NBI 2018

Lec 2

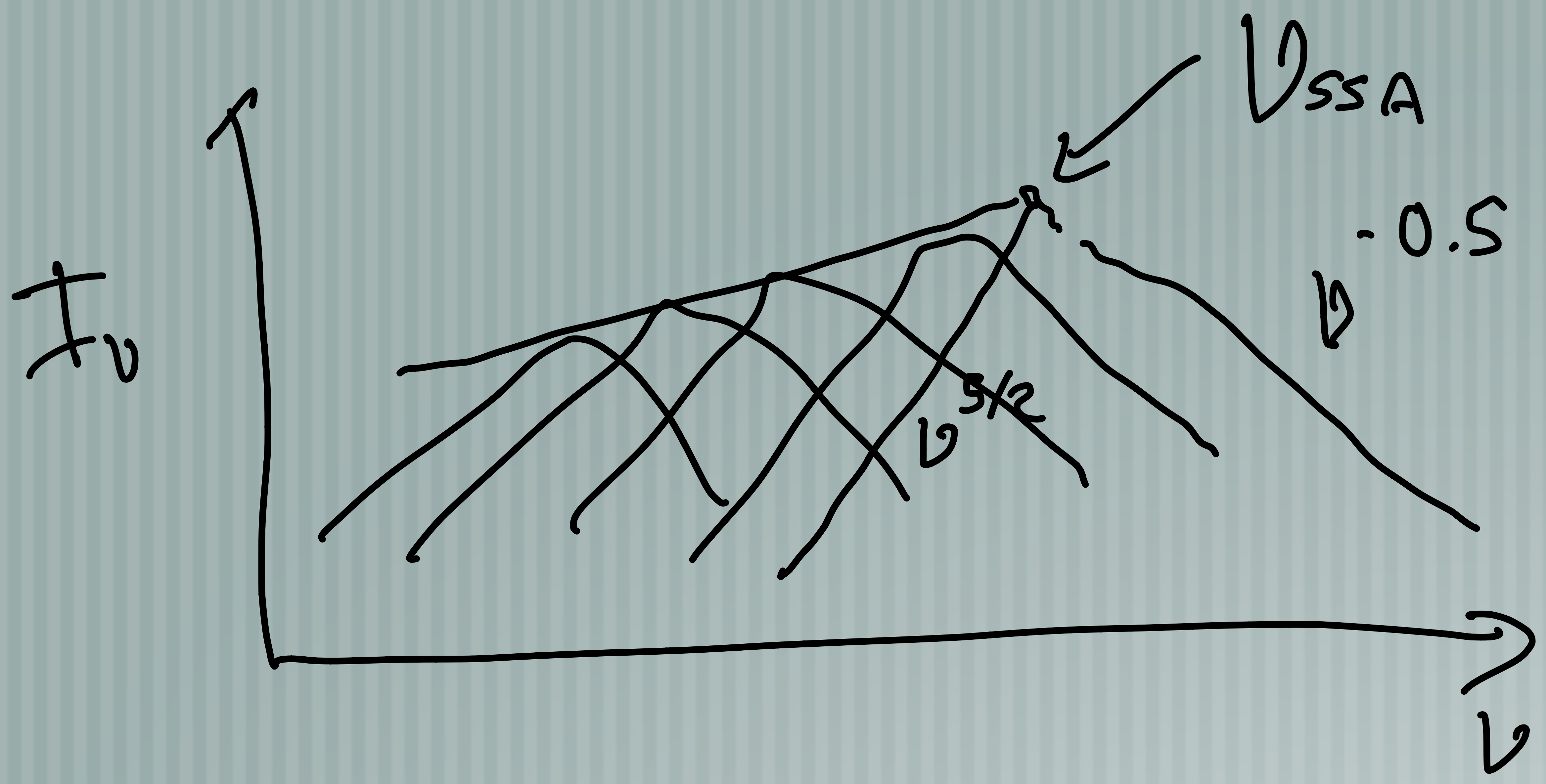
High-Energy Radiative Processes and Jets

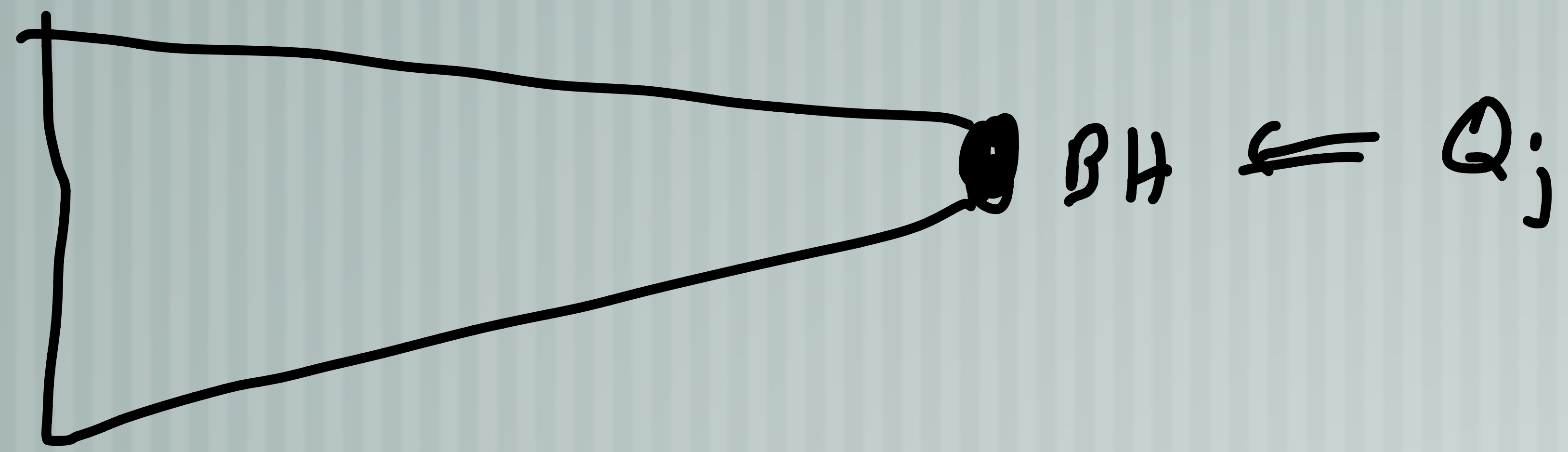
Lecture 2

Sera Markoff (API/GRAPPA, U Amsterdam)

Optical depth in jets: refresher

$\tau_{SSA} > 1 \implies$ flat spectrum





$\tau_{SSA} \propto r_j \cdot \alpha_\nu \sim \nu^{-(x)}$

$N(E) \sim E^{-s}$

"canonical" value of s?

$s \approx 2$

Synchrotron $\alpha \sim \frac{p-1}{2} \sim 0.5$

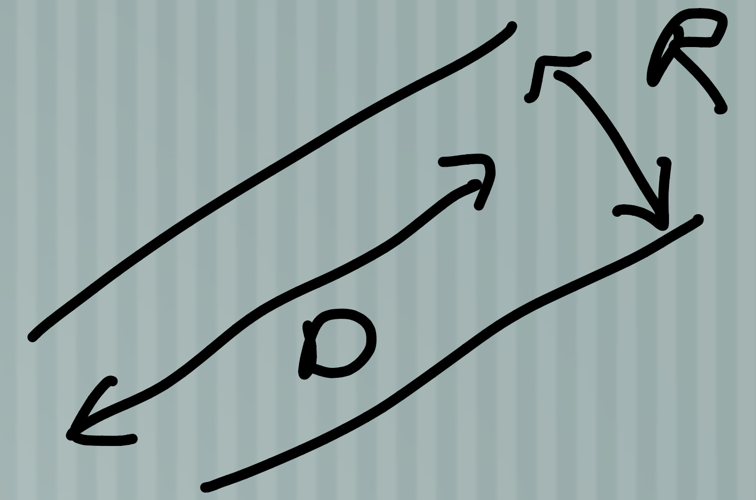
Some useful simple scalings for "flat" (synch.self-absorbed) jet cores

"Ancient days of AGN observing" [Longair, Falcke + Biermann]

$$\tau_{SSA} \sim 1.6 \times 10^{-3} \left(B_{mG}\right)^{4} \left(R_{los,kpc}\right) \nu_{GHz}^{-3}$$

When look at optically thick objects → only see "in" ≈ $1/\alpha_\nu$

$\tau = 1$ surface = "photosphere"



Solve + assumptions about geometry:

(1) $\nu_{SSA} \sim 100\ \text{MHz} \left(B_{mG}\right)^{4/3} \left(R_{los,kpc}\right)^{1/3}$

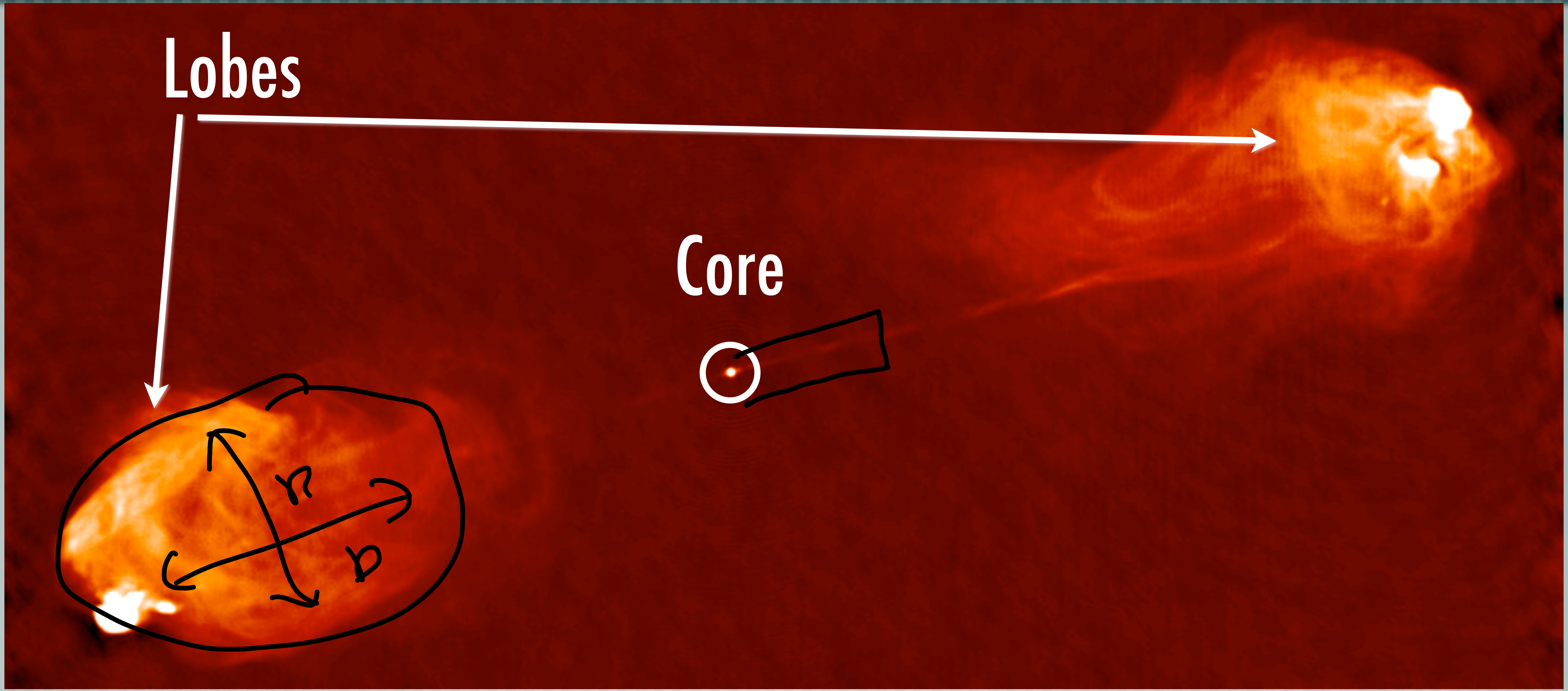
(2) $\nu_{SSA} \sim 0.2\ \text{MHz} \left(S_{\nu,Jy}\right)^{8/17} \left(D/R\right)^{8/17} R_{kpc}^{-9/17}$

Bright AGN, $S_\nu \sim 1$ Jy

Example: Cygnus A (again), the famous radio galaxy

$\nu_{SSA} \ll 0.2$ MHz

$D \sim R$



Core/inner jet

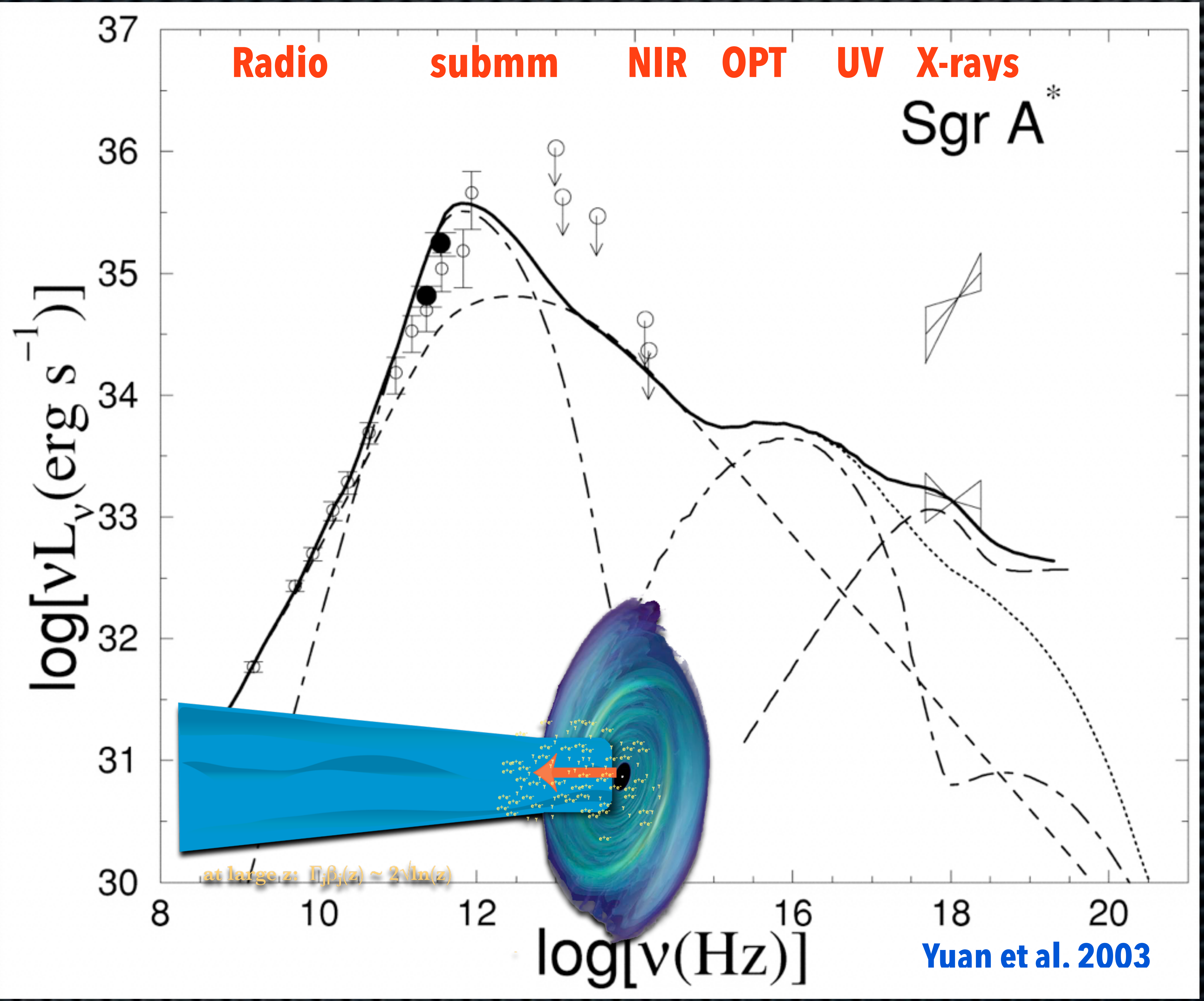
$R \ll D$

$\nu_{SSA} \gg 0.2$ MHz

→ mm band

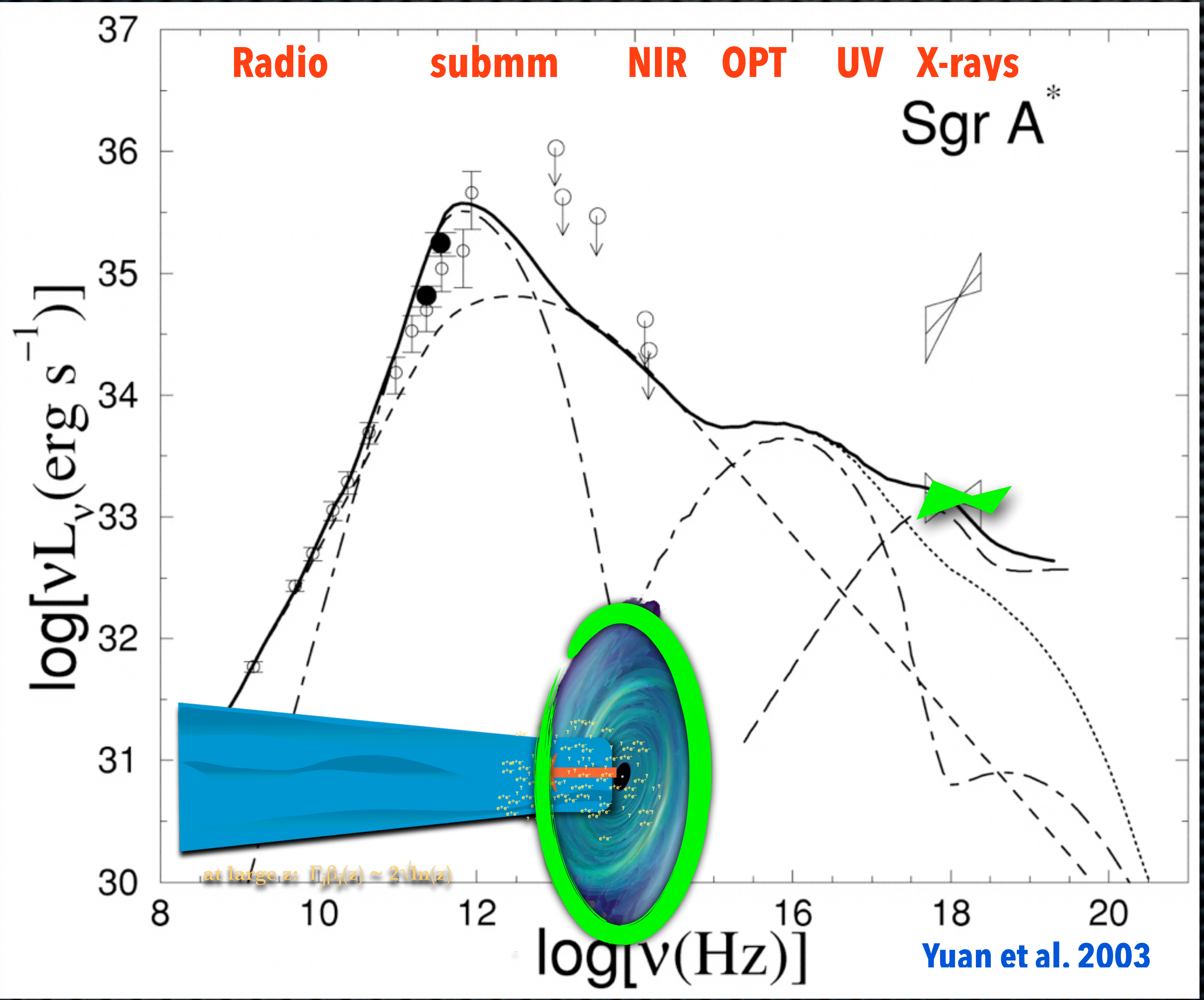
$S_\nu \sim 1$ Jy $\rightarrow$ $\nu_{SSA} \sim 0.2\ \mathrm{MHz}\ (D/R)^{8/17}\ R^{-9/17}$

Sgr A* spectrum – all the "ins" and "outs"

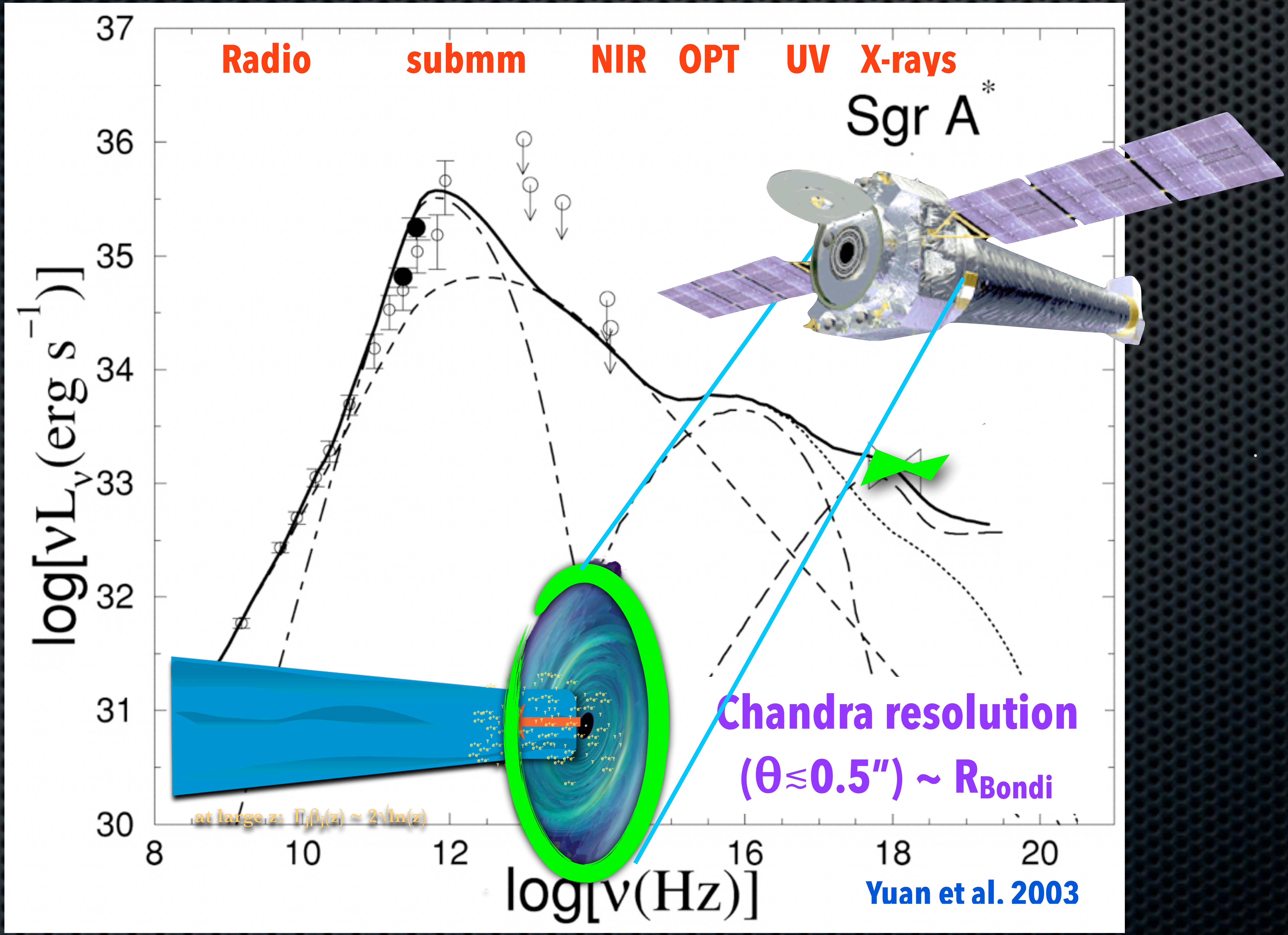


Yuan et al. 2003

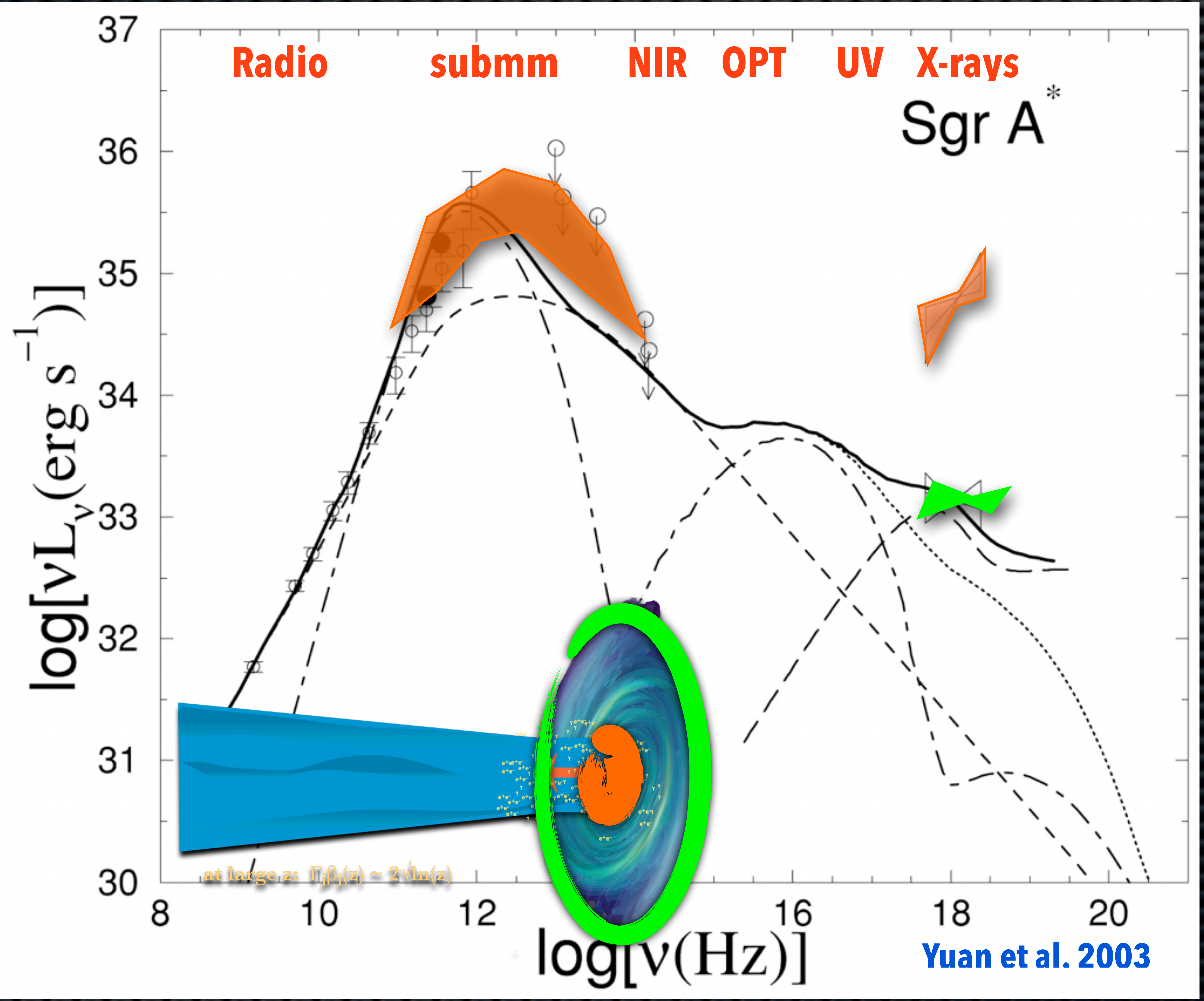
Sgr A* spectrum – all the "ins" and "outs"



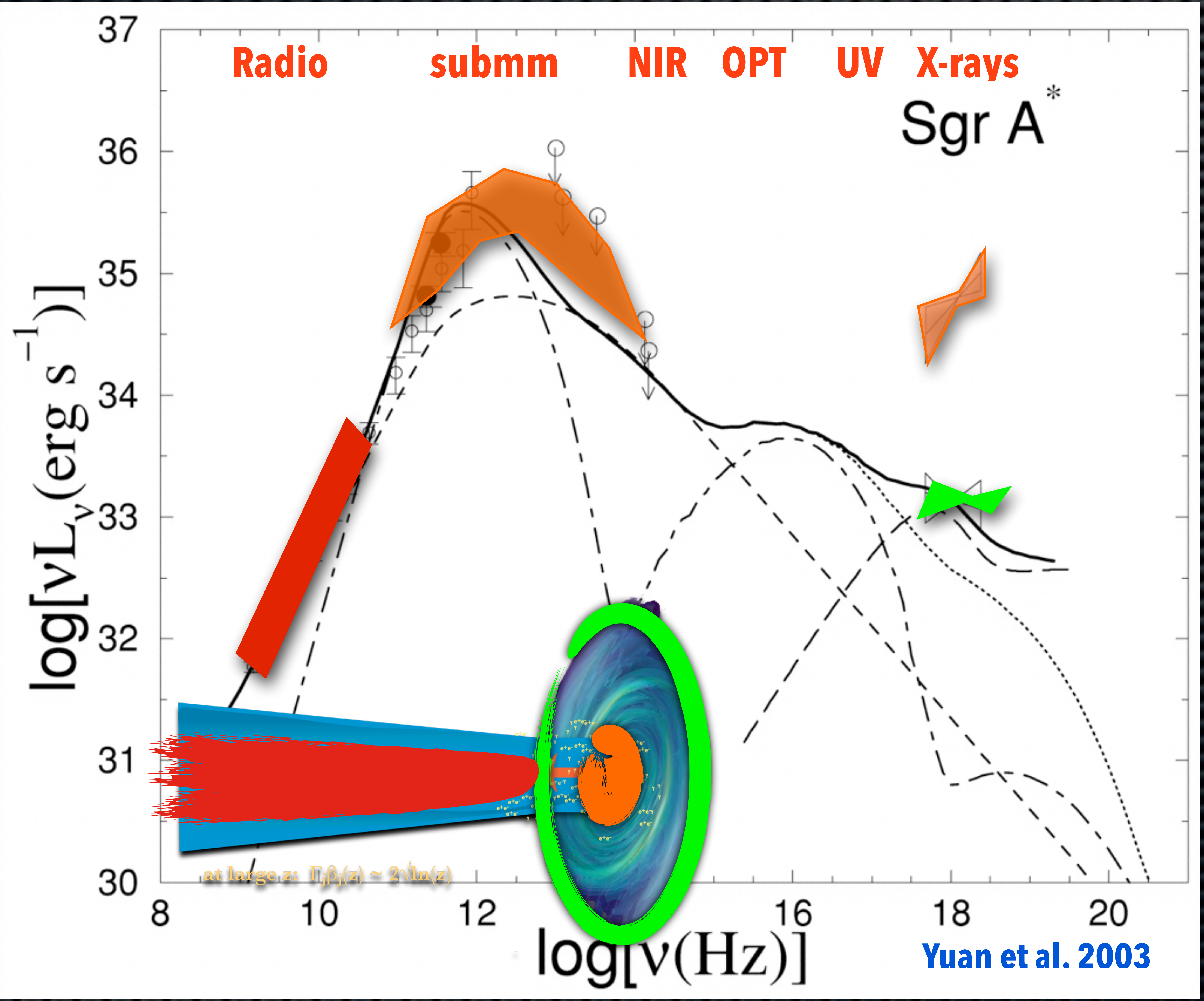
Sgr A* spectrum – all the "ins" and "outs"



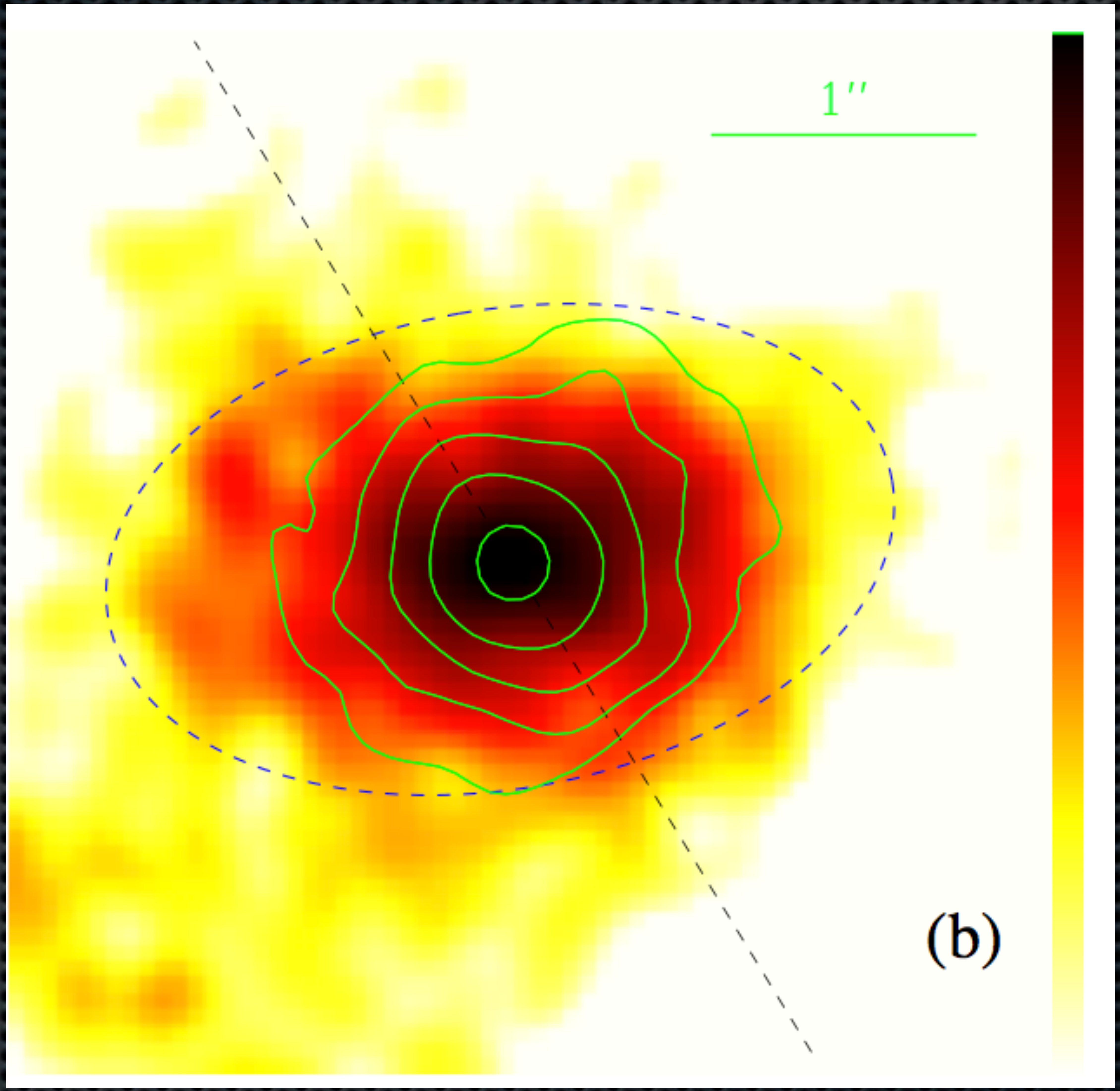
Sgr A* spectrum – all the “ins” and “outs"



Sgr A* spectrum – all the "ins" and "outs"

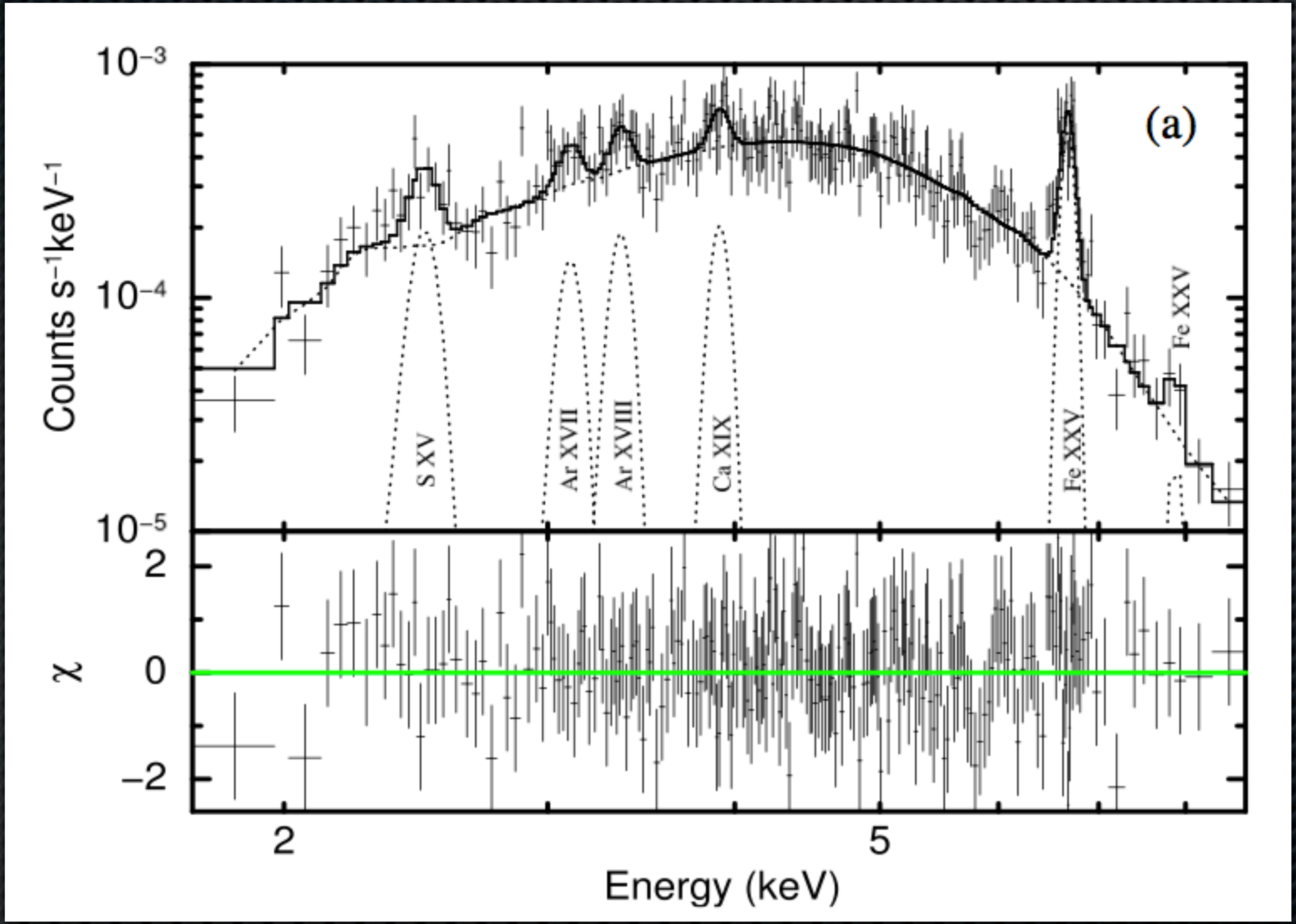


First (and deepest) Chandra-HETG observations of Sgr A*:
Evidence for elongation of quiescent emission



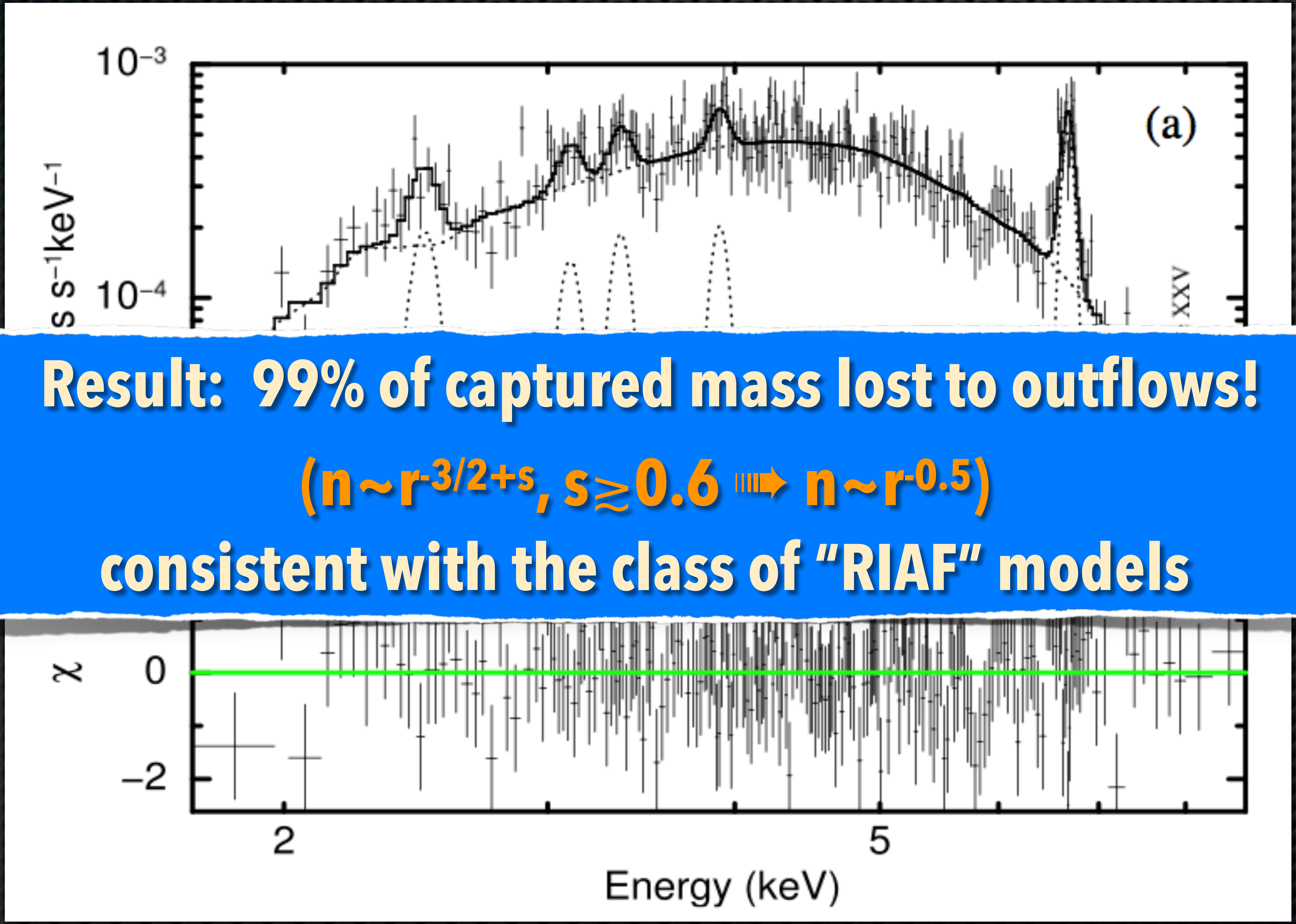
(Wang, Nowak, SM++, Science, 2013)

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



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

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



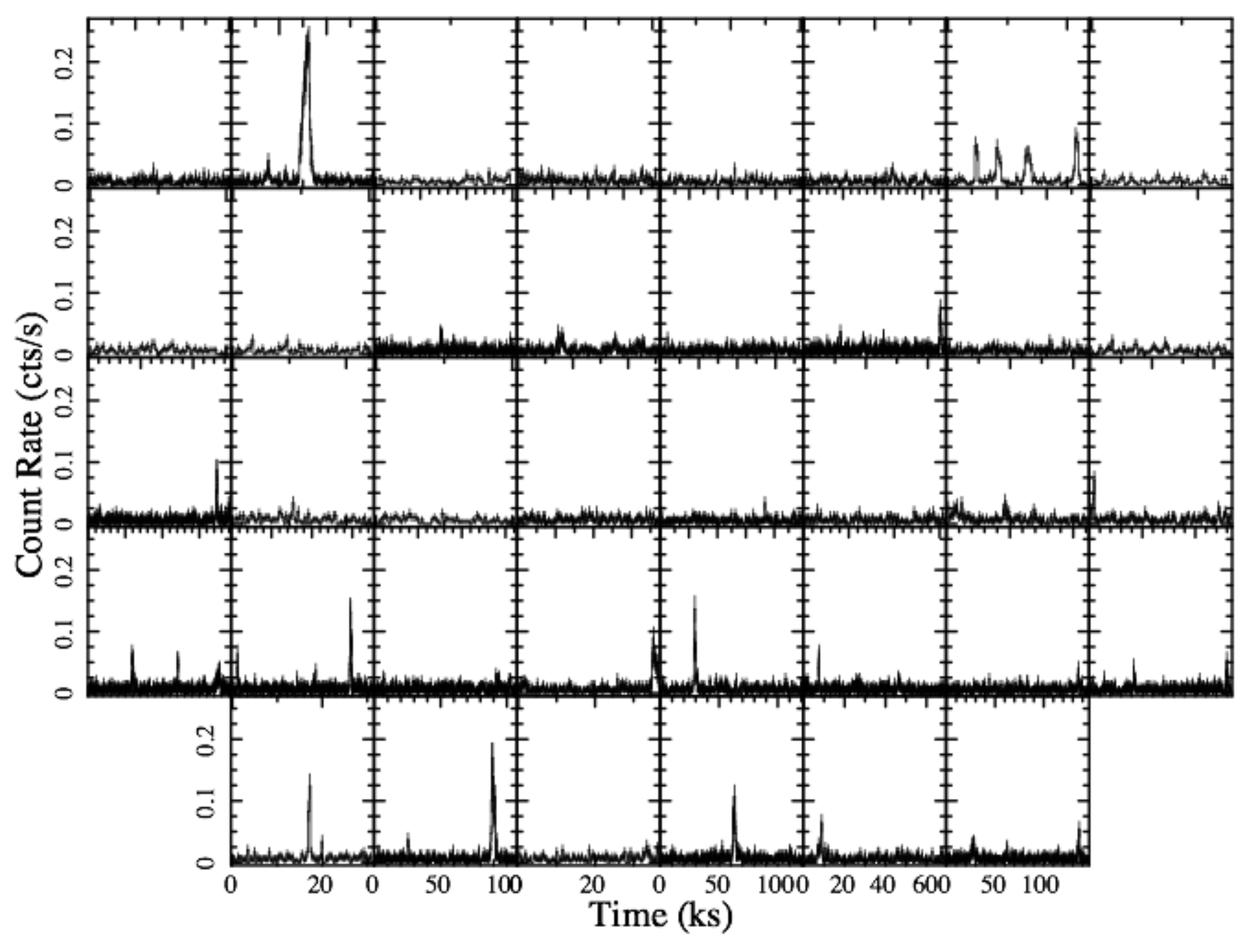
Result: 99% of captured mass lost to outflows!

($n \sim r^{-3/2+s}$, $s \gtrsim 0.6 \Rightarrow n \sim r^{-0.5}$)

consistent with the class of "RIAF" models

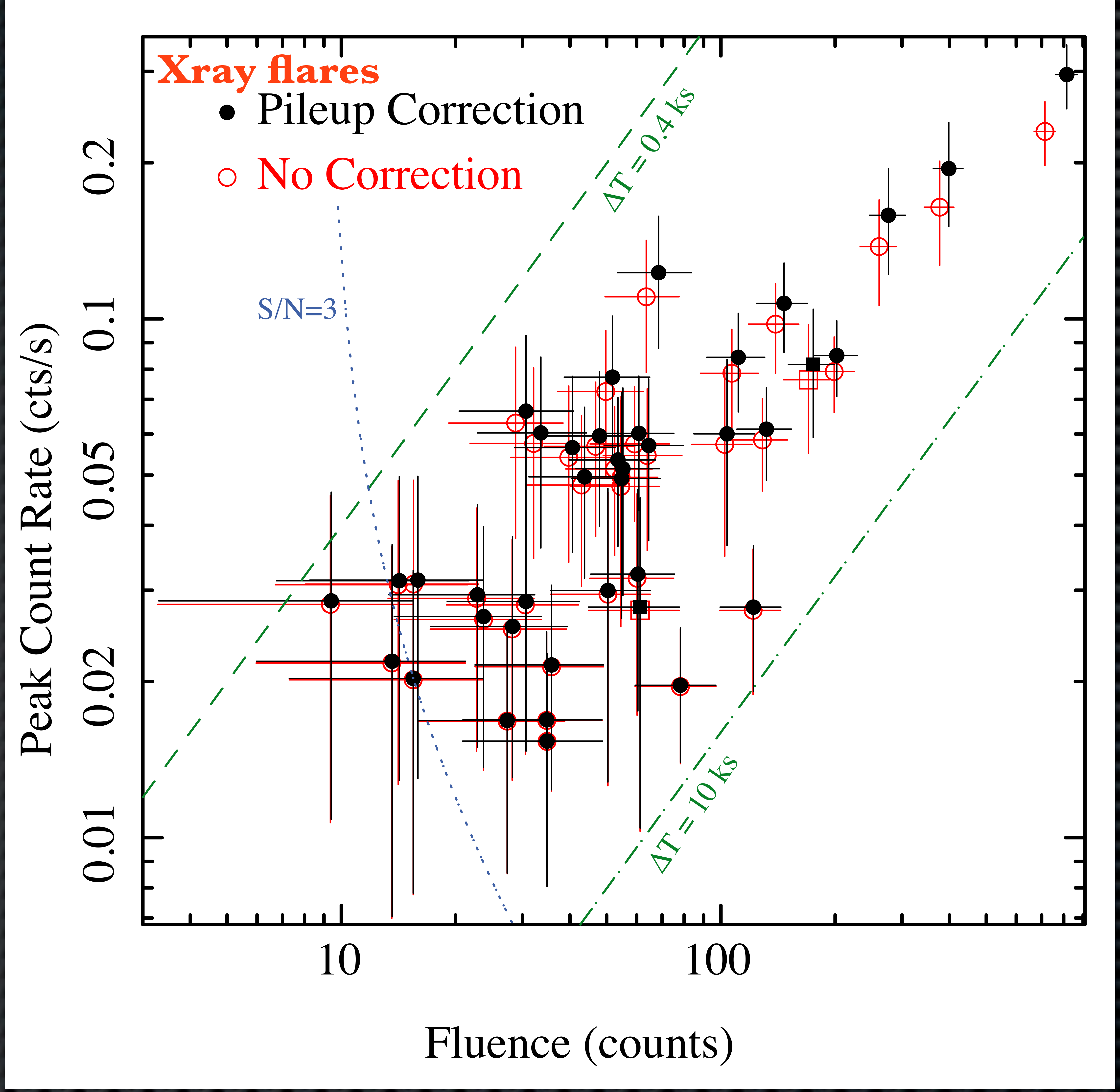
(Wang, Nowak, SM++, Science, 2013)

Sgr A* experiences ~daily nonthermal flaring



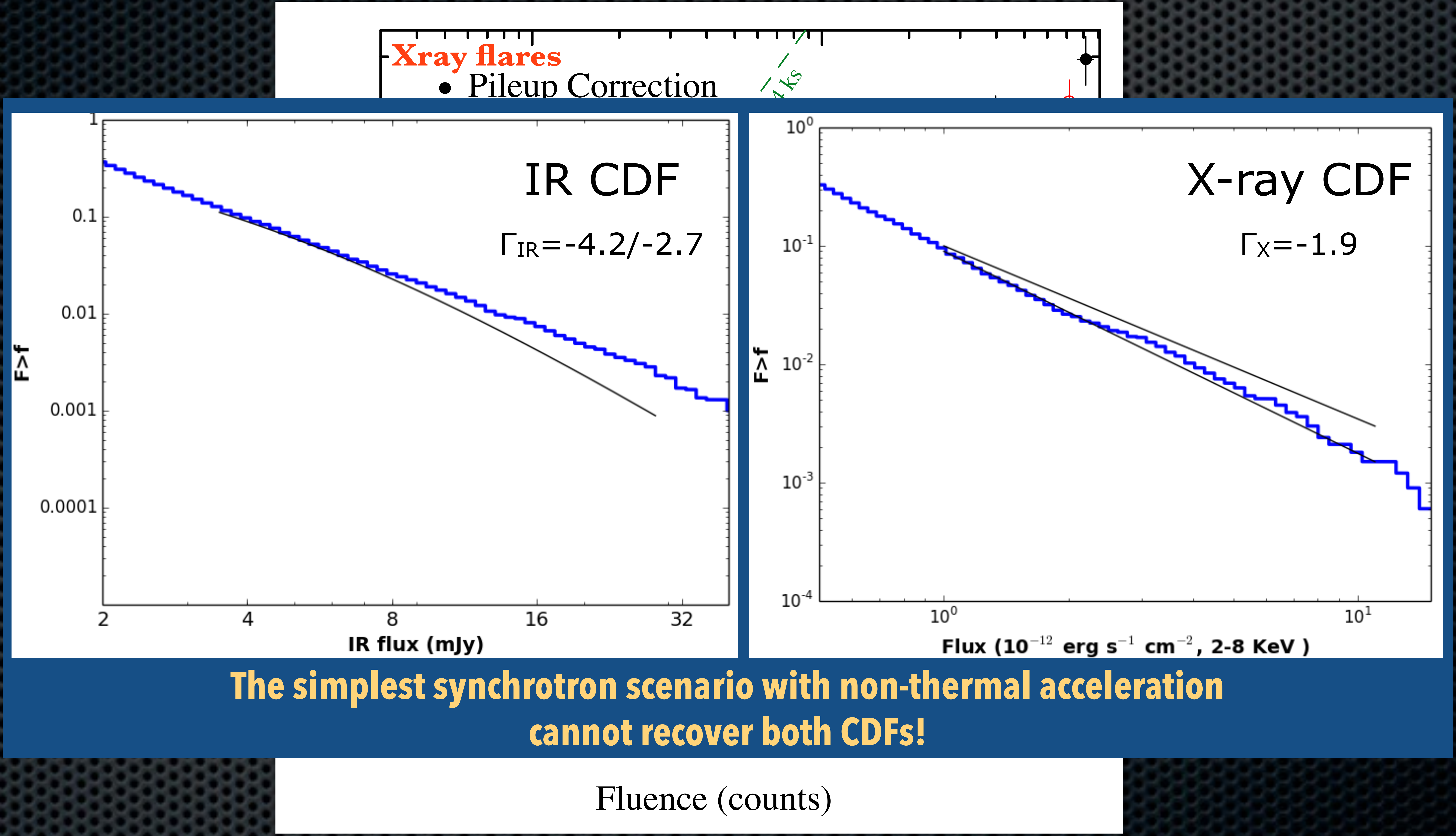
(Nielsen++ 2013)

Variability & plasma constraints:
Finally enough flares to perform statistics!



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

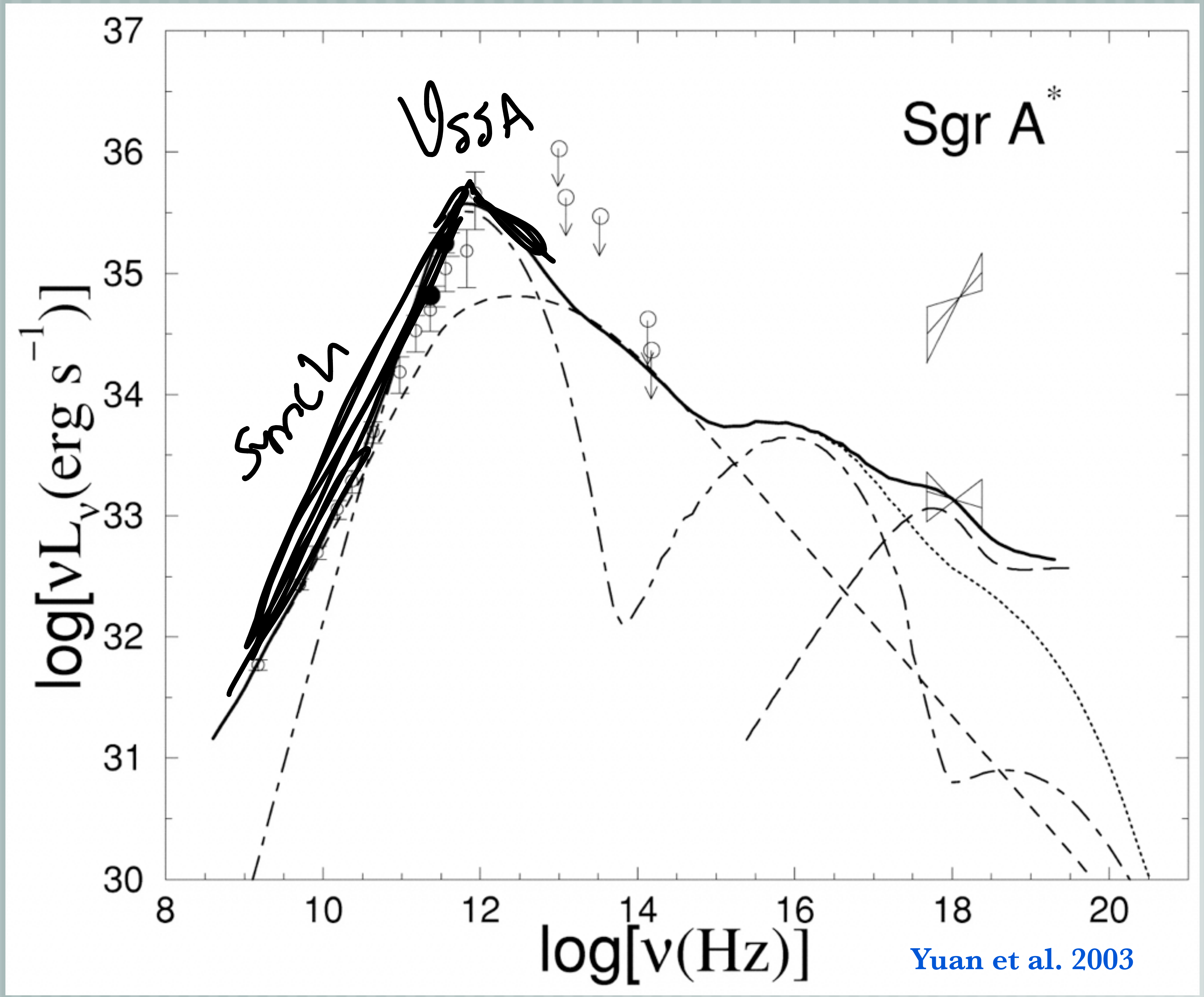
Variability & plasma constraints:
Finally enough flares to perform statistics!



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

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

Sgr A*: Which synchrotron formula can you already use?



Yuan et al. 2003

$$P_{\rm syn,e} = \frac{4}{3}\sigma_T c \gamma_e^2 \beta^2 U_B$$

const. $\quad U_B = B^2/8\pi$

$$\nu_c = \frac{3}{4\pi}\gamma^3 \omega_B \sin\alpha$$

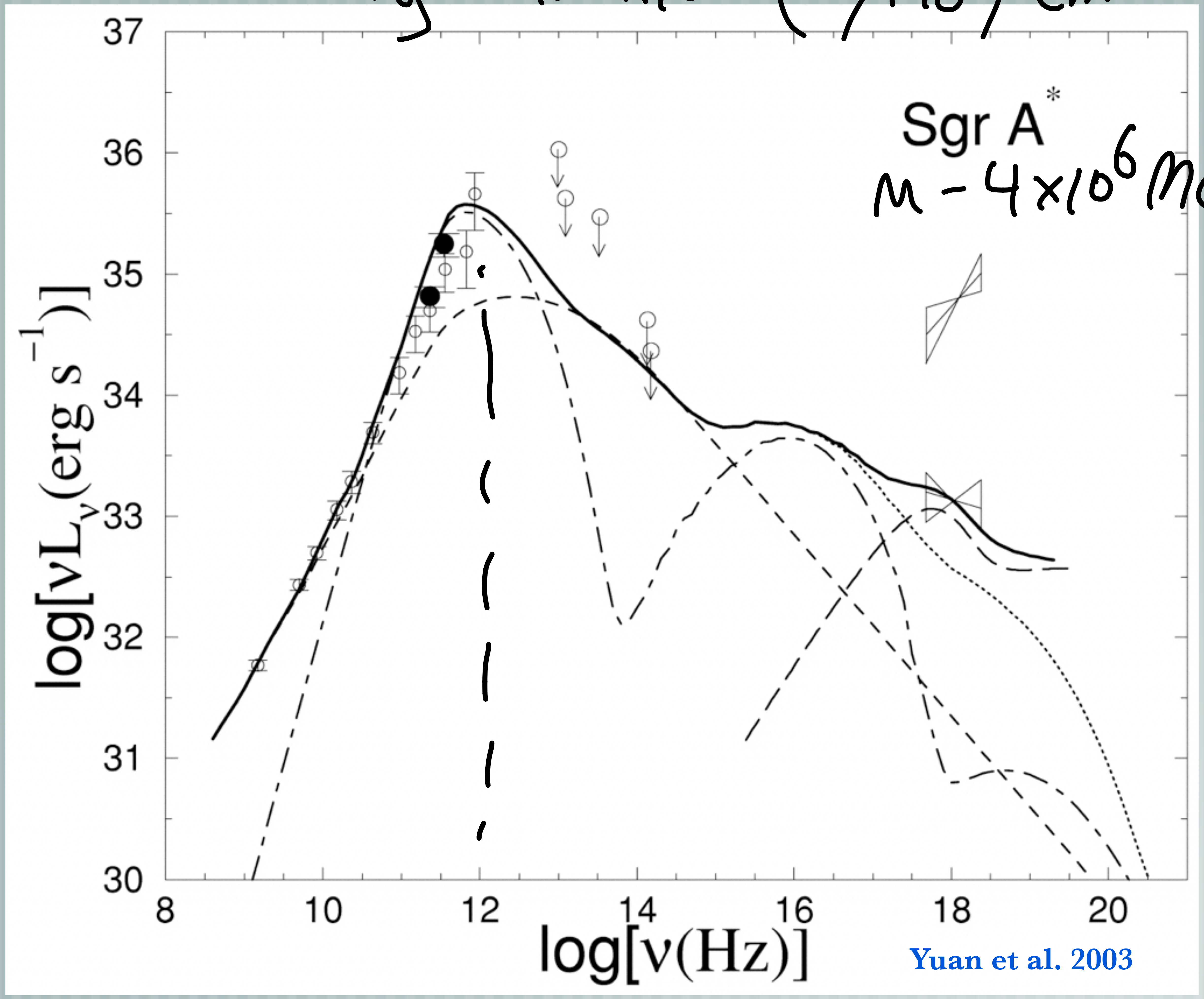
$\omega_B = \frac{1}{\gamma}\frac{eB}{mc}$

$$\nu_{\rm SSA} = 100\ {\rm MHz}\,(B_{\rm mG})^{4/3}\,(R_{\rm los,kpc})^{1/3}$$

$R_{\rm los,kpc} = 10\, r_g$

Sgr A* an AGN like others?: ν_{SSA}

$r_g = 1.5\times10^5 \,(M/M_\odot)$ cm



$M \sim 4\times10^6 M_\odot$

$\nu_{SSA} \sim 100_{\,MHz} \,(B_{mG})^{4/3} R_{kpc}^{1/3}$

cgs

$10^{12} \sim 10^8\,\mathrm{Hz}\,(B_{mG})^{4/3} \left[\frac{10\cdot1.5e5\cdot4e6}{3e21}\right]^{1/3}$

$10^{[1+11.6-21.5]/3} \sim 10^{-3}$

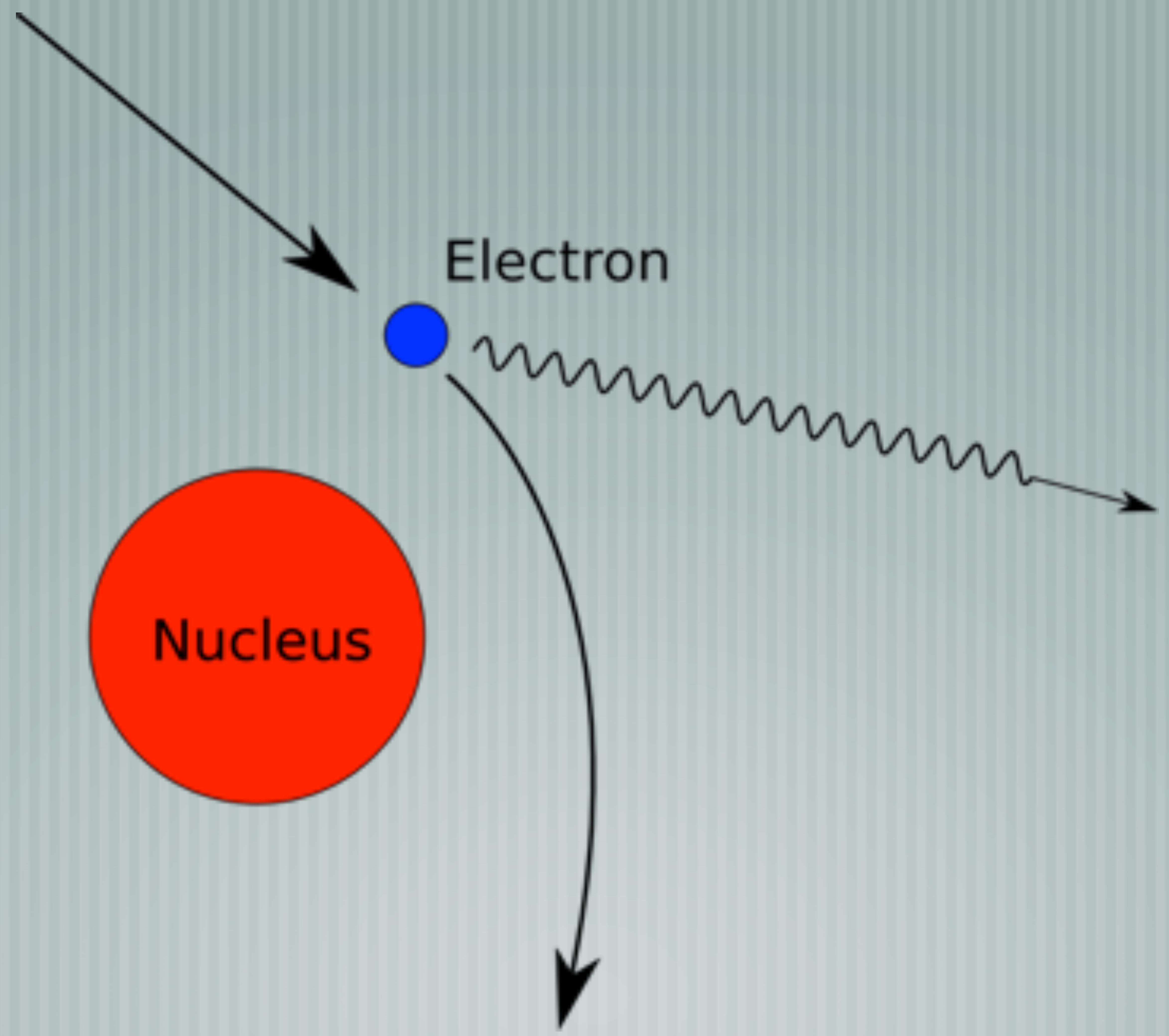
$B_{mG} \sim \left(10^{4+3}\right)^{3/4} \sim 10^{21/4}$

$\sim 10^5\,{}_{mG}$

~ 100 G

reasonable?

Bremsstrahlung



Bremsstrahlung

Radiation emitted as a particle de/accelerates in the Coulomb field of another charge

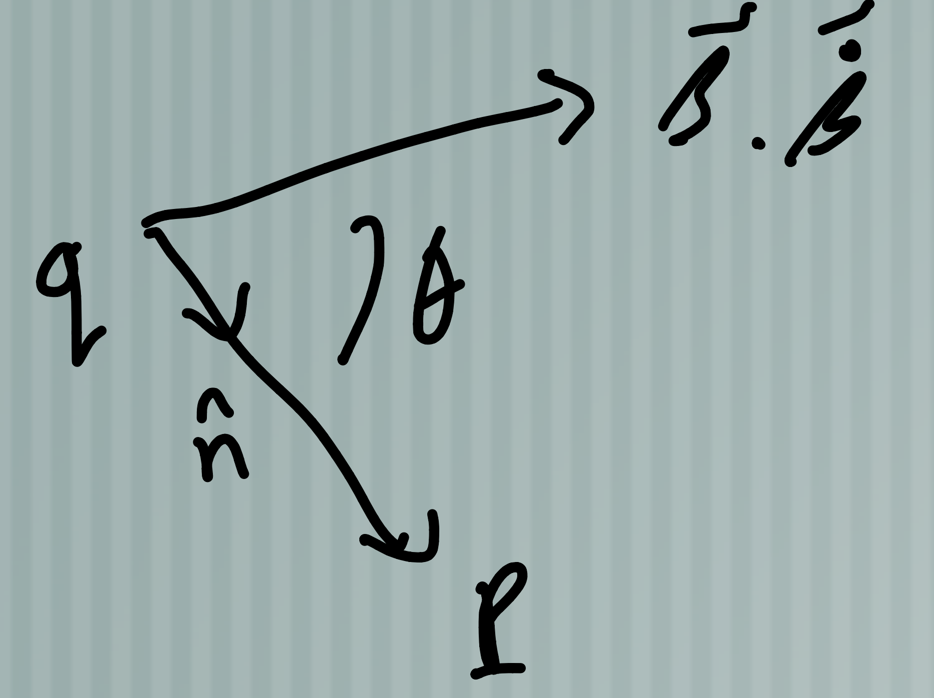
- "Braking radiation", also called "free-free" emission
- QED process, but we can go pretty far with classical picture using dipole approximation for case of e-ion interactions
- If interested in seeing the real derivations:
  - e-p: Karzas & Latter 1961 ApJ Suppl., 6, 167
  - e-e+: Haug 1987, A&A, 178, 292
  - e-e: Haug 1989, A&A, 218, 330

What happens to dipole radiation pattern in the relativistic case?

$$\frac{dP}{d\Omega} = \frac{dW}{dt\,dA} = \frac{dW'}{dt'\,dA}\frac{dt'}{dt} = \left[\frac{dP}{d\Omega}\right]_{ret} \kappa = R^2\left[\vec{S}'_{rad}\right]\kappa = \frac{R^2 c}{4\pi}\left[\vec{E}'_{rad}\right]^2 \kappa$$

$$= \frac{q^2}{4\pi c}\left[\frac{\hat{n}\times\{(\hat{n}\times\{(\hat{n}-\vec{\beta})\times\dot{\vec{\beta}}\}\}}{(1-\hat{n}\cdot\vec{\beta})^5}\right]^2_{t'}$$

let's consider $\vec{\beta} \parallel \dot{\vec{\beta}}$

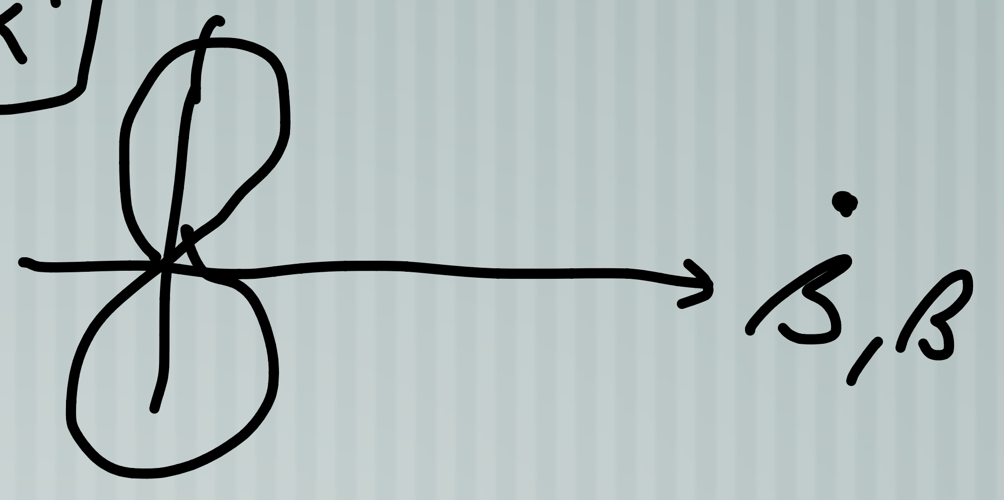


$$n\times\dot{\beta} = \dot{\beta}\sin\theta$$
$$n\times\beta = \beta\sin\theta$$
$$n\cdot\beta = \beta\cos\theta$$

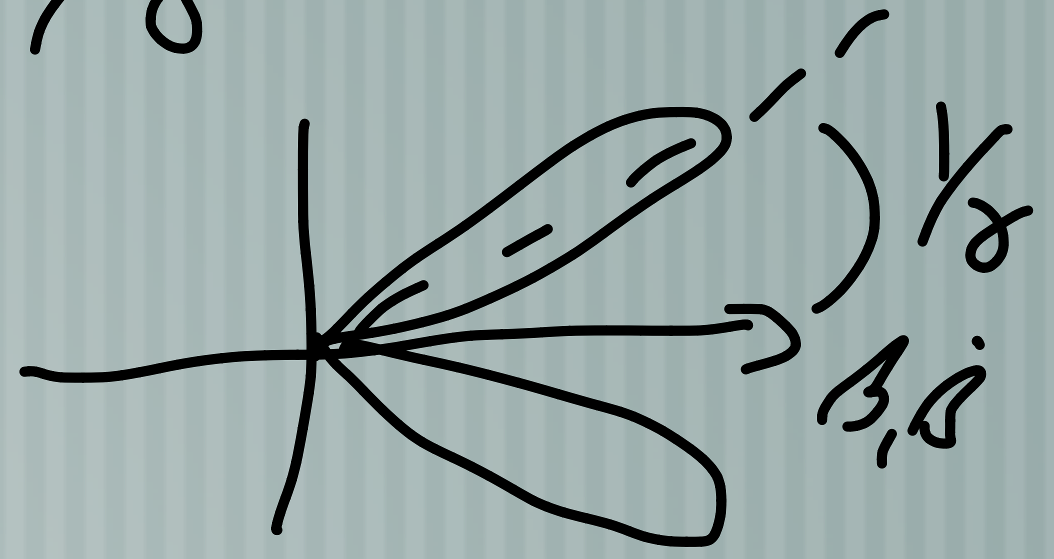
$$\frac{dP}{d\Omega} = \frac{q^2}{4\pi c}\frac{\dot{\beta}^2\sin^2\theta}{(1-\beta\cos\theta)^5} \Rightarrow \text{small}$$

Solve max $\frac{dP}{d\Omega} \Rightarrow \theta \sim 1/\gamma$

$\boxed{K'}$



$\xrightarrow[\text{lab}]{}$



Relating frequency to particle acceleration via dipole approximation

want : $\mathcal{E}_\nu = \dfrac{dW}{dt\,d\omega\,dV\,d\Omega} = \underbrace{\dfrac{dP}{d\Omega}}_{\text{rad.}} \cdot \underbrace{\dfrac{1}{dV}}_{\text{geom}} \cdot \underbrace{\dfrac{1}{d\omega}}_{\text{time info}}$ $\Longrightarrow$ Fourier?

want $\dfrac{dW}{d\omega}$

$\omega = 2\pi\nu$

Larmor's fm. $\dfrac{dP}{d\Omega} = \dfrac{\ddot{d}^2 \sin^2\theta}{4\pi c^3} = R^2 \dfrac{c}{4\pi} |E_{rad}|^2$

So $|E_{rad}| = \dfrac{\ddot{d} \sin\theta}{c^2 R}$

$\ddot{d} = qc\dot{\beta}$

Fourier of $\ddot{d}$

$$d(t) = \int_{-\infty}^{\infty} \hat{d}(\omega)\, e^{-i\omega t}\, d\omega$$

$$\ddot{d}(t) = \int_{-\infty}^{\infty} (-\omega^2)\, \hat{d}(\omega)\, e^{-i\omega t}\, dt$$

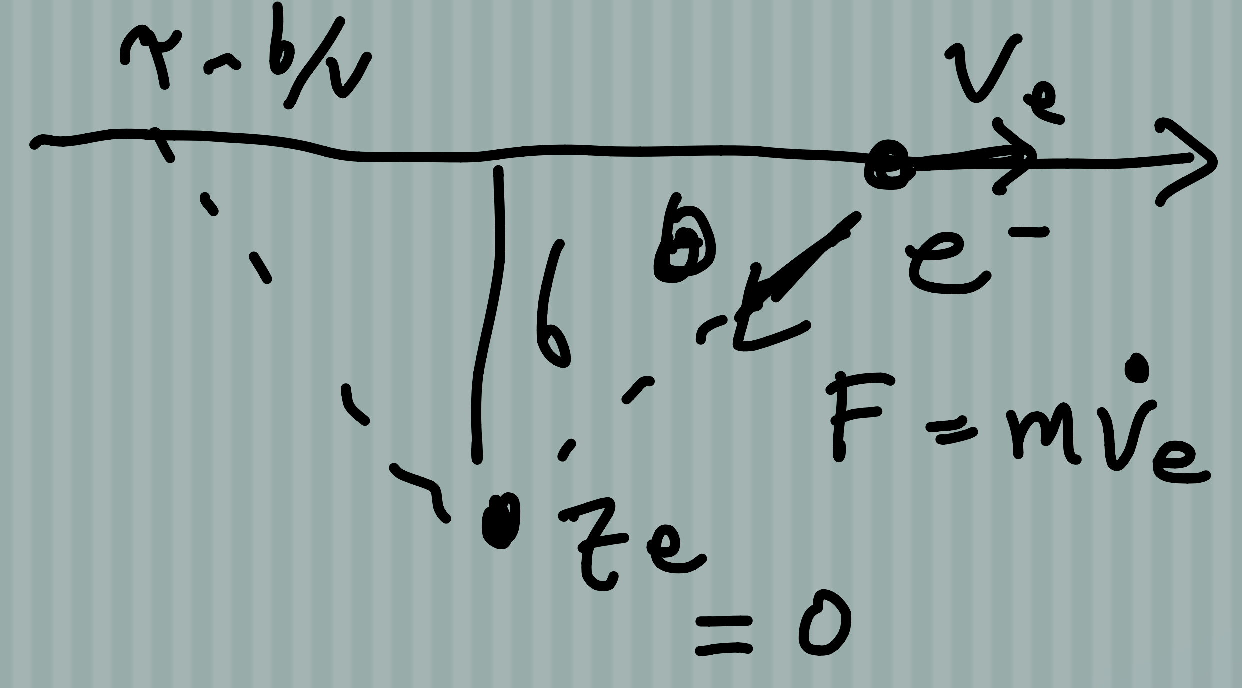
infer : $\tilde{E}_{rad}(\omega) \simeq \dfrac{\tilde{d}(\omega)(-\omega^2)\sin\theta}{c^2 R}$

$$\frac{dW}{d\omega\, d\Omega} \propto R^2 \frac{c}{4\pi} |\tilde{E}(\omega)|^2 = \underbrace{\frac{\tilde{d}(\omega)^2 \omega^4 \sin^2\theta}{4\pi c^3}}$$

$$\frac{dW}{d\omega} \sim \int \frac{dW}{d\omega\, d\Omega}\, d\Omega = \left(\frac{8\pi}{3}\right)$$

$\rightarrow$ except 4π because of Parsevals Thm –

Semi-classical "dipole" approximation for bremsstrahlung



$\vec{d} = -e\vec{r}_e$ so $\ddot{\vec{d}} = -e\dot{v}_e$

$$\ddot{d}(t) = \int_{-\infty}^{\infty} (-\omega^2)\,\tilde{d}(\omega)\,e^{-i\omega t}$$

impact $\longrightarrow$ $(-\omega^2)\,\hat{d}(\omega) = \frac{1}{2\pi}\int_{-\cancel{\infty}\ -\tau}^{\cancel{\infty}\ \tau} \ddot{d}(t')\,e^{i\omega t'}\,dt'$

$\tau \ll 1/\omega$

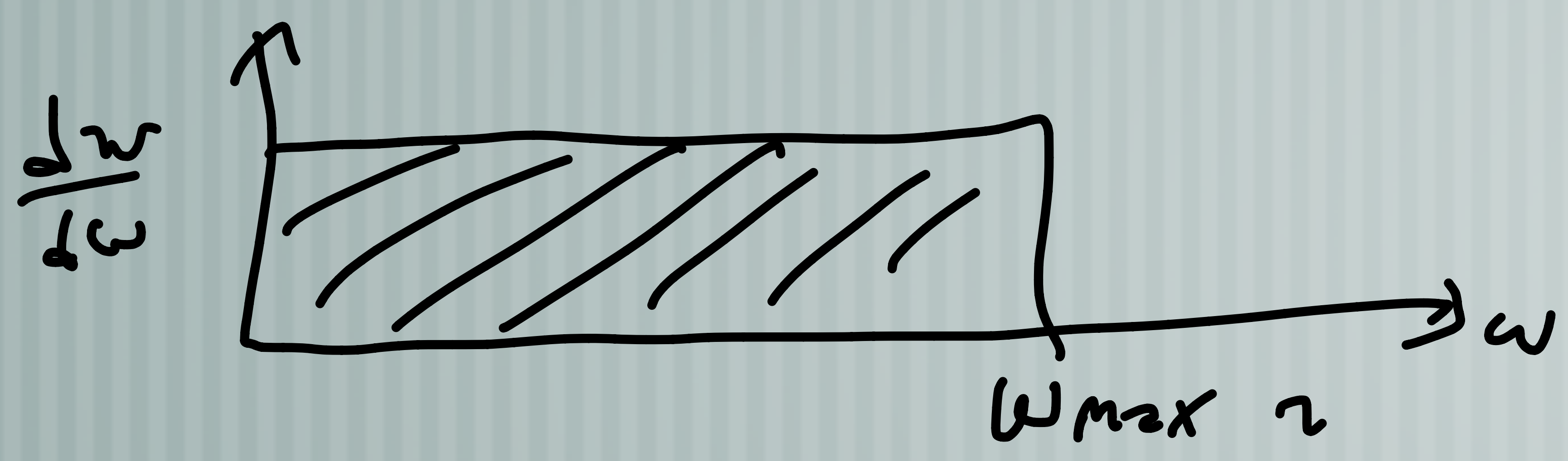
$e^{i\omega\tau} \sim 1$

$F = m\dot{v}_e = -\frac{Ze^2}{r^2}$

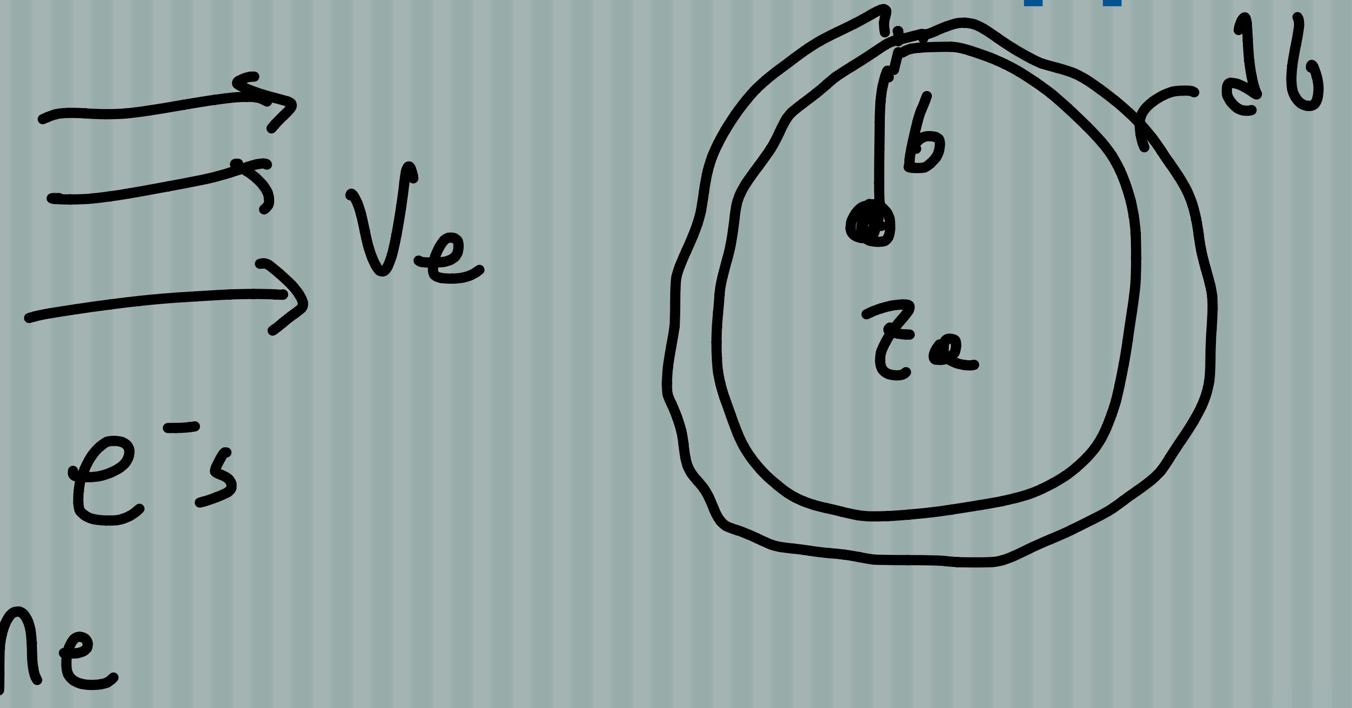
$$\simeq \frac{1}{2\pi}\int_{-\tau}^{\tau} -e\,\dot{v}_e(t')\,dt'$$

Small angle $\Rightarrow$ $-(\omega^2)\,\hat{d}(\omega) \simeq \frac{e}{2\pi}\,\frac{2Ze^2}{mvb}$

so: $\frac{dW}{d\omega} = \frac{8\pi}{3}\,\frac{\omega^4}{c^3}\,|\hat{d}(\omega)|^2 = (\text{const})\,\frac{Z^2e^4}{m^2v^2b^2}$



Application: astrophysical thermal plasma n_e, n_i, T



How many e^-'s go through ring $n_e v \cdot 2\pi b\, db$

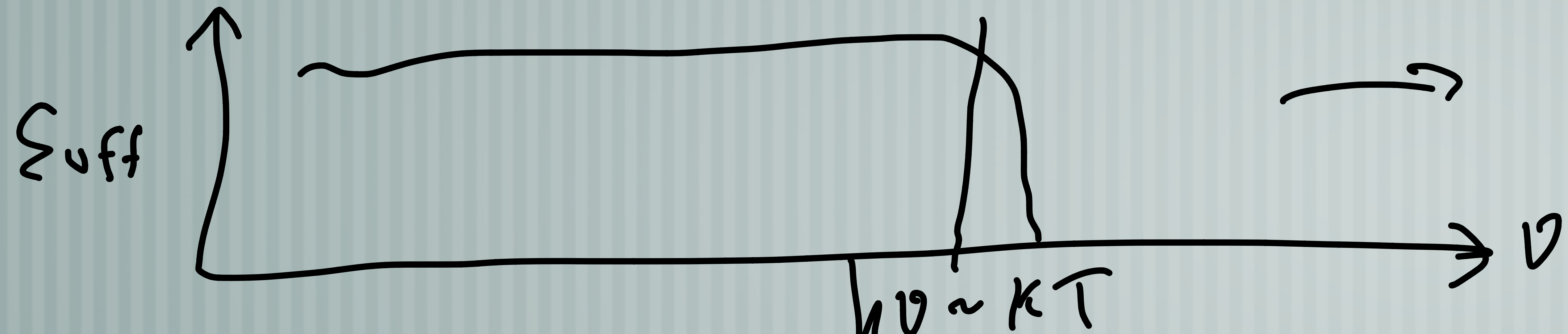
$$\frac{dW}{d\omega\, dt} \text{ per ion} = \int_{b_{min}}^{\infty} \frac{dW}{d\omega} \cdot n_e v_e 2\pi b\, db$$

If n_i = # ion/cm^3 ⇒ emission $\displaystyle \frac{dW}{dt\, d\omega\, dV} = n_e n_i 2\pi v_e \int_{b_{min}}^{b_{max}} (\ ) \frac{1}{b}\, db$

We don't b_{min}/b_{max} but $\ln(?) < ?$ $\quad \Delta x \Delta p \geq \hbar$, $\quad b m v \geq \hbar$

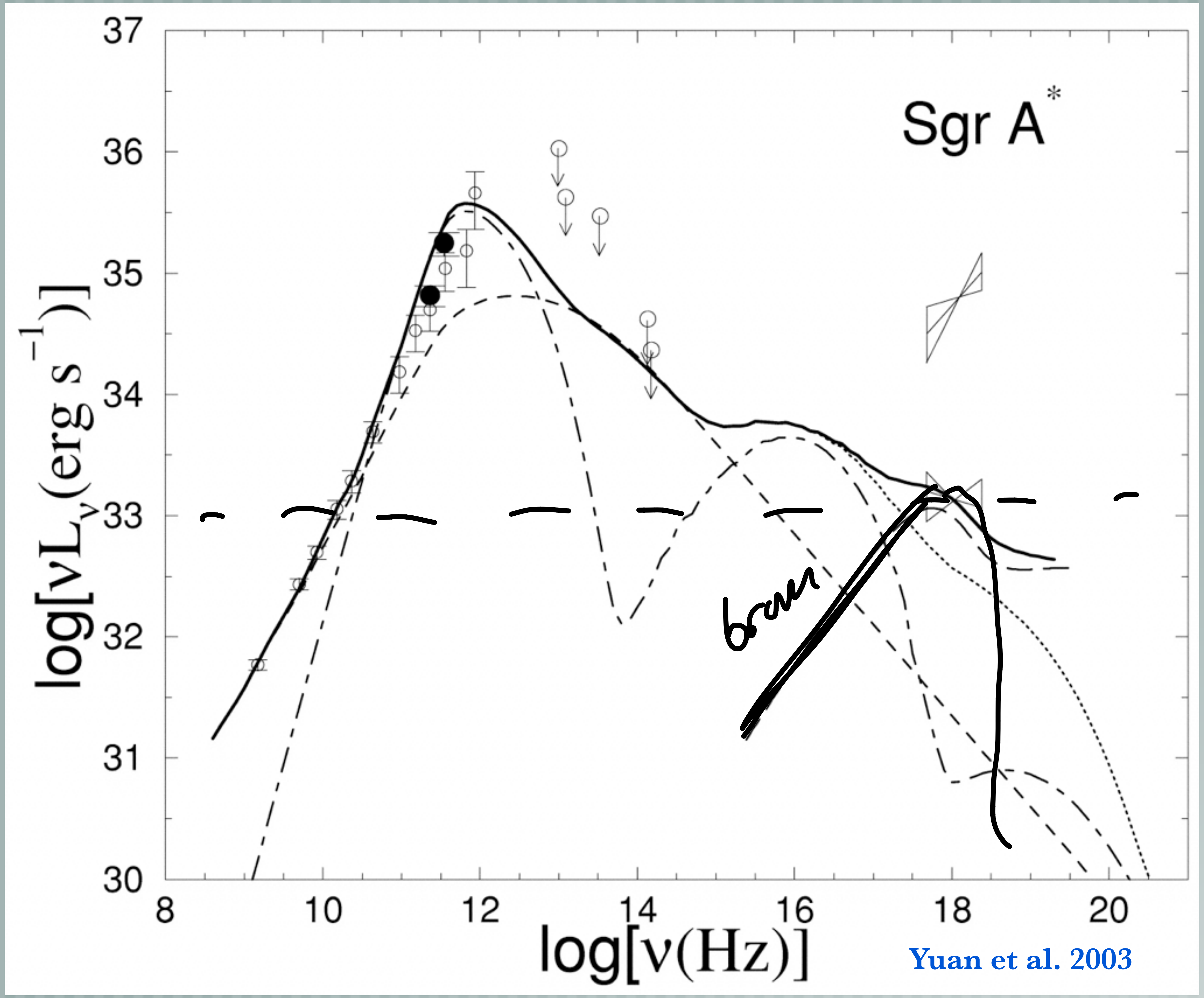
QED → integrate + av. M-B distn v's $\quad$ QED ⇒ Gaunt

$$\epsilon_\nu^{ff} \simeq 7 \times 10^{-38} Z^2 n_e n_i T^{-1/2} e^{-h\nu/kT} \overset{(1-5)}{\bar{g}_{ff}} \quad \text{erg/cm}^3\text{/s/Hz}$$



→ big diagnostic

Sgr A*: What's the T?



$T_{plasm} \Rightarrow h\nu = h(10^{18.5}) = kT$

$= 4 \times 10^{7}\ K^{o}$

$R_A \sim 10^{5} r_g \sim 10^{17.5}$ cm

$(n_e = n_i = n)$

$L_x \sim 10^{33}$ erg/s $= \varepsilon_\nu^{ff} \cdot \nu \cdot Vol$

$n \sim 10^{[33 - 0.85 + 38 + 3.8 - 18 - 52.5 - 0.6]/2}$

$\sim 1.5\ \#/cm^{3}$

$c_s \sim$ few $\times 10^{7}$ cm/s $\quad n = \dfrac{\dot{M}}{4\pi R^2 c_s m_p}$

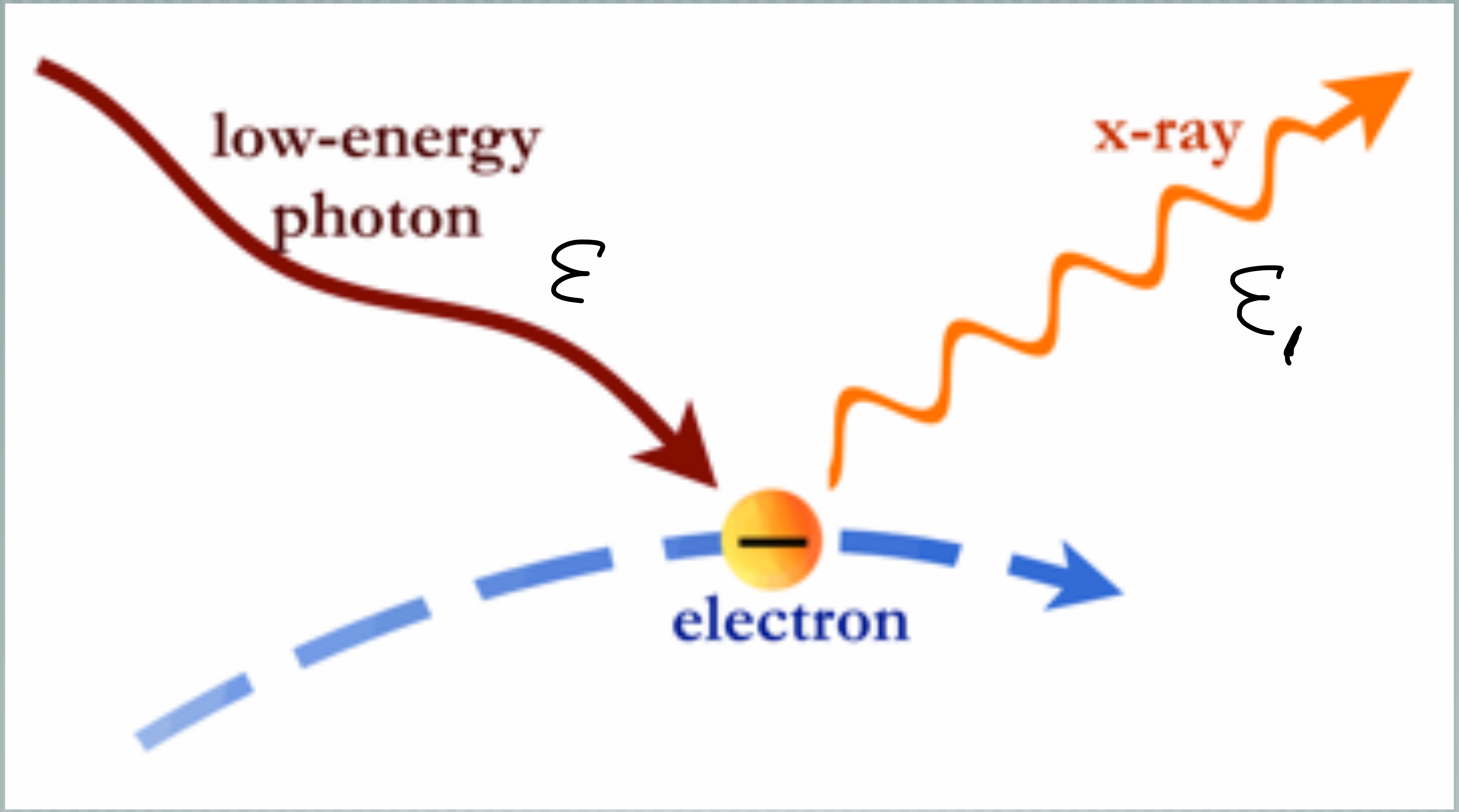
$\dot{M} \sim 10^{-6}\ M_\odot/yr$

Chandra 99% lost so $\dot{M}_{BH} \sim 10^{-8}\ M_\odot/yr$

independently → Faraday rotation → $10^{-9} - 10^{-7}\ M_\odot/yr$

efficiency? $\varepsilon_\nu^{ff} \propto \dot{m}^2$ → fits!

Inverse Compton Pt I



Relativistic scattering: Klein-Nishina & recoil

$$\left.\frac{d\sigma}{d\Omega}\right)_{KN} = \frac{r_0^2}{2}\left(\frac{\varepsilon_1}{\varepsilon}\right)\left(\frac{\varepsilon}{\varepsilon_1} + \frac{\varepsilon_1}{\varepsilon} - \sin^2\theta\right)$$

$\boxed{K'}$ rest of e^-

$$\varepsilon_1' = \frac{\varepsilon'}{1 - \frac{\varepsilon'}{mc^2}(1-\cos\theta_1')}$$

if $\overset{=\varepsilon}{h\nu} \ll E_e$ in lab frame

K': $\underset{\varepsilon'}{\underset{\shortparallel}{h\nu'}} < mc^2 \Rightarrow$ Thompson

"no recoil"

$$\varepsilon_1' = \varepsilon'$$

$$\varepsilon_1 = \frac{\varepsilon(1-\beta\cos\theta)}{(1-\beta\cos\theta_1)}$$

Inverse Compton (IC) scattering: energy gain

$$\varepsilon_1 = \frac{\varepsilon(1-\beta\cos\theta)}{(1-\beta\cos\theta_1)}$$

$$\varepsilon_{1,max} = \frac{\varepsilon(1+\beta)}{(1-\beta)} \times \frac{(1+\beta)}{(1+\beta)} = \varepsilon(1+\beta)^2\gamma^2$$

$N \Rightarrow \theta \to \pi$

$D \Rightarrow \theta \sim 0$

$1-\beta^2 = 1/\gamma^2$

$\beta \simeq 1$ $\quad \varepsilon_{1max}$ (head-on) $\sim 4\gamma^2\varepsilon \rightarrow$ important!

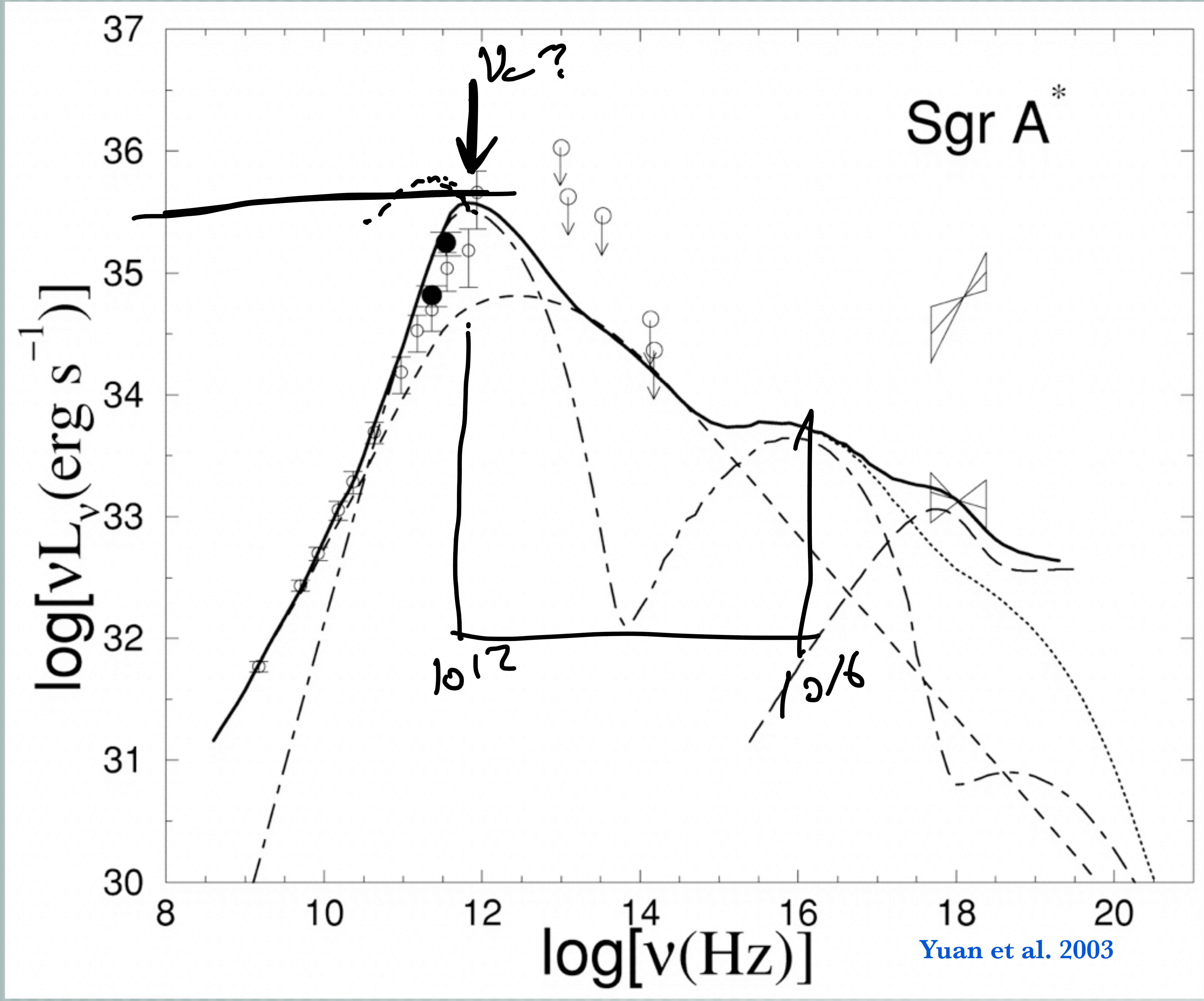
hard limit $\varepsilon_{1max} < E_e$

$\langle \varepsilon_{1,max} \rangle \sim \frac{4}{3}\gamma^2\varepsilon$

ε_{1min} (tail-on) $\sim \frac{1}{4\gamma^2}\varepsilon$

$\varepsilon : \varepsilon_1' : \varepsilon_1 \Rightarrow 1 : \gamma : \gamma^2$

Sgr A*: SSC (synchrotron-self Compton)



$\langle \varepsilon_{1,max} \rangle \sim \frac{4}{3}\gamma^2 \varepsilon$

$10^4 \sim \frac{4}{3}\gamma^2 \sim \langle \gamma_e \rangle \sim 87$

$$\nu_c = \frac{\frac{3}{4\pi}(87)^2\, 5.\times 10^{-10}\, B}{9.e^{-28}\ 3.e10}$$

$B \sim 30\ G$

know $\dot{m} \sim 10^{-8}\ M_\odot/yr$, $G_{BH} \sim 0.4c$

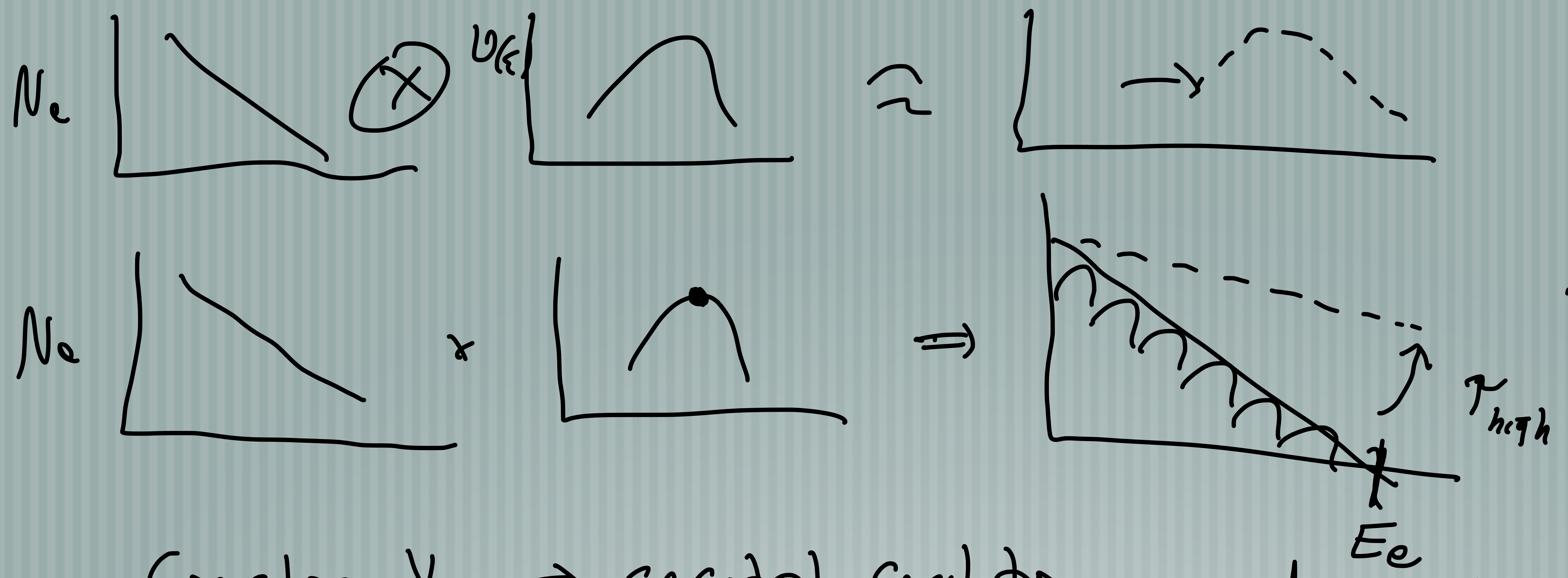
$\hookrightarrow n_{BH},\ \gamma$

$P_{synch,tot} = (n, B, \gamma) = 10^{35.5}$

$\downarrow$

solve B

Spectrum and Compton Y parameter



Single scatt
(semi-analytical)

→ MC!

amplification

Compton Y ⇒ spectral evolution → $N_{scatt}(\tau)$, $\eta = \frac{\Delta\varepsilon}{\varepsilon} = \frac{\varepsilon_1 - \varepsilon}{\varepsilon}$

$Y = \eta \cdot N$ → just compound function

after N scatter : $\frac{\varepsilon_1}{\varepsilon} \approx (1+\eta)^N \approx 1 + \eta N + \frac{(\eta N)^2}{2!} \dots \approx e^{N\eta}$

$\frac{\varepsilon_1}{\varepsilon} = e^Y$

$N \sim \max(\tau^2, \tau)$

Spectrum and Compton Y parameter II

3 regimes :

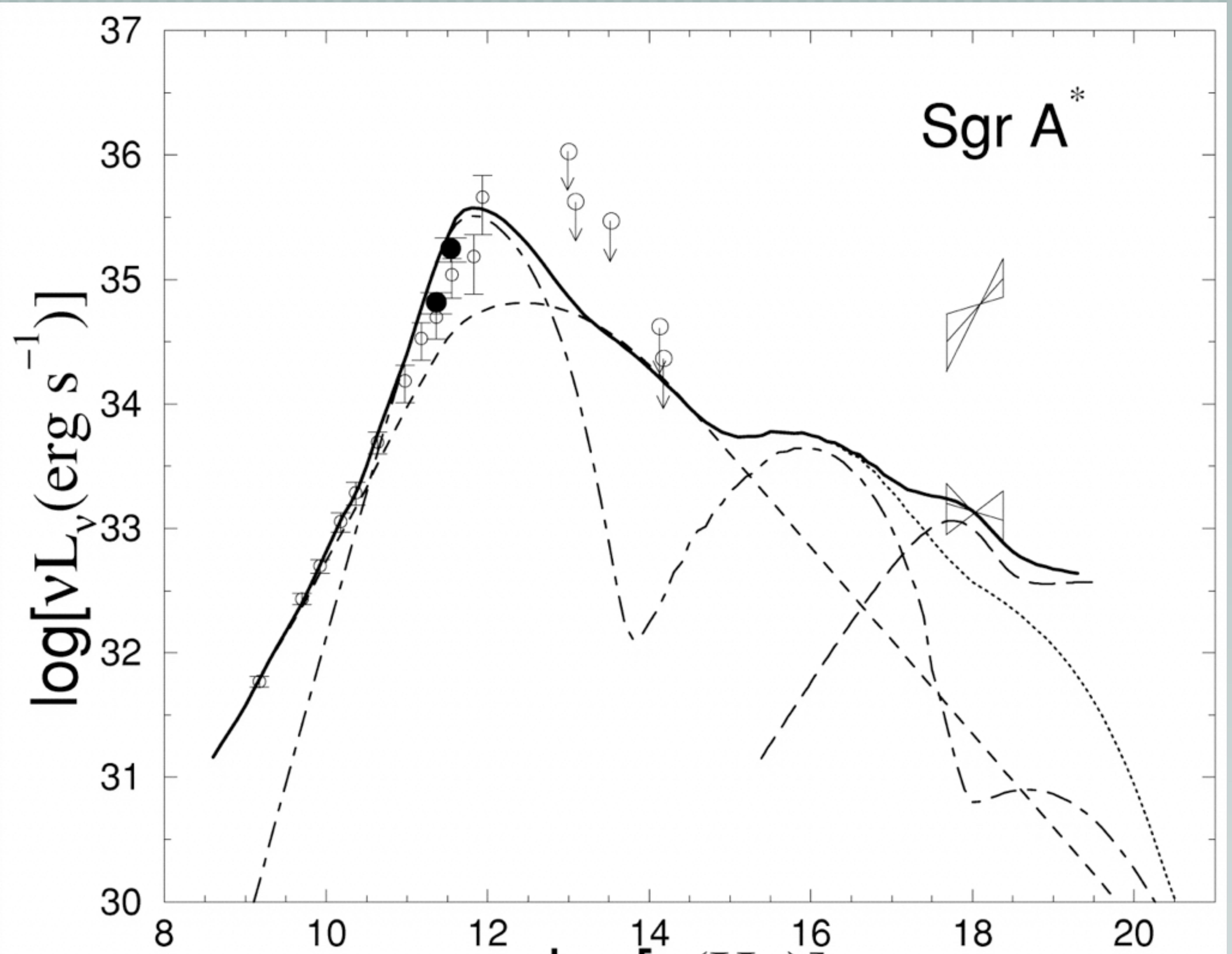
1) "Easy" $y \ll 1 \Rightarrow$ single scatt. $\rightarrow$ spectrum doesn't evolve

2) $\underline{y \lesssim 1}$: hard, very common $\rightarrow$ PL w/ cutoff @ $\varepsilon_{max} \sim E_e$ "unsaturated IC"

3) $y \underline{\gg 1}$: saturate $\rightarrow$ so many scatters $\Rightarrow$ Thermal eq : BB

M.W thermal distribution $\quad y_{th} : \underbrace{\left\{ \begin{array}{ll} \frac{4kT}{mc^2}, & \text{nonrel} \\ 16\left(\frac{kT}{mc^2}\right)^2, & \text{rel.} \end{array} \right\}}_{\eta} \times \underbrace{\max(\tau, \tau^2)}_{N}$

Sgr A*: SSC (synchrotron-self Compton): y?



Yuan et al. 2003

$\langle \gamma \rangle \sim 87 \qquad \gamma = \frac{3kT}{mc^2}$

$\eta = 16 \left(\frac{kT}{mc^2}\right)^2 \sim 16 \left(\frac{87}{3}\right)^2 \sim 10^4$

$\tau = n \sigma R \simeq 10^{4-5} \sigma_T \, 10 r_g$

$\sim 10^{-6}$

$y \sim 10^{-2}$

Non-saturated Compton (y≤1): statistical approach

- What is reason you get PL and how does it depend on y?

- going back to "banking", after k scatters $\left\langle \frac{\varepsilon_k}{\varepsilon_0} \right\rangle \sim (1+\eta)^k$ $\quad \eta = \frac{\Delta\varepsilon}{\varepsilon}$

so $\ln\left(\frac{\varepsilon_0}{\varepsilon_k}\right) = k \ln(1+\eta) \Longrightarrow k = \ln(\varepsilon_k/\varepsilon_0) / \ln(1+\eta)$

The intensity of photons w/ energy ε_k, I_k, has to be proportional to the probability of k scatters, $I_k \propto p^k = \left(e^{\ln p}\right)^k = e^{\ln p \, \ln(\varepsilon_k/\varepsilon_0)/\ln(1+\eta)}$

$$= \left(\frac{\varepsilon_k}{\varepsilon_0}\right)^{\ln p/\ln(1+\eta)} = \left(\frac{\varepsilon_k}{\varepsilon_0}\right)^{-\ln(1/p)/\ln(1+\eta)} = \left(\frac{\varepsilon_k}{\varepsilon_0}\right)^{-\alpha}$$

$\Longrightarrow$ use statistical arguments to relate α to y!

if p = probability of one scatter, $q = 1 - p$ = probability of escape

$\Longrightarrow$ photon with ε_n had to scatter n times and escape $\rightarrow \mathcal{P}_n = p^n q$

Non-saturated Compton (y≤1): statistical approach II

Av. number of scatters $\langle N\rangle = \sum_{n=1}^{\infty} n\cdot \mathcal{P}_n = \sum_{n=1}^{\infty} n p^n q = pq \sum_{n=1}^{\infty} n p^{n-1} = pq \underbrace{\frac{\partial}{\partial p}\left(\sum_{n=1}^{\infty} p^n\right)}_{\frac{\partial}{\partial p}\left(\frac{p}{1-p}\right)}$

so $\langle N\rangle = pq \left(\frac{1}{\underbrace{1-p}_{q}}\right)^2 = \frac{p}{q} = \frac{p}{1-p}$

$\langle N\rangle(1-p) = p \implies p = \frac{\langle N\rangle}{1+\langle N\rangle} = 1 - \frac{1}{1+\langle N\rangle}$ $\quad \langle N\rangle \gg 1$

go back to expression for α: $\frac{\ln(1/p)}{\ln(1+\eta)} = \frac{\ln\left(1 + \overset{\searrow \text{Taylor}}{\frac{1}{1+N}}\right)}{\ln(1+\eta)}$ $\quad \ln(1+x) \approx x,\ x \ll 1$

$= \frac{1 + 1/(1+N)}{\eta} \sim \frac{1}{N\eta} = \frac{1}{y}\,!$

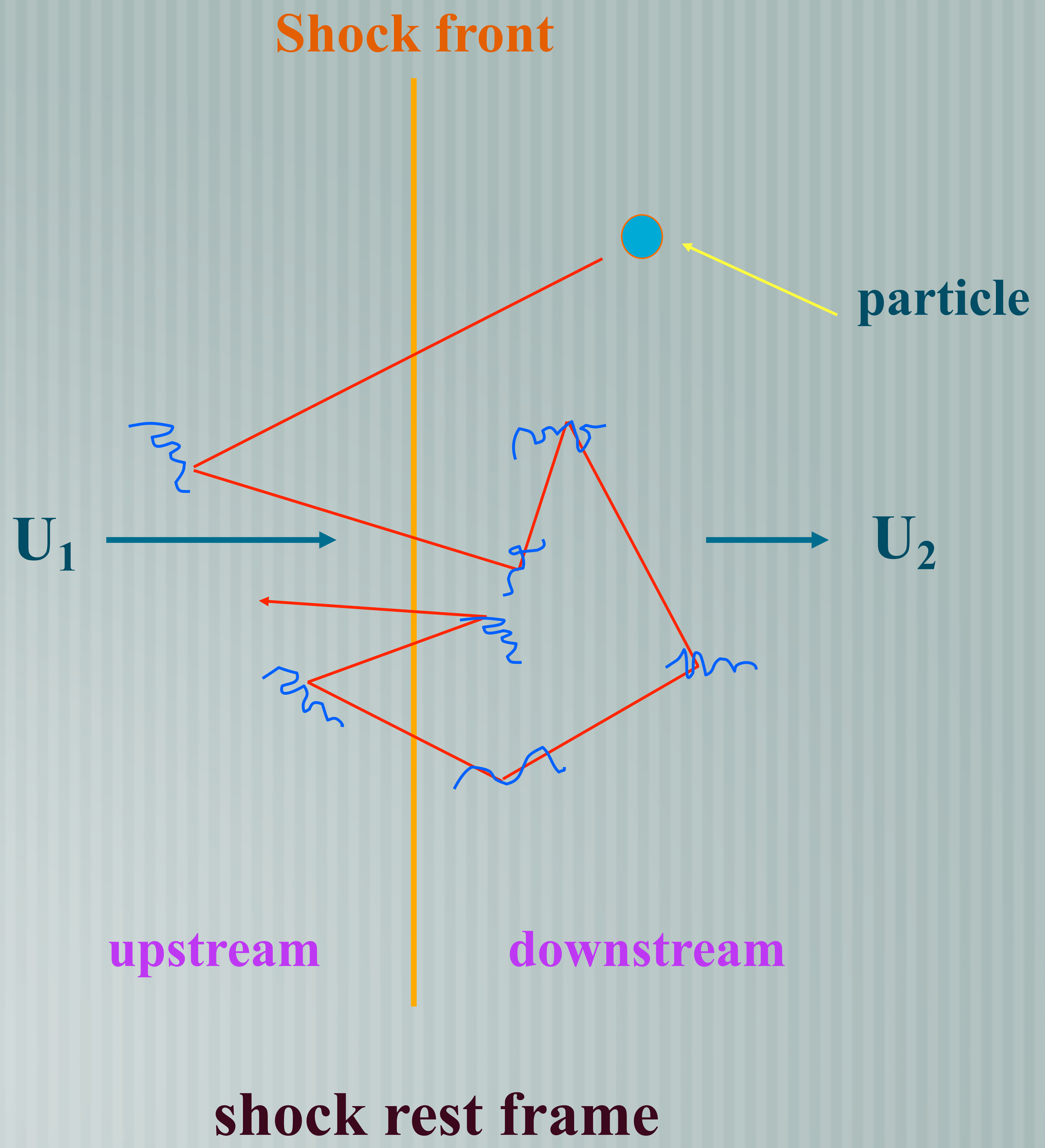
$$\boxed{\text{so } I_K \propto \varepsilon_K^{-1/y}}$$

→ when you see PL and know it's IC, slope gives you a constraint on τ, η !

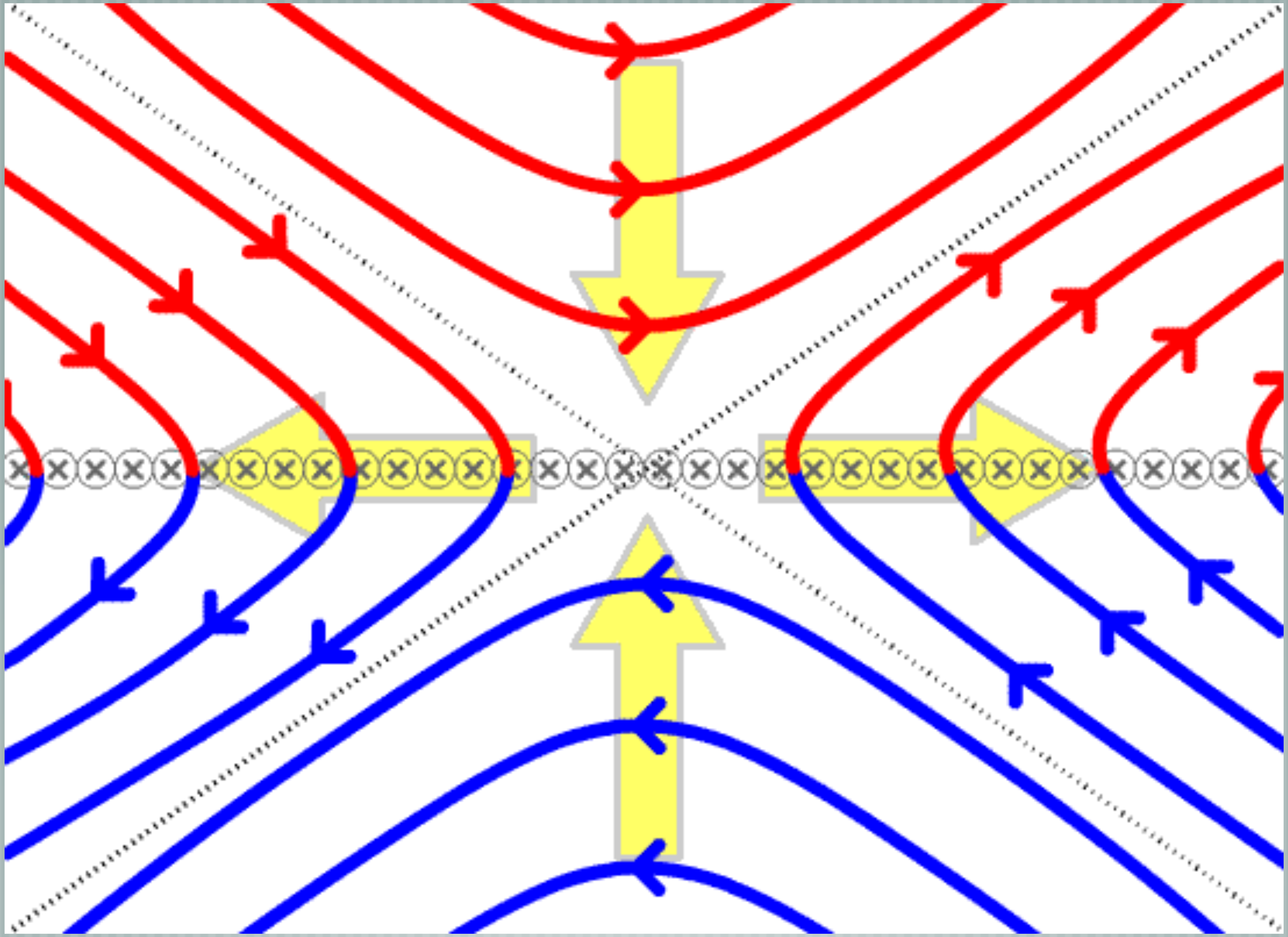
Probability in particle acceleration

Schematic of 1st order Fermi Acceleration

- Deceleration/acceleration of a supersonic flow produces a thin shock layer full of compressed magnetic fields
- In the particle rest frame, system looks like converging flow (think of two pingpong racquets)
- Particle scatters back and forth (with probability of escaping increasing), gaining energy during each crossing



Another mechanism is completely different: magnetic reconnection



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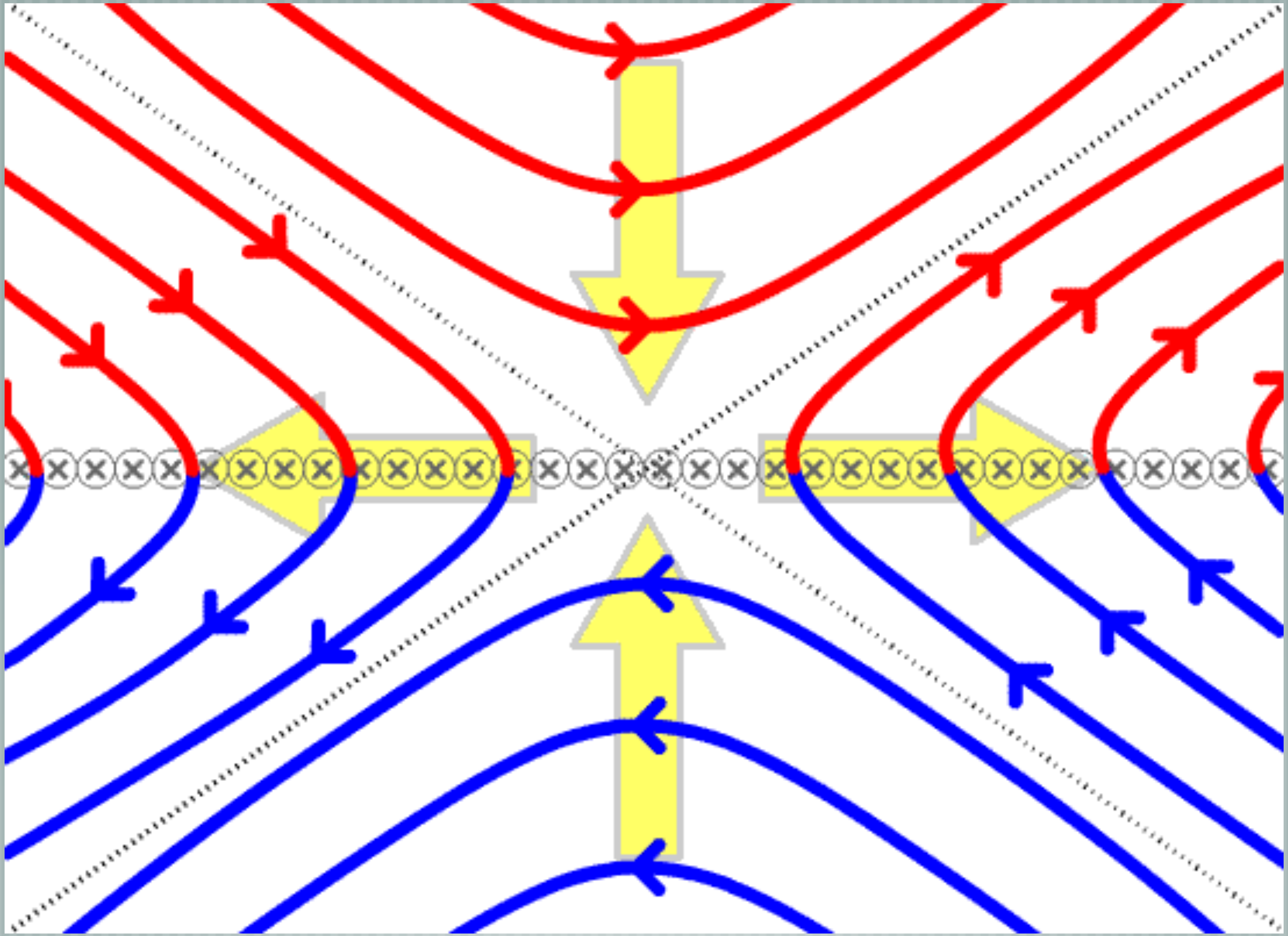
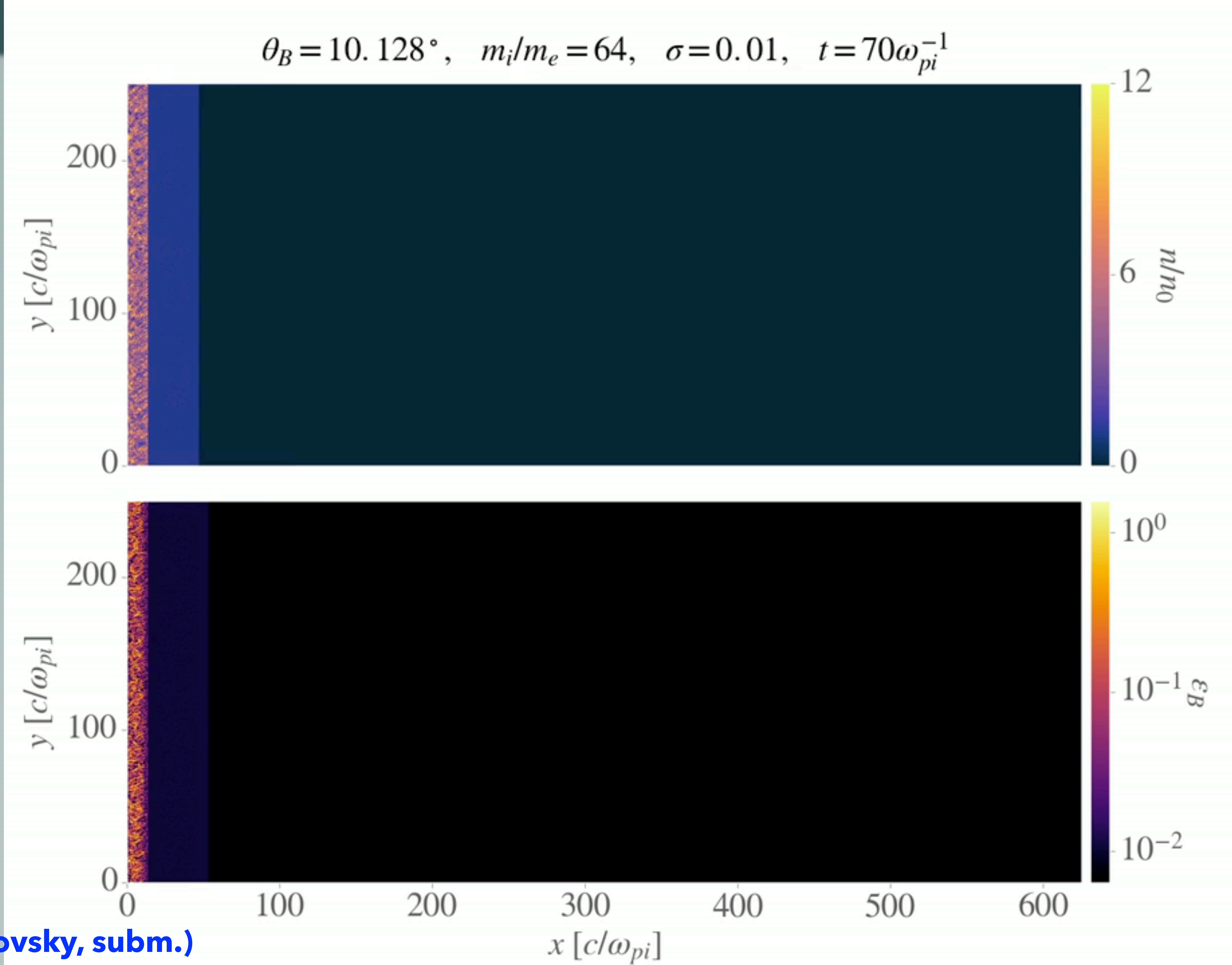


Particle-in-cell (PIC) Simulations



(Crumley, Caprioli, SM, Spikovsky, subm.)

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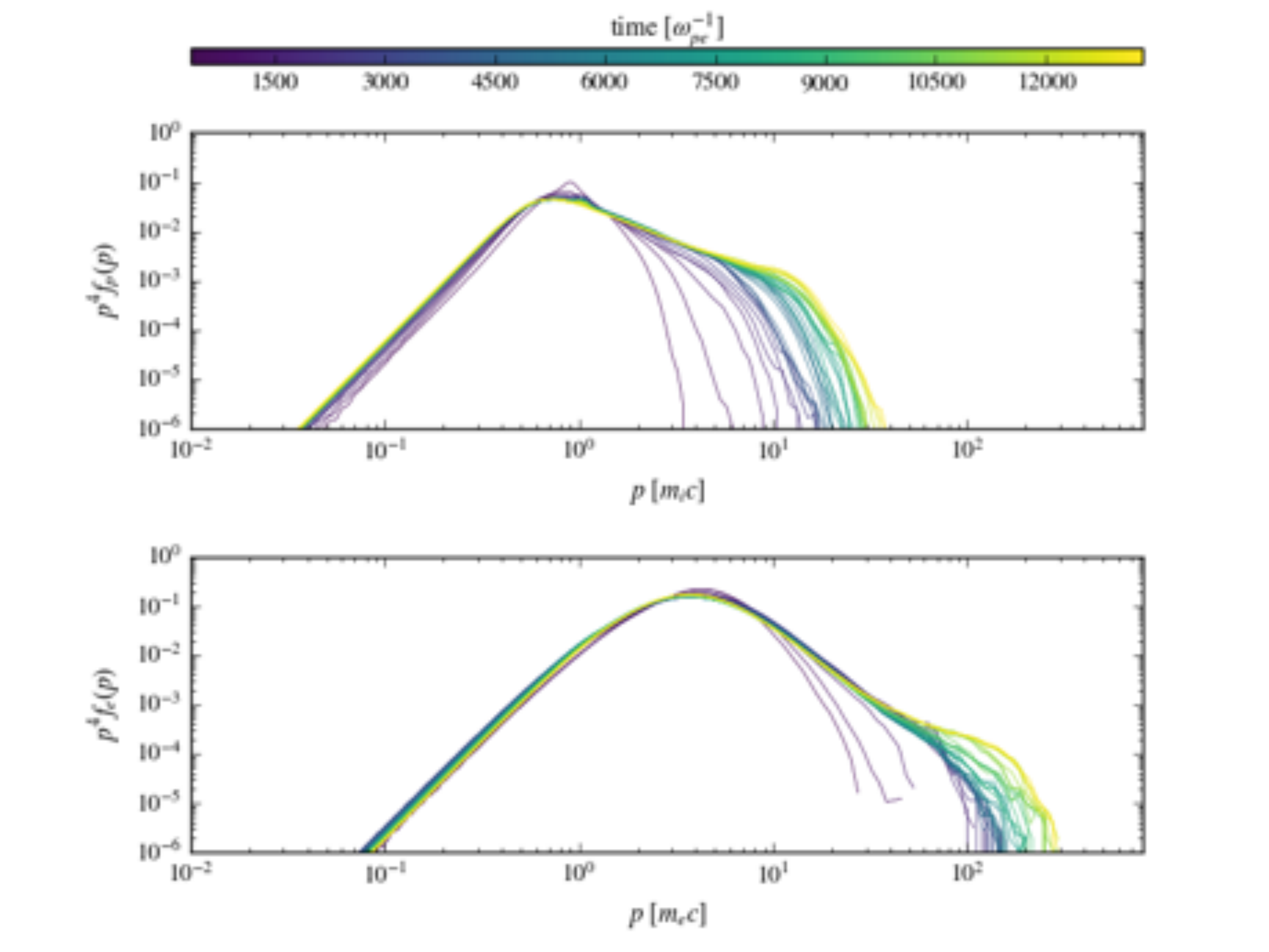
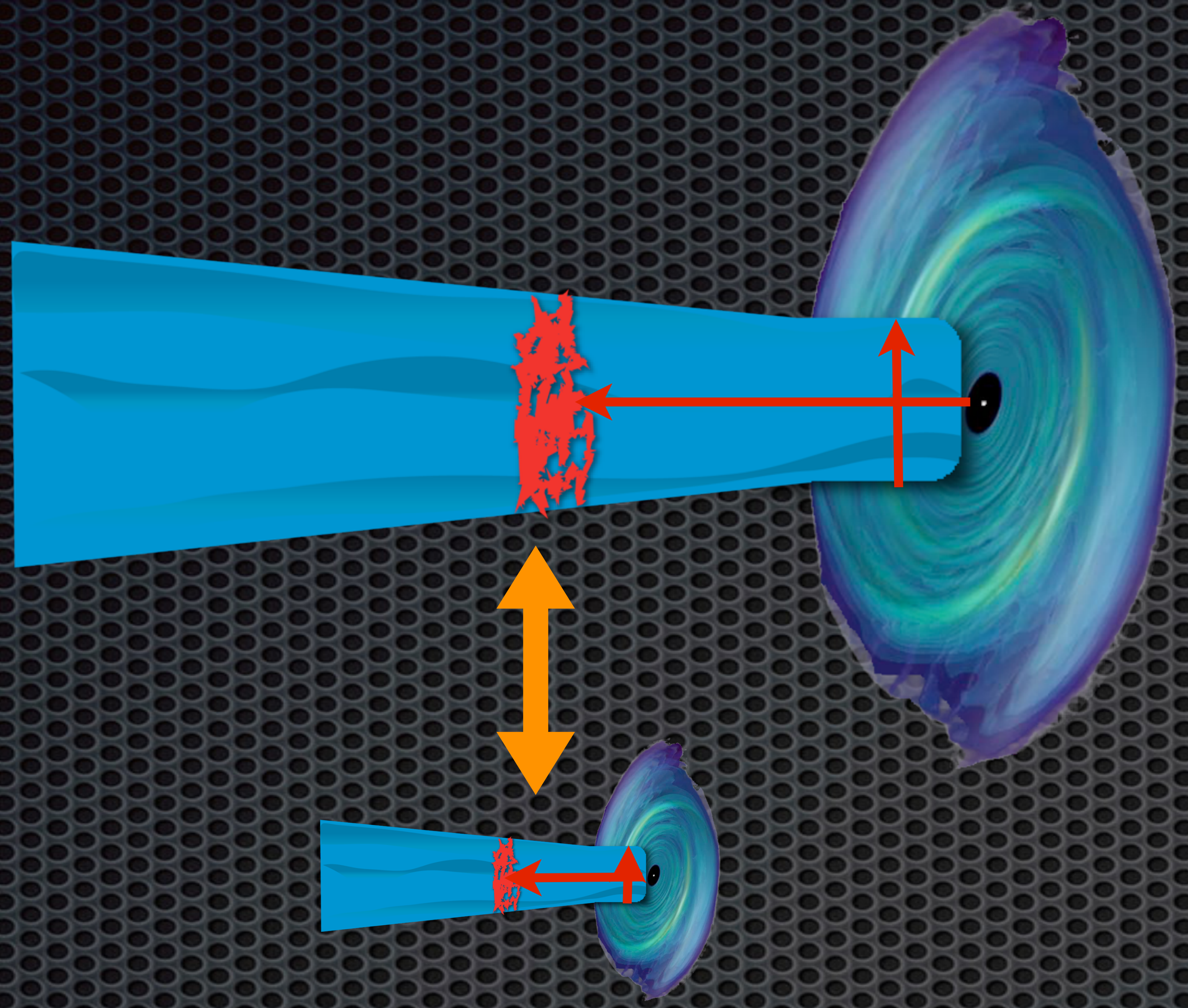
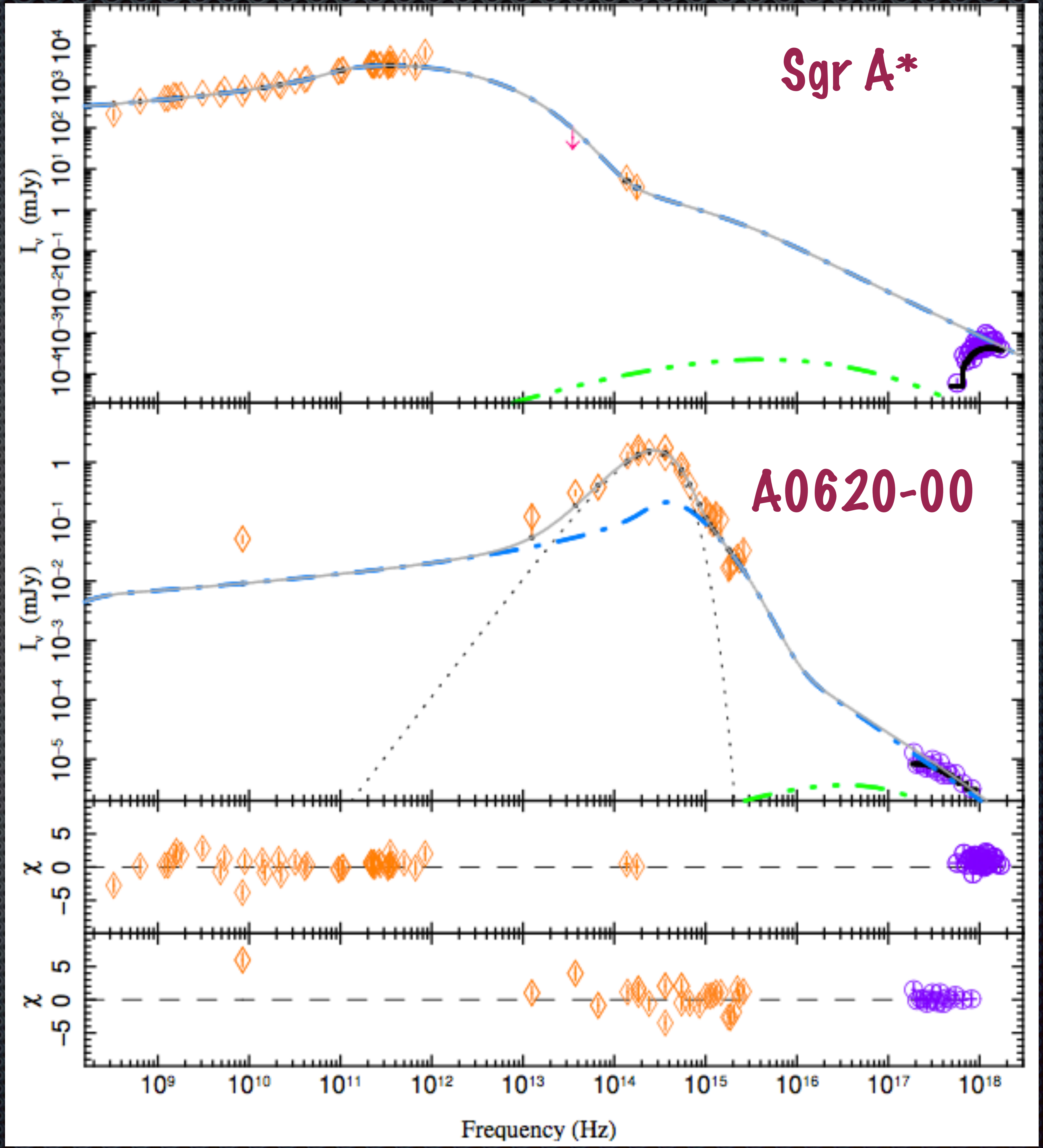


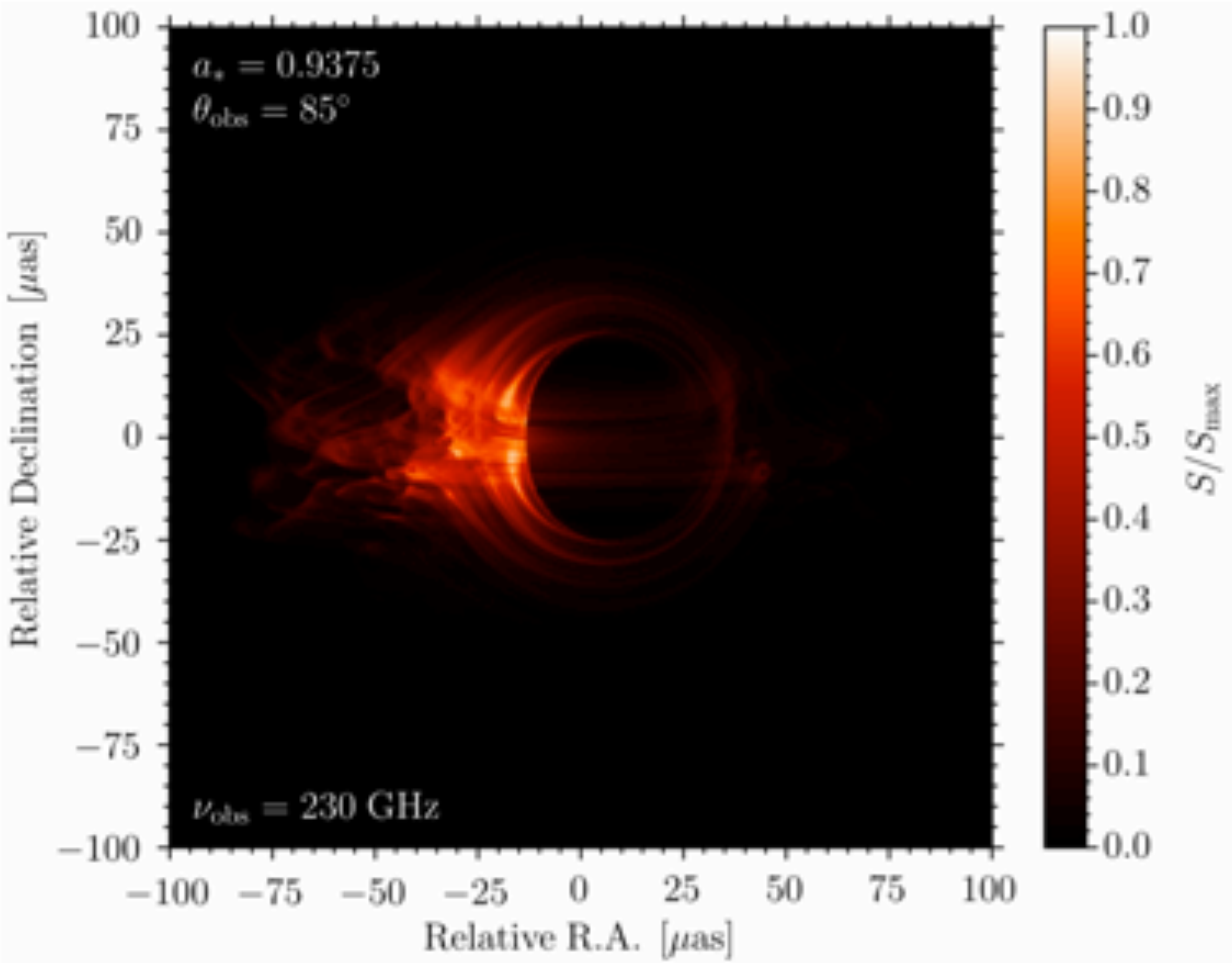
Few final examples of HEA “in action”

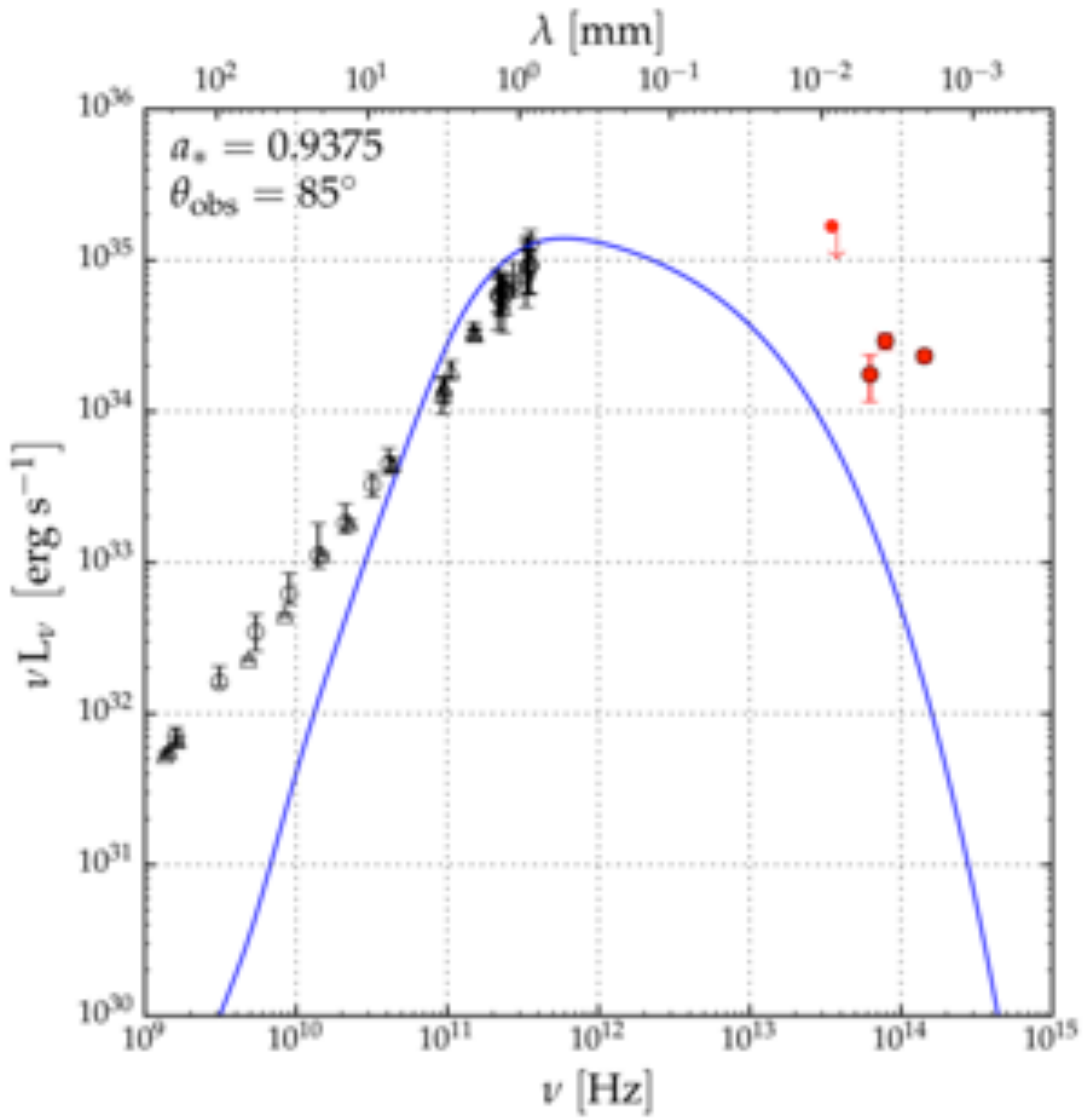
Mass scaling works for black holes!





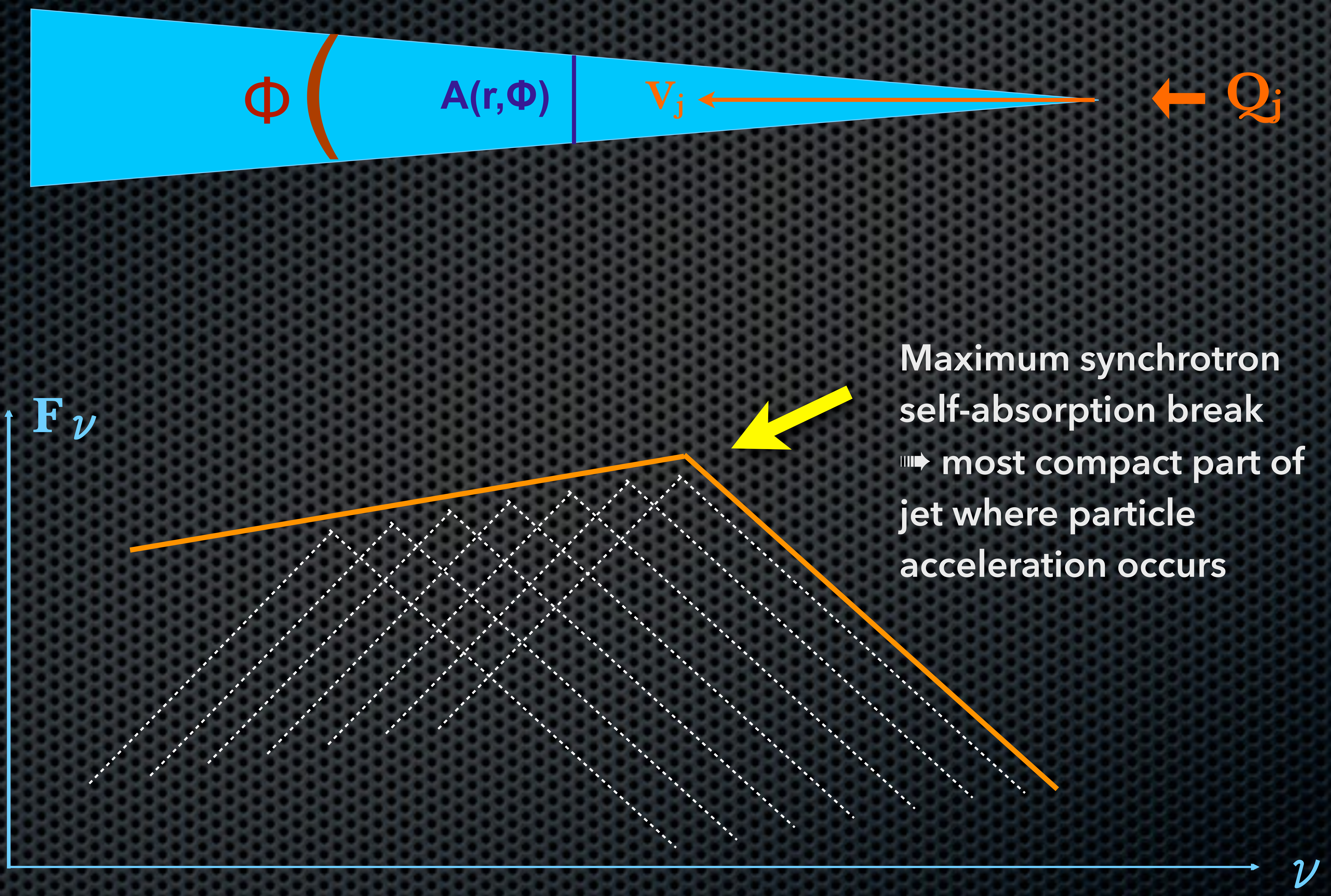
Back to Sgr A* simulations





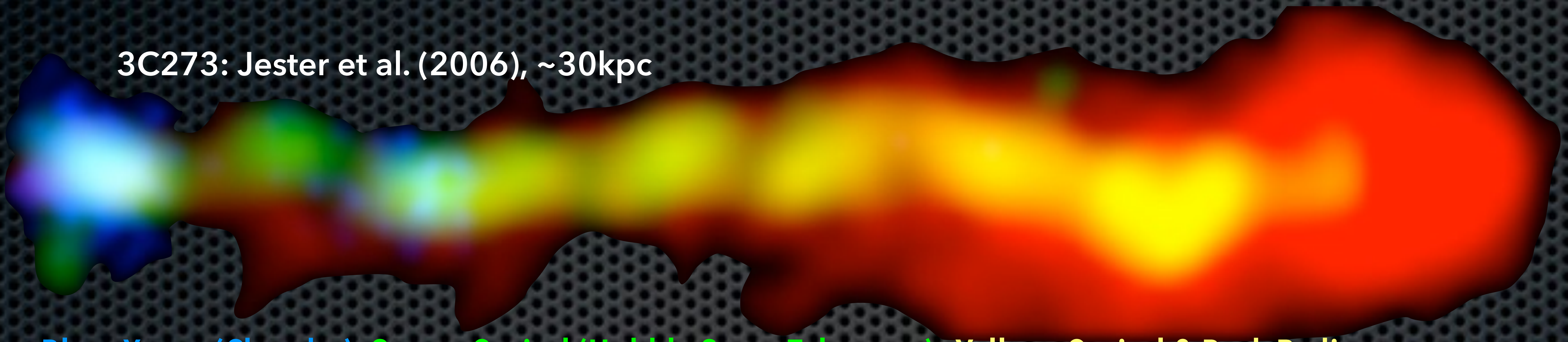
(van Eijnatten, SM, Younsi, Tchekhovskoy++)

Blandford & Königl 1979: flat jet spectra = high τ_{SSA}



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

How do we recognize particle acceleration?



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

Red: Radio (Very Large Array)

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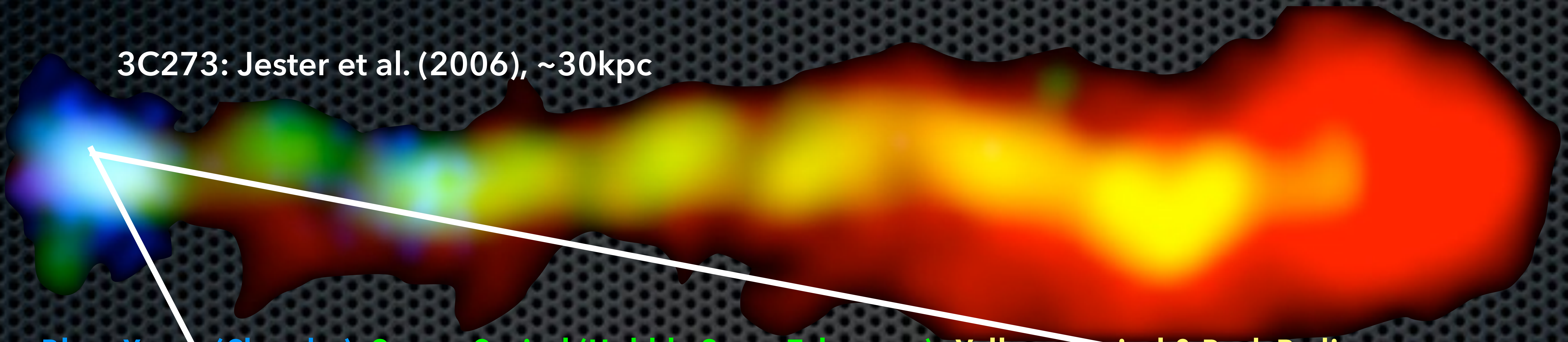

3C273: Jester et al. (2006), ~30kpc

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

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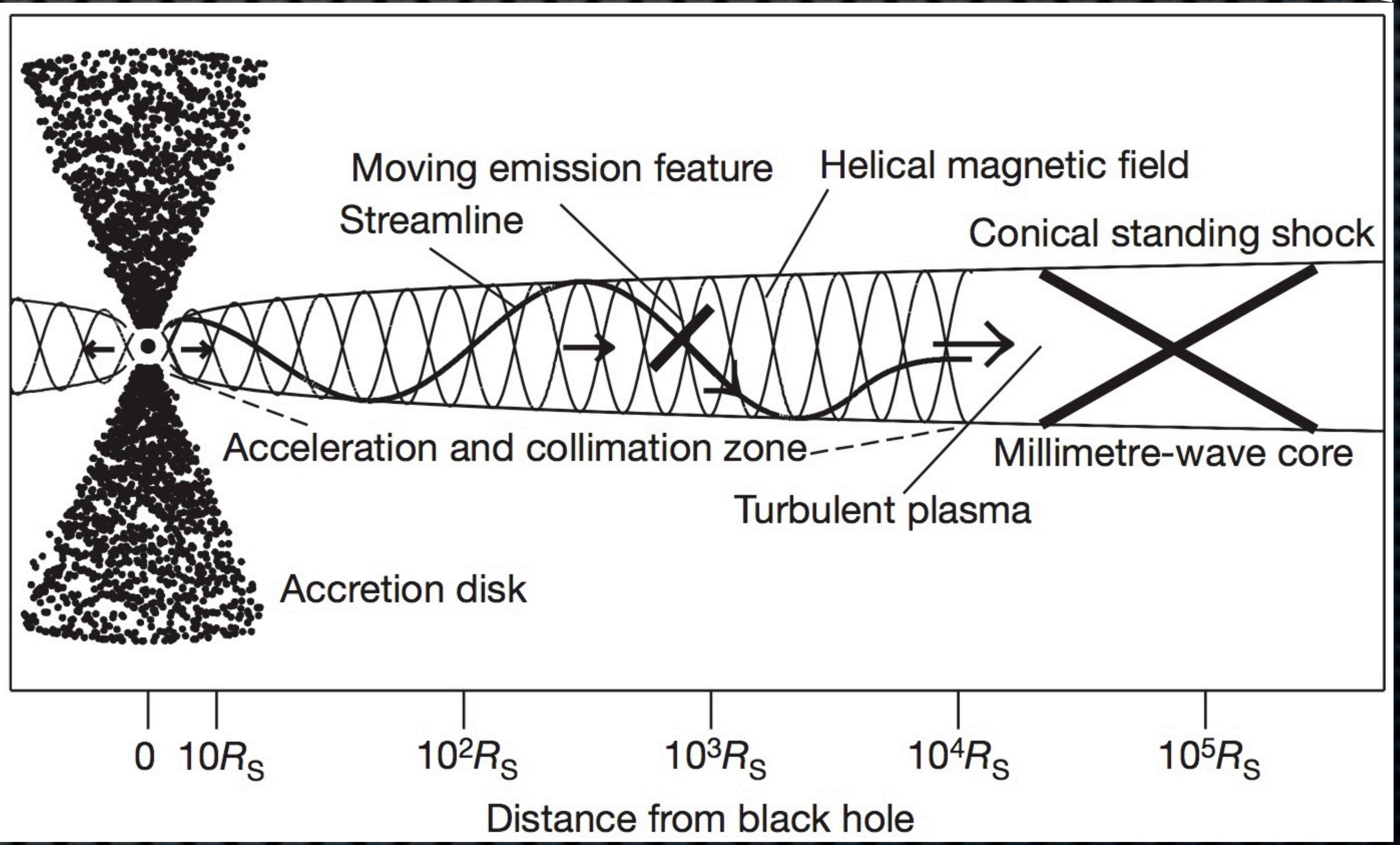
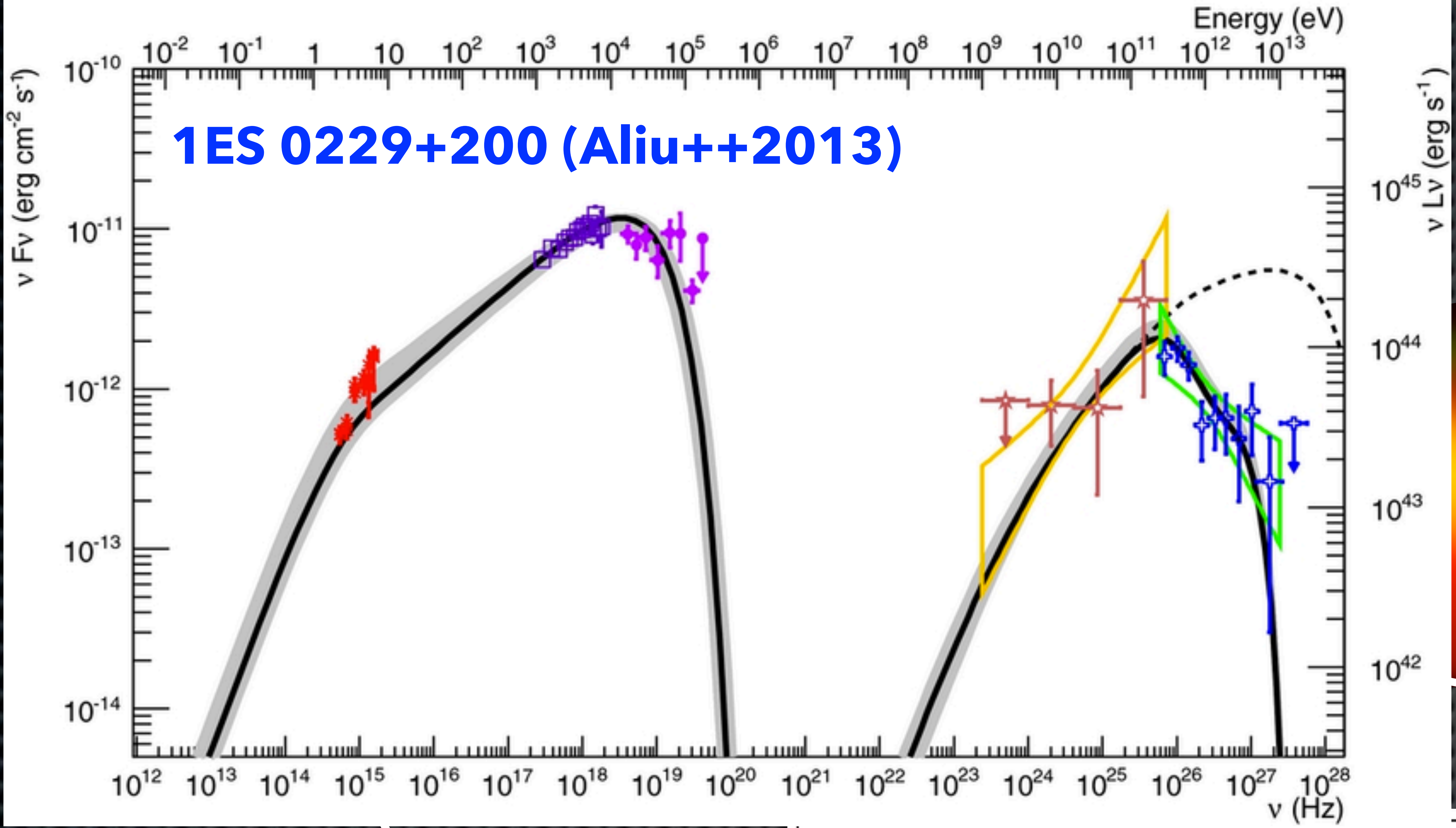
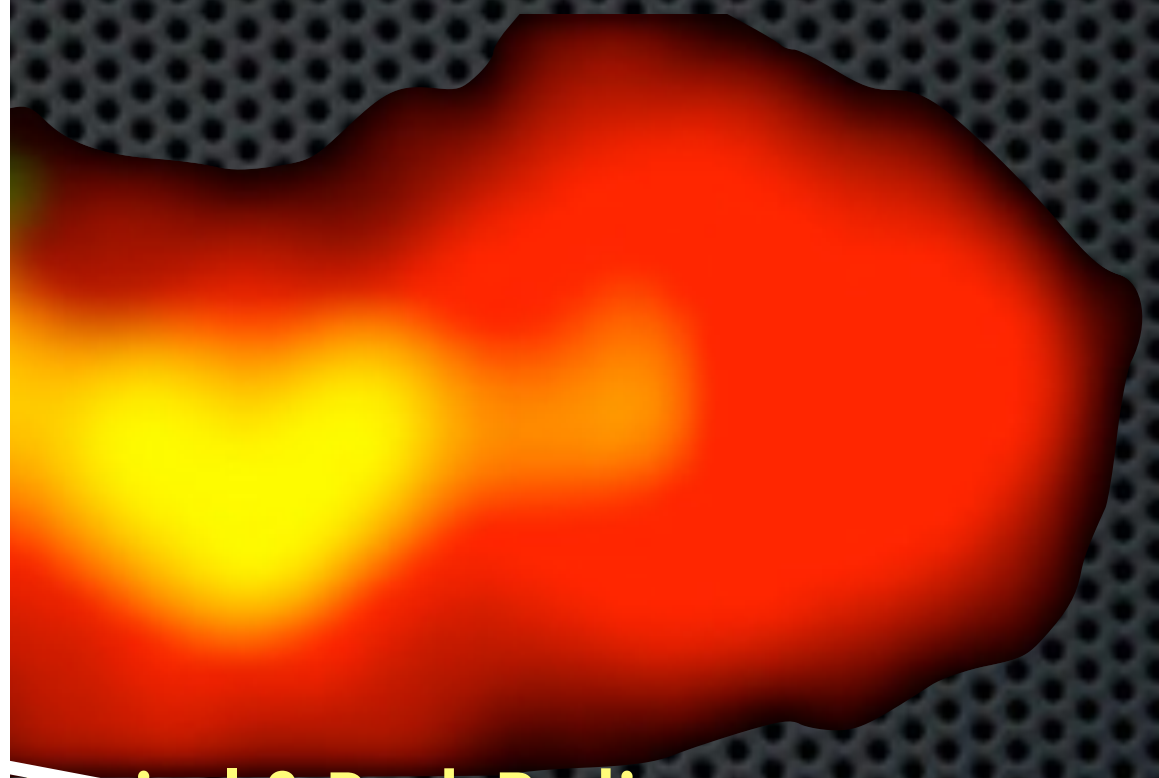
Marscher++2008, 2014; Cohen++2014/ MOJAVE picture: Standing/recollimation shock where most of the “action” takes place, 10^3-10^5 r_g from the black hole



acceleration?





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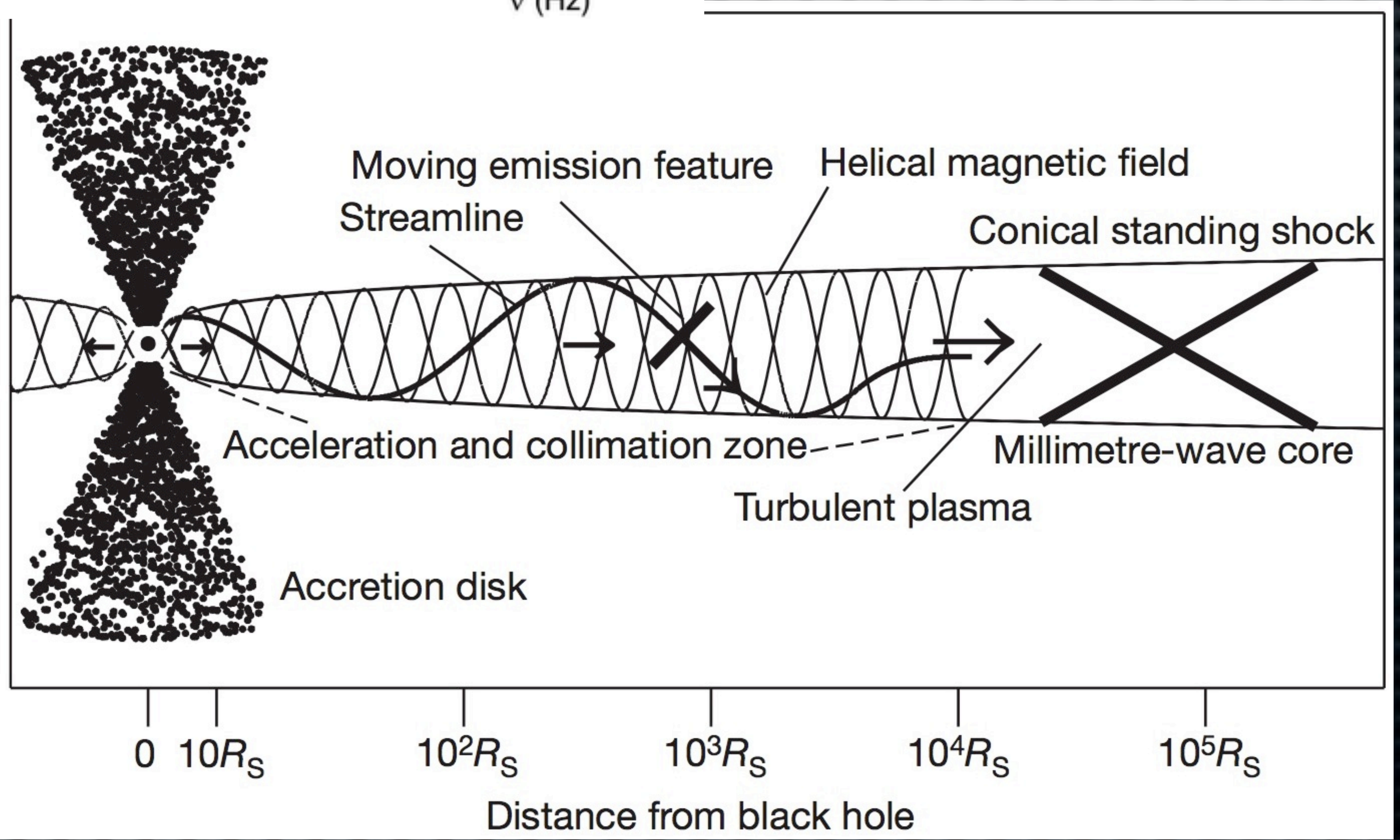

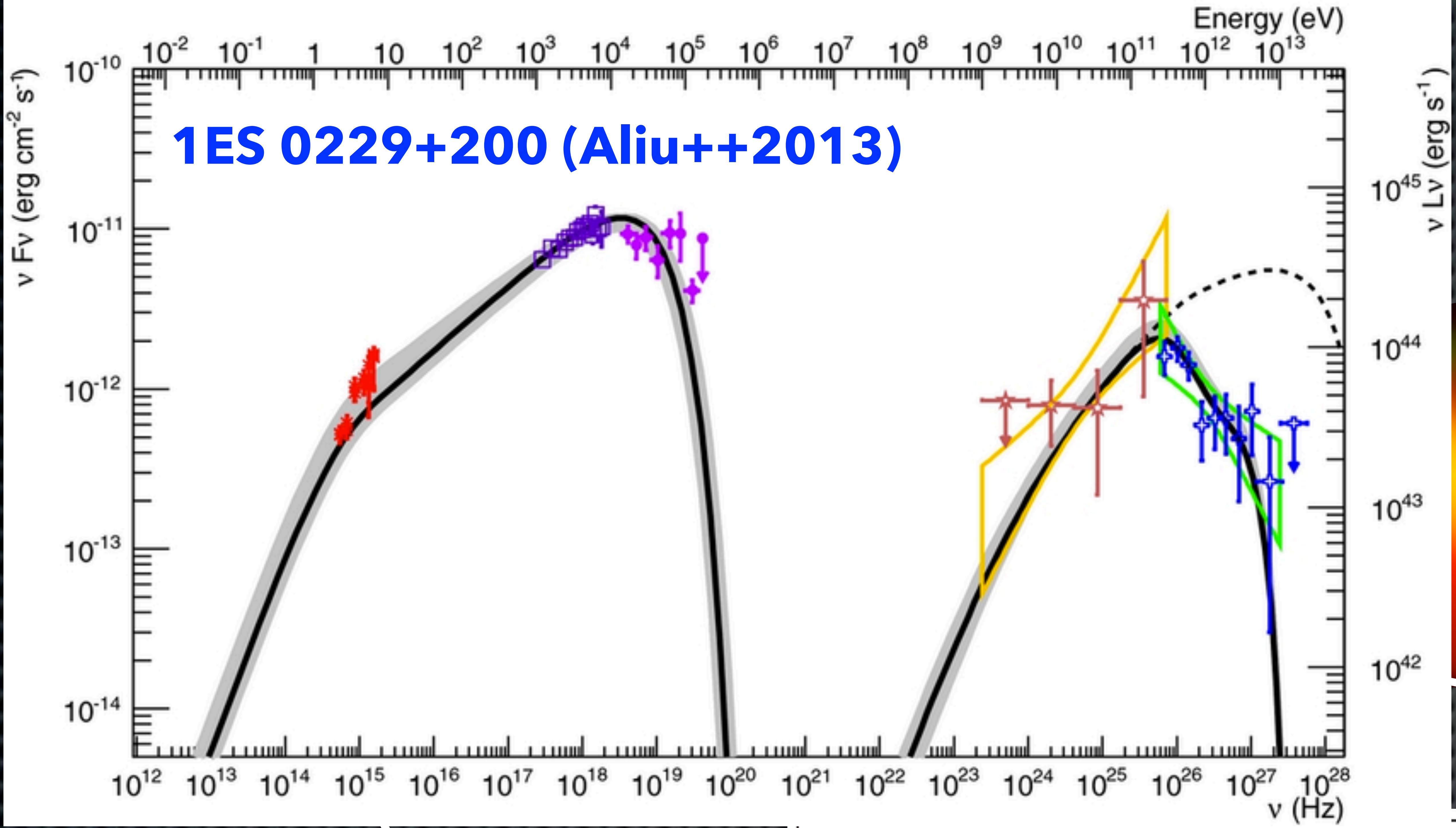

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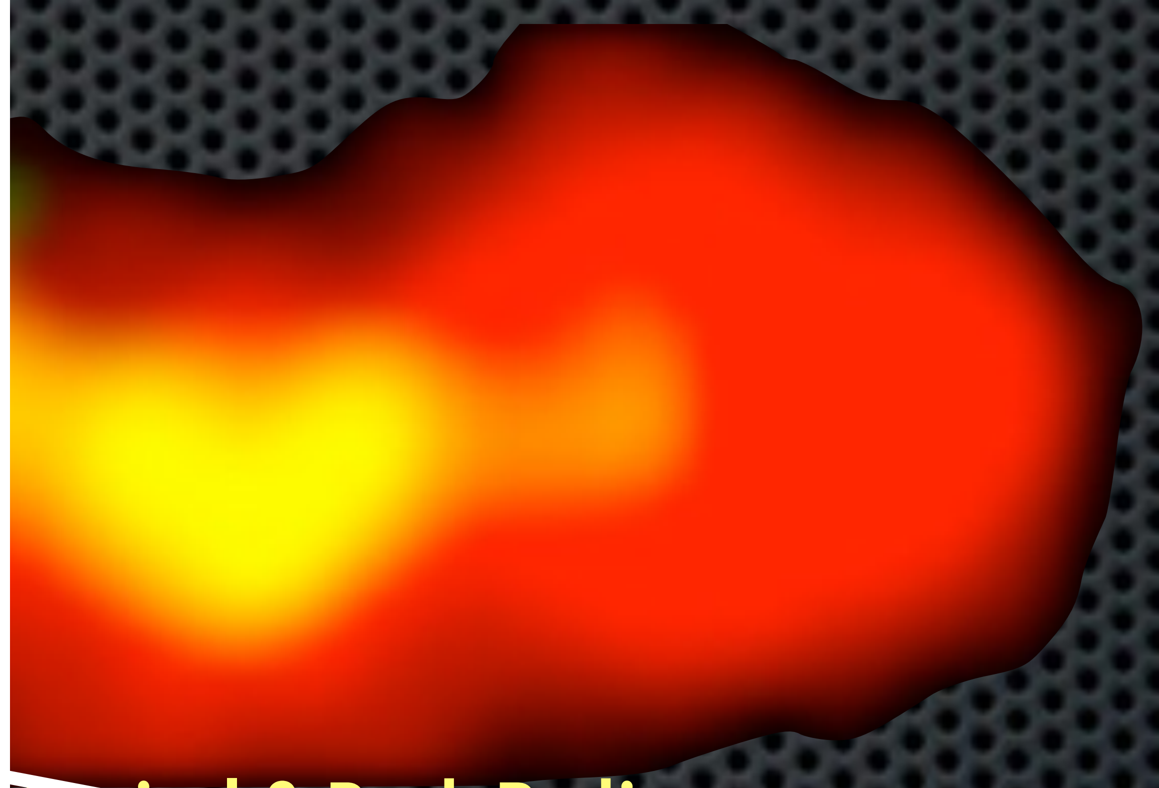

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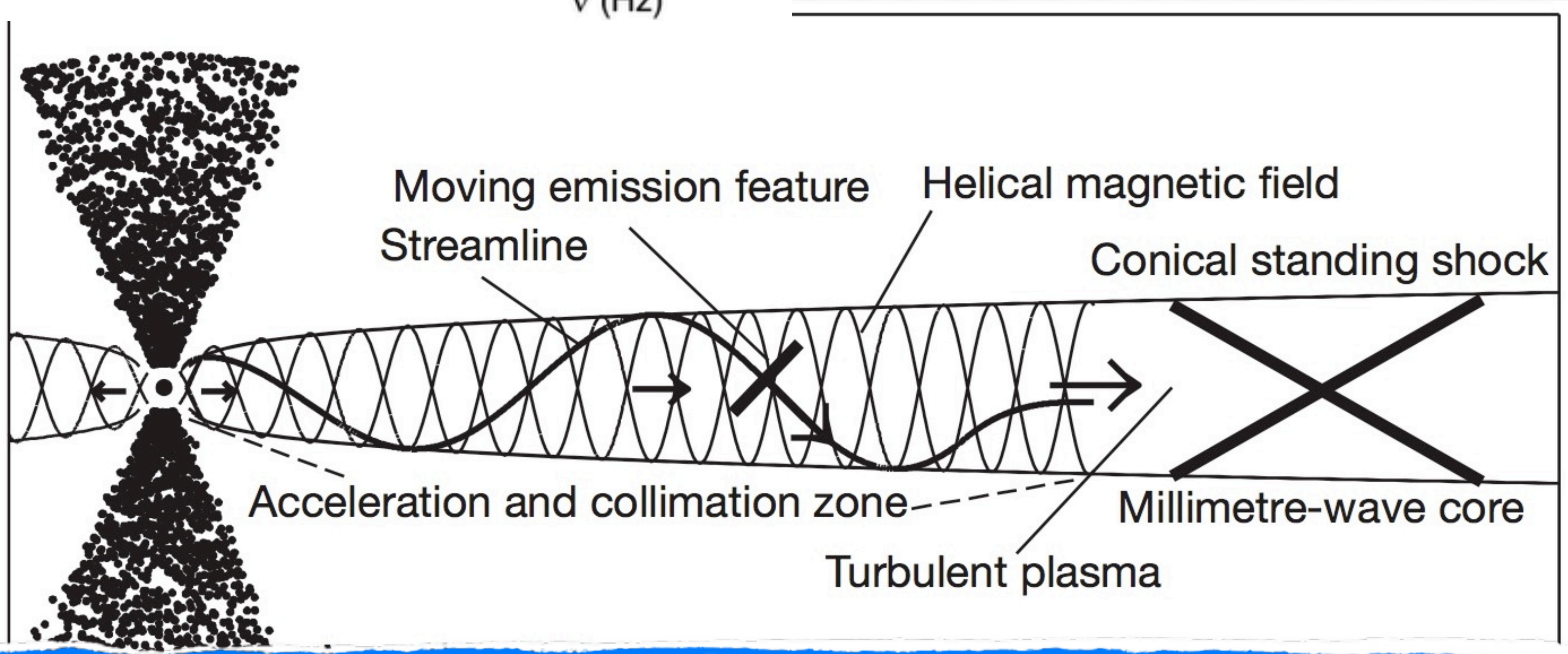
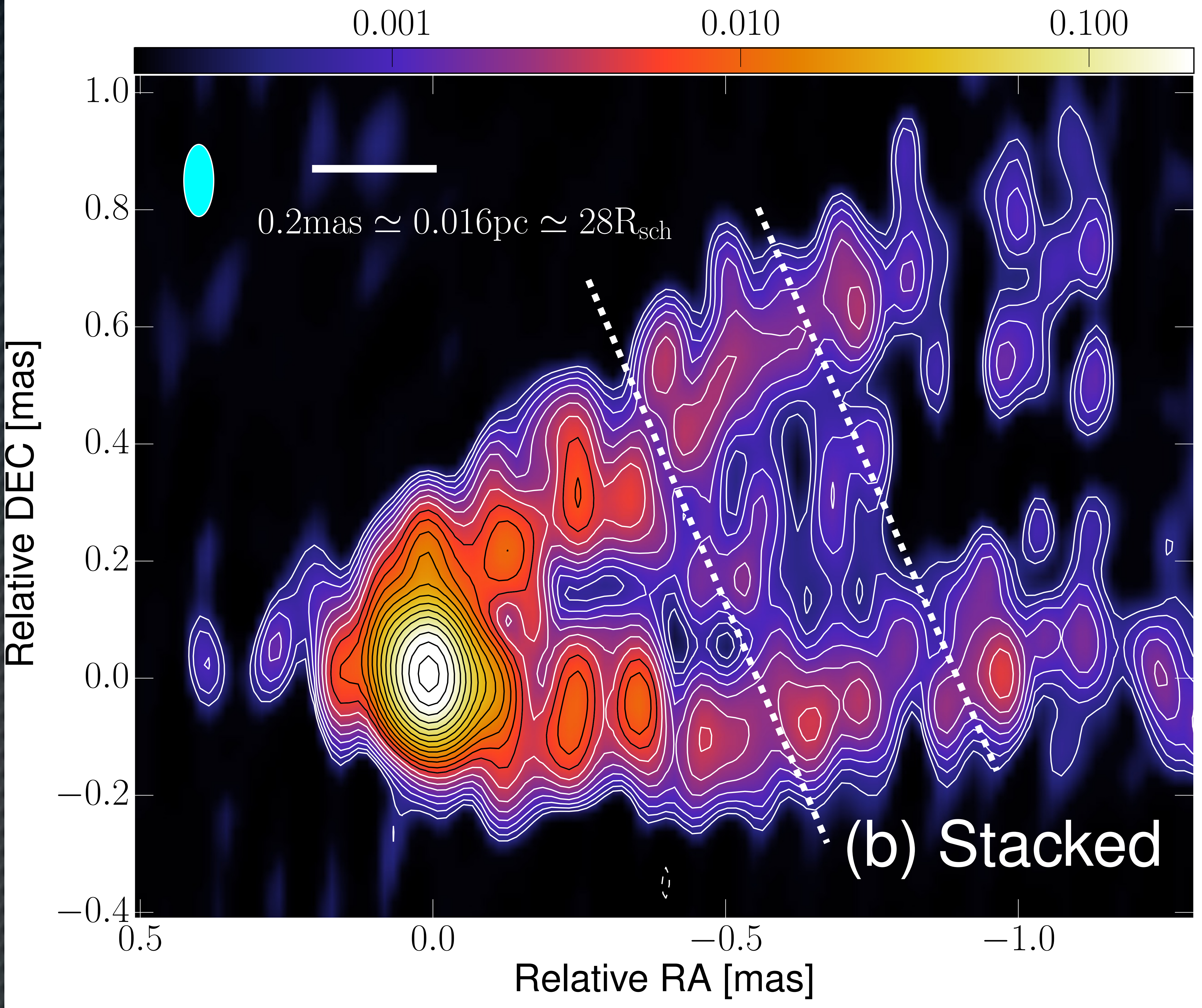


But why the offset from the black hole?
And what is going on upstream in the jets?

Best view of inner jets so far: M87



Timing analysis of γray flares ➟ 40-100r_g, but jets near core estimated to be dominated by thermal particles (1000:1)

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

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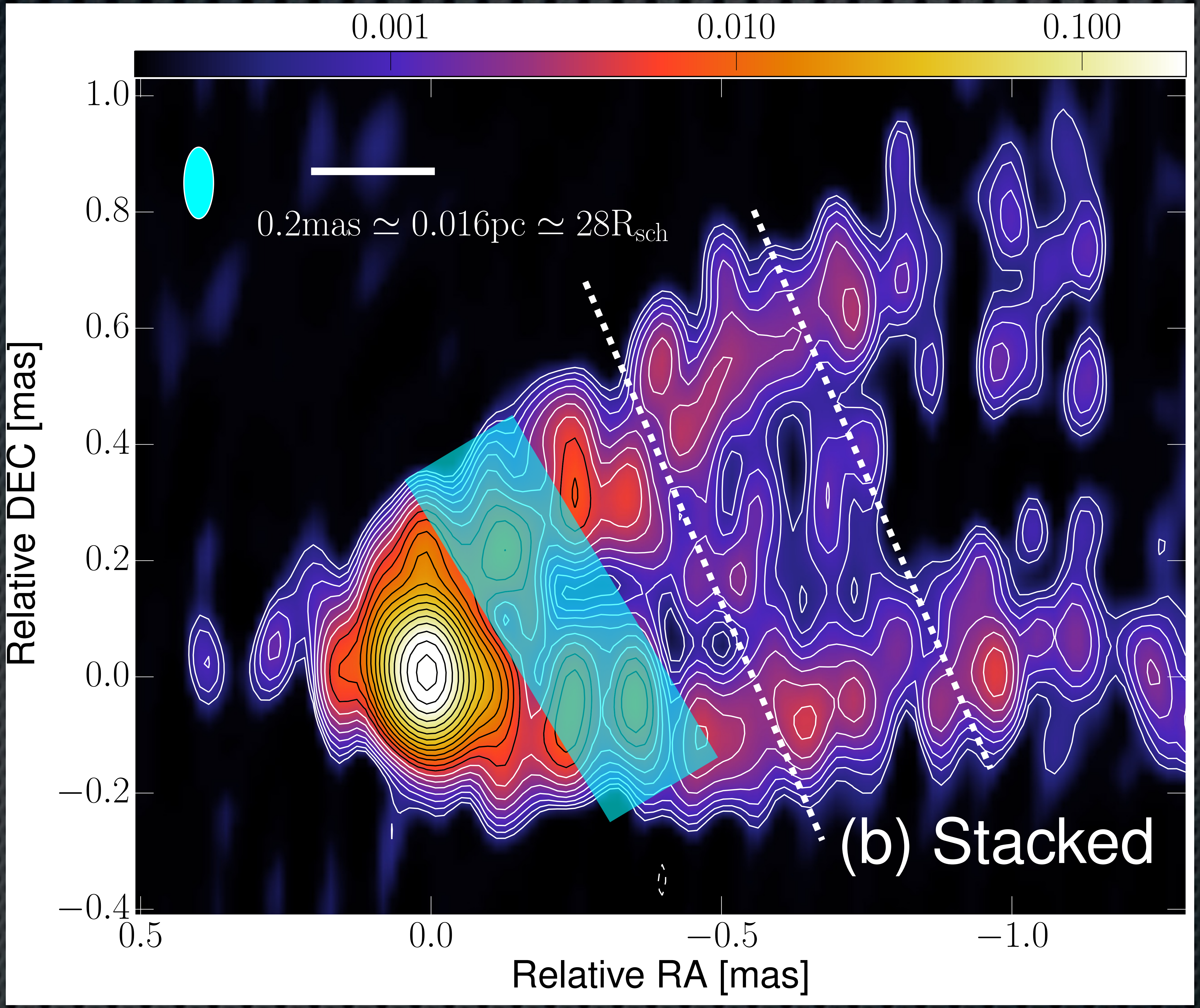

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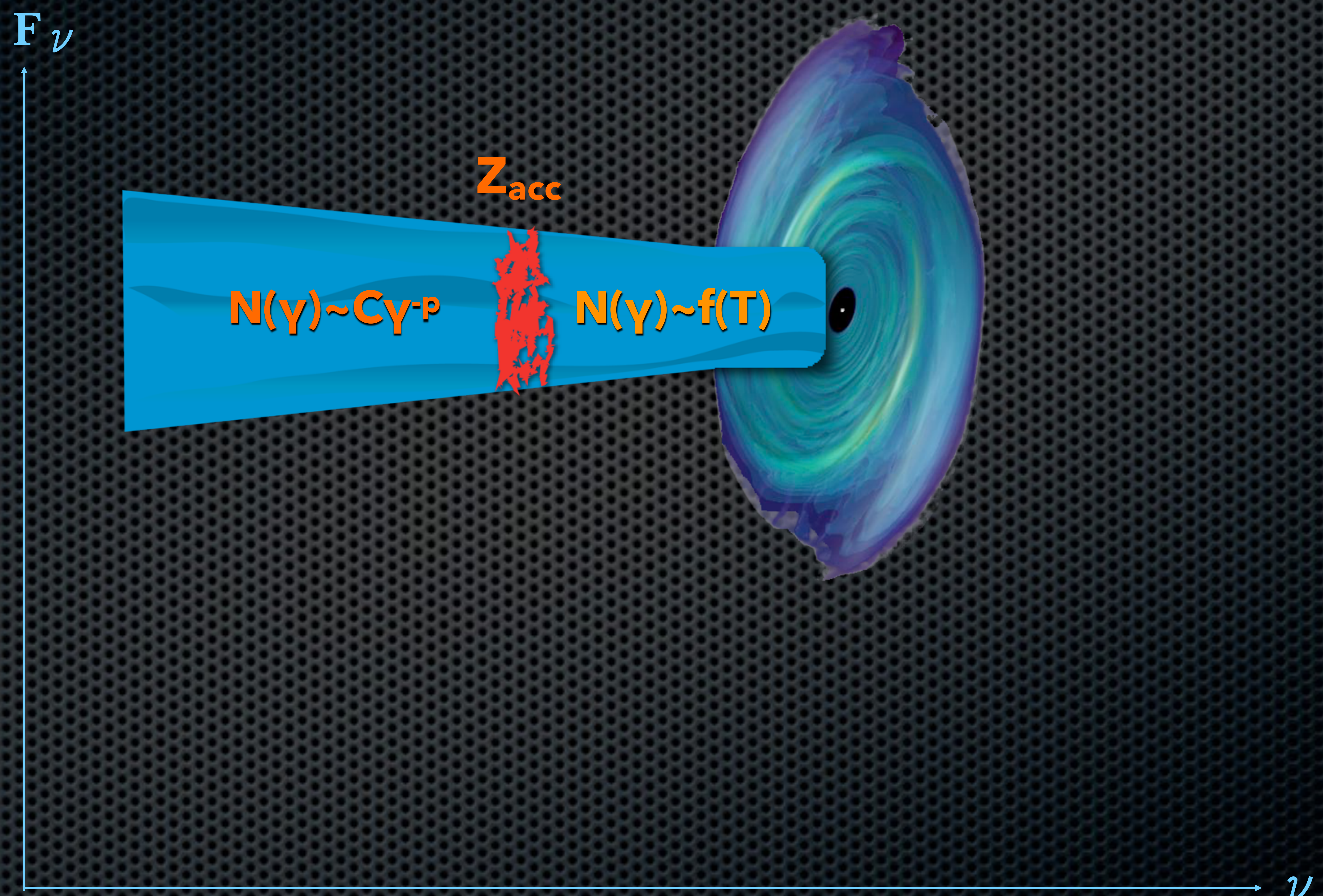
Schematic of thermal/nonthermal jet spectrum



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

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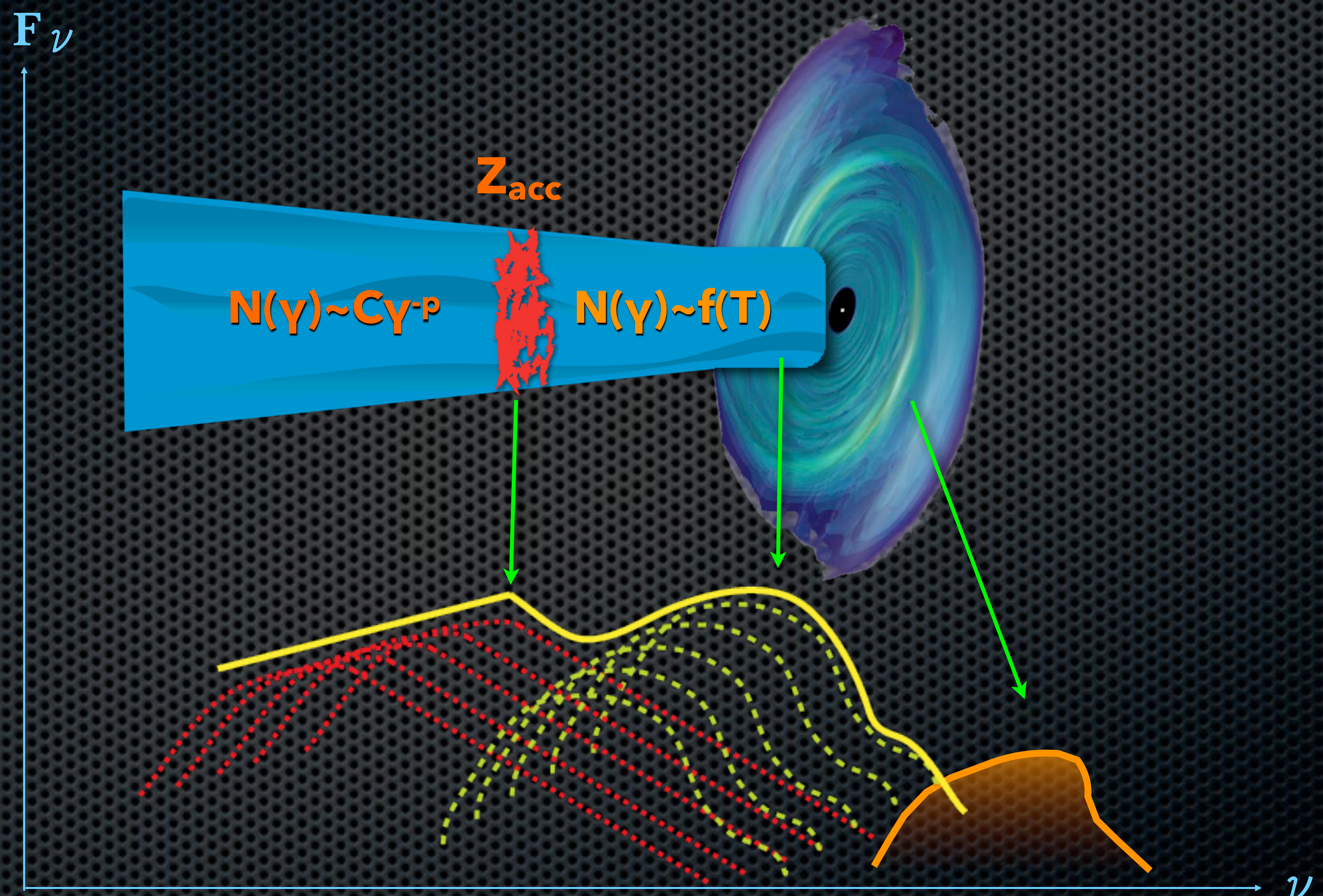

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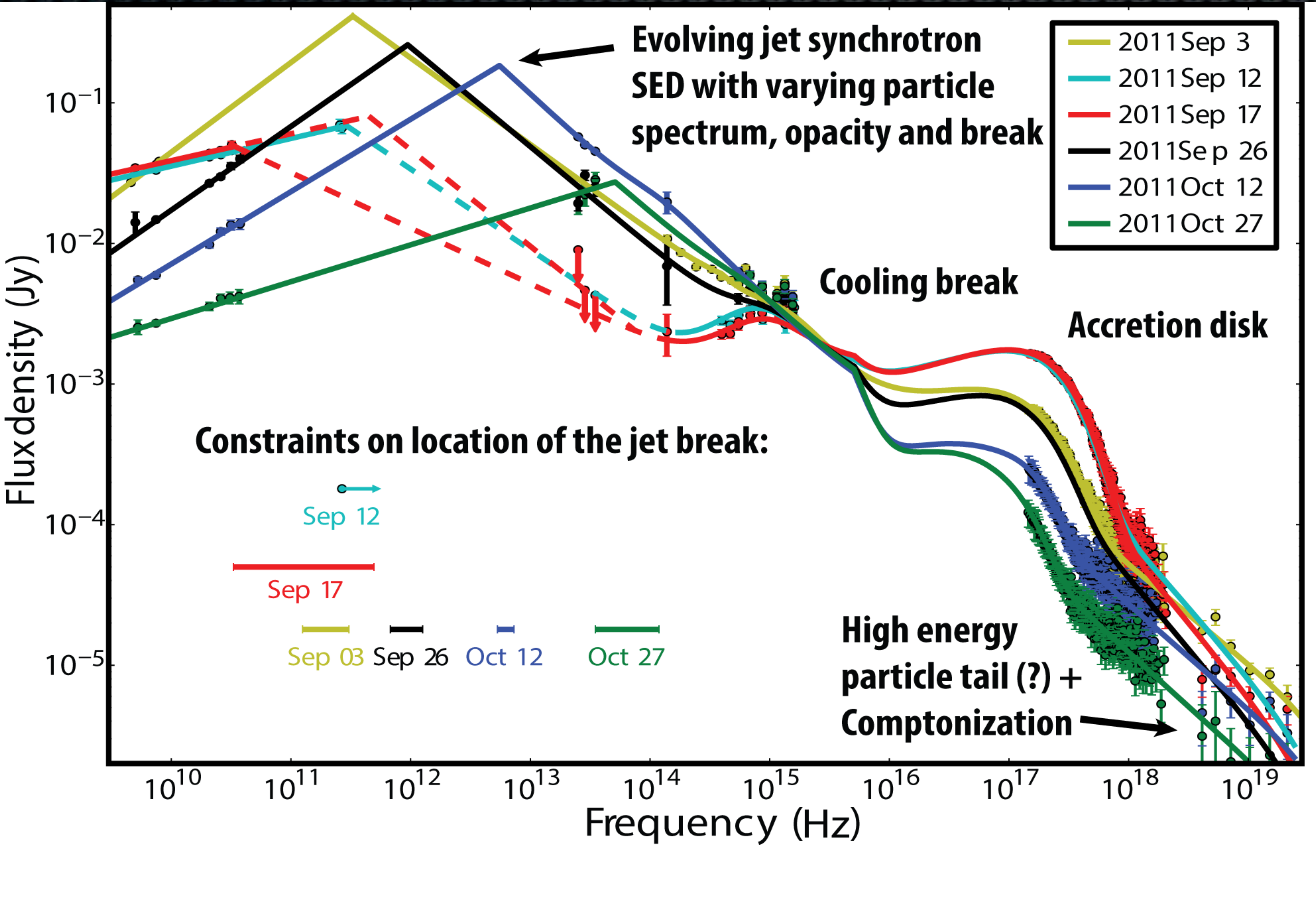
“Next gen” XRB monitoring campaigns: MAXI J1836-194



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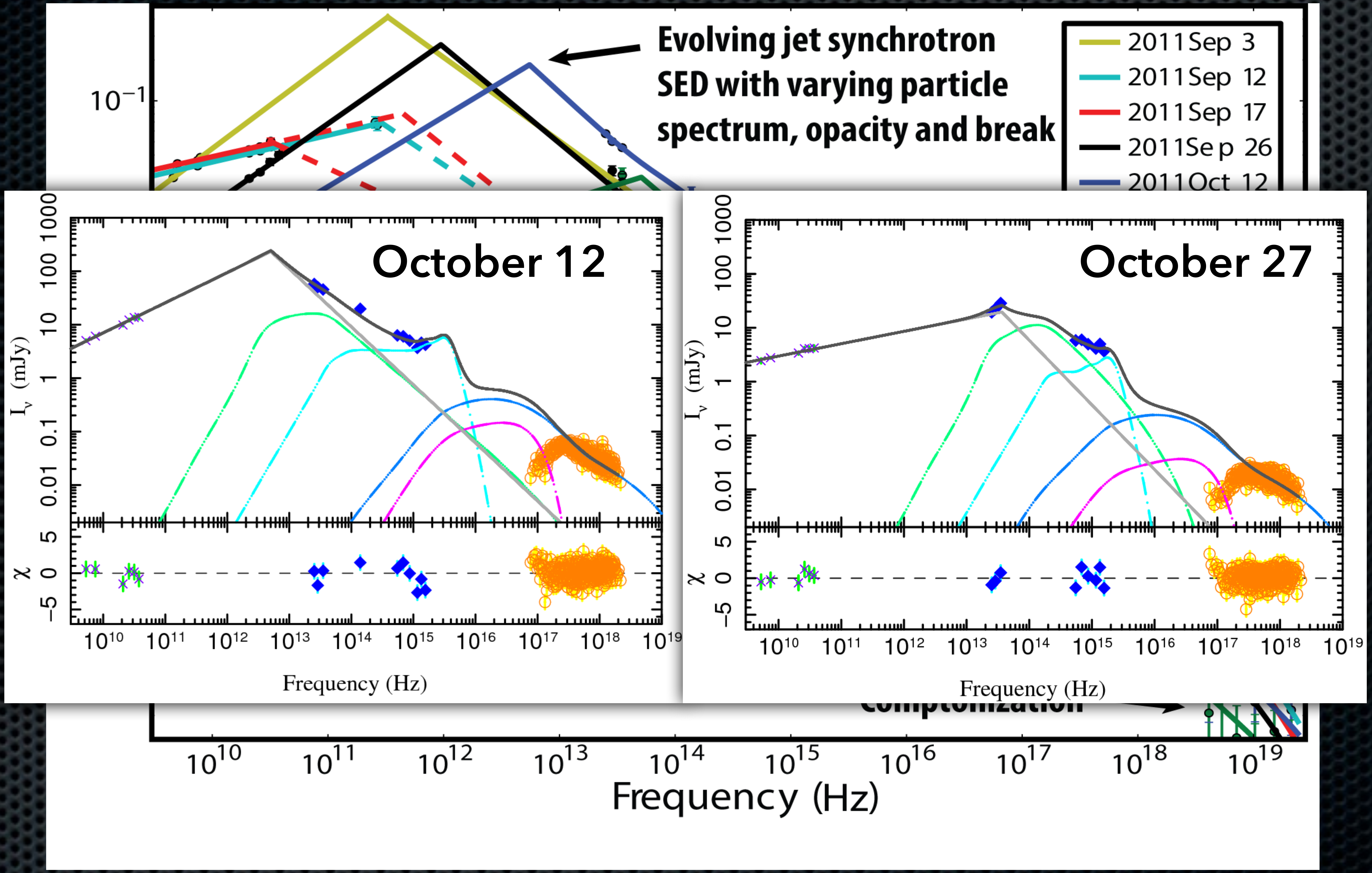

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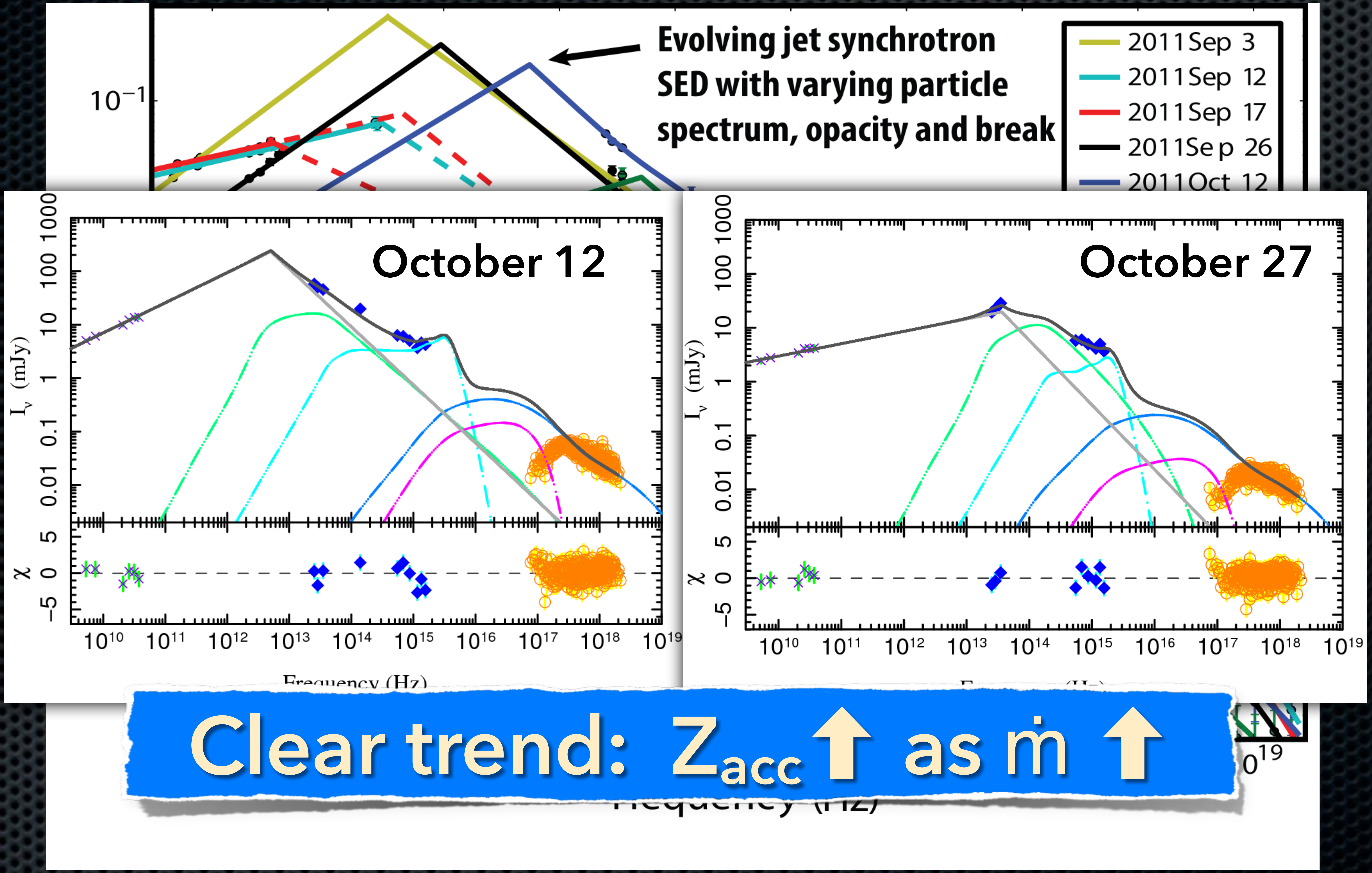

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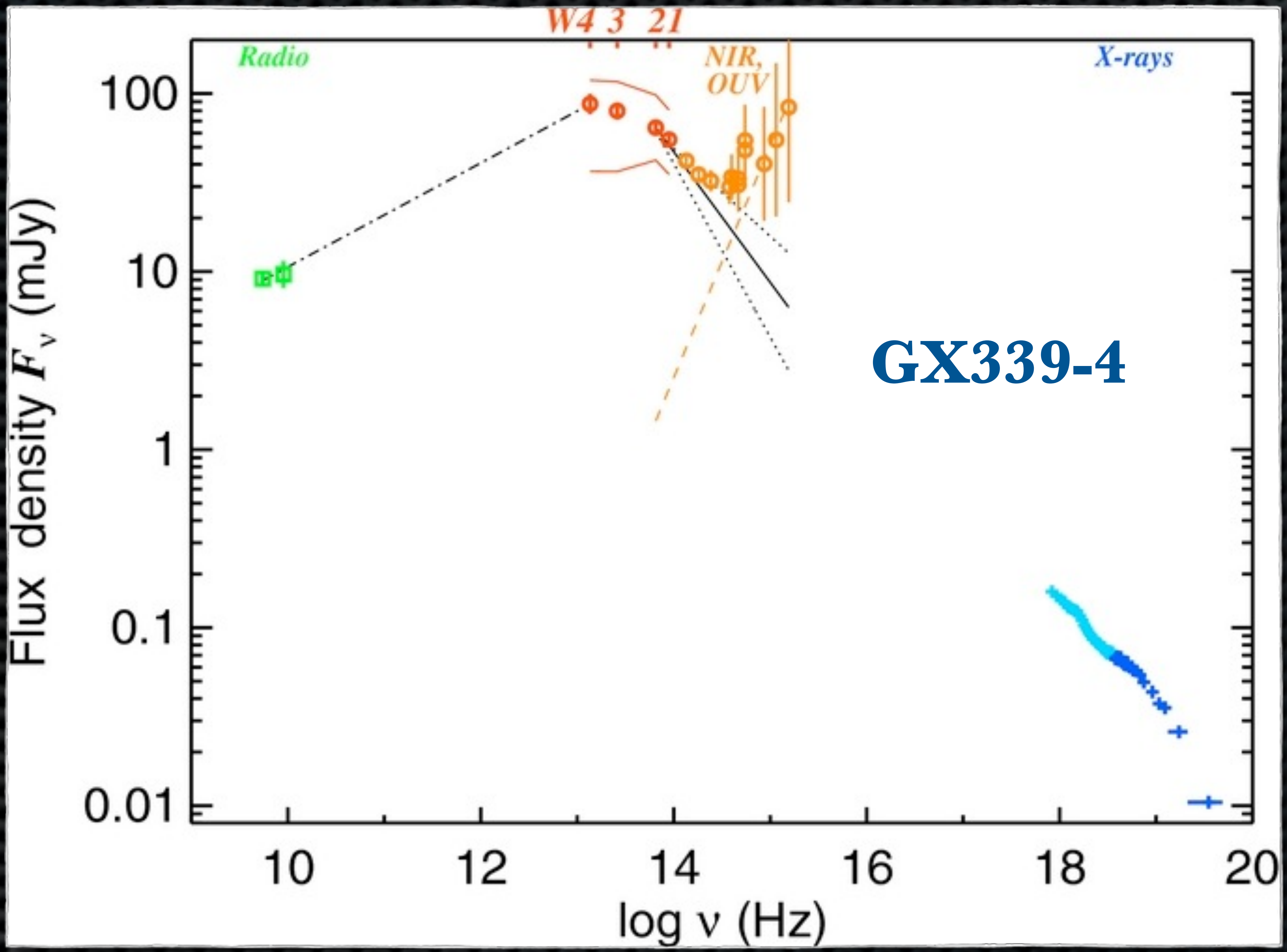
Independent determination of Z_{acc}



(Kalamkar++2016; Gandhi++ 2017)

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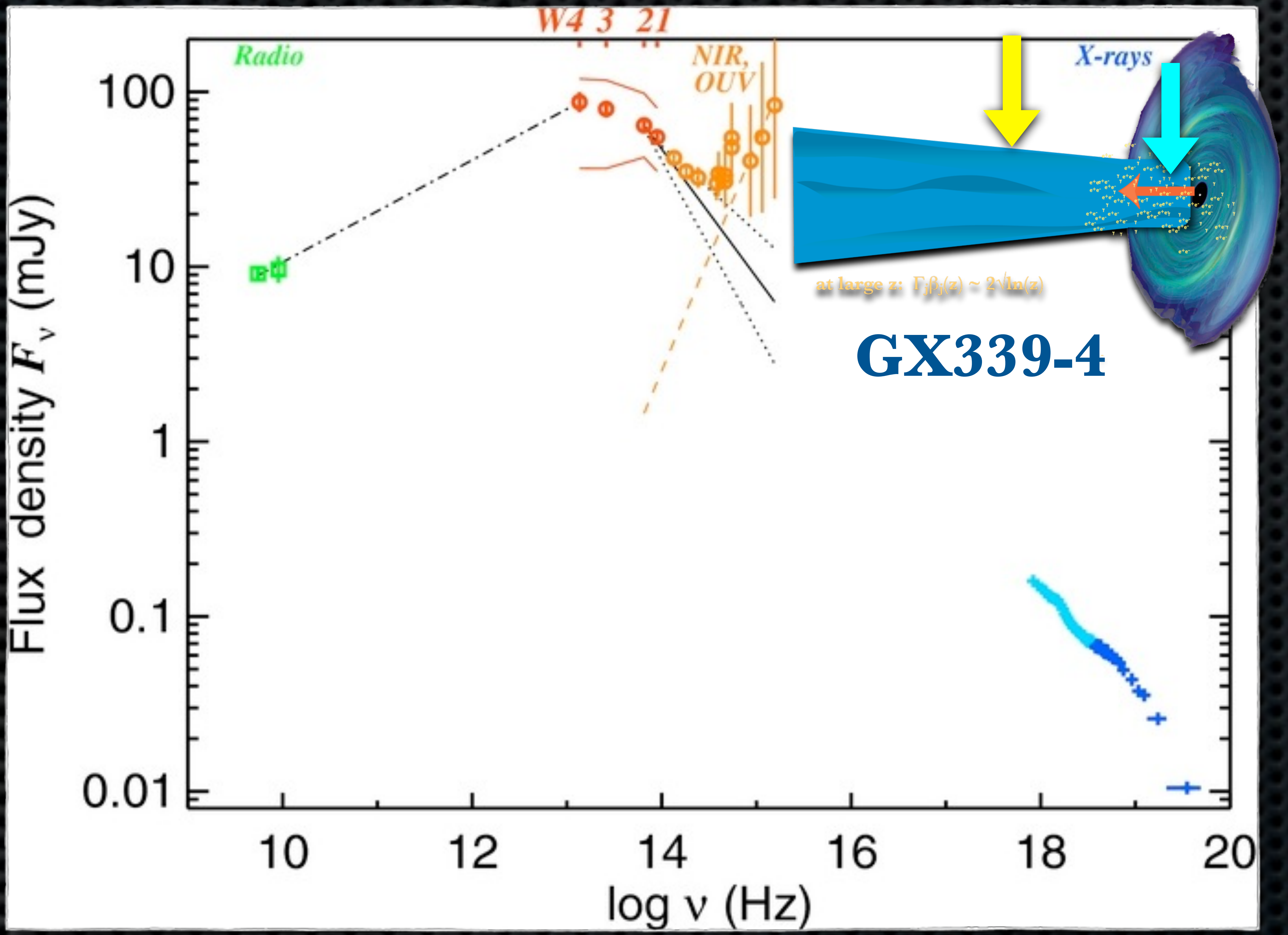

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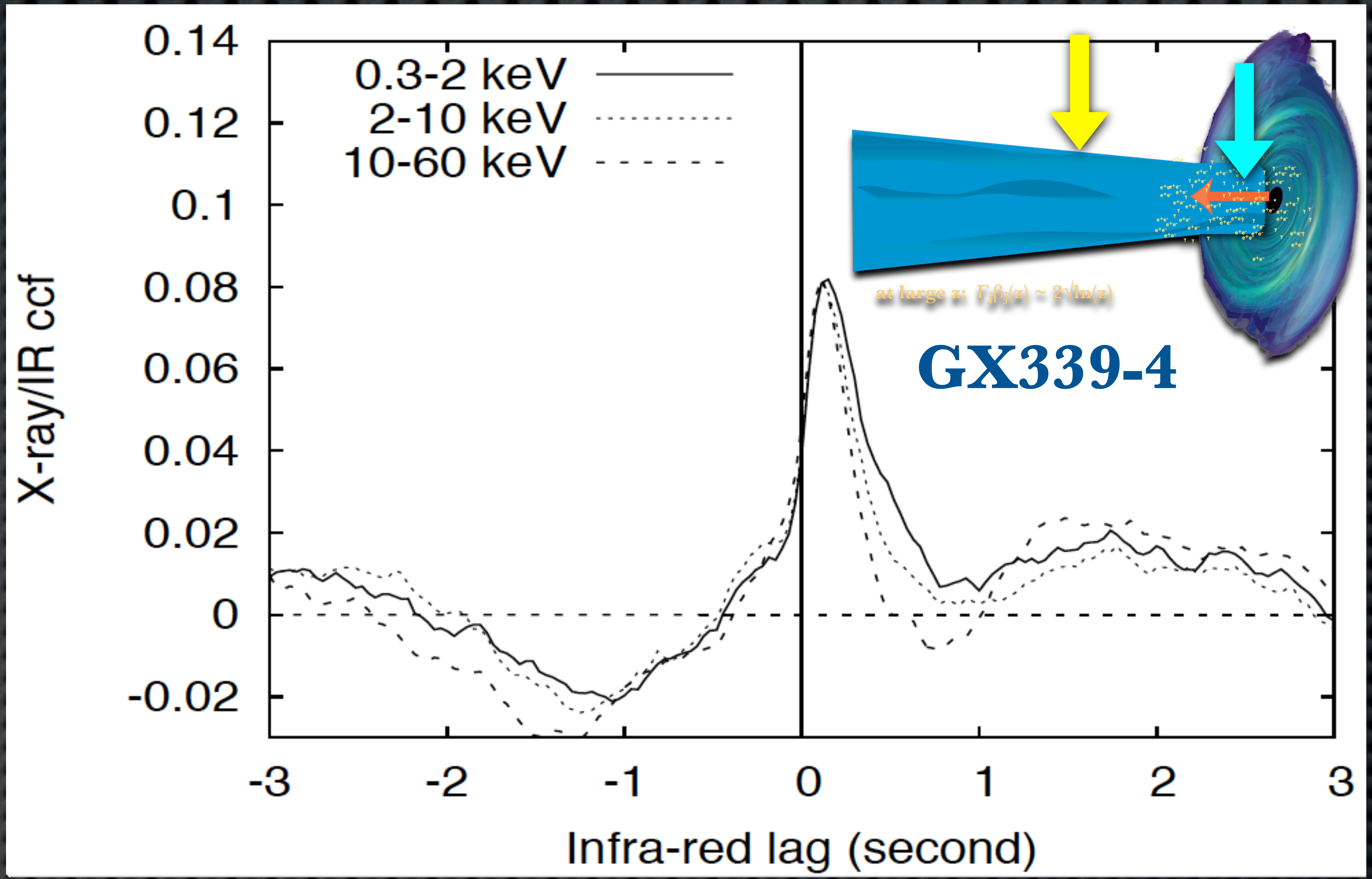

- Broadband noise: IR lags X-ray by ~110ms ➠ largest scale ~ 2×10^9cm (few 10^3 r_g), consistent with spectral fitting. Now found in three sources, all 0.1-0.2ms!

(Kalamkar++2016; Gandhi++ 2017)

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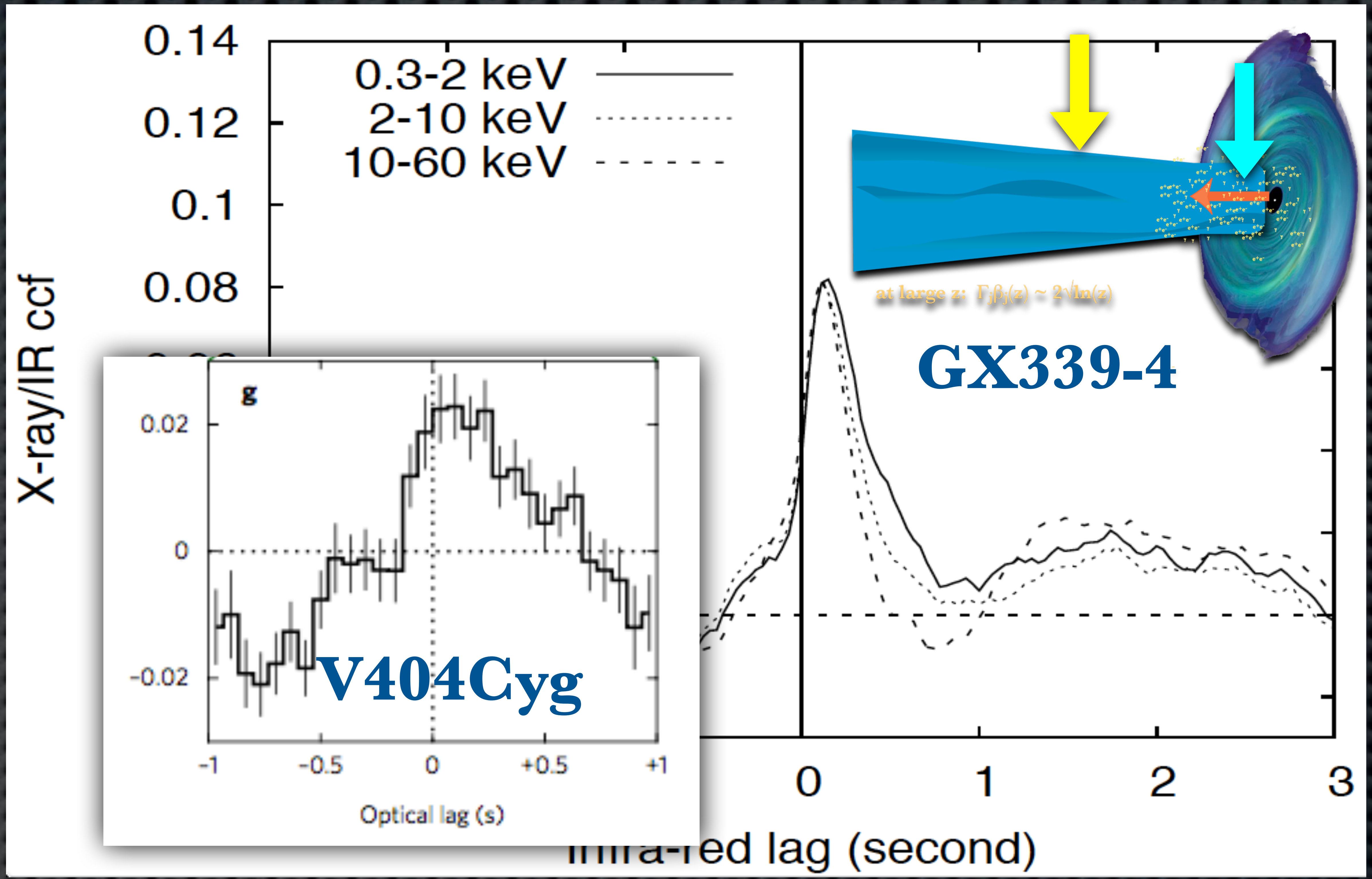

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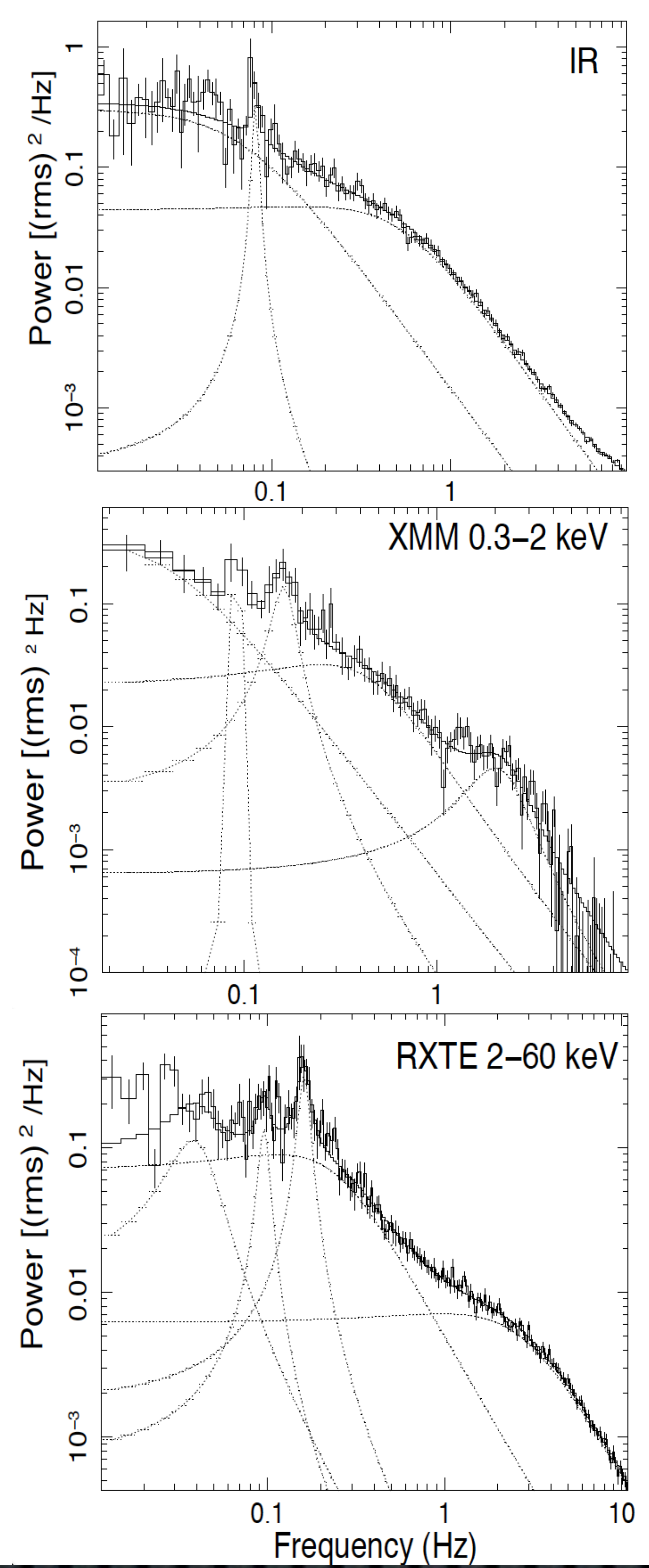
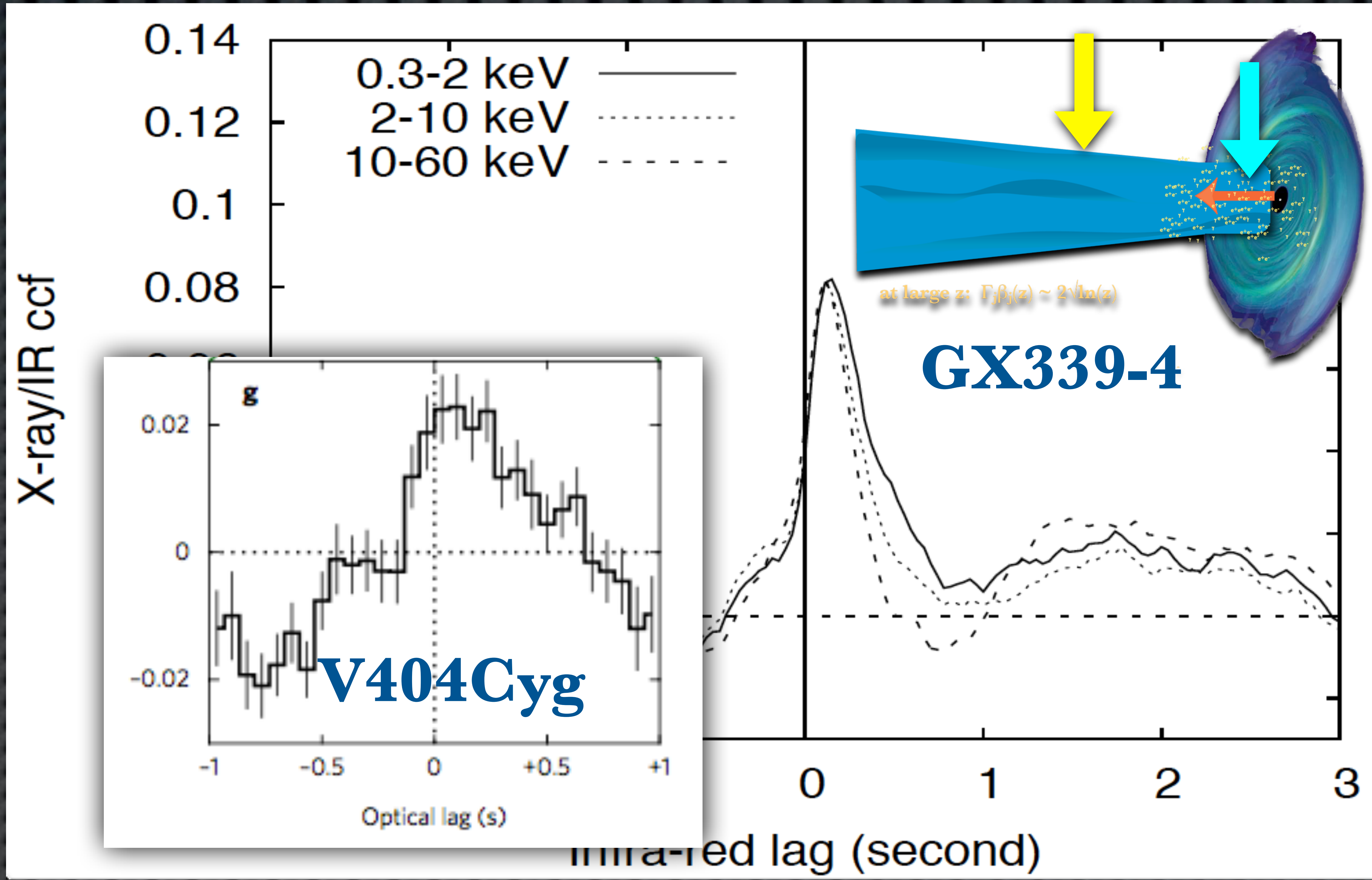
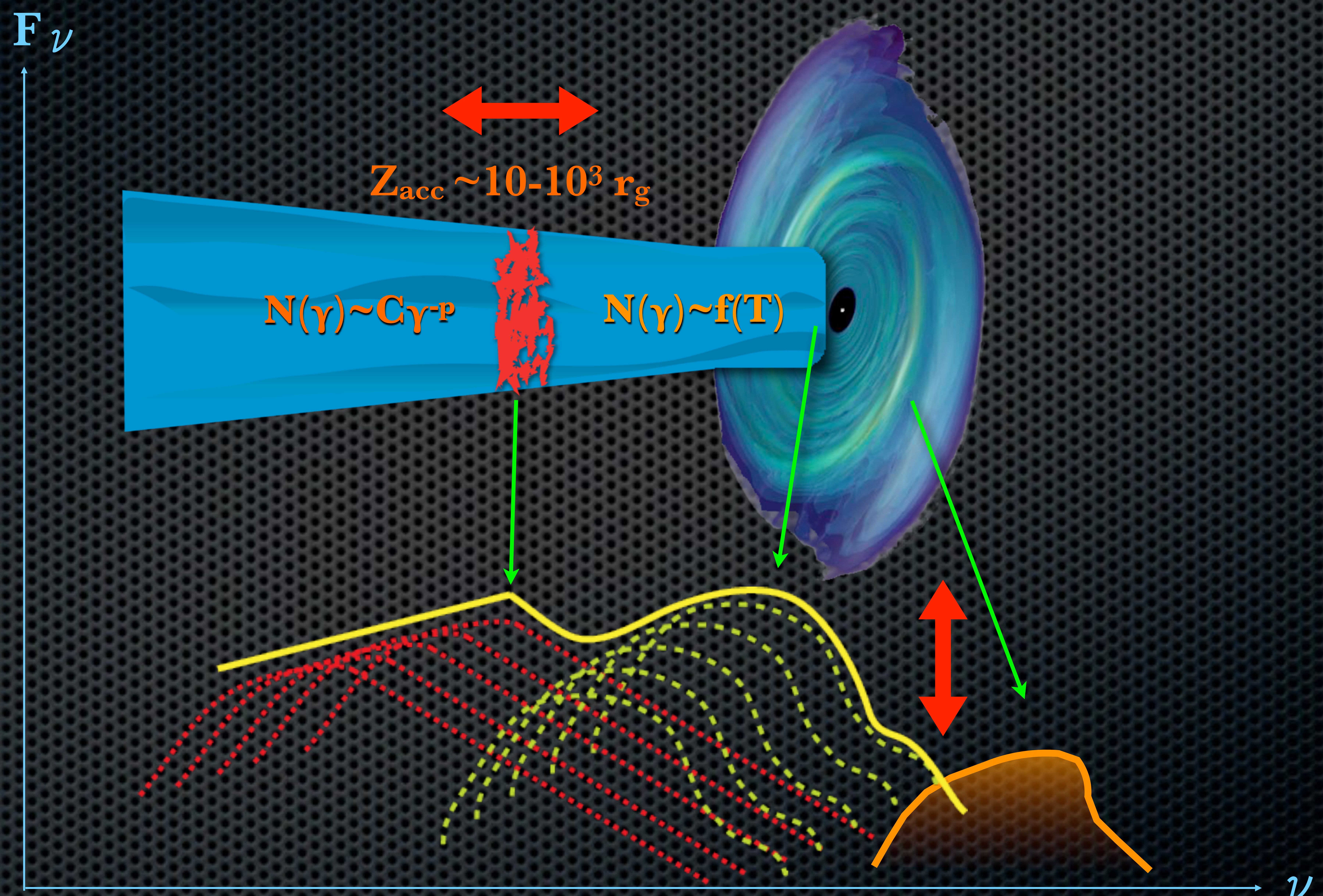




- Broadband noise: IR lags X-ray by ~110ms ➡ largest scale ~ 2x10⁹cm (few 10^3 r_g), consistent with spectral fitting. Now found in three sources, all 0.1-0.2ms!
- First IR LFQPO's! Half the Xray frequency

(Kalamkar++2016; Gandhi++ 2017)

Z_{acc} offset real, responds to changes in the accretion flow

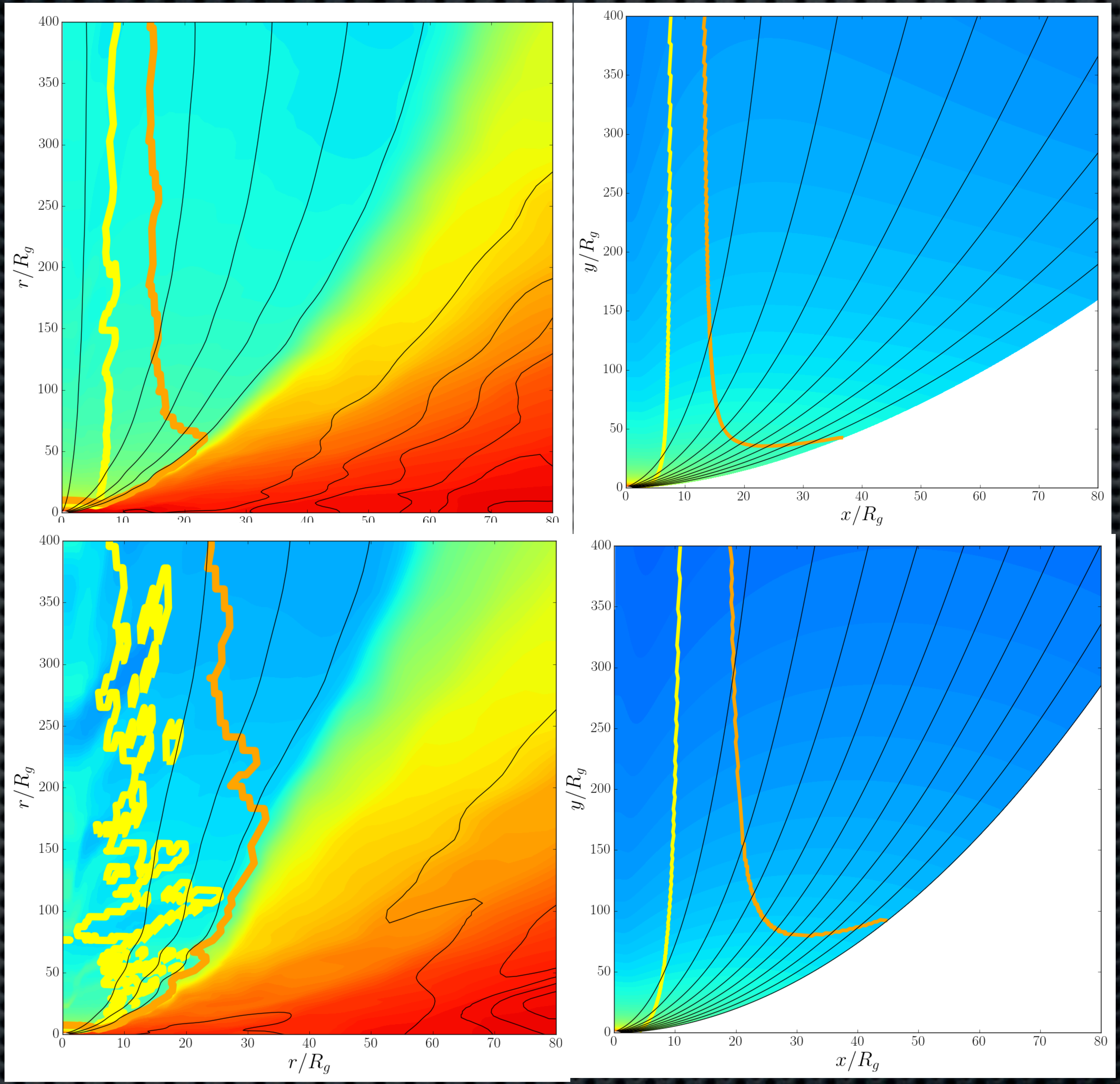


(SM, Falcke & Fender 2001; SM, Nowak & Wilms 2005)

Studying causality in GRMHD

$\sigma_0=10$

$\sigma_0=60$



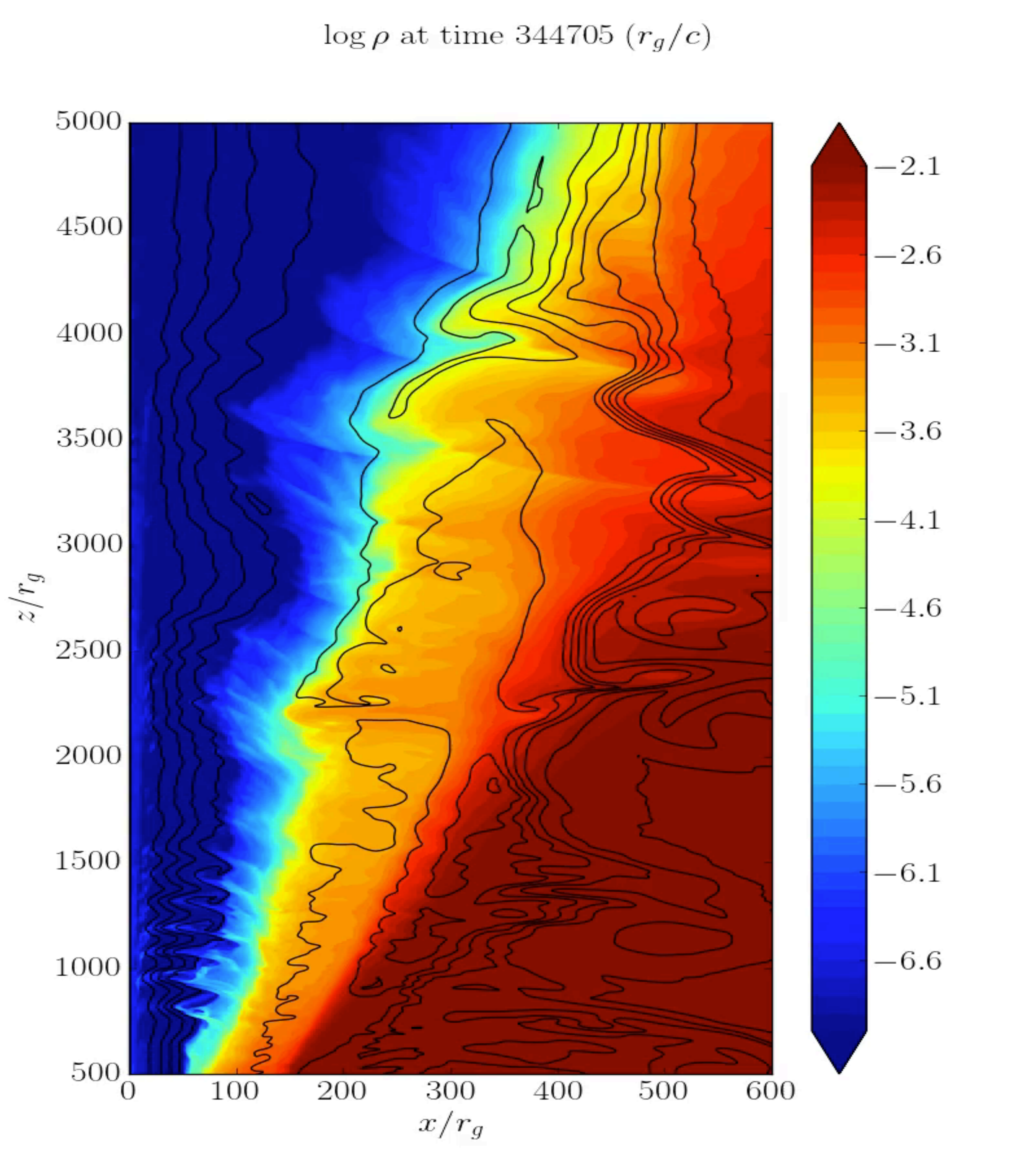
Alfvén Surface

M-S Fast Surface

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

Entrainment

- K-H eddies pick up matter from disk (~800 r_g), reconnect inside jet, freeing matter to travel with the jet
- Explains deceleration we see, changes jet collimation profile



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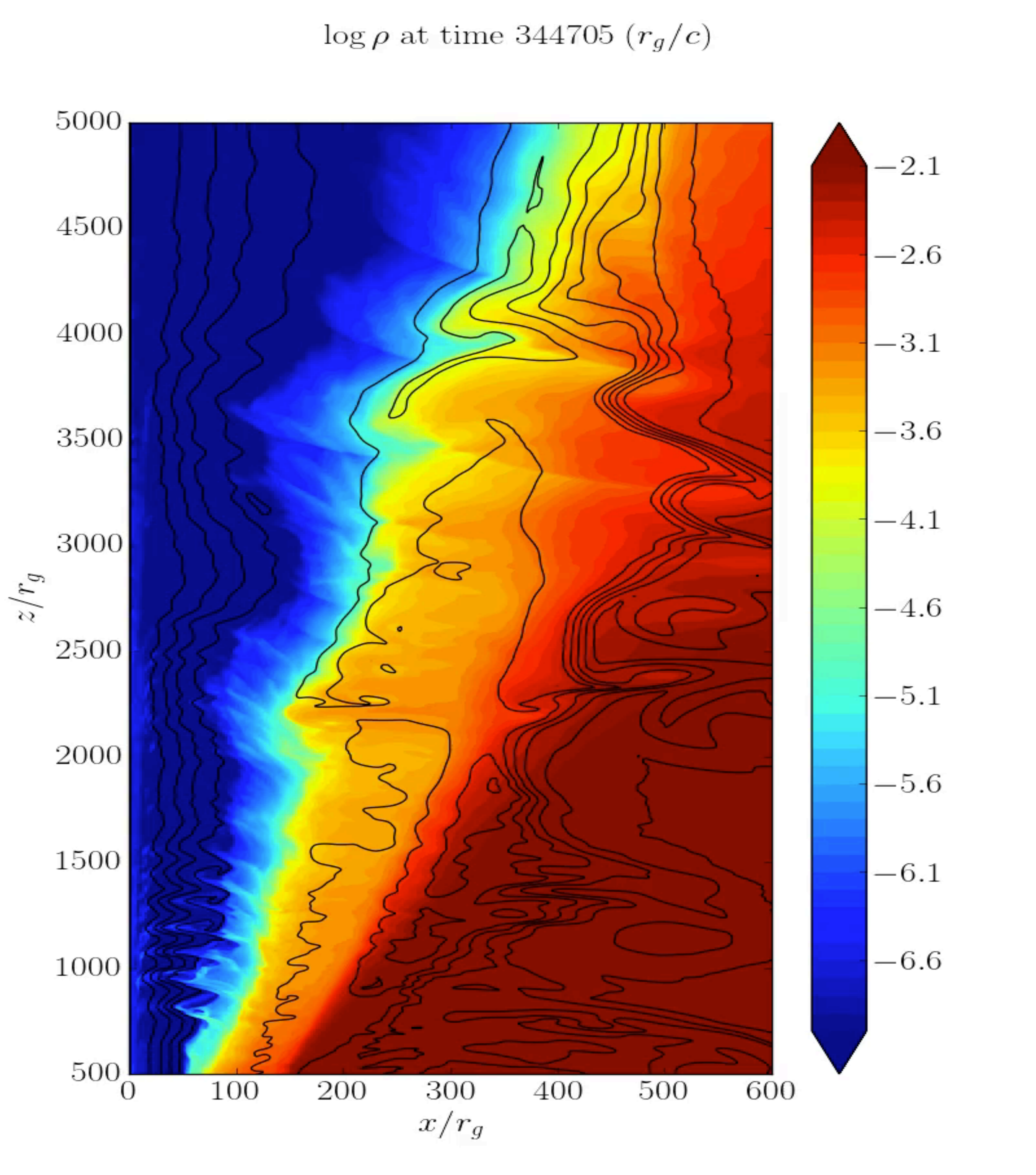

QUESTIONS FROM LECTURES

- How does warp of spacetime effect jets?
- PIC simulations => connection to larger scale sims/models?
- What would we need to verify SGRB + NS-NS merger scenario?
- Structured jets => can we see/constrain in all BHs?
- What are the most exciting open questions in nuclear astrophys.?
- How do jets in NS-NS binaries affect GW waveforms?
- To constrain models: better to go deep on one source or broadly w/ population (spec. for jets)?
- Connection b/w jets in XRBs/AGN + GRB/GW-EM mergers?
- What is physical process driving state transitions in BHs/NS?

- where are local XRBs w/ $<15 \odot$ sized BHs?
- How does ν cooling create asymmetry in explosion?