SM, Brunthaler,++ 2014; Bower, SM++ in prep.)

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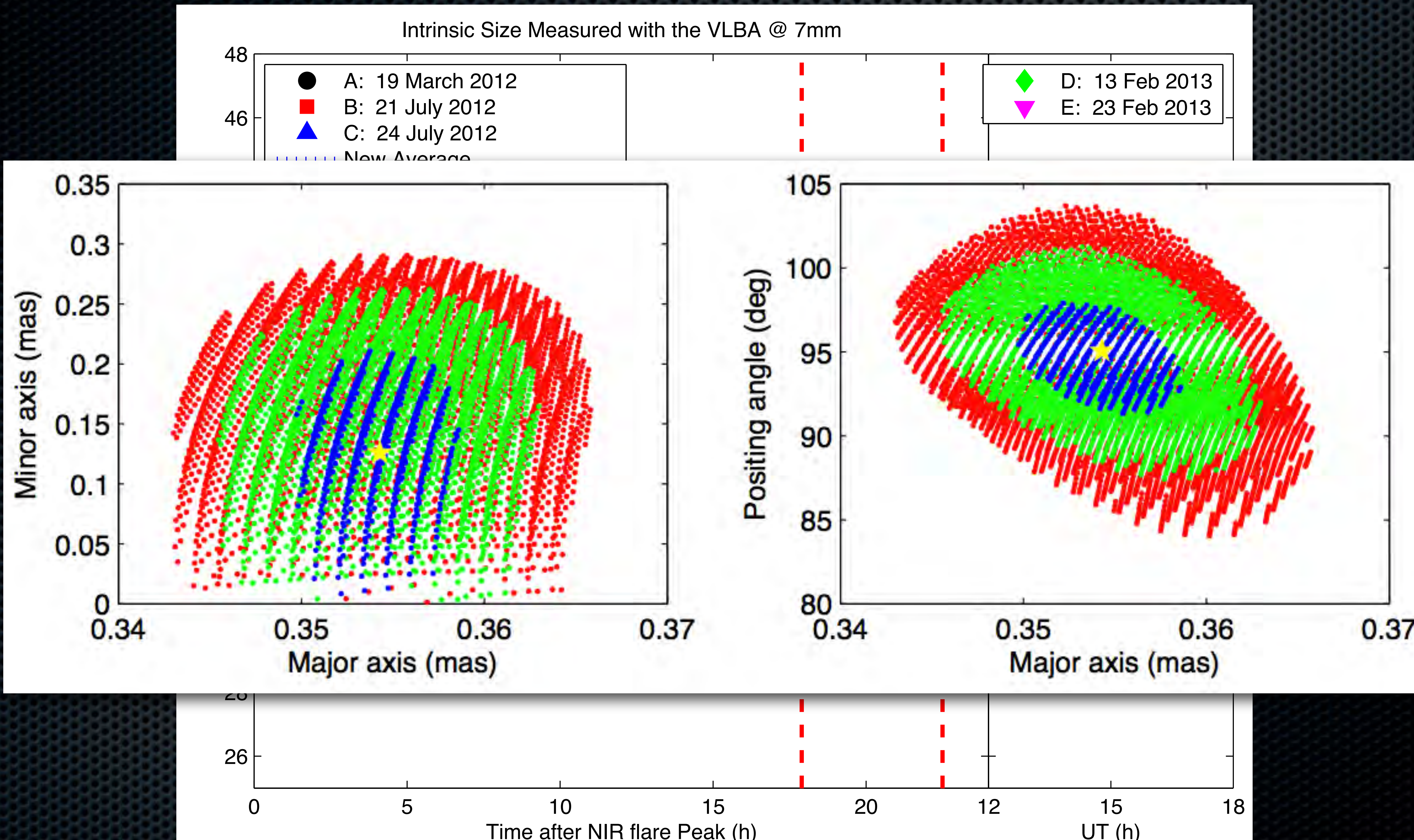


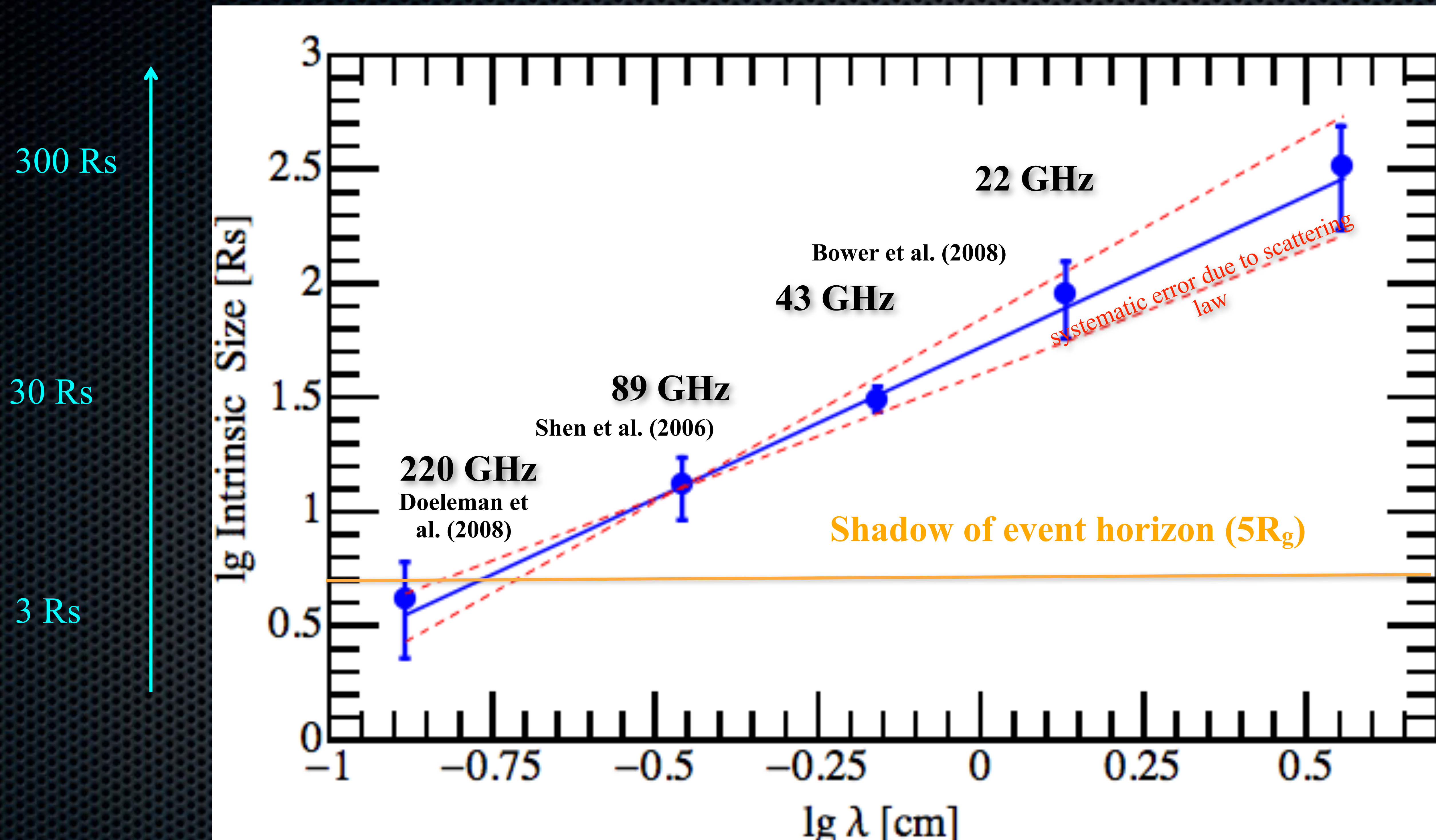
(Bower, SM, Brunthaler,++ 2014; Bower, SM++ in prep.)

Future mm-VLBI (Event Horizon Telescope)

- Existing facilities:
  - JCMT, CARMA, SMT, SPT
  - SPT-JCMT: 15.000km (~5µas)
  - ALMA
- Under construction:
  - LMT, GLT
- New ones?
  - LLAMA (Argentina)
  - Peru …?
- **BlackHoleCam (ERC synergy project: Falcke, Kramer, Rezzola)**

(EHT: Doeleman et al. 2011)

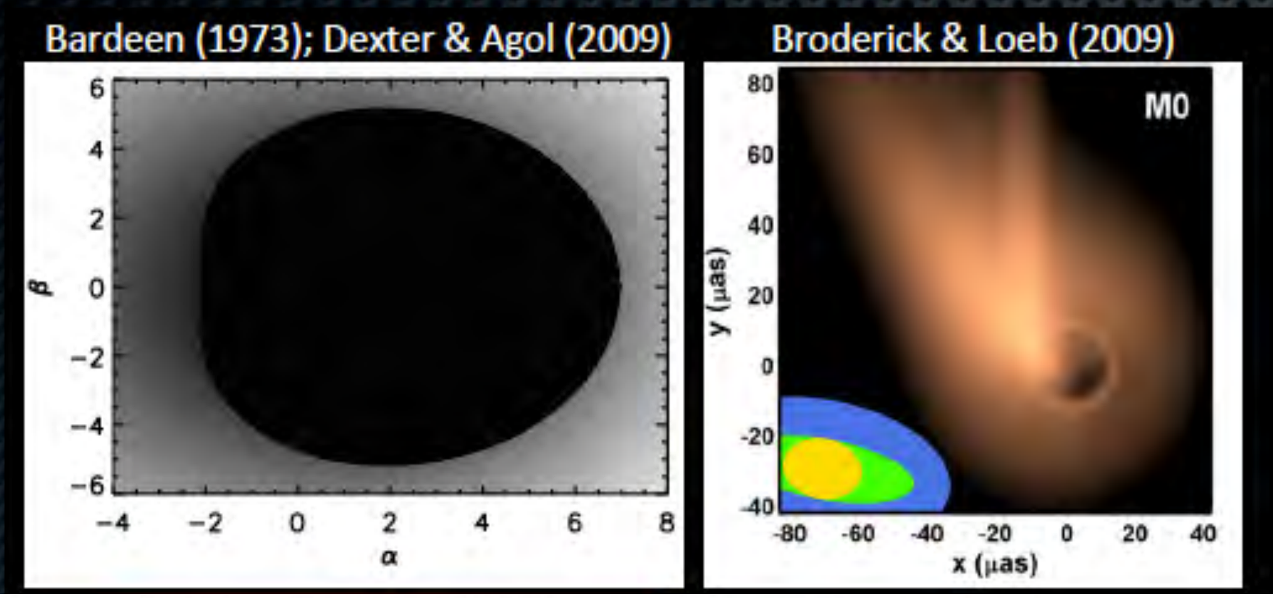
Sgr A*: predicted size of radio source



(Falcke, SM, Bower 2009)

"Shadow Industry"

(See review Falcke & SM 2013, CQG)



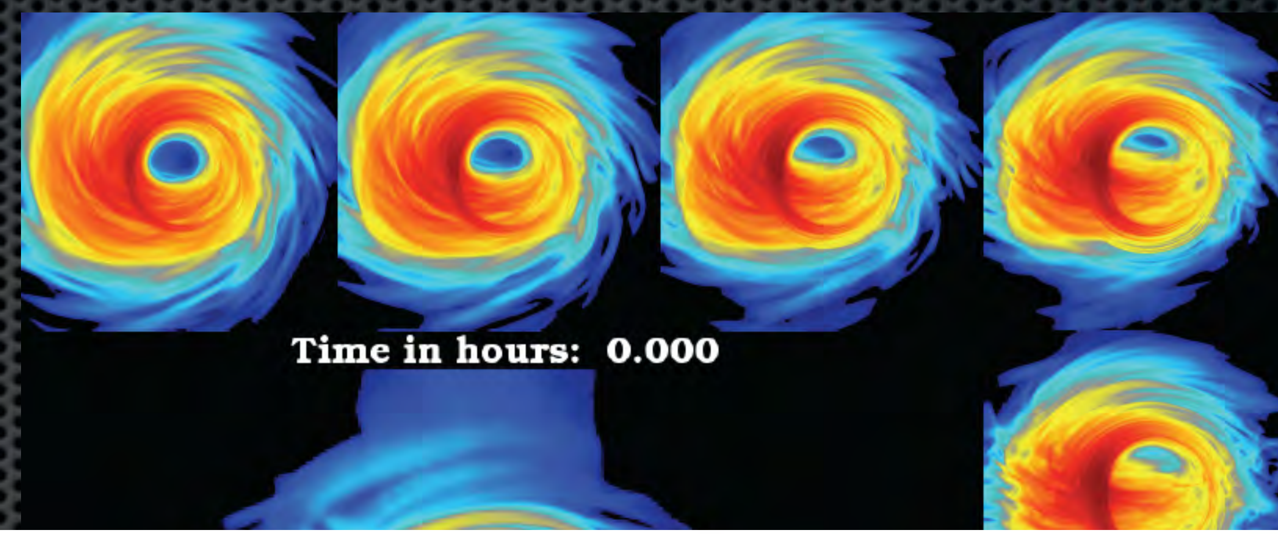
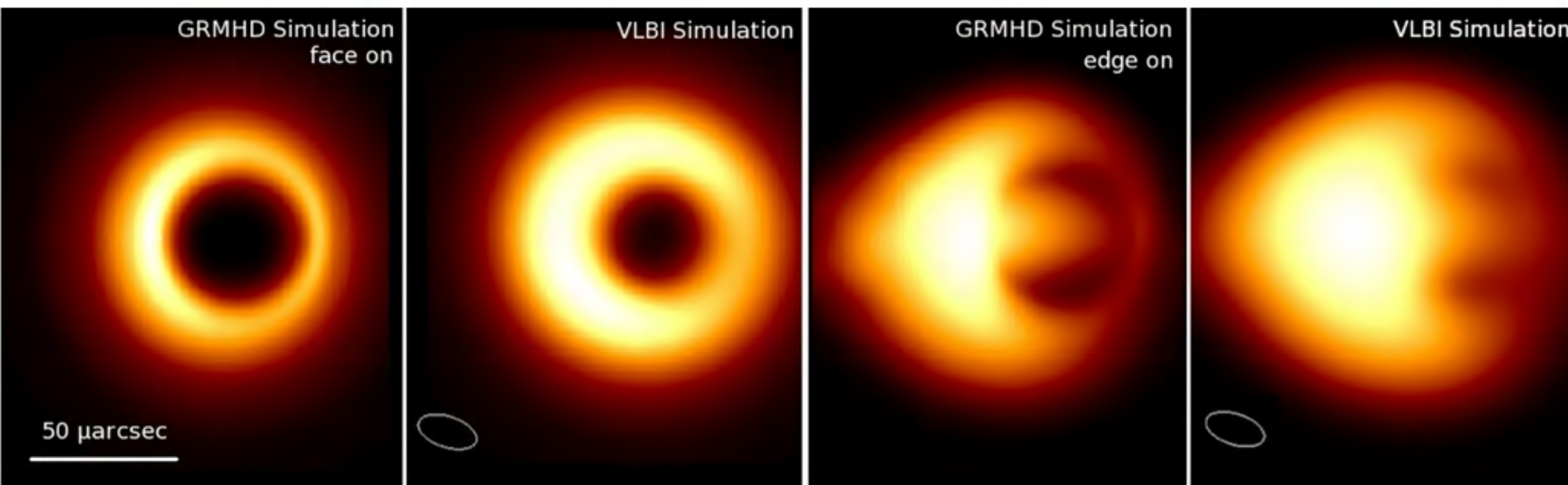


Figure 5 from H Falcke and S B Markoff 2013 Class. Quantum Grav. 30 244003



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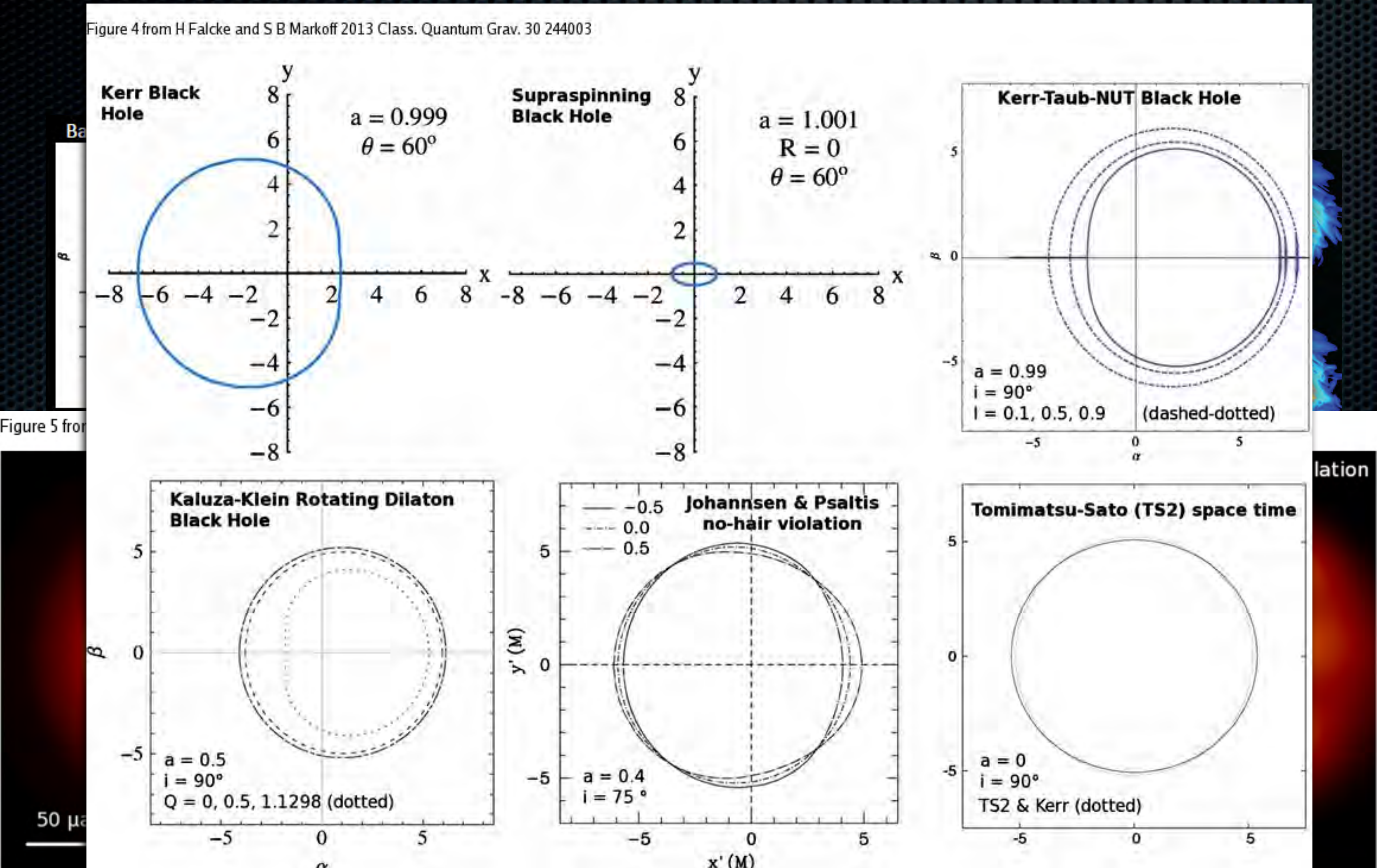

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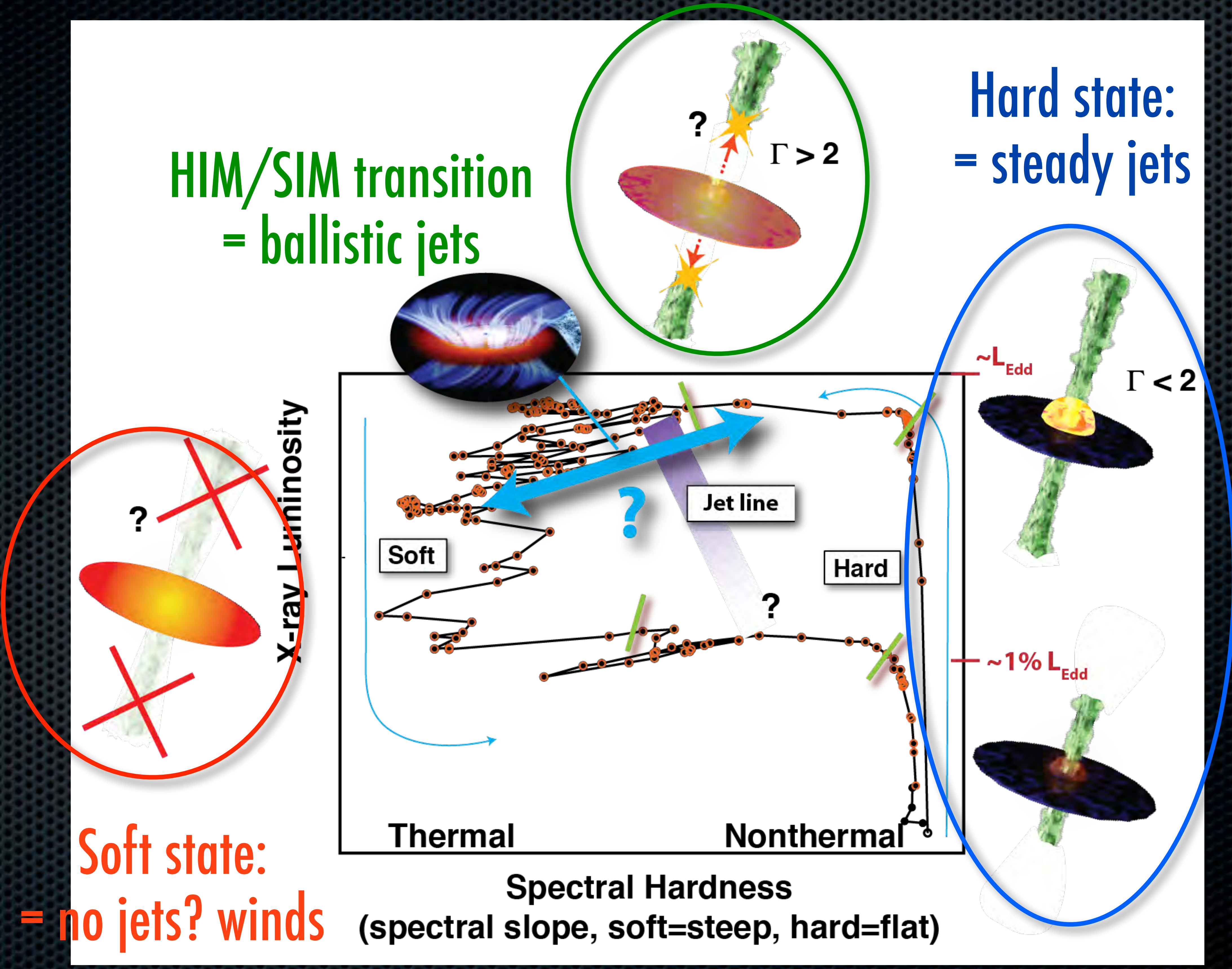
Different power channels: jets, winds or disk/radiation:
Do X-ray binary "channels" correspond to AGN?



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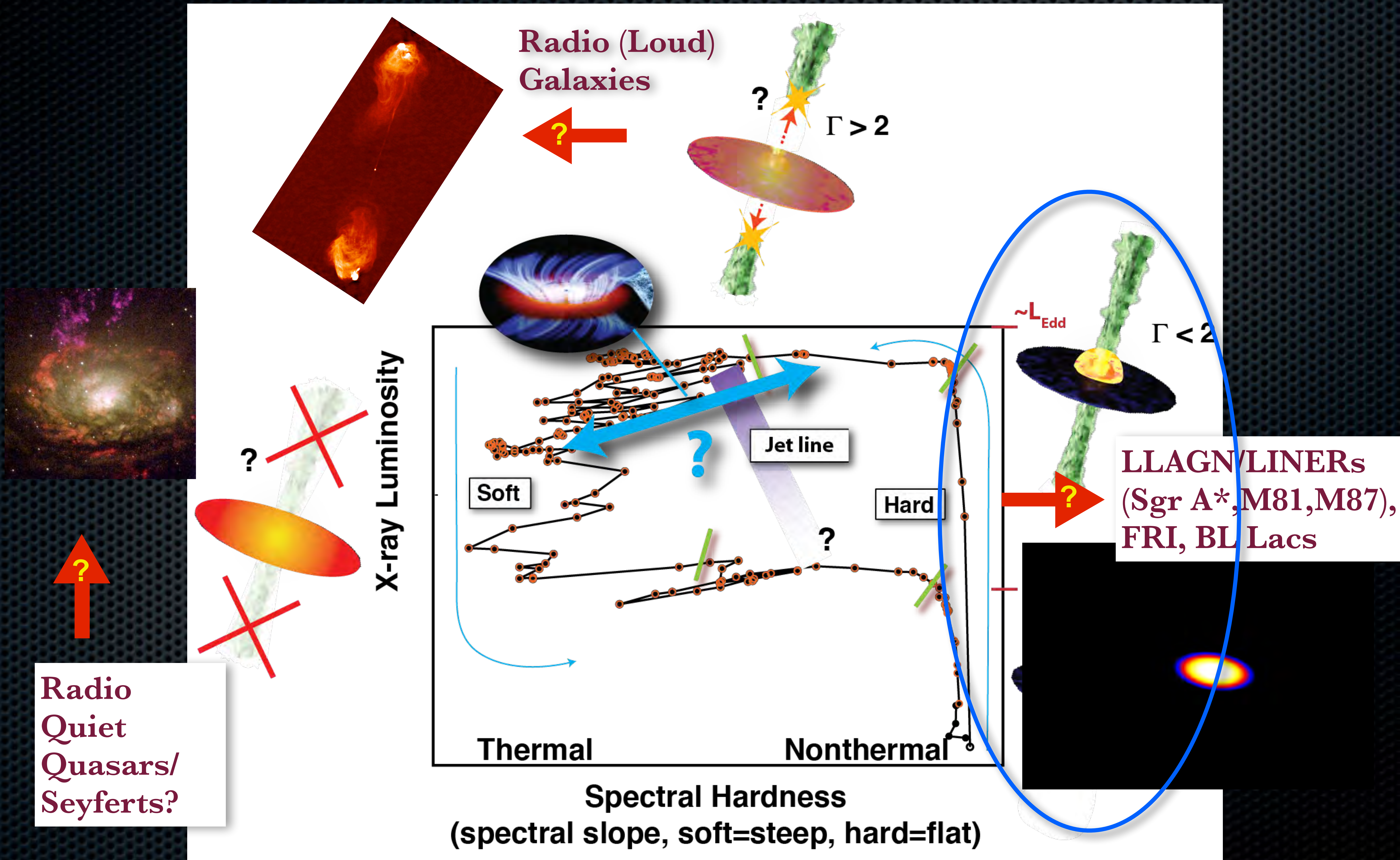
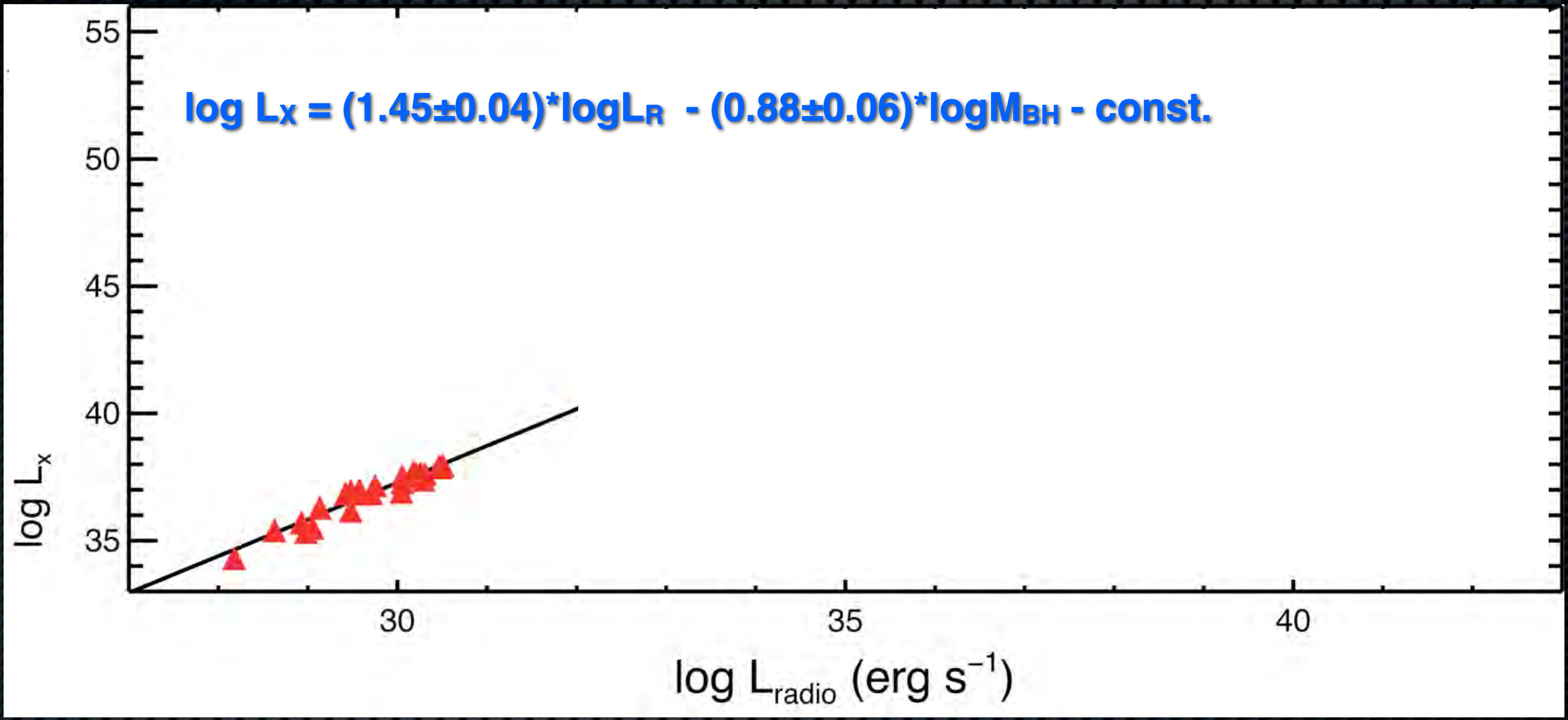


Fundamental Plane of Black Hole Accretion:
connecting black holes of all masses



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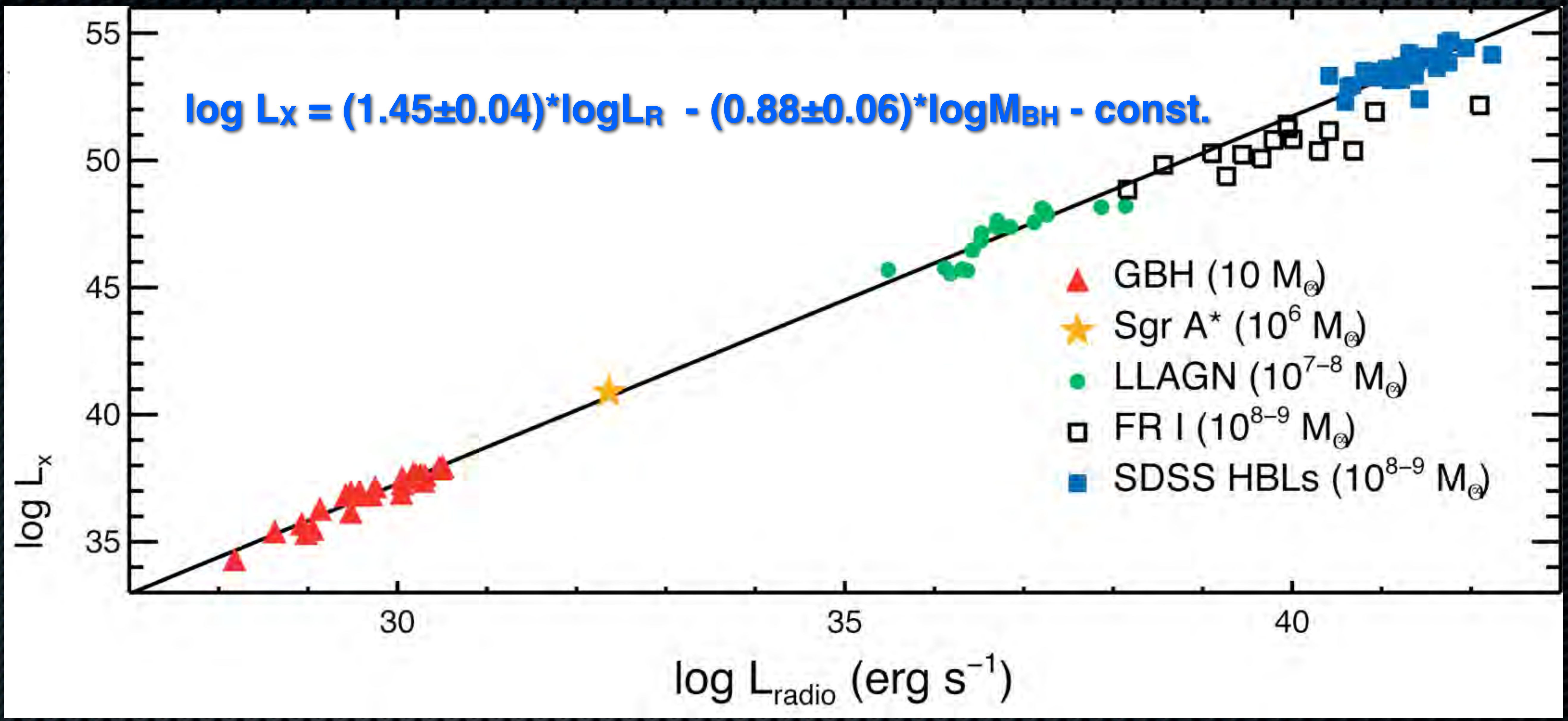

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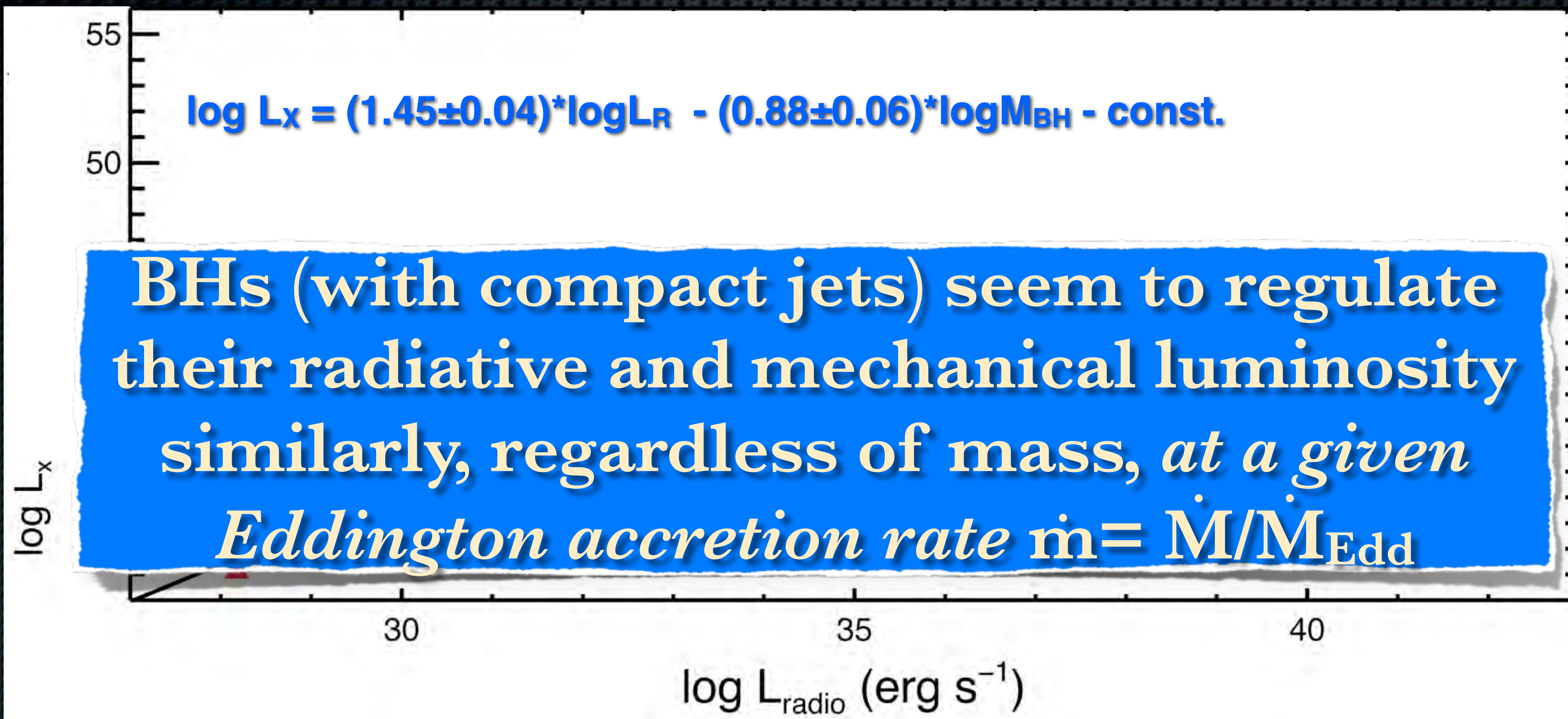
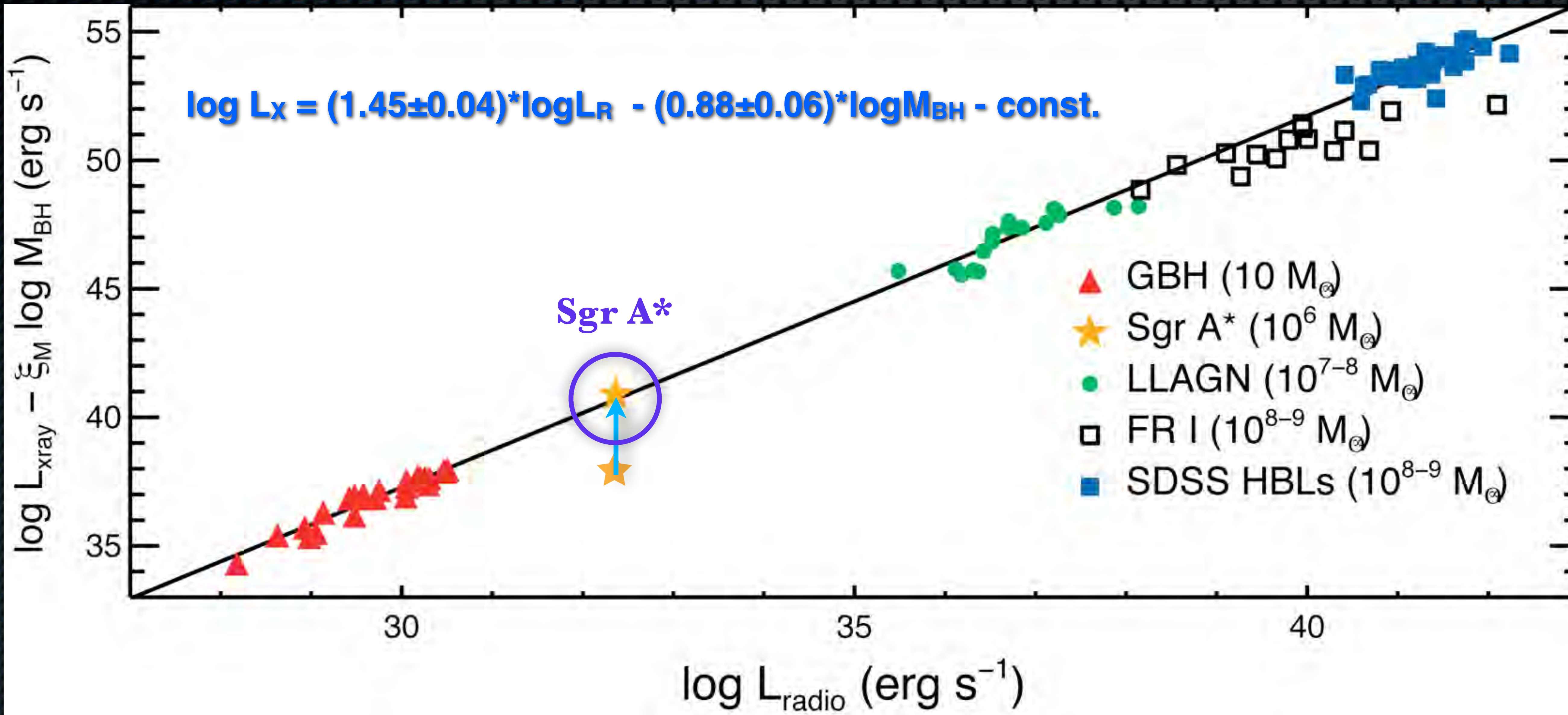


BHs (with compact jets) seem to regulate their radiative and mechanical luminosity similarly, regardless of mass, *at a given Eddington accretion rate* $\dot{m} = \dot{M}/\dot{M}_{Edd}$

(SM ea. 2003; Heinz & Sunyaev 2003; Merloni, Heinz & diMatteo 2003; Falcke, Körding, SM 2004; SM 2005; Körding et al. 2006; Plotkin, SM, Kelly, Körding & Anderson 2012)

Sgr A*'s link to other "weak" BHs:
The "Fundamental Plane" of BH accretion



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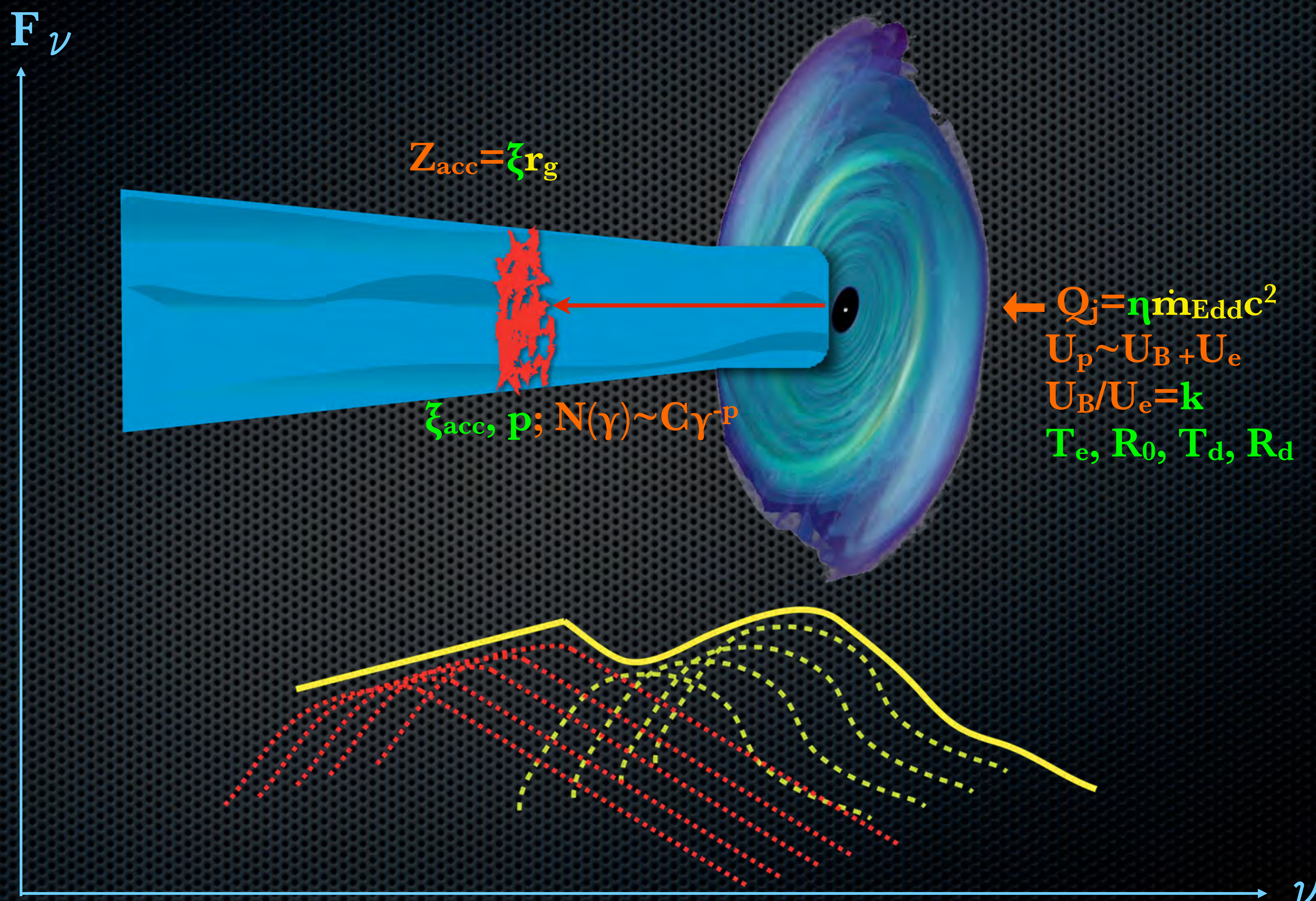
Schematic of outflow model (v1.0)



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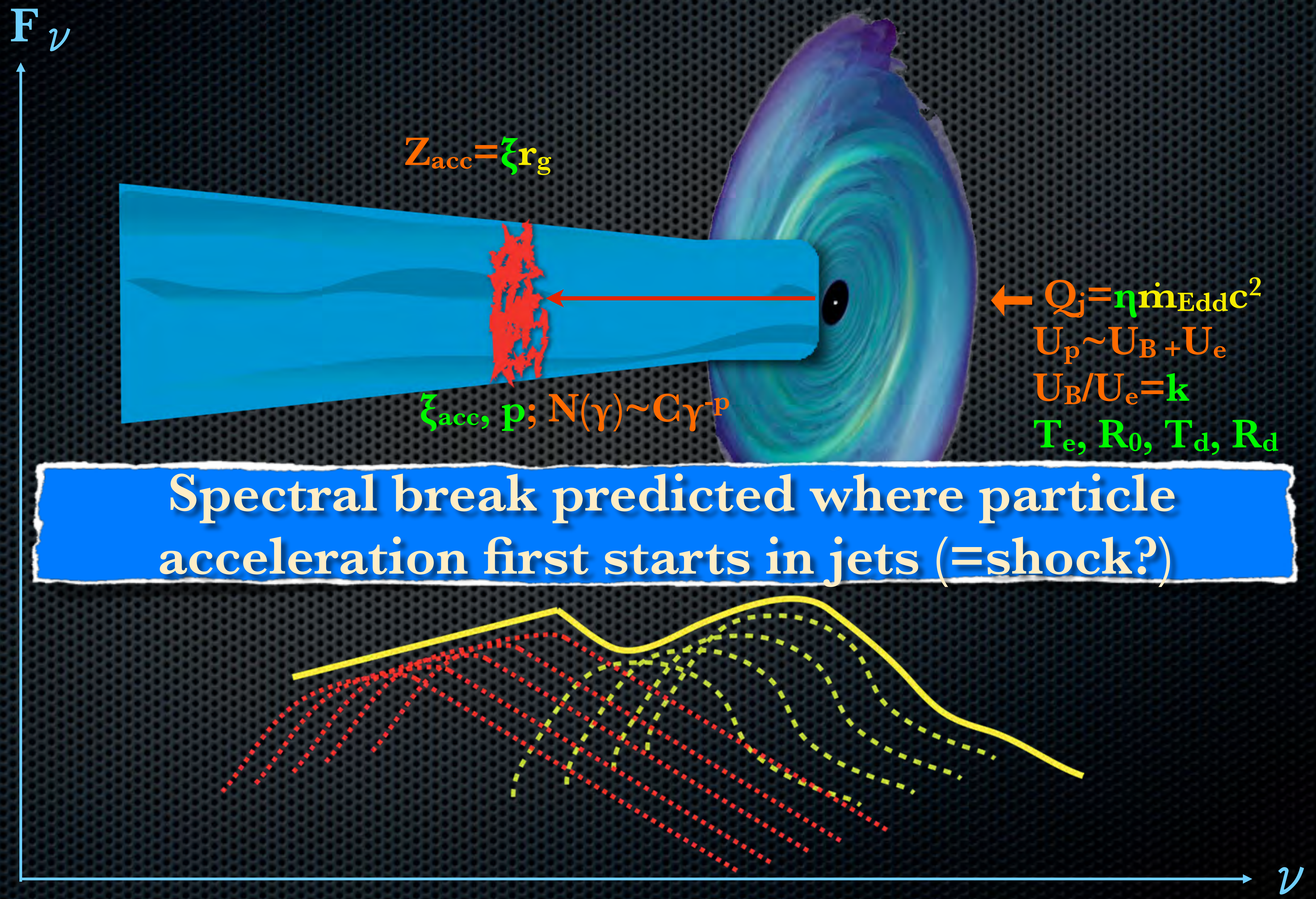
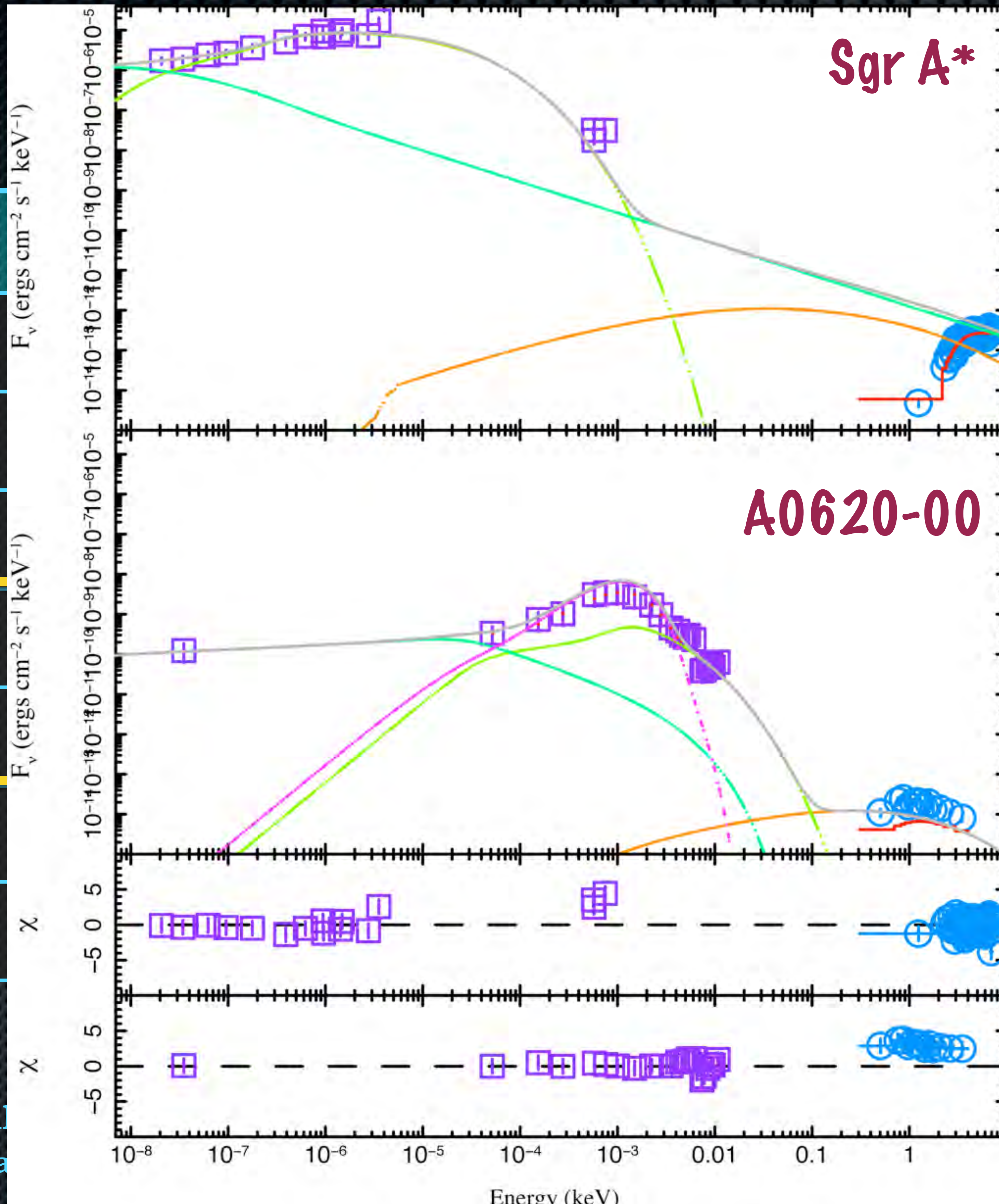


Spectral break predicted where particle acceleration first starts in jets (=shock?)

General trend: particle acceleration fizzles at very low $\dot{m}$



0^{-7} L_{Edd}

Parameter	Sgr A*
M (M	4x10
Q	10
R	2.5
z	>10
p	>3.8
T	1x10
equip (1/β)	>10

(SM, Nowak & Wi… Falcke 2007,
SM et al. 2008, Ma… SM++ in prep.)

General trend: particle acceleration fizzles at very low $\dot{m}$

$L < 10^{-7} L_{Edd}$

Parameter	HS-XRBs	M81	A0620	Sgr A*
M (M	~	7x10	~	4x10
Q	10	10	10	10
R	2–20	2.4	2–7	2.5
z	10–400	144	1250	>10
p	2.4–2.9	2.4	3.4	>3.8
T	2–5x10	1x10	2x10	1x10
equip (1/β)	1–5	1.4	1.5	>10

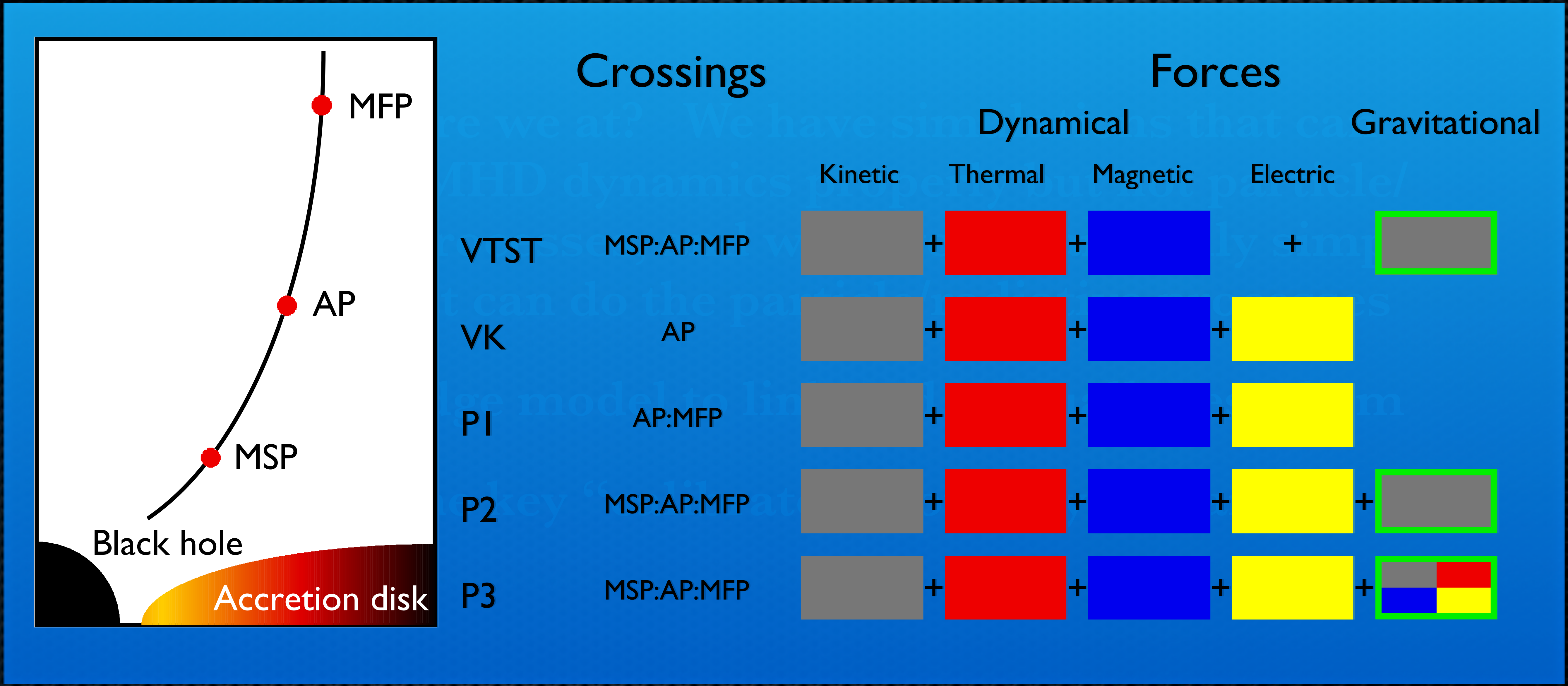
(SM, Nowak & Wilms 2005, Migliari et al. 2007, Gallo et al. 2007, SM, Bower & Falcke 2007, SM et al. 2008, Maitra et al. 2009, van Oers, SM et al., 2010, Nowak et al. 2011, SM++ in prep.)

Outlook: semi-analytical relativistic MHD outflow models

- So where are we at? We have simulations that can model GRMHD dynamics properly but not particle/radiative processes, and we have dynamically simpler models that can do the particle/radiative processes
- Need a bridge model to link and mutually test them
- Sgr A* is the key "calibrator" source yet again

(Vlahakis et al. 2000, Vlahakis & Königl 2003, Polko, Meier & SM 2010, 2013, 2014)

Outlook: semi-analytical relativistic MHD outflow models



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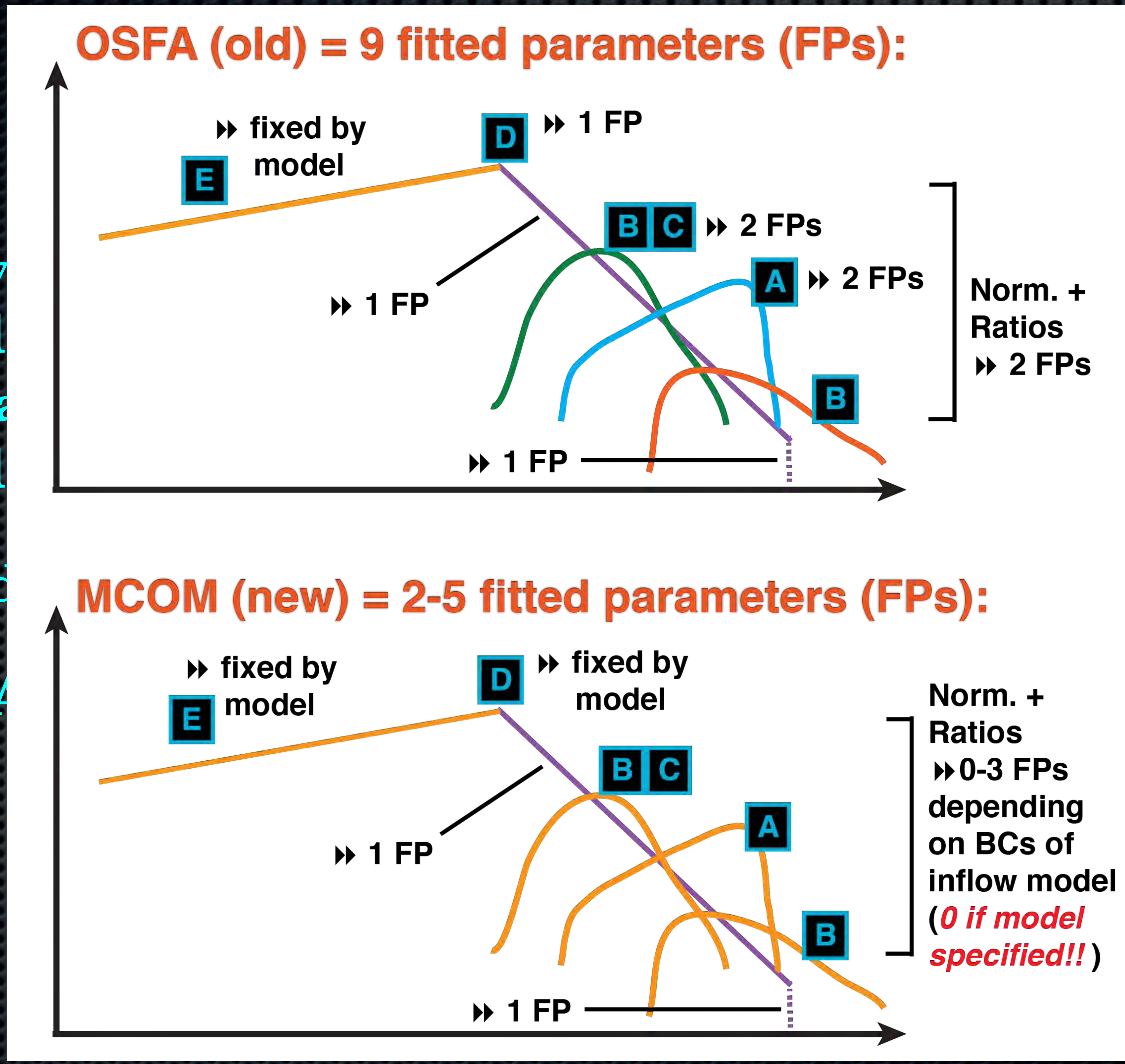
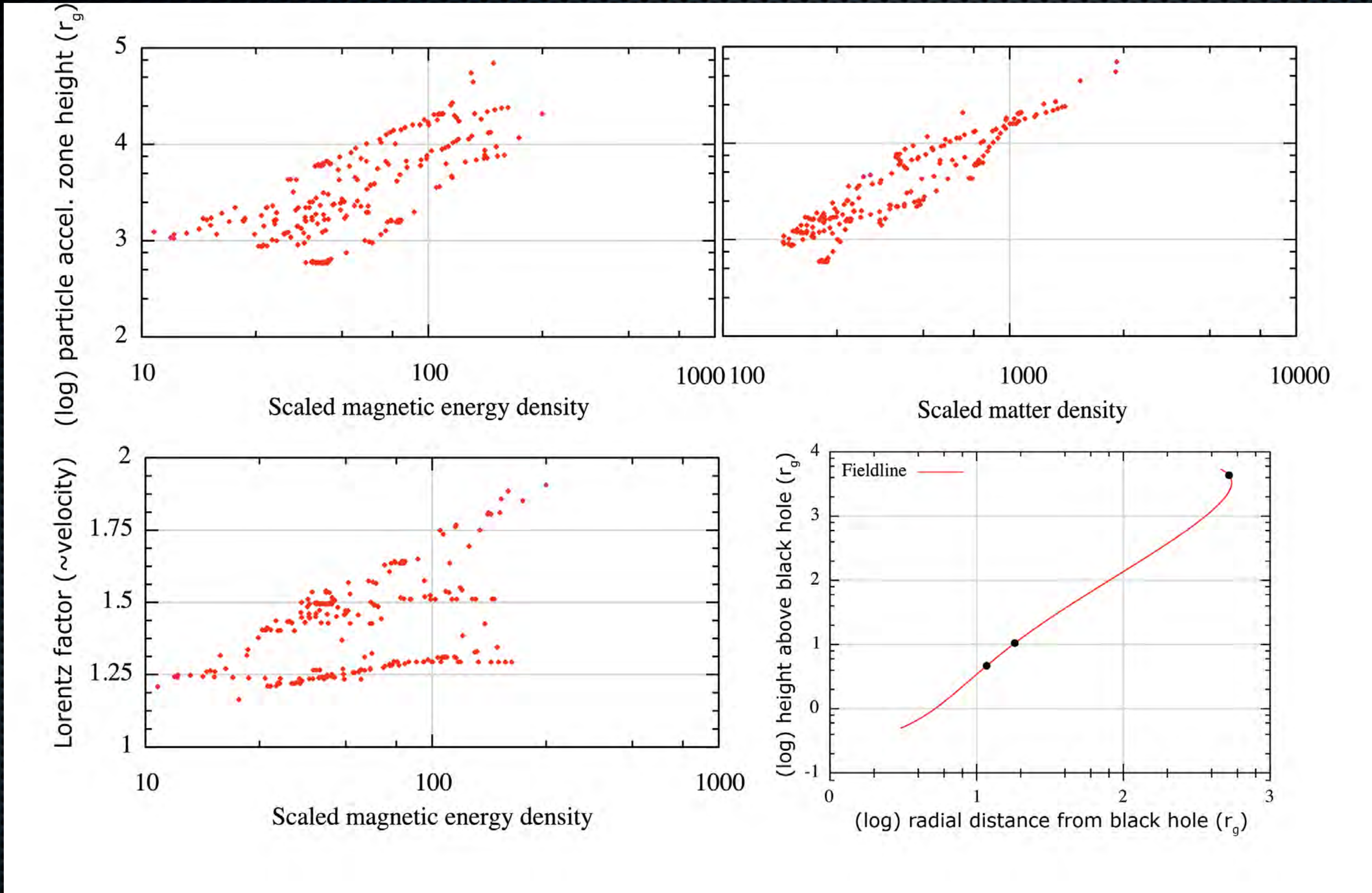
- Need… them
- Sgr A…



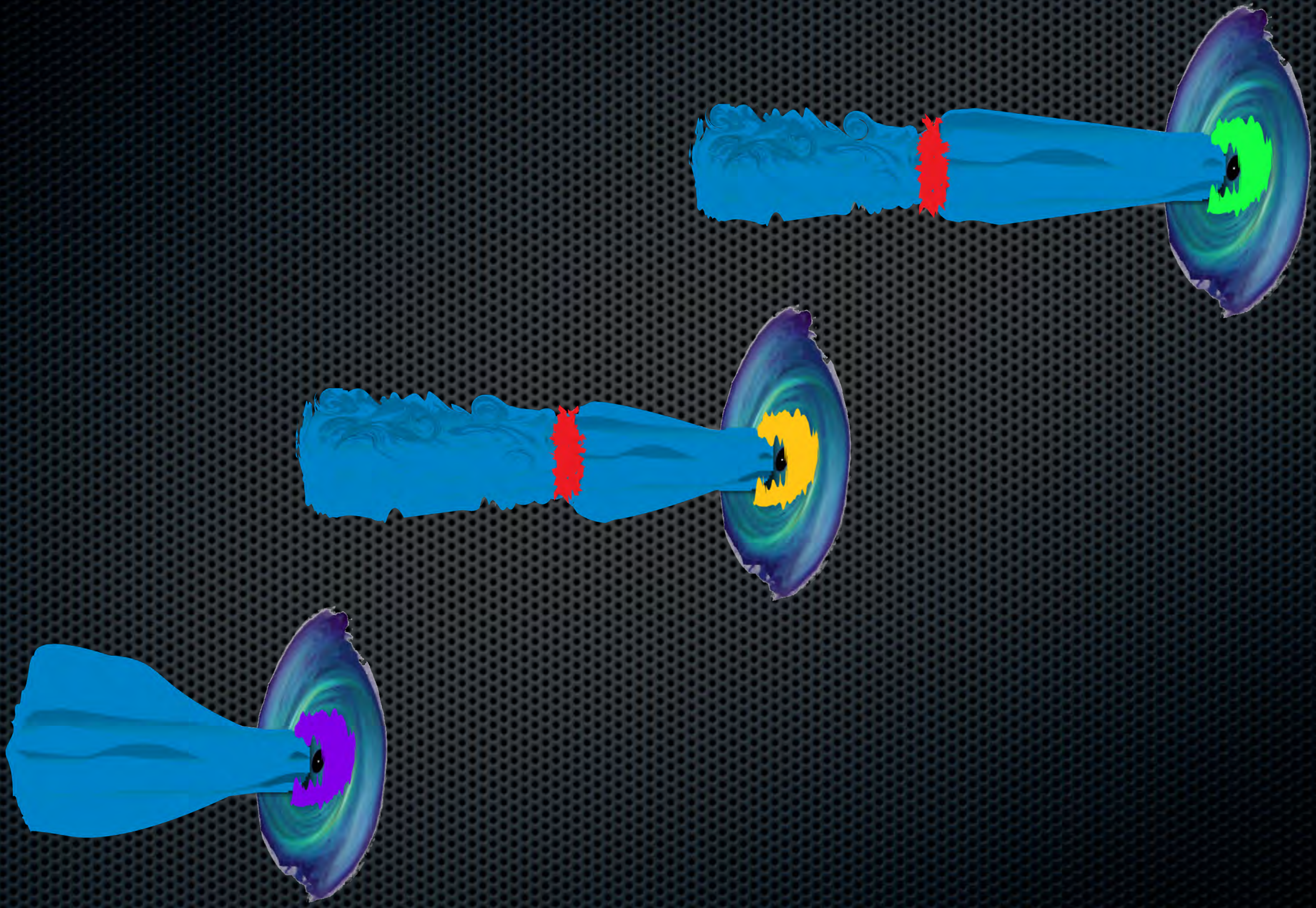
(Vlahakis et al. 2000, Vlahakis & Königl 2003, Polko, Meier & SM 2010, 2013, 2014)

New generation of semi-analytical relativistic MHD jet models

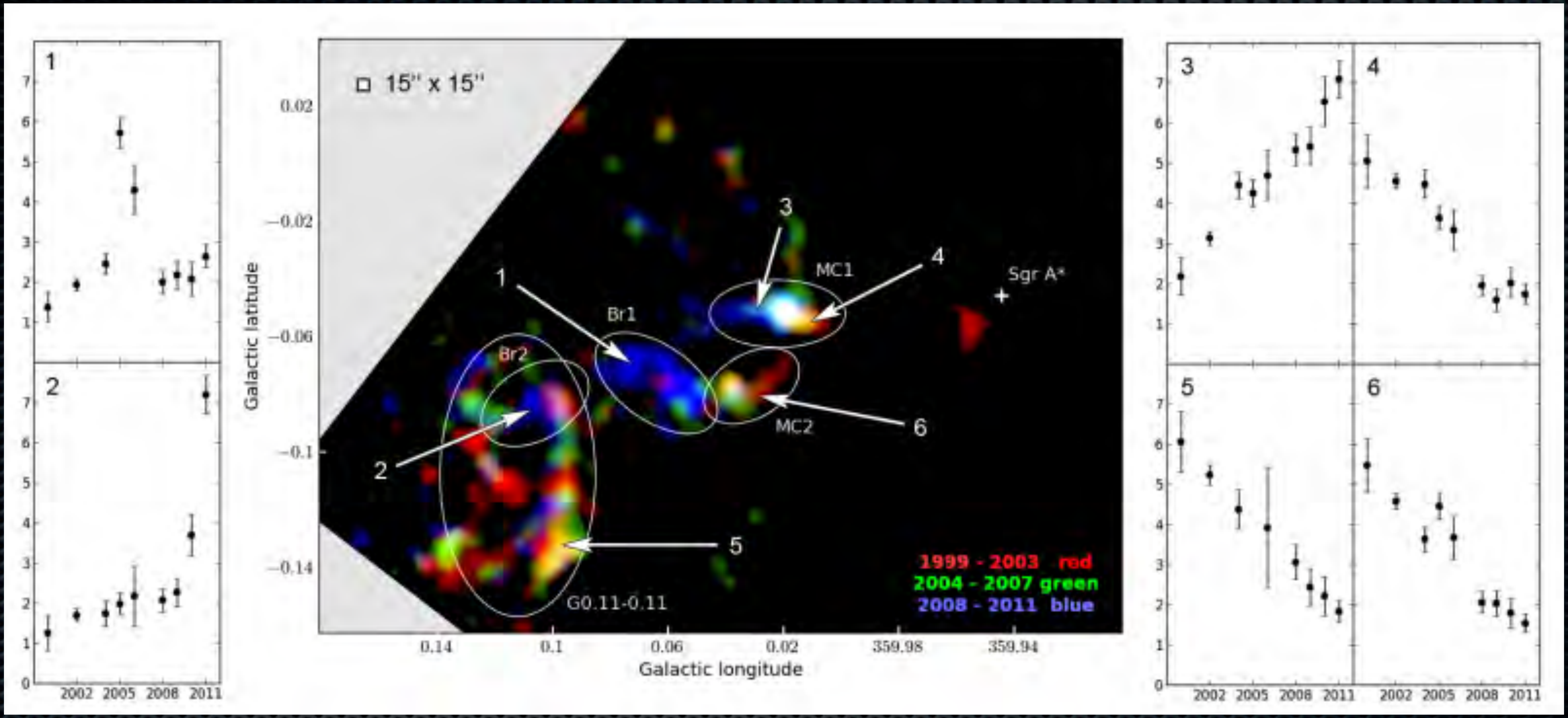


(Vlahakis et al. 2000, Vlahakis & Königl 2003, Polko, Meier & SM 2010, 2013, 2014)

No longer "one size fits all"



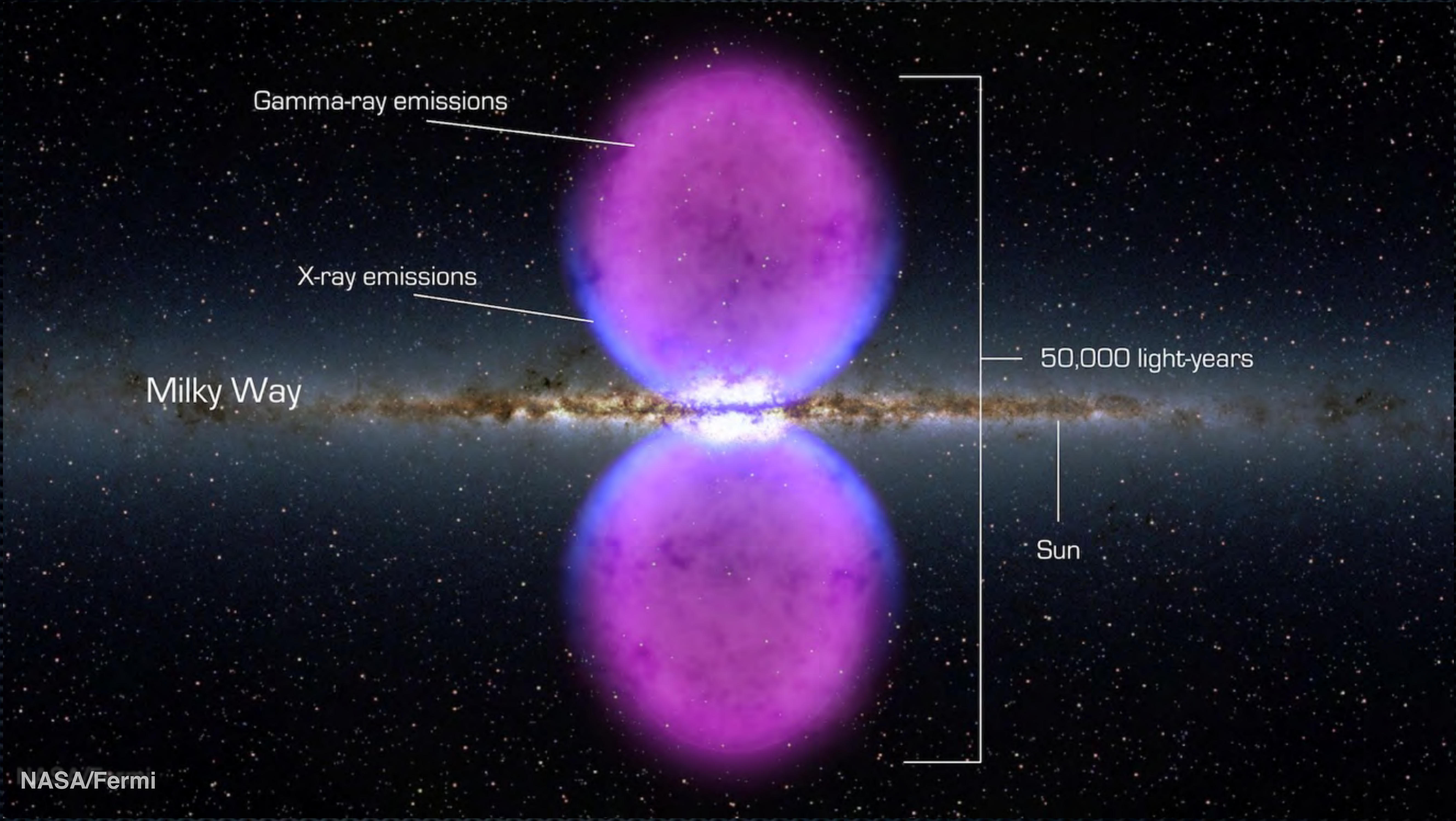
Can use to model Sgr A*'s prior outbursts



(Muno et al. 2002-2005; Ponti et al. 2010, Clavel et al 2013)

- Has been suggested that the best source is prior activity of Sgr A* (Koyama ea. 96, Murakami ea 00, Revnivtsev ea. 04) but some controversy about source of ionization
- Chandra can actually resolve the "wave" of fluorescence, must be hard photons
  - Implies $L \leq 10^{39}$ erg/s outburst lasting ~10 yrs, about 100 years ago!

…and even the last AGN phase?



(**Fermi Bubbles: Finkbeiner, Su & Slatyer 2010 ++**)

Back to the "overarching" questions

- "Fueling" ➠ *$\dot{M}$ onto Sgr A* ≪ $\dot{M}_{Bondi}$ (by ~10^{-4}-10^{-3}). Accretion physics seems similar to other sources (FP): "Bondi" approximation overestimation? Outer environment (> R_{circ}) less important than inner 100R_g?*

- "Power output channel","Inflow/outflow problem" ➠ *At low luminosities, (jet) outflows play a key role, launched on scales < 20R_g. Disk winds and likely jets present.*

- "Particle acceleration" ➠ *Strong link between launching conditions and particle acceleration properties in the jets (development of decollimation shock?)*

Summary & Outlook

- Sgr A*: Very weak but very close! Allows us to directly observe the accretion flow on all scales, down to (almost) the event horizon.
- Convergence: agreement between semi-analytical work and GRMHD simulations ➟ we have a good handle on the physical conditions
- Uniqueness: Fits in with wider class of low-luminosity black holes (AGN and XRBs), just with weaker particle acceleration ➟ Sgr A* can be used as a template of weak activity to build up from

Outlook:

- XVP + G2: immense data sets to be studied in the coming years
- Event Horizon Telescope: Prototype run in 2015 with ALMA
- Connecting to other sources: Extensions to M87, nearby AGN, training the new models in time for "Transient factories"
- Connecting to environs: necessary steps on the way to understanding black hole accretion and feedback in all its forms (cosmological, ionization, CR ⇔ star formation, astrophysical "background" for indirect DM searches, etc…)