The Galactic Center

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with slides from R. Genzel, S. Gillessen, and the MPE GC group
mpe.mpg.de/ir/GC

ESO/Y. Beletsky

The Galactic Center

1. Seminar: strong gravity around Sgr A* (30.05)

2. Low-luminosity accretion onto Sgr A* (today)
   i. Why is Sgr A* so faint? (accretion theory)
   ii. Sgr A* IR / X-ray flares

3. Resolving the event horizon of a black hole with interferometry (01.06)

About the lectures

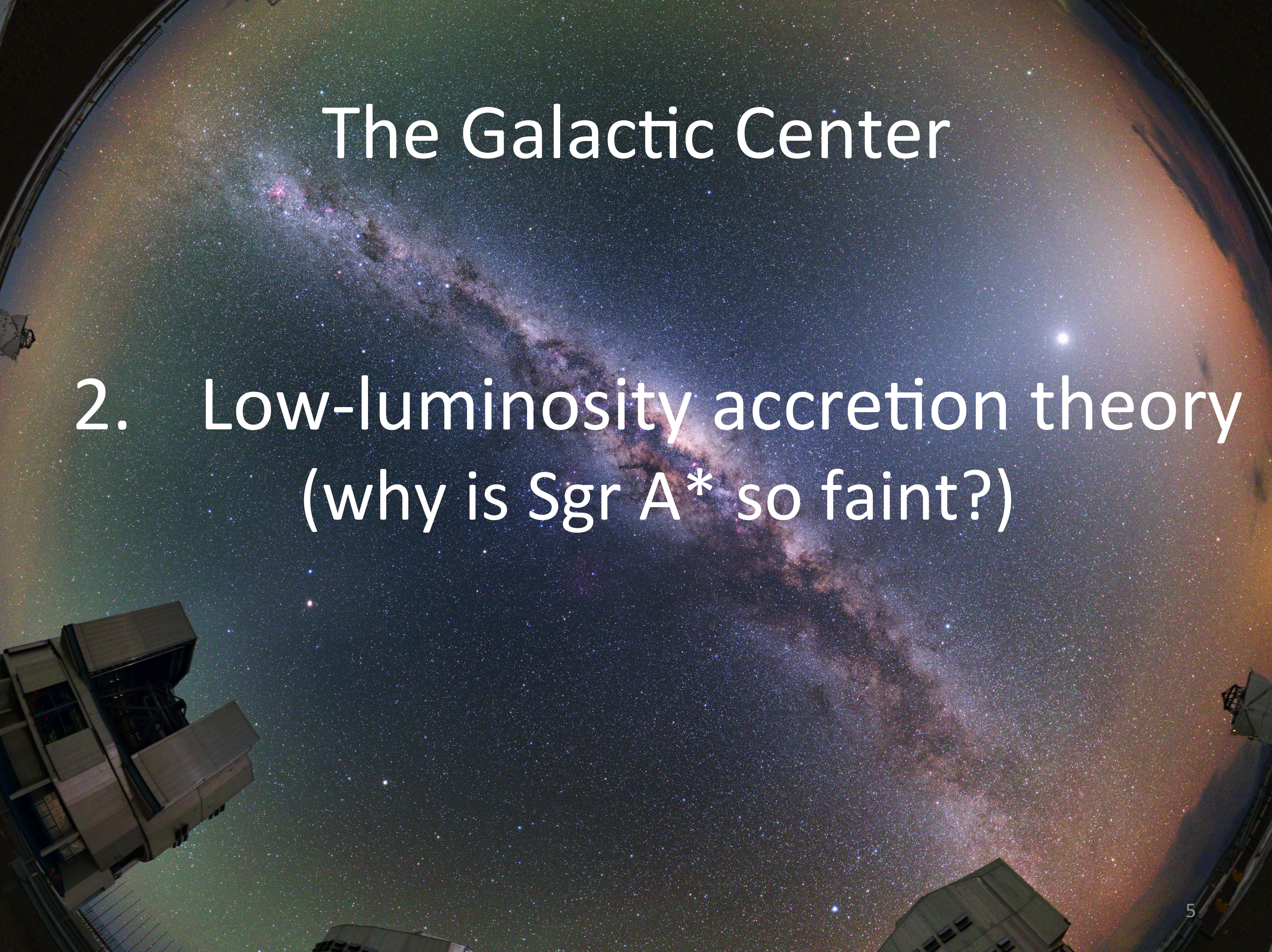
- Selected topics: highly biased
- Please ask questions!

- ~1 interactive Q / lecture:
  ~10 mins to think/calculate, discuss, share

About the lectures

- pdf of slides online: mpe.mpg.de/~jdexter/GCslides

- Further reading: Genzel+2010, Morris+2012, Falcke & Markoff 2013



The Galactic Center

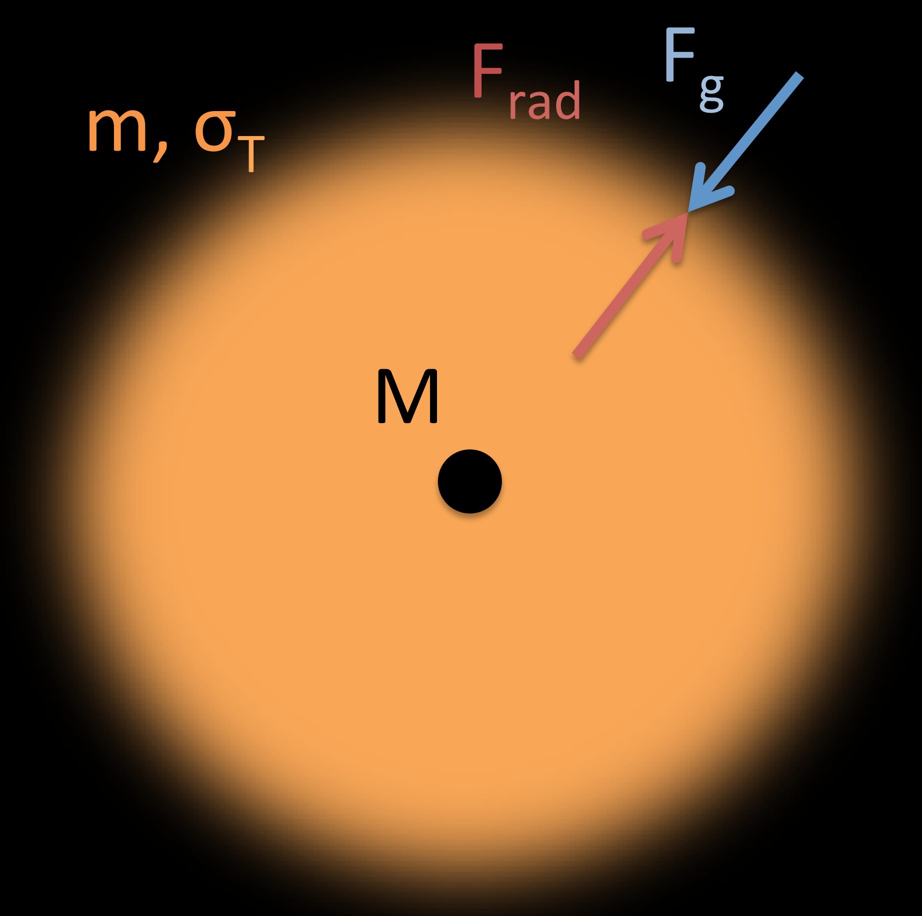
2. Low-luminosity accretion theory (why is Sgr A* so faint?)

Accretion power

- Infalling gas radiates its gravitational energy

Eddington Luminosity

- How bright can accretion be?



$F_g = F_{rad}$

$GMm_p/r^2 = L / 4\pi r^2 \;\; \sigma_T / c$

$L_{edd} = 4\pi G m_p c \, M / \sigma_T$

$\sim 10^{38}$ ergs / s (M/M_{sun})

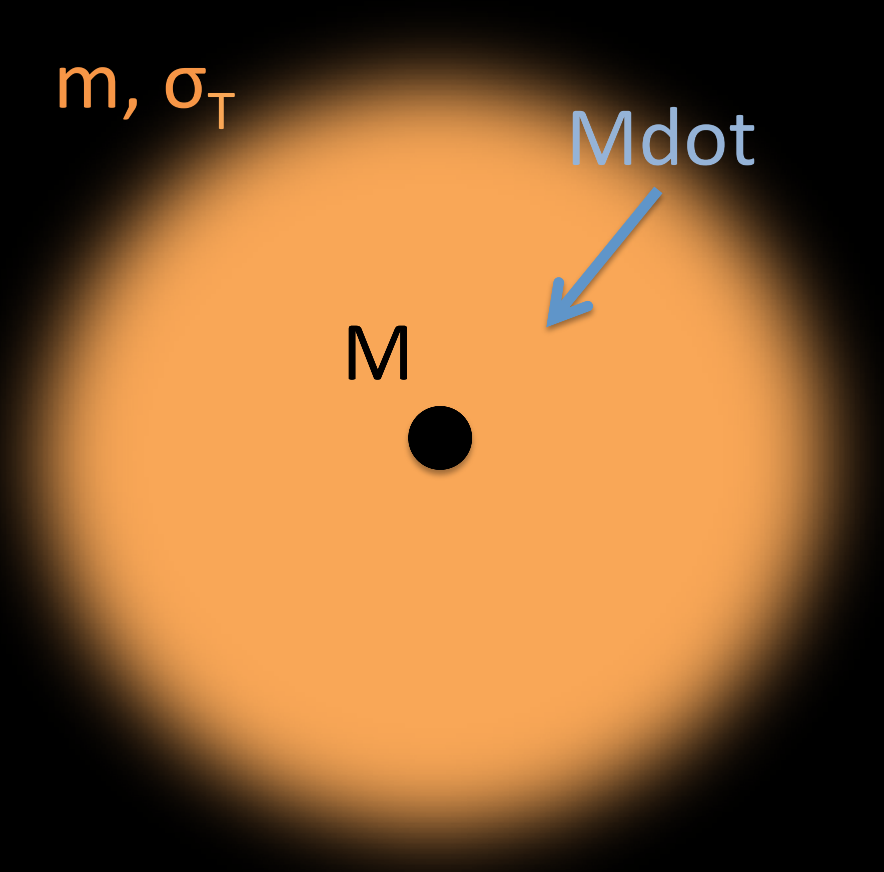
Sgr A*:

$L_{edd} \sim 10^{45}$ ergs / s

$L_{bol} < 10^{37}$ ergs / s

Eddington accretion rate

- What is minimum amount of infalling material to get L?



Maximum L:

L = dE/dt = d/dt(mc2)

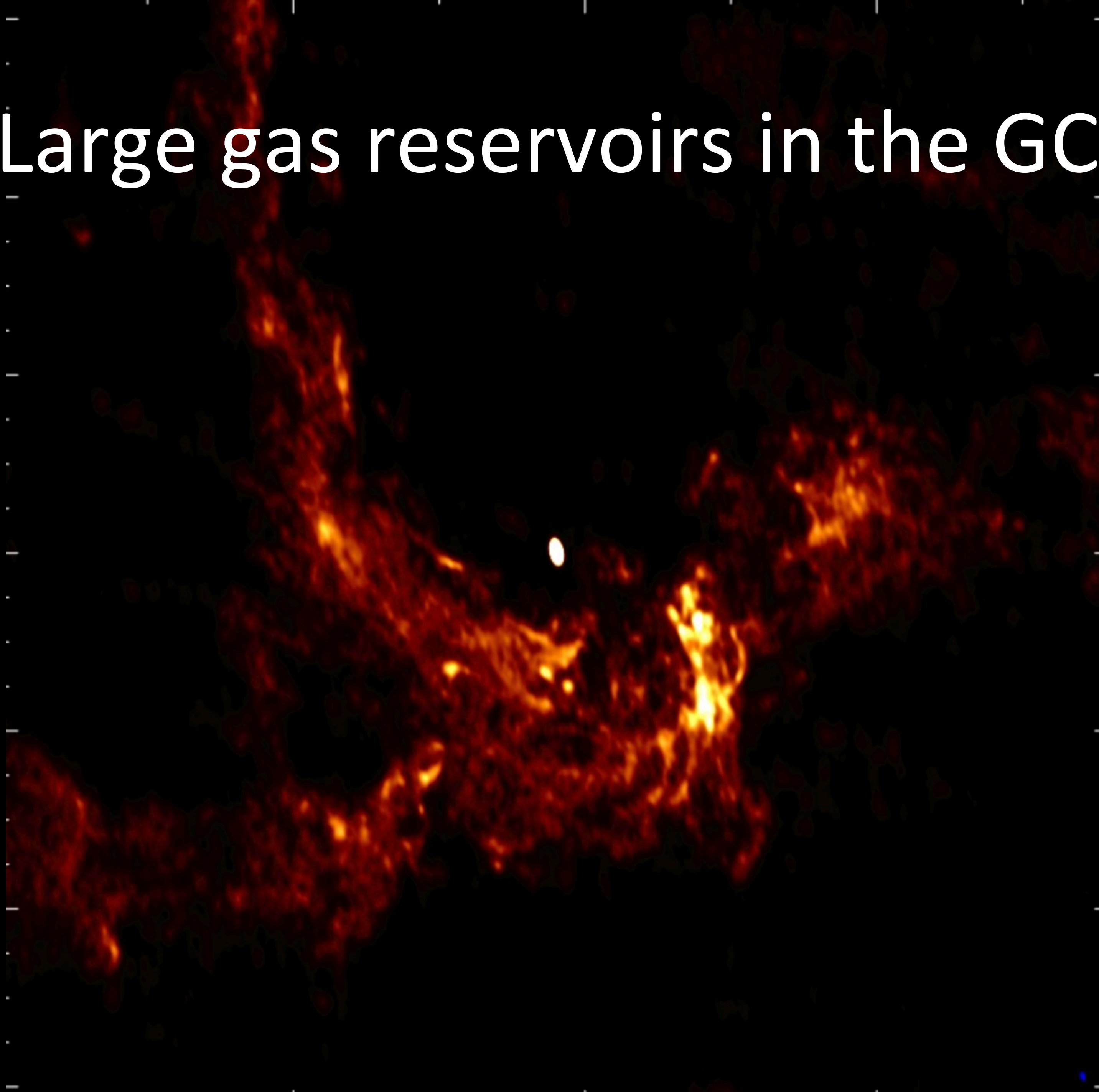
L = Mdot c^2

General L:

L = ε Mdot c^2

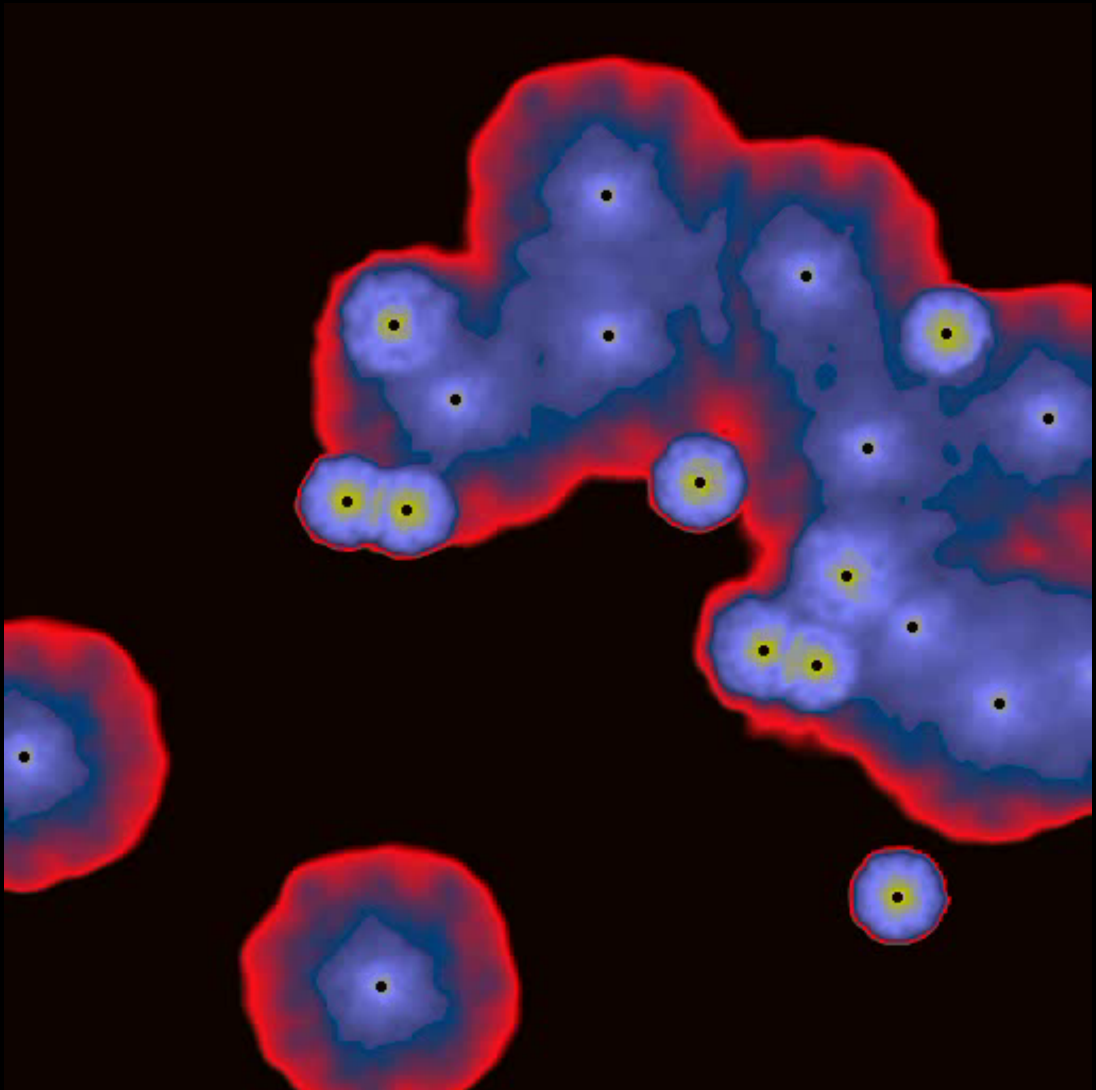
ε = "accretion efficiency"

Large gas reservoirs in the GC



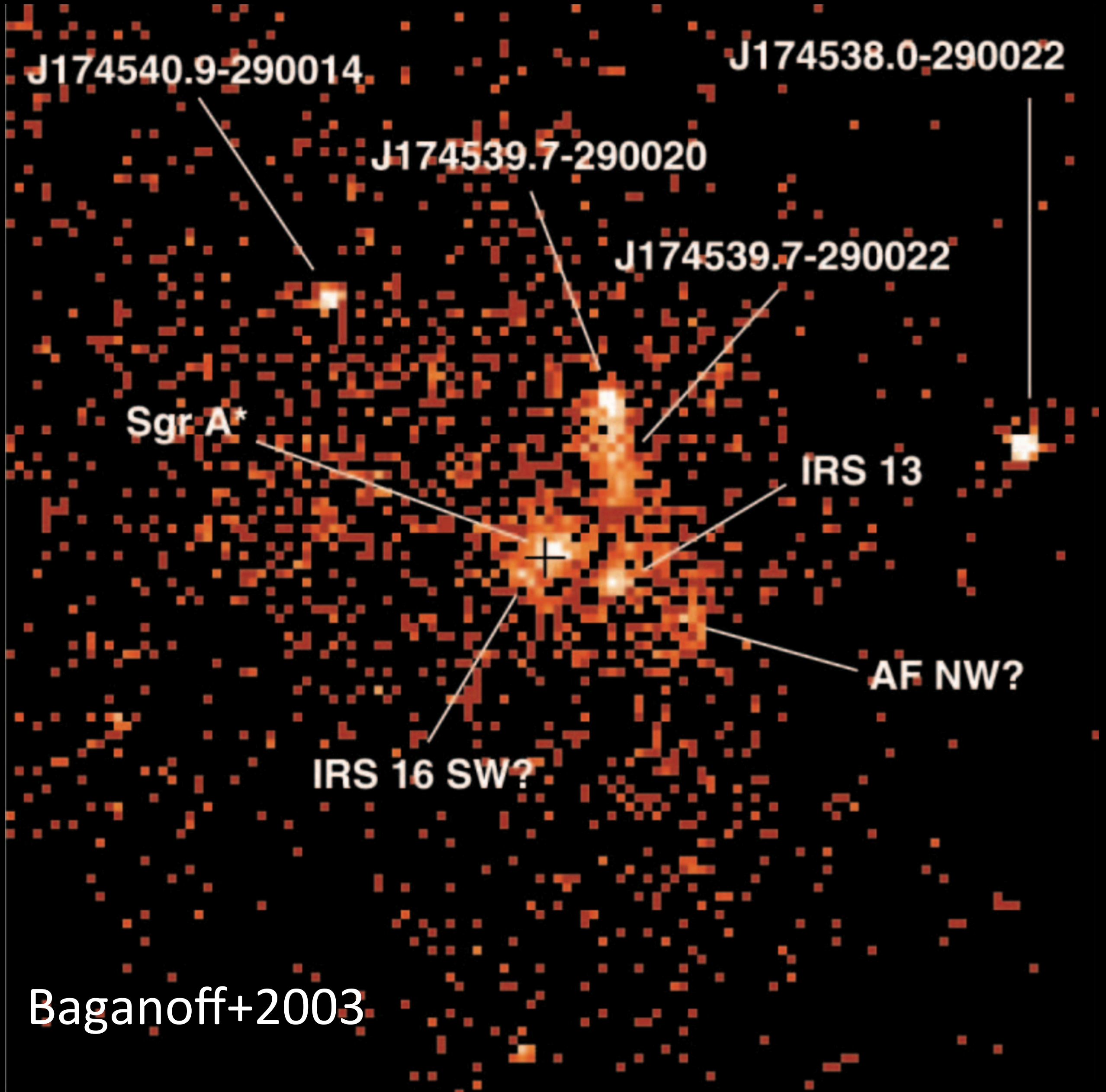
Stellar winds: black hole fuel

- Mdot ~ $10^{-4} – 10^{-3}$ Msun / yr (Martins+2007)



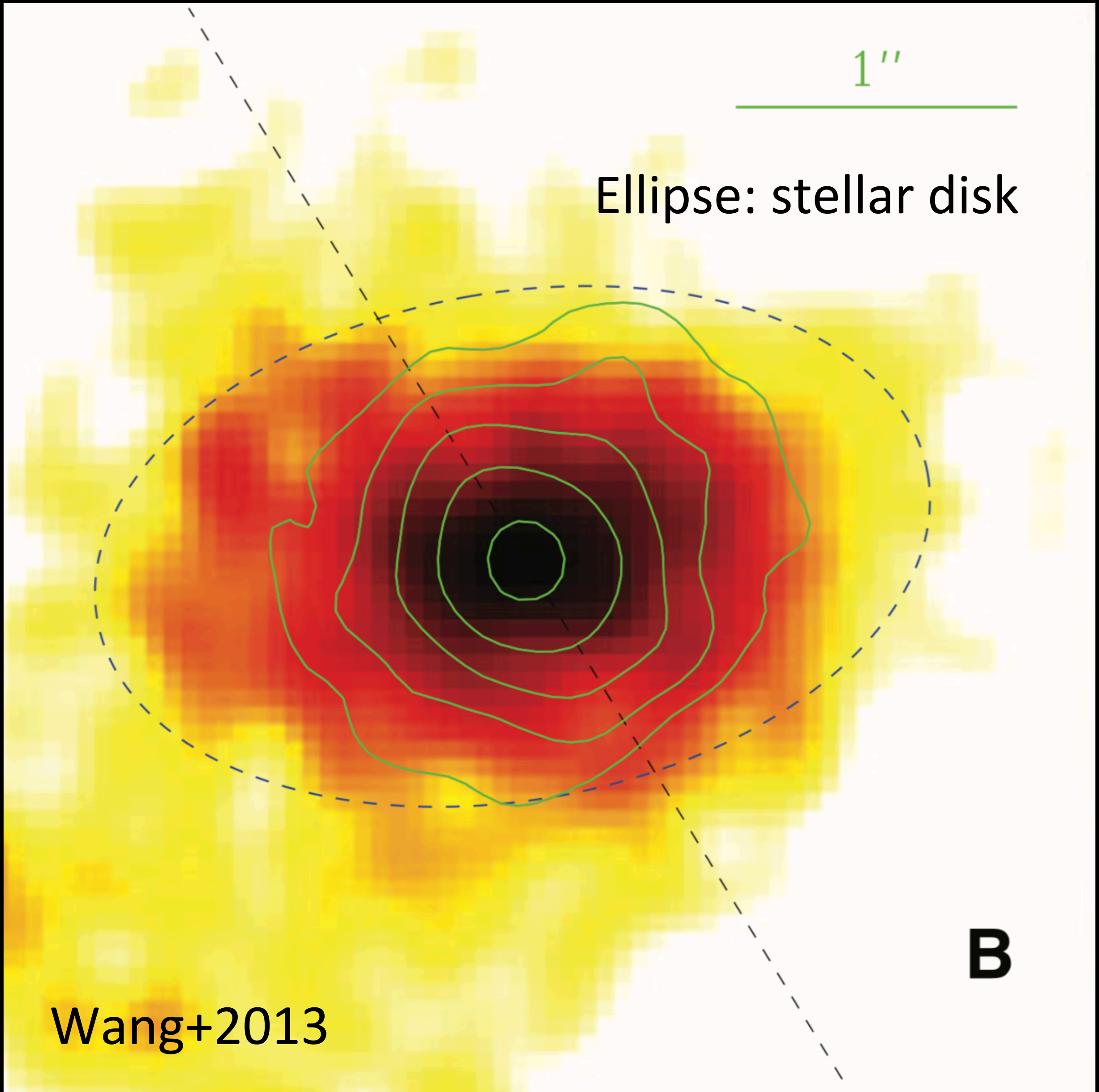
Cuadra +2006, 2008

X-rays from Sgr A*



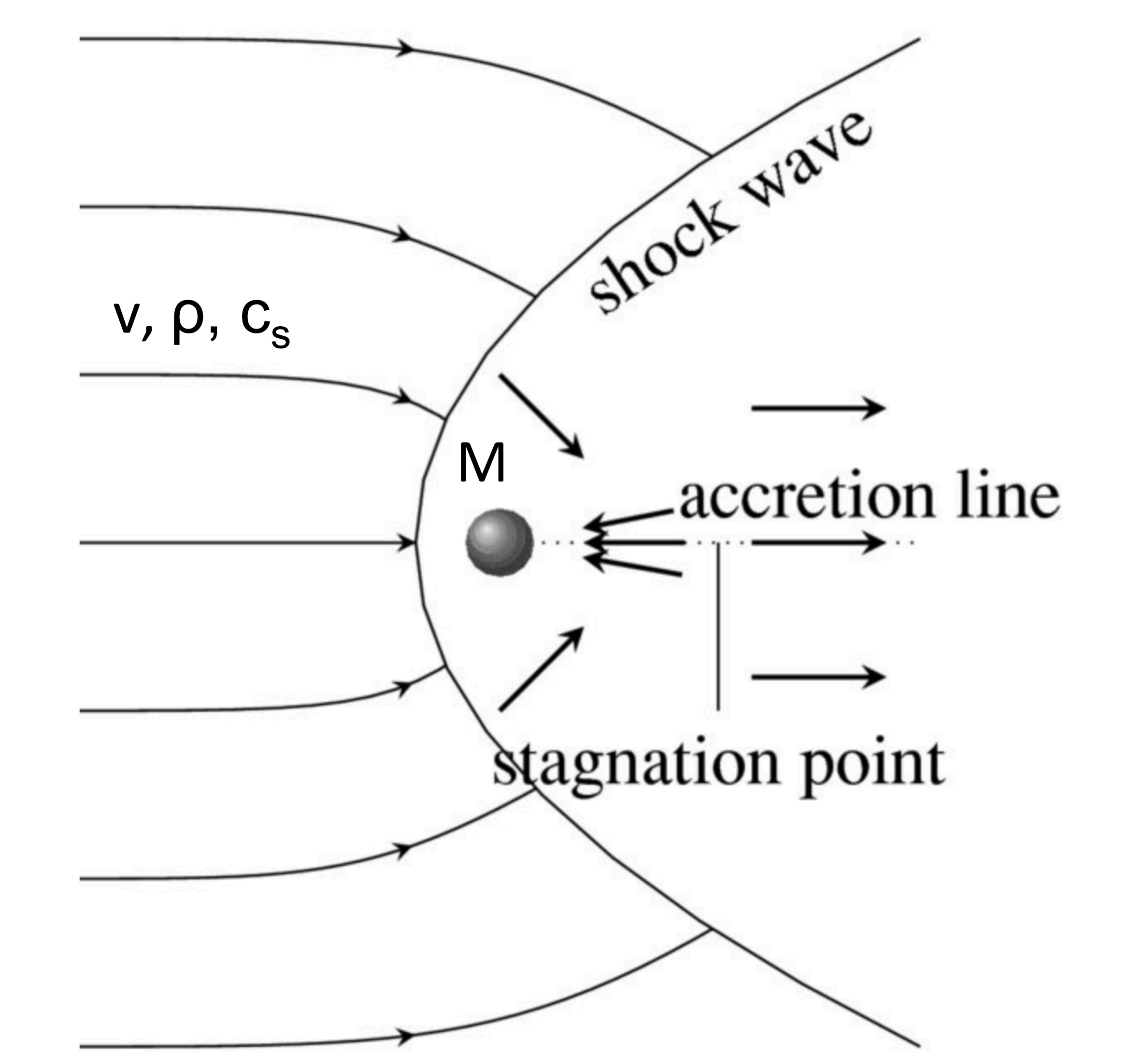
Baganoff+2003

X-rays from Sgr A*



Bondi-Hoyle accretion

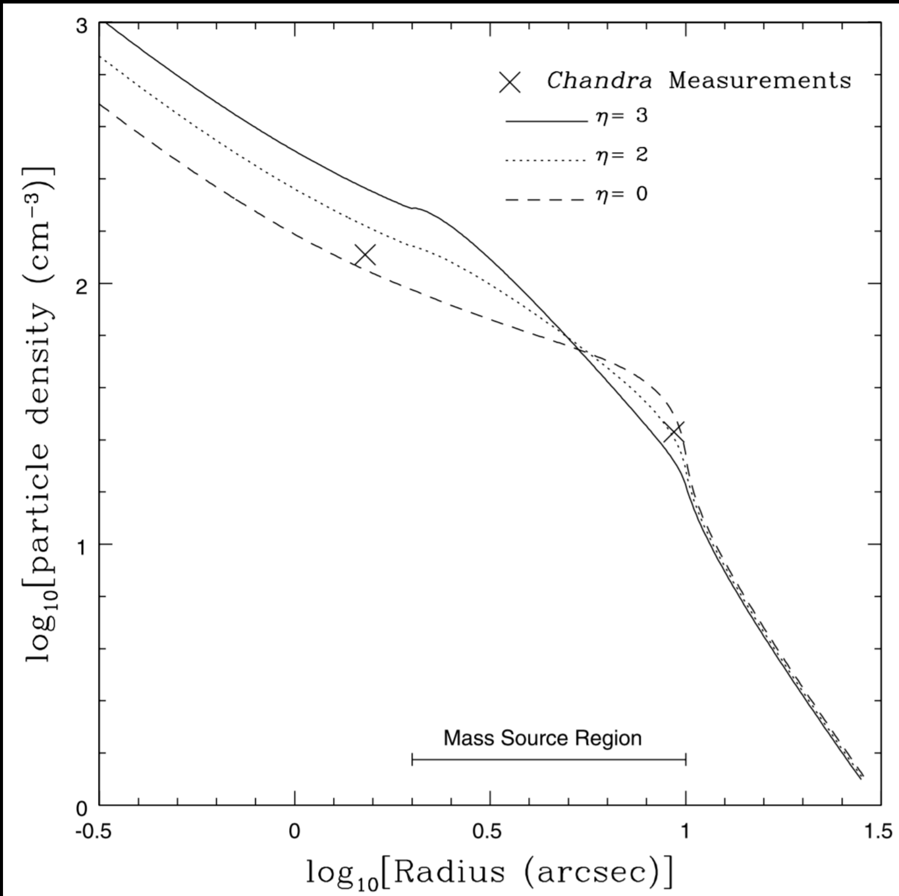
- Mdot = $4\pi\rho G^2M^2$ / $(v^2+c_s{}^2)^{3/2}$



Bondi-Hoyle accretion

- Mdot = $4\pi\rho G^2 M^2 / (v^2 + c_s^2)^{3/2}$
- X-rays: $n \sim 100\ \mathrm{cm}^{-3}$, $T \sim 10^7$ K
- Winds: $v \sim 1000$ km / s
- Mdot ~ $10^{-5}\ M_{sun}$ / yr

Quataert+1999, 2004

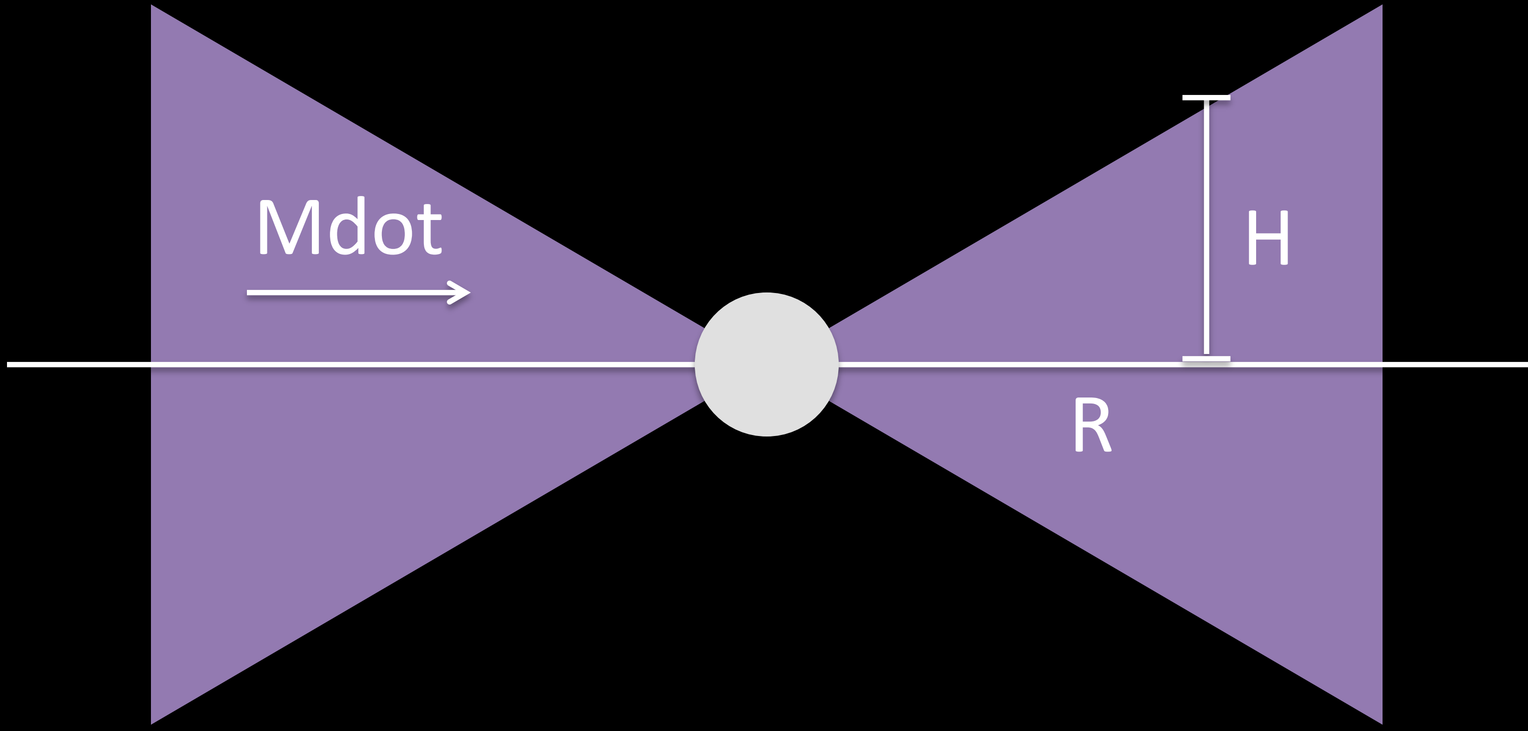


Q: Why is it difficult for gas to fall into a black hole?

- Sgr A* Bondi radius R ~ 0.1 pc: what is the angular momentum of a circular orbit?
- What fraction of this must be lost to reach the event horizon, R ~ 10^{-6} pc?
- Or: what eccentricity is needed for orbit from Bondi radius to reach event horizon?

Standard accretion theory

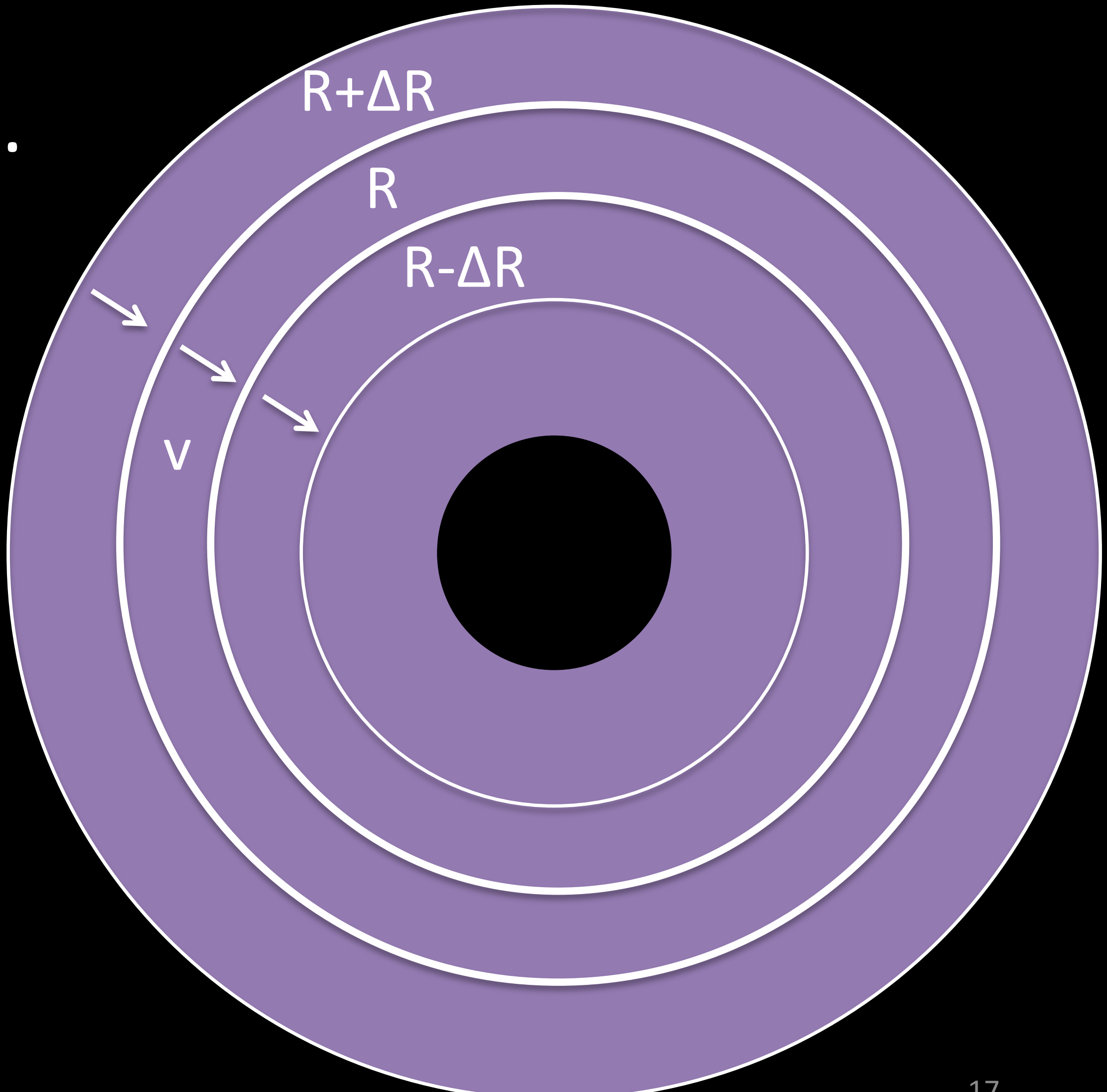
- Hydrodynamics equations (collisional, viscous fluid)
- Stationary, axisymmetric ($d_t = d_\phi = 0$)
- Vertically integrate over z (H/R < 1)
- Parameters: Mdot = constant, H/R < 1, alpha



Standard accretion theory

- Mass flux = const.
  = ρ v A
- A = 2πR 2H

$$\dot{\mathbf{M}} = \mathbf{4}\pi\mathbf{RH}\rho\mathbf{v}$$

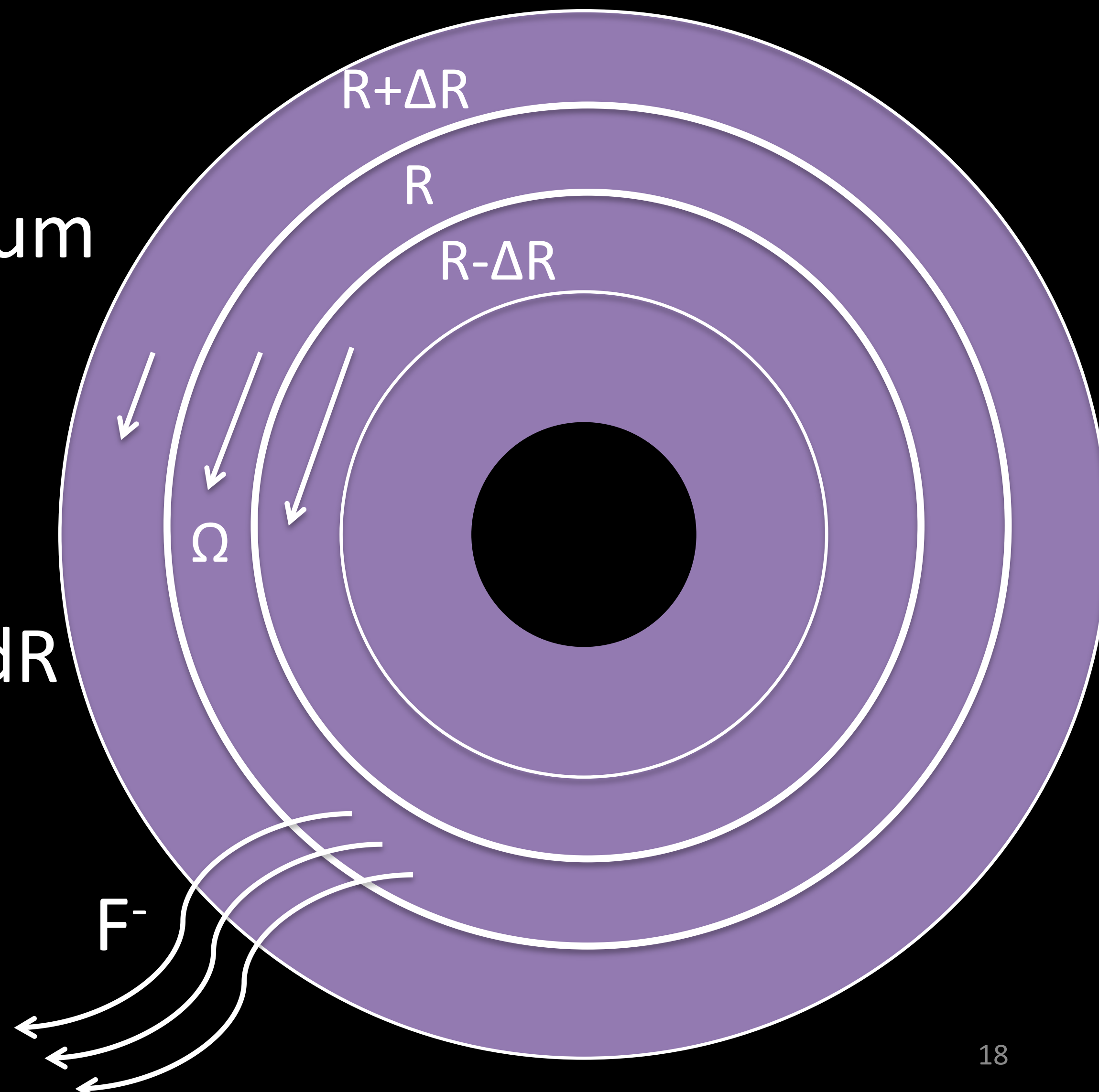


Standard accretion theory

- Stress transports angular momentum

$G(R)=\tau A$, $L(R)=R^2\Omega$

Mdot dL/dR = -dG/dR

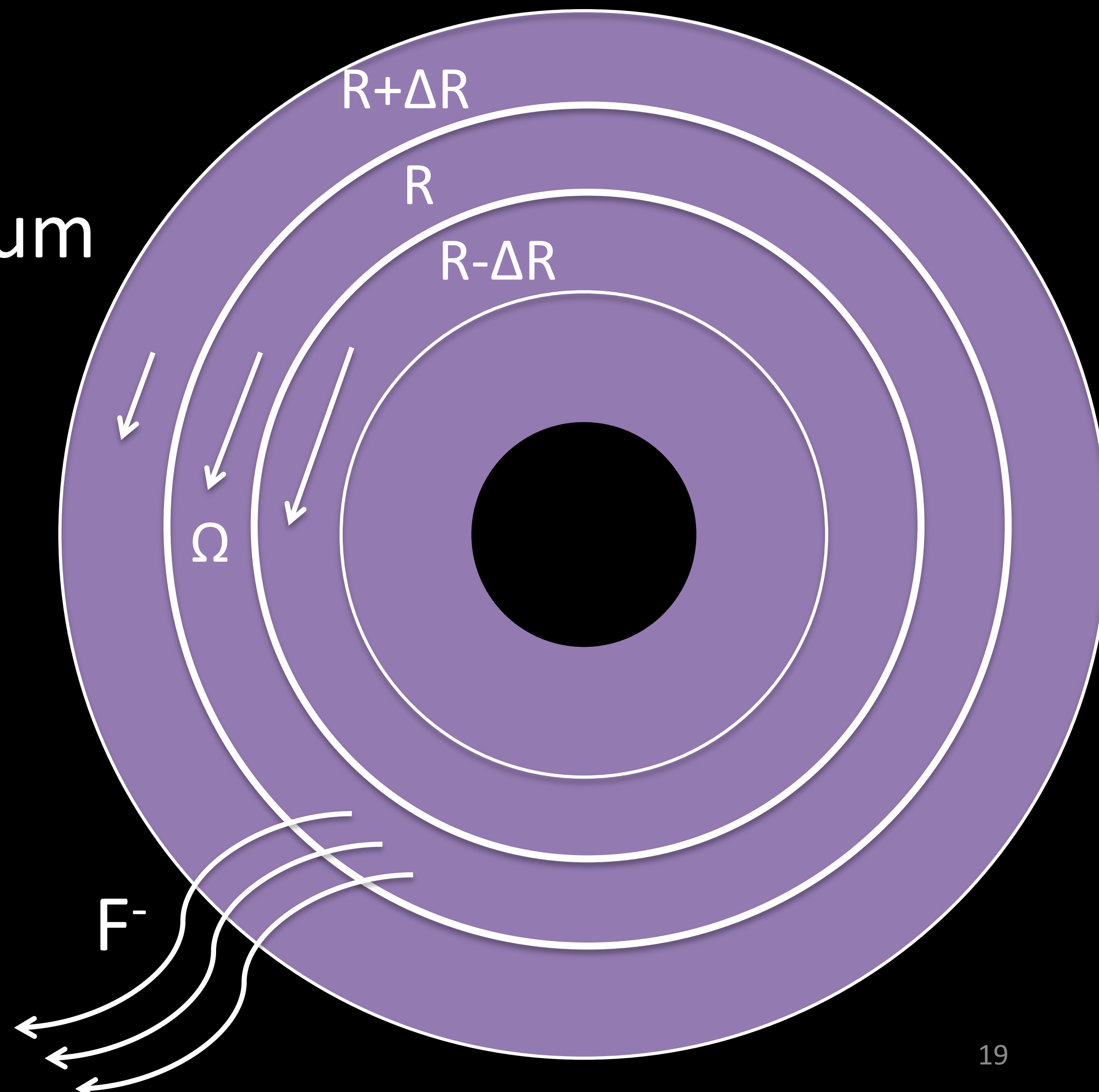


Standard accretion theory

- Stress transports angular momentum
- What is τ?

$$\tau_{\mathbf{r}\phi} = \rho\nu \mathrm{R}\frac{\mathrm{d}\Omega}{\mathrm{dR}}$$

$$= \alpha \mathrm{P}\frac{\mathrm{R}}{\Omega_{\mathrm{K}}}\frac{\mathrm{d}\Omega}{\mathrm{dR}}$$



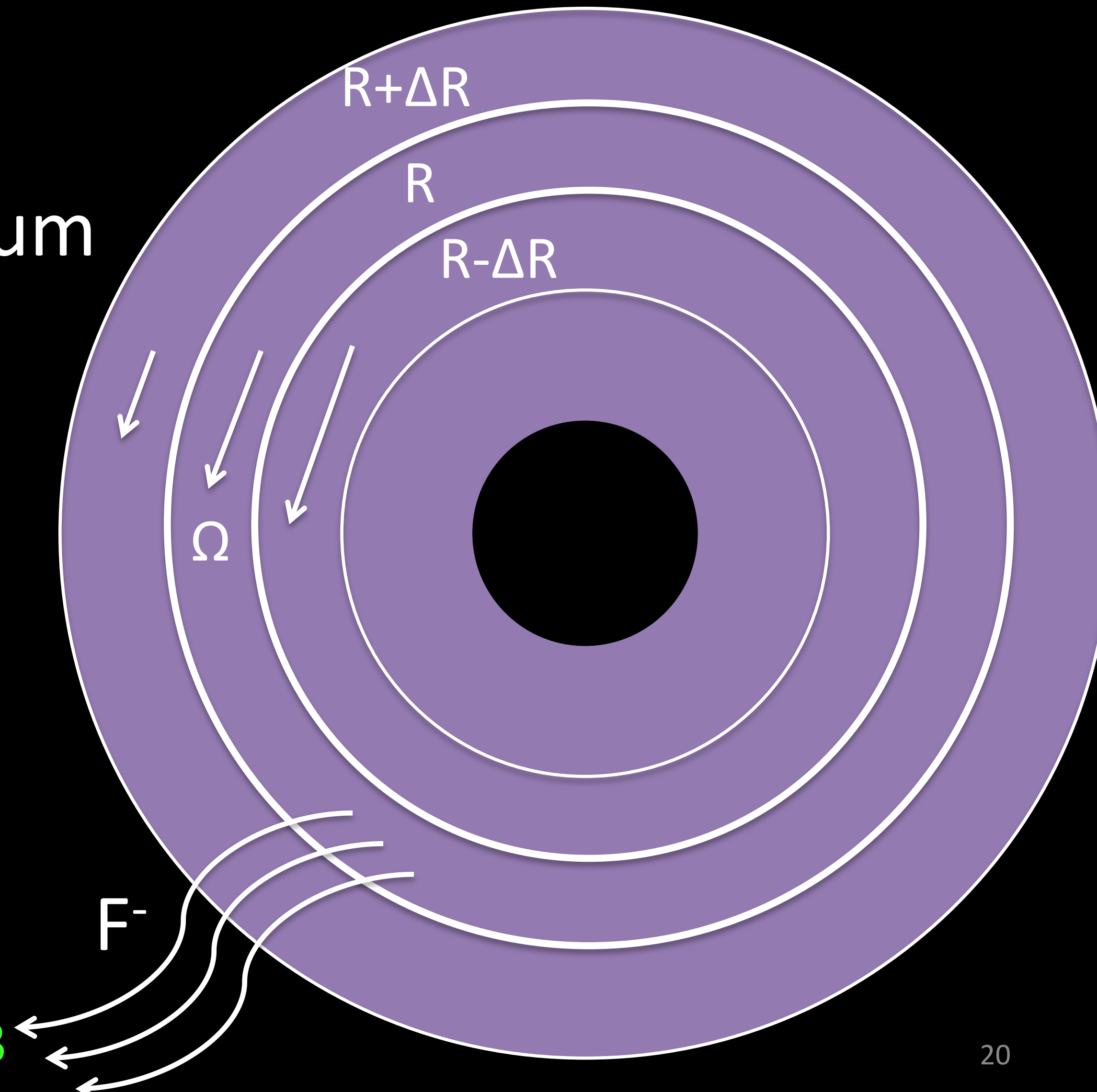
Standard accretion theory

- Stress transports angular momentum
- What is τ?

$$\tau_{r\phi} = \rho\nu R\frac{d\Omega}{dR}$$

$$= \alpha P \frac{R}{\Omega_K}\frac{d\Omega}{dR}$$

"α model"
Shakura & Sunyaev 1973



Standard accretion theory

Shakura & Sunyaev 1973, here following Blaes 2004

- Mass:

$$\dot{\mathbf{M}} = \mathbf{4}\pi\mathbf{RH}\rho\mathbf{v}$$

- Momentum:

$$\rho\mathbf{v}\,\mathbf{d_R v} = \rho(\mathbf{\Omega^2} - \mathbf{\Omega_K^2})\mathbf{R} - \mathbf{d_R p}$$

- Angular momentum:

$$\dot{\mathbf{M}}\,\mathbf{d_R}(\mathbf{\Omega R^2}) = \mathbf{d_R}(\mathbf{4}\pi\mathbf{R^2H}\tau_{\mathbf{R}\phi})$$

- Energy:

Q^{adv} = Q^{+} - Q^{-}

$$\frac{\dot{\mathbf{M}}}{\mathbf{2}\pi\rho\mathbf{R}}\mathbf{T}\,\mathbf{d_R s} = \mathbf{2RH}\tau_{\mathbf{R}\phi}\,\mathbf{d_R\Omega} + \mathbf{2F^-}$$

Thin disk accretion

- $\Omega = \Omega_K$, Mdot = constant, $Q^+ = Q^-$ ($Q^{adv} = 0$), no torque at inner edge (R_i)
- Angular momentum:

$$\dot{\mathbf{M}}\,\mathbf{d_R}(\mathbf{\Omega R^2}) = \mathbf{d_R}(\mathbf{4\pi R^2 H}\tau_{\mathrm{R}\phi})$$

$$\dot{\mathbf{M}}(\mathbf{\Omega_K R^2} - \mathbf{\Omega_{K,i} R_i^2}) = \mathbf{4\pi H R^2}\tau_{\mathbf{R}\phi}$$

Thin disk accretion

- $\Omega = \Omega_K$, Mdot = constant, $Q^+ = Q^-$ ($Q^{adv} = 0$), no torque at inner edge (R_i)
- Angular momentum:

$$\mathbf{\dot{M}\, d_R(\Omega R^2) = d_R(4\pi R^2 H \tau_{R\phi})}$$

$$\mathbf{\dot{M}(\Omega_K R^2 - \Omega_{K,i} R_i^2) = 4\pi H R^2 \tau_{R\phi}}$$

- Energy:

$$\mathbf{\frac{\dot{M}}{2\pi\rho R} T\, d_R s = 2RH\tau_{R\phi}\, d_R\Omega + 2F^-}$$

$$\mathbf{F^- = -RH\tau_{R\phi} d_R \Omega_K}$$

Thin disk accretion

- Solve for flux emerging from disk, F^-

$$\dot{M}(\Omega_K R^2 - \Omega_{K,i} R_i^2) = 4\pi H R^2 \tau_{R\phi}$$

$$F^- = -RH\tau_{R\phi} d_R \Omega_K$$

Thin disk accretion

- Solve for flux emerging from disk, F^-

$$\mathbf{\dot{M}(\Omega_K R^2 - \Omega_{K,i} R_i^2) = 4\pi H R^2 \tau_{R\phi}}$$

$$\mathbf{F^- = -RH\tau_{R\phi} d_R \Omega_K}$$

- $\Omega_K^2 = GM/R^3$, $d_R\Omega_K = -3/2\ \Omega_K / R$:

$$\mathbf{F^-(r) = \frac{3GM\dot{M}}{8\pi R^3}\left(1 - \sqrt{\frac{R_{in}}{R}}\right)}$$

$$\mathbf{L = 2\int_{R_i}^{\infty} dR\, 2\pi R\, F^-(R)}$$

Thin disk accretion

- Solve for total luminosity integrated over disk:

$$\mathbf{L = 2\int_{R_i}^{\infty} dR\, 2\pi R\, F^{-}(R)}$$

$$\mathbf{L = \frac{GM\dot{M}}{2R_i}}$$

Thin disk accretion

- Solve for total luminosity integrated over disk:

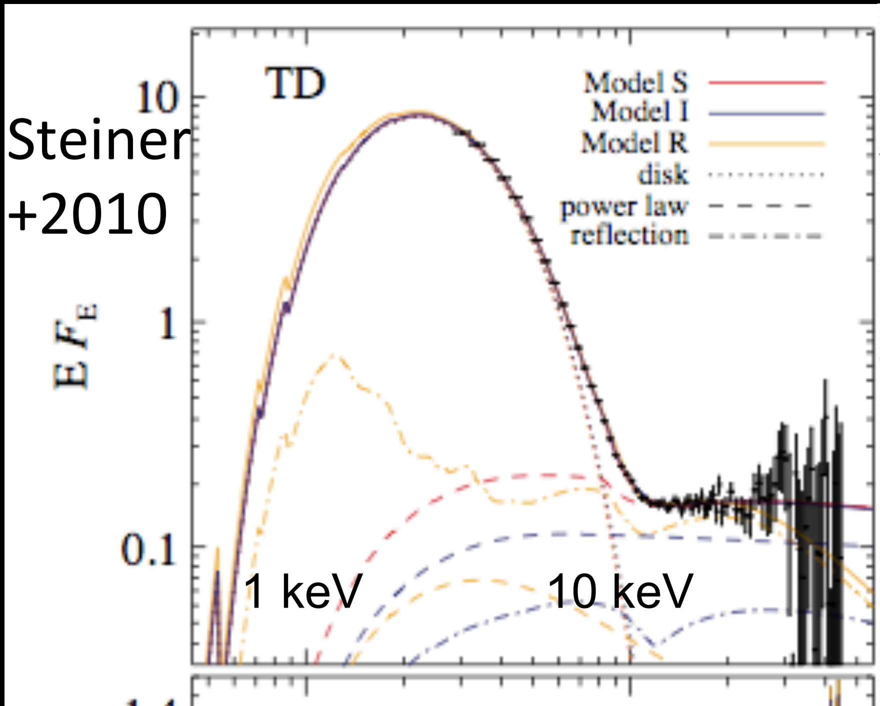
$$\mathbf{L = 2\int_{R_i}^{\infty} dR\, 2\pi R\, F^{-}(R)}$$

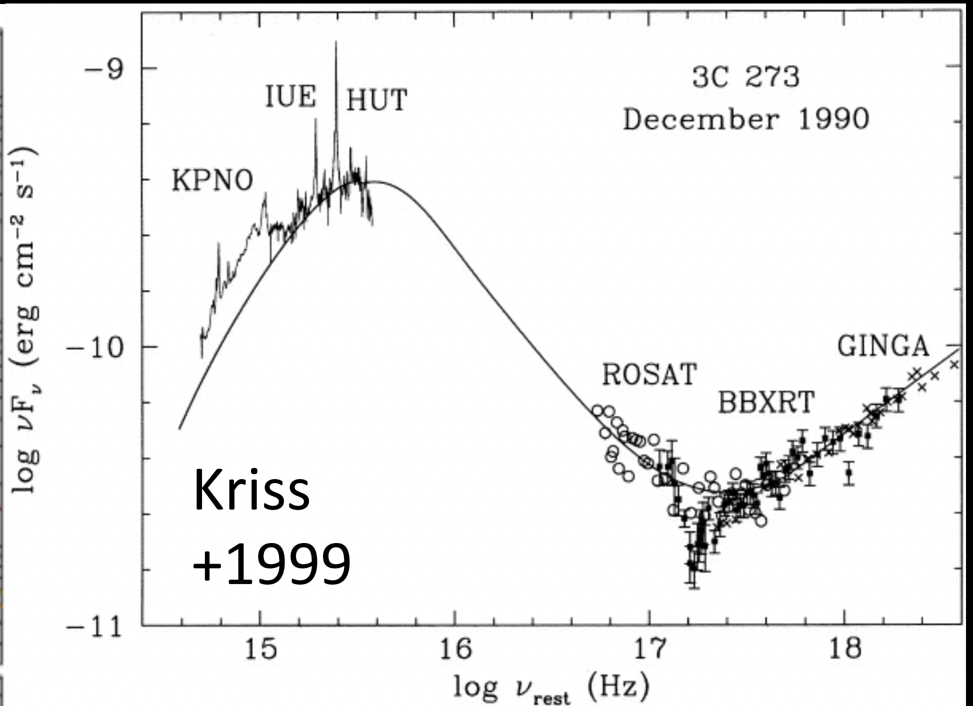
$$\mathbf{L = \frac{GM\dot{M}}{2R_i}}$$

- R_i ~ innermost stable circular orbit of a black hole = 6 GM/c^2 = 6 r_g = for spin zero
- L ~ 10% Mdot c^2!
- Compare: nuclear fusion ~ 0.1% Mdot c^2

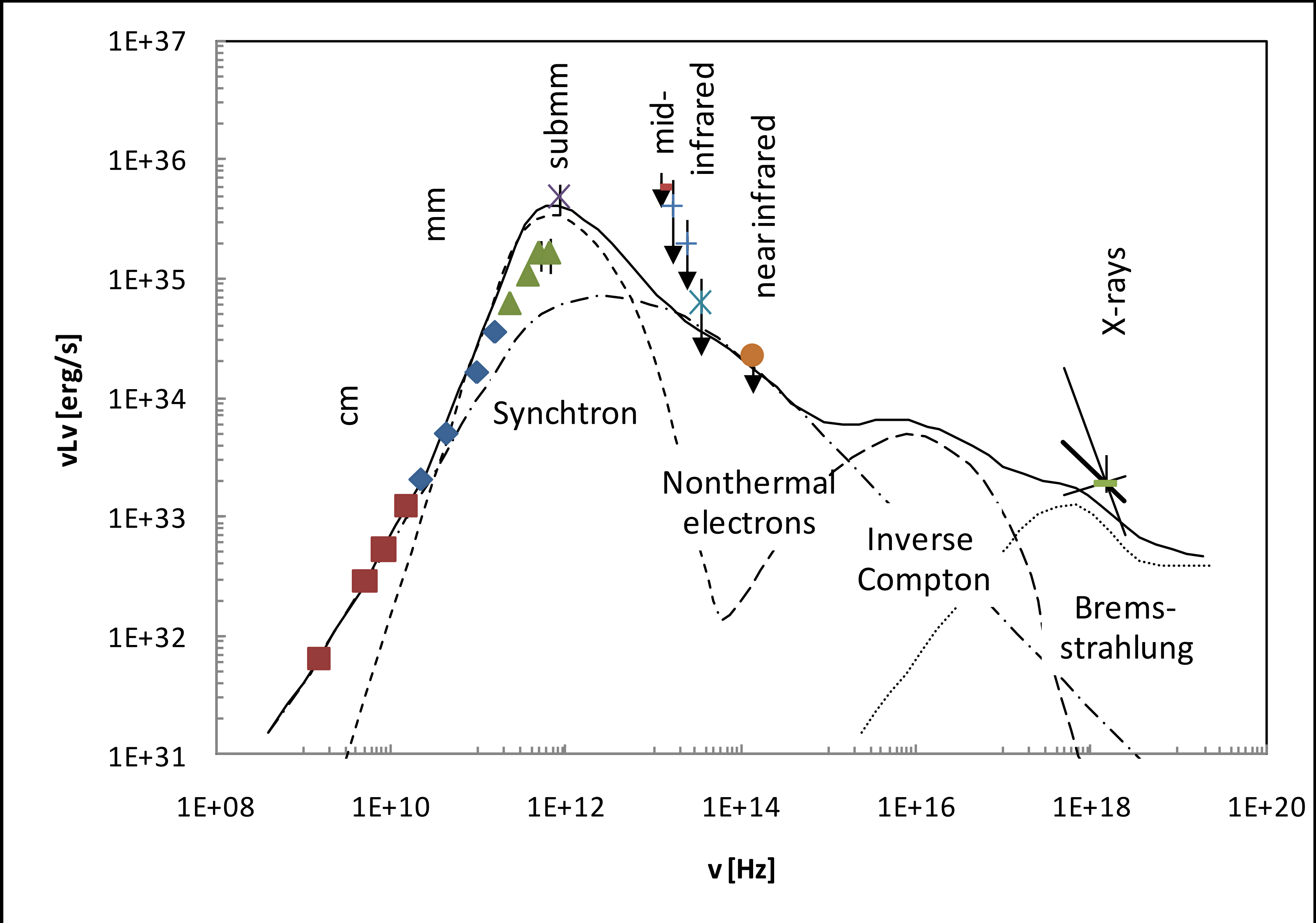
Thin disk accretion

- opt. thick, so $L = 4\pi R^2 \sigma T_{eff}^4$
- $R \sim M$, $\dot{m} = \dot{M} c^2 / L_{edd}$ (mdot = Mdot c² / L_edd)
- $T_{eff} \sim \text{mdot}^{1/4} M^{-1/4}$
- Stellar black holes in X-rays, AGN in UV





Sgr A* SED

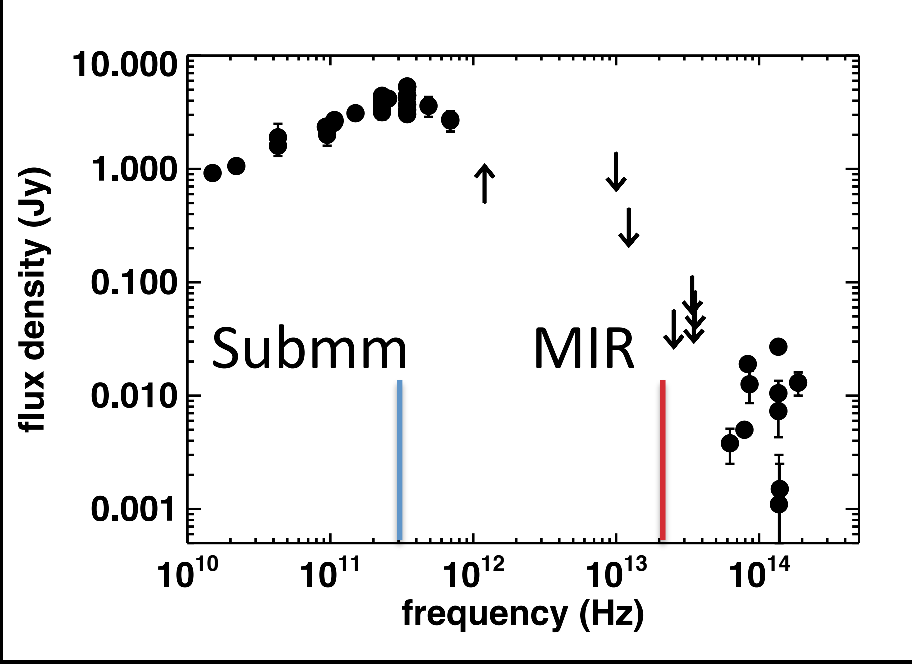


1E+37
1E+36
1E+35
1E+34
1E+33
1E+32
1E+31
vLv [erg/s]
1E+08
1E+10
1E+12
1E+14
1E+16
1E+18
1E+20
v [Hz]
cm
mm
submm
mid-
infrared
near infrared
X-rays
Synchtron
Nonthermal
electrons
Inverse
Compton
Brems-
strahlung

Thin disks don't work for Sgr A*

- Thin disk:
  L ~ 10^5 too bright;
  spectrum should peak in IR not submm

- If Mdot ~ $\mathrm{Mdot}_{\mathrm{Bondi}}$,
  $\varepsilon = L / \mathrm{Mdot}\, c^2 \sim 10^{-5}$!
- Why is Sgr A* so faint?



ADAF theory

- Thin disk assumes rapid cooling. Breaks down when cooling time becomes long (Rees+1982).

- $t_{cool}/t_{inflow} < 1$:

$t_{cool} = u / \varepsilon \sim nkT / n^2\Lambda$; $t_{inflow} = \Omega^{-1} \alpha^{-1} (H/R)^{-2}$

$t_{cool}/t_{inflow} \sim (kT)^{1/2}/n\ \Omega\alpha$

ADAF theory

- Vertical hydrostatic equilibrium:
  $p/n = kT \sim GMm_p/R^3H \sim m_pc^2\ r_g/R\ (H/R)^2$
- $mdot = Mdot/Mdot_{Edd} \sim n\ t_{inflow}^{-1}\ (H/R)^{-1}$

ADAF theory

- Vertical hydrostatic equilibrium:
  $p/n = kT \sim GMm_p/R^3H \sim m_pc^2\ r_g/R\ (H/R)^2$
- $mdot = Mdot/Mdot_{Edd} \sim n\ t_{inflow}^{-1}\ (H/R)^{-1}$

  $t_{cool}/t_{inflow} \sim (kT)^{1/2}/n\ \Omega\ \alpha$

  ➔$t_{cool}/t_{inflow} \sim mdot^{-1}\ \alpha^2$

- At small mdot, cooling cannot keep disk thin and solution no longer applies
- Sgr A*: $mdot \sim 10^{-6}$

ADAF theory

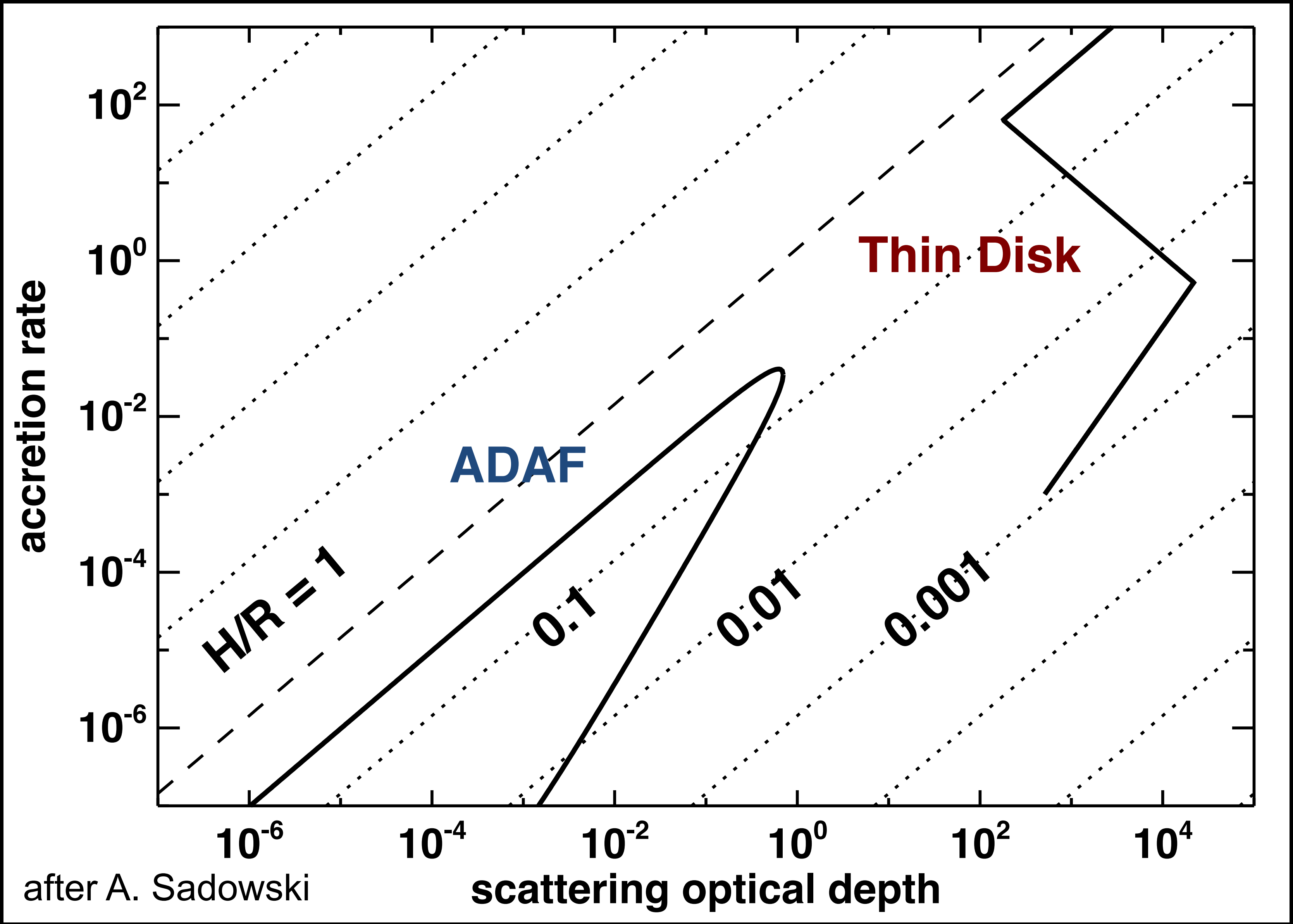
- Parameterize fraction of local heating advected (Narayan & Yi 1994): $Q^{adv} = f\, Q^{+}$
  - f=0 ($Q^{-} = Q^{+}$): cooling, $\Omega = \Omega_K$, thin disk
  - f=1 ($Q^{adv} = Q^{+}$): advection, $\Omega \ll \Omega_K$, spherical

- Self-similar scalings:

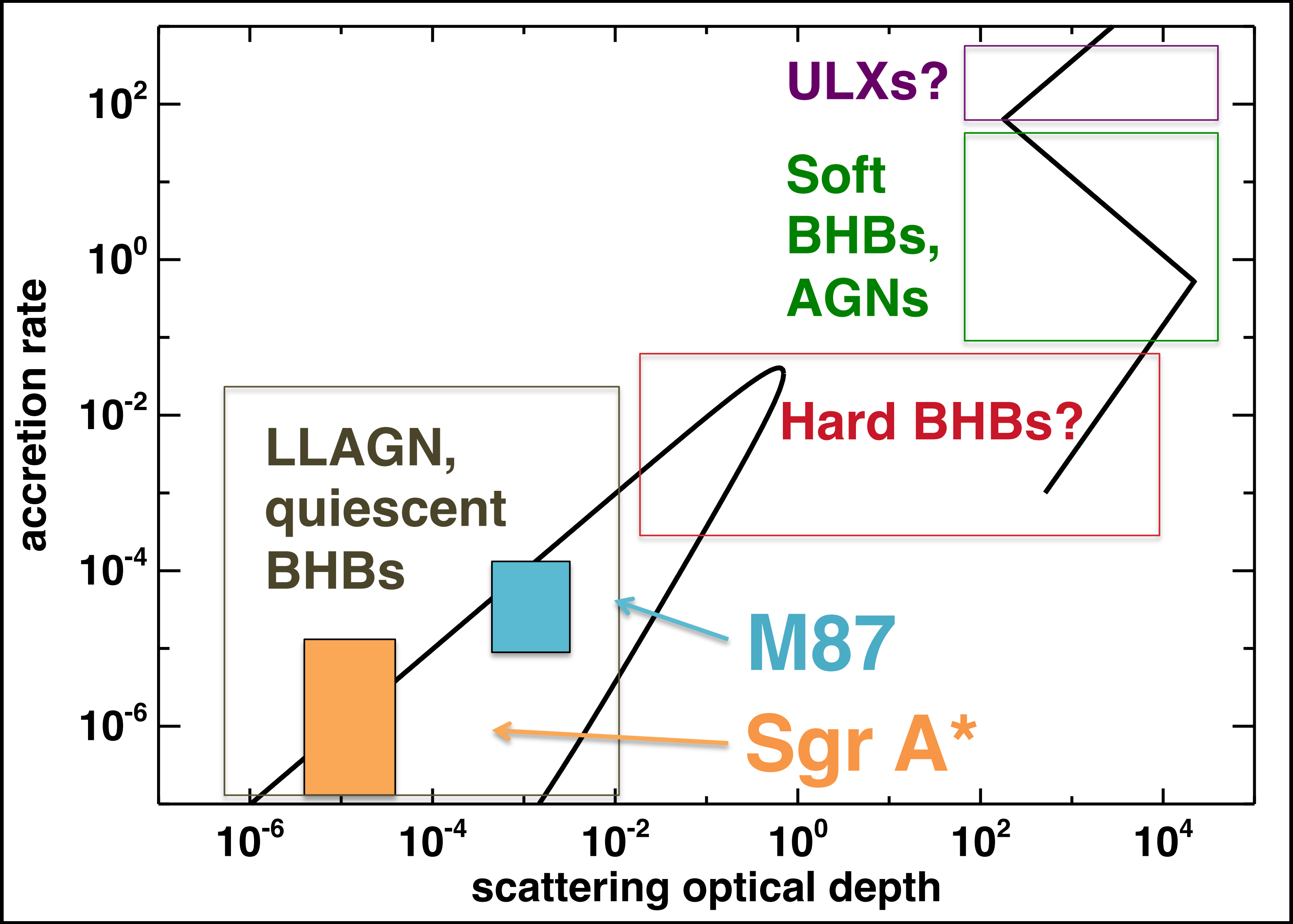
$$\rho, \mathbf{\Omega} \propto \mathbf{R}^{-3/2}; \;\; \mathbf{v}, \mathbf{c_s} \propto \mathbf{R}^{-1/2}$$

- f=1 solutions: $v \sim 0.2\, v_{ff}$, $\Omega \sim 0.4\, \Omega_K$, $H/R \sim 1$

Standard accretion theory



Standard accretion theory

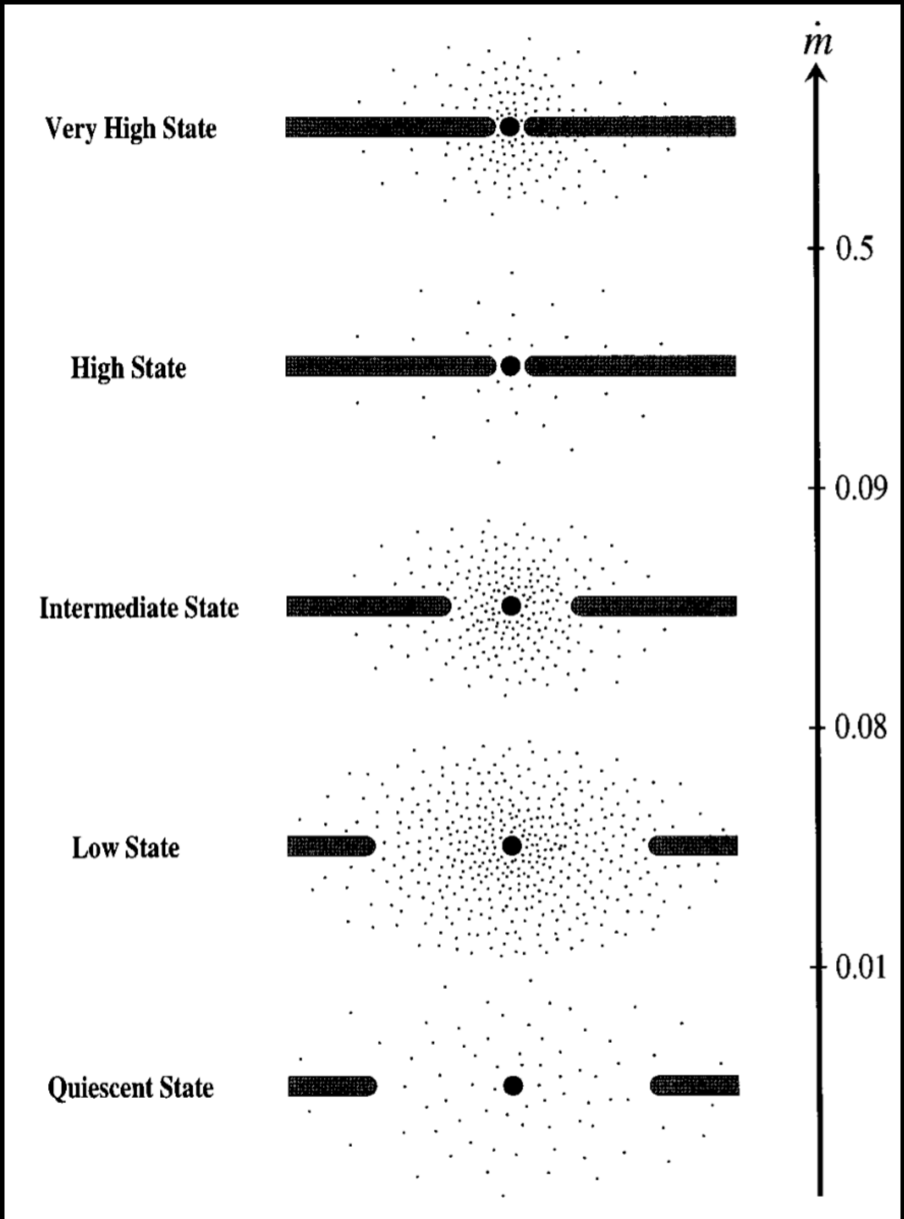


Observed states as function of mdot

Soft states

Hard states

Sgr A*



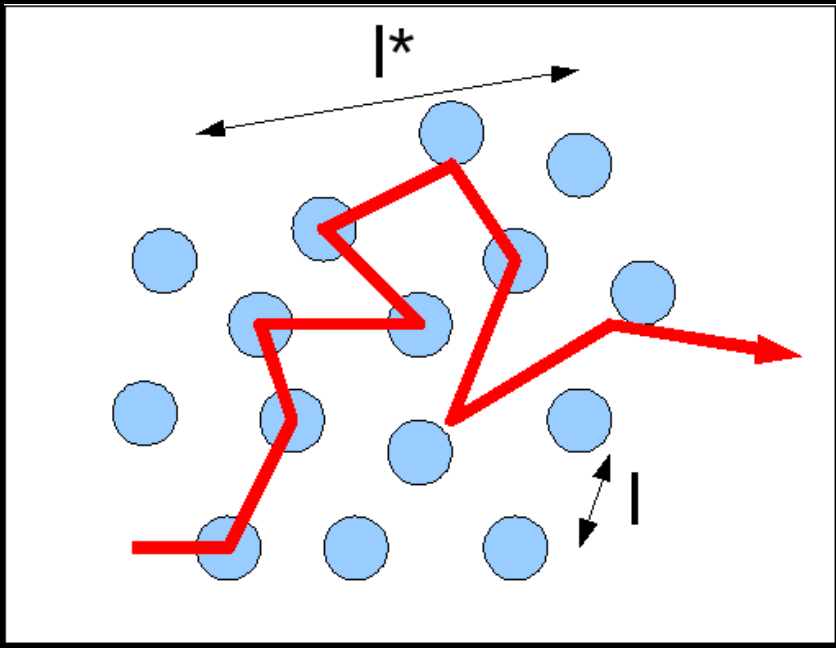
Large mdot

Small mdot

Esin+1997

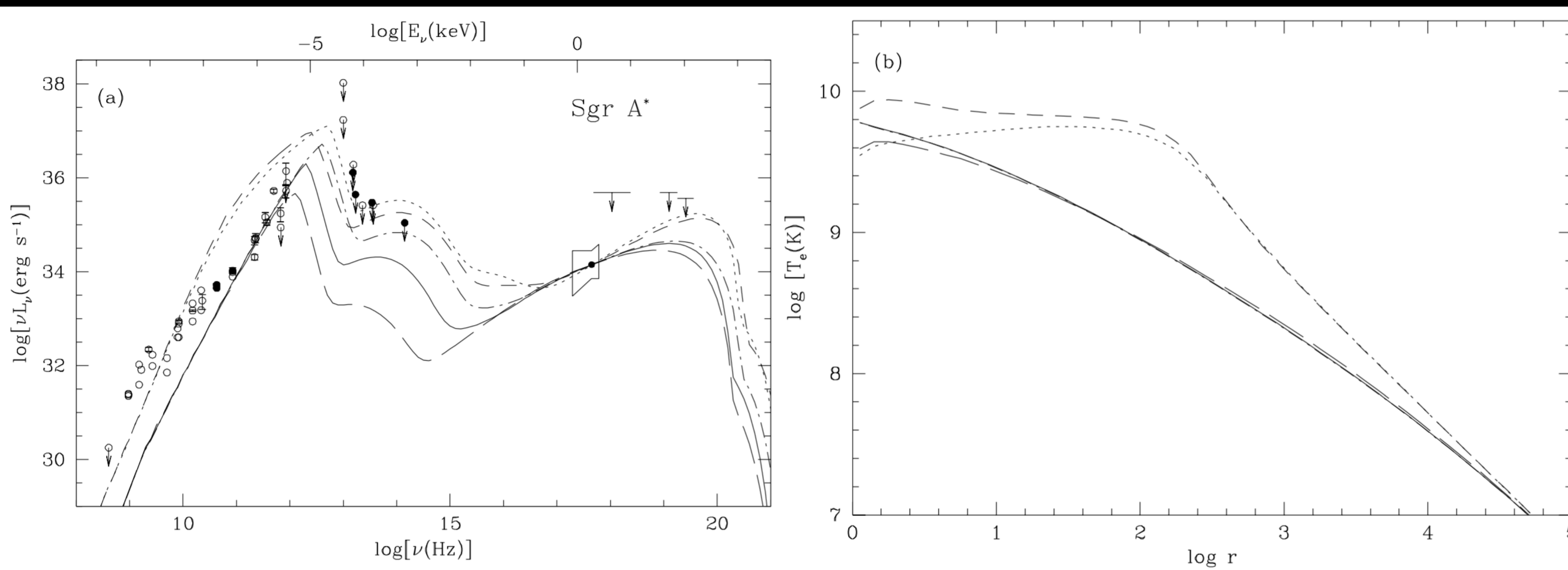
ADAF thermodynamics

- Low density, "collisionless," → $T_e << T_p$, e- heating is an important open Q
- Plasma effects can be important



ADAF model of Sgr A*: low density, hot

- $T_i \sim 10^{12}$ K, $T_e < 10^{10}$ K, $n \sim 10^9$ cm^{-3}
- e- cannot radiate away heat, energy lost to BH

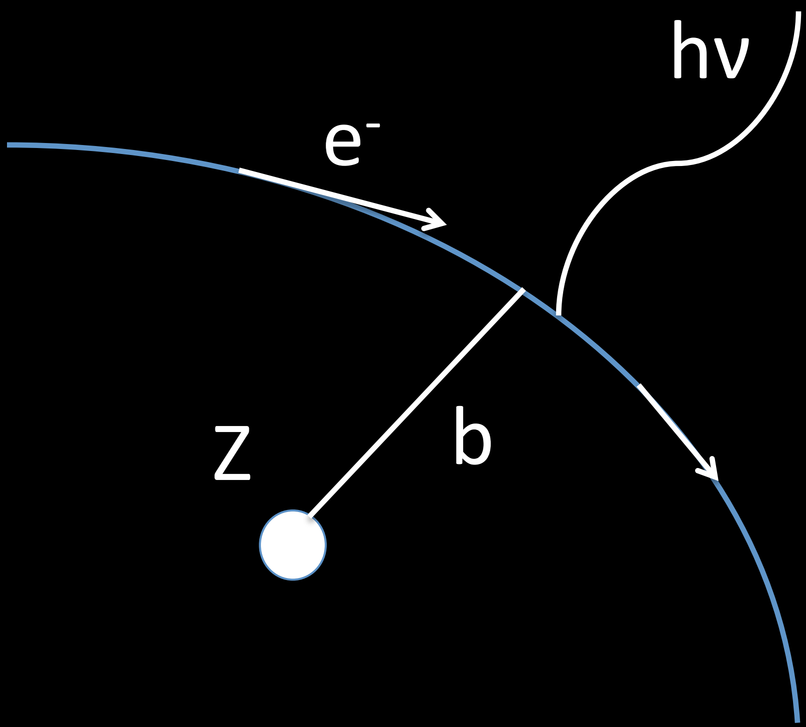


Radiation processes in disks

- Bremsstrahlung ~ n^2
- $a \sim e^2/mb$

$$\mathbf{P = \frac{2e^2a^2}{3c^3}}$$

$$\mathbf{P_{br} = \frac{3}{16}\sigma_T c\, Z U_E}$$



(not so useful b/c U_E depends on b)

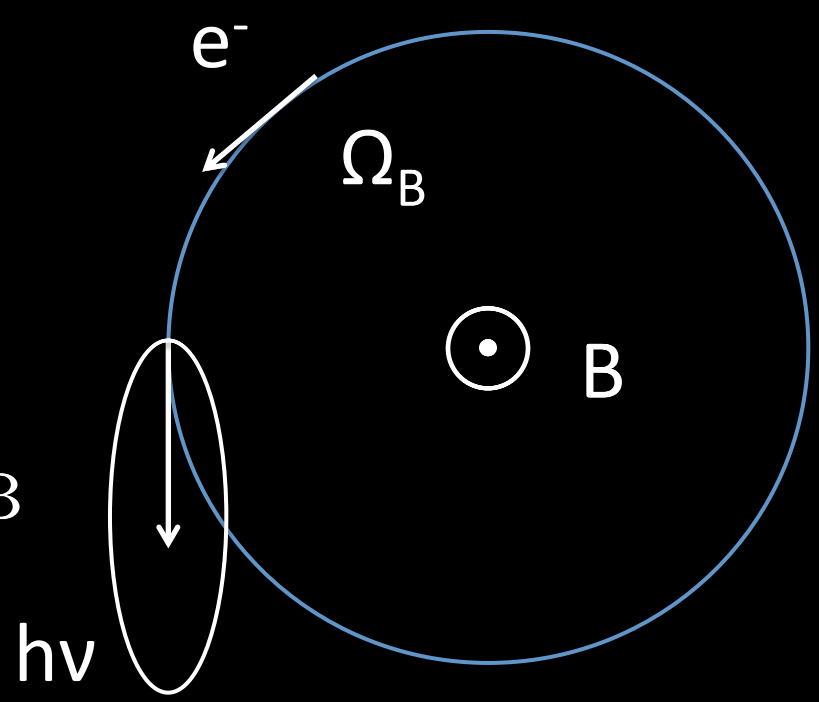
Radiation processes in disks

- Synchrotron ~ nB^2
- $a = e\, v\, B \sin\theta / m\, c$

$$\mathbf{P = \frac{2e^2a^2}{3c^3}}$$

- $U_B = B^2 / 8\pi$

$$\mathbf{P_S = \frac{4}{3}\sigma_T c \beta^2 \gamma^2 U_B}$$

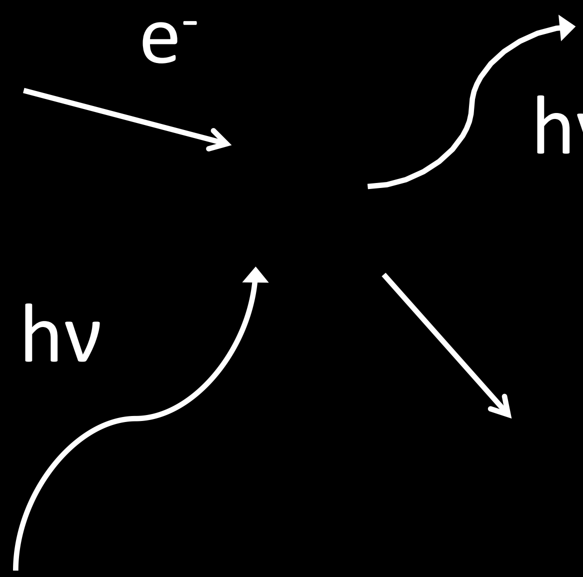


Radiation processes in disks

- (inverse) Compton scattering ~ n n_{ph}
- $U_{ph} = 4\pi/c \, J$

$$\mathbf{P_C = \frac{4}{3}\sigma_T c \beta^2 \gamma^2 U_{ph}}$$

$$\Rightarrow \mathbf{\frac{P_C}{P_S} = \frac{U_{ph}}{U_B}}$$



Radiation processes in Sgr A*

- $L \sim 10^{36}$ erg / s, $R \sim 5\ R_S = 5 \times 10^{12}$ cm, $B \sim 30$ G, $T_e \sim 3 \times 10^{10}$ K, $n \sim 3 \times 10^{6}\ cm^{-3}$
- $U_{ph} = 4\pi/c\ J$
- $U_B = B^2/8\pi$

Radiation processes in Sgr A*

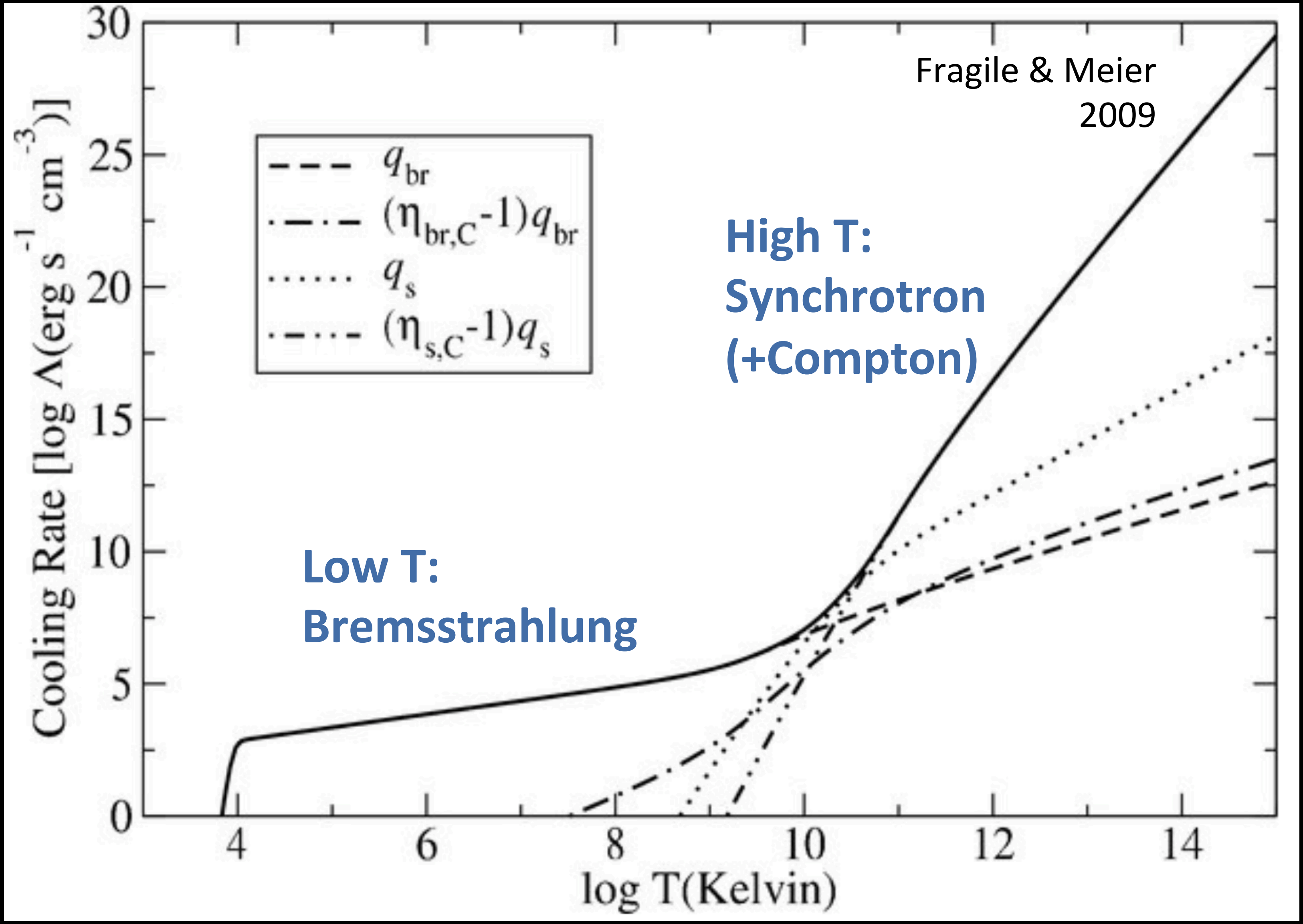
- $L \sim 10^{36}$ erg / s, $R \sim 5\ R_S = 5\times10^{12}$ cm, $B \sim 30$ G, $T_e \sim 3\times10^{10}$ K, $n \sim 3\times10^{6}\ cm^{-3}$
- $U_{ph} = 4\pi/c\ J \sim 1$ erg / cm^3
- $U_B = B^2/8\pi \sim 40$ erg / cm^3

➡ $P_S > P_C$

- for thermal: $P_{Br} \sim n^2\ T^{1/2}$, $P_S \sim n\ B^2\ T^2$

➡ $P_{Br} / P_S \sim 10^{-3}\ \beta\ \theta_e^{-3/2}$

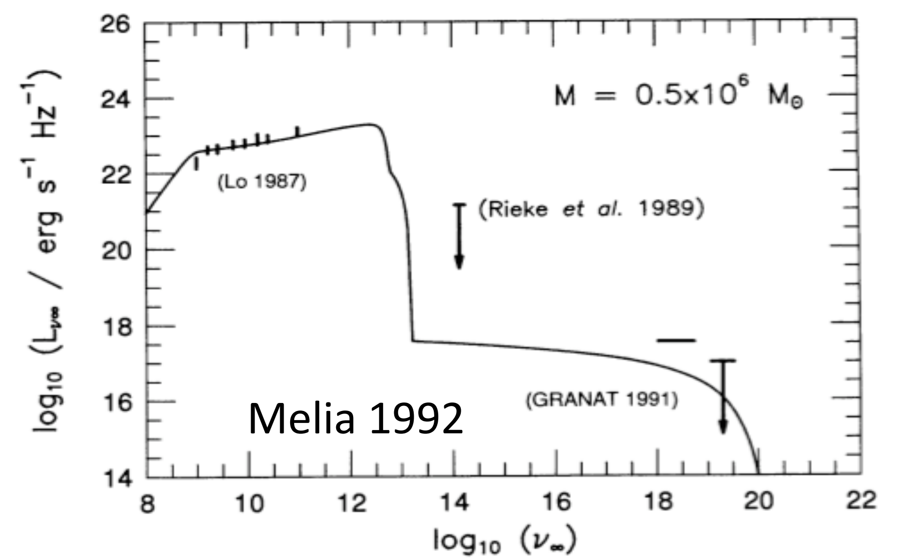
Example: relative importance

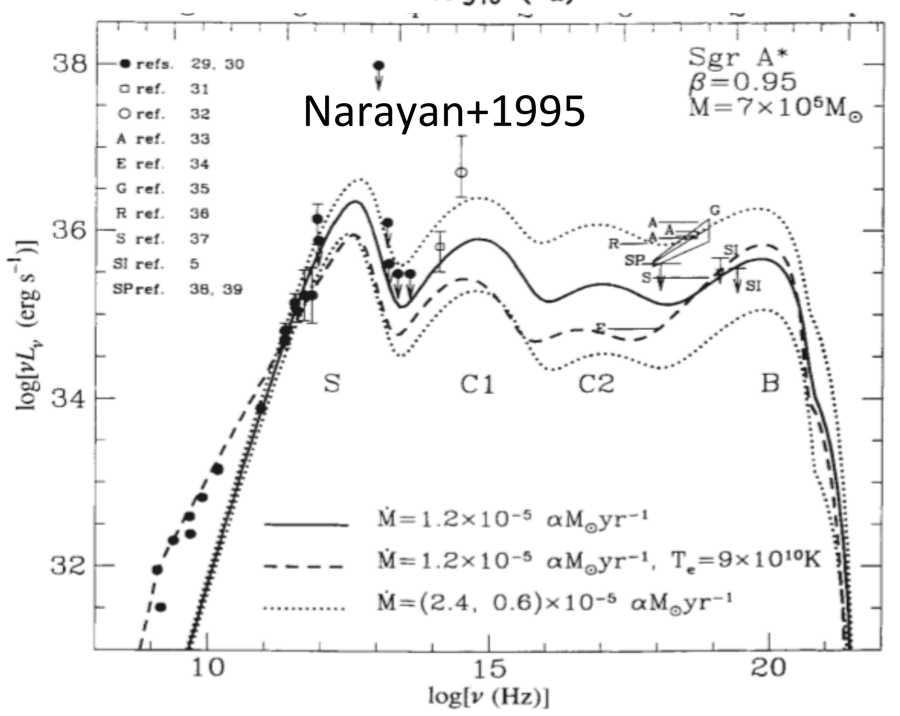


Accretion Flow Models of Sgr A*

- Spherical (Melia 1992)
  ADAF (Narayan+1995)
  - $dM/dt \approx dM/dt_{Bondi}$
  - Lower T_e, large central density ($n \sim r^{-3/2}$)

- Accretion energy is carried into the black hole!



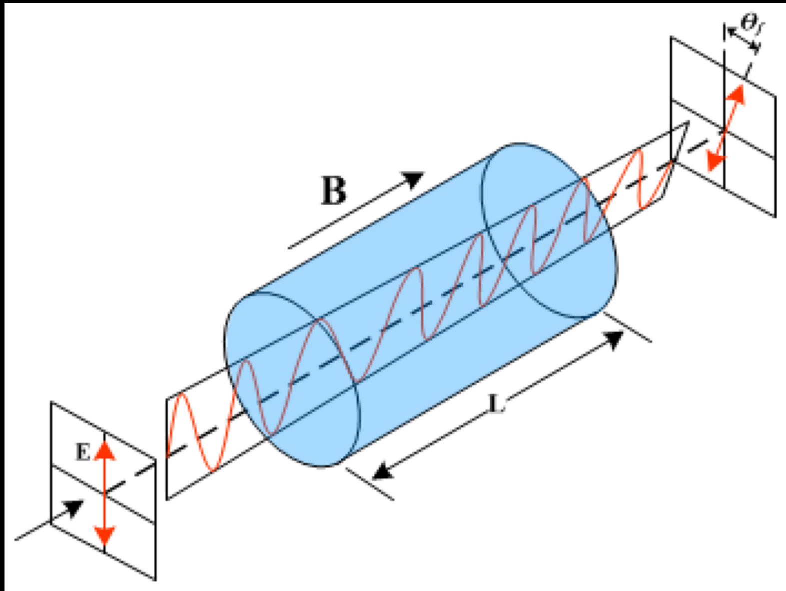


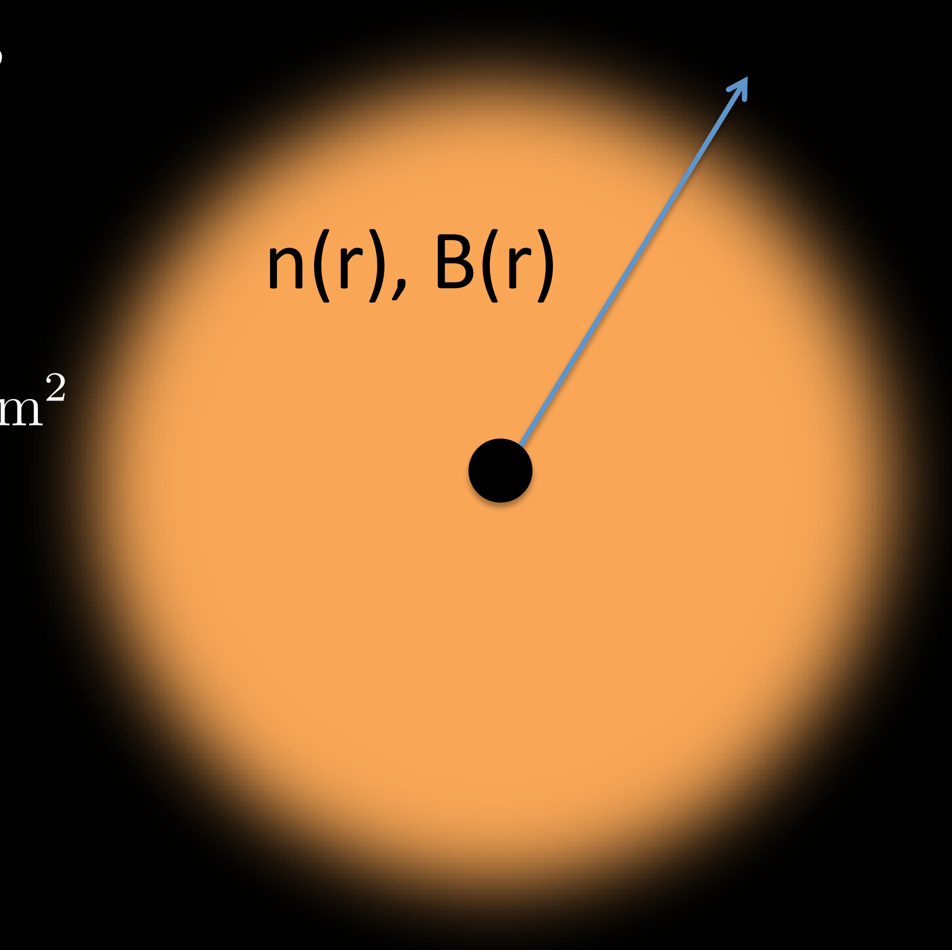
Polarization, Faraday rotation, and the Sgr A* accretion rate

- Magnetic field rotates polarization direction

$\chi(\nu) \sim \nu_0 + \mathrm{RM}\, c^2/\nu^2$

$$\mathrm{RM} \simeq 2.6 \times 10^{-13} \int \mathrm{dl} \cdot \mathrm{B\, n\, rad/m^2}$$





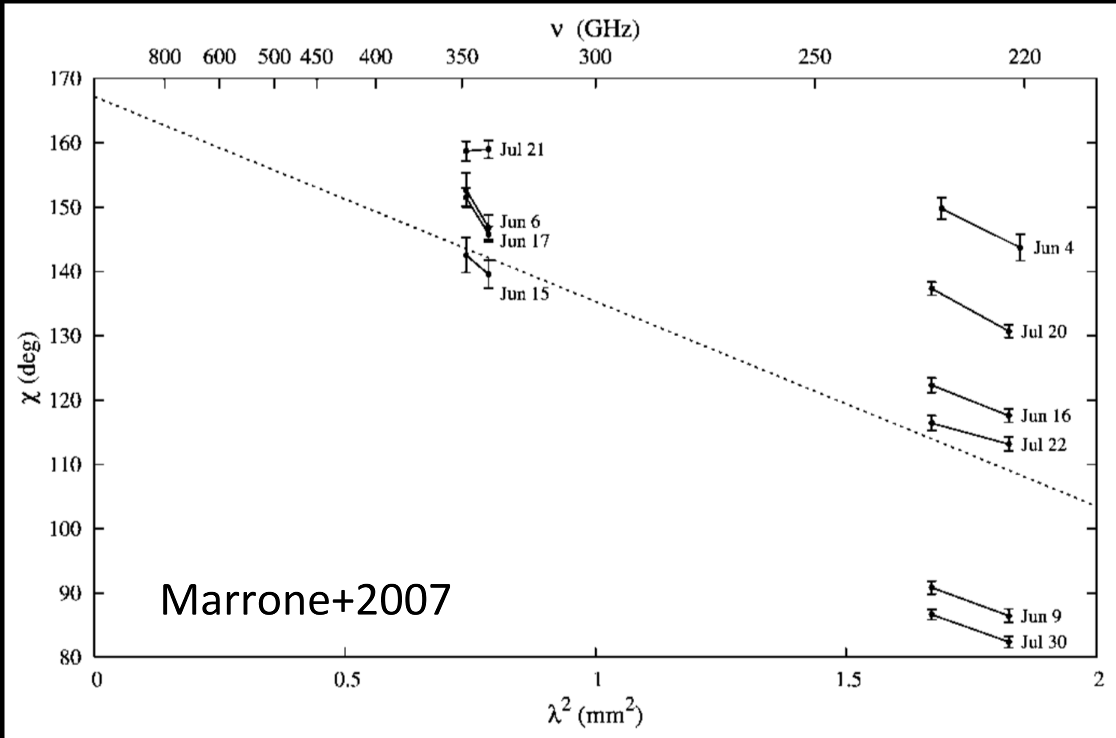
Polarization, Faraday rotation, and the Sgr A* accretion rate

- RM ~ M^{-2} $Mdot^{3/2}$ (Marrone et al. 2006)

$$\dot{M} \simeq 10^{-9} r_{NR}^{7/6} M_{\odot} yr^{-1}$$

r ~ 1-100 R_S

- > 99% of the mass doesn't accrete!
(Aiken+2000, Agol 2000, Quataert & Gruzinov 2000, Bower+2003, Marrone+2006,2007)



Sgr A* e- temperature

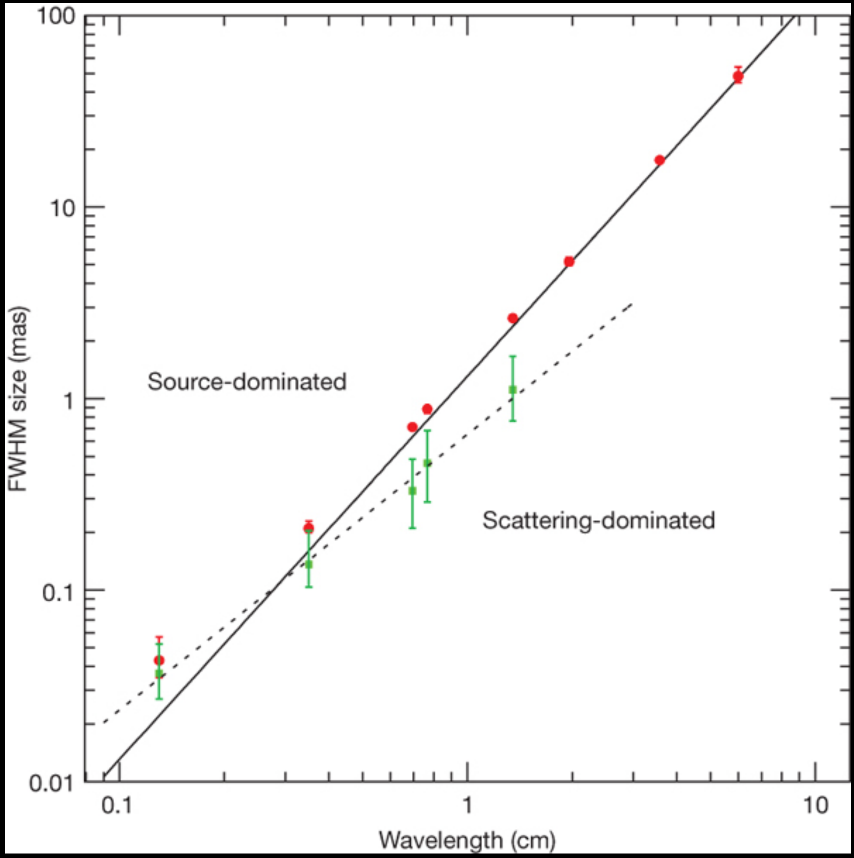
- For known flux, angular size "brightness" temperature is $B_\nu(T_b) = I_\nu$
- Sgr A* at 230 GHz:

$$T_b = \frac{c^2 I_\nu}{2k\nu^2}$$

$$\simeq 6 \times 10^{10} \mathrm{K}$$

cf. $T_i \approx T_{vir} \approx 10^{12}$ K

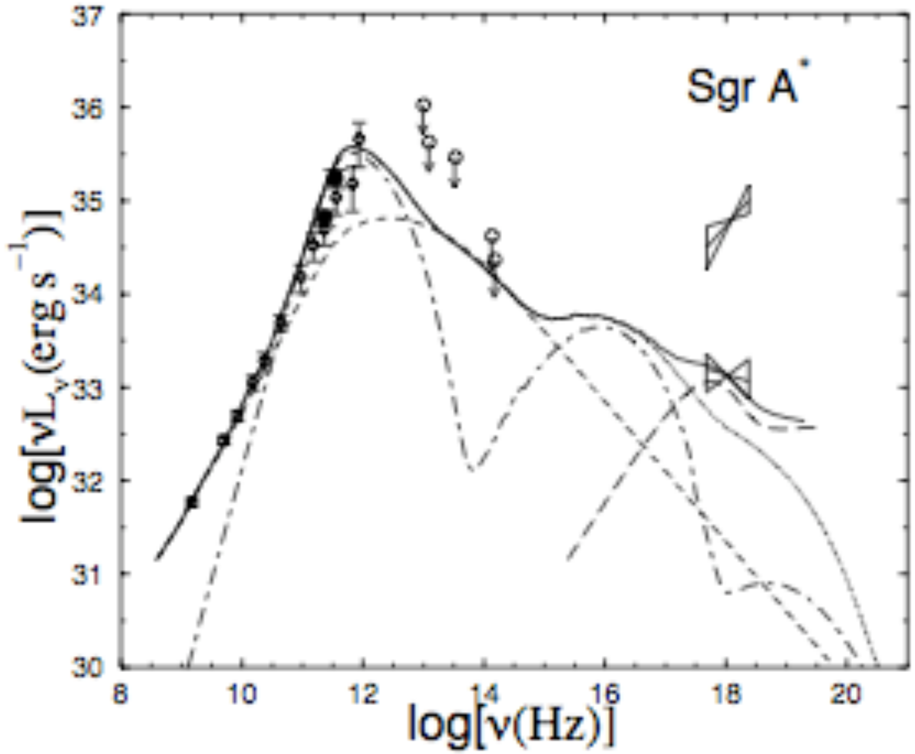
- Lower limit to T_e, >> 10^9 K in ADAF
- n ~ 3×10^6 cm^{-3}, B ~ 50 G



Doeleman et al. 2008

Accretion flow models of Sgr A*

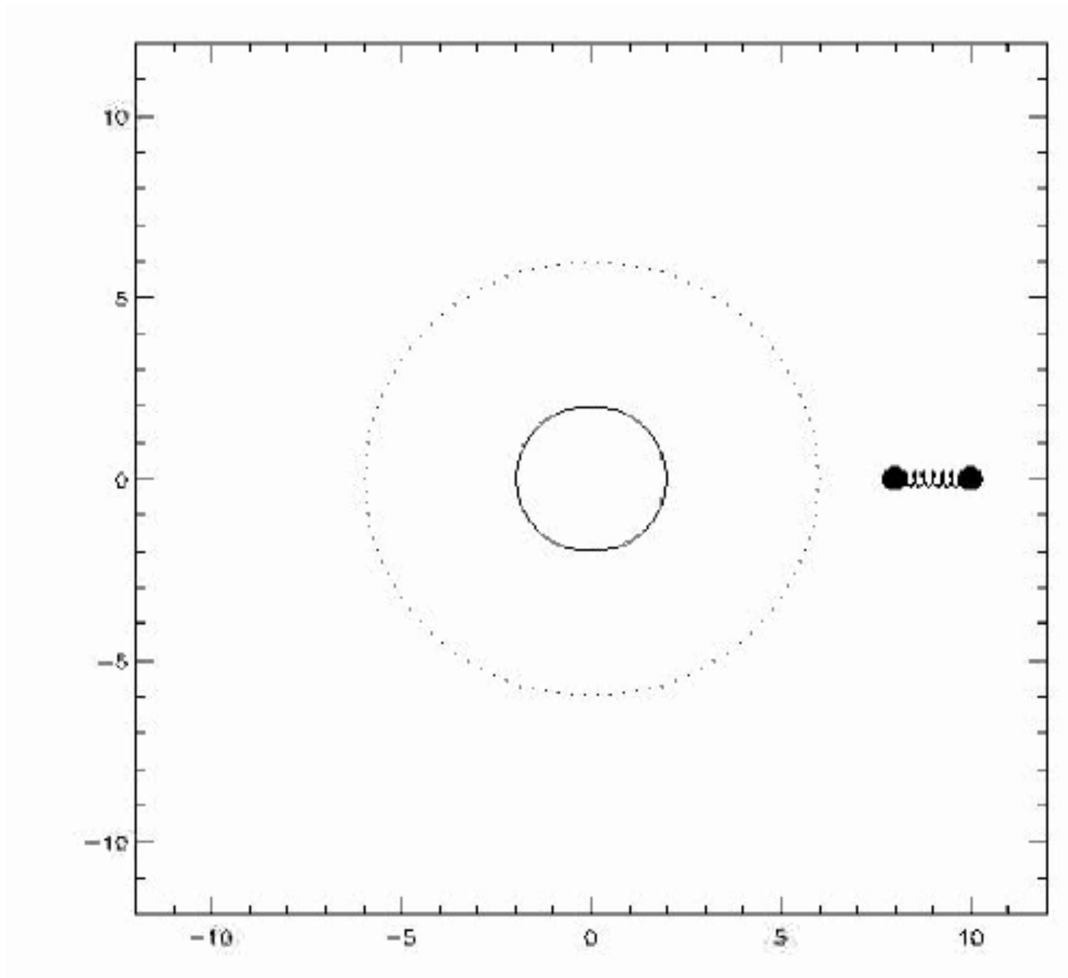
- Outflows → ADIOS
  (Blandford & Begelman 1999)
- Convection → CDAF
  (Quataert & Gruzinov 2000)
- ADAF/CDAF/ADIOS/ … → "RIAF"
  - Mass loss
  - Non-thermal e- or jet for polarization



Yuan et al. (2003)

How does gas fall into a black hole?

- Weakly magnetized gas: field is dragged along, restoring force when stretched (torque!)

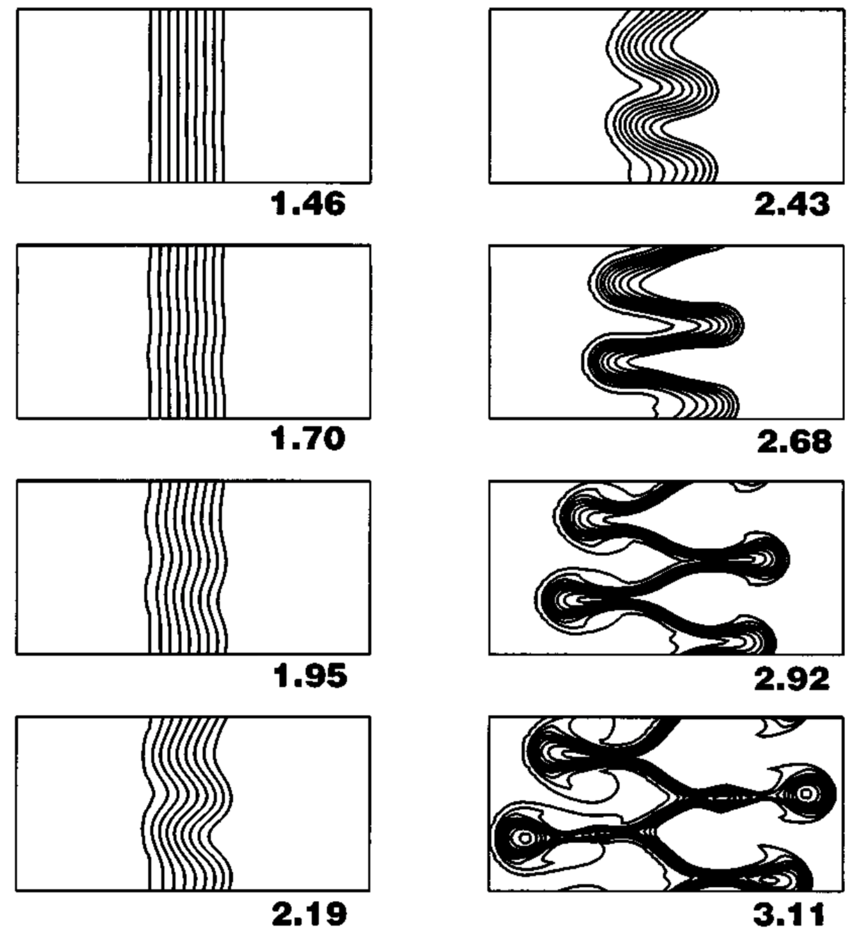


The MRI can cause accretion

Instability → turbulence, stresses → torque

- Stress tensor:
- $T_{r\varphi} = -B_r B_\varphi/4\pi + \rho\, v_r v_\varphi$

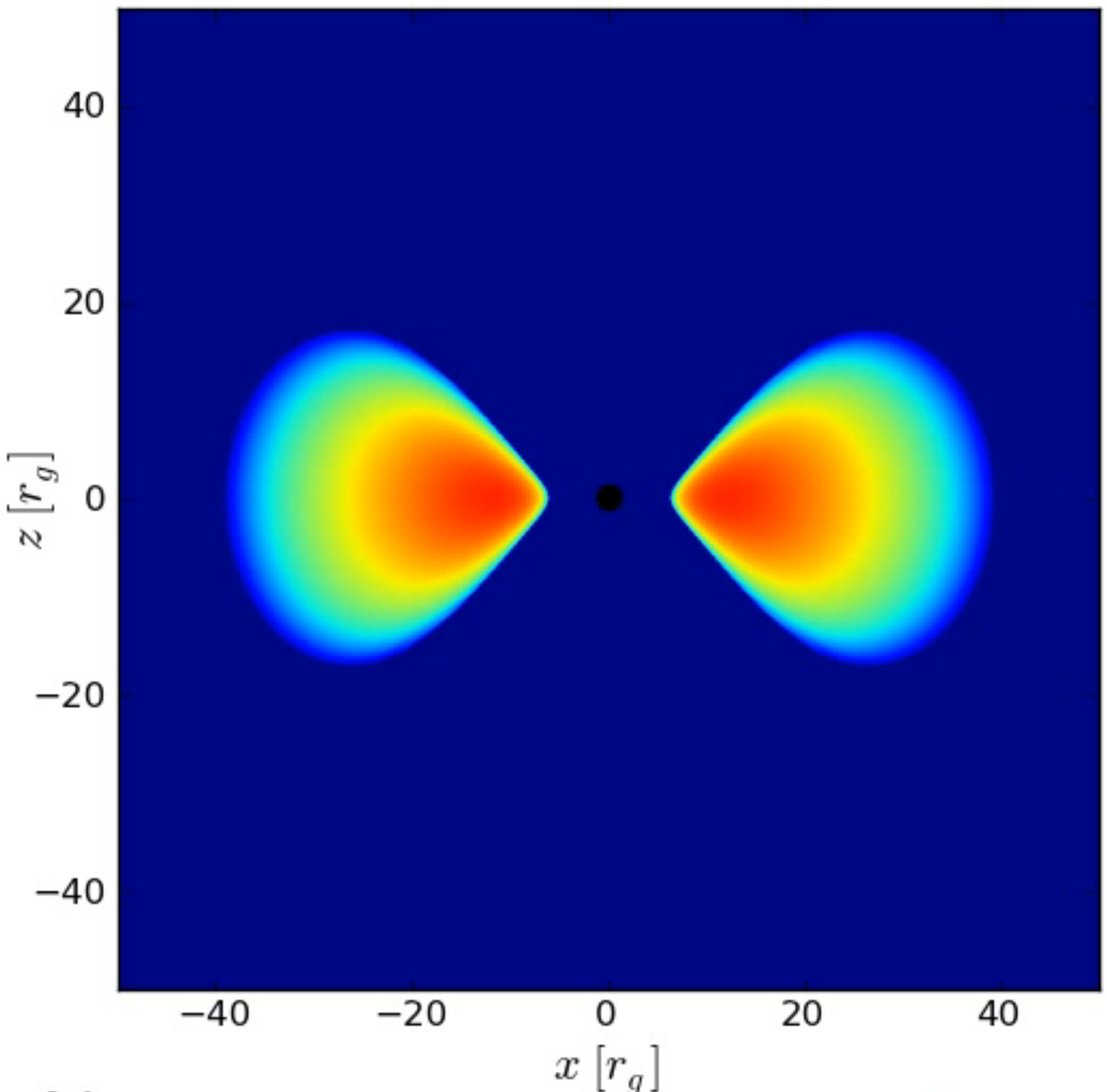
- Simulations:
  - Maxwell stress is larger
  - $\alpha \sim -B_r B_\varphi/4\pi P \sim 0.01\text{-}0.1$



Balbus & Hawley 1998

The MRI can cause accretion

Instability → turbulence, stresses → torque



McKinney & Blandford 2009

MHD simulations of BH accretion

- Good: physical theory of accretion!
- Bad: turbulence, magnetic fields, time-dependence, 3D → numerical simulations
- Work in progress: plasma physics

- Sgr A* is a great laboratory for MRI accretion theory

Why is Sgr A* so faint?

	Radius (Rs or pc)	Accretion rate (M_{sun} / yr)	Accretion efficiency
Giant molecular clouds	10-100 pc	10^{-2}	10^{-8}
Circumnuclear disk	1-7 pc	10^{-3}	10^{-7}
Winds from massive stars	< 0.5 pc ~ 10^{6} R_s	10^{-4} – 10^{-3}	10^{-6} – 10^{-7}
Winds at Bondi radius	< 0.1 pc ~ 10^{5} R_s	10^{-5}	10^{-5}
Inner accretion flow	1-10^{3} R_s	10^{-9} – 10^{-7}	10^{-1} – 10^{-3}

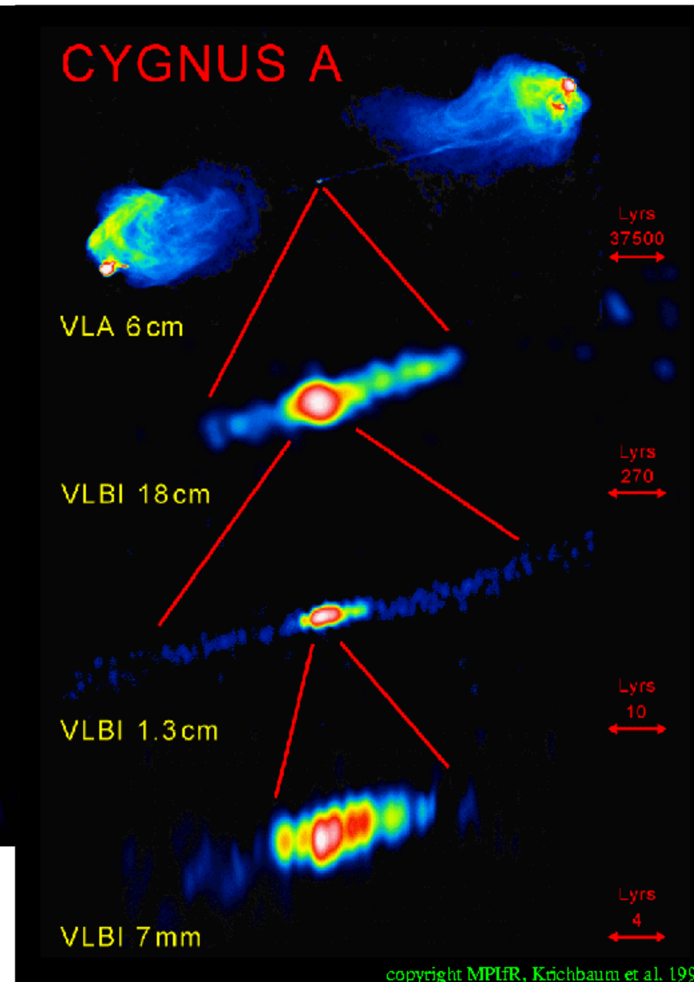
Sgr A* is faint because

- Gas supply (stellar winds) is not large enough
- A tiny fraction of gas supplied reaches the black hole!
- The accretion flow is inefficient at radiating away its gravitational binding energy

Jet models of Sgr A*

- If $T_e << T_p$ in RIAF, may not see it ($P_S \sim \gamma^2$)
- Alternative: jet? (Falcke & Markoff 2000)

Centaurus A

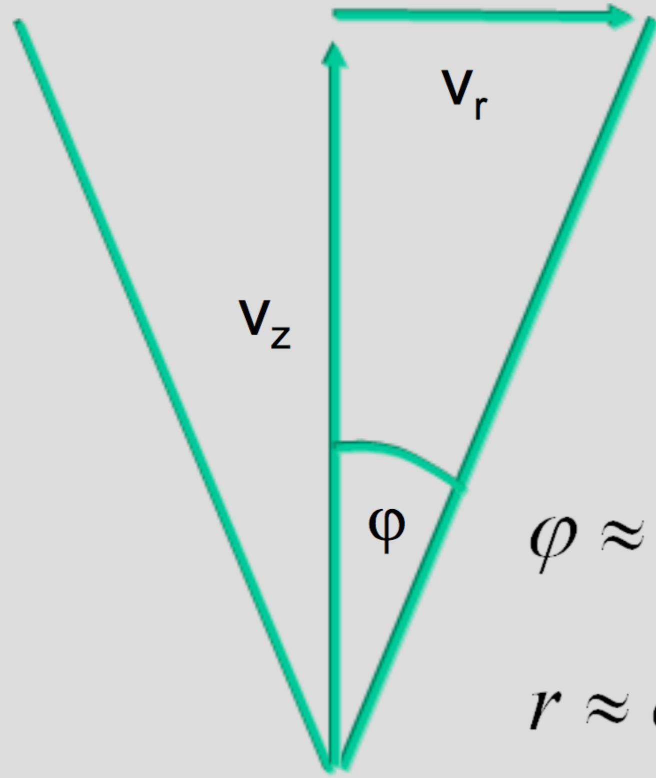


Jet models of Sgr A*

- Simple jet model (Blandford & Königl 1979)

- Plasma propagates at a constant proper speed $\Rightarrow v_z=\gamma_j\beta_j c$.
- The (isothermal) plasma expands with sound speed $\Rightarrow v_r=\gamma_s\beta_s c$.
- The resulting shape is a cone with Mach number

$$M = \frac{\gamma_j\beta_j}{\gamma_s\beta_s} \approx \gamma_j\sqrt{c}$$



$$\varphi \approx \frac{1}{M}$$

$$r \approx \varphi z$$

Taken from
http://slideplayer.com/slide/5083341/

Jet models of Sgr A*

- Again hydro conservation laws

- Particle conservation:

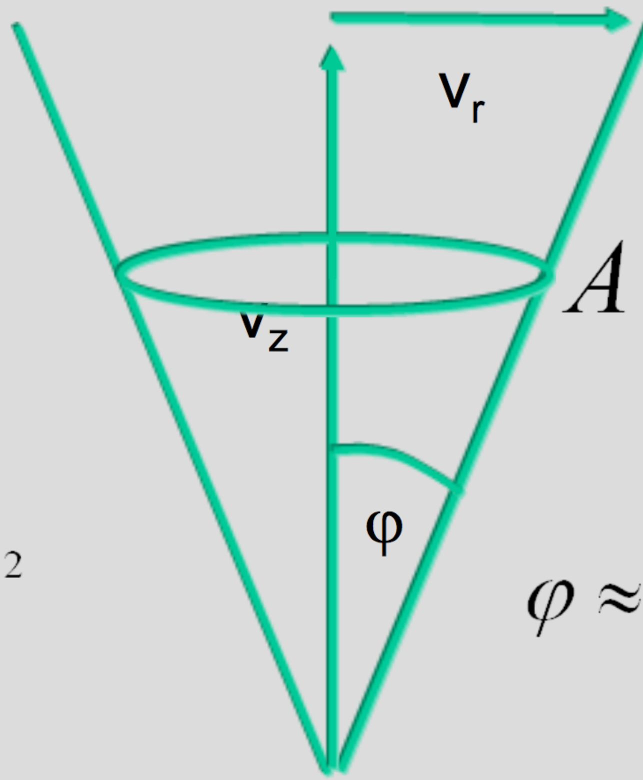
$$\dot{M}_j = \rho \cdot \mathrm{v} \cdot A = m_p n(r) \cdot \gamma\beta c \cdot \pi r^2$$

$$\Rightarrow n(r) = \frac{\dot{M}_j}{m_p \cdot \gamma\beta c \cdot \pi r^2} \propto r^{-2}$$

- Energy conservation:

$$\dot{E}_{j,mag} = \rho_B \cdot \mathrm{v} \cdot A = \frac{B^2(r)}{8\pi} \cdot \gamma\beta c \cdot \pi r^2$$

$$\Rightarrow B(r) = \sqrt{\frac{8L_{j,B}}{\gamma\beta c \cdot r^2}} \propto r^{-1}$$



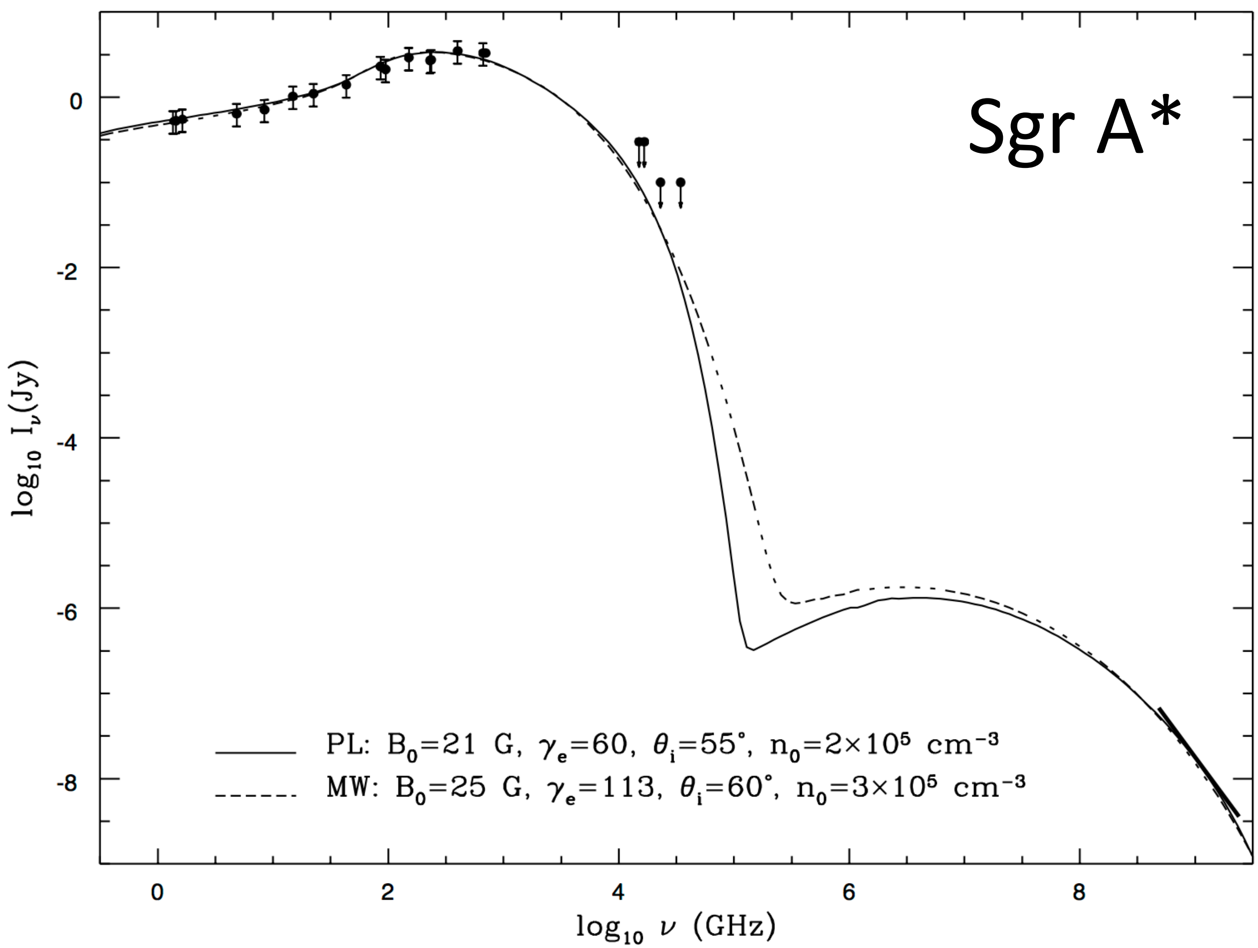
$$A = \pi r^2$$

$$\varphi \approx \frac{1}{M}$$

Taken from
http://slideplayer.com/slide/5083341/

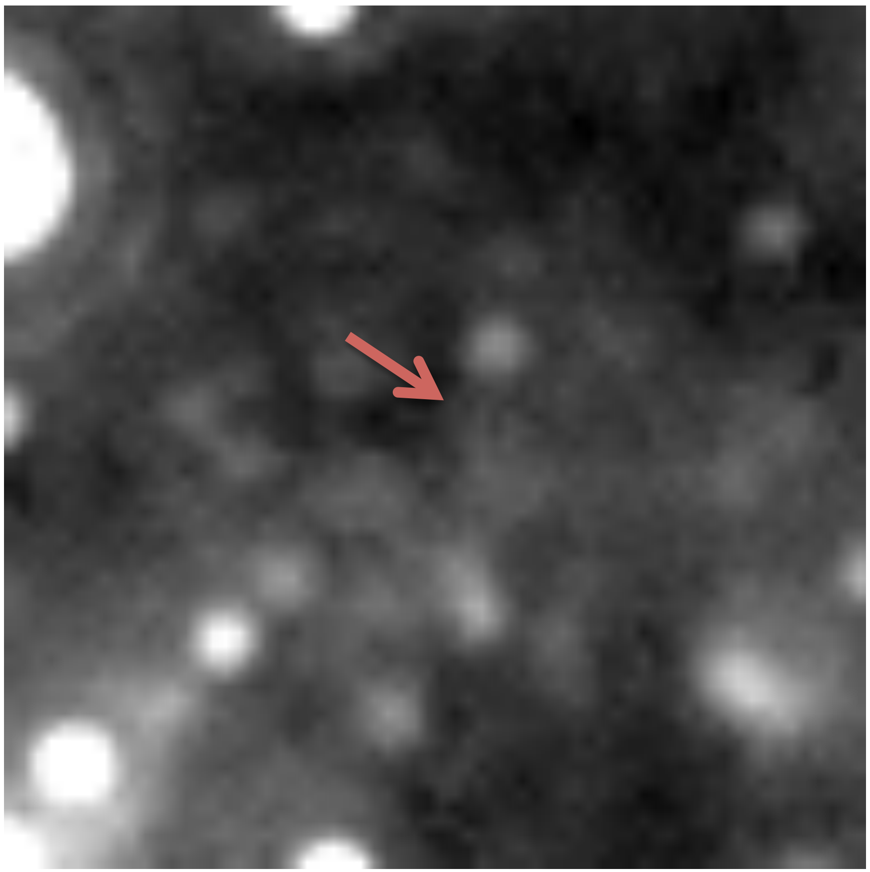
Jet models of Sgr A*

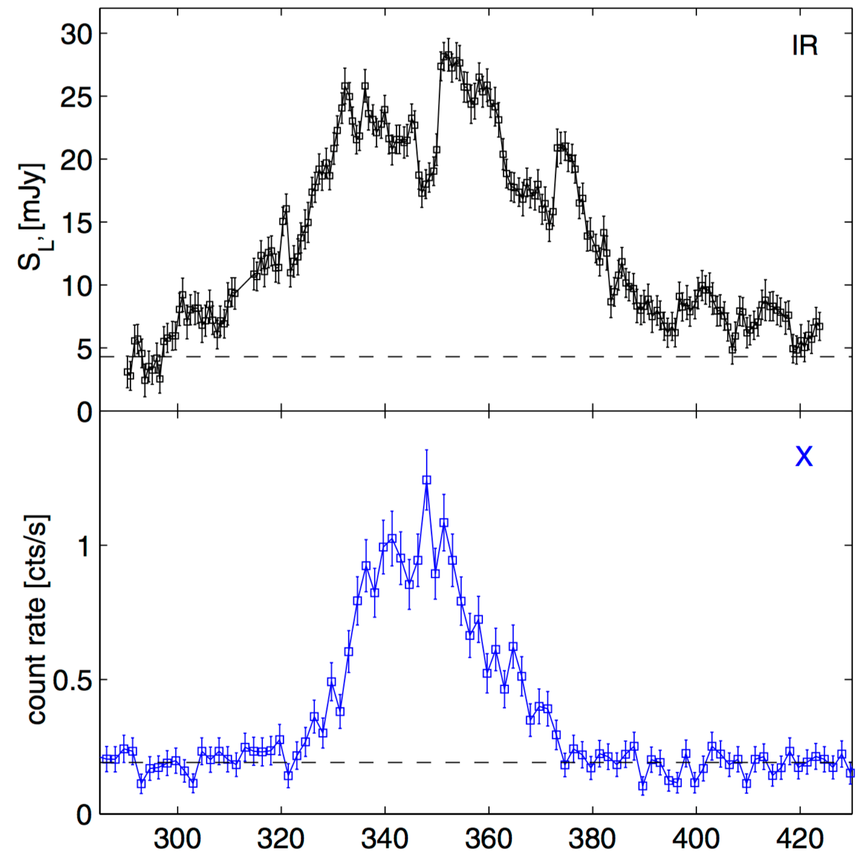
- If $T_e << T_p$ in RIAF, may not see it at all!
- Alternative: jet? (Falcke & Markoff 2000)



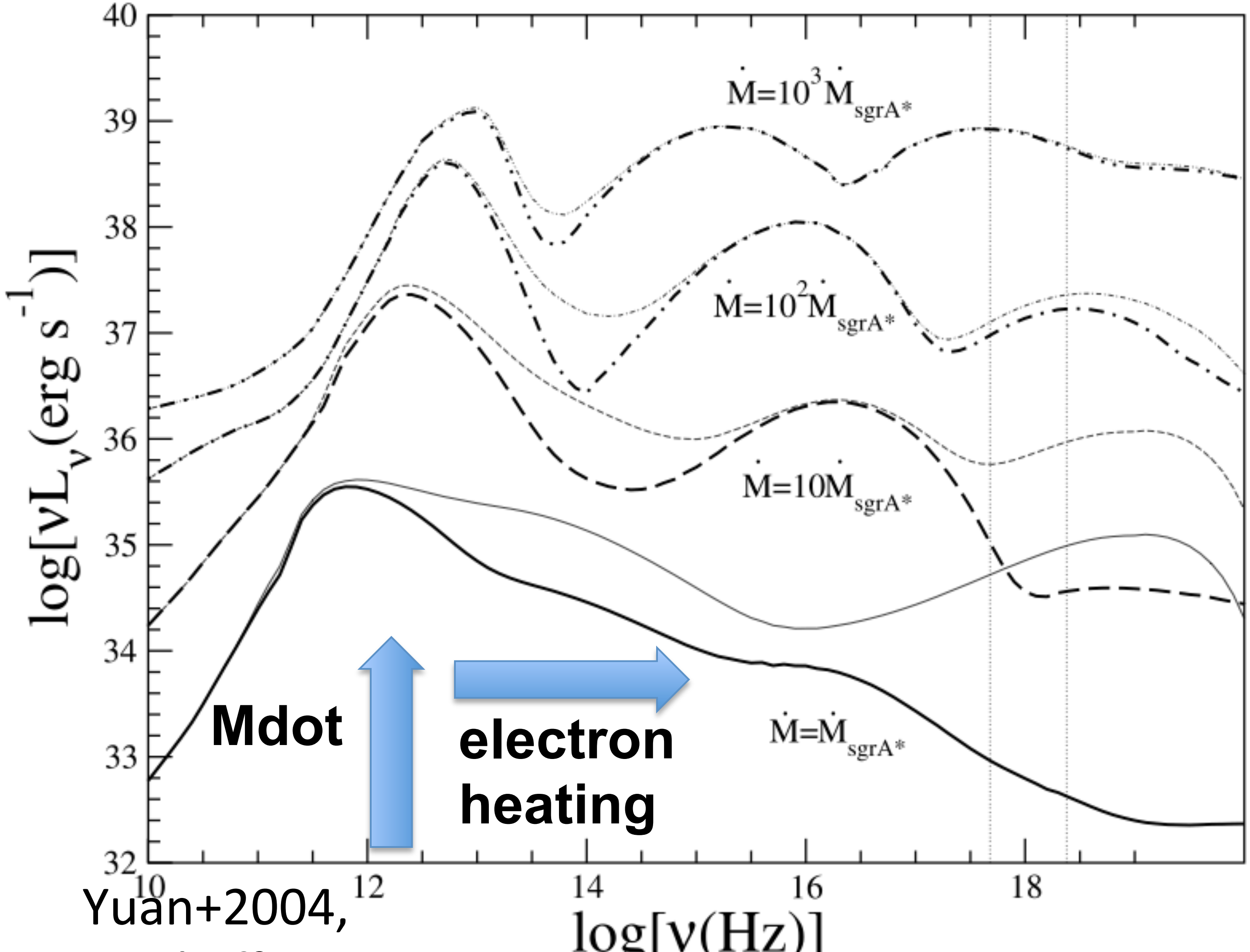
Infrared/X-ray flares from Sgr A*

- Sgr A*: rapidly variable IR/X-ray emission (Baganoff+2001, Genzel+2003, Ghez+2004)





Flares must be particle heating



Yuan+2004, Markoff+2001

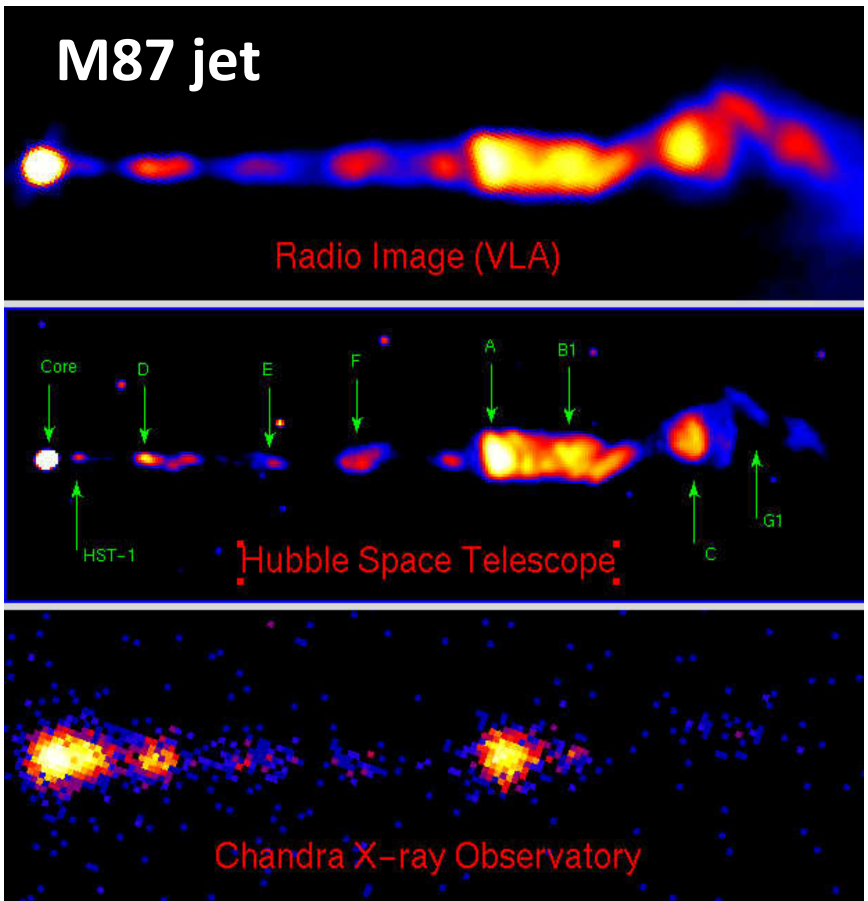
$U_B = B^2 / 8\pi \sim$ Mdot

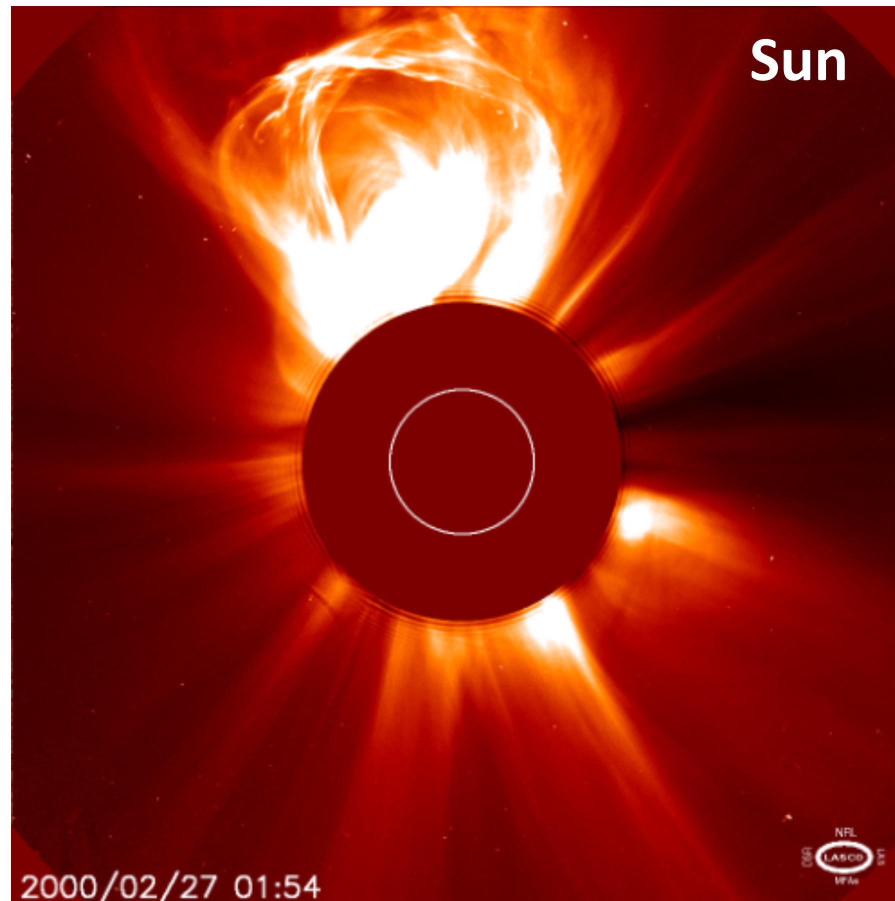
$U_{ph} = 4pi/c\ L/R^2 \sim$ Mdot^2

$P_C/P_S \sim U_{ph}/U_B \sim$ Mdot

Electron heating near black holes

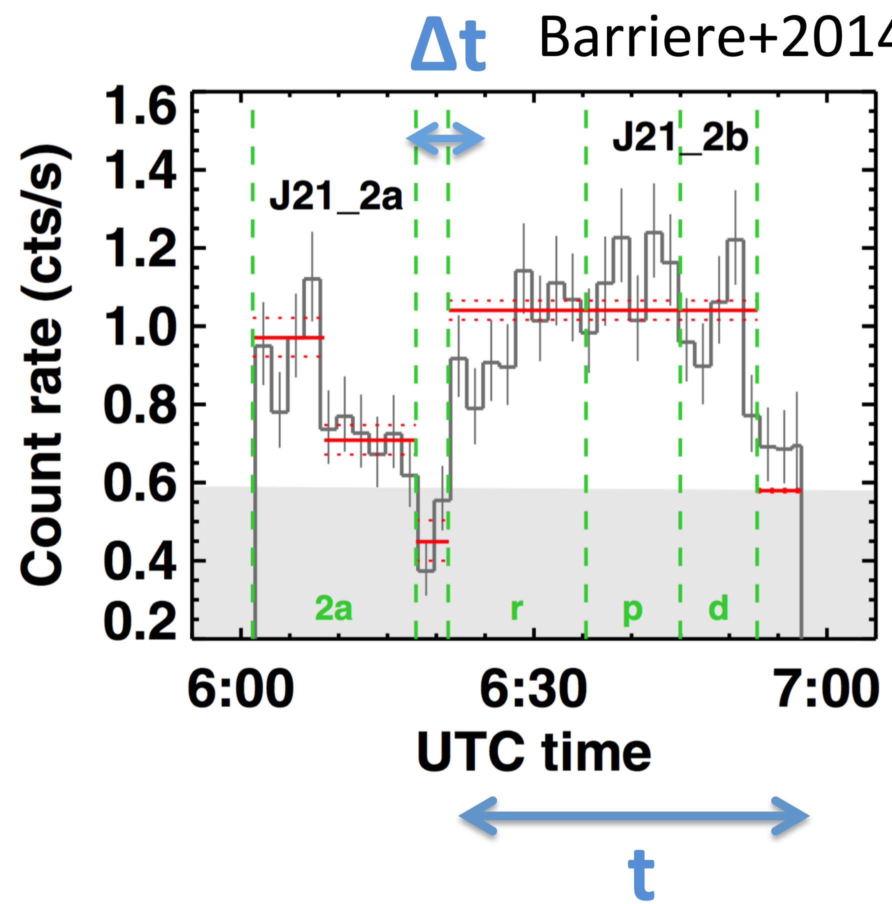
- Shock acceleration (jet? tilted disk?) or magnetic reconnection (corona?)





Flares originate close to the black hole

- Assume:
  - flare is powered by accretion
  - RIAF: B(r) ~ 100G r_g / R (~same as jet!)
- Observed flare:
  - Region size < c Δt < 3×10^{12} cm (~$5 r_g$)
  - L_X ~ 2×10^{35} erg / s, t = 1838 s



Flares originate close to the black hole

- $E_{total} > E_{flare}$:

$U_B V > L_X t$

RIAF: $B(r) \sim 100\ G\ r_g / R$

(~same as jet!)

Flares originate close to the black hole

- $E_{total} > E_{flare}$:

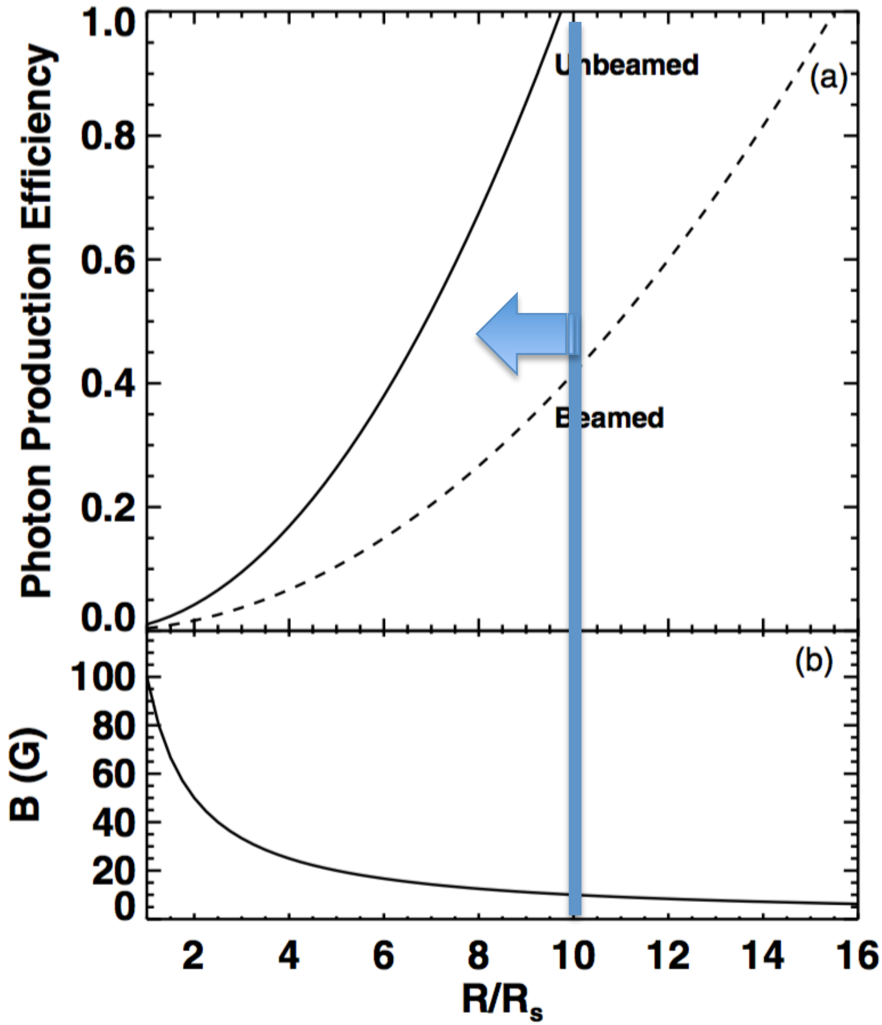
$U_B V > L_X t$

RIAF: $B(r) \sim 100$ G r_g / R

(~same as jet!)

- $B_0^2 (rg/R)^2/8\pi\ 4/3\pi R^3 > L_X t$

  ➔ $R/rg < 10\ (B_0/100G)$

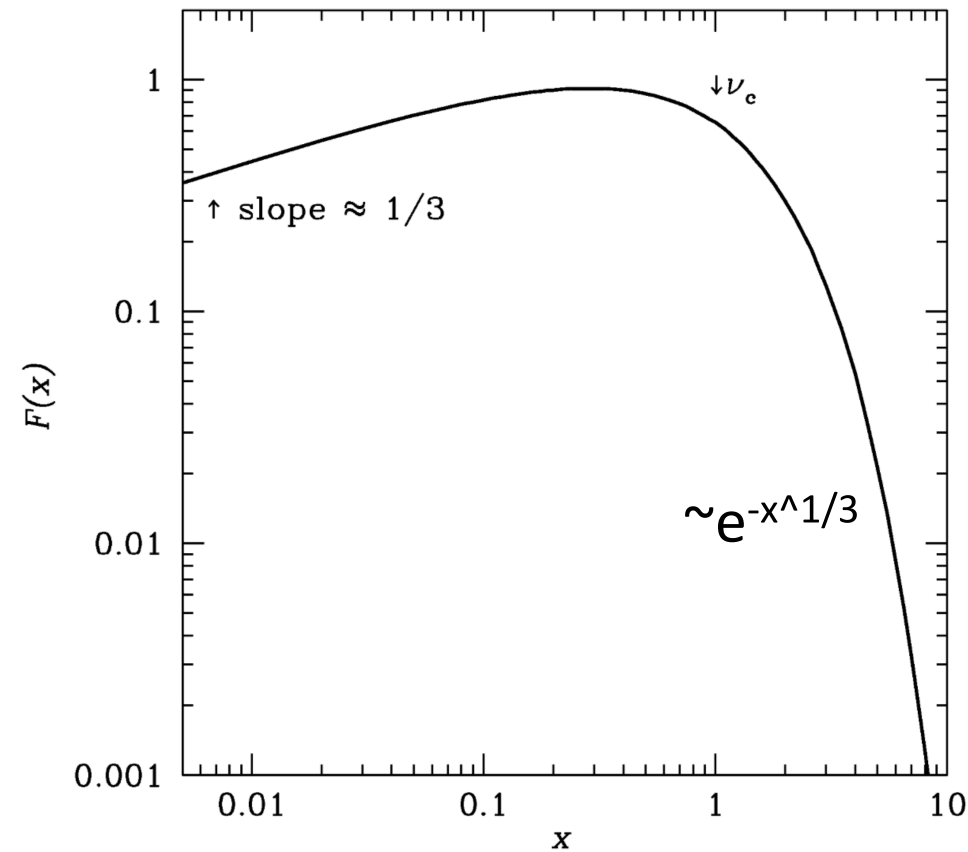


Barriere+2014

Synchrotron spectra

Rybicki & Lightman 1979

- $P_S = 4/3\ \sigma_T c\ \gamma^2\ U_B \sin^2\theta$
- Critical frequency
  $\nu_c = 3/4\pi\ \Omega_B \gamma^2 \sin\theta$
- $dP_S/d\nu \sim P_S / \nu_c \sim$
  $e^3/mc^2\ B \sin\theta\ F(\nu/\nu_c)$



Synchrotron spectra

Rybicki & Lightman 1979

- Power law particle dist.

n(Y) ~ γ^{-p}

$$\mathbf{P}_{\rm tot}(\nu) = \int \mathbf{d}\gamma \mathbf{n}(\gamma) \frac{\mathbf{dP_S}}{\mathbf{d}\nu}$$

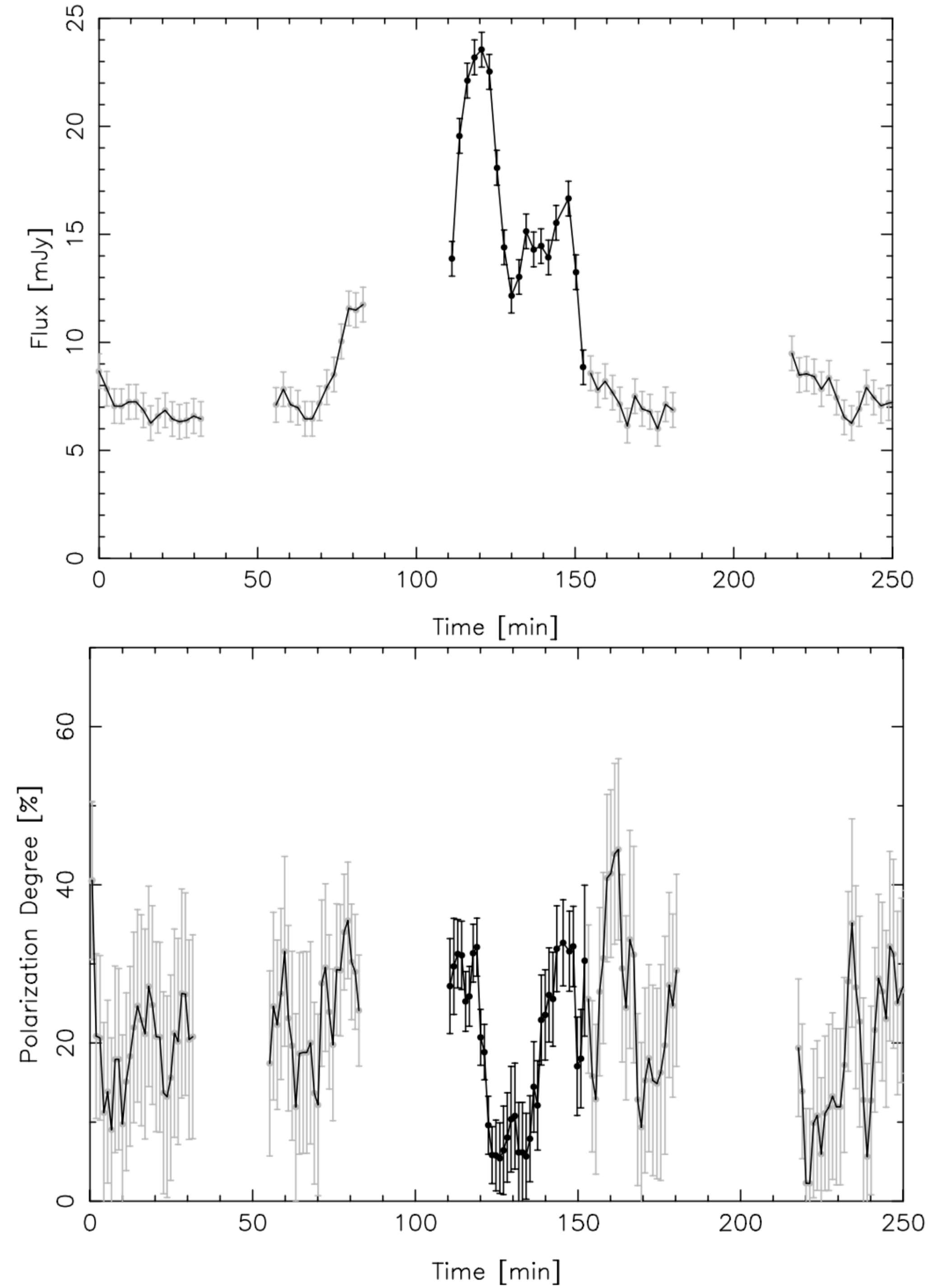
$$\mathbf{P}_{\rm tot}(\nu) \propto \int \mathbf{d}\gamma\, \gamma^{-\mathbf{p}}\, \mathbf{F}(\nu/\nu_{\mathbf{c}})$$

let x = ν/ν_c, x ~ γ^{-2}

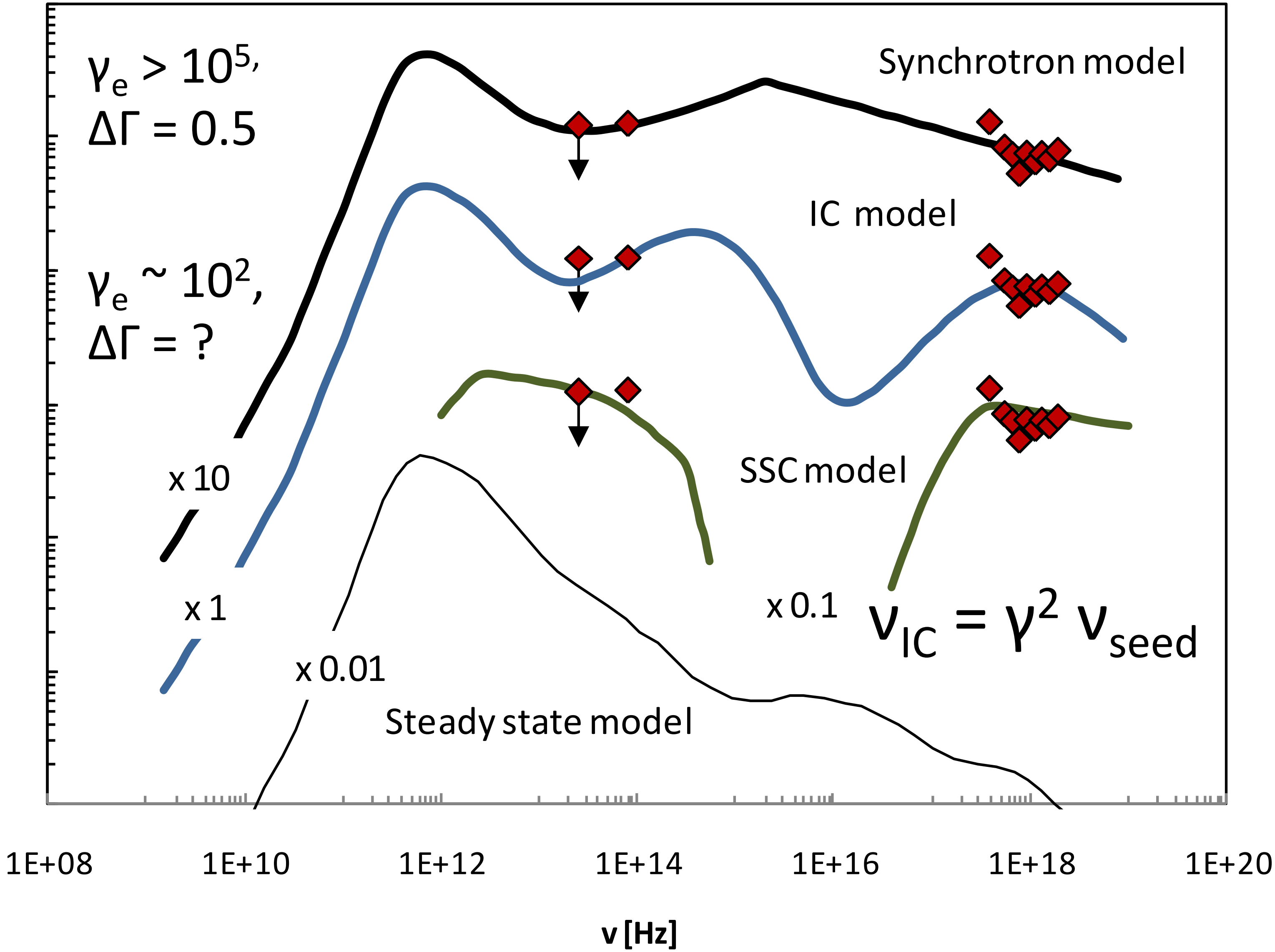
$$\mathbf{P}_{\rm tot}(\nu) \propto \nu^{-(\mathbf{p}-\mathbf{1})/\mathbf{2}} \int \mathbf{dx}\, \mathbf{x}^{-(\mathbf{p}-\mathbf{3})/\mathbf{2}}\, \mathbf{F}(\mathbf{x})$$

IR flares are synchrotron radiation

Eckart+2006, 2008



X-ray flare radiation mechanisms



Particle heating and cooling

- Why would synchrotron X-rays have a break?
- Synchrotron radiation:
  - $n(\Upsilon) \sim \Upsilon^{-p}$, $P_\nu \sim \nu^{-(p-1)/2}$

Particle heating and cooling

- Why would synchrotron X-rays have a break?
- Synchrotron radiation:
  - $n(\gamma) \sim \gamma^{-p}$, $P_\nu \sim \nu^{-(p-1)/2}$
  - Electron energy evolution (Blumenthal & Gould 1970):

$$\frac{\partial \mathbf{n}(\gamma, \mathbf{t})}{\partial \mathbf{t}} = \mathbf{Q} - \frac{\partial (\dot{\gamma} \mathbf{n})}{\partial \gamma} - \frac{\mathbf{n}}{\mathbf{t}_{\mathrm{esc}}}$$

heating cooling escape

Cooling: $\dot{\gamma} = -\gamma / \mathbf{t}_{\mathrm{cool}} \sim -\gamma^{\mathbf{2}}$

$$\mathbf{t}_{\mathrm{cool}} \sim \gamma^{-\mathbf{1}} \mathbf{B}^{-\mathbf{2}}$$

Cooling fast at X-rays, ~slow in IR!

Particle acceleration and cooling

– Electron energy evolution (Blumenthal & Gould 1970):

$$\frac{\partial \mathbf{n}(\gamma, \mathbf{t})}{\partial \mathbf{t}} = \mathbf{Q} - \frac{\partial (\dot{\gamma} \mathbf{n})}{\partial \gamma} - \frac{\mathbf{n}}{\mathbf{t}_{\rm esc}}$$

Steady state, no cooling:

$n(\gamma) = Q\, t_{esc}$

– Particles heat until they escape; input e- spectrum → output IR spectrum with $s = (p-1)/2$

Particle acceleration and cooling

– Electron energy evolution (Blumenthal & Gould 1970):

$$\frac{\partial \mathbf{n}(\gamma,\mathbf{t})}{\partial \mathbf{t}} = \mathbf{Q} - \frac{\partial(\dot{\gamma}\mathbf{n})}{\partial \gamma} - \frac{\mathbf{n}}{\mathbf{t}_{\rm esc}}$$

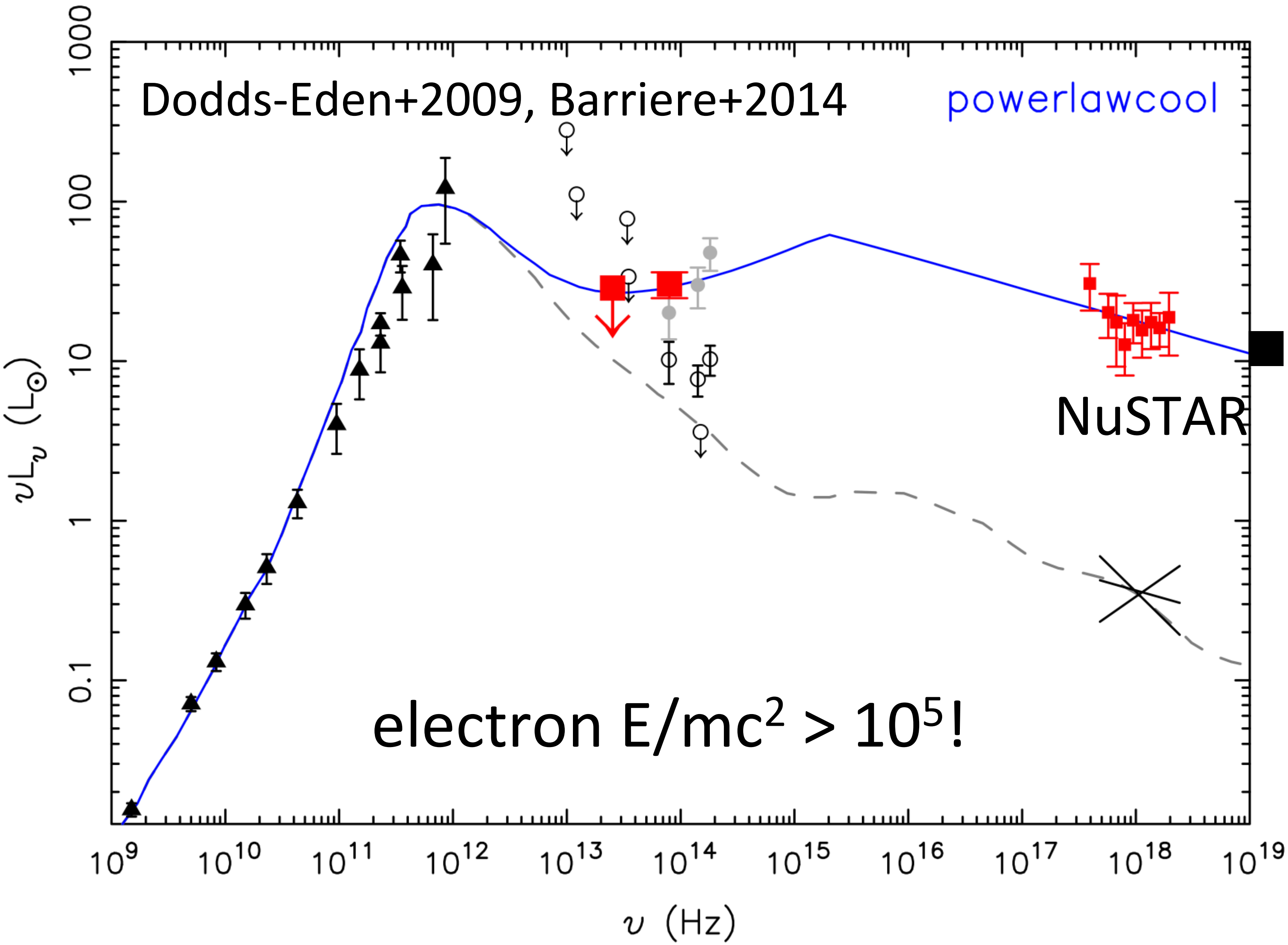
Steady state, rapid cooling:

look for solution n ~ γ^{-s} with Q ~ γ^{-p}:

$$\mathbf{Q} \sim \frac{\dot{\gamma}\mathbf{n}}{\gamma} \quad \text{OR} \quad \mathbf{n}(\gamma) \sim \mathbf{Q}/\gamma$$

→ "Cooling break" in spectrum between IR, X-rays

Evidence for synchrotron X-rays



Evidence for synchrotron flares

Dodds-Eden+2009

- For inverse Compton:

  $\gamma^2 < \nu_{X\text{-ray}} / \nu_{NIR} < 1000$

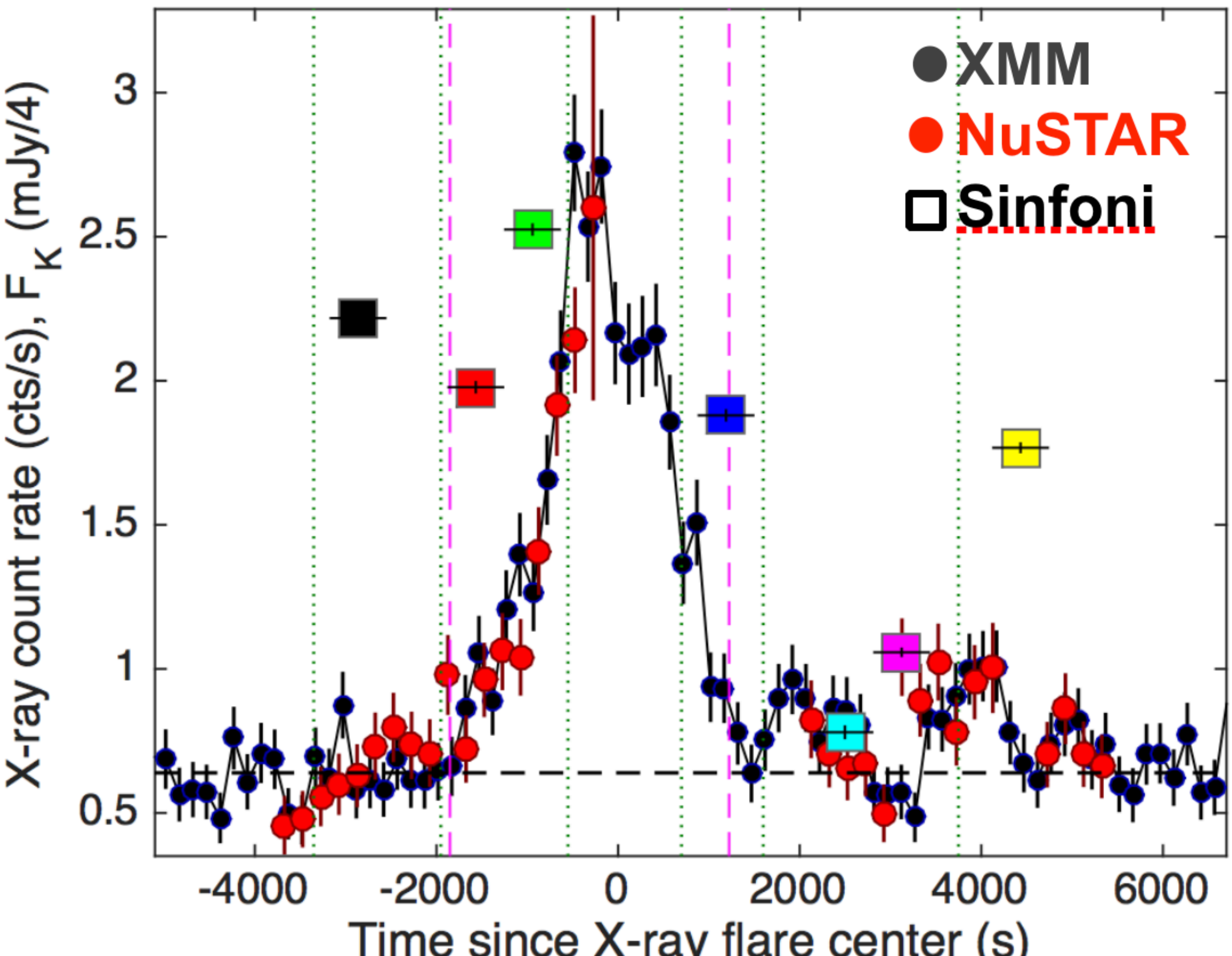
  $\nu_C = 4.2\text{x}10^6\, B\, \gamma^2 > \nu_{NIR}$ ➔ $B > 25$ G

  $P_S / P_C = U_B / U_{ph} \sim 1$

  Synchrotron size < 0.1 r_g tiny!

  → Unrealistic emission region sizes (and/or other parameters) for Compton scenarios

Simultaneous IR/X-ray spectra



Even stronger evidence!