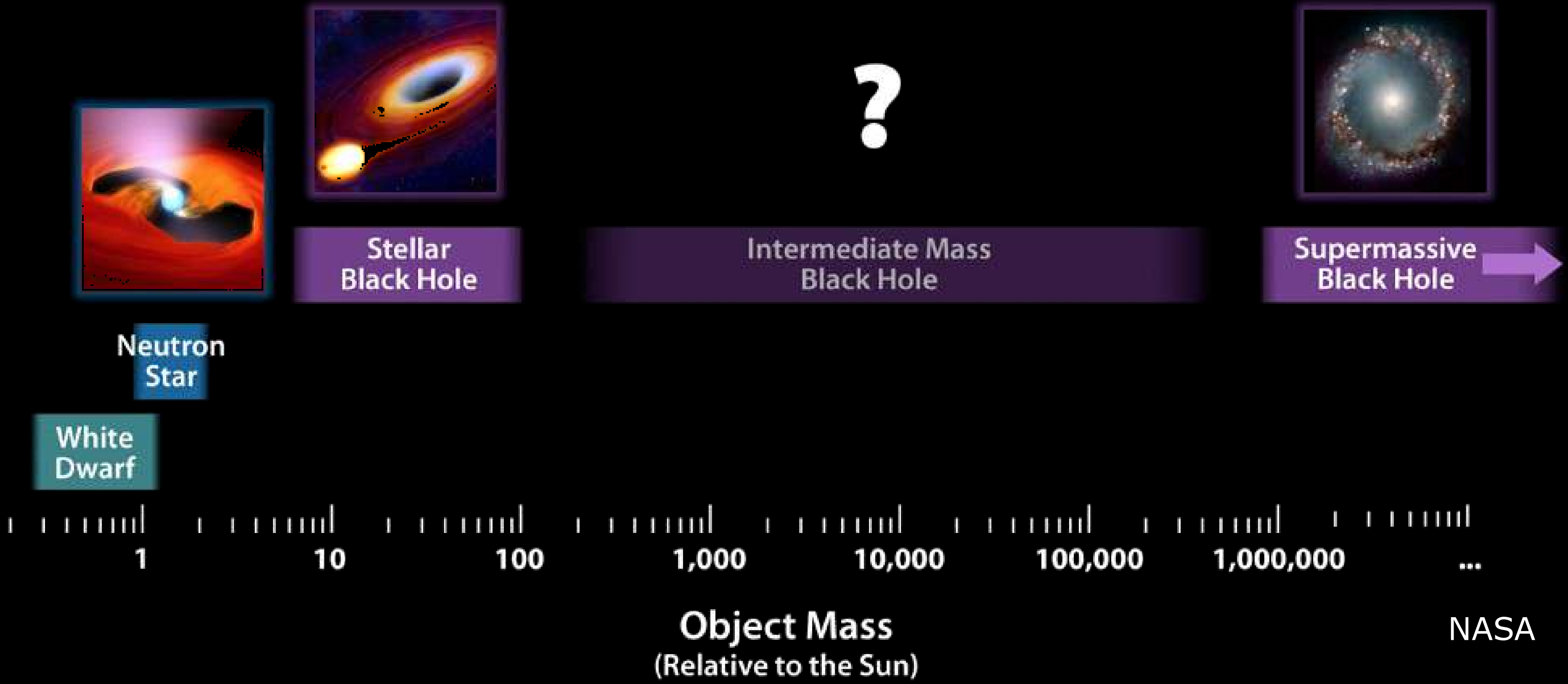
Is Dark Matter made of Primordial Black Holes?

Günther Hasinger

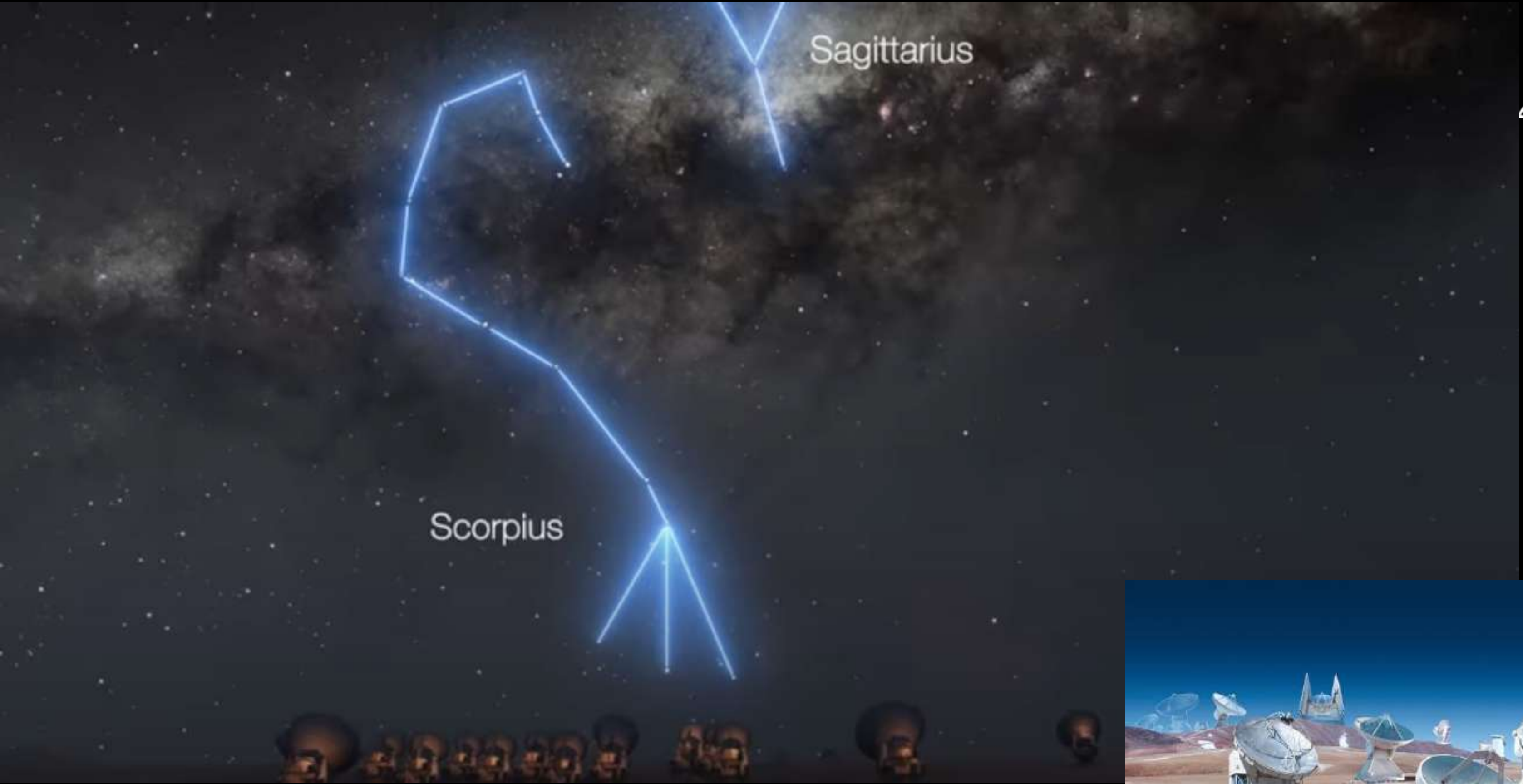
60th Karpacz Winter School on Theoretical Physics
& WE-Heraeus Physics School, Wrocław
17. May 2024

Deutsches Zentrum für Astrophysik

Observed Mass Ranges of Compact Objects



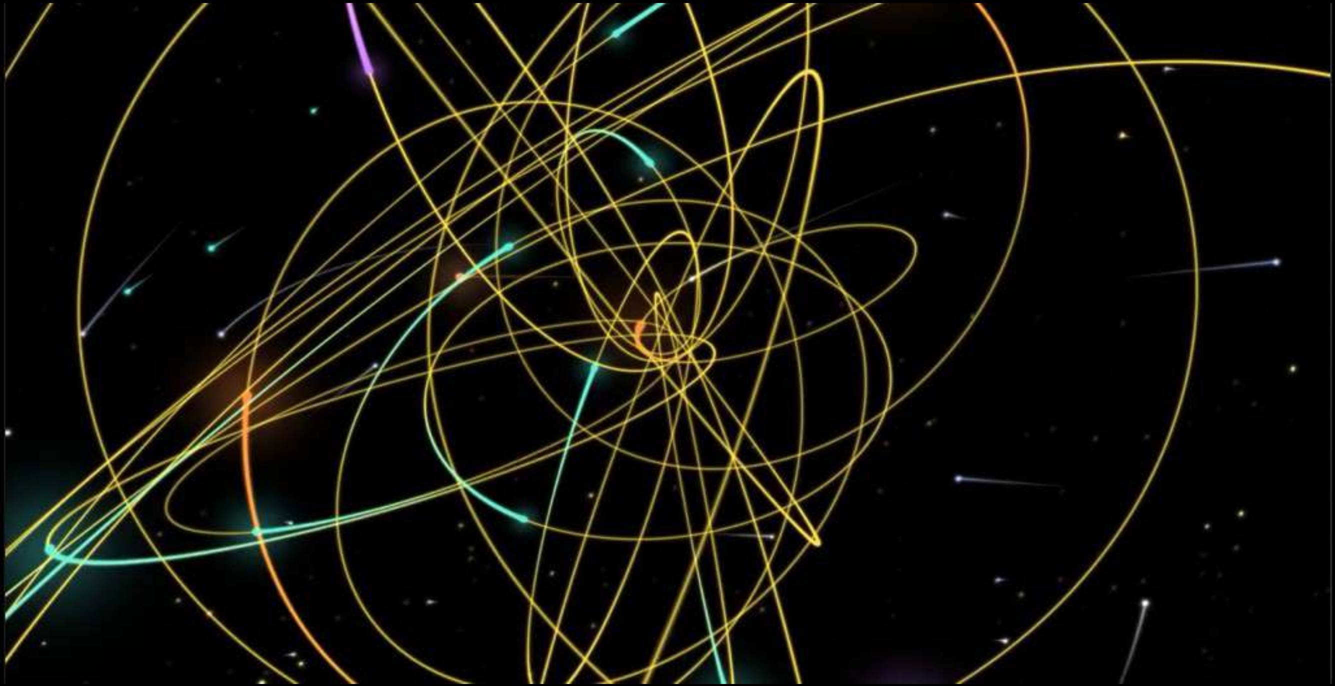
NASA



$4 \times 10^6\ M_\odot$

Video at https://youtu.be/Zml0dZCjaFw?t=2

The Galactic Center Black Hole



Physics
Nobel
Prize 2020

Video available at

$3 \times 10^9\ M_\odot$

Video available at https://youtu.be/v_Bk2997YMA?t=5

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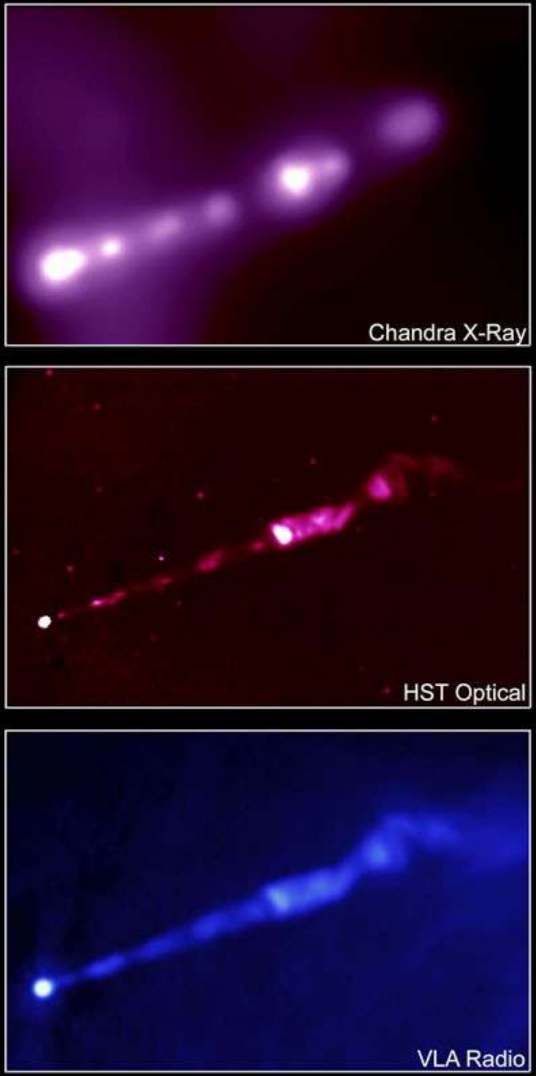
Active Black Holes

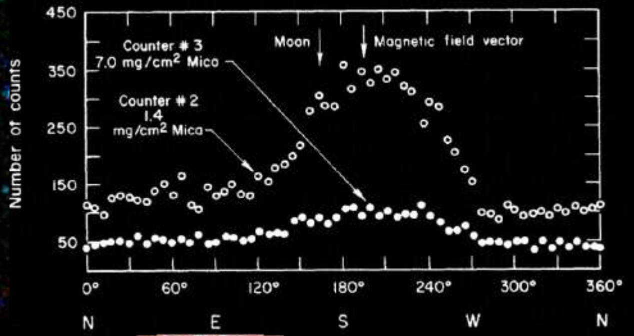


... accrete, radiate, and accelerate relativistic particle beams.

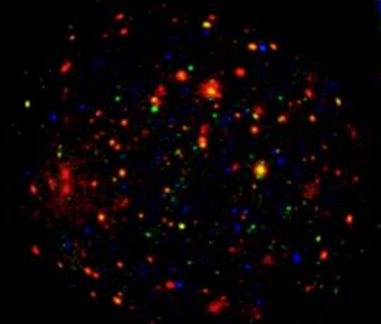
The X-ray background

ROSAT 1998

Giacconi 1962



ROSAT 1991



XMM-Newton 2012

Chandra 2011

ROSAT 1998

Keck >1994
VLT >2001

Resolving the 0.5-2 keV X-ray background

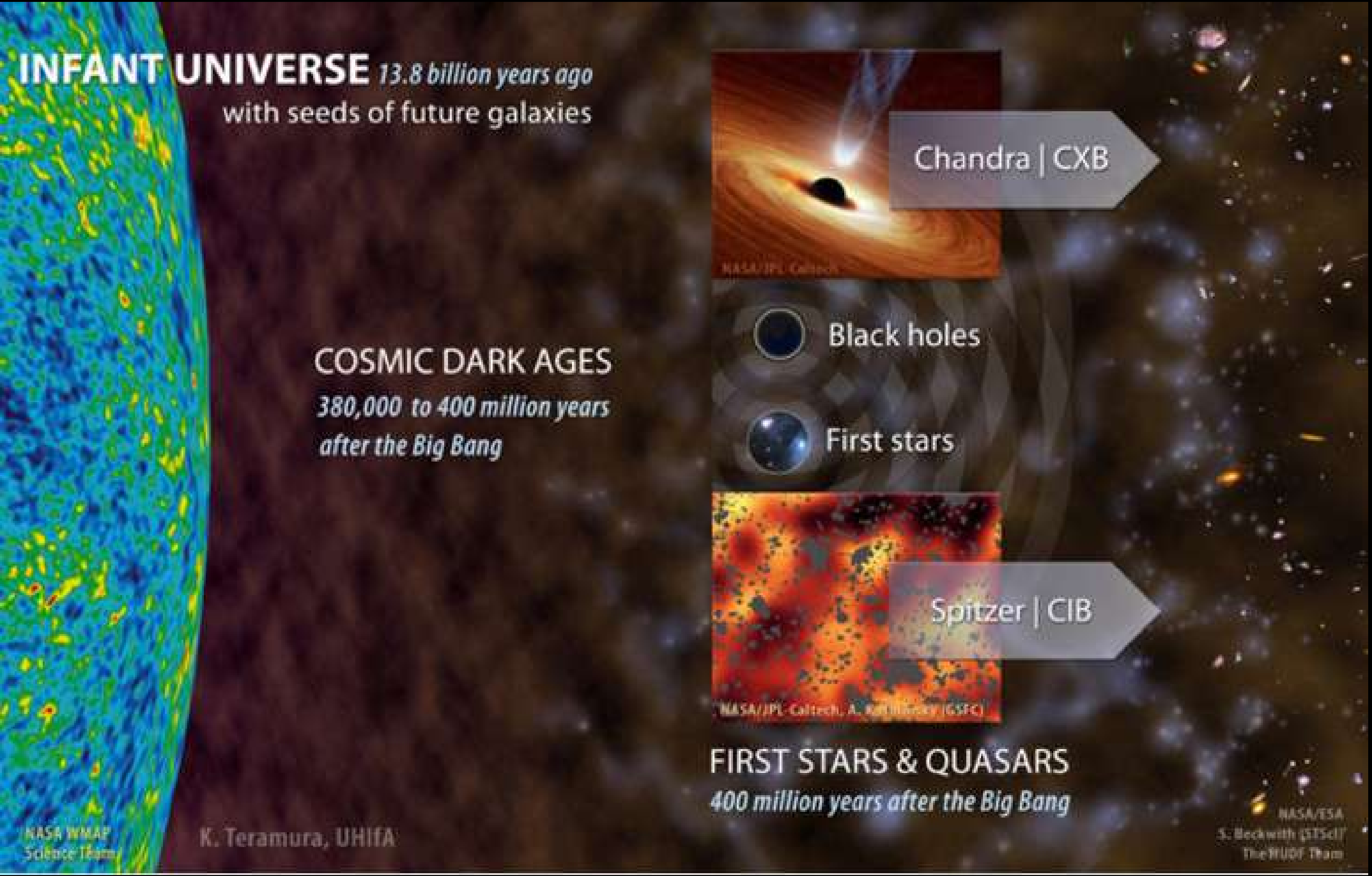
75-80% ROSAT sources

90-95% Chandra/XMM sources

Few % Stacking Galaxies

1% Correlation with CIB

CIB x CXB fluctuations indicate high-z BH population



Significant cosmic background fluctuations have been found both in the NIR and in X-rays.

The strong CIB/CXB cross-correlation signal indicates a substantial contribution of Black Holes to the signal.

There is no correlation with fluctuations in the deepest HST images, therefore the signal likely comes from redshifts z>13.

Large angular scale also points to high-z origin.

Could these be primordial?

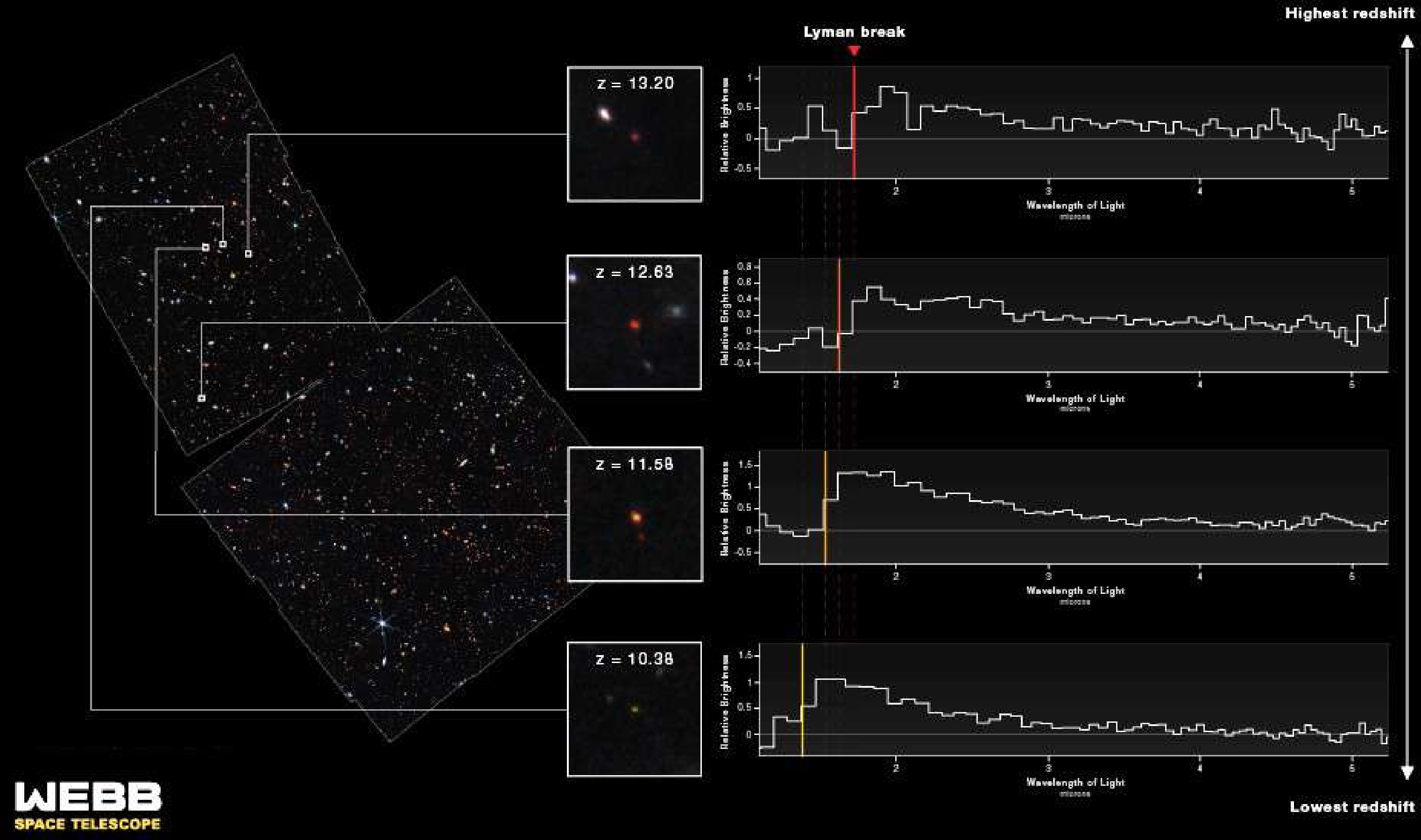
Cappelluti et al., 2013

The first JWST Deep Image revealed by President Biden!

esa

→ THE EUROPEAN SPACE AGENCY

JWST: new distance records!



325 Myr

346 Myr

390 Myr

454 Myr

after Big Bang

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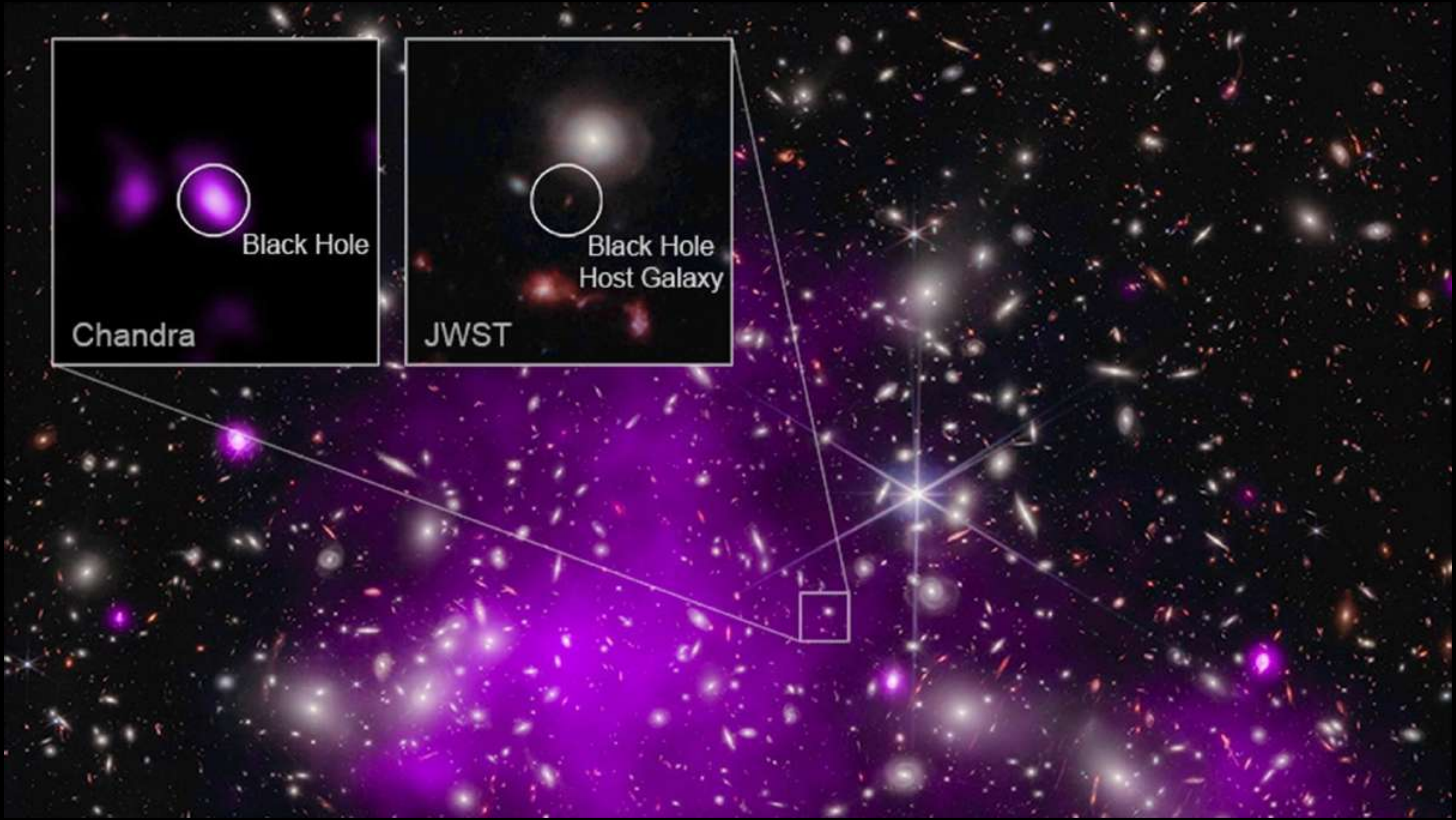
Chandra and JWST Discovery of an Over-Massive Black Hole

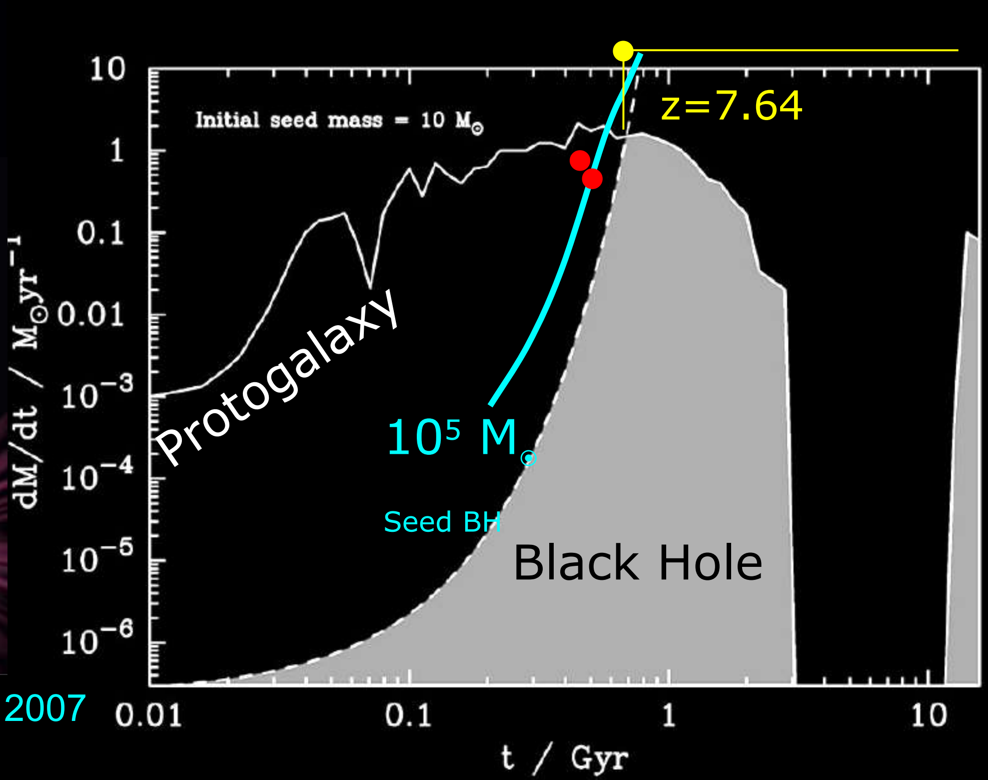


z=10.1
$M = 4\ 10^7\ M_\odot$
Stellar Mass comparable to BH mass!

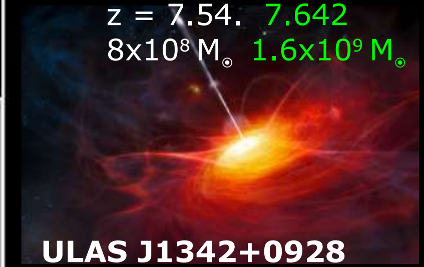
Natarajan et al., 2023, arXiv.2308.02654

How to produce the first proto-quasars

Li, Hernquist, et al. 2007



known QSO



ULAS J1342+0928
(Bañados et al. 2018)

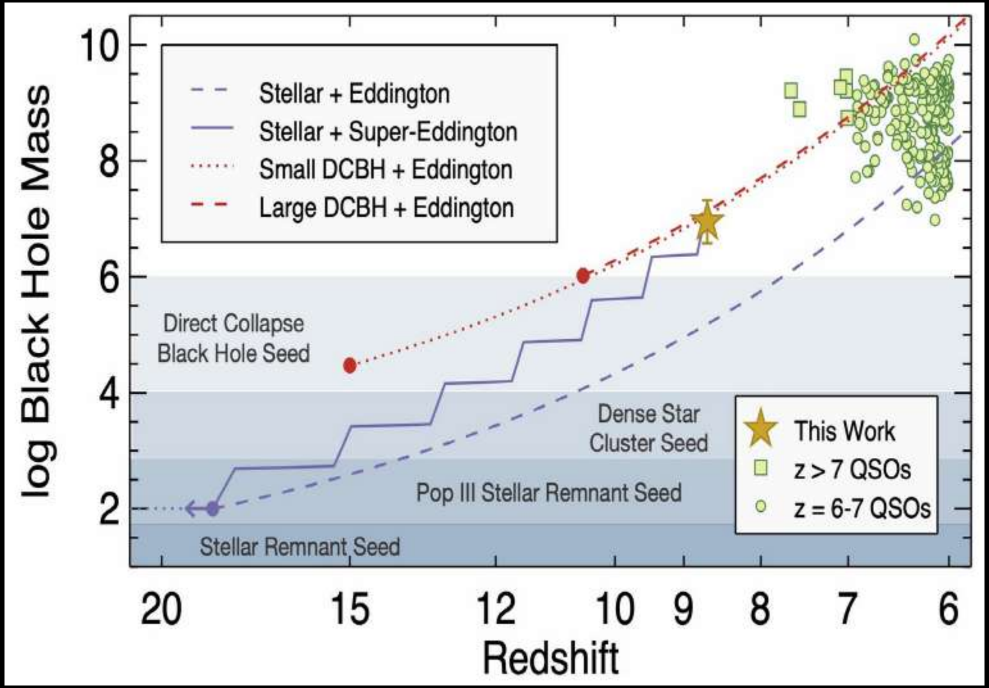
J0313-1806
(Wang et al. 2021)

Larsen et al. 2023 & Goulding et al. 2023: JWST discoveries of most distant BHs at z=9&10.1 at 10^{7-8} M$_\odot$

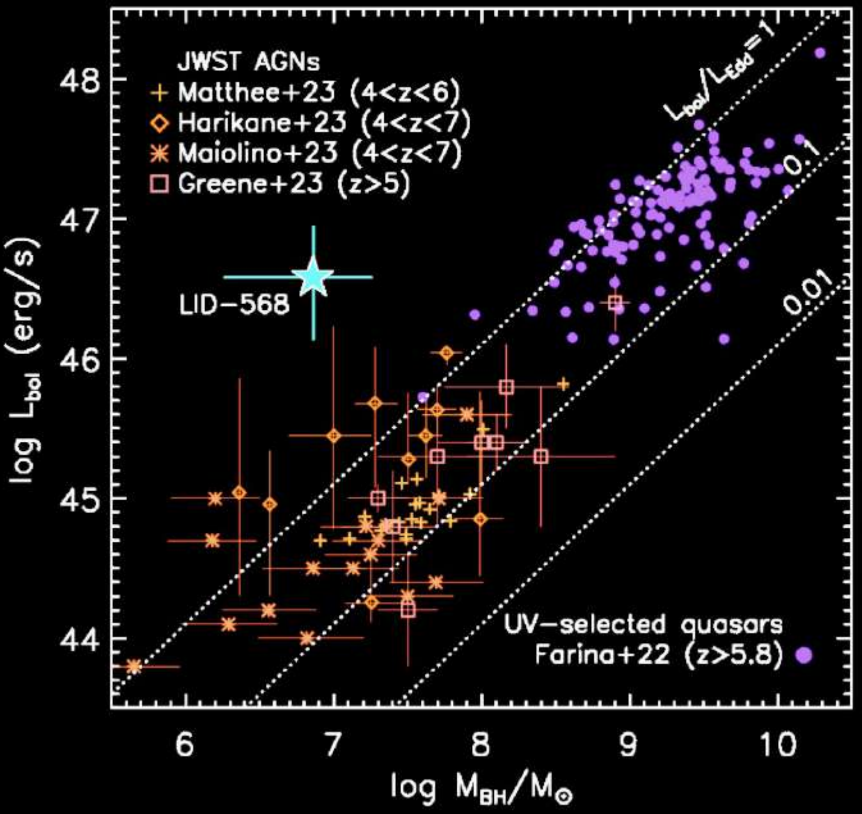
Archibald et al., 2001

Need massive (10^{5-7} M$_\odot$) seed Black Holes early in the Universe !

How to produce the first proto-quasars

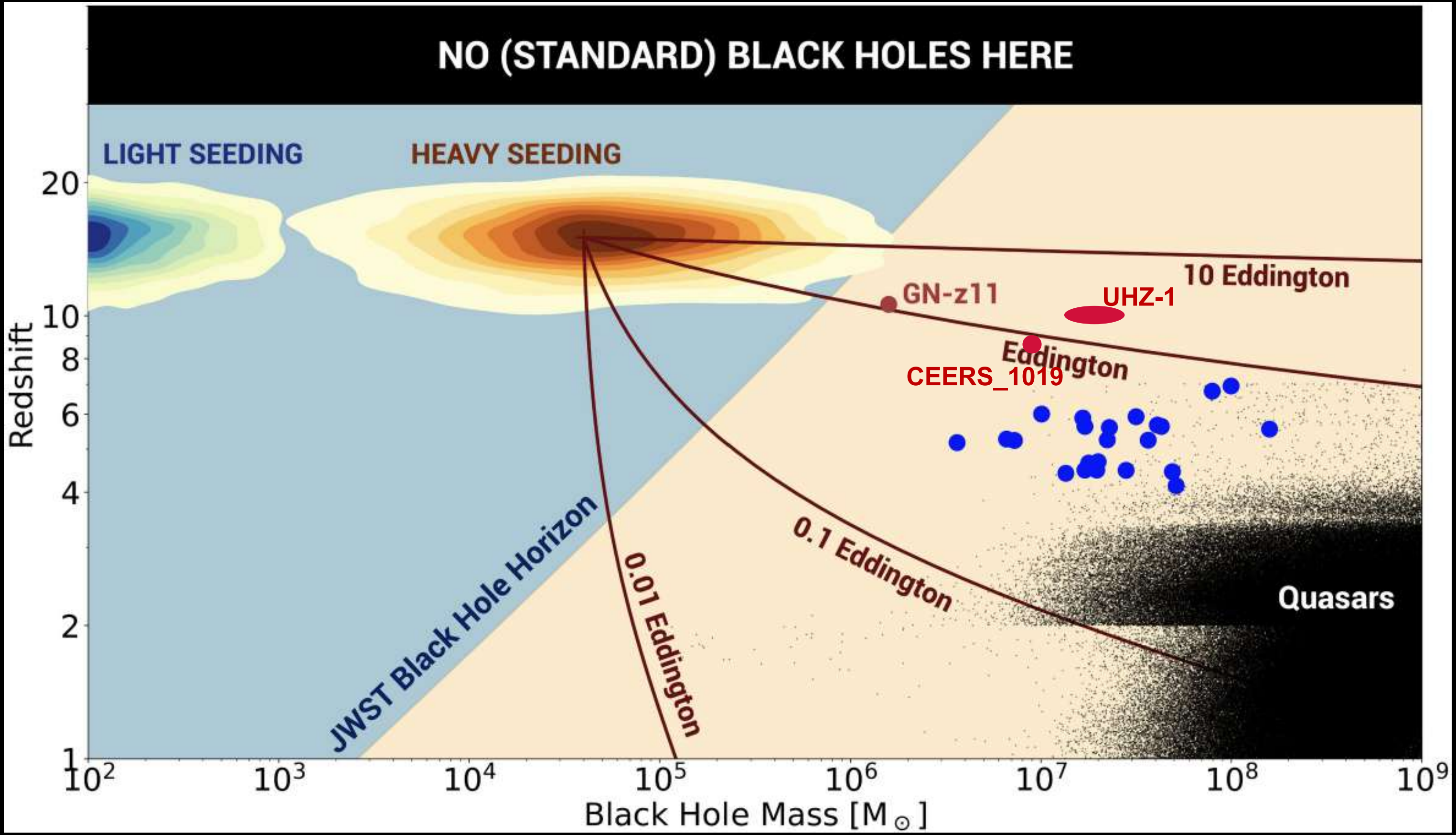


Maiolino et al., 2023



Suh et al., 2023

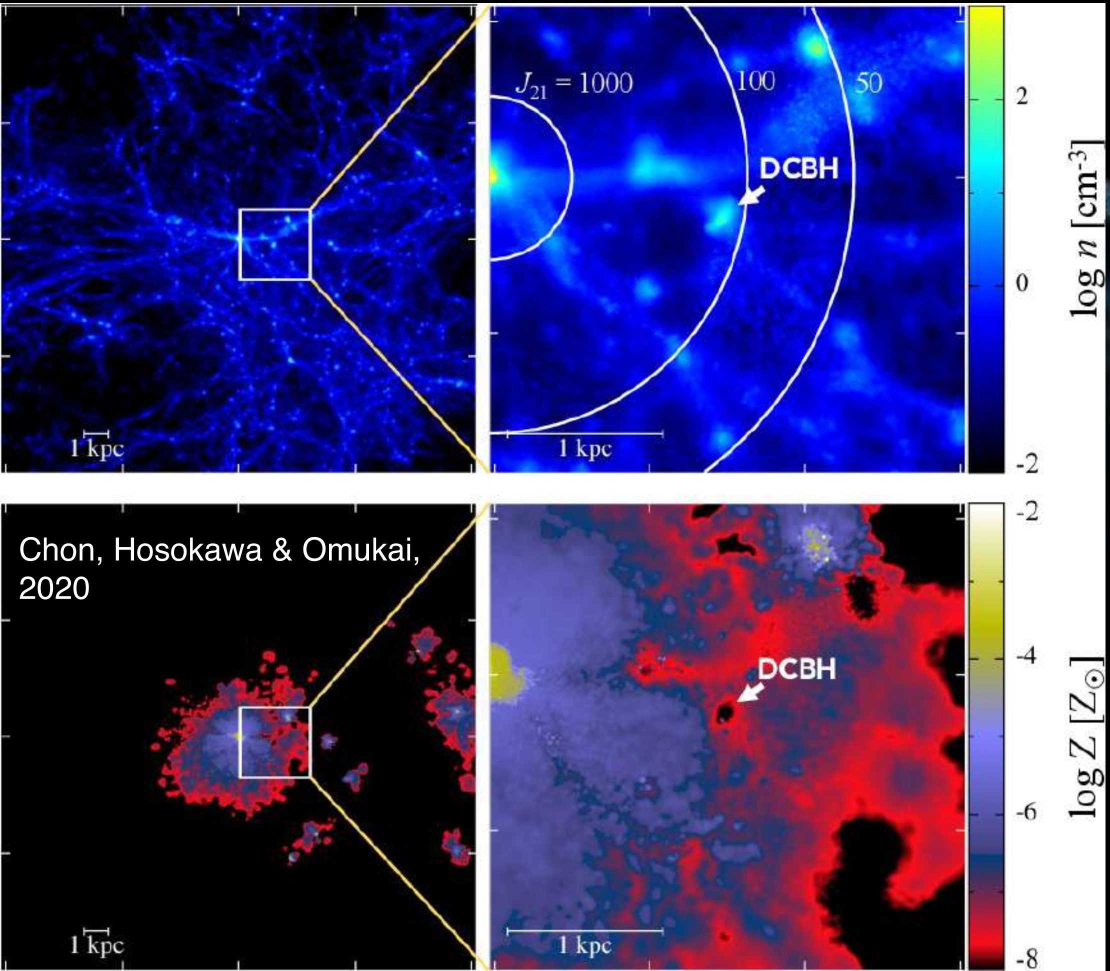
Evidence for Heavy Seeds gets stronger!



Pacucci et al., *arXiv:2308.12331v1*

UHZ-1: Goulding et al., 2023
CEERS_1019: Larson et al., 2023

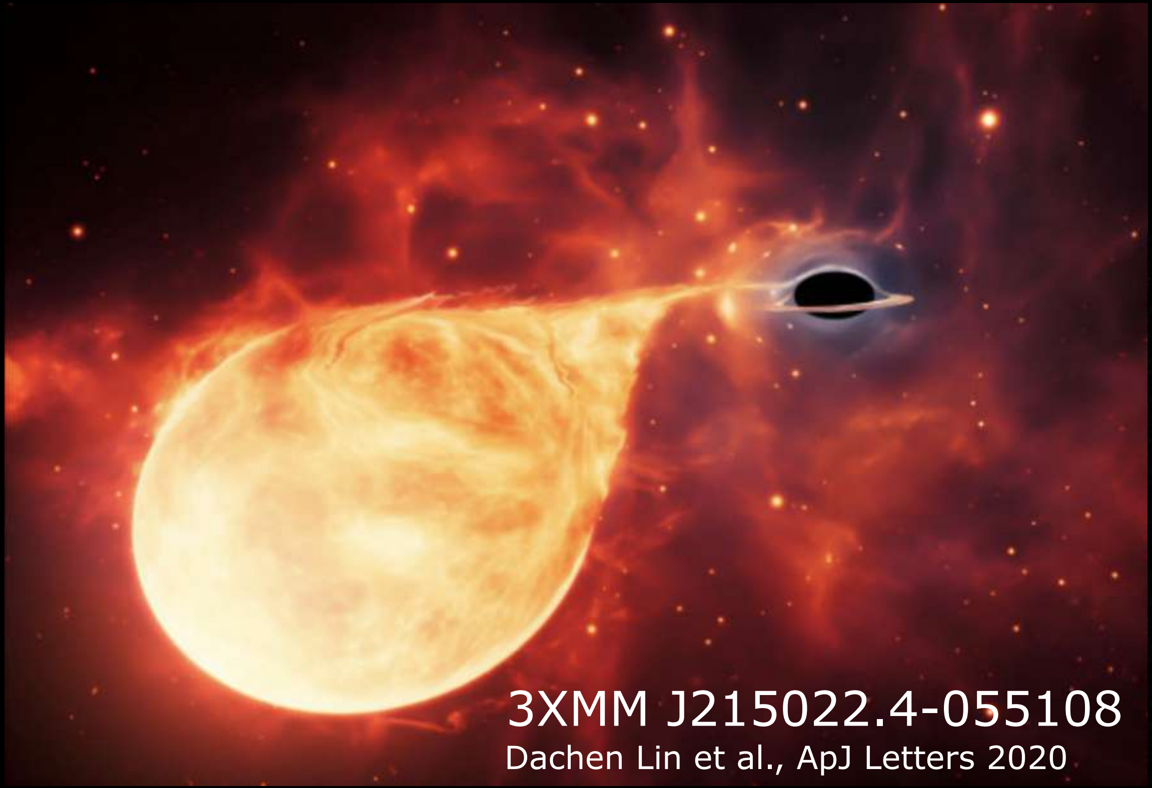
Direct Collapse Black Hole (DCBH) Seed Formation?



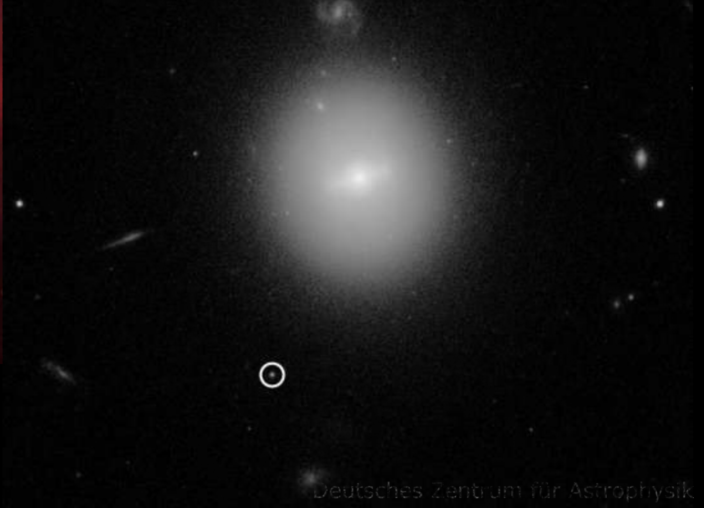
Requires Metal-free gas (gas containing only hydrogen and helium) & sufficiently large flux of ultraviolet Lyman–Werner photons from nearby young stars, in order to destroy hydrogen molecules, which are very efficient gas coolants.

Hubble reveals an “Intermediary” Black Hole

DZA

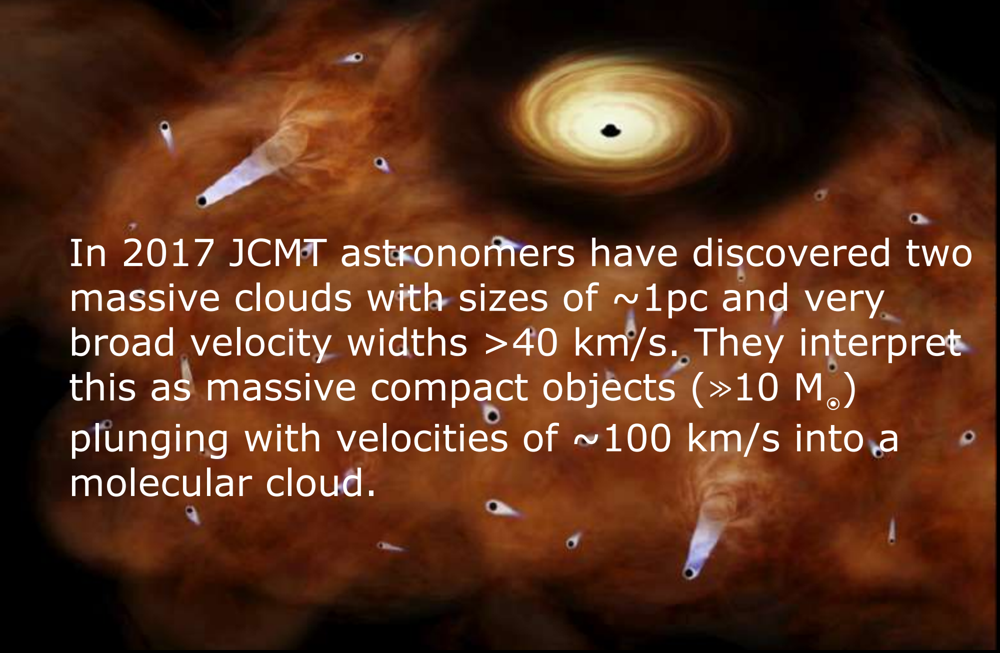


The X-ray telescopes XMM-Newton and Chandra have detected a Black Hole, which is just in the process of disrupting and swallowing a star. The Hubble Space Telescope showed that this is an “Intermediary” Black Hole of about 50.000 solar masses in a globular cluster of another galaxy.

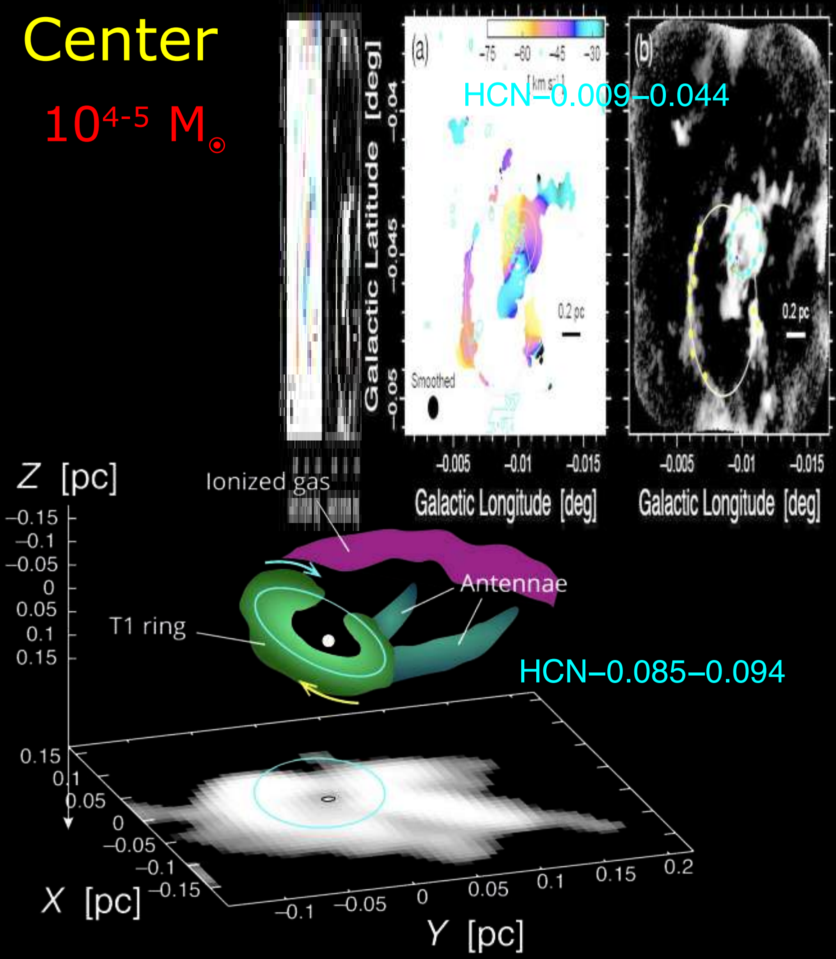


"Stray Black Holes" in the Galactic Center

$10^{4\text{-}5}\ M_\odot$



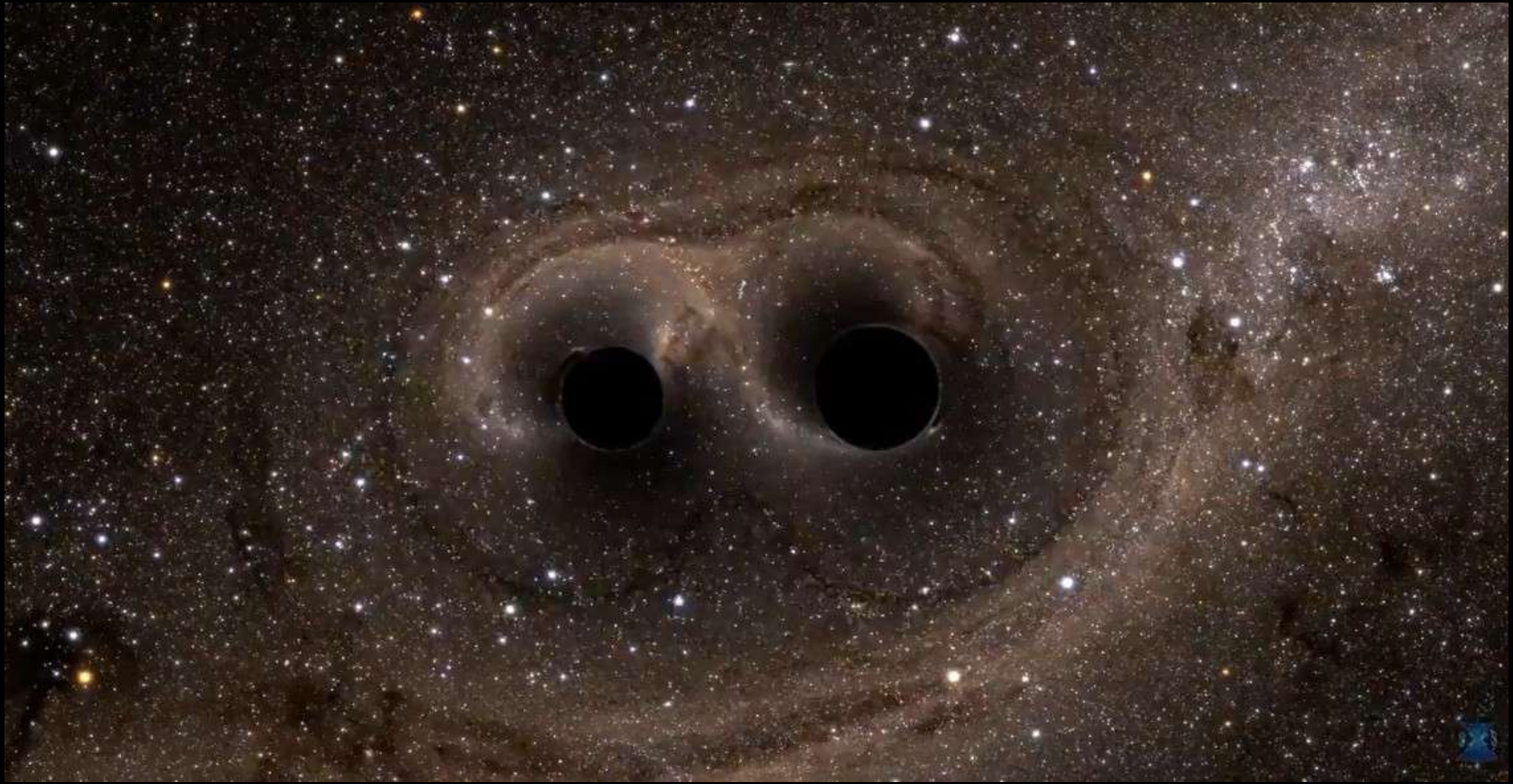
In 2017 JCMT astronomers have discovered two massive clouds with sizes of ~1pc and very broad velocity widths >40 km/s. They interpret this as massive compact objects (»10 $M_\odot$) plunging with velocities of ~100 km/s into a molecular cloud.



A total of 5 Intermediate-Mass Black Holes ($10^{4\text{-}5}\ M_\odot$) have now been identified in the Central Molecular Zone from high angular resolution ALMA and radio data.

Takekawa et al., 2017, 2019, 2020

Simulation of the merger between two Black Holes

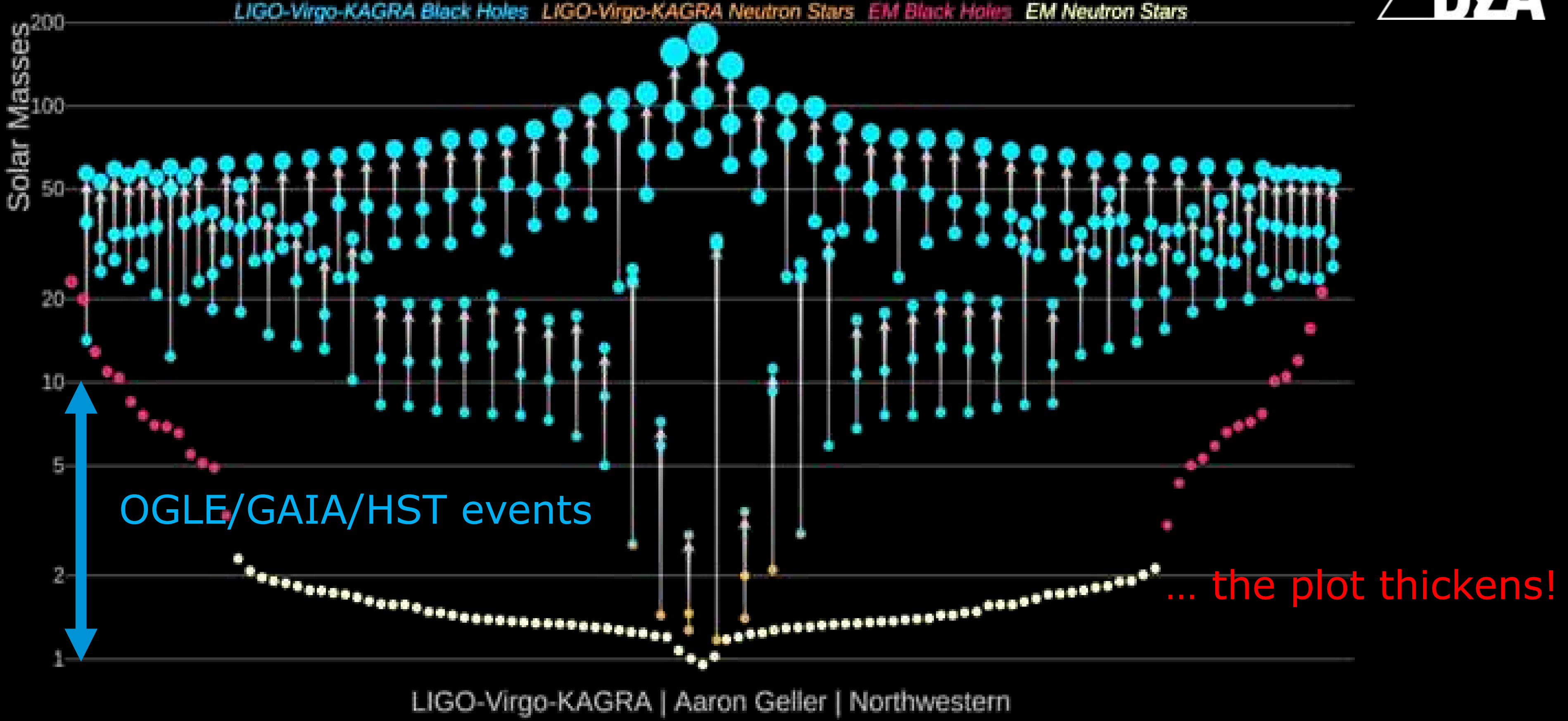


LIGO/Virgo/Kagra/GEO O4 observing run ongoing since May 2023!

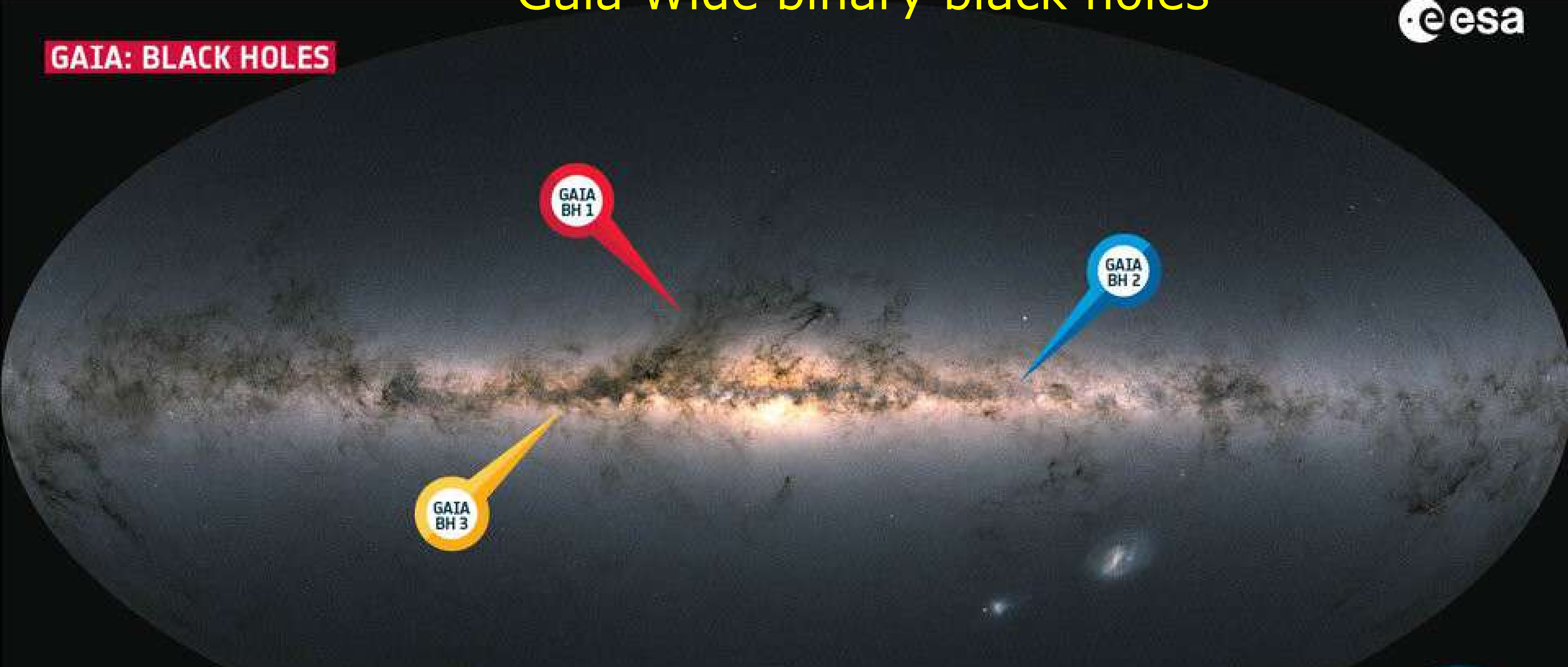
About 2 events per week are being detected.

Video available at https://youtu.be/ENd8Sz0AFOk

Masses in the Stellar Graveyard

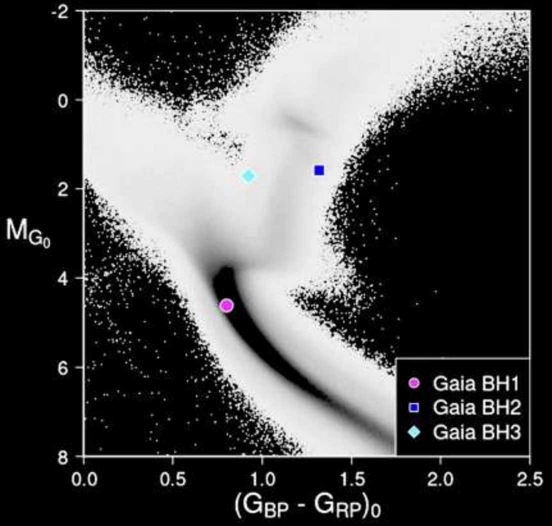


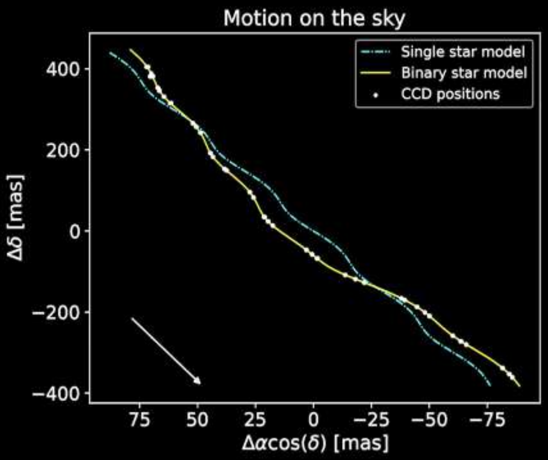
Gaia Wide binary black holes

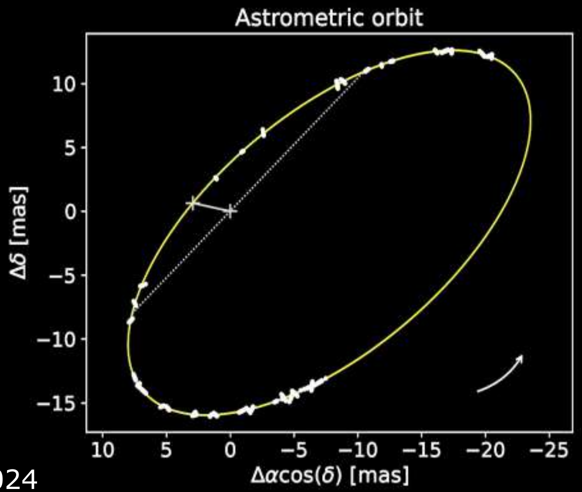


Gaia has discovered astrometric orbits of three dormant wide binary black holes so far. A large additional number of BHs is expected in the Gaia DR4 data release.

Gaia Wide binary black holes







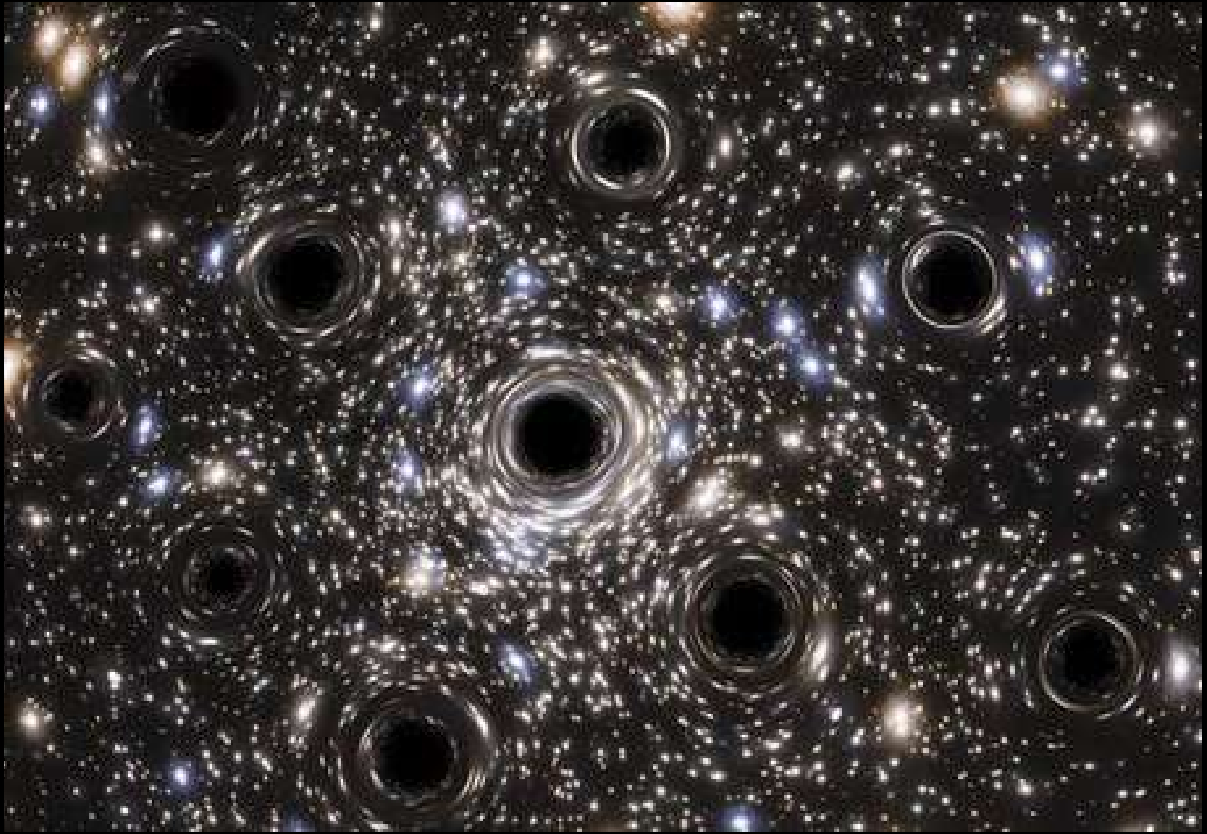
Gaia BH3 is a a 32.7±0.8 $M_{\odot}$ BH in a wide binary system with a period of 11.6 yr, more massive than any other Galactic stellar-class BH known thus far.

P. Pannuzzo & Gaia collaboration, 2024

Gaia BH3 and its companion move through the galactic disc in a retrograde halo orbit. They belong to a structure recently discovered by Gaia named ED-2, which appears to have emerged from the remains of a globular cluster captured and then torn apart by our Galaxy. The very low-metallicity companion star is not polluted from a recent supernova explosion and thus has likely been captured in the high-density environment of the globular cluster.

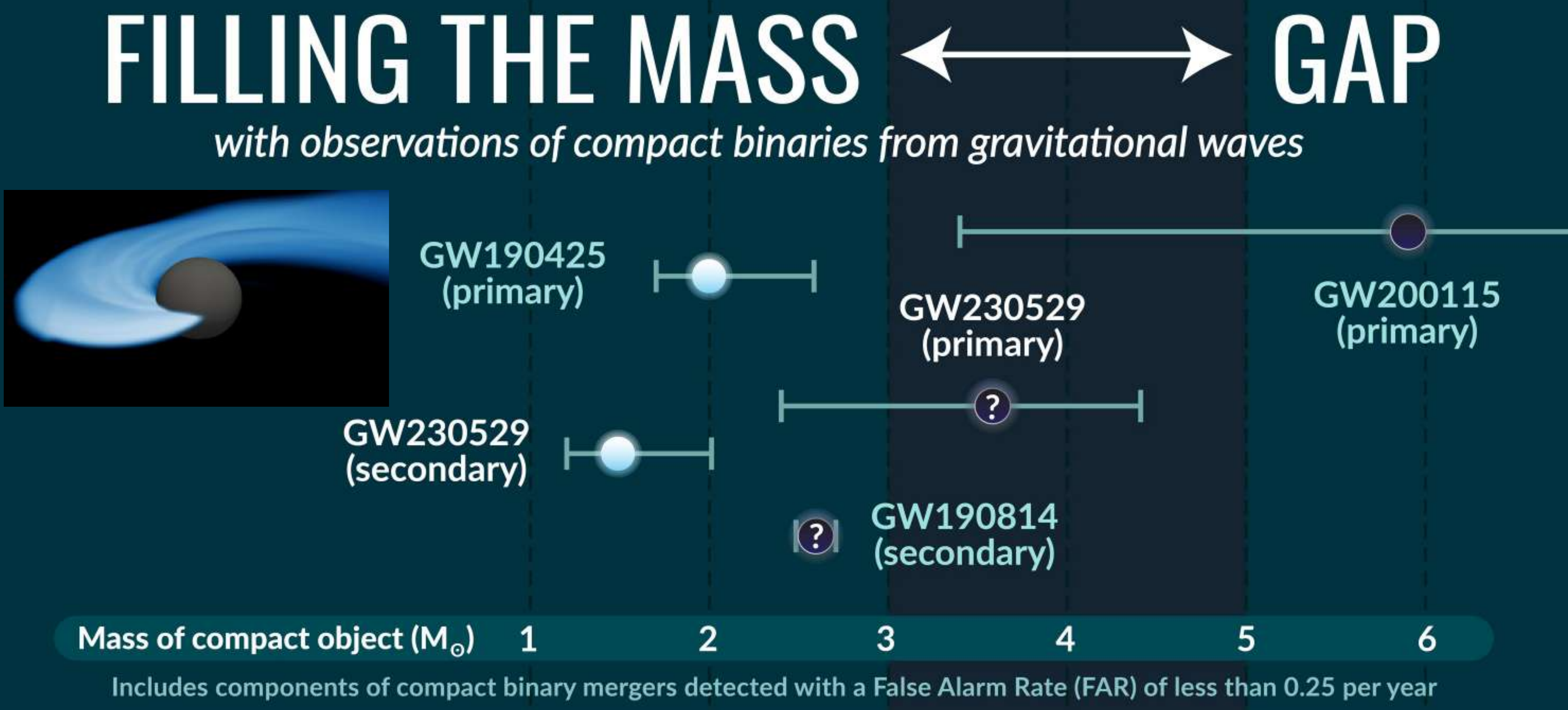
Pina D.M. et al. 2024

A large number of compact objects detected in GC



Vitral, E. et al., 2022, MNRAS: Clusters of ~1000 compact objects (WD?, BH?, PBH?) detected in Globular Clusters NGC 3201 and NGC 6397 with Gaia and HST.

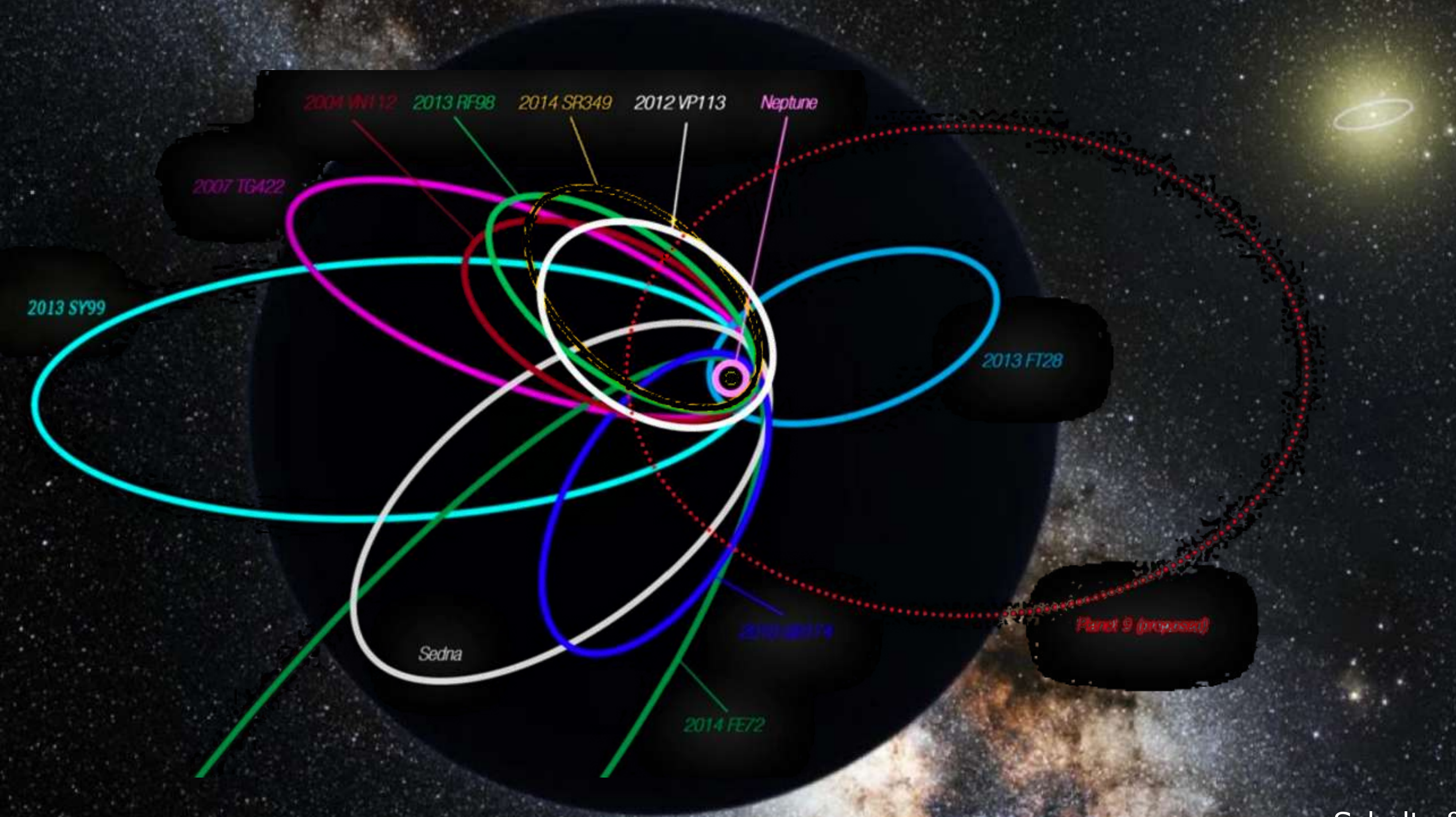
LIGO/MPG Press release, April 5, 2024



Credit: S. Galaudage, Observatoire de la Côte d’Azur.)

Is Planet 9 (Planet X) a Black Hole?

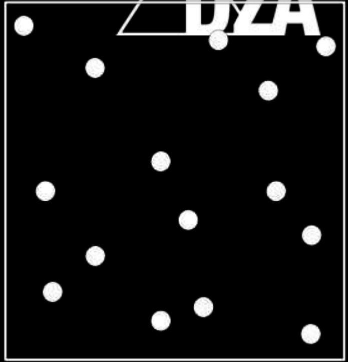
$10^{-5}\ M_\odot$



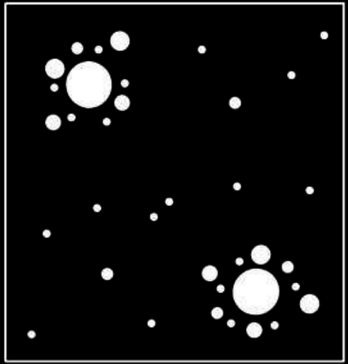
Scholtz & Unwin, 2019

Hubble finds Clumping of Dark Matter

Meneghetti et al, 2020, Science

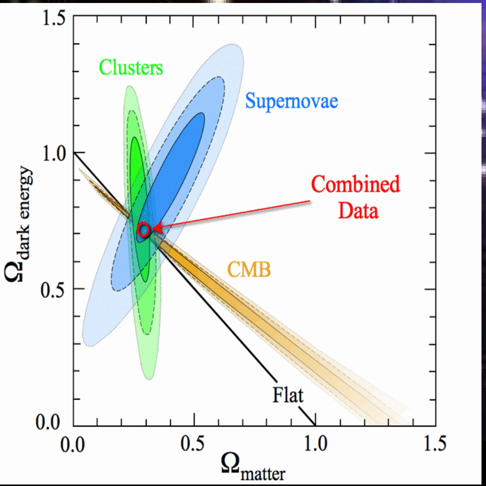


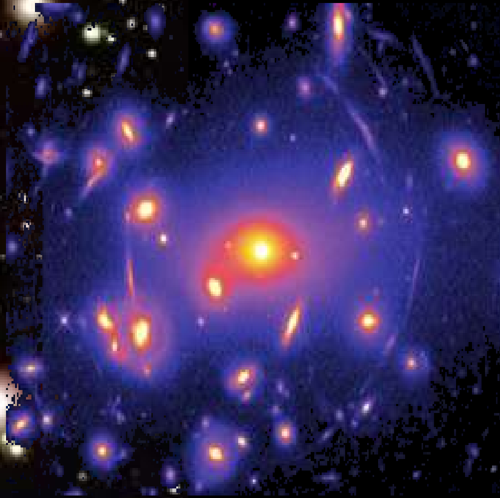
Uniform single mass Dark Matter



Clustered wide mass distribution Dark Matter

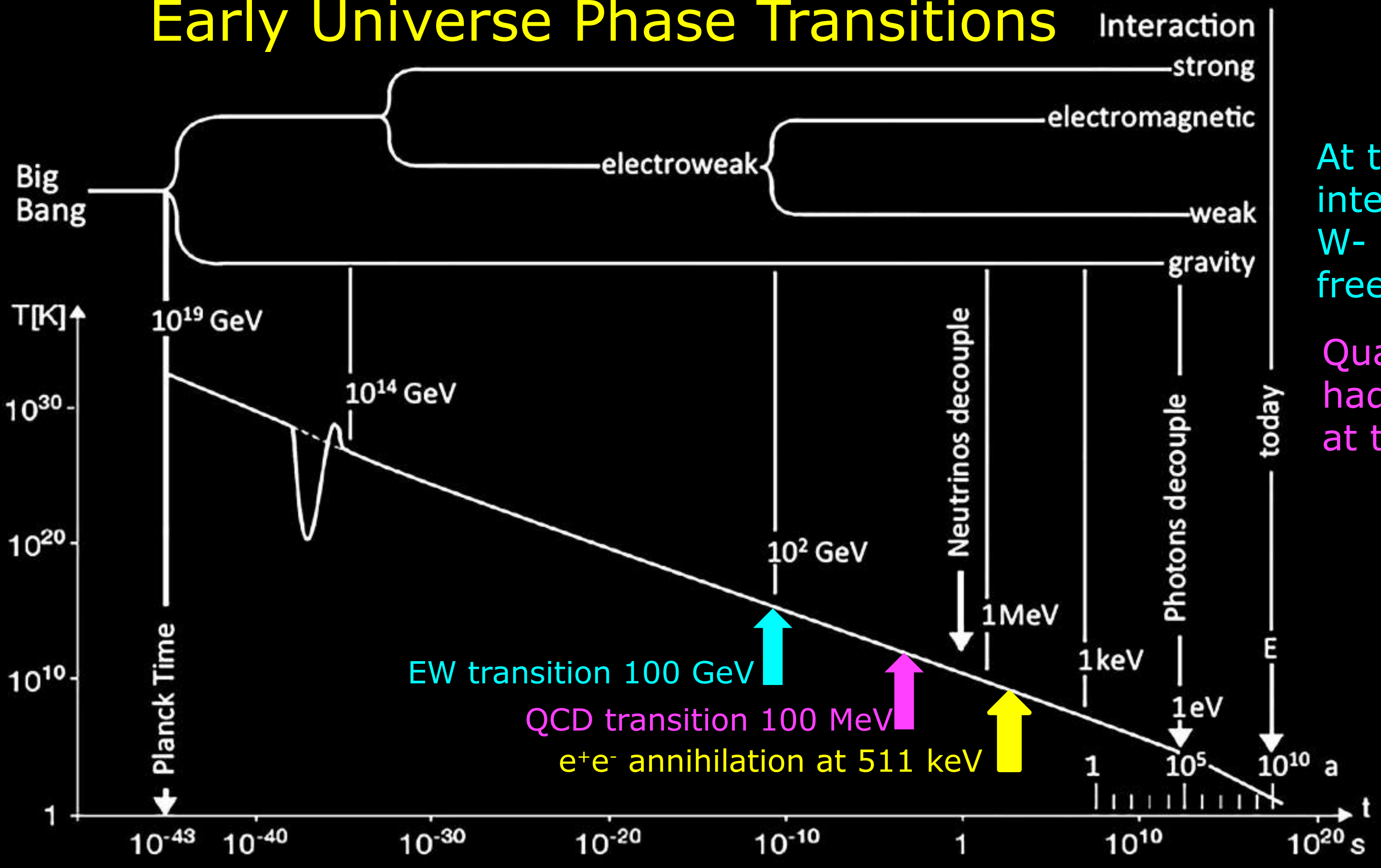
What is Dark Matter?





Generations of physicists are desperately searching the Dark Matter particle. Primordial Black Holes may be an alternative.

Early Universe Phase Transitions

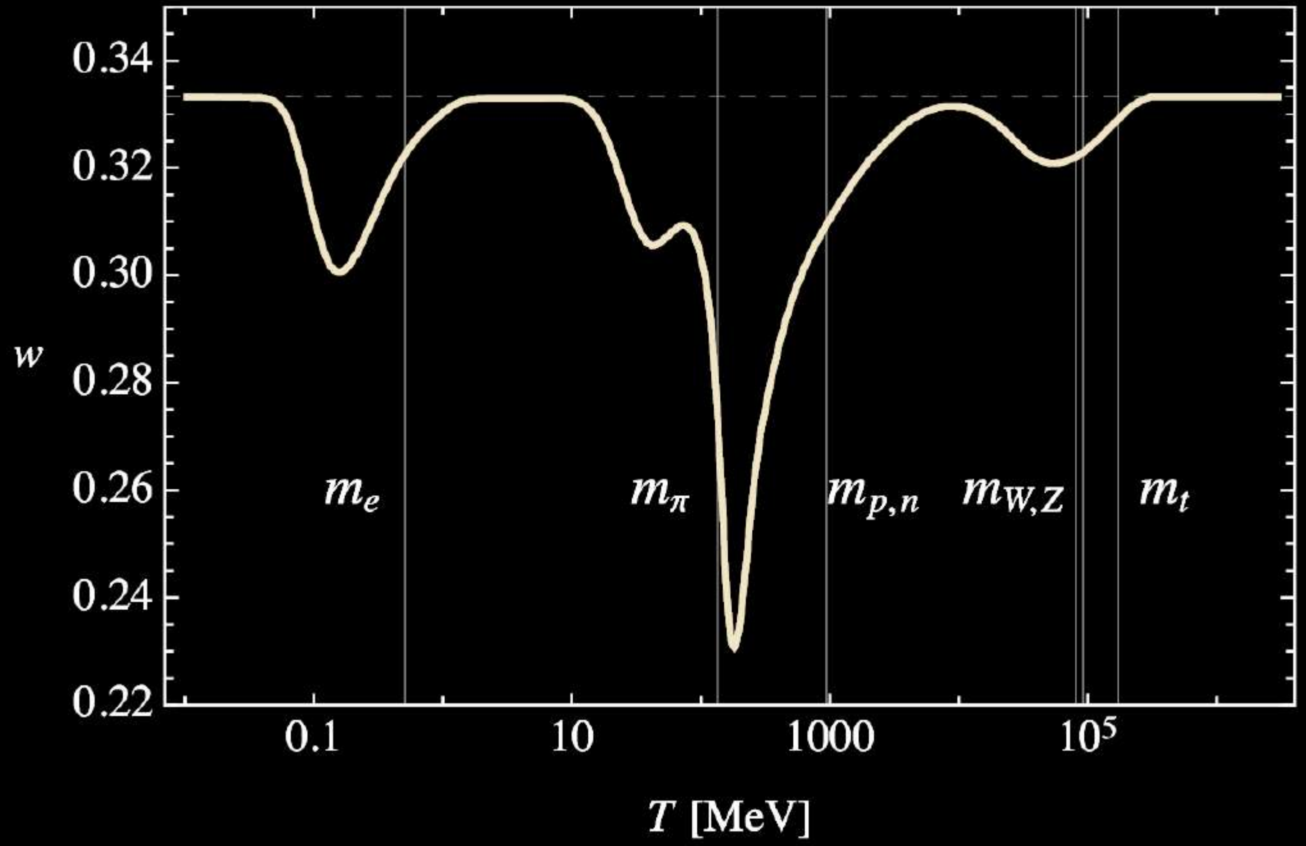


At the electroweak interaction scale the first W- and Z-bosons are freezing out.

Quarks freeze out to form hadrons (baryons, pions) at the QCD transition.

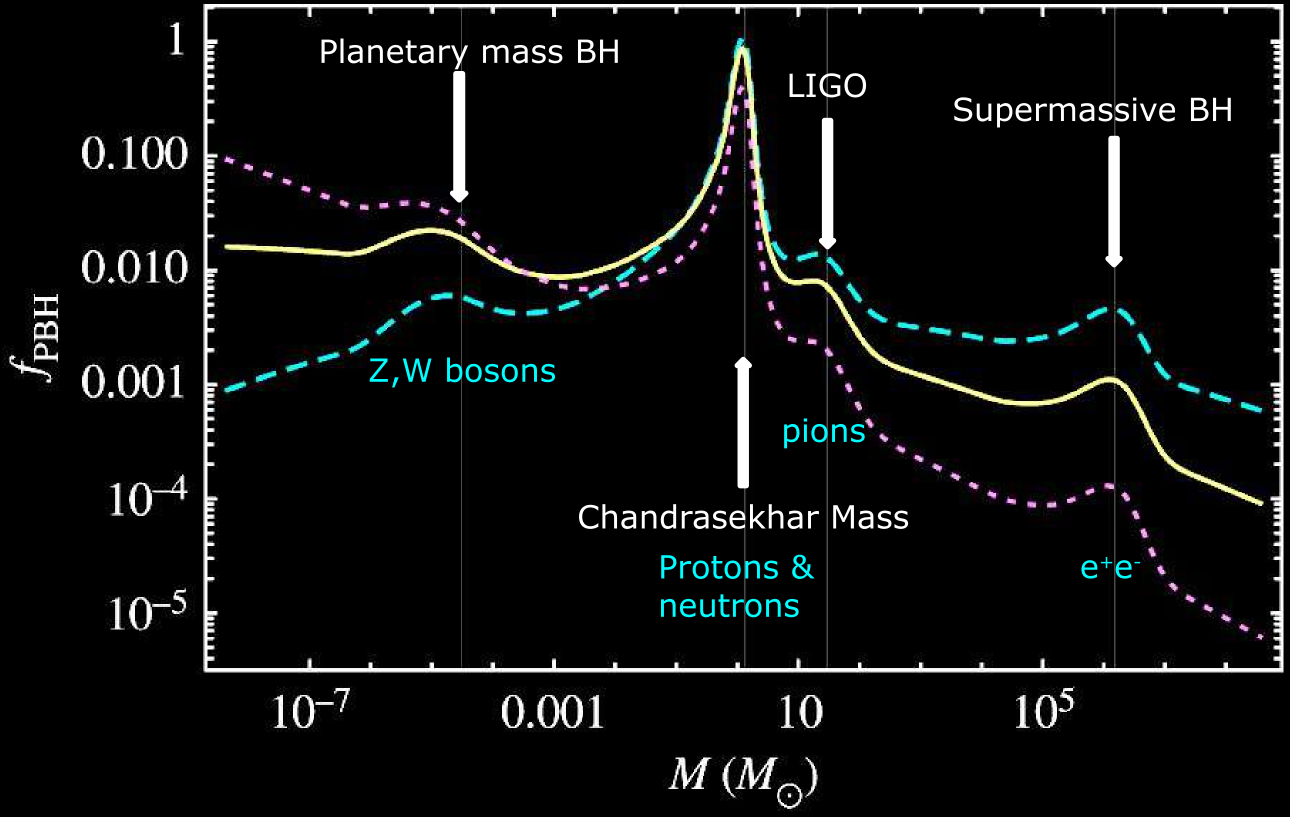
Each of these transitions leaves an imprint on the thermal history of the universe and enables black hole collapse.

Sound speed due to early phase transitions



Carr, B., Clesse, S., Garcia-Bellido, J., Kühnel, F.. *"Cosmic Conundra Explained by Thermal History and Primordial Black Holes" arXiv: 1906.08217, 2019*

PBH Mass Spectrum



Different peaks correspond to different particles created at the early universe phase transitions and the corresponding reduction in the sound velocity.

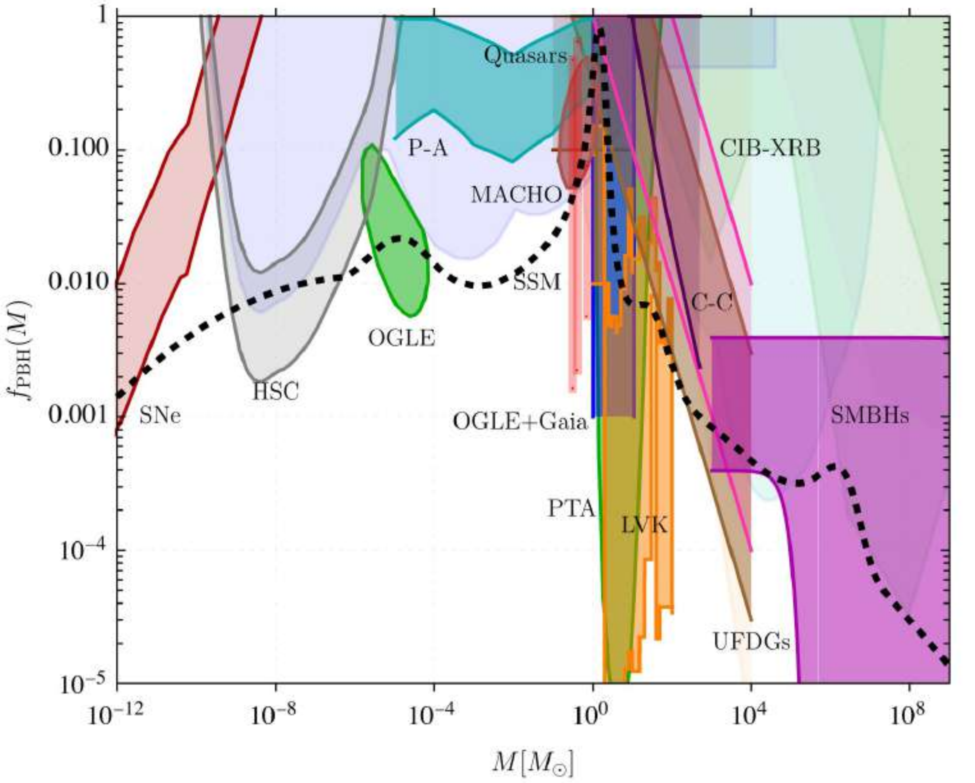
BH mass corresponds to the horizon size at each time.

Only requirement is enough fluctuation power in a volume fraction of 10^{-9} of the early Universe.

Carr, Clesse, García-Bellido 2019

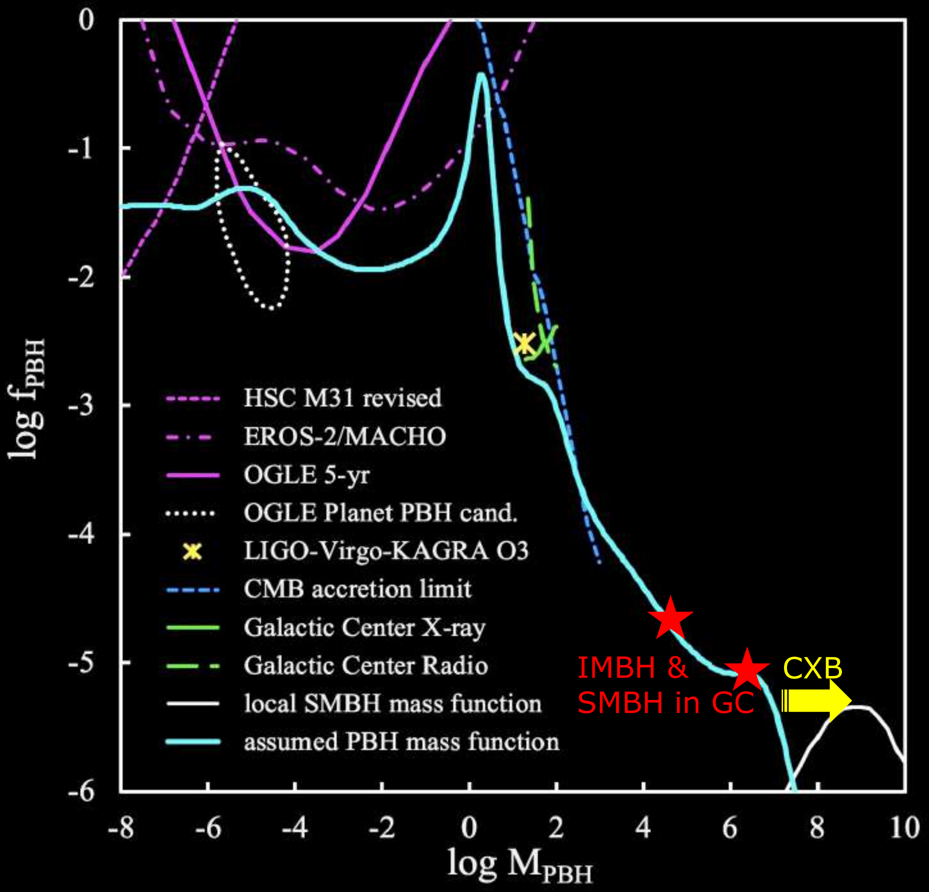
Observational Evidence for Primordial Black Holes: A Positivist Perspective

B. J. Carr,[1,*] S. Clesse,[2,†] J. García-Bellido,[3,‡] M. R. S. Hawkins,[4,§] and F. Kühnel[5,¶]



arXiv:2306.03903v1 [astro-ph.CO] 6 Jun 2023

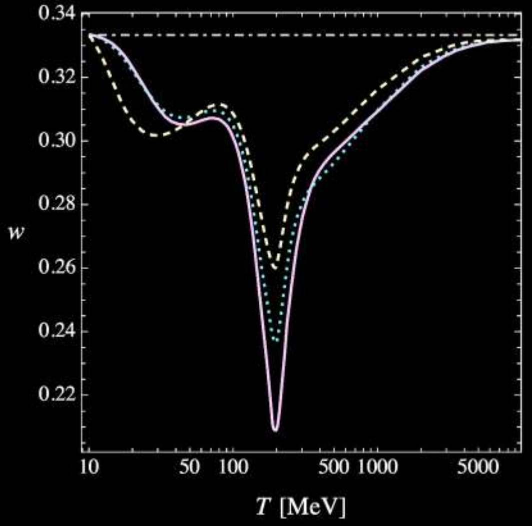
PBH mass spectrum assumed for our work

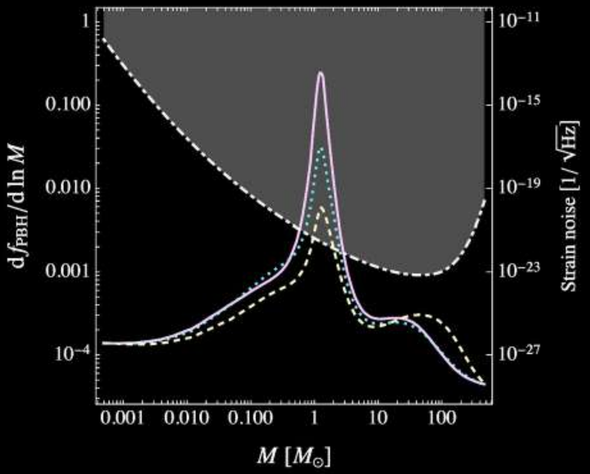


Bernard Carr, Juan García-Bellido et al. are working on a new version of their PBH mass spectrum, which assumes a rolling index of the primordial power spectrum and thus has a steeper decline at large PBH masses. This is now fully consistent with all observational constraints.

This is, what we use to estimate the PBH contribution to the extragalactic backgrounds.

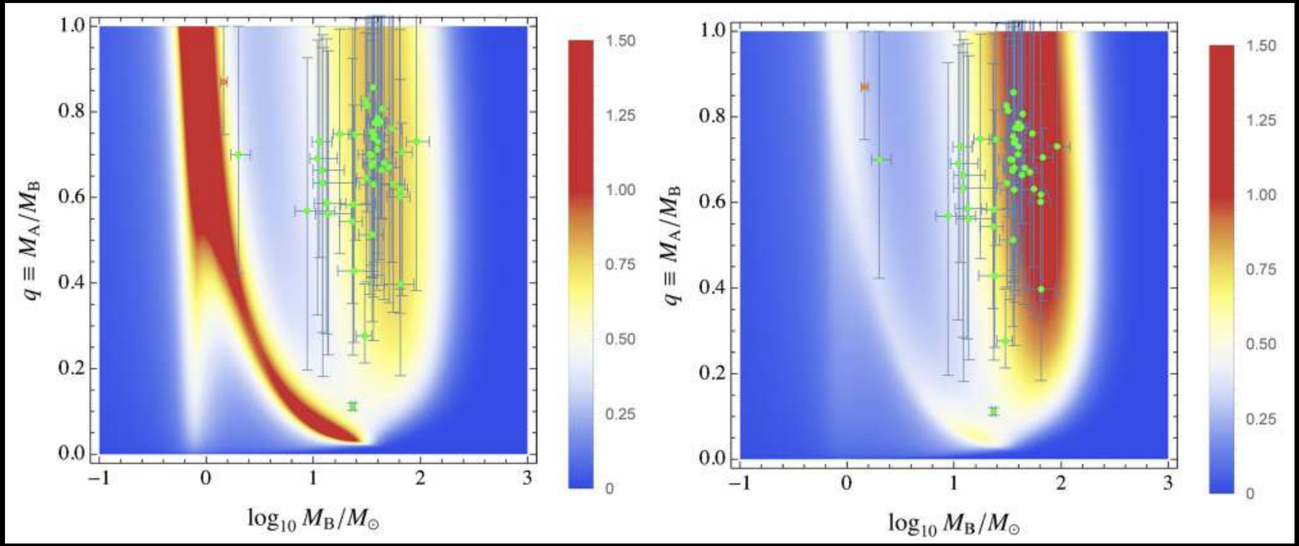
Hasinger 2020





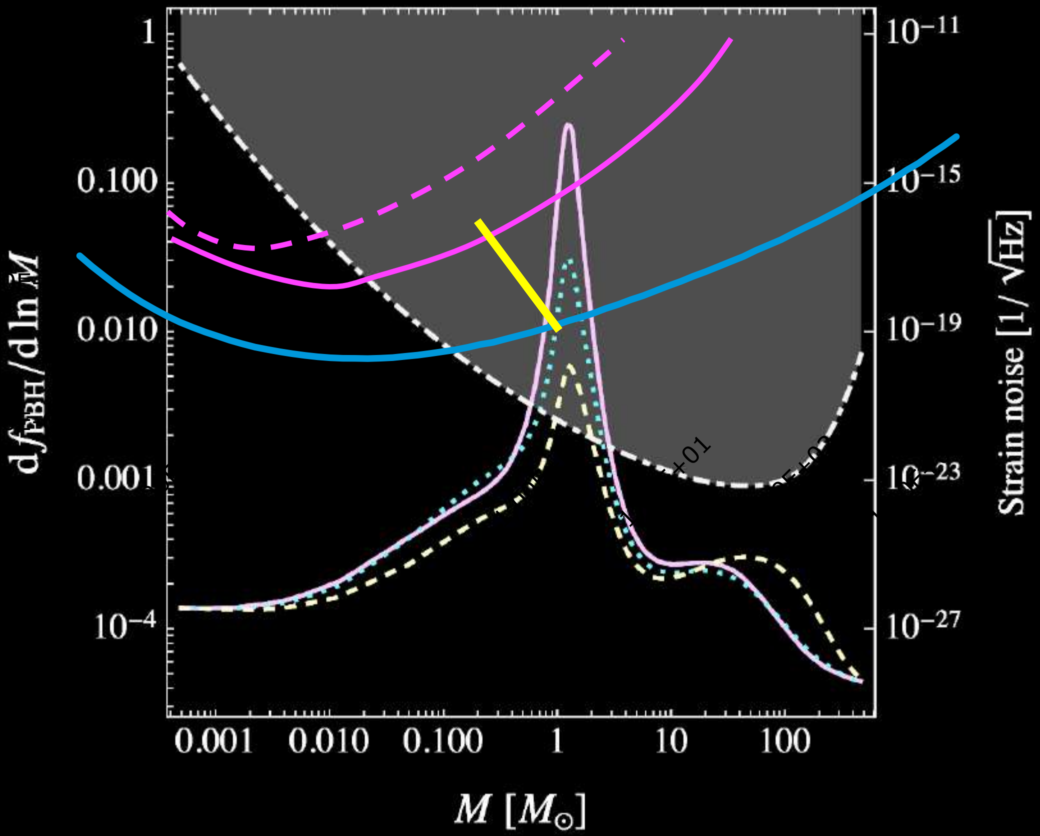
Lepton Flavor Asymmetries

Baryon asymmetry is roughly 10^{-11}.
Lepton flavor asymmetry could be as large as 10^{-2}.
This has significant consequences for the QCD phase transition!



Bödecker, D., et al. 2021, Phys. Rev. D

New constraints on PBH mass function



Original MACHO & OGLE microlensing constraints (Wyrzykowski, L., et al. 2011, solid). Reanalysis of the MACHO constraints on PBH in the light of the new Gaia MW rotation curve (Garcia-Bellido, J. & Hawkins, M., 2024, dashed)

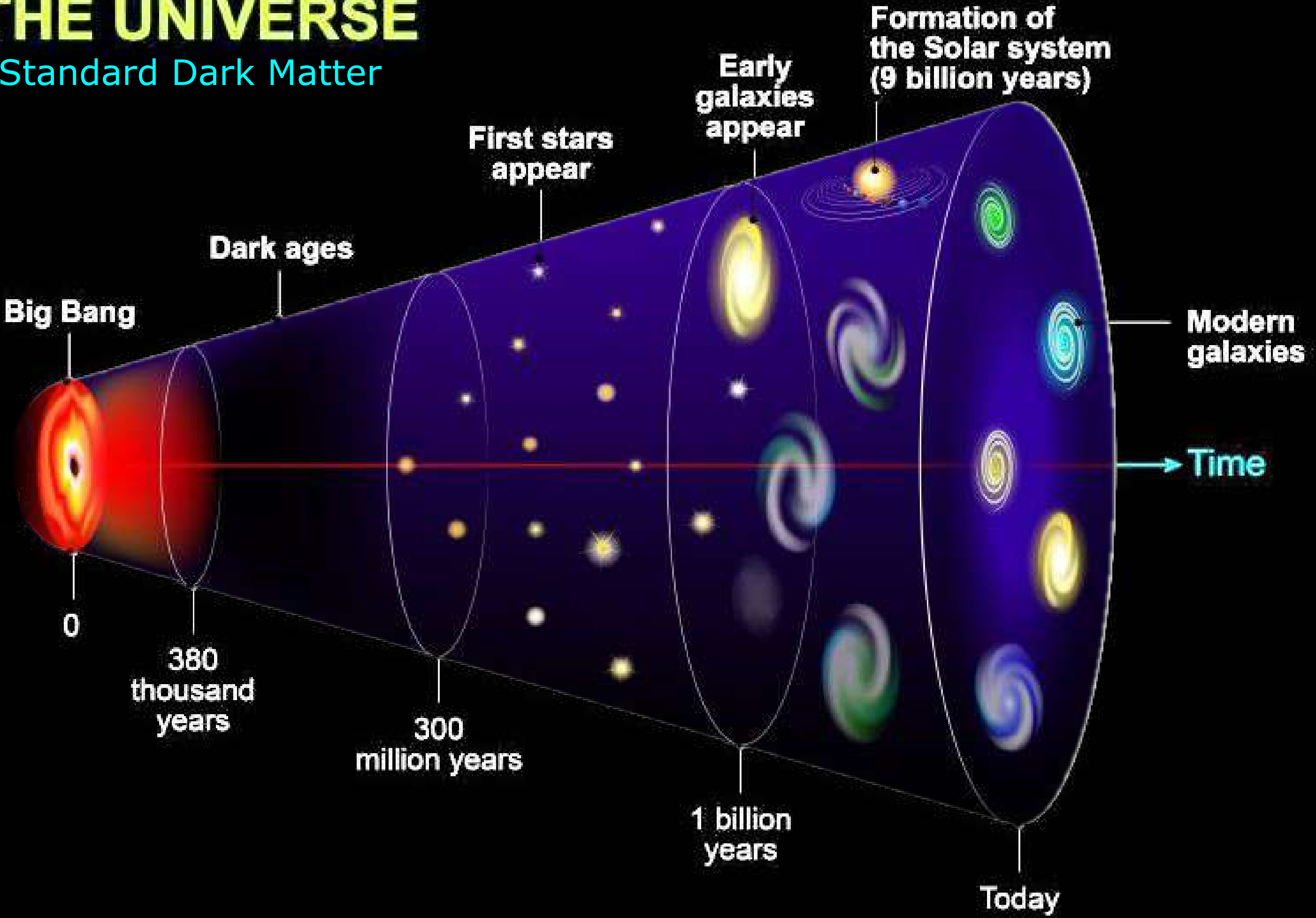
New 20-yr OGLE microlensing constraints (Mroz, P. et al., arXiv 2403.02386).

Search for Subsolar-Mass Binaries in the First Half of Advanced LIGO's and Advanced Virgo's Third Observing Run.

➔ Just about fits!

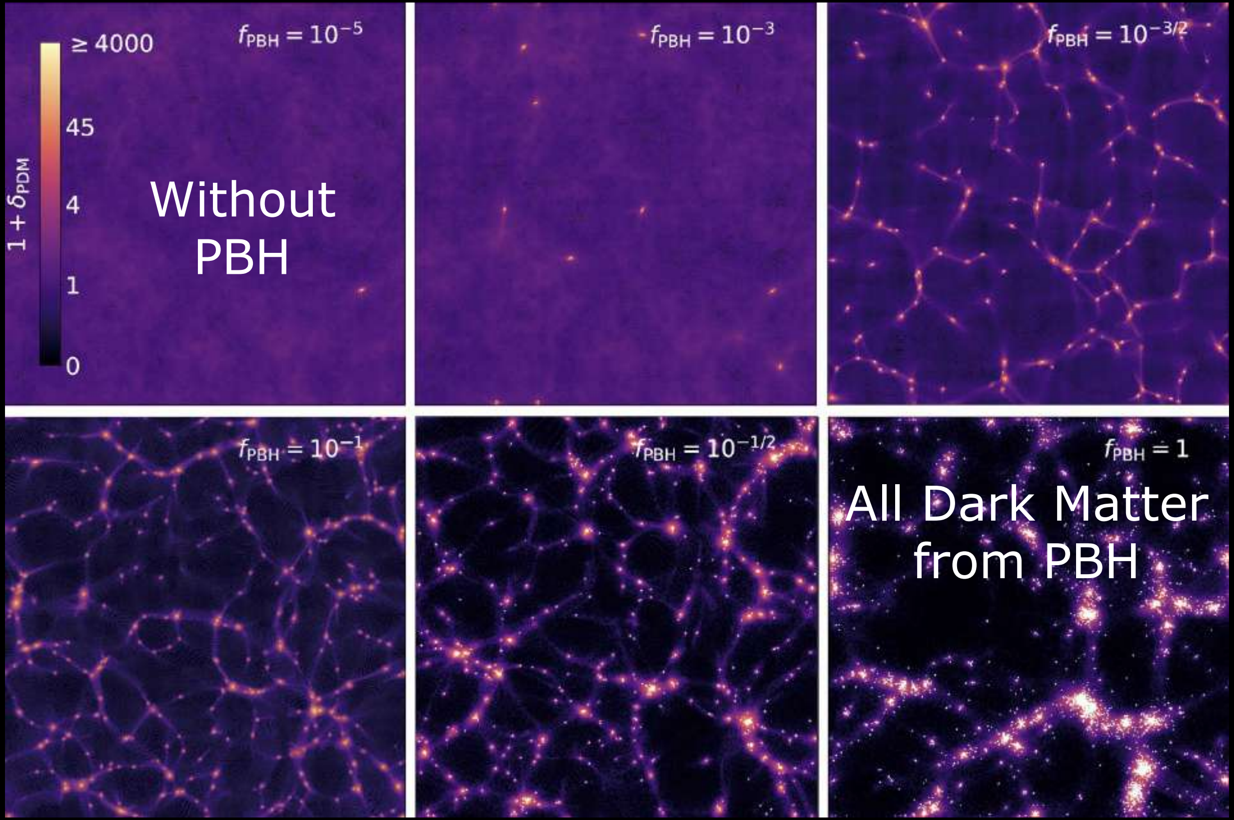
EVOLUTION OF THE UNIVERSE

Standard Dark Matter



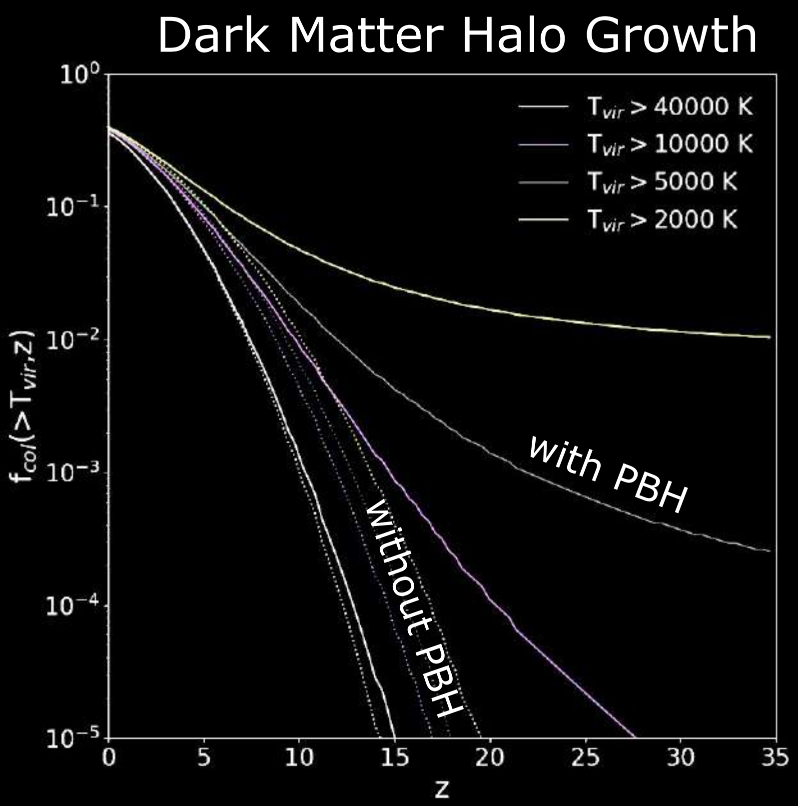
DZA

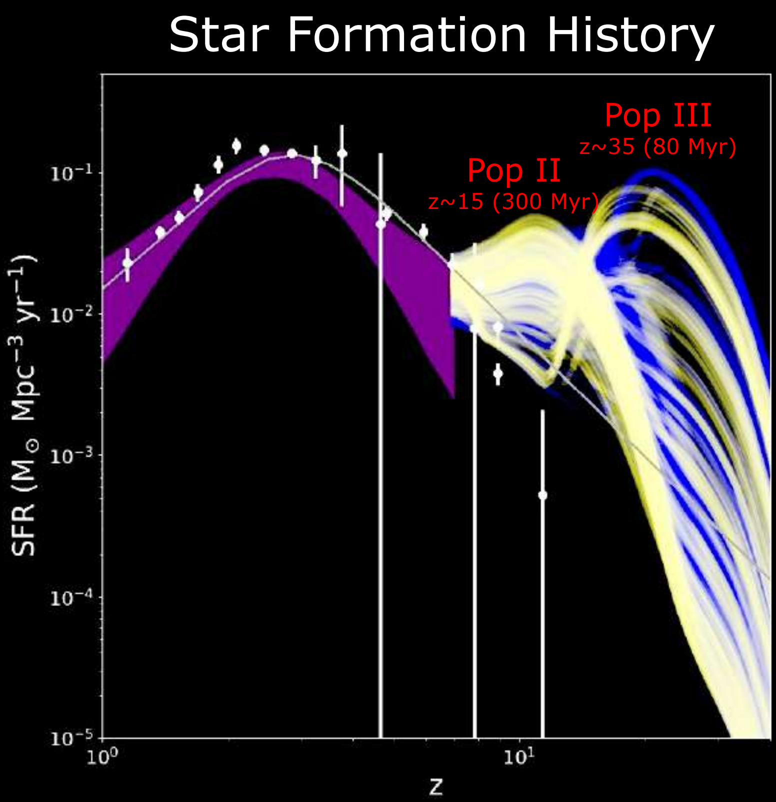
Growth of Large-Scale Structure at z=10



D. Inman and Y. Ali-Haïmoud, Early structure formation in primordial black hole cosmologies, Phys. Rev. D 100, 083528 (2019), arXiv:1907.08129

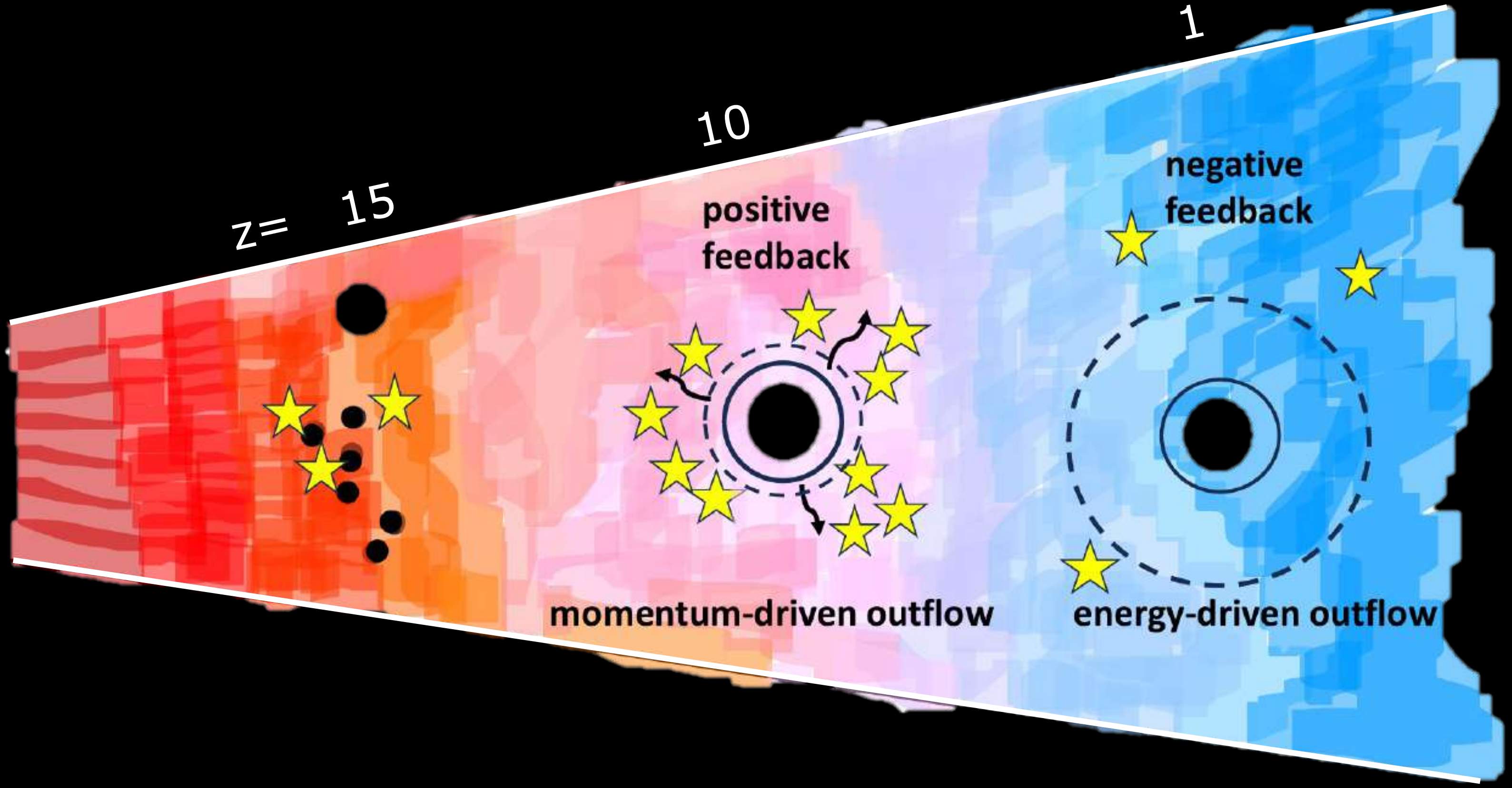
PBH add small DM haloes and early star formation





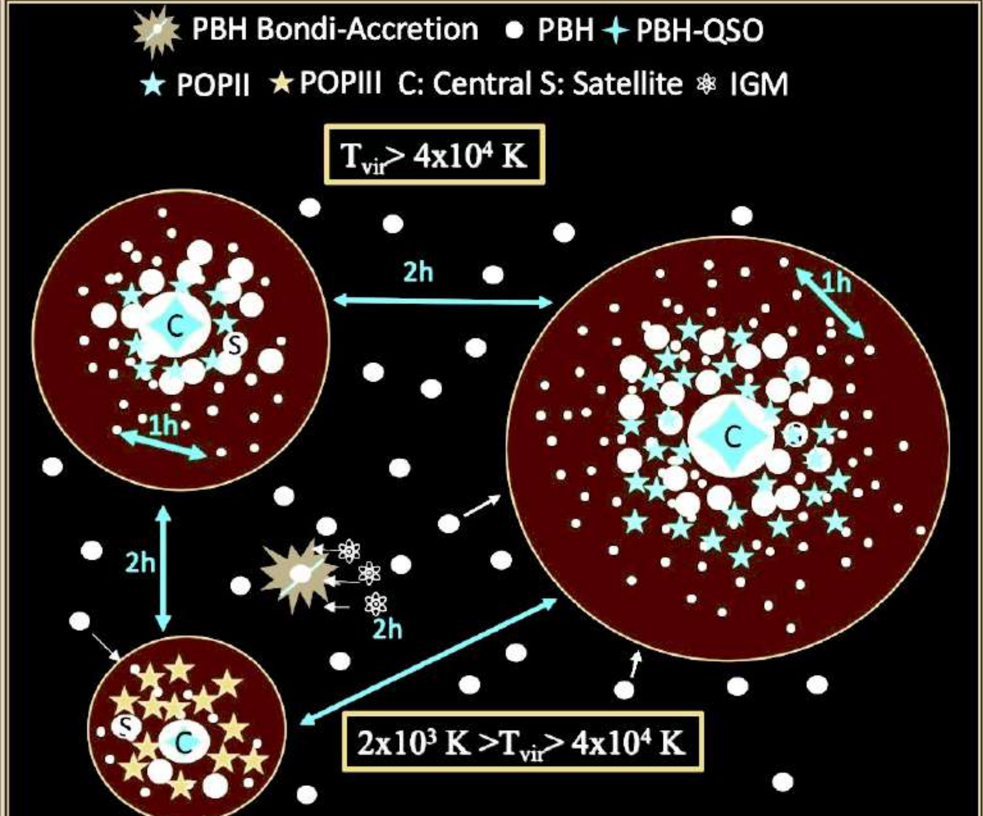
Cappelluti, Hasinger, Natarajan, 2022, ApJ

Effect of Black Holes on Galaxy Evolution

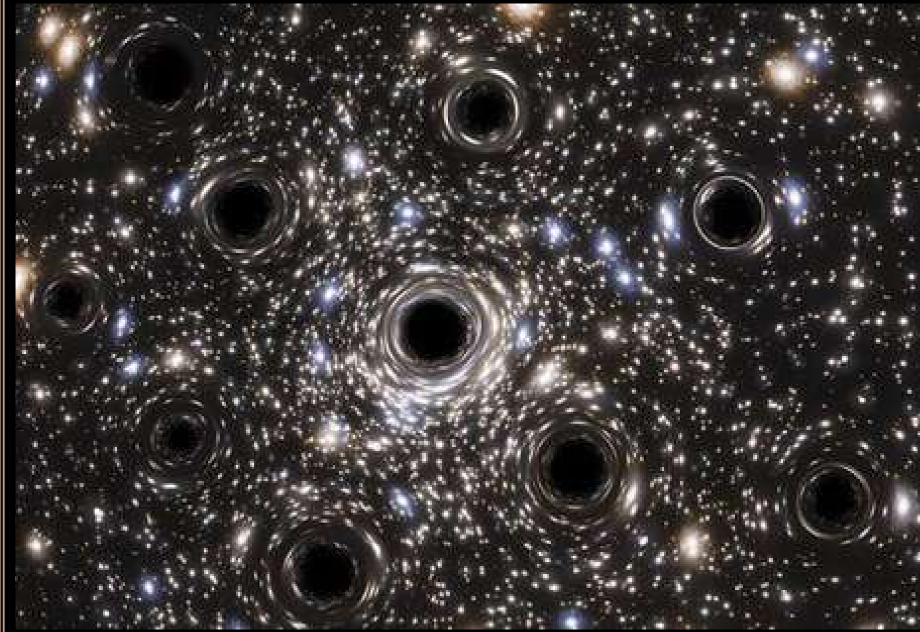


Silk, J., Begelman, M.C., Norman, C., et al. 2024

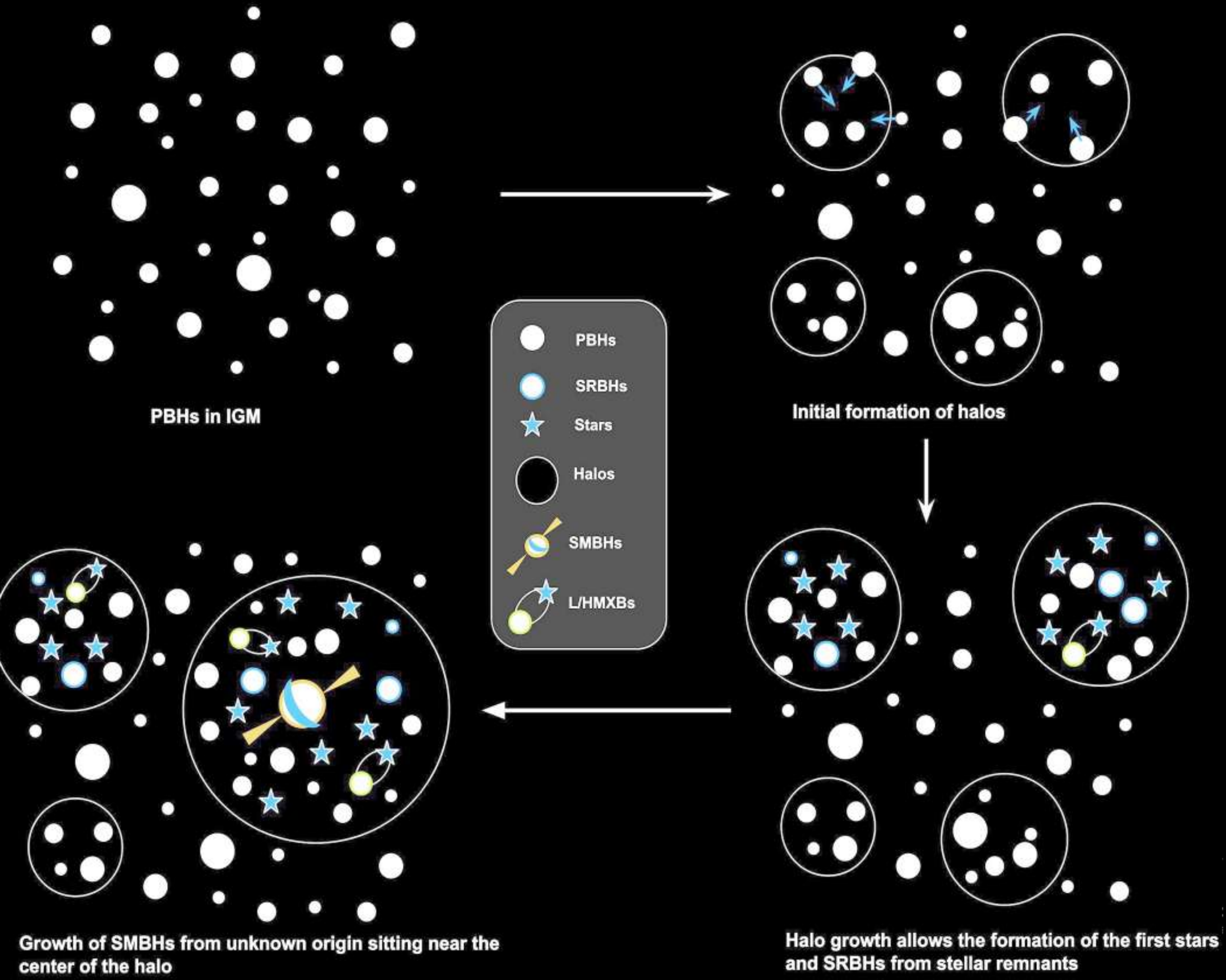
Primordial Black Hole Dark Matter Scheme



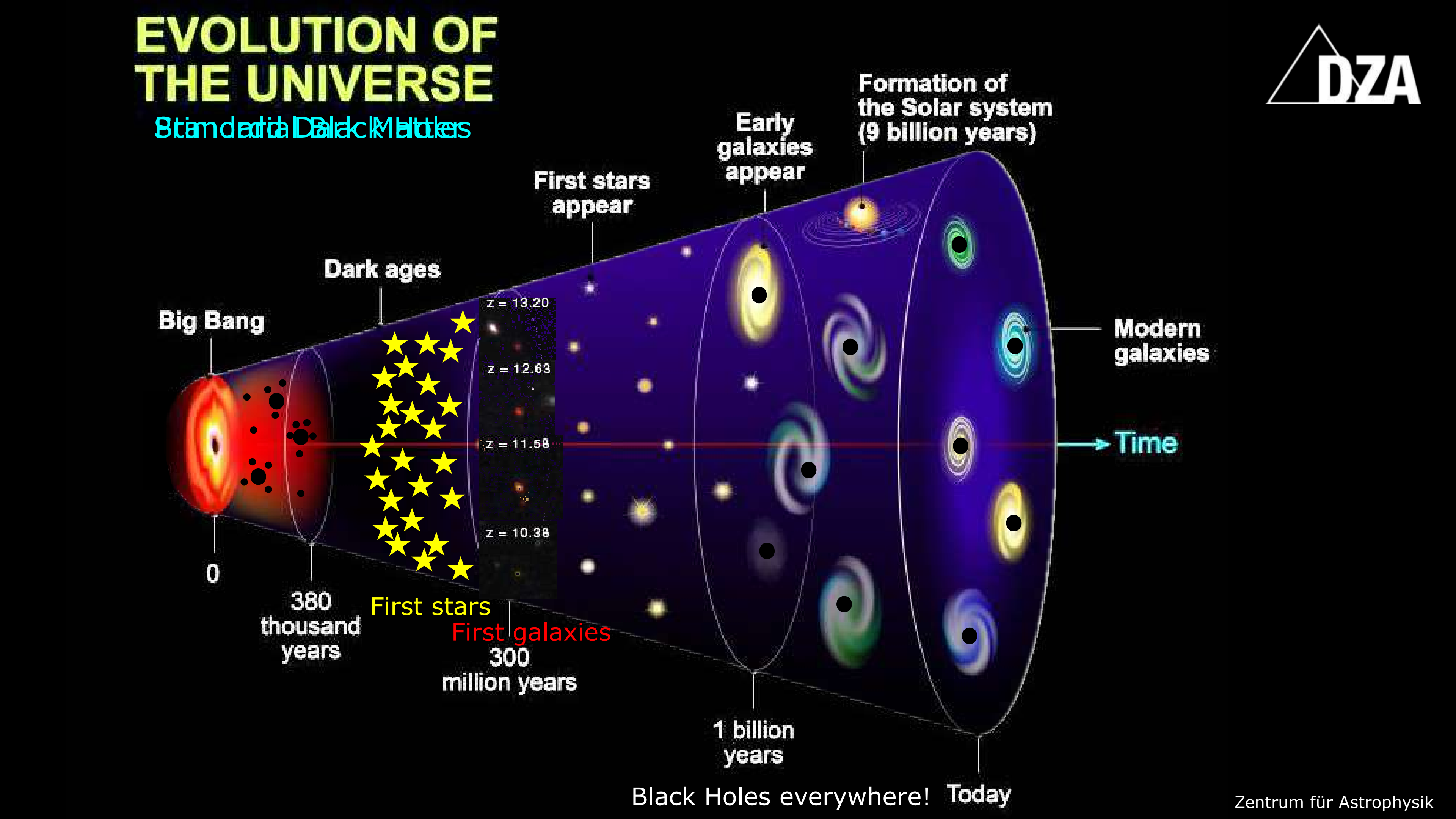
Cappelluti, Hasinger & Natarayan, ApJ 2021



Vitral, E. et al., 2022, MNRAS: Clusters of ~1000 compact objects (WD?, BH?, PBH?) detected in Globular Clusters NGC 3201 and NGC 6397 with GAIA and HST.



Refinement of the Cappelluti, Hasinger & Natarajan 2023 scznario by Zhang, Liu & Bromm 2024.

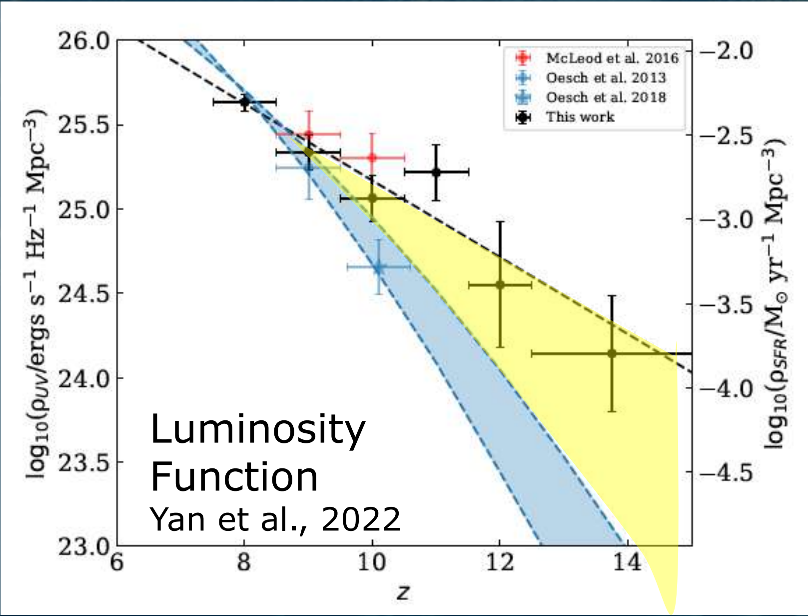


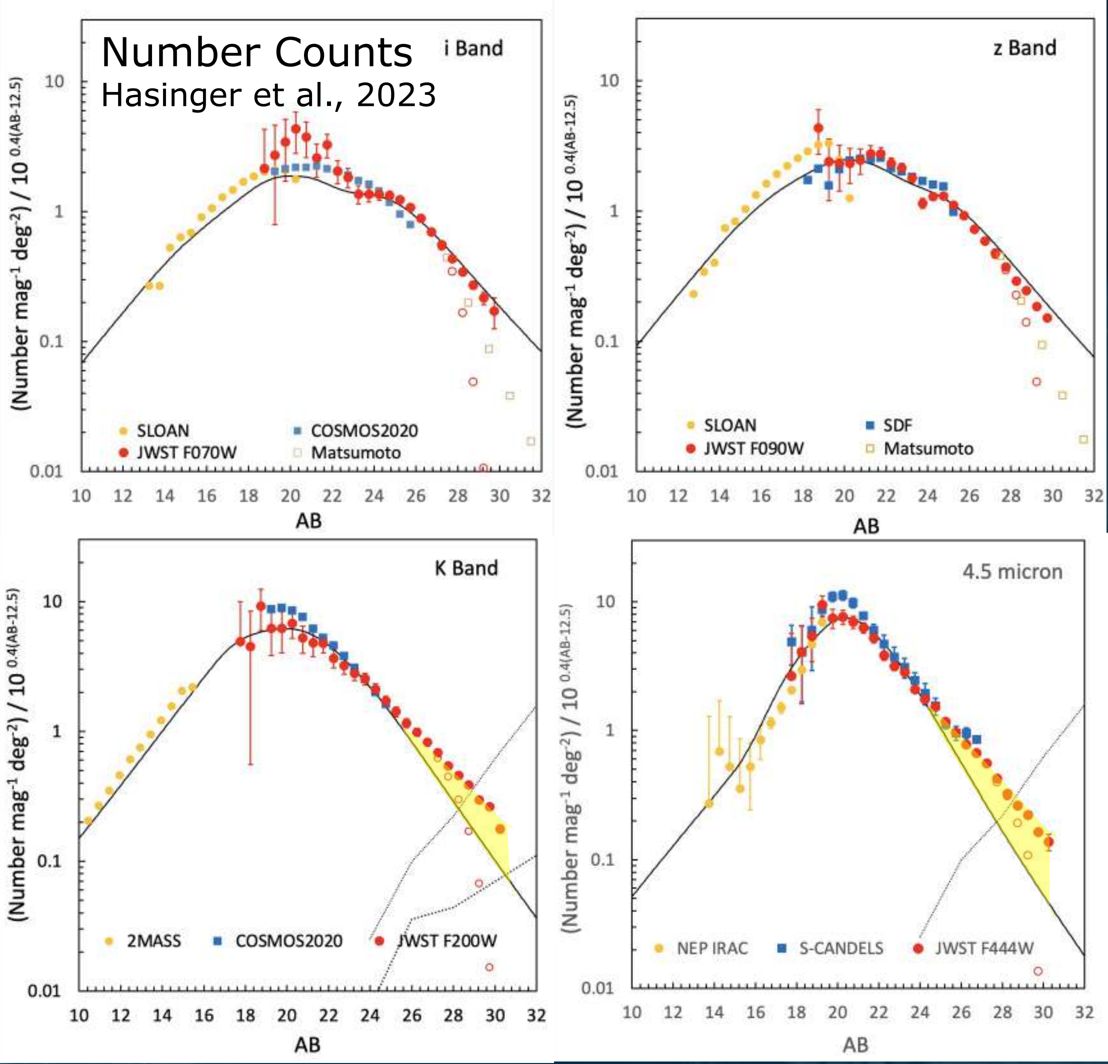
EVOLUTION OF THE UNIVERSE
DZA
Big Bang
Dark ages
First stars appear
Early galaxies appear
Formation of the Solar system (9 billion years)
Modern galaxies
Time
z = 13.20
z = 12.63
z = 11.58
z = 10.38
0
380 thousand years
First stars
First galaxies
300 million years
1 billion years
Today
Black Holes everywhere!
Zentrum für Astrophysik

Number of Galaxies
in JWST Medium-Deep Fields

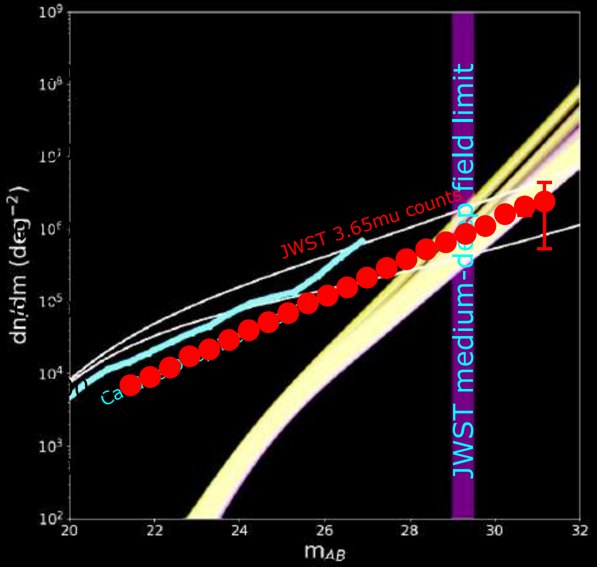
First hints for a new population of early galaxies.

This has been predicted by the primordial black hole dark matter model!

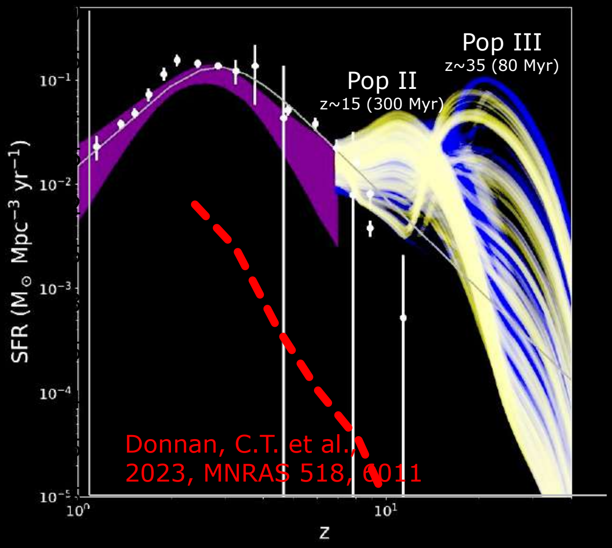




Faint JWST Galaxy Counts



Star Formation History

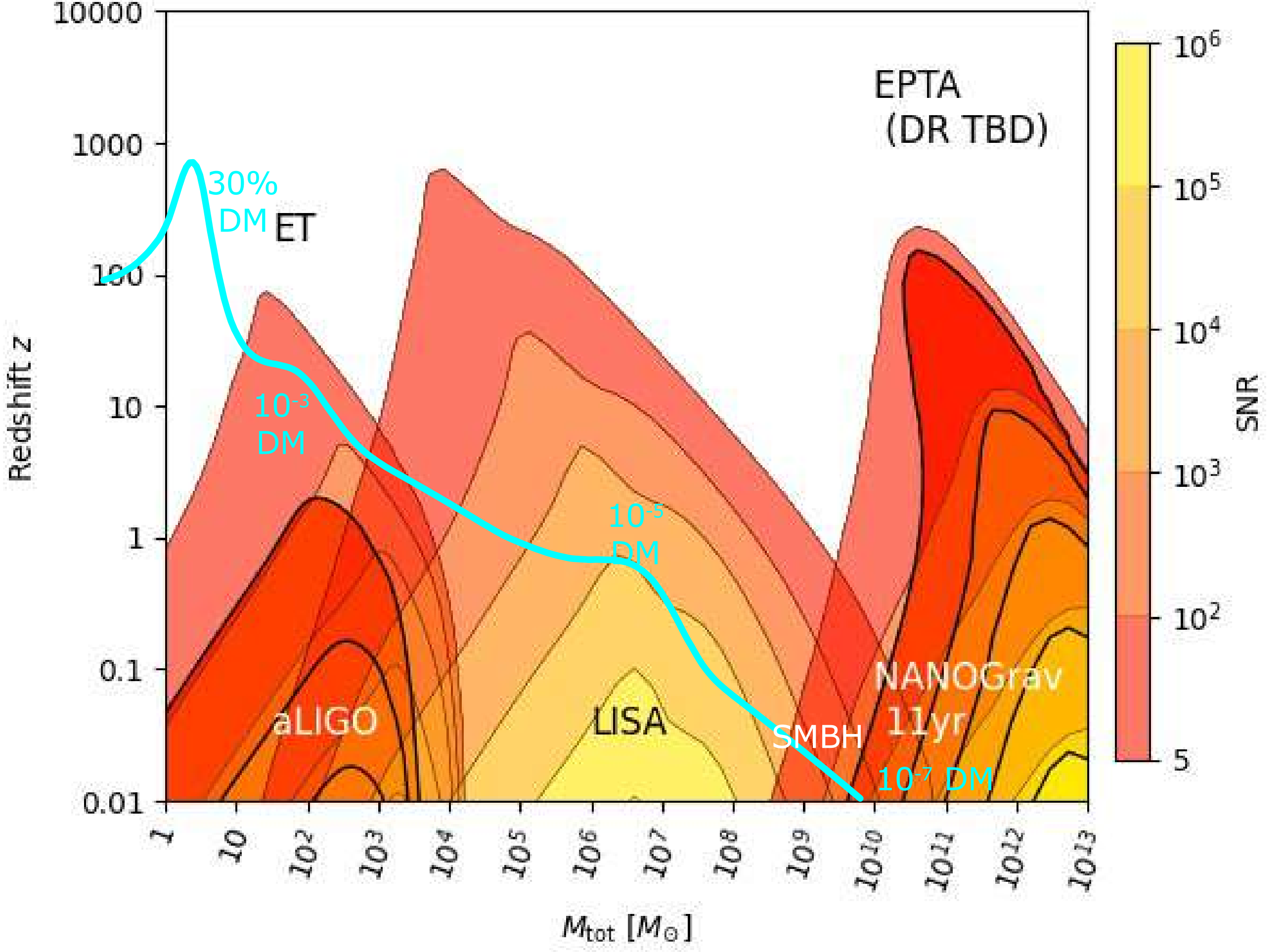


Cappelluti, Hasinger, Natarajan, Hasinger, 2022

So far, all of these "fingerprints" are tantalizing, but only circumstantial evidence.

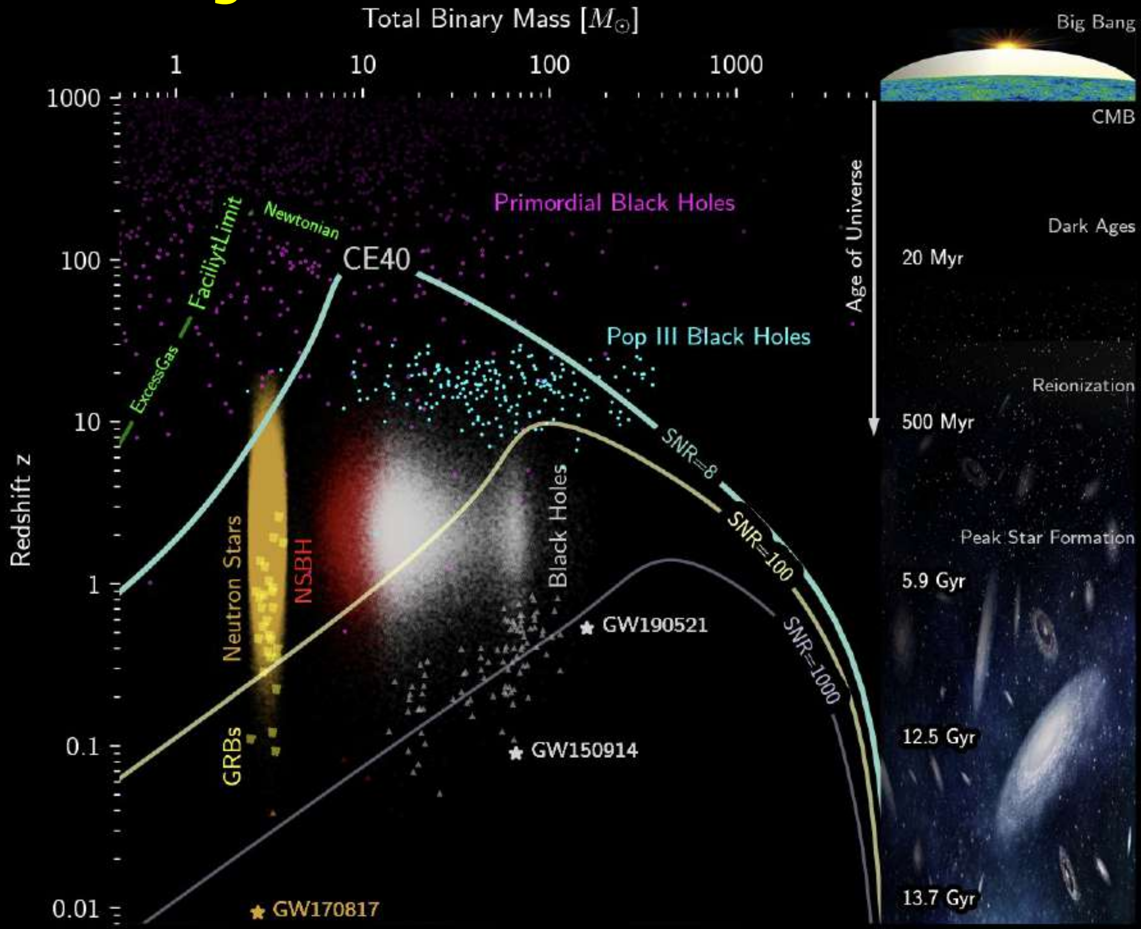
However, future Gravitational Wave observations can uniquely discriminate between astrophysical and primordial black holes!

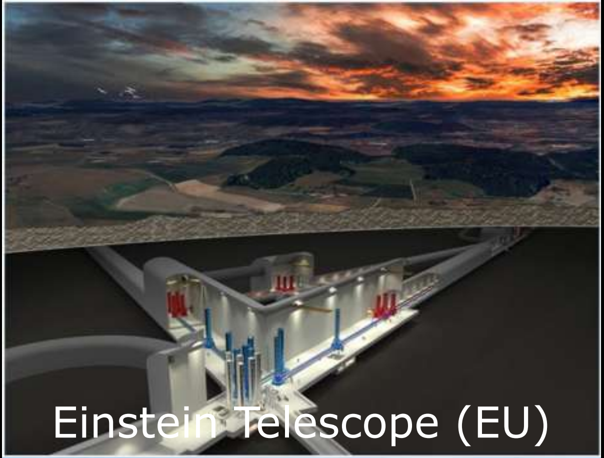
Sensitivity to BH-BH Mergers

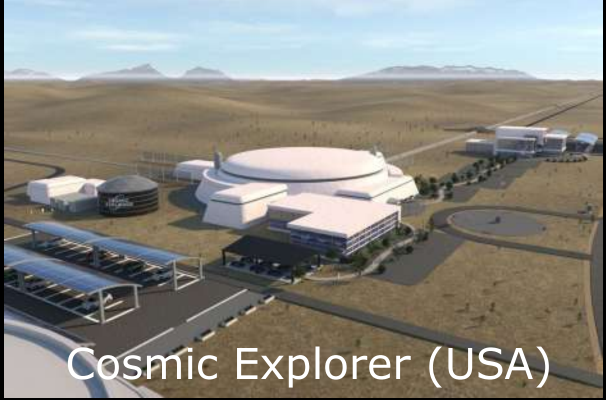


Sensitivity of the next generation groundbased gravitational wave interferometers

DZA







Thank you very much!