The Galactic Center

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MPE Garching

with slides from R. Genzel, S. Gillessen, and the MPE GC group

mpe.mpg.de/ir/GC

ESO/Y. Beletsky

The Galactic Center

1. Evidence for a massive black hole (14.11)
2. A paradox of youth (16.11)
3. Sgr A* and the faintest black holes (today)
4. Outbursts from Sgr A* and the high energy GC (23.11)

Seminar: strong gravity around Sgr A* (23.11)

About the lectures

- Selected topics: central parsec, highly biased
- Please ask questions!

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

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

About the lectures

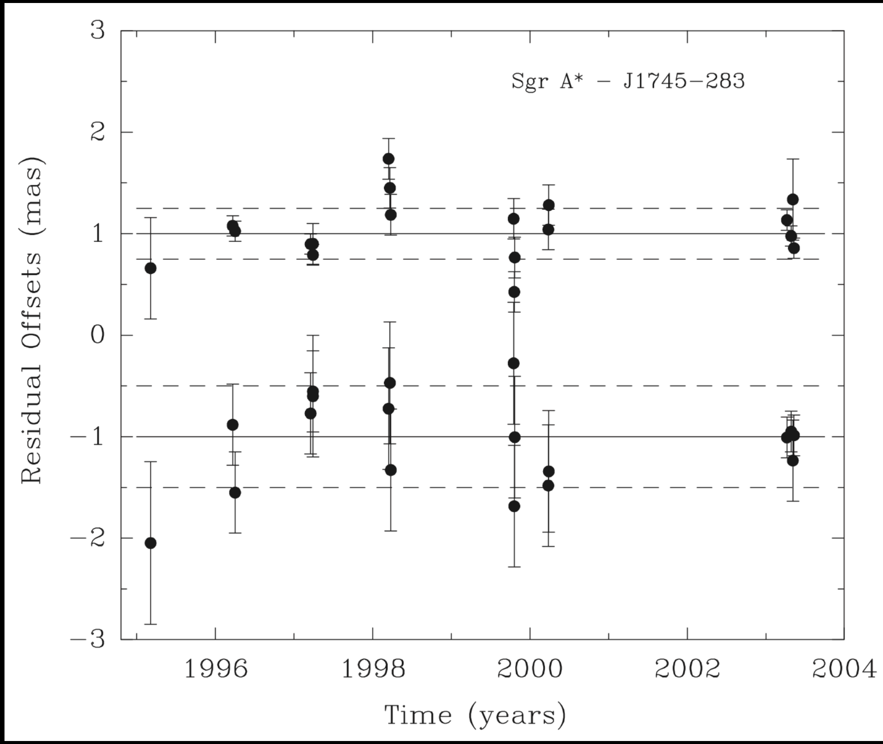
- pdf of slides online: mpe.mpg.de/~jdexter/GCslides
- Requests for topics: now or e-mail jdexter@mpe.mpg.de
- Any other Q's: around after, Wed

2. The Galactic Center:
young stars near a massive black hole

Recap

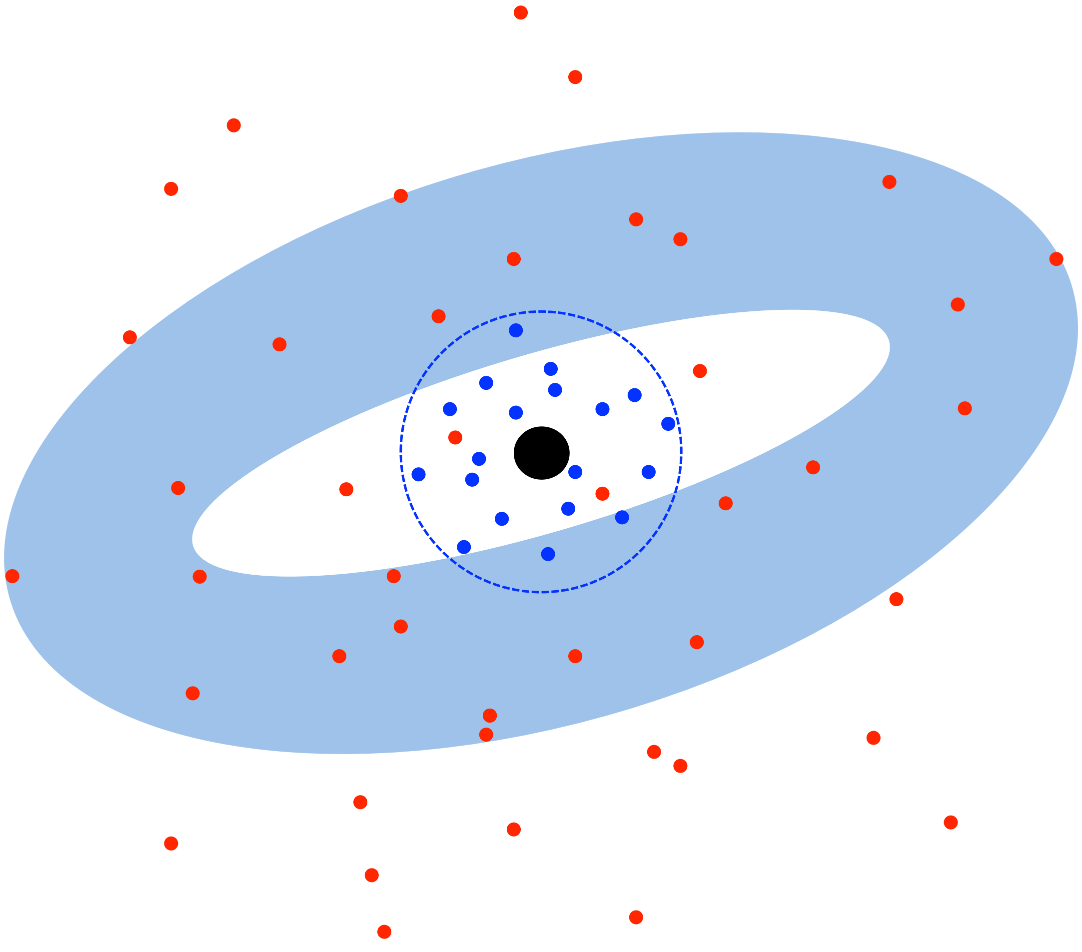
Sgr A* is a black hole

- $4x10^6$ M_{sun} inside of S2
  (Schödel+ 2002, Gillessen+ 2009)
- > 10% of this is Sgr A*
  (Reid & Brunthaler 2004)
- Sgr A* radio size: ~4 R_s
  (Bower+2006, Doeleman+2008)



- density: ~10^{-2} of black hole

Cartoon version of the stellar system



- S-stars
  - young, 10^8 yr
  - r < 0.05 pc
  - orbits
- Stellar disk
  - younger, 10^7 yr
  - 0.05 pc < r < 0.5 pc
- Old stars
  - everywhere
- and more:
  - stellar black holes
  - neutron stars
  - white dwarfs
  - fainter MS stars

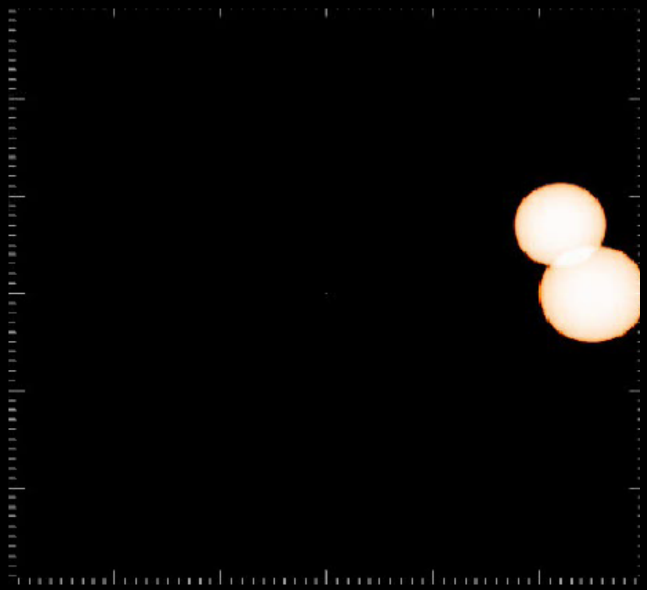
Two paradoxes of youth

O/WR stars

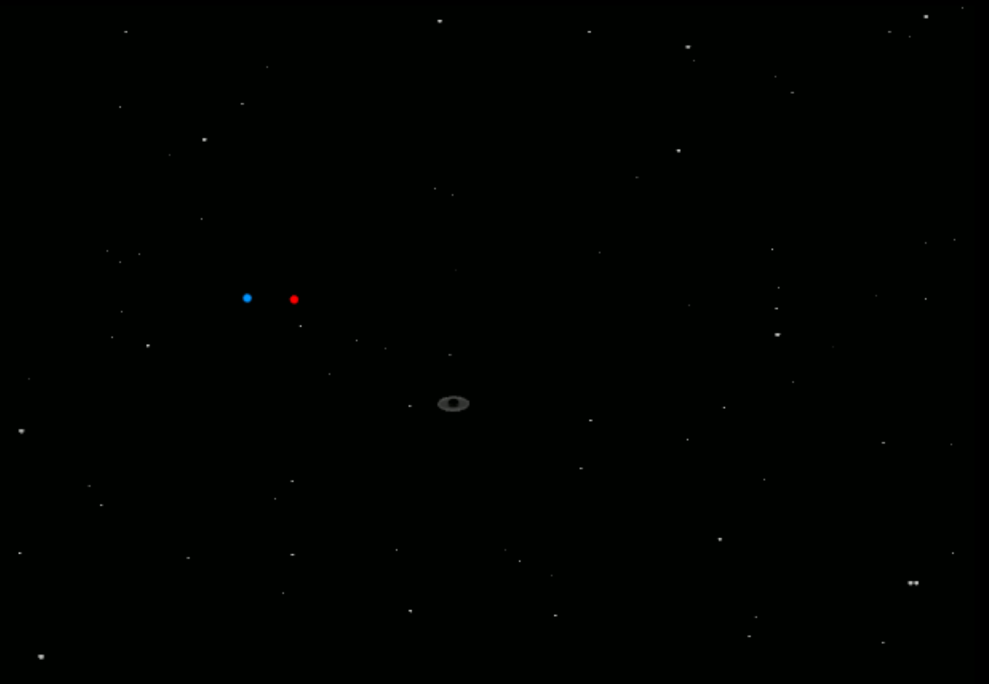
- 6 Myr young
- mean eccentricity 0.35
- disk configuration
- top-heavy IMF

B stars

- typical age 100 Myr
- eccentricities > 0.8
- randomly oriented
- normal IMF



Bonnell+ 2008, Hobbs+ 2009



Hills 1998, Perets+ 2007, Genzel+ 2010

Last time: tidal radius

- Binary a, m; black hole M
- i) Forces: $F_t = F_g$ or $GMm\, a / r^3 = Gm^2/a^2$

- ii) Energy: $W = U_B$ or

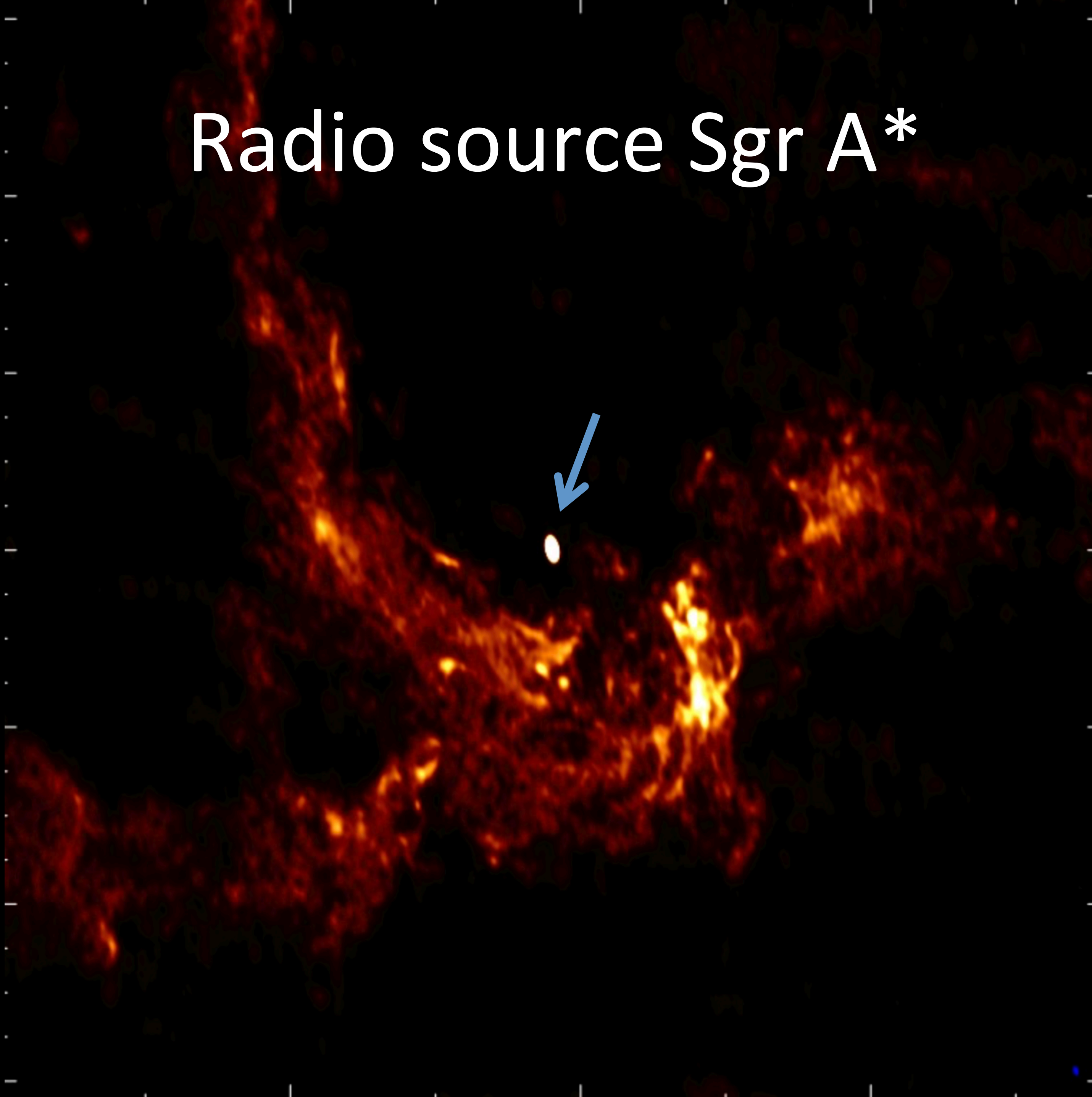
$$\int_0^a \mathbf{F_t dx} = \int_0^a \mathbf{F_g dx}$$

→ $F_t = F_g$

3. The Galactic Center

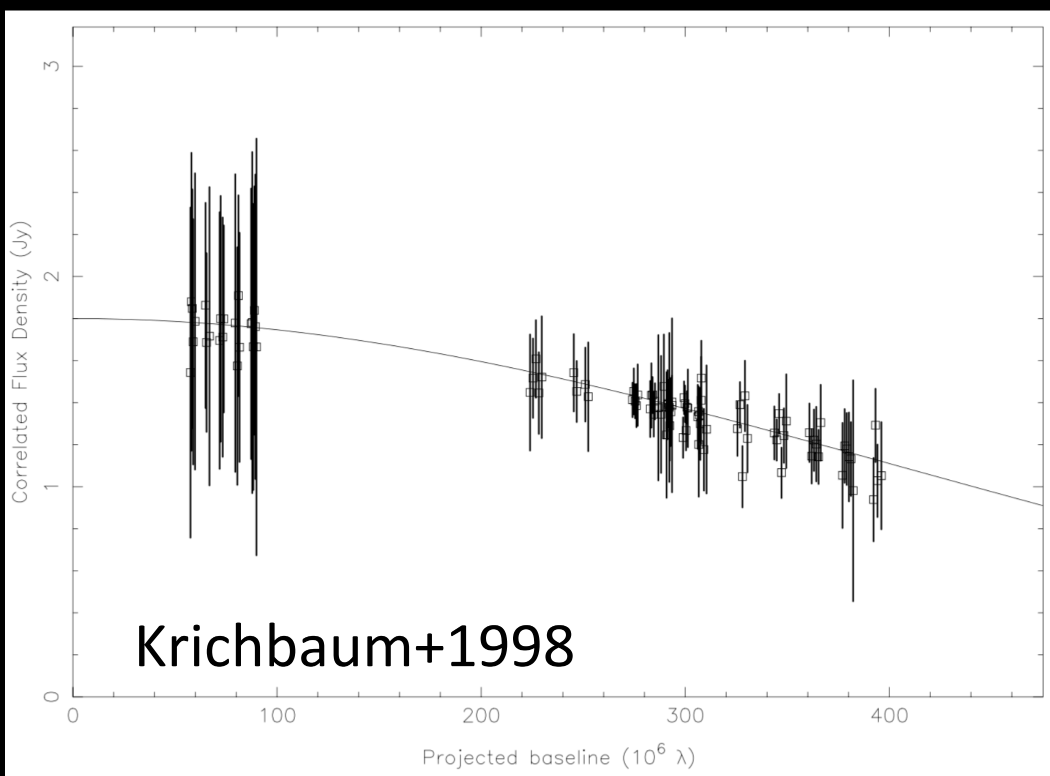
Sgr A* and the faintest black holes

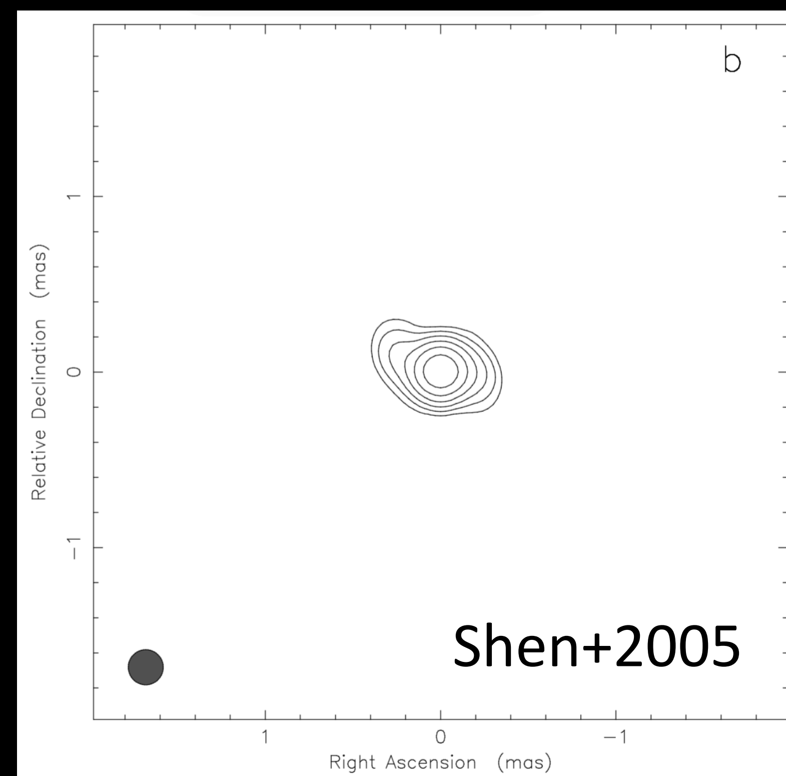
Radio source Sgr A*



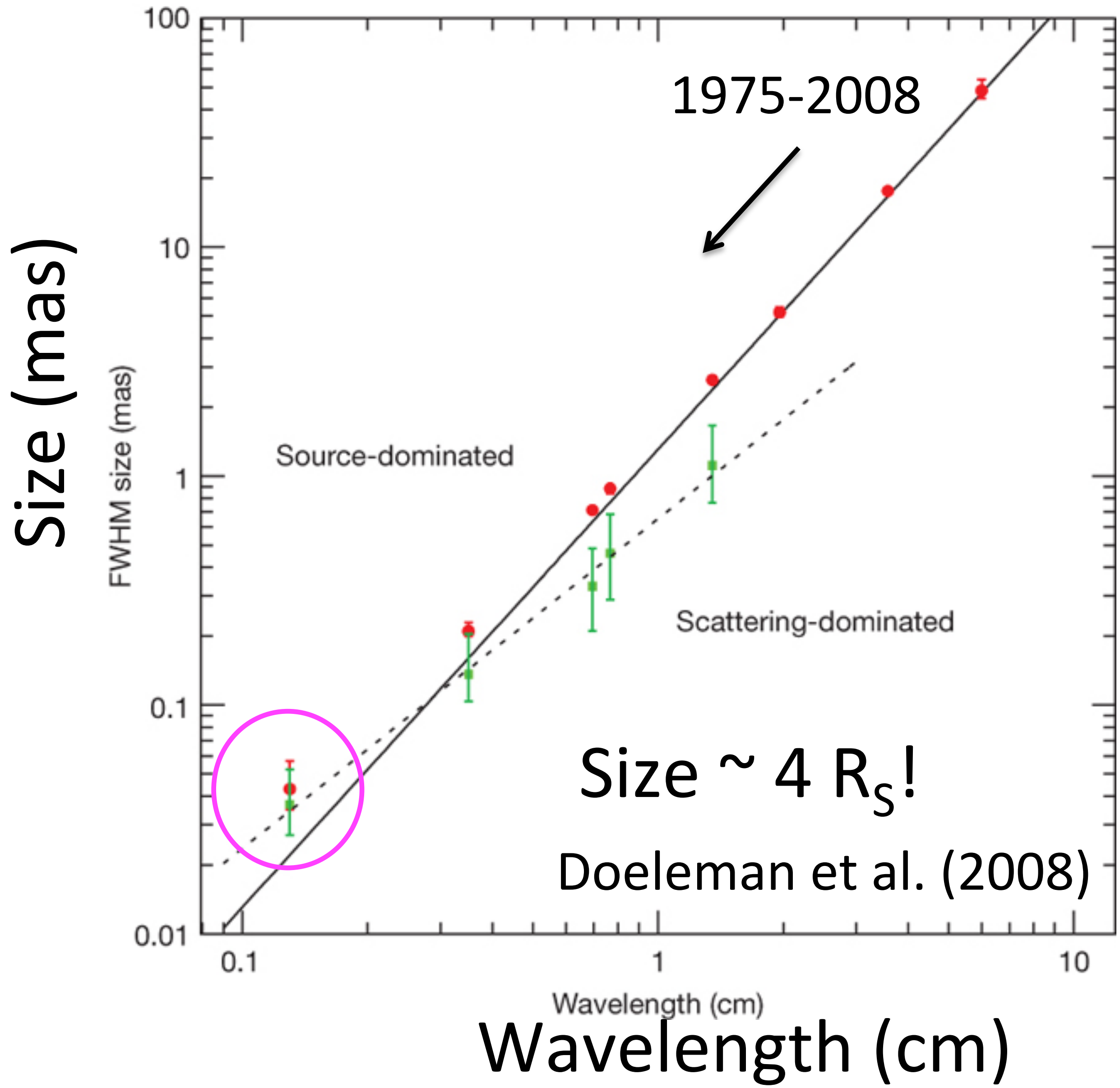
Push to higher resolution

- VLBI (VLBA, EVN) observations
  (Lo, Moran, Krichbaum, Bower, …)
- Atmosphere changes every ~10-100s





The radio size of Sgr A*

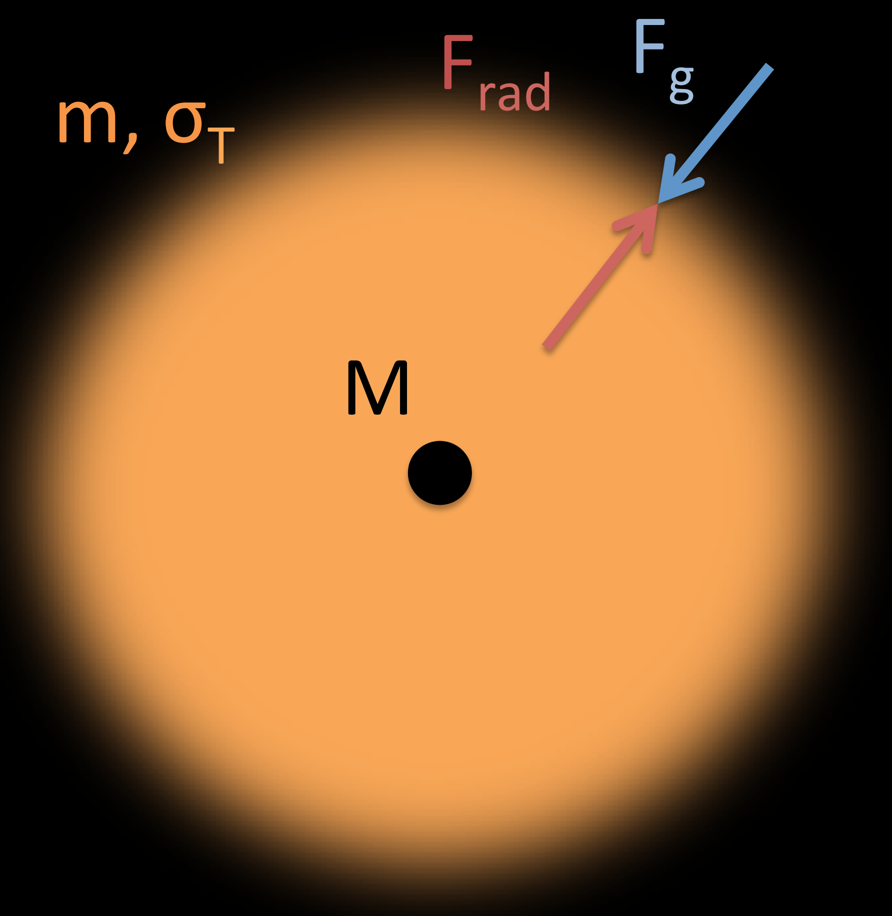


Accretion power

- Infalling gas radiates its gravitational energy

Eddington Luminosity

- How bright can accretion be?



$F_g = F_{rad}$

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

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

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

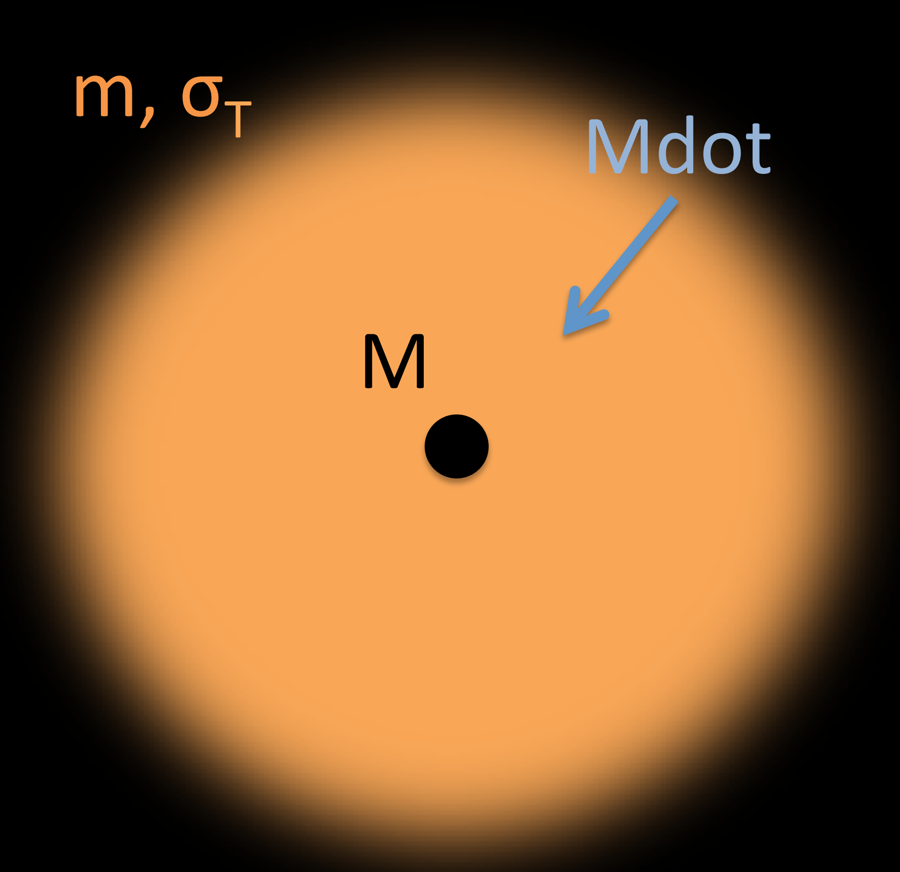
Sgr A*:

$L_{edd} \sim 10^{45}$ 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)

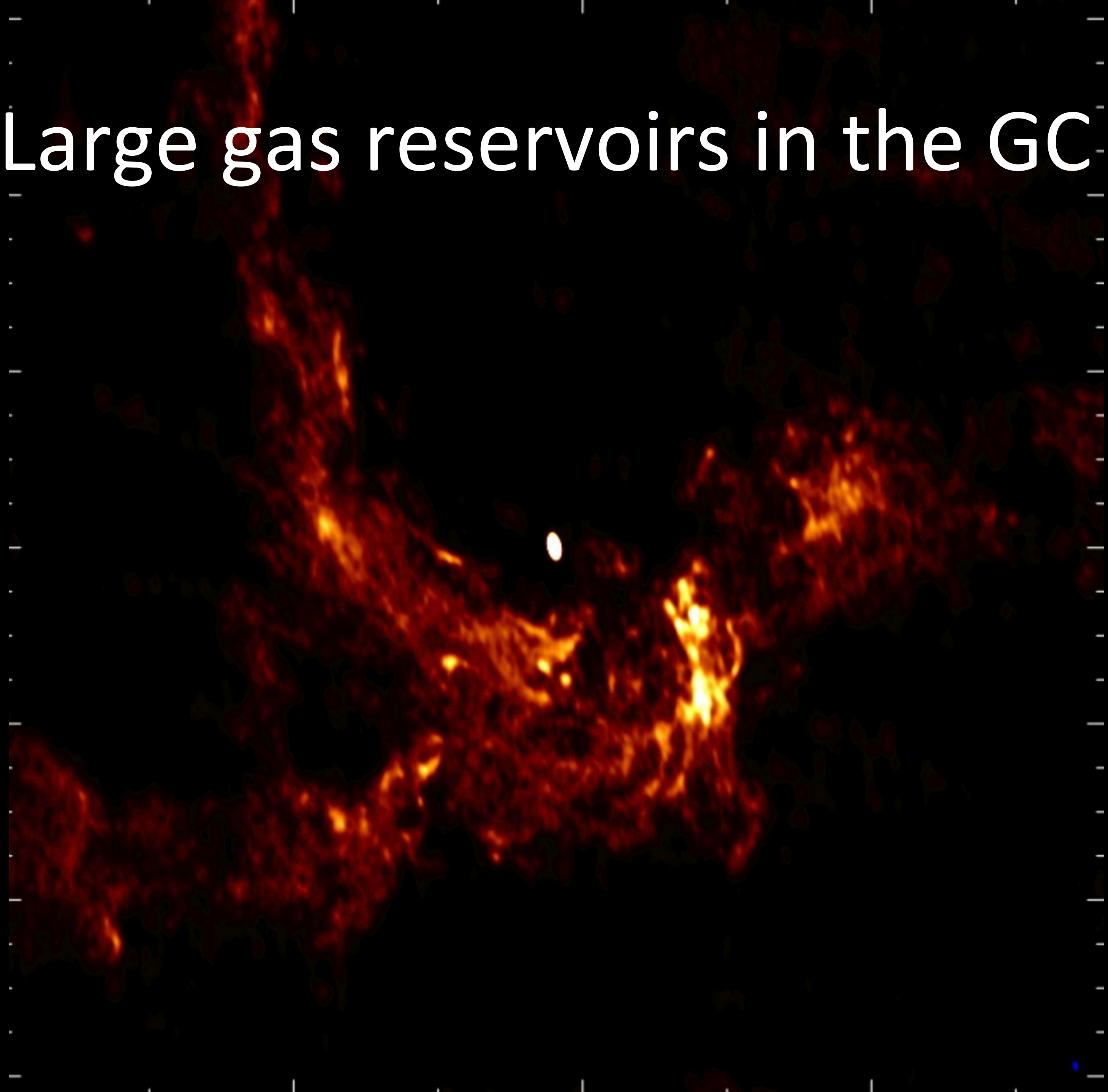
L = Mdot c^2

General L:

L = ε Mdot c^2

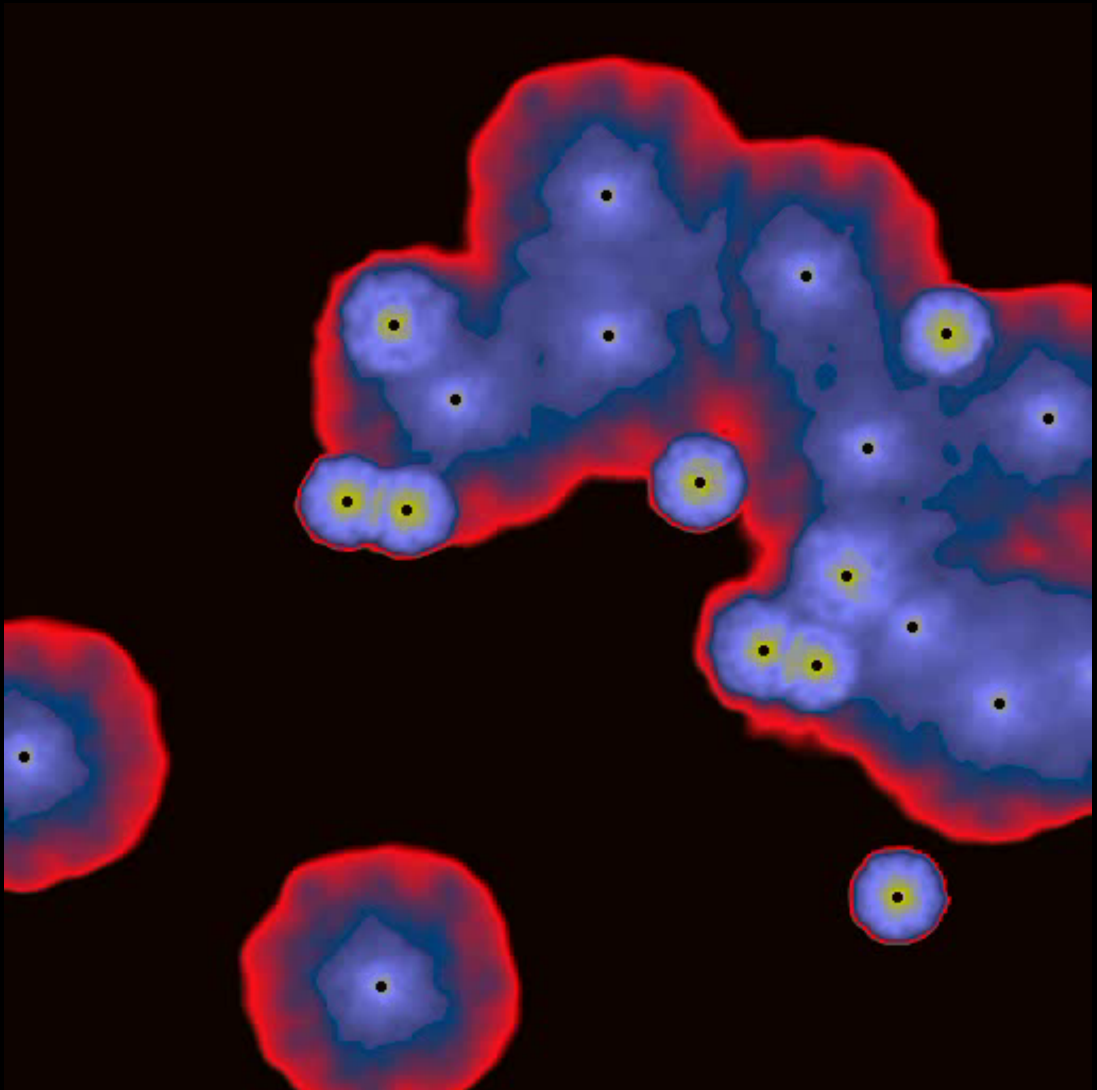
ε = "accretion efficiency"

Large gas reservoirs in the GC



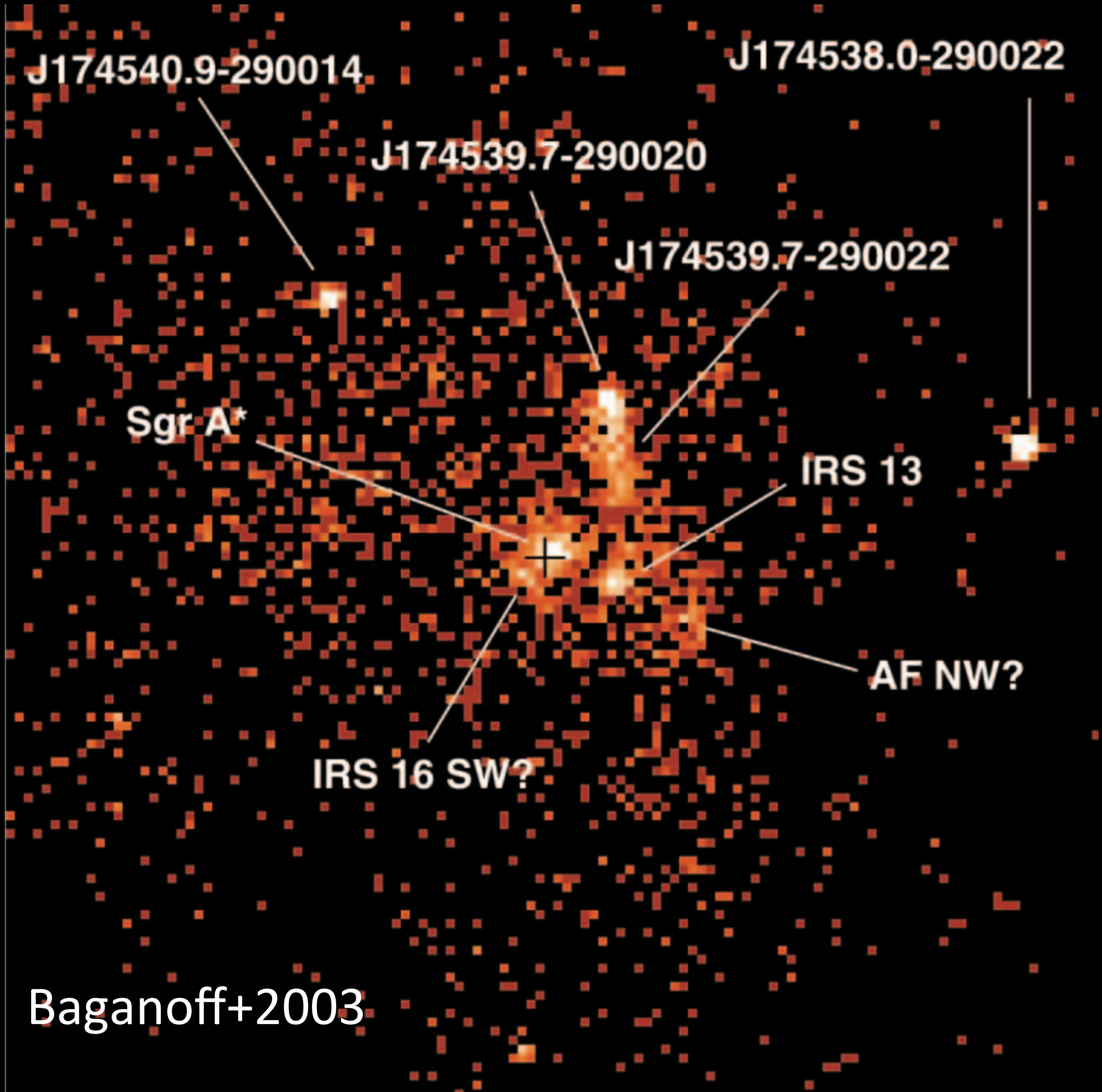
Stellar winds: black hole fuel

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

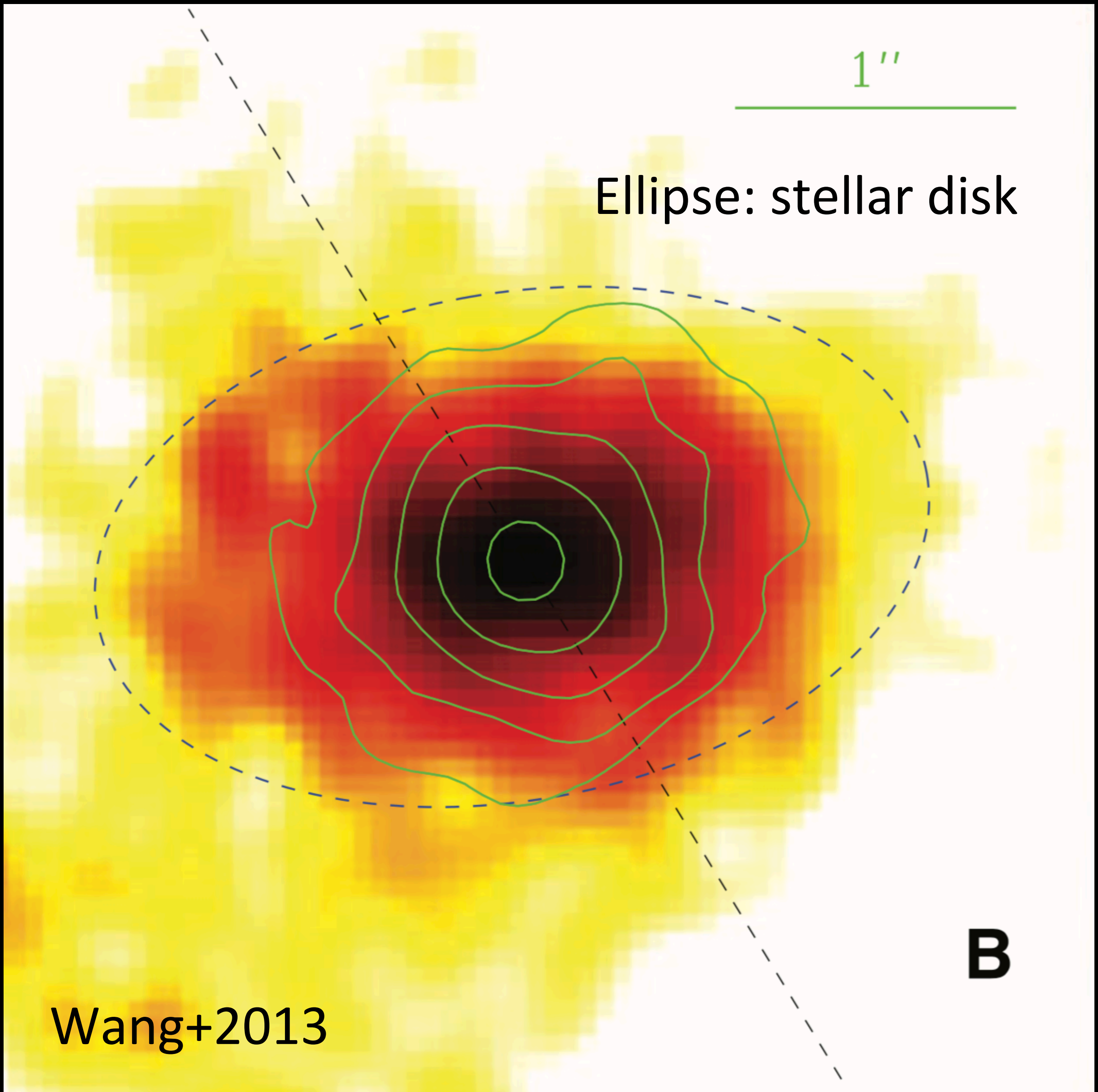


Cuadra
+2006, 2008

X-rays from Sgr A*

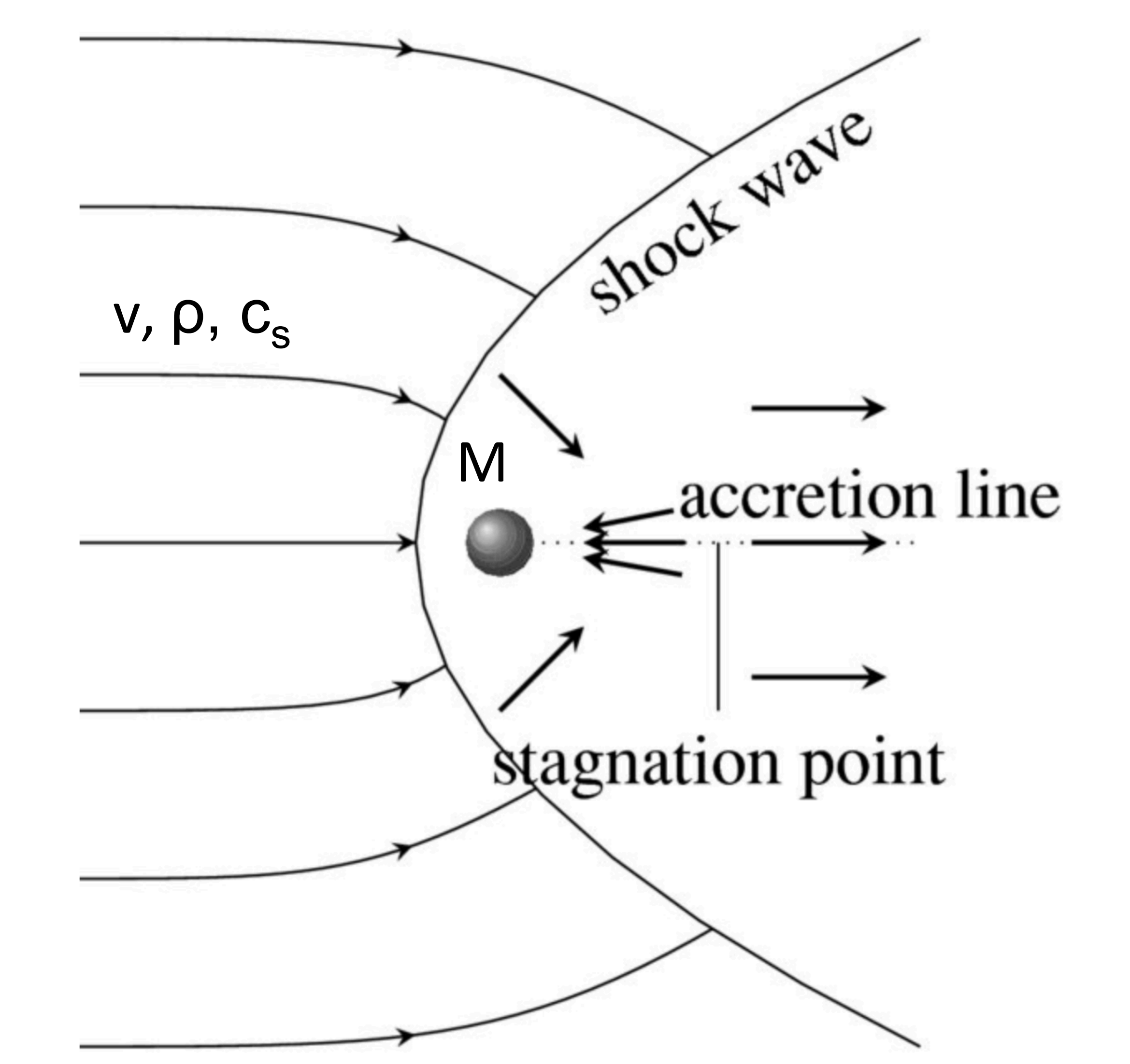


X-rays from Sgr A*



Bondi-Hoyle accretion

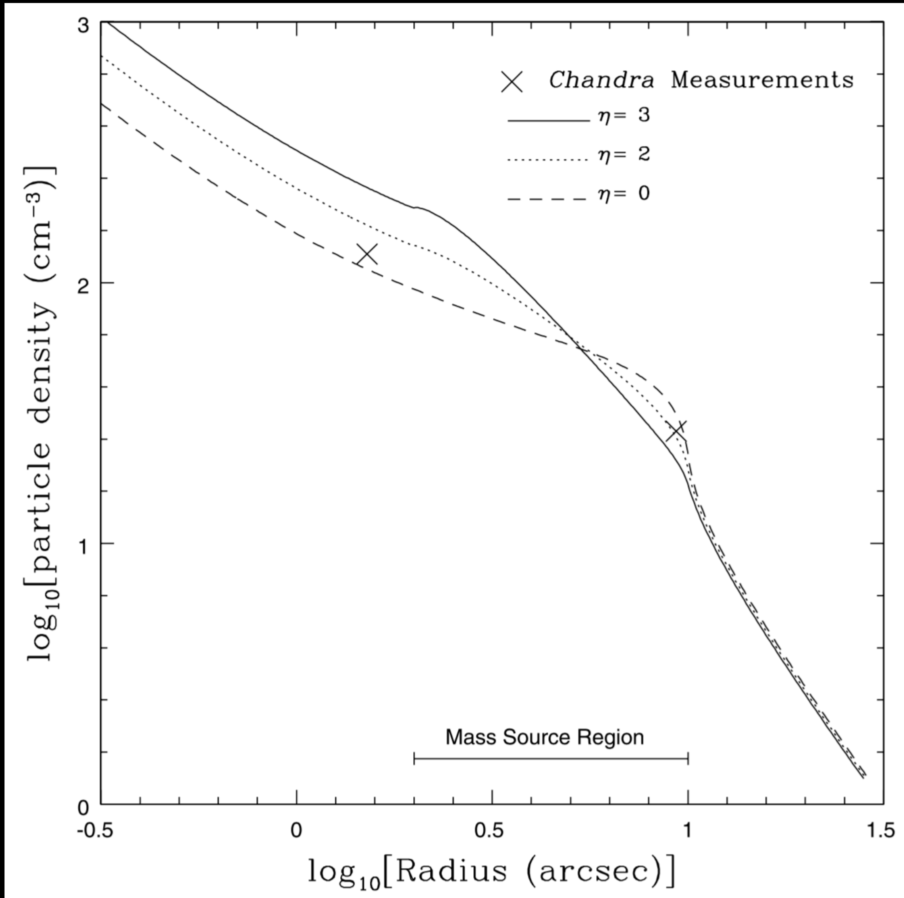
- Mdot = $4\pi\ \rho\ G^2\ M^2 / (v^2+c_s^2)^{3/2}$



Bondi-Hoyle accretion

- Mdot =
  $4\pi \rho G^2 M^2 / (v^2+c_s^2)^{3/2}$
- X-rays:
  $n \sim 100$ 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?

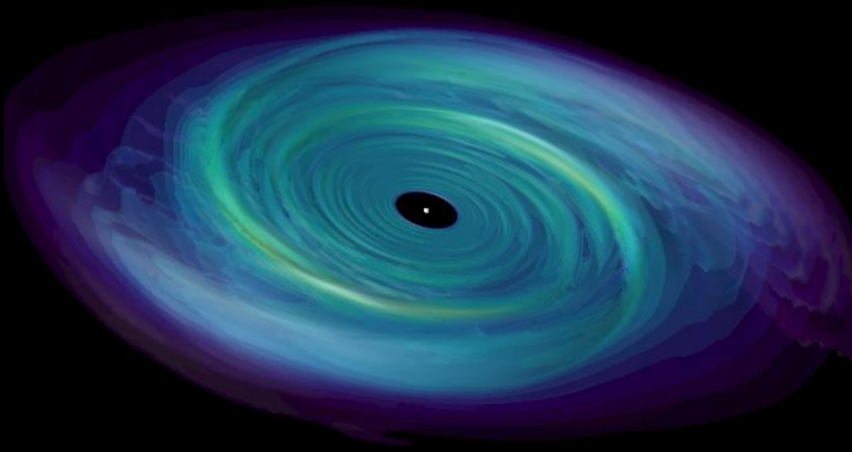
- Sgr A* Bondi radius ~ 0.1 pc: what is the angular momentum of a circular orbit?

- What fraction of this angular momentum 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?

Accretion theory

- Hydrodynamics equations
  - Collisional, "viscous" infalling material
- Approximations:
  - Stationary, axisymmetric ($d_t = d_\phi = 0$)
  - Mdot = constant
  - Vertically integrated
    - "Thin" disk $H/R << 1$, in practice $H/R \leq 1$



Standard accretion theory

After Blaes (2004)

- Mass:

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

- Momentum:

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

- Angular momentum:

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

- Energy:

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

Thin disk accretion

Shakura & Sunyaev 1973)

- $\Omega = \Omega_K$, Mdot = constant, cooling is fast, no torque at inner edge (R_i)
- Angular momentum:

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

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

- Energy:

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

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

Thin disk accretion

Shakura & Sunyaev 1973)

- Solve for flux emerging from disk, F^-

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

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

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

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

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

Thin disk accretion

Shakura & Sunyaev 1973)

- Solve for total luminosity integrated over disk:

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

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

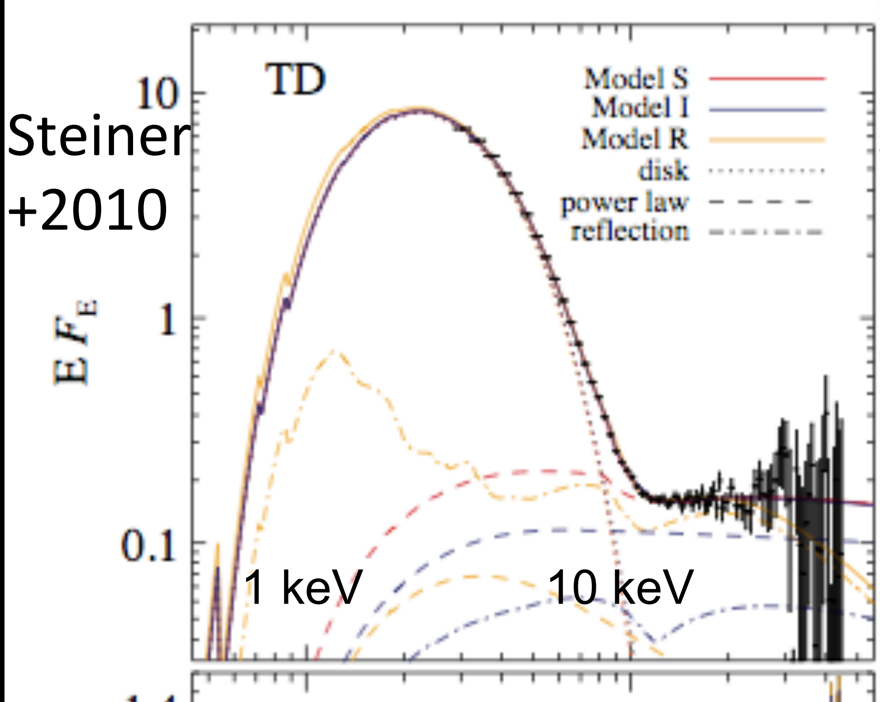
- R_i ~ innermost stable circular orbit of a black hole = 6 GM/c^2 for spin zero
- L ~ 10% Mdot c^2!
- Compare: nuclear fusion ~ 0.1% Mdot c^2

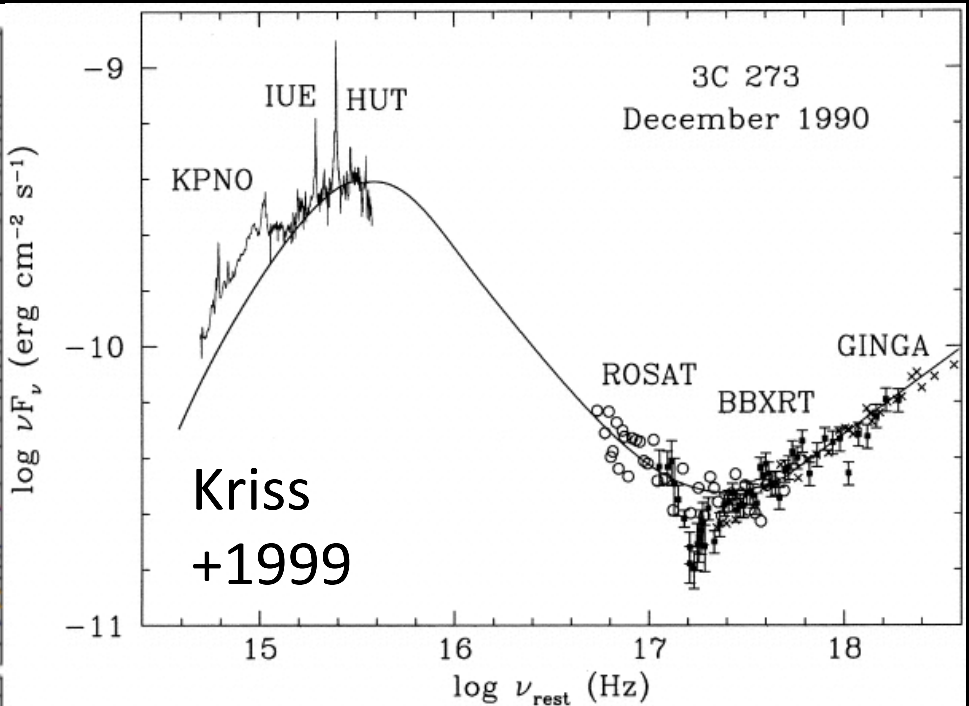
Thin disk accretion

Shakura & Sunyaev 1973)

- opt. thick, so $F^{-}(R) = \sigma T_{eff}(R)^4$
- $R \sim M$, $mdot = Mdot\ c^2 / L_{edd}$
- $T_{eff}(r) \sim mdot^{1/4} M^{-1/4} r^{-3/4}$
- Stellar black holes in X-rays, AGN in UV

Steiner +2010





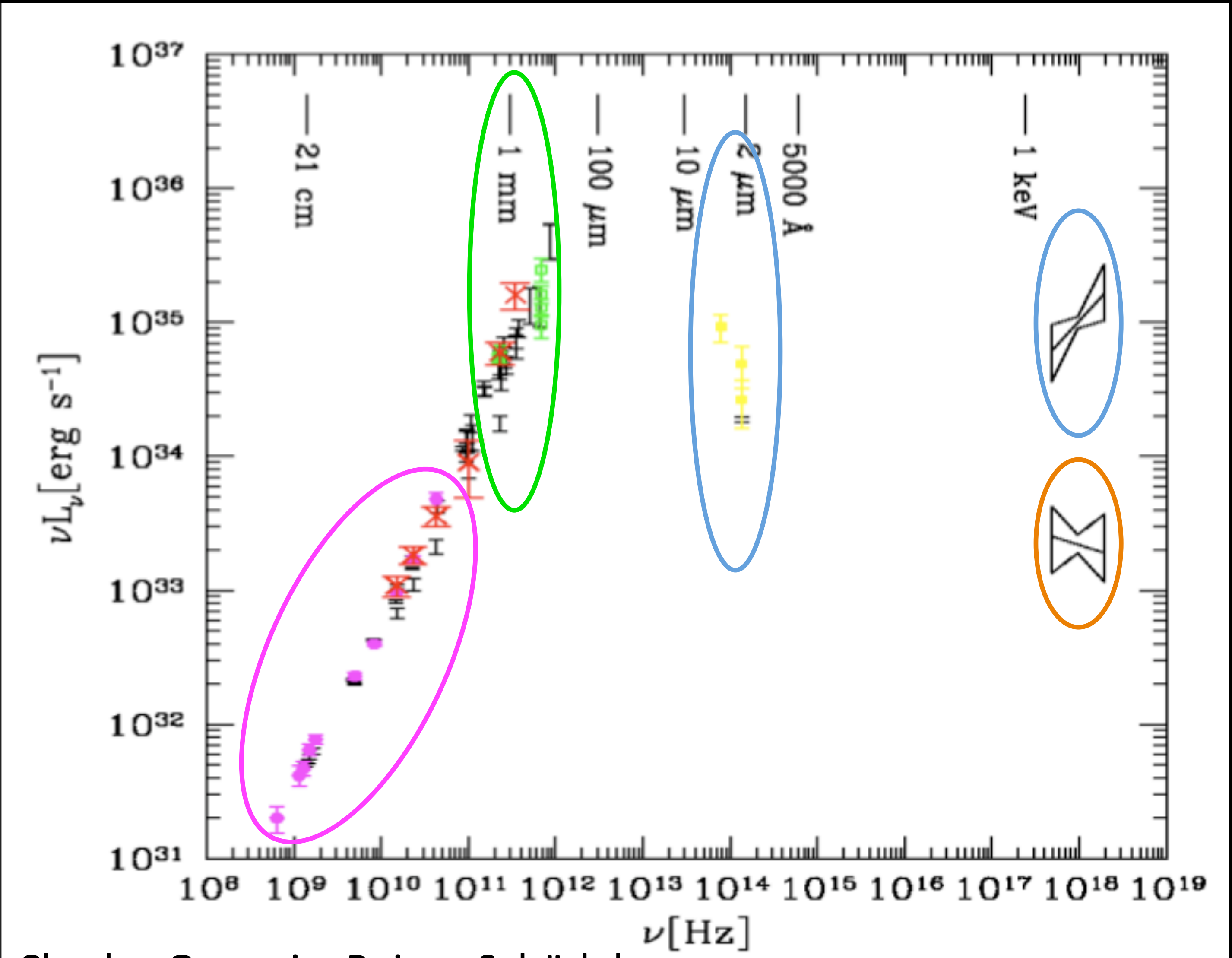
Sgr A* spectrum

Radio: Balick & Brown 1974

mm: Zylka & Mezger 1988

NIR/X-ray: Genzel+2003; Ghez+2004; Baganoff+2001

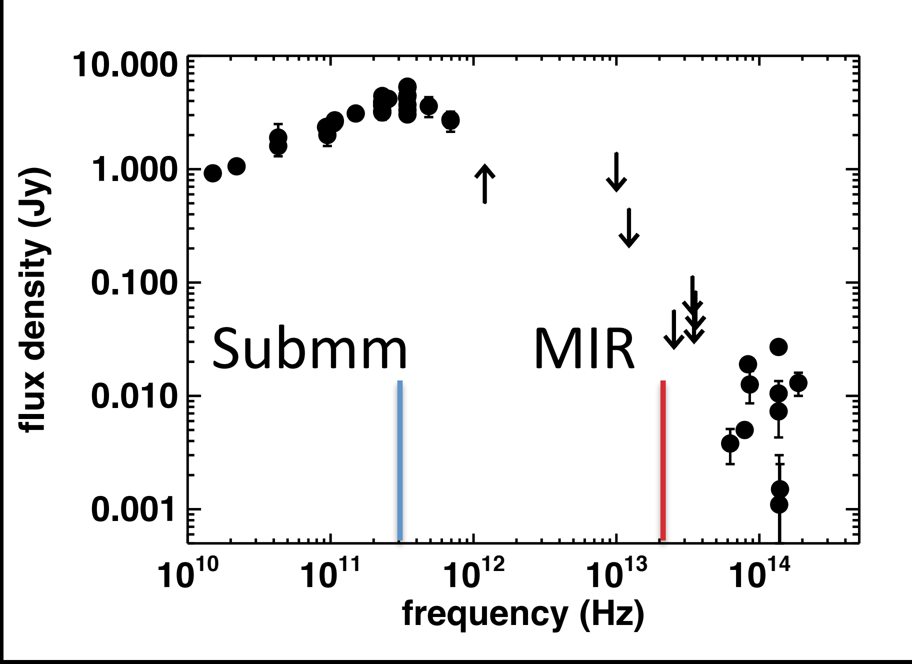
X-ray: Baganoff 2003



Charles Gammie, Rainer Schödel

Thin disks don't work for Sgr A*

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



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

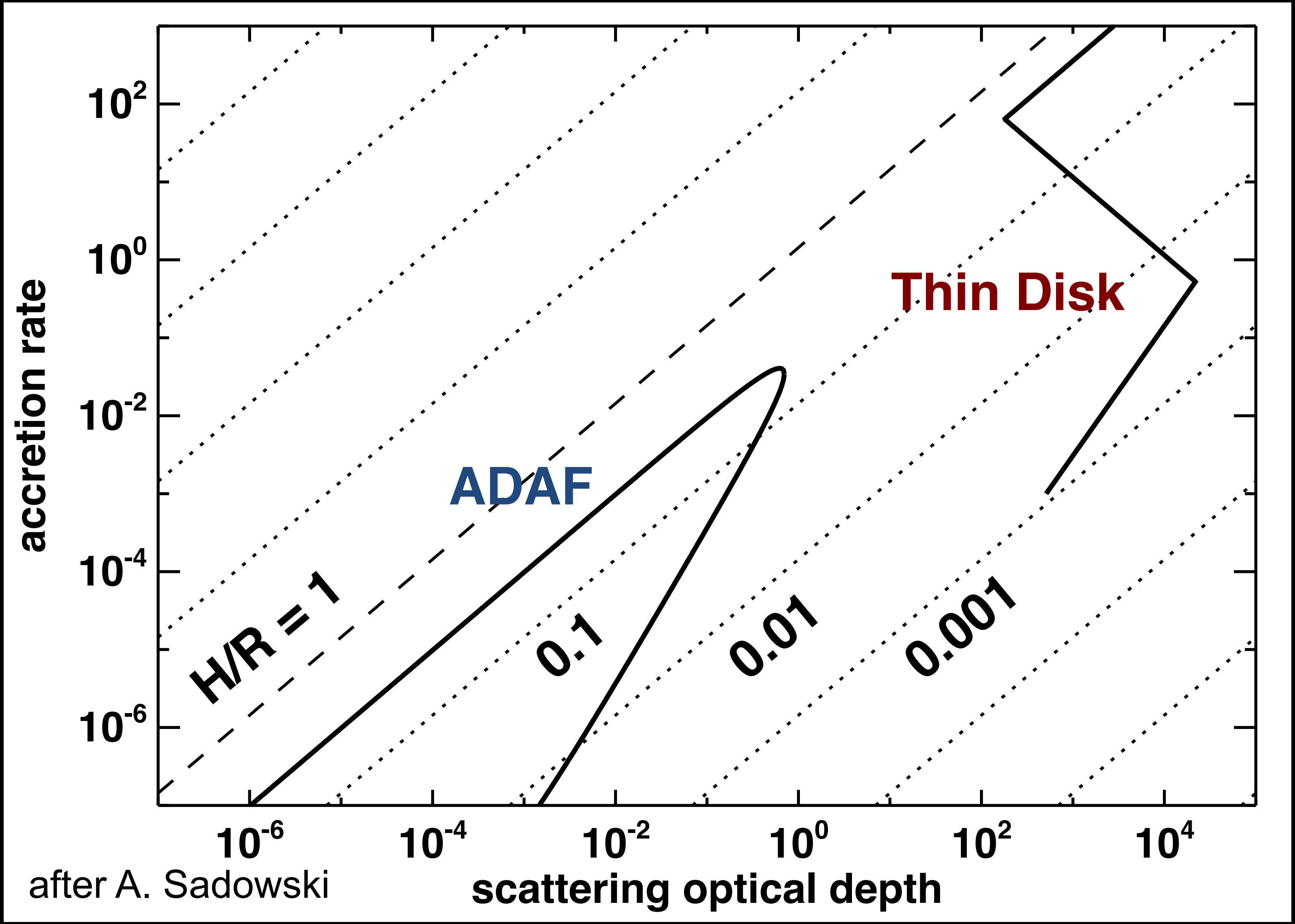
Standard Accretion Theory

- ADAF (Narayan & Yi 1994, also Ichimaru 1977, Rees+1982)
  - Parameterize fraction of local heating advected:
    - f=0: $\Omega = \Omega_K$, thin disk
    - f=1: $\Omega = 0$, spherical (Bondi) accretion
  - Self-similar scalings like spherical accretion:

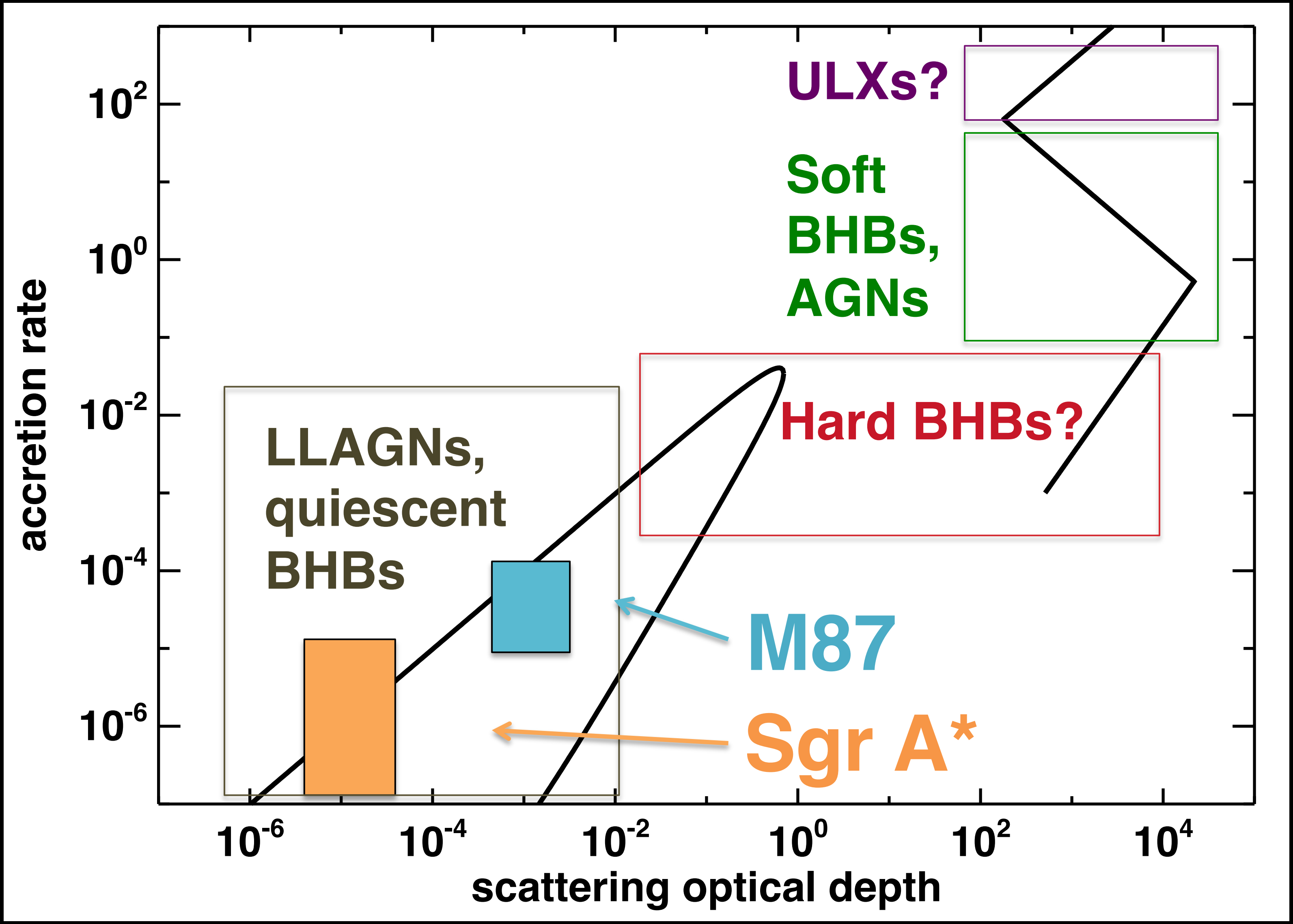
$$\rho, \mathbf{\Omega} \propto \mathbf{R^{-3/2}}; \;\; \mathbf{v}, \mathbf{c_s} \propto \mathbf{R^{-1/2}}$$

  - Low density, "collisionless," → different proton and electron temperatures!

Standard Accretion Theory

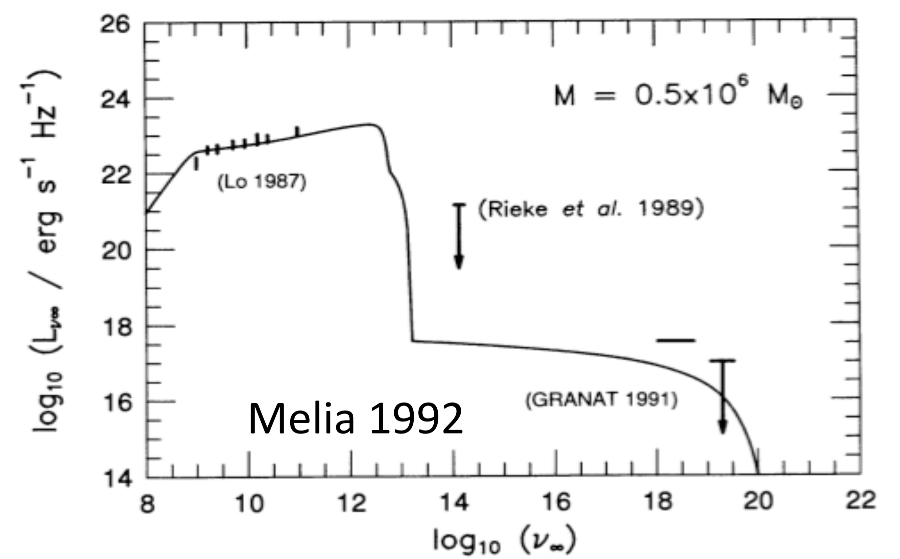


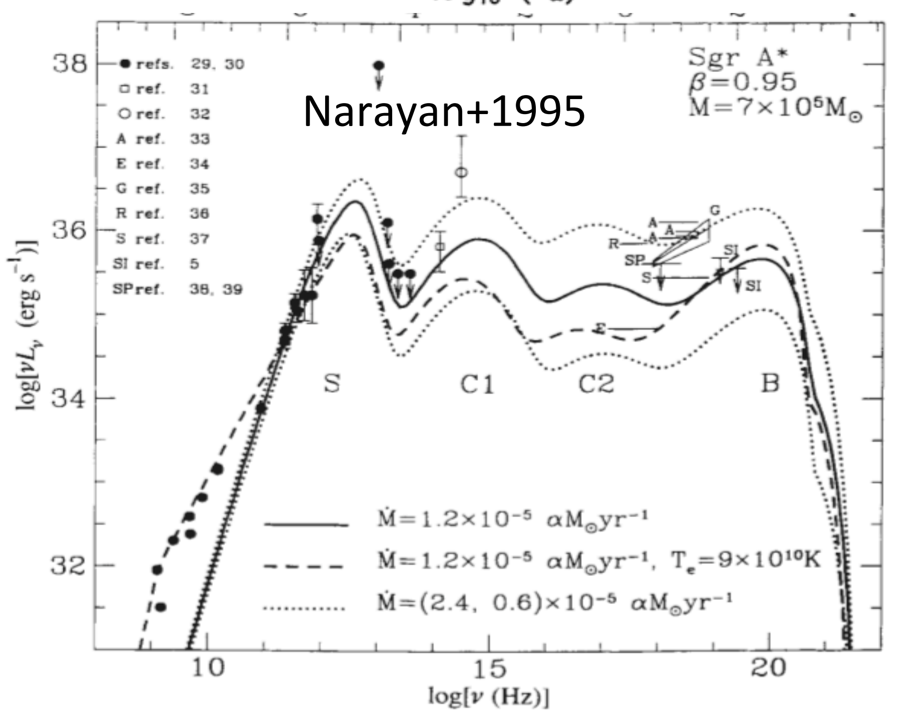
Standard Accretion Theory



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!



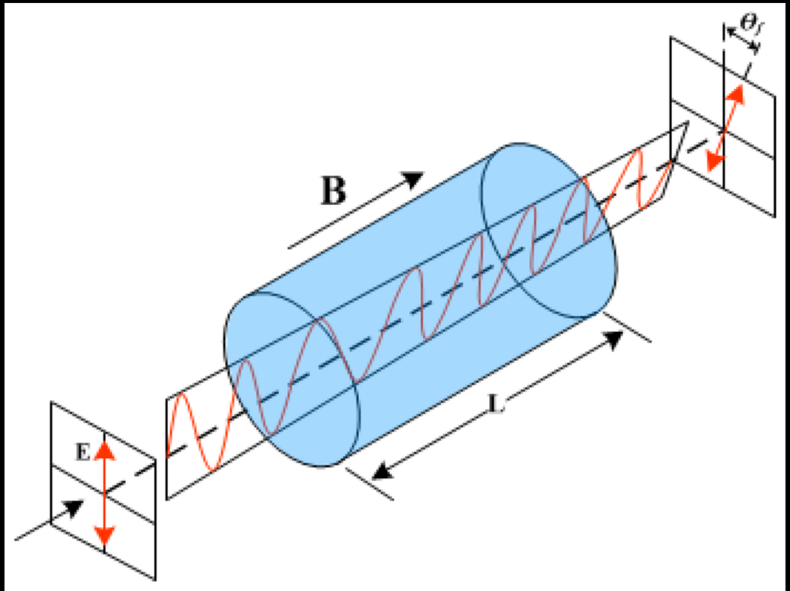


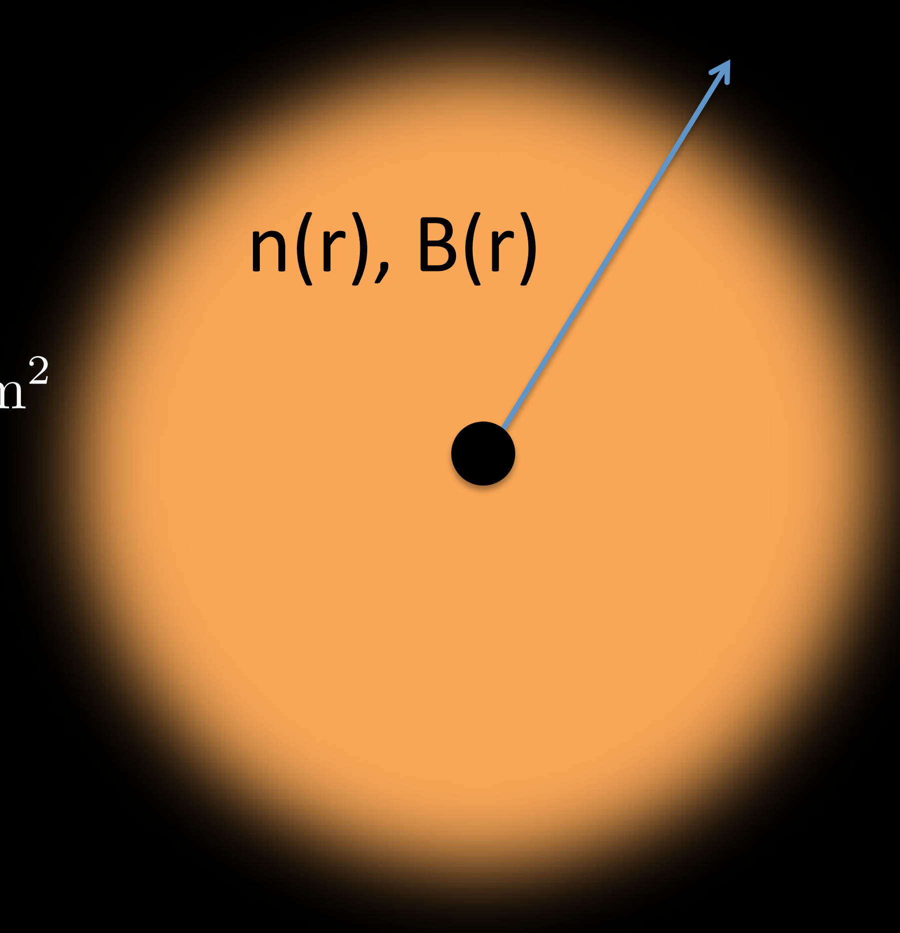
Polarization, Faraday rotation, and the Sgr A* accretion rate

- Magnetic field rotates polarization direction

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

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





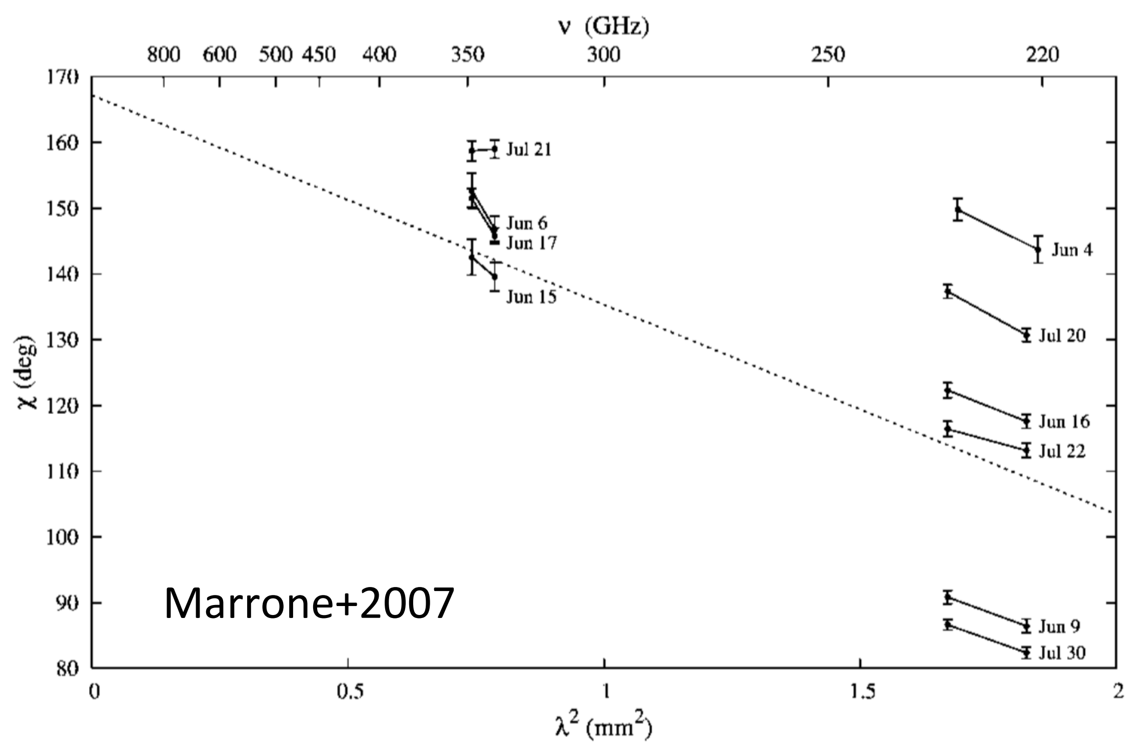
Polarization, Faraday rotation, and the Sgr A* accretion rate

- 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 make it!
  (Aiken+2000, Agol 2000, Quataert & Gruzinov 2000, Bower+2003, Marrone+2006,2007)



Sgr A* e- temperature

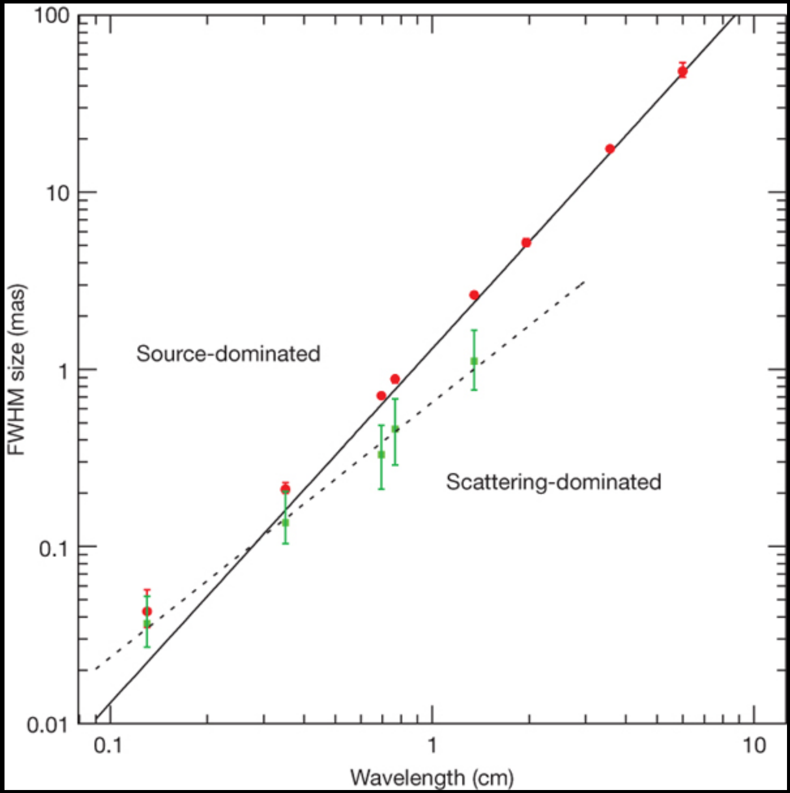
- For known flux, angular size "brightness" temperature is $B_\nu (T_b) = I_\nu$
- Sgr A* at 230 GHz:

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

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

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

- Lower limit to T_e, >> 10^9 K in ADAF

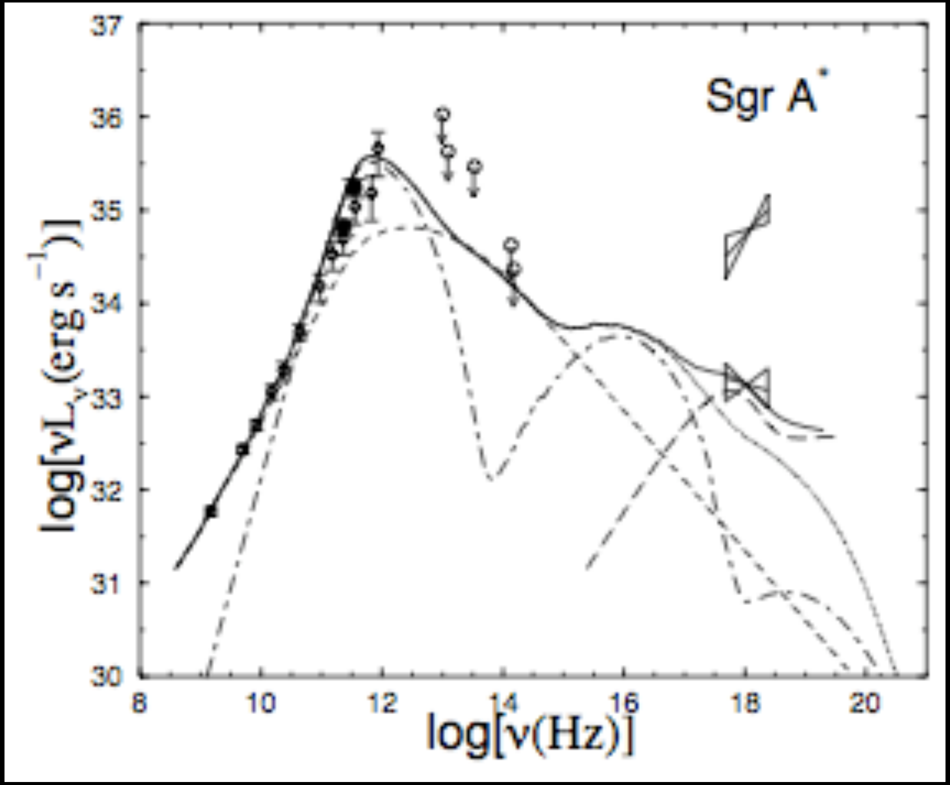


Doeleman et al. 2008

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)

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

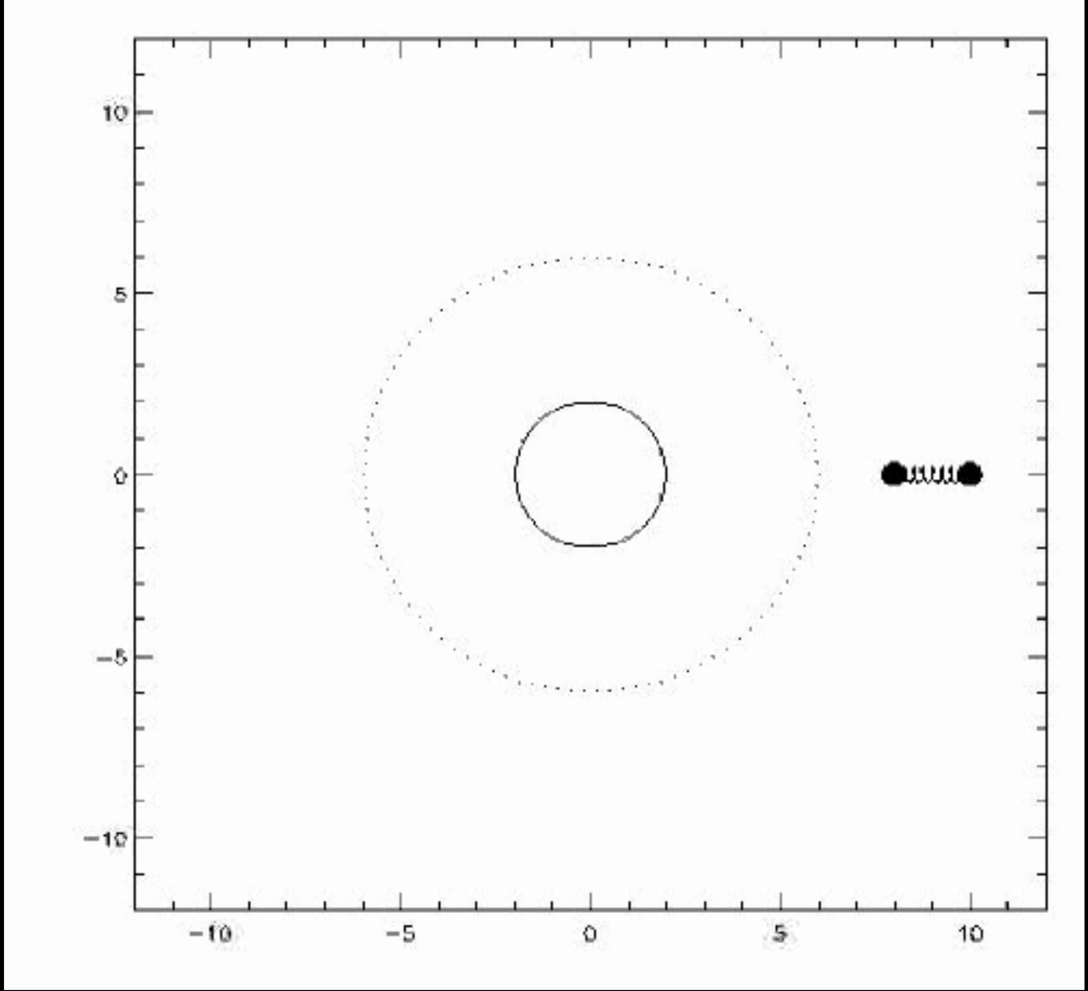
- Gas supply (stellar winds) is not large enough

- A tiny fraction of gas supplied reaches the black hole!

- The accretion flow is inefficient at radiating away its gravitational binding energy

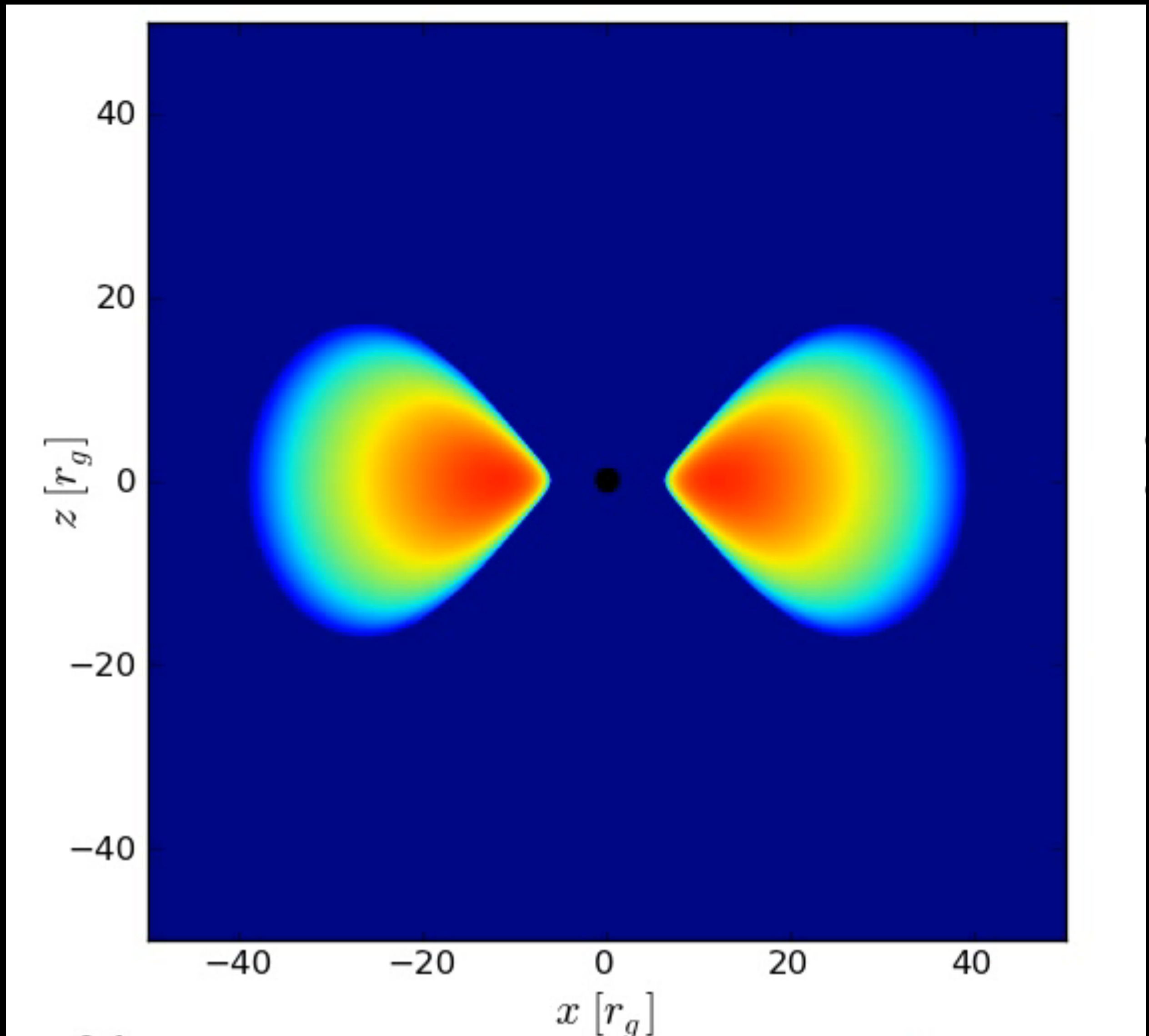
How does gas fall into a black hole?

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



The MRI can cause accretion

- Instability → turbulence, stresses → torque



McKinney & Blandford 2009

MHD simulations of BH accretion

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

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

Next time:

Has Sgr A* always been so faint?