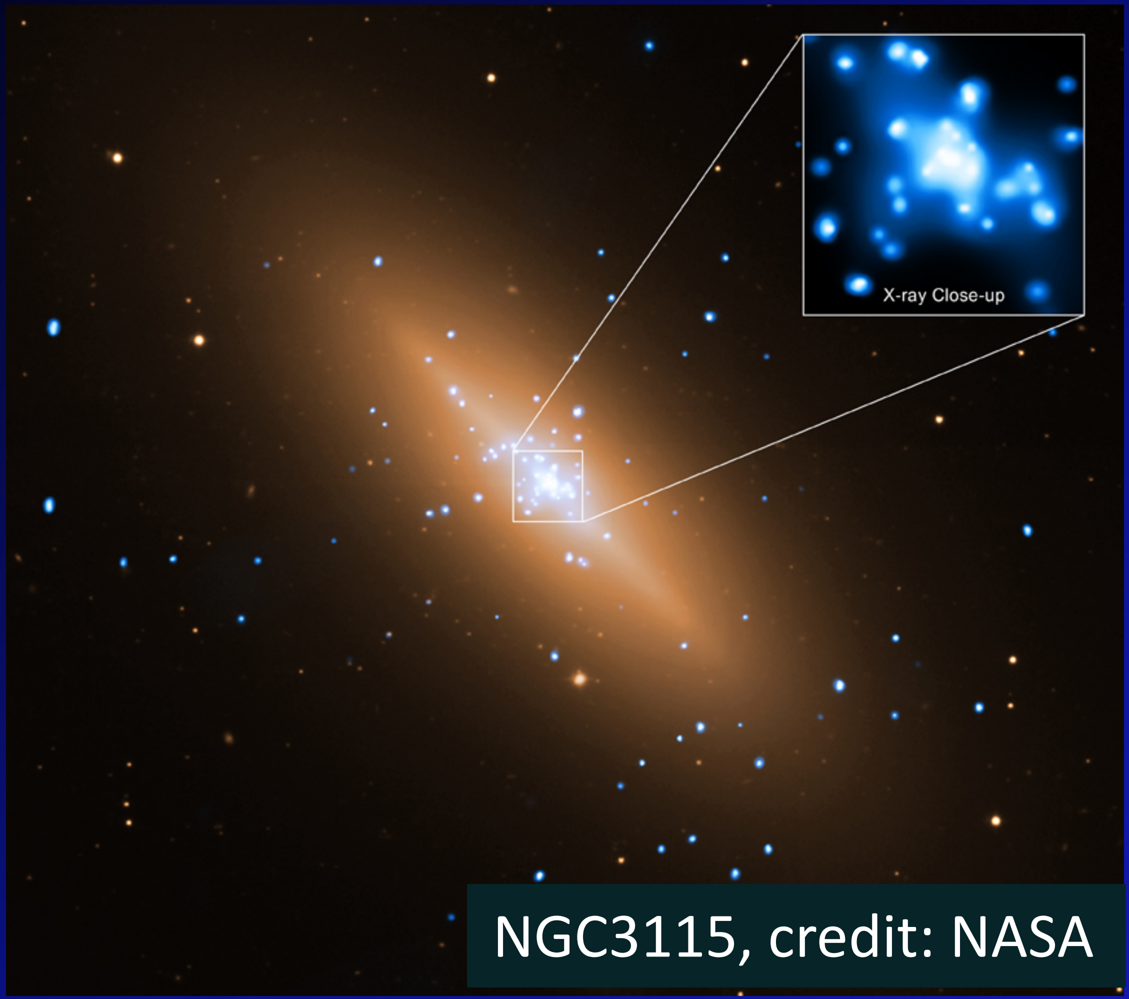
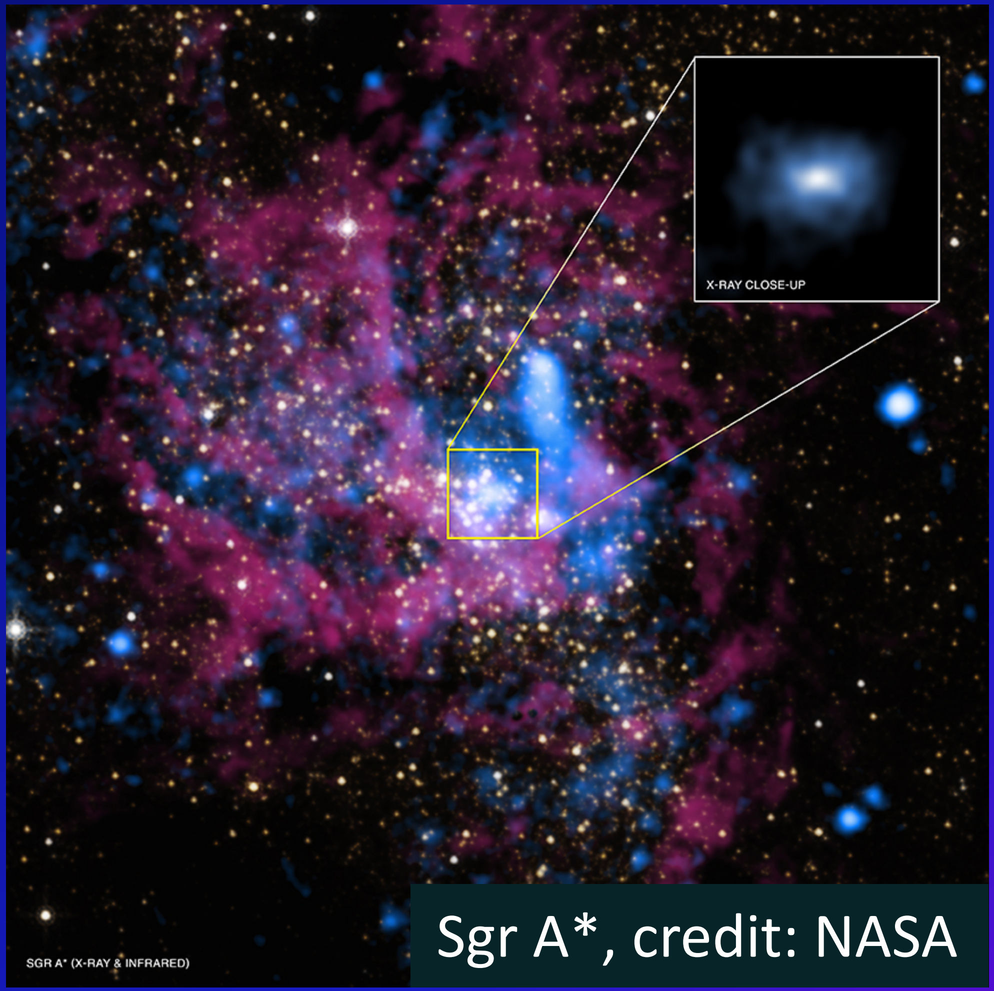
Feeding and Feedback in Nearby Low-Luminosity AGNs



NGC3115, credit: NASA



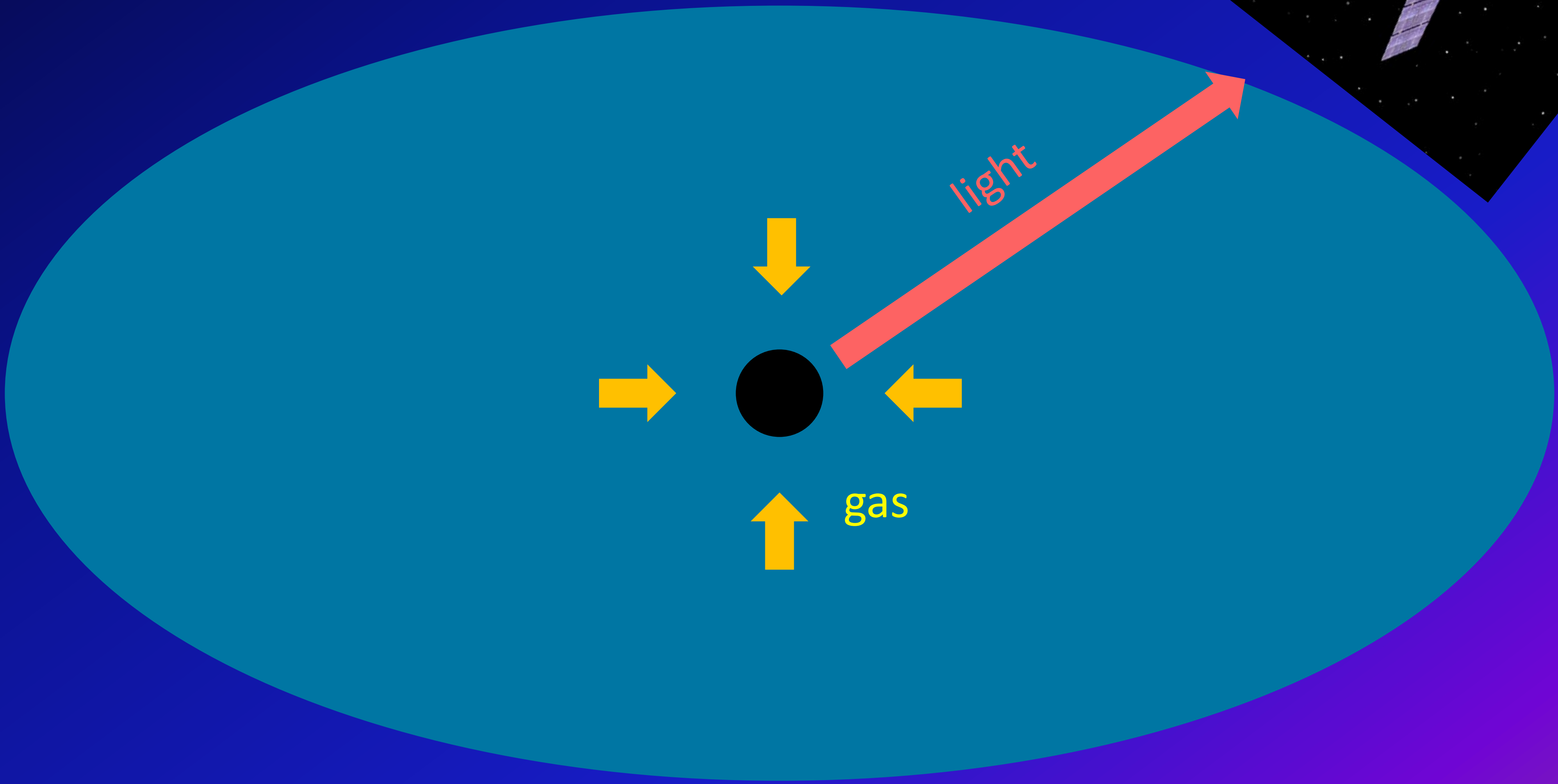
Sgr A*, credit: NASA

Roman Shcherbakov (University of Maryland, Hubble Fellow),
Ka-Wah Wong, Jimmy Irwin (University of Alabama),
Chris Reynolds (UMD), Fred Baganoff (MIT), Daniel Wang (UMass) etc.

UMass Colloquium
17 Oct 2013

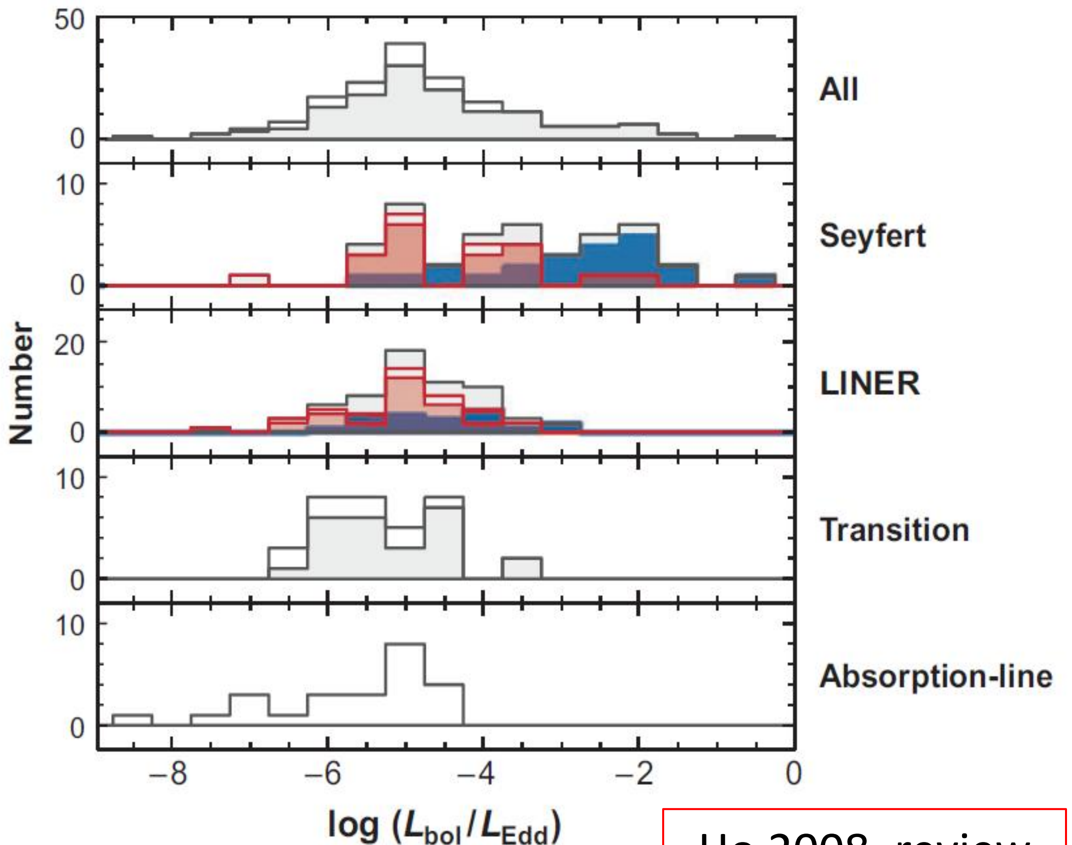
AGNs are powered by accretion onto SMBHs in galactic centers

AGN = active galactic nucleus
SMBH = supermassive black holes
Accretion = gas inflow



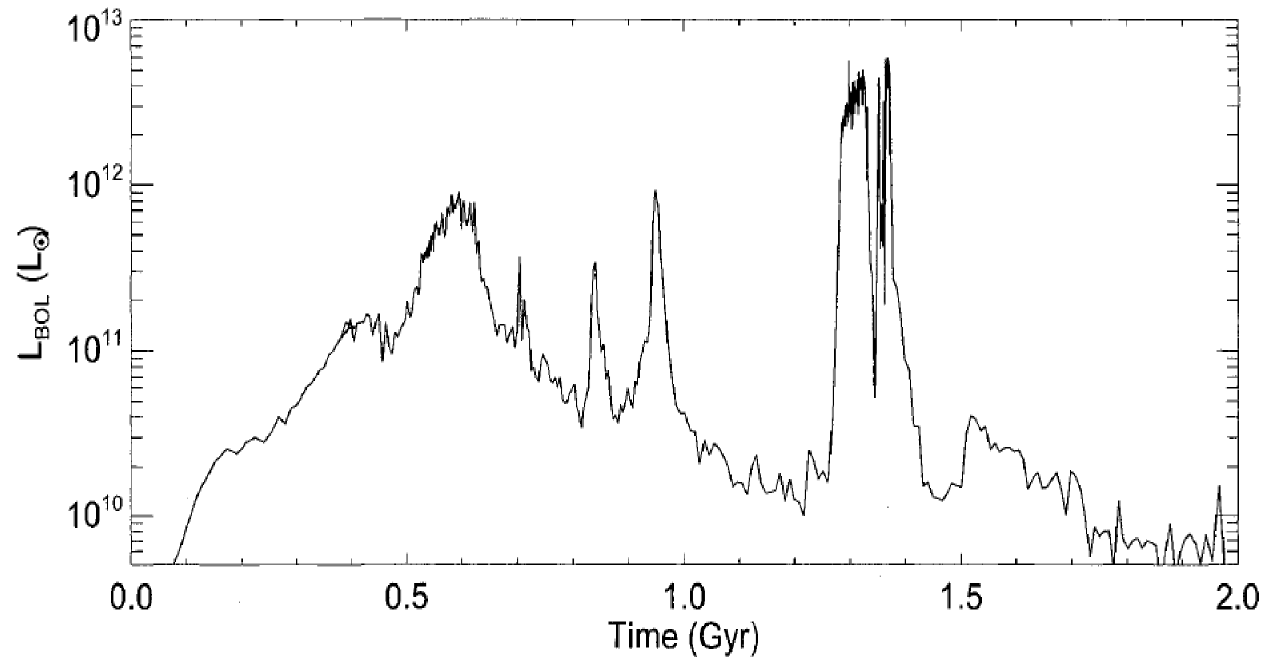
Typical AGN is not very active

Survey of nearby galactic nuclei



Ho 2008, review

Luminosity of a major galaxy merger



Hopkins 2008, thesis

L_{bol} – total luminosity

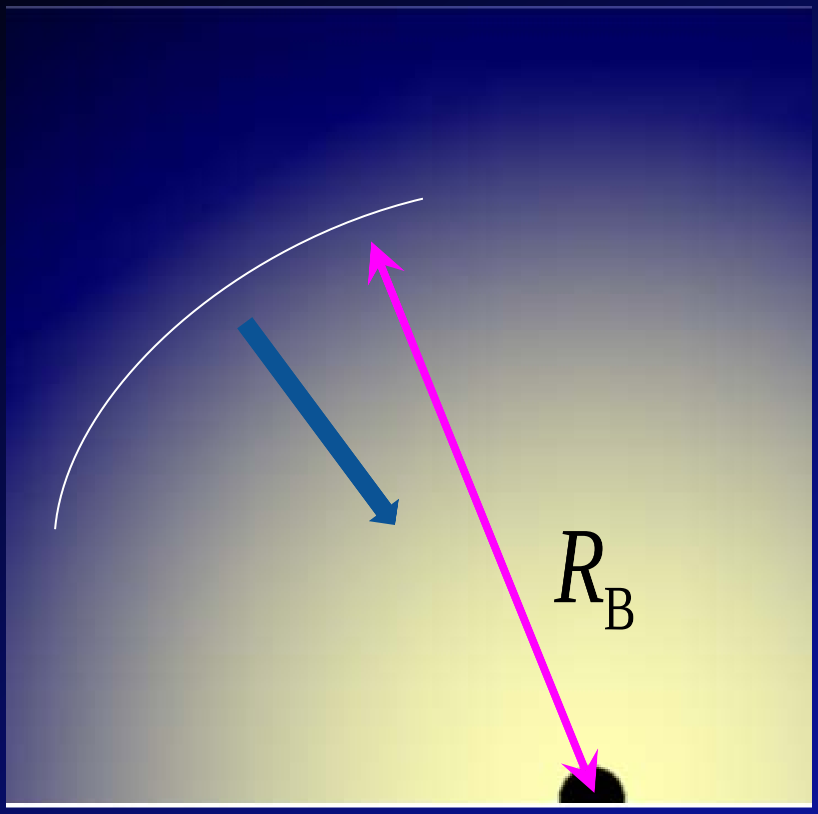
L_{Edd} – Eddington luminosity
(theoretical maximum AGN luminosity)

An AGN shines at Eddington luminosity for only a short time

Typical AGN has $L_{bol}/L_{edd} \sim 10^{-5}$, but lower L_{bol} objects may still be missed

To study common supermassive black holes (BH) and environments = to study low-luminosity AGNs

Region of black hole influence



Bondi radius R_B – radius of BH gravitational influence, where thermal energy of particle ~ gravitational energy

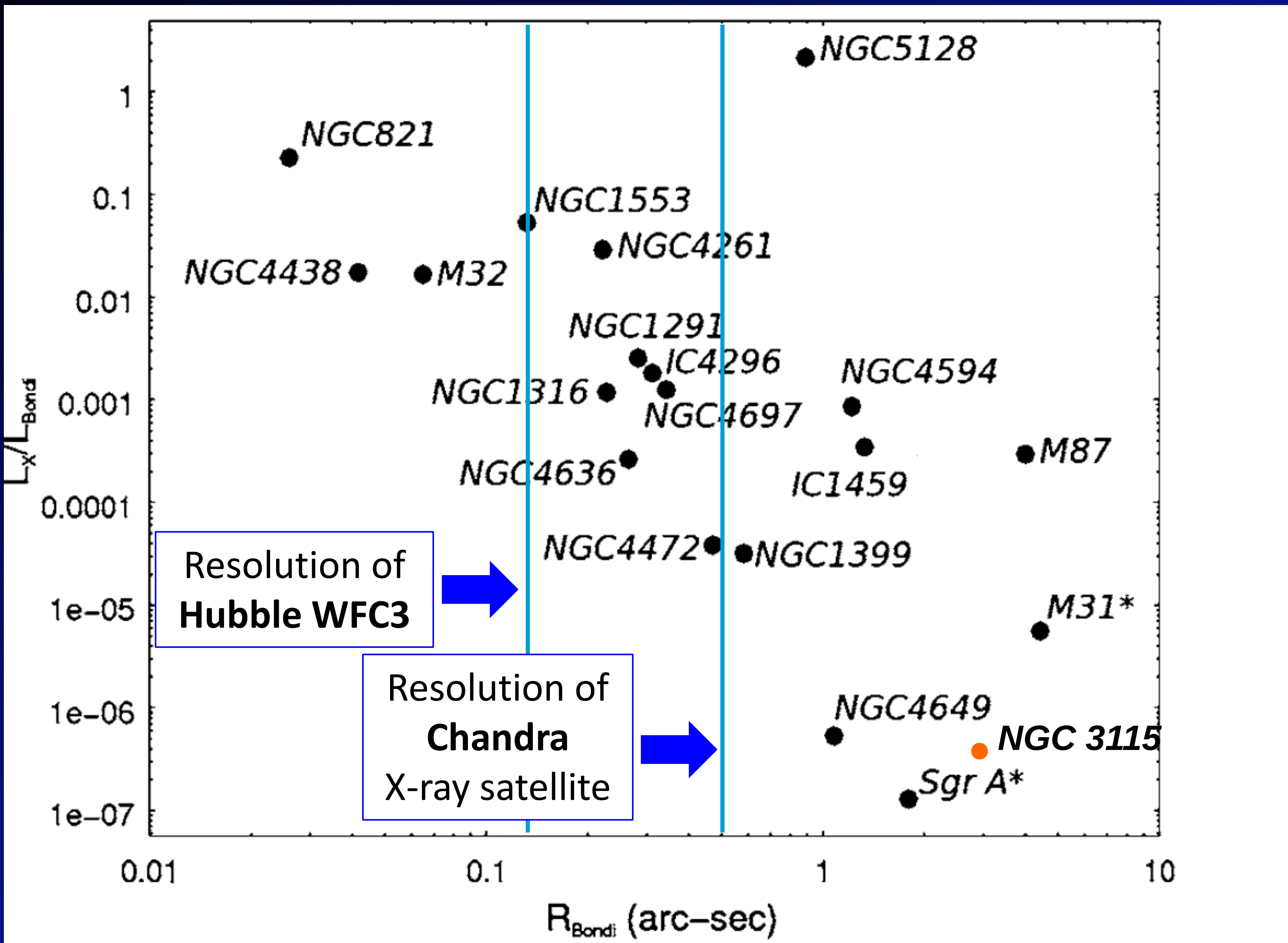
$$R_B = \frac{2GM_{BH}}{{c_s}^2} \propto \frac{M_{BH}}{T}$$

Which LLAGNs to study:

1. large BH mass,
2. “low” gas temperature ($T=10^6$-10^7K),
3. nearby.

Resolve the BH sphere of influence => study gas dynamics and radiative processes

Selection of galaxies to study LLAGNs



updated from Garcia et al. 2010

M87 – bright jet interferes with Bondi region observations

M31 – too underluminous

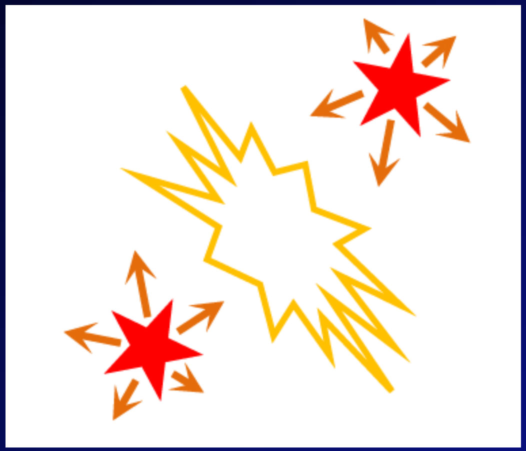
NGC3115 – best of sources

Sgr A* – second best

Can resolve Bondi radius and study in detail Sgr A* and NGC3115

Fuel sources of LLAGNs

Mass loss by stars in the nuclear star clusters (NSCs)



Supermassive BHs concentrate stars around them => NSCs
Young stars => intense winds; old stars => planetary nebulae

Mass loss is large enough
to sustain the observed LLAGN activity

Ho et al. 2009

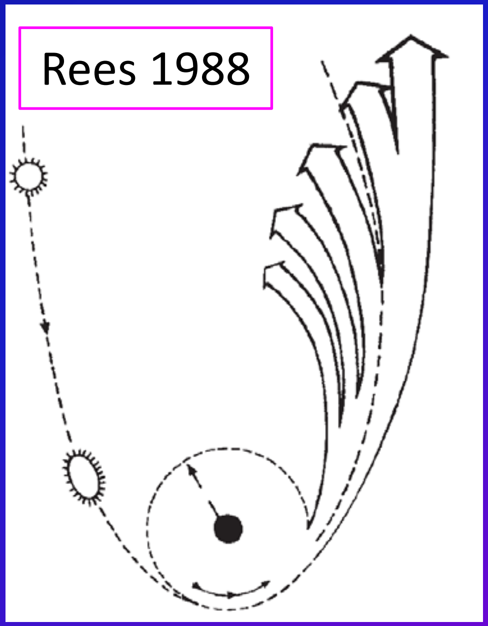
Stellar tidal disruptions

Some NSC stars get too close to BHs

BHs tear apart those stars
and gradually feed on the debris

This fuel source is subdominant (10%)
for most LLAGNs

Milosavljevic et al. 2006



Rees 1988

Gas descending from large radii

Active AGNs are fed this way,
but LLAGNs would have been brighter with large scale gas inflow

Hopkins & Hernquist 2006

Energy sources near LLAGNs

Sgr A*

Cuadra et al 2005+

Stellar (winds) feedback

1. Energy of stellar winds with respect to stars

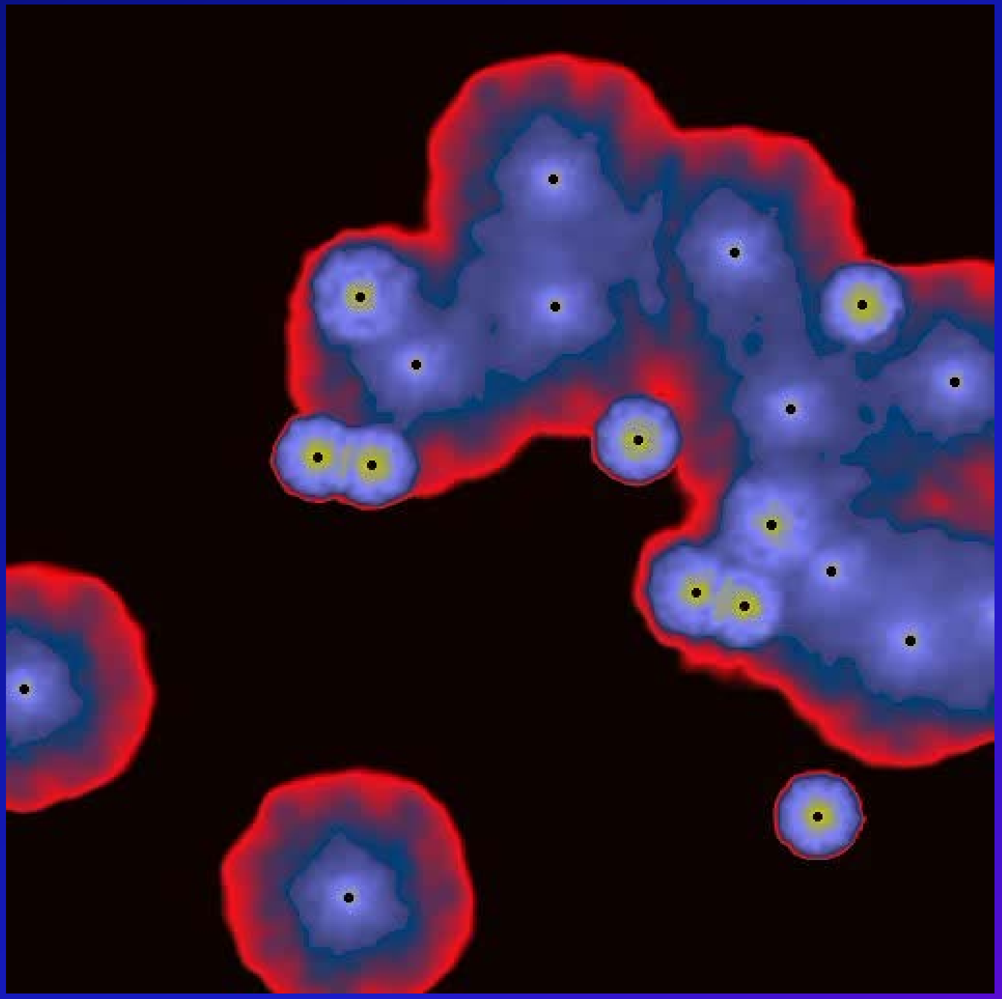
Young stars near Sgr A* =>
wind velocities 300-1200km/s

Gas heats up to 10^7K,
when winds collide

2. Extra energy due to stellar motions

Stars move (mostly at random)
at the dispersion velocity σ~300km/s

Gas temperature ~ virial temperature (10^6-10^7K)



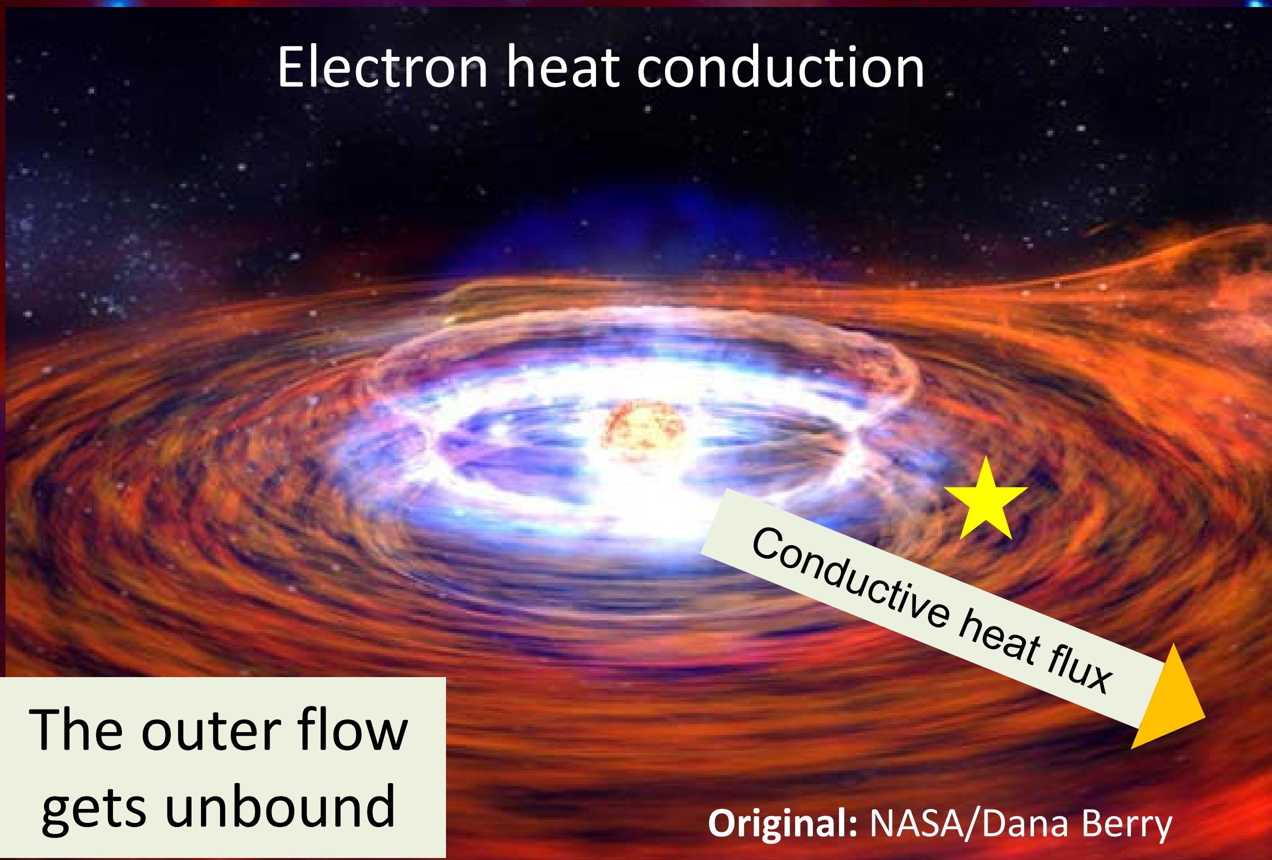
~10''=0.4pc

Supernova feedback

Type Ia supernovae effectively heat gas
even for old stellar populations (5Gyr)

Equivalent to stellar winds
w/ effective velocity v_{SN}≈500km/s (NGC3115)

(Small scale) AGN feedback: heat conduction



The outer flow gets unbound

The binding energy of a gram of gas at a few r_g drives off 100 kg of gas from 10^5 r_g

Blandford & Begelman 1999

Now we know how!

$r_g = G M/c^2$ – characteristic BH size

Convection is less efficient in Sgr A* and NGC3115

The flow is hotter closer to the BH
=> outward heat flux
=> the outer flow gets overheated/unbound

Gas inflow onto the BH can practically stop!

Studying gas dynamics in LLAGNs

Gas:

1. is injected by stellar winds (ignore other mechanisms),
2. is heated by stellar feedback / supernova feedback / AGN feedback,
3. can cool via metal lines cooling,
4. feels the gravitational force of the BH and the enclosed stars.

↓

Quantify the effects near supermassive BHs

↓

Construct gas dynamical model and compute radiation

↓

Compare simulated radiative signatures with observations, constrain free parameters of modeling

Assumption: the flow is spherical symmetric

Well-motivated for the inner stellar distribution

Modeling gas dynamics in NGC 3115

Shcherbakov et al. 2013, ApJ positive referee report, arXiv:1308.4133

Also Wong et al. (2011);
Wong, Irwin, Shcherbakov et al. (2013), ApJ submitted

1Ms Chandra X-ray visionary project
(PI: Irwin)

The S0 Galaxy NGC 3115

ESO/VLT – Wong et al. 2011

D = 9.7 Mpc — Tonry et al. 2001

$M_{BH} = 0.7\text{-}2.0 \times 10^9\ M_{Sun}$

Kormendy et al. 1996

Emsellem et al. 1999

$R_B = 2.5''\text{-}5''$

$kT_{gas} \sim 0.35\text{keV} = 4{\cdot}10^6\text{K at } R_B$

Wong et al. 2011

No bright X-ray AGN/jet at its center

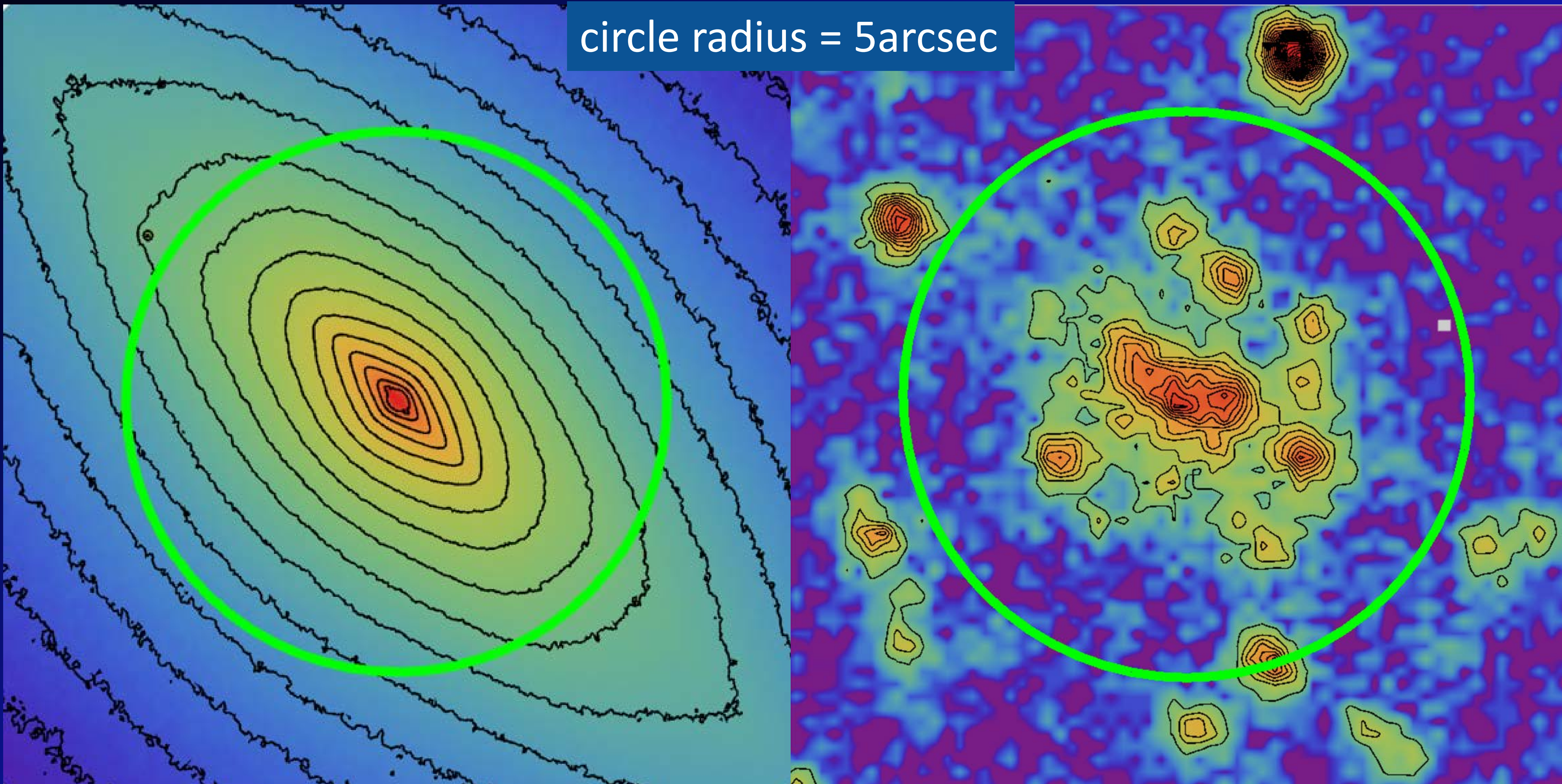
Very low radio flux

Nyland & Wrobel 2012

Bondi region in the optical and X-rays

Hubble ACS – optical

Chandra ACIS-S (1.1Ms) – X-rays



Massive old nuclear star cluster

stellar winds
+ planetary nebulae

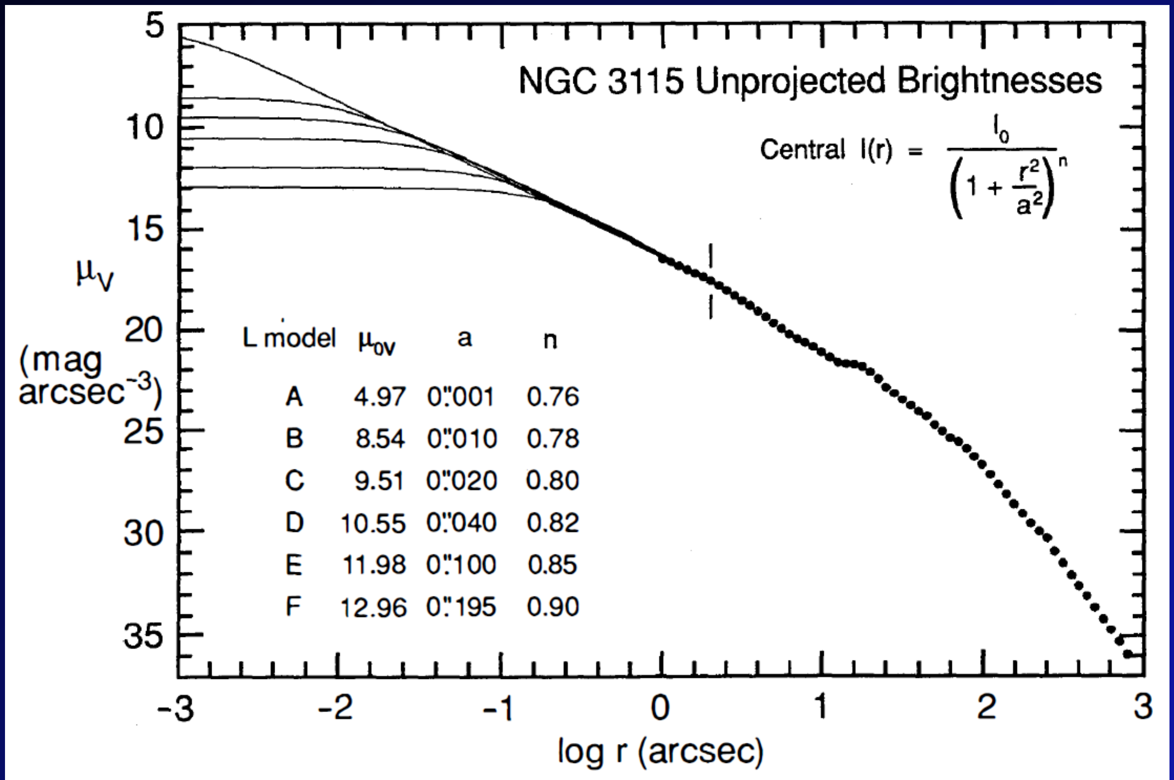
Diffuse soft X-rays + point sources

Tenuous gas that feeds the black hole

Mass + energy sources, galactic potential

The optical profile of nuclear star cluster (Hubble + ground-based)

Kormendy & Richstone 1992



Mass-to-light ratio and age:

$M/L_V = 4.0$ $t \sim 5$ Gyr Kormendy & Richstone 1992

Conversion of brightness to mass loss rate:

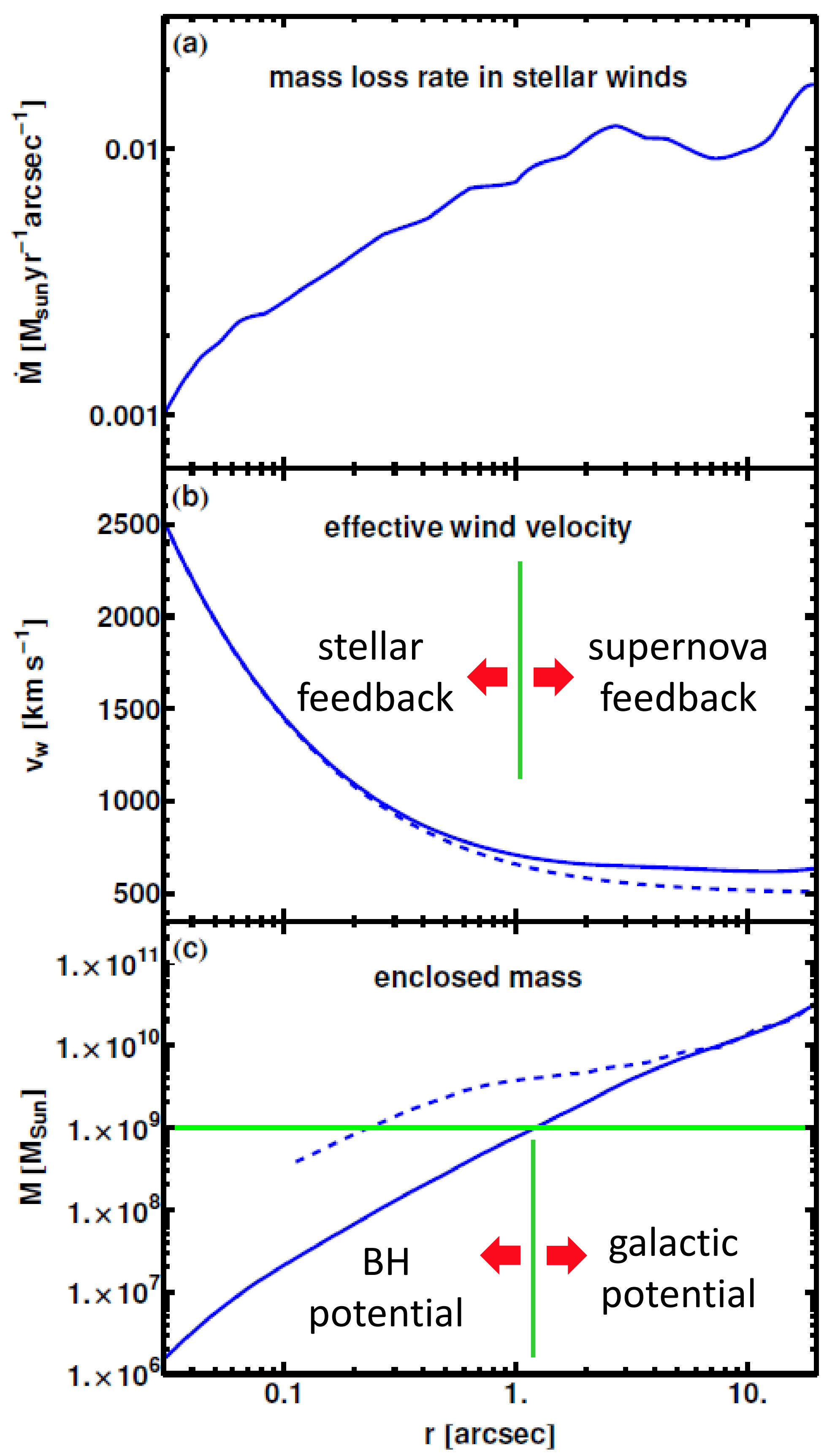
$$\dot{M}_\star \approx 3\times10^{-11}\left(\frac{L_V}{L_{\odot,V}}\right) M_\odot \mathrm{yr}^{-1}$$

Padovani & Matteucci (1993); Ho et al. (2009)

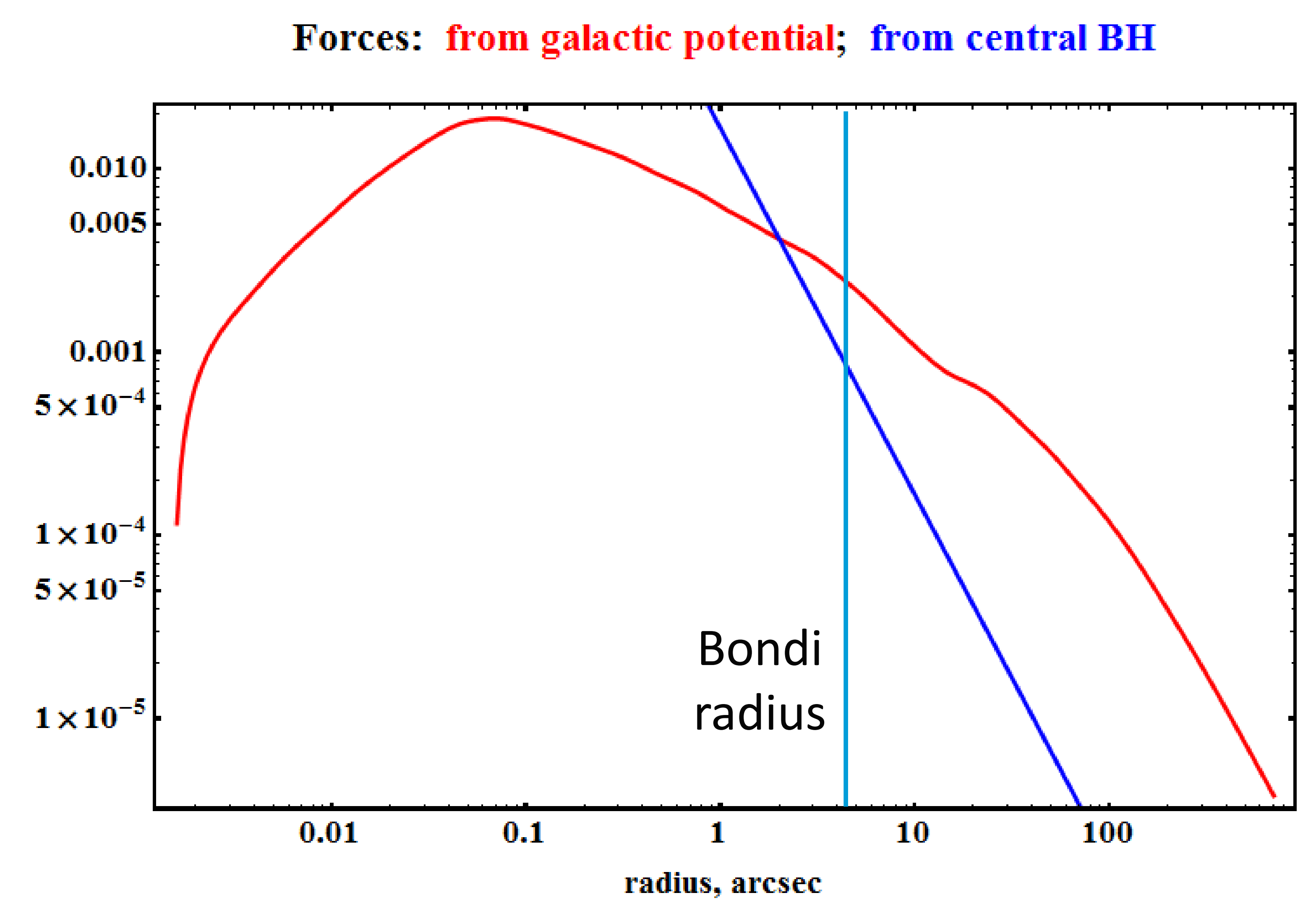
Supernova rate per unit mass:

$$R_{SN} \sim 4\times10^{-14} M/M_\odot \mathrm{yr}^{-1}$$

Mannucci et al. 2005



Galactic potential



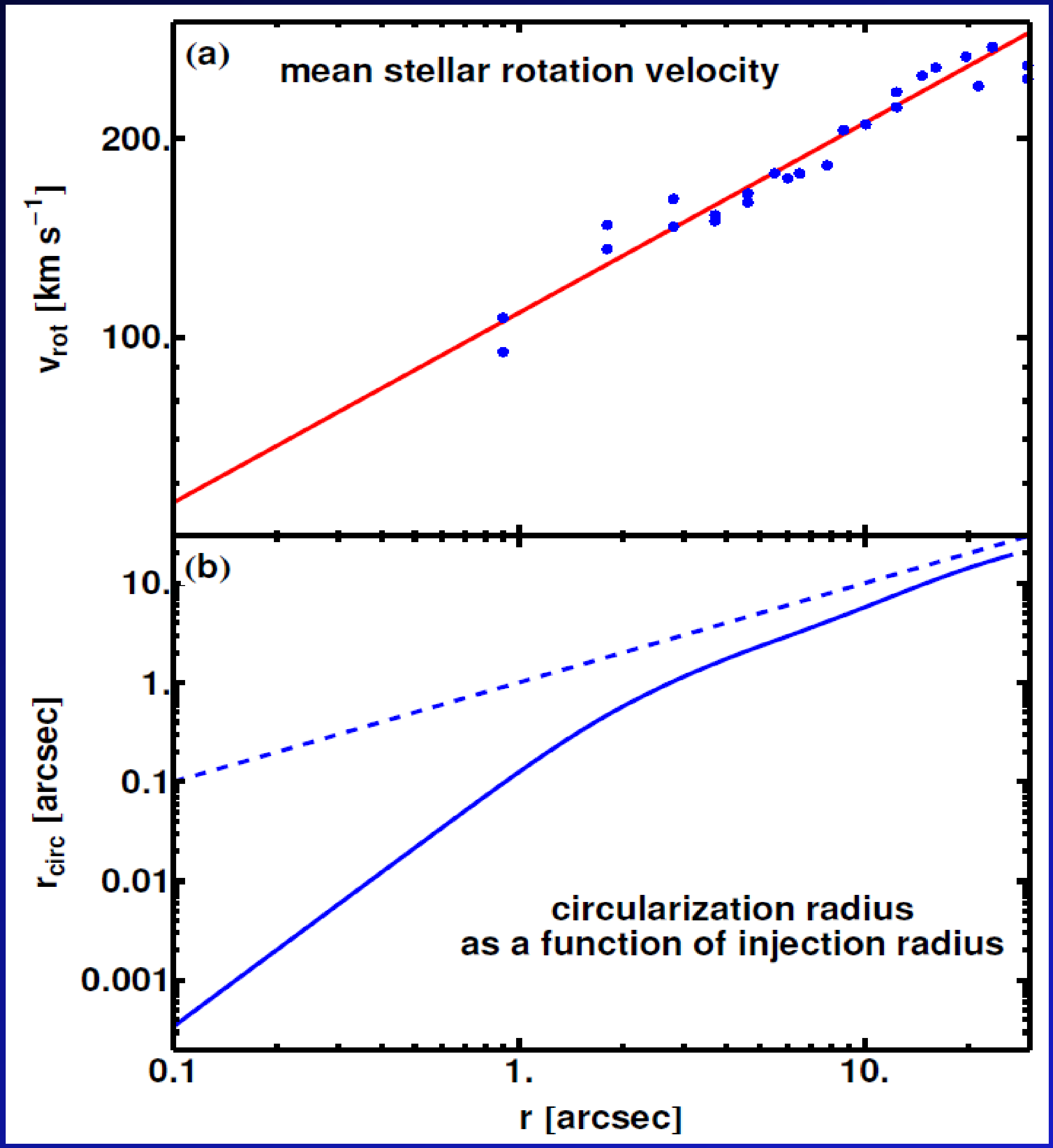
Gravitational force from enclosed stars dominates at r>2arcsec

Not just an "accretion flow",
but a transition
from galactic flow to flow onto the BH

Spherical vs. disk accretion: is gas rotation important?

Compilation from

Kormendy & Richstone 1992



Gas angular velocity is determined by mean rotation of stars

If the BH is fed by gas injected at r<1arcsec, then the flow is mostly radial and circularizes only very close to the BH

Emission from gas distribution

Gas temperature T=10^6-10^7K → X-ray continuum emission + strong Fe-L and O lines at 0.6-0.9keV

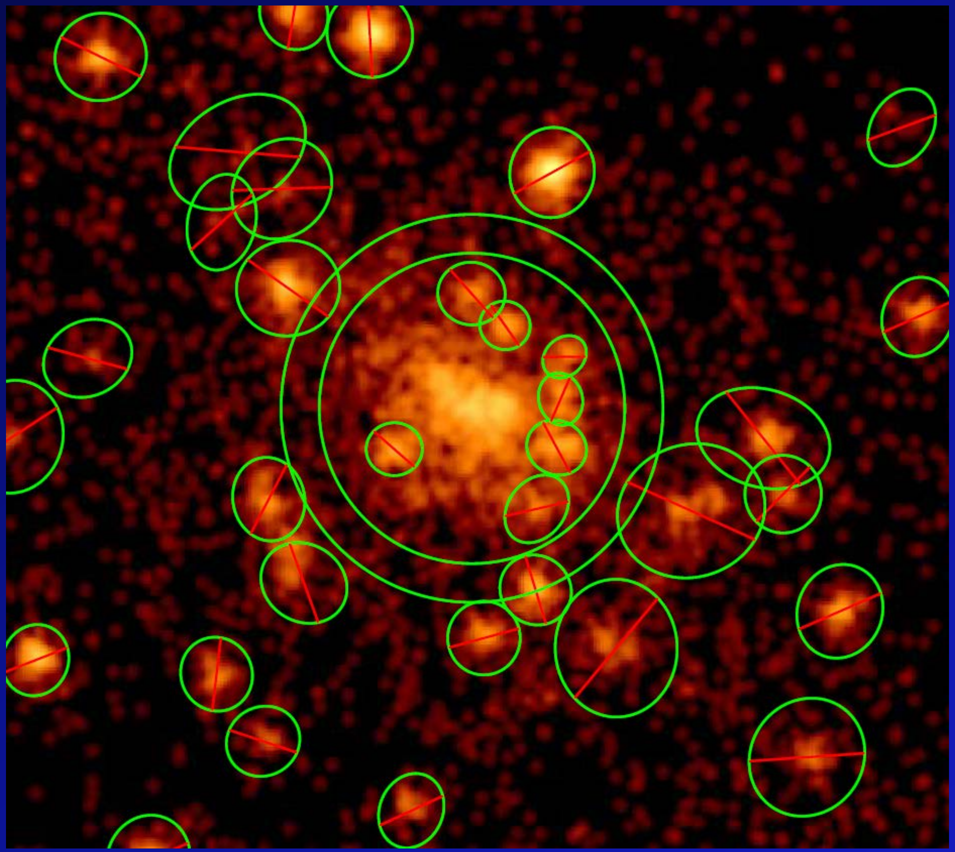
↓

state-of-the art spectra based on AtomDB 2.0.1

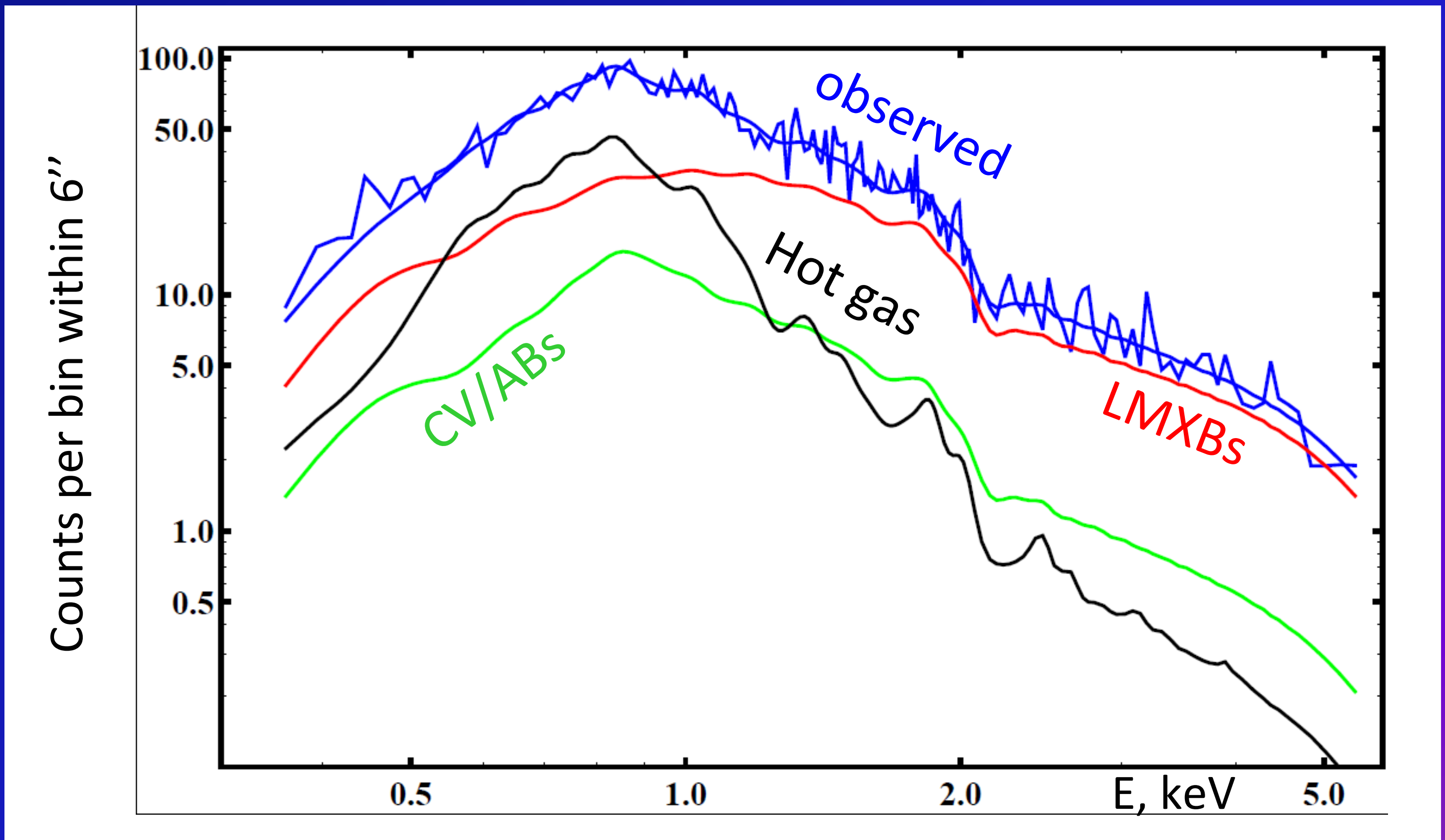
Foster et al. 2012

Contributions of point sources:

1. LMXBs w/ powerlaw spectrum
2. CV/ABs w/ powerlaw + thermal spectrum



Wong et al. 2013, subm



Sample spectrum convolved w/ *Chandra* response

How to deal w/ *Chandra* X-ray data: spatially resolved spectroscopy

Option 1: extract spectrum of the entire (spherical) region

loss of spatial information

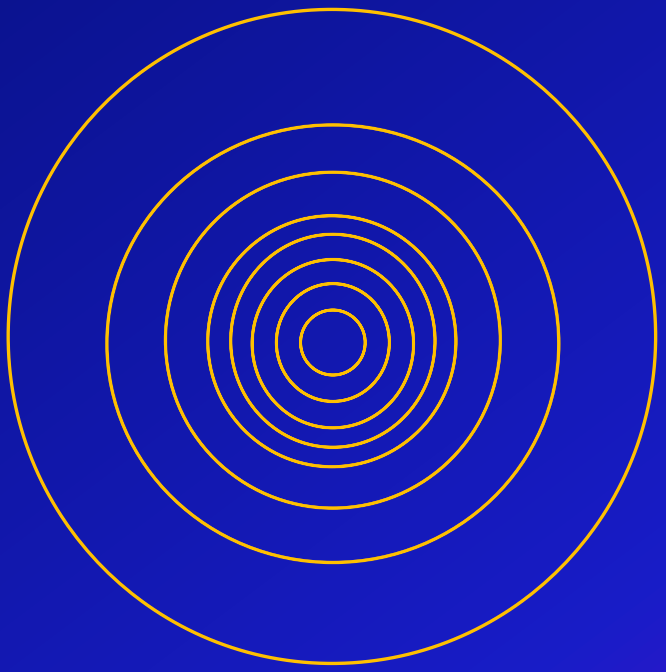
Option 2: extract surface brightness profile

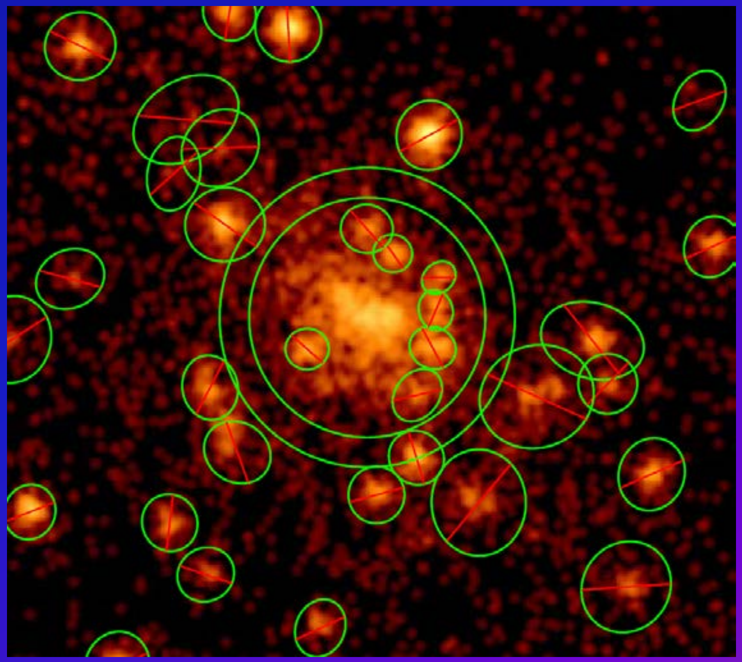
cannot disentangle spectra of components

Option 3: extract spectra in a set of concentric annuli

retains spatial and spectral data

8 radial annuli
0-1'', 1-2'',
2-3'', 3-4'',
4-5'', 5-8'',
8-12'', 12-20''





Jointly fit extracted spectra with simulated model emission

Radial profiles in best-fitting model

$\chi^2/\mathrm{dof} = 1.00$ for $\mathrm{dof} = 236$

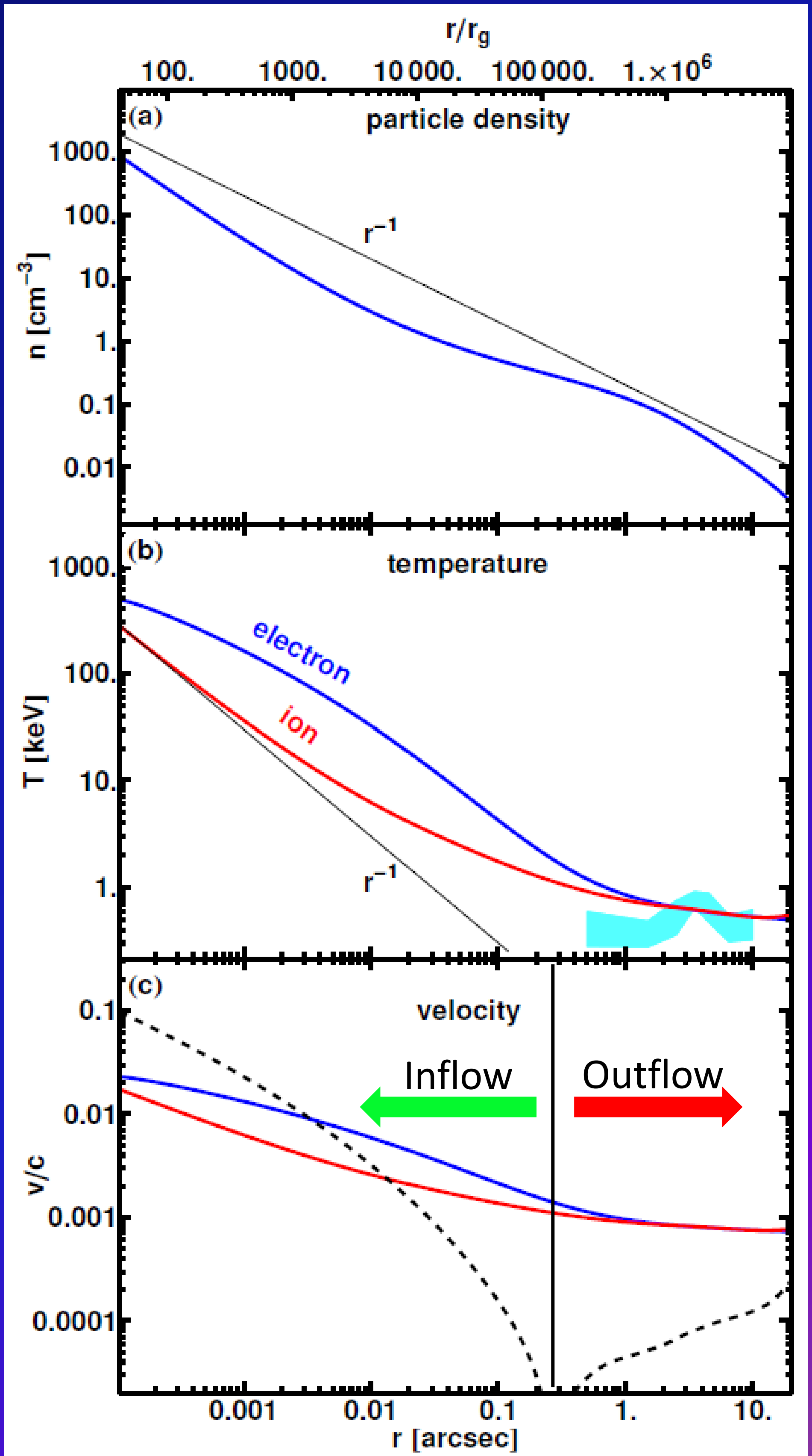
Density profile $n \sim r^{-1}$ over large range of radii
=> accretion rate Mdot<$2 \cdot 10^{-3} M_{Sun}$/yr

Electrons are hotter than ions –
because conduction heats the electrons

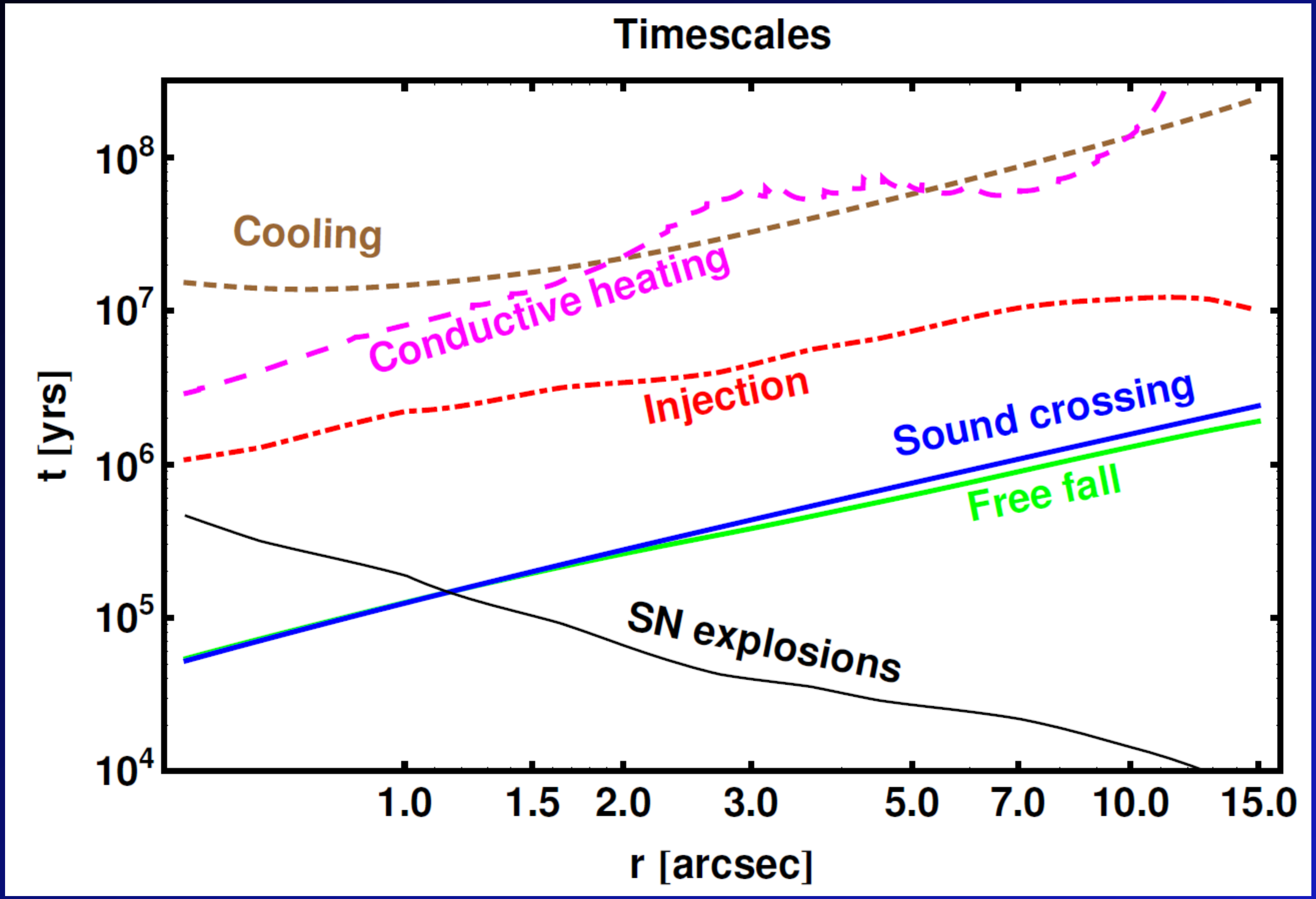
Temperature is close to virial T_V
in a joint gravitational potential $T \sim \sigma^2$
=> temperature is almost constant at r>1arcsec

Gas at r<0.3arcsec is flowing onto the BH
Gas at r>0.3arcsec outflows (to infinity?)
=> self-consistent to ignore rotation (in a radial model)

Too much stellar winds are produced =>
most of these outflow from the region



Comparison of timescales



Supernova feedback: r>1arcsec
stellar feedback: 0.1<r<1arcsec
AGN feedback (conduction): r<0.1arcsec

Cooling time t_{cool}/t_{ff}~100 => cooling is weak

Time between SN explosions t_{SN} is small => continuous treatment of SN feedback

Temperature is virial everywhere $T \sim \sigma^2$

Are we sensitive to the BH mass?

BH mass based on stellar velocity dispersion is uncertain

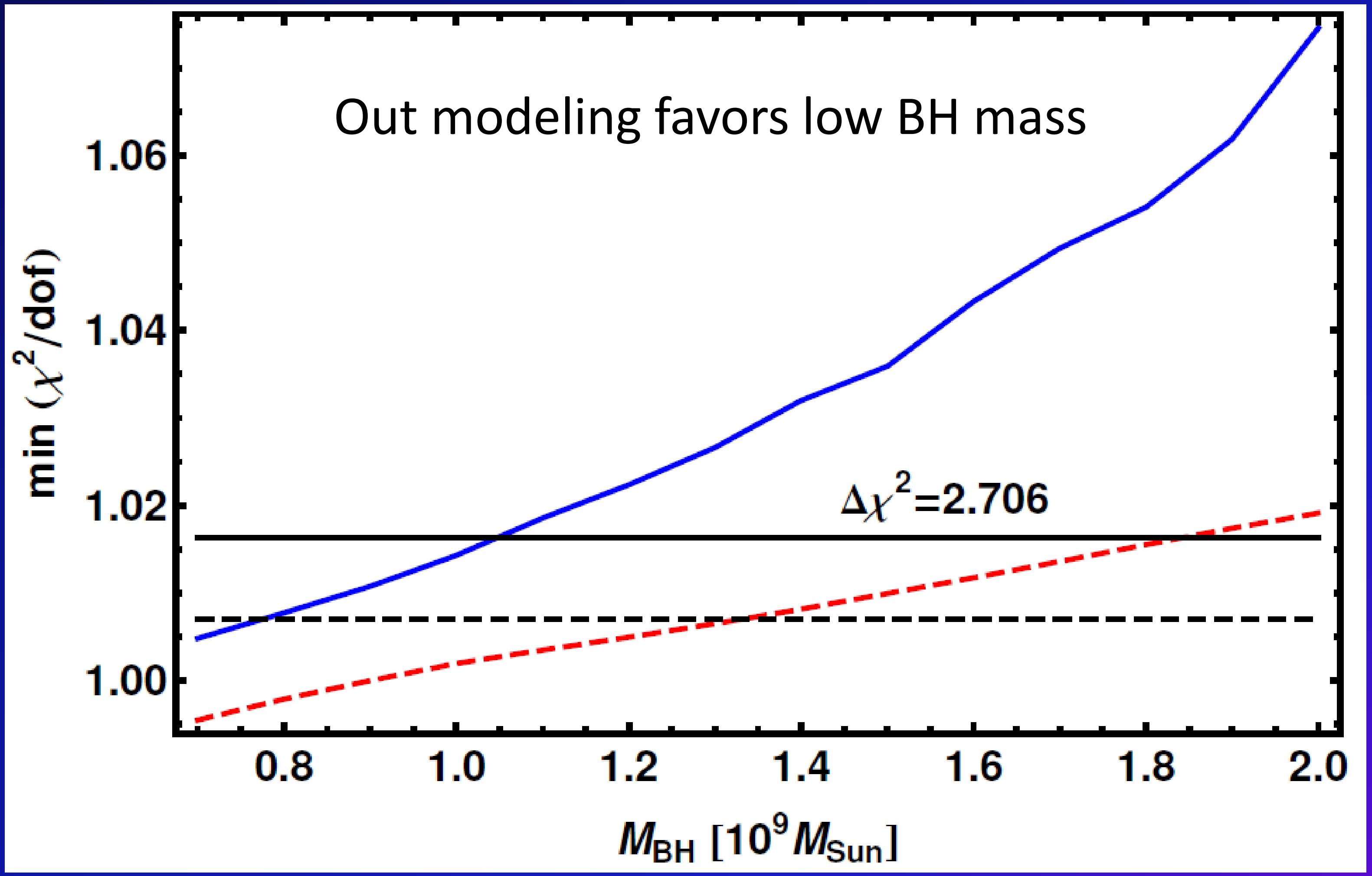
$M_{BH} = 0.7\text{-}2.0 \times 10^9\ M_{Sun}$

Kormendy et al. 1996

Emsellem et al. 1999

However, M-σ relation predicts lower $M=0.24 \times 10^9 M_{Sun}$

Gultekin et al. 2011



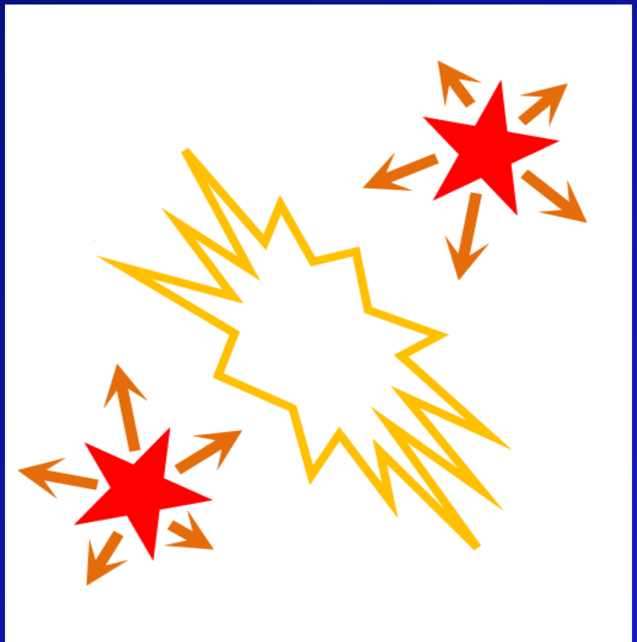
Definitely sensitive to BH mass,
but should perform 2D modeling before drawing conclusions on M_{BH}

What if SN feedback does not rid of gas: accumulation/accretion cycles

Stage 1.
Stellar winds inject material, which accumulates

→

Stage 2.
Material cools down and starts actively accreting



Stage 3.
Feedback from jet/outflow unbinds the mass reservoir

←

Stage 4.
Accretion ceases, leaving an empty cavity

We may be witnessing the accumulation phase of these cycles in NGC3115

Modeling gas dynamics in Sgr A*

Shcherbakov & Baganoff (2010);
Shcherbakov et al. (2012);
Wang et al. (2013), Science

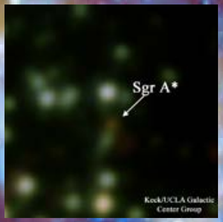
3Ms Chandra X-ray visionary project
(PIs: Baganoff, Nowak, Markoff)

Galactic Center Black Hole Sgr A*

Closest to us – easier to study?
Not really

Discovered as a radio source

Balick & Brown 1974



Keck-UCLA
GC group

Dramatically underluminous

$L < 10^{-8} L_{Edd}$

Narayan et al. 1998

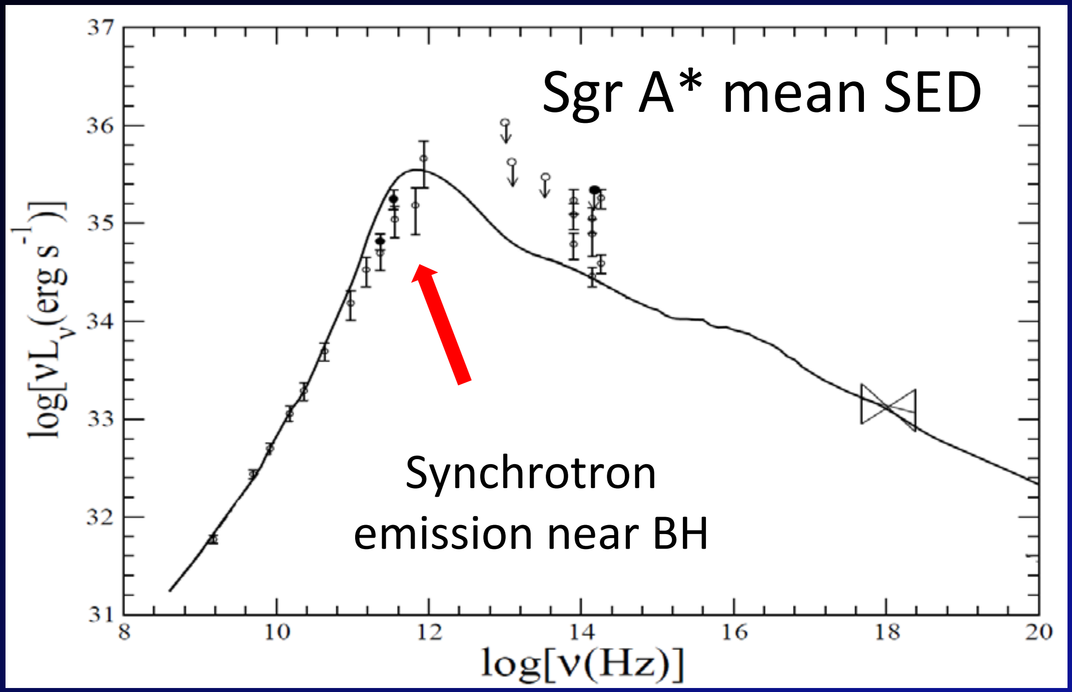
Monitoring of stellar orbits
=> black hole inside

Ghez et al. 2008; Gillessen et al. 2009

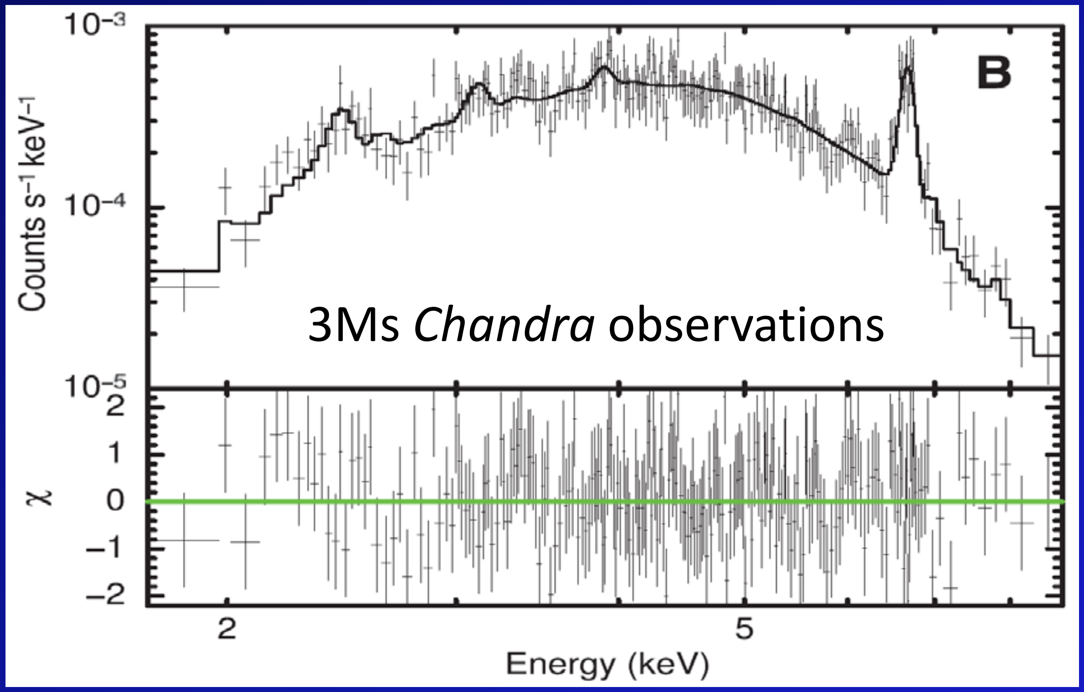
$M = 4.3 \cdot 10^{6} M_{sun}$ $\quad d = 8.3 kpc$

vs

Evidence for AGN (small-scale) feedback



Yuan et al. 2004



Spectrum in Bondi region consistent w/ thermal emission kT_e=1.3keV, n=100cm^{-3}, accretion rate M_{dot}~$3\cdot10^{-6}M_{sun}$/yr w/o feedback

Wang et al. 2013; Baganoff et al. 2003

The synchrotron peak is produced near the event horizon

density n_e~10^6cm^{-3} at $6r_g$

M_{dot}~$3\cdot10^{-8}M_{sun}$/yr

Shcherbakov et al. 2012

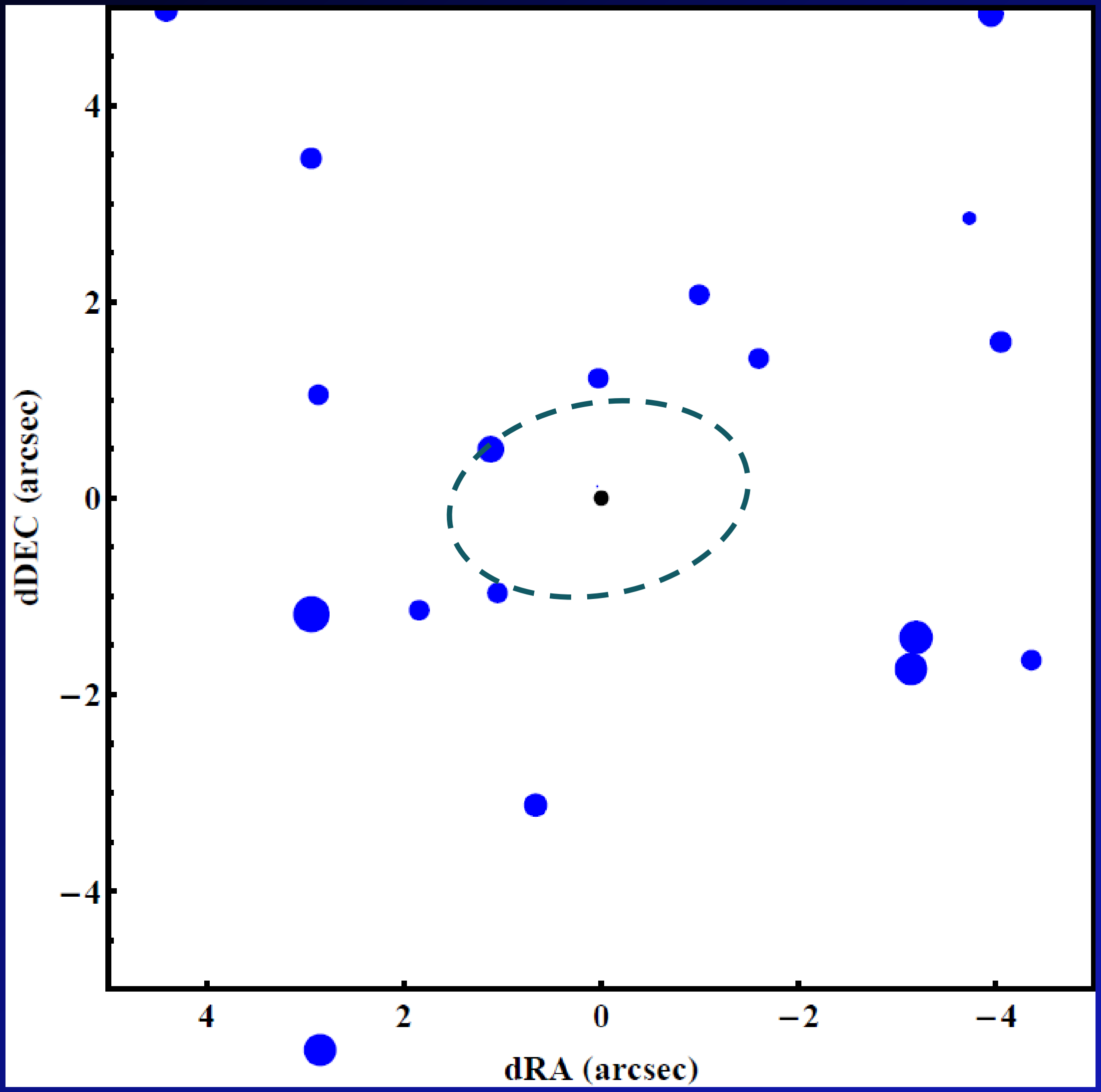
Shallow density profile $n \propto r^{-(0.8-0.9)}$

matter outflows/stagnates not reaching BH

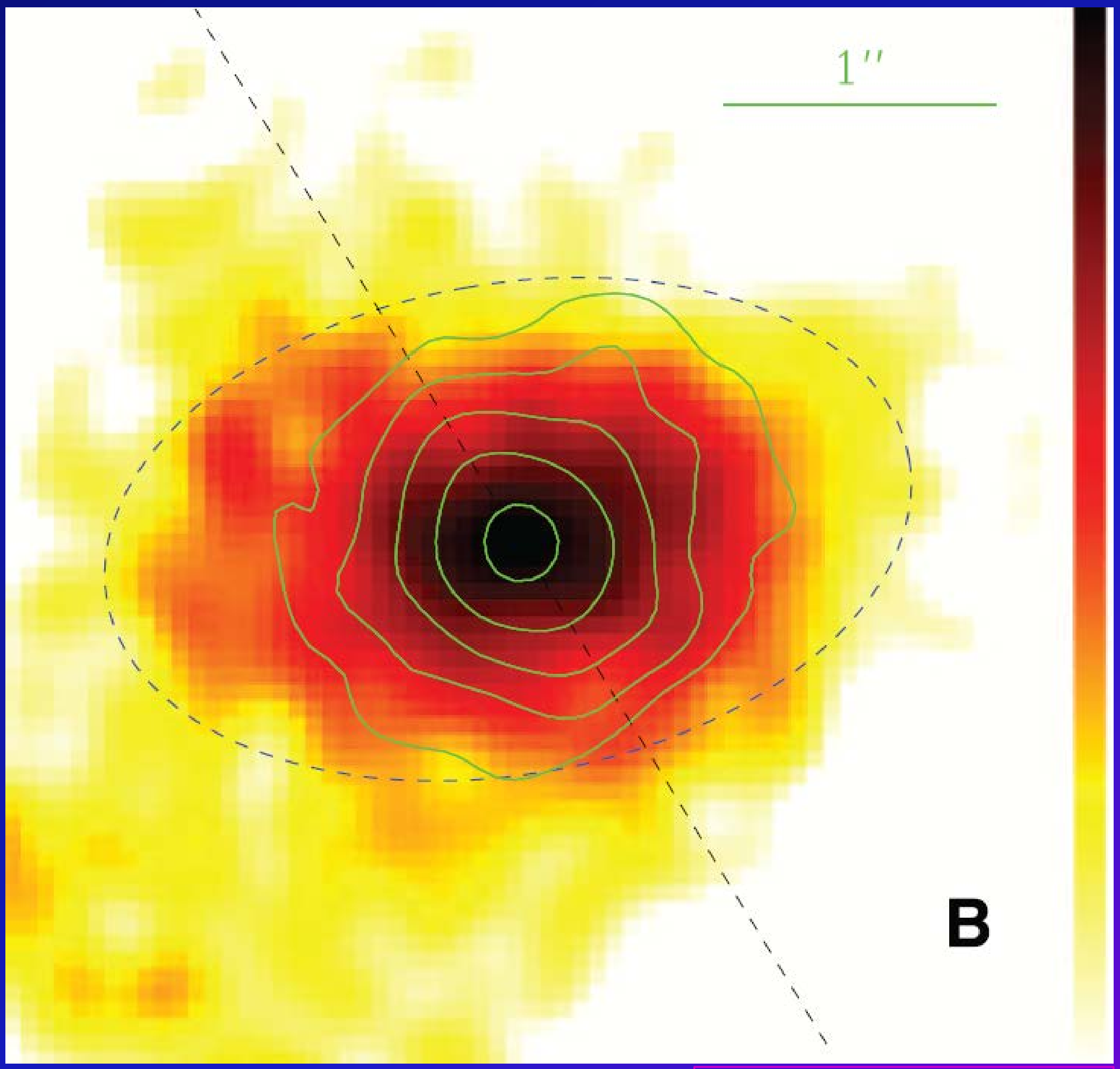
Only under 1% of available material reaches the BH due to AGN feedback (conduction)

Evidence for feeding by stellar winds

Positions of wind-emitting stars



X-ray anatomy of hot gas near Sgr A*



Wang et al. 2013

Spatially resolved spectroscopy is underway:
stay tuned for qualitatively new results!

Conclusions

- Low-luminosity AGNs reside in centers of typical galaxies
- Can be fed by stellar mass loss in nuclear star clusters (NSC)

- Optical studies of NSCs => detailed info on feeding
- Gas is seen in a hot mode with co-existing inflow & outflow
- *Chandra/Hubble* can resolve feeding region of Sgr A*/NGC3115
- Deep Chandra X-ray visionary projects allow to study intricate processes of feeding and feedback

- Three kinds of feedback influence the flow: stellar feedback, supernova feedback (large r), and small-scale AGN feedback (near BH)
- Matter inflow stagnates => very low BH activity
- X-ray data potentially allow to weigh the BHs
- Exciting field, much more work to be done (numerical simulations)!