DEEP-Theory group meeting Monday 26 November & 3 December 2018

Highlights of the Conference on the Coevolution of Galaxies and their Central Regions
Dali, Yunan Province, China - 5-9 November 2018

http://web.shnu.edu.cn/keylab/74/17/c22816a685079/page.htm

OUTLINE OF THIS SUMMARY

26 November

Sandy Faber's Highlights Overview

James Aird - SMBH Demographics

Mark Morris - Galaxy Centers, Fermi Bubbles, etc.

3 December

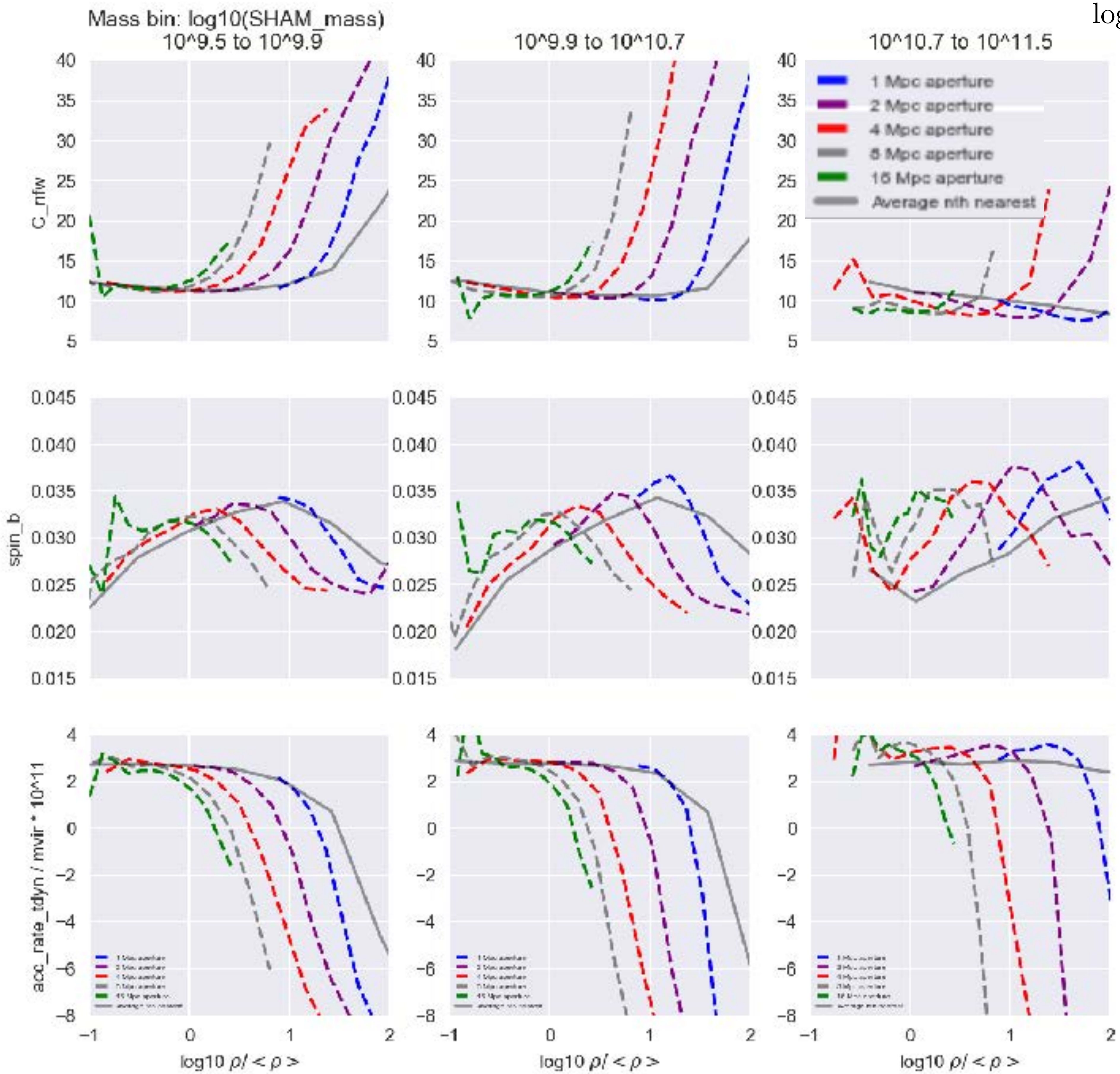
[progress report by Graham Vanbenthuysen - 1st slide]

Luis Ho - Measuring M_{BH} etc.

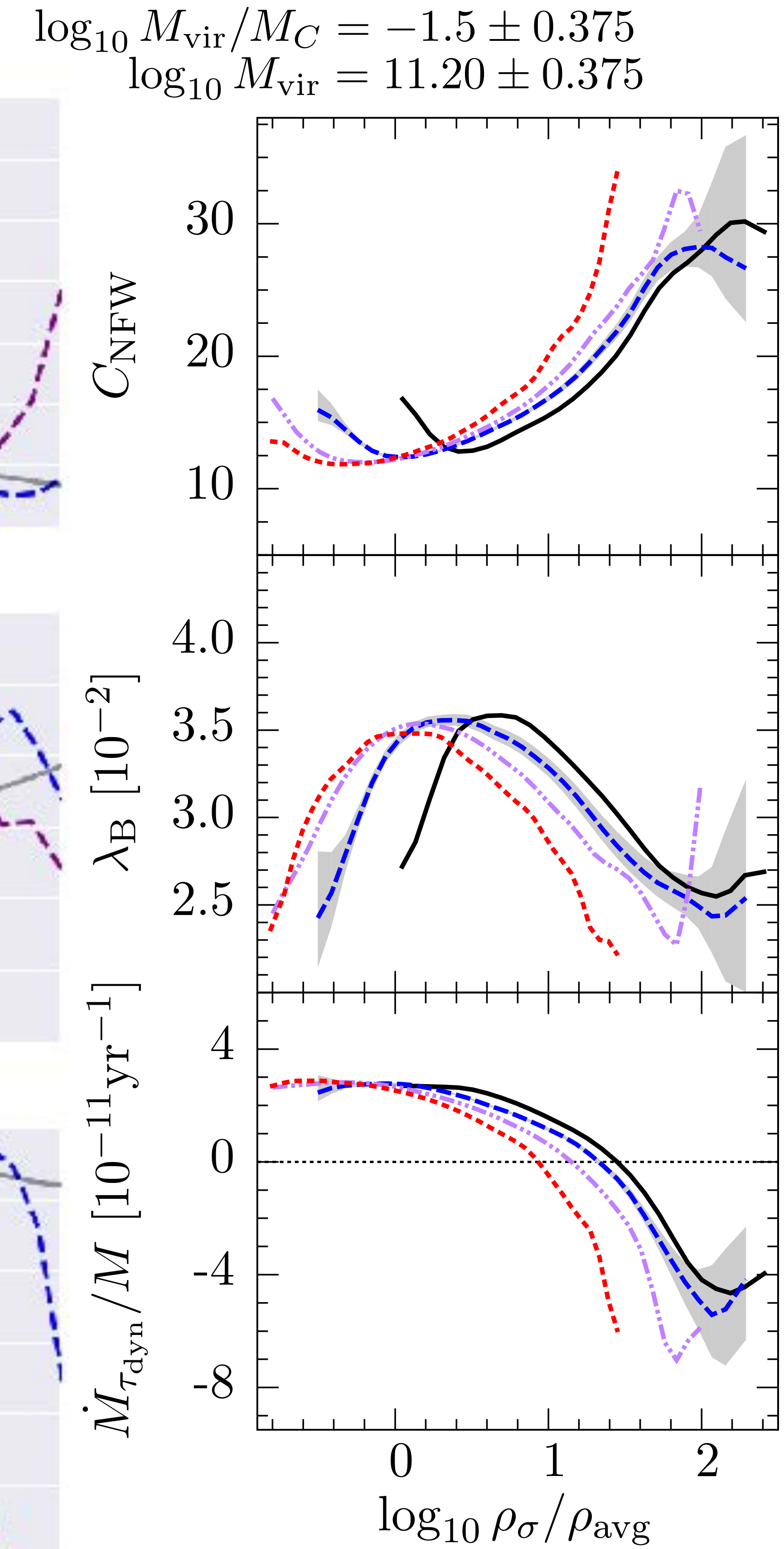
Steve Longmore - Galaxy Centers, Gas Flows, etc.

Recreation of Lee+17 Figure 5 using observer methods

by Graham Vanbenthuysen



Christoph Lee+2017 Figure 5



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Sandy's Summary of the Really Big Ideas

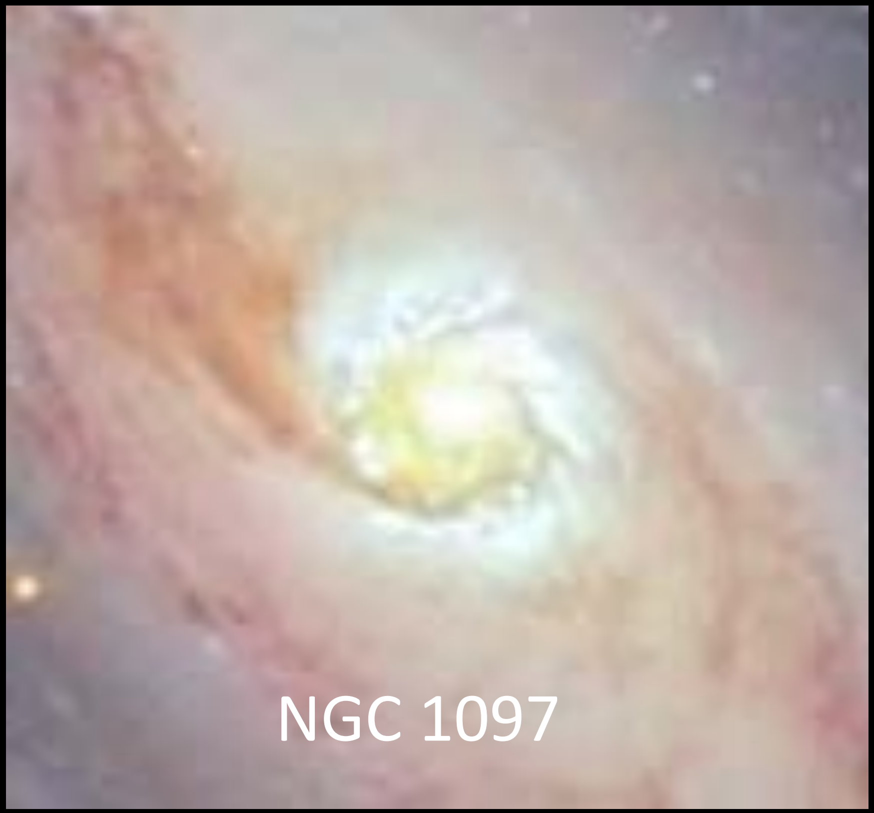
- Morphological structures at galaxy centers may modulate inward gas flows (and build bulges and BHs?). Some < 1kpc. How do these evolve over time? How do they relate to global Reff and M*?
  - – Mass profiles M*(r) >> rotation curves >> stall points
  - – Use dust lanes to measure inward flow rates?
  - – Star-formation over time may modify mass distributions, flows – What about non-bars?
  - – How do central features scale with the key global properties: R_{eff}, M*

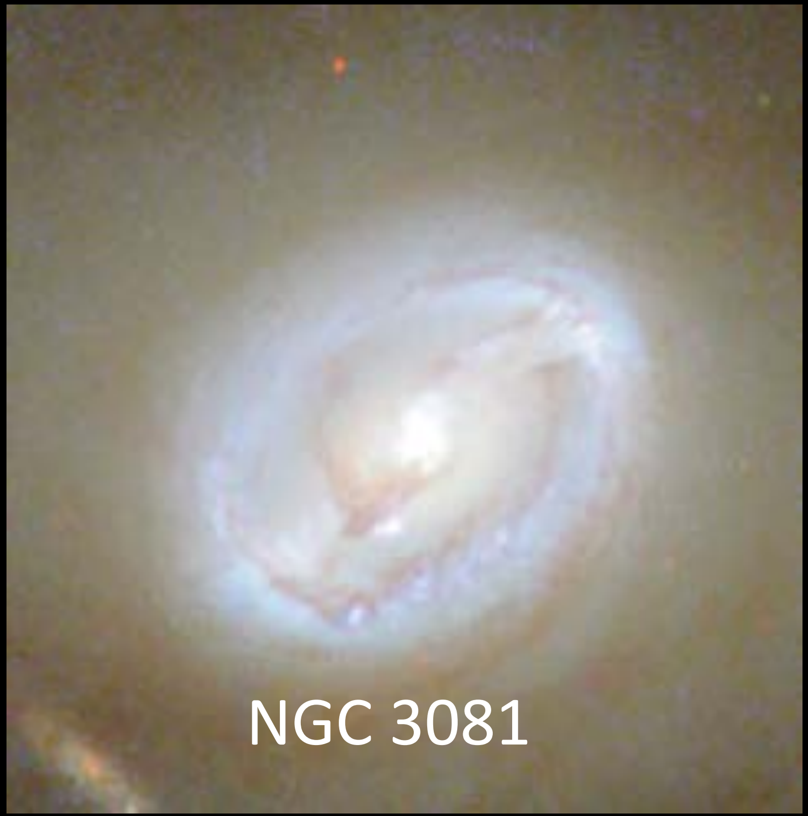
- Events at galaxy centers may be cyclical. Can data be phased to reveal the cycle? E.g., ring, SFR dust, AGN, BPT.
  - – Many data indicate past activity at Galactic Center a few million yr ago:X-ray, Fermi Bubble, partly filled ring. Consistent with a ring event now re-forming?
  - – Can same patterns be seen in other galaxies?


NGC 1512


NGC 3368


NGC 1433


NGC 1097


NGC 3081


NGC 4736

Smaller Big Ideas

- Magnetic fields may modulate gas motions in Galactic Center

QSO properties:

  - Eta varies enormously with BH accretion rate. Remember this!
  - Spectra are 2-D family. One is metallicity.
  - Metallicity of QSOs is 4-5 $Z_{\odot}$. **Implies strong local SF. E_{SF} ~ E_{BH}?**
  - Fermi Bubbles could be long-lived, ubiquitous and play a role in quenching.
- All properties of local galaxies vary smoothly through the green valley, consistent with a steady evolutionary flow.
  - S0s have same H I gas as spirals. How is this?
  - E's don't, yet have Lyα. How is this?
  - S0s quench because they lose their H2. How happen?
- Both major and minor mergers are needed to create E's.
- Confirming evidence that major mergers trigger the brightest QSOs and SF rates.
- More massive E's are harder to clean out but AGNs can do it.

Challenges/Unanswered Questions/Controversies

- How do we convert all these minutiae into laws like $M \sim \sigma^4$?
- Where is the "valve" that regulates mass flow onto the circum-nuclear disk? Is it global properties: bar, Reff, M*? Or is it local: i.e., structure of the BH region?
- How do BHs grow in small bulges? suppressed by SNae? wandering? lack of differential rotation? lack of bars?
  - Why is the BH in the Milky Way so small? Why is the BH in M31 so big? Is there inner structure/properties not captured by Σ_1?
- Do AGNs play a role in quenching spirals?
  - If not, then why are bulges red?
- Can jets provide feedback?
- How was our Fermi Bubble inflated? By SF activity? By AGN?

Take home points - James Aird

- AGN samples identified at *any* wavelength are severely affected by **selection biases** and can give a biased view of which galaxies have AGN

- AGN exhibit a broad distribution of accretion rates, indicating **variability** on timescales ~0.1-1 Myr
  i.e. faster than changes in global galaxy properties

- Incidence of AGN in main-sequence star-forming galaxies correlates with SFR => both are related to **cold gas**?
  But… **not *just* cold gas** - additional mechanisms appear to trigger and fuel AGN in galaxies that are *not* on the main sequence.

James Aird

Conclusions: 1) Select AGN - measure host properties

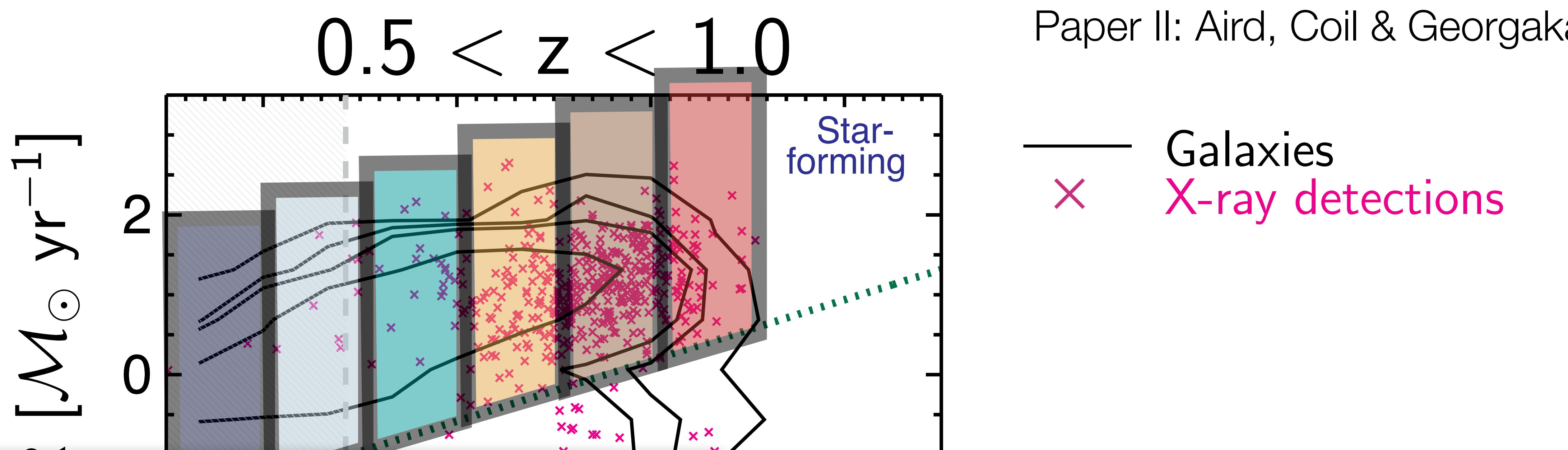
- Primarily find AGN in moderate-to-high mass galaxies (selection bias)
- Average SFRs of AGN are roughly consistent with the main sequence of star formation (for equivalent $M_{stellar}$)
- Large **scatter** in $M_{stellar}$ and SFR at fixed L_X - no clear correlation between instantaneous level of black hole growth (traced by L_X) and the host galaxy properties

James Aird

X-ray selected AGN in star-forming galaxies

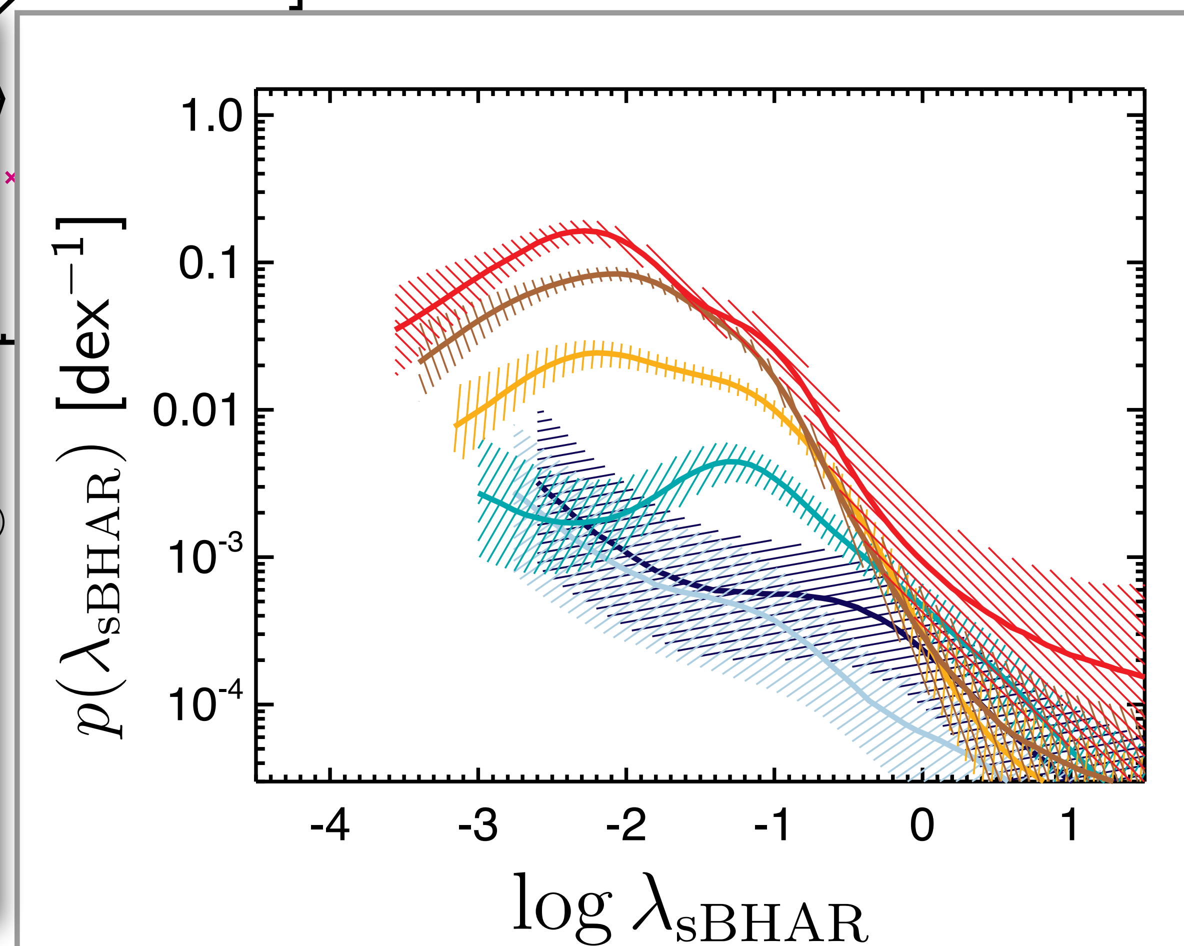
***along* the main sequence**

Paper II: Aird, Coil & Georgakakis, 2018



- Broad distribution of accretion rates at ***all*** M_*
  - Lower mass galaxies host AGN of *all* accretion rates, including rapidly accreting black holes
- Stellar mass dependence:
  - The fraction of galaxies with a moderate-accretion-rate AGN is lower for lower mass galaxies

(after accounting for selection bias i.e. that AGN *appear* less luminous for lower masses)



James Aird

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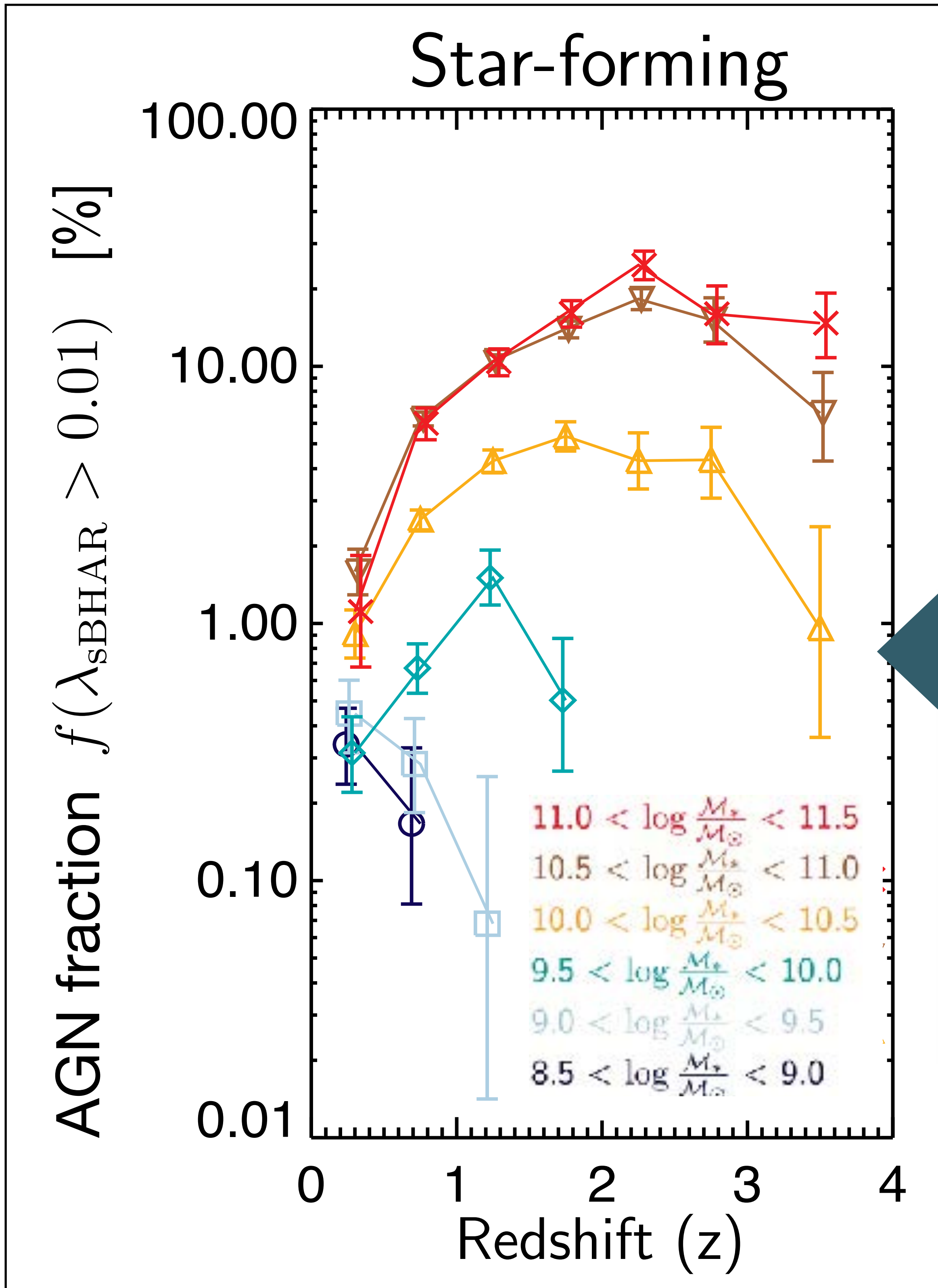
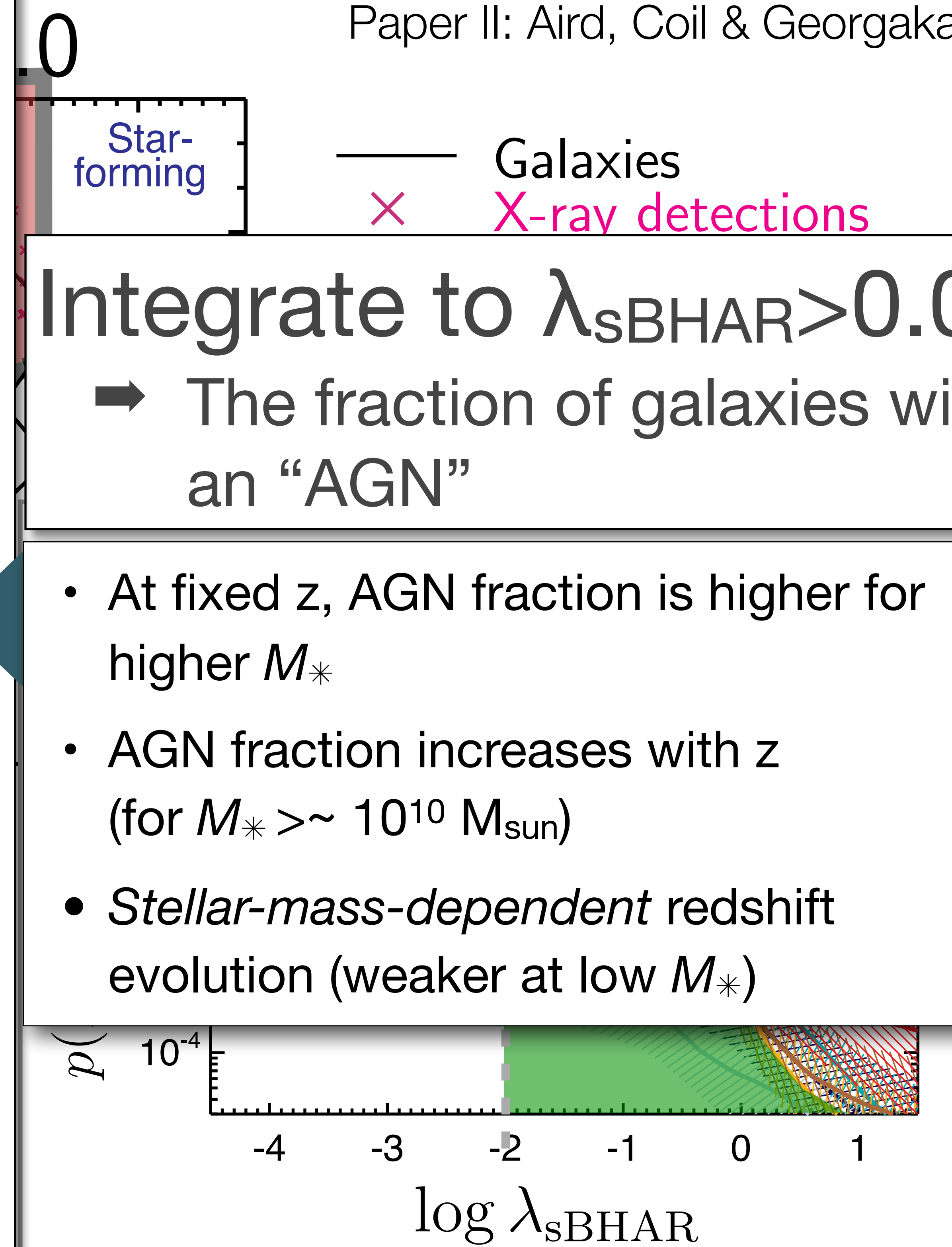




Integrate to λ_{sBHAR}>0.01

➡ The fraction of galaxies with an “AGN”

- At fixed z, AGN fraction is higher for higher M_*
- AGN fraction increases with z (for $M_* >\sim 10^{10}$ M_{sun})
- *Stellar-mass-dependent* redshift evolution (weaker at low M_*)

James Aird

Conclusions: 2) Select galaxies - measure the incidence of AGN

- Use near-infrared (~stellar-mass) selected samples of galaxies combined with deep *Chandra* X-ray data to measure the **distribution** of *specific black hole accretion rates*

Broad distribution of accretion rates reflecting ***variability*** of AGN (on ~galactic timescales)

- In **main-sequence star-forming** galaxies:

Incidence of AGN correlates with the SFR
=> AGN fuelled by the *stochastic* accretion of cold gas?

- But for galaxies that are **below the main sequence**

Enhanced AGN fraction
=> broader range of triggering/fuelling mechanisms
i.e. not *just* cold gas that determines AGN activity

James Aird

Take home points

- AGN samples identified at *any* wavelength are severely affected by **selection biases** and can give a biased view of which galaxies have AGN

- AGN exhibit a broad distribution of accretion rates, indicating **variability** on timescales ~0.1-1 Myr
i.e. faster than changes in global galaxy properties

- Incidence of AGN in main-sequence star-forming galaxies correlates with SFR => both are related to **cold gas**?
But… **not *just* cold gas** - additional mechanisms appear to trigger and fuel AGN in galaxies that are *not* on the main sequence.

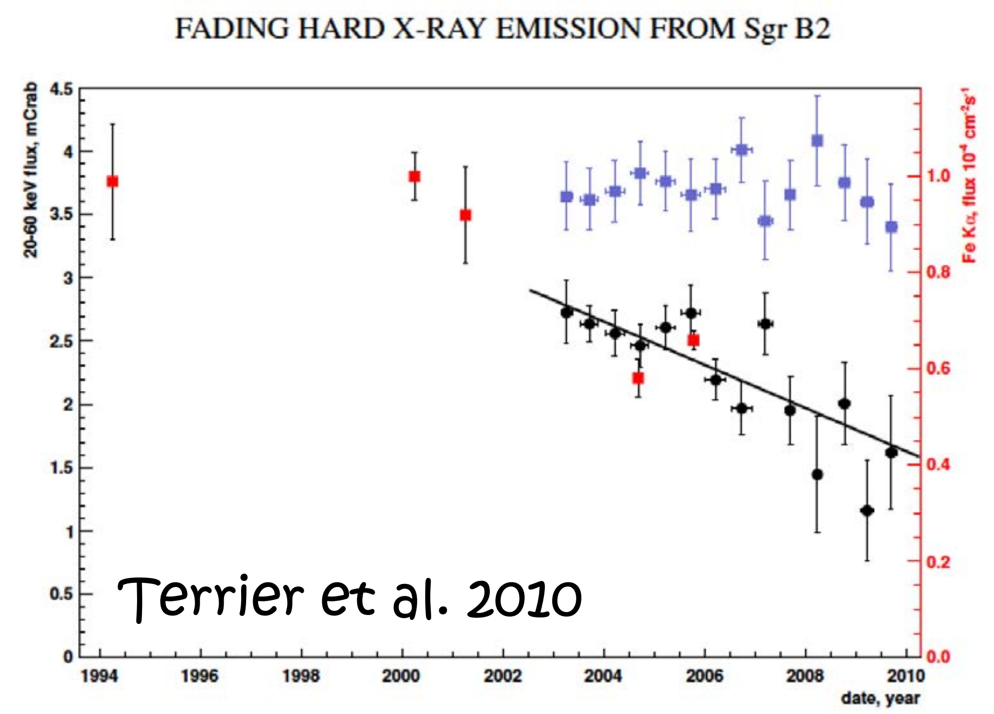
The Center of the Galaxy
and
Its Influence on Larger-Scale Galactic Structures

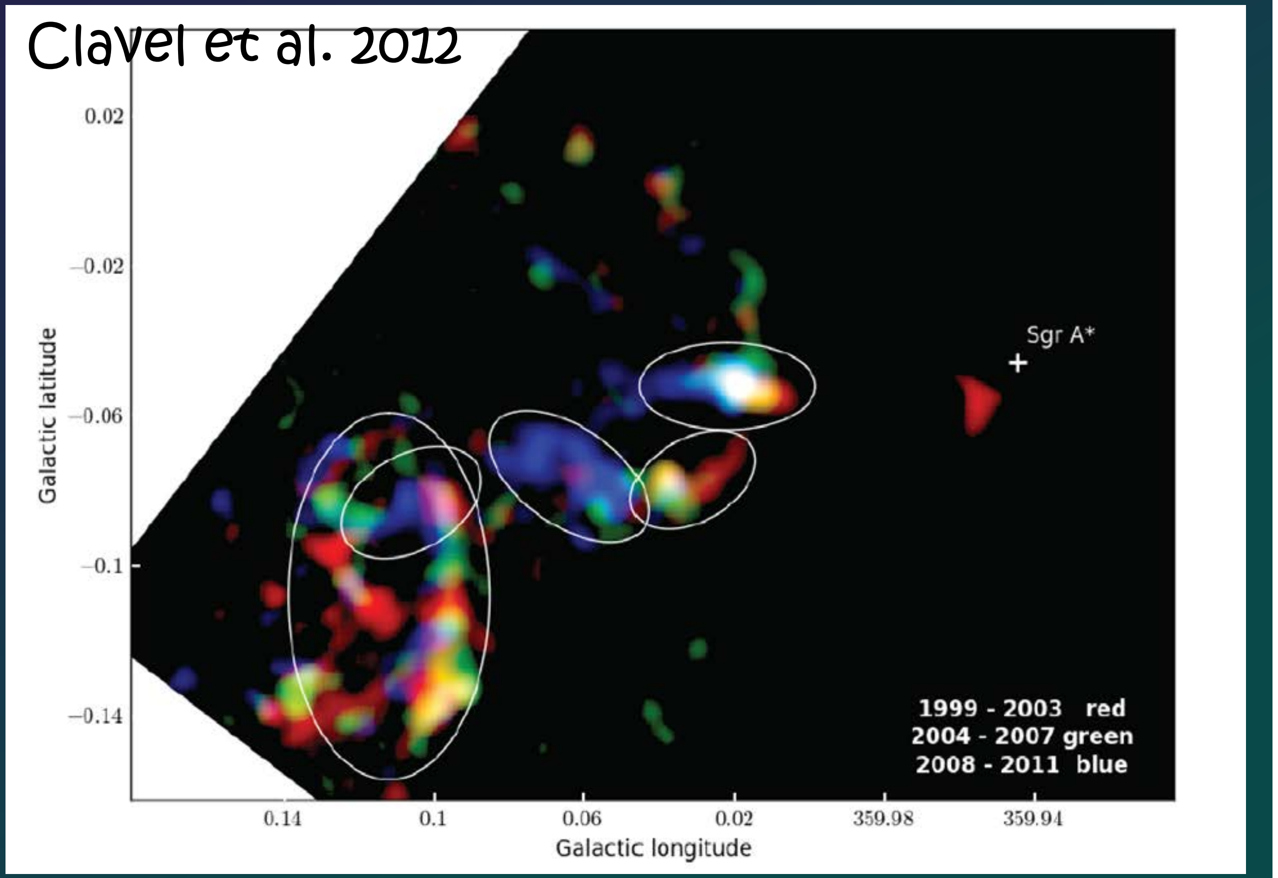
Mark Morris
University of California, Los Angeles

No change of state in the 4+ decades since Sgr A* was discovered …

BUT, there have been multiple extreme events on 100 – 200 year time scales

→ Moving fluorescent Fe^{0} line emission at 6.4 keV interpreted as flares of 2- to >10-year duration and energies of several $\times 10^{39}$ ergs s^{-1}





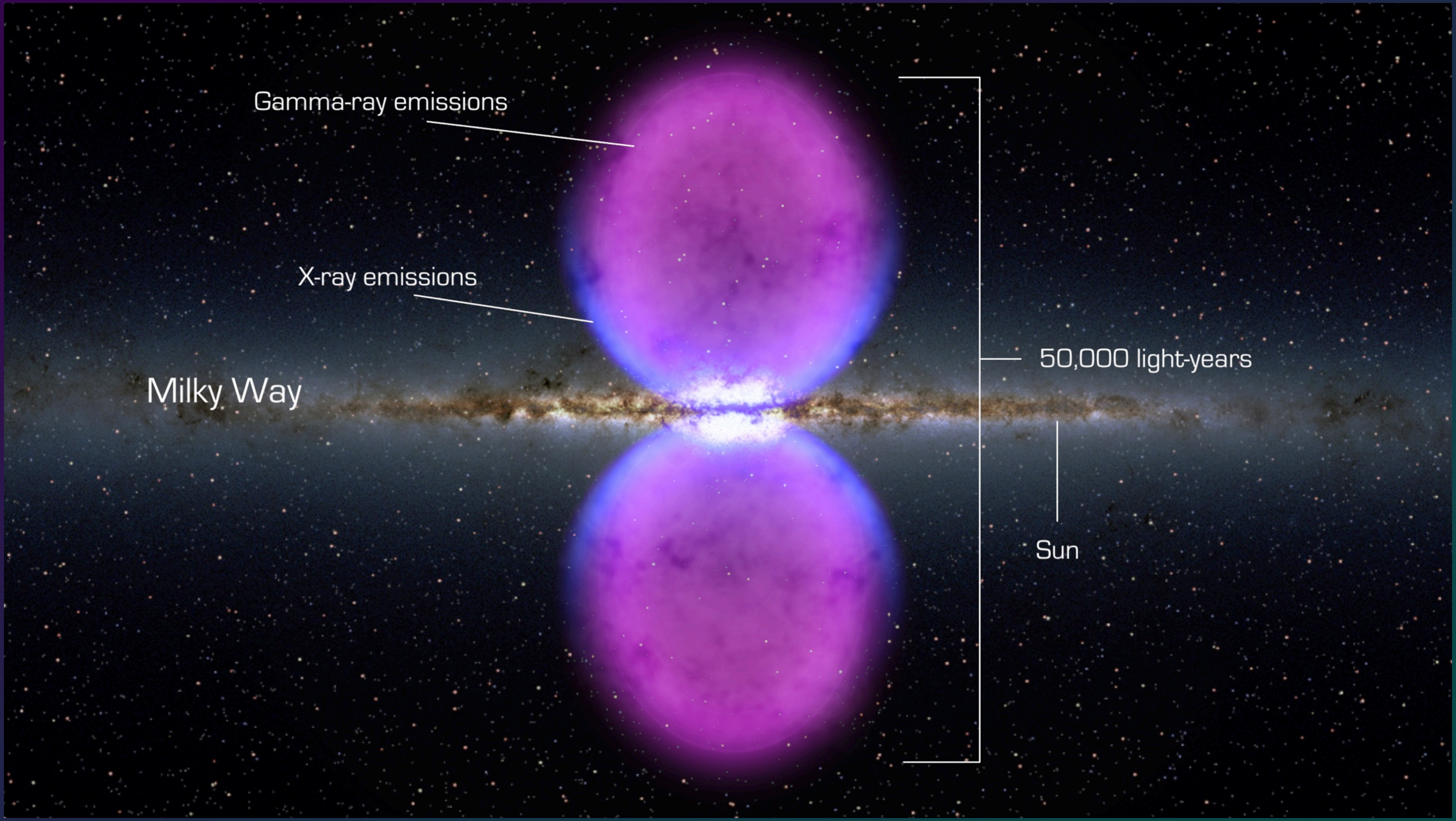
Past high levels of activity involving accretion near the Eddington rate is highly probable. Evidence:

- Central young star cluster — $10^4\ M_\odot$, age 4 – 6 × 10^6 years
  → Star formation in immediate vicinity (< 0.5 pc) of black hole means abundant gas, in contrast to present situation

- Residual ionization in the Magellanic stream from a UV flash several million years ago (Bland-Hawthorne et al. 2013)

- Fermi Bubbles – created by a brief accretion event?

Fermi Bubbles – high energy gamma rays



In contrast to jets,

broadly collimated outflows

from the Galactic center

The Fermi Bubbles, for example, are broadly collimated

A small-scale (5 pc) example:

Deformed magnetic field features on opposite sides of Sgr A*
Has a plasma jet from the center deformed the field?

In contrast to jets,

broadly collimated outflows

from the Galactic center

Two more broadly collimated examples on scales of 15 pc and 150 pc:

15-pc: Bipolar X-ray/radio lobes

150-pc: The Galactic Center Chimney

Fermi Bubbles – two fundamentally different hypotheses

I. Star formation throughout the Central Molecular Zone (300 pc)

Crocker & Aharonian 2011
Crocker 2012, Lacki 2014
Crocker et al. 2015

Hadronic, long-lived (> 10^8 years), plus secondary electron component to account for: microwave haze, polarized radio emission, and soft X-rays at lower boundary

II. Outflow launched by nuclear activity – inner parsec

Su et al. 2010, Zubovas, King & Nayakshin 2011
Zubovas & Nayakshin 2012
Guo & Mathews 2012, Yang et al. 2012

Leptonic, produced on short time scales (few Myrs), and could be identified with event that produced the central young cluster

What collimates the large-scale outflows?

(inner accretion disk tends to make jets)

→ Vertical density gradient, which is present and obvious

- scale height of gas layer ~ 30 pc

→ The Galactic center's vertical (dipole) magnetic field

<> B ~ 0.1 – 1 mG

<> magnetic pressure, $B^2/8\pi$, may be dominant

<> Strong implications for cosmic ray diffusion: the field basically escorts cosmic rays vertically out of the Galaxy. → favors hadronic model.


Dali, Yunnan Province, China


IP
超
市


牛中王

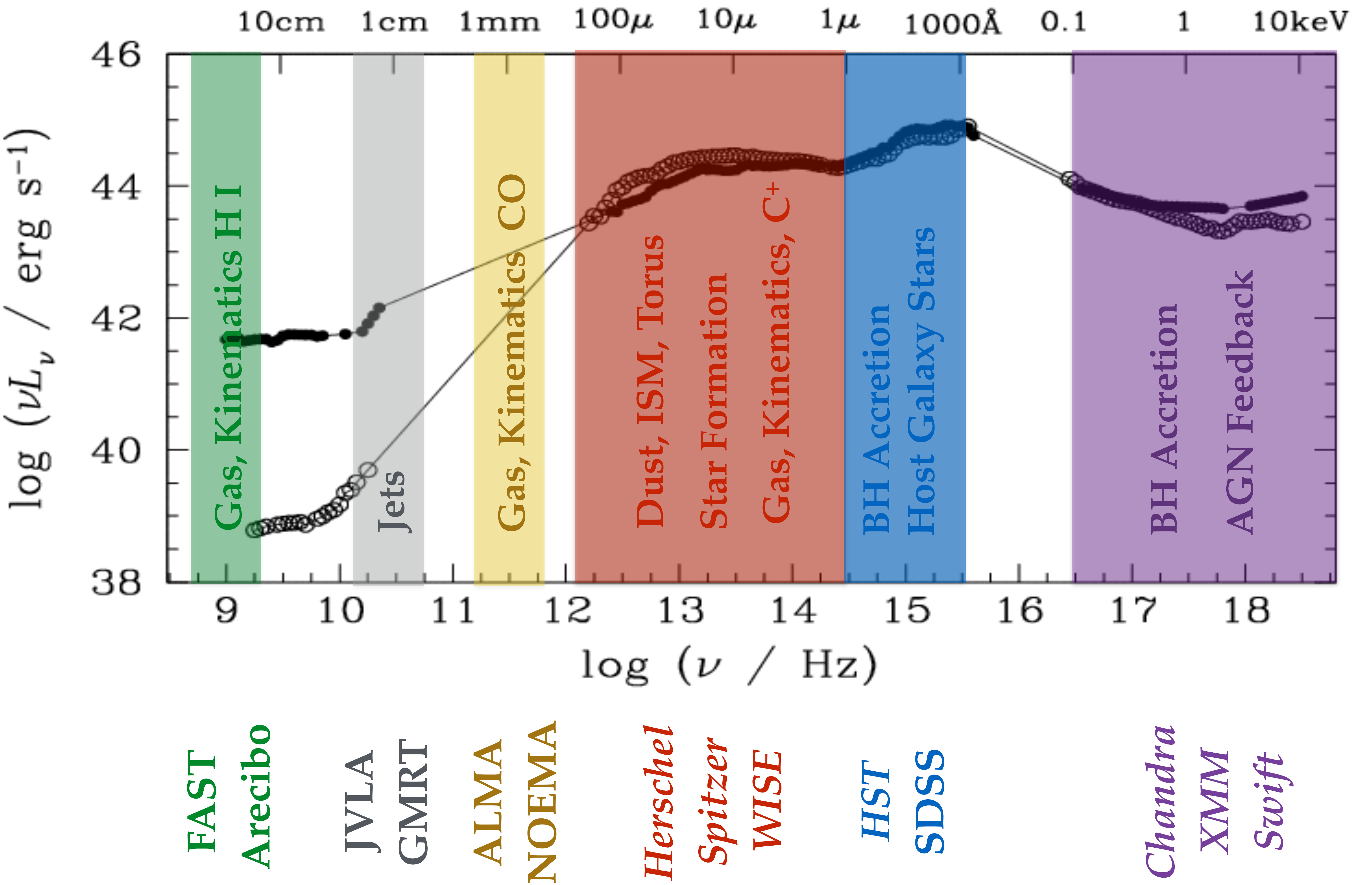
Some Thorny Problems for AGNs

Luis C. Ho（何子山）

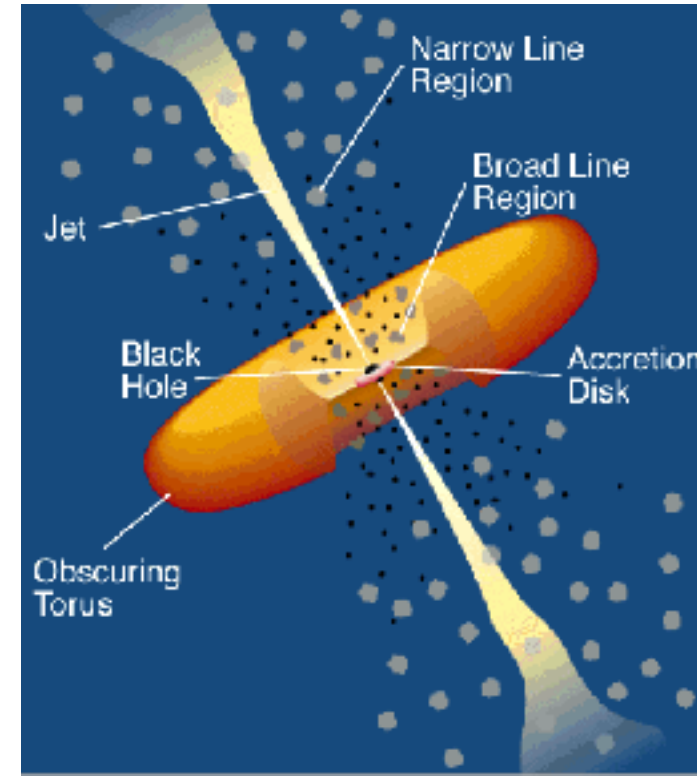
Kavli Institute for Astronomy and Astrophysics

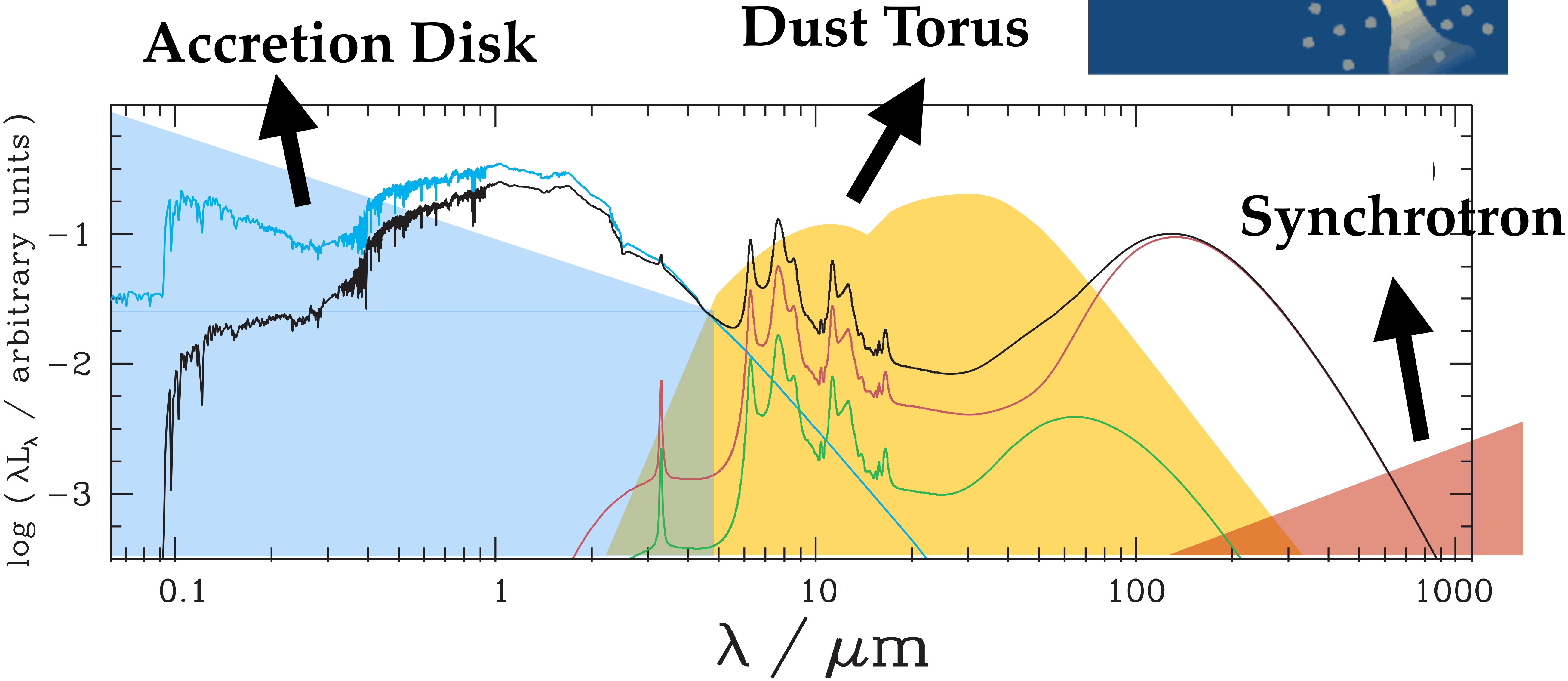
Peking University

Spectral Energy Distribution



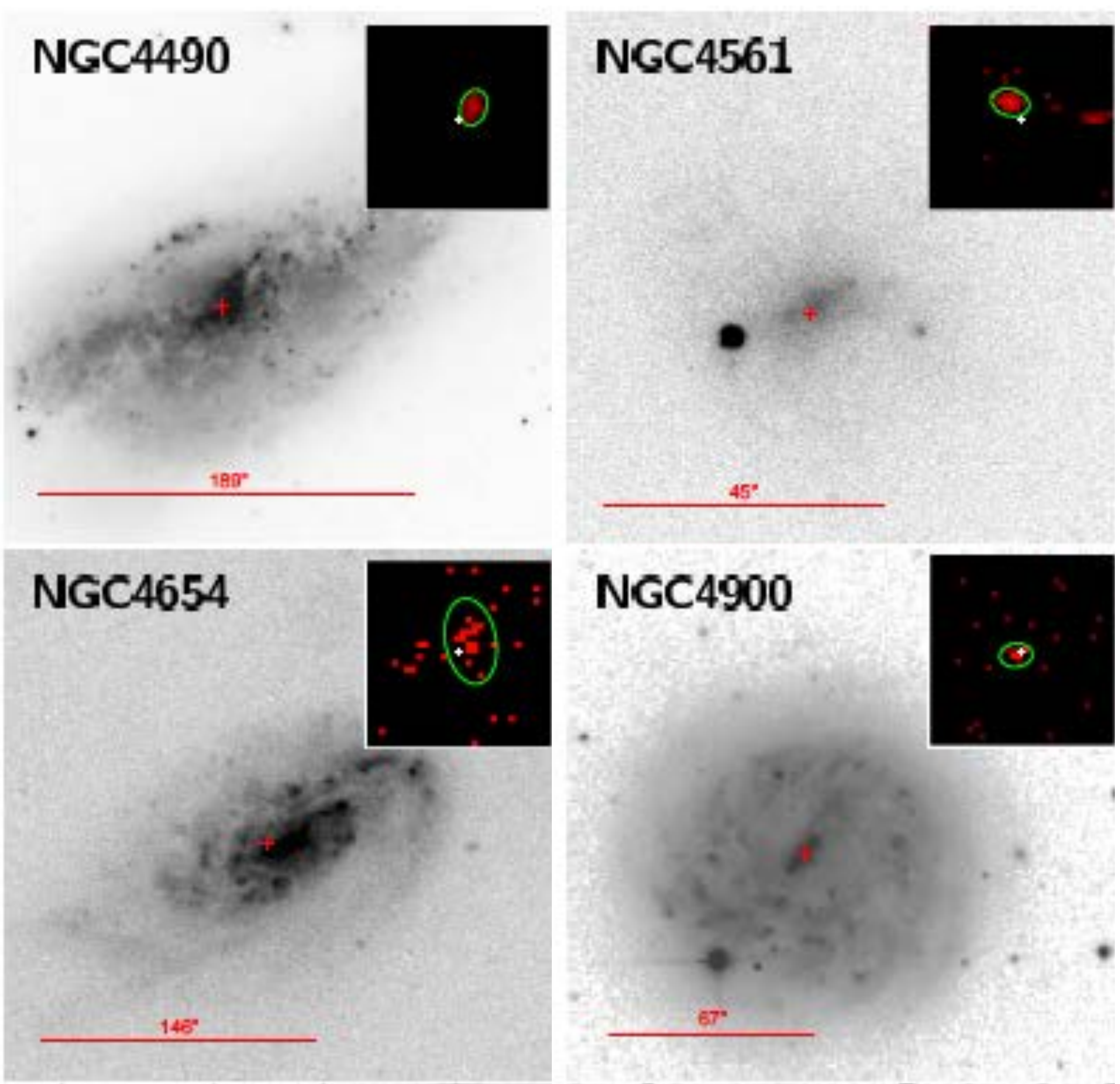
The AGN outshines most of SED

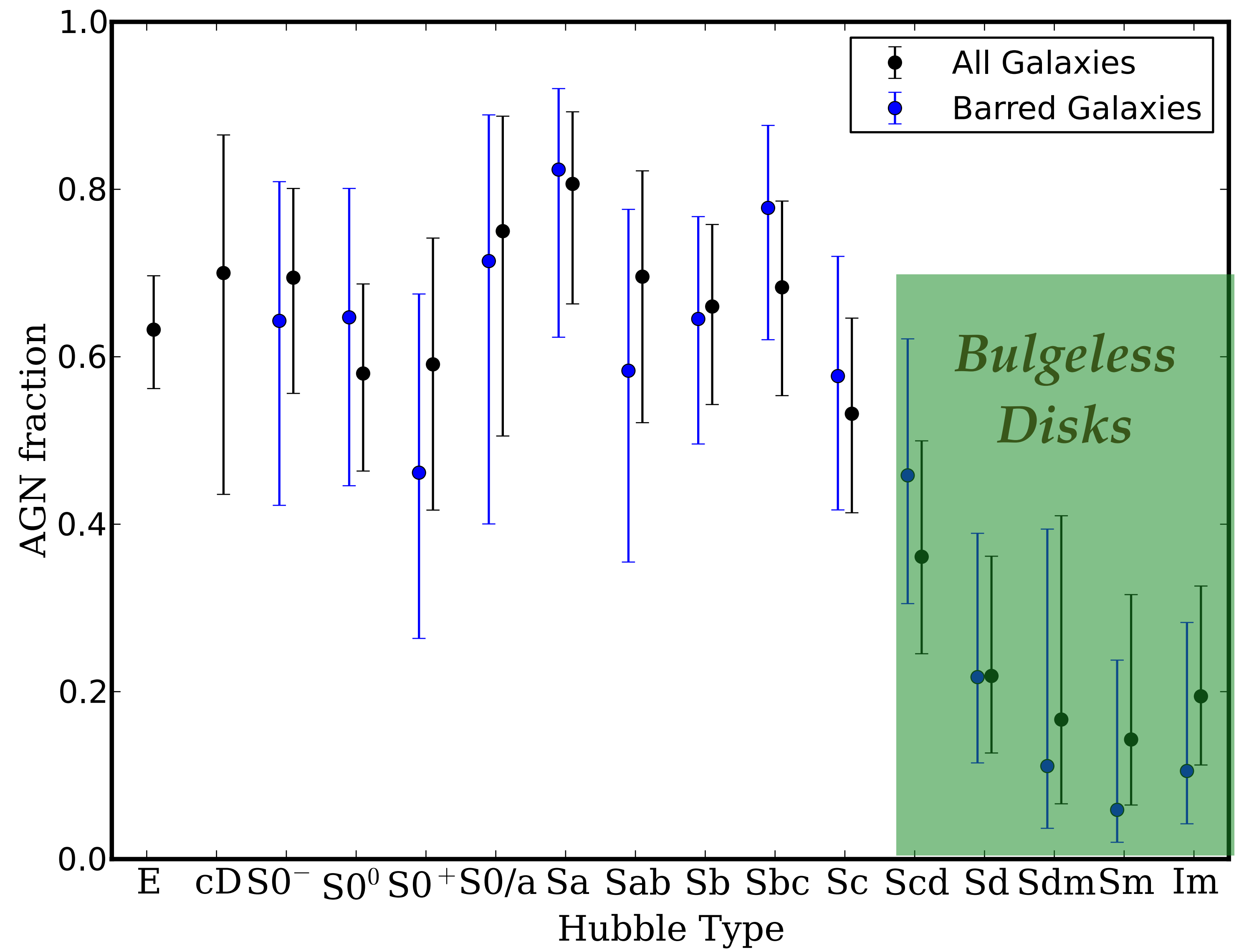




Chandra Survey of Nearby Galaxies: A Significant Population of Candidate Central Black Holes in Late-type Galaxies

Rui She[1], Luis C. Ho[2,3], Hua Feng[1]

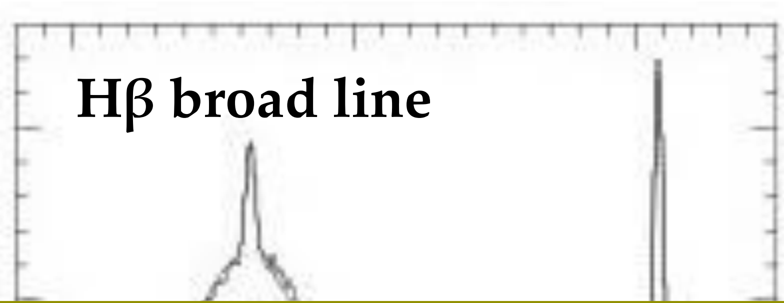




M 87 (stars): $M_\bullet = (6.2 \pm 0.38) \times 10^9\, M_\odot$ *(Gebhardt et al. 2011)*

M 87 (gas): $M_\bullet = (3.5 \pm 0.85) \times 10^9\, M_\odot$ *(Walsh et al. 2013)*

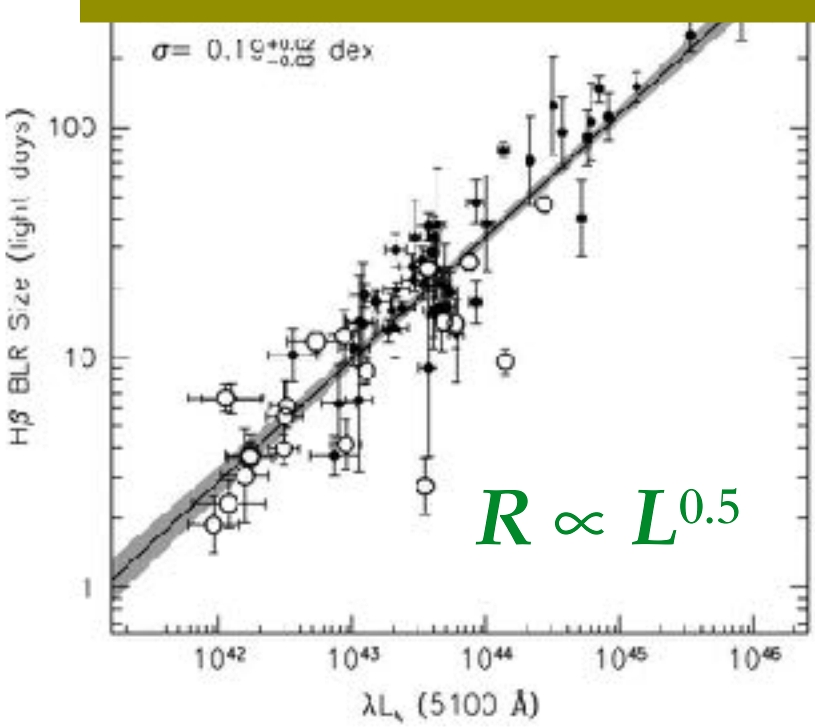
Reverberation Mapping

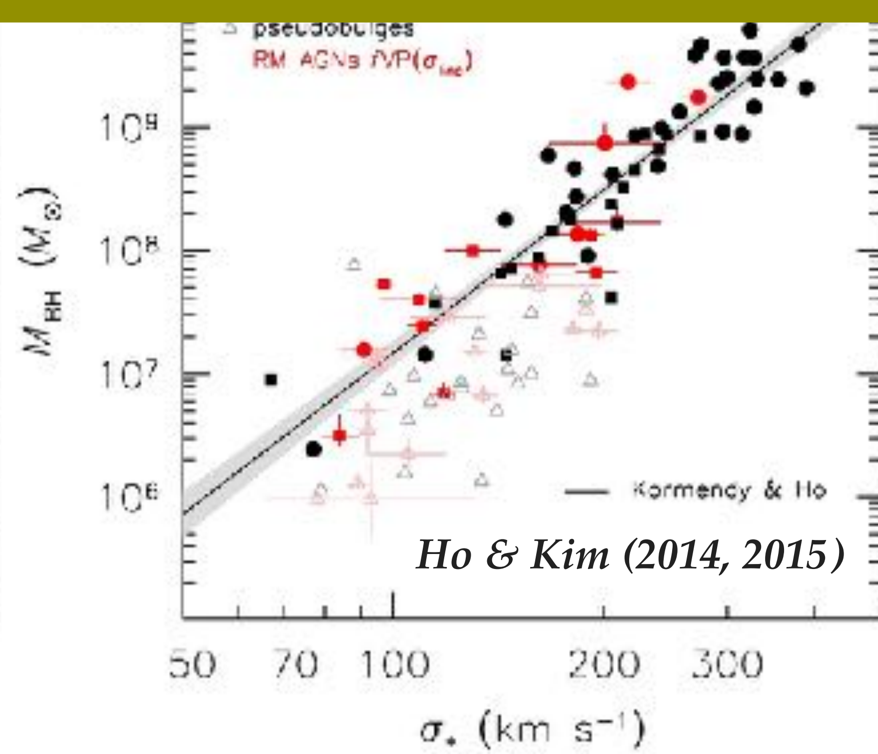


$$M_{\rm virial} = f\, R V^2/G$$

f virial factor

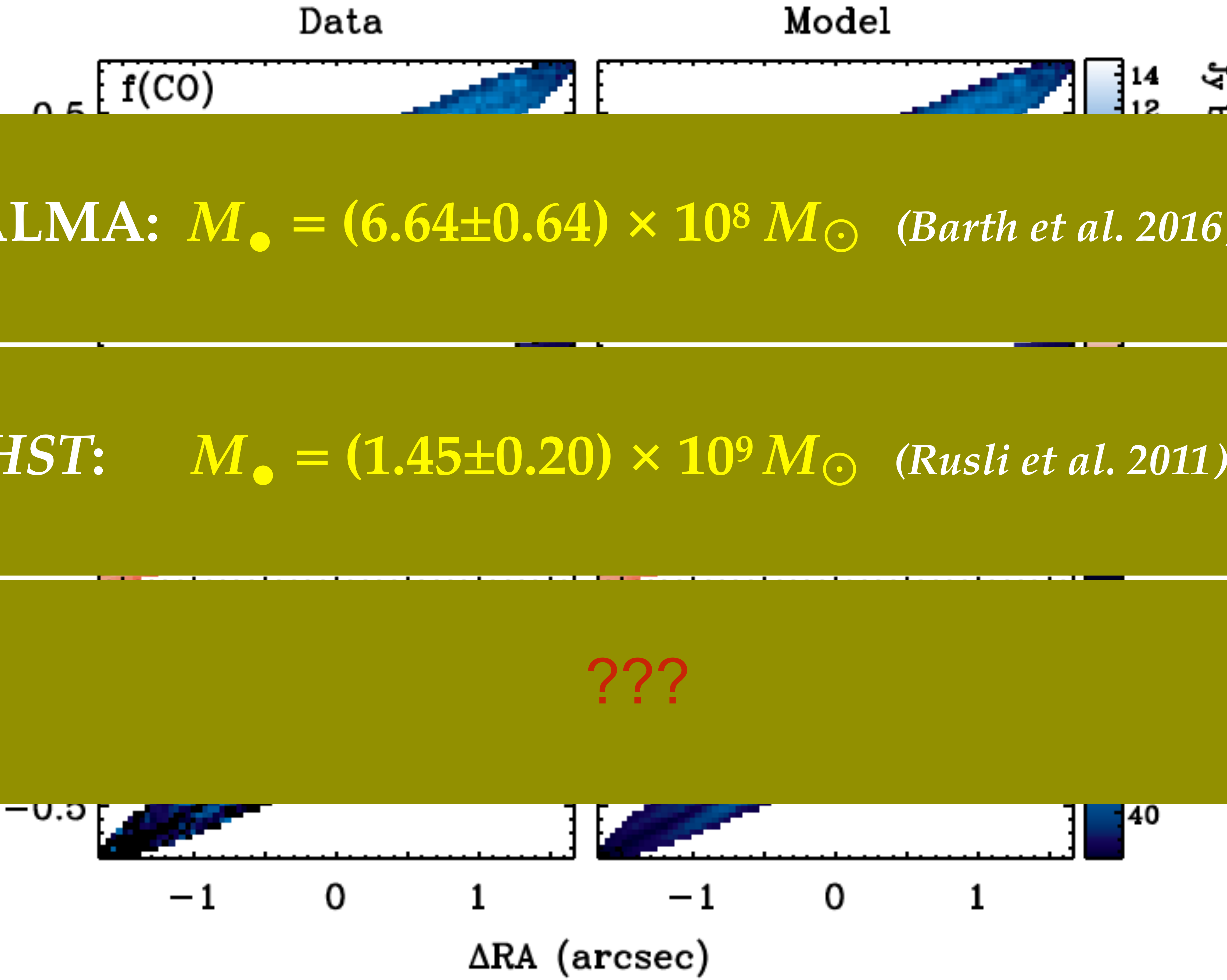
Can we *ever* estimate BH masses for AGNs better than a factor of 2–3?





uncertainty: $\dfrac{\Delta M_\bullet}{M_\bullet} \sim 2 - 3$

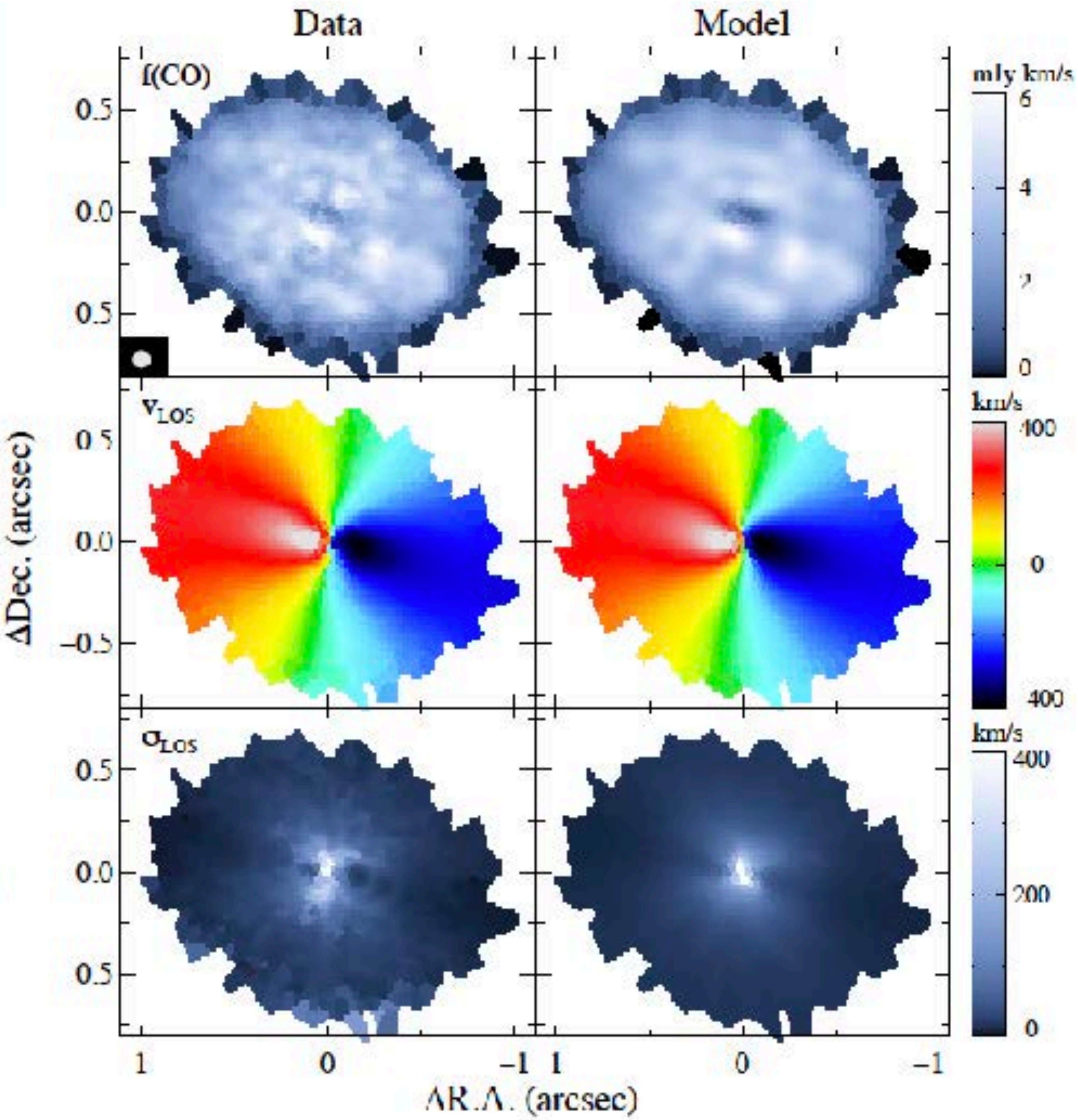
$\Delta \log M_\bullet \sim 0.3 - 0.5$



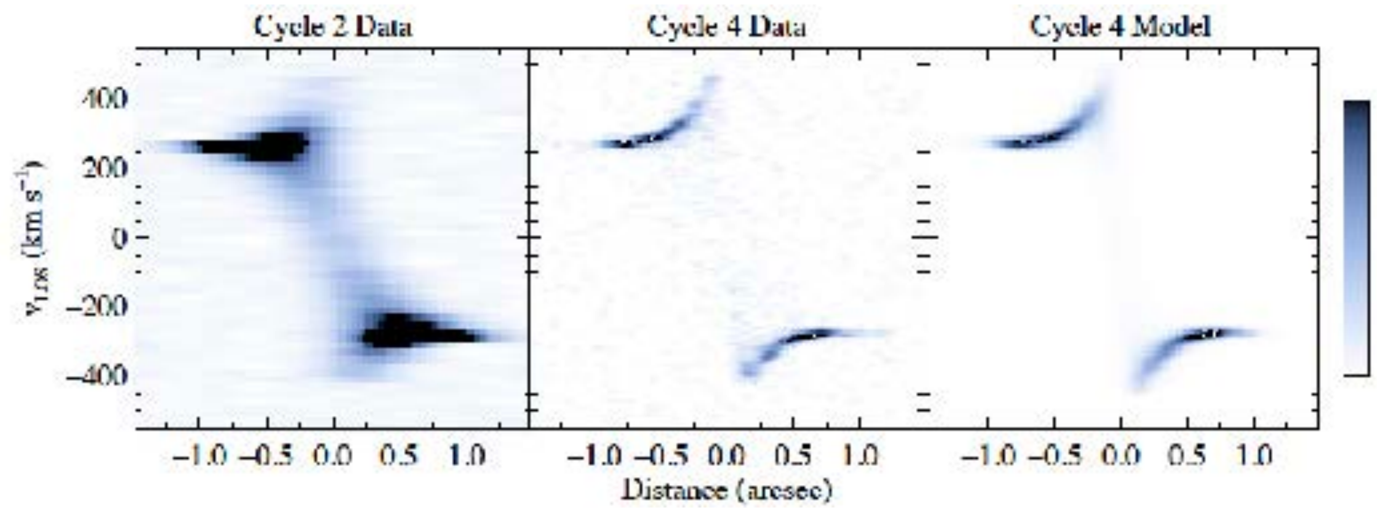
ALMA: $M_\bullet = (6.64 \pm 0.64) \times 10^8 \, M_\odot$ *(Barth et al. 2016)*

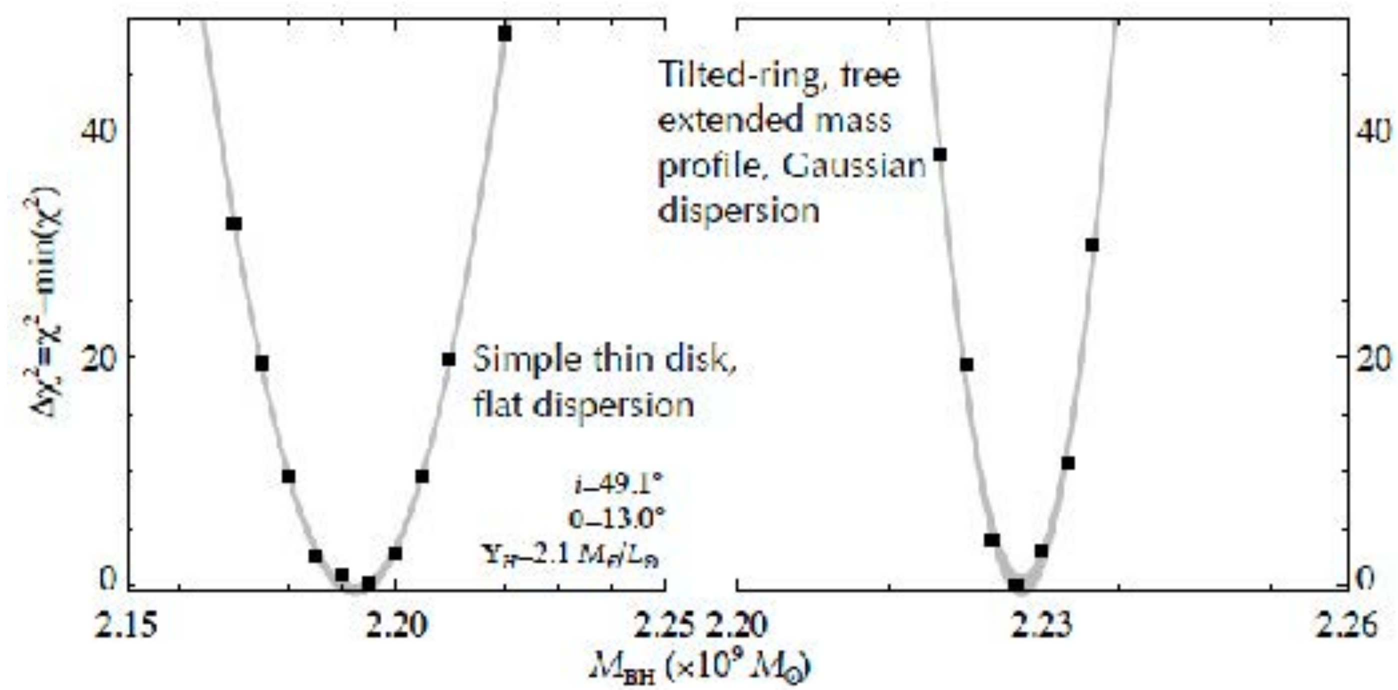
***HST*:** $M_\bullet = (1.45 \pm 0.20) \times 10^9 \, M_\odot$ *(Rusli et al. 2011)*

???

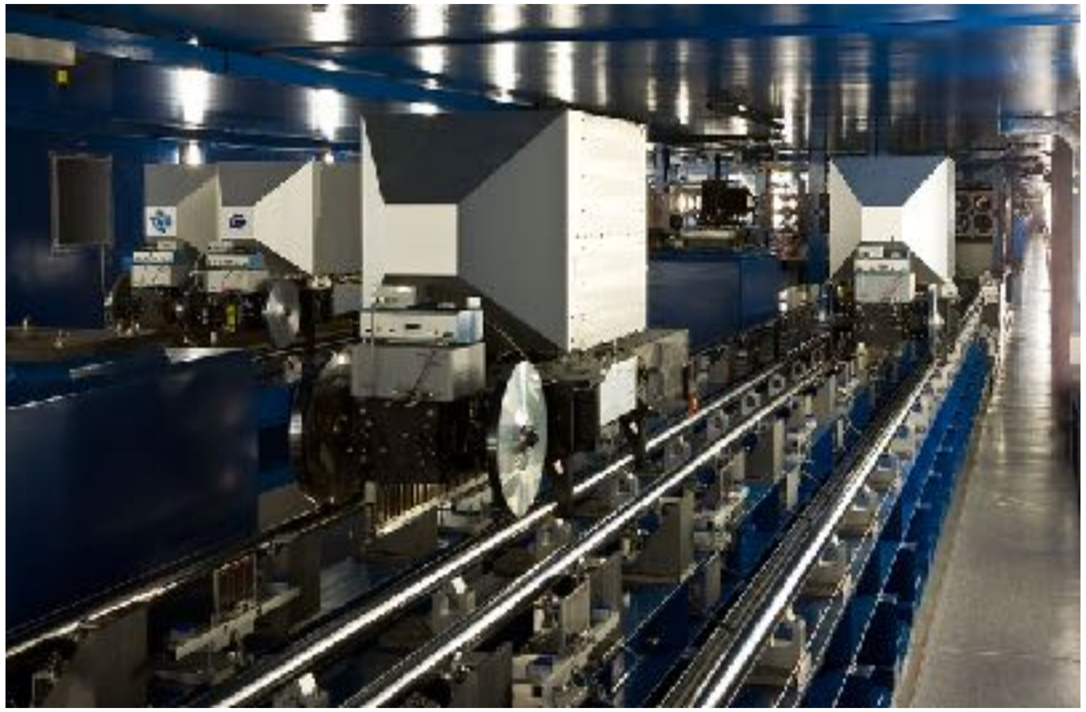


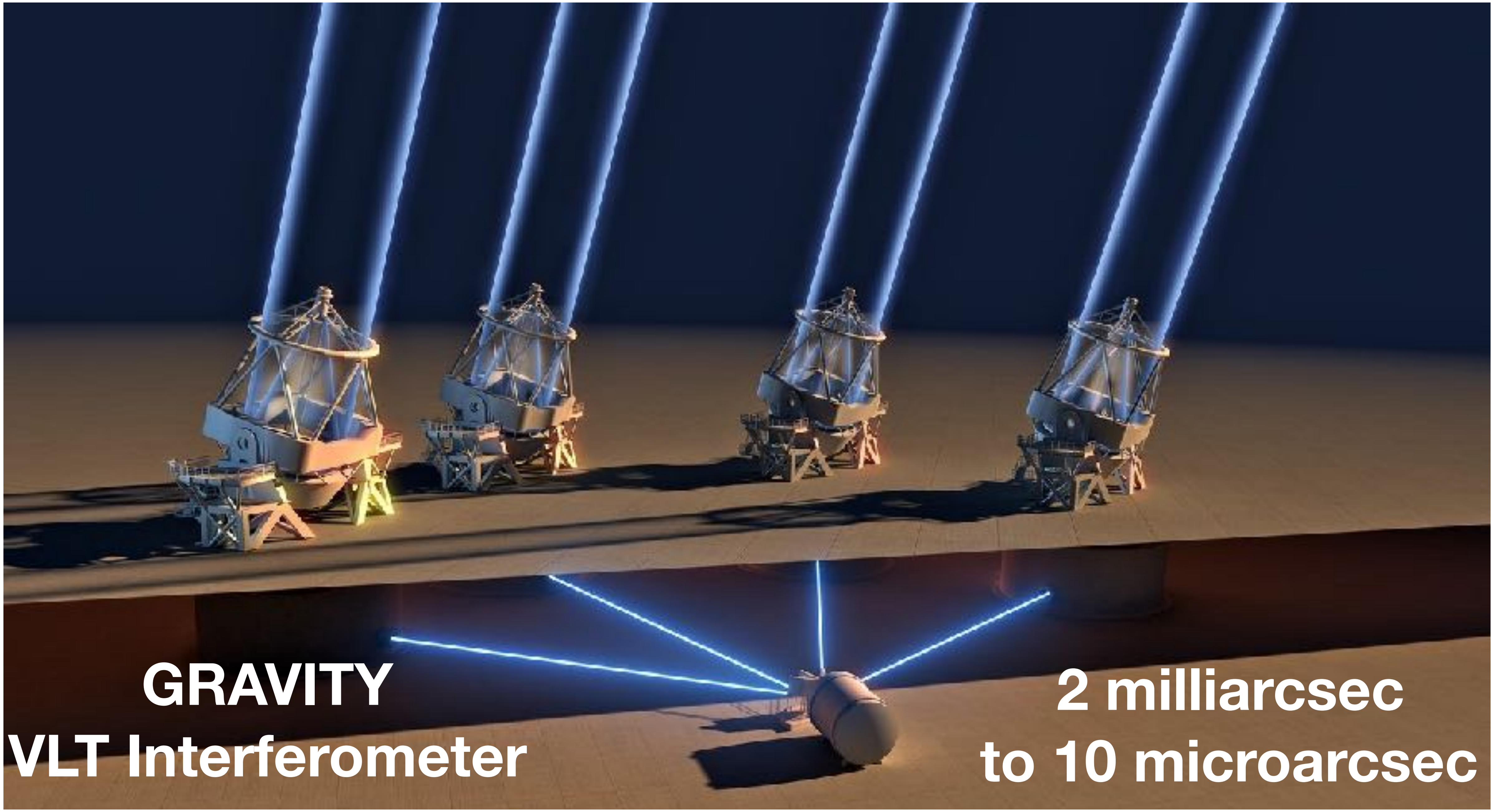
Boizelle, Barth, Ho, et al. (2018)



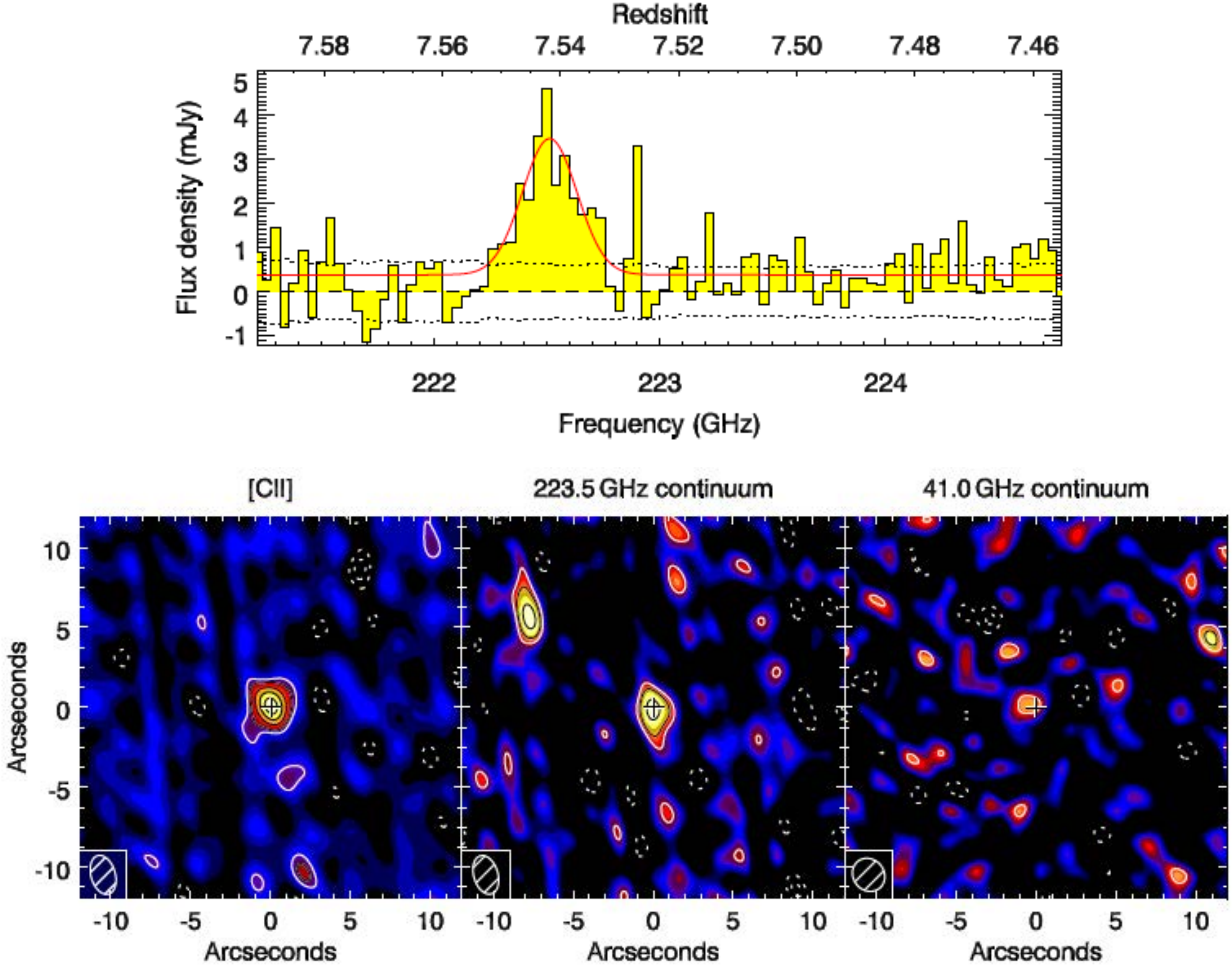


- ☐ **resolution < 0.1″**
- ☐ **ALMA CO(2-1)**
- ☐ ***M_{BH}* uncertainty < 6%**

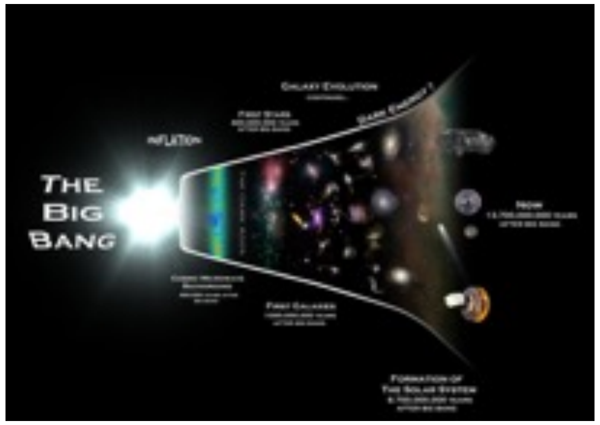


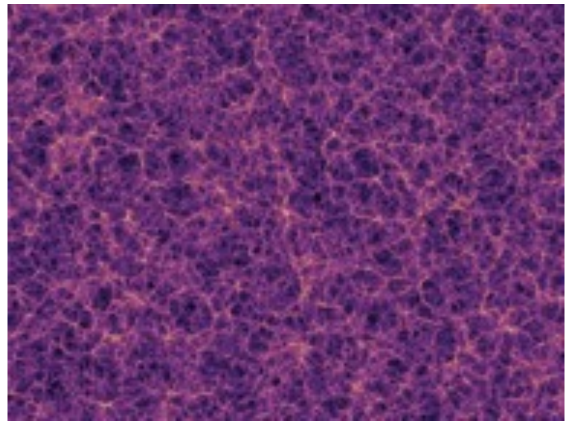

GRAVITY
VLT Interferometer
2 milliarcsec
to 10 microarcsec

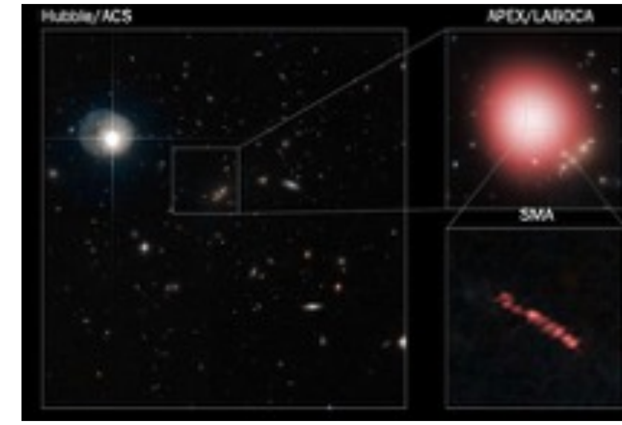
Dynamical Masses Using Radio Lines



Venemans et al. (2017b)

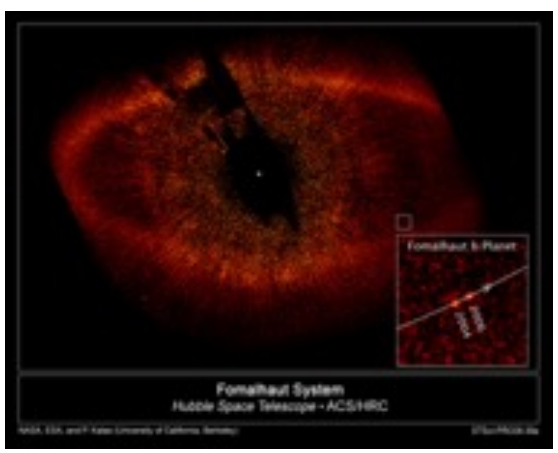







Central Star Formation in Galaxies

Steve Longmore






LIVERPOOL JOHN MOORES UNIVERSITY


Review: $\dot{M}$(r,t) and SFR(r,t)

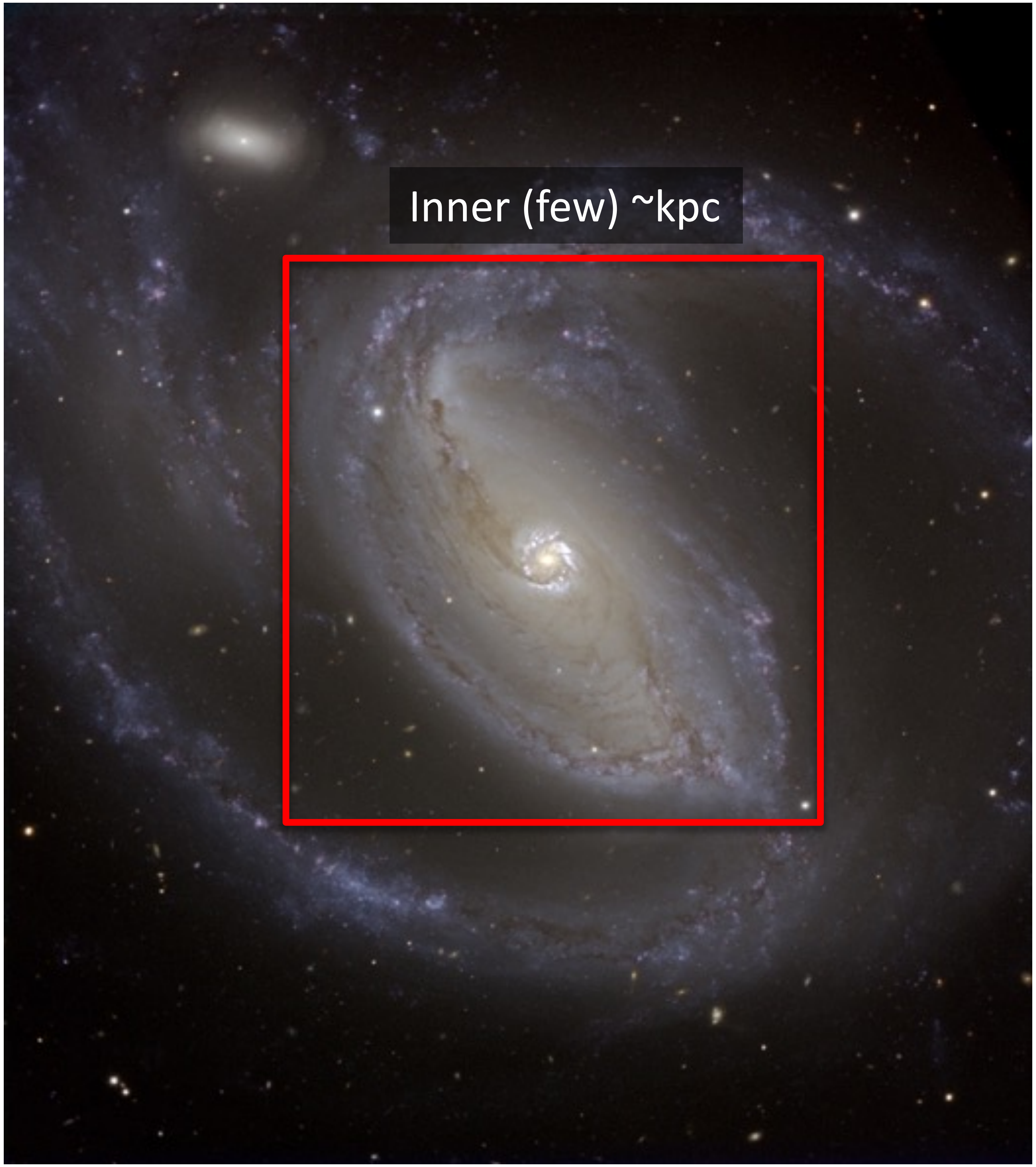
Talk outline

Goal**:** review our current understanding of the physical mechanisms controlling the mass inflow and star formation in the centres of galaxies.

Enormous amount of literature on this topic and secular evolution of galaxies (e.g. Kormendy & Ho ARAA)

Focus on recent developments driven by improvements in numerical simulations and high resolution/sensitivity gas observations.

Review: $\dot{M}$(r,t) and *SFR*(r,t)

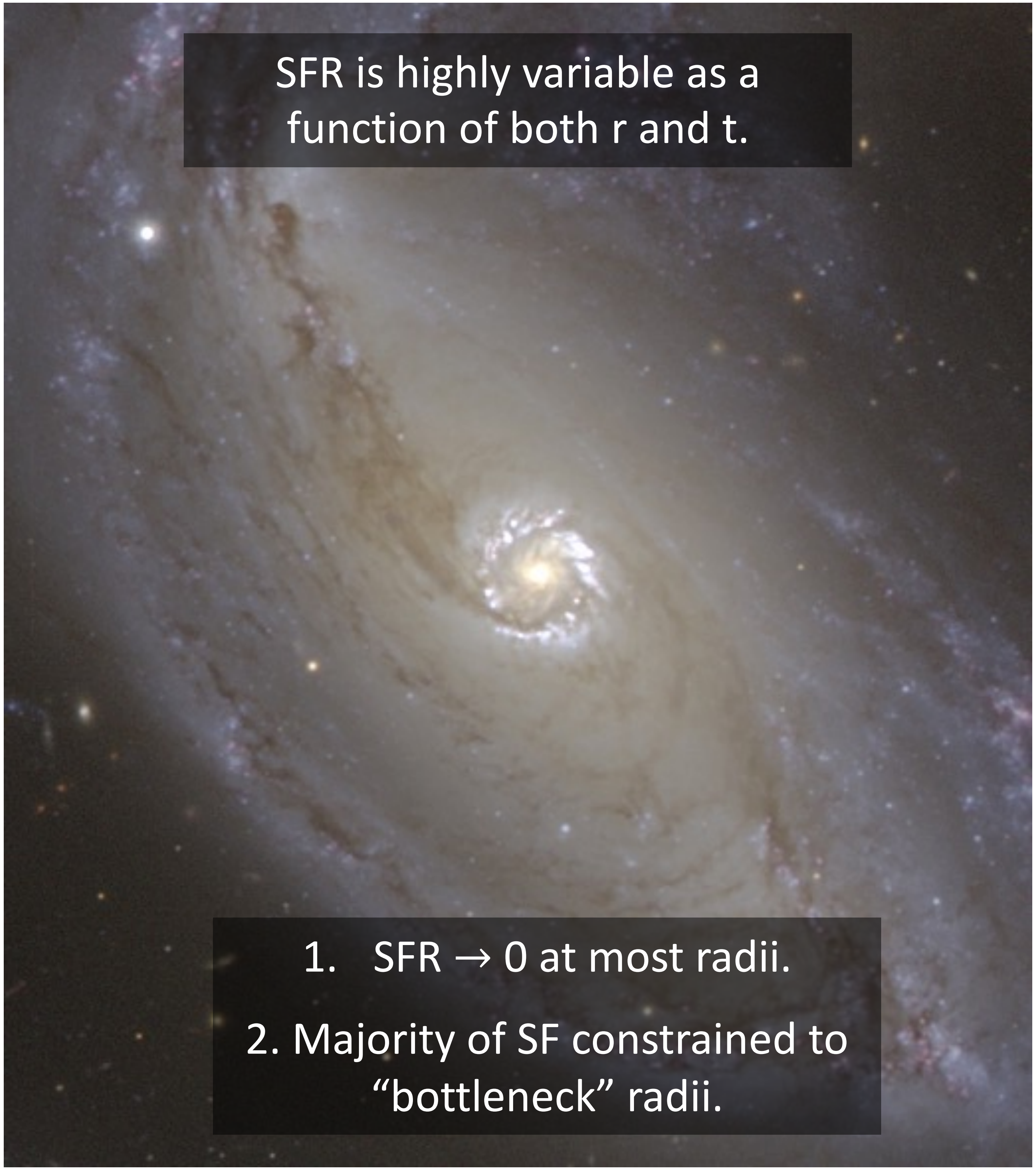


Review: $\dot{M}$(r,t) and *SFR*(r,t)

$\dot{M}$ is highly variable as a function of both r and t.

Bottlenecks in mass inflow at specific radii driven by shear, minima, instabilities or orbital pile up.

Review: $\dot{M}$(r,t) and SFR(r,t)



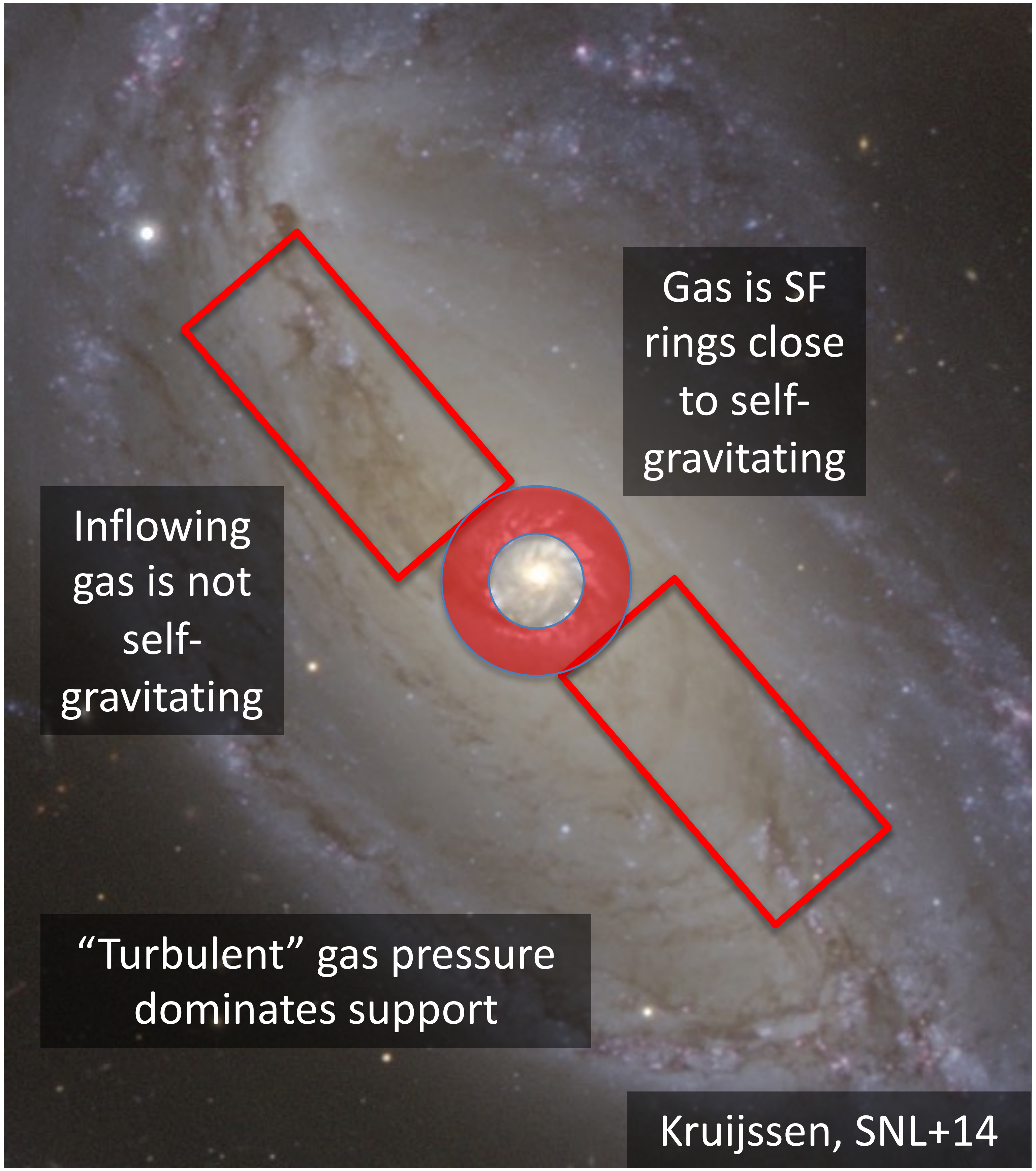
SFR → Not proportional to Σ^a, ρ^b, M(N>10^{21}cm^{-2})

Longmore+13, Leroy+, Bigiel+, Usero+, Meidt+, Barnes+

SFR → Incompatible with environmentally independent SF relations

SFR → Broadly consistent with environmentally dependent predictions

Review: $\dot{M}$(r,t) and SFR(r,t)



SFR → Not proportional to Σ^a, ρ^b, $M(N>10^{21}\text{cm}^{-2})$

Longmore+13, Leroy+, Bigiel+, Usero+, Meidt+, Barnes+

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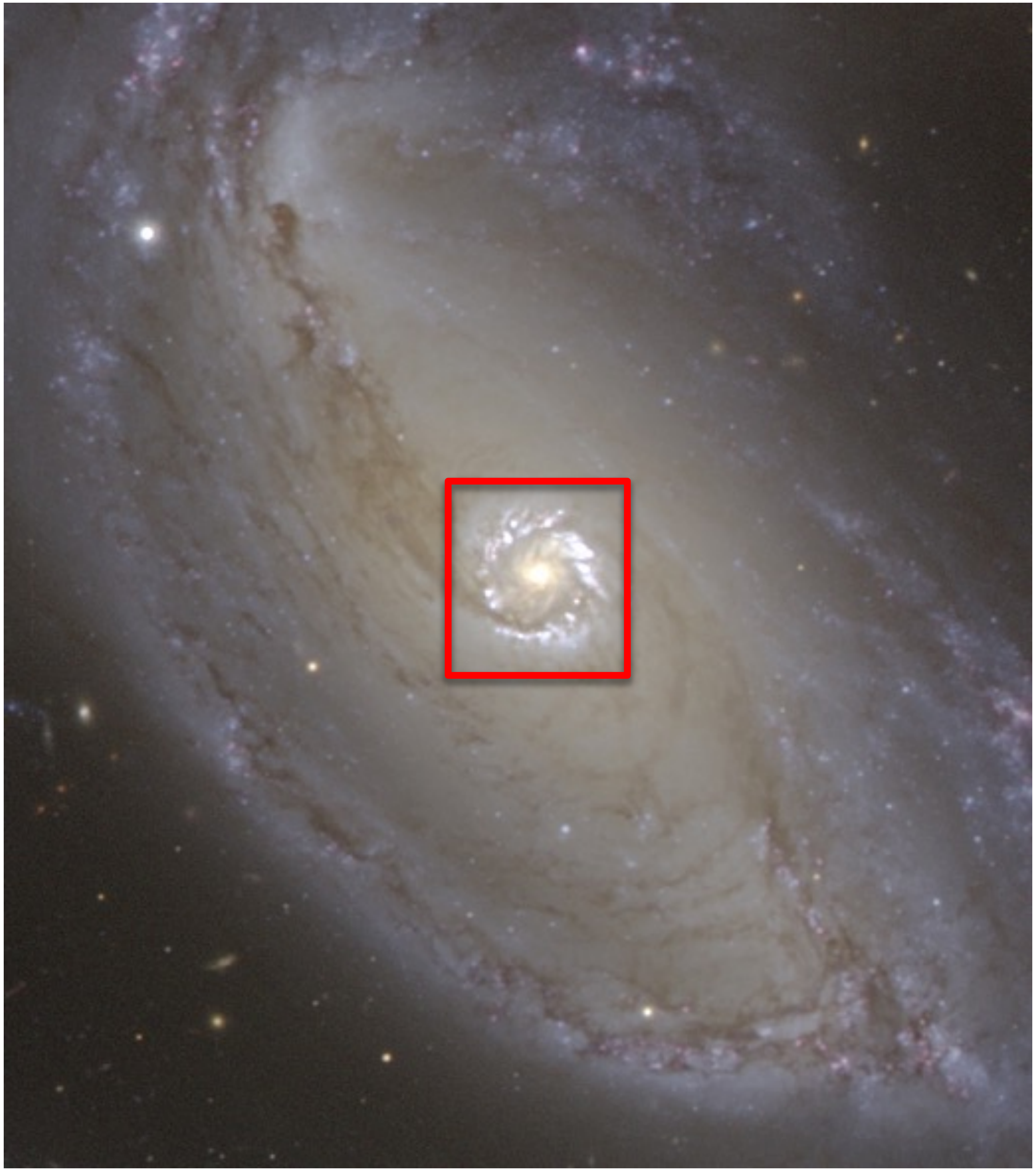
Review: $\dot{M}$(r,t) and *SFR*(r,t)



Review: $\dot{M}$(r,t) and *SFR*(r,t)

Very high degree of turbulence means the gas gets to very high density before forming stars

Initial (proto) stellar density MUCH higher than in the disk (1e4 stars/pc^3)

Star formation highly clustered: e.g. in the MW 50% of stars form in clusters of 1e4 Msun, radius ~pc.

Ginsburg & Kruijssen 2018

Some key open questions

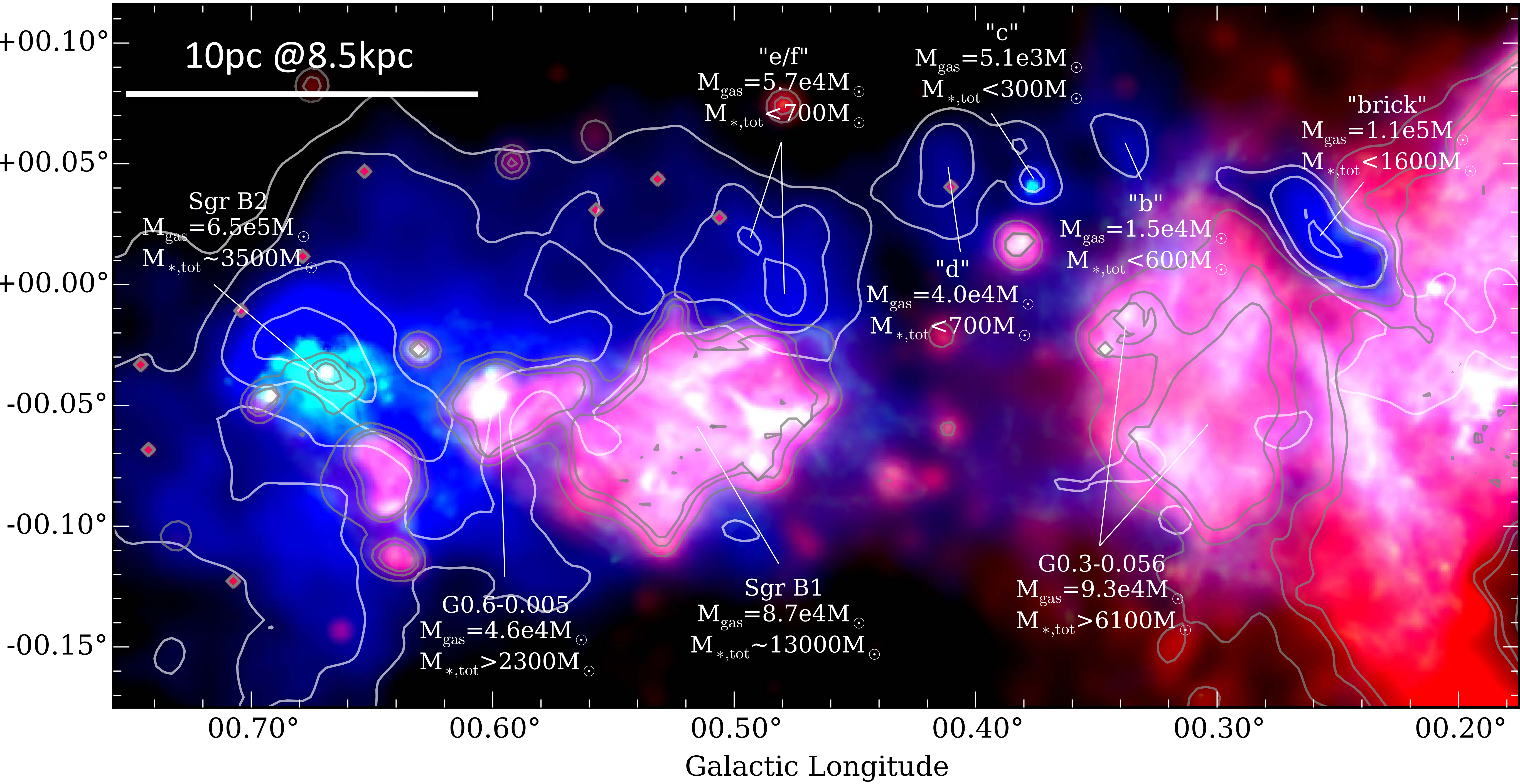
What physical mechanisms are responsible for determining the rate at which the gas piled up at bottleneck radii is transported towards the black hole?

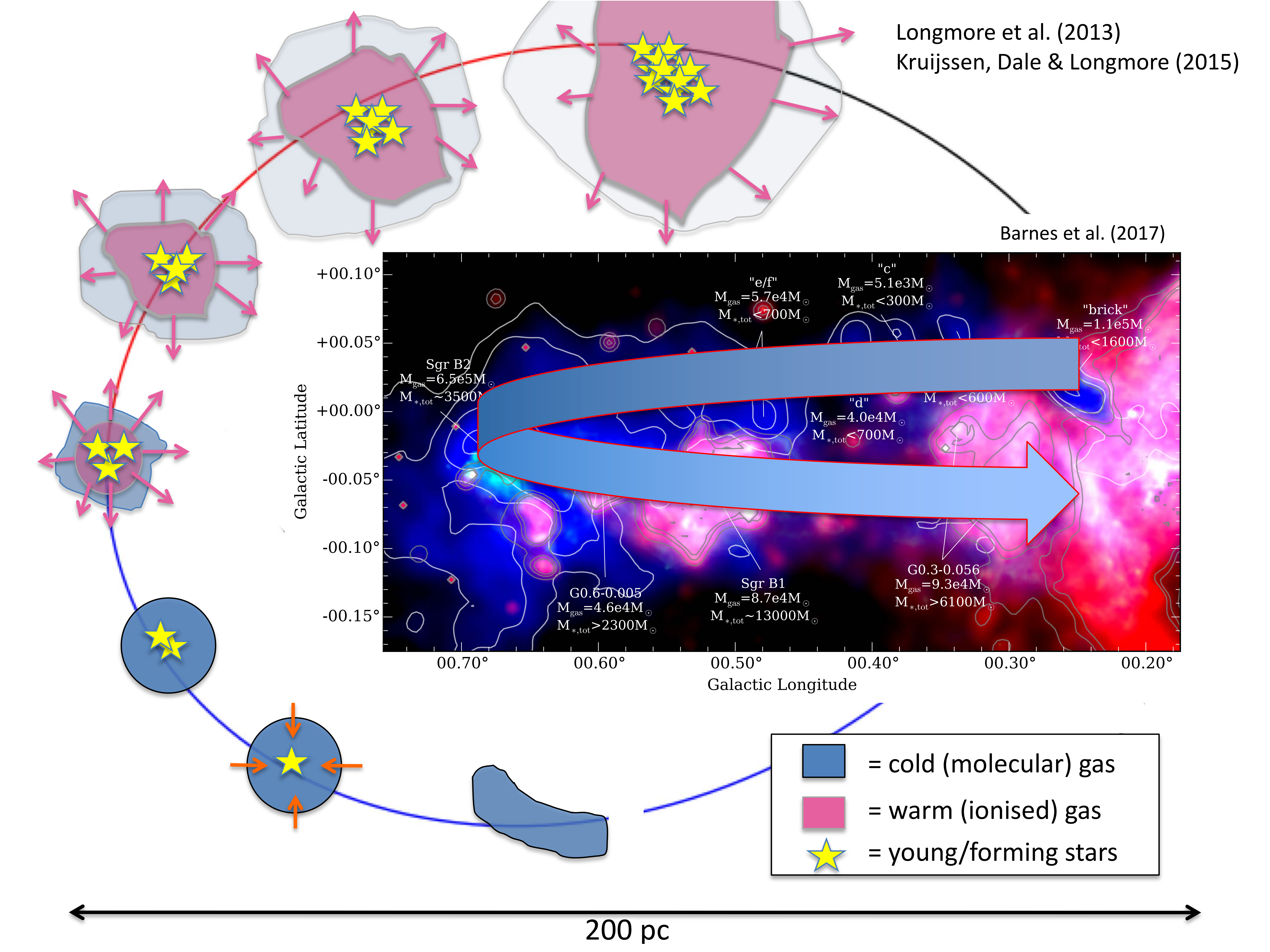
Is (feedback from) star formation important in this further inward transport of gas (e.g helping to remove angular momentum)?

If so, do we expect a link between the timescales for star formation activity and feedback at ~100pc scales, and black hole feeding and feedback?

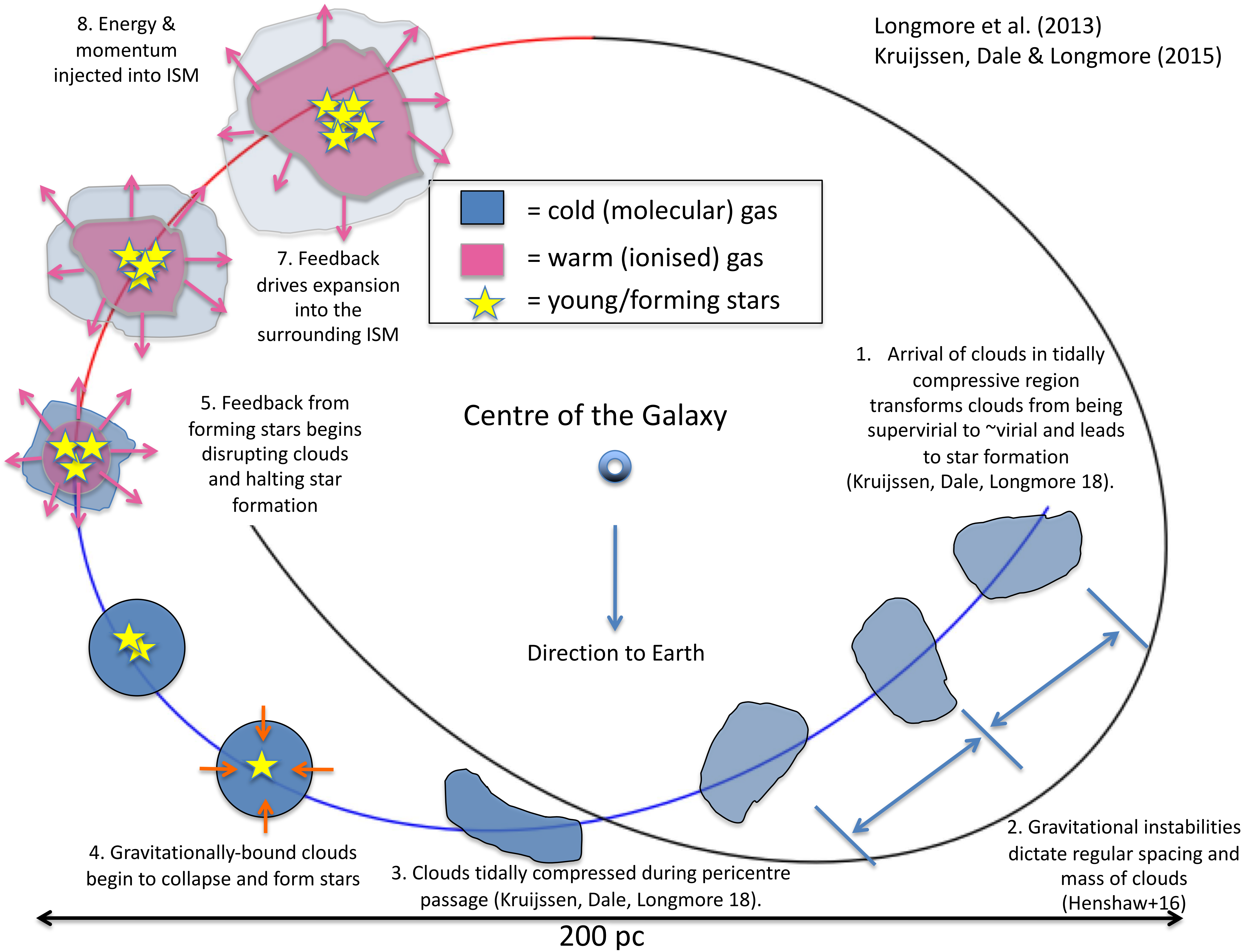
Is the black hole passive or active in such a cycle?

Comparing the distribution of gas and young stars





Longmore et al. (2013)
Kruijssen, Dale & Longmore (2015)
Barnes et al. (2017)
+00.10°
+00.05°
+00.00°
-00.05°
-00.10°
-00.15°
Galactic Latitude
00.70°
00.60°
00.50°
00.40°
00.30°
00.20°
Galactic Longitude
"e/f"
M_gas=5.7e4M⊙
M_*,tot<700M⊙
"c"
M_gas=5.1e3M⊙
M_*,tot<300M⊙
"brick"
M_gas=1.1e5M⊙
<1600M⊙
Sgr B2
M_gas=6.5e5M⊙
"d"
M_gas=4.0e4M⊙
M_*,tot<700M⊙
M_*,tot<600M⊙
G0.6-0.005
M_gas=4.6e4M⊙
M_*,tot>2300M⊙
Sgr B1
M_gas=8.7e4M⊙
M_*,tot~13000M⊙
G0.3-0.056
M_gas=9.3e4M⊙
M_*,tot>6100M⊙
= cold (molecular) gas
= warm (ionised) gas
= young/forming stars
200 pc



Longmore et al. (2013)
Kruijssen, Dale & Longmore (2015)
8. Energy & momentum injected into ISM
7. Feedback drives expansion into the surrounding ISM
= cold (molecular) gas
= warm (ionised) gas
= young/forming stars
5. Feedback from forming stars begins disrupting clouds and halting star formation
Centre of the Galaxy
1. Arrival of clouds in tidally compressive region transforms clouds from being supervirial to ~virial and leads to star formation (Kruijssen, Dale, Longmore 18).
Direction to Earth
4. Gravitationally-bound clouds begin to collapse and form stars
3. Clouds tidally compressed during pericentre passage (Kruijssen, Dale, Longmore 18).
2. Gravitational instabilities dictate regular spacing and mass of clouds (Henshaw+16)
200 pc

Conclusions: $\dot{M}$(r,t) and *SFR*(r,t)

$\dot{M}$(r,t) → highly variable with r , t

Bottlenecks in $\dot{M}$ at specific r.

SFR → highly variable with r and t.

M, α, ρ_0 → ρ_{crit}

M($\rho > \rho_{crit}$) → SFR_{ff} ~2%

Feedback in MW GC

Gas around young stellar clusters expelled to >10pc within ~Myr

- P_{HII} dominant by 2 orders of magnitude
- Gas cleared to tens of pc before SNe explode
- Energy and momentum feedback efficiency few %

Feedback shaping baryon cycles

SF bursty/episodic:
~20 Myr duty cycle, SFR varies by 1-2 dex

↓

Stellar feedback highly localised in space and time

↓

Important part of galactic-scale feedback cycle