Dark Matter and Black Holes, December 1-5th 2025

Dark matter around black holes: tracing spikes

Based on *"A novel method to trace the dark matter density profile around supermassive black holes with AGN reverberation mapping"*
arXiv: 2506.10122
Much thanks to collaborators Gonzalo Herrera and Mayank Sharma

Shunsaku Horiuchi

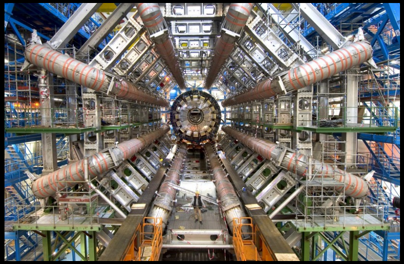
Institute of Science Tokyo
Virginia Tech
Kavli IPMU

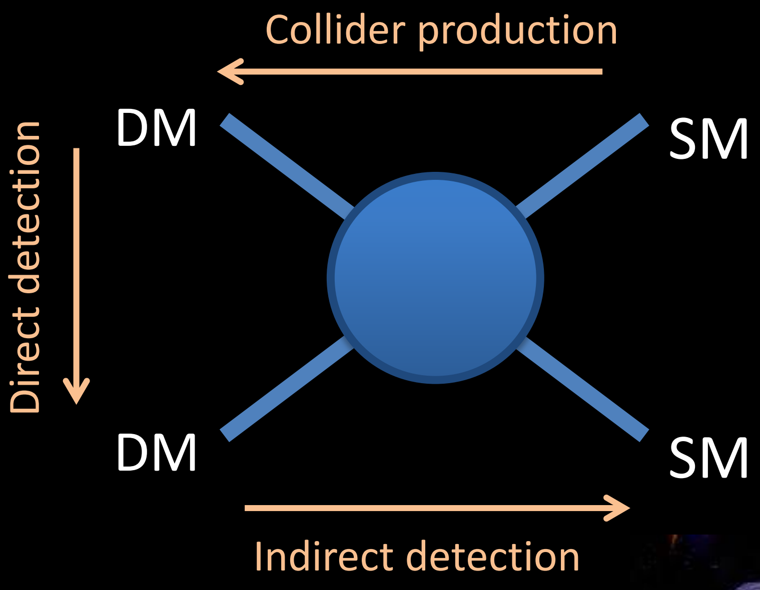
Dark matter probes

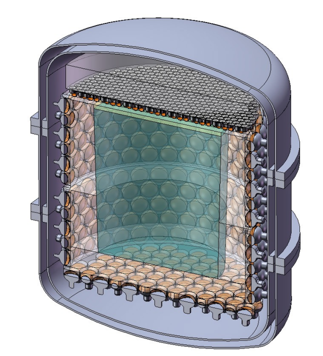
Many ways to seek dark matter:

- Indirect detection
- Direct detection
- Collider production

- Structure formation and evolution





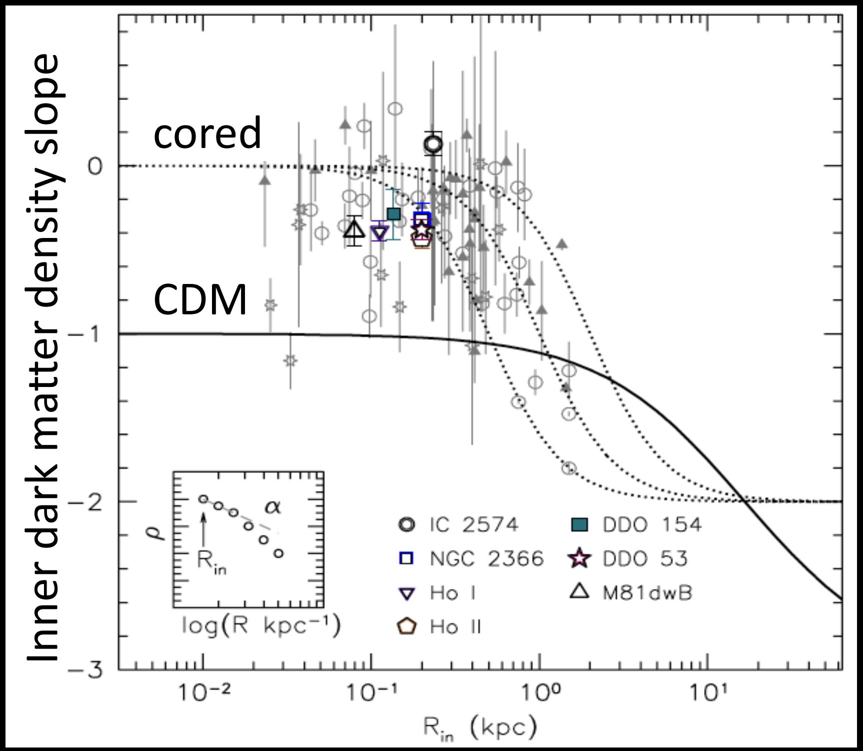


Dark matter distributions

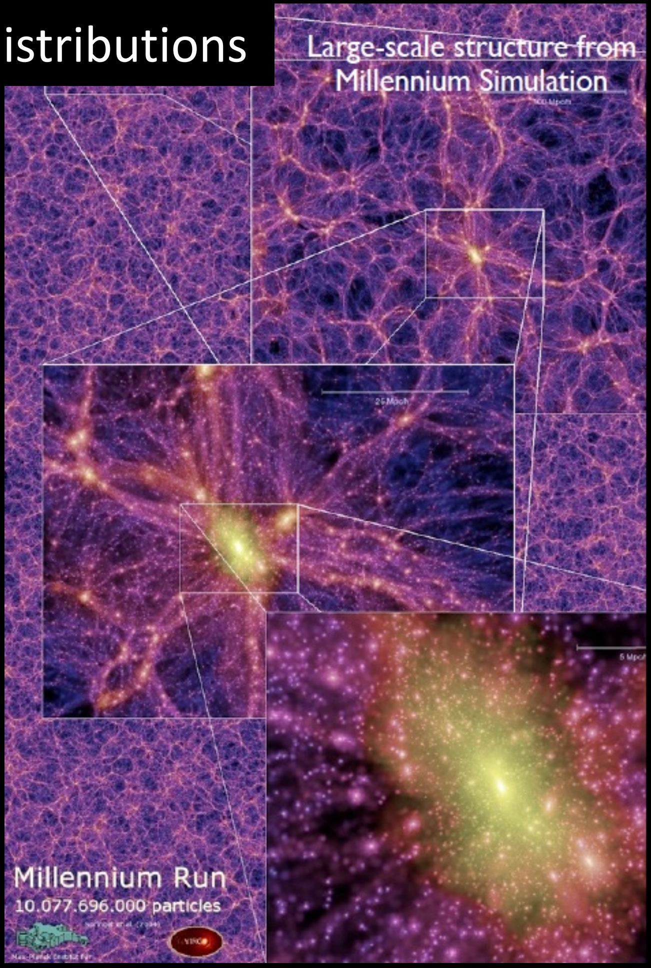
Sub-galactic → Galactic → Cosmological

Affected by baryons
Affected by dark matter models
Peaked? Cored? Many studies

Dark matter dominated
Universal, NFW-like distributions



Oh et al (2011) [THINGS]



Dark matter around black holes

In the sphere of influence of black holes, the DM distribution should be heavily influenced by the black hole (eg Milky Way: M ~ a few x 10^6 Msun, r ~ parsec)

Adiabatic growth of black hole: if mass accretion is slow (wrt orbital timescales) and sustained after initial BH formation leading to substantial mass increase

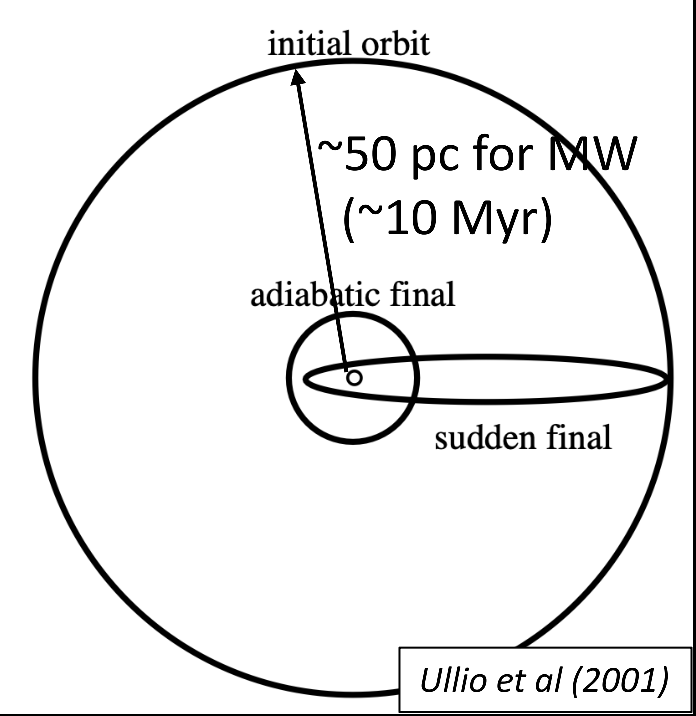
$$t_{\rm dyn} = G M_{\rm BH}/\sigma^3$$

$$t_S = M_{\rm BH}/\dot{M}_{\rm Edd}$$

For most SMBH: $t_{\rm dyn} \ll t_S$

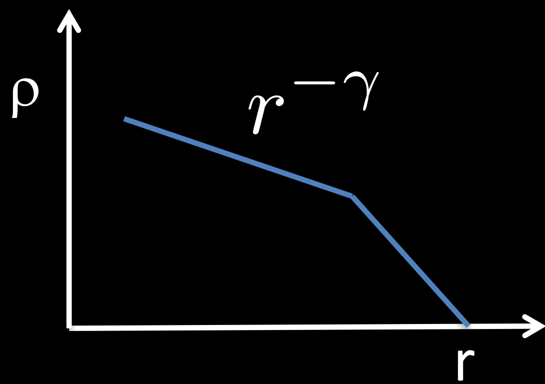
→ DM response: can model with
- Conservation of phase-space distribution
- Adiabatic invariants: angular momentum & radial action

Gondolo & Silk (1999)

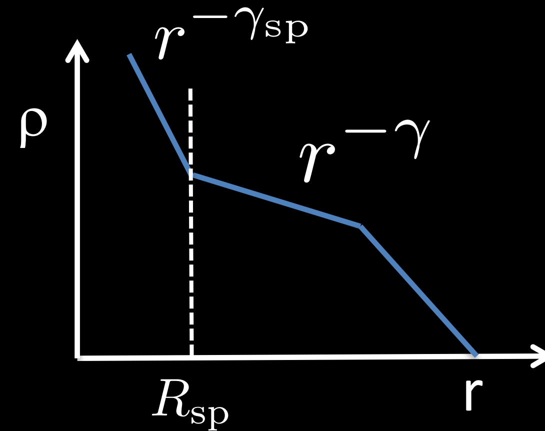


Ullio et al (2001)

Dark matter spike profile



Central BH growth



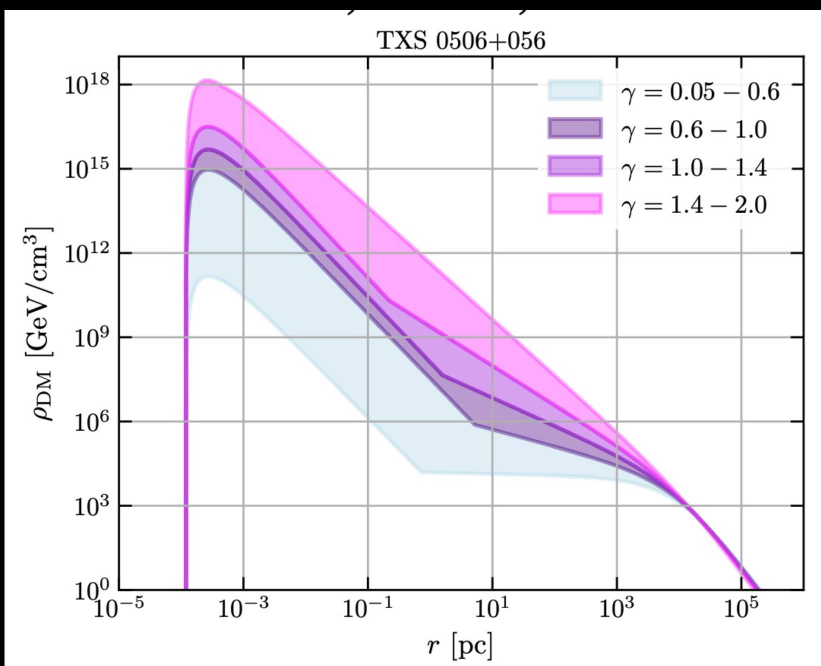
Spike profile:

Gondolo & Silk (1999)

$$\rho_{\rm sp}(r) = \rho_R \, g_\gamma(r) \left(\frac{R_{\rm sp}}{r}\right)^{\gamma_{\rm sp}}$$

Cuspiness of spike $$\gamma_{\rm sp} = \frac{9-2\gamma}{4-\gamma}$$

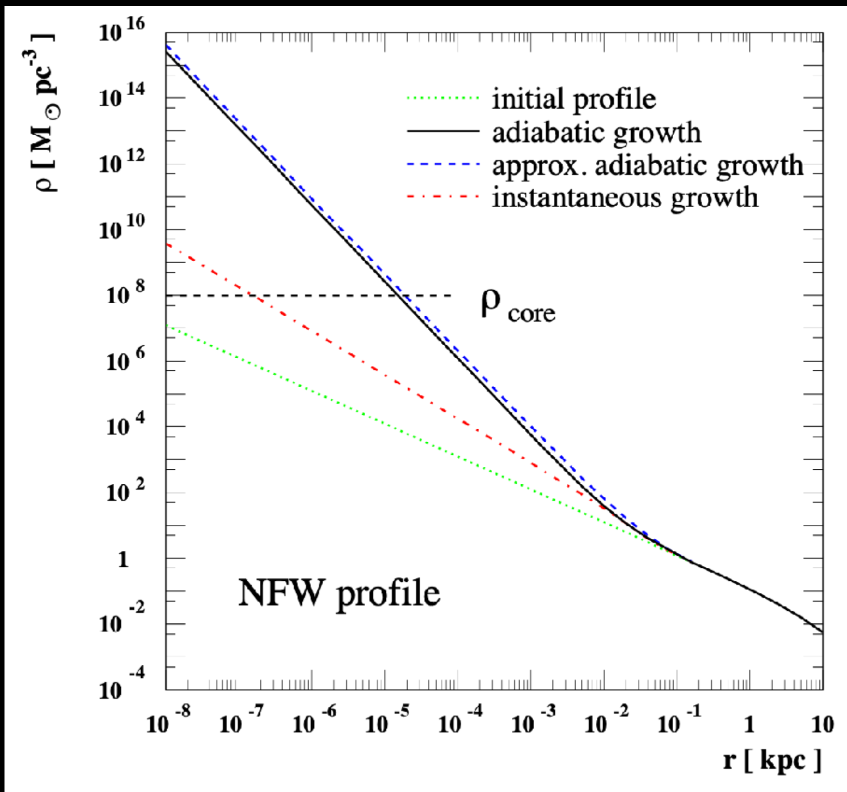
Starting from NFW, one expects a steeper -2.33 slope



Herrera & Murase (2023)

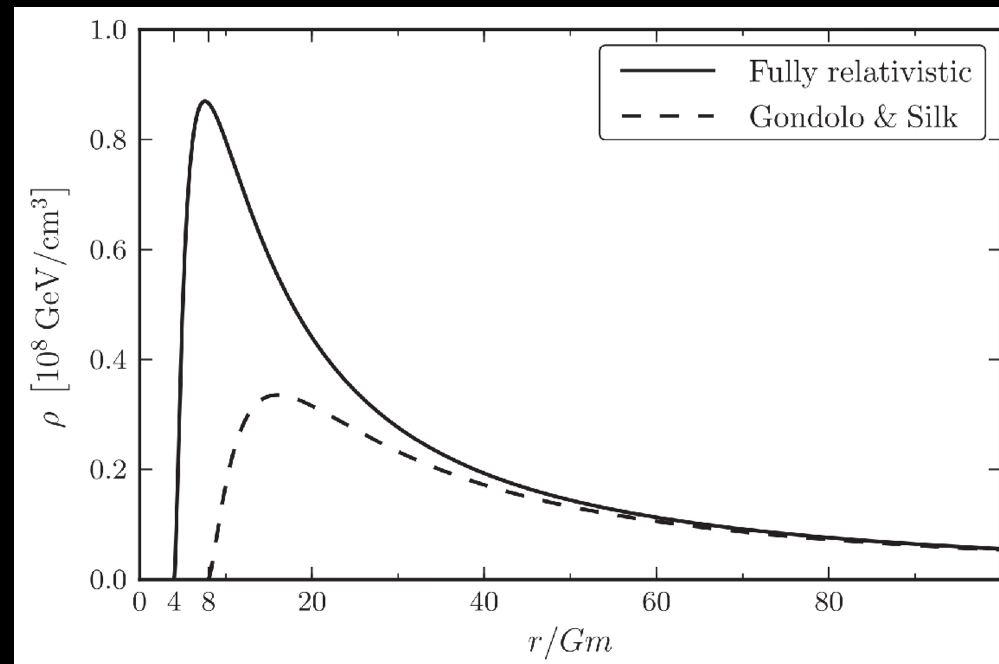
Variations

Instantaneous case



Ullio et al (2001)

Relativistic adiabatic

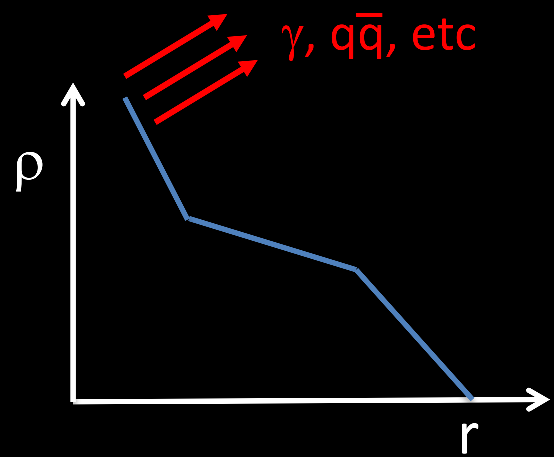


Divergence is cutoff by the black hole horizon: 2 R_S (radius of unstable marginally bound circular orbit)

Sadeghian et al (2013), Ferrer et al (2017)

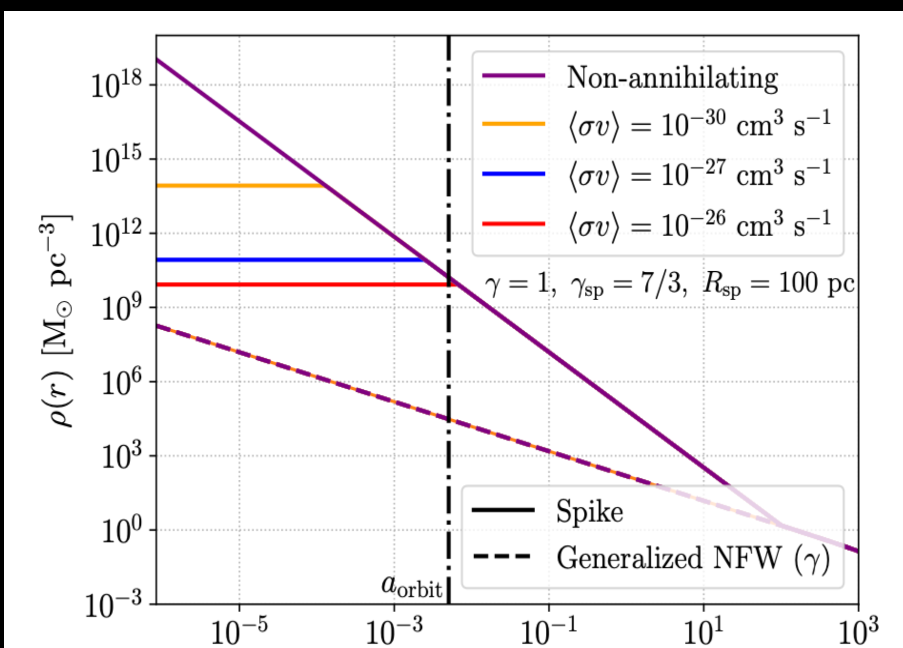
Reduction to dark matter spike

DM models can also limit: e.g., self-annihilations place an upper cap on the DM density possible

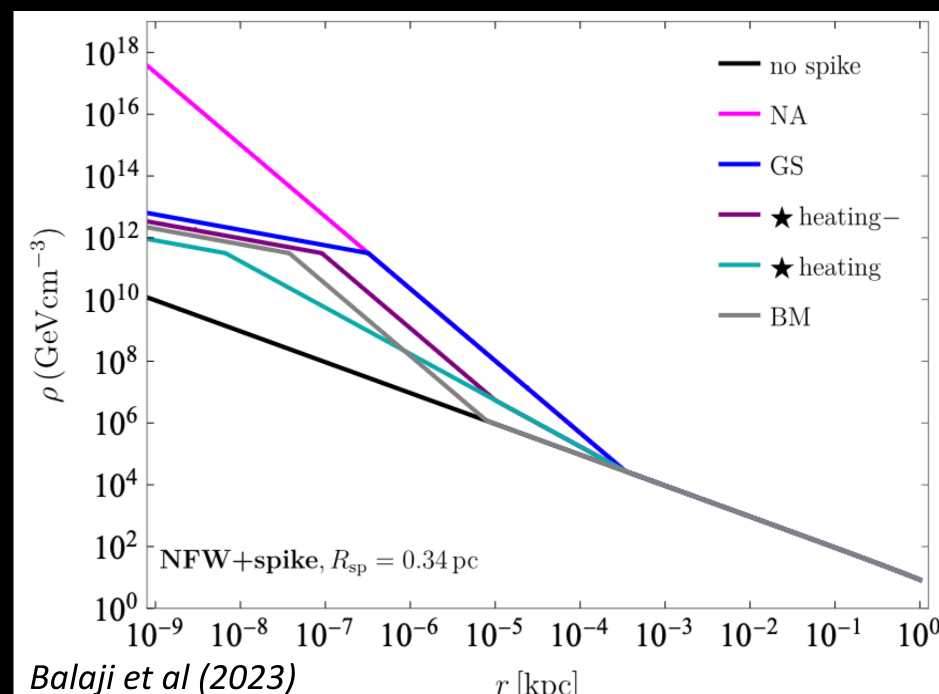


Astrophysical processes such as mergers and gravitational scattering with stars can reduce or disrupt the spike

Merrit et al (2002)
Merrit (2004)
Gnedin & Primack (2004)
Shapiro & Heggie (2022)



Lacroix (2018)



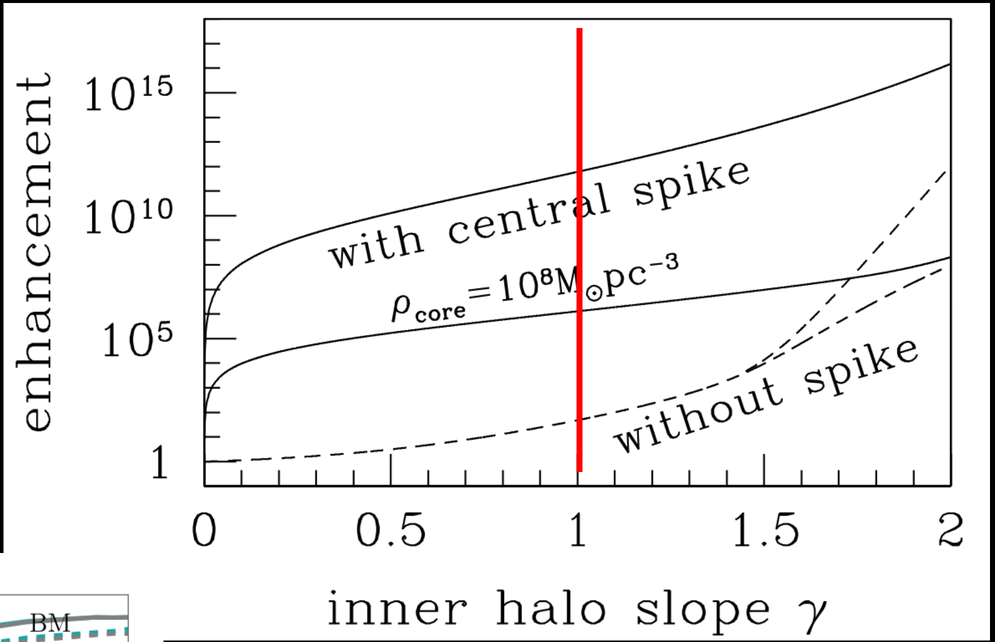
Balaji et al (2023)

Impacts

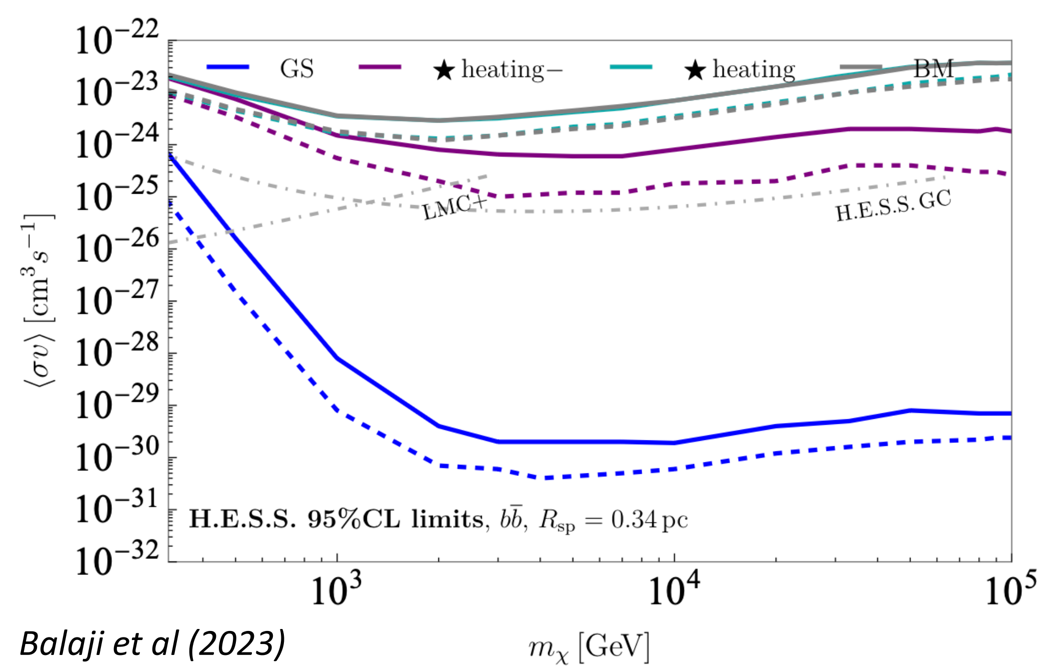
Enhanced annihilation signals: many orders of magnitude

Many studies!

e.g., limits set by null gamma-ray observations improves accordingly



Gondolo & Silk (1999)



Balaji et al (2023)

More broadly, increased DM density means many probes are improved, e.g., dark matter neutrino interactions

(e.g., Fujiwara et al 2025)

Probes

Challenge: extremely small (parsec) scales. Many ideas:

- Gravitational waves: affects potential & dynamical friction, LISA-era

  Eda et al (2013, 2015), Kavanagh et al (2020), Speeney et al (2022),
  Feng et al (2025), Tiwari et al (2025)

- Black hole binary orbital decays, e.g., OJ 287 showing hints already?

  Chan & Lee (2023, 2024)

- Stellar-orbit astrometry: possible in Milky Way

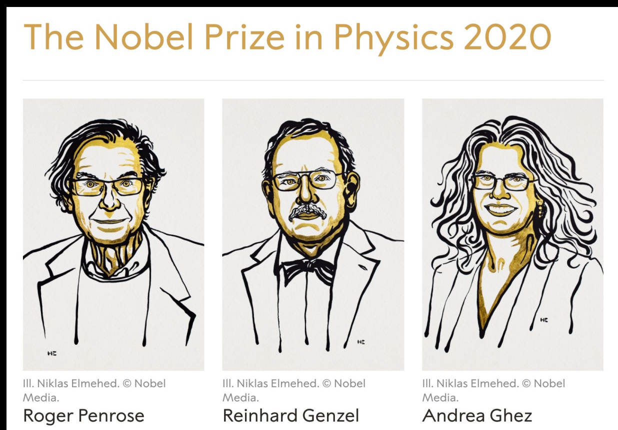
  Lacroix (2018), Abuter et al (2020), Nampalliwar et al (2021), Shen et al (2022)

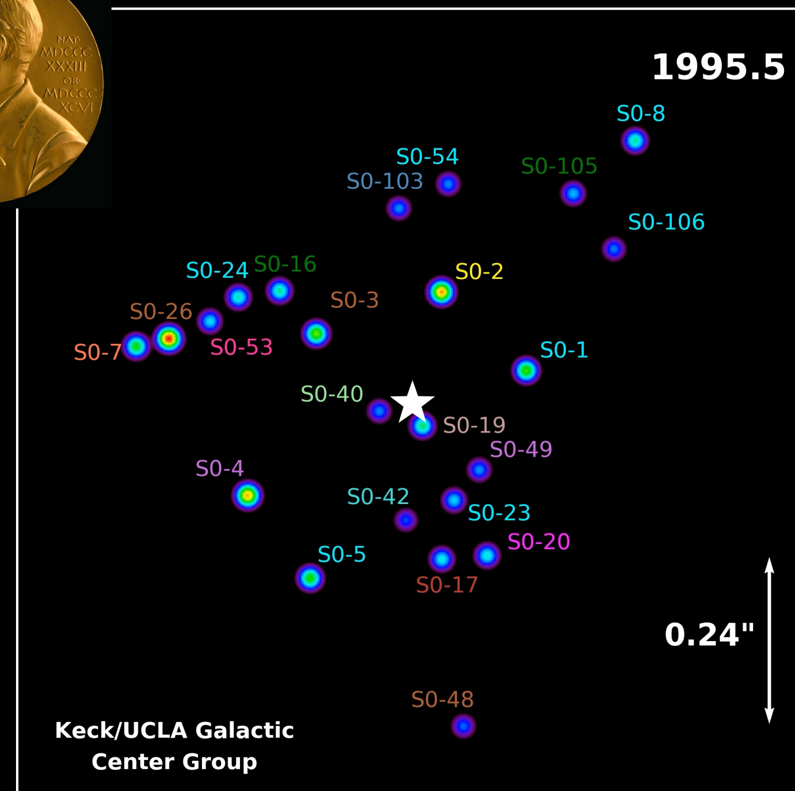
- Reverberation mapping: can go beyond Milky Way

  Sharma et al (2025)

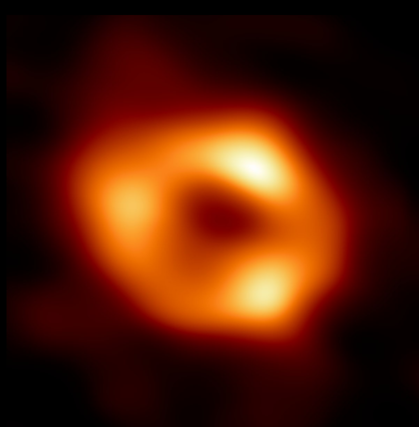
How are SMBH masses determined?

By studying the dynamics of objects in the gravitational influence of the SMBH





Some ~40 S-stars known/monitored by high-resolution Keck & VLT obs

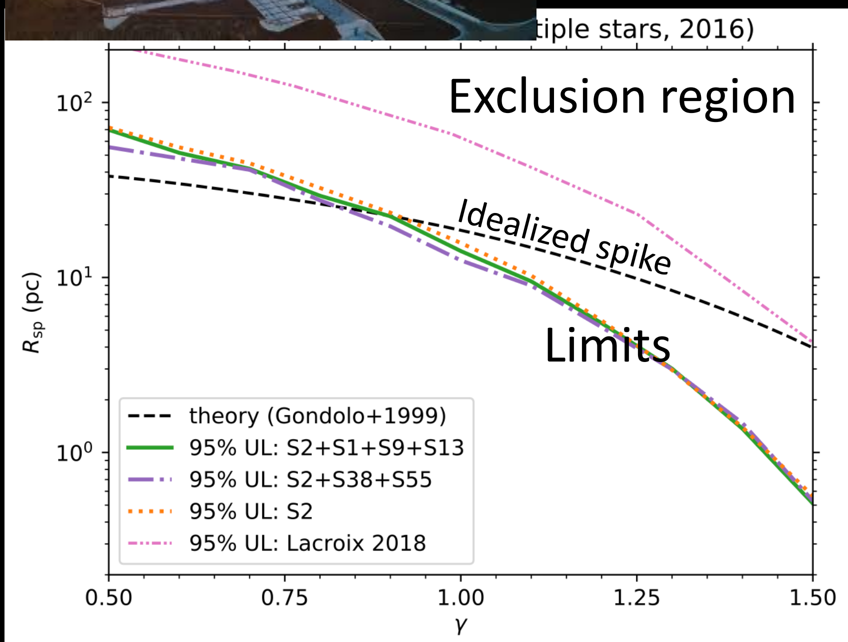


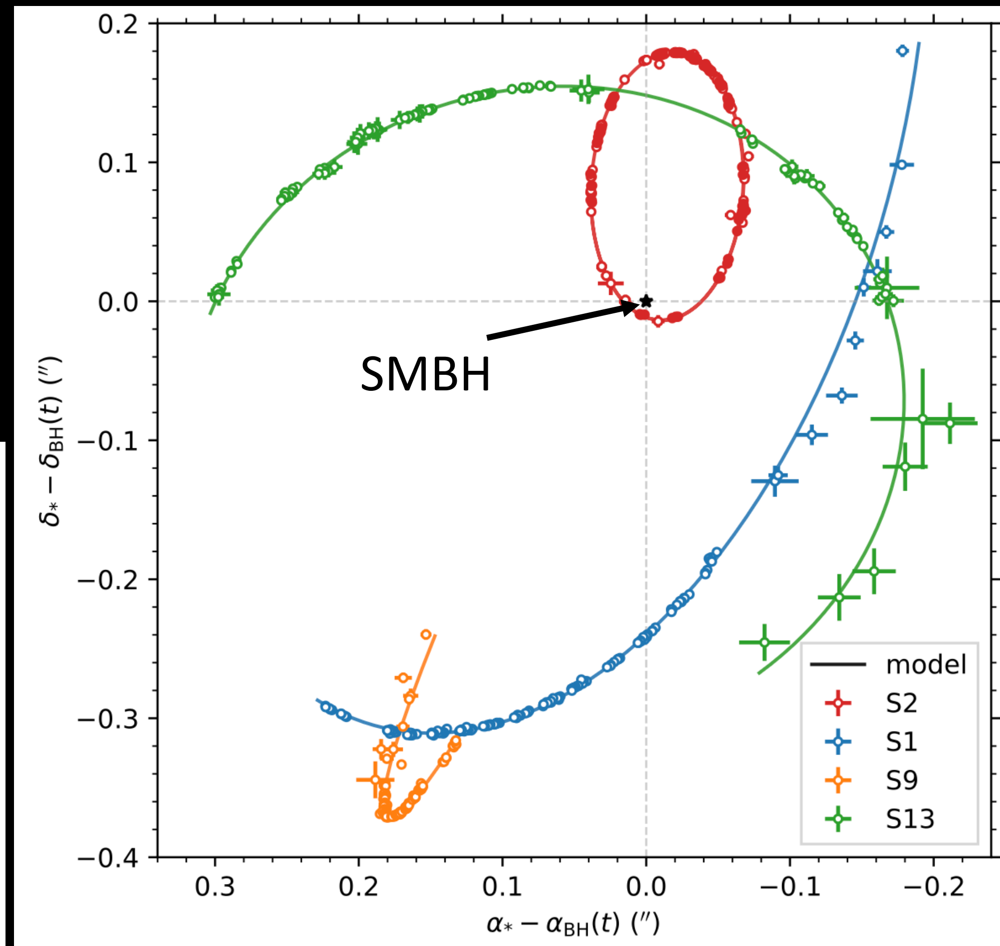
$$M_{BH} \propto \frac{rv^2}{G}$$

BH spikes from Motion of S2

S-stars orbits within/nearby the spike region can be used to search for the spike

VLT, Keck → Radii: $10^{-3} \sim 0.1$ pc





Shen et al (2022)
See also Lacroix (2018), Abuter et al (2020), and Nampalliwar et al (2021) who also used the EHT Sgr A shadow image*

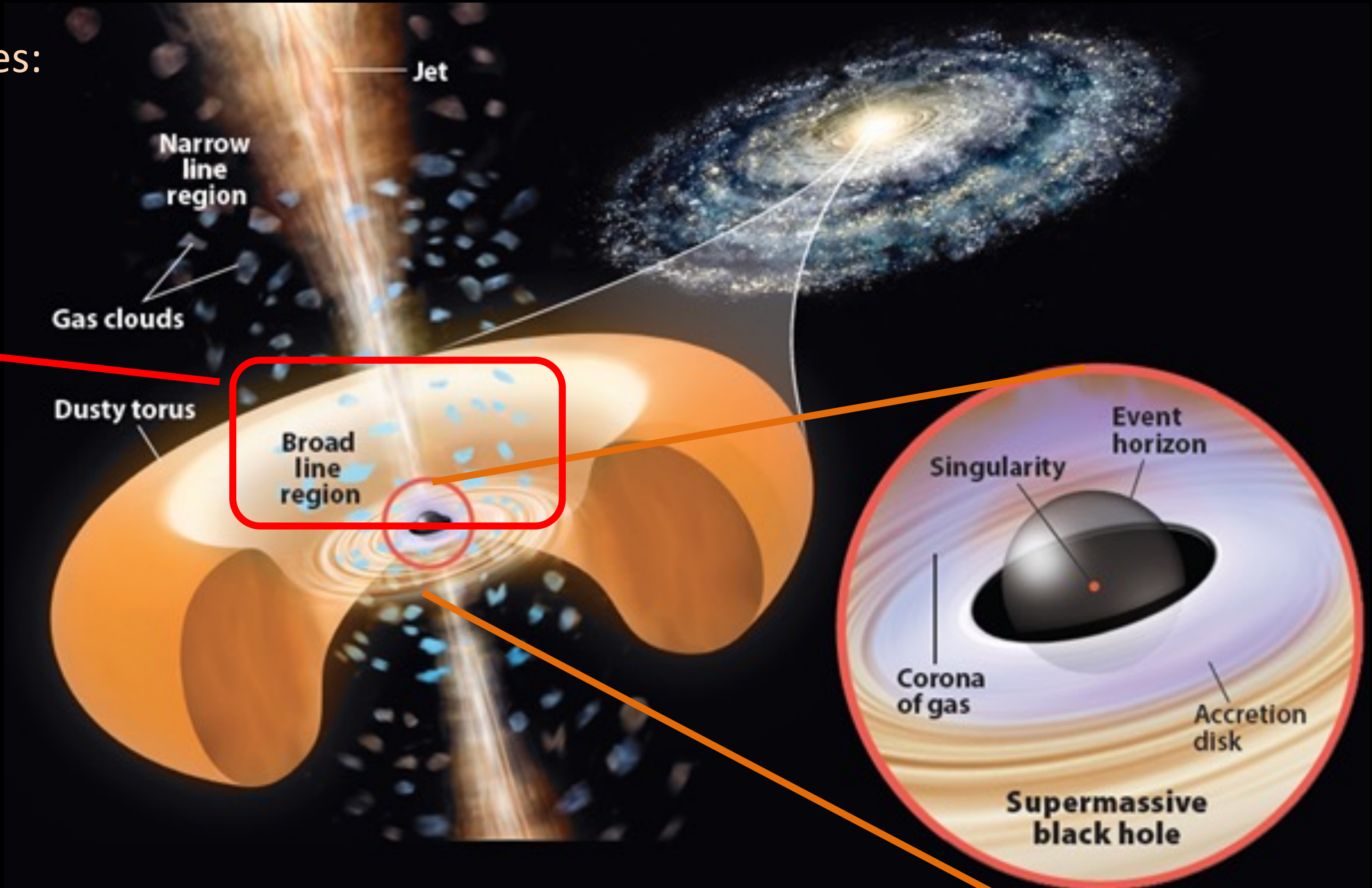
Tracing stars are possible only for the nearest tagets...

Cosmological scales: Active Galactic Nuclei

- On cosmological scales, angular scales are far too small to revolve.
- But we can use powerful targets like Active Galactic Nuclei (AGNs)

AGN structures:

Exploit the broad line region (BLR)

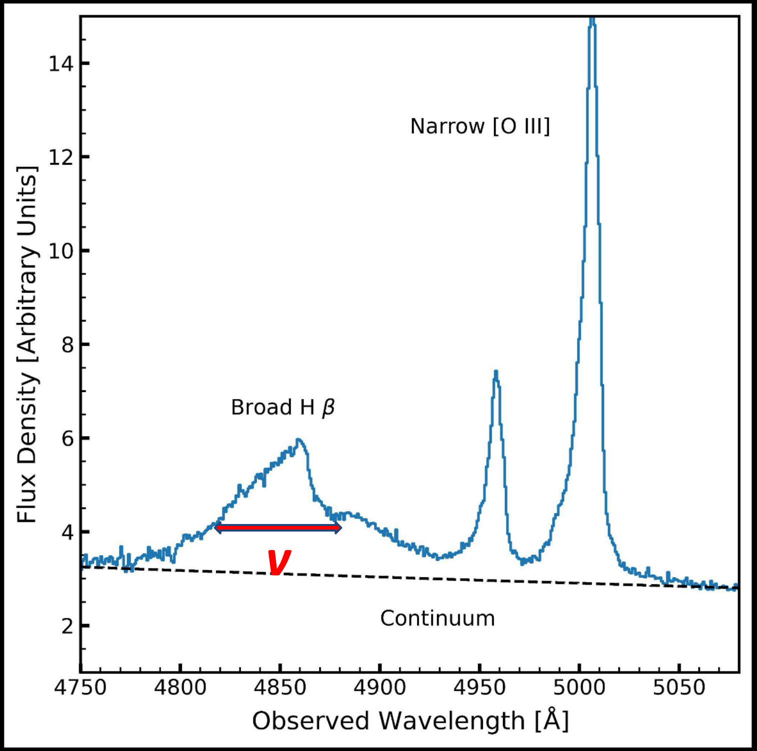


Astronomy Magazine

Estimating the BH mass

Estimating the mass:

$$M_{BH} = f \frac{R_{BLR} v_{BLR}^2}{G}$$



- v: velocity of emitting gas

  Emission lines are Doppler broadned; obtain from the widths of broad emission lines (thousands of km/s)

- R: distance of the gas from the black hole

  ??

- f: fudge factor to account for geometry, orientation, and kinematics of emitting stuff

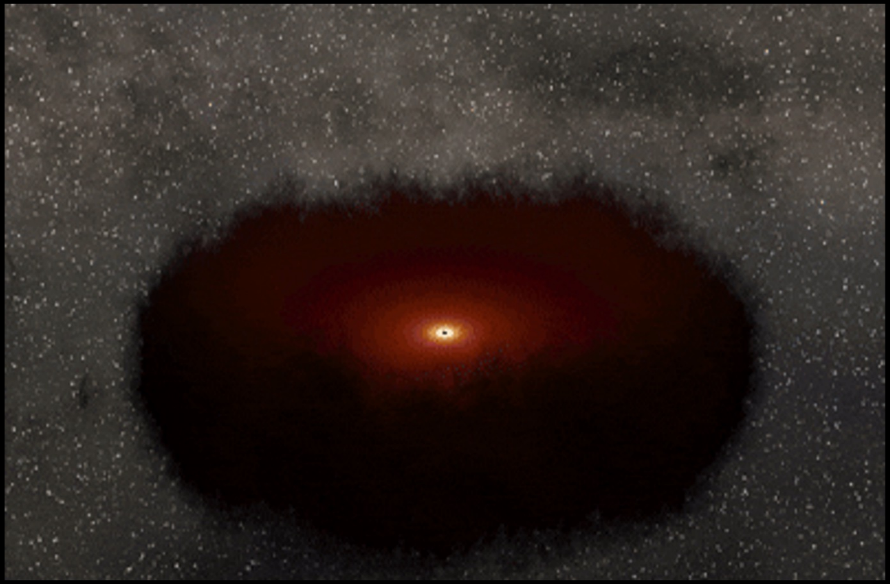
  ??

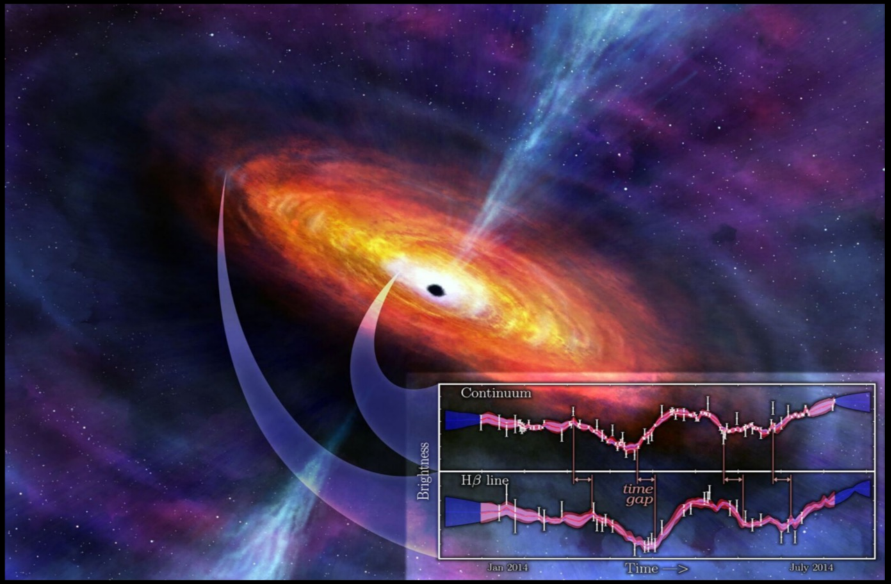
Thanks: Mayank Sharma

Reverberation mapping

AGN hosts various time variability due to non-constant mass accretion

→ Exploit the echos of light as these signatures arrive later in time





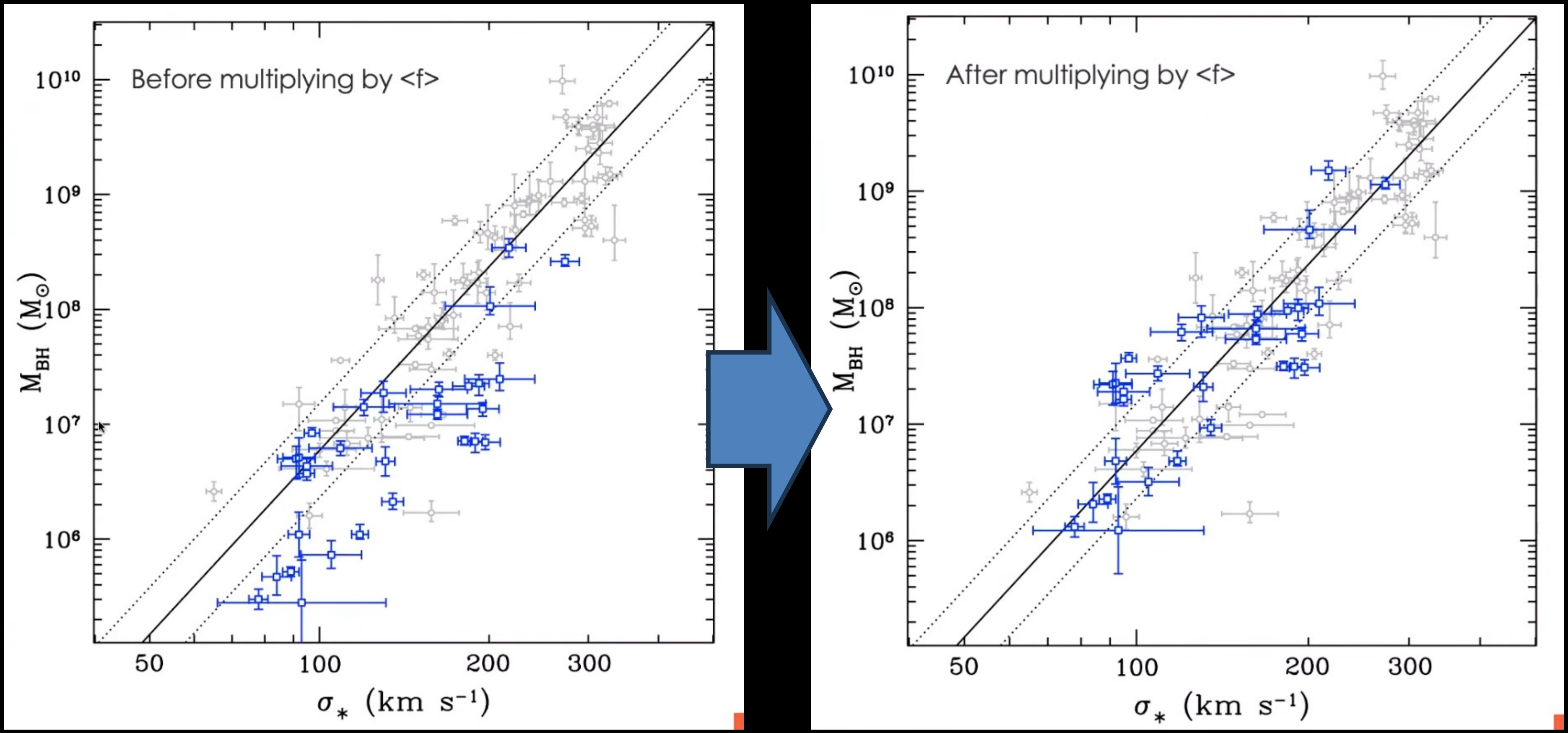
Thanks: Nahks Tr'Ehnl, Dr. Kate Grier, NASA/JPL

Time delay between continuum & broad lines → Distance

Fudge factor, f

Factor f captures the geometry, orientation, and kinematics of the broad line region

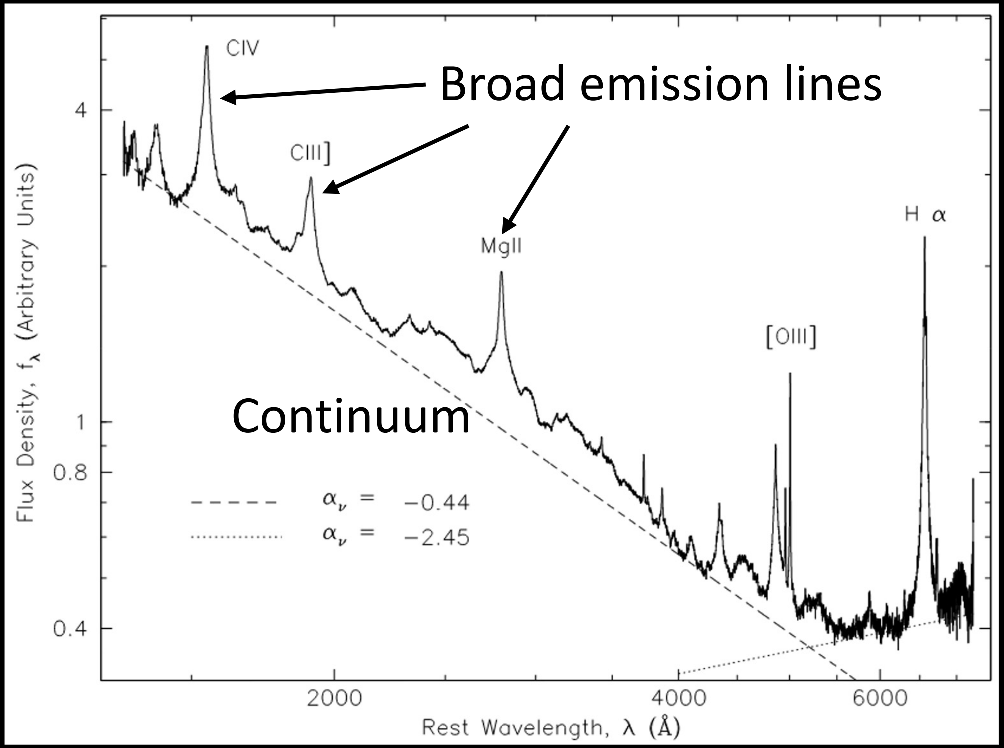
Typically fit to other relations and fix the factor f



Grier, OSU colloquium (2021)

Tracing the mass profile

AGNs have numerous broad emissions lines – we can exploit this



Vanden Berk et al (2001)

Some emission lines need different ionization states thus must originate from different regions within the BLR

In principle, this allows tracing the enclosed mass at different radii within the BLR !

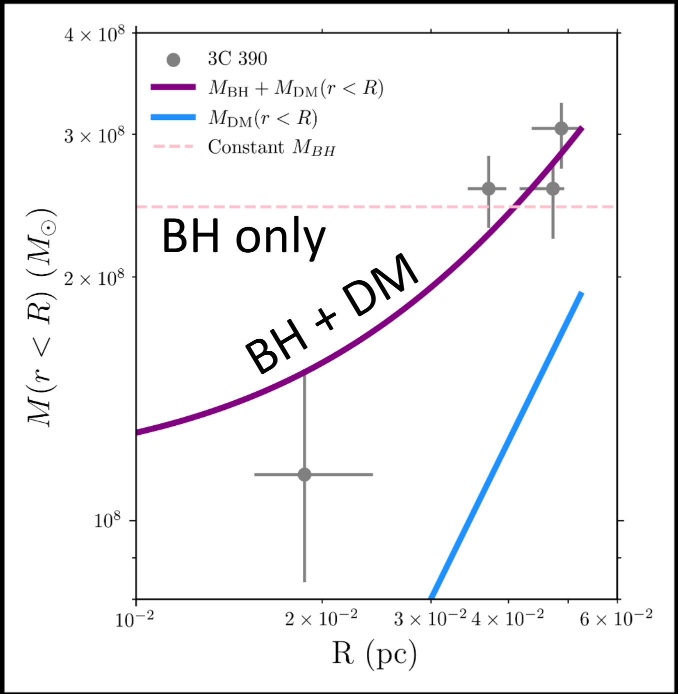
Multi-line RM results

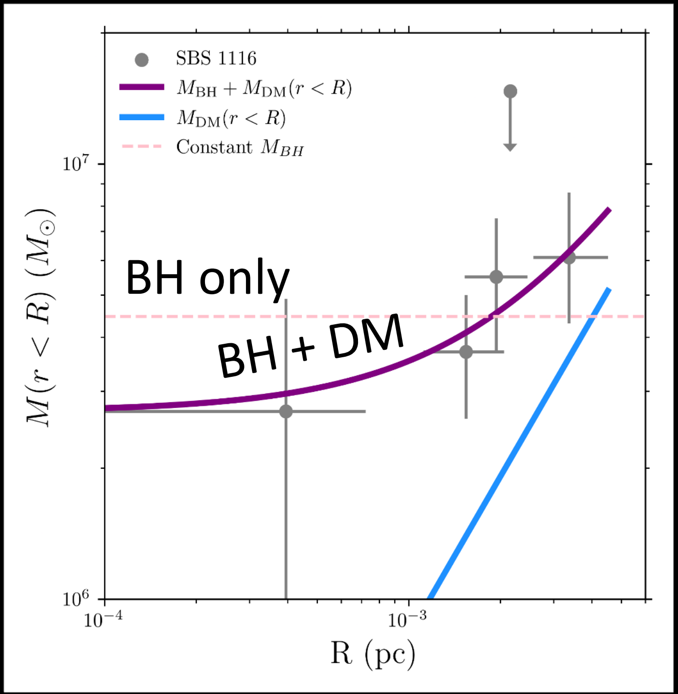
A sample of 14 AGNs with multi-line reverberation mapping was identified.

Fitting to a simple BH model vs BH + DM model:

- 2 strongly prefer the BH + DM model
- 4 strong prefer the BH only model
- 8 show no preference

Sharma et al (2025)





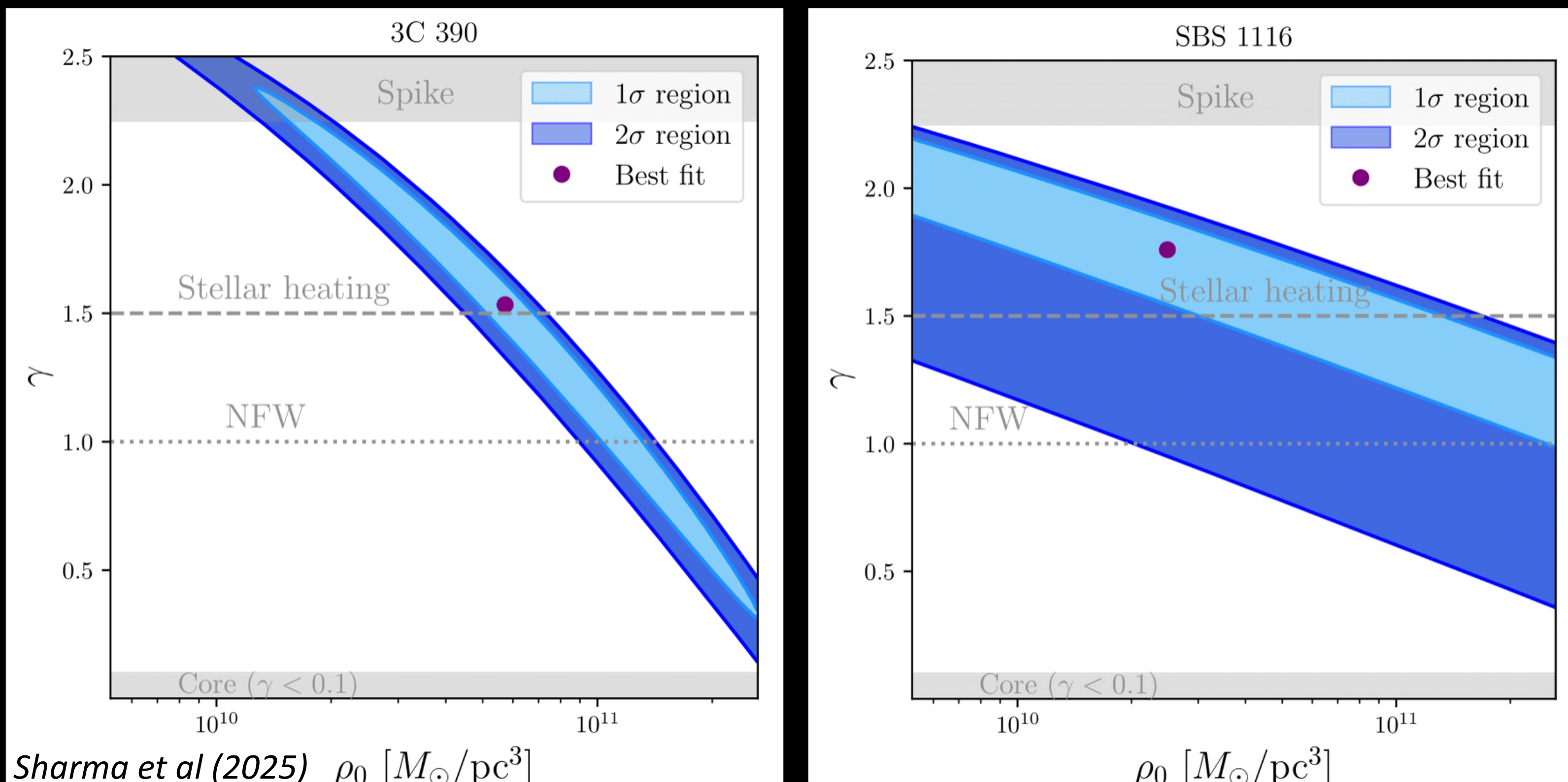
Source	Lines	r_c (lt. days)	$M_{\rm BH}$ (10^7 $M_\odot$)	Ref.
Mrk 335	He II	$2.7^{+0.6}_{-0.6}$	$2.6^{+0.8}_{-0.8}$	(1)
	H β	$13.9^{+0.9}_{-0.9}$	$2.7^{+0.3}_{-0.3}$	
3C 120	He II	$12.0^{+7.5}_{-7.0}$	$17.3^{+10.5}_{-10.5}$	(2)
	H γ	$23.9^{+4.6}_{-3.9}$	$19.4^{+8.9}_{-8.9}$	
	He I	$26.8^{+6.7}_{-7.3}$	$14.8^{+4.6}_{-4.6}$	
	H β	$27.9^{+7.1}_{-5.9}$	$10.8^{+2.6}_{-2.6}$	
	H α	$28.5^{+9.0}_{-8.5}$	$7.7^{+2.3}_{-2.3}$	
MCG+08-11-011	He II	$1.21^{+0.29}_{-0.33}$	$0.63^{+1.28}_{-0.42}$	(3)
	H γ	$12.38^{+0.46}_{-0.49}$	$2.76^{+5.37}_{-1.82}$	
	H β	$14.98^{+0.34}_{-0.28}$	$2.82^{+5.50}_{-1.86}$	
NGC 2617	He II	$1.75^{+0.34}_{-0.38}$	$0.62^{+1.43}_{-0.43}$	(3)
	H γ	$0.81^{+0.59}_{-0.61}$	$0.66^{+2.16}_{-0.51}$	
	H β	$6.38^{+0.44}_{-0.50}$	$3.24^{+6.32}_{-2.14}$	
Mrk 110	He II	$3.9^{+2.8}_{-0.7}$	$2.25^{+1.63}_{-0.45}$	(4)
	He I	$10.7^{+8.0}_{-6.0}$	$1.81^{+1.36}_{-1.03}$	
	H β	$24.2^{+3.7}_{-3.3}$	$1.63^{+0.33}_{-0.31}$	
	H α	$32.3^{+4.3}_{-4.9}$	$1.64^{+0.33}_{-0.35}$	
NGC 5273	He II	$< 0.35^{+2.17}$	$< 0.176^{+1.075}$	(5)
	H γ	$2.14^{+1.09}_{-1.08}$	$0.456^{+0.237}_{-0.232}$	
	H β	$2.22^{+1.19}_{-1.61}$	$0.443^{+0.245}_{-0.327}$	
	H α	$2.06^{+1.42}_{-1.31}$	$0.550^{+0.383}_{-0.353}$	
3C 390.3	He II	$22.3^{+6.5}_{-3.8}$	$11.4^{+4.0}_{-3.0}$	(6)
	H γ	$58.1^{+4.3}_{-6.1}$	$30.5^{+2.3}_{-3.3}$	
	H β	$44.3^{+3.0}_{-3.3}$	$25.7^{+2.5}_{-2.7}$	
	H α	$56.3^{+2.4}_{-6.6}$	$25.7^{+2.0}_{-3.4}$	
NGC 7469	He II	$1.3^{+0.9}_{-0.7}$	$0.13^{+0.09}_{-0.07}$	(7)
	H β	$10.8^{+3.4}_{-1.3}$	$0.34^{+0.13}_{-0.08}$	
Mrk 142	He II	$< 1.20^{+1.53}$	$< 1.2^{+1.9}$	(8)
	He I	$1.81^{+1.99}_{-1.20}$	$0.24^{+0.28}_{-0.19}$	
	H γ	$2.86^{+1.22}_{-1.05}$	$0.33^{+0.15}_{-0.13}$	
	H β	$2.74^{+0.73}_{-0.83}$	$0.207^{+0.074}_{-0.080}$	
	H α	$2.78^{+1.17}_{-0.88}$	$0.248^{+0.109}_{-0.085}$	
SBS 1116+583A	He II	$0.47^{+0.39}_{-0.47}$	$0.27^{+0.22}_{-0.26}$	(8)
	He I	$< 2.57^{+1.59}$	$< 0.88^{+0.56}$	
	H γ	$1.84^{+0.61}_{-0.51}$	$0.37^{+0.13}_{-0.11}$	
	H β	$2.31^{+0.62}_{-0.49}$	$0.55^{+0.20}_{-0.18}$	
	H α	$4.01^{+1.37}_{-0.95}$	$0.61^{+0.25}_{-0.18}$	
Mrk 1310	He II	$0.94^{+0.61}_{-0.81}$	$0.33^{+0.22}_{-0.29}$	(8)
	H γ	$1.82^{+0.63}_{-0.71}$	$0.133^{+0.054}_{-0.059}$	
	He I	$2.56^{+0.90}_{-1.05}$	$0.51^{+0.21}_{-0.24}$	
	H β	$3.66^{+0.59}_{-0.61}$	$0.214^{+0.086}_{-0.086}$	
	H α	$4.51^{+0.66}_{-0.61}$	$0.238^{+0.061}_{-0.059}$	
Mrk 202	He II	$1.47^{+2.40}_{-1.19}$	$0.59^{+0.97}_{-0.49}$	(8)
	H γ	$3.31^{+1.57}_{-1.38}$	$0.170^{+0.112}_{-0.095}$	
	H β	$3.05^{+1.73}_{-1.12}$	$0.136^{+0.082}_{-0.057}$	
NGC 4748	He II	$< 1.0^{+7.8}$	$< 0.4^{+2.9}$	(8)
	H γ	$6.92^{+2.60}_{-3.22}$	$0.58^{+0.29}_{-0.33}$	
	H β	$5.55^{+1.62}_{-2.22}$	$0.25^{+0.10}_{-0.12}$	
	H α	$7.50^{+2.97}_{-4.57}$	$0.82^{+0.35}_{-0.52}$	
NGC 6814	He II	$5.00^{+1.98}_{-1.83}$	$3.4^{+1.4}_{-1.3}$	(8)
	He I	$3.09^{+1.33}_{-0.84}$	$3.4^{+2.7}_{-2.5}$	
	H γ	$6.05^{+2.65}_{-2.34}$	$0.98^{+0.47}_{-0.43}$	
	H β	$6.64^{+0.87}_{-0.90}$	$1.76^{+0.33}_{-0.34}$	
	H α	$9.46^{+1.90}_{-1.56}$	$1.13^{+0.25}_{-0.22}$	

Shunsaku Horiuchi

Implications for DM spikes

Assuming the growing enclosed mass is due to DM spikes:

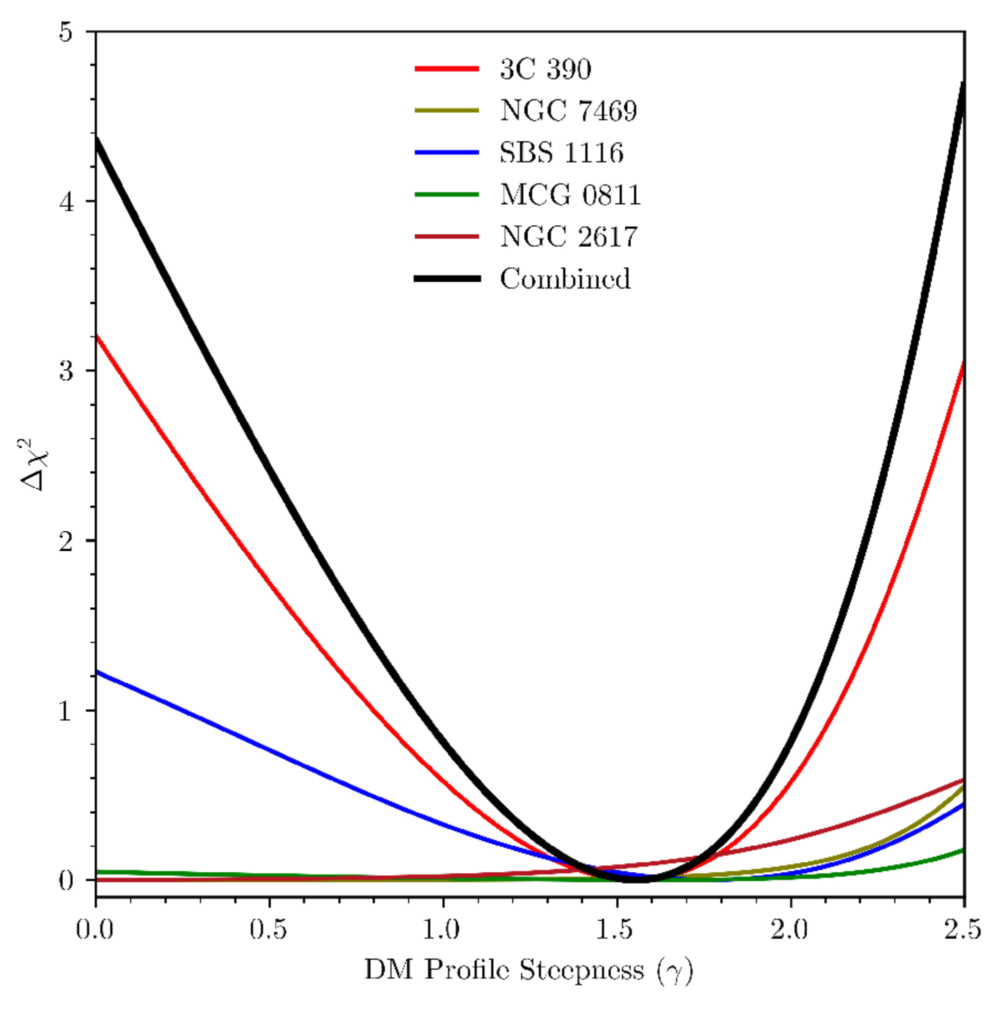
$$\rho_{\rm DM}(r) = \rho_0 r^{-\gamma} \;\; \text{for} \;\; 2R_S < r < R_{\rm sp}.$$



Despite the large statistical errors, this method already traces a similar parameter space to that expected from theoretical models.

Implications for DM spikes

Not all AGNs should habour spikes – but for those that do, do the spike density and slope vary source by source?



Source	$M_{\rm DM}(r < R_{\rm sp})/M_{\rm tot}(r < R_{\rm sp})$
3C 390	$0.60^{+0.04}_{-0.04}$
NGC 7469	$0.62^{+0.14}_{-0.21}$
SBS 1116	$0.58^{+0.15}_{-0.27}$
MCG 0811	$0.81^{+0.13}_{-0.57}$
NGC 2617	$< 0.80^{+0.15}$

- Spike masses are ~60% of total enclosed mass
- Global slope of 1.6 (large errors and dominated by 3C 390).
  → This is steeper than NFW and consistent with a DM spike depleted over time due to interactions with stars

Sharma et al (2025)

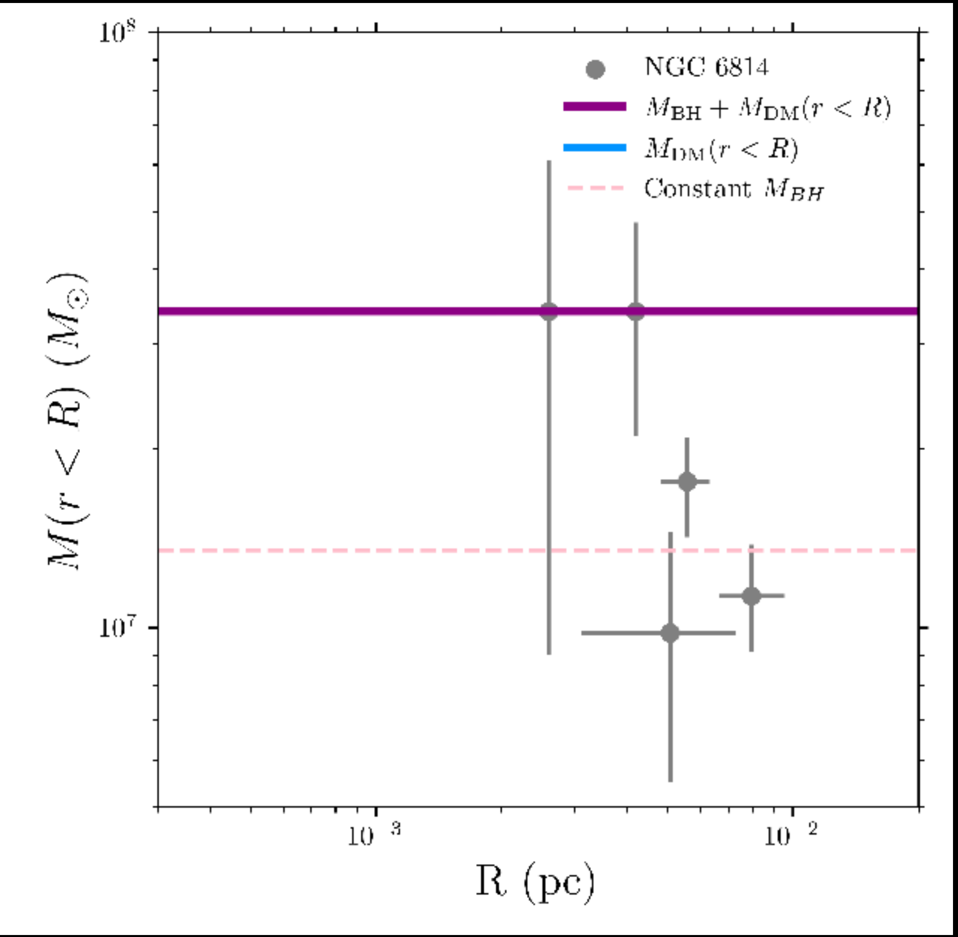
Systematics

Systematics dominated: at least 2 objects show mass decreasing with radius (!)

Causes? Likely simplifying treatment of the Broad Line Region, e.g.: described by single fudge factor per object

Geometry: spherical, uniform.

Kinematics: isotropic, virialized motion



Sharma et al (2025)

Summary

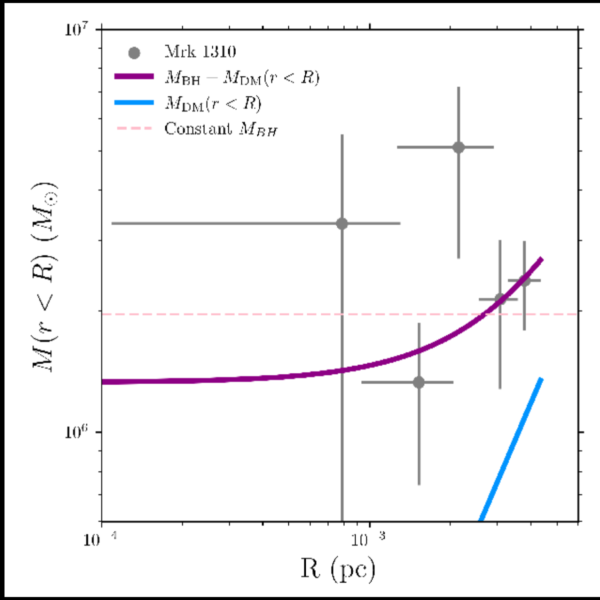
- **Adiabatic growth of black holes predicts the formation of a DM spike at sub-parsec scales.**
- **Whether the spike is present for any given galaxy, and if so its profile, both remain uncertain**
- **Confirming a DM spike will probe DM properties & boost indirect DM searches, as well as the history of the BH**
- **New ideas for observational tests are underway. Reverberation Mapping of AGNs trace the Broad Line Region, which is on similar scales as DM spikes, allowing observational tests for DM spikes.**
- **Current observations offer a mixed bag of results for the presence of a DM component. The results obtained, however, are close to theoretical predictions of DM spikes.**

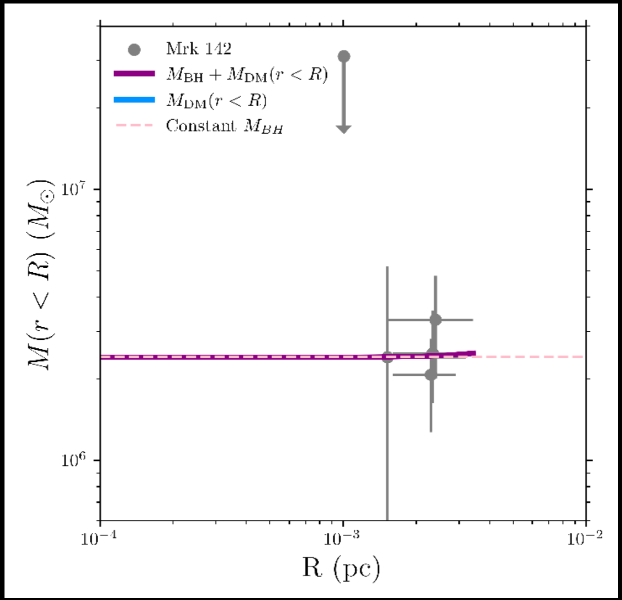
full results

Source	z	n	$M_{BH,\text{best}}$	$\rho_{0,\text{best}}$	γ_{best}	$\Delta\chi^2_{\text{BIC}}$	DM Evidence
3C 390	0.30	4	24.40	5.5×10^{10}	1.548	-9.43	Strong (in favor)
NGC 7469	0.016	2	0.25	6.8×10^{11}	0.001	-2.35	Positive (in favor)
SBS 1116	0.028	4	0.45	2.4×10^{10}	1.764	-0.37	Weak (in favor)
MCG 0811	0.020	3	1.70	5.5×10^{10}	1.594	-0.29	Weak (in favor)
NGC 2617	0.014	3	1.25	4.0×10^{13}	0.001	-0.03	Weak (in favor)
Mrk 1310	0.020	5	0.20	3.7×10^{10}	1.313	+0.35	Weak (against)
NGC 4748	0.015	3	0.29	1.7×10^{12}	0.001	+0.55	Weak (against)
Mrk 335	0.044	2	2.69	1.4×10^{11}	0.031	+0.68	Weak (against)
NGC 5273	0.0036	3	0.47	-	-	+1.38	Weak (against)
Mrk 142	0.0446	4	0.24	-	-	+1.38	Weak (against)
Mrk 110	0.035	4	1.76	-	-	+7.01	Positive (against)
3C 120	0.033	5	10.26	-	-	+21.88	Strong (against)
Mrk 202	0.023	3	0.16	-	-	+44.95	Strong (against)
NGC 6814	0.0052	5	1.35	-	-	+129.27	Strong (against)

No preference, BH only preference

No preference cases: large errors or data doesn't probe enough distance range





Prefers BH only: mass typically declines, although most have large errors