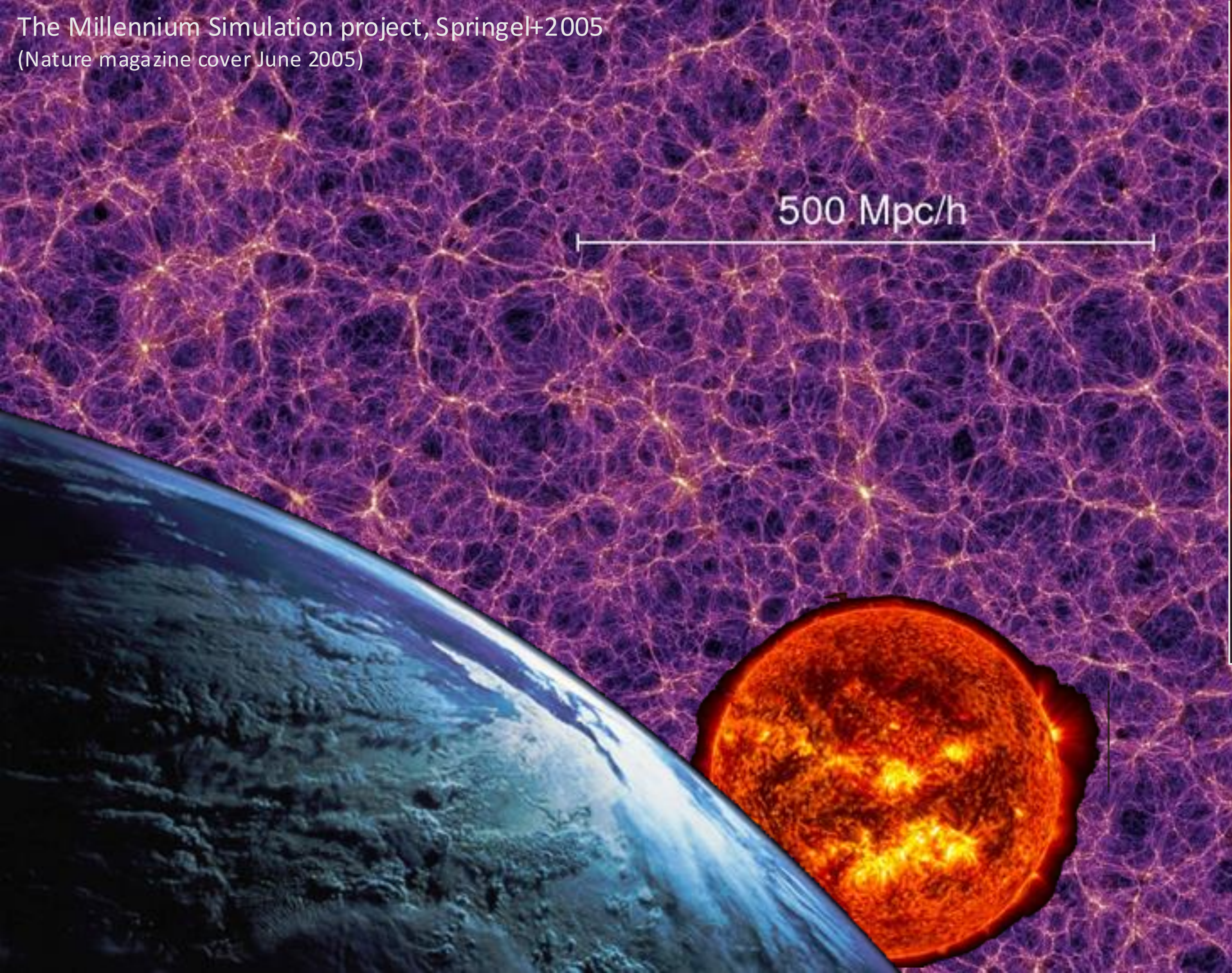
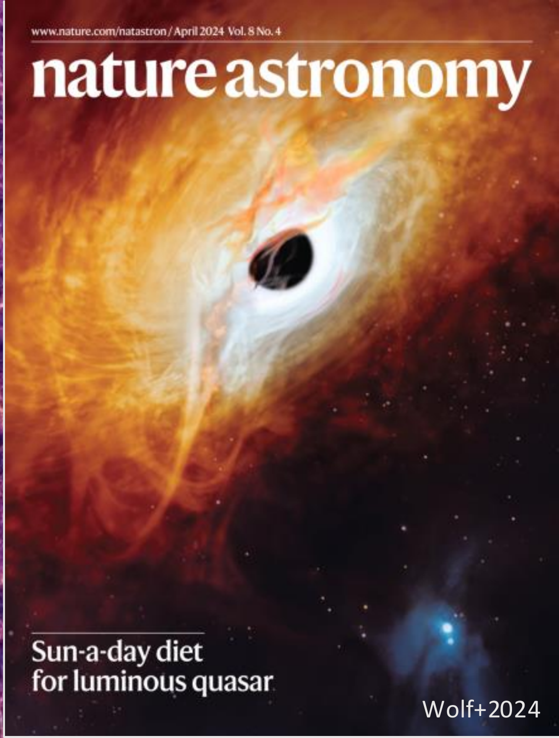
# Supermassive Black Holes Across the Universe

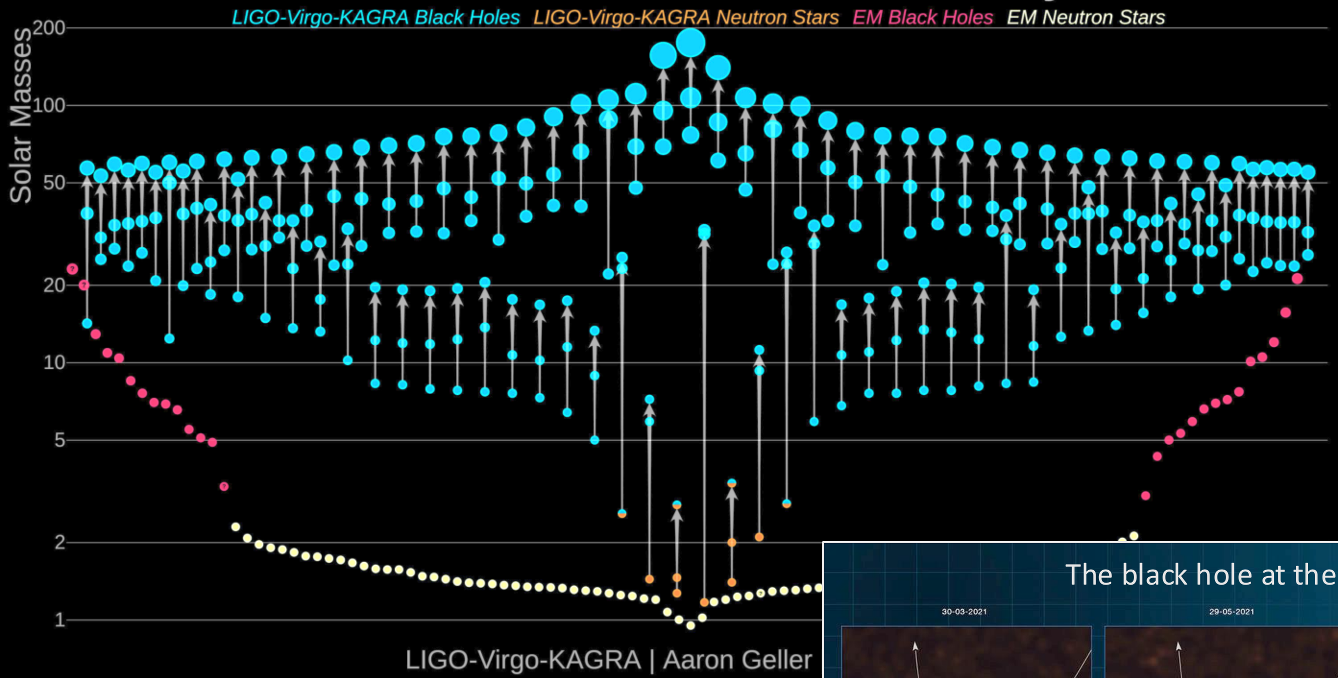
Christian Wolf (ANU/RSAA)

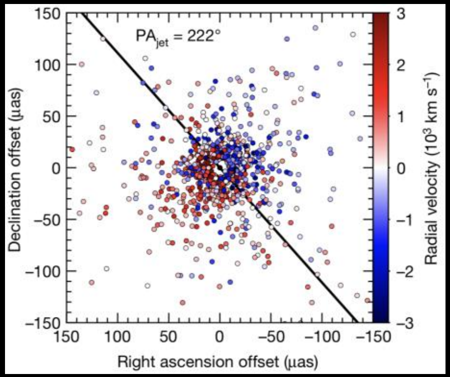
30 Years of Gravity Research in Australasia:
Past Reflections and Future Ambitions


The Millennium Simulation project, Springel+2005
(Nature magazine cover June 2005)
500 Mpc/h

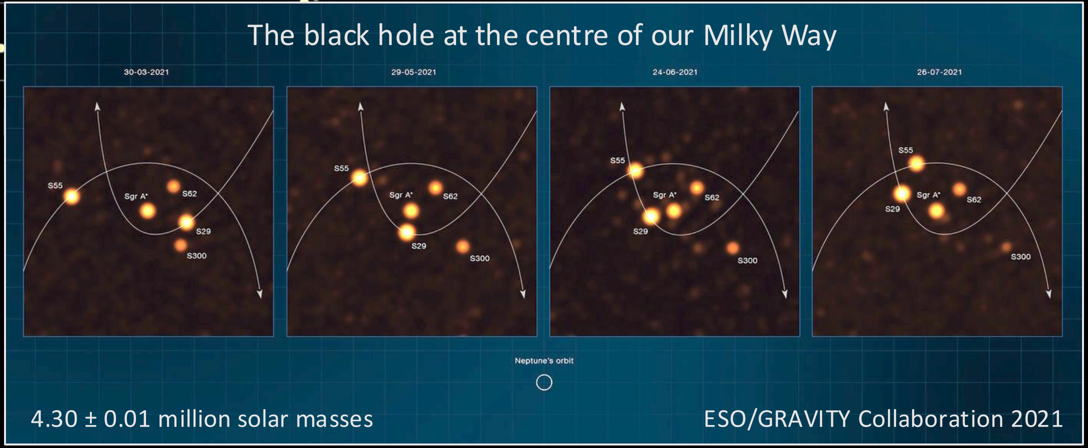

www.nature.com/natastron / April 2024 Vol. 8 No. 4
nature astronomy
Sun-a-day diet
for luminous quasar
Wolf+2024

# Masses in the Stellar Graveyard



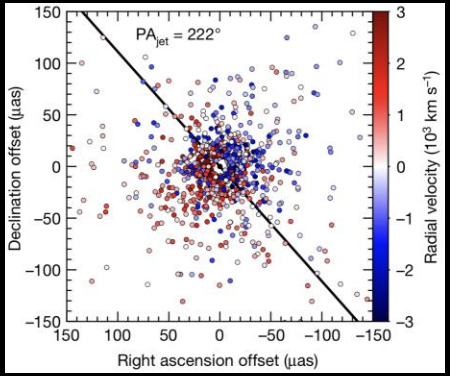

Quasar 3C 273 at redshift 0.157
200 to 500 million solar masses
ESO/GRAVITY Collaboration 2018




At low-mass end: primordial black holes?

For $M < 10^{12}$ kg, lifetime < age of Universe
(evaporated now due to Hawking radiation)


# The Discovery of Quasars 3C 273




Quasar 3C 273 at redshift 0.157
200 to 500 million solar masses
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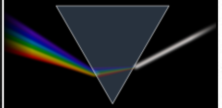
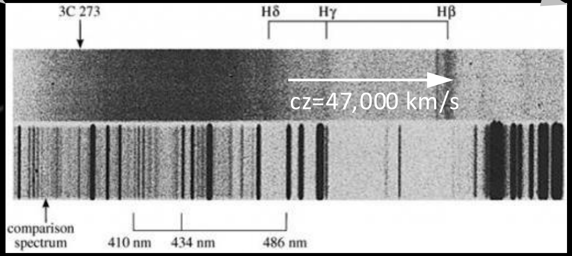
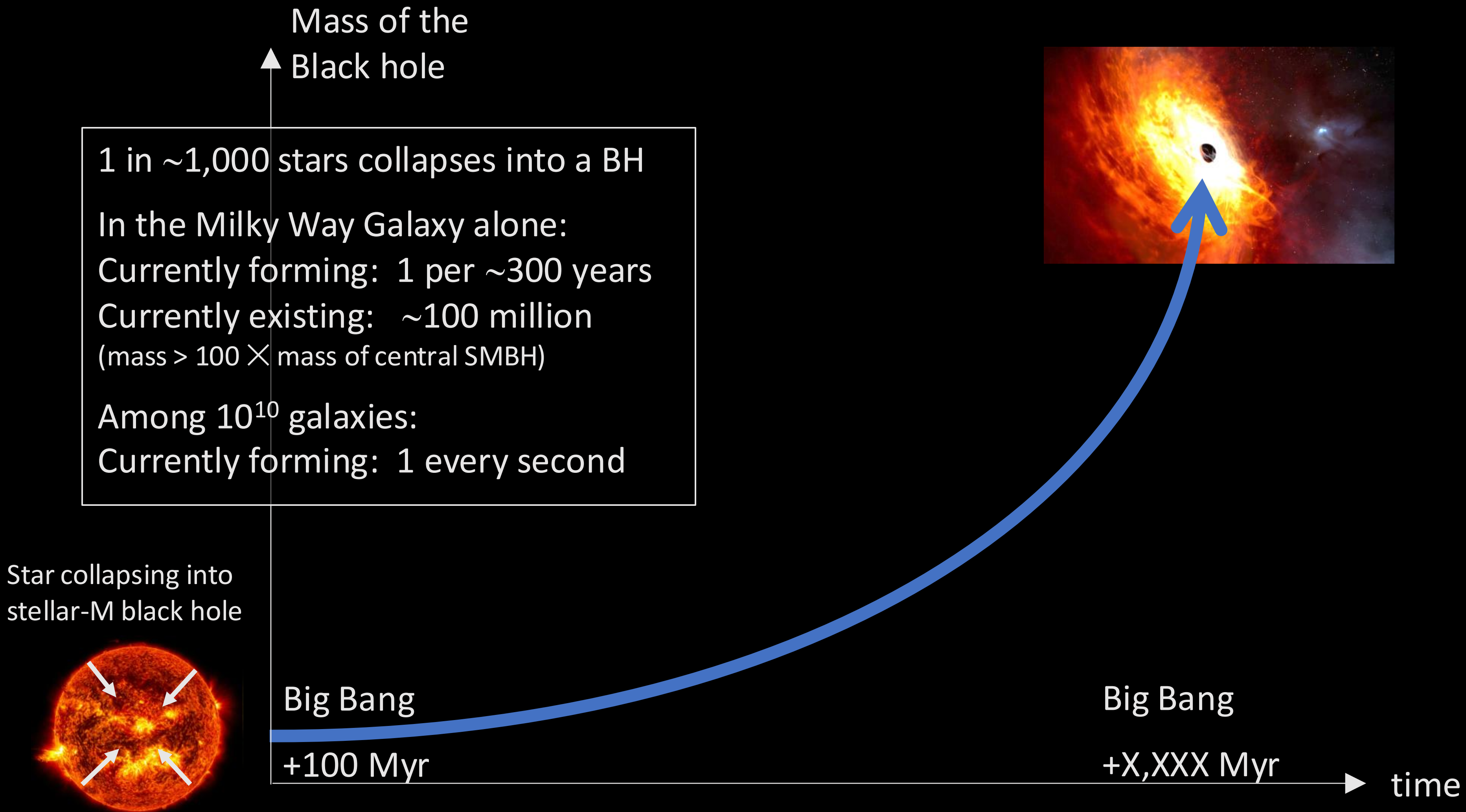
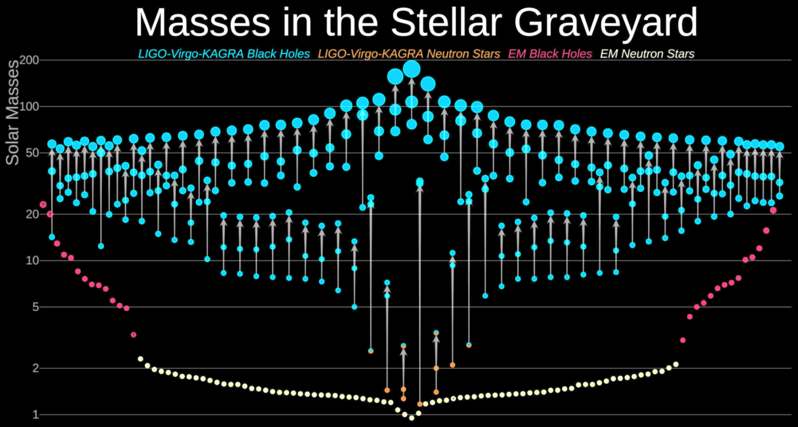
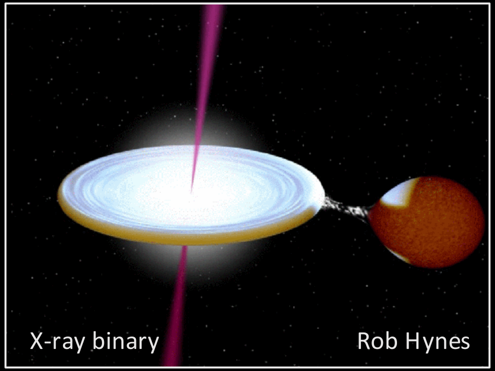
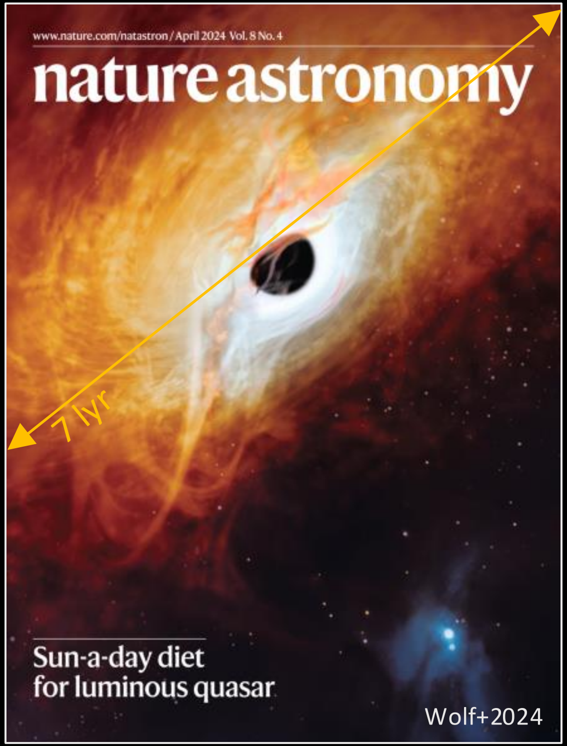





Mass of the
Black hole
1 in ~1,000 stars collapses into a BH
In the Milky Way Galaxy alone:
Currently forming: 1 per ~300 years
Currently existing: ~100 million
(mass > 100 × mass of central SMBH)
Among 10^10 galaxies:
Currently forming: 1 every second
Star collapsing into
stellar-M black hole
Big Bang
+100 Myr
Big Bang
+X,XXX Myr
time


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1


X-ray binary
Rob Hynes


www.nature.com/natastron / April 2024 Vol. 8 No. 4
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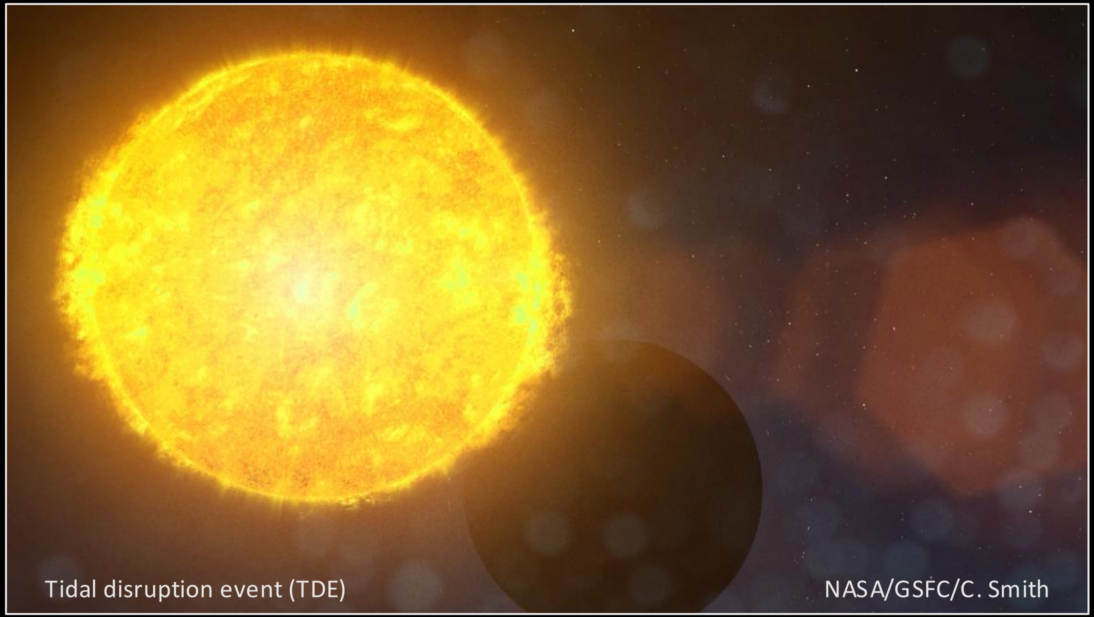
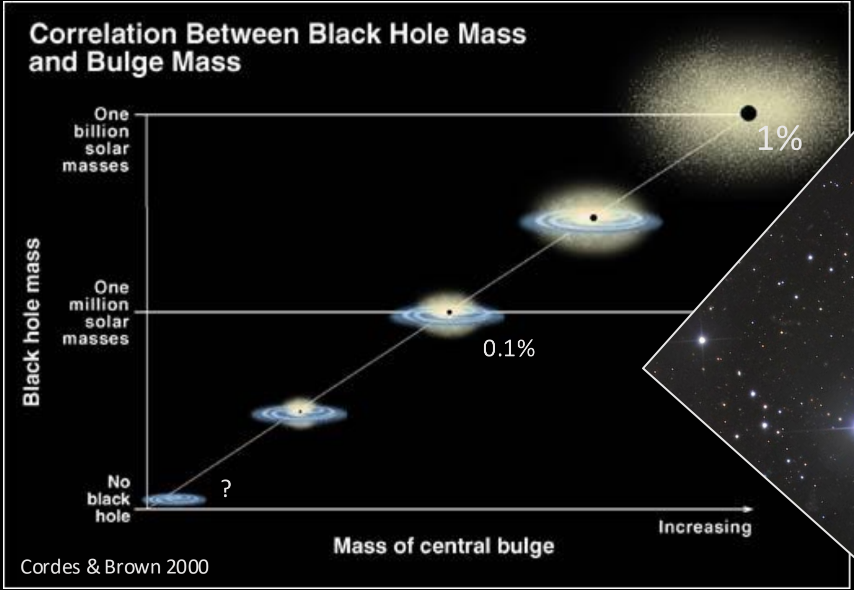
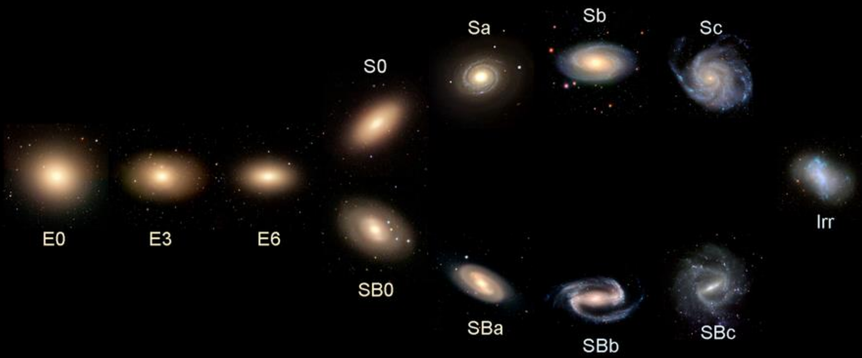
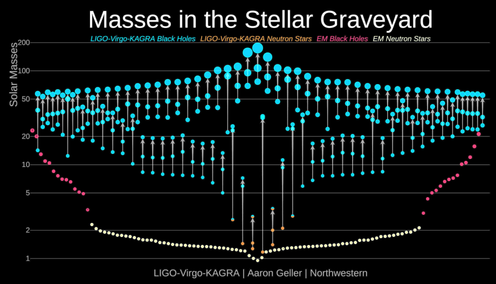

Tidal disruption event (TDE)
NASA/GSFC/C. Smith

## As galaxies merge, so would their SMBHs, except for the final parsec problem




# Problems?



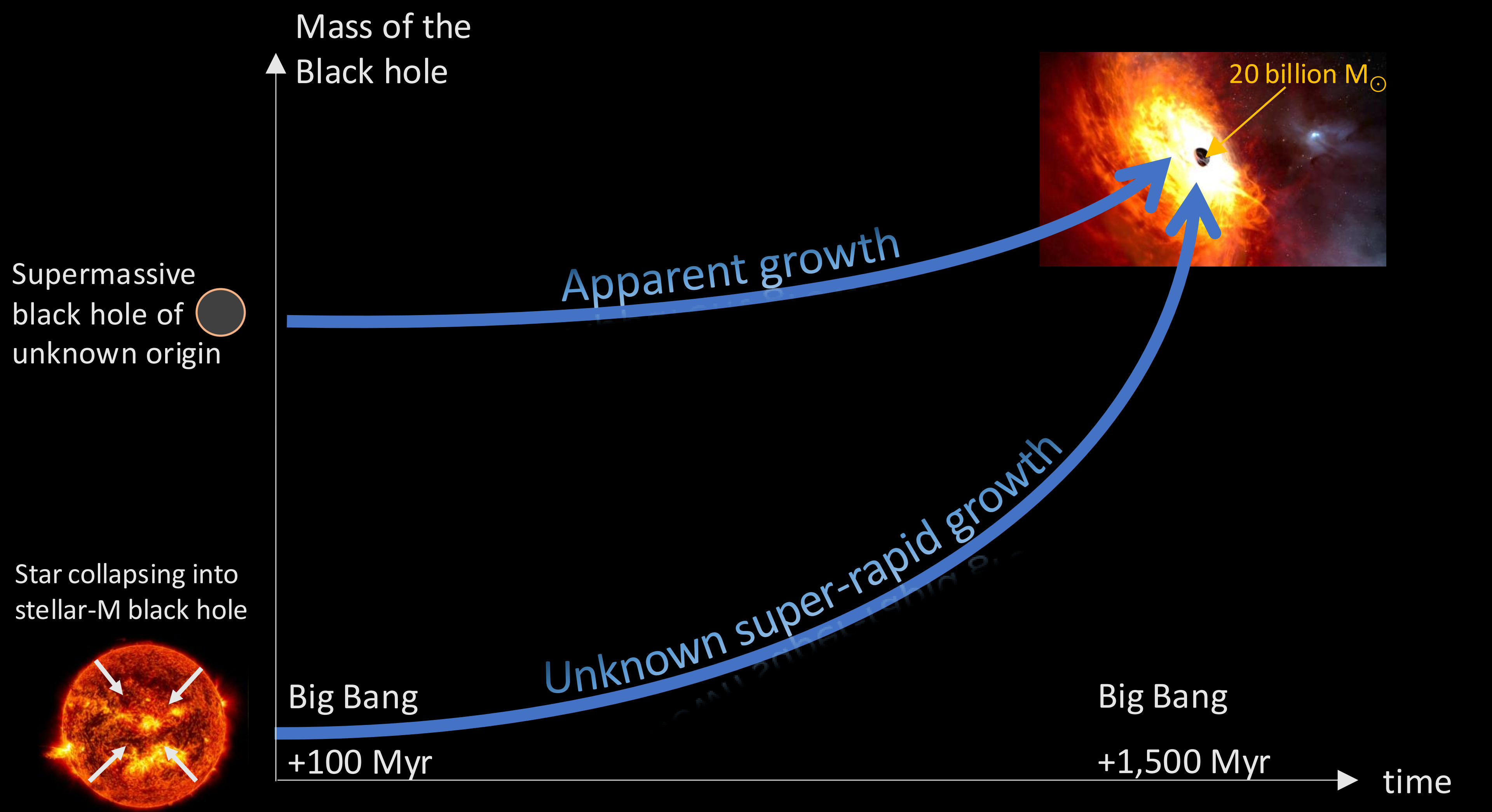

- Stellar-mass BBHs more massive than expected (< few 100 $M_\odot$)?
  - Observational selection effects for BBHs vs BHs
  - New channels & environments for binary evolution (star clusters, quasar discs)

- IMBHs (Intermediate-mass black holes) elusive?
  - Better-precision instruments, longer time baselines, start finding them

- SMBHs in the early Universe are too massive
  - Focus of this talk …


NASA/ESA/Häberle

Most massive Milky Way star cluster, Ω Centauri, harbouring an ~8,000 $M_\odot$ IMBH


Mass of the
Black hole
Supermassive
black hole of
unknown origin
Star collapsing into
stellar-M black hole
20 billion $M_\odot$
Apparent growth
Unknown super-rapid growth
Big Bang
+100 Myr
Big Bang
+1,500 Myr
time

# Three Questions

1. What are the real masses of SMBHs?
   - Especially, are early SMBHs as massive as they seem?

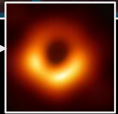
2. How does the accretion process manifest itself
   - Would we notice super-Eddington accretion?

3. Once we know the true SMBH demographics – how did they from?
   - Primordial black holes (Zeldovich & Novikov 1967) undergoing a renaissance now
   - Paradigm check: do black holes form in galaxies, or galaxies around black holes?

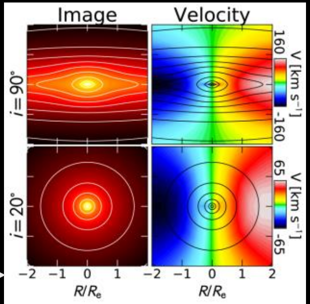
# What are the real masses of SMBHs?

- Stellar dynamics
  - N=1, ±0.01 dex, Nobel Prize 2020

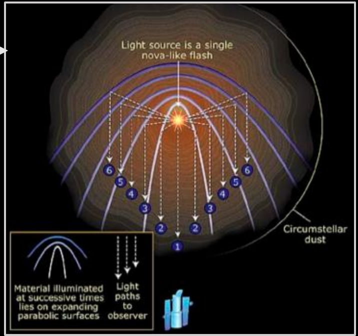
- Photon ring/shadow imaging
  - N=2, ±0.05 dex, Event Horizon Telescope



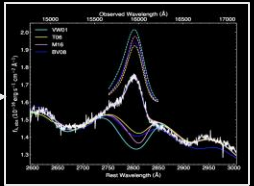
- 2D spectroscopy with dynamical models
  - N=$10^2$, ±0.1-0.5 dex



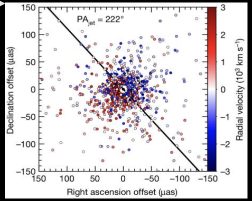

- BLR Reverberation mapping
  - N=$10^3$, ±0.4 dex, geometric biases



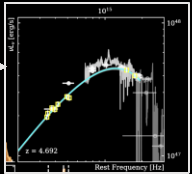

- Virial-model single-epoch BLR spectroscopy
  - N=$10^6$, ±0.5 dex, many biases




- Broad-line region (BLR) spatio-kinematics
  - N=$10^1$, ±0.2 dex, only near bright stars




- Accretion disc spectral modelling
  - N=$10^1$, >$10^9$ $M_\odot$ objects, model biases

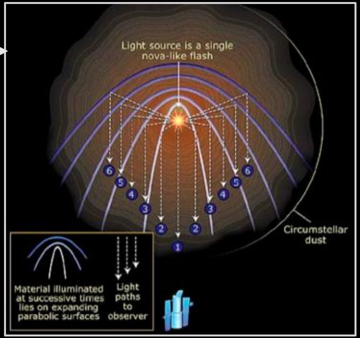


# What are the real masses of SMBHs?

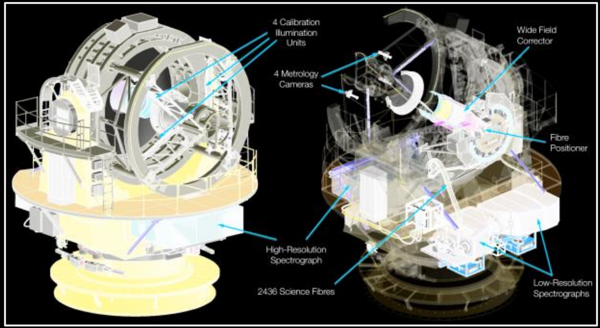
Tamara Davis (UQ), Chris Lidman (ANU), Seb Hönig (Portsmouth UK) et al. 2025-2030

- Observing thousands of BLRs through 4MOST/TIDES @ESO VISTA 4m-telescope
- Modelling radiation hydrodynamics in BLRs

- BLR Reverberation mapping
  - $N=10^3$, ±0.4 dex, geometric biases

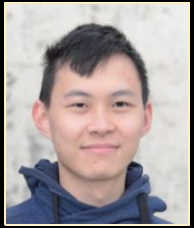



4most.eu



# What are the real masses of SMBHs?

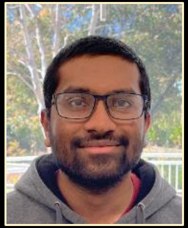
Christian Wolf
ANU



Samuel Lai
CSIRO Perth

Christopher Onken
ANU

Fuyan Bian
ESO Chile



Neelesh Amrutha
PhD student

Ashley Hai Tung Tan
Honours student

Patrick Tisserand
U Sorbonne Paris

Prof. Rachel Webster
U of Melbourne

- Virial-model single-epoch BLR spectroscopy
  - $N=10^6$, ±0.5 dex, many biases
- Broad-line region (BLR) spatio-kinematics
  - $N=10^1$, ±0.2 dex, only near bright stars
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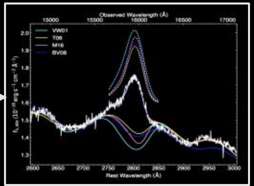
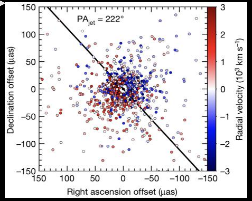
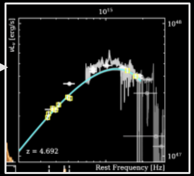
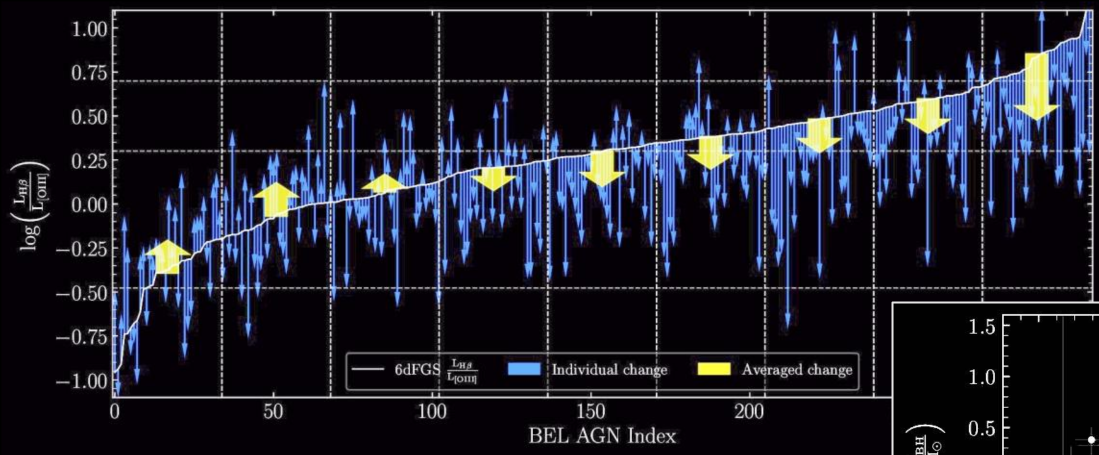


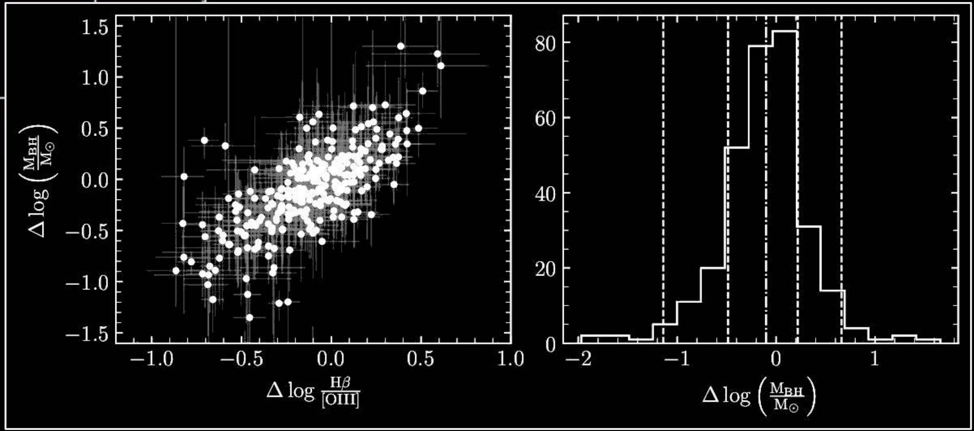




- Finding the most massive, hardest-to-explain, SMBHs

# Virial BLR Model & Non-virial Accretion Disc Variability




Amrutha+
in preparation

Virial BLR masses of $10^6$-$10^{7.5}$ $M_\odot$ SMBHs: 6dF Galaxy Survey vs ANU 2.3m @ +20 years ➞ ±0.5 dex rms

Publications of the Astronomical Society of Australia (PASA)
doi: 10.1017/pas.2018.xxx.

Discovery of the most ultra-luminous QSO using Gaia, SkyMapper and WISE

CNN World Africa Americas Asia Australia China Europe India

## The fastest-growing black hole in universe has a massive appetite

By Ashley Strickland, CNN
Updated 2:53 PM EDT, Thu July 2, 2020

The New York Times

SCIENCE

## *A Very Hungry Black Hole Is Found, Gorging on Stars*

Astronomers in Australia say they have discovered a fast-growing black hole swallowing stars in a baby galaxy 12 billion light-years from here.

Trilobites
By DENNIS OVERBYE MAY 17, 2018

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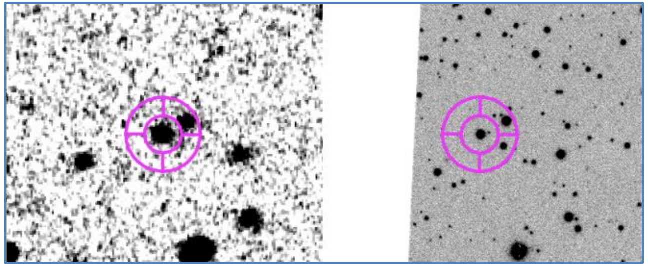
SCIENCE

## Fastest-growing black hole of past 9 billion years discovered in bright constellation of Centaurus

ABC Science / By science reporter Gemma Conroy
Posted Wed 15 Jun 2022 at 4:30am, updated Wed 15 Jun 2022 at 8:40am



Harvard sky plate 08 June 1901 SkyMapper 21 Apr 2018
Recorded but unrecognized for 121 years

J2157 @ z=4.69, PASA 2018
J1144 @ z=0.83, PASA 2022
J0529 @ z=3.96, NatAs 2024


EL MERCURIO

Noticias | Economía | Deportes | Espectáculos | Tendencias | Autos | Servicios

Astrónomos observan el agujero negro que crece más rápido en todo el Universo

Este cuerpo celeste, que es capaz de absorber una masa equivalente a nuestro Sol cada dos días, se encuentra a 12 mil millones de años luz del Sistema Solar.

15 de Mayo de 2018 | 12:37 | EFE

ANU SkyMapper Telescope

# CATALYST

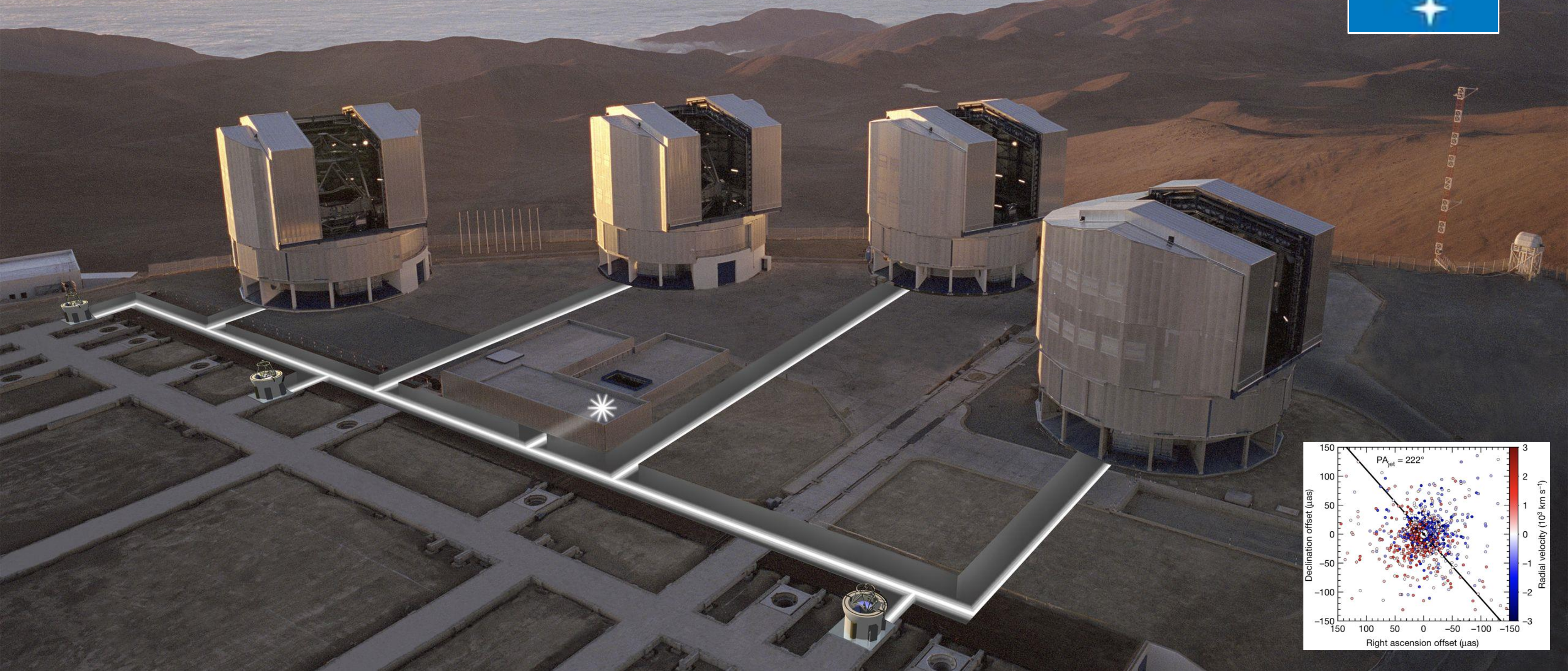
## > BLACK HOLE HUNTERS


Prof Tamara Davis<

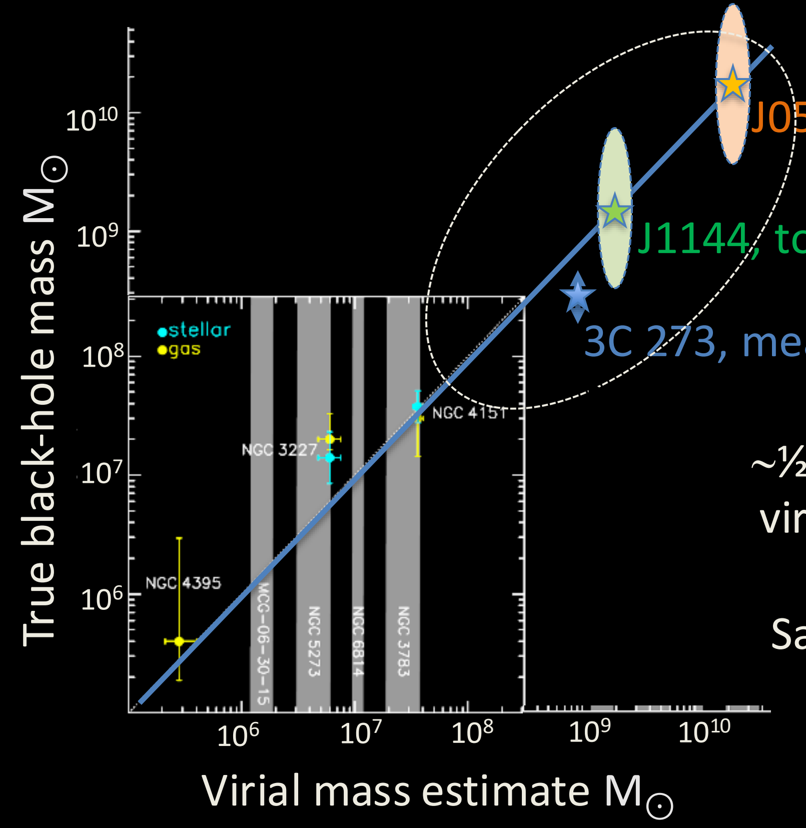

Brad Tucker's beagle

European Southern Observatory in Chile – "Very Large Telescope Interferometer"
Australian access 2018-2027, bid for full membership

VLTI/GRAVITY QSO group Eisenhauer, Genzel, Shimizu+ at MPE Garching
collaborating with Webster, Wolf+; Ireland+ to extend facility to JH-band



# The Mass Scale of Quasar Black Holes




J0529, to be measured by VLTI GRAVITY+

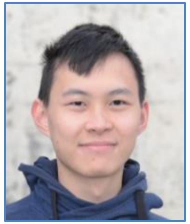
J1144, to be measured by VLTI GRAVITY+

3C 273, measured by VLTI GRAVITY

~½ million quasars at redshift 0.5…7.5 have virial mass estimates, uncertain by 1/3…3x

⇩

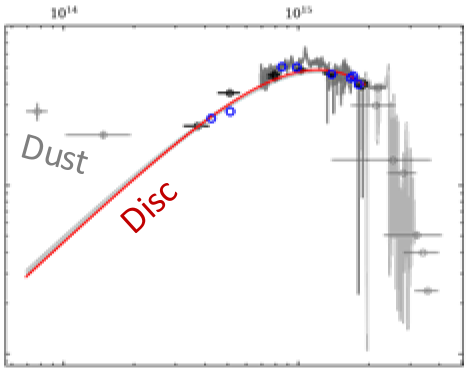
Sample across population and recalibrate



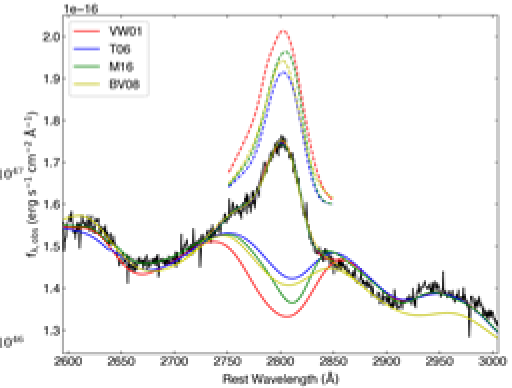
# Virial Estimate vs Accretion Disc Model

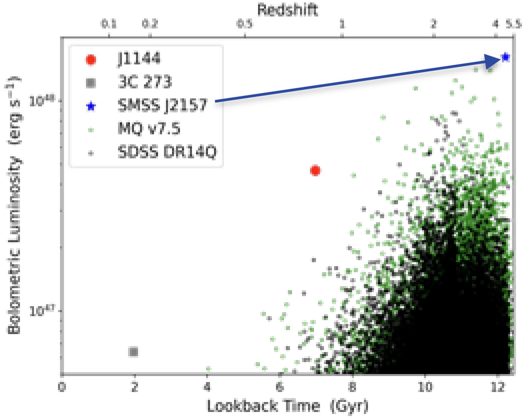
## Bright Quasar SMSS J2157-3602 @ z=4.69

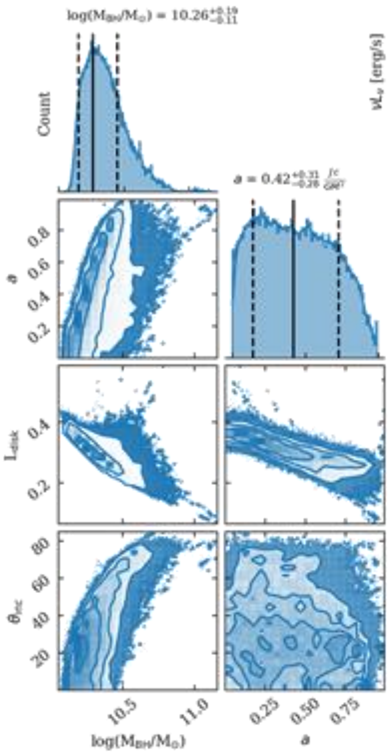
Accretion disk SED

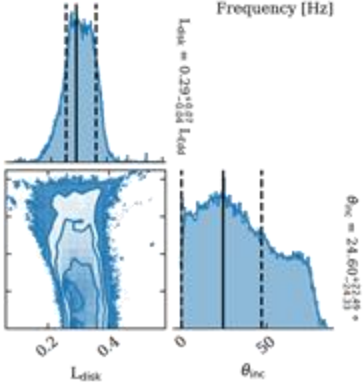


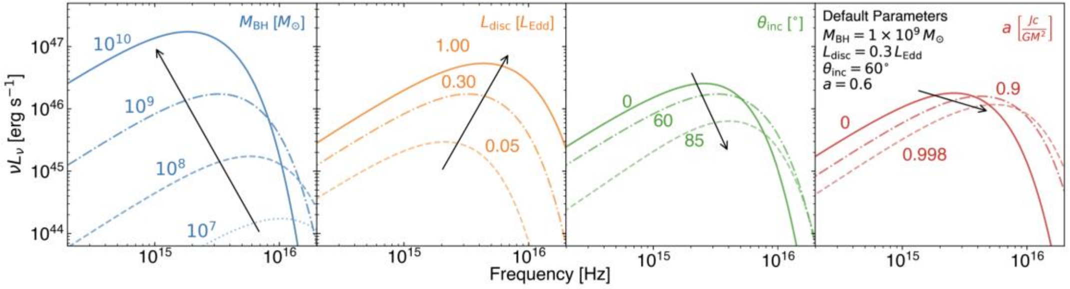

MgII virial single-epoch



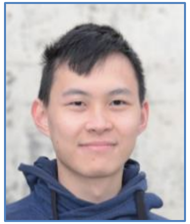






Slim Disc models “SlimBH” (GR ray tracing)



# Virial Estimate vs Accretion Disc Model

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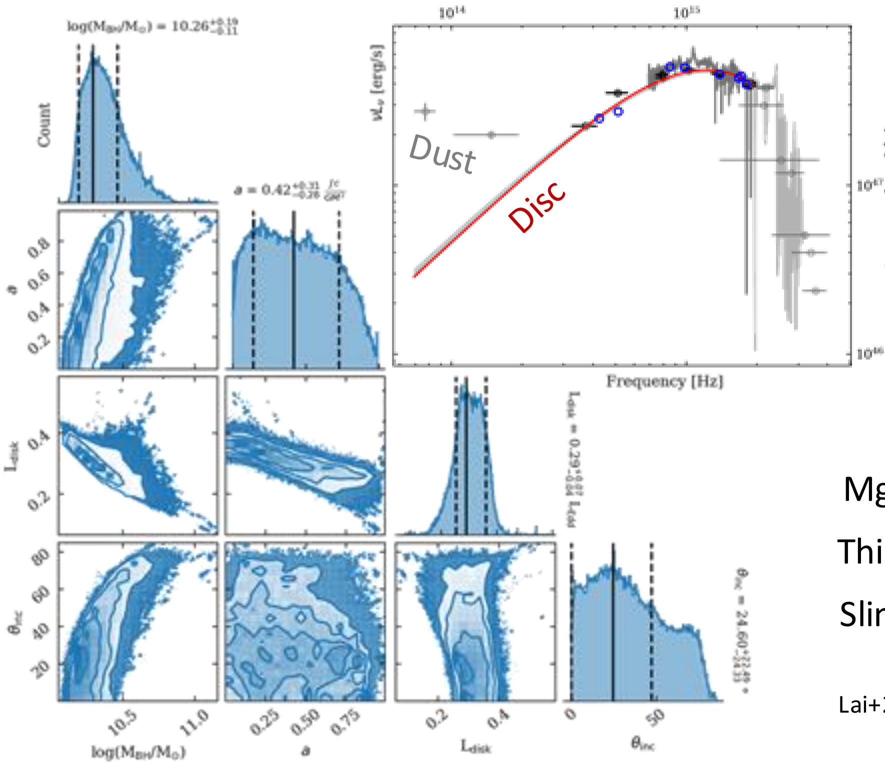
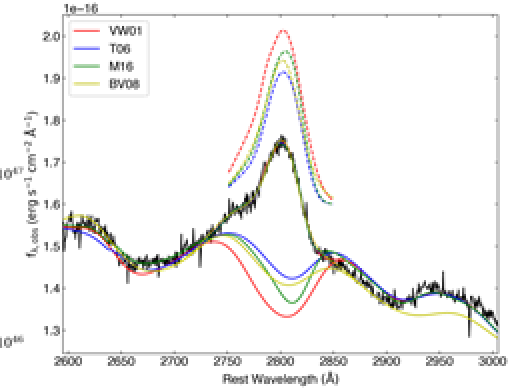
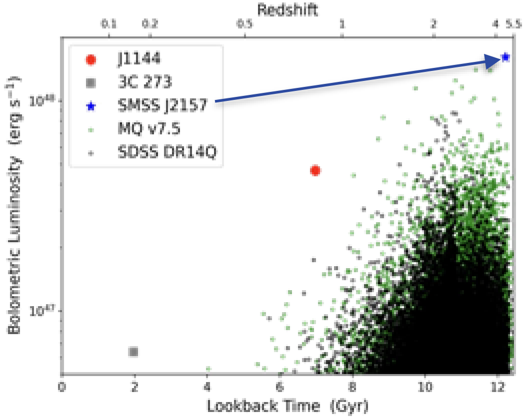
Accretion disk SED

MgII virial single-epoch



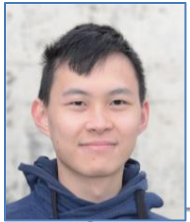




MgII virial SE: $\log\left(M_{BH}/M_{\odot}\right) = 10.33 \pm (0.08)_{stat} \pm (0.50)_{sys}$

Thin disc SED: $\log\left(M_{BH}/M_{\odot}\right) = 10.43 \pm (0.17)_{stat} \pm (0.20)_{sys}$

Slim disc SED: $\log\left(M_{BH}/M_{\odot}\right) = 10.31 \pm (0.15)_{stat} \pm (0.20)_{sys}$

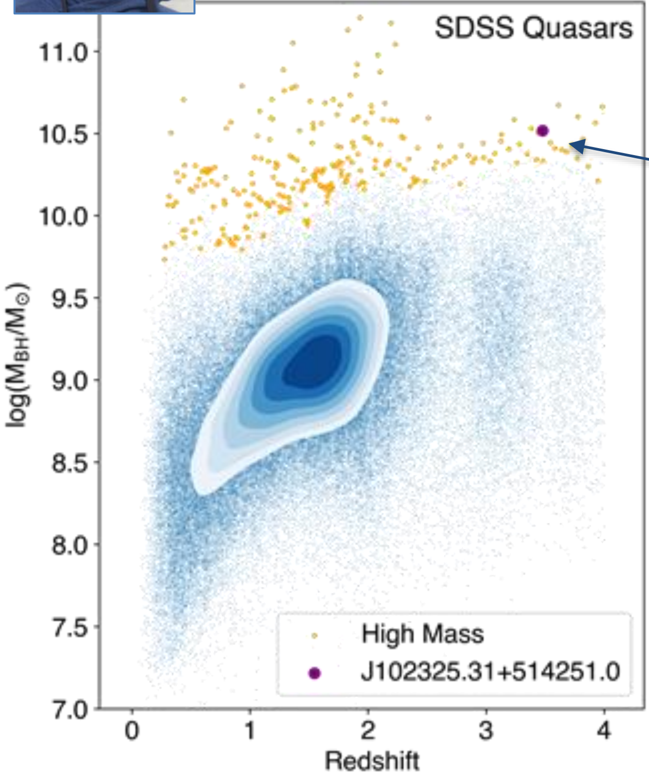
Lai+2023



# Virial Estimate vs Accretion Disc Model

## Revisiting the most massive black holes

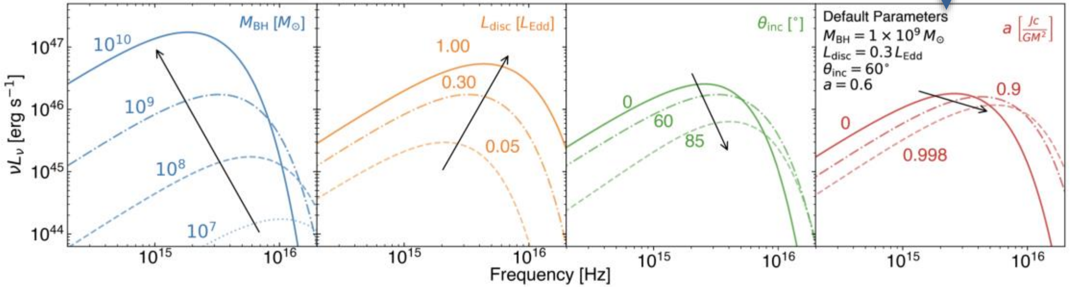

Figure 5. Cross-section view of the steady-state tilt oscillation formed in a disc initially inclined at 15° to the black hole spin (spin axis is vertical with respect to the page, i.e. along the z-axis). The colour scale shows density. Disc parameters are the same as in Fig. 4, but with a larger initial inclination.



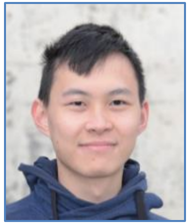

| QSO | SE($Mg_{II}$) | SE($H_\beta$) | AD SED |
|---|---|---|---|
| J102325.31 +514251.0 | $10.52 \pm 0.08$ | $9.58 \pm 0.14$ | $9.62 \pm 0.18$ |

Masses from IR spectra by Zuo+2015

Lai+2023




Slim Disc models “SlimBH” (GR ray tracing)

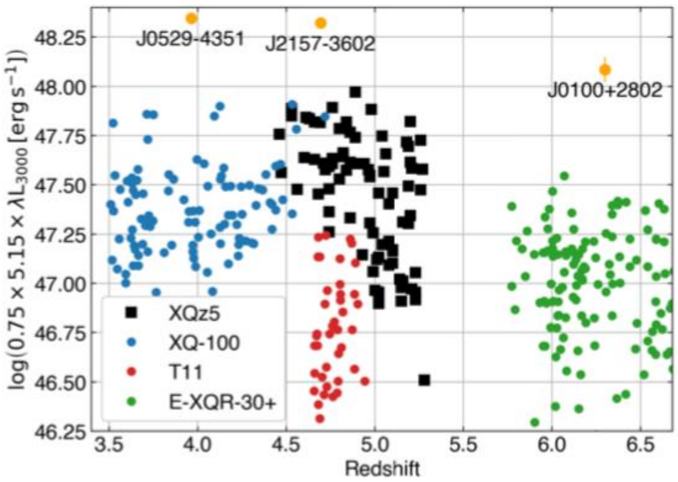


# Samuel Lai PhD Thesis

February 2024

## XQz5: a new ultraluminous $z \sim 5$ quasar legacy sample

Samuel Lai[1★], Christopher A. Onken[1,2], Christian Wolf[1,2], Fuyan Bian[3] and Xiaohui Fan[4]
[1]Research School of Astronomy and Astrophysics, Australian National University, Canberra, ACT 2611, Australia
[2]Centre for Gravitational Astrophysics, Research Schools of Physics, and Astronomy and Astrophysics, Australian National University, Canberra, ACT 2611, Australia
[3]European Southern Observatory, Alonso de Córdova 3107, Casilla 19001, Vitacura, Santiago 19, Chile
[4]Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA




Slow mass growth in z~5 black holes needs $10^8\ M_\odot$ SMBHs at z=20

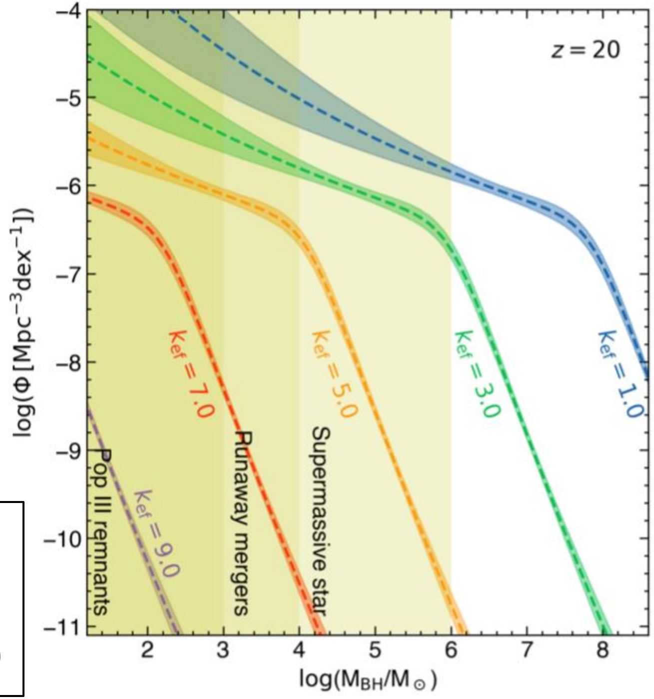



Figure 4.6: Black hole mass functions evolved to $z = 20$ through the continuity equation based on the reference mass function model at $z \sim 5$ and effective dimensionless

## Supermassive black holes are growing slowly by z~5

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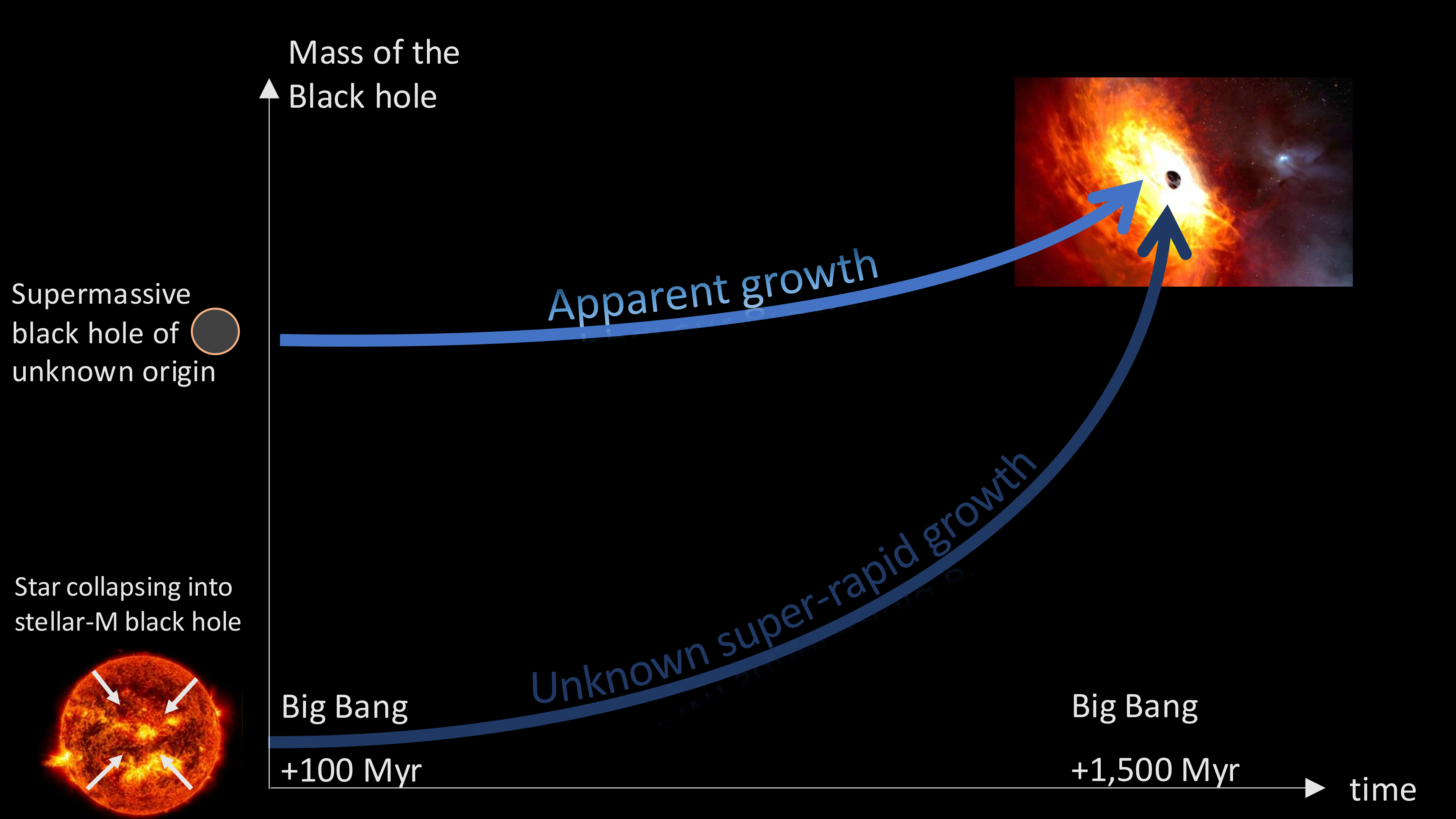
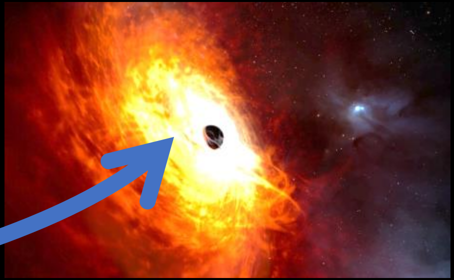


Mass of the
Black hole
Supermassive
black hole of
unknown origin
Star collapsing into
stellar-M black hole
Apparent growth
Unknown super-rapid growth
Big Bang
+100 Myr
Big Bang
+1,500 Myr
time

Mass of the Black hole

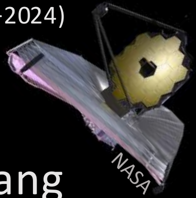
Supermassive black hole of unknown origin

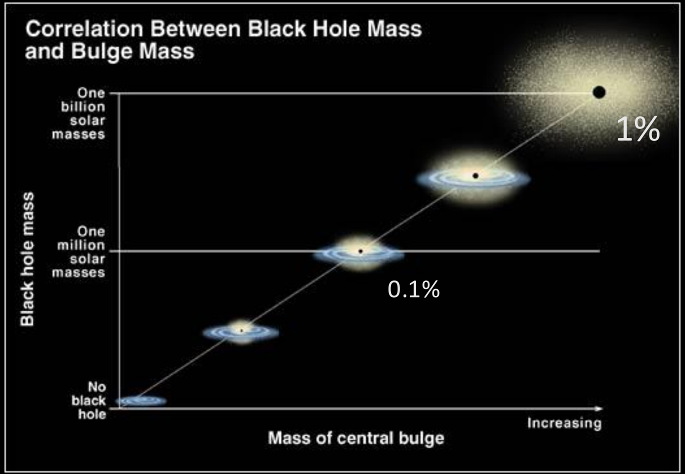
Apparent growth



Were black holes seeds for galaxy formation?

Most extreme JWST result @ z~10
Mass ratio of Galaxy : SMBH 50:50
(Bogdan+2024)




Big Bang +100 Myr

Big Bang +450 Myr

time

Were black holes seeds
for galaxy formation?

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https://doi.org/10.3847/2041-8213/ad1bf0


# Which Came First: Supermassive Black Holes or Galaxies? Insights from JWST

Joseph Silk[1,2,3], Mitchell C. Begelman[4,5], Colin Norman[2], Adi Nusser[6], and Rosemary F. G. Wyse[2]

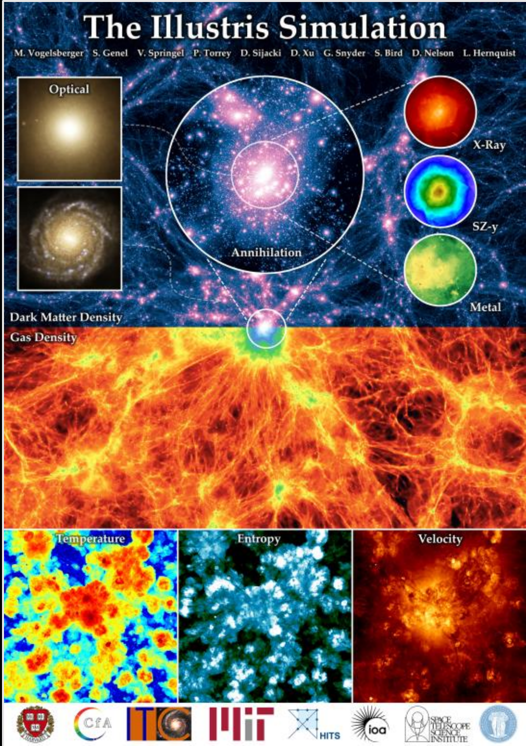
After half-century of work:

We thought we had the right recipe for galaxy evolution
(matter density, expansion history, star formation, feedback, chemical evolution)

but we did not predict:
1) over-massive early SMBHs in small galaxies
2) surprisingly massive early (high-z) galaxies

Star formation recipes wrong – or galaxy formation seeds wrong?

Black holes from 'direct collapse' – or primordial black holes?



# Outlook to the Future

- Nail SMBH population and masses (VLTI/GRAVITY+ etc.) ➞ M
- Improve physical understanding of accretion processes ➞ dM/dt
  - Deviations from virial equilibrium, mass corrections, BH spins, dust, etc.
  - Disc instabilities and BH mass, spin, disc structure ➞ light curves (NASA/ATLAS, LSST)
- Push to higher redshift (JWST, Euclid, Roman, SKA etc.)
  - Extreme objects so rare, need all-sky, larger simulation volumes
  - Hidden dust-enshrouded SMBH growth
- IMBH and SMBH mergers (PTA, LISA, SKA-PTA)
  - Fill plane of mass vs cosmic epoch
  - Might learn about mix of I/SMBH origin between stellar collapse and direct collapse/primordial origin?


Matthew Bailes
Talk Tue 12:30pm