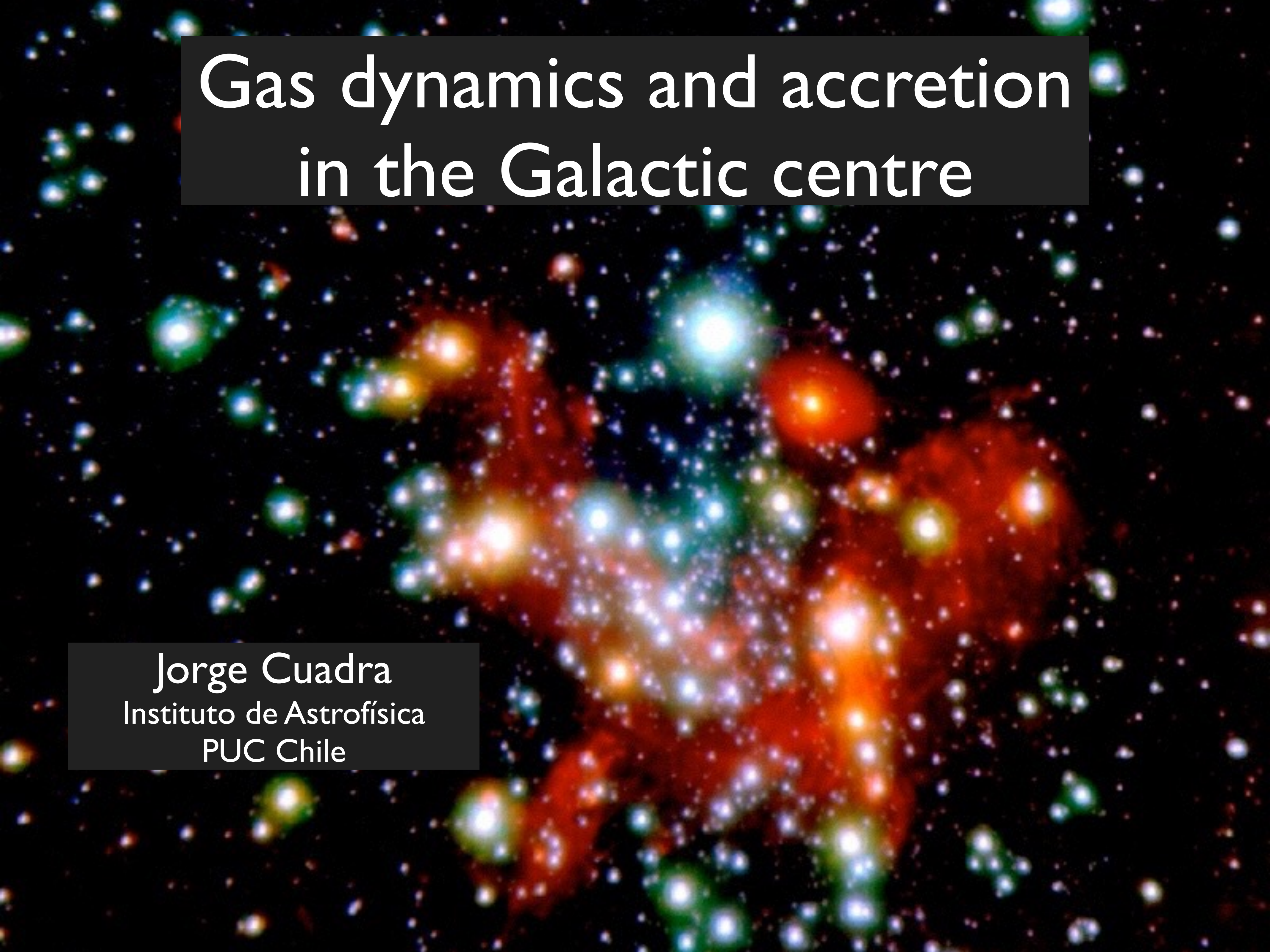
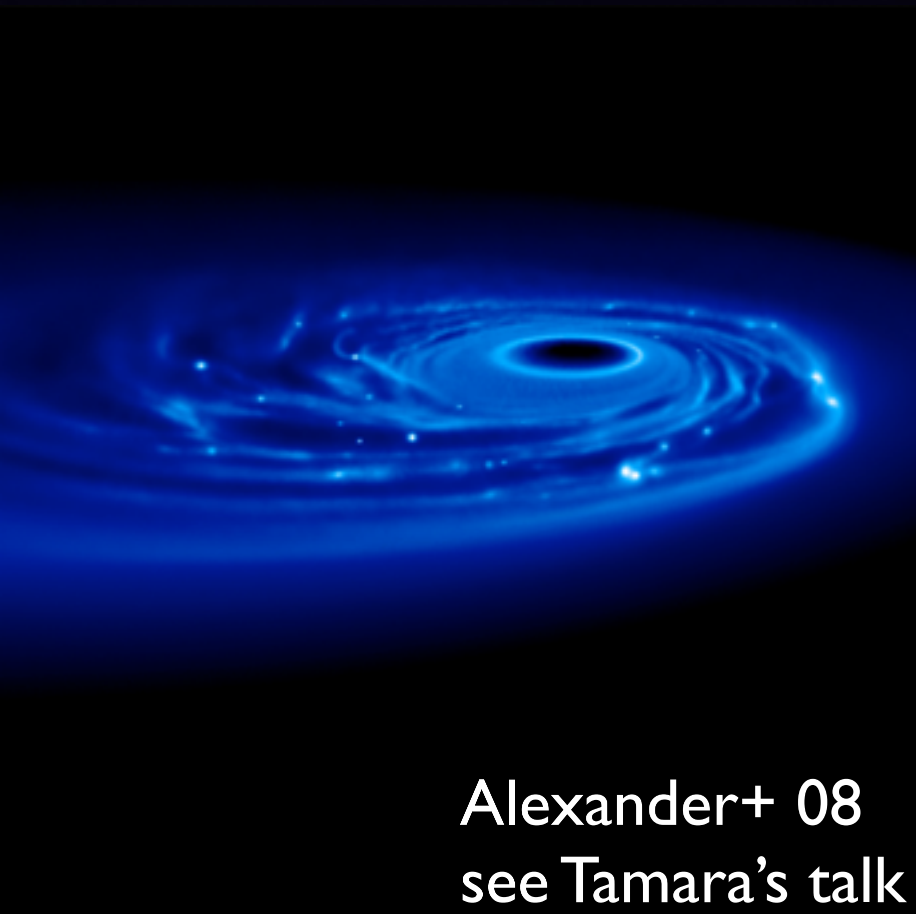


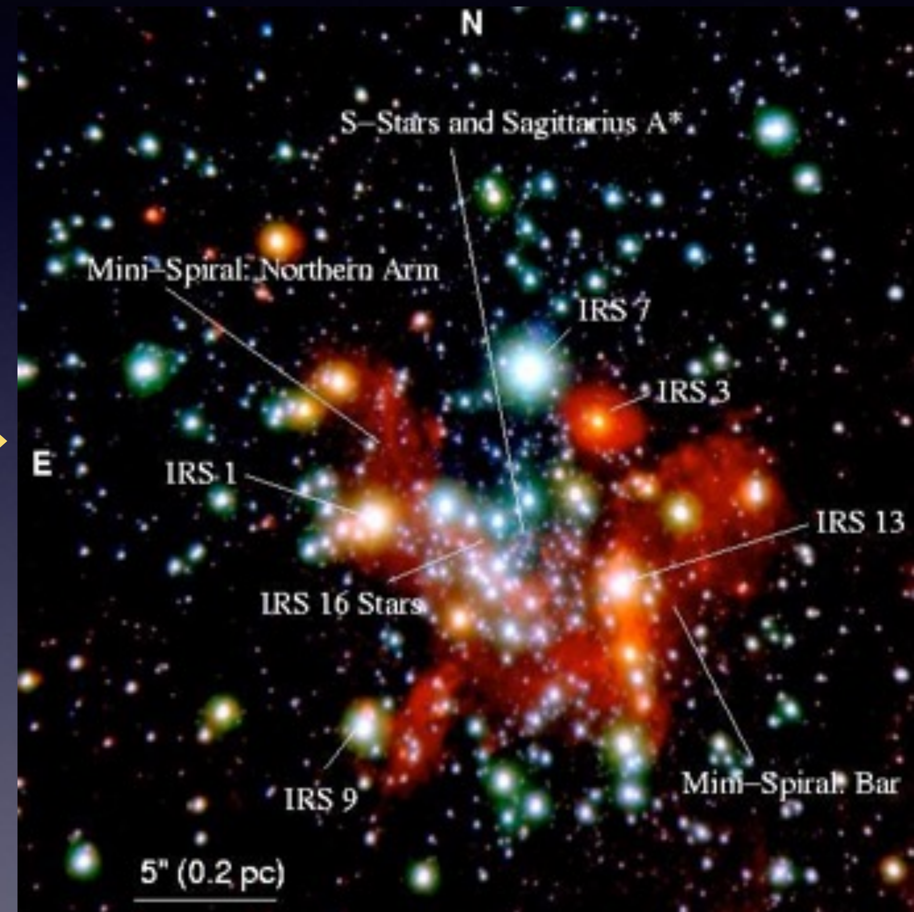
Gas dynamics and accretion in the Galactic centre

Jorge Cuadra
Instituto de Astrofísica
PUC Chile

A few million years ago…



Alexander+ 08
see Tamara's talk

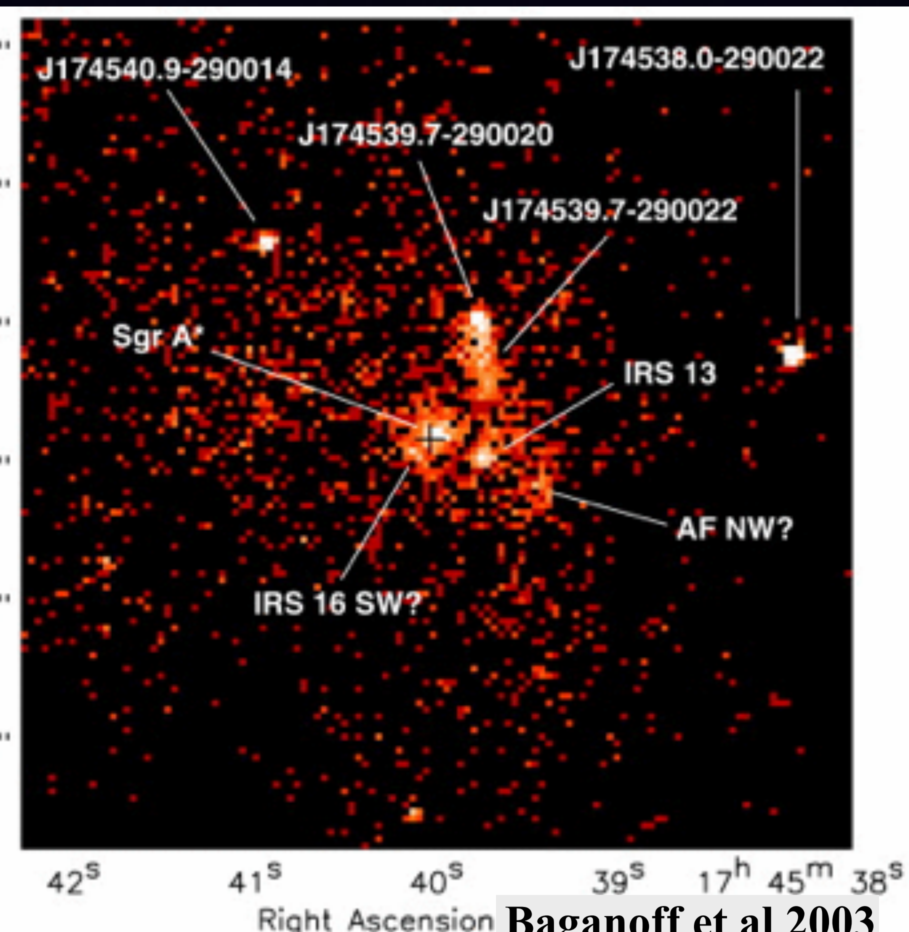


Mass losing stars in the GC

- Young massive stars.
- Many of them are Wolf-Rayet's.
- Mass loss rate up to ~ 10^{-4} $M_\odot$ / yr each.
- Measured from individual spectra and confirmed by bow shocks.

Gemini Observatory/Francois Rigaut

X-ray GC observations



Baganoff et al 2003

- Density and temperature of gas around Sgr A* are measured.
- Bondi model can be constructed.

$$\dot{M}_{\rm B} = 4\pi\lambda(GM)^2\rho c_s^{-3} \simeq 1\times10^{-6}\left(\frac{n_e}{26\eta_f^{-1/2}\ \mathrm{cm}^{-3}}\right) \times \left(\frac{kT}{1.3\ \mathrm{keV}}\right)^{-3/2} M_\odot\ \mathrm{yr}^{-1}\ ,$$

Bondi accretion

Bondi Accretion is spherical accretion onto an object. It is generally used in the context of neutron star and black hole accretion for compact objects traveling through the interstellar medium. It is named after Hermann Bondi.

To achieve an approximate form of the Bondi accretion rate, accretion is assumed to occur at a rate $\dot{M} = \pi r^2 \rho v$ where ρ is the ambient density, v is either the velocity of the object or the sound speed c_s in the surrounding medium if the object's velocity is lower than the sound speed, and the radius r provides an effective area. The effective radius is acquired by equating the object's escape velocity and the relevant speed, i.e. $\sqrt{\frac{2GM}{R}} = c_s$ or $R = \frac{2GM}{c_s^2}$. The accretion rate therefore becomes $\dot{M} = \frac{4\pi \rho G^2 M^2}{c_s^3}$.

This derivation is only approximate, using scaling relations rather than rigorous definitions. A more complete solution can be found in Bondi's original work and two other papers.

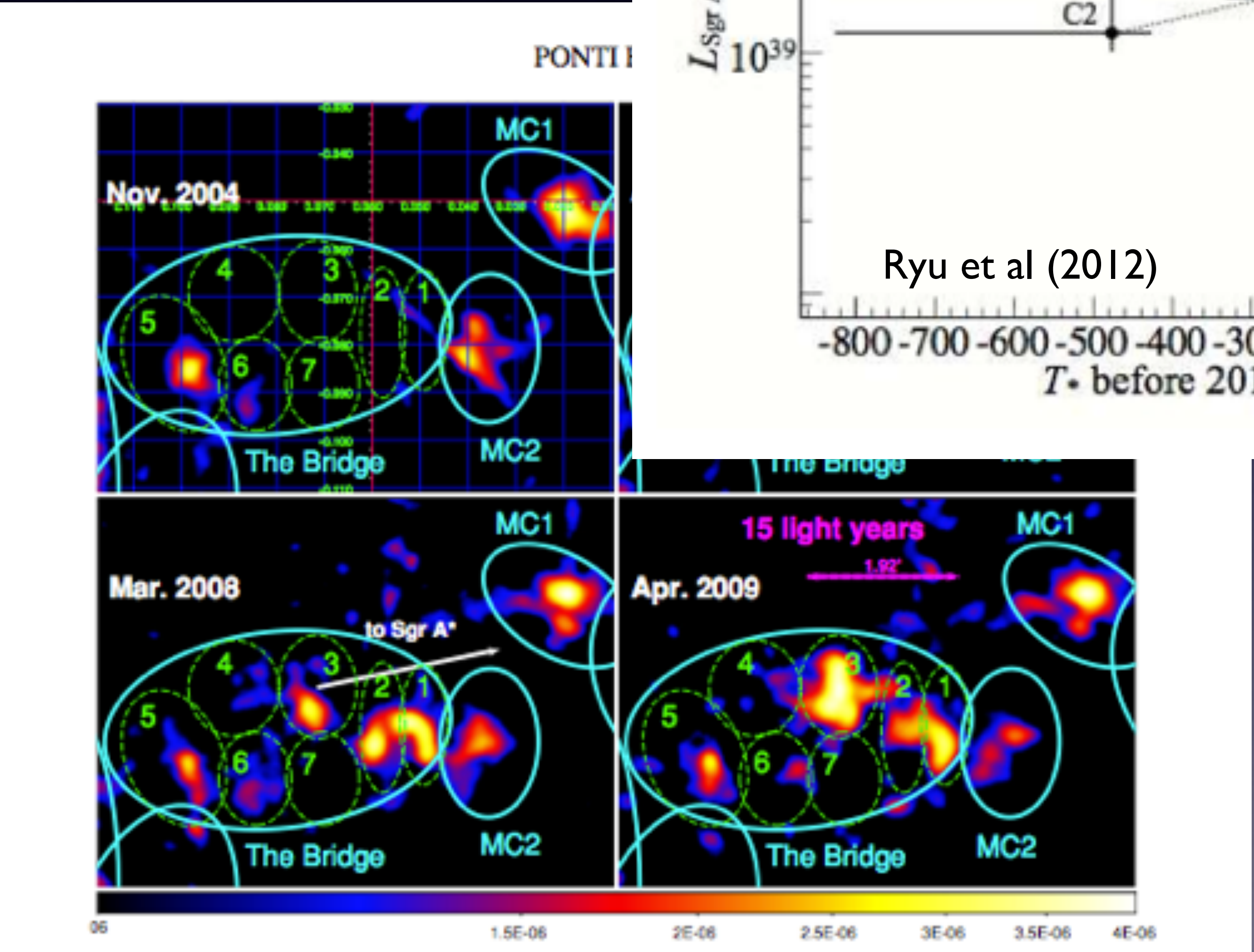
Bibliography

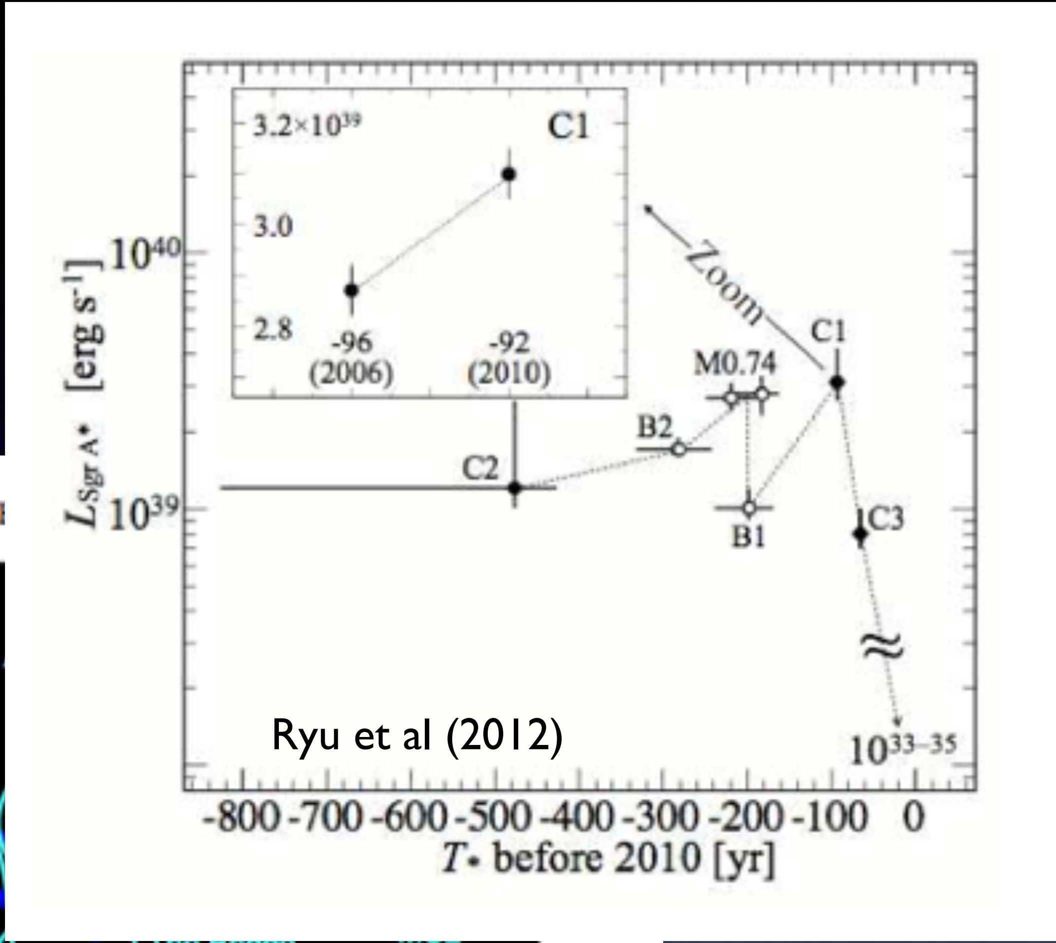
Bondi (1952) MNRAS 112, 195

Mestel (1954) MNRAS 114, 437

Hoyle and Littleton (1941) MNRAS 101,27

X-ray reflection shows past activity



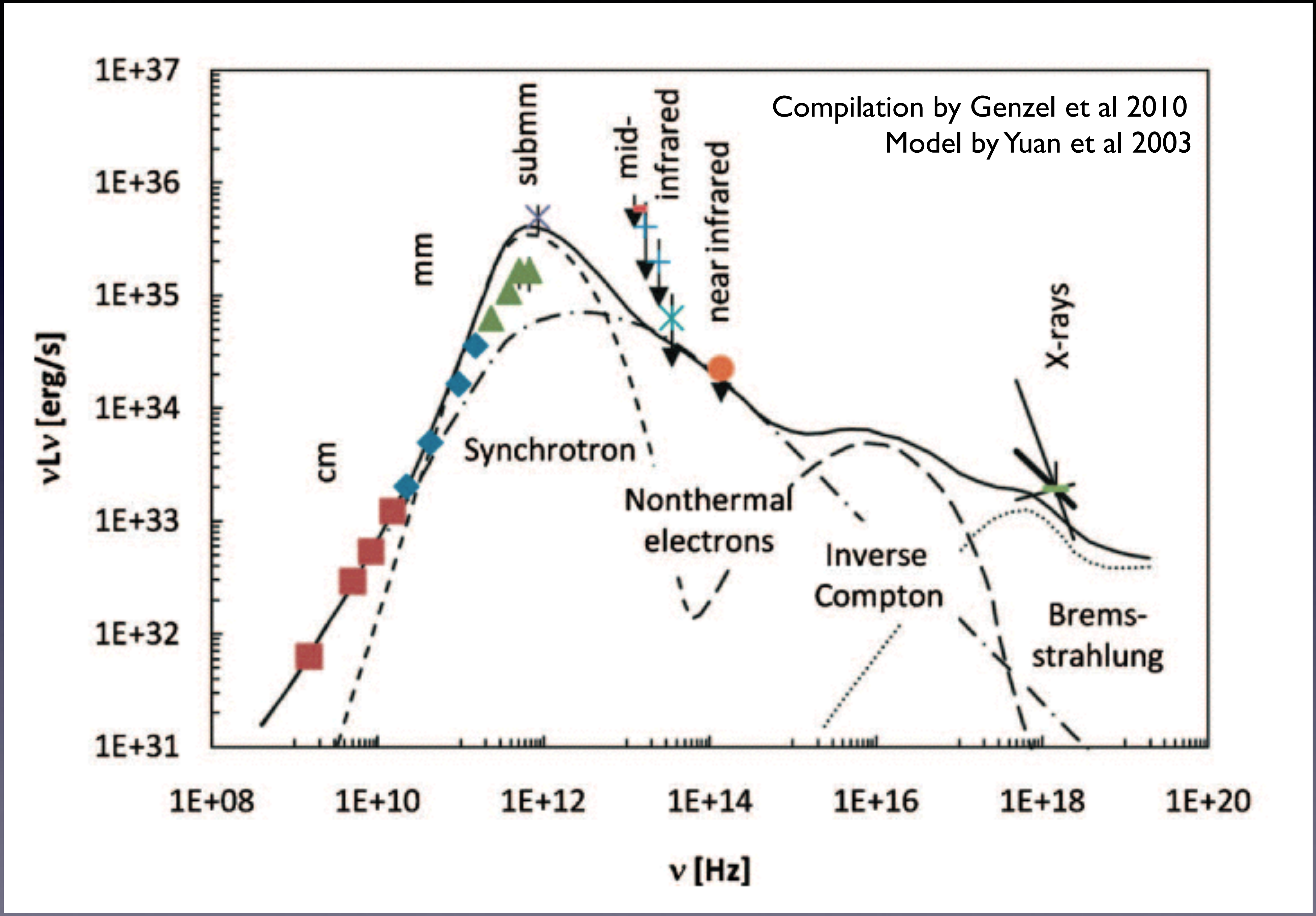


Accretion rates and luminosities

- Total available stellar winds:
  $\sim 10^{-3}$ M_{sun} / yr.
- Bondi estimate:
  $\sim 10^{-6}$ M_{sun} / yr ($L \sim 10^{40}$ erg / s).
- Observed luminosity:
  $L \sim 10^{35}$ erg / s ... maybe 10^{39} erg / s ?
- Eddington limit:
  $L \sim 10^{44}$ erg / s

Can we explain this?

Part of the solution:
"Radiatively inefficient accretion flows" (RIAF)



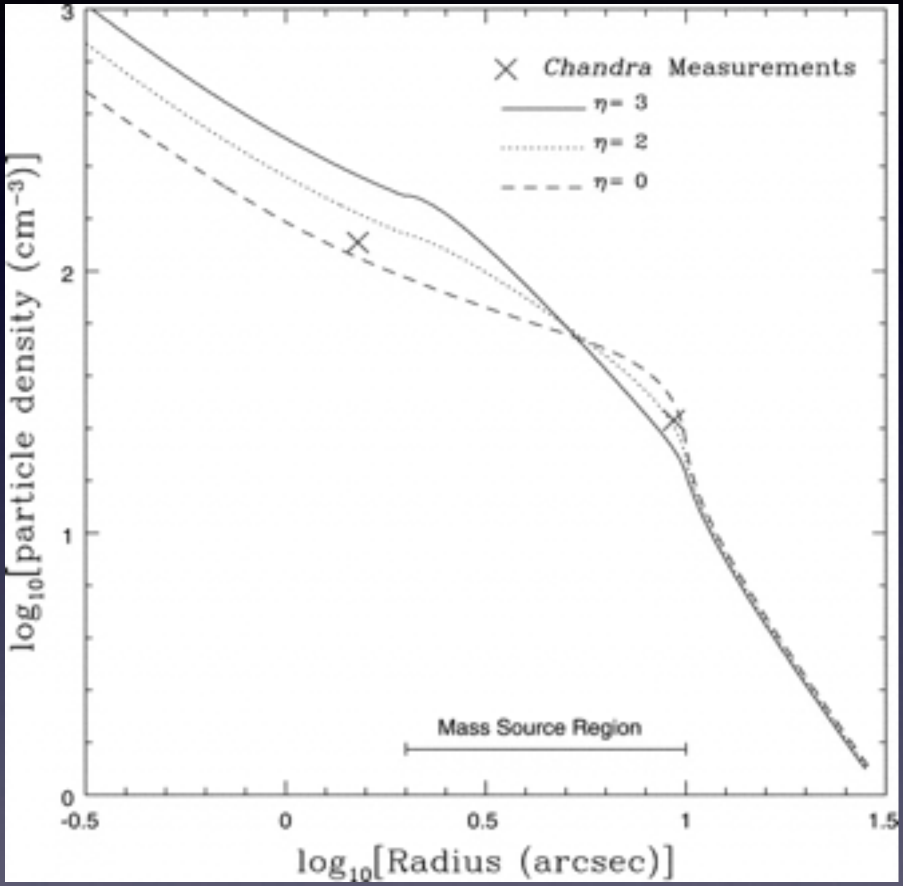
Modelling the gas dynamics

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r} r^2 \rho v = q(r), \qquad (1)$$

$$\rho \frac{dv}{dt} = -\frac{\partial p}{\partial r} - \rho \frac{GM}{r^2} - q(r) v, \qquad (2)$$

and

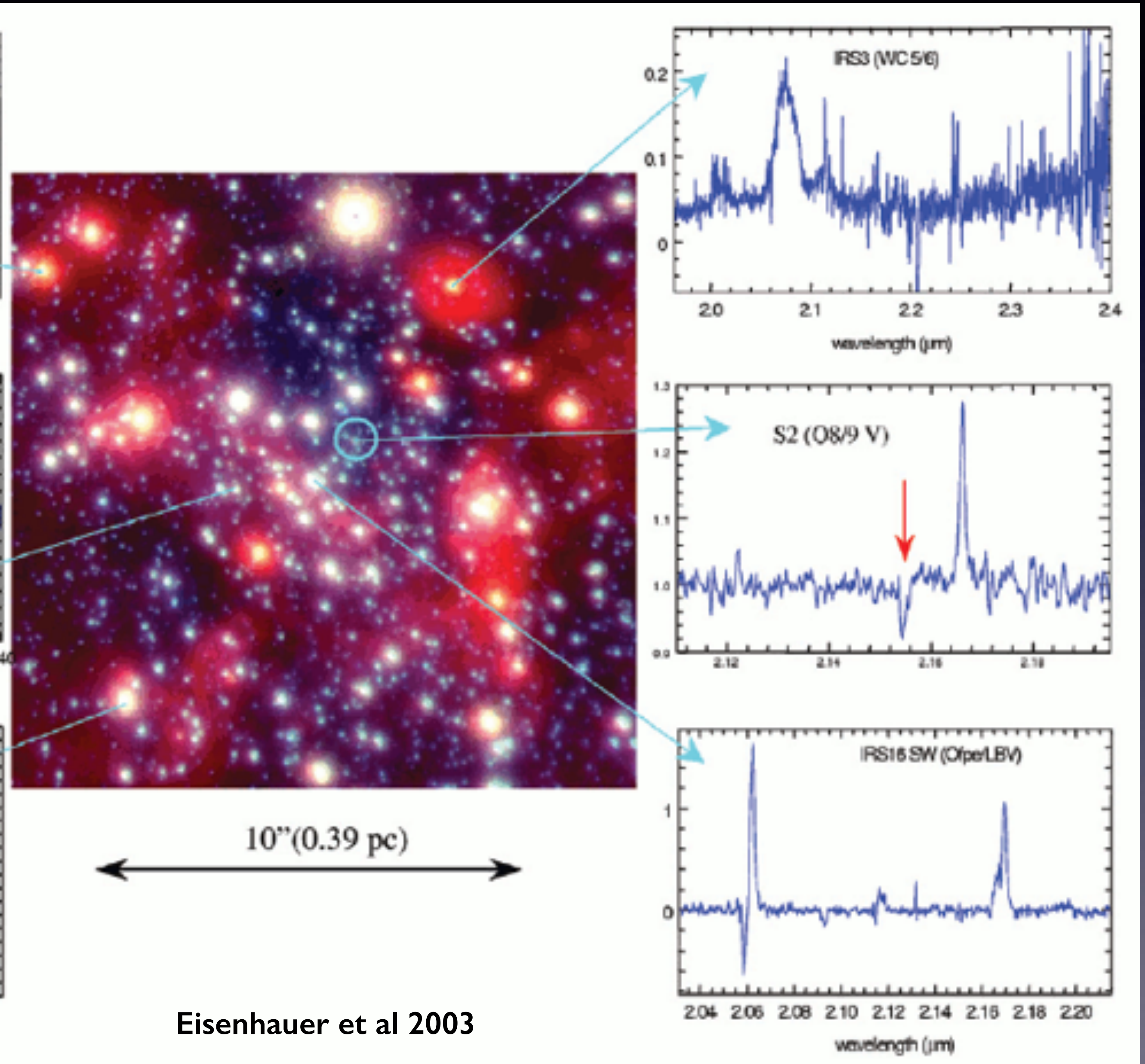
$$\rho T \frac{ds}{dt} = q(r)\left[\frac{v^2}{2} + \frac{v_w^2}{2} - \frac{\gamma}{\gamma - 1} c_s^2\right], \qquad (3)$$



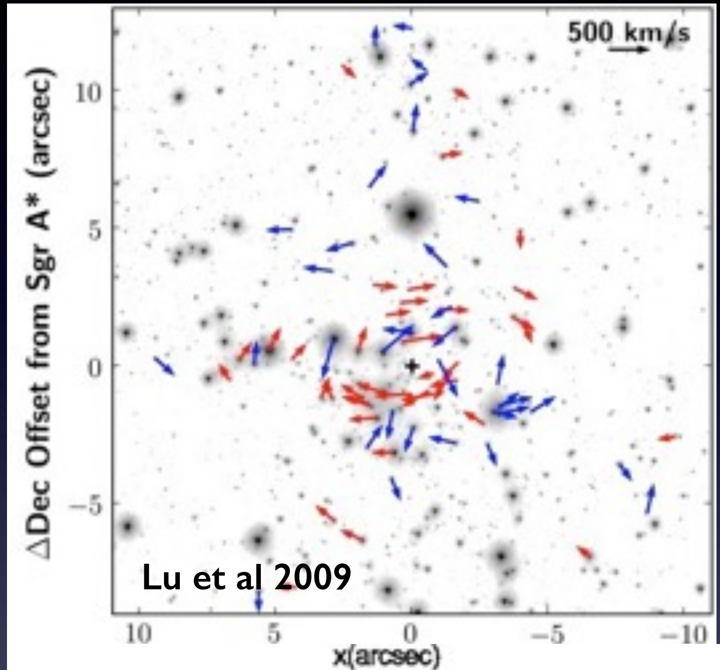
Analytical model including source (winds) reproduces Bondi rate (Quataert 04).

Can we learn more from simulations?

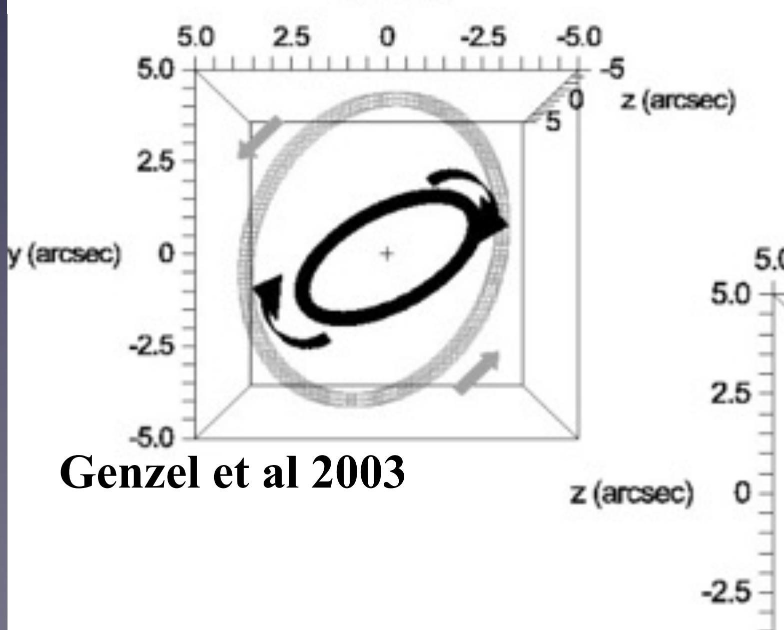
Data available: stellar spectra and dynamics



Eisenhauer et al 2003



Lu et al 2009



Genzel et al 2003

Simulating the Galactic Centre Winds

- Use 30 Wolf-Rayet stars as gas sources.

(Paumard et al 2006)

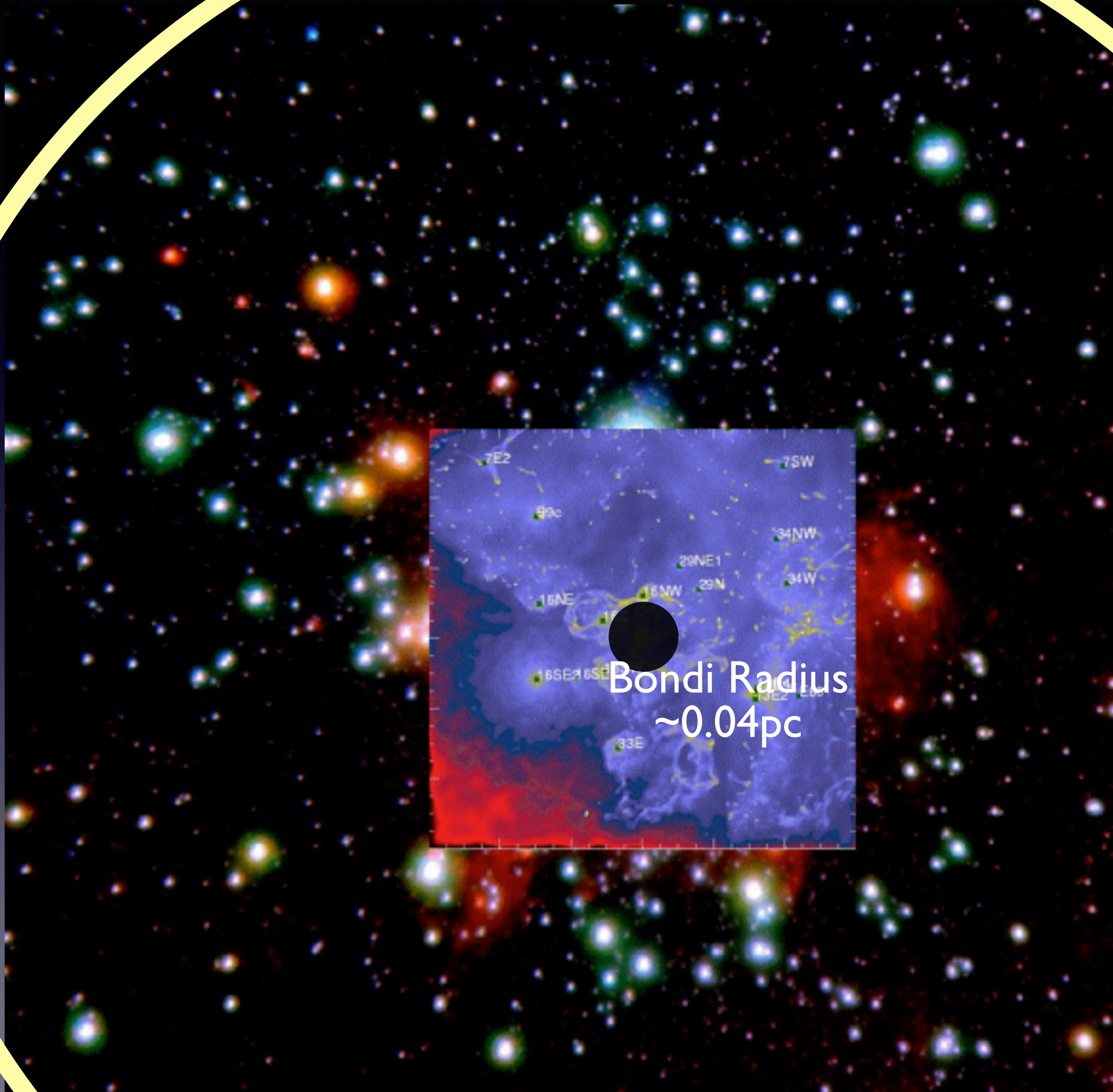
– Measured 2d positions and 3d velocities.
- Different assumptions for the 3d positions.

– Stellar wind properties measured for many of the stars.

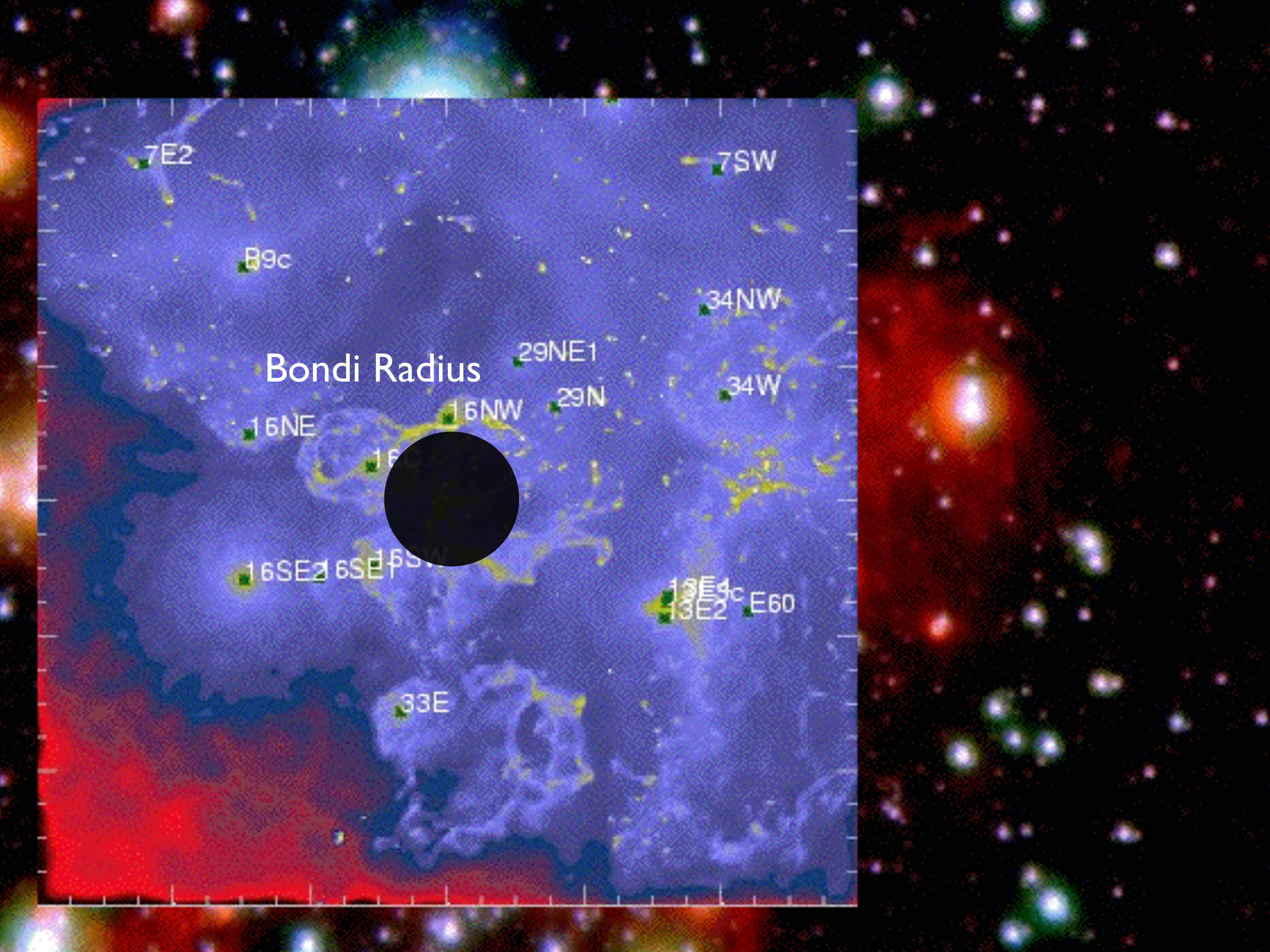
(Paumard et al 2001, Martins et al 2007)
- Typical mass loss rates ~ 10^{-5} M_{Sun} / yr .
- Typical wind velocities ~ 600 - 2000 km/s (cooling can be important).

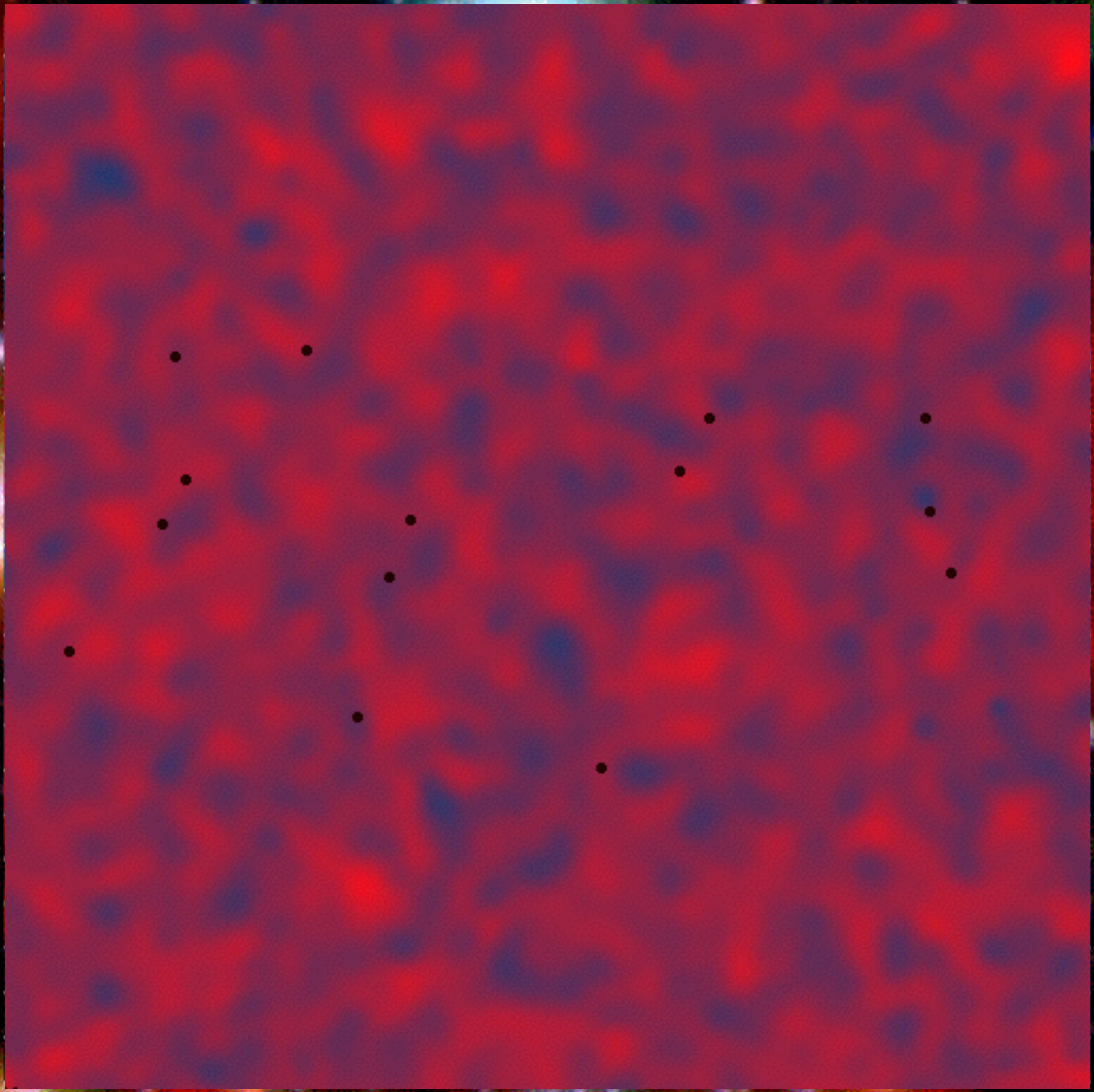
– Start the simulations ~1200 yr ago and let it evolve until the present time.

(Cuadra, Nayakshin, et al 2005, 2006, 2008, 2015)



Simulated region
R~1pc


Bondi Radius
7E2
7SW
B9c
34NW
29NE1
34W
29N
16NW
16NE
16SE2
16SE1
13E2
E60
33E

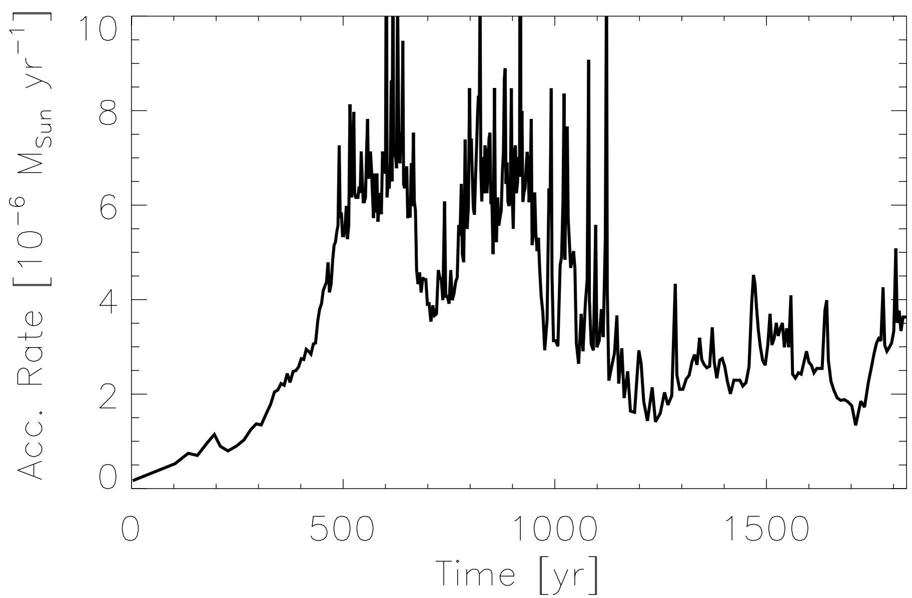


Cooling instabilities drive clump formation.
(e.g., Vishniac 1994, Burkert & Lin 2000, Calderón et al 2015)

Many clumps form; a few in radial orbits produce a variable accretion rate.

Possible origin for G2. (Gillessen+ '12,'13)

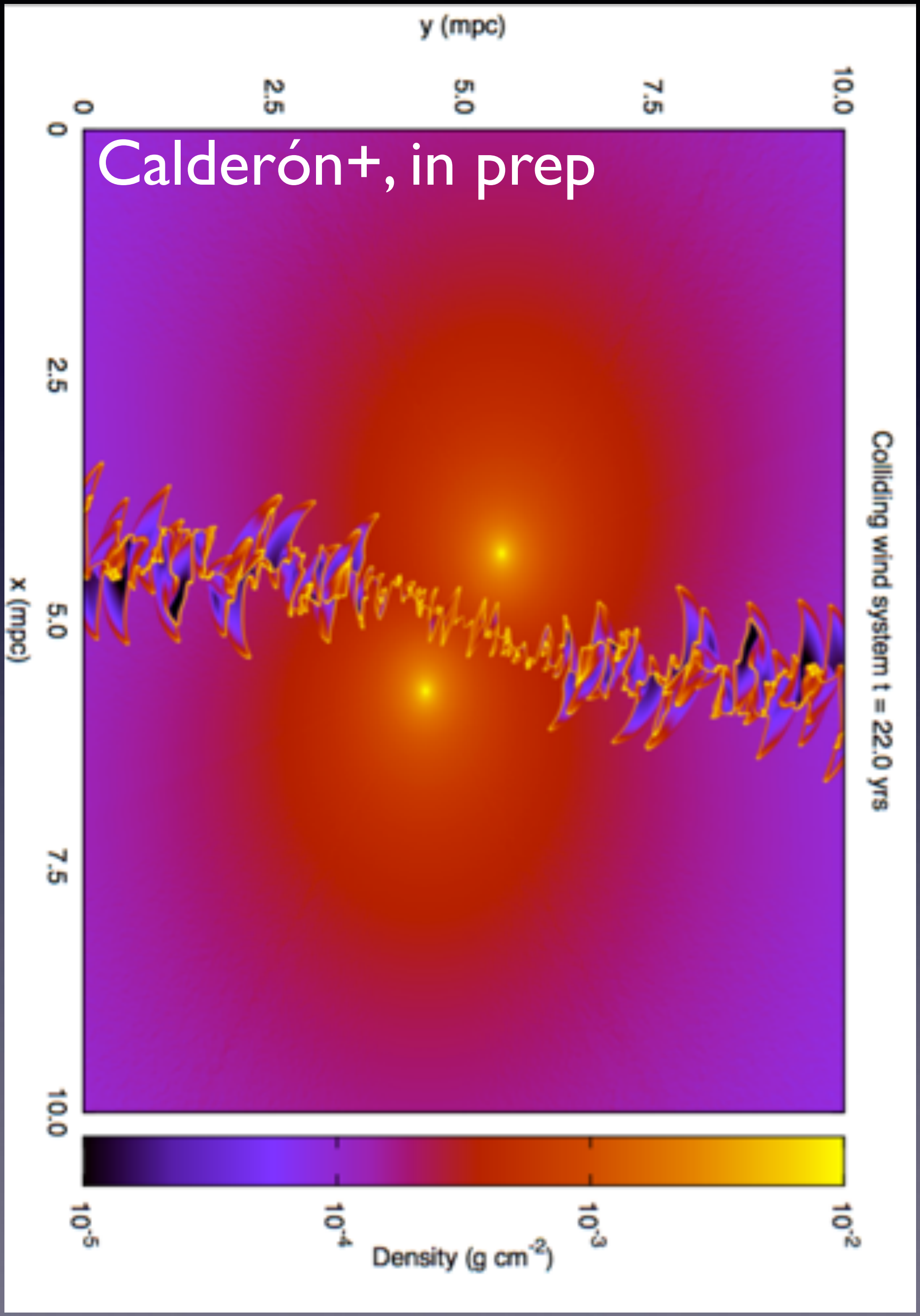
(Cuadra, Nayakshin, et al 2005, 2006, 2008, 2015)



Accretion rate as a function of time, measured at R_{sink} ~< 0.1 R_{Bondi}.

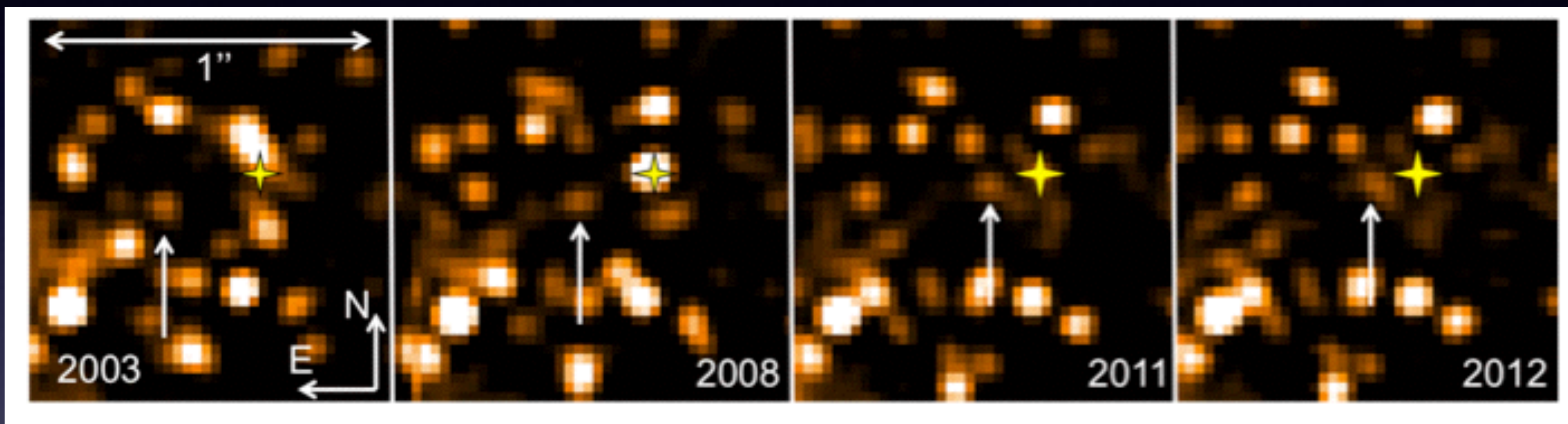
Clump formation in wind collision shocks

- Happens due to non-linear thin-shell instability.
  (Vishniac '94)
- However, analytical models show is not as effective as it appears from SPH simulations.
  (Calderón, Ballone, Cuadra+'15)
- Currently working on AMR models.



Discovery of an infalling cloud

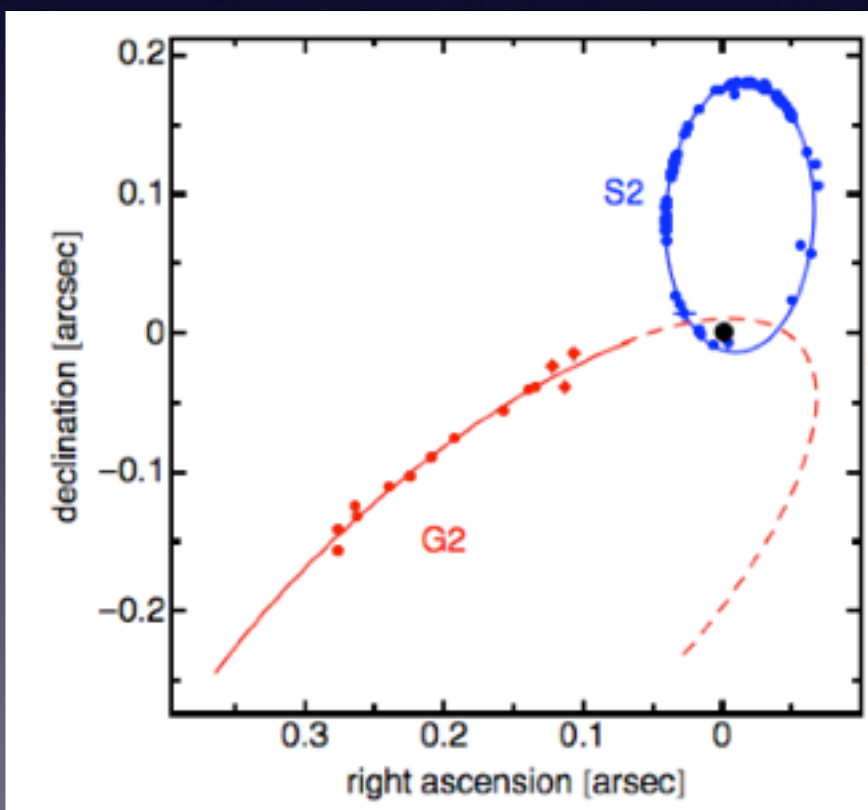
Gillessen et al 2012, '13

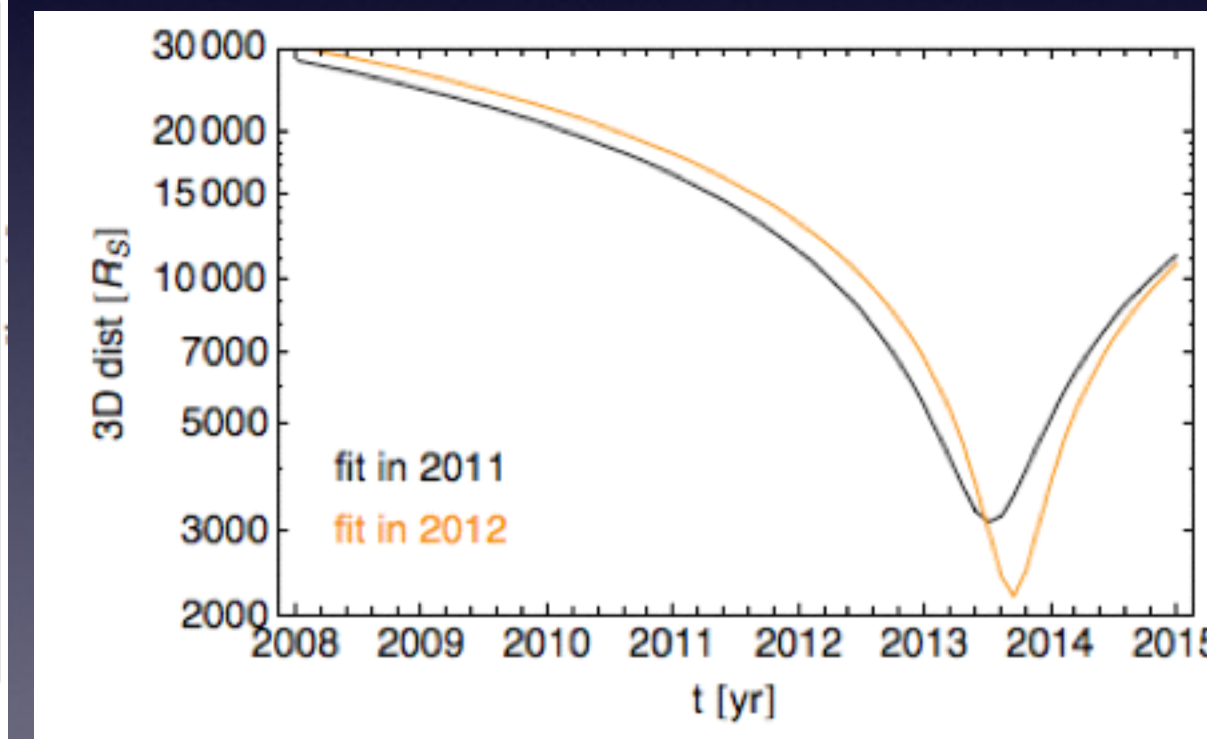


- VLT infrared observations (NACO and SINFONI)
- Mass ~ 3 M_{Earth}.

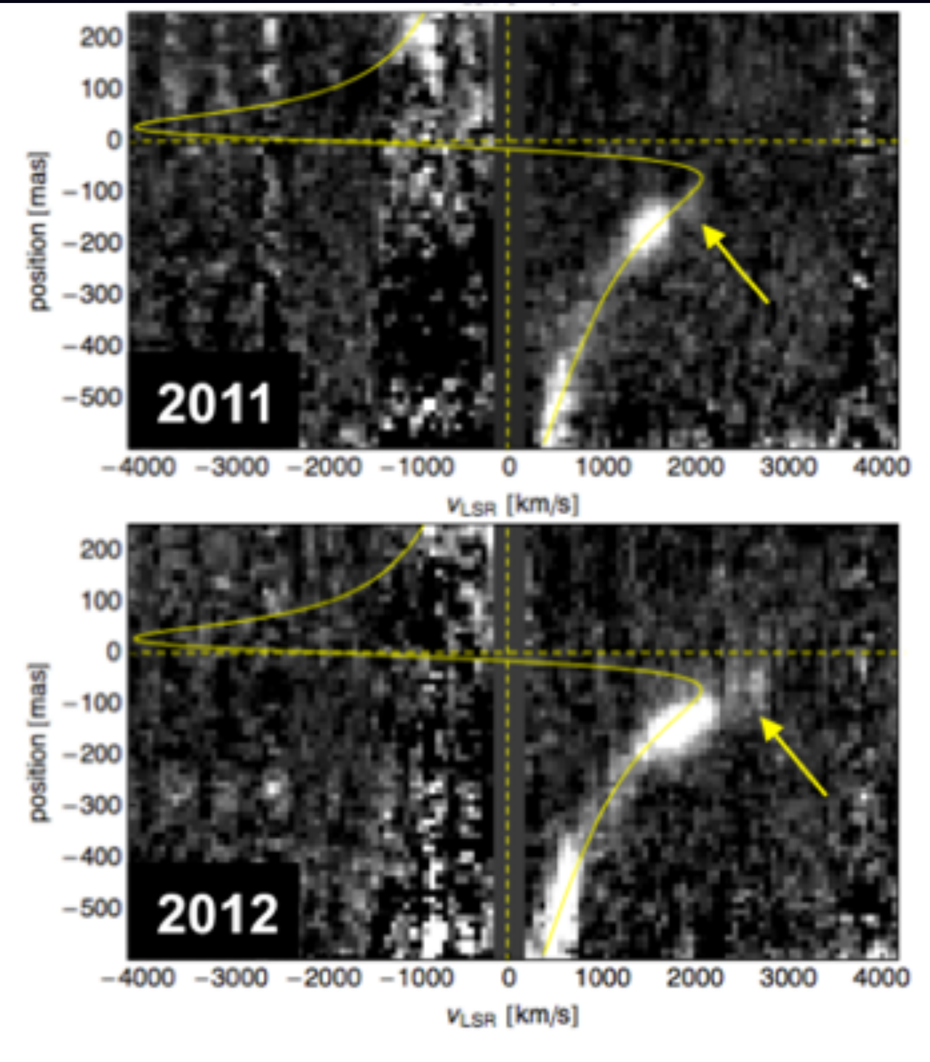
Very eccentric orbit

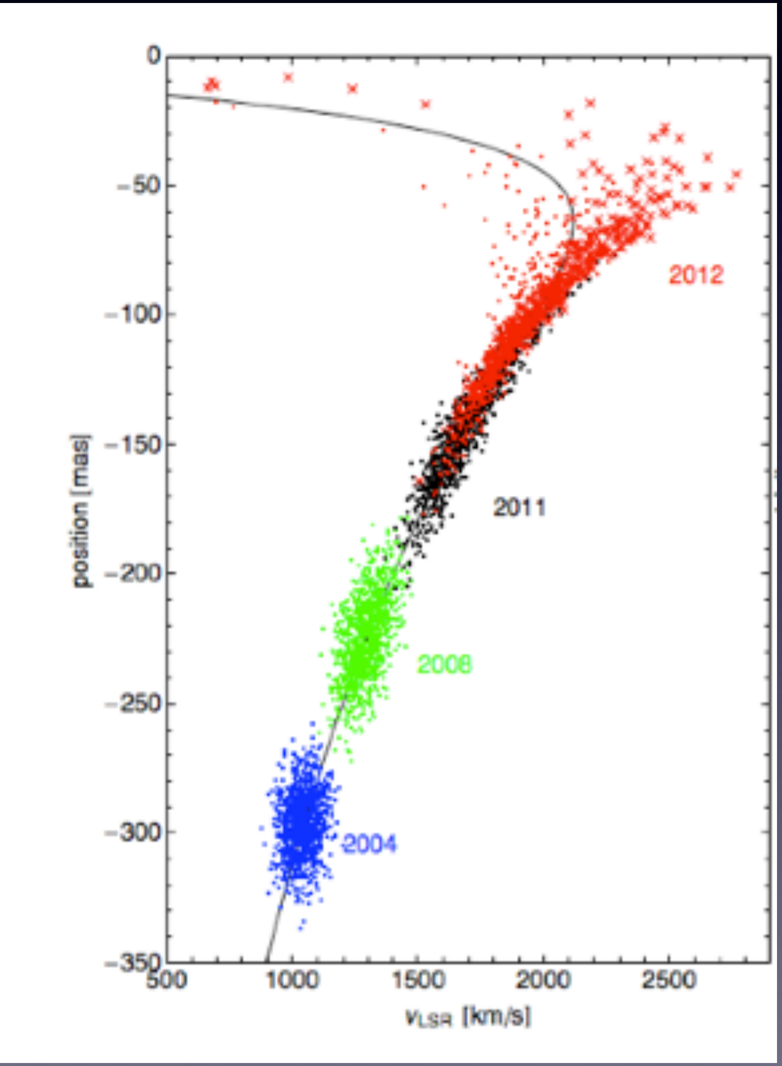
Got within ~2000 R_{Sch} of the black hole by ~~the end of 2013~~ ~march 2014.





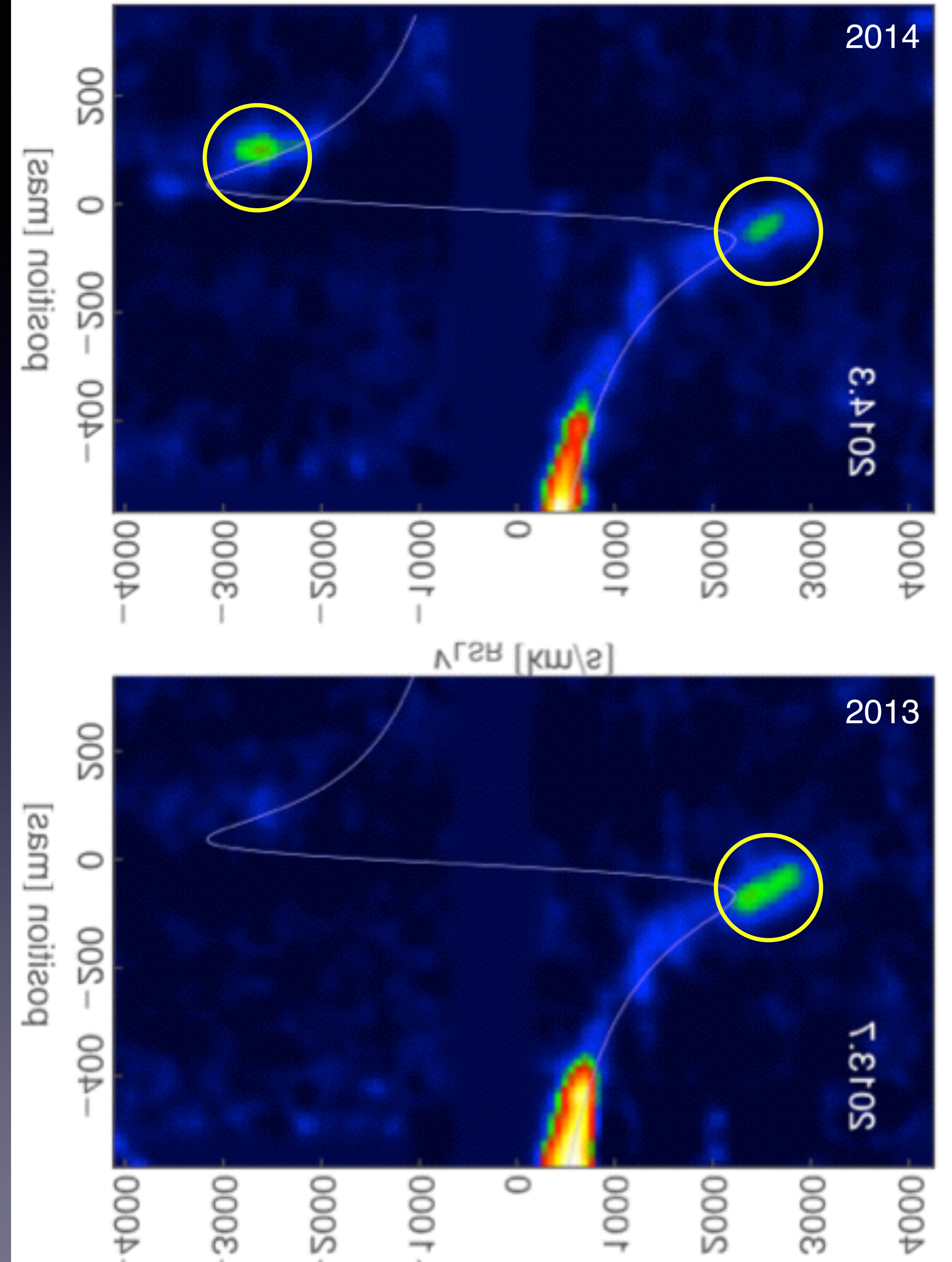
Tidal stretching detected: it must be a cloud!





2014: observed pericentre passage

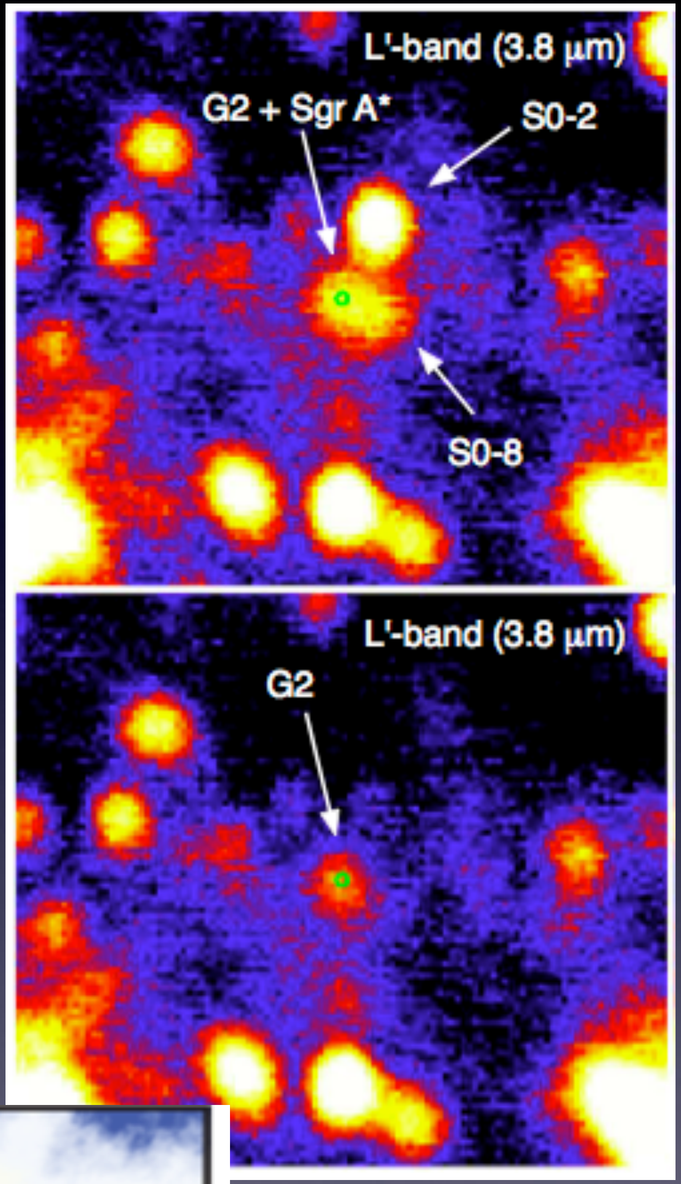
(Pfuhl+ 2014)



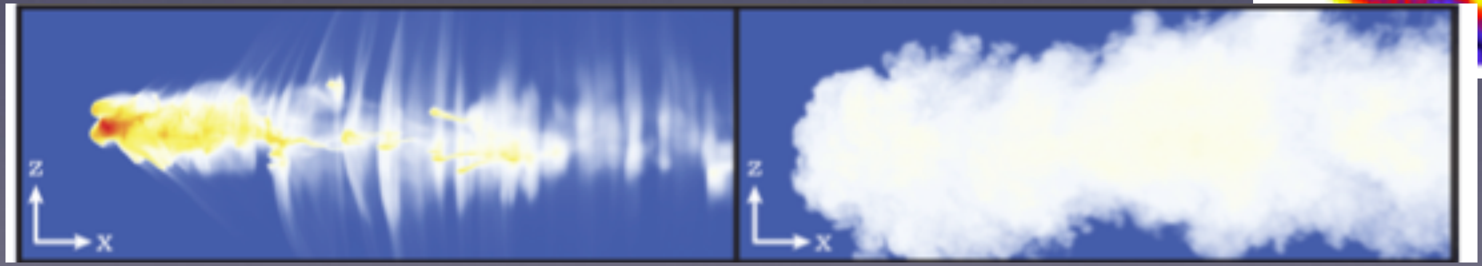
Other groups, however, don't detect extended emission in 2014 (Witzel+, Valencia+).

G2 would have survived intact.

It means either G2 is bound by a star (Murray-Clay & Loeb '12, Scoville & Burkert '13, Ballone+'13, etc), or disruption is avoided by magnetic field (McCourt+'15).



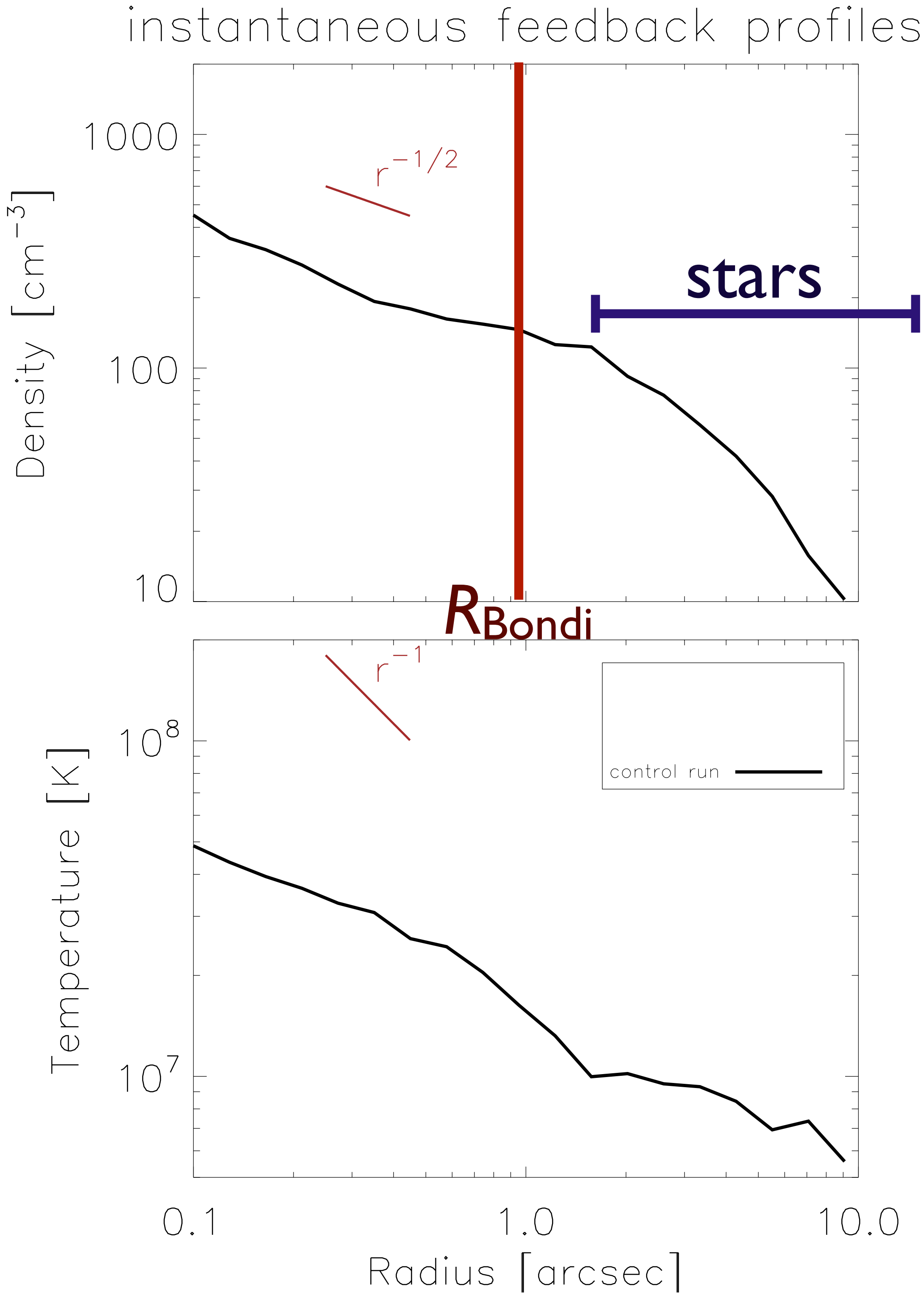
Witzel+'14



McCourt+'15

Institute of Astrophysics, PUC, Santiago, Chile

- Research: from exoplanets to stars, compact objects, globular clusters, galaxies, AGN, clusters & large-scale structure, CMB
- International, active scientific environment
- Preferential access to telescopes in Chile
- In-house computer clusters
- 14 faculty, ~40 postdocs, ~40 grad students
- Grad school applications every May and November
- National postdoc "Fondecyt" fellowships every May



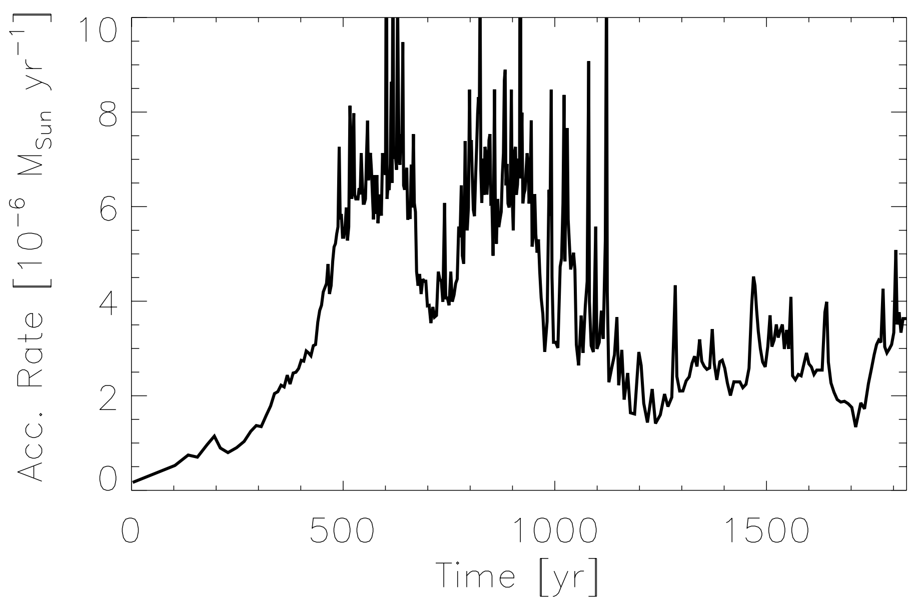
Temperature profiles from simulations and observations (Wang+'13) don't match very well…

Adding an Outflow from Sgr A*

- From simulations and x-ray observations, we know accretion at Bondi radius $\sim 10^{-5\text{–}6}$ M_{sun}/yr.
  (e.g., Baganoff et al 2003)
- Faraday rotation measurements imply accretion close to horizon $\sim 10^{-7\text{–}9}$ M_{sun}/yr.
  (e.g., Marrone et al 2007)
- => Majority of captured gas must outflow!
- RIAF have hot, unbound particles
  => convection, outflows.
  (e.g., Blandford & Begelman ‘99; Narayan+ 2000; Quataert & Gruzinov 2000; Yuan’s talk)
- Recent X-ray observations also imply outflow.
  (Wang et al 2013)
- Infall of G2 => higher accretion, stronger outflow?
  (e.g., Gillessen+ 2012,13; Phifer+ 2013)

Instantaneous “mini-feedback” mode

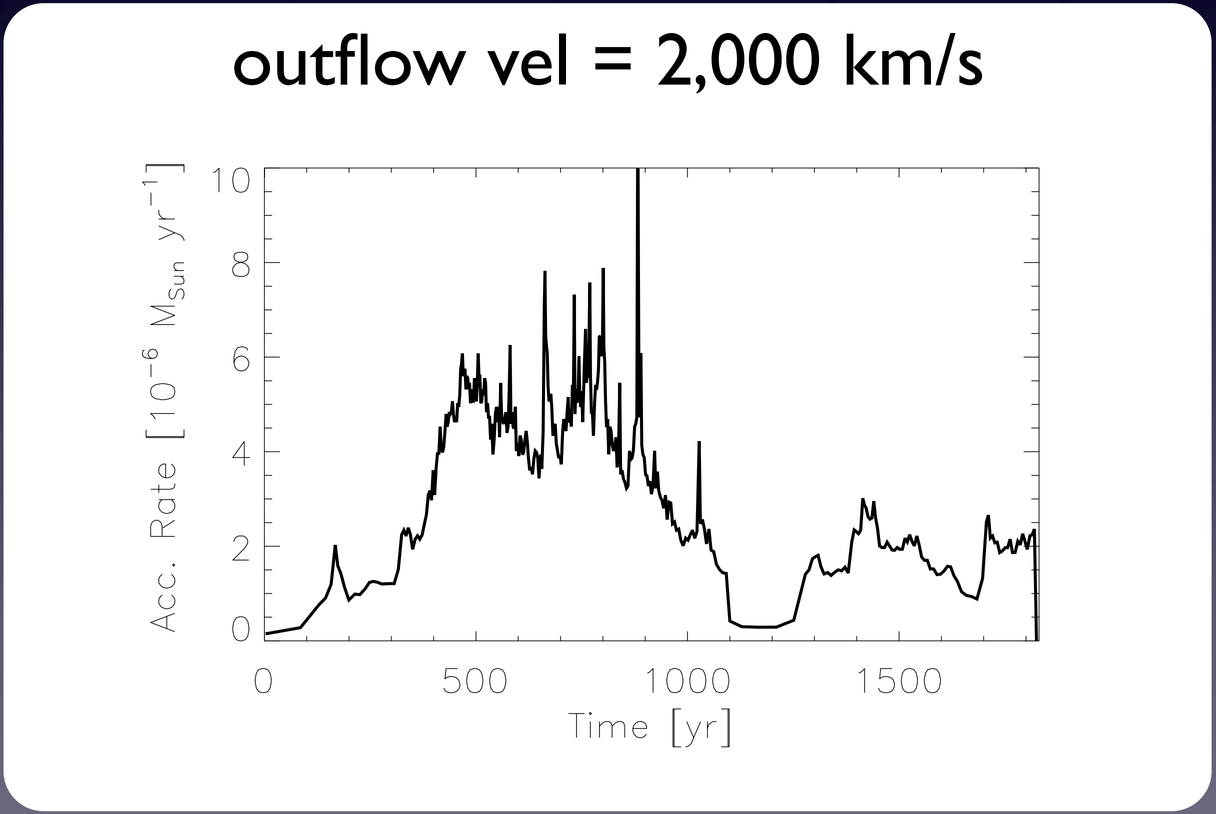
Control run, no outflow



Capture rate as a function of time.

Instantaneous "mini-feedback" mode

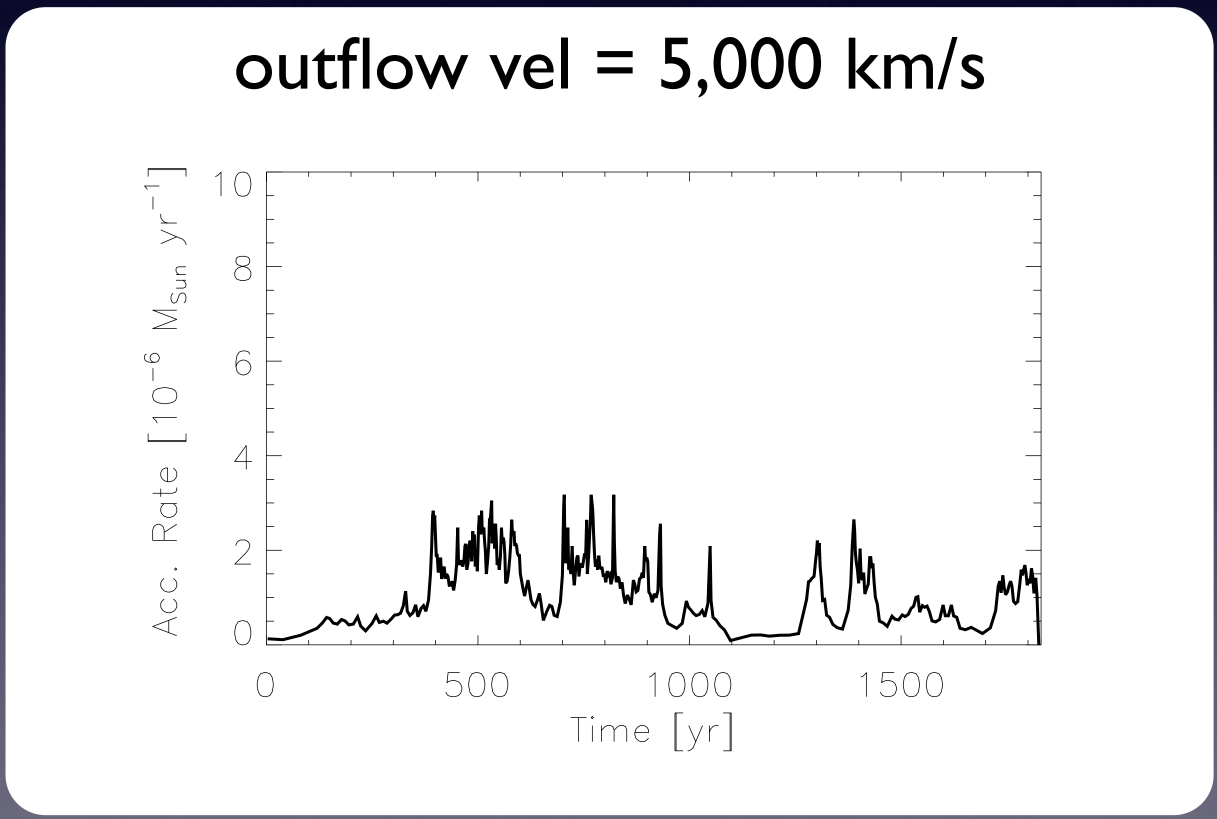
Expel captured mass as soon as it enters 0.1" ≈$10^4 R_{Sch}$.
Measure suppression of capture rate at that radius.



Capture rate as a function of time.

Instantaneous "mini-feedback" mode

Expel captured mass as soon as it enters 0.1" $\approx 10^4 R_{Sch}$.
Measure suppression of capture rate at that radius.



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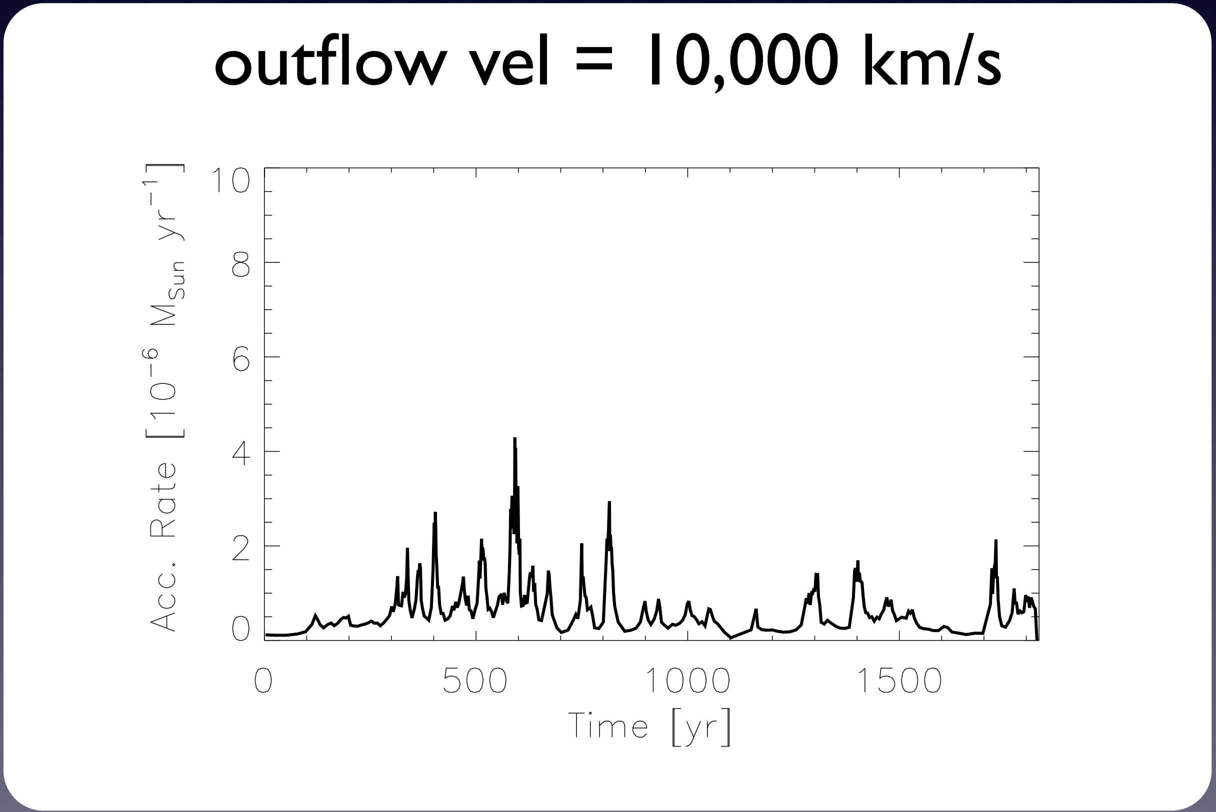
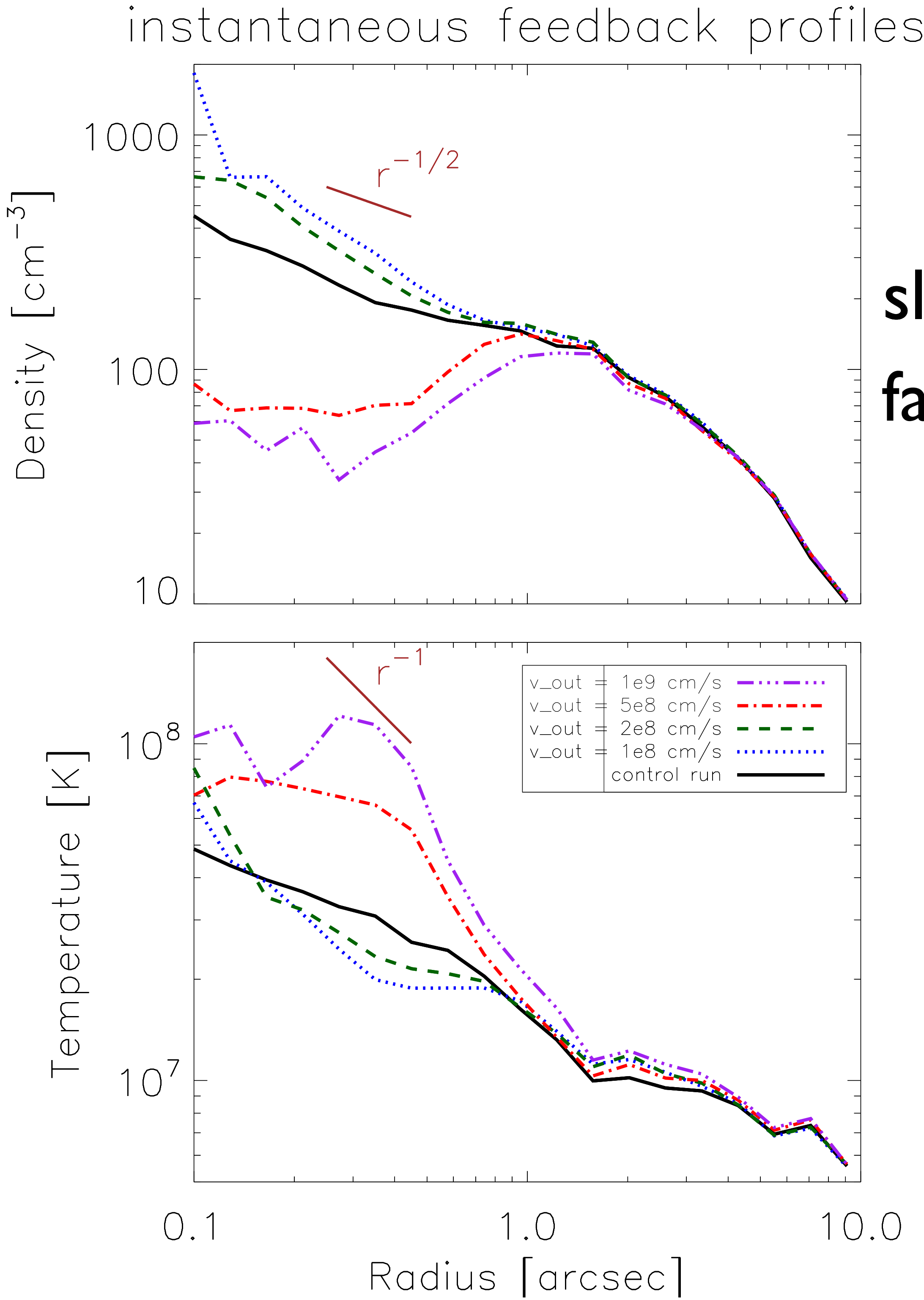


Capture rate as a function of time.



Control run, no outflow

slow outflow, 1000-2000 km/s

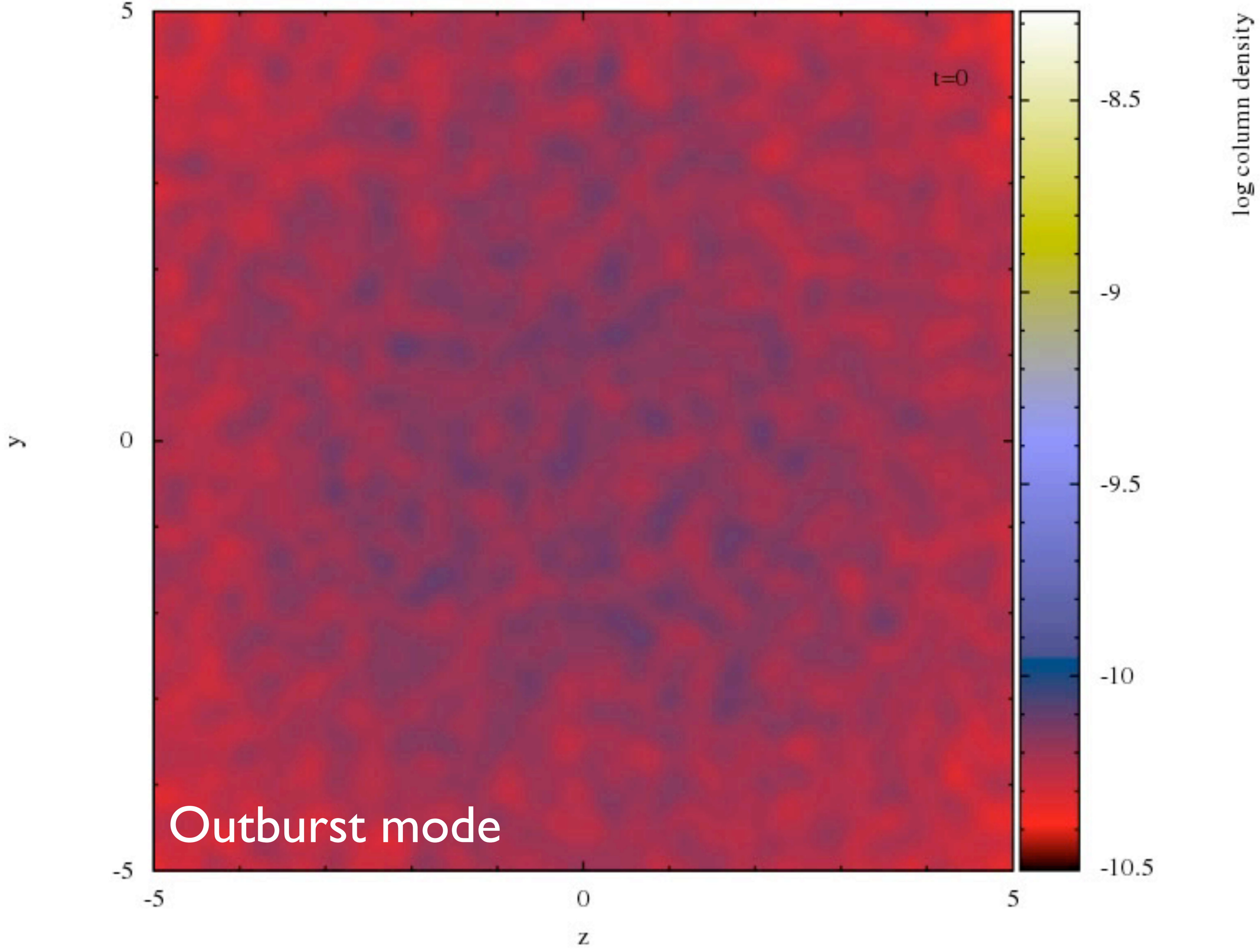
fast outflow, 5000-10000 km/s

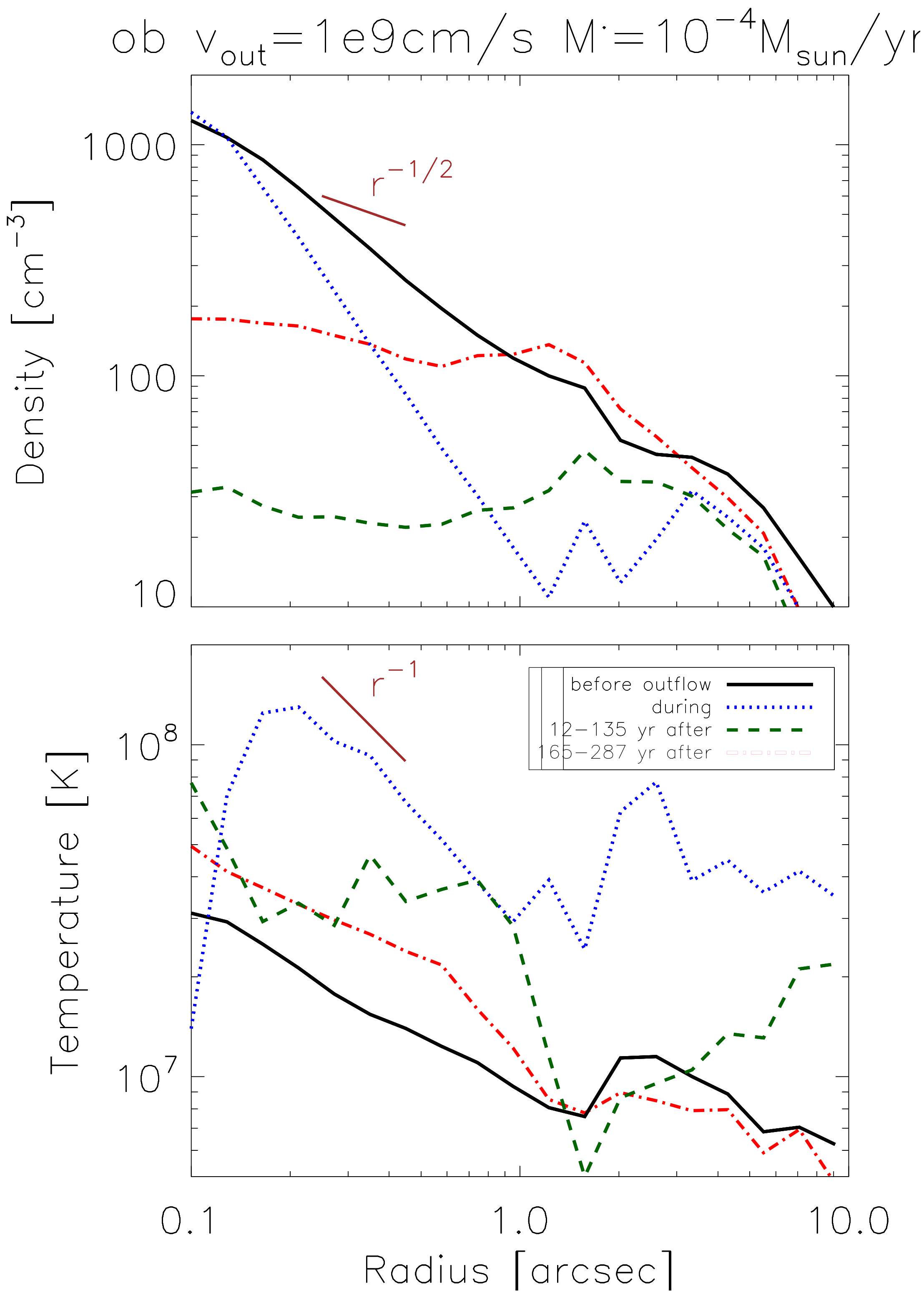
None seems to fit observational constraints.
(Wang+'13)

In any case, same physical conditions at Bondi radius give different capture rates there!

“Outburst” mode

- Sgr A* was more active in the past, as implied by X-ray echoes.
- Assume there was a relatively strong outflow, with mechanical power ~ 10^{39} erg/s.
- Have that outflow active for 300 yr and then turn it off.


t=0
Outburst mode
y
z
5
0
-5
-5
0
5
log column density
-8.5
-9
-9.5
-10
-10.5

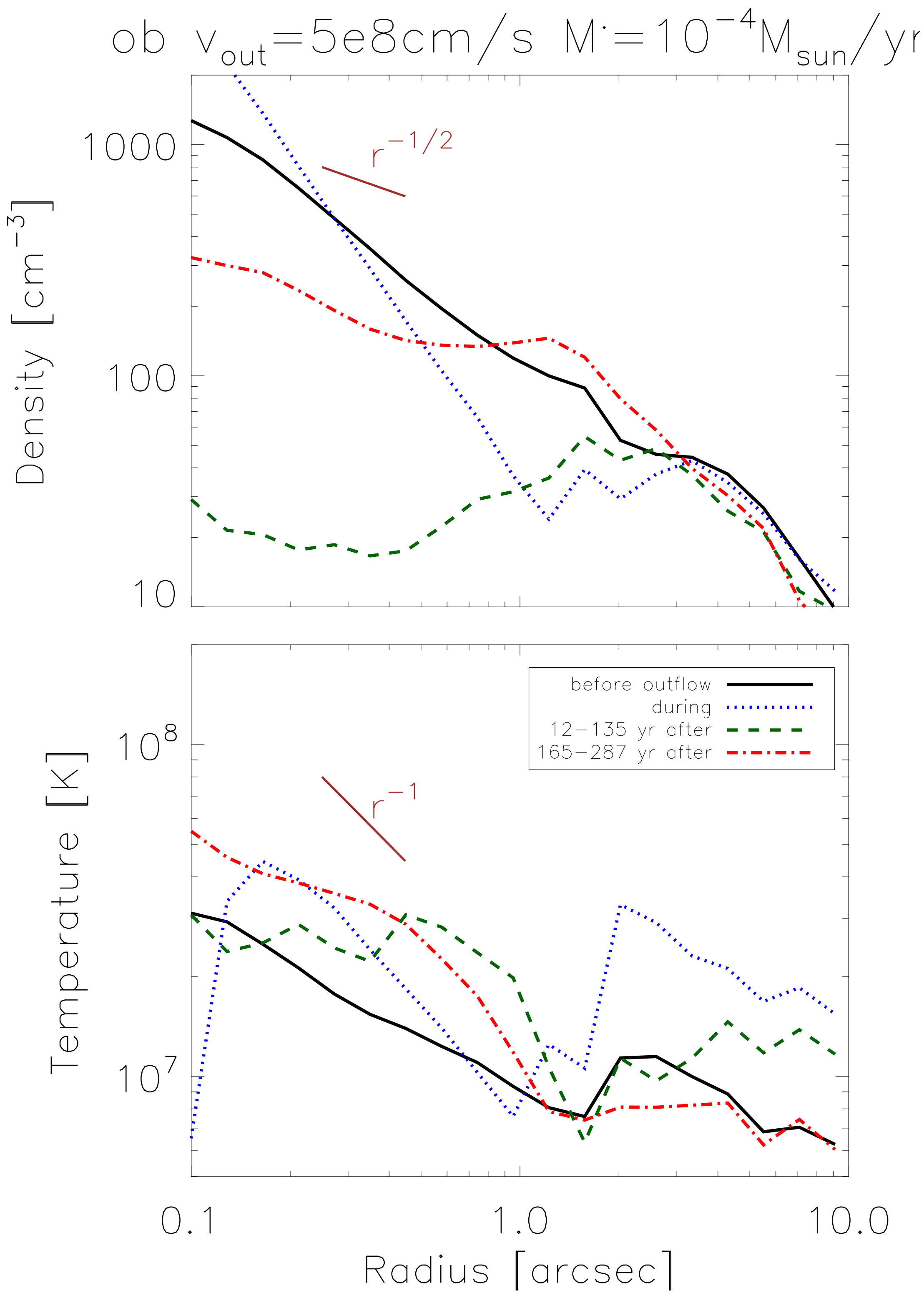


Outburst mode

vel = 10,000 km/s

dM/dt = 10^{-4} M_{sun}/yr

After ~200 yr density profiles still too flat.



Outburst mode
vel = 5,000 km/s
dM/dt = 10^{-4} M_{sun}/yr

This model seems to match better the constraints.

Notice Sgr A* would then still be "recovering" from past outflow.

Summary

- The Galactic centre provides a unique opportunity to model and observe the material feeding a SMBH.
- Models show that accretion rate is low, but variable at different time-scales.
- Formation and accretion of clumps. Related to G2?
- Outflows expected from SgrA* have impact on accretion and gas dynamics at Bondi radius and beyond.
- Observed X-ray emission consistent with strong outflow ($\dot{M}$~$10^{-4}M_{sun}$/yr, v~5000km/s → 10^{39}erg/s) ~200 yr ago, but not later.