Active Galactic Nuclei disks: The largest population of planets in the Universe?

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Active Galactic Nucleus Tori: Potential Birthplace to Millions of Planets

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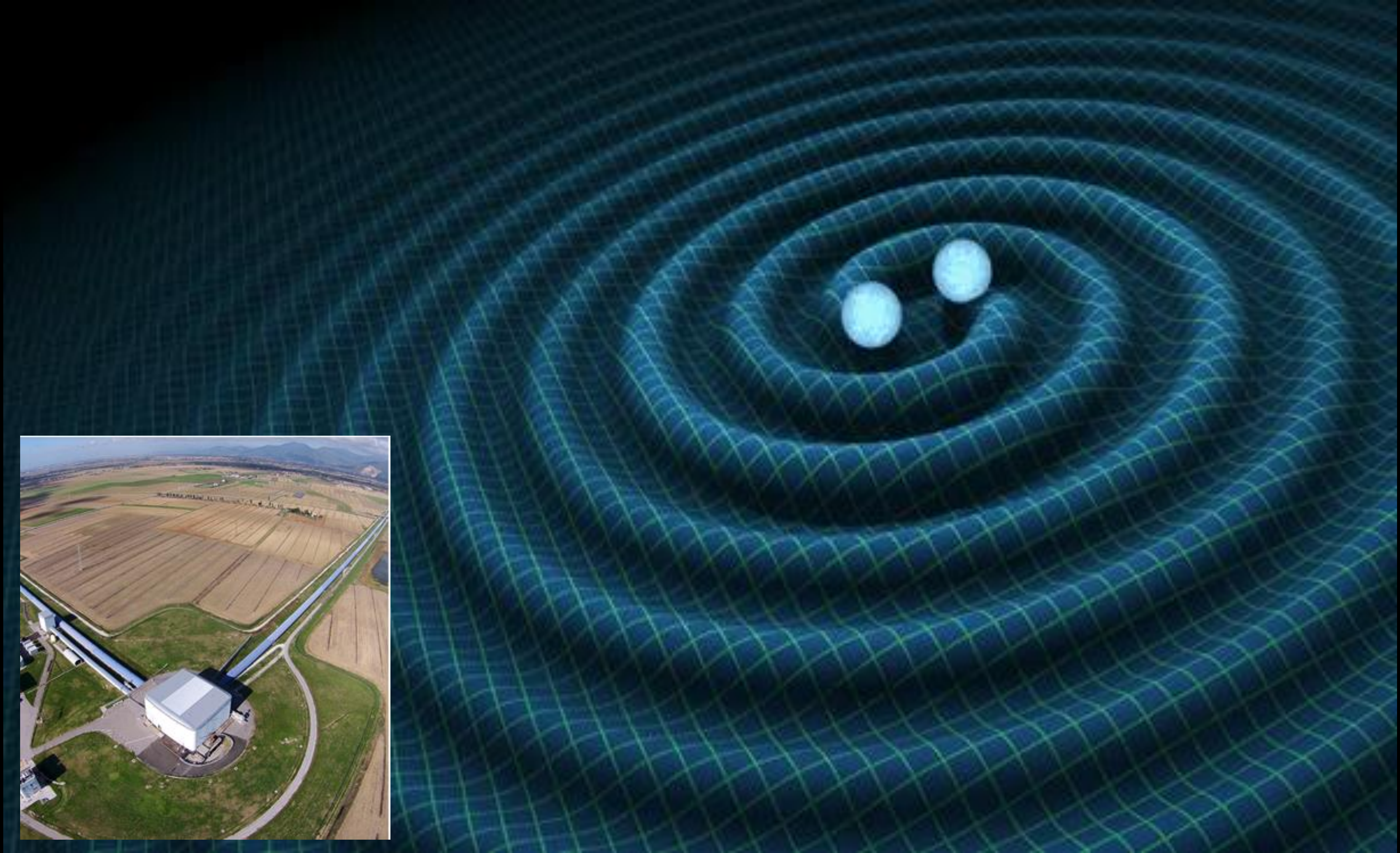
ABSTRACT

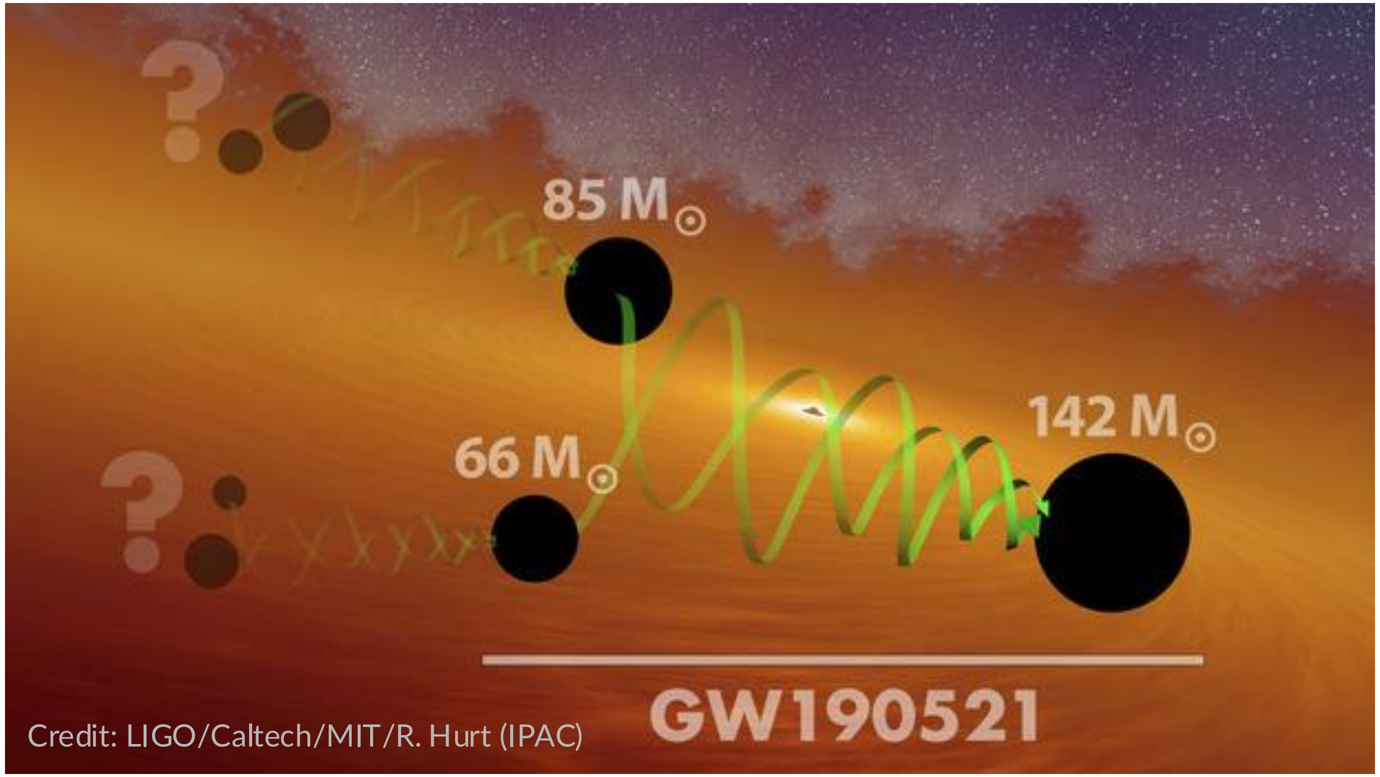
The outer regions of AGN disks have temperatures similar to those of circumstellar disks, permitting dust condensation. Therefore, planet formation and growth could be active in these dust tori through similar mechanisms. We aim at quantifying the parameter space for the occurrence of streaming instability, and its outcomes in terms of the masses of the objects formed, their total number, and their continued growth via pebble accretion. We use a a recently proposed disk model with strong magnetization to keep the disk gravitationally stable. We find that the dust grain sizes required for streaming instability are easily attained through coagulation; the dust filaments it produces can contain solar masses, collapsing into tens of millions of "planetesimals" ranging from Earth to super-Jupiter masses. These planets are usually born in the 3D Bondi regime of pebble accretion, and have mass-doubling times from 10^3 to 10^7 yrs, though 3D Hill and geometric accretion are also realized. Gas accretion occurs concurrently, and crossover mass can be attained while still in the planetary mass range. As a result, vigorous accretion can occur, leading to objects with stellar masses—defining a core accretion channel for star formation. The pebble isolation mass is beyond the hydrogen burning limit, so accretion is limited by stellar feedback instead of gap carving. Our model also predicts a population of exotic objects directly formed above the hydrogen burning limit, yet of pure dust. Our approximate model suggests that AGN dust tori host the largest populations of planets in the universe.

Keywords: planet formation, streaming instability, active galactic nuclei



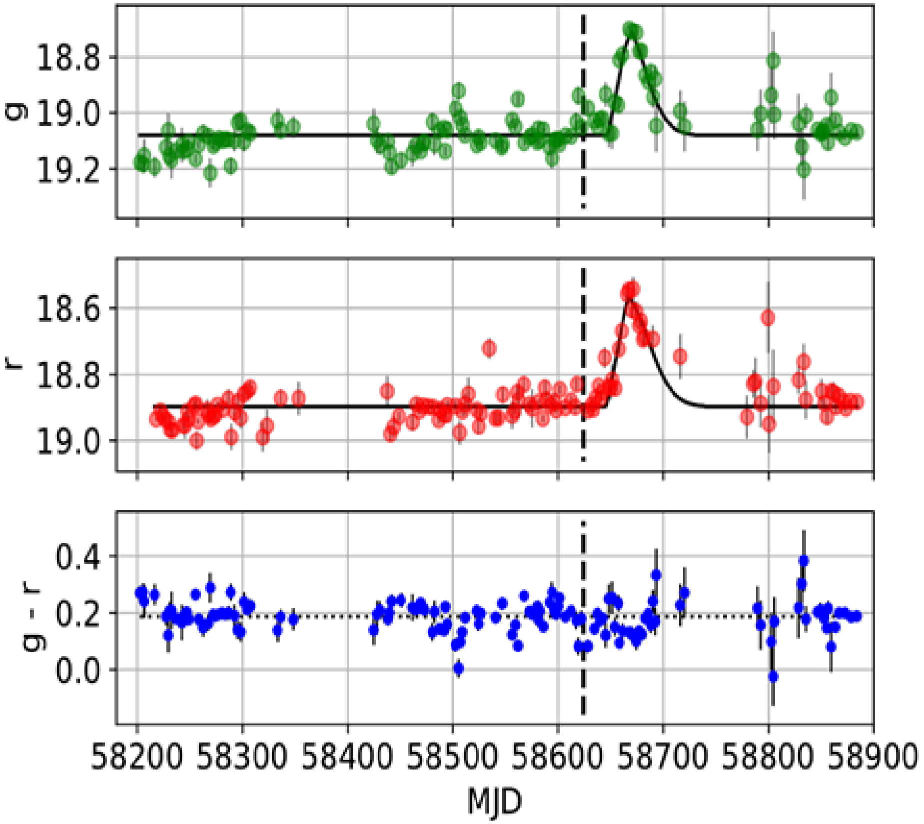
Gravitational wave event GW 190521

Hierarchical merging
First intermediate-mass black hole
Progenitors not products of stellar evolution.
Suggest progenitors themselves result from previous mergers



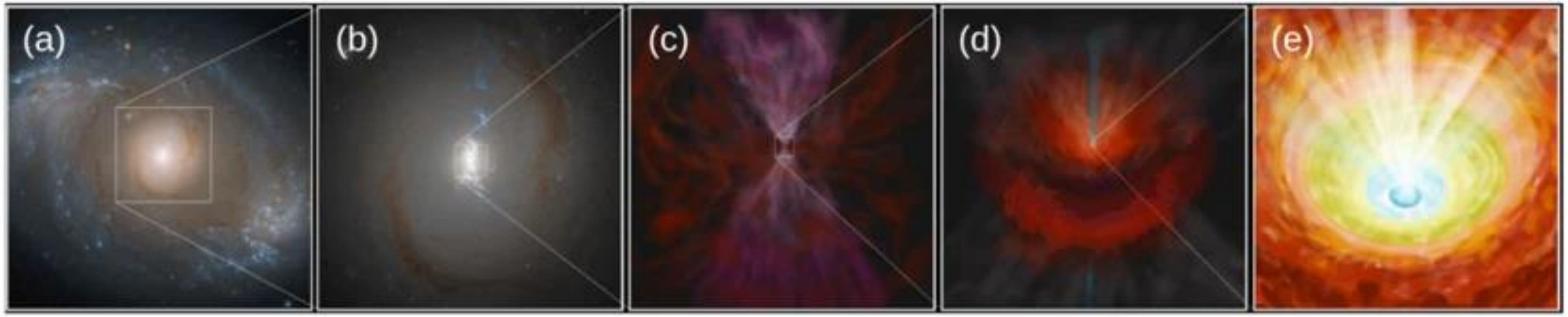
Possible EM counterpart
Flare alert: ZTF19abanrhr
AGN: J124942.3+344929
- z~0.438
- LIGO 78% spatial contour

Peaked ~50 days later



Abbott et al. (2020), Graham et al (2020)

Active Galactic Nuclei accretion disks



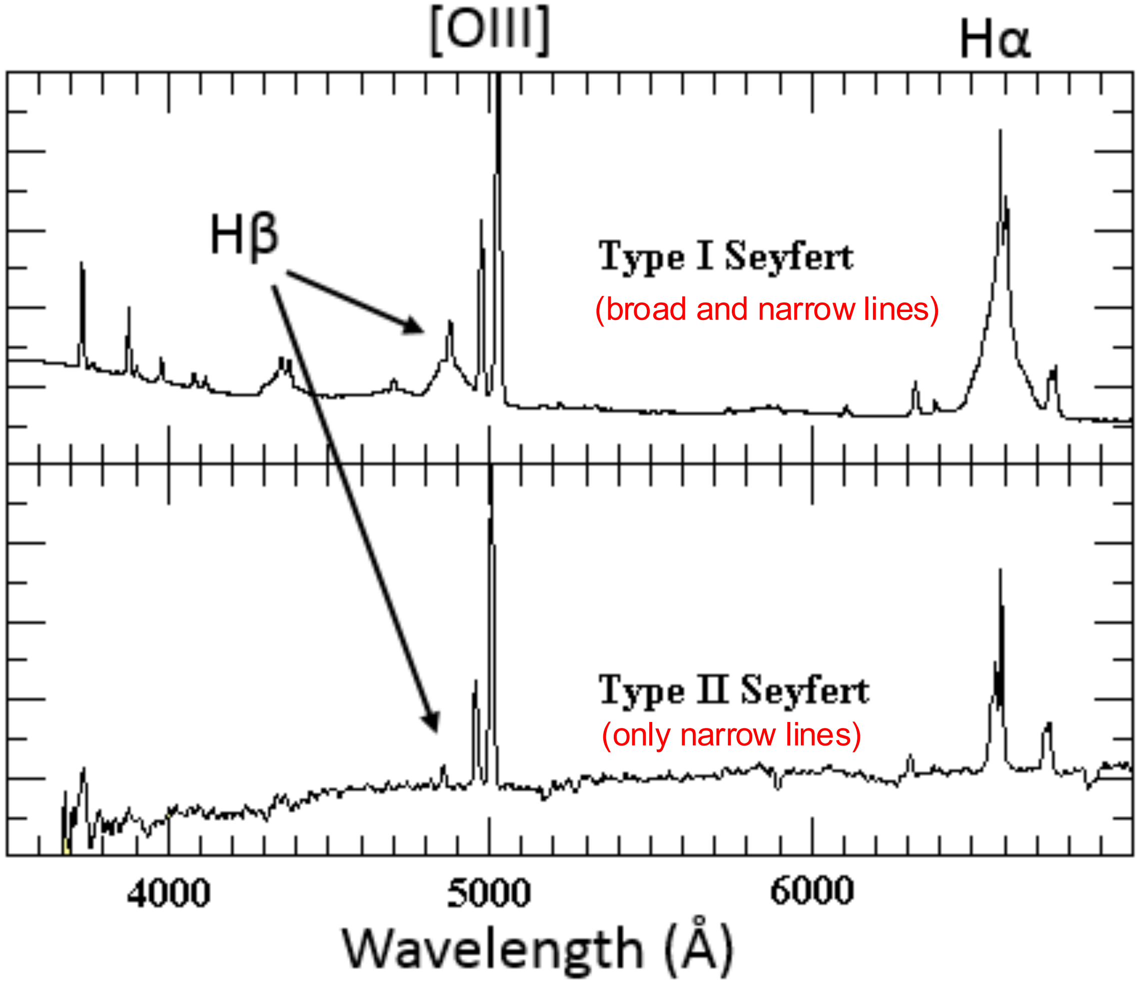
~10-100 kpc	~1-10 kpc	~0.1-1 kpc	~1-100 pc	~0.01-1 pc
whole galaxy	galactic nuclei region	NLR/polar dust	dusty torus	dust sublimation zone
near- to far-IR	near- to far-IR	mid- to far-IR	near- to mid-IR	near-IR

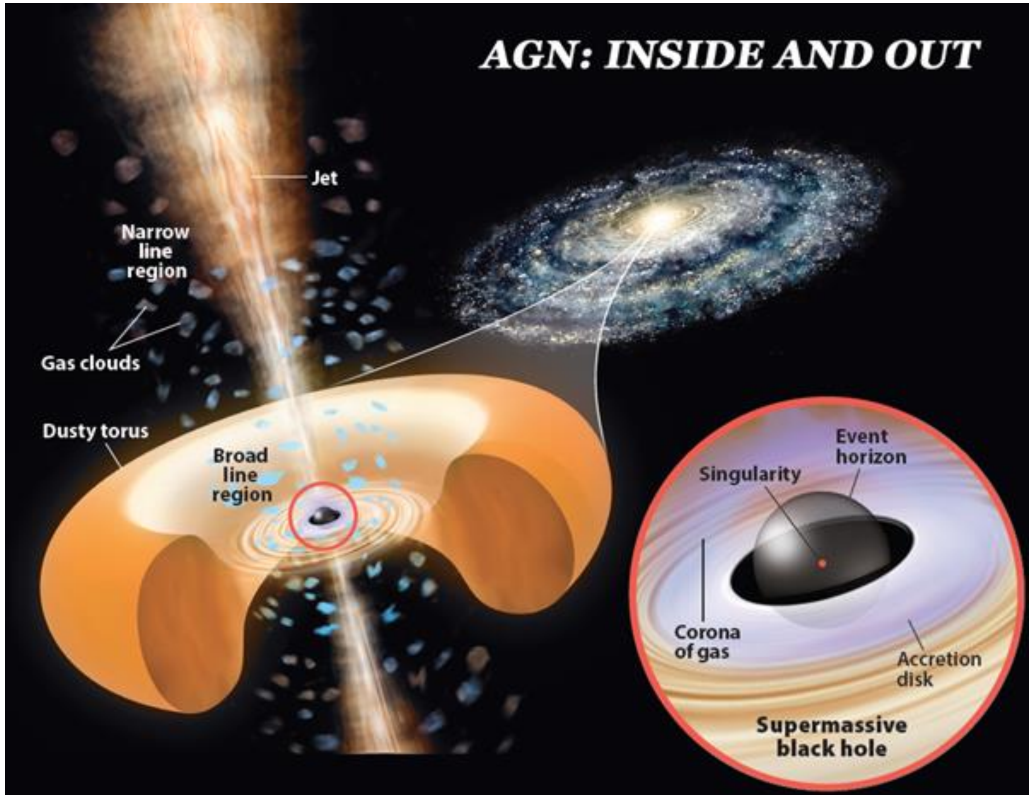
Lyu & Rieke (2022)

Structure of AGN Disks

Broad lines and narrow lines

Broad lines, Hα, Hβ, Mg: 1,000–10,000 km/s
Narrow lines, [OIII], [NII] : 100–1000 km/s



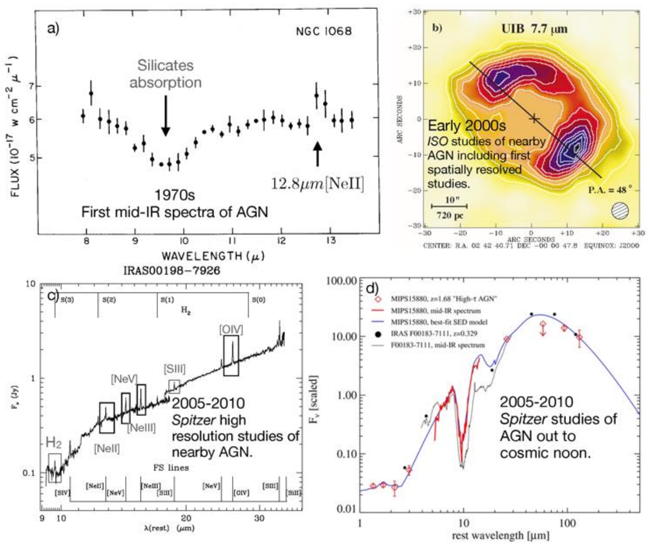


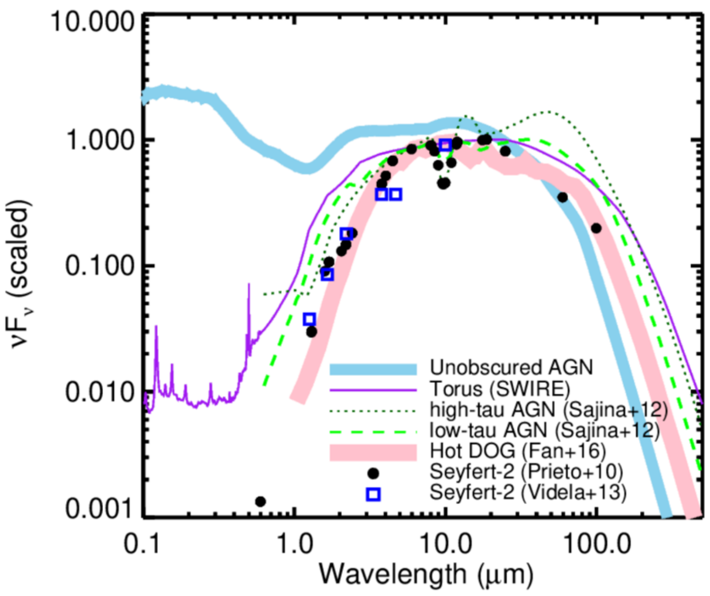
Runco (2015)

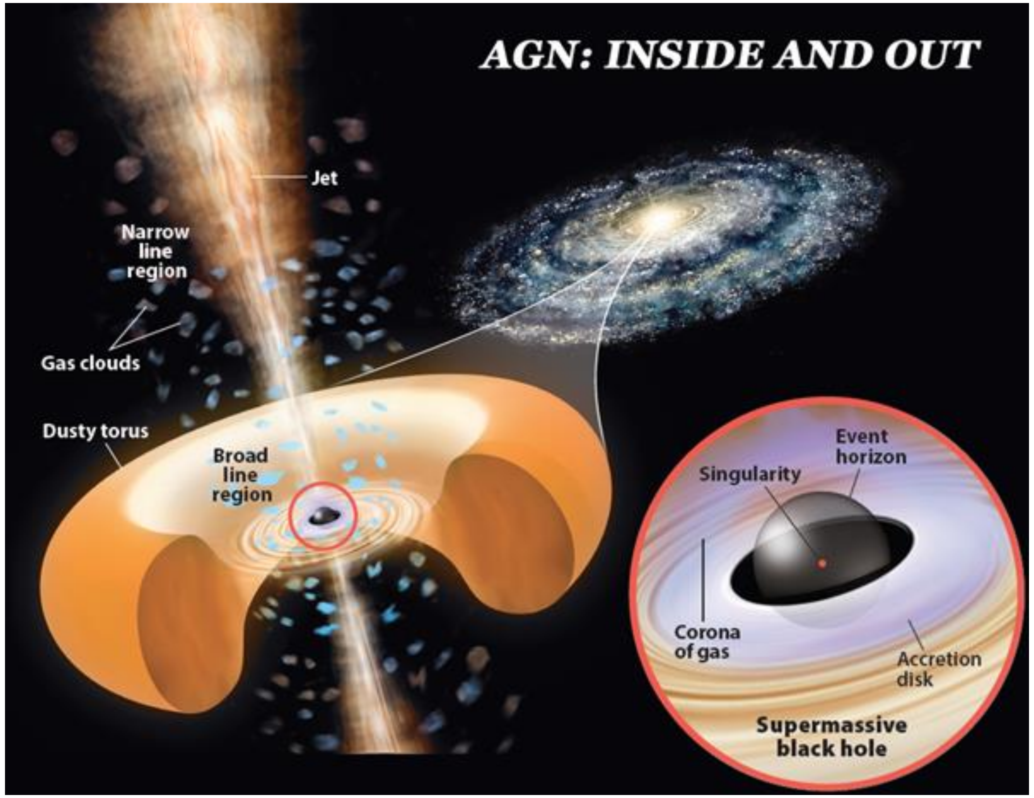
Structure of AGN Disks

The dust torus

Strong mid-infrared bump, hot and warm dust (~<1500K), 10 μm silicate feature.





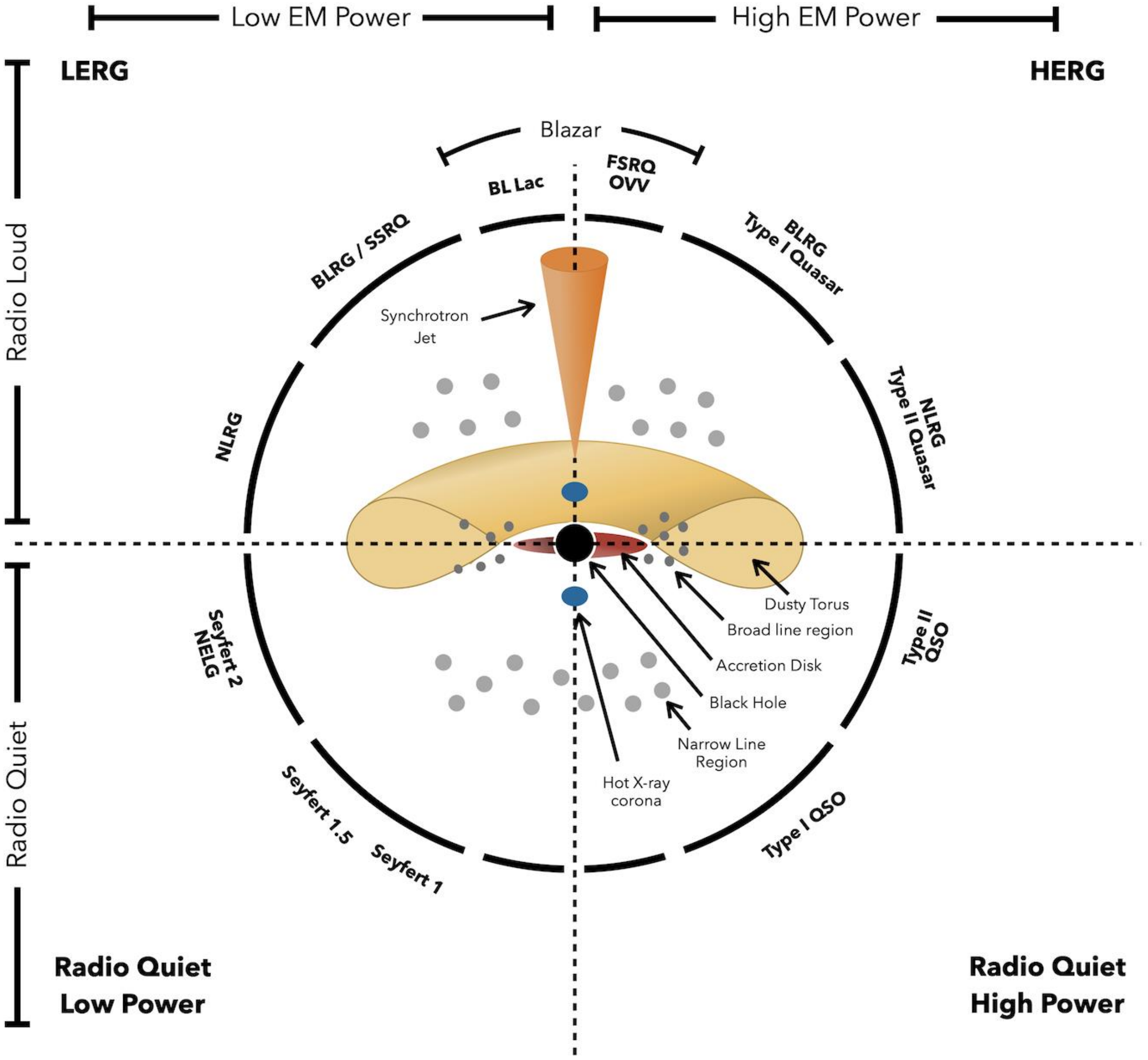


Sajina et al. (2022), Lyu & Rieke (2022)

AGN Unification

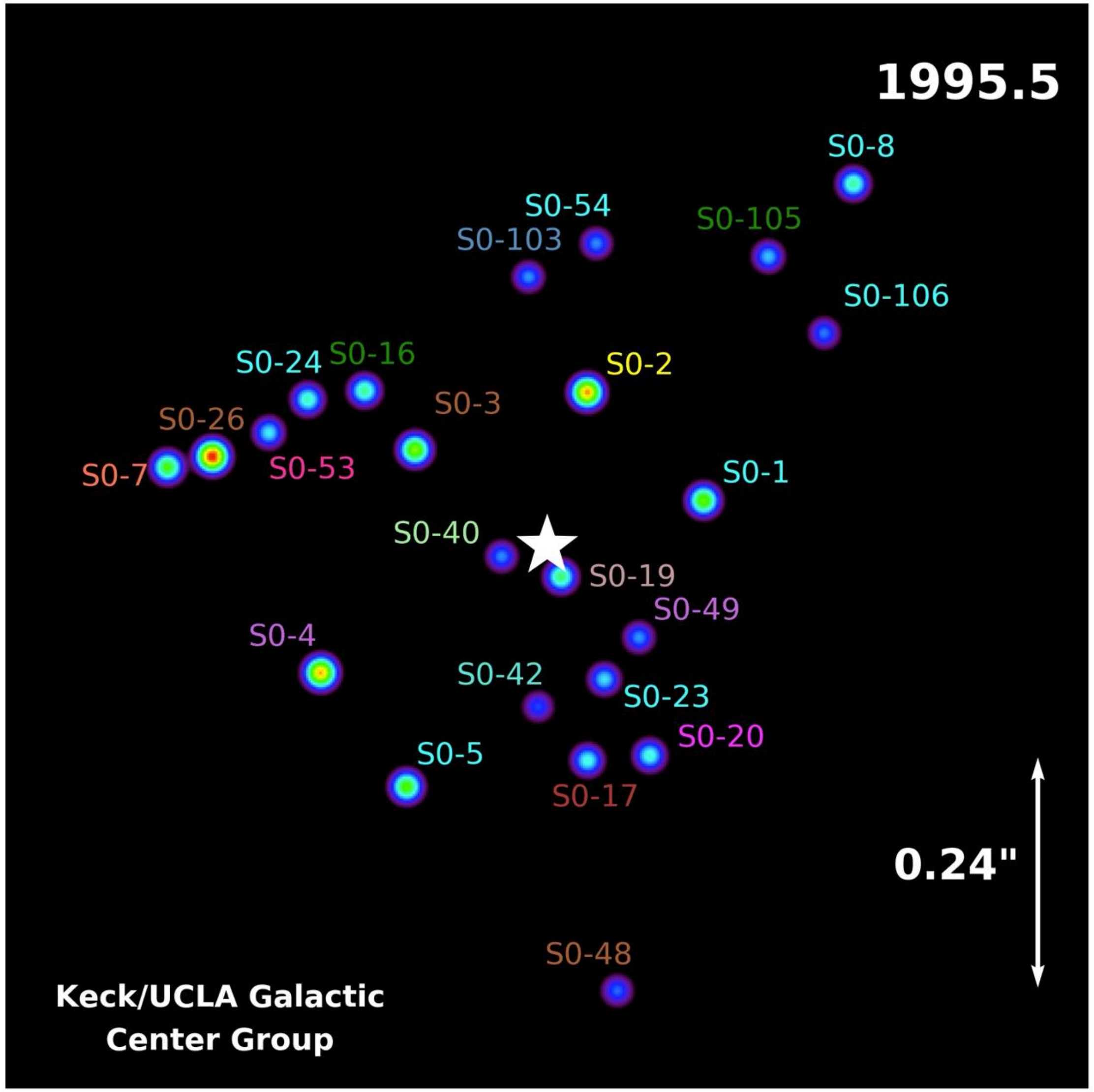
List of acronyms

LERG: Low excitation radio galaxy
HERG: High excitation radio galaxy
BLRG: Broad Line Radio Galaxy
SSRQ: Steep-Spectrum Radio Quasar
FSRQ: Flat-Spectrum Radio Quasar
OVV: Optically Violently Variable
NLRG: Narrow Line Radio Galaxy
NELG: Narrow-Emission-Line Galaxy
QSO: Quasi-Stellar Object (Quasar)



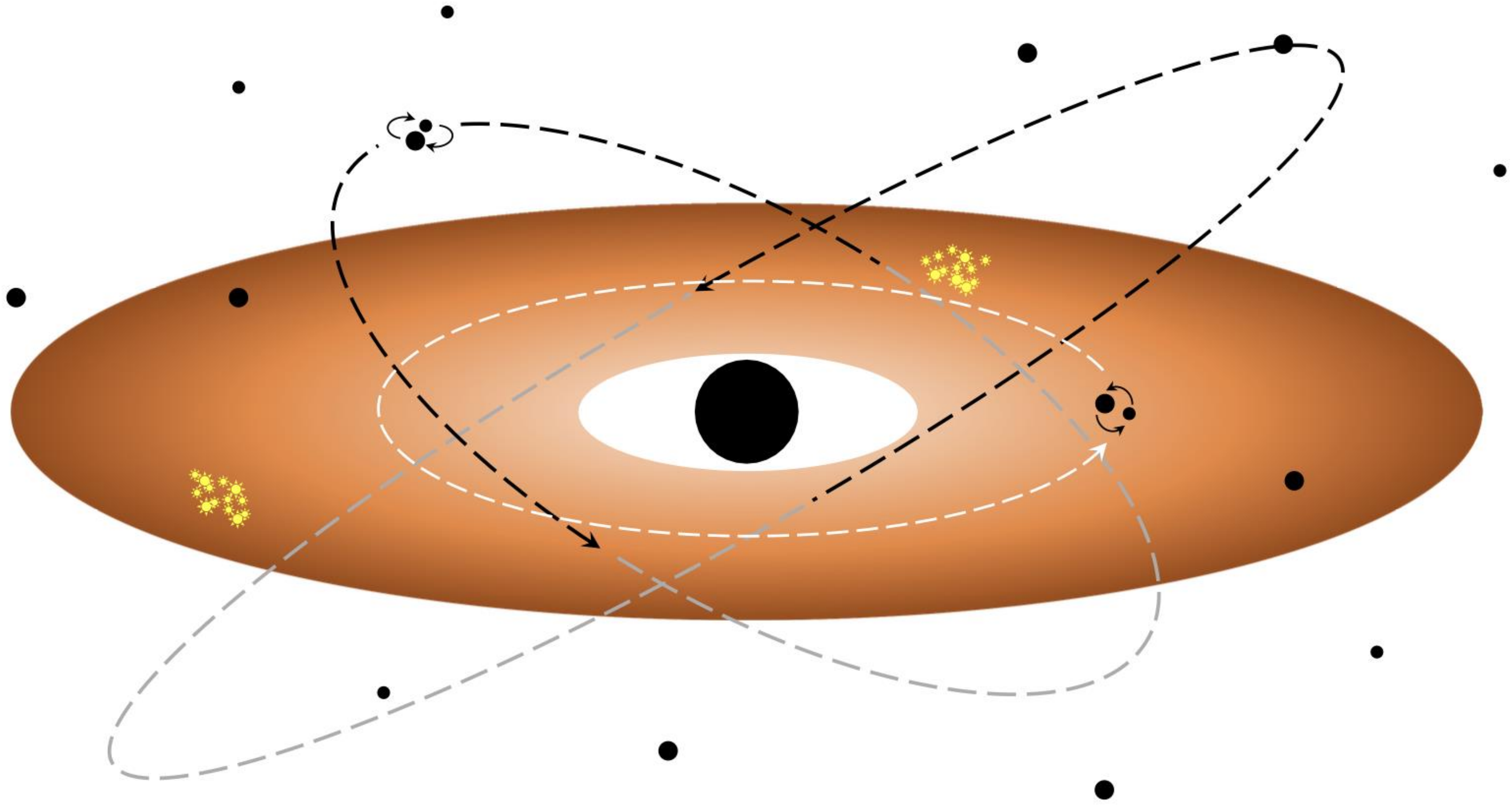
Thorne et al (2022)

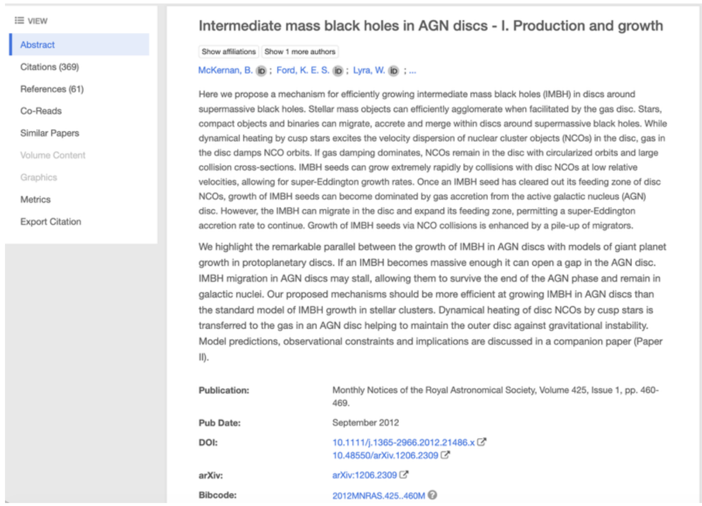
Supermassive Black Hole in the Galactic Center



Supermassive Black Hole in the Galactic Center

A cartoon AGN accretion disk





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Intermediate mass black holes in AGN discs - I. Production and growth

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McKernan, B. ; Ford, K. E. S. ; Lyra, W. ; ...

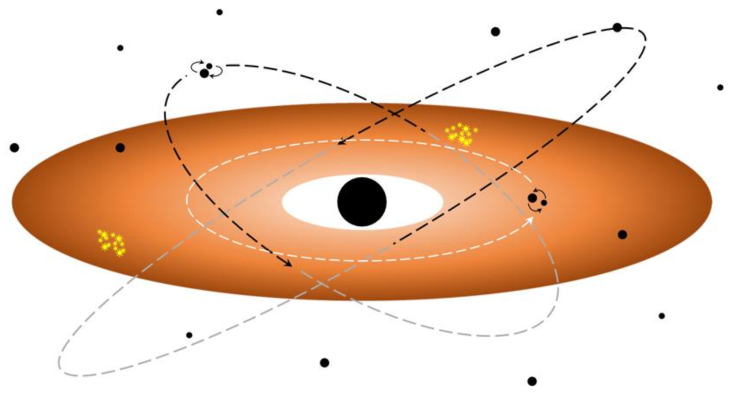
Here we propose a mechanism for efficiently growing intermediate mass black holes (IMBH) in discs around supermassive black holes. Stellar mass objects can efficiently agglomerate when facilitated by the gas disc. Stars, compact objects and binaries can migrate, accrete and merge within discs around supermassive black holes. While dynamical heating by cusp stars excites the velocity dispersion of nuclear cluster objects (NCOs) in the disc, gas in the disc damps NCO orbits. If gas damping dominates, NCOs remain in the disc with circularized orbits and large collision cross-sections. IMBH seeds can grow extremely rapidly by collisions with disc NCOs at low relative velocities, allowing for super-Eddington growth rates. Once an IMBH seed has cleared out its feeding zone of disc NCOs, growth of IMBH seeds can become dominated by gas accretion from the active galactic nucleus (AGN) disc. However, the IMBH can migrate in the disc and expand its feeding zone, permitting a super-Eddington accretion rate to continue. Growth of IMBH seeds via NCO collisions is enhanced by a pile-up of migrators.

We highlight the remarkable parallel between the growth of IMBH in AGN discs with models of giant planet growth in protoplanetary discs. If an IMBH becomes massive enough it can open a gap in the AGN disc. IMBH migration in AGN discs may stall, allowing them to survive the end of the AGN phase and remain in galactic nuclei. Our proposed mechanisms should be more efficient at growing IMBH in AGN discs than the standard model of IMBH growth in stellar clusters. Dynamical heating of disc NCOs by cusp stars is transferred to the gas in an AGN disc helping to maintain the outer disc against gravitational instability. Model predictions, observational constraints and implications are discussed in a companion paper (Paper II).

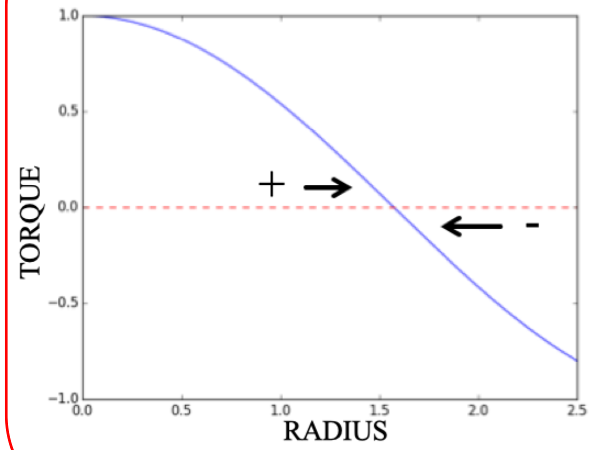
Publication:	Monthly Notices of the Royal Astronomical Society, Volume 425, Issue 1, pp. 460-469.
Pub Date:	September 2012
DOI:	10.1111/j.1365-2966.2012.21486.x 10.48550/arXiv.1206.2309
arXiv:	arXiv:1206.2309
Bibcode:	2012MNRAS.425..460M

The AGN channel for black hole mergers

The AGN nuclear cluster

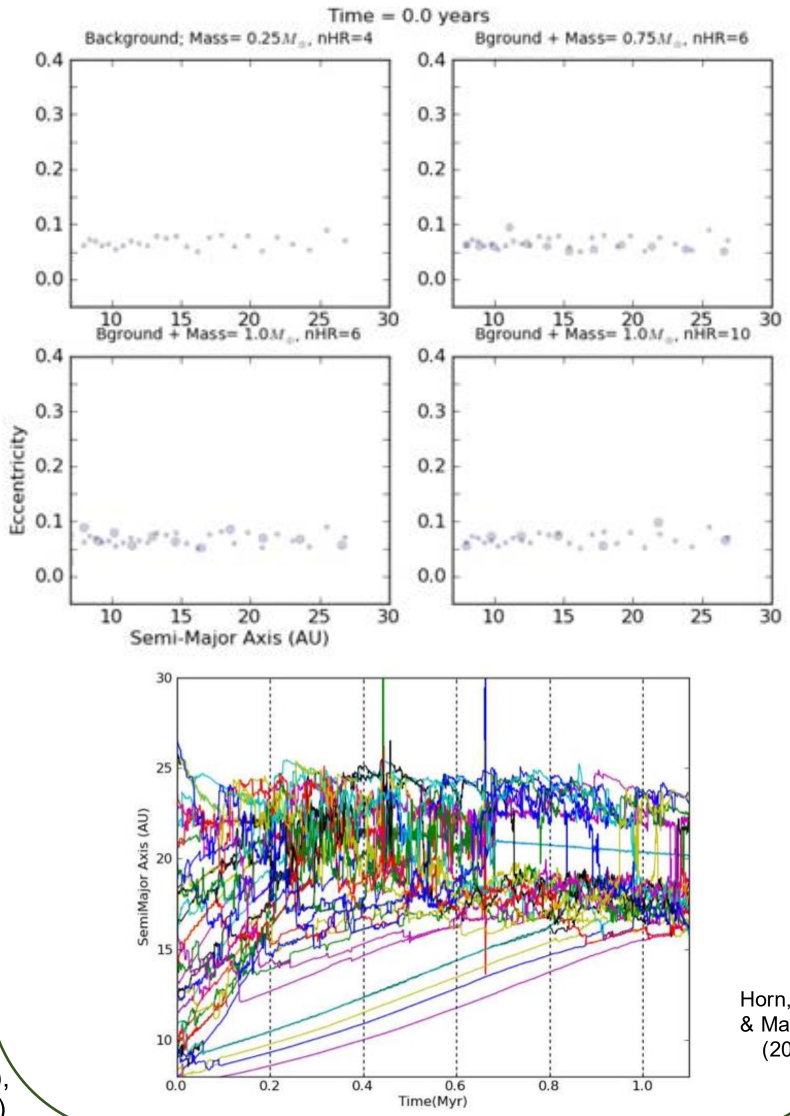


Migration Traps



Lyra, Paardekooper & Mac Low (2010)

Circumstellar Disks



Horn, Lyra, & Mac Low (2012)

McKernan et al. (2011, 2012, 2014, 2018, 2019), Leigh et al. (2018), Secunda et al. (2019, 2020), Nasim et al. (2023), Cook et al. (2026)

Why can’t we simply sed ‘s/protoplanetary/AGN/g’

Ionization

- AGN fully ionized; ppdisks poorly ionized

Relativity

- Unimportant in ppdisks,
- But even for AGNs only important for the central engine

Retrograde and highly inclined orbiters

- Inexistent in ppdisks

Feeback

- Stellar (SN) / sBH

Structure of AGN Disks

The Sirko-Goodman model

$$\sigma T_{\rm eff}^4 = \frac{3}{8\pi}\dot{M}'\Omega^2$$

$$T^4 = \left(\frac{3}{8}\tau + \frac{1}{2} + \frac{1}{4\tau}\right)T_{\rm eff}^4$$

$$\tau = \frac{\kappa\Sigma}{2}$$

$$\beta^b c_s^2 \Sigma = \frac{\dot{M}'\Omega}{3\pi\alpha}$$

$$p_{\rm rad} = \frac{\tau\sigma}{2c}T_{\rm eff}^4$$

$$p_{\rm gas} = \frac{\rho k T}{m}$$

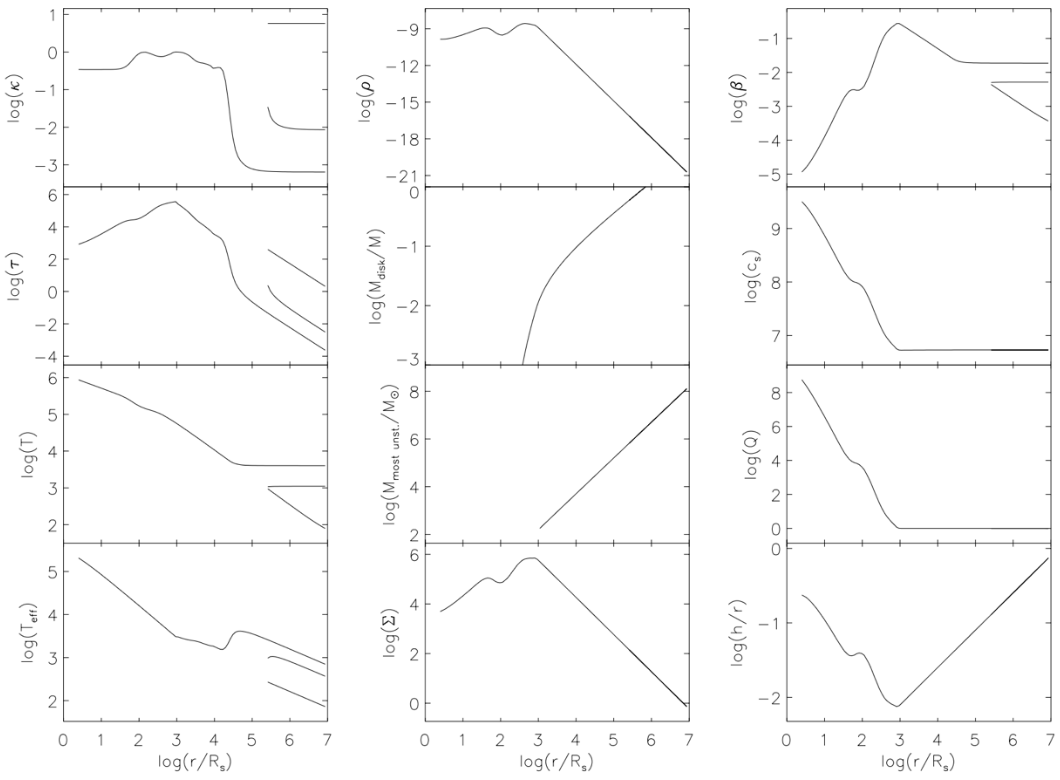
$$\beta = \frac{p_{\rm gas}}{p_{\rm gas} + p_{\rm rad}}$$

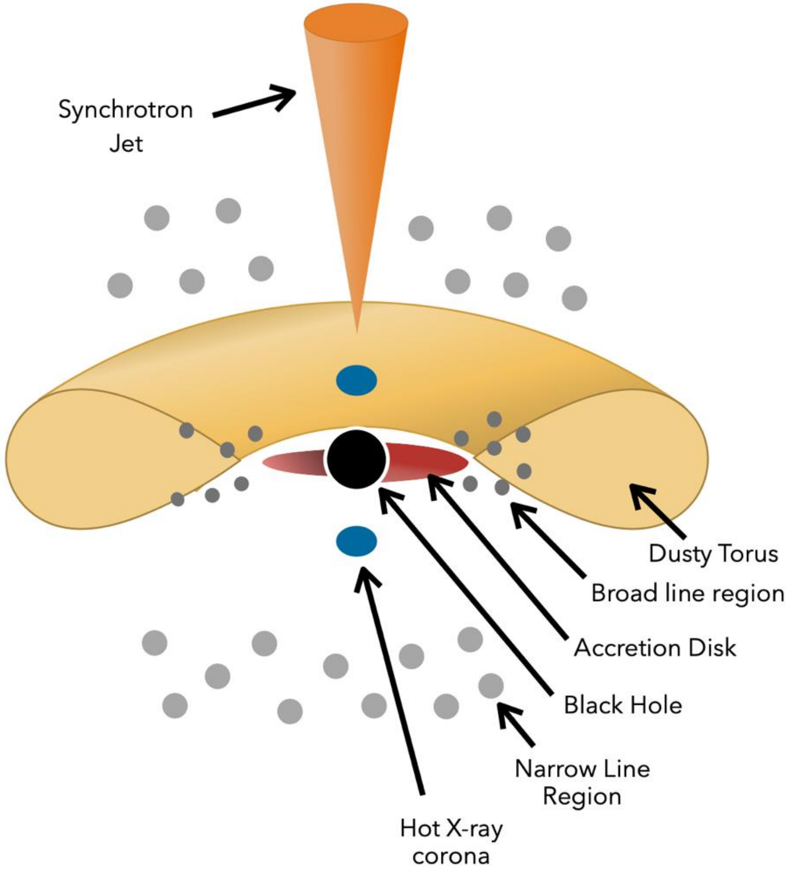
$$\Sigma = 2\rho h$$

$$h = \frac{c_s}{\Omega}$$

$$c_s^2 = \frac{p_{\rm gas} + p_{\rm rad}}{\rho}$$

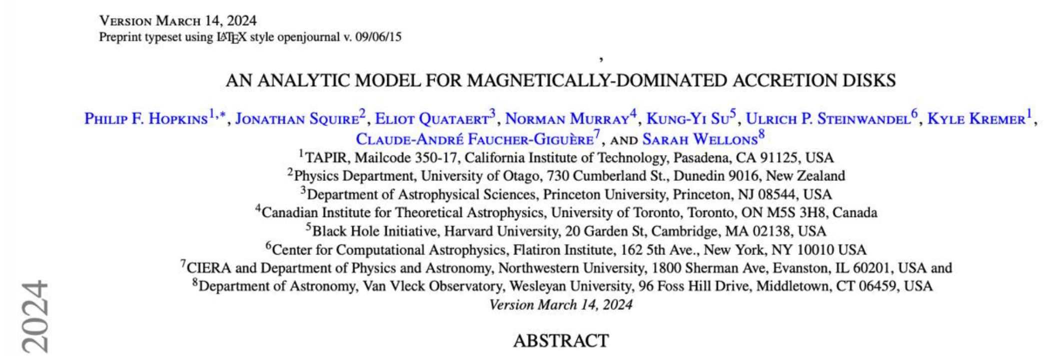
$$\kappa = \kappa(\rho, T).$$





Sirko & Goodman (2003)

Magnetized dust torus


Version March 14, 2024
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AN ANALYTIC MODEL FOR MAGNETICALLY-DOMINATED ACCRETION DISKS

Philip F. Hopkins[1,*], Jonathan Squire[2], Eliot Quataert[3], Norman Murray[4], Kung-Yi Su[5], Ulrich P. Steinwandel[6], Kyle Kremer[1], Claude-André Faucher-Giguère[7], and Sarah Wellons[8]
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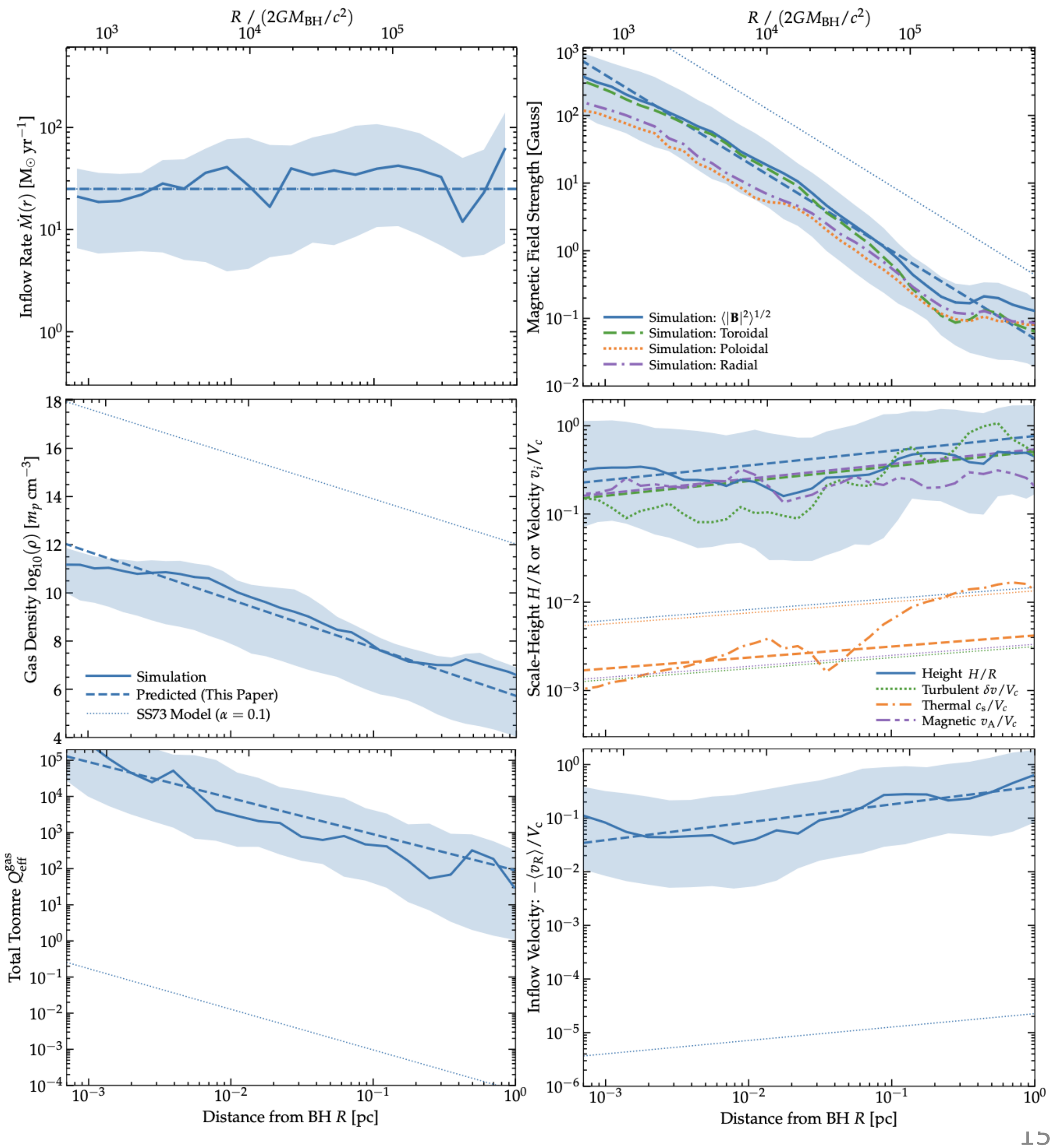
Version March 14, 2024

ABSTRACT

2024

- Hopkins et al. (2024) “flux-frozen” disk
  - Cosmological simulations resolving galaxy and AGN torus
  - Magnetic flux is brought in from the galaxy
  - Generates a magnetically supported torus of β<<1
  - Cold enough to allow for dust
  - High Q prevents catastrophic star formation



Hopkins et al. (2024)

Base (magnetized) AGN disk model

$$\Omega = \sqrt{\frac{G M_{\rm SMBH}}{r^3}} \quad (1)$$

$$\rho = \frac{\Omega^2}{2\pi G} \quad (2)$$

$$T^4 = T_{\rm irr}^4 + T_{\rm b}^4 \quad (3)$$

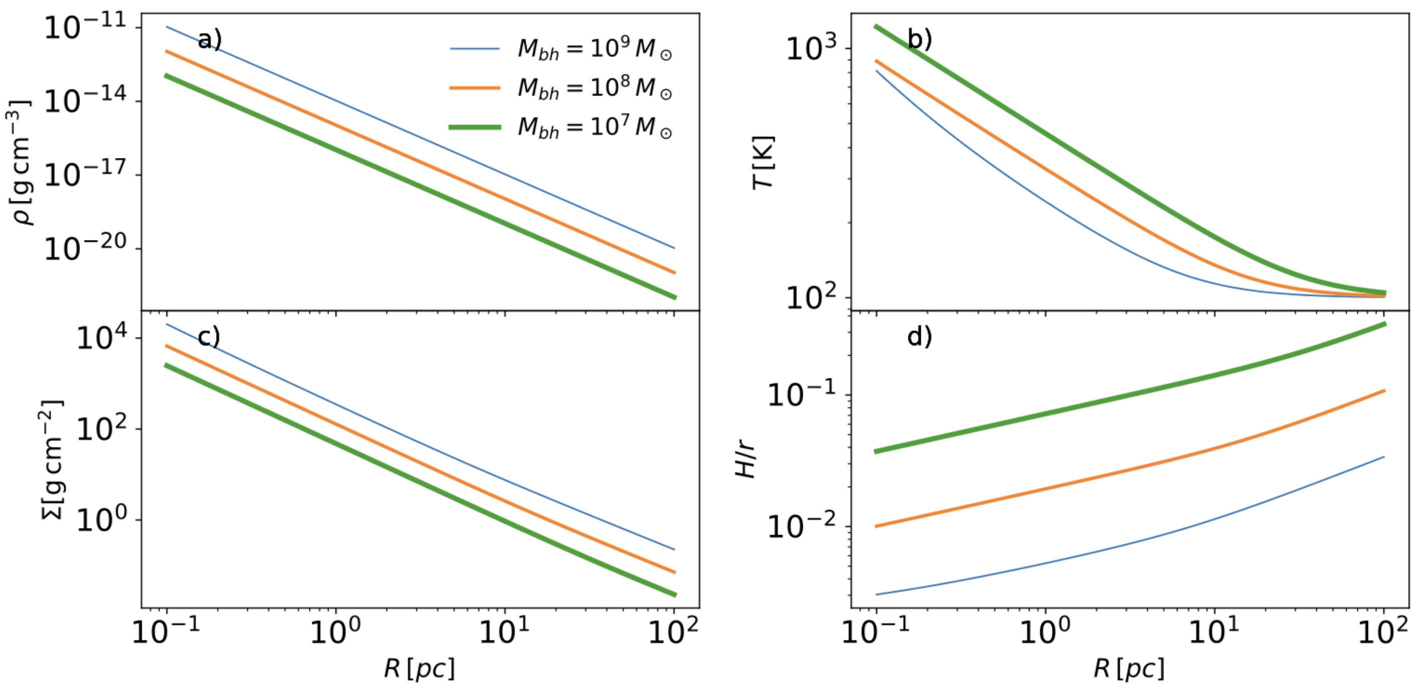
$$T_{\rm irr}^4 = T_\star^4 \left(\frac{r_\star}{r}\right)^2 \left\{\max\left[\frac{2}{3\pi}\frac{r_\star}{r} + \frac{H_{\rm ph}}{r}\left(\frac{d\ln H}{d\ln r} - 1\right)\right], 0\right\} \quad (4)$$

$$c_{\rm s} = \sqrt{\frac{\gamma k T}{\mu m_{\rm H}}} \quad (5)$$

$$H = \frac{c_{\rm s}}{\Omega}\sqrt{1 + \beta_m^{-1}} \quad (6)$$

$$\Sigma = 2H\rho \quad (7)$$

$$P_{\rm gas} = \rho c_{\rm s}^2/\gamma \quad (8)$$



Fragmentation and Drift

$$\mathrm{St}_{\mathrm{frag}} = \frac{v_{\mathrm{frag}}^2}{3\delta c_s^2},$$

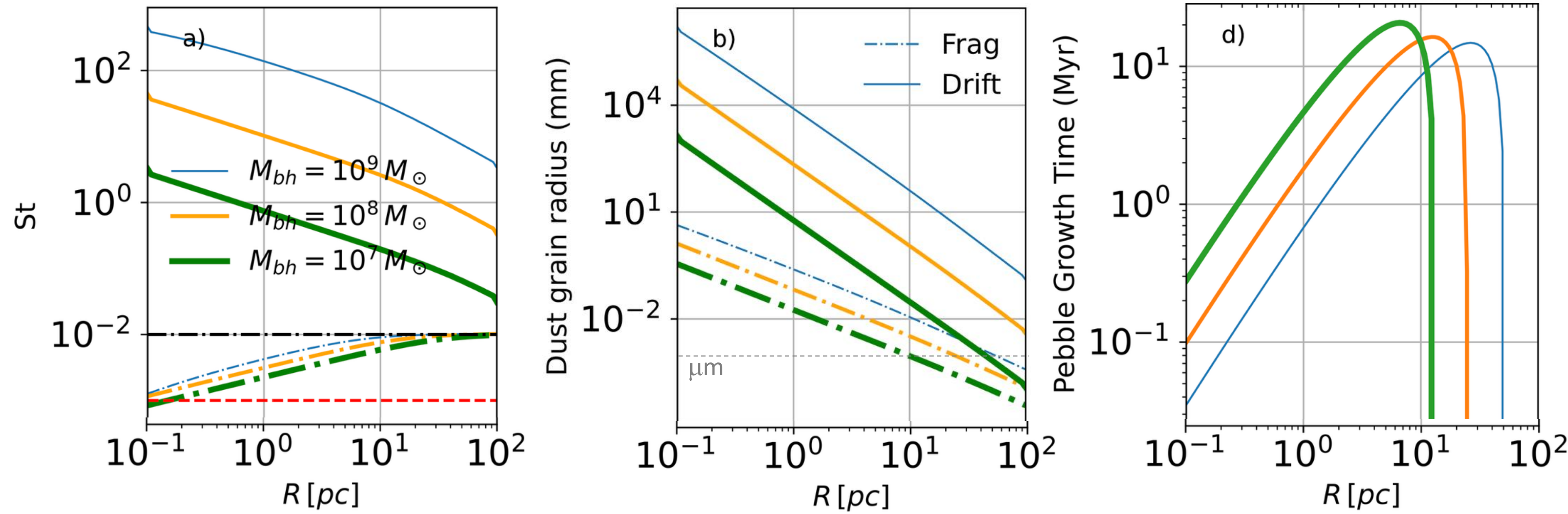
$$\mathrm{St}_{\mathrm{drift}} = \frac{3\pi^{1/2}\xi_c Z}{4\eta},$$

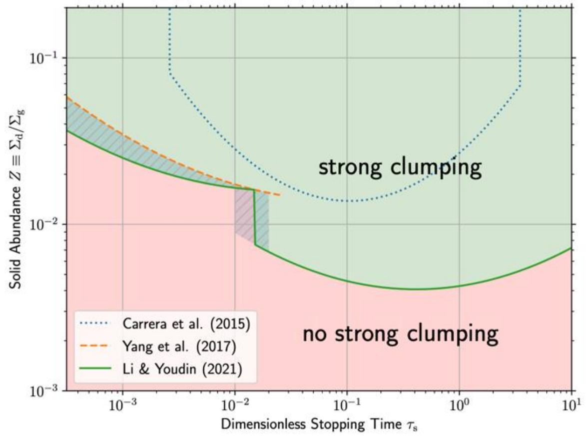
v_{frag} = 1 m/s

$$t_{\mathrm{grow}} = \frac{2}{\pi^{1/2}\xi_c Z \Omega},$$

$$a_{\mathrm{SI}} = \mathrm{St}_{\mathrm{SI}} \frac{c_s \rho}{\Omega \rho_\bullet}.$$

$$t_{\mathrm{SI}} = t_{\mathrm{grow}} \log\left(a_{\mathrm{SI}}/a_0\right),$$



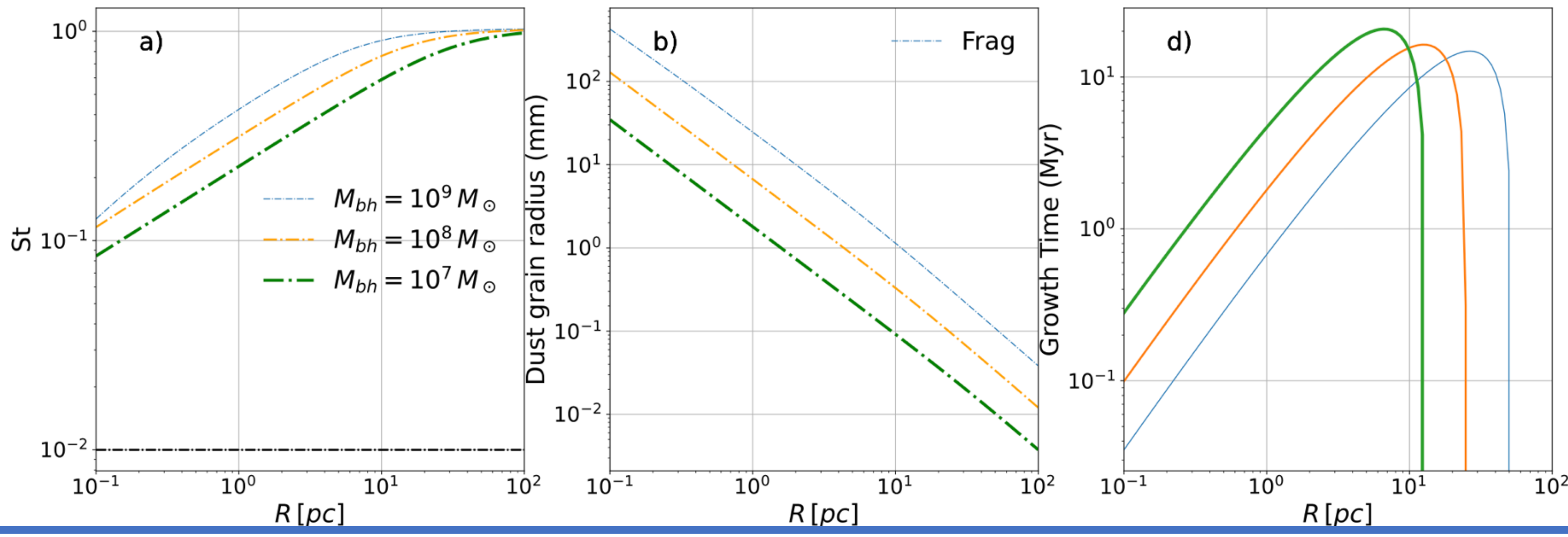


Fragmentation and Drift

Higher fragmentation speed threshold

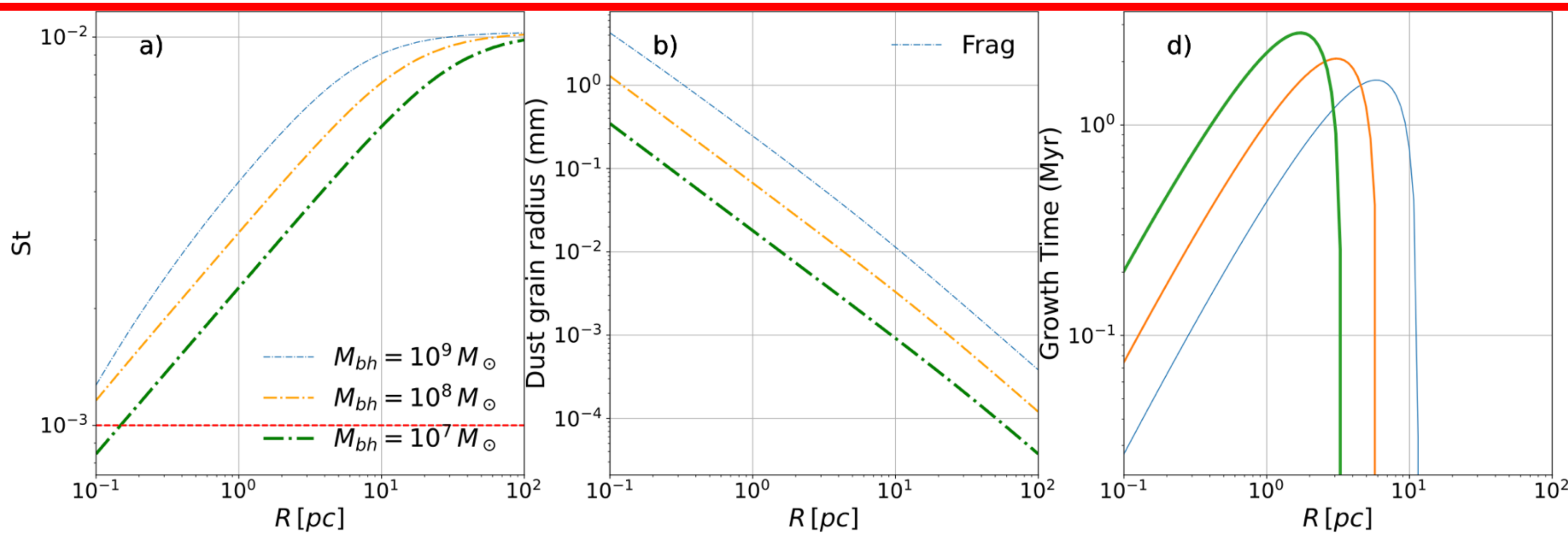
v_{frag} = 10 m/s
St_{SI} = 10^{-2}

Possible, but may hit AGN lifetime



Lower streaming instability St clumping threshold

v_{frag} = 1 m/s
St_{SI} = 10^{-3}



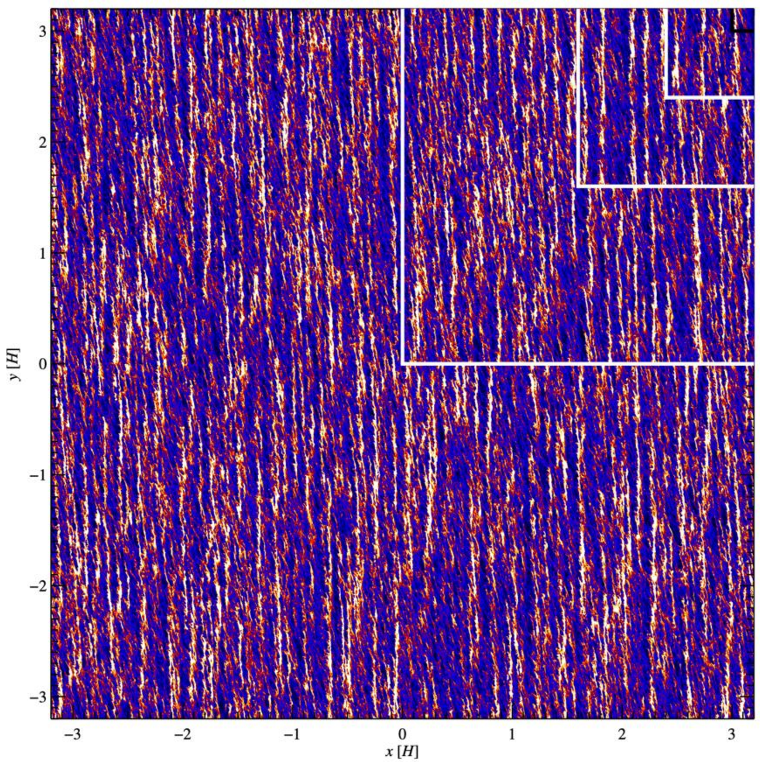
Mass of Filaments

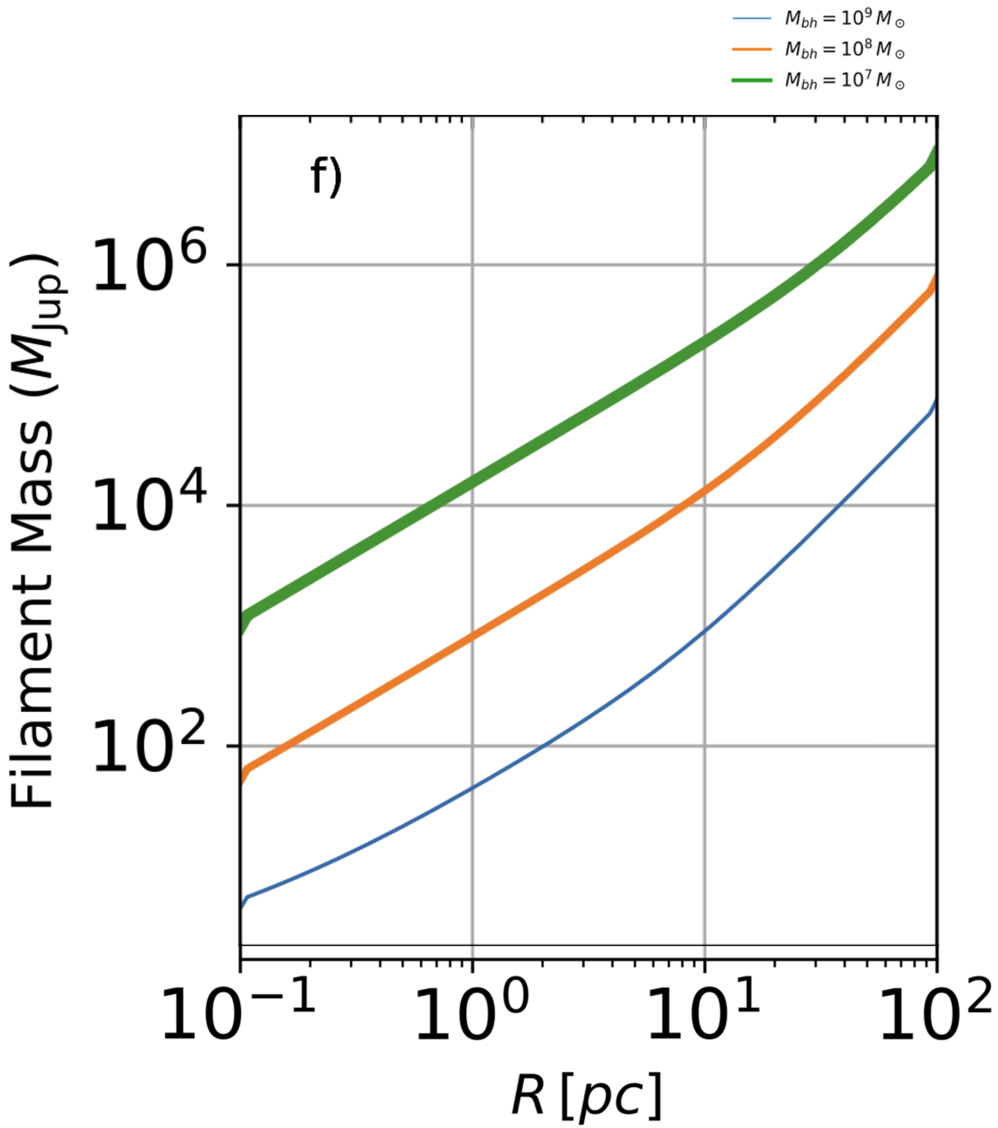
$$m_{\mathrm{f}} = \eta r H \Sigma Z_{\mathrm{f}},$$

width

length

column density





Yang & Johansen (2016), Li et al. (2018), Liu et al. (2019), Lorek & Johansen (2022), Schafer et al. (2024)

Typical planetesimal mass

Liu et al. (2020)

$$m_{\rm p} = C \left(\frac{Z_{\rm f}}{0.02}\right)^{0.5} \left(\frac{\tilde{G}}{\pi^{-1}}\right)^{0.5} \left(\frac{\Pi}{0.05}\right)^{3} \hat{M}.$$

$$\tilde{G} \equiv 4\pi G\rho/\Omega^2$$

$$\hat{M} \equiv \rho H^3$$

$$m_{\rm p} = 3.1 M_{\rm Jup} \left(\frac{C}{10^{-5}}\right) \left(\frac{Z_{\rm f}}{0.02}\right)^{1/2} \left(\frac{4\pi^2 G\rho}{\Omega^2}\right)^{3/2} \left(\frac{h}{0.05}\right)^{3} \left(\frac{M_{\rm SMBH}}{10^8 M_\odot}\right).$$

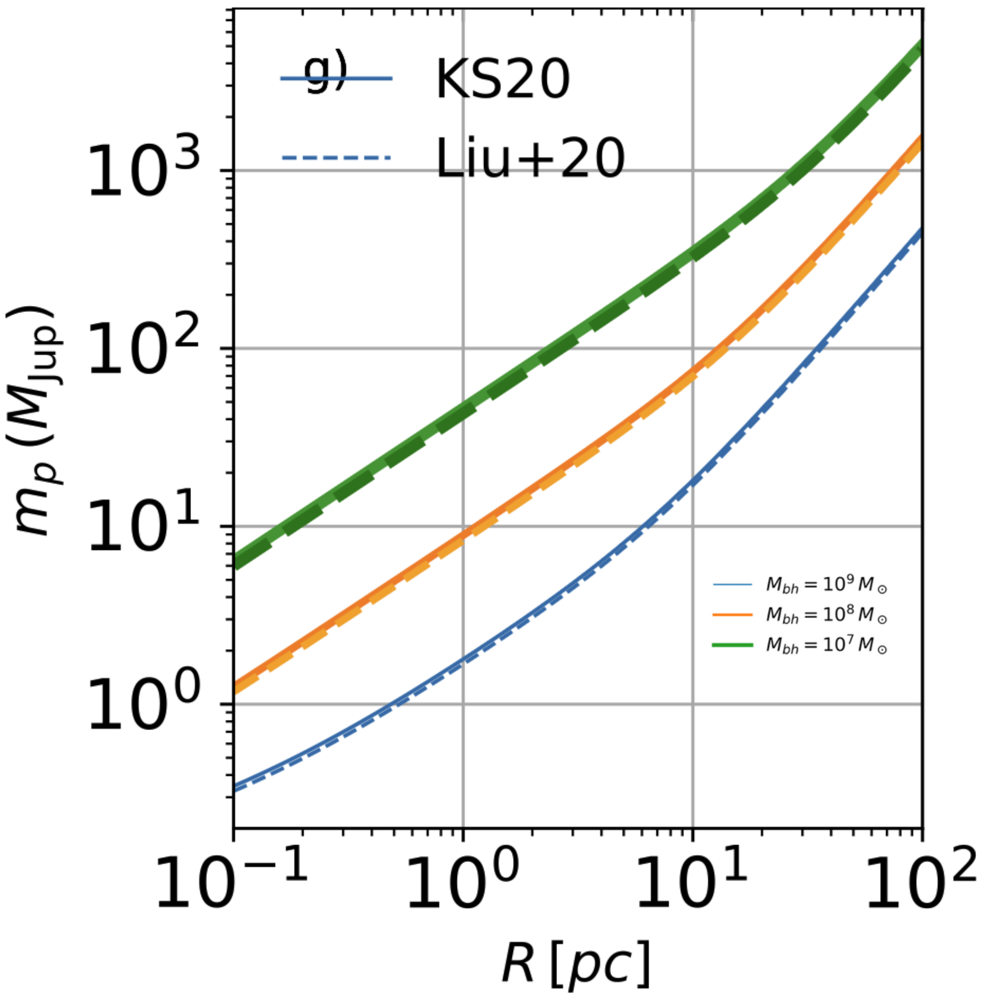
Klahr & Scheiber (2020)

$$m_{\rm p} = \frac{1}{9}\left(\frac{\delta}{\rm St}\right)^{1.5} h^3 M_{\rm SMBH},$$

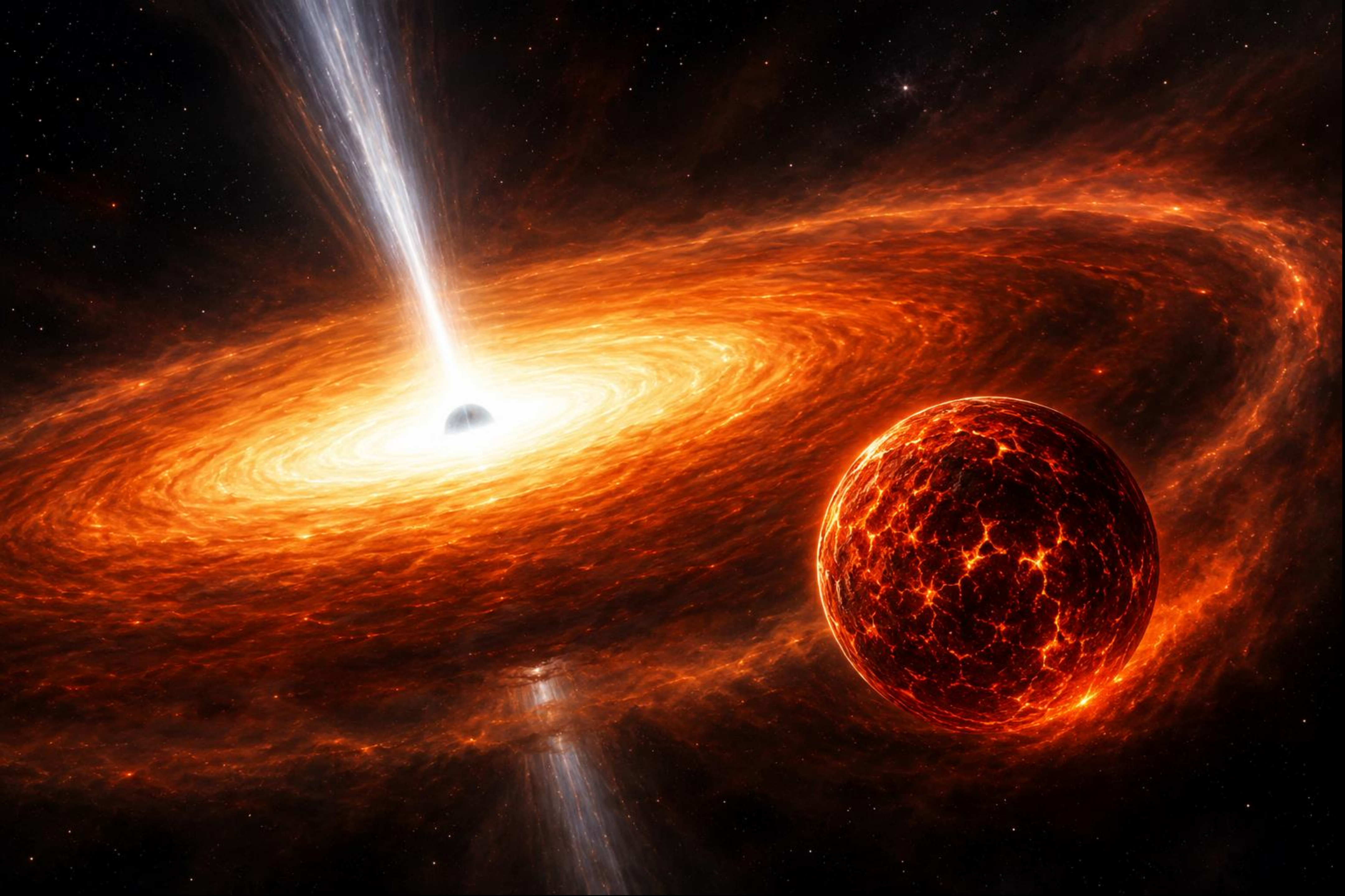
Thermal mass propto *Mh^3*

Typical masses

- *From Jupiter masses to solar masses*
- *Pure dust*
- *Structure?*
    - *Degenerate interior*
    - *Magma ocean surface*



Schafer et al. (2017), Liu et al. (2020), Klahr & Schreiber (2020)



Exotic objects: stellar mass objects of pure dust

THE ASTROPHYSICAL JOURNAL, 797:59 (16pp), 2014 December 10 doi:10.1088/0004-637X/797/1/59

SOME STARS ARE TOTALLY METAL: A NEW MECHANISM DRIVING DUST ACROSS STAR-FORMING CLOUDS, AND CONSEQUENCES FOR PLANETS, STARS, AND GALAXIES

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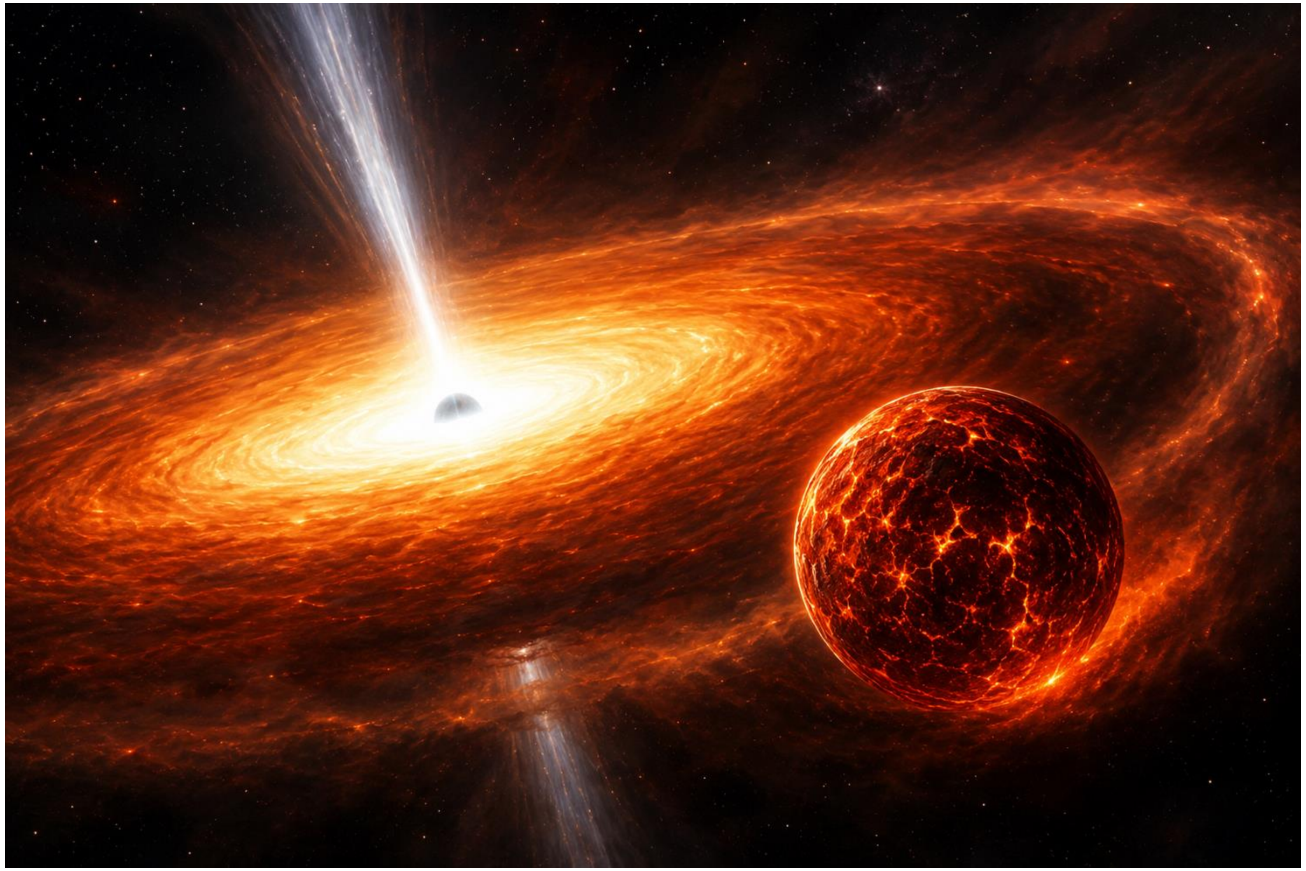
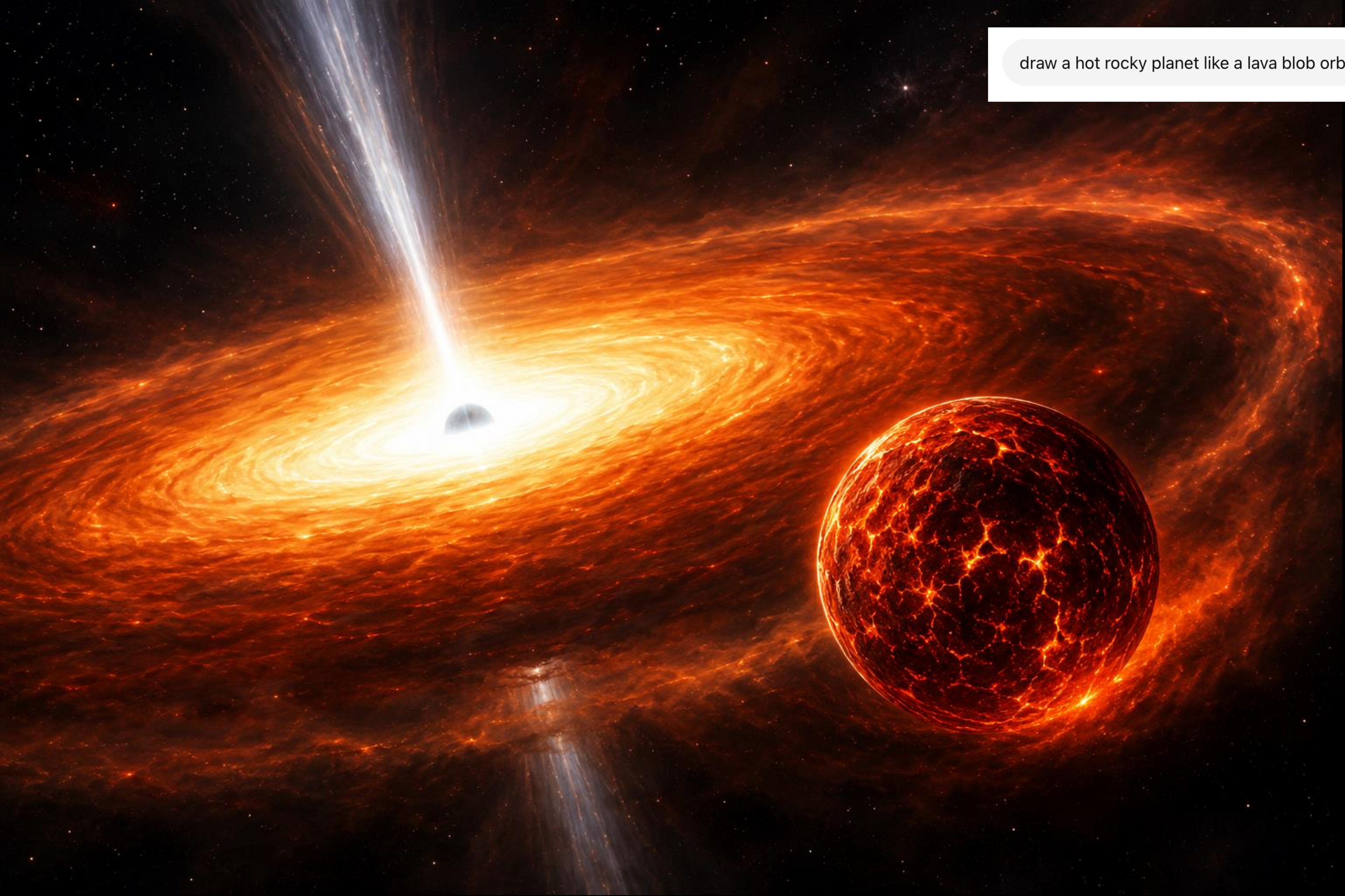
ABSTRACT

Dust grains in neutral gas behave as aerodynamic particles, so they can develop large local density fluctuations entirely independent of gas density fluctuations. Specifically, gas turbulence can drive order-of-magnitude "resonant" fluctuations in the dust density on scales where the gas stopping/drag timescale is comparable to the turbulent eddy turnover time. Here we show that for large grains (size $\gtrsim 0.1\,\mu$m, containing most grain mass) in sufficiently large molecular clouds (radii $\gtrsim$ 1–10 pc, masses $\gtrsim 10^4\,M_\odot$), this scale becomes larger than the characteristic sizes of prestellar cores (the sonic length), so large fluctuations in the dust-to-gas ratio are imprinted on cores. As a result, star clusters and protostellar disks formed in large clouds should exhibit significant abundance spreads in the elements preferentially found in large grains (C, O). This naturally predicts populations of carbon-enhanced stars, certain highly unusual stellar populations observed in nearby open clusters, and may explain the "UV upturn" in early-type galaxies. It will also dramatically change planet formation in the resulting protostellar disks, by preferentially "seeding" disks with an enhancement in large carbonaceous or silicate grains. The relevant threshold for this behavior scales simply with cloud densities and temperatures, making straightforward predictions for clusters in starbursts and high-redshift galaxies. Because of the selective sorting by size, this process is not necessarily visible in extinction mapping. We also predict the shape of the abundance distribution—when these fluctuations occur, a small fraction of the cores may actually be seeded with abundances $Z \sim 100\,\langle Z \rangle$ such that they are almost "totally metal" ($Z \sim 1$)! Assuming the cores collapse, these totally metal stars would be rare (1 in $\sim 10^4$ in clusters where this occurs), but represent a fundamentally new stellar evolution channel.

Key words: galaxies: evolution – galaxies: formation – hydrodynamics – protoplanetary disks – stars: formation

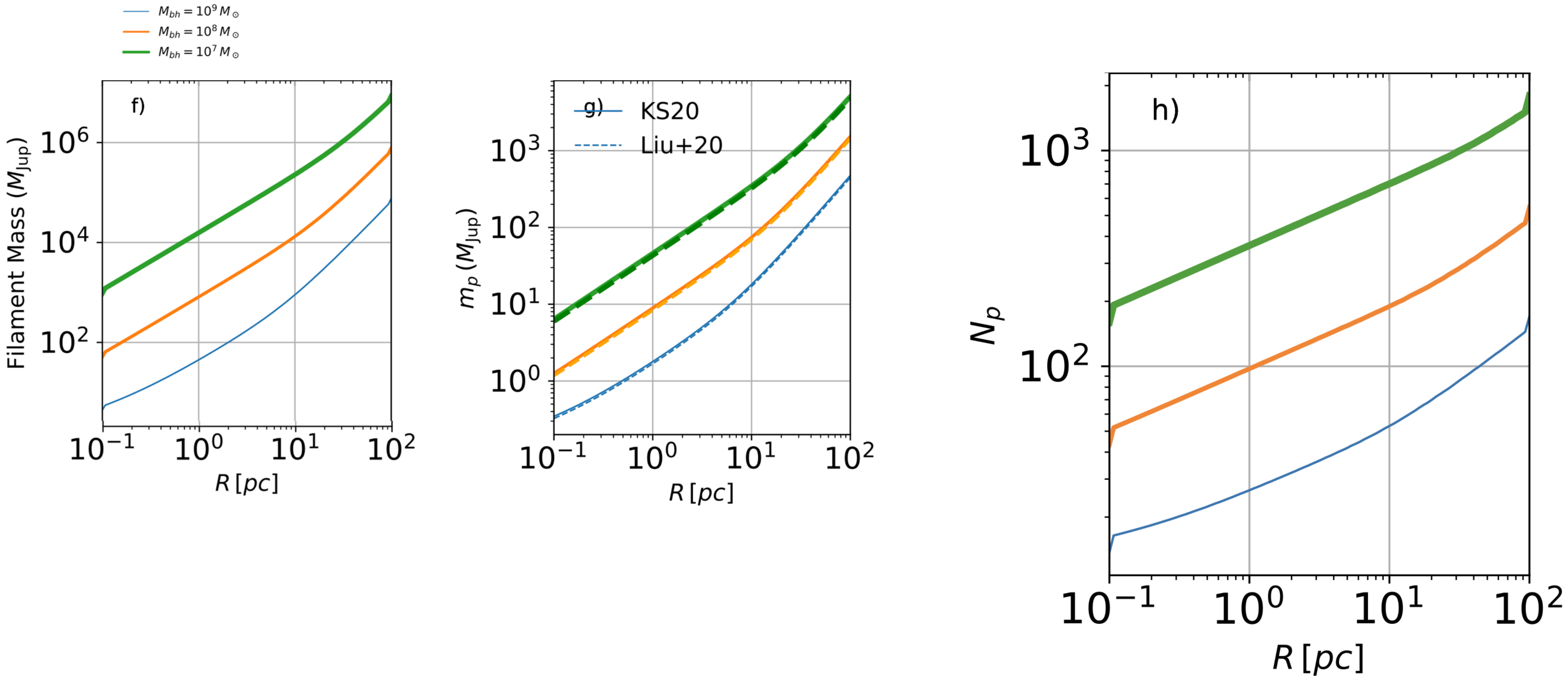
Online-only material: color figures





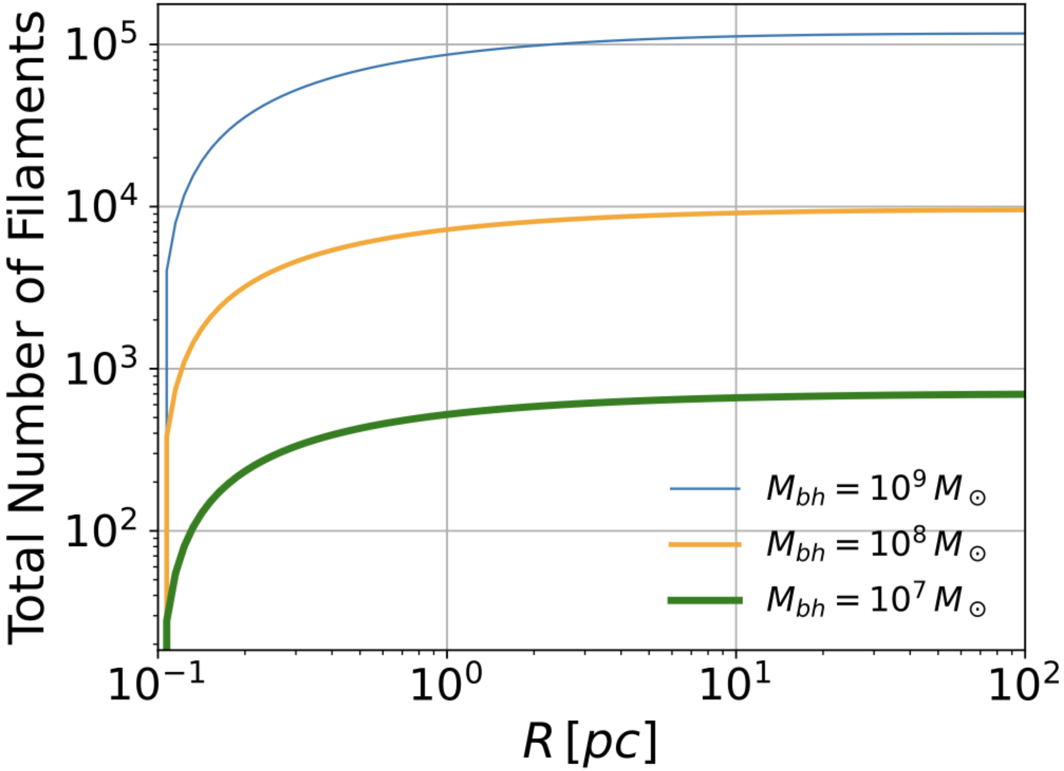
draw a hot rocky planet like a lava blob orbiting around an AGN disk

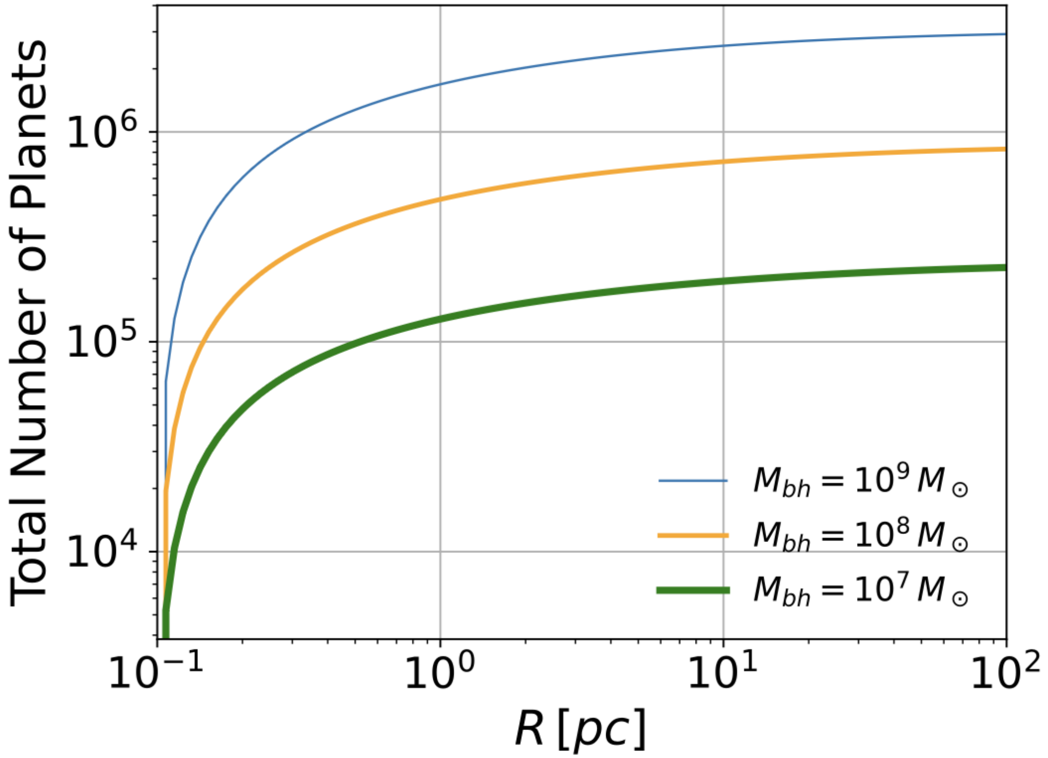
Planets per filament



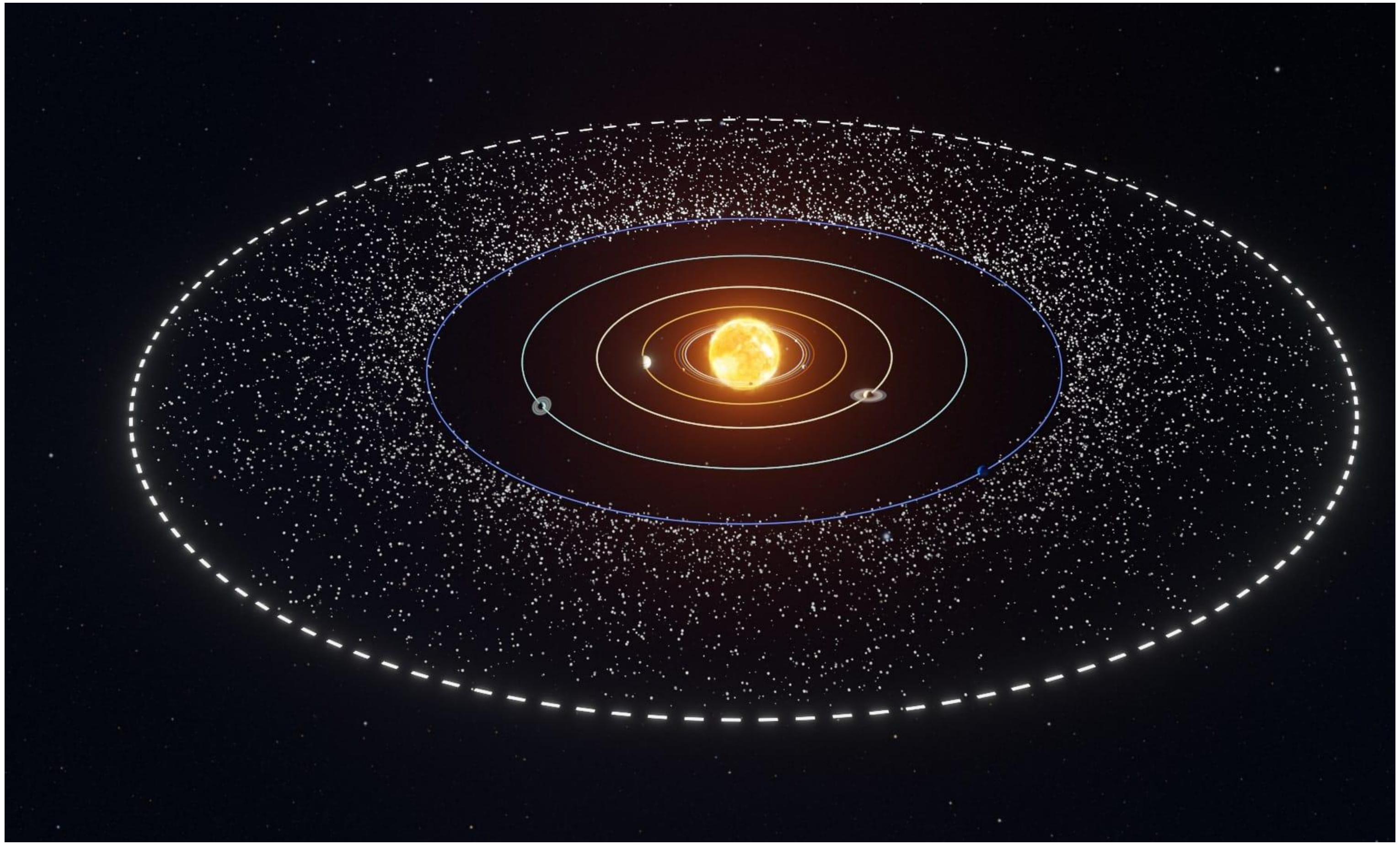
Cumulative number of planets

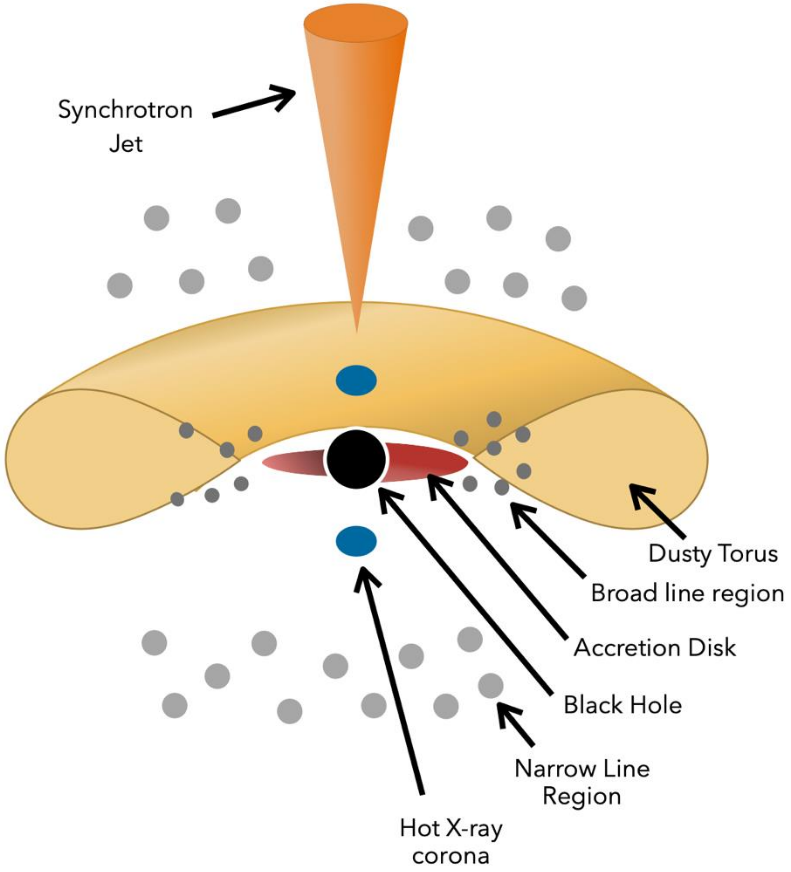
2 x 10^5 – 3 x 10^6 planets per AGN





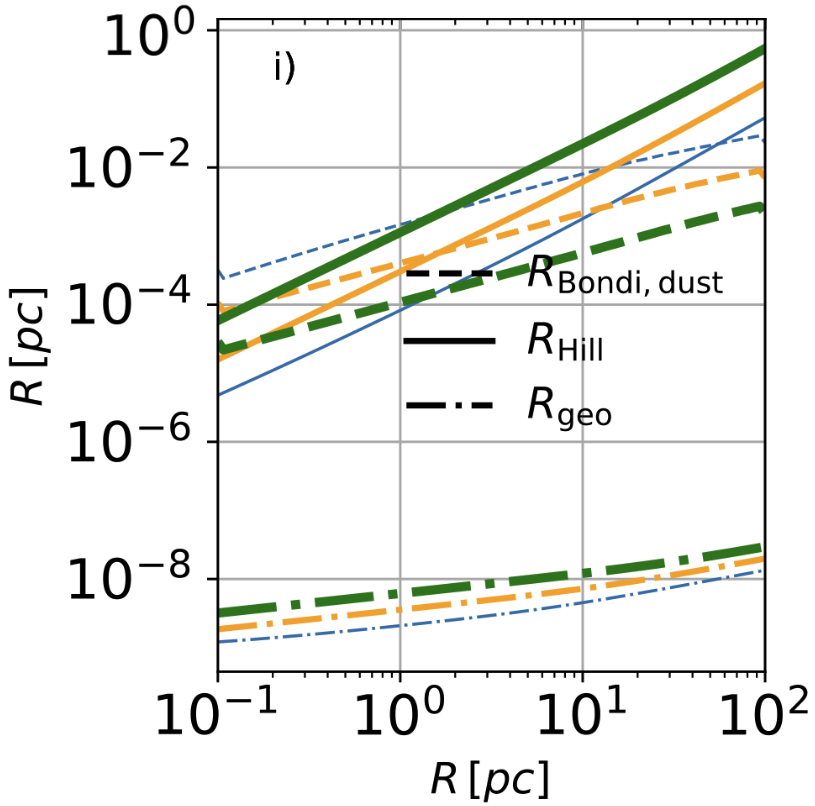
Solar System Analogy: Kuiper Belt

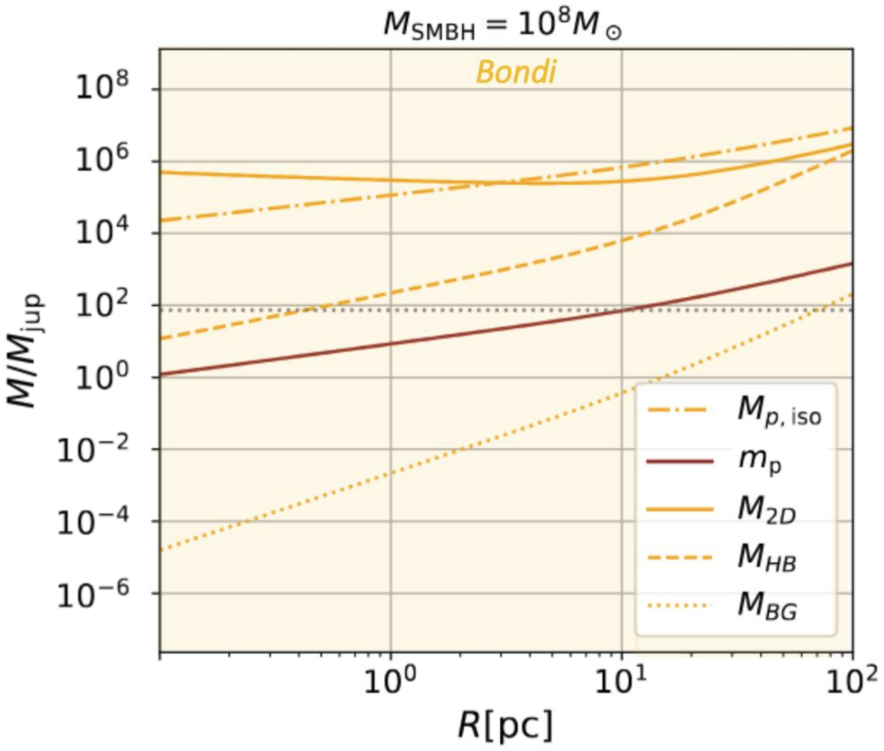




Fate of the seeds – Pebble accretion?

- Seeds generally start at 3D Bondi
- Rarely get to 2D accretion
- Pebble isolation mass beyond hydrogen burning limit
  - If gas accretion occurs, pebble accretion is terminated by stellar feedback, not by gap opening.





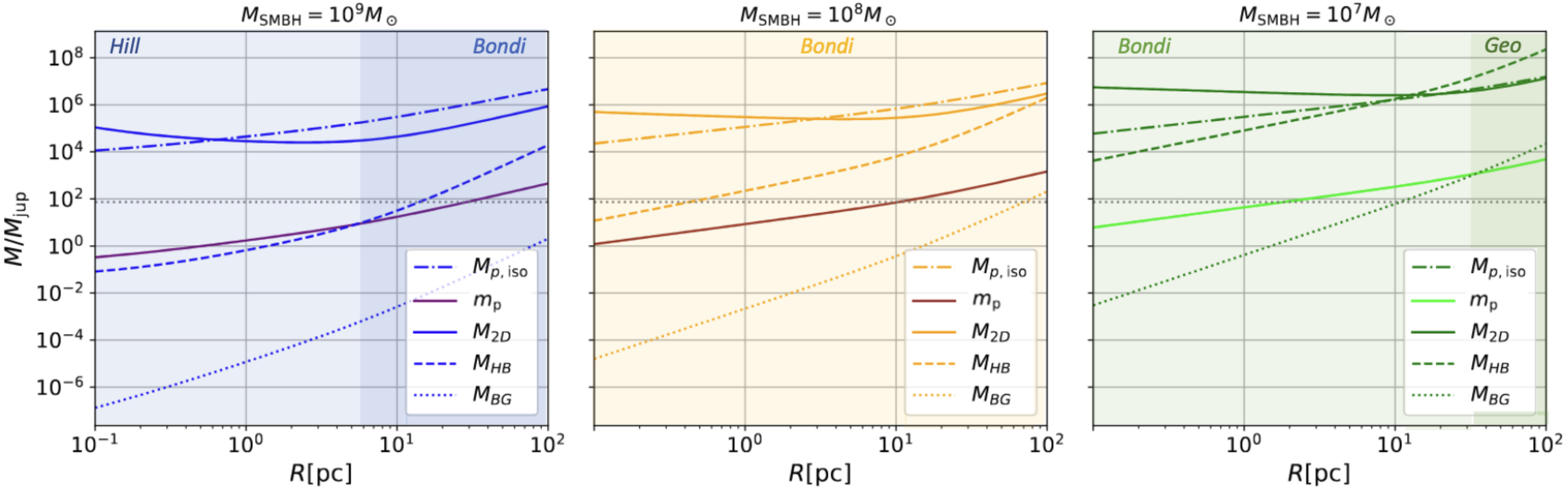
$M_{p,\,\rm iso}$ – pebble isolation mass
m_p – typical planetesimal mass
M_{2D} – 3D/2D transition
M_{HB} – Hill-Bondi transition
M_{BG} – Bondi-Geometric transition

Pebble accretion

Progression from:

Hill, Hill/Bondi, Bondi, and Bondi/Geometric

as the central mass object decreases

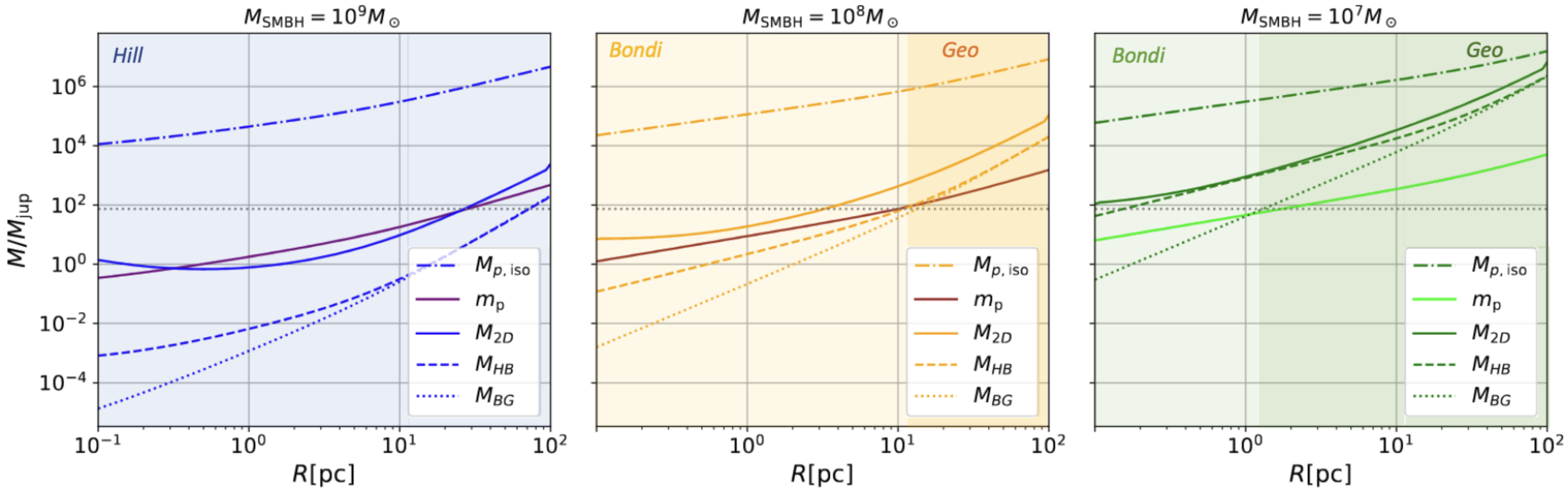


Pebble accretion

v_{frag} = 10 m/s

Higher Stokes number means 2D accretion becomes possible

Efficient 2D Hill accretion on much of the parameter space of 10^9 M_{sun} SMBH



Concurrent pebble and gas accretion

$$dm = 4\pi r^2 \rho dr$$

$$\frac{dm}{dt} = 4\pi r^2 \rho \frac{dr}{dt}$$

$$r = R_{\rm Bondi,gas} = Gm_{\rm p}/c_{\rm s}^2,$$

$$dr/dt = G\dot{m}/c_{\rm s}^2$$

$$\dot{m}_{XY} = 4\pi R_{\rm Bondi,gas}^2 \rho G \dot{m}_z / c_{\rm s}^2 = 4\pi G^3 m_{\rm p}^2 \rho \dot{m}_z / c_{\rm s}^6 \qquad R_{\rm Bondi,gas} < R_{\rm Hill}$$

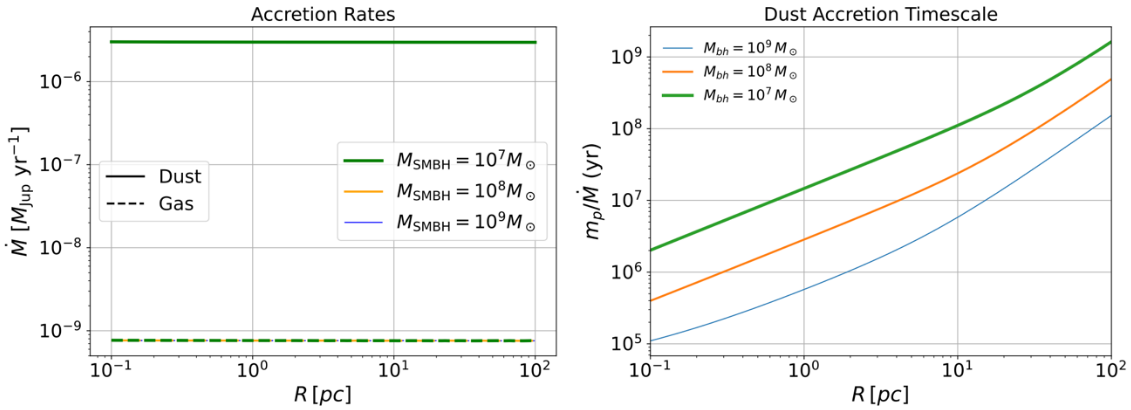
$$\dot{m}_{XY} = \frac{4\pi \rho G}{9\Omega^2} \dot{m}_z \qquad R_{\rm Hill} < R_{\rm Bondi,gas}$$

Ratio $\dot{m}_{xy}/\dot{m}_z$ propto m_p^2

Gas accretion will catch up
if m_z increases by factor ~30

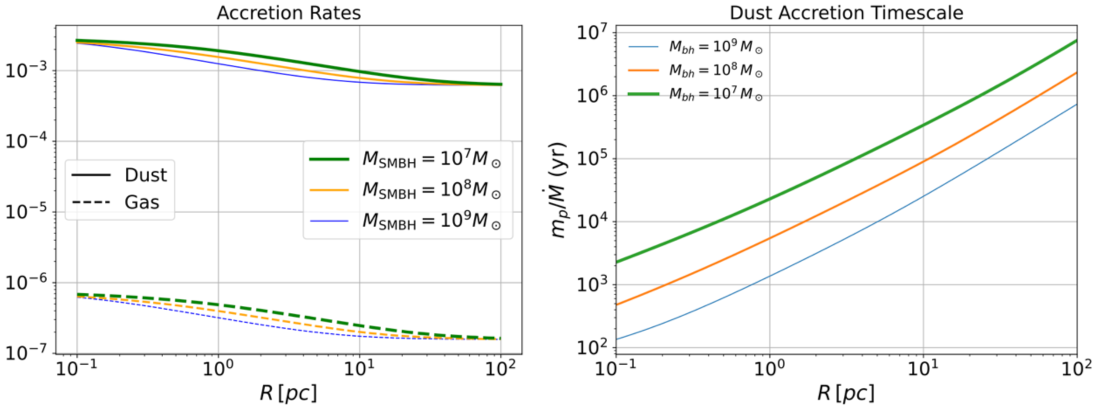
$v_{\rm frag}$ = 1 m/s

Negligible gas accretion
Also low dust accretion



$v_{\rm frag}$ = 10 m/s

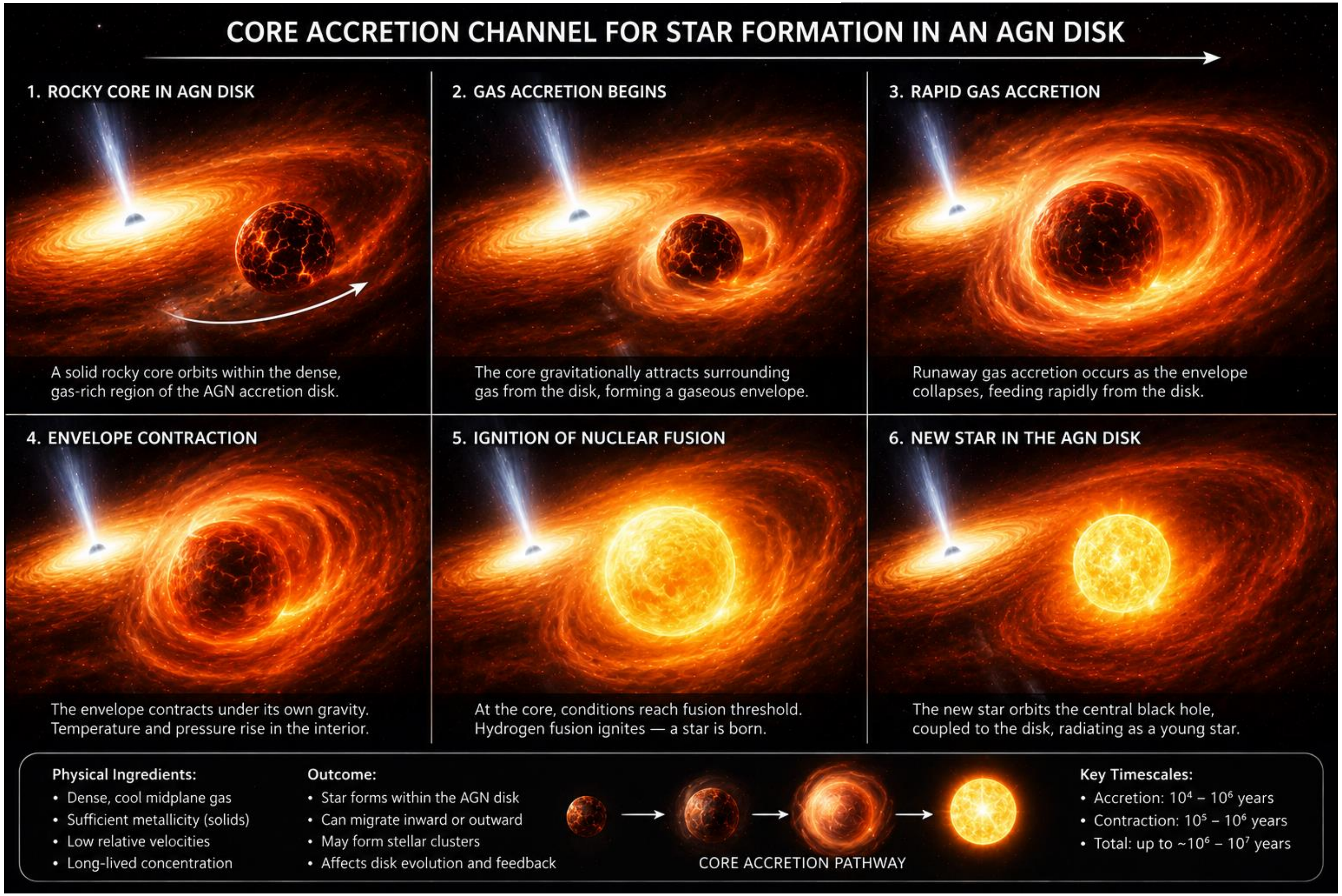
Significant pebble and gas accretion
Possible “core accretion” channel
for star formation.



Pollack et al. (1996)

“Core accretion” channel for star formation

draw a "core accretion" channel for star formation, in which this planet accretes enough gas from the AGN disk to form a star



ChatGPT
“hallucination slide”

Previous work

Based on the fluffy pebble model

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Planet Formation around Supermassive Black Holes in the Active Galactic Nuclei

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Abstract

As a natural consequence of the elementary processes of dust growth, we discovered that a new class of planets can be formed around supermassive black holes (SMBHs). We investigated a growth path from submicron sized icy dust monomers to Earth-sized bodies outside the "snow line," located several parsecs from SMBHs in low luminosity active galactic nuclei (AGNs). In contrast to protoplanetary disks, the "radial drift barrier" does not prevent the formation of planetesimals. In the early phase of the evolution, low collision velocity between dust particles promotes sticking; therefore, the internal density of the dust aggregates decreases with growth. When the porous aggregate's size reaches 0.1–1 cm, the collisional compression becomes effective, and the decrease in internal density stops. Once 10–100 m sized aggregates are formed, they are decoupled from gas turbulence, and the aggregate layer becomes gravitationally unstable, leading to the formation of planets by the fragmentation of the layer, with 10 times the mass of the Earth. The growth timescale depends on the turbulent strength of the circumnuclear disk and the black hole mass M_{BH}, and it is comparable to the AGN's lifetime ($\sim 10^8$ yr) for low mass ($M_{BH} \sim 10^6 M_{\odot}$) SMBHs.

Unified Astronomy Thesaurus concepts: Planetary system formation (1257); Supermassive black holes (1663); Active galactic nuclei (16); Interstellar dust (836); Exoplanet formation (492)

The Astrophysical Journal, 909:96 (9pp), 2021 March 1
https://doi.org/10.3847/1538-4357/abd40a

Formation of "Blanets" from Dust Grains around the Supermassive Black Holes in Galaxies

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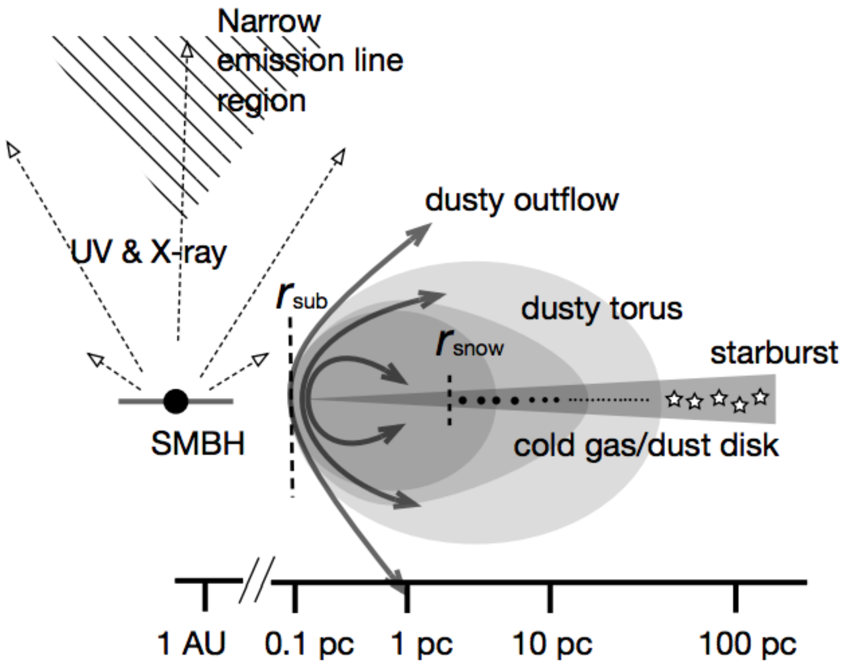
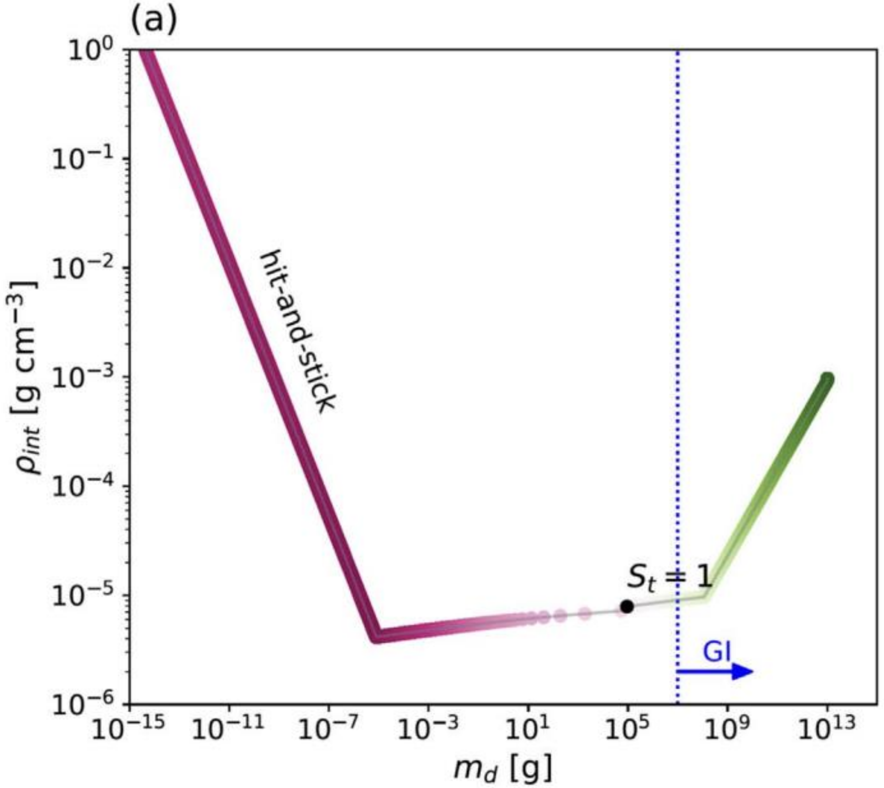
Abstract

In Wada et al. (2019), we proposed for the first time that a new class of planets, *blanets*, can be formed around supermassive black holes in the galactic center. Here, we investigate the dust coagulation processes and physical conditions of the blanet formation outside the snowline ($r_{snow} \sim$ several parsecs) in more detail, especially considering the effect of the radial drift of the dust aggregates. We found that a dimensionless parameter $\alpha = v_t^2/c_s^2$, where v_t is the turbulent velocity and c_s is the sound velocity, describing the turbulent viscosity should be smaller than 0.04 in the circumnuclear disk to prevent the destruction of the aggregates due to collision. The formation timescale of blanets τ_{GI} at r_{snow} is, $\tau_{GI} \simeq 70$–80 Myr for $\alpha = 0.01 - 0.04$ and $M_{BH} = 10^6 M_{\odot}$. The mass of the blanets ranges from $\sim 20 M_E$ to $3000 M_E$ in $r < 4$ pc for $\alpha = 0.02$ (M_E is the Earth mass), which is in contrast with $4M_E$–$6M_E$ for the case without the radial drift. Our results suggest that blanets could be formed around relatively low-luminosity active galactic nuclei ($L_{bol} \sim 10^{42}$ erg s^{-1}) during their lifetime ($\lesssim 10^8$ yr).

Unified Astronomy Thesaurus concepts: Supermassive black holes (1663); Exoplanet astronomy (486); Exoplanet formation (492); Interstellar dust (836); Galaxy circumnuclear disk (581)





Wada et al. (2019, 2021)

Conclusions

• AGN dust tori are cool enough for dust survival
  • Regions of the parameter space allow for grain growth,
  • Other regions grind down dust grains

• Streaming instability can be triggered across a wide range of SMBH masses (10^7–10^9 M_{sun})
  • Filaments contain solar masses of pure dust.

• Tens of millions of "planetesimals" can form per AGN disk, ranging from Earth to super-Jupiter masses
  • Largest planet population in the universe

• Planets are born predominantly in the 3D Bondi pebble accretion regime, with mass-doubling times of 10^3–10^7 yr

• Core accretion channel for star formation: Gas accretion occurs concurrently; crossover mass can be reached.

• Massive enough objects can collapse into IMBHs (>300 M_{sun})
  •AGN tori a plausible IMBH formation site

• Pebble isolation mass exceeds the hydrogen burning limit
  • Accretion is halted by stellar feedback, not gap carving

• Exotic stellar-mass objects composed of pure dust: "degenerate lava drops" with no known analogs

• Observational tests: search for occultation and microlensing signatures in AGN X-ray/UV lightcurves