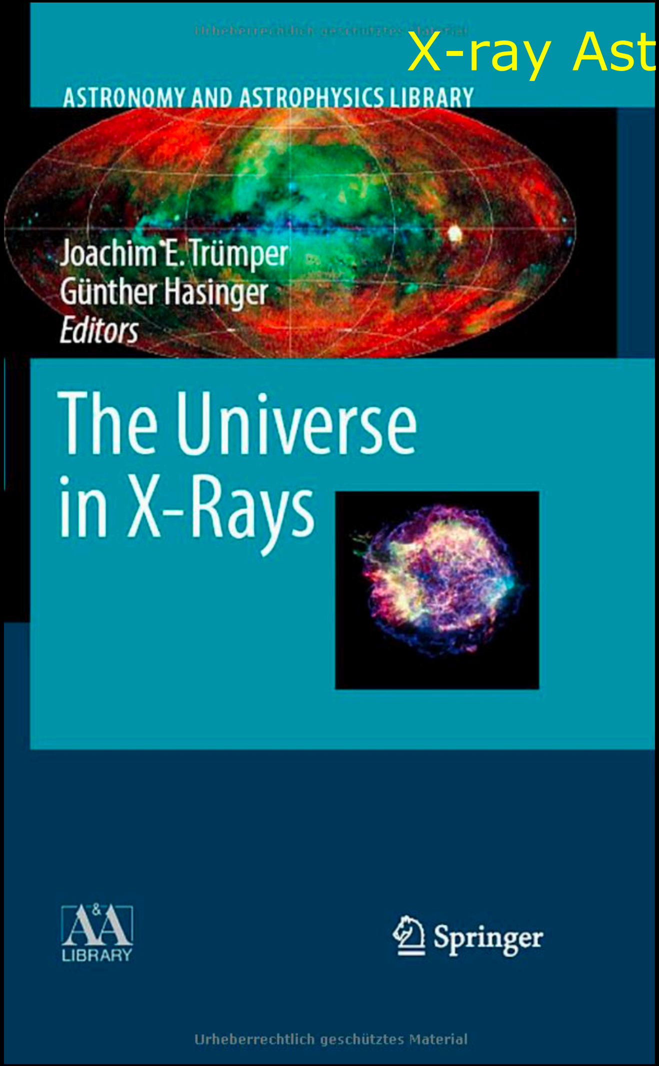
Illuminating the Dark Ages: cosmic backgrounds from accretion onto primordial black hole dark matter

Günther Hasinger, ESA Director of Science

Concluding talk of the Caltech X-ray Club, Pasadena (virtual)
March 12, 2020

https://iopscience.iop.org/article/10.1088/1475-7516/2020/07/022

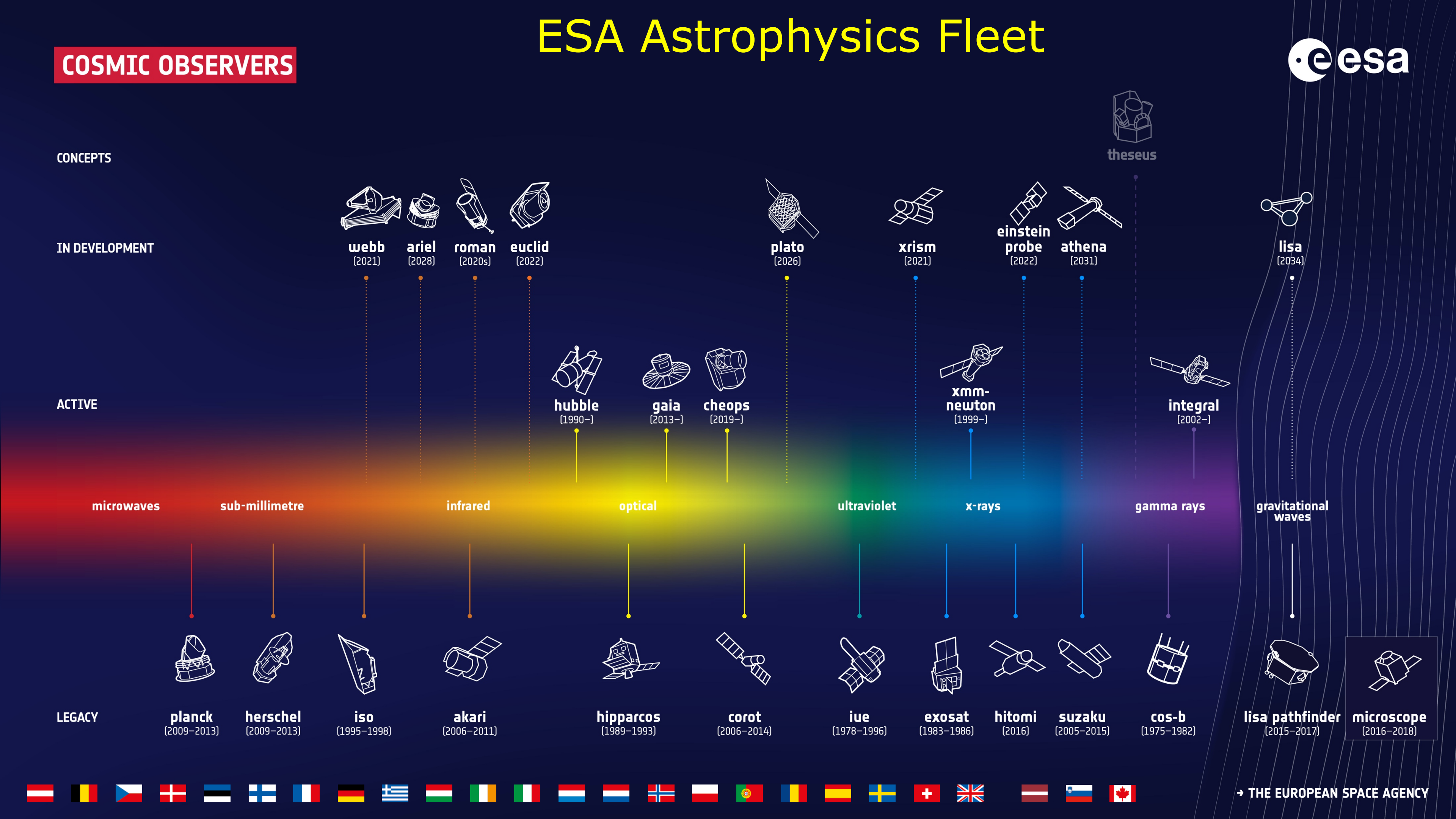
X-ray Astronomy Overview Status 2006



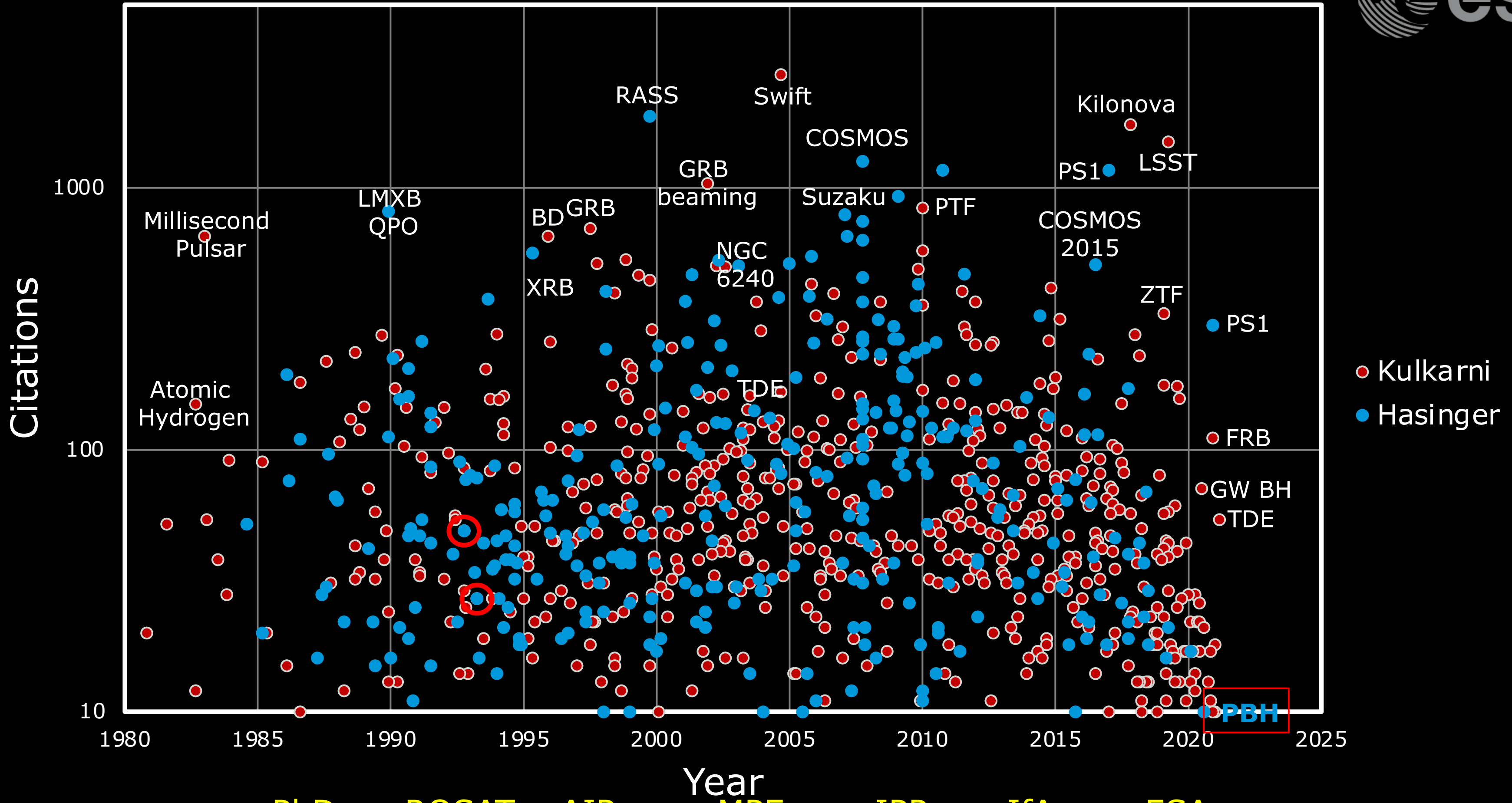
Missions		Period	Lead country/ institution
Ariel V	The fifth Ariel Satellite	1974–1980	United Kingdom
ANS	Astronomische Nederlandse Satelliet	1974–1976	The Netherlands
ASCA	The Advanced Satellite for Cosmology and Astrophysics	1993–2001	Japan
BeppoSAX	Satellite per Astronomia X (SAX)	1996–2002	Italy
CGRO	Compton Gamma Ray Observatory	1991–2000	NASA
Chandra	Short for Chandrasekhar (AXAF, CXO)	1999–	NASA
COBE	Cosmic Background Explorer	1989–1993	NASA
Copernicus	The Copernicus Satellite (OAO-3)	1972–1991	NASA
Einstein	Einstein Observatory (HEAO-2)	1978–1981	NASA
EUVE	Extreme Ultraviolett Explorer	1992–2001	NASA
EXOSAT	European X-ray Observatory Satellite	1983–1986	ESA
Ginga	Japanese for Galaxy	1987–1991	Japan
Granat		1988–1998	USSR/Russia
HEAO-1	High Energy Astrophysics Observatory 1	1977–1979	NASA
HETE-2	High Energy Transient Explorer	2000–2008	NASA
INTEGRAL	International Gamma-Ray Astrophysics Laboratory	2002–	ESA
ROSAT	Roentgen Satellite	1990–1999	Germany
RXTE	Rossi X-Ray Timing Explorer	1995–2012	NASA
SAS-3	The Third Small Astronomy Satellite	1975–1979	NASA
Suzaku	Japanese for Zhū Què (Astro-E2)	2005–2015	Japan
Swift		2004–	NASA
Tenma	Japanese for Pegasus	1983–1985	Japan
Uhuru	Swahili for freedom	1970–1973	NASA
XMM-Newton	(=XMM X-ray Multi-Mirror Mission)	1999–	ESA
Yohkoh	Japanese for sunbeam	1991–2001	Japan

>2006
Fermi (2008-18)
NuSTAR (2012)
ASTROSAT (2015)
HITOMI (2016-16)
NICER (2017)
SRG (2019)

Future
IXPE (2021)
XRISM (2022)
Einstein Probe (2022)
eXTP (2027?)
Athena (2032)


ESA Astrophysics Fleet
COSMIC OBSERVERS
esa
CONCEPTS
theseus
IN DEVELOPMENT
webb (2021)
ariel (2028)
roman (2020s)
euclid (2022)
plato (2026)
xrism (2021)
einstein probe (2022)
athena (2031)
lisa (2034)
ACTIVE
hubble (1990–)
gaia (2013–)
cheops (2019–)
xmm-newton (1999–)
integral (2002–)
microwaves
sub-millimetre
infrared
optical
ultraviolet
x-rays
gamma rays
gravitational waves
LEGACY
planck (2009–2013)
herschel (2009–2013)
iso (1995–1998)
akari (2006–2011)
hipparcos (1989–1993)
corot (2006–2014)
iue (1978–1996)
exosat (1983–1986)
hitomi (2016)
suzaku (2005–2015)
cos-b (1975–1982)
lisa pathfinder (2015–2017)
microscope (2016–2018)
→ THE EUROPEAN SPACE AGENCY

Shri’s and Günther’s scientific careers

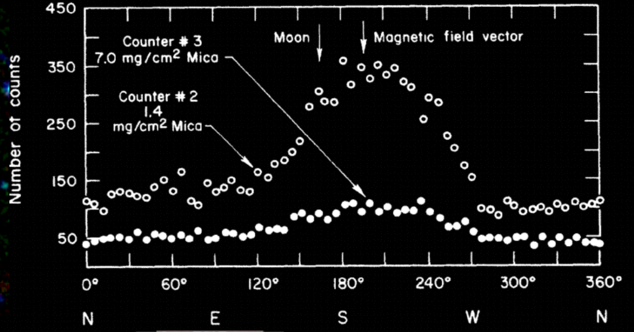


PhD ROSAT AIP MPE IPP IfA ESA

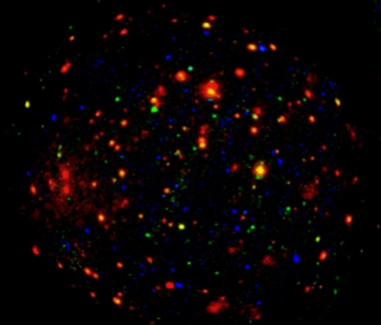
The X-ray background


ROSAT 1998

Giacconi 1962



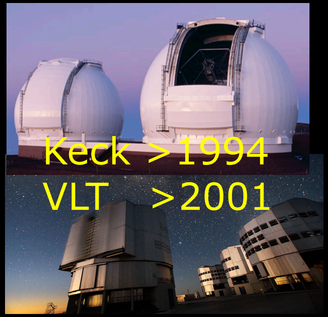

ROSAT 1991


XMM-Newton 2012

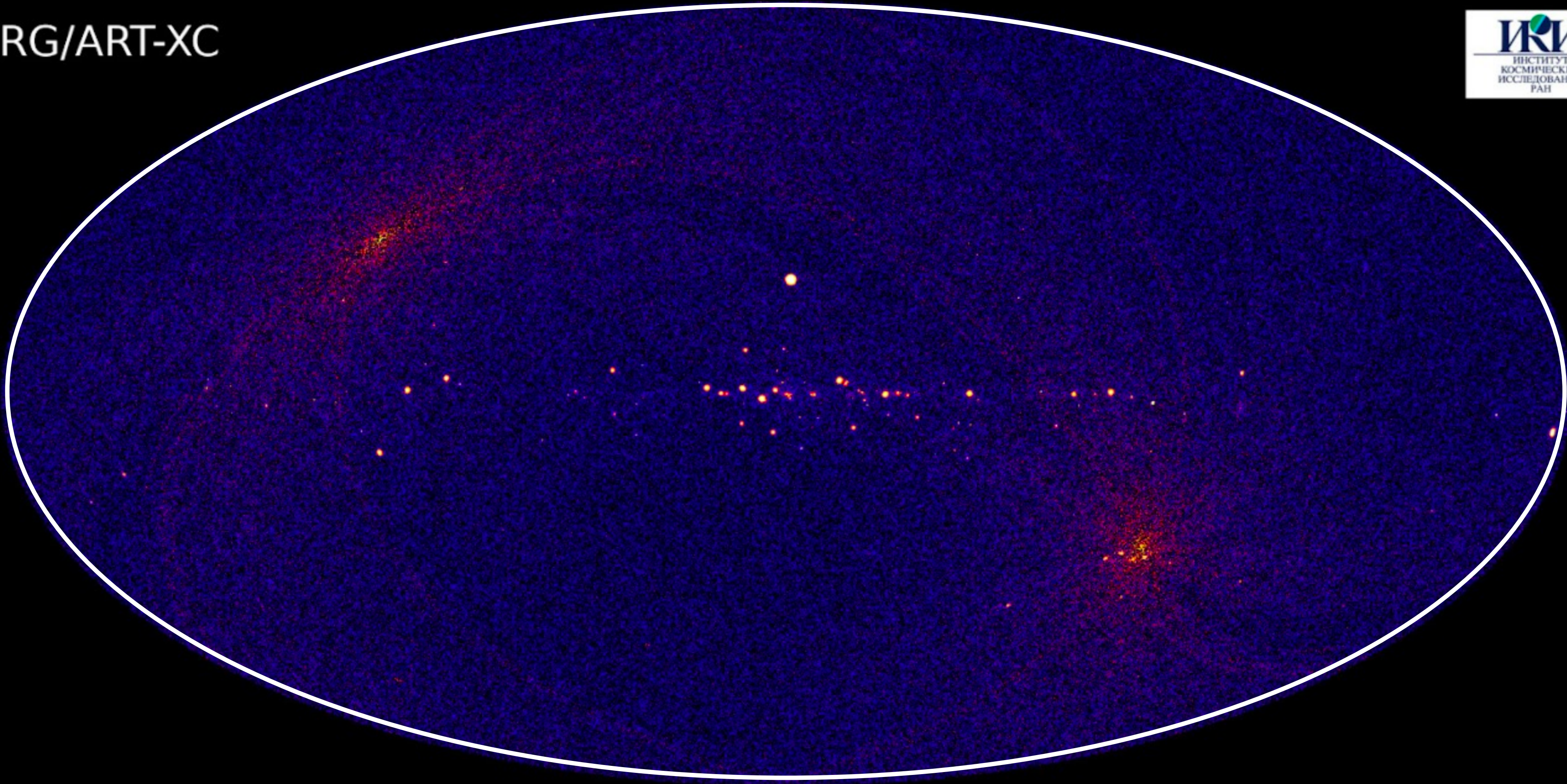

Chandra 2011


The background is the echo of black hole formation and growth over cosmic time.

ROSAT 1998

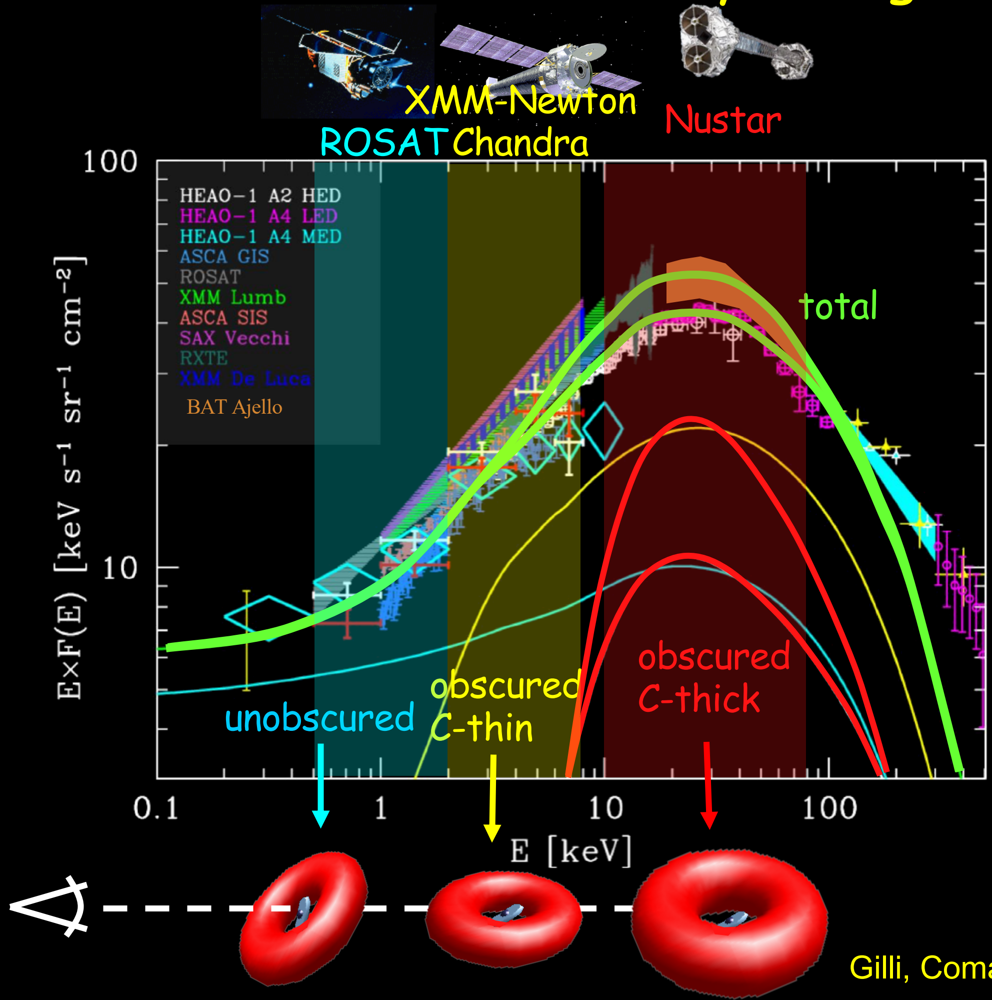

Keck >1994
VLT >2001

SRG/ART-XC



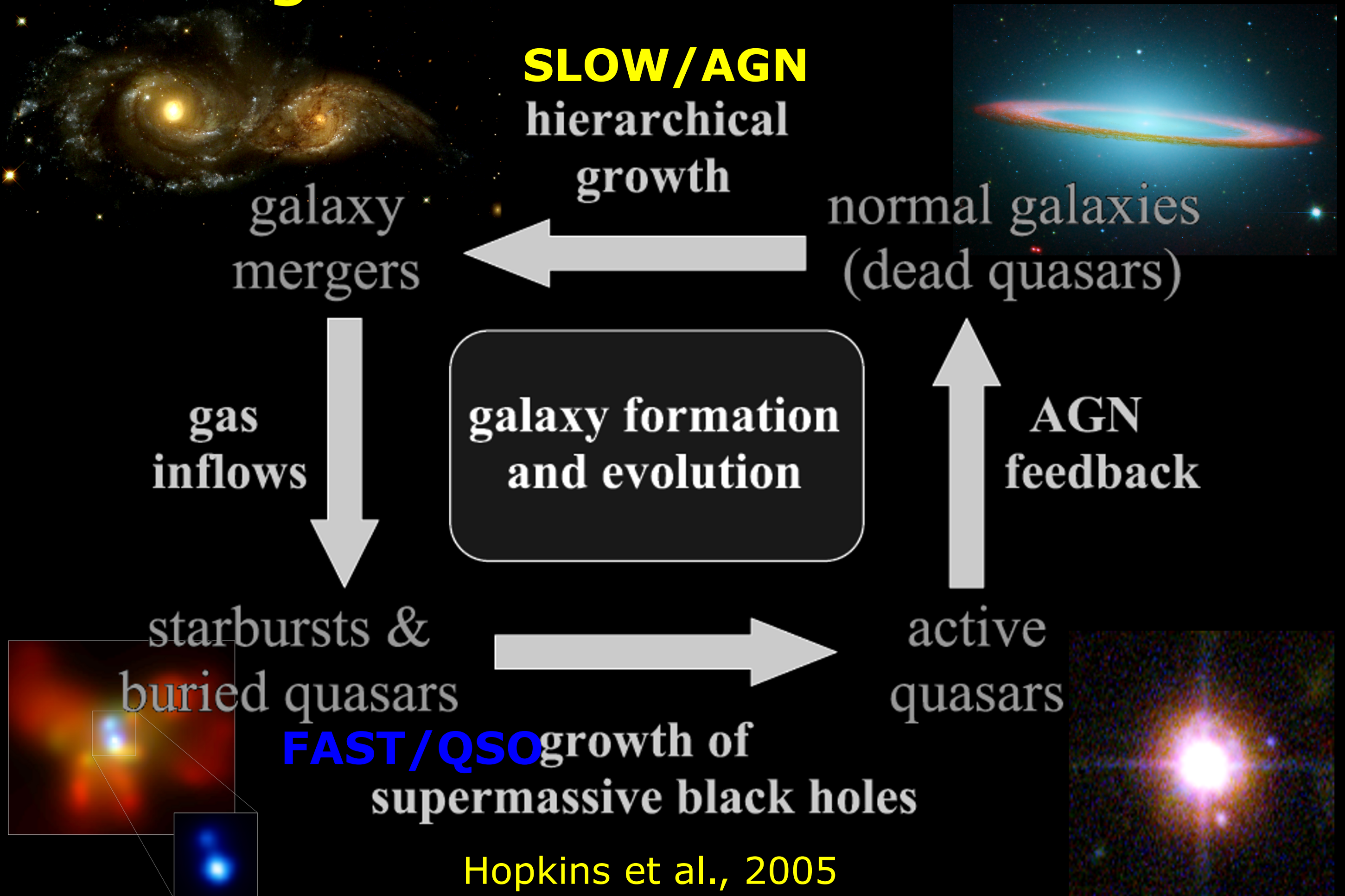
ИКИ
ИНСТИТУТ
КОСМИЧЕСКИХ
ИССЛЕДОВАНИЙ
РАН

AGNs and the cosmic X-ray background



Gilli, Comastri & G.H., 2007

Merger & Accretion Evolution



Hopkins et al., 2005

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

Black Holes of various sizes

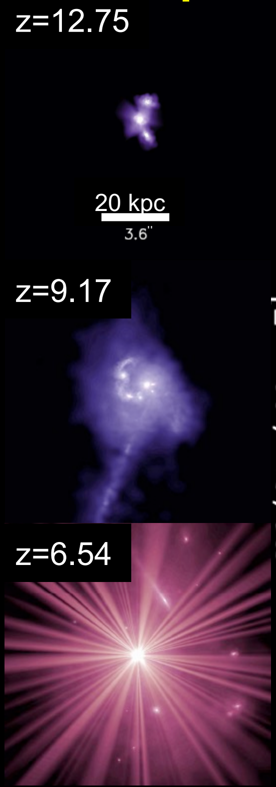
May I introduce to you:

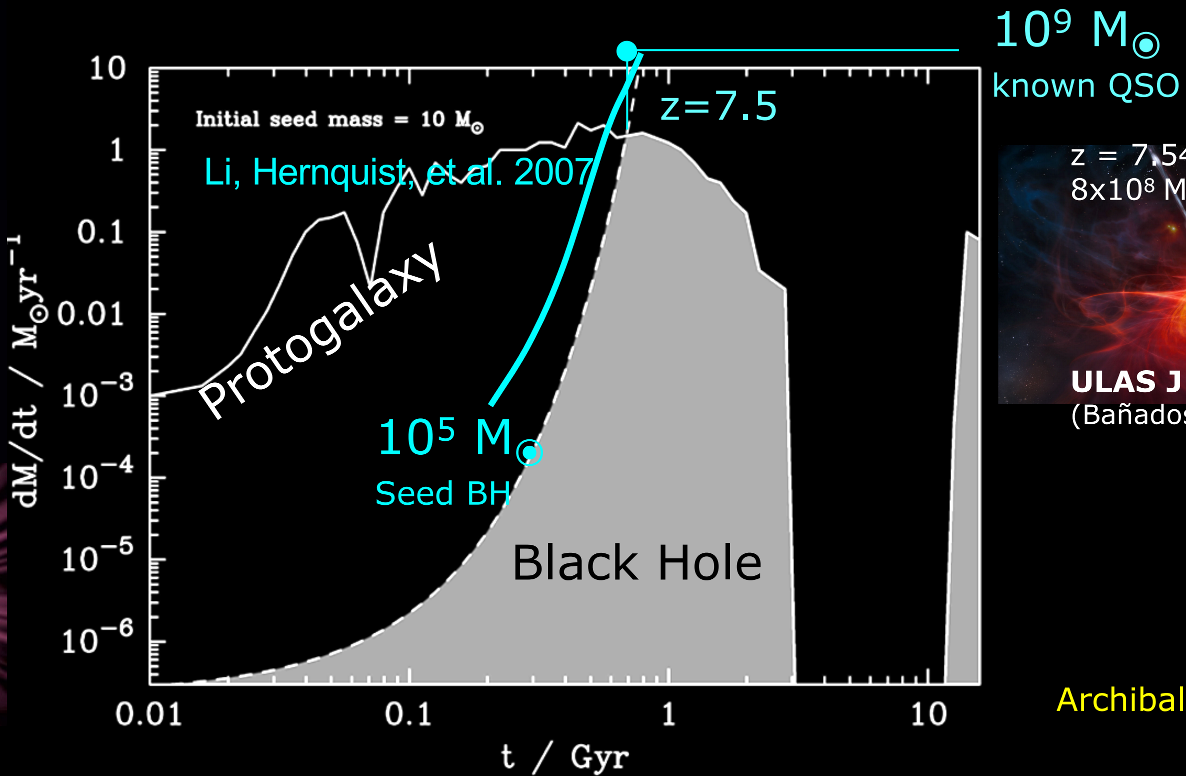
$3 \times 10^9 \, M_\odot$

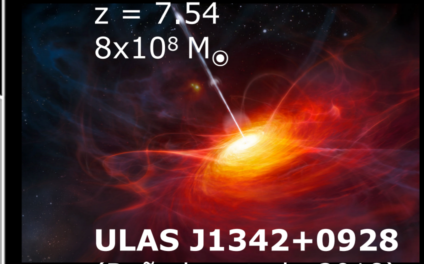
Pōwehi

"*the adorned fathomless dark creation*"
from the Hawaiian generation chant *Kumulipo.*
Courtesy of the Event Horizon Telescope Collaboration.

How to produce the first proto-quasars







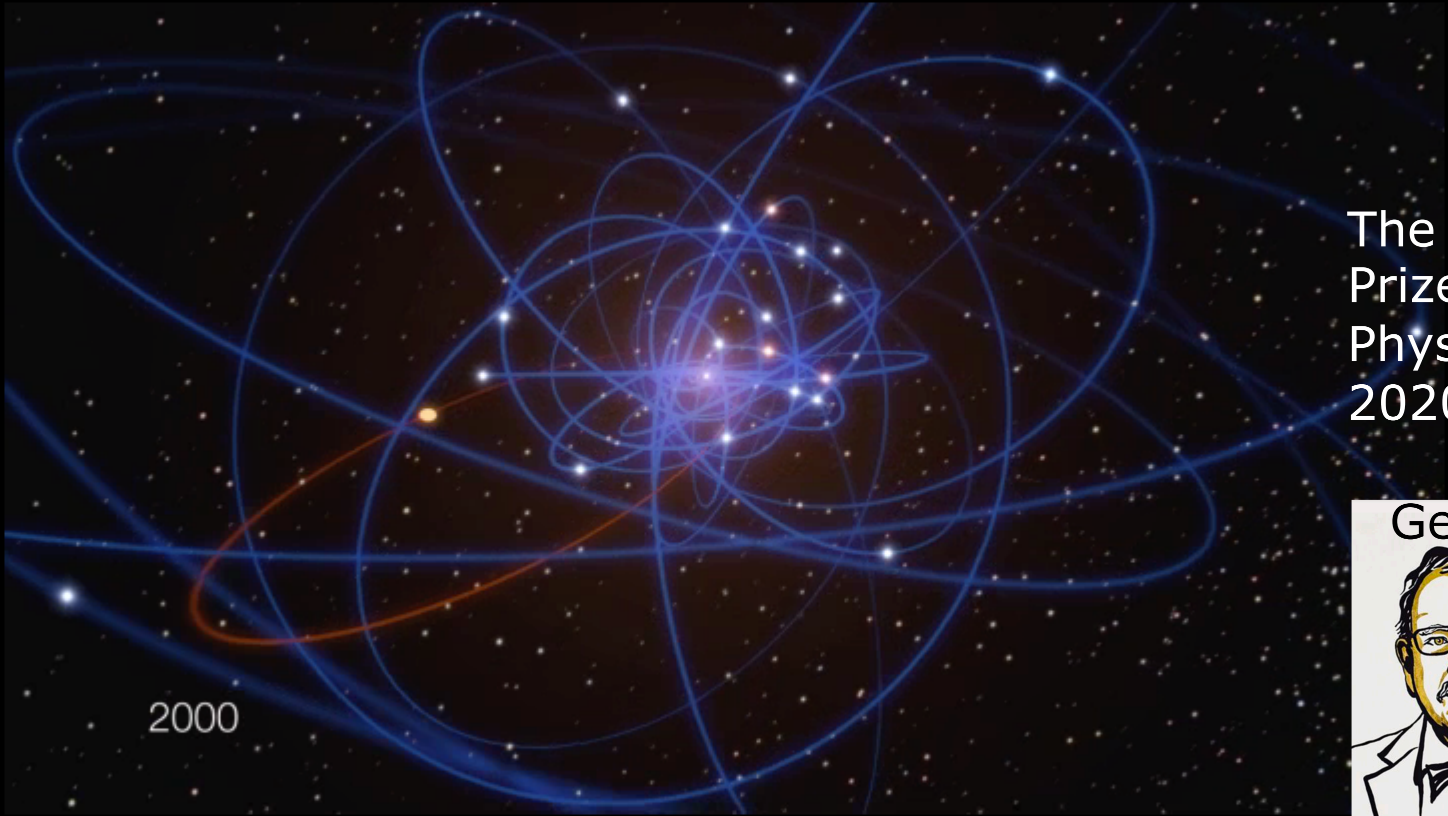
(Bañados et al., 2018)

Archibald et al., 2001

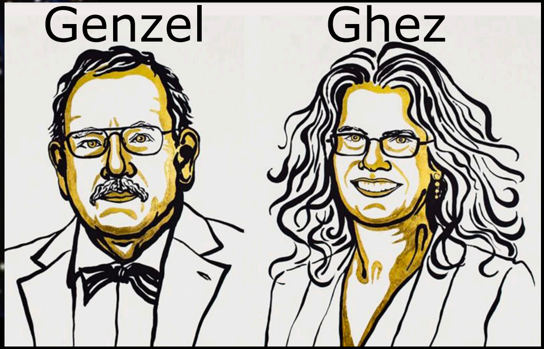
Need massive seed Black Holes early in the Universe !

The Galactic Center Black Hole (Genzel version)

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

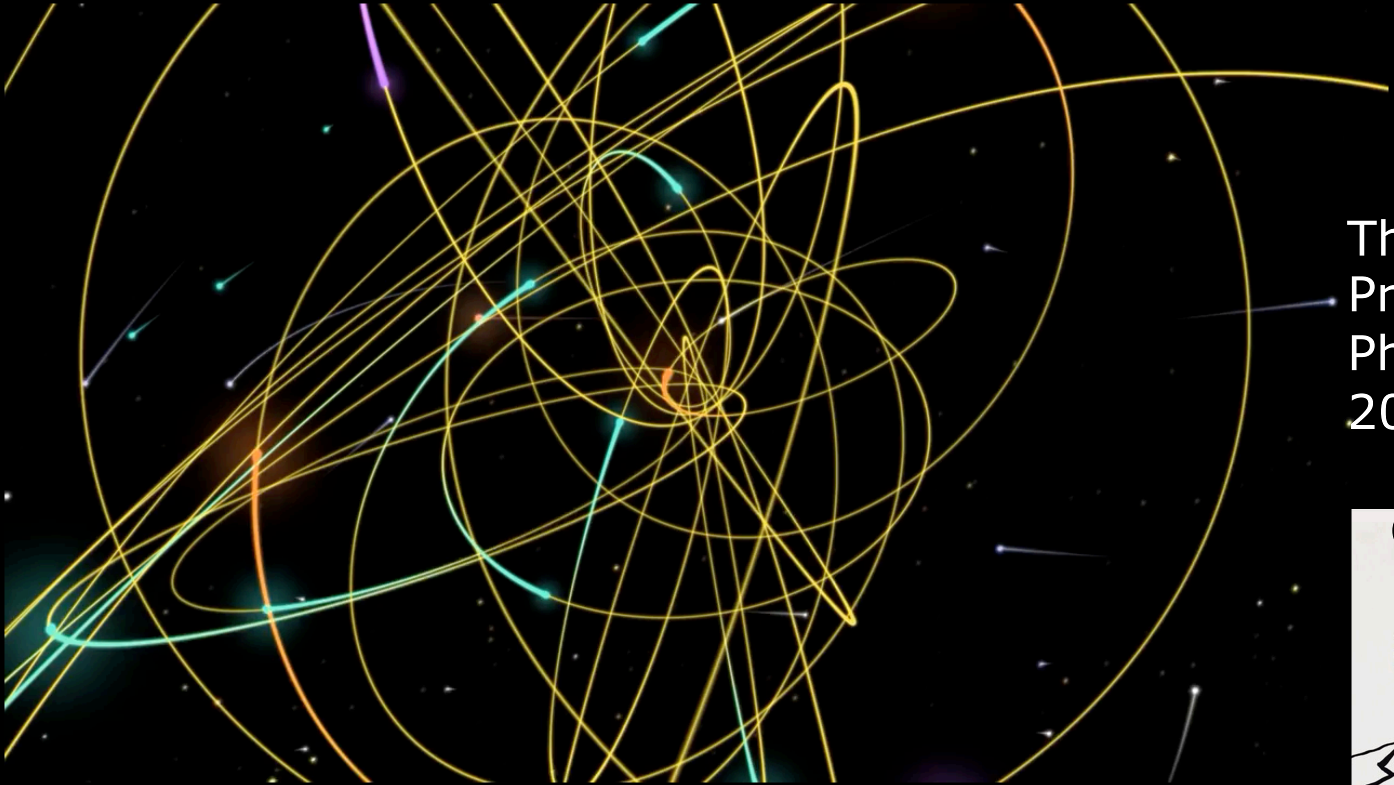


The Nobel Prize in Physics 2020

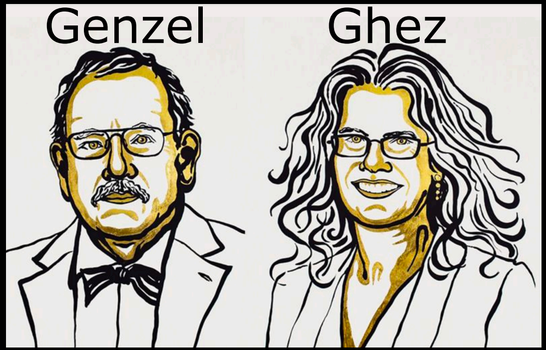


The Galactic Center Black Hole (Ghez version)

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

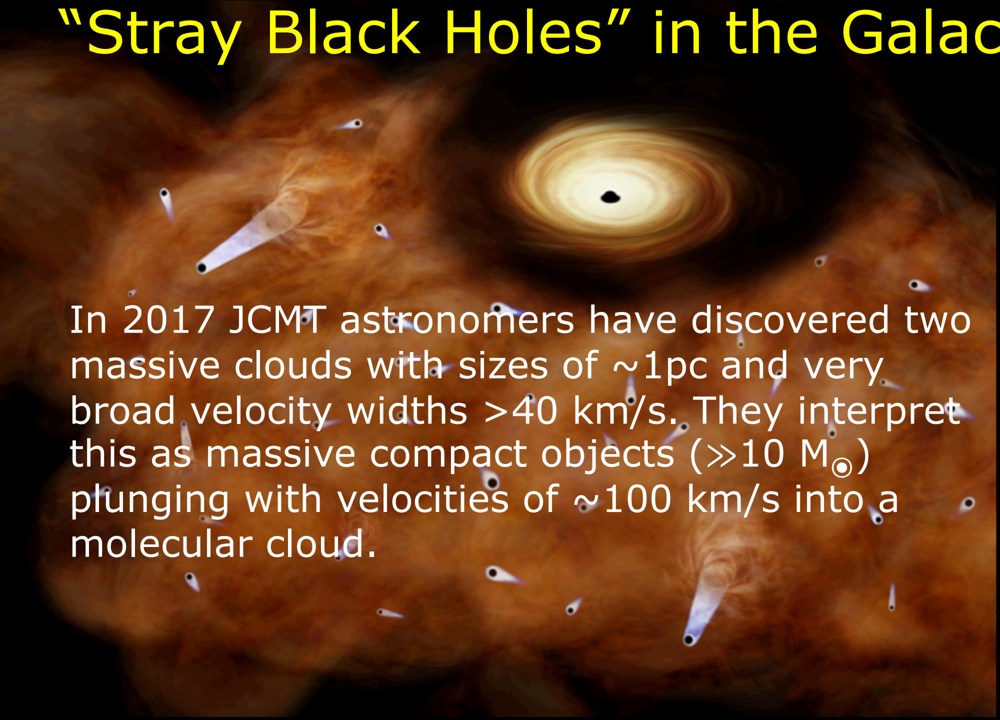


The Nobel Prize in Physics 2020

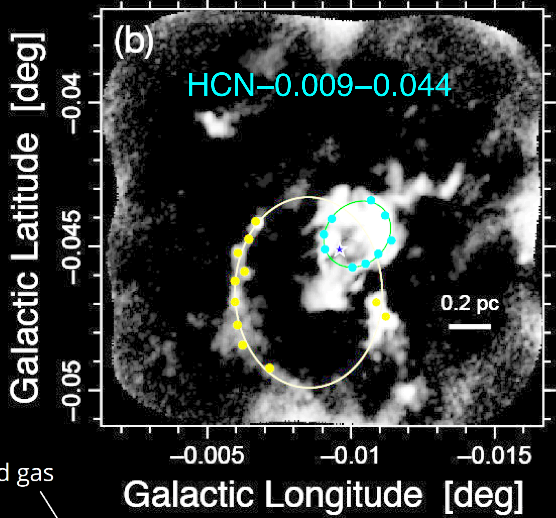


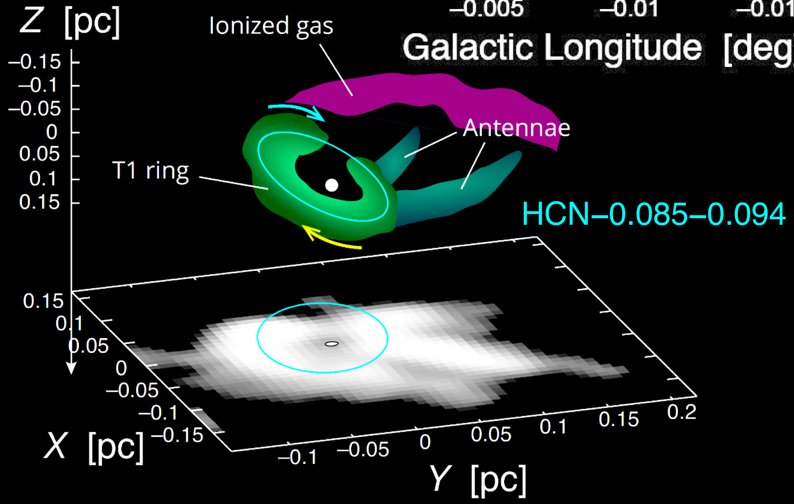
"Stray Black Holes" in the Galactic Center

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



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 ($\gg 10\ M_{\odot}$) plunging with velocities of ~100 km/s into a molecular cloud.



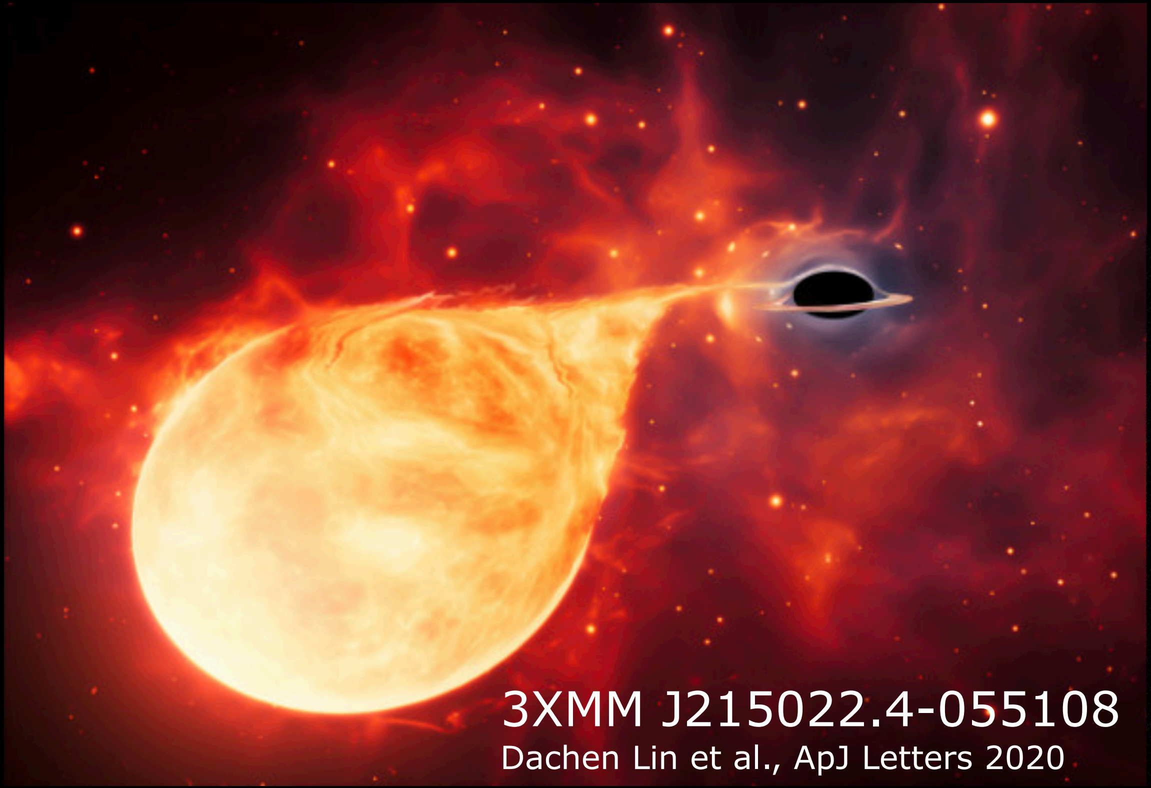


A total of 5 Intermediate-Mass Black Holes ($10^{4\text{-}5}\ M_{\odot}$) have now been identified in the Central Molecular Zone from high angular resolution ALMA and radio data.

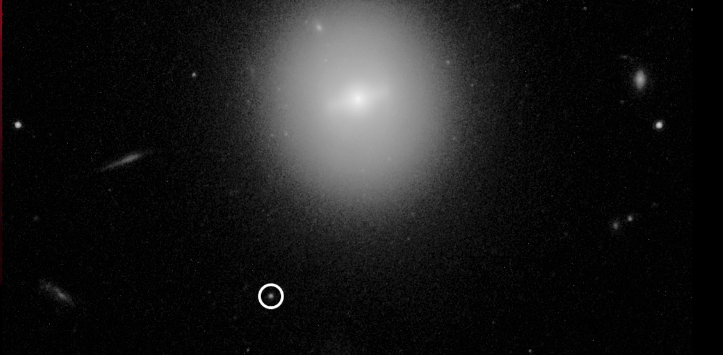
Takekawa et al., 2017, 2019, 2020

Hubble finds best evidence for extragalactic IMBH

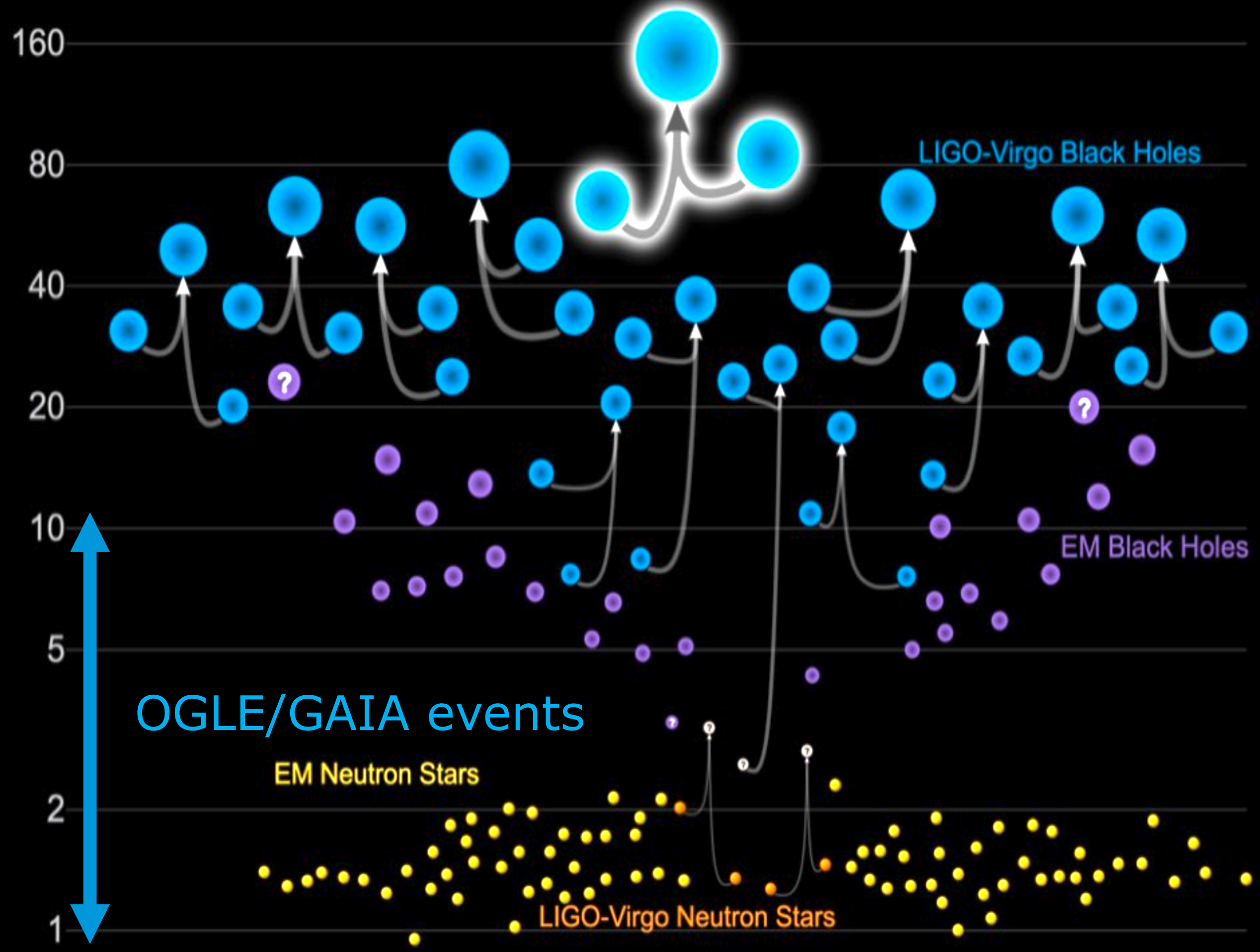
$5 \times 10^4\ M_\odot$



Following up the discovery of a tidal capture event by XMM-Newton and Chandra, new data from the NASA/ESA Hubble Space Telescope have provided the strongest evidence yet for mid-sized black holes in the Universe. Hubble confirms that this "intermediate-mass" black hole dwells inside a dense star cluster of a nearby galaxy.



$3\text{-}150\ M_{\odot}$



LIGO/Virgo BH mergers

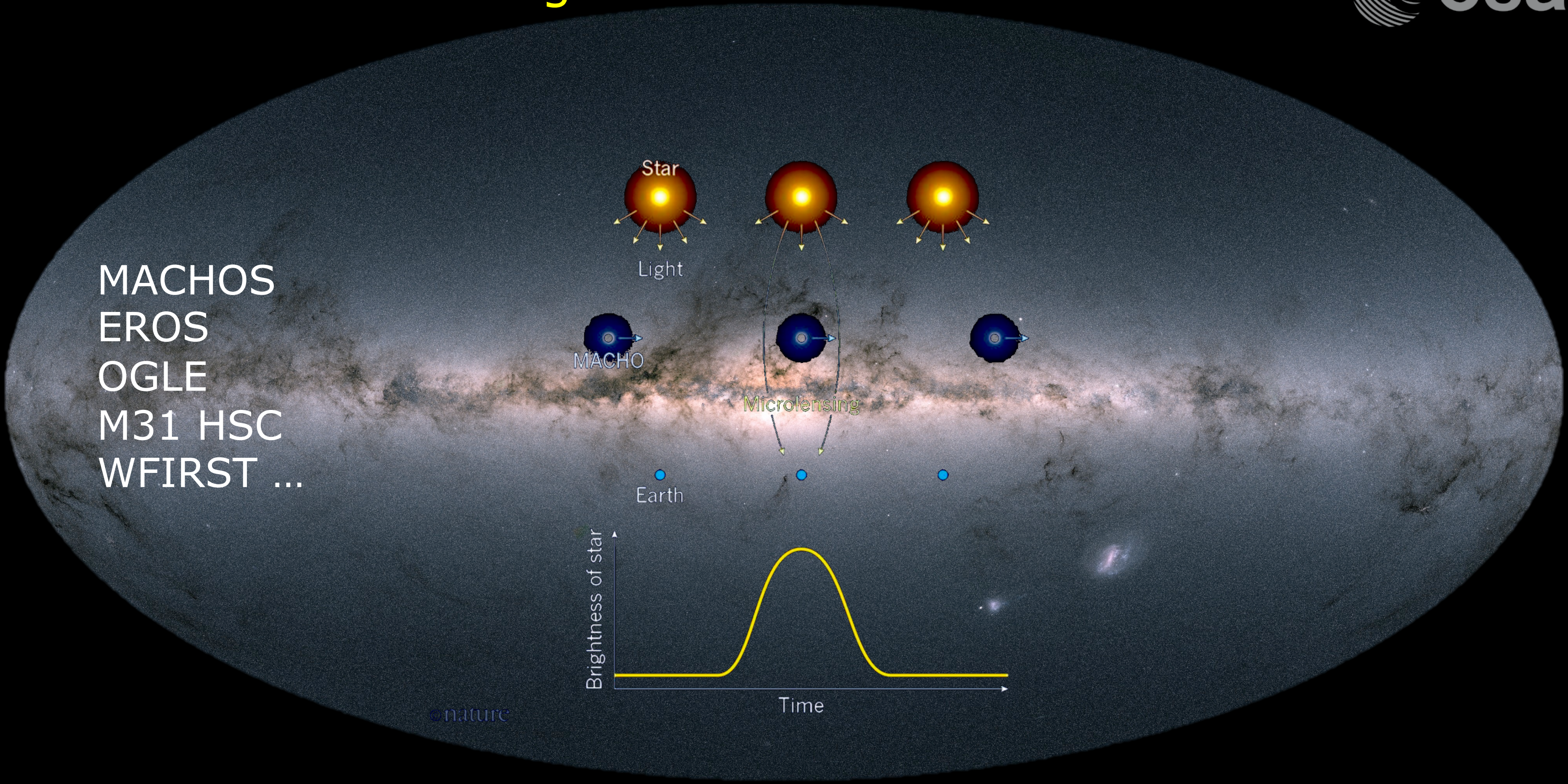
GW190521: Record BH Merger

GW190412: Mass-gap object

… the plot thickens!

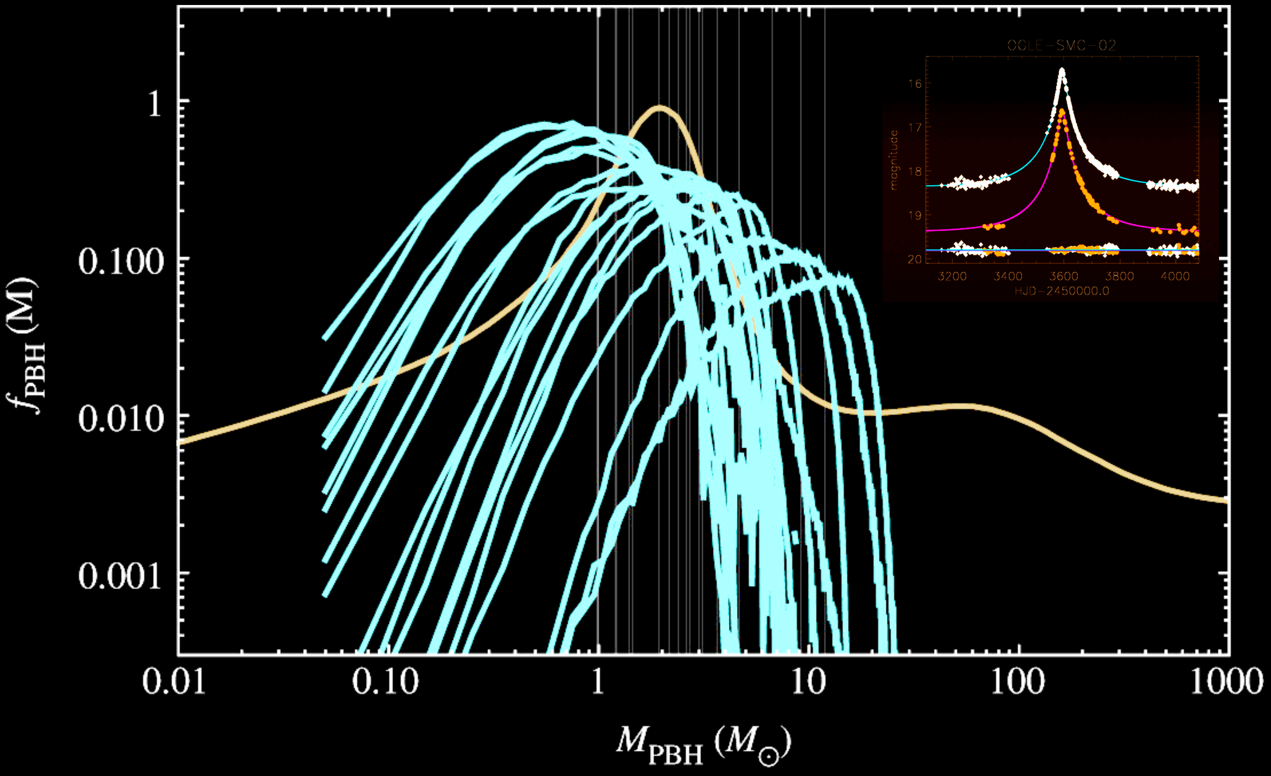
Microlensing and the ESA GAIA Mission

MACHOS
EROS
OGLE
M31 HSC
WFIRST ...



OGLE/GAIA Microlensing events

1-10 $M_\odot$



Wyrzykowski L, Mandel I., 2019; García-Bellido 2019

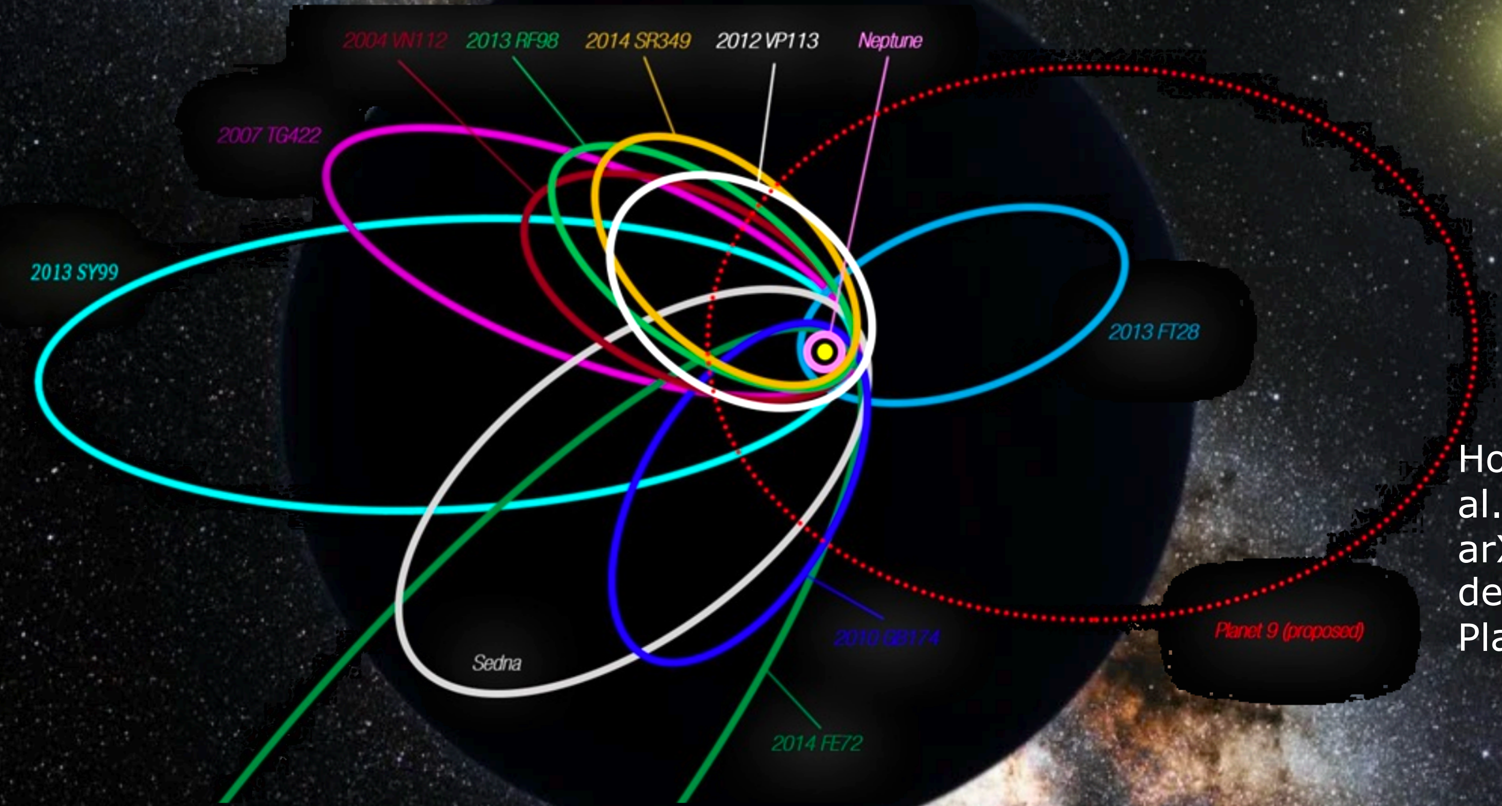
OGLE has detected ~60 long-duration microlensing events. ~20 of these have GAIA parallax distances of a few kpc, which break the mass–distance degeneracy of microlensing and allow the determination of masses in the few solar mass range, which imply that they are probably black holes, since stars at those distances would be visible by OGLE.

Their masses overlap the stellar BH mass gap, and are consistent with the predicted peak around 2 $M_\odot$ in the PBH mass distribution.

Scholtz & Unwin, 2019

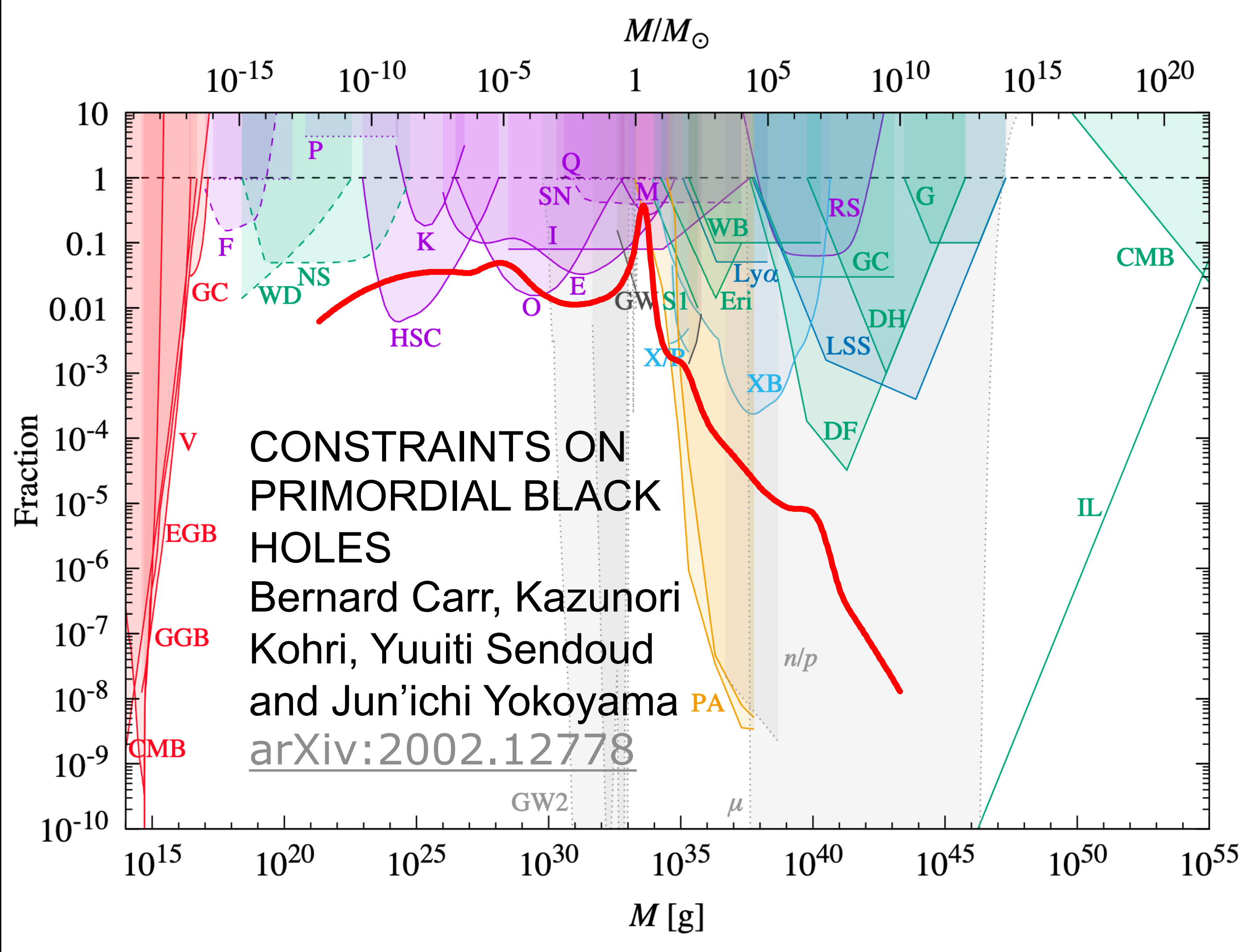
Is Planet 9 (Planet X) a Black Hole?

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



However, see Napier et al., 2021 arXiv:2102.05601v3 debunking the claim for Planet X!

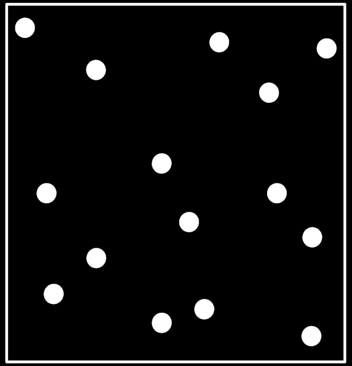
There are more indications for possible Planetary-mass Primordial BH



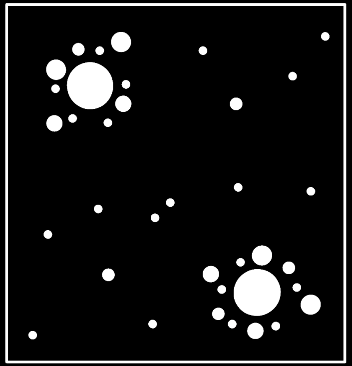
CONSTRAINTS ON PRIMORDIAL BLACK HOLES

Bernard Carr, Kazunori Kohri, Yuuiti Sendoud and Jun’ichi Yokoyama

arXiv:2002.12778



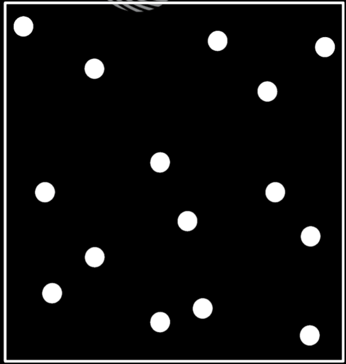
Uniform single mass PBH ruled out



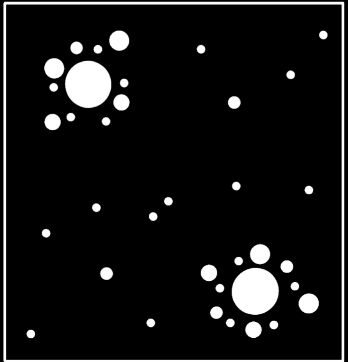
Clustered wide mass distribution feasible

Hubble finds Clumping of Dark Matter

Meneghetti et al, 2020, Science



Uniform single mass Dark Matter



Clustered wide mass distribution Dark Matter

A paper that threw me off my chair …

Primordial black holes and the origin of the matter–antimatter asymmetry

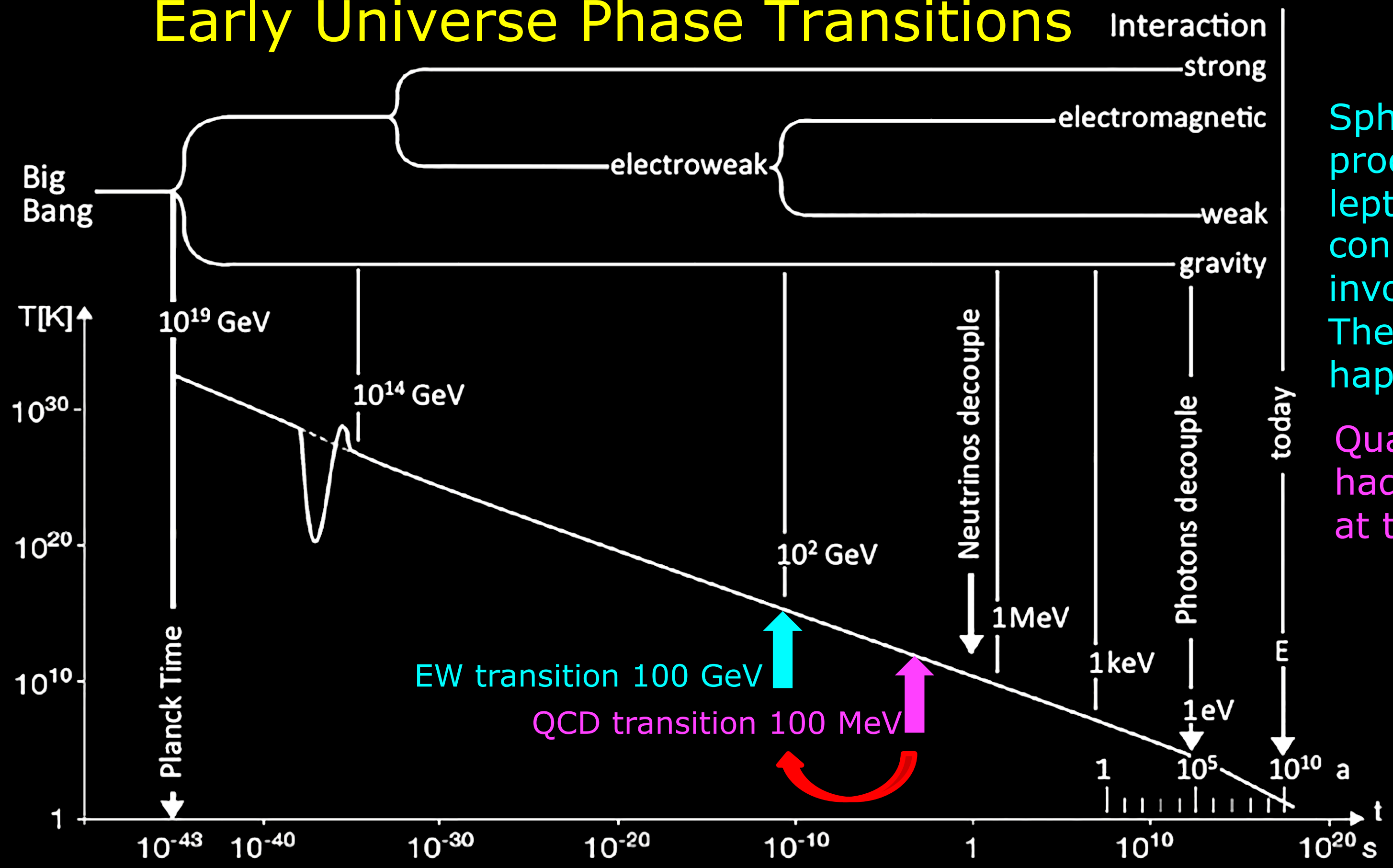
Juan García-Bellido

Phil. Trans. Roy. Soc. Volume: 377, Issue: 2161

Published: **11 November 2019** | https://doi.org/10.1098/rsta.2019.0091

Primordial Black Holes are created by large inflationary curvature fluctuations at the QCD phase transition, when pions, neutrons and protons are formed, as well as at the e^+e^- annihilation. The abrupt reduction of the sound velocity at each of these events exponentially enhances gravitational collapse, ejecting hadron jets and engaging "funny" physics (generating over-the-barrier electroweak sphaleron transitions responsible for Higgs windings around the EW vacuum or, through the chiral anomaly, baryon number generation) creating the matter-antimatter asymmetry. The preferred mass scale corresponds to the size of the horizon at the corresponding transition. Baryons correspond to the Chandrasekhar mass. The baryon/photon ratio of 10^{-9} is naturally explained.

Early Universe Phase Transitions

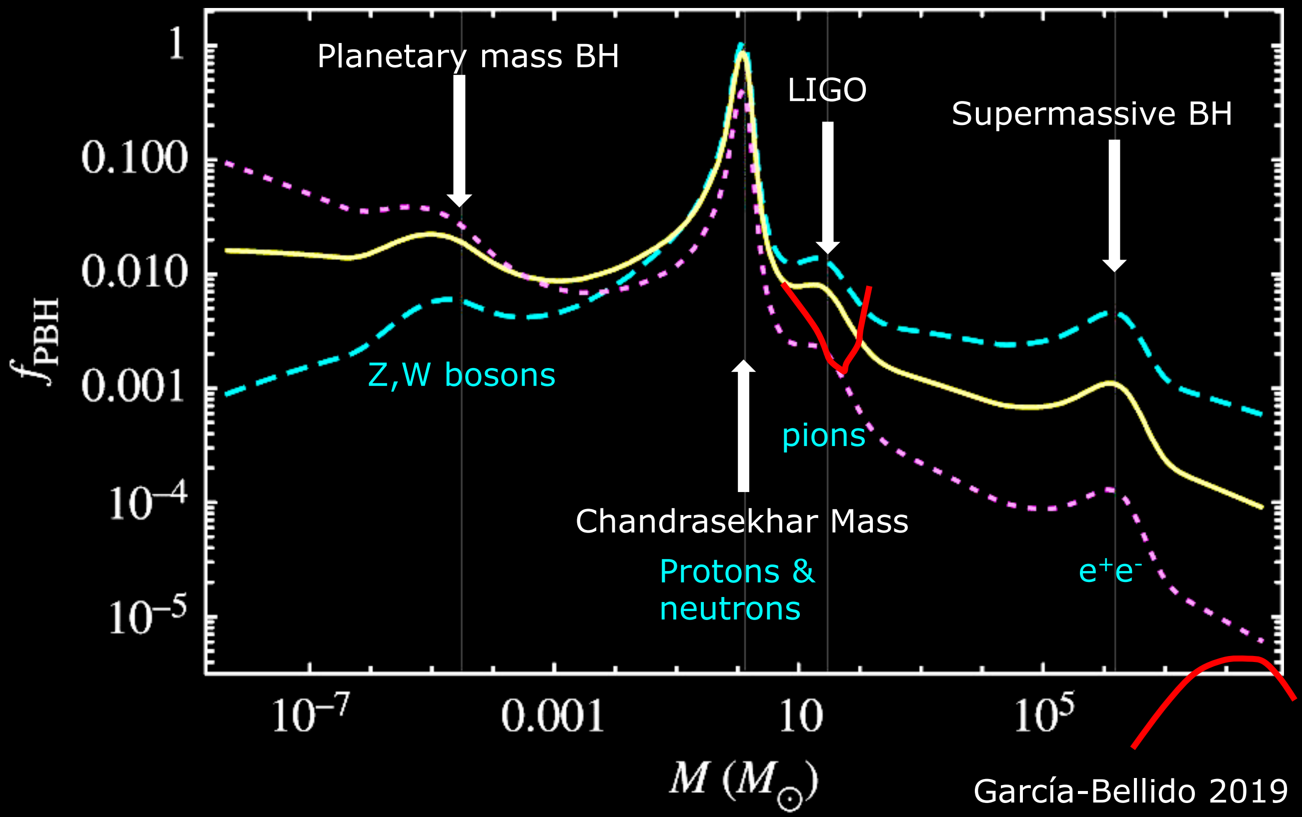


Sphaleron transitions are processes violating the lepton and baryon number conservation and are invoked for baryogenesis. They are expected to happen at the EW scale.

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

PBH collapse locally re-heats hot spots to the EW scale

PBH Mass Spectrum

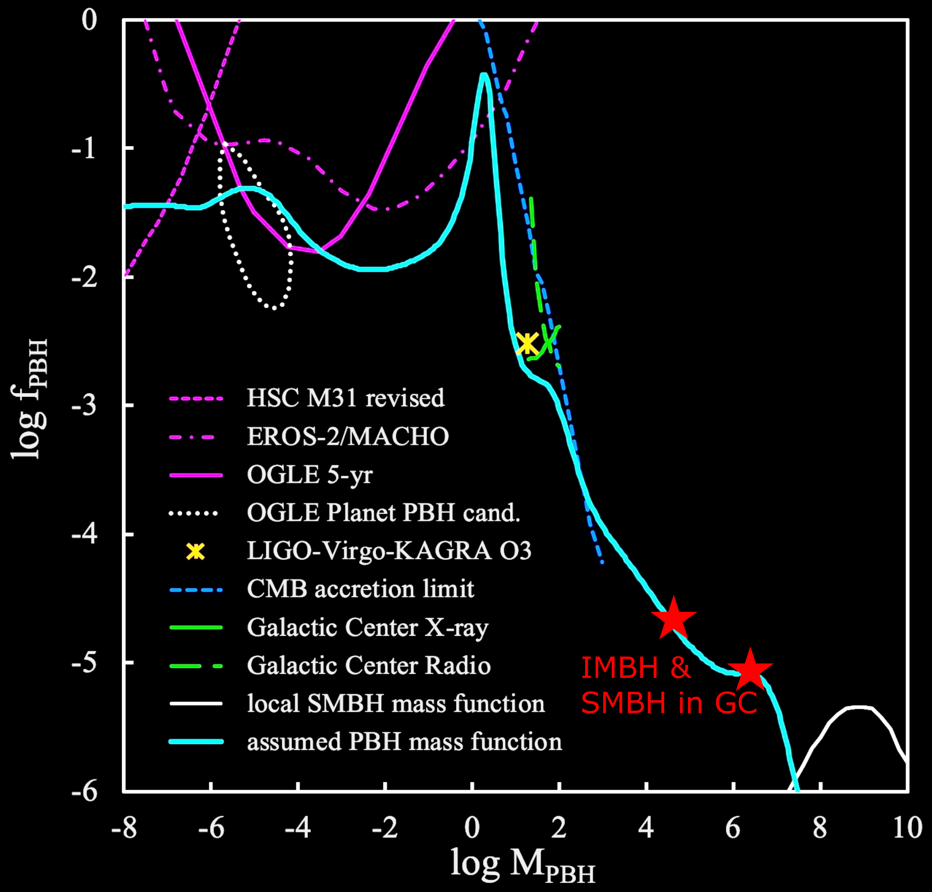


García-Bellido 2019

Different peaks correspond to different baryons created at the QCD phase transition and e^+e^- annihilation and the corresponding reduction in the sound velocity.

However, the original PBH mass spectra were somewhat in conflict with important observational constraints in the LIGO and SMBH mass range.

PBH mass spectrum assumed for this work

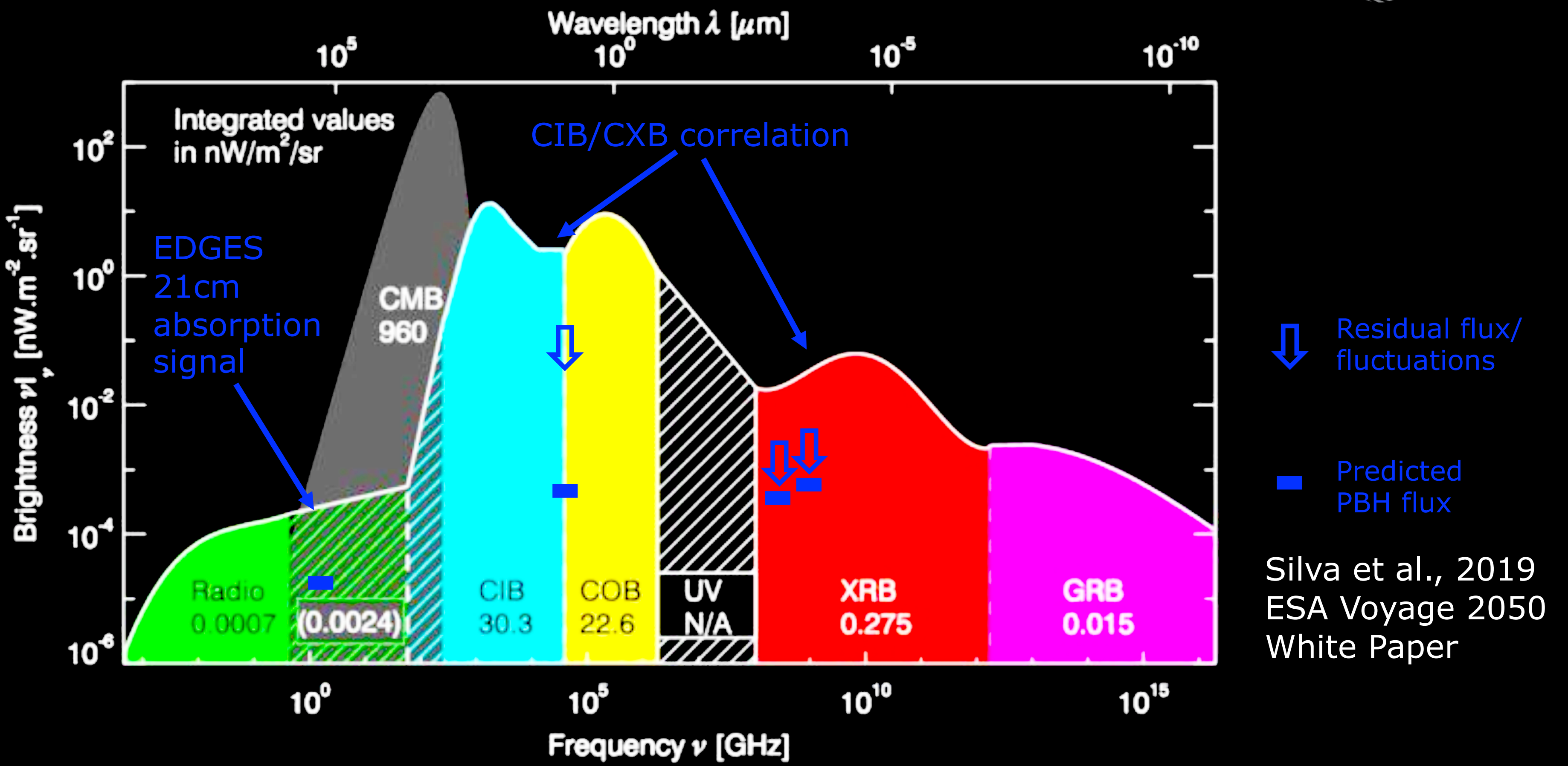


García-Bellido et al. (2020) are working on a new version of their PBH mass spectrum, which has a steeper decline at large PBH masses and is now practically fully consistent with all observational constraints.

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

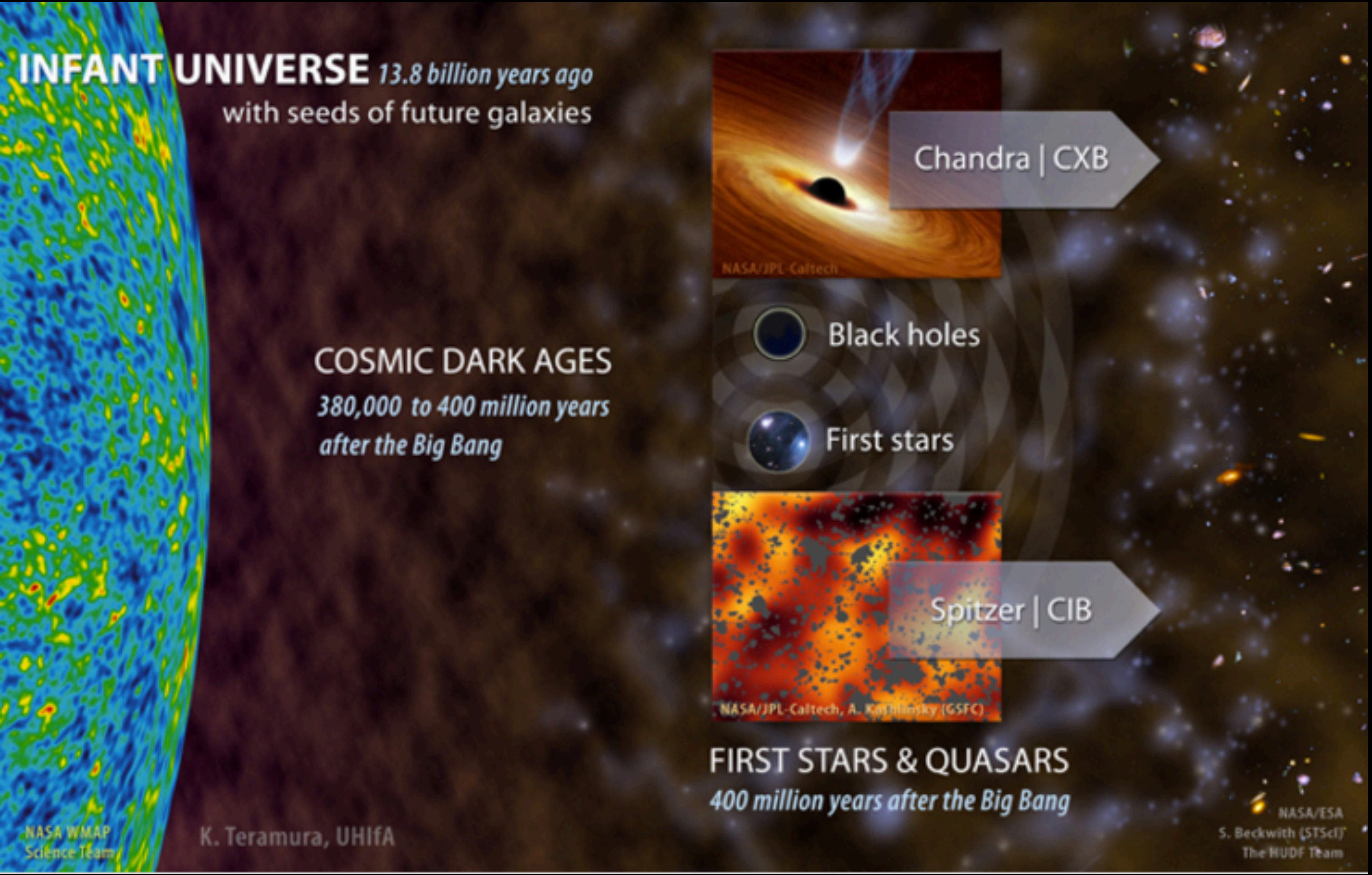
Cosmic Background Radiations

The Extragalactic Background Light



Silva et al., 2019
ESA Voyage 2050
White Paper

CIB x CXB fluctuations indicate high-z BH population



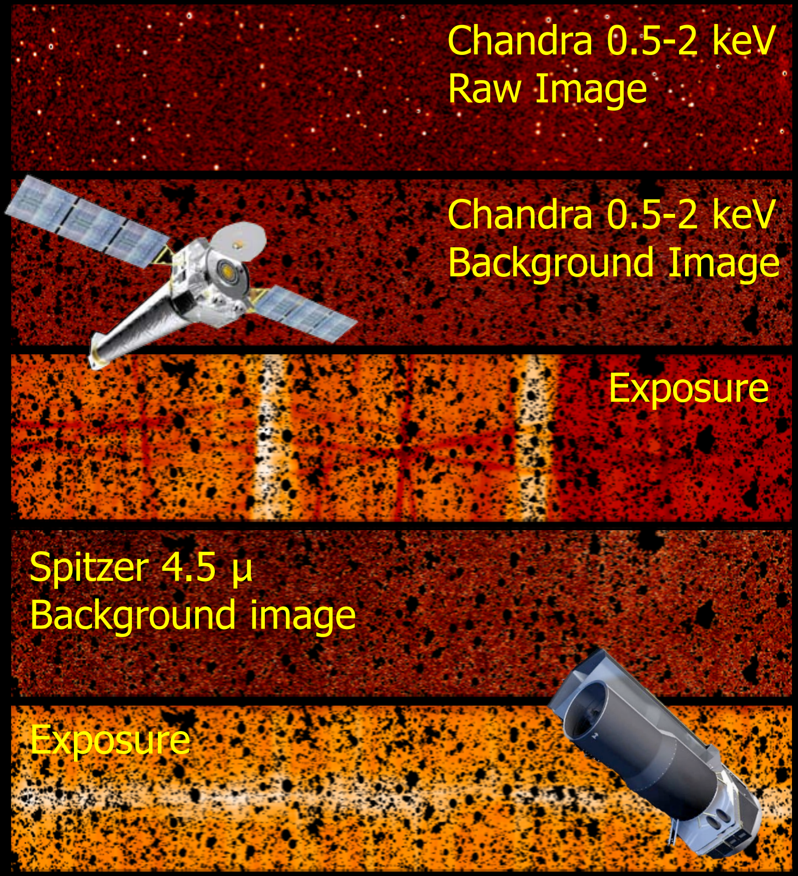
Significant cosmic background fluctuations have been found both in the NIR and in X-rays.

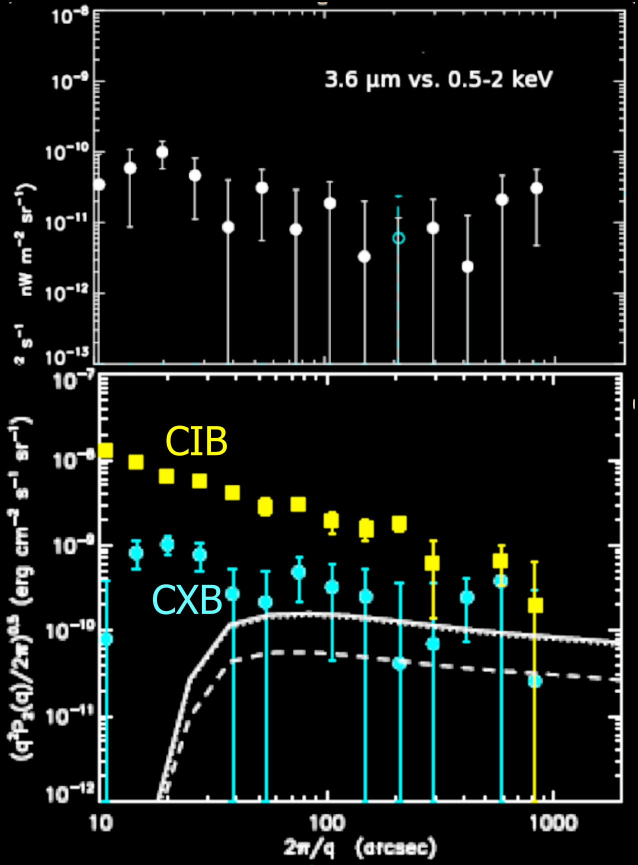
The strong CIB/CXB cross-correlation signal indicates a substantial contribution of Black Holes to the signal.

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.

CIB x CXB Cross-Power



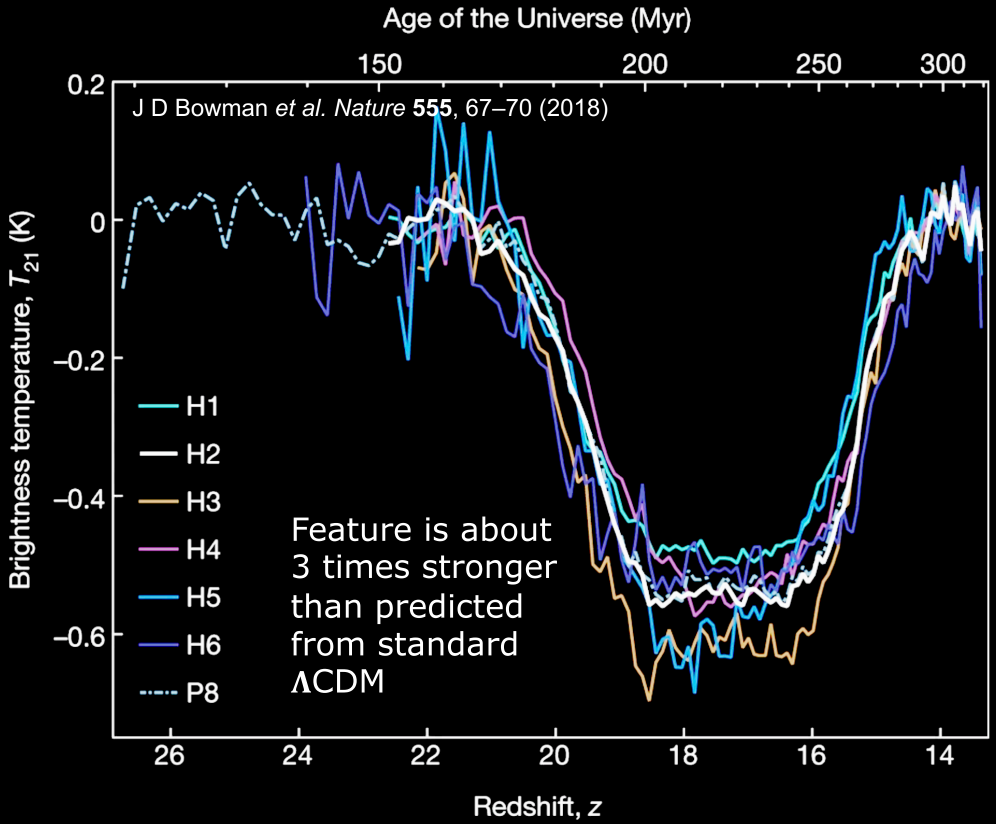


Cappelluti+13, Mitchell-Wynne+16, Yue+13, Pacucci+15, Helgason+14

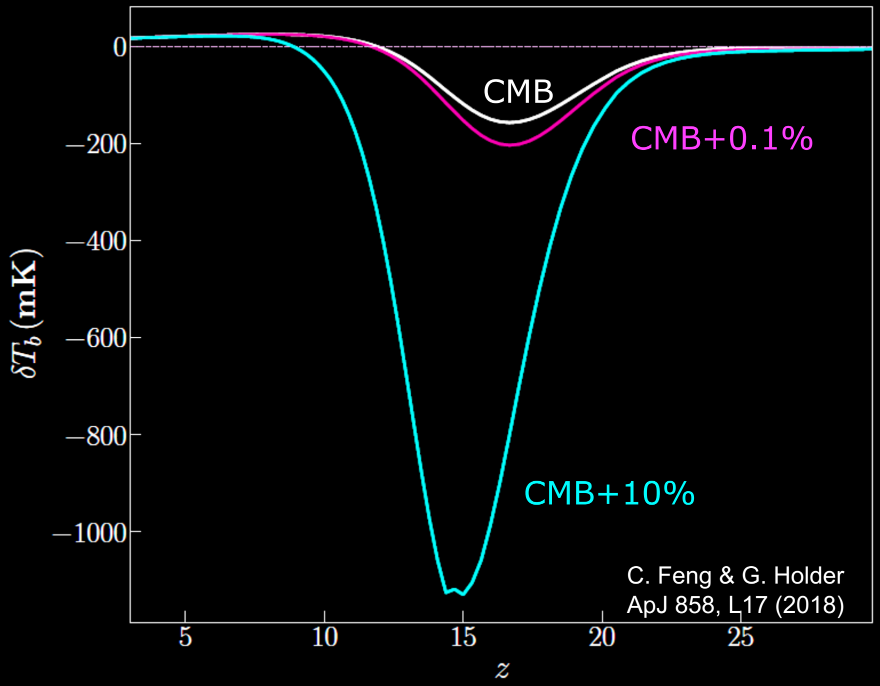
Fingerprint of th first Black Holes

A redshifted 21cm absorption feature in the sky-averaged spectrum

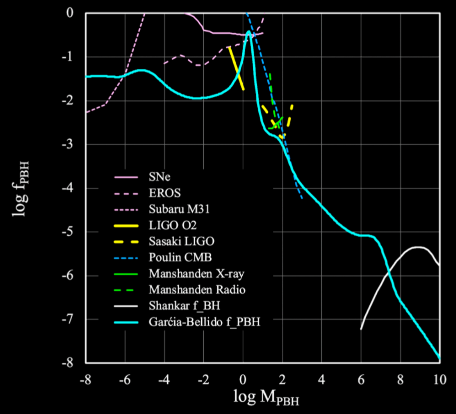
Experiment to Detect the Global Epoch of Reionization Signature (EDGES)



Independent prediction of a 21cm signal enhanced by additional radio background emission. ➔ 5% additional radio background can explain the EDGES data.

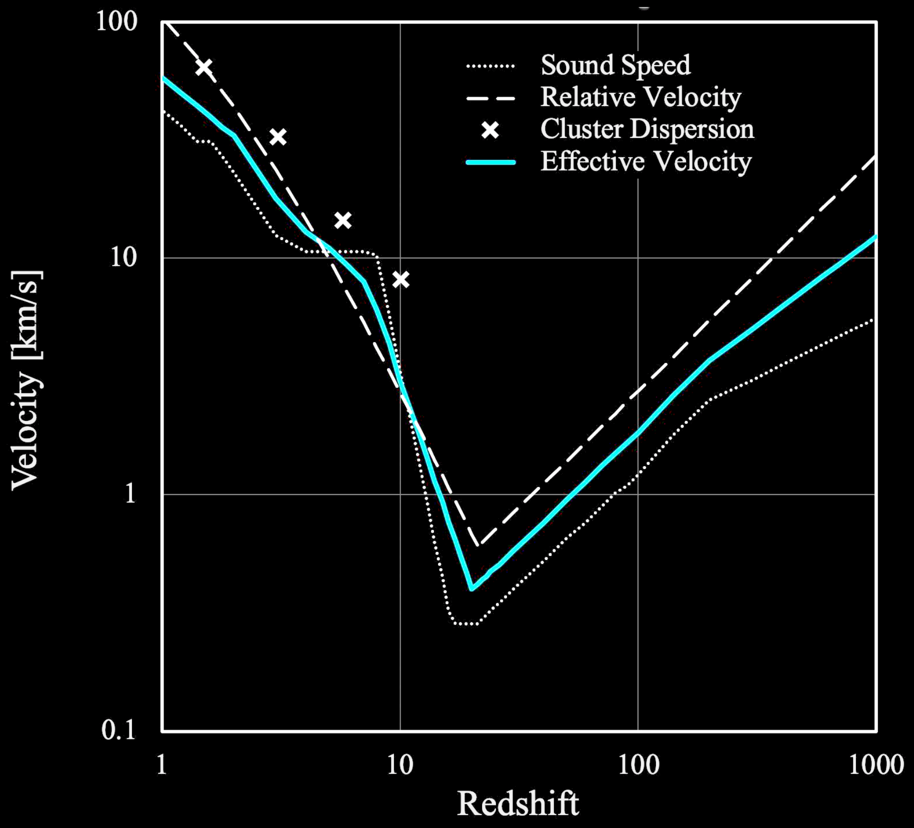


The PBH Model



Effective velocity between PBH and baryons

esa



Bondi & Hoyle discriminate between two approximations to the accretion problem (1) velocity-limited case, where $v_{eff}=v_{rel}$ (relative velocity), and (2) the temperature-limited case, where $v_{eff}=c_s$ (sound speed). In the case of a Gaussian distribution of v_{rel}, the effective velocity can be approximated by the harmonic mean:

$$v_{eff} = \sqrt{\langle v_{rel} \rangle \; c_s}$$

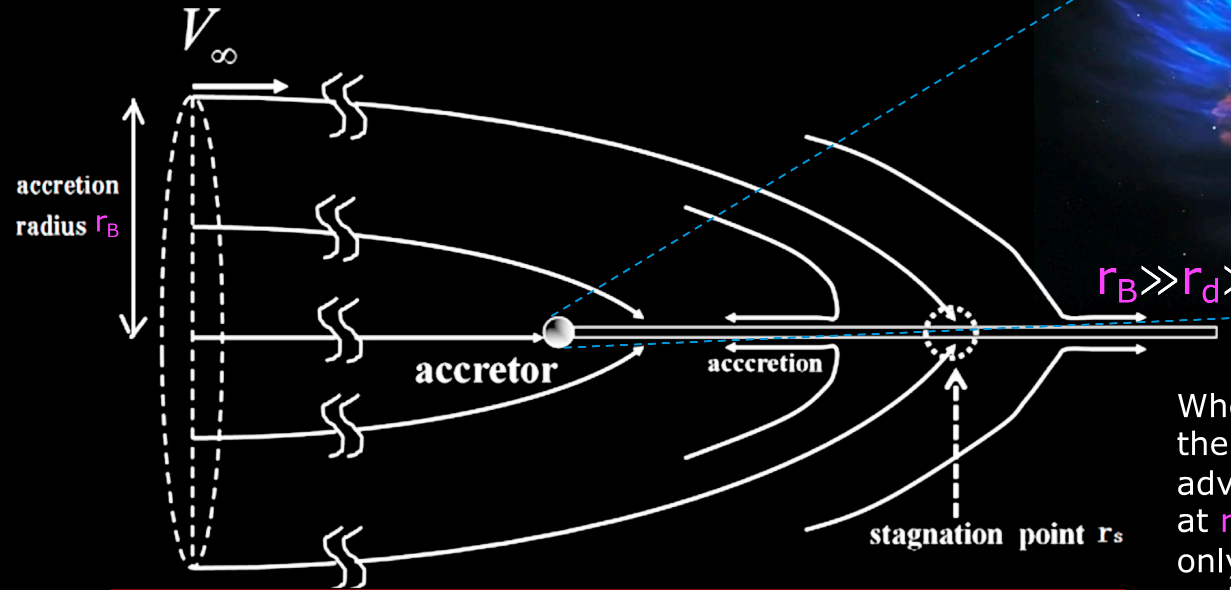
Ali-Haïmoud & Kamionkowski (2017)

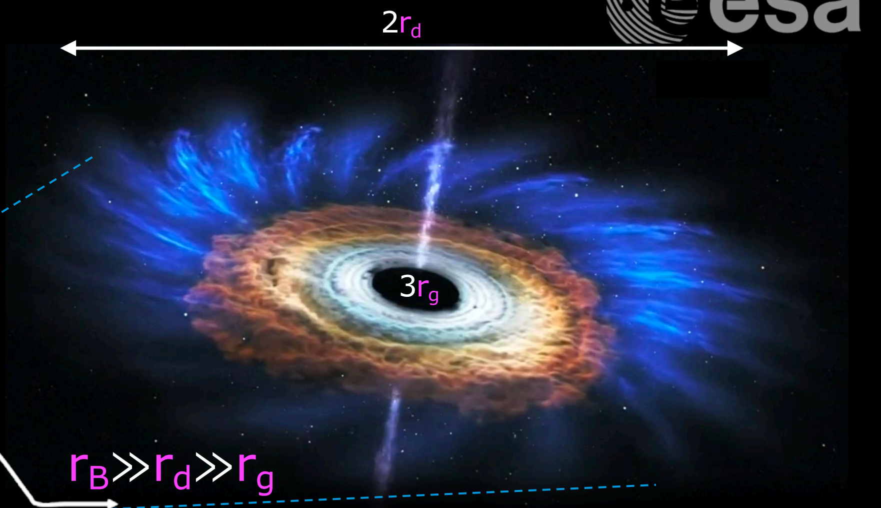
The effective velocity starts after the Baryonic Acoustic Oscillations decouple at z~1100 with relative velocities ~30 km/s, and slows down with the expansion of the Universe.

The smallest effective velocity, and thus the largest mass accretion rate, is achieved around z~20, when non-linear effects become dominant.

Bondi capture & advection dominated disk flow

Bondy-Hoyle-Lyttleton capture: magnetic field plays an important role for the fluid to get rid of the angular momentum at the stagnation point. The magnetic field and is amplified towards the accretor.

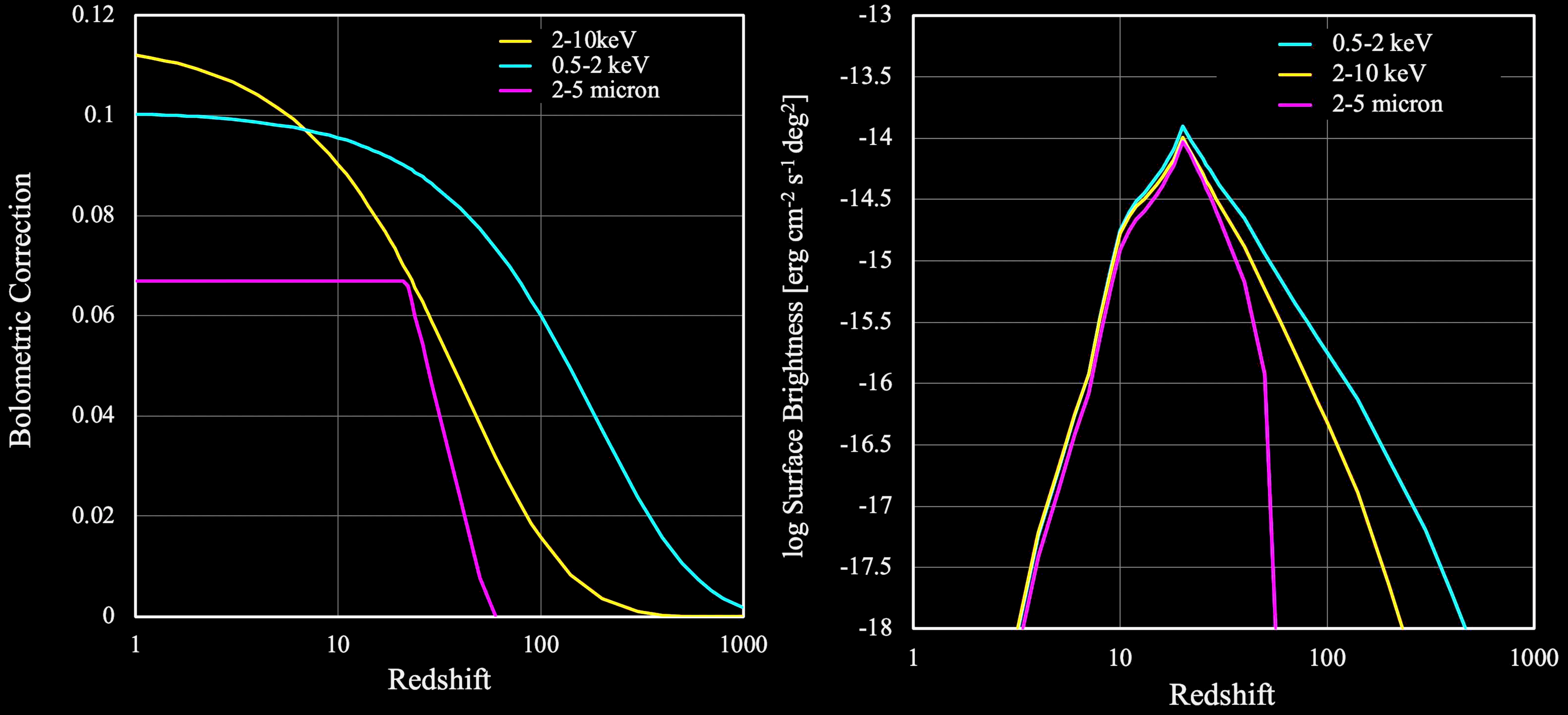




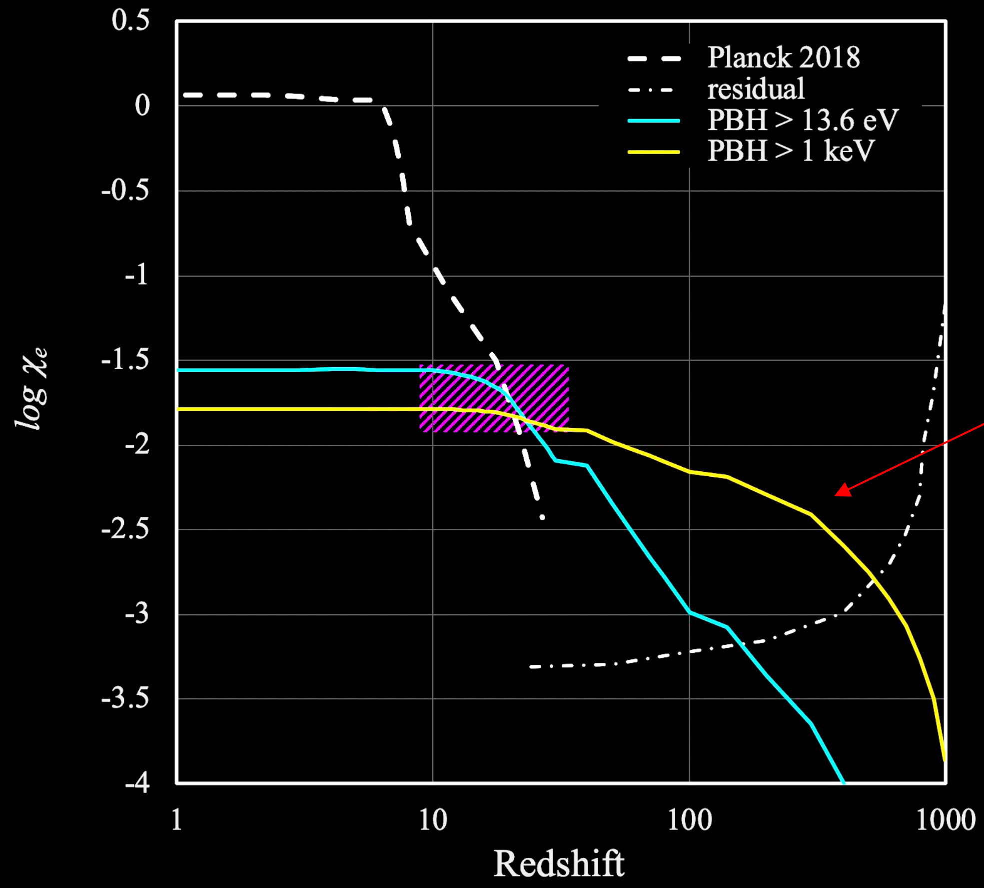
$$r_B = \frac{G\,M}{v_{eff}^2} \approx 1.34 \cdot 10^{16} \left(\frac{M}{M_\odot}\right) \left(\frac{v_{eff}}{1\ \mathrm{km\ s^{-1}}}\right)^{-2} cm$$

When the turbulence and inhomogeneity at the Bondi radius r_b is large enough an advection dominated accretion disk forms at r_d. Until about 10 Schwarzschild radii r_g only a small fraction (~5%) of the captured matter is actually accreted. Then standard Shakura-Sunyaev accretion down to last stable orbit $3r_g$.

Bolometric correction and band fluxes

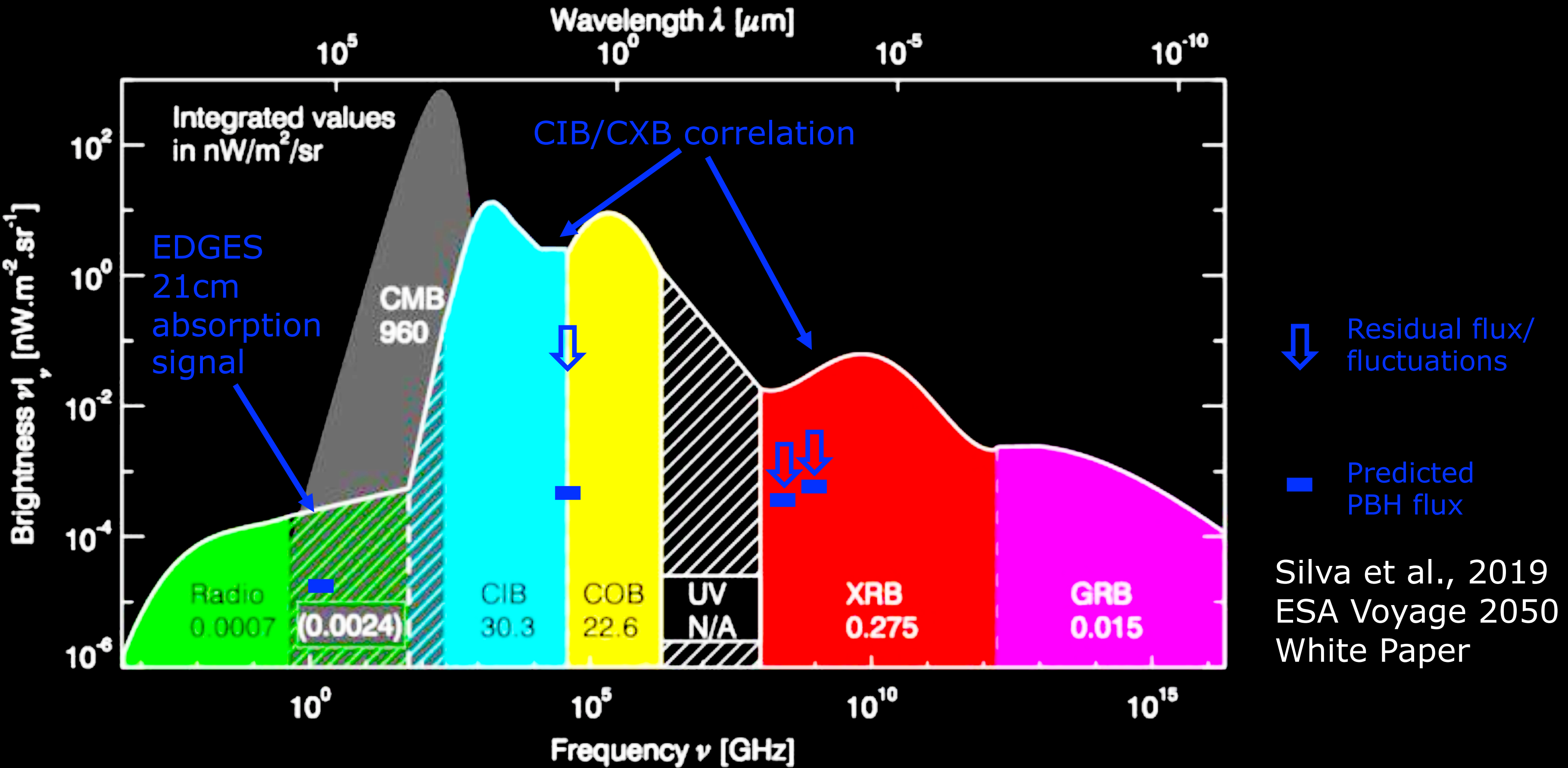


Re-Ionization and baryon heating



Prediction of significant high-redshift pre-ionization and X-ray heating, which can be tested by future microwave polarization experiments!

The Extragalactic Background Light



Silva et al., 2019
ESA Voyage 2050
White Paper

Summary

Cosmic X-ray and Infrared Background fluctuations reveal a tantalizing indication for a new population of early black holes (z>13).

This goes hand in hand with other tensions: early QSOs, the LIGO discovery of many massive merging BHs with low spin, and the large amplitude of the 21cm absorption.

Speculation: Are Primordial Black Holes the Dark Matter?

This conjecture could solve several puzzles in one go and makes exciting astrophysical predictions. It could even explain other fundamental physics problems.

We may already have seen the first glimpse in the Galactic Center, in OGLE/GAIA microlensing events and in free-floating planetary PBH.

The putative PBH Dark Matter does not violate any observational constraints.

Strong case for synergy in the future space science programs between X-rays (eROSITA, Athena), Gravitational Wave Astrophysics (LISA) and infrared (JWST, Euclid, WFIRST)!

“Bringing sound to the cosmic movies”

esa

Athena
hot gas structures
supermassive black holes

LISA
gravitational wave observation


Thank you
very much!
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