Sébastien Clesse
IRMP-CP3, Louvain University
Namur Institute for Complex Systems (naXys), Namur University

Unveiling the abundance, mass, clustering and formation of primordial black holes with the Einstein Telescope

based on arXiv:1711.10458, 1710.04694, 1707.04206, 1610.08479, 1603.05234, 1501.00460
(with J. Garcìa-Bellido, P. Serpico, V. Poulin, F. Calore,...)
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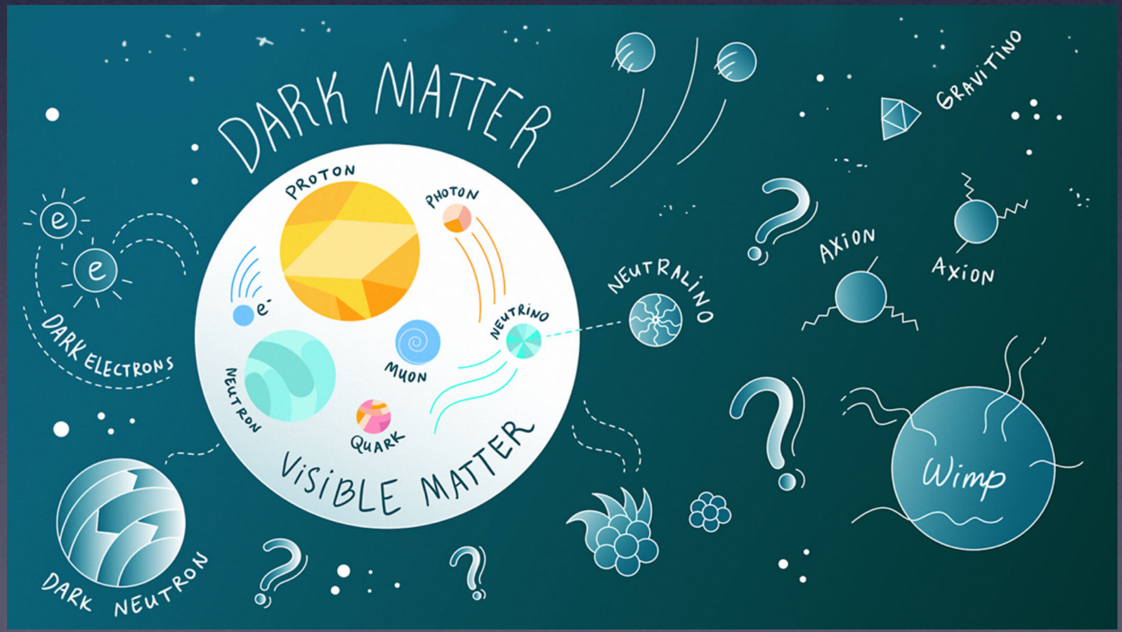

COSPA - Einstein Telescope meeting
January 31, 2018, Université de Liège

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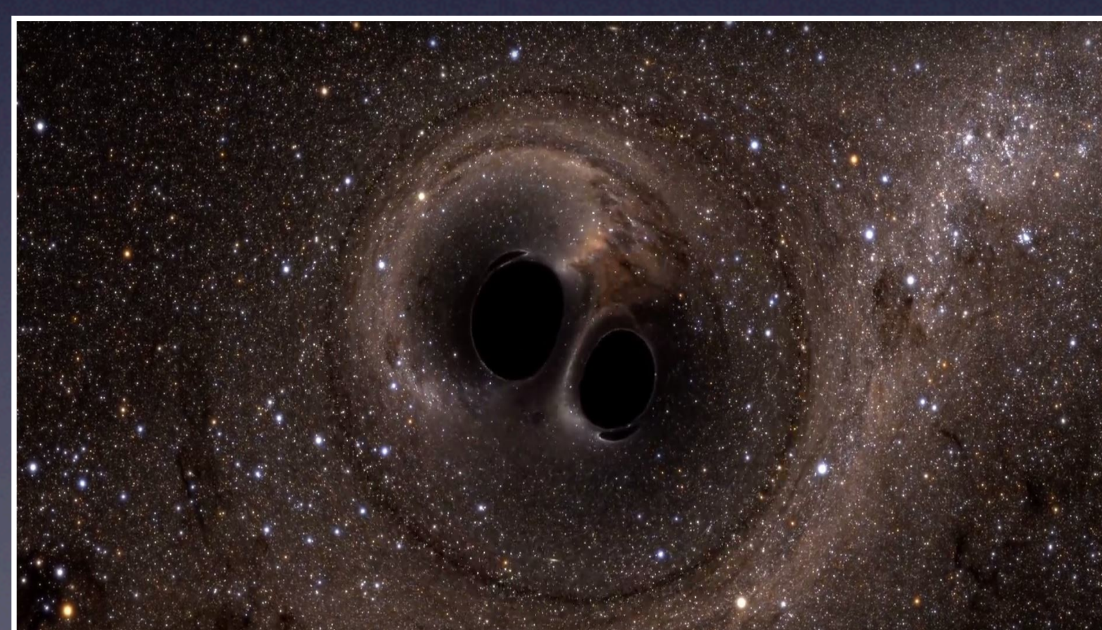

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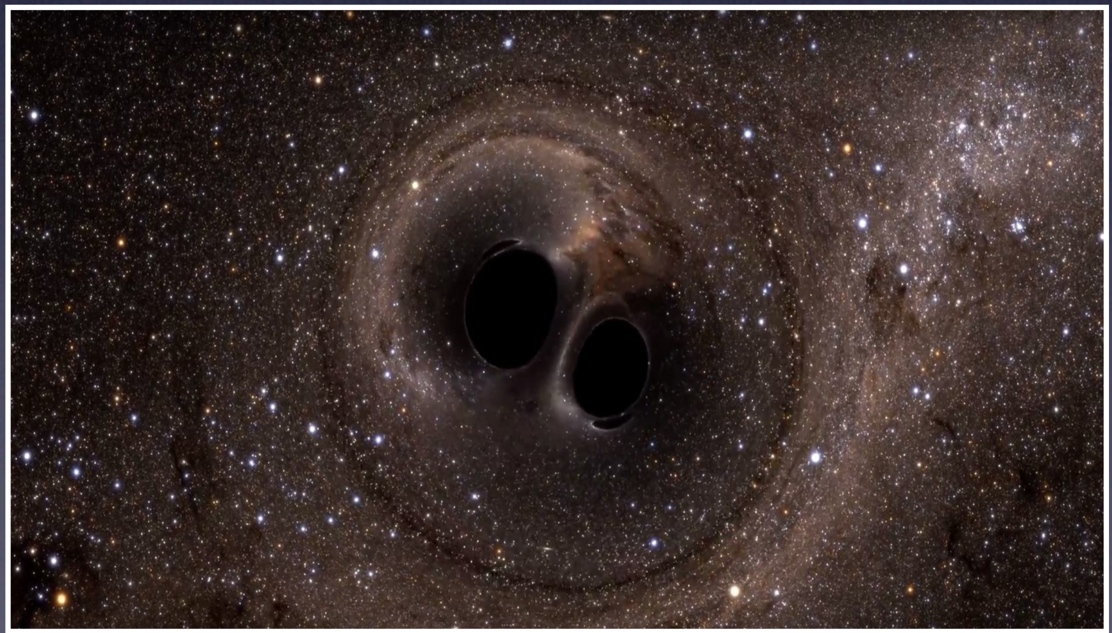

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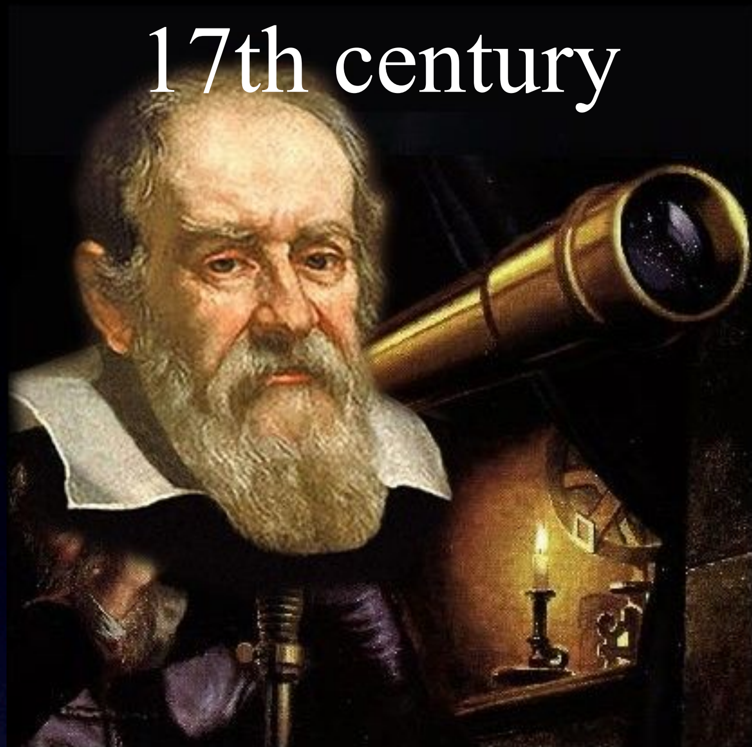
Cosmology with the Einstein Telescope

Galileo,
17th century



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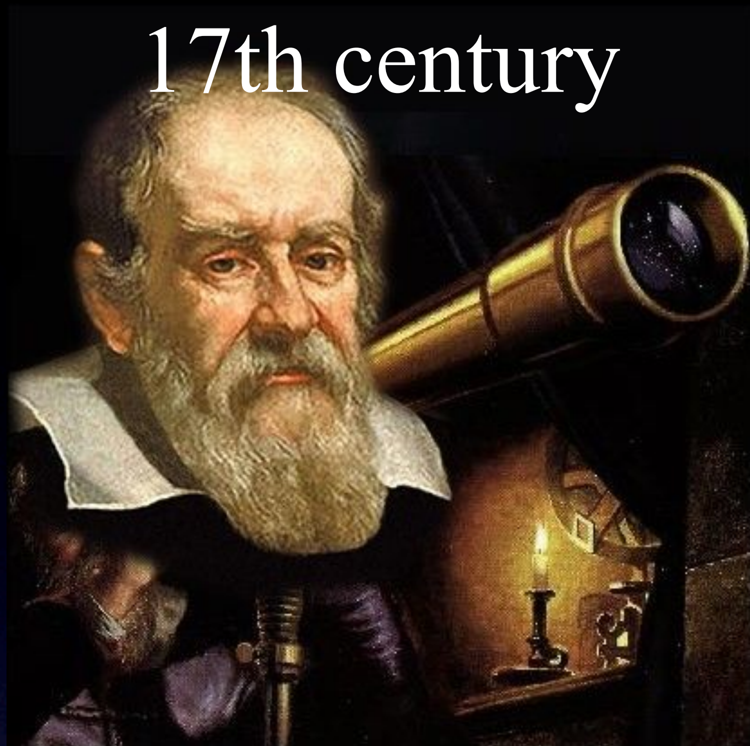
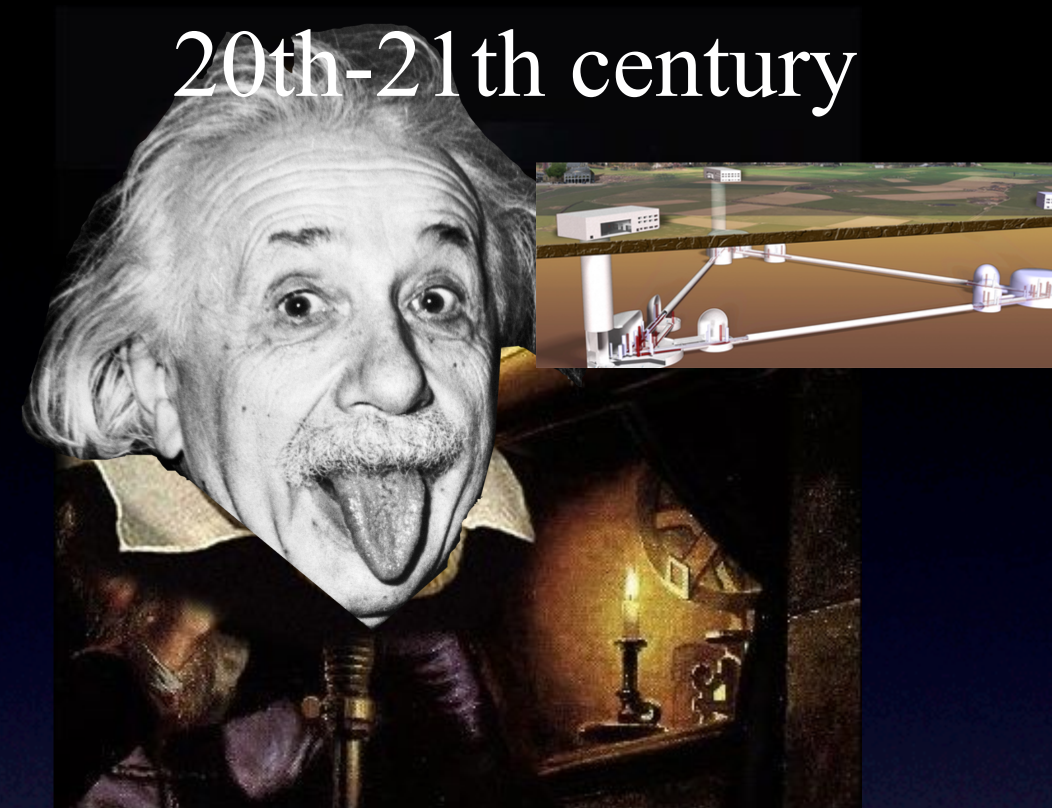


Einstein and ET
20th-21th century



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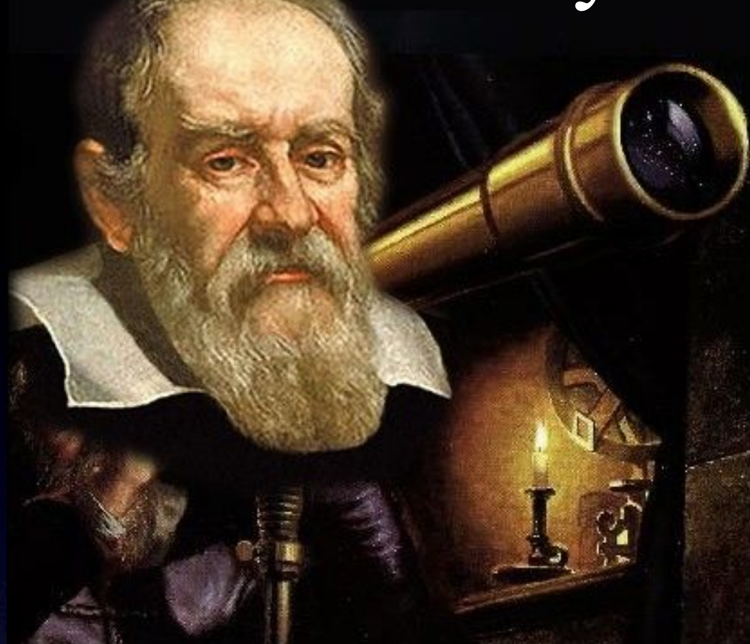

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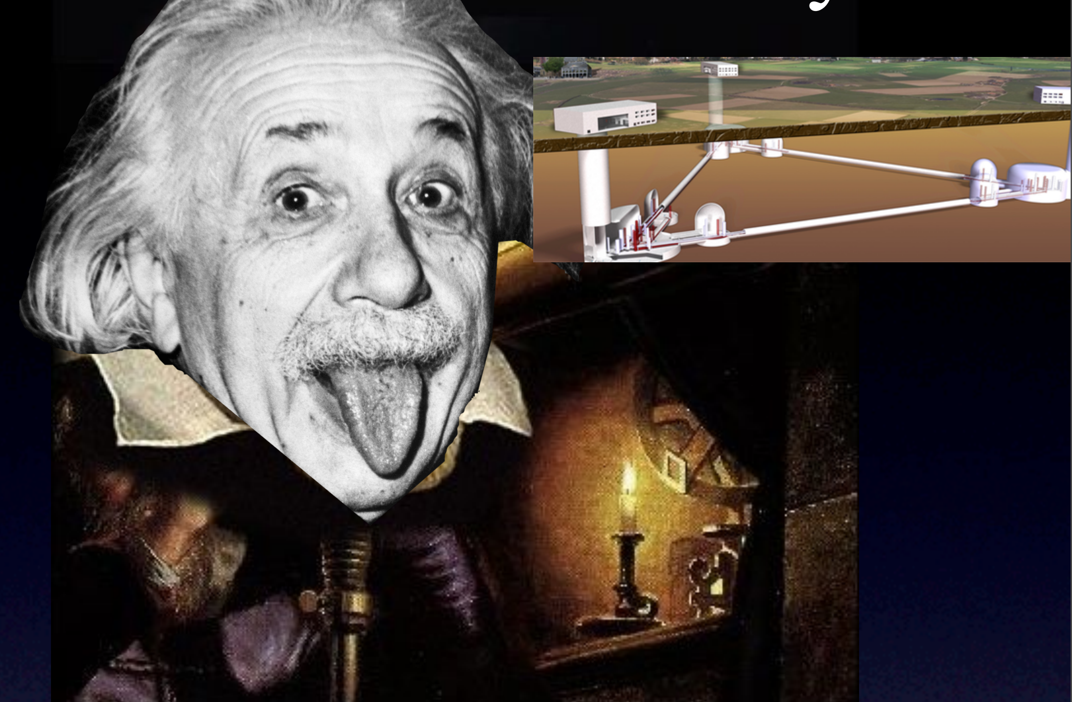

GW and ET: a new era of Astronomy

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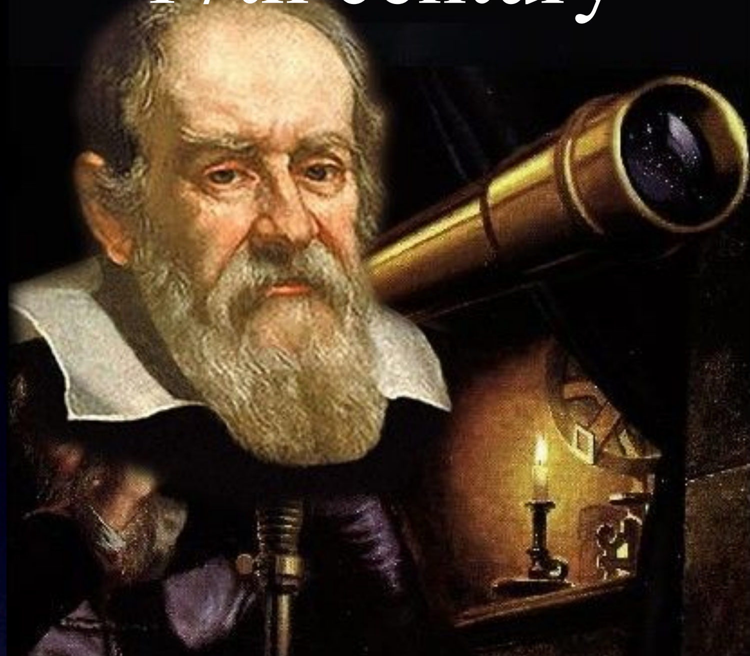

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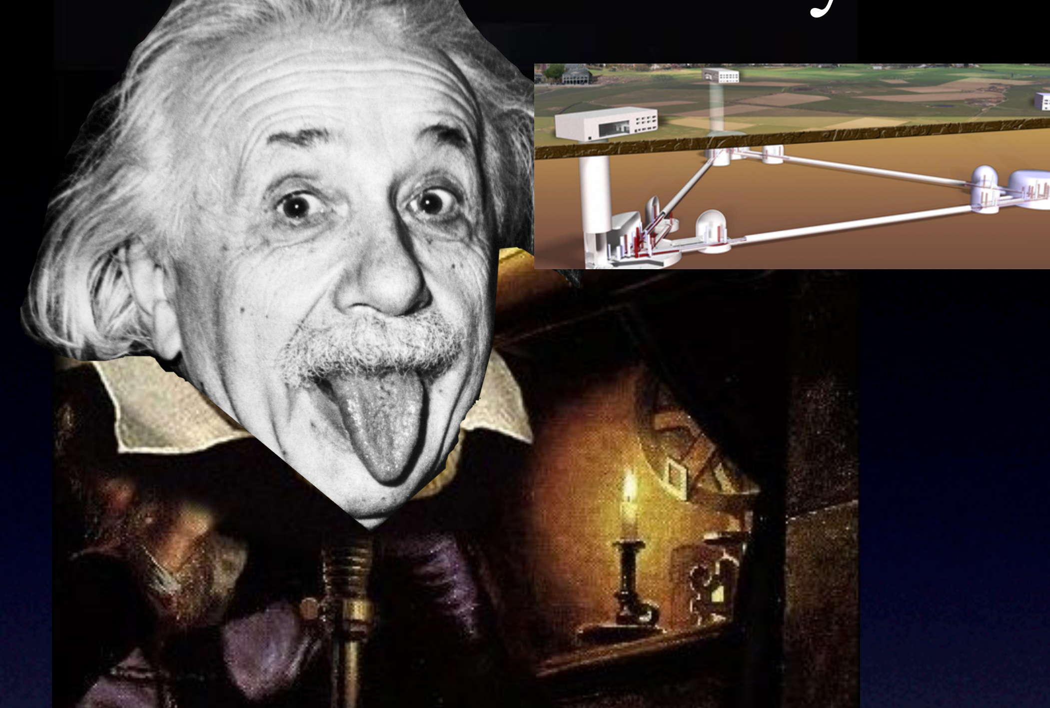

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100 000 BH mergers/year

Any BH collision in our observable Universe will be detected by ET

strain h~1/distance vs. flux density ~1/distance^2

no «opacity» effect like in CMB

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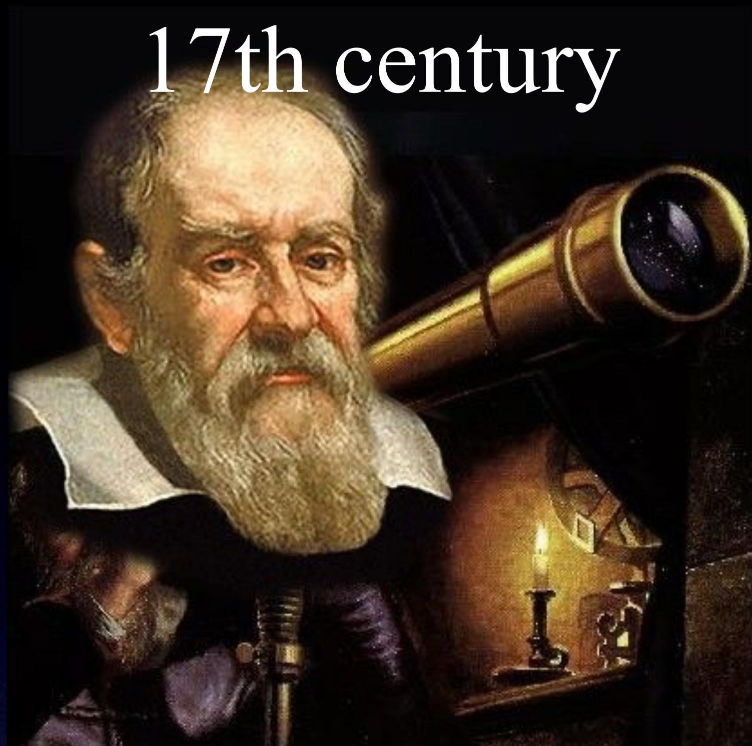

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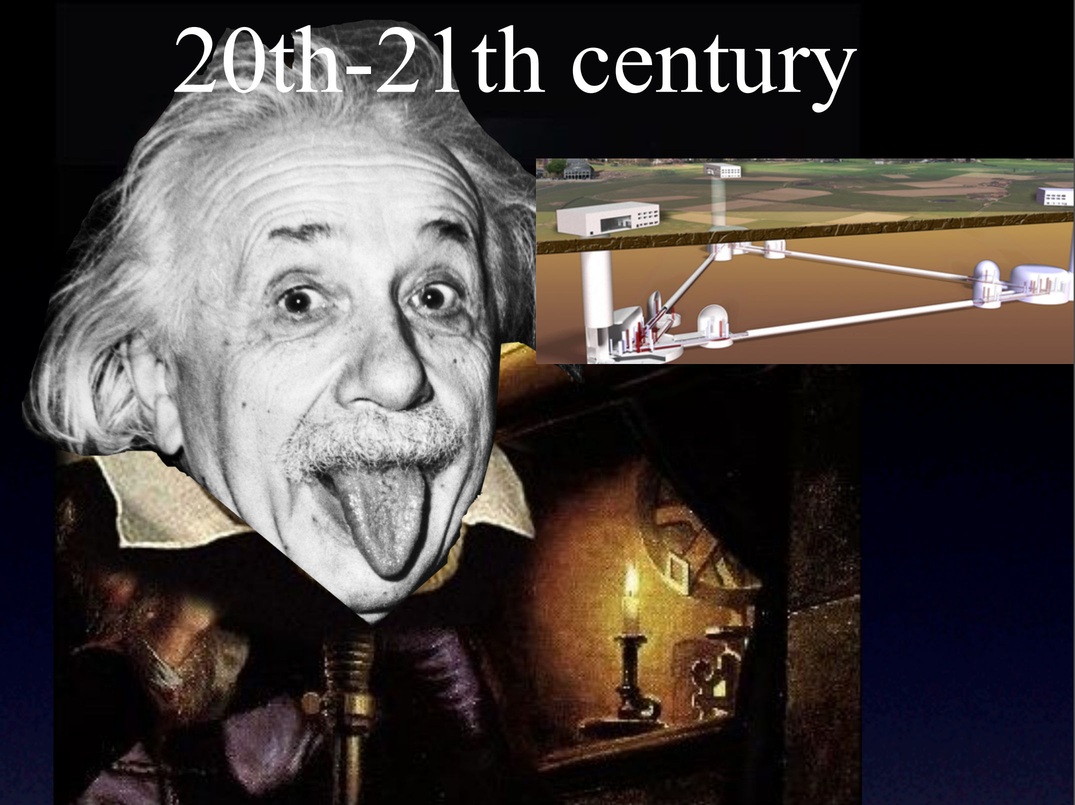

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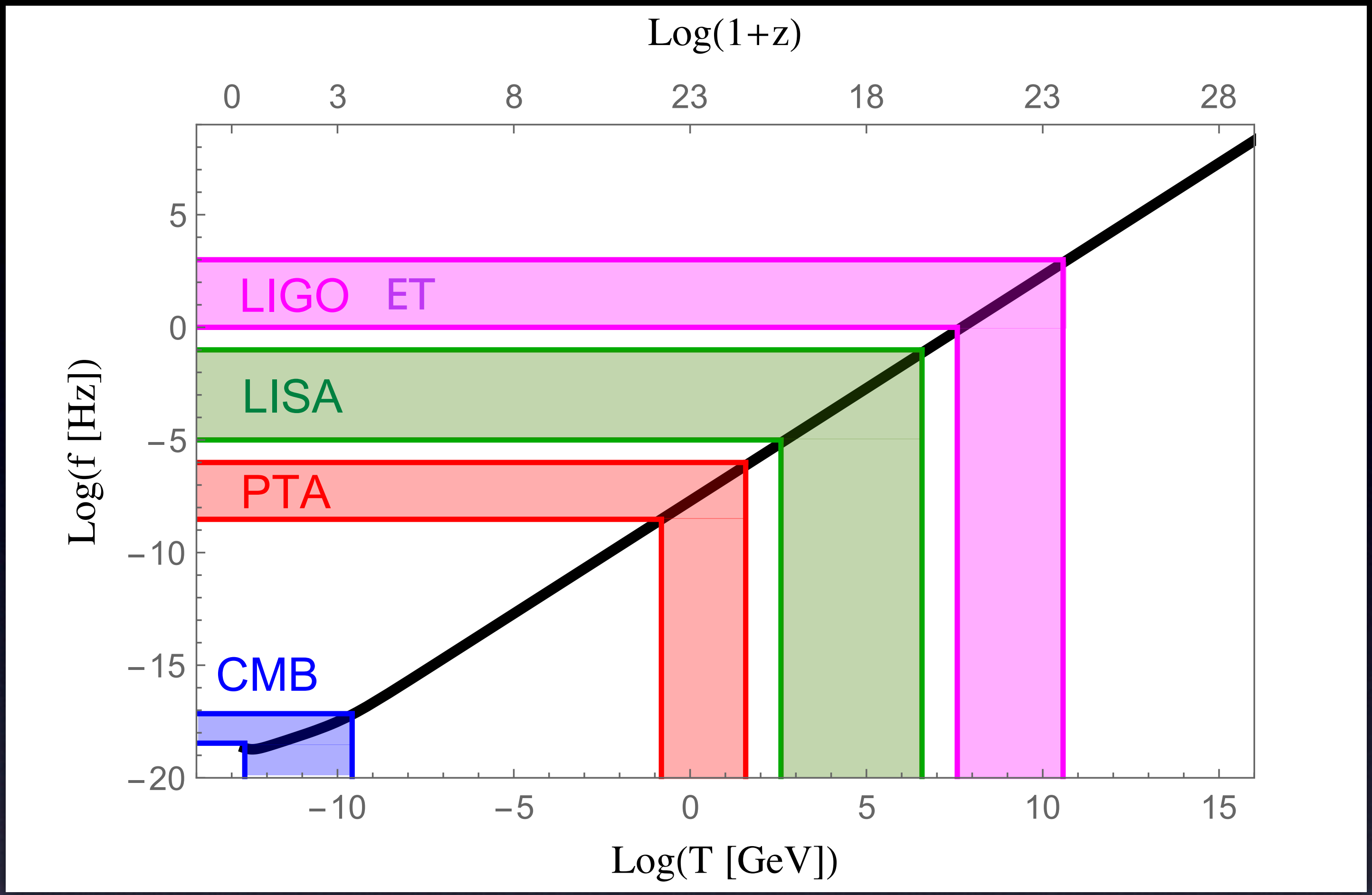

Caprini, Figueroa, 1801.04268

link between GW frequency and energy scale/redshift

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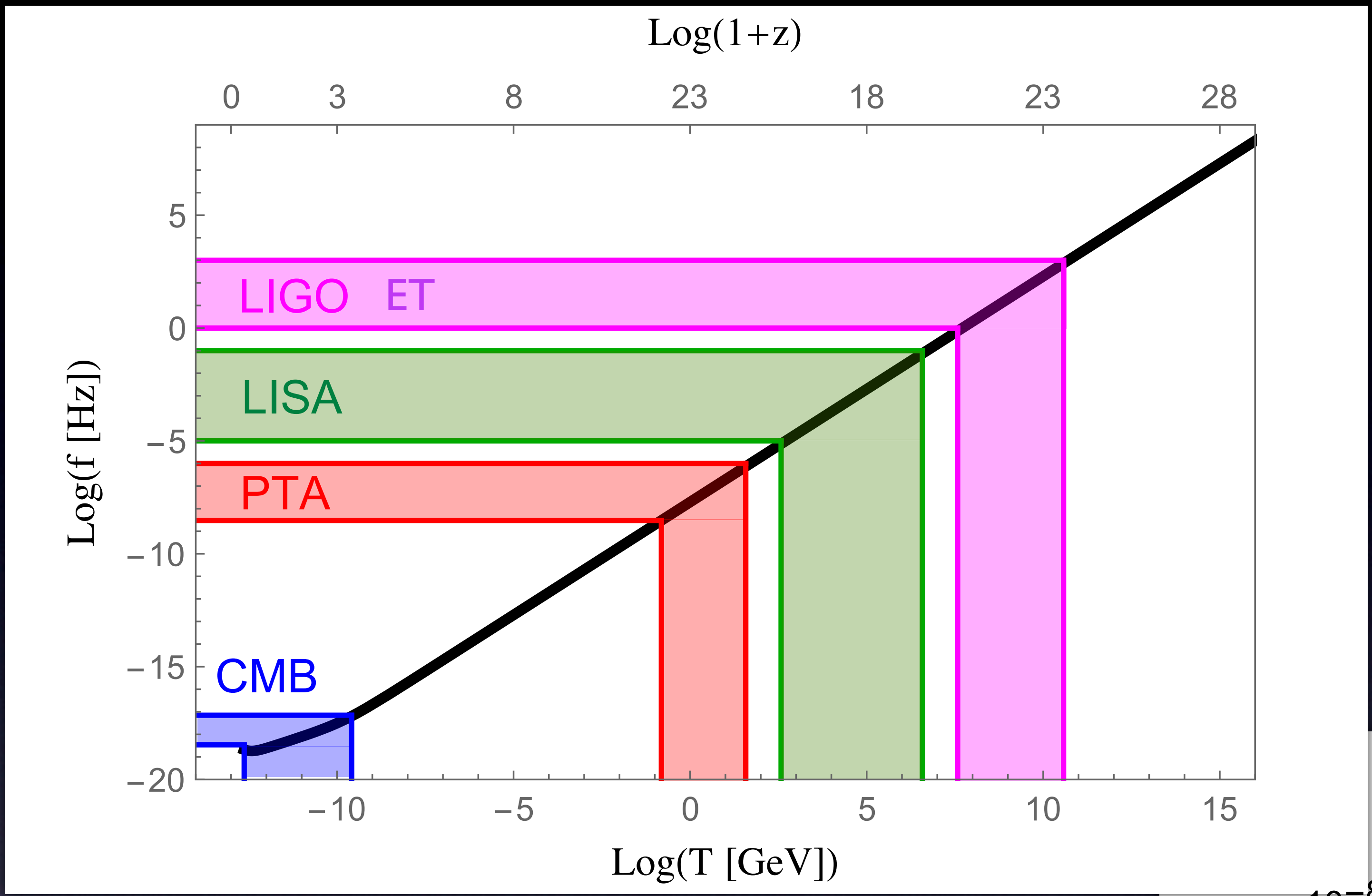

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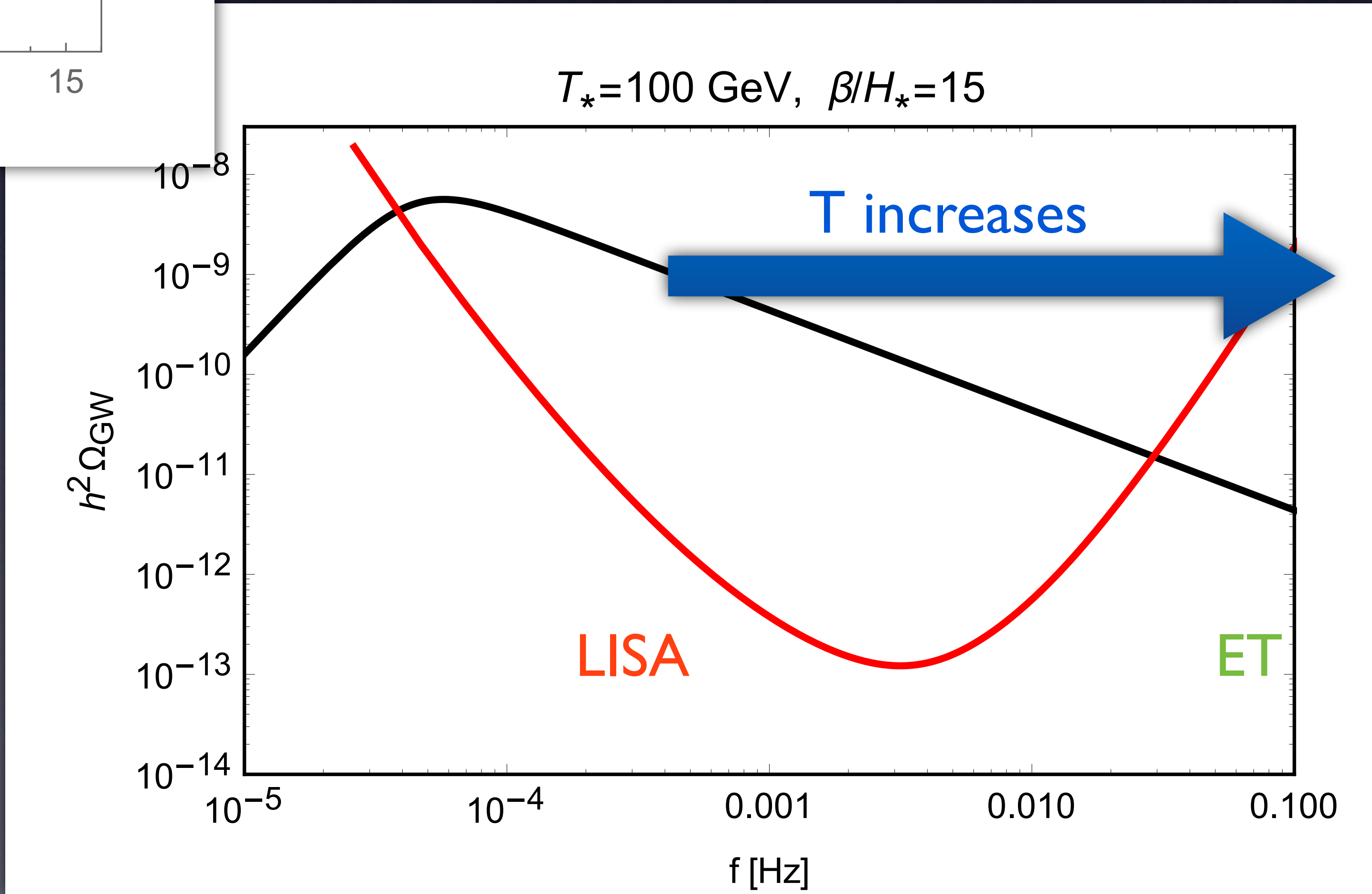
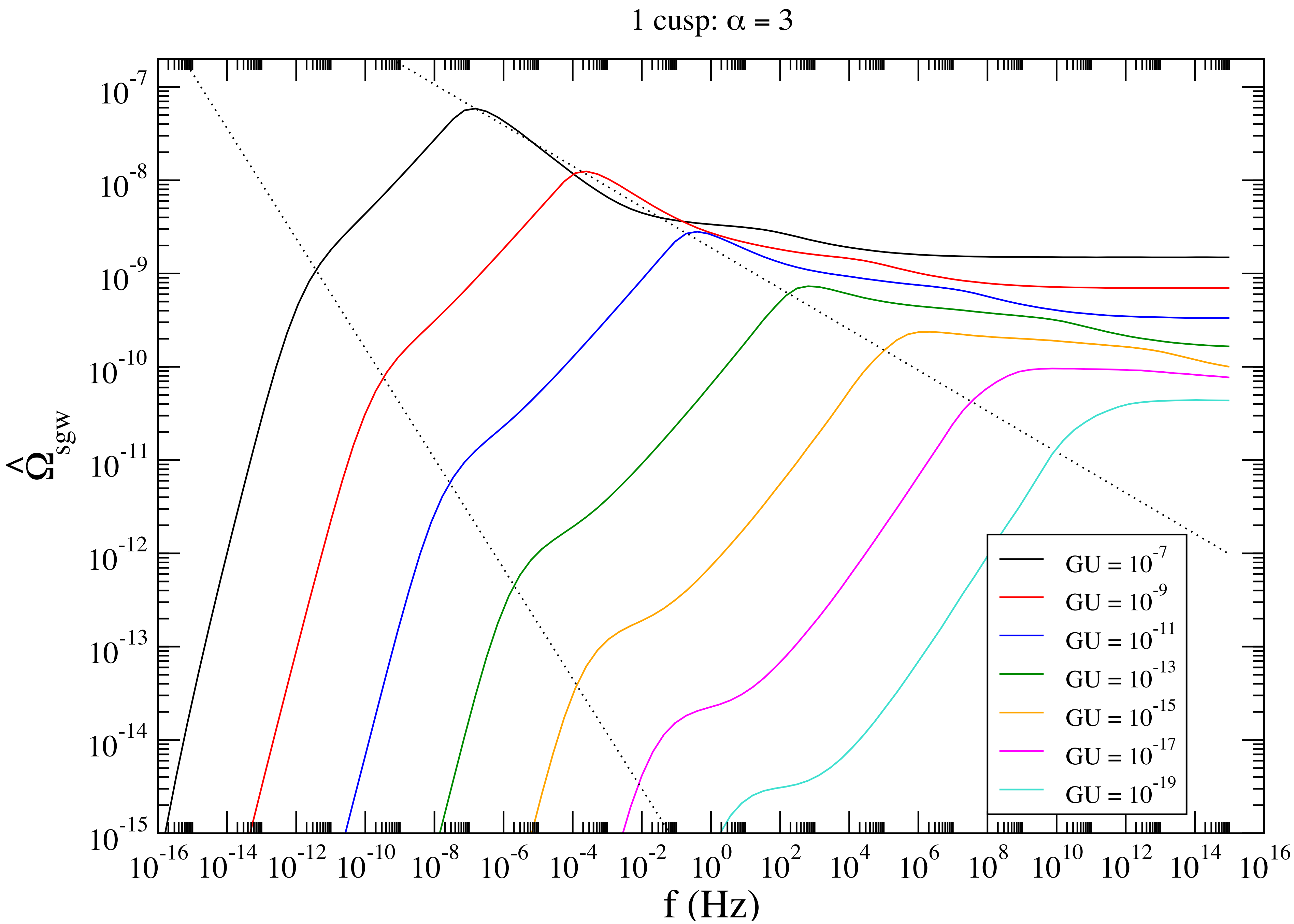


example of GW background from a first-order transition

Cosmic strings



Ringeval, Suyama, 1709.03845

LIGO/VIRGO already set the best constraints on the string tension

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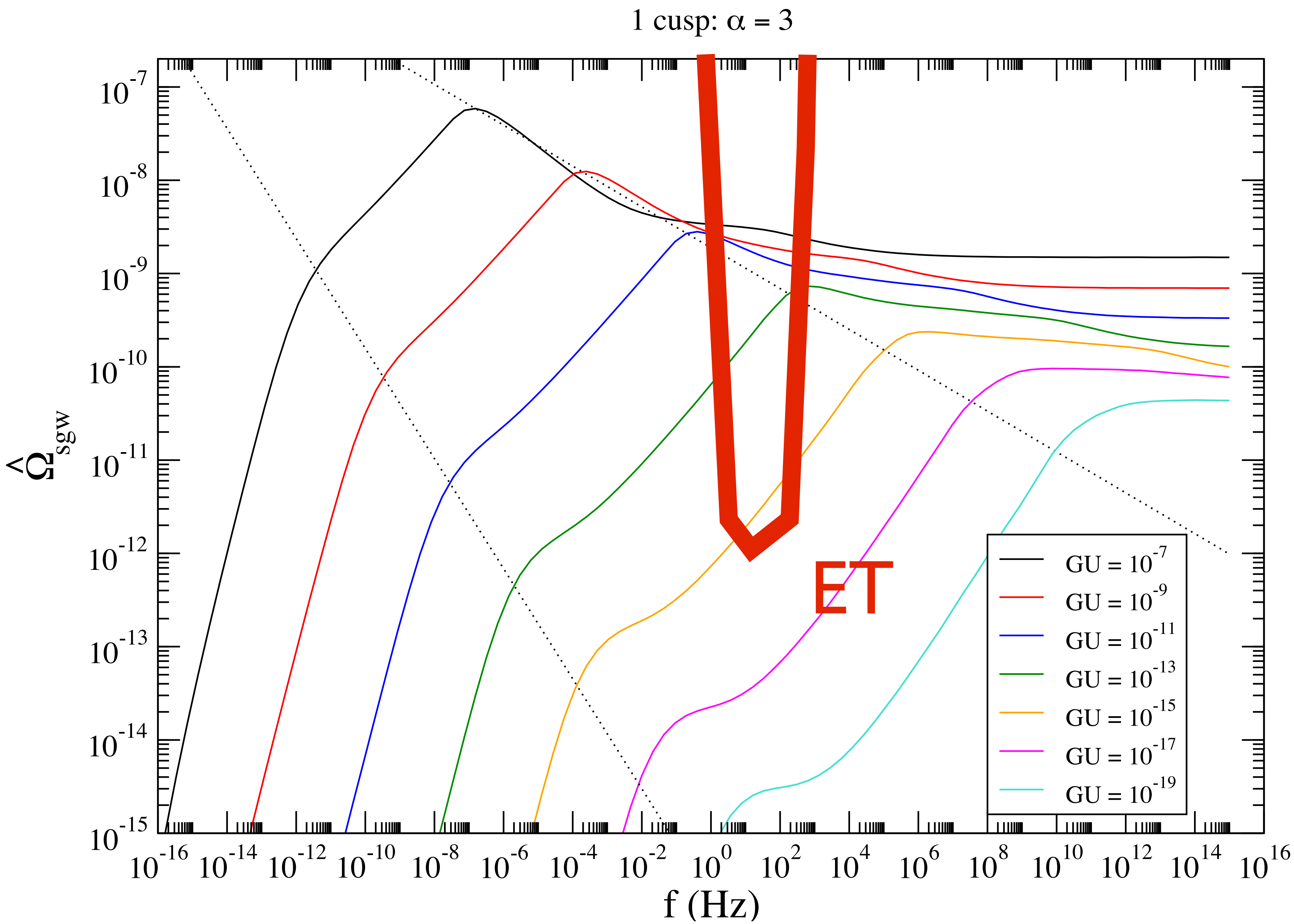

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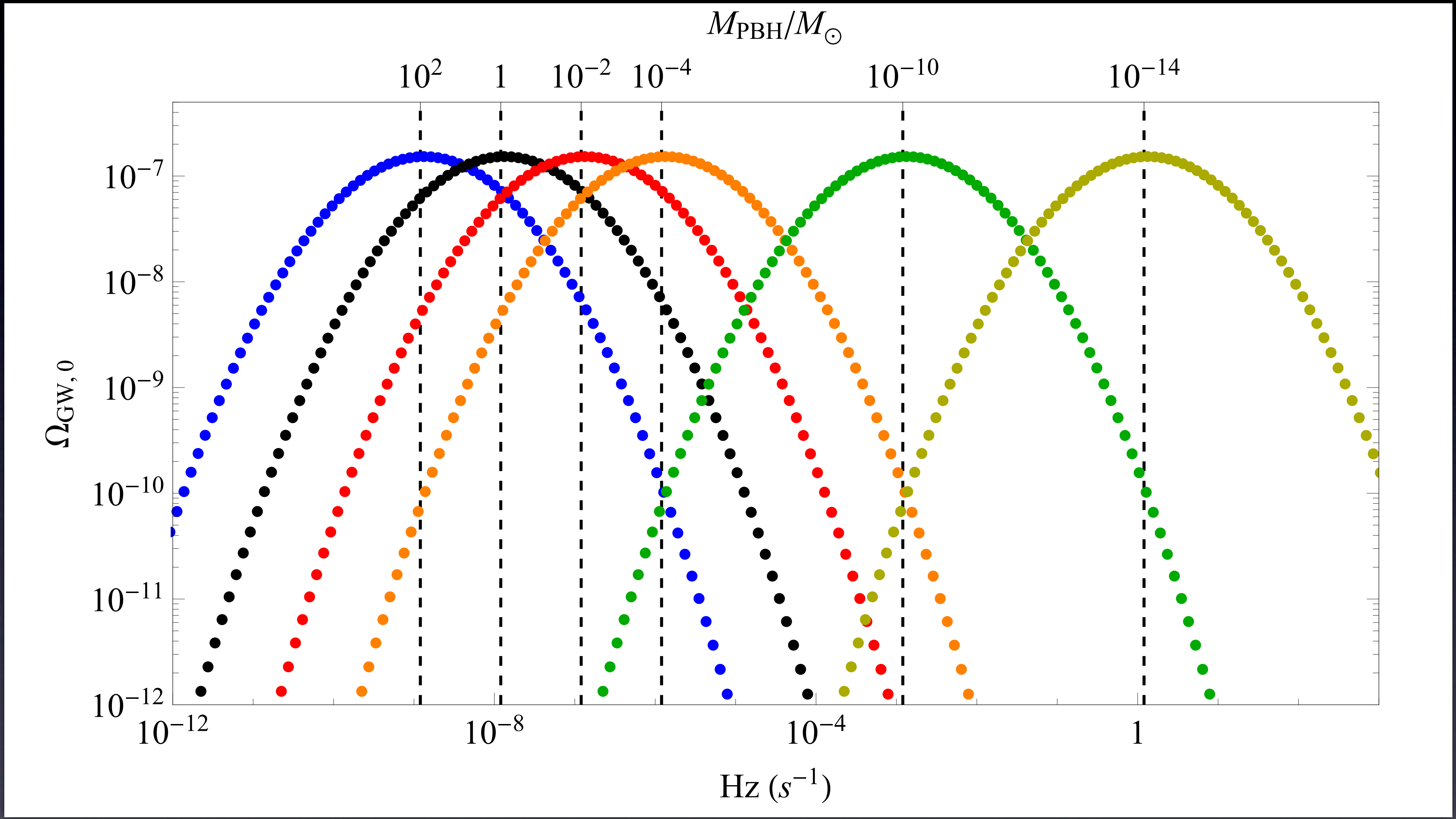

SC, J. Garcia-Bellido, S. Orani, *in preparation*

metric perturbations at second order sourced by curvature

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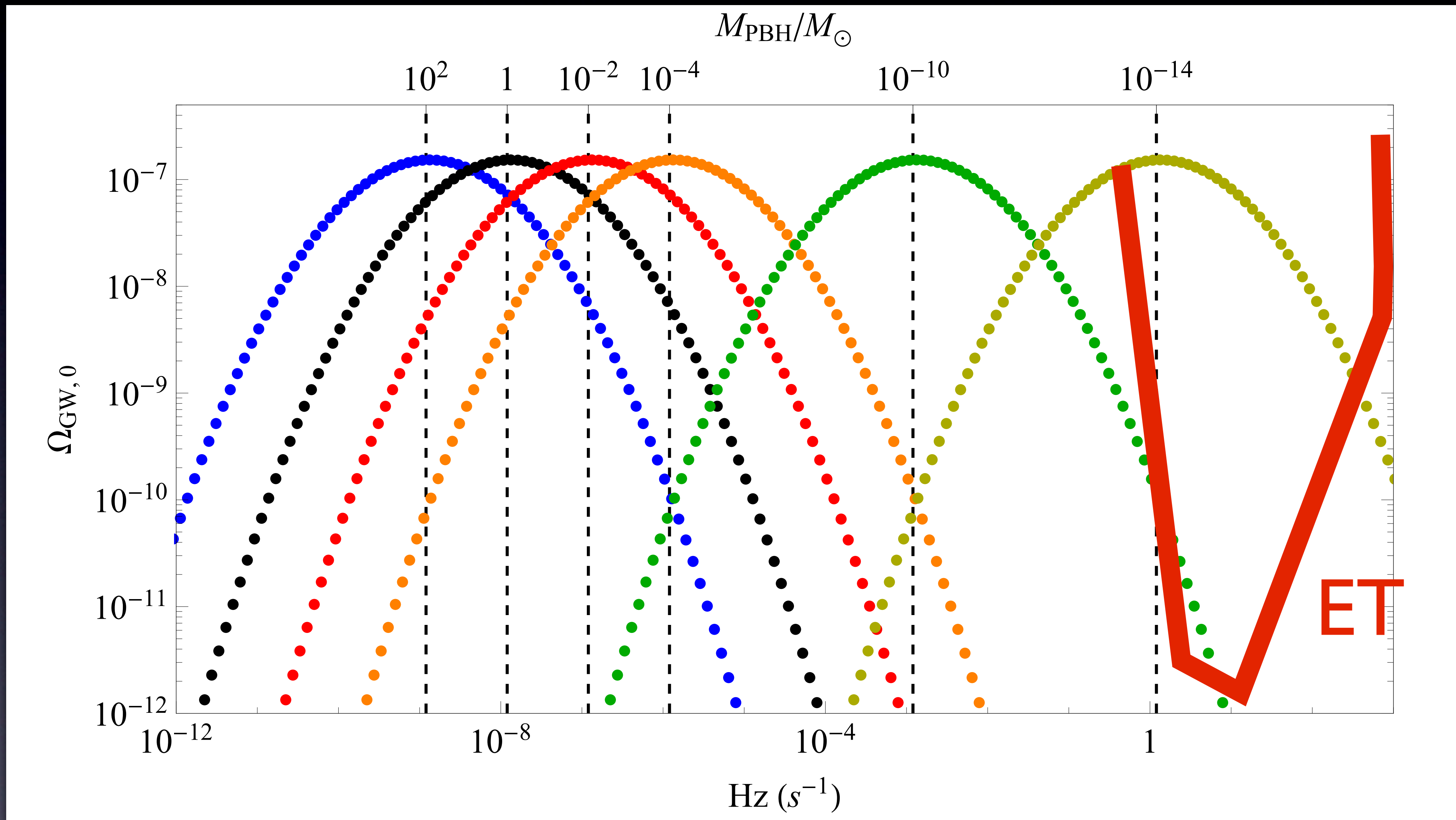

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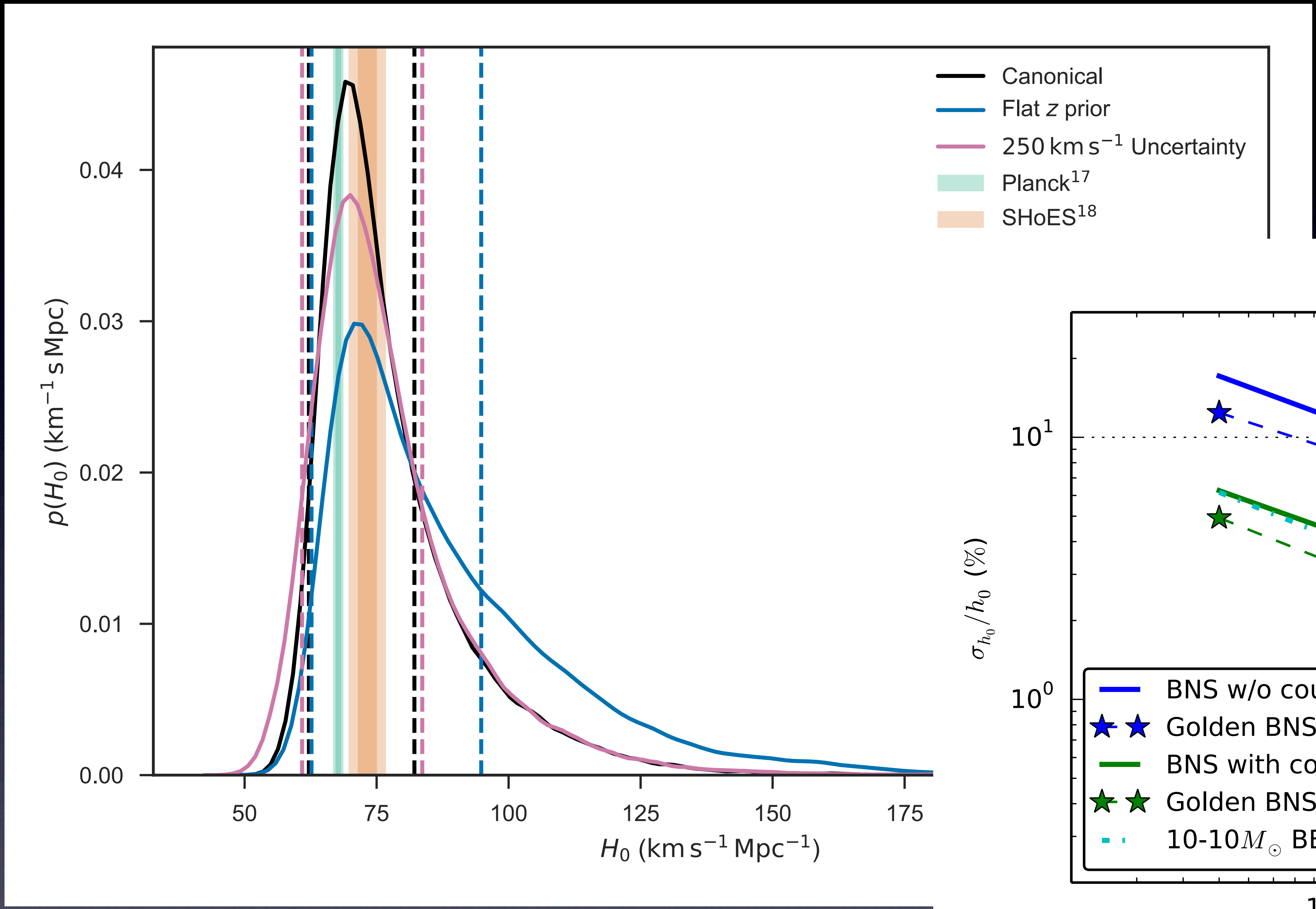
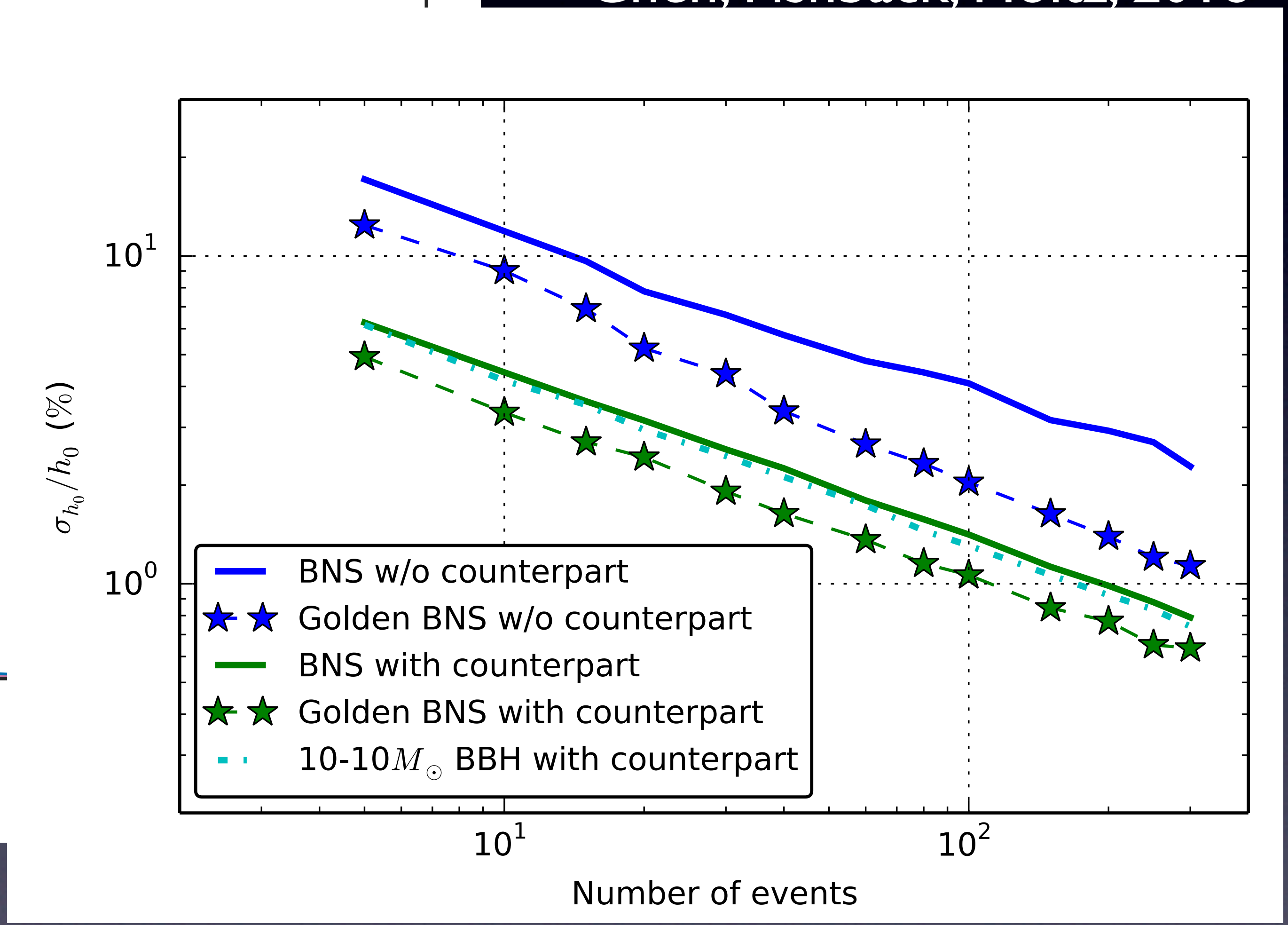
GW as standard sirens



Chen, Fishback, Holtz, 2018



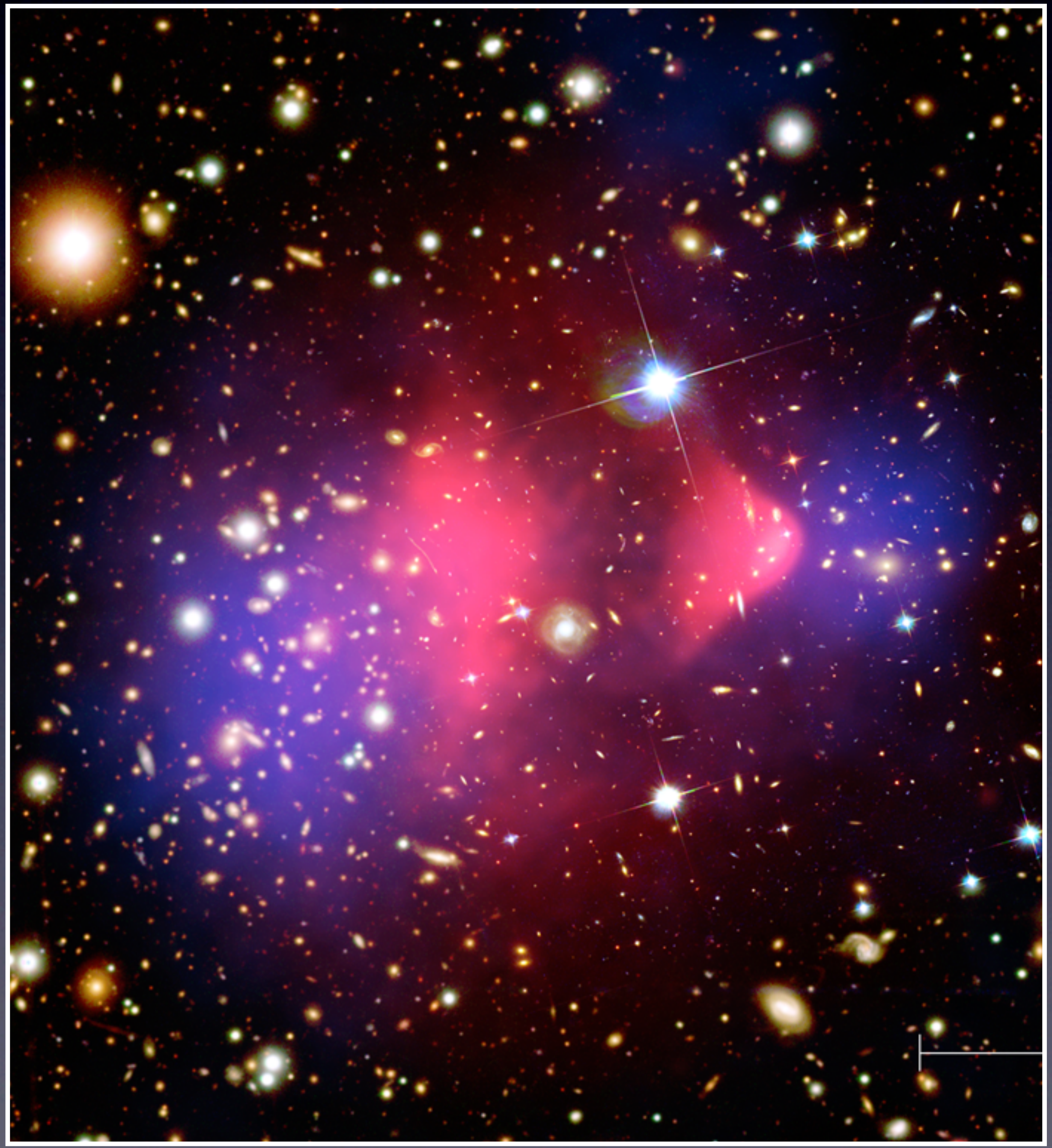
LIGO/VIRGO collaboration, 2017

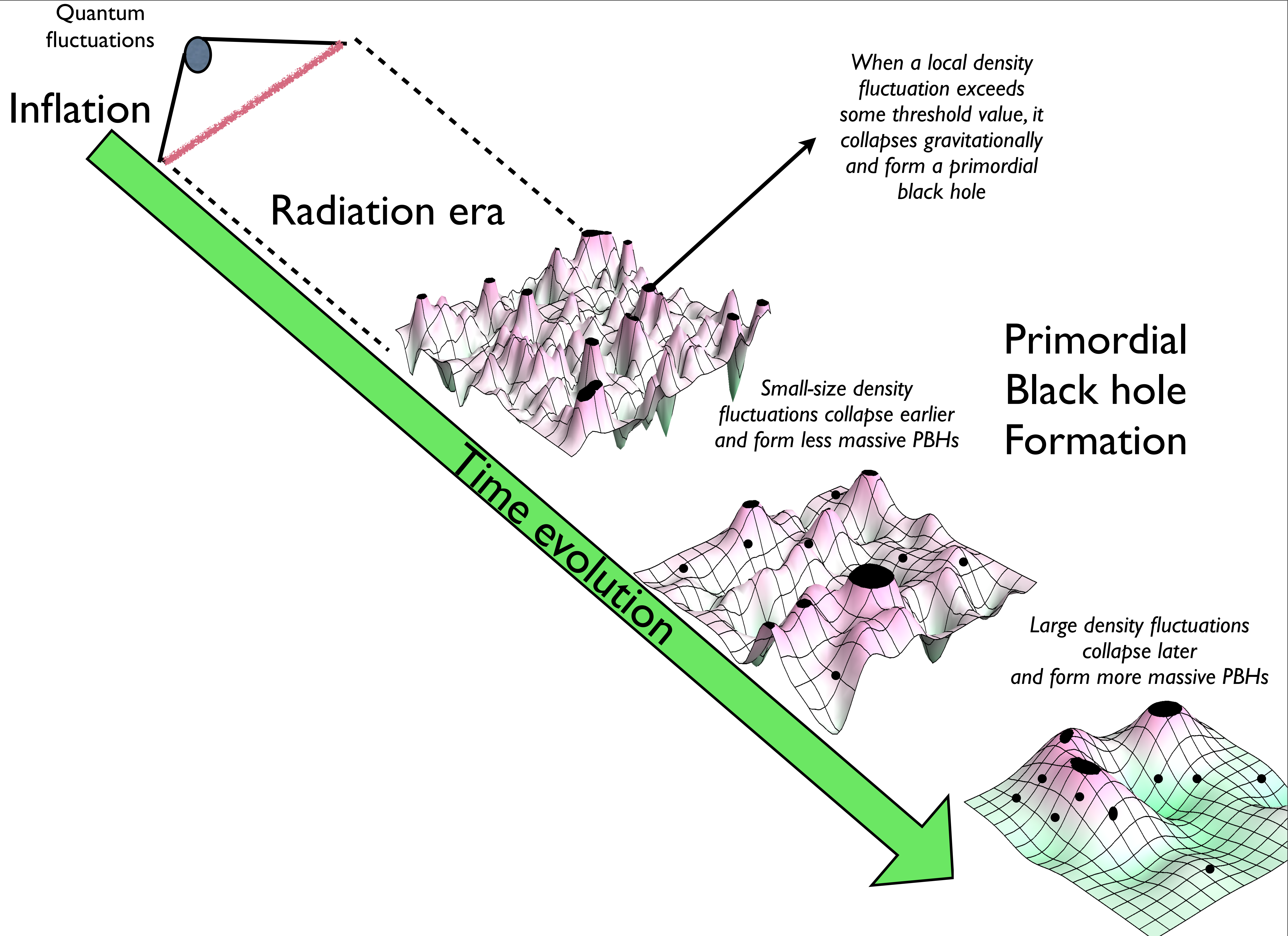
Measurement of H_0 at sub-percent accuracy with ET
Other cosmological parameters (dynamical dark energy)
Go to higher redshifts than galaxy surveys
Tests of the cosmological principle (homogenity/isotropy)

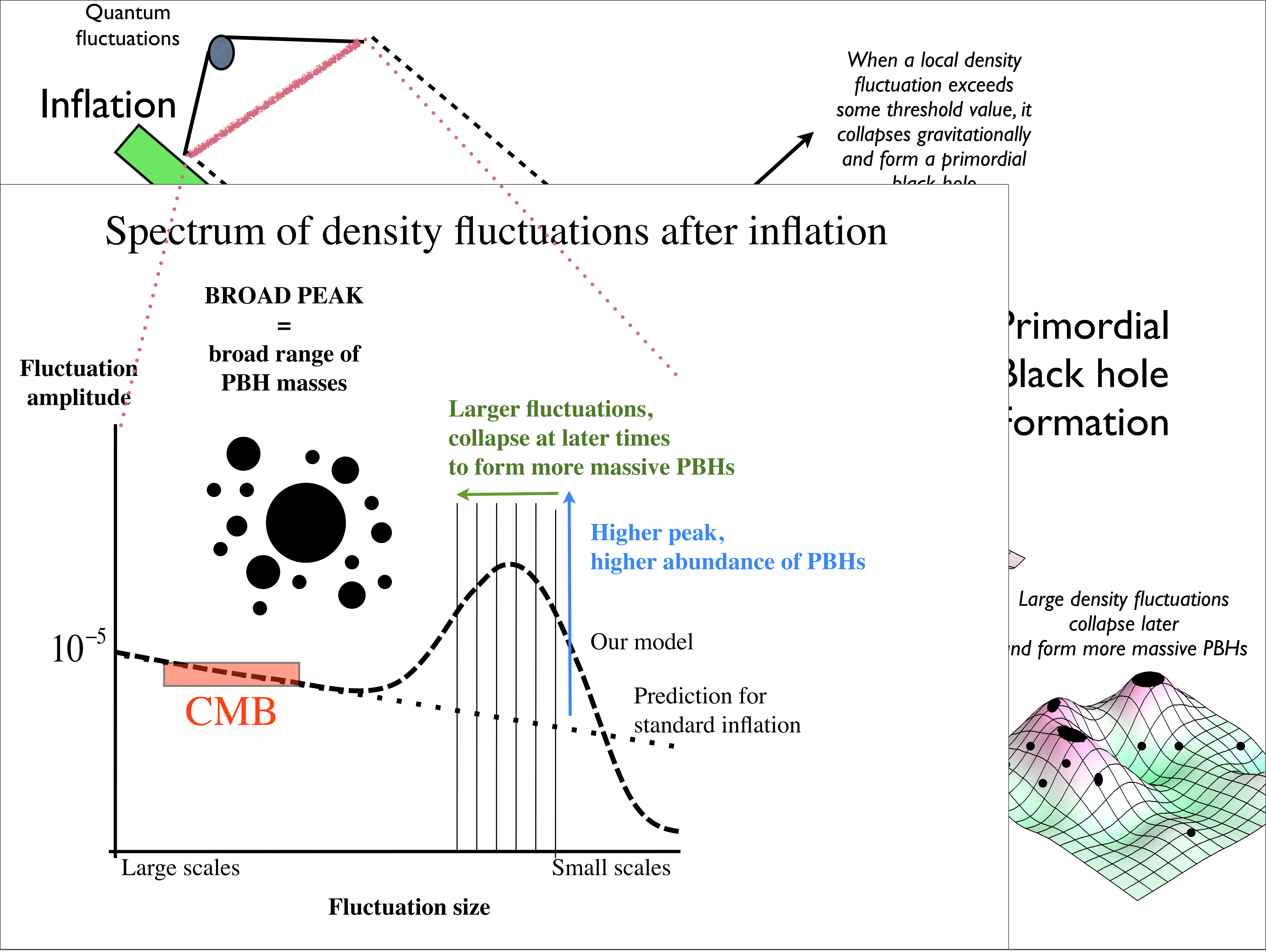
Primordial Black Holes (Dark Matter) with the Einstein Telescope

A good Dark Matter candidate

- Do not emit light by nature
- Non-relativistic
- Nearly collisionless
- Formed in the early Universe




Quantum
fluctuations
Inflation
Radiation era
When a local density
fluctuation exceeds
some threshold value, it
collapses gravitationally
and form a primordial
black hole
Primordial
Black hole
Formation
Small-size density
fluctuations collapse earlier
and form less massive PBHs
Time evolution
Large density fluctuations
collapse later
and form more massive PBHs


Quantum
fluctuations
Inflation
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Spectrum of density fluctuations after inflation
BROAD PEAK
=
broad range of
PBH masses
Fluctuation
amplitude
Larger fluctuations,
collapse at later times
to form more massive PBHs
Higher peak,
higher abundance of PBHs
10^{-5}
Our model
Prediction for
standard inflation
CMB
Large scales
Small scales
Fluctuation size
rimordial
lack hole
ormation
Large density fluctuations
collapse later
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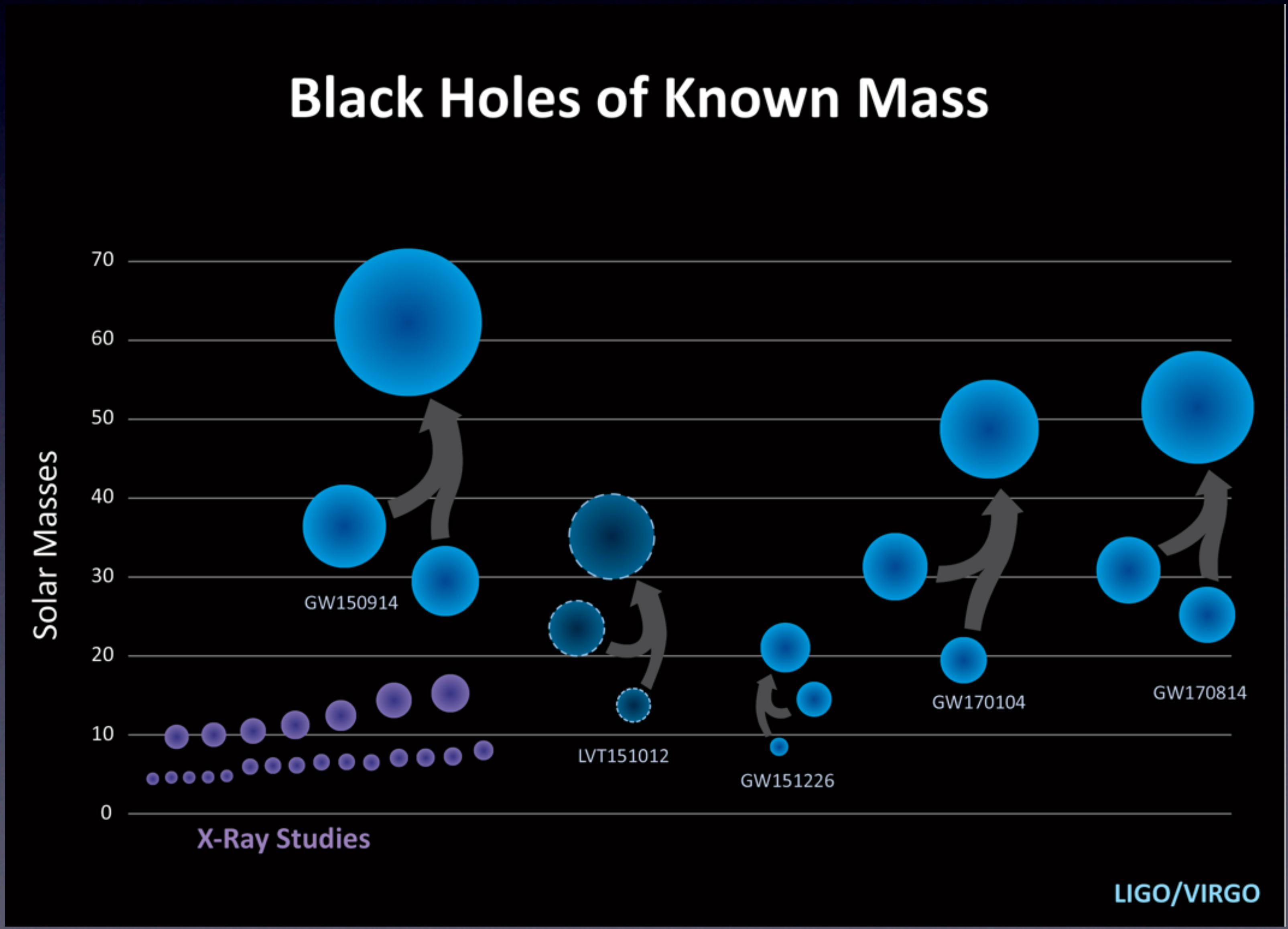
LIGO/VIRGO and the unexpected BH mergers

- Unexpected large masses for GW150914
- 4 other events > 15 Msun (several events not yet released)
- Inferred rates: 14-158 $Gpc^{-3}\ yr^{-1}$
- Non-aligned, low spins



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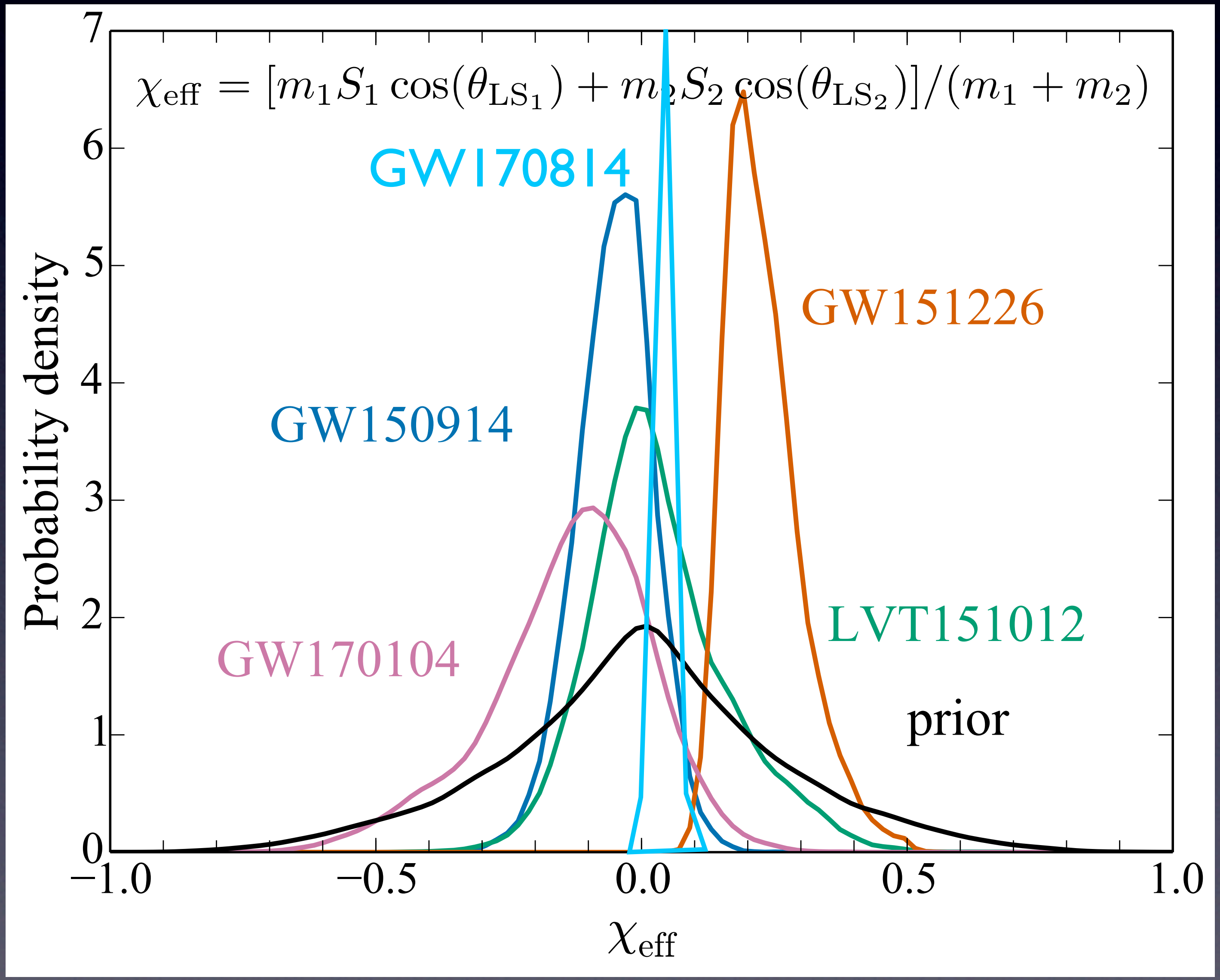

Adapted from Adv.LIGO/VIRGO June release (supl. material)

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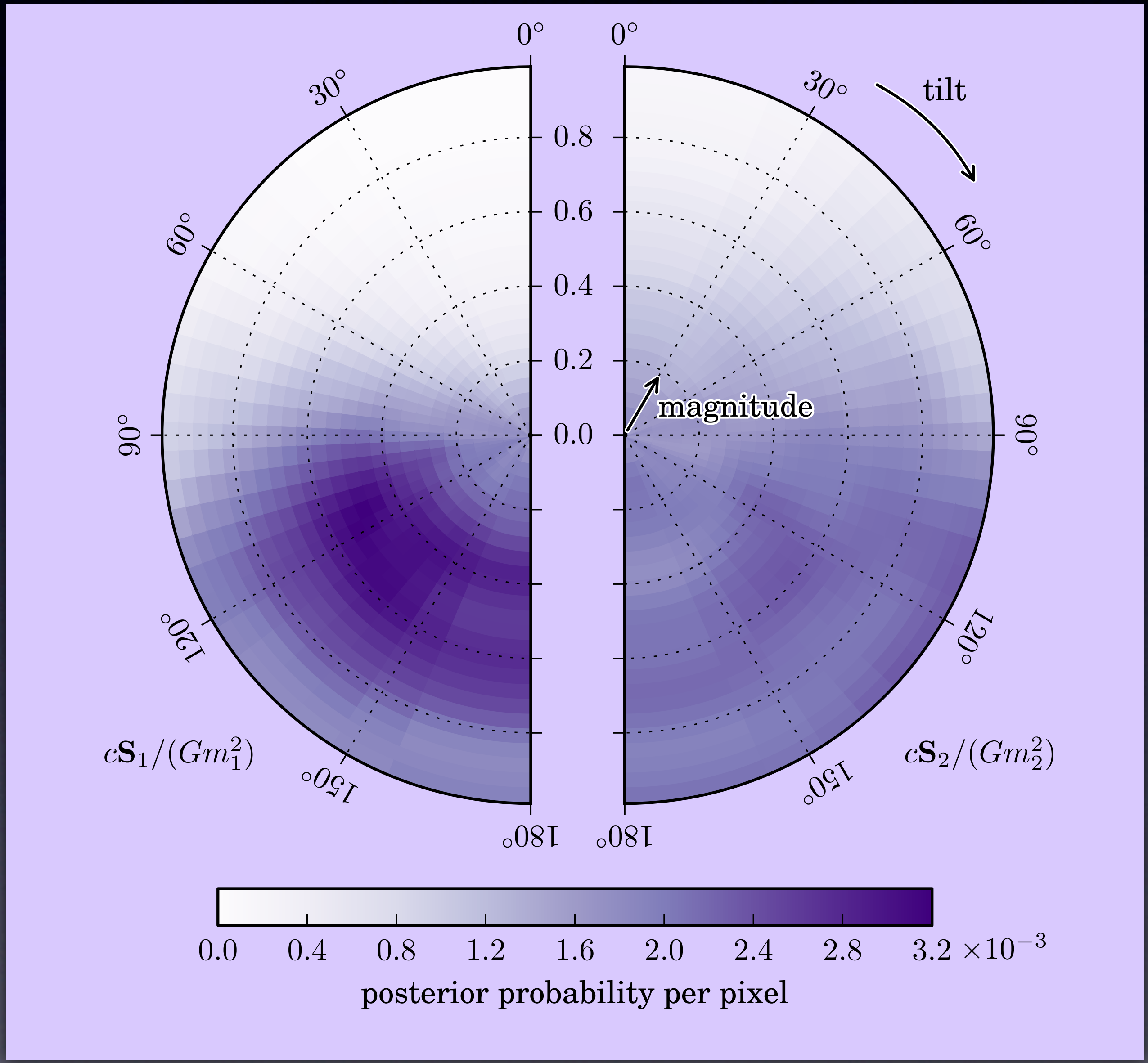

Adv.LIGO/VIRGO June release (supl. material)

« a new population of black holes »

In March 2016...

- S. Bird et al., 1603.00464
  Monochromatic spectrum, extended halo mass function

$$\tau_{\rm merg} \sim 2 f_{\rm HMF} f_{\rm DM} \left(M_{\rm crit.halo}/400 M_\odot\right)^{-11/21} \, {\rm Gpc^{-3} yr^{-1}}$$

Most mergings come from mini-halos

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- S.C., J. Garcìa-Bellido, 1603.05234
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Faint Dwarf Galaxies or Globular Clusters

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Faint Dwarf Galaxies or Globular Clusters

- M. Sasaki et al., 1603.08338
  Monochromatic spectrum, BH binaries from Early Universe

$$\tau_{\rm merg} \sim f_{\rm DM} 10^{4} {\rm Gpc}^{-3}{\rm yr}^{-1}$$

PBH cannot be the Dark Matter except if they have a broad mass distribution and/or are initially clustered

In March 2016...

- S. Bird et al. 1603.00464
  M ...on
  ...ergings
  ...mini-halos
- S.
  Br...
  ...Galaxies
  ...Clusters
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  ...atter
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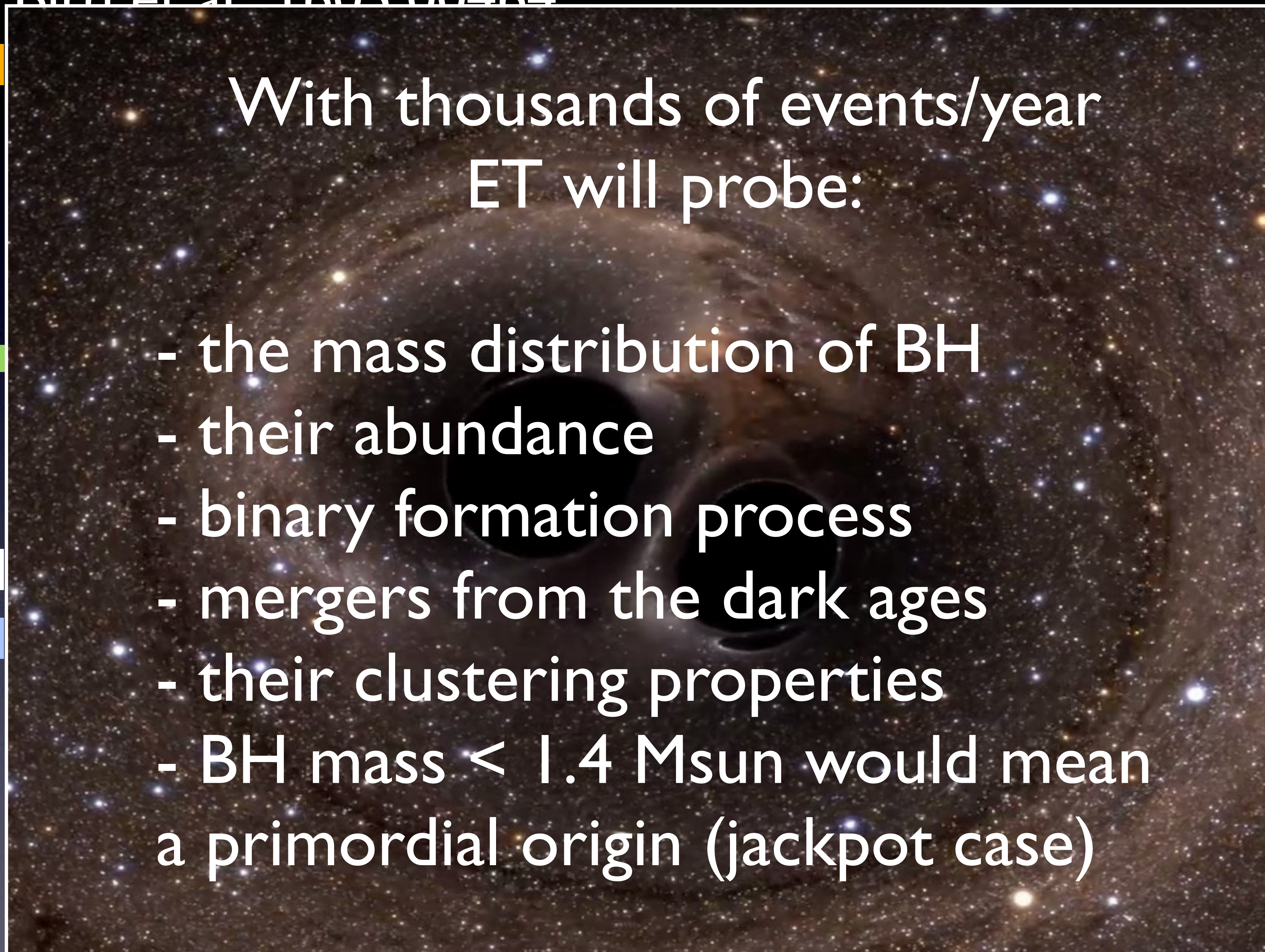
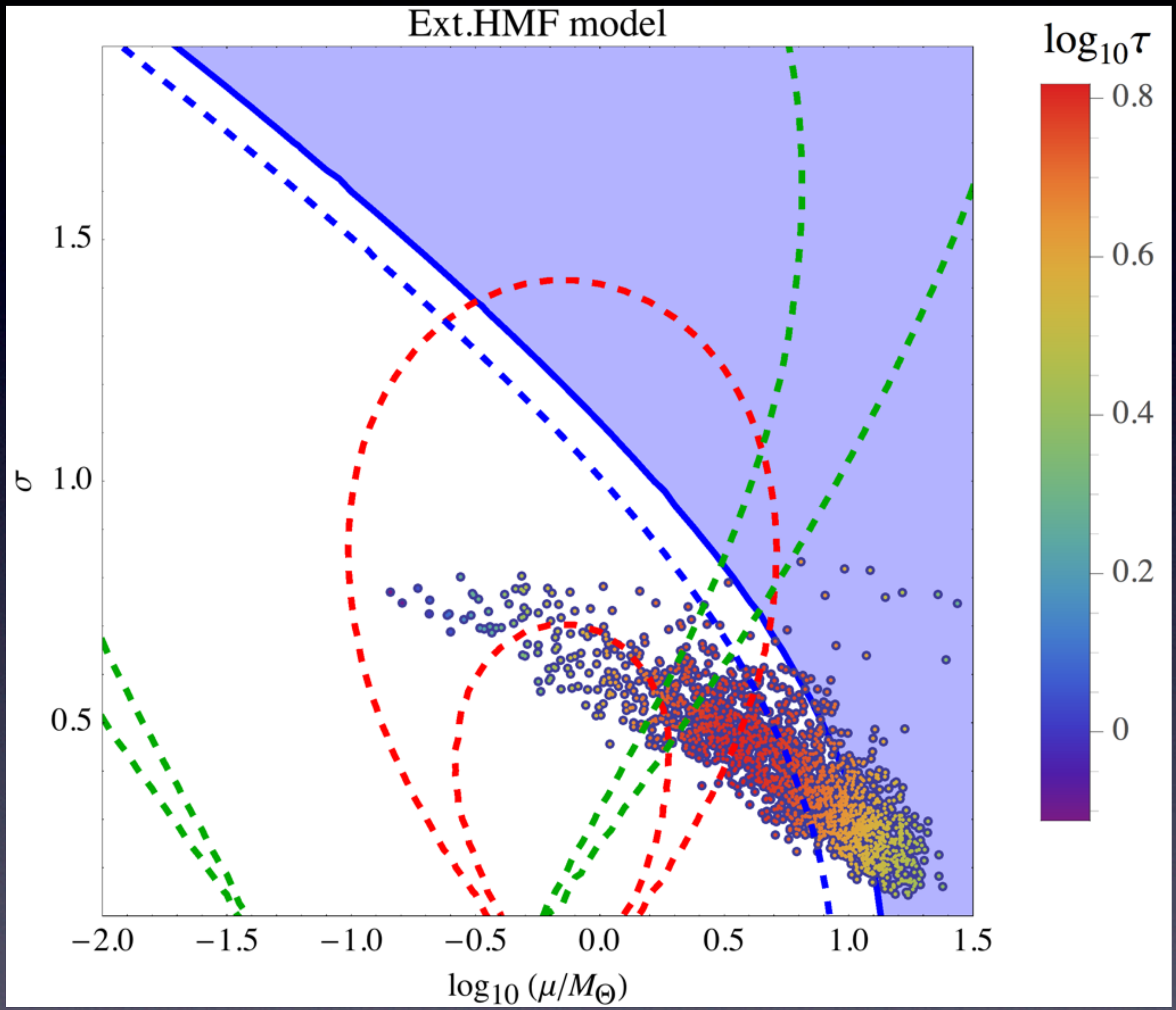


Seven clues for PBH-DM



S.C., J. Garcia-Bellido, 1711.10458

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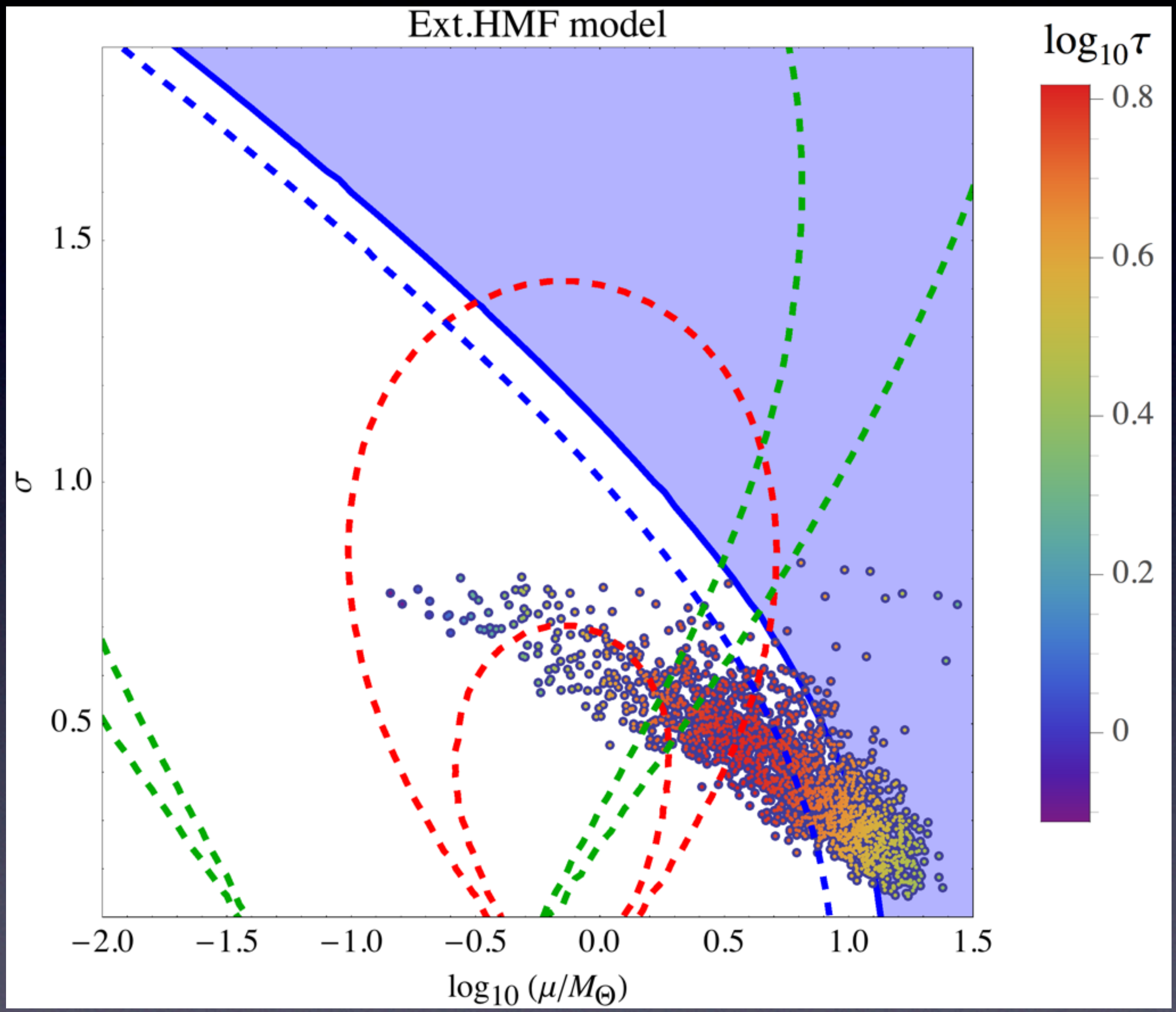

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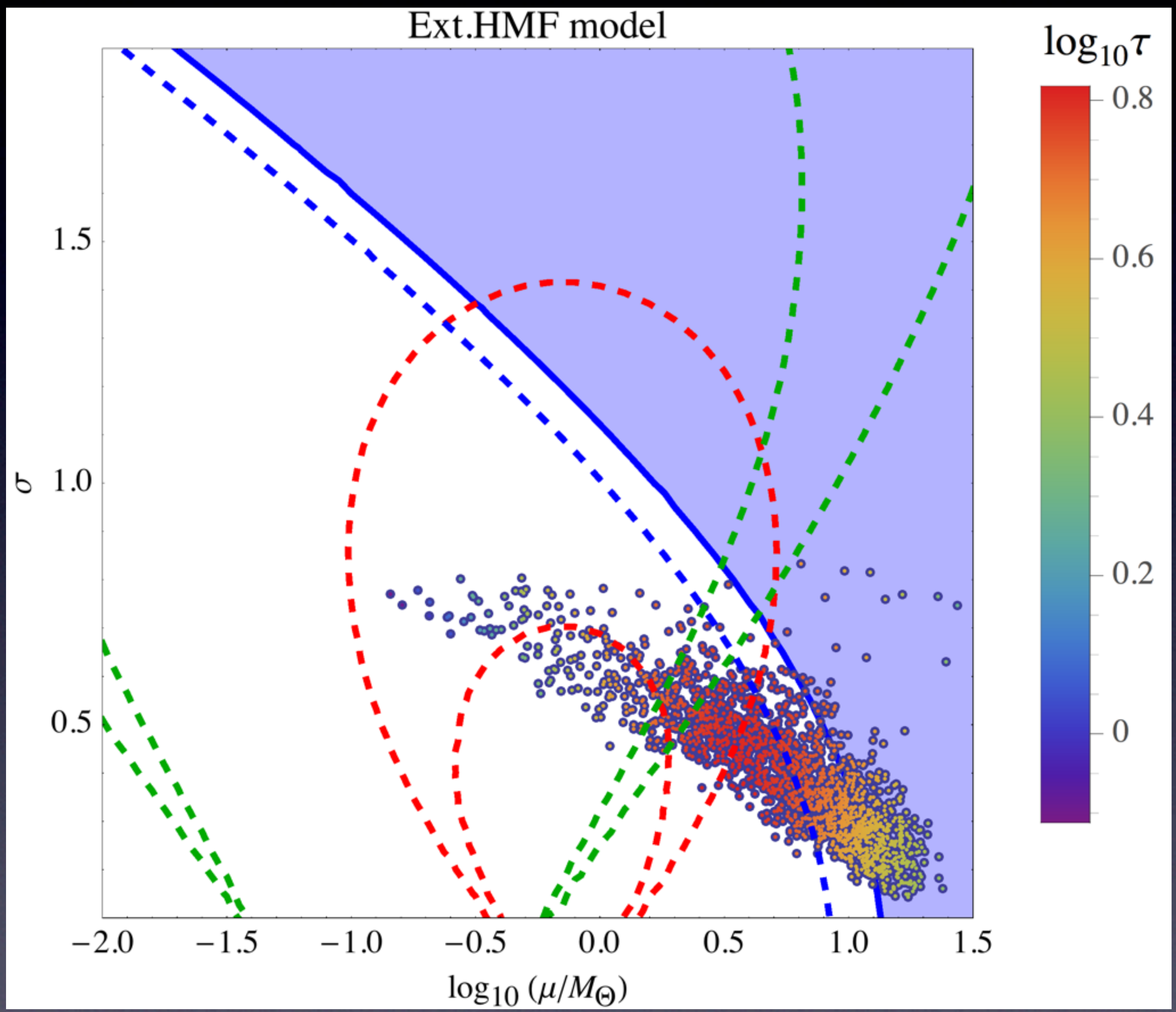

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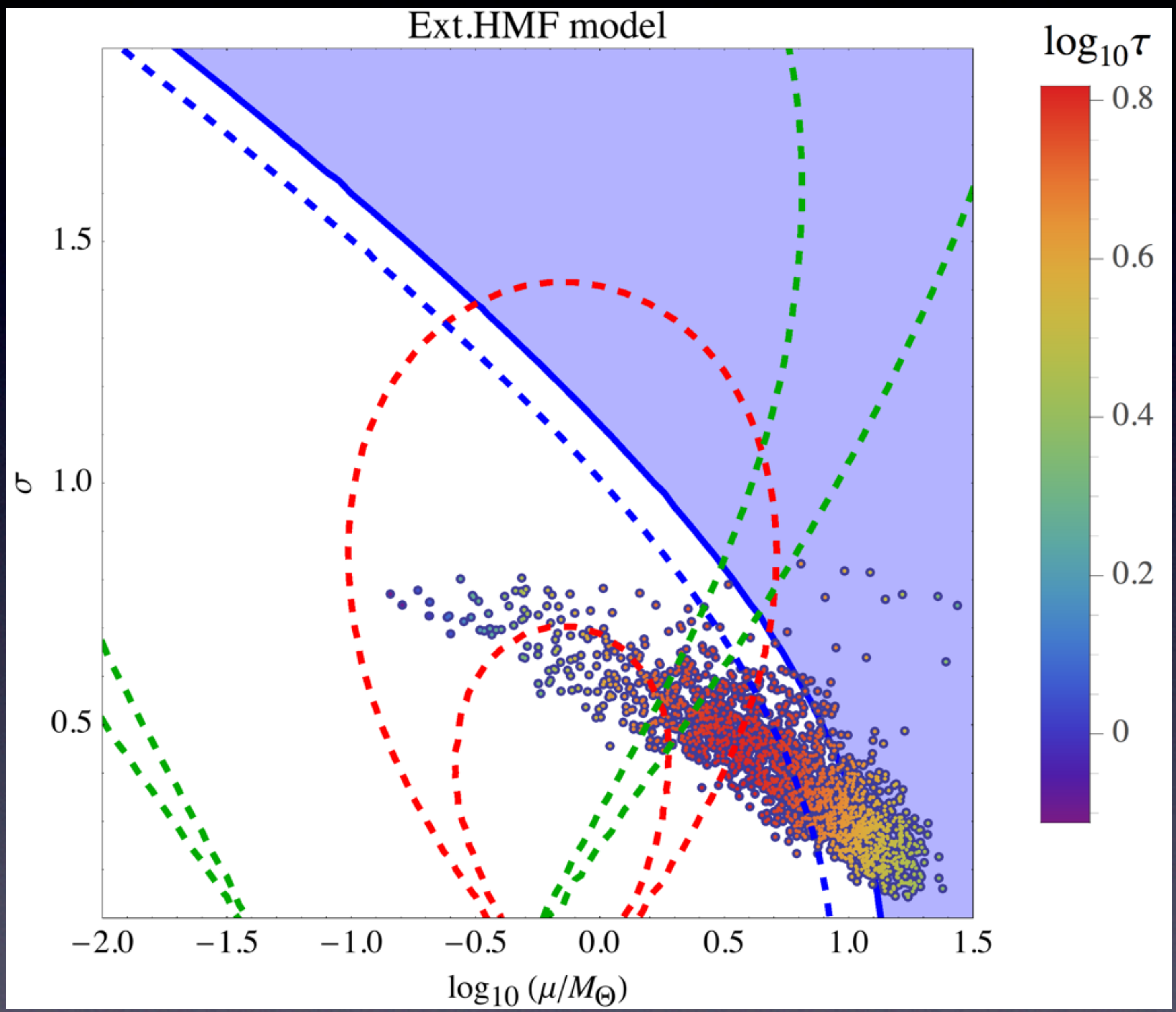

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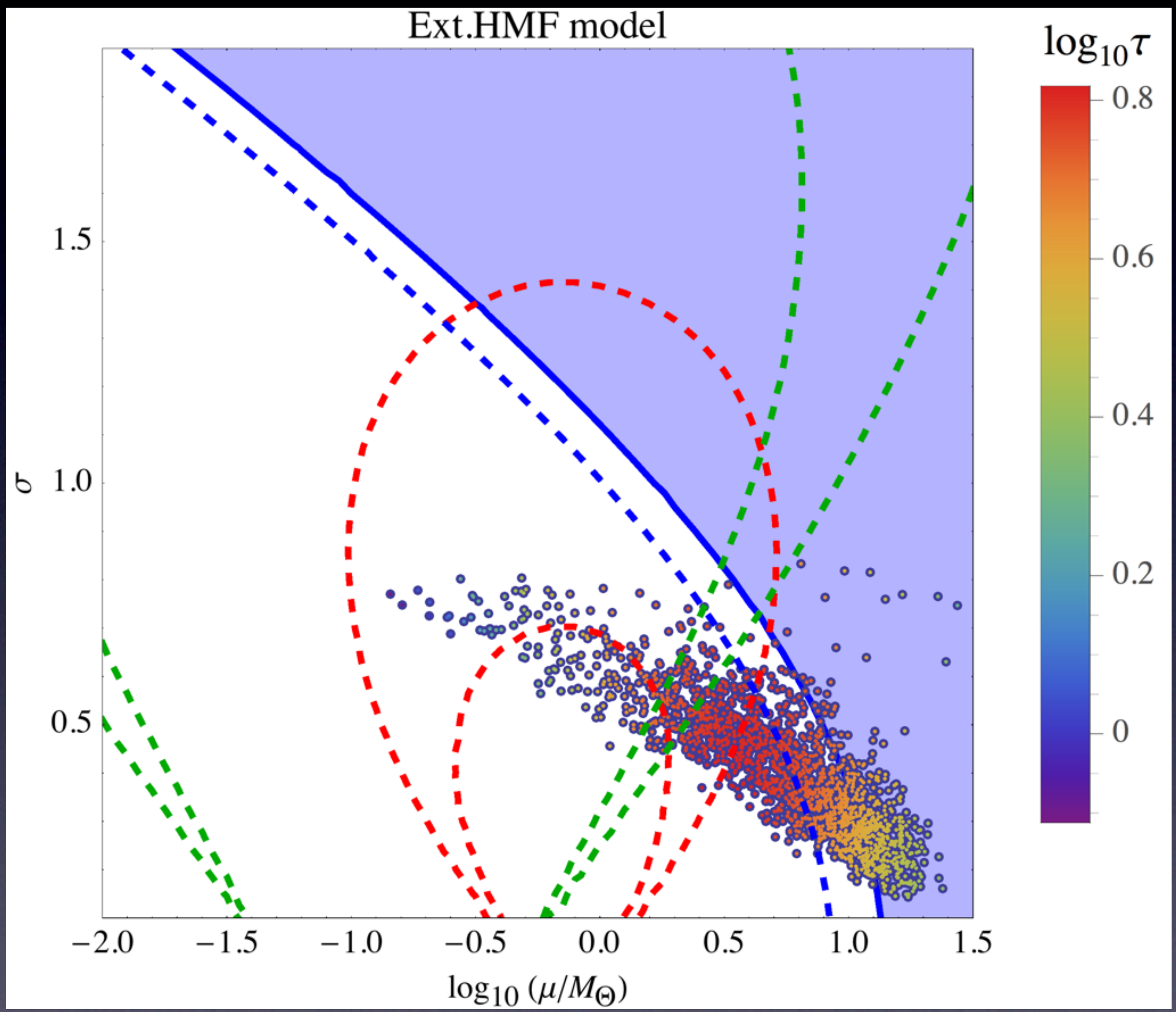

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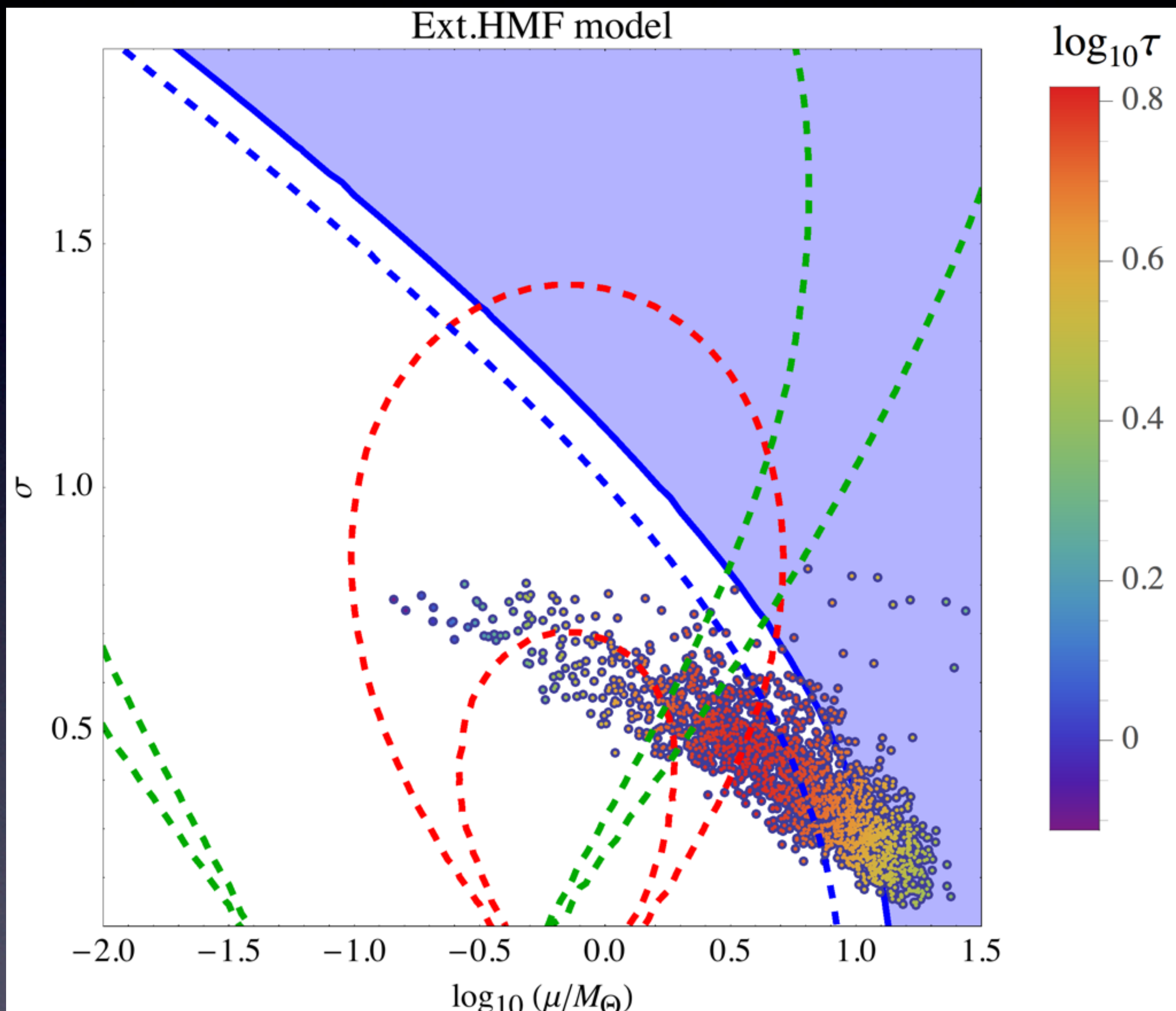

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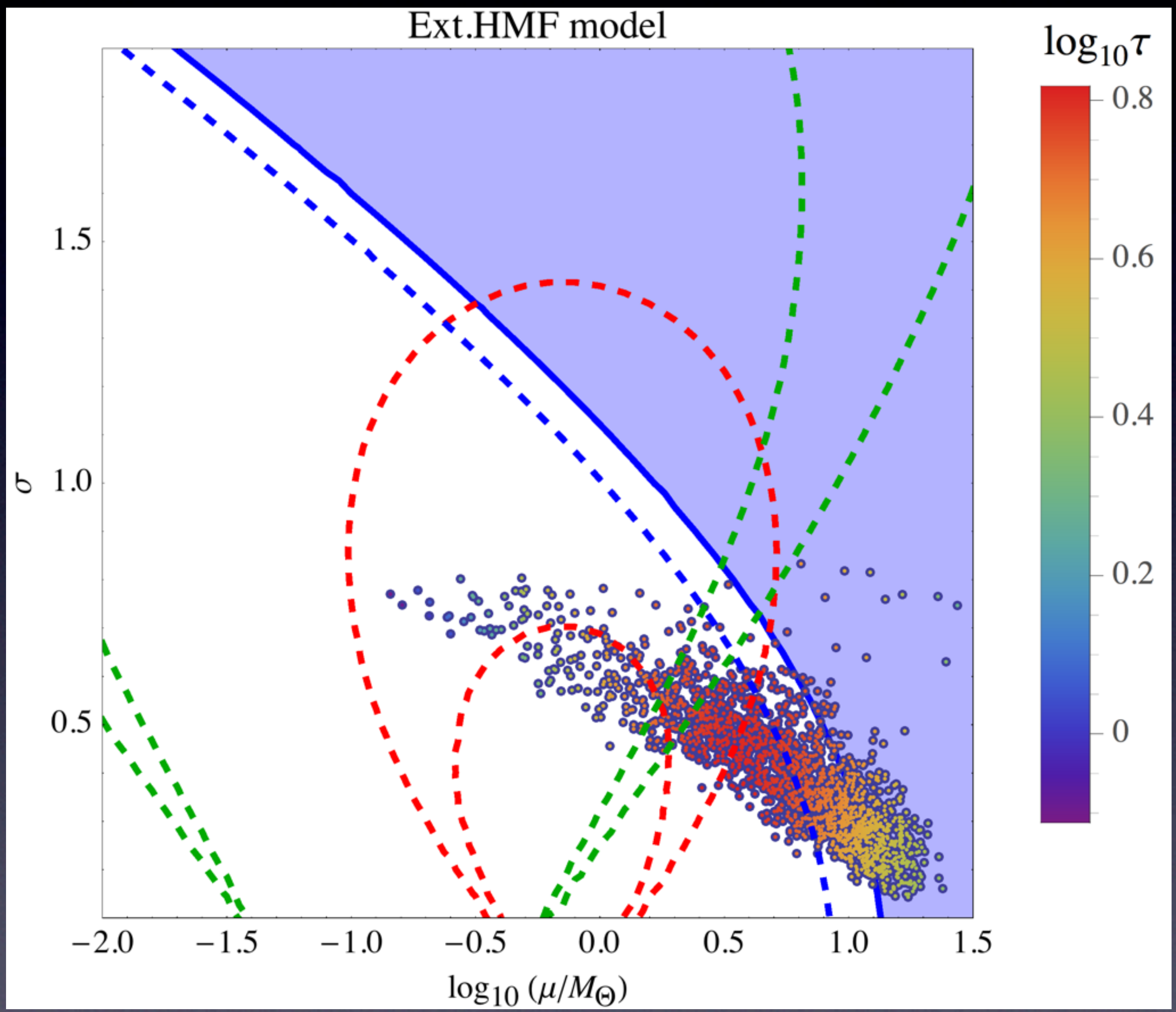

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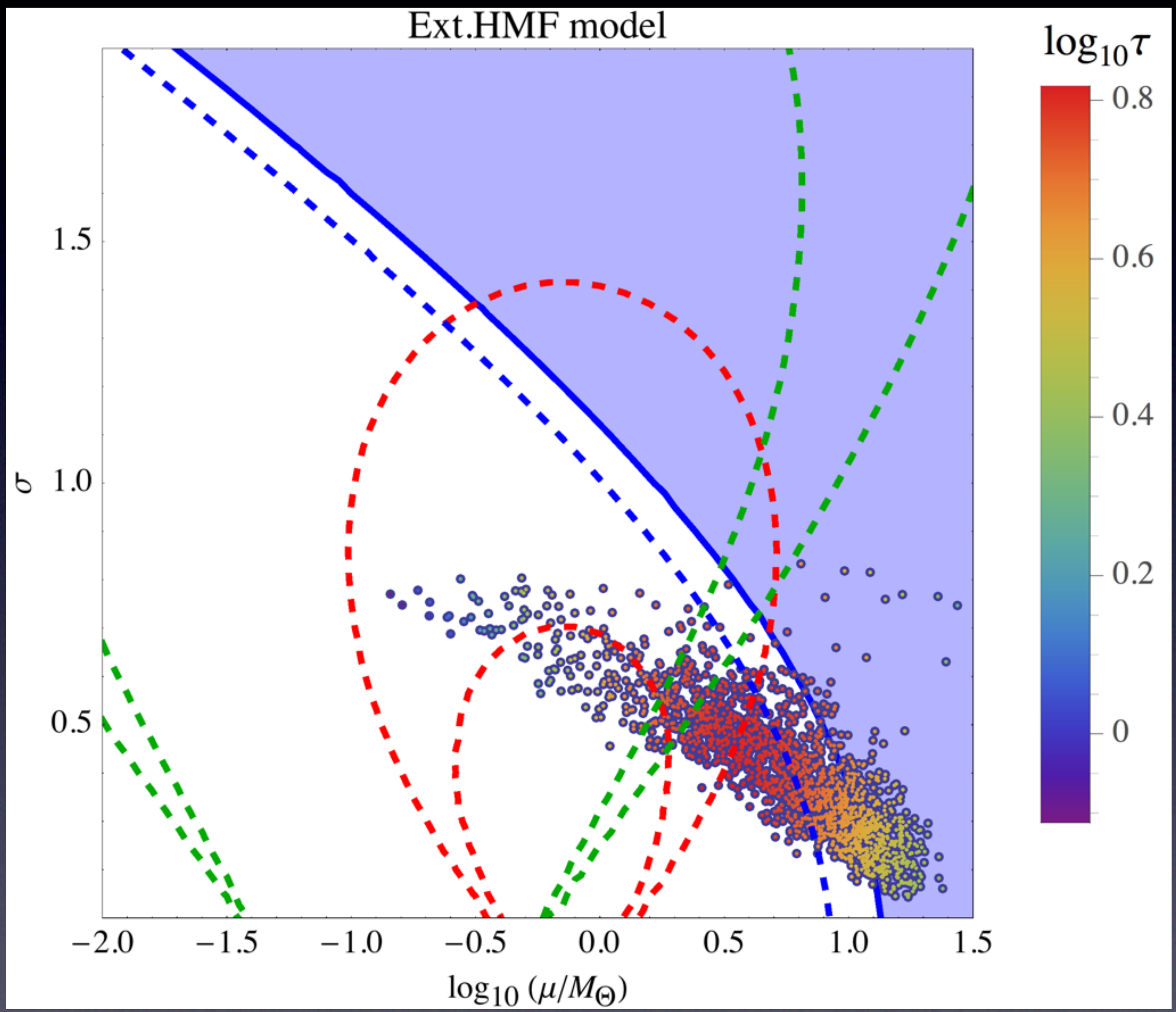

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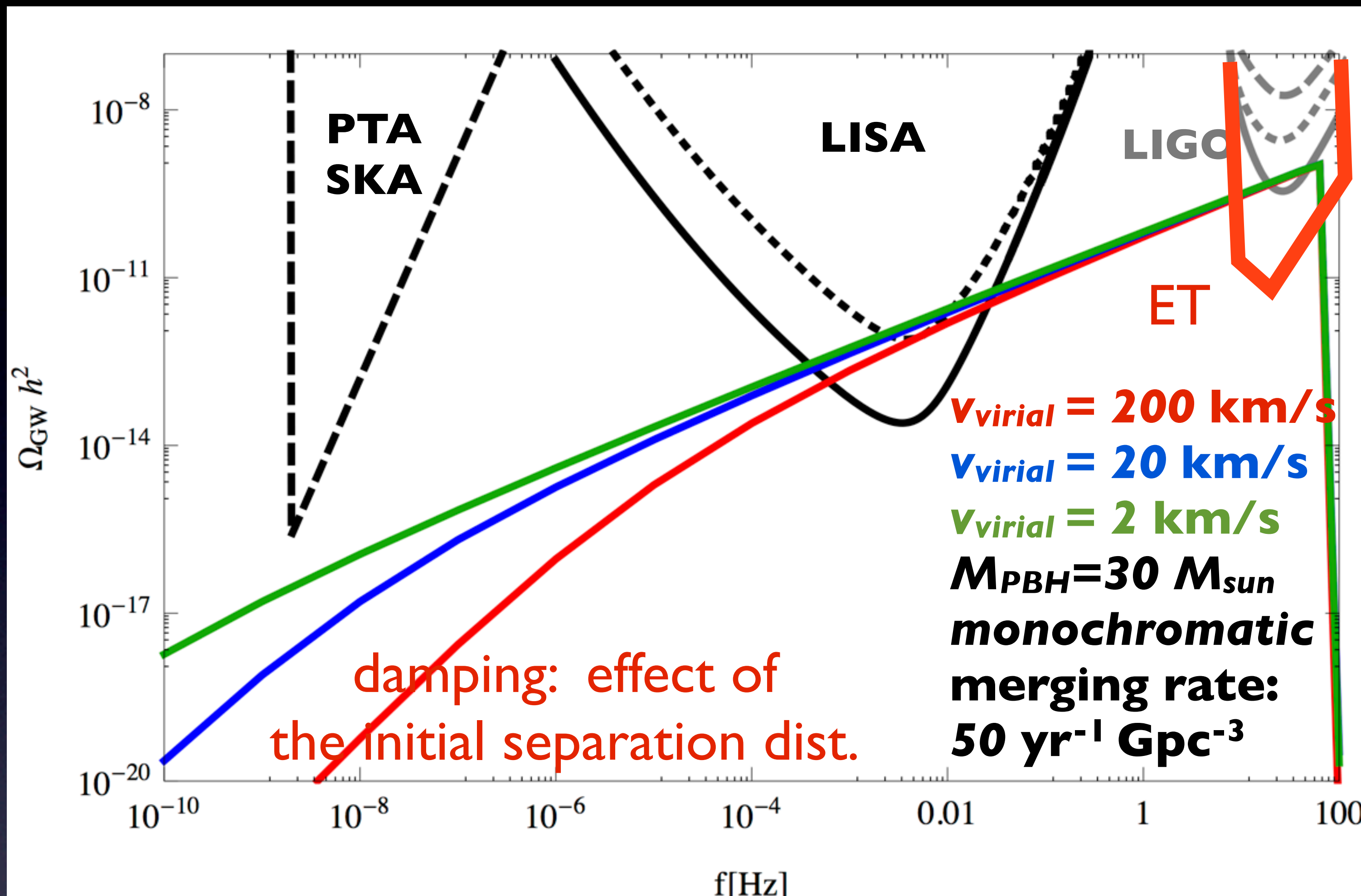
- Clue 7: Supermassive BH at high redshifts

Stochastic background



S.C., J. Garcia-Bellido, 1610.08479

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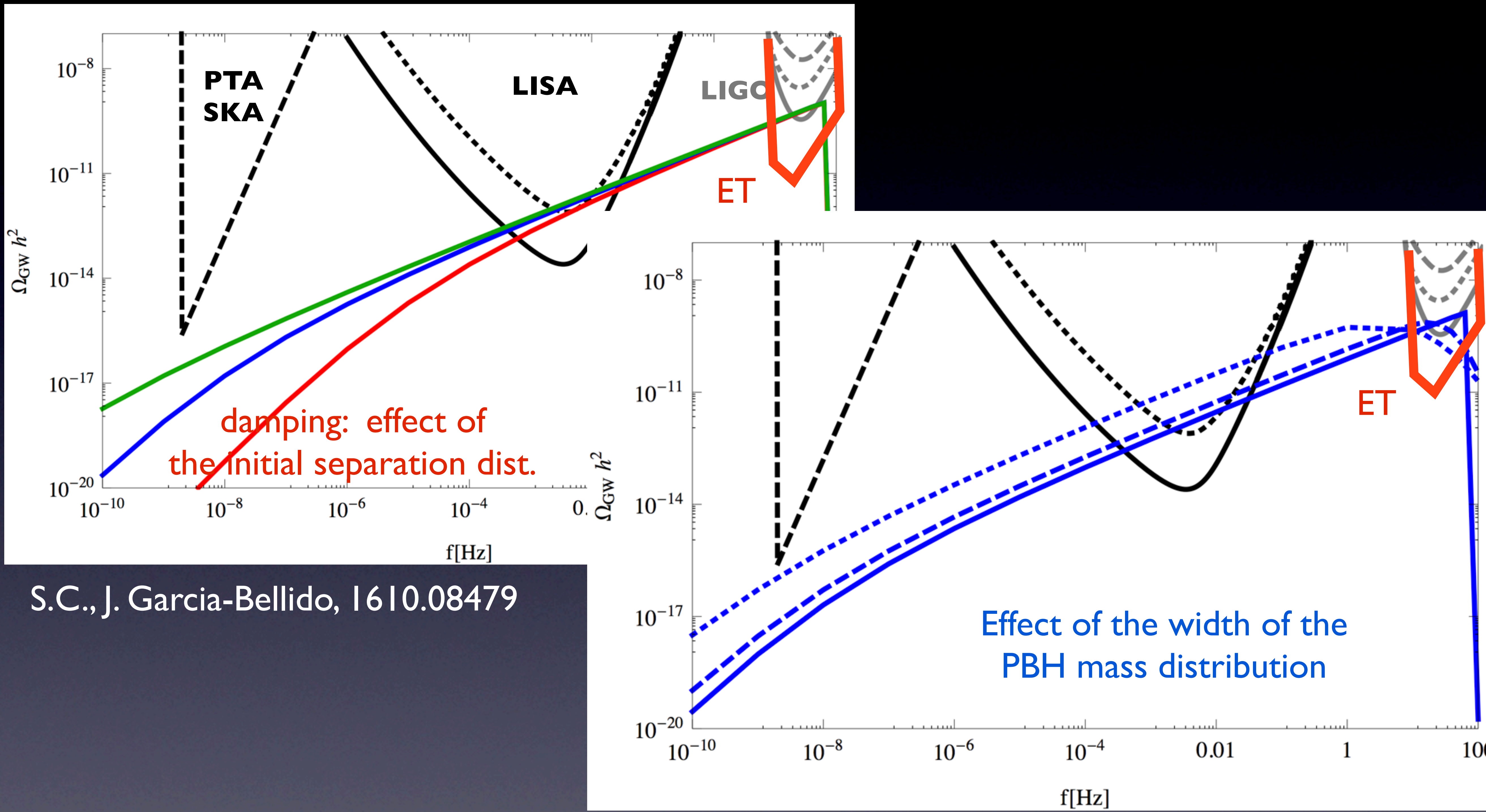

S.C., J. Garcia-Bellido, 1610.08479

Stochastic background depends on
clustering and width of the mass distribution

Conclusion

- ET will probe the early Universe, up to $T\sim10^{10}$ GeV, $z\sim10^{23}$
- Many possible stochastic backgrounds: inflation, reheating, phase transitions, oscillons, cosmic strings, PBH formation/mergers/encounters...
- Precision cosmology with standard sirens
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LIGO/VIRGO and the unexpected BH mergers

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The bright scenario

- From star explosion
- Low-metallicity environment
- Super-dense clusters
- BUT: why so massive?
- BUT: unrealistic rates
- Need a new model...

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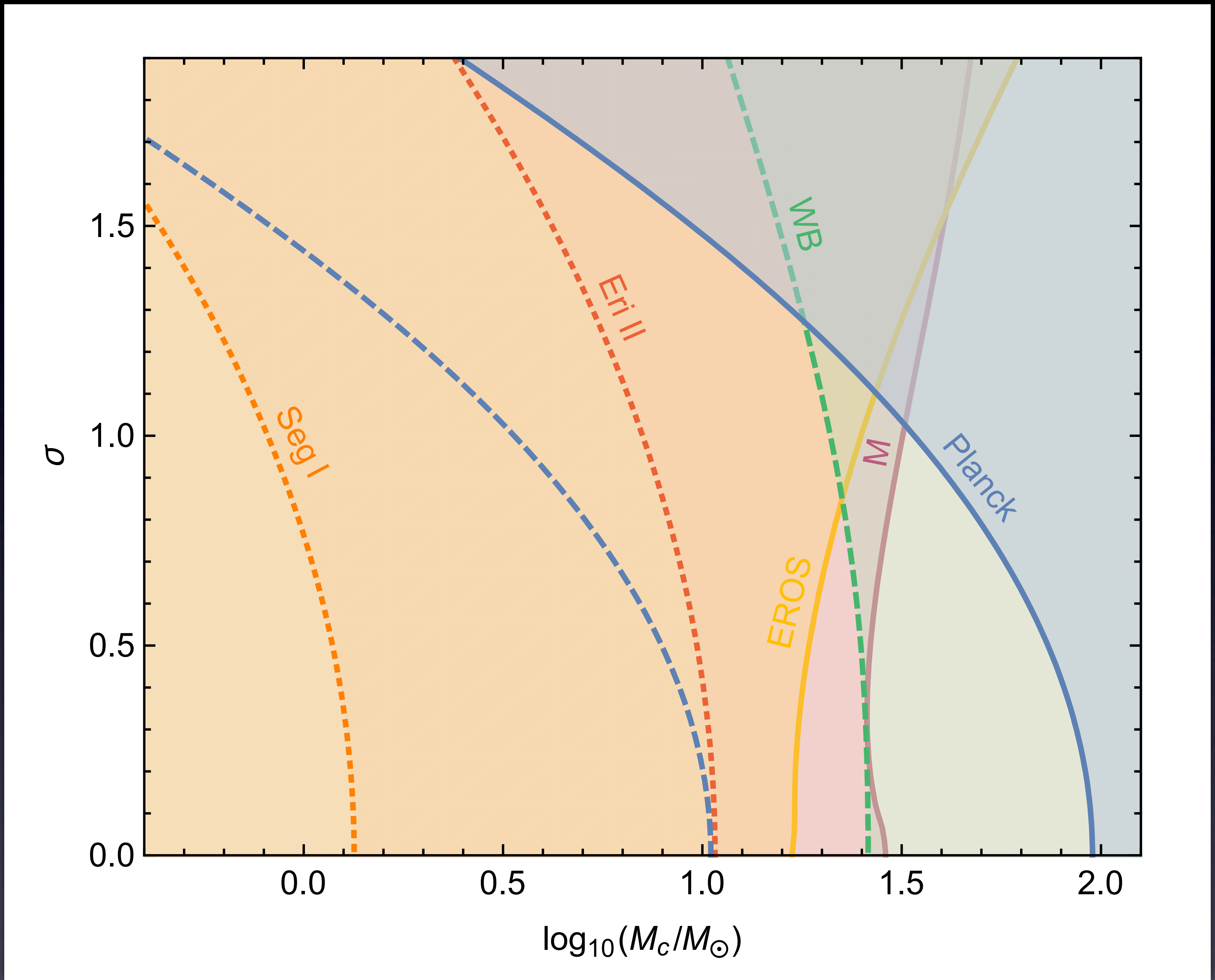

B. Carr et al., 1705.05567

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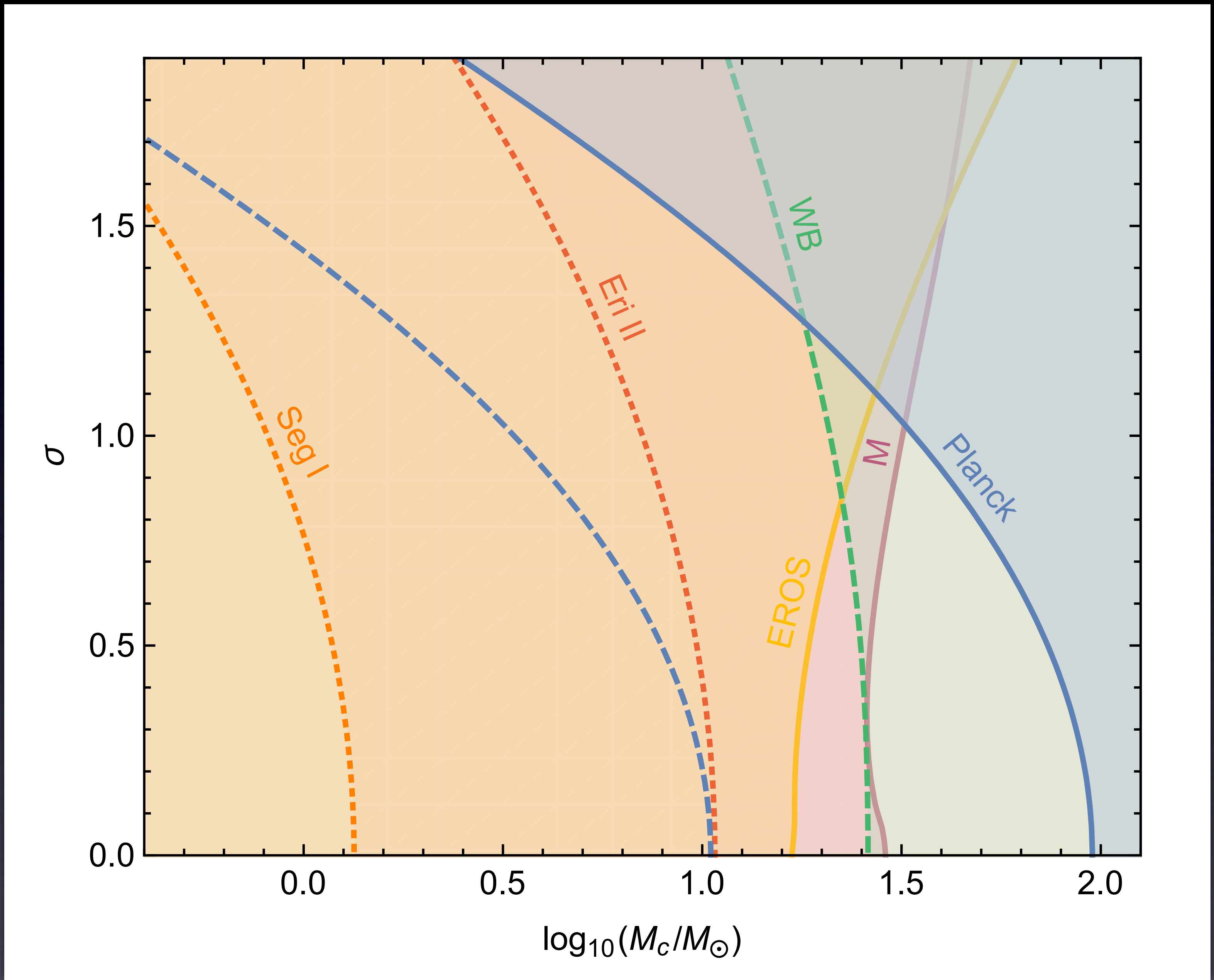
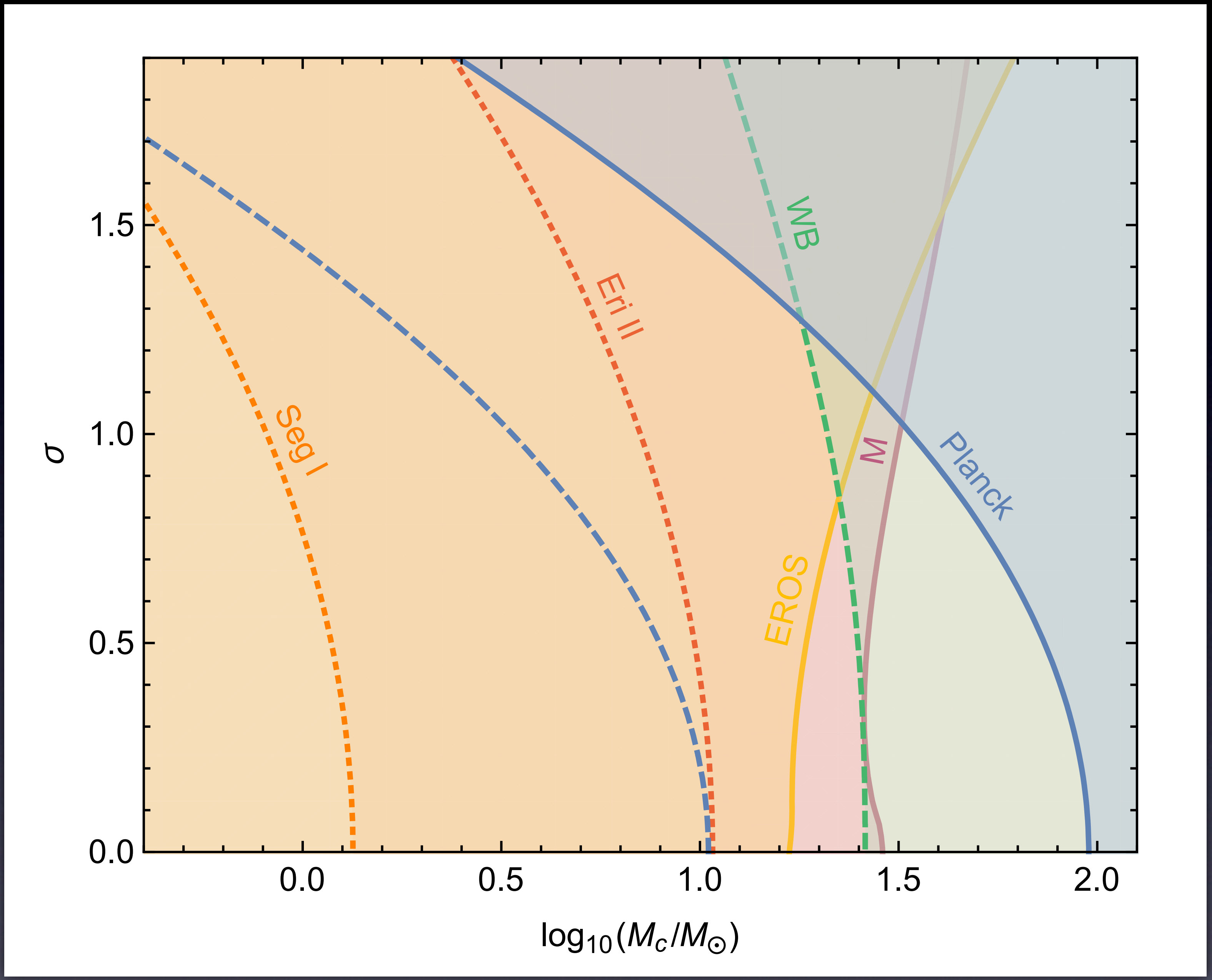


Broad spectrum (log-normal dist): PBH-DM looks excluded in the whole parameter range

B. Carr et al., 1705.05567

Constraints on PBH abundances



B. Carr et al., 1705.05567

Broad spectrum (log-normal dist): PBH-DM looks excluded in the whole parameter range

Microlensing constraints controversial and evaded if PBH are clustered

J. Garcia-Bellido, S.C., 1710.04694

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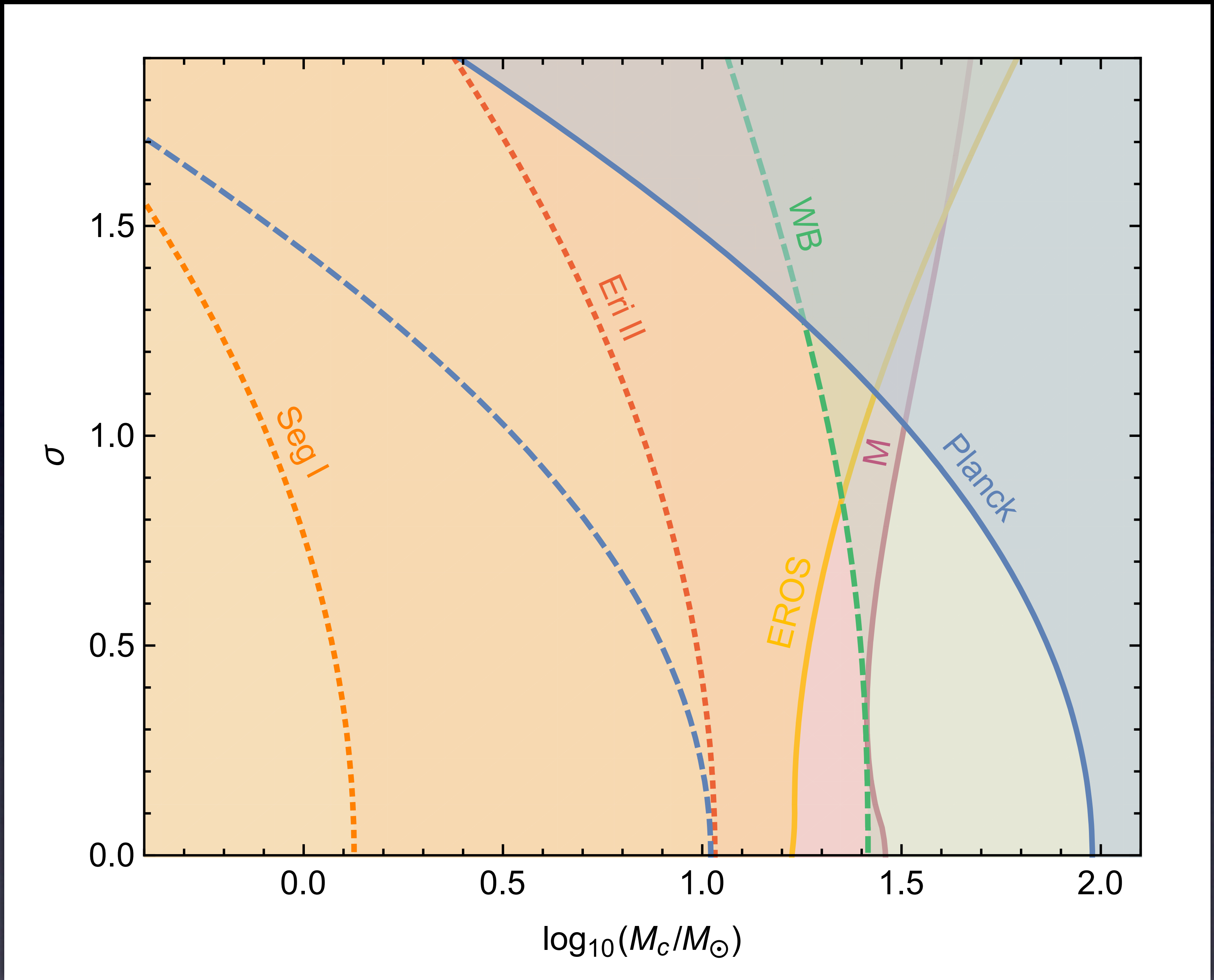

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Segue 1 constraints cannot be simply extrapolated to the broad case

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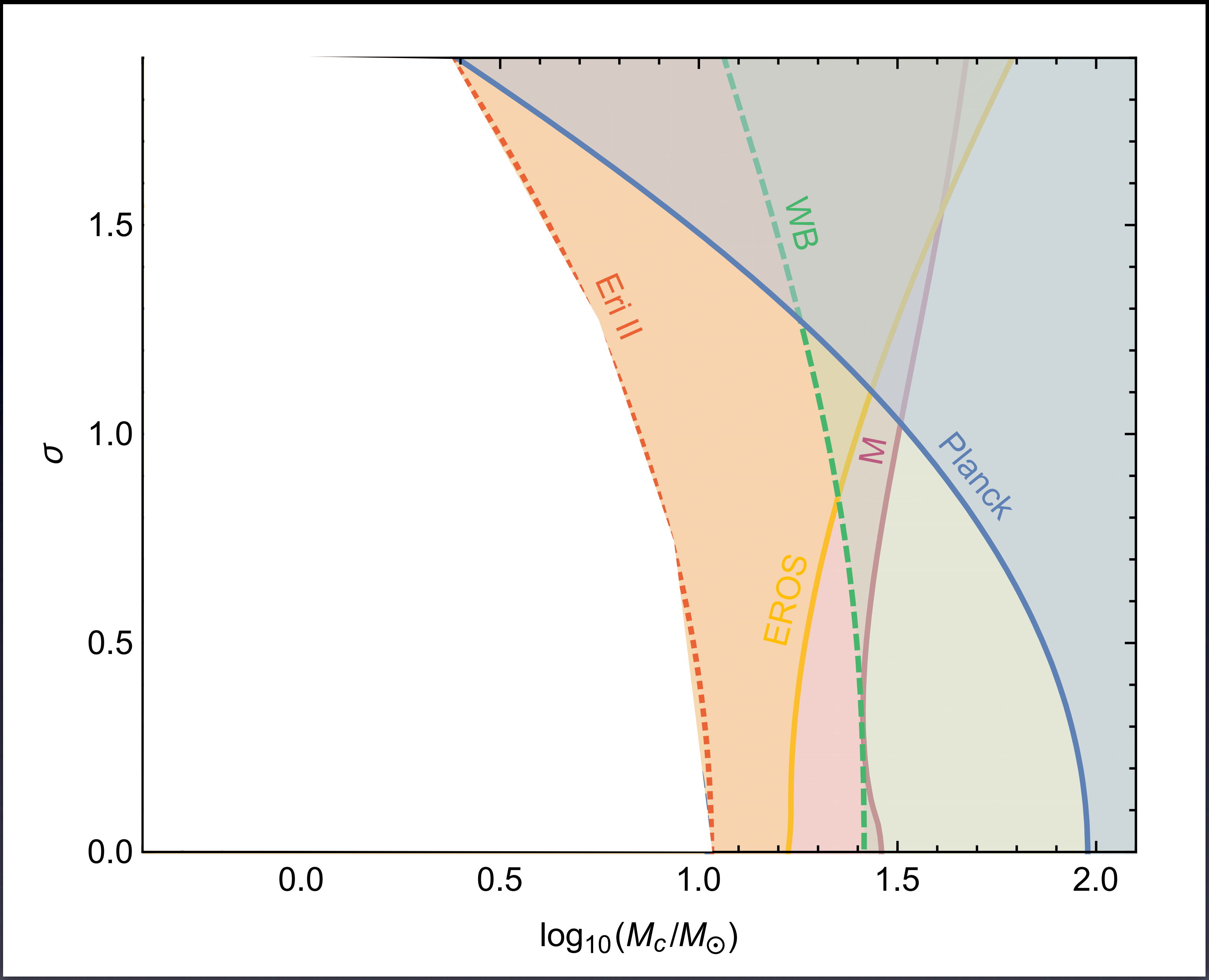

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J. Garcia-Bellido, S.C., 1710.04694

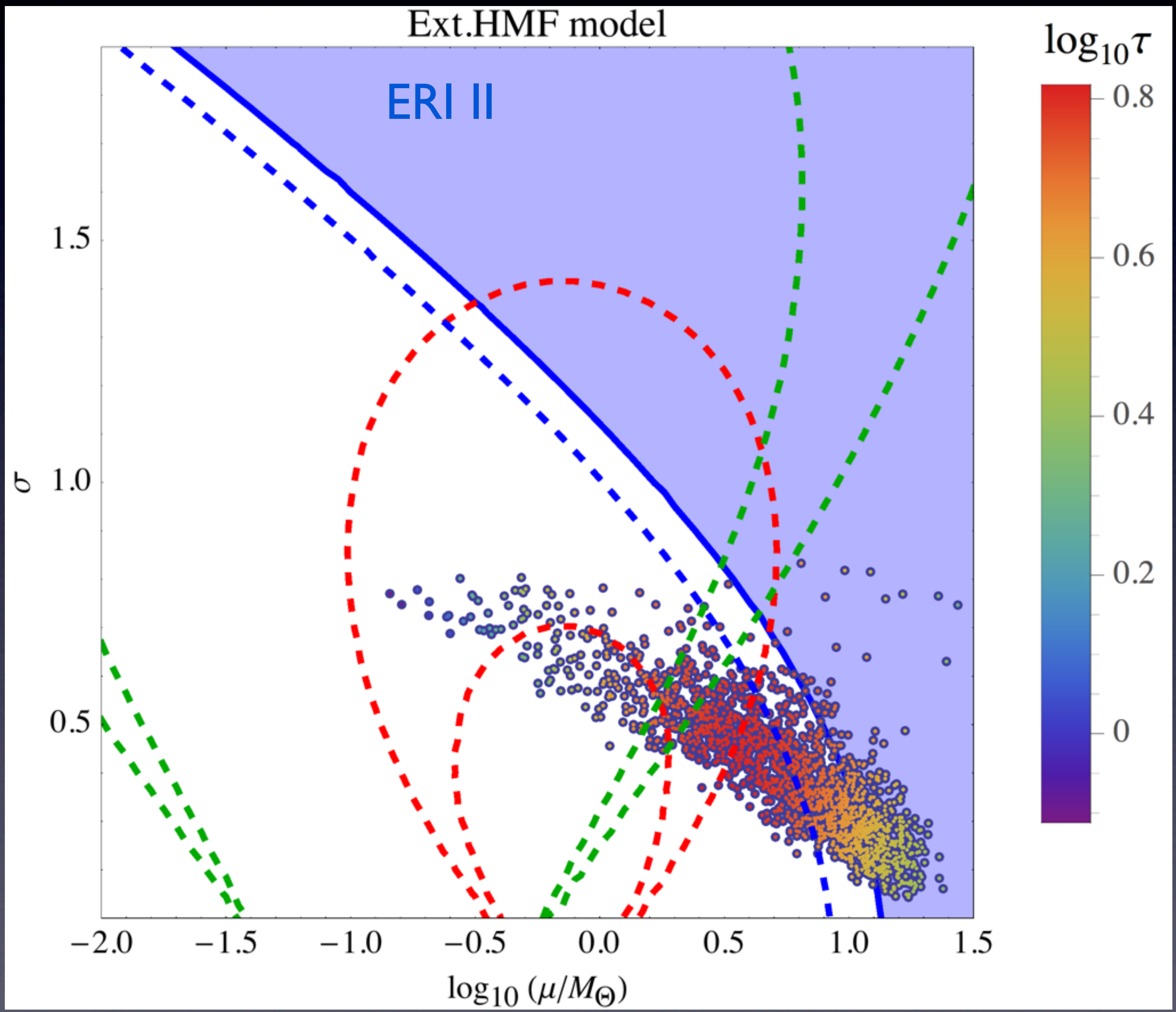
Segue I constraints cannot be simply extrapolated to the broad case

Part II: Seven hints (clues) for PBH Dark Matter

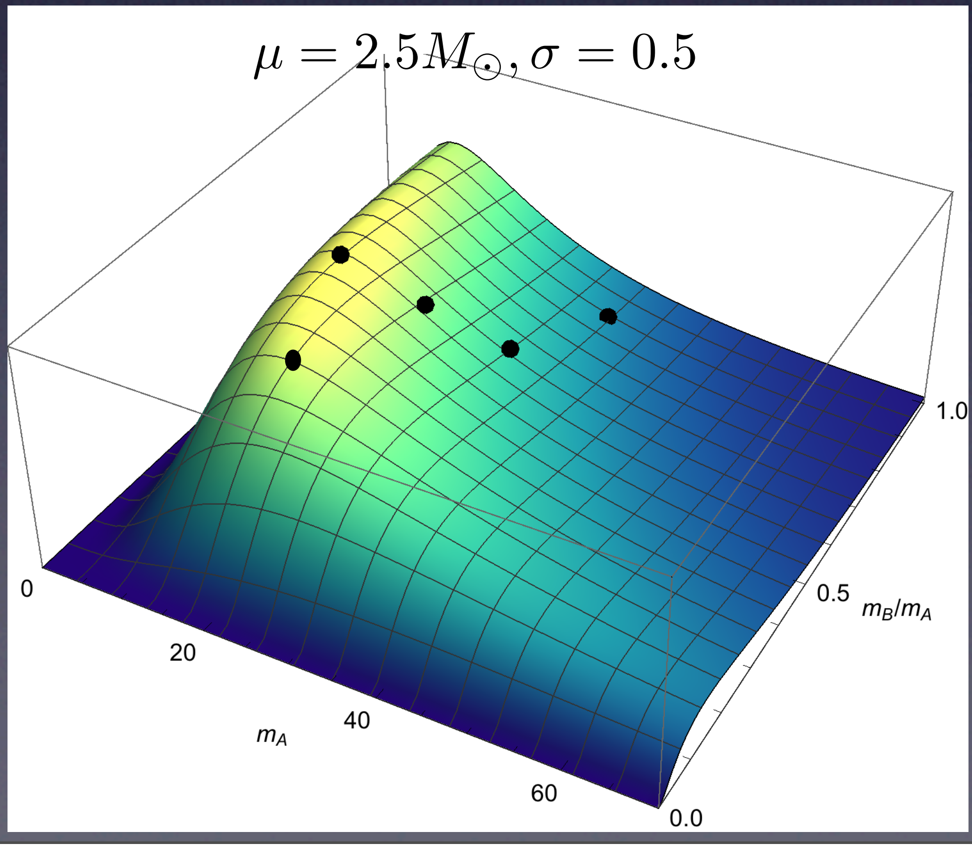
S.C., J. Garcia-Bellido, arXiv:1711.10458

Seven hints for PBH-DM

Hints 1 and 2: BH merger masses, rates, and spins

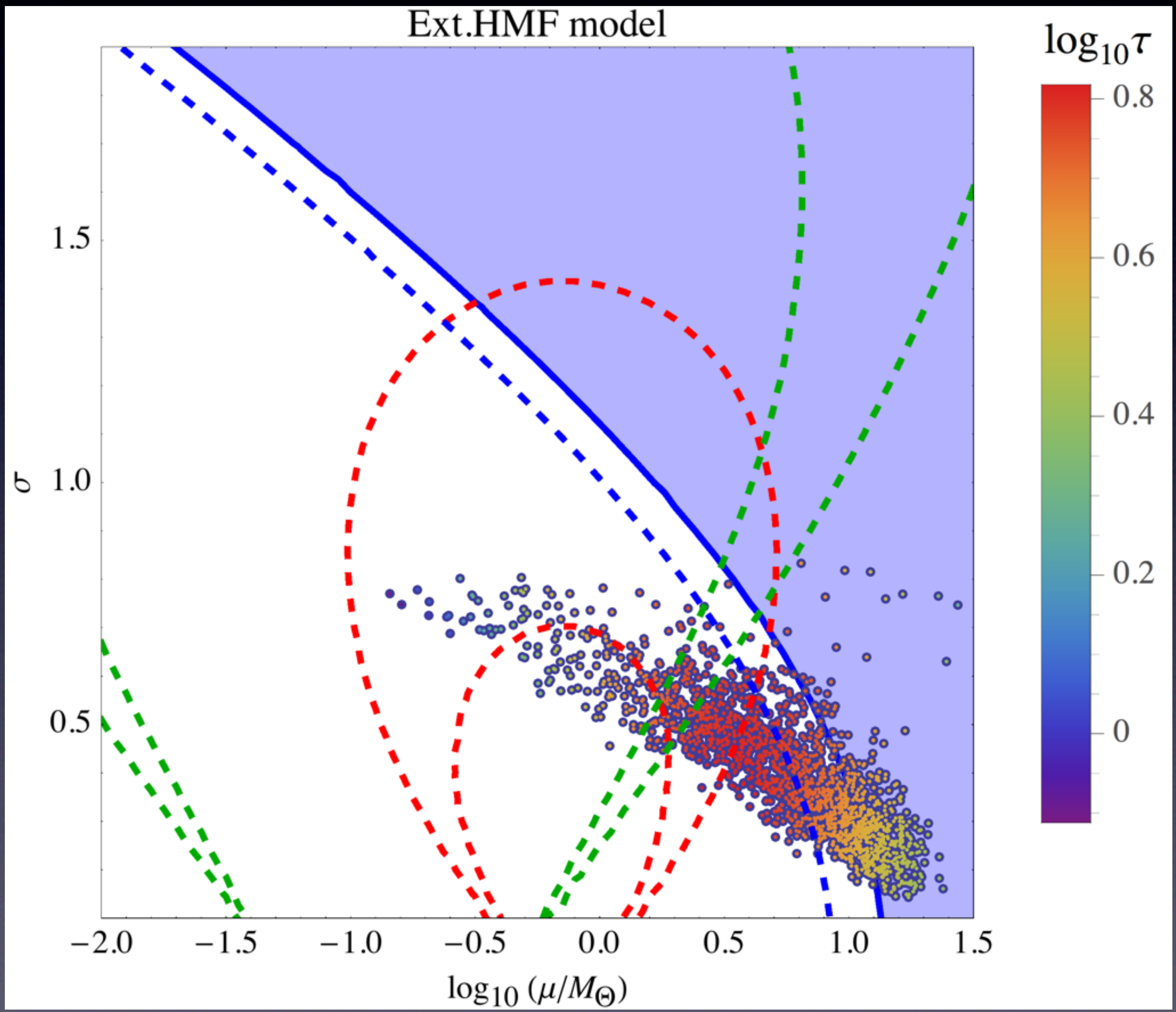


- MCMC mass spectrum reconstruction from LIGO events and rates
- Event likelihood peaks on large masses: LIGO detectability scales like inverse distance



Seven hints for PBH-DM

Hint 3: Microlensing of M31 and quasars



- 56 microlensing events in M31: between 15% and 30% of halo compact objects in range [0.5-1] Msun (1504.07246)
- 24 micro-lensing of quasars by galaxies: between 15% and 25% of halo compact objects in range [0.05-0.45] Msun (1702.00947)
- Also in Magellanic cloud surveys, but still controversial

Seven hints for PBH-DM

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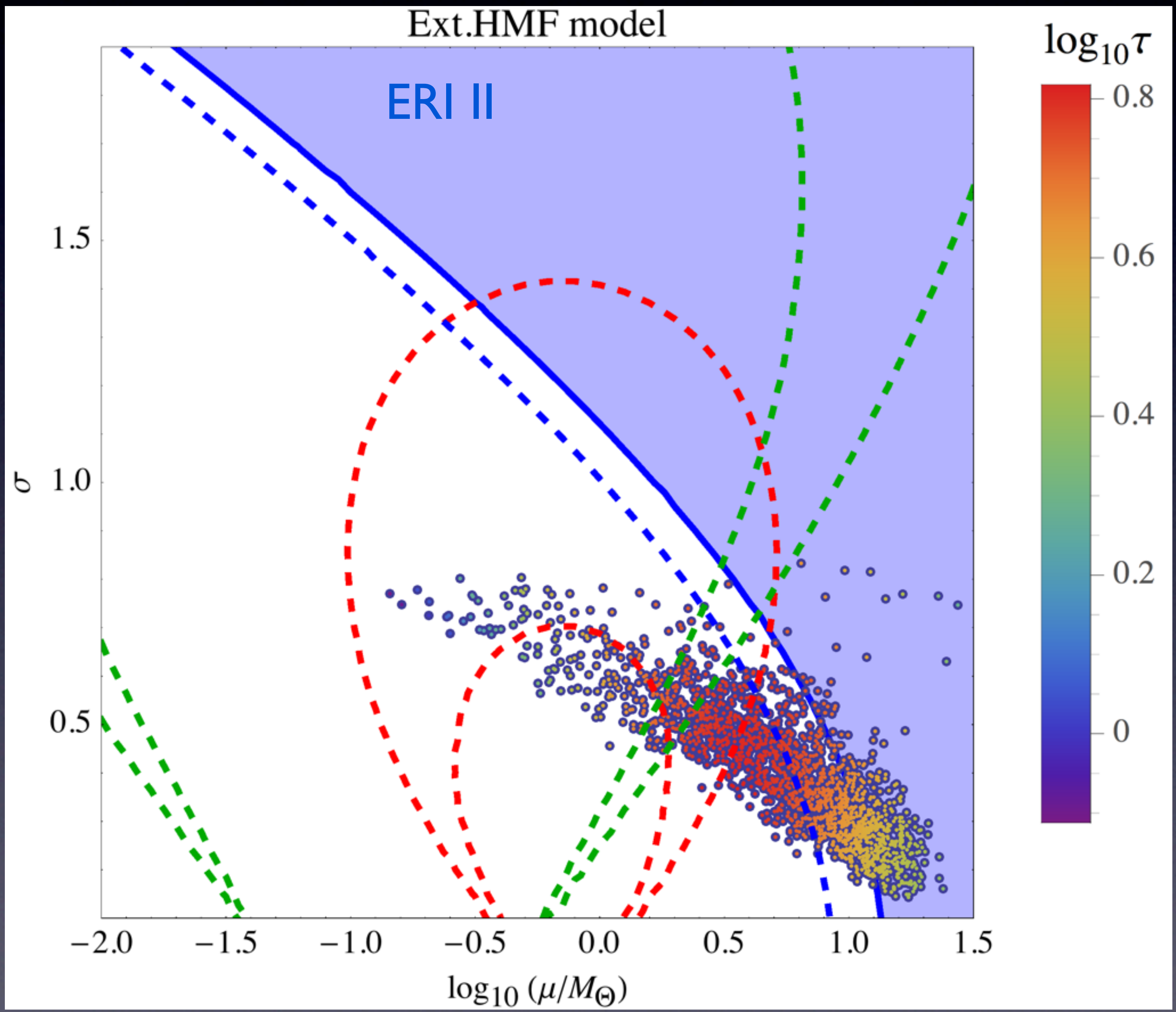

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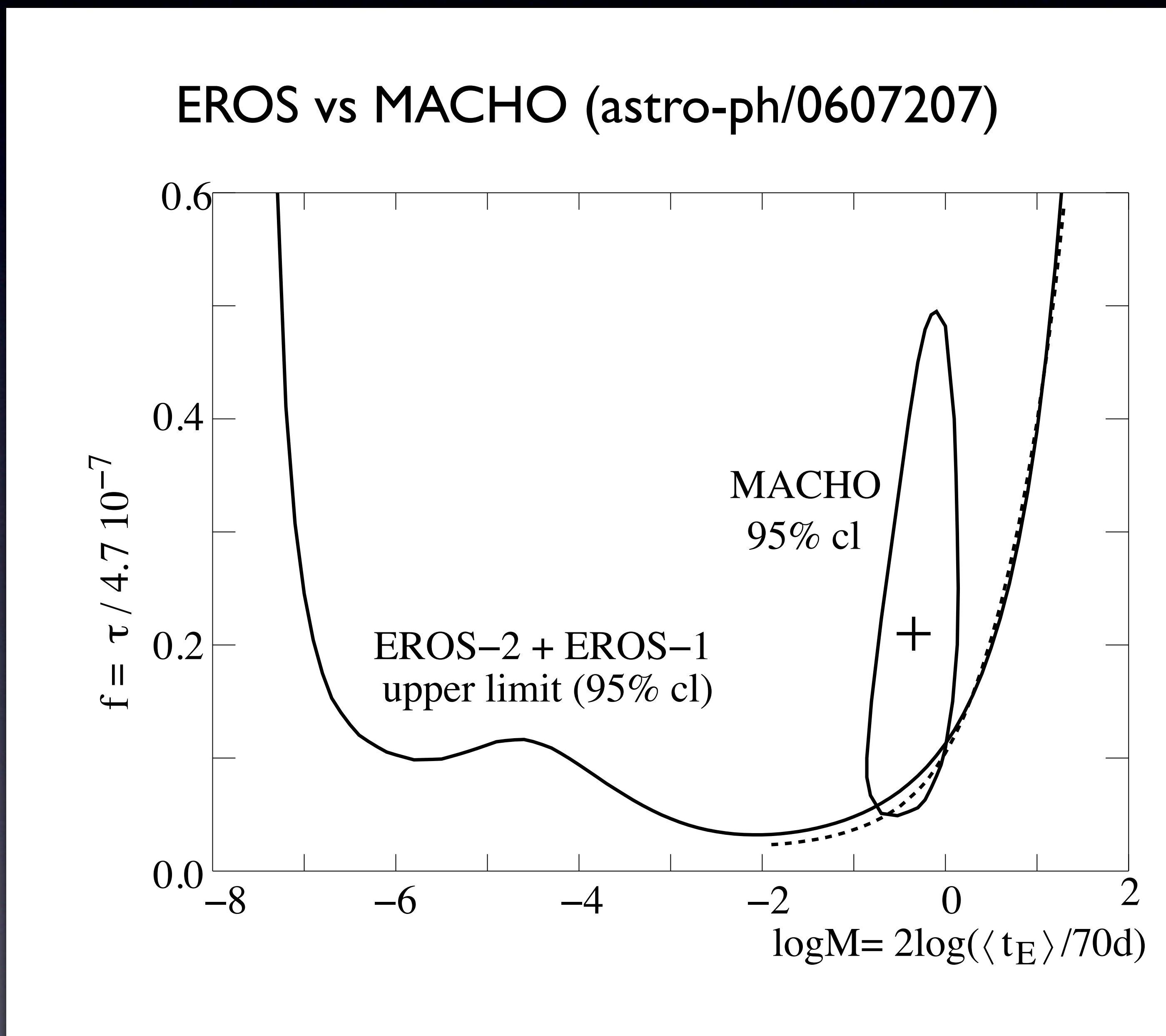

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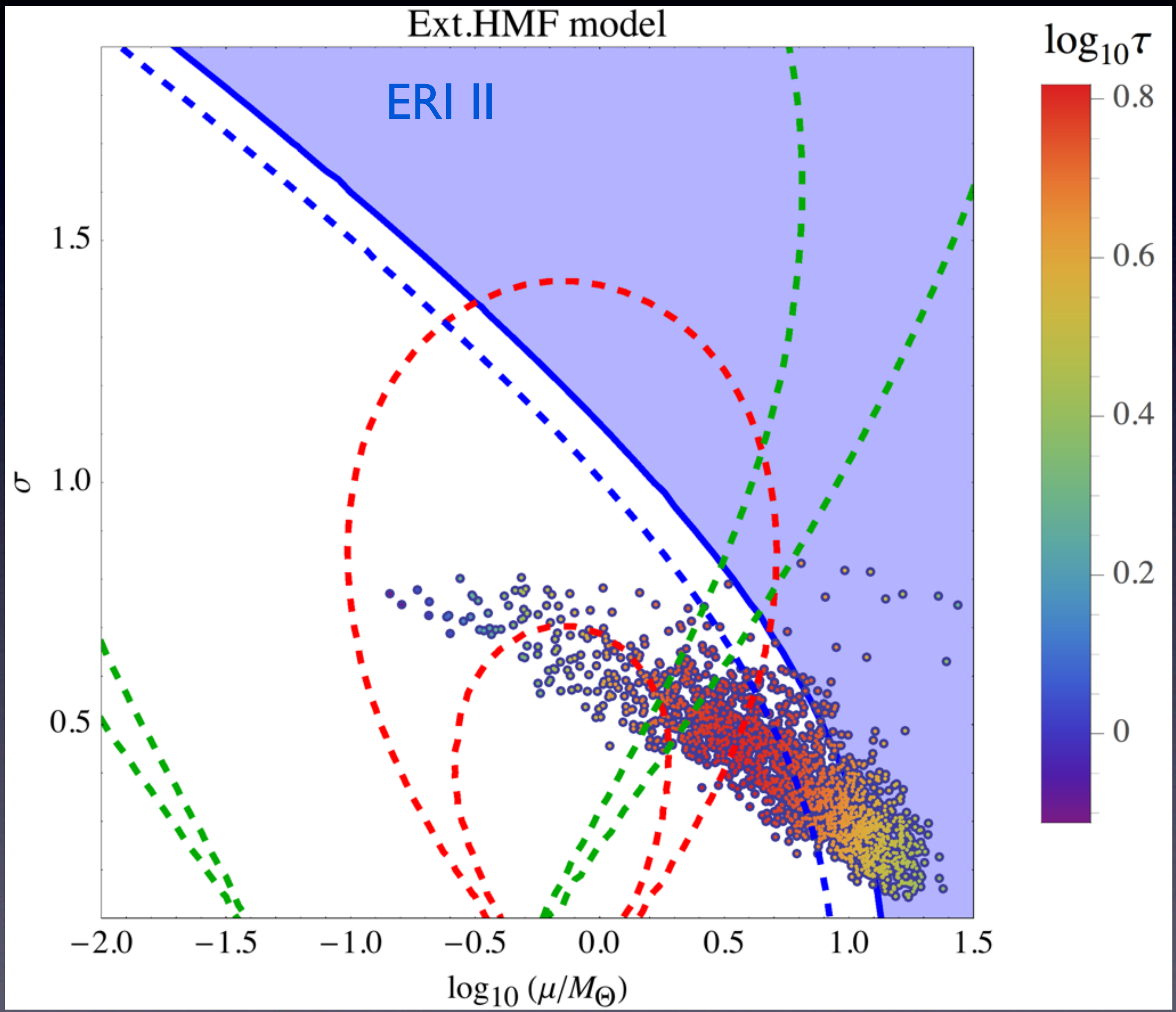
Seven hints for PBH-DM

Hint 4: Star clusters and dynamics of faint dwarf galaxies



- Dynamical heating of faint dwarfs and their star clusters
- Stable star clusters are fine-tuned or require core profile: Amorisco 1704.06262 Contena et al, 1705.01820
- Solve the missing satellite/too big to fail problems, missing baryons due to matter accretion
- Re-analysis and N-body simulations in progress...

Seven hints for PBH-DM

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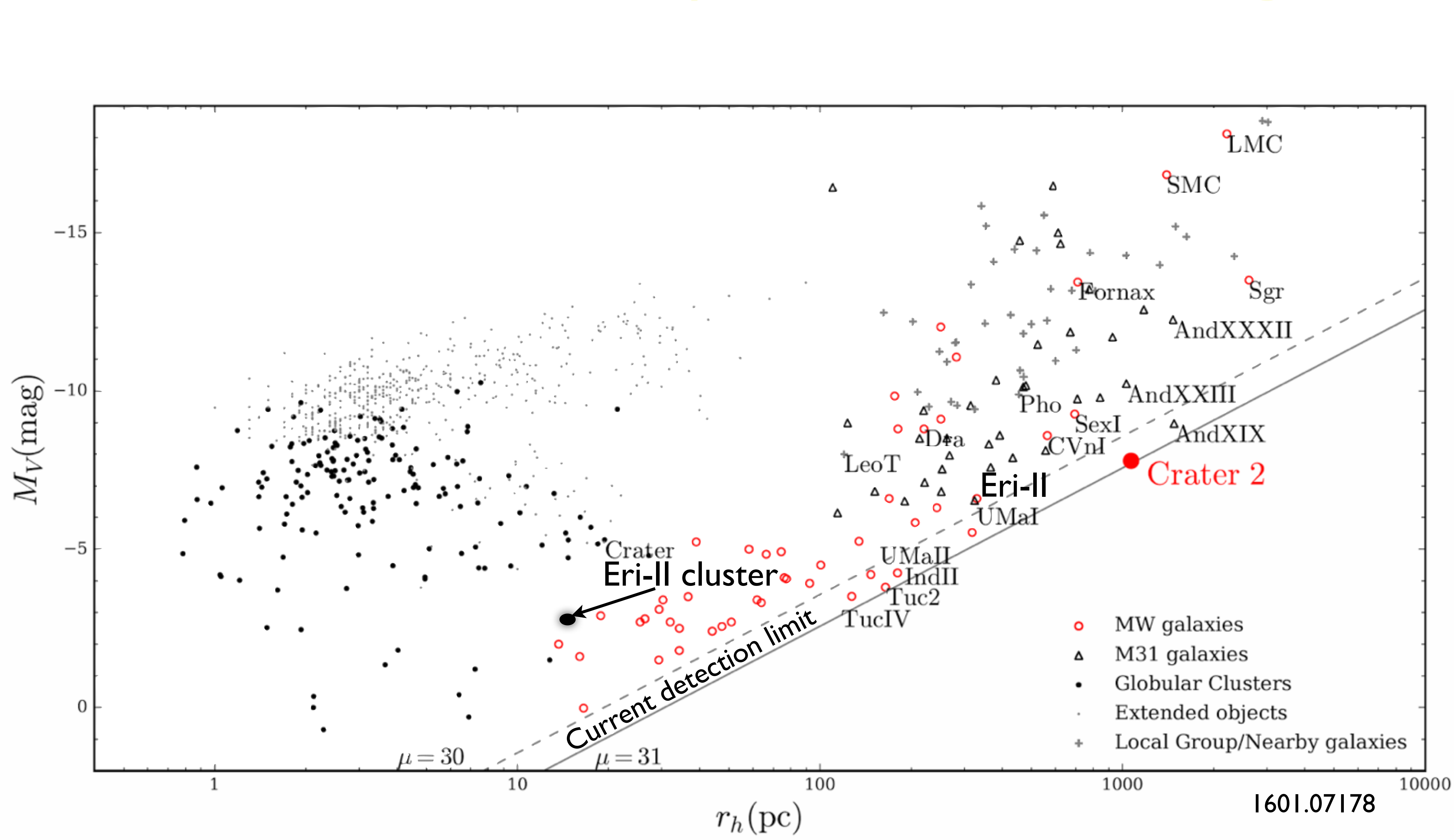

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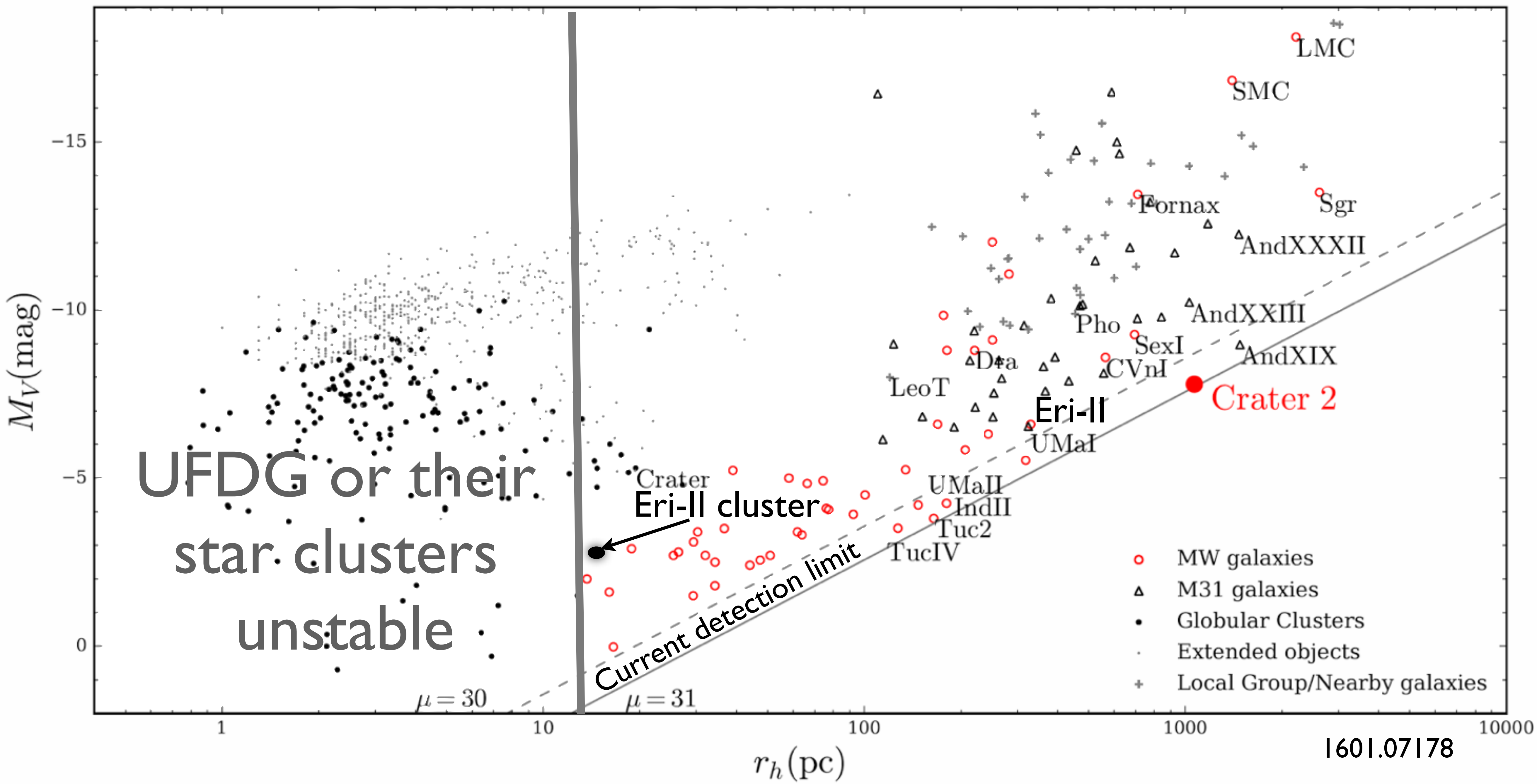

1601.07178

Seven hints for PBH-DM

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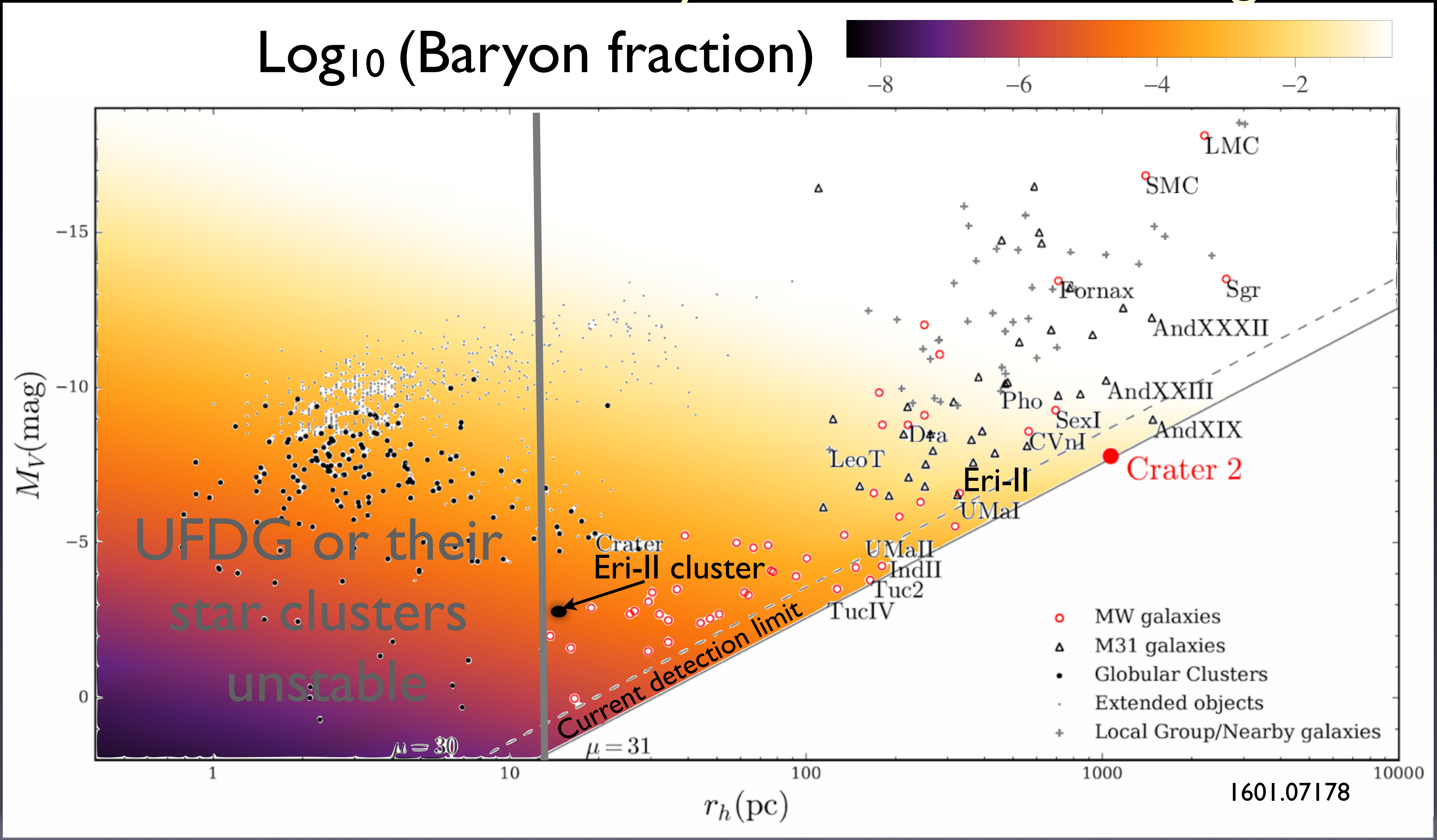

Seven hints for PBH-DM

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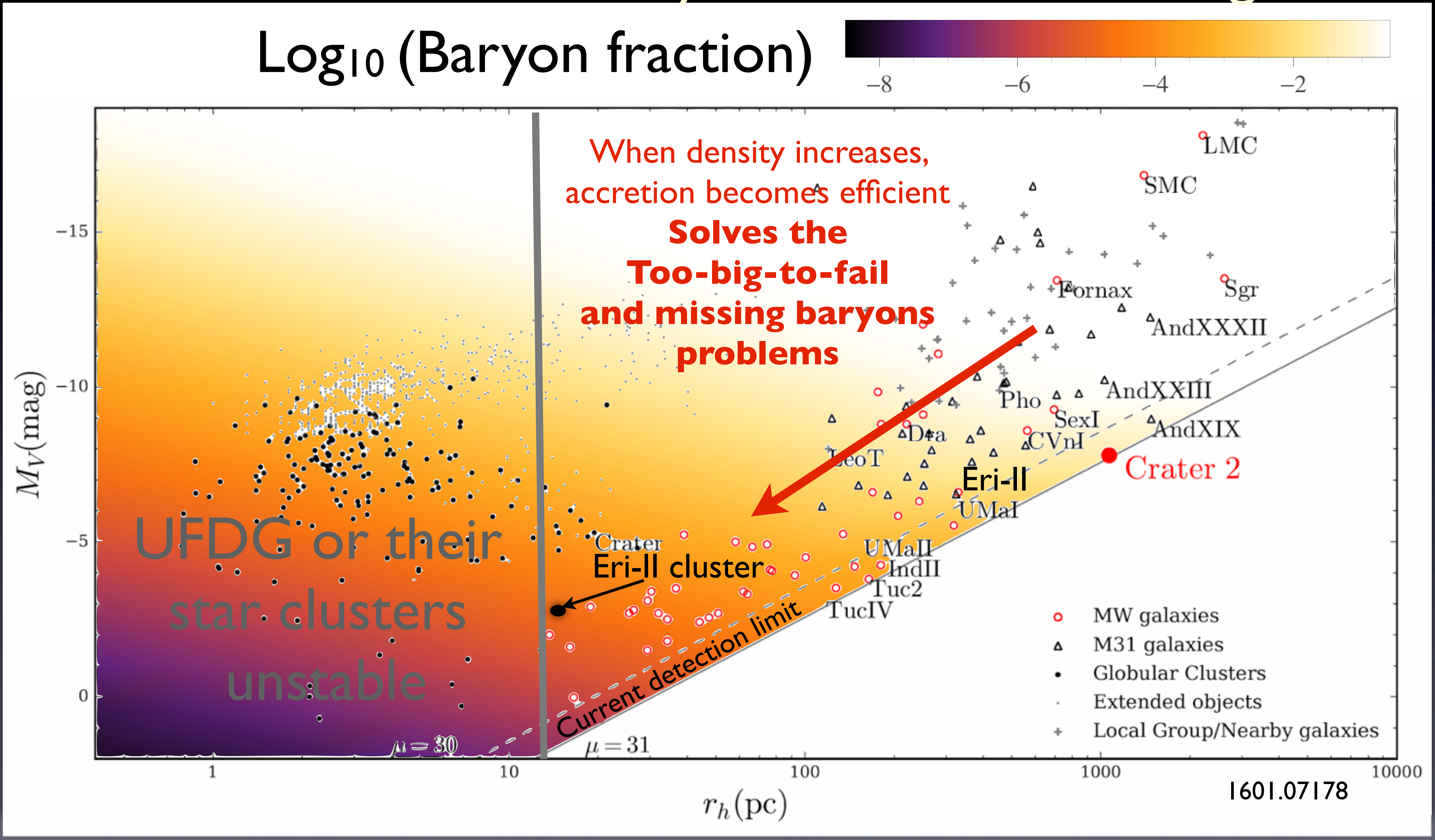

Seven hints for PBH-DM

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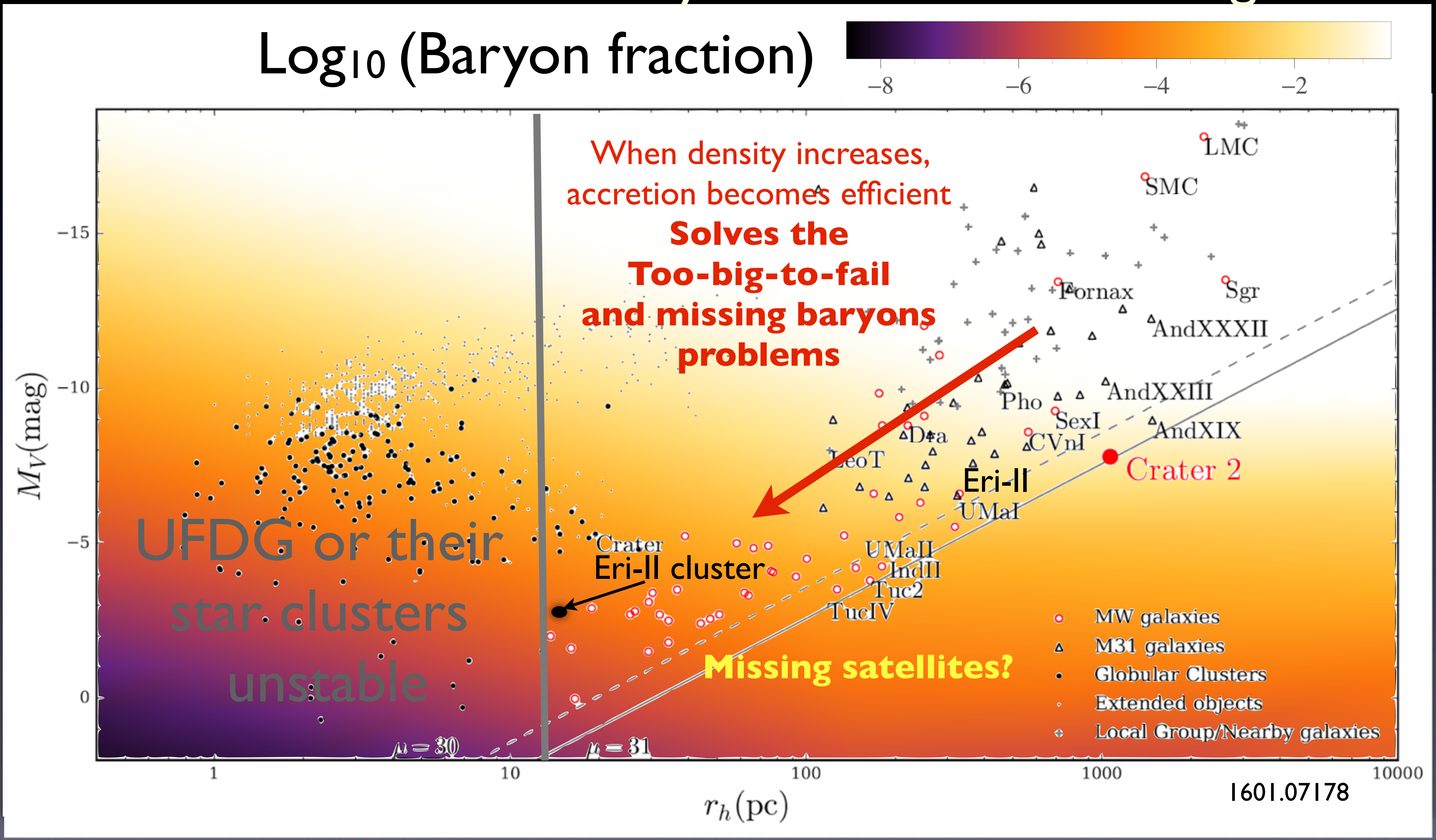

Seven hints for PBH-DM

Hint 5: Core DM density profiles

- Gravitational scattering between PBH: $\frac{\sigma}{m_{\rm PBH}} \sim 0.1 - 1 {\rm cm}^2/{\rm g}$
- Dynamical heating of cusps due to two-body interactions
- Relaxation time scale: $$t_{\rm rel} \approx \frac{r}{v} \frac{N_{\rm PBH}}{8 \ln N_{\rm PBH}}$$

- **Cusps homogenized in ~10 Gyrs up to a radius ~ 1kpc**
- Naturally solves the **core-cusp problem**

Seven hints for PBH-DM

Hint 6: Spatial correlations in CIB and X-ray background

LIGO gravitational wave detection, primordial black holes and the near-Il cosmic infrared background anisotropies

A. Kashlinsky[1],

ABSTRACT

LIGO's discovery of a gravitational wave from two merging black holes (BHs) of similar masses rekindled suggestions that primordial BHs (PBHs) make up the dark matter (DM). If so, PBHs would add a Poissonian isocurvature density fluctuation component to the inflation-produced adiabatic density fluctuations. For LIGO's BH parameters, this extra component would dominate the small-scale power responsible for collapse of early DM halos at $z \gtrsim 10$, where first luminous sources formed. We quantify the resultant increase in high-z abundances of collapsed halos that are suitable for producing the first generation of stars and luminous sources. The significantly increased abundance of the early halos would naturally explain the observed source-subtracted near-IR cosmic infrared background (CIB) fluctuations, which cannot be accounted for by known galaxy populations. For LIGO's BH parameters this increase is such that the observed CIB fluctuation levels at 2 to 5 μm can be produced if only a tiny fraction of baryons in the collapsed DM halos forms luminous sources. Gas accretion onto these PBHs in collapsed halos, where first stars should also form, would straightforwardly account for the observed high coherence between the CIB and unresolved cosmic X-ray background in soft X-rays. We discuss modifications possibly required in the processes of first star formation if LIGO-type BHs indeed make up the bulk or all of DM. The arguments are valid only if the PBHs make up all, or at least most, of DM, but at the same time the mechanism appears inevitable if DM is made of PBHs.

1605.04023
1709.02824

Seven hints for PBH-DM

Hint 7: Existence of super-massive BH at high redshifts

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Letter | Accelerated Article Preview

An 800-million-solar-mass black hole in a significantly neutral Universe at a redshift of 7.5

Eduardo Bañados, Bram P. Venemans, Chiara Mazzucchelli, Emanuele P. Farina, Fabian Walter, Feige Wang, Roberto Decarli, Daniel Stern, Xiaohui Fan, Fred Davies, Joseph F. Hennawi, Rob Simcoe, Monica L. Turner, Hans-Walter Rix, Jinyi Yang, Daniel D. Kelson, Gwen Rudie & Jan Martin Winters

Nature
doi:10.1038/nature25180
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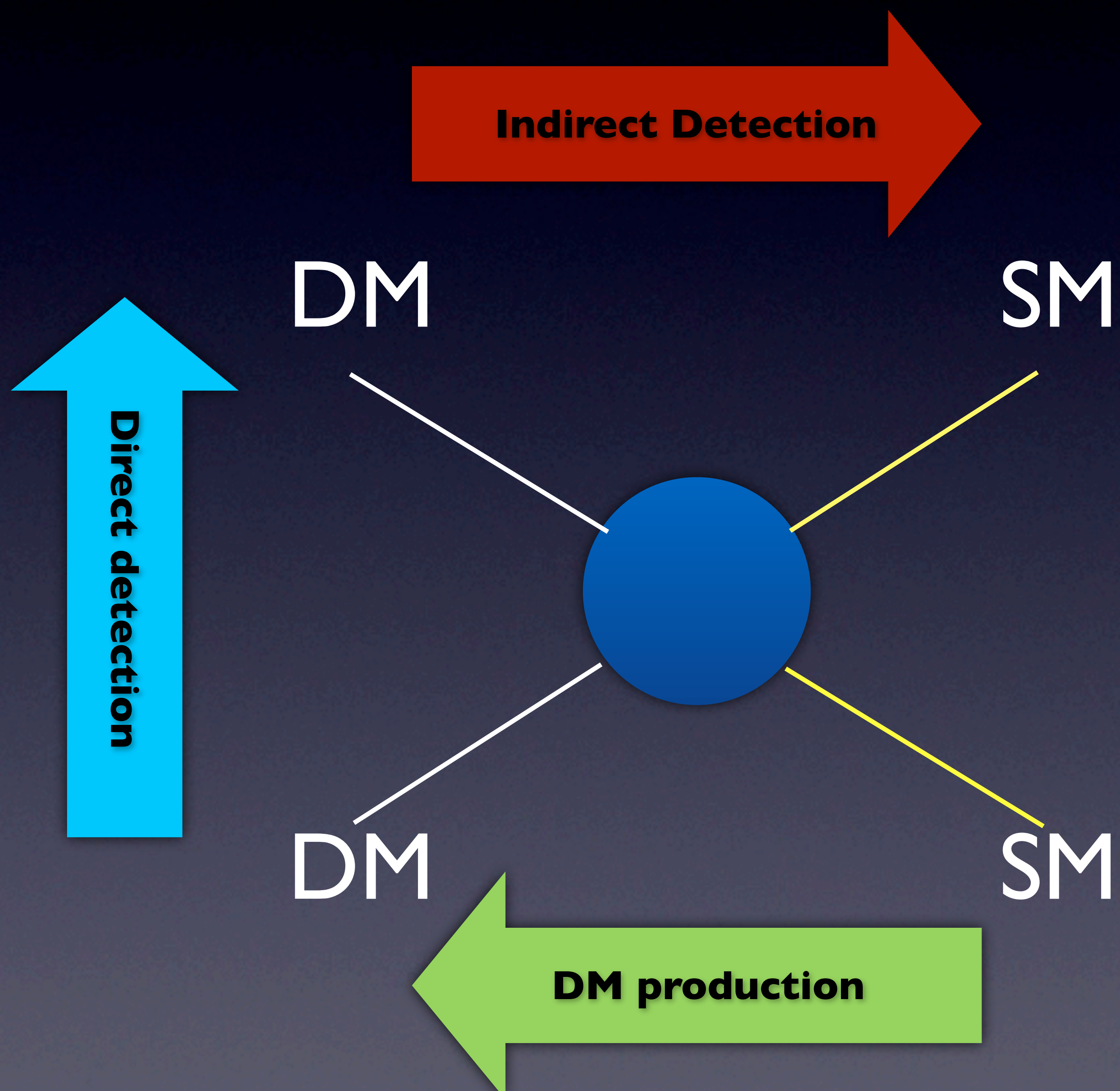
Published online: 06 December 2017

1712.01870

PBH provide the right number of seeds for SMBH

Rethinking DM interactions



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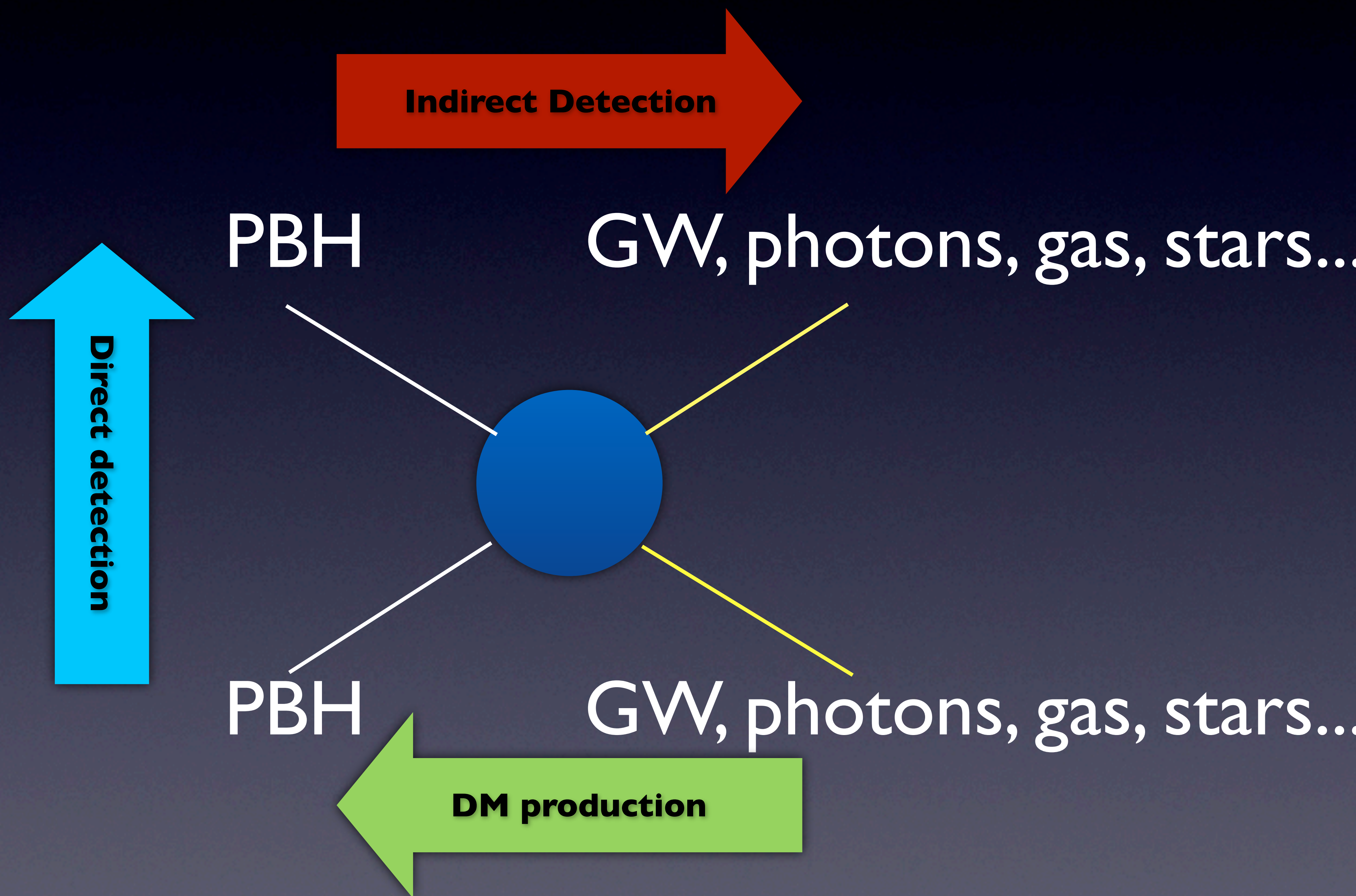

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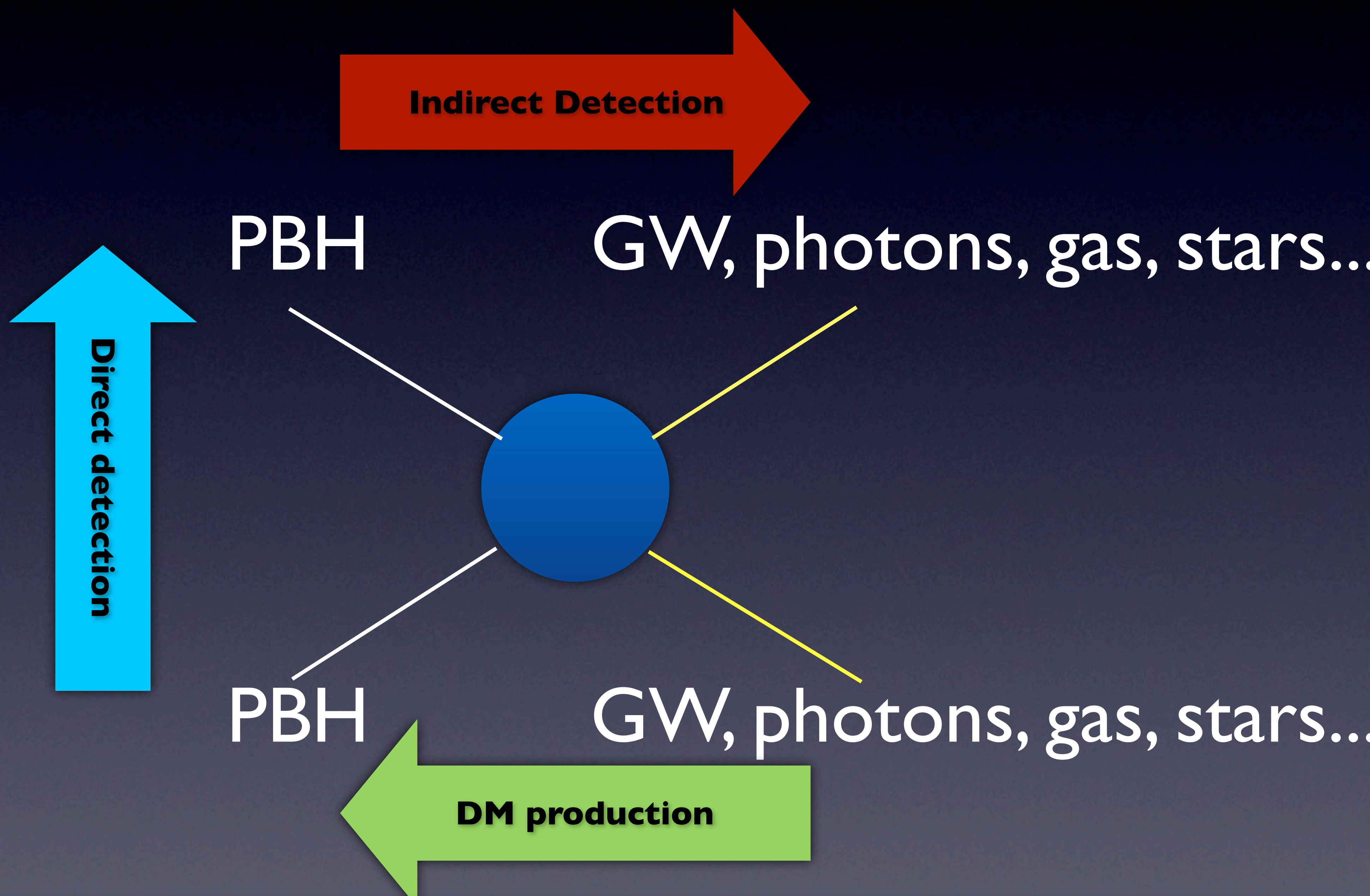
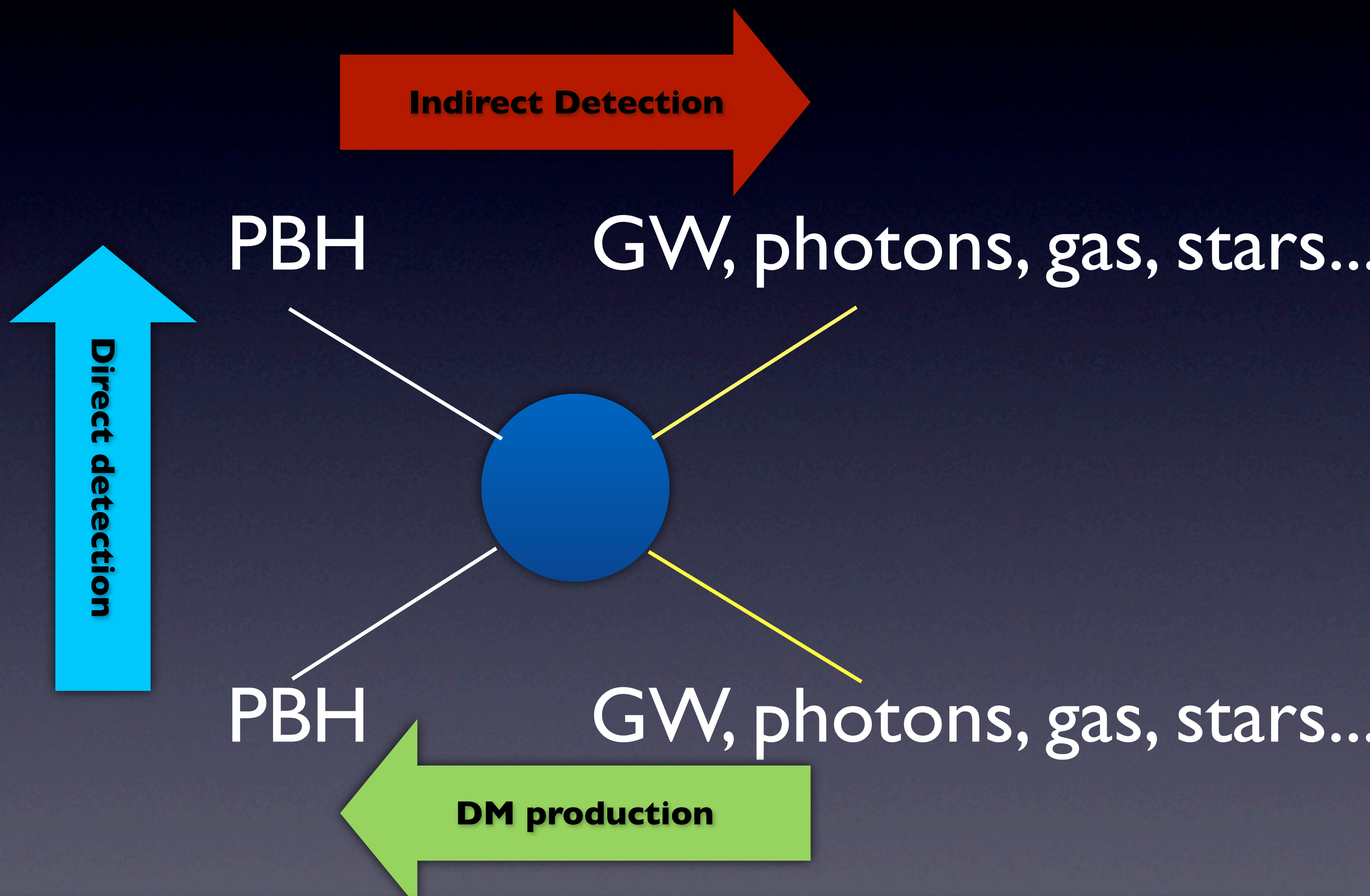


Matter accretion: missing satellites, missing baryons, too-big-to-fail, CMB/LSS effects?

Rethinking DM interactions

PBH-PBH and PBH-star scattering: UFDG observations

High-energy photons from accretion disks X-ray/CIB correlations



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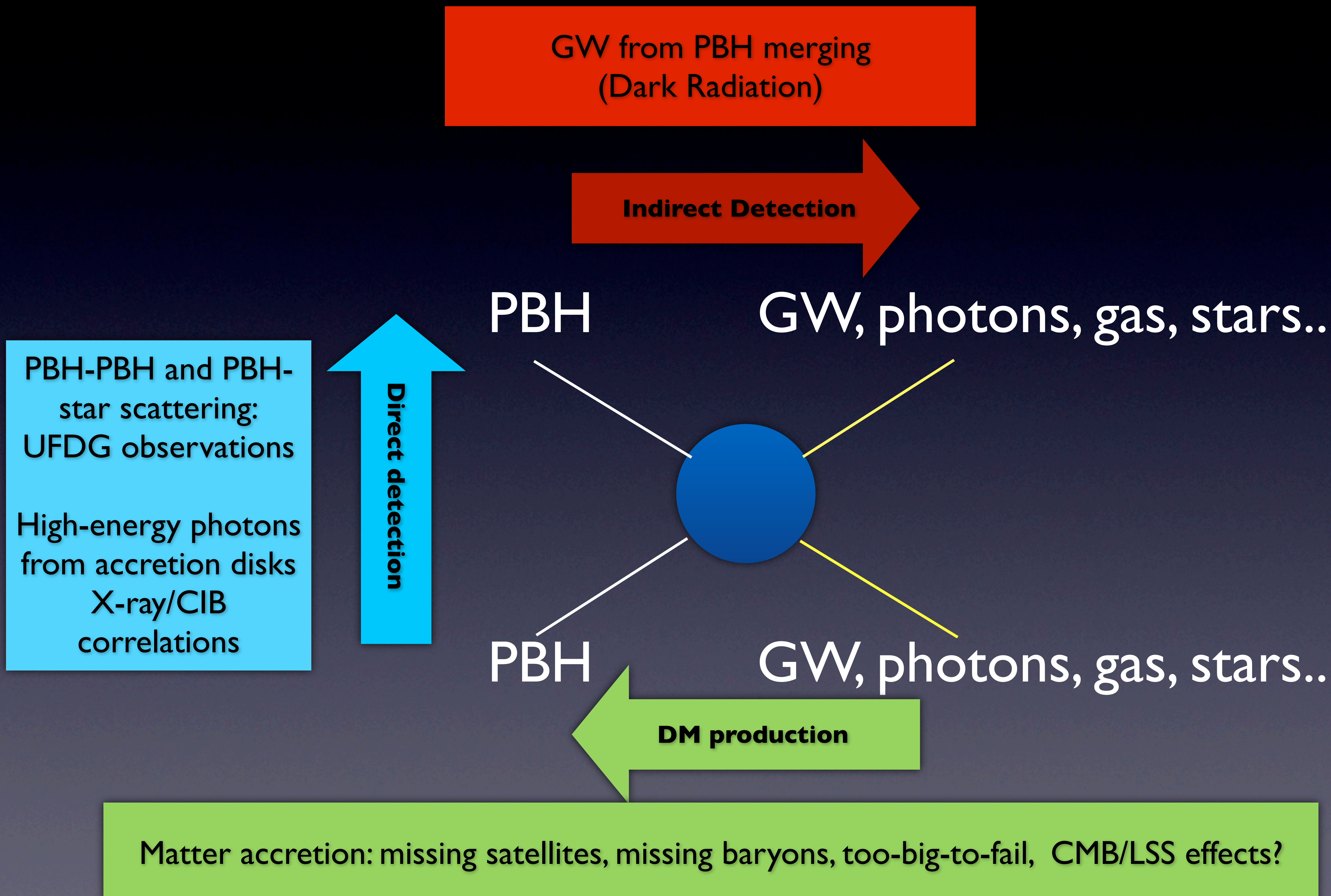

...and future prospects

- Detecting a BH below the Chandrashekar mass (LIGO)
- Numerous merging events seen in GW detectors (LIGO, VIRGO, ET...)
- GW Stochastic Background (PTAs, LISA, LIGO)
- Detecting faint dwarf galaxies (DES, Euclid)
- Microlensing surveys (Euclid)
- 21cm signal (SKA)
- CMB (Planck, S4, LiteBird)
- Star position and velocities (GAIA), LMXB, PS in GC

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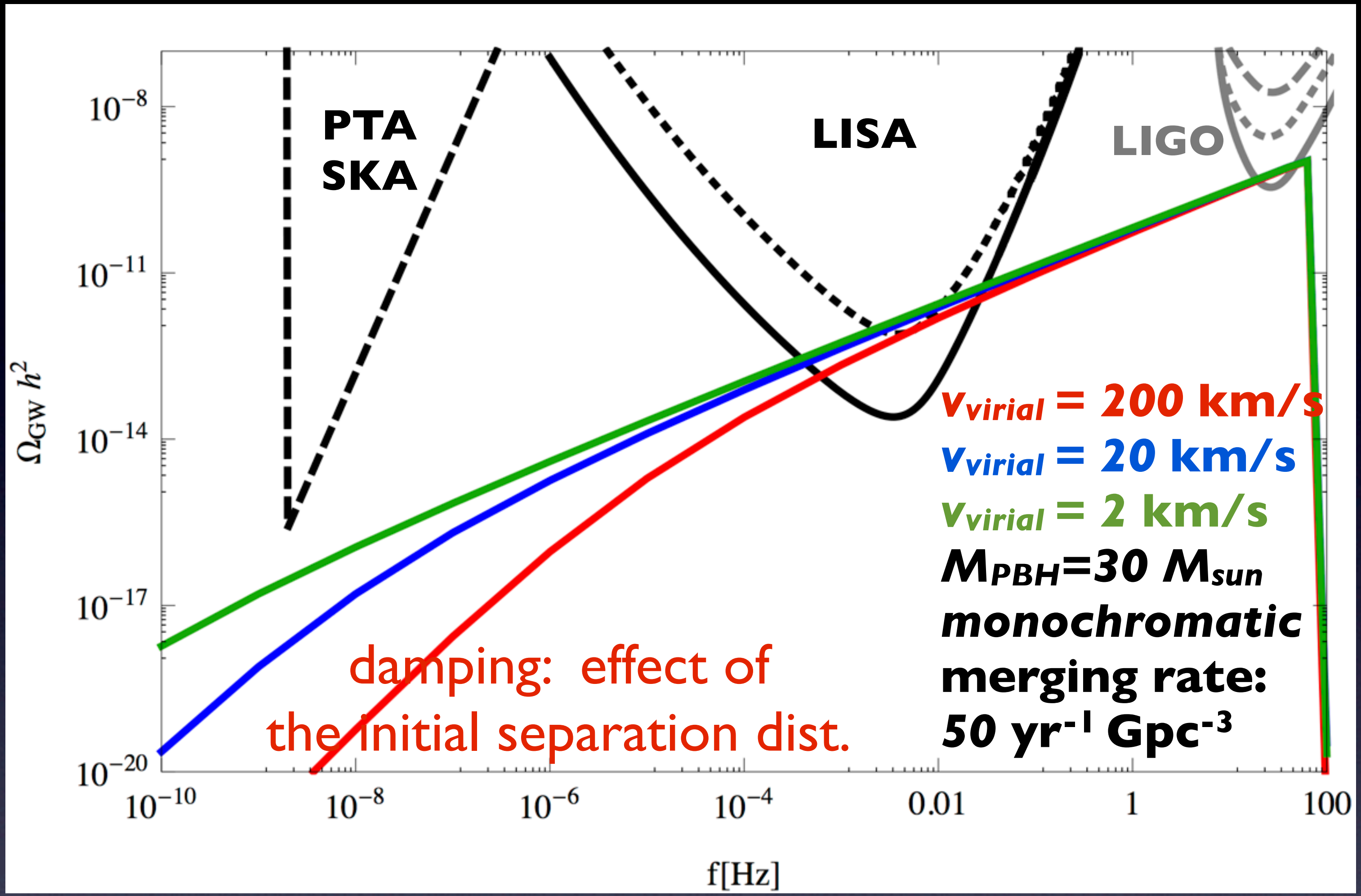

Clustering allows to distinguish stellar and primordial origins
SC, JGB, 1610.08479

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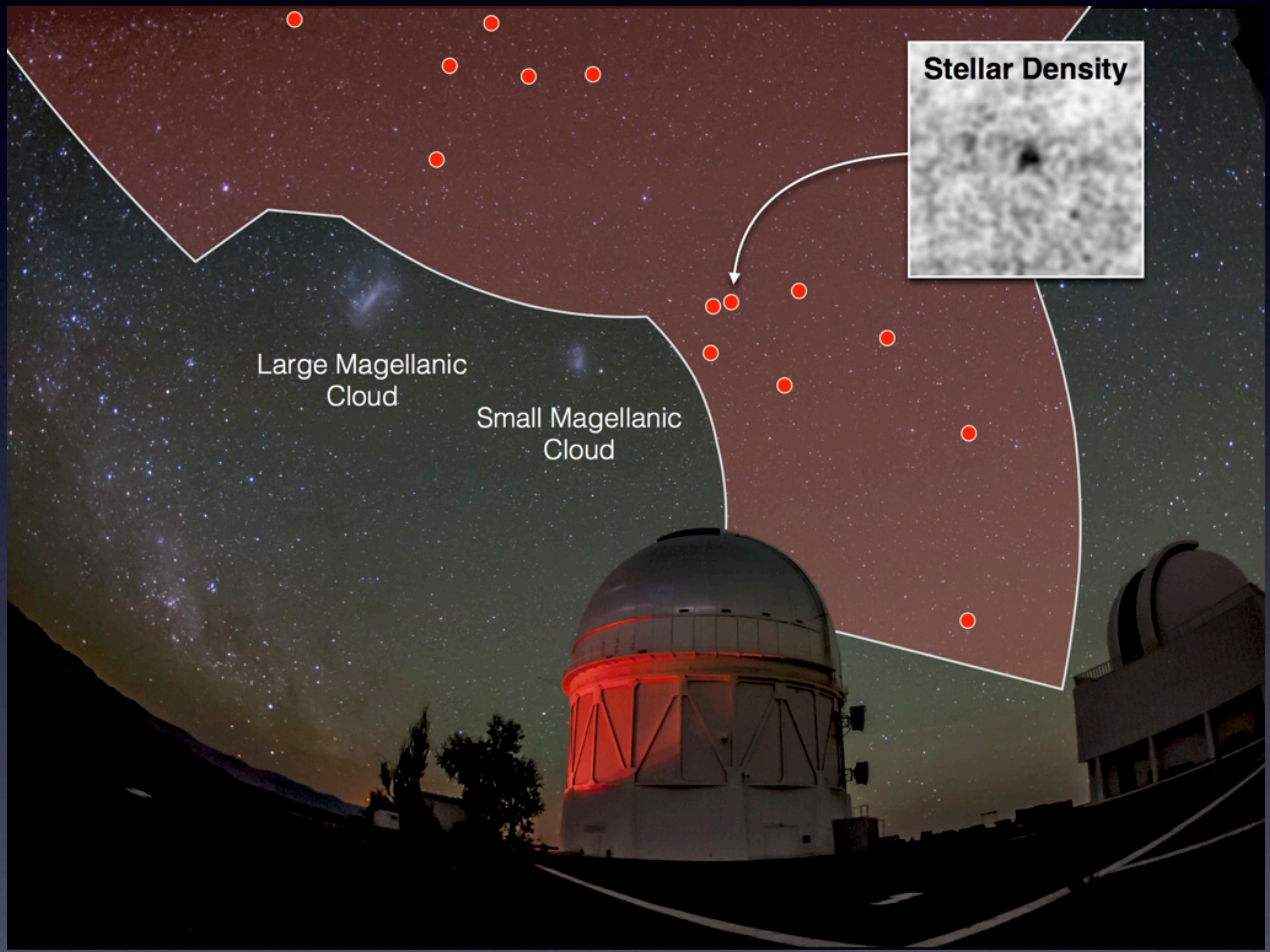

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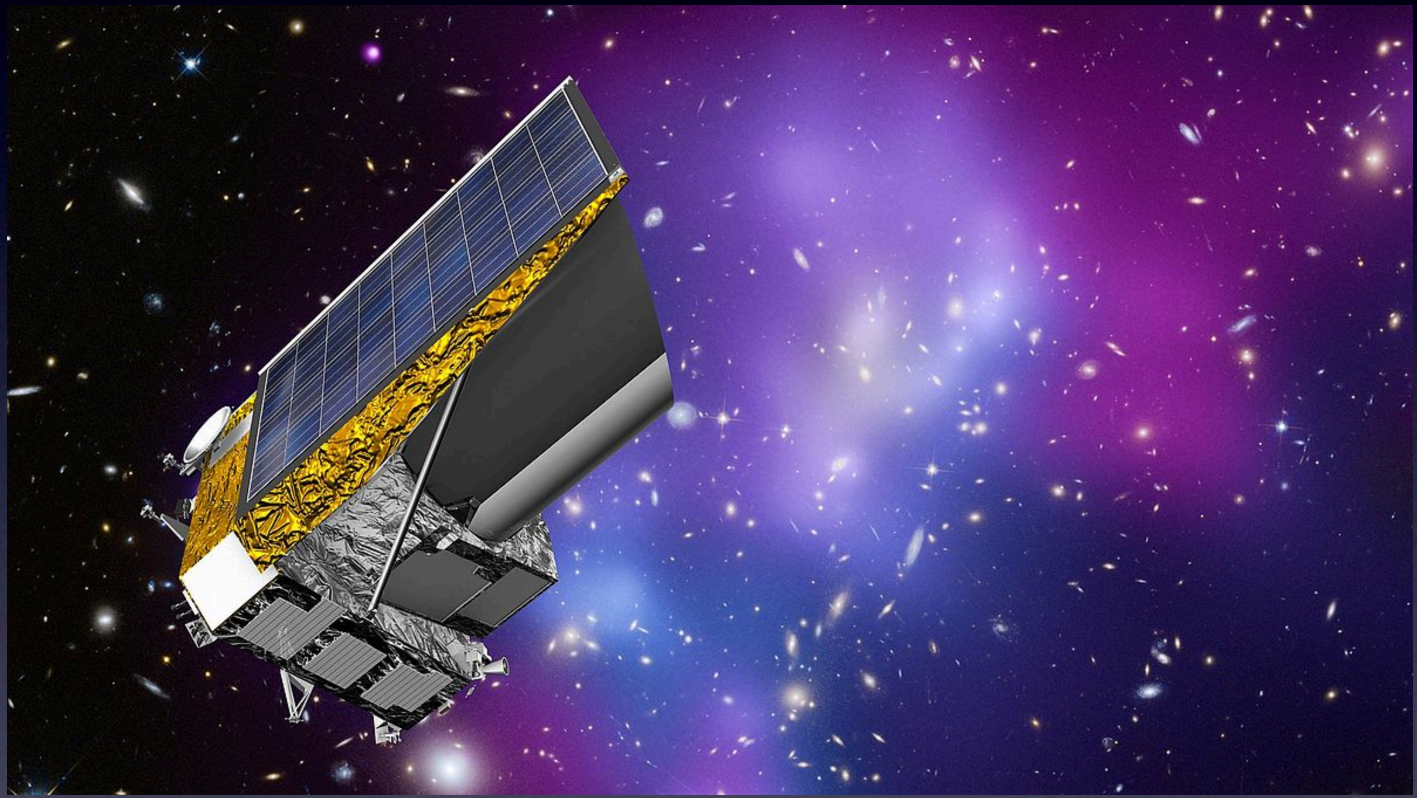

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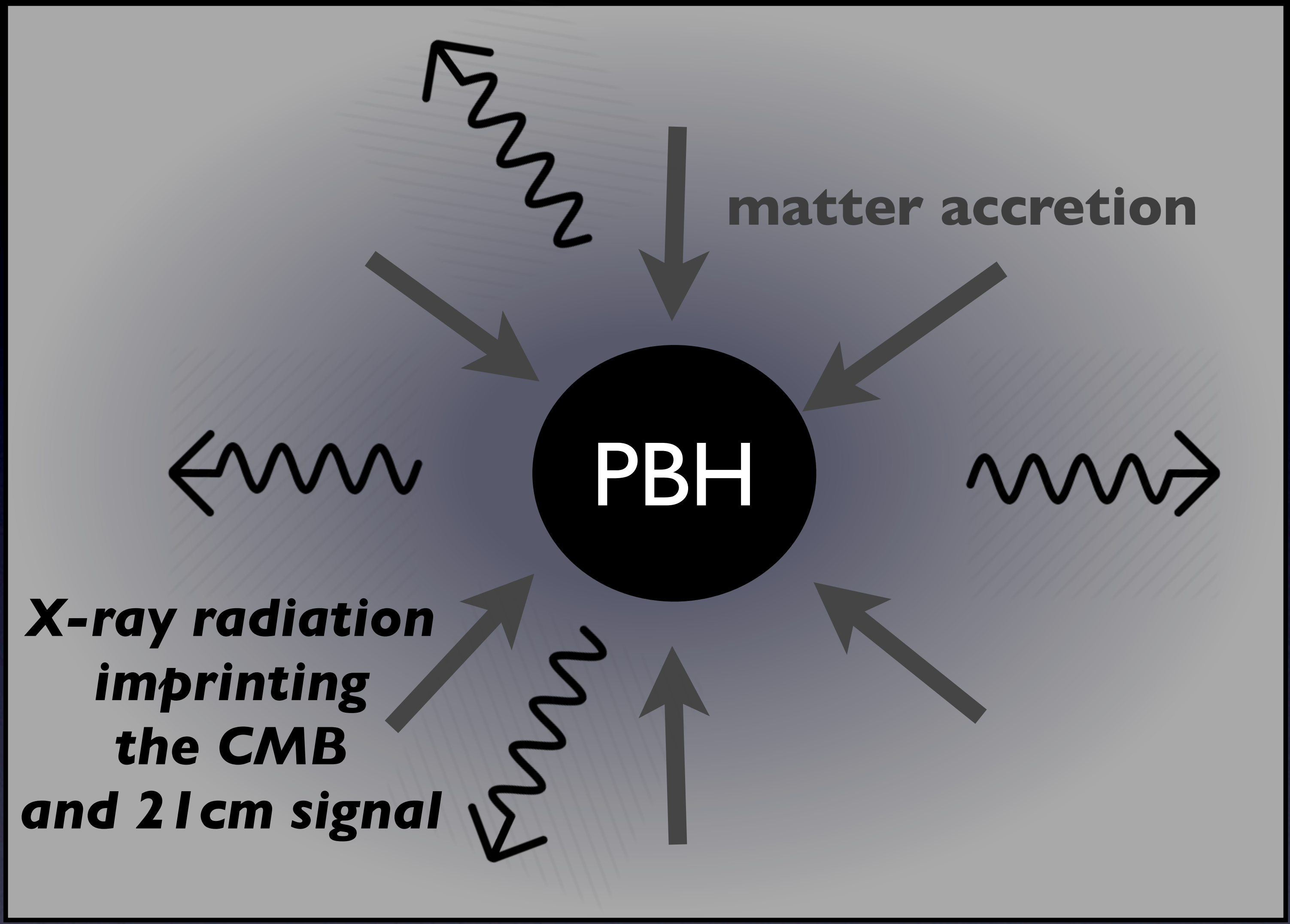

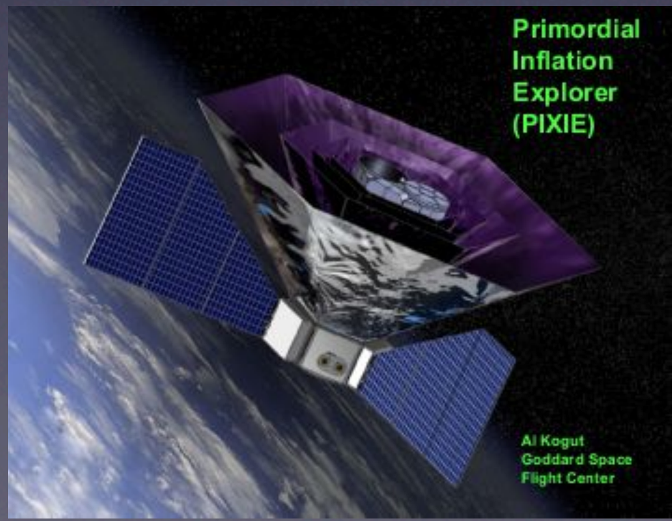

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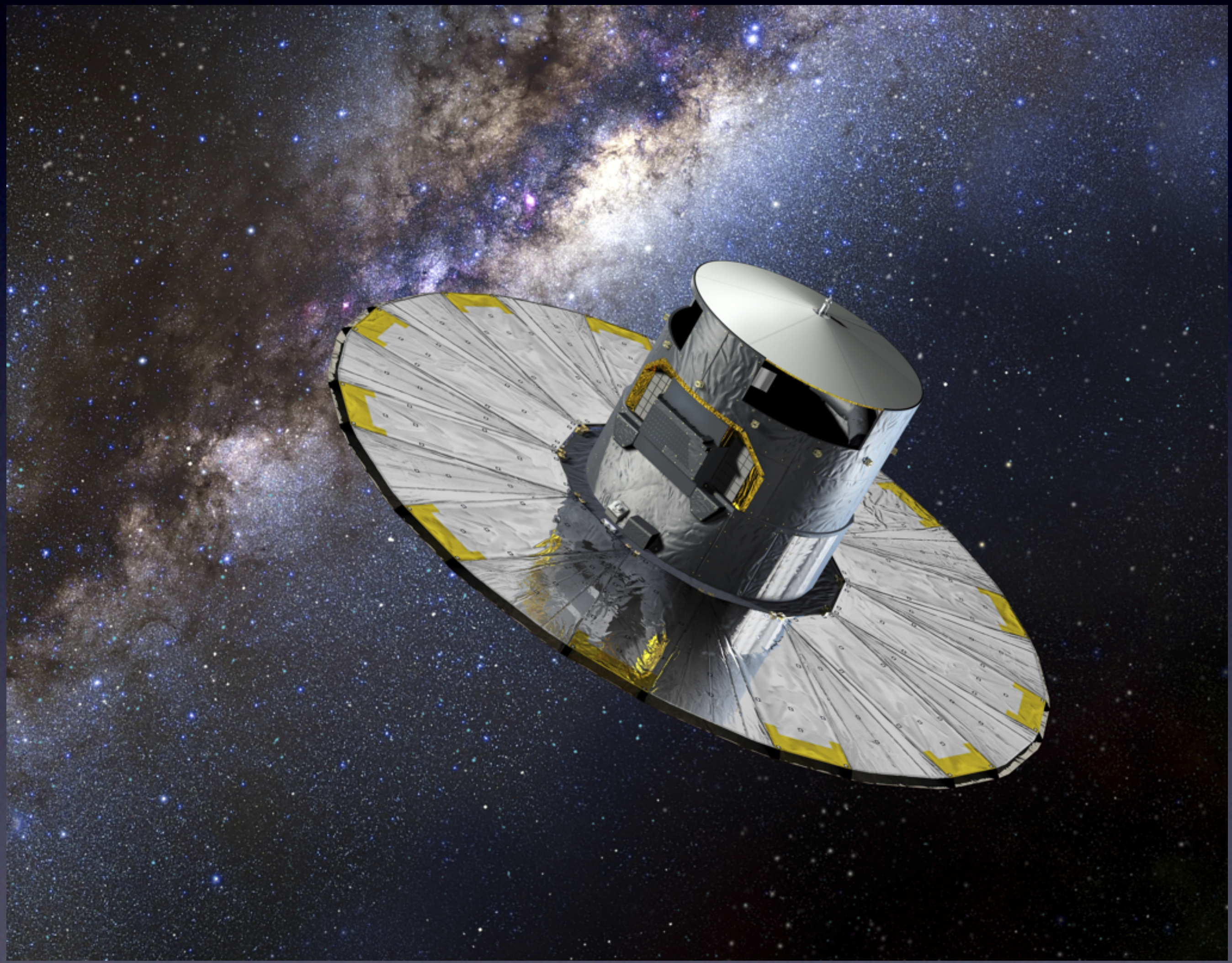

Thank you
for your attention

LIGO and the strange

PBH Dark Matter interaction 1

Gravitational waves from BH mergers

Dark Matter decay
in «Dark Radiation» (GW)

CMB: No more than ~3.8% of the DM
Poulin et al., 1606.02073
Constraints the PBH merging history

Th

- F
- L
- S
- E
- E
- Need a new model...

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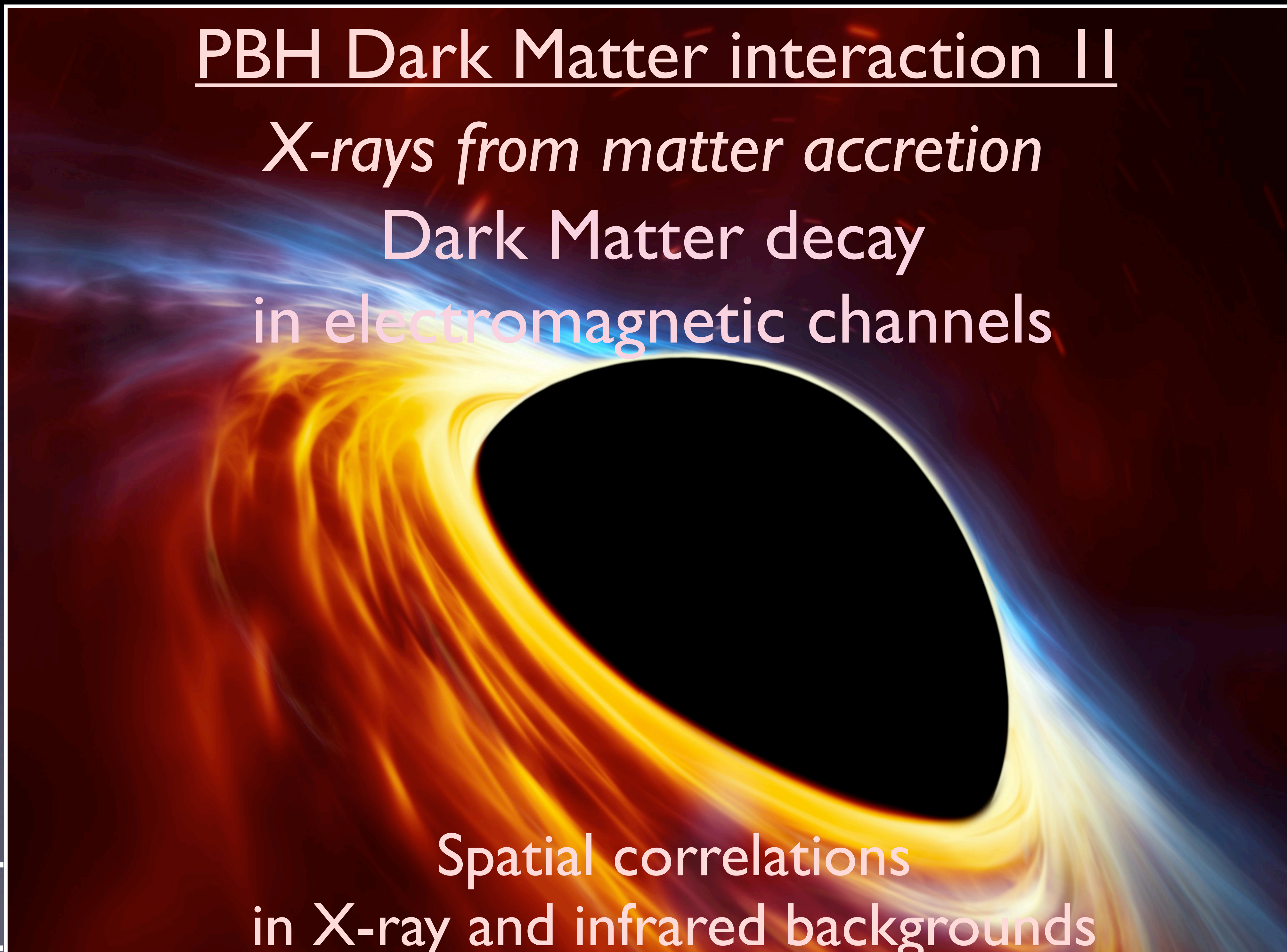
observational constraints

Four clues for PBH-DM

Hint 4: Spatial correlations in CIB and X-ray background



1605.04
1709.02

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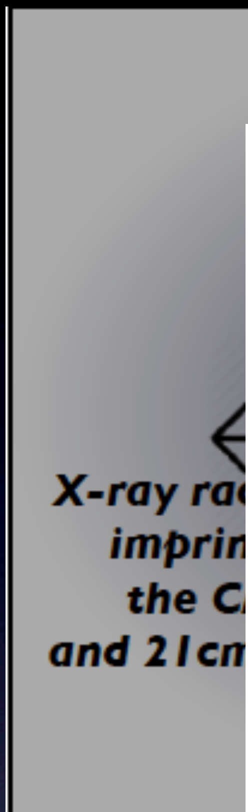
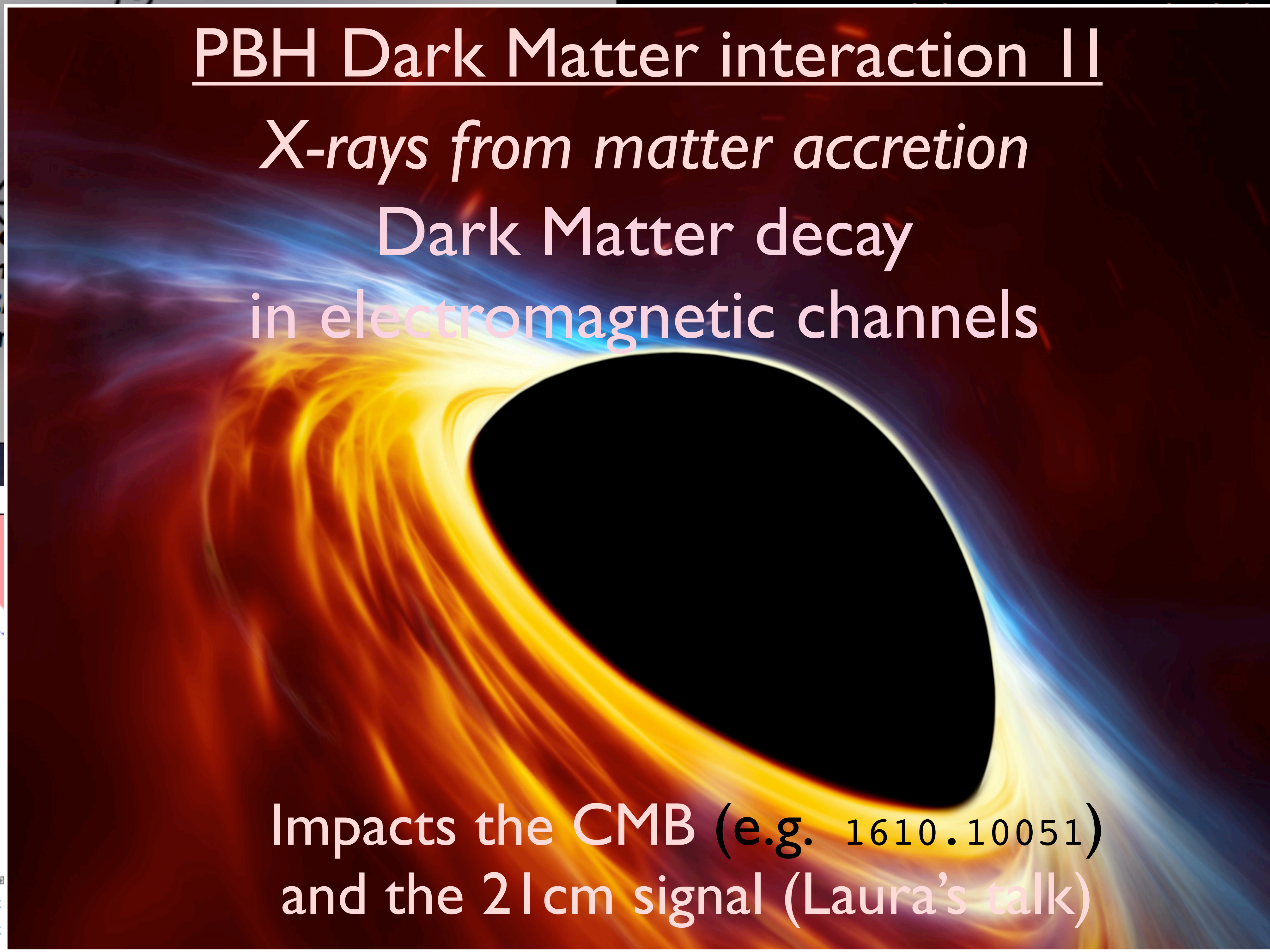


Disk accretion at high redshifts



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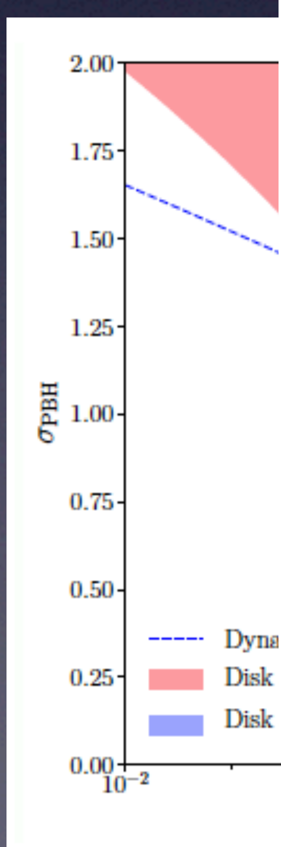
n

Universe

MB

$^{8} \left(\frac{0.01}{\lambda}\right)^{1.6}$



Poulin et al., 1707.04296

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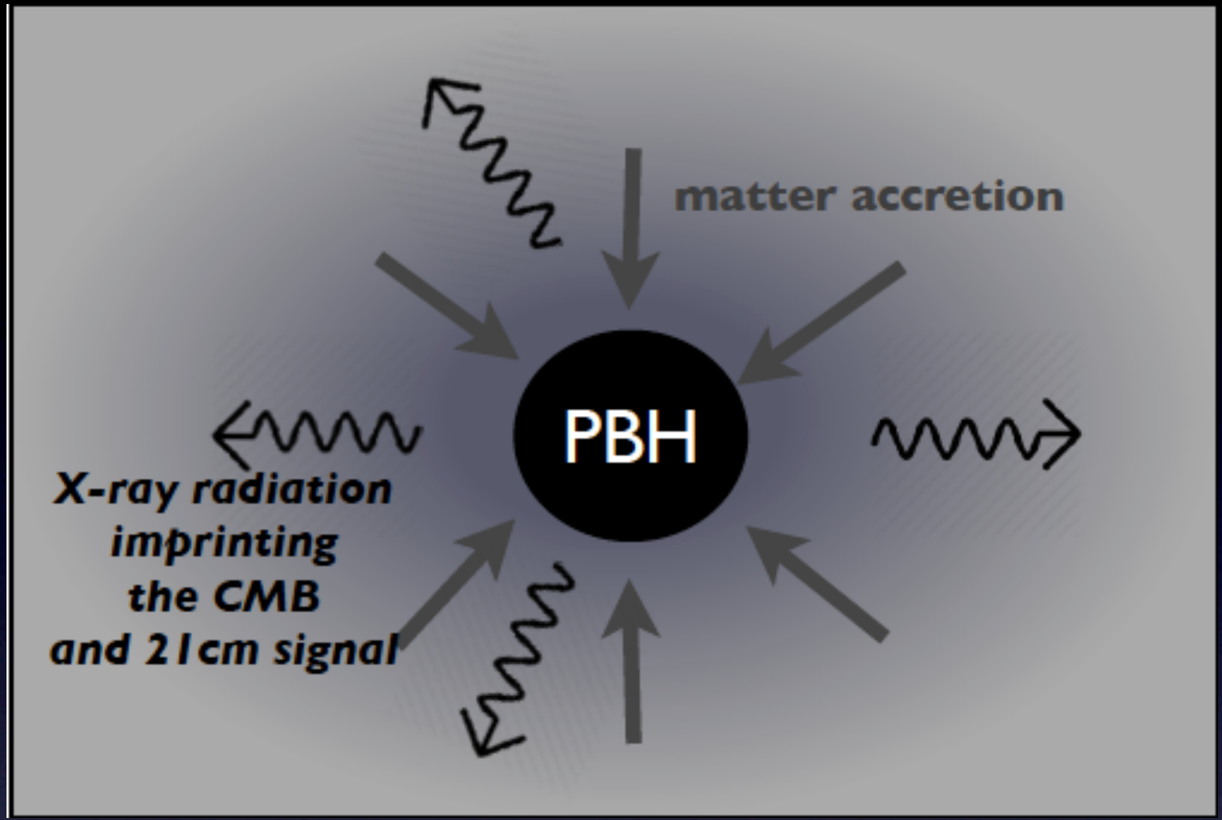

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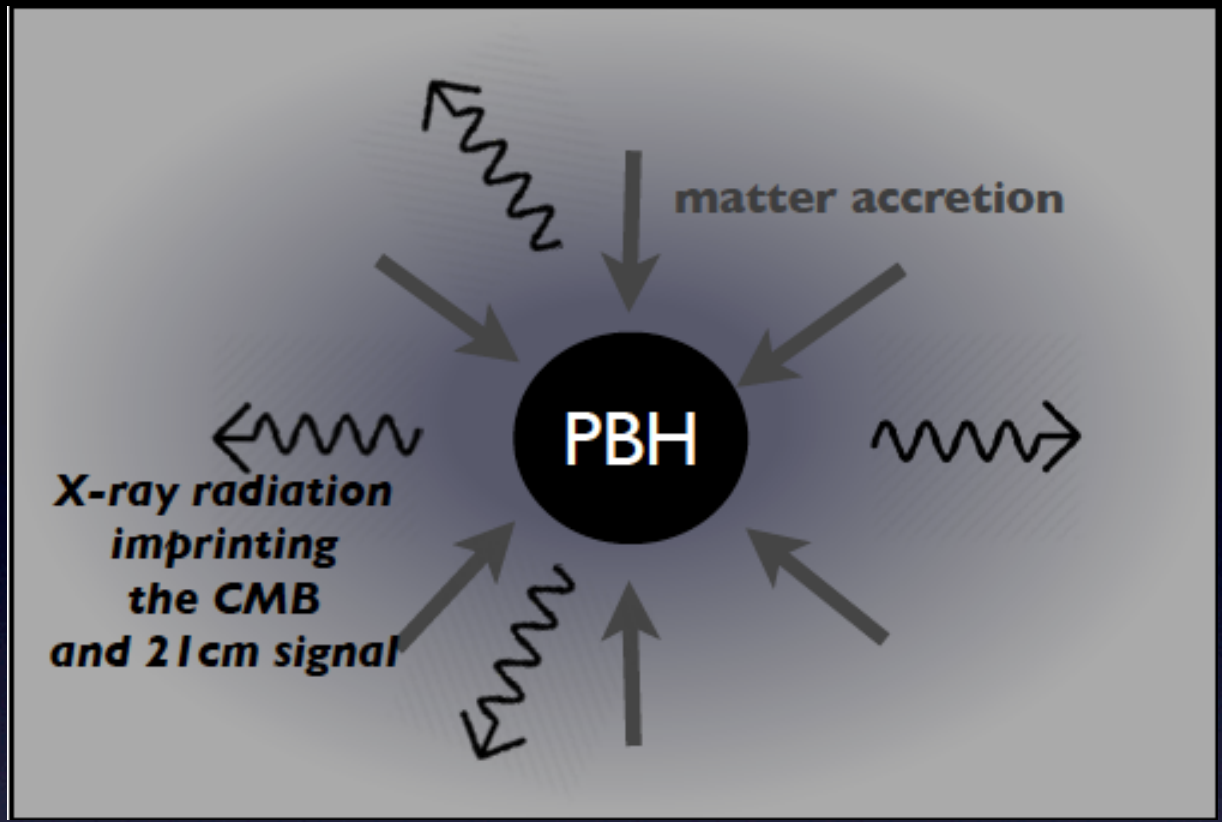
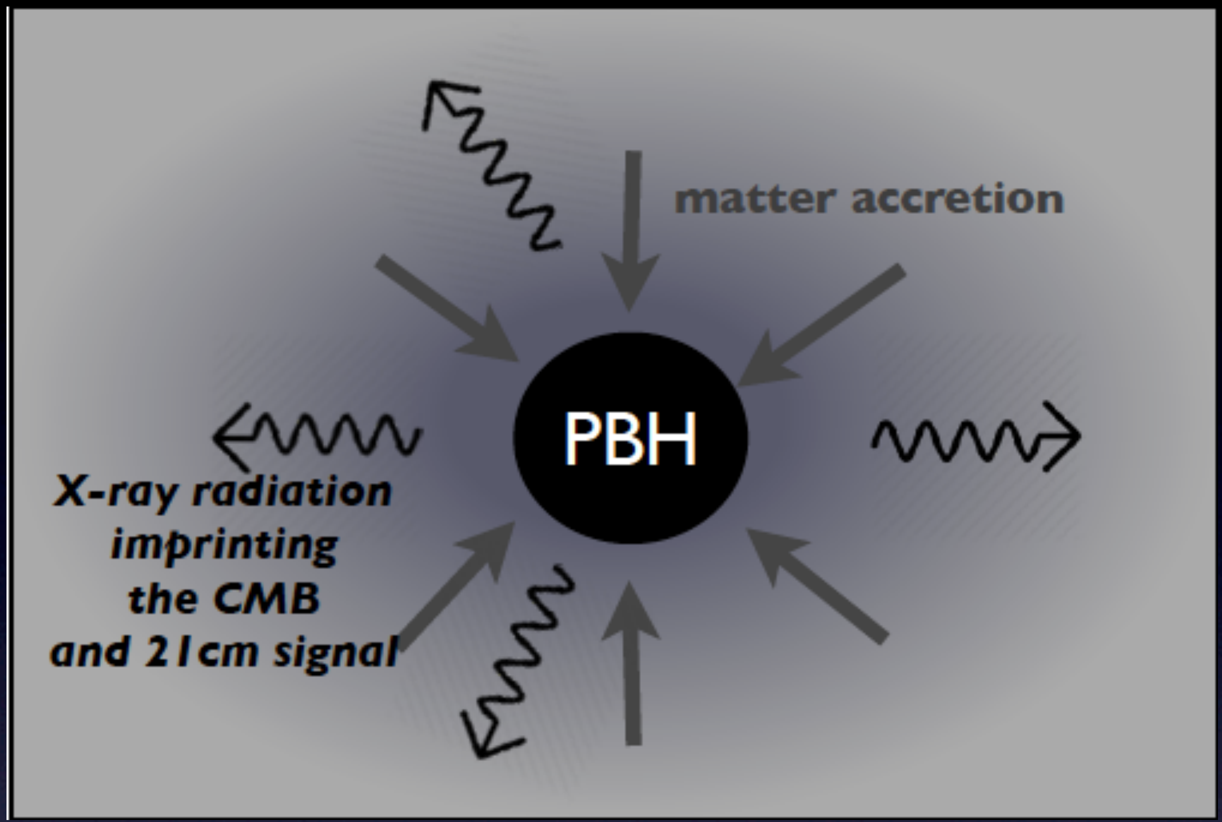


Disk accretion at high redshifts
$100 < z < 10\,000$

Constraints on PBH abundances



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Accretion Luminosity

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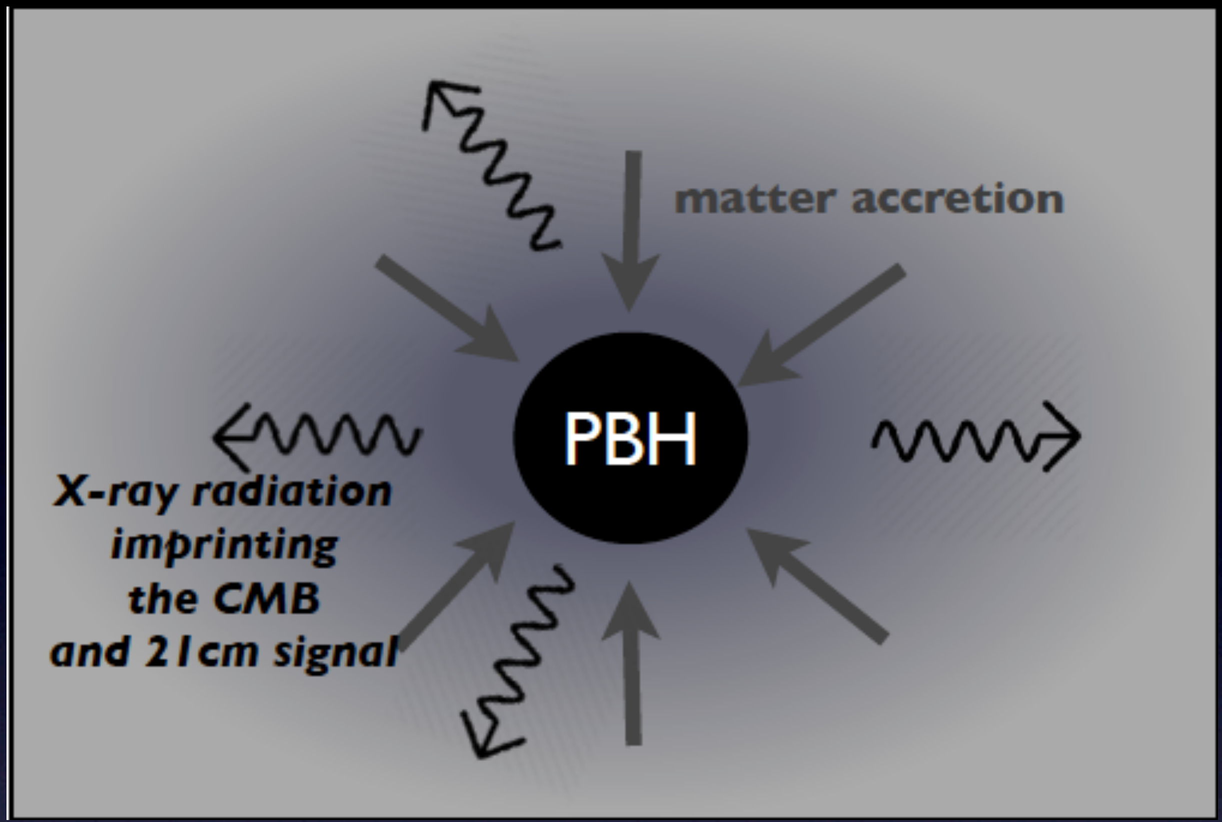
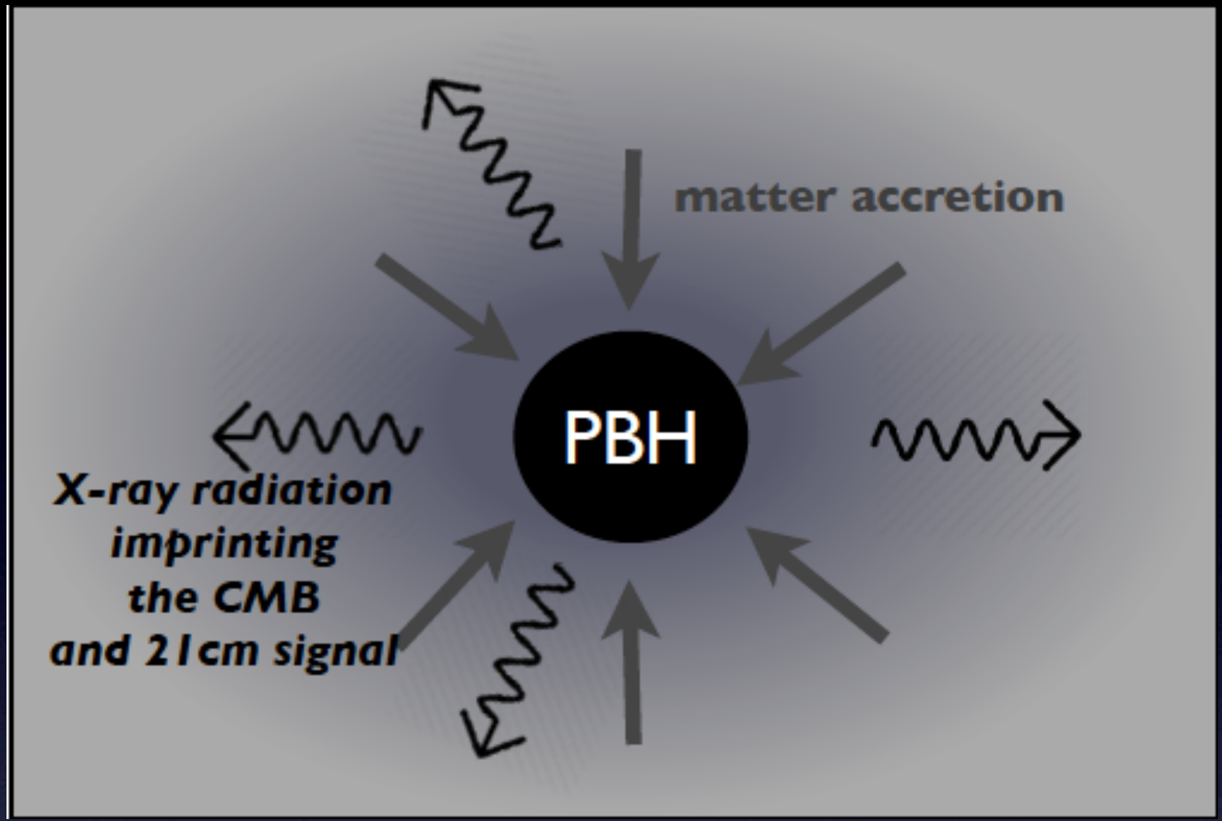


Disk accretion at high redshifts
$100 < z < 10\ 000$

Accretion Luminosity

Energy deposition

Constraints on PBH abundances



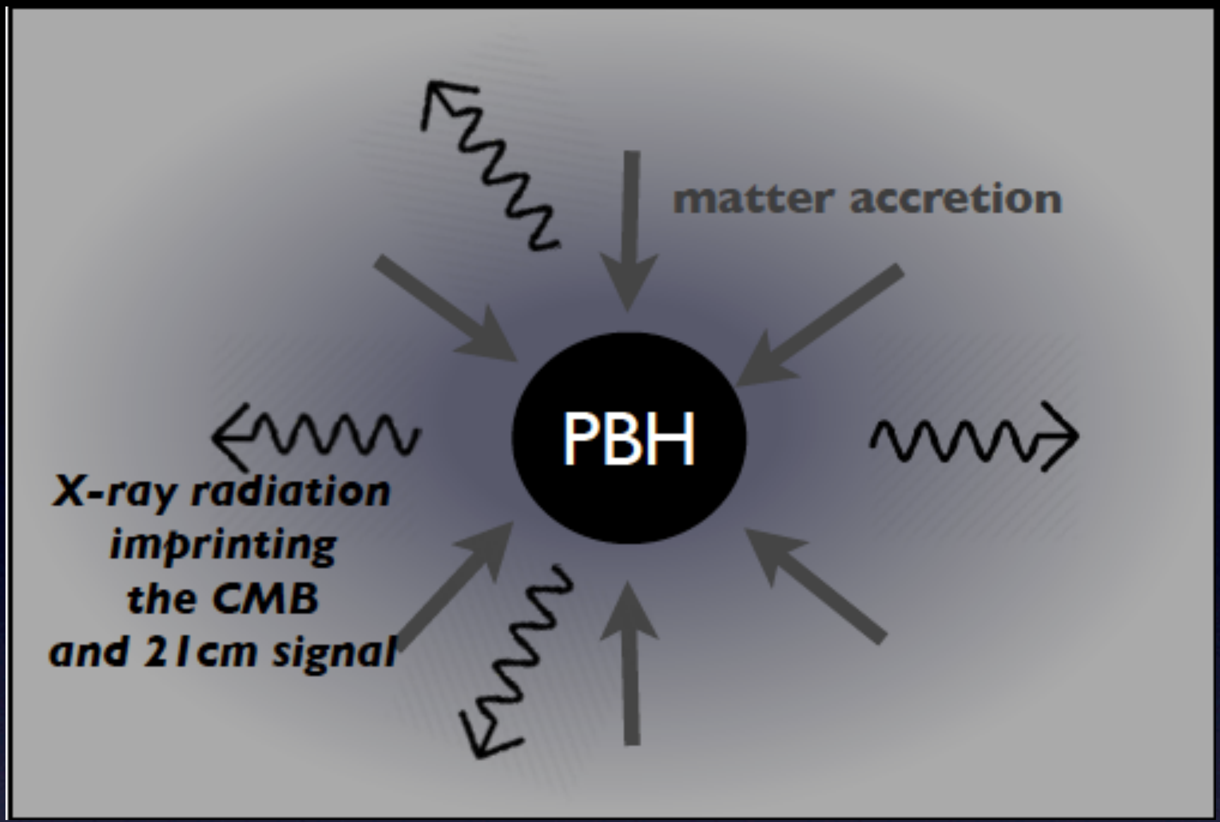
Disk accretion at high redshifts
100 < z < 10 000

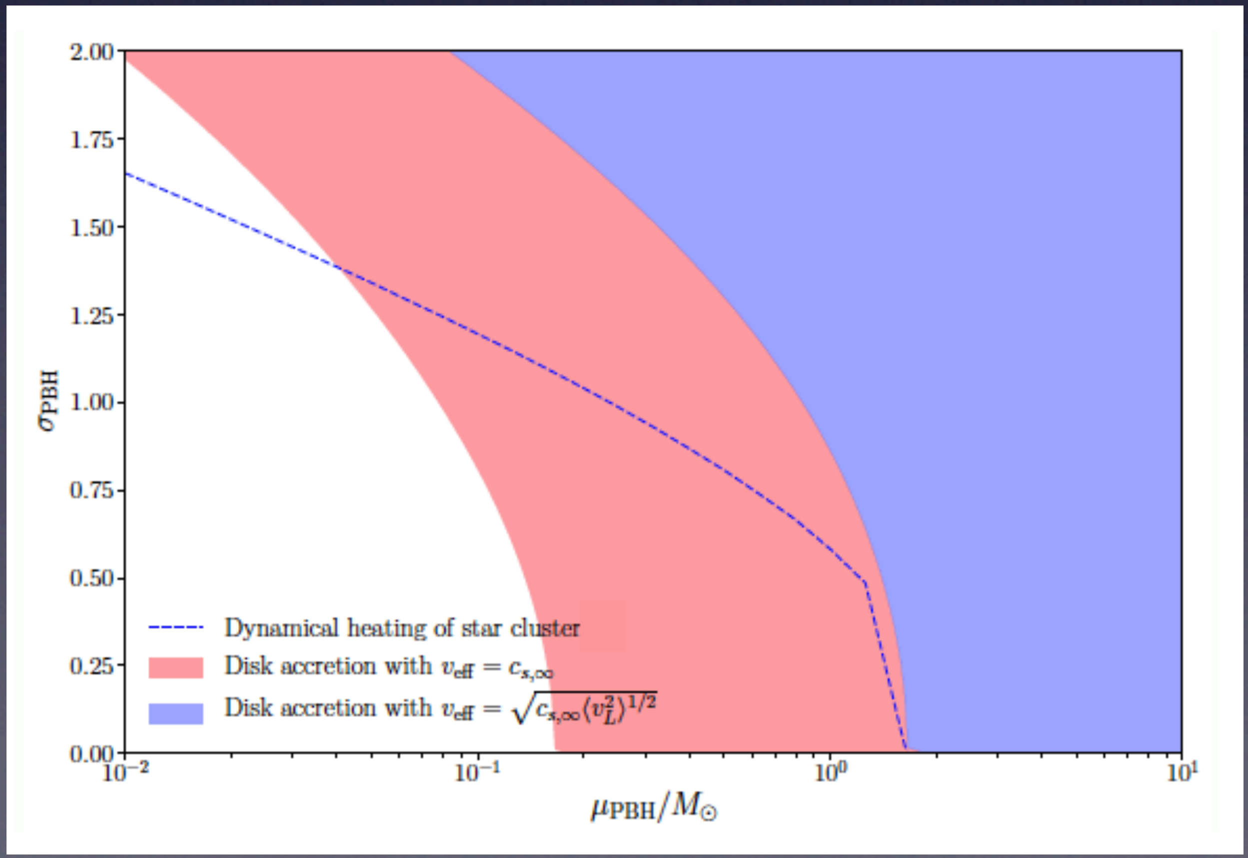
Accretion Luminosity

Energy deposition

Thermal History of the Universe
and effects on the CMB

Constraints on PBH abundances





Disk accretion at high redshifts
100 < z < 10 000

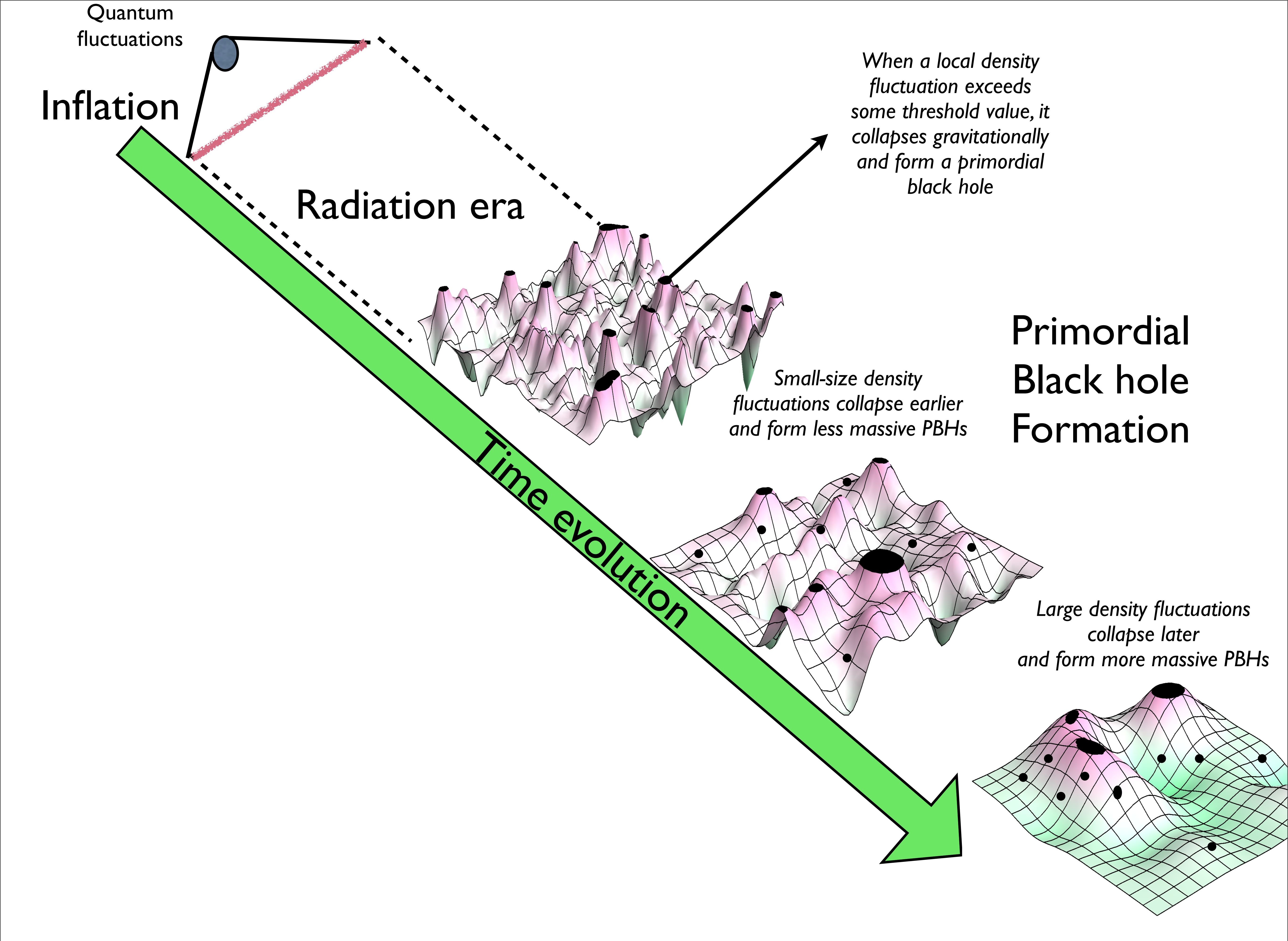
Accretion Luminosity

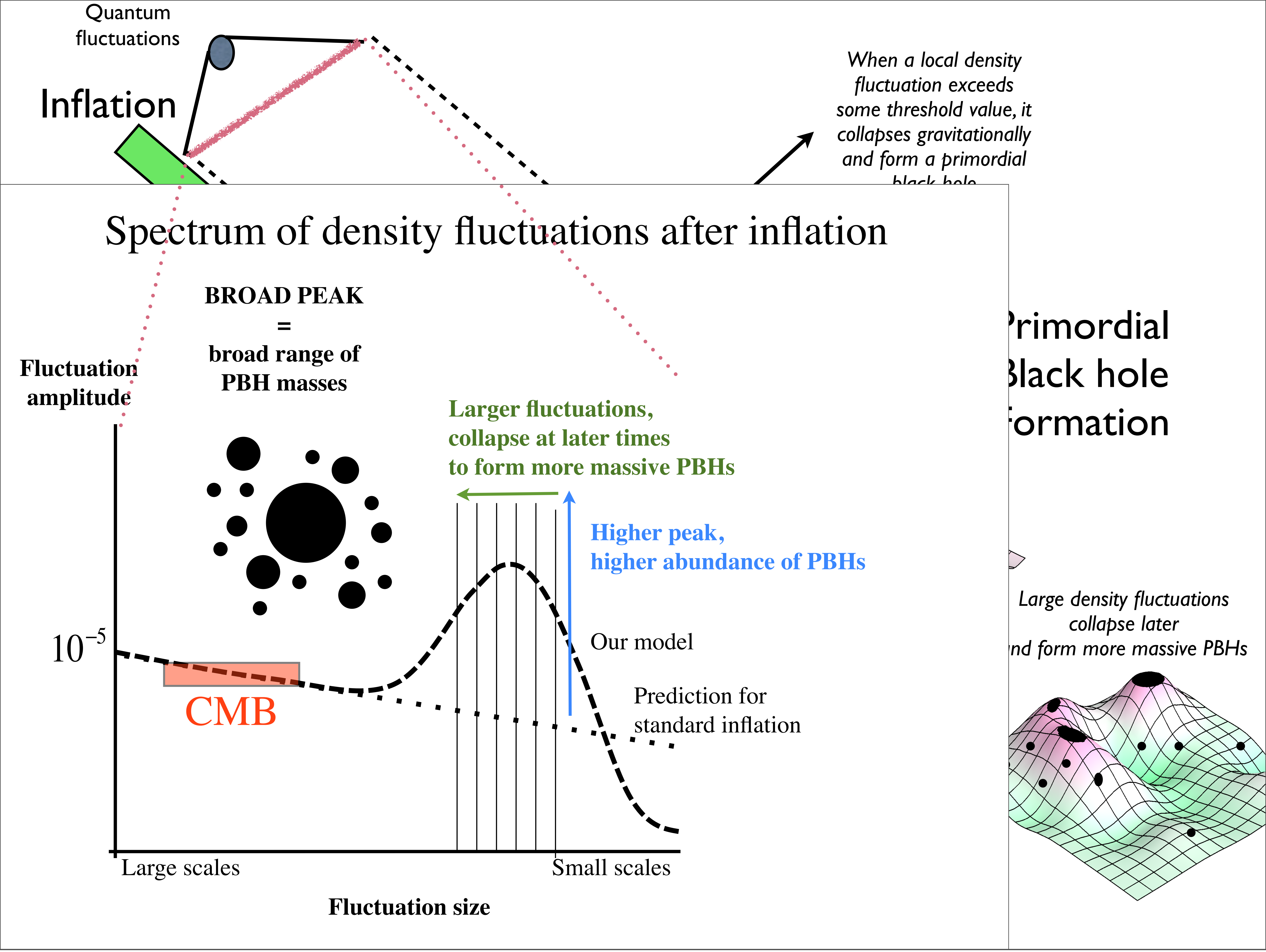
Energy deposition

Thermal History of the Universe and effects on the CMB

$$f_{\rm PBH} < \left(\frac{4\,M_\odot}{M}\right)^{1.6}\left(\frac{v_{\rm eff}}{10\ {\rm km/s}}\right)^{4.8}\left(\frac{0.01}{\lambda}\right)^{1.6}$$

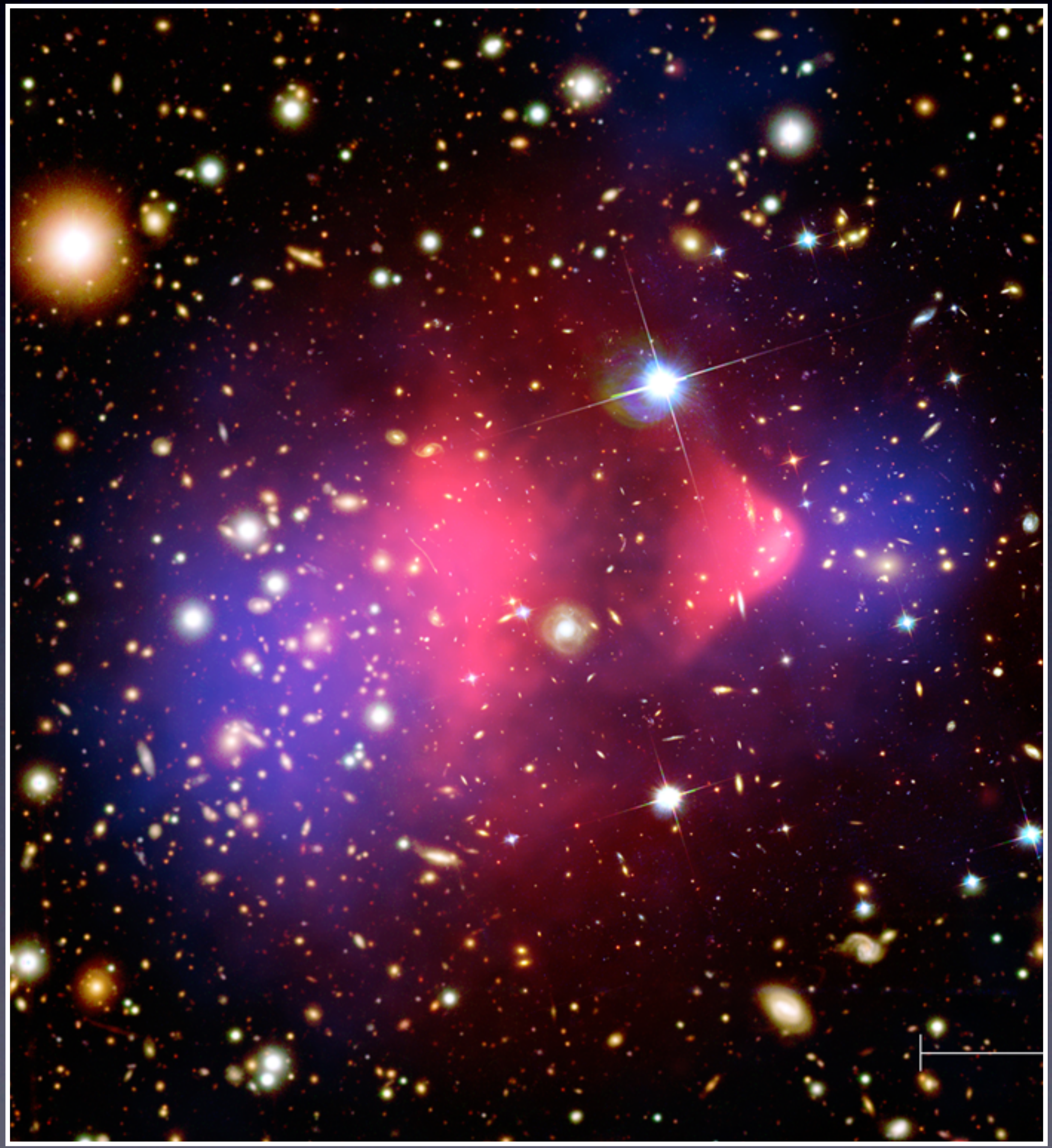
Poulin et al., 1707.04296


Quantum fluctuations
Inflation
Radiation era
When a local density fluctuation exceeds some threshold value, it collapses gravitationally and form a primordial black hole
Primordial Black hole Formation
Small-size density fluctuations collapse earlier and form less massive PBHs
Time evolution
Large density fluctuations collapse later and form more massive PBHs


Quantum fluctuations
Inflation
When a local density fluctuation exceeds some threshold value, it collapses gravitationally and form a primordial black hole
Spectrum of density fluctuations after inflation
BROAD PEAK
=
broad range of PBH masses
Fluctuation amplitude
Larger fluctuations, collapse at later times to form more massive PBHs
Higher peak, higher abundance of PBHs
10^{-5}
Our model
Prediction for standard inflation
CMB
Large scales
Small scales
Fluctuation size
rimordial
lack hole
ormation
Large density fluctuations collapse later
nd form more massive PBHs

A good Dark Matter candidate

- Do not emit light by nature
- Non-relativistic
- Nearly collisionless
- Formed in the early Universe



In March 2016...

- S. Bird et al., 1603.00464
  Monochromatic spectrum, extended halo mass function

$$\tau_{\rm merg} \sim 2 f_{\rm HMF} f_{\rm DM} \left(M_{\rm crit.halo}/400 M_\odot\right)^{-11/21} {\rm Gpc}^{-3} {\rm yr}^{-1}$$

Most mergings come from mini-halos

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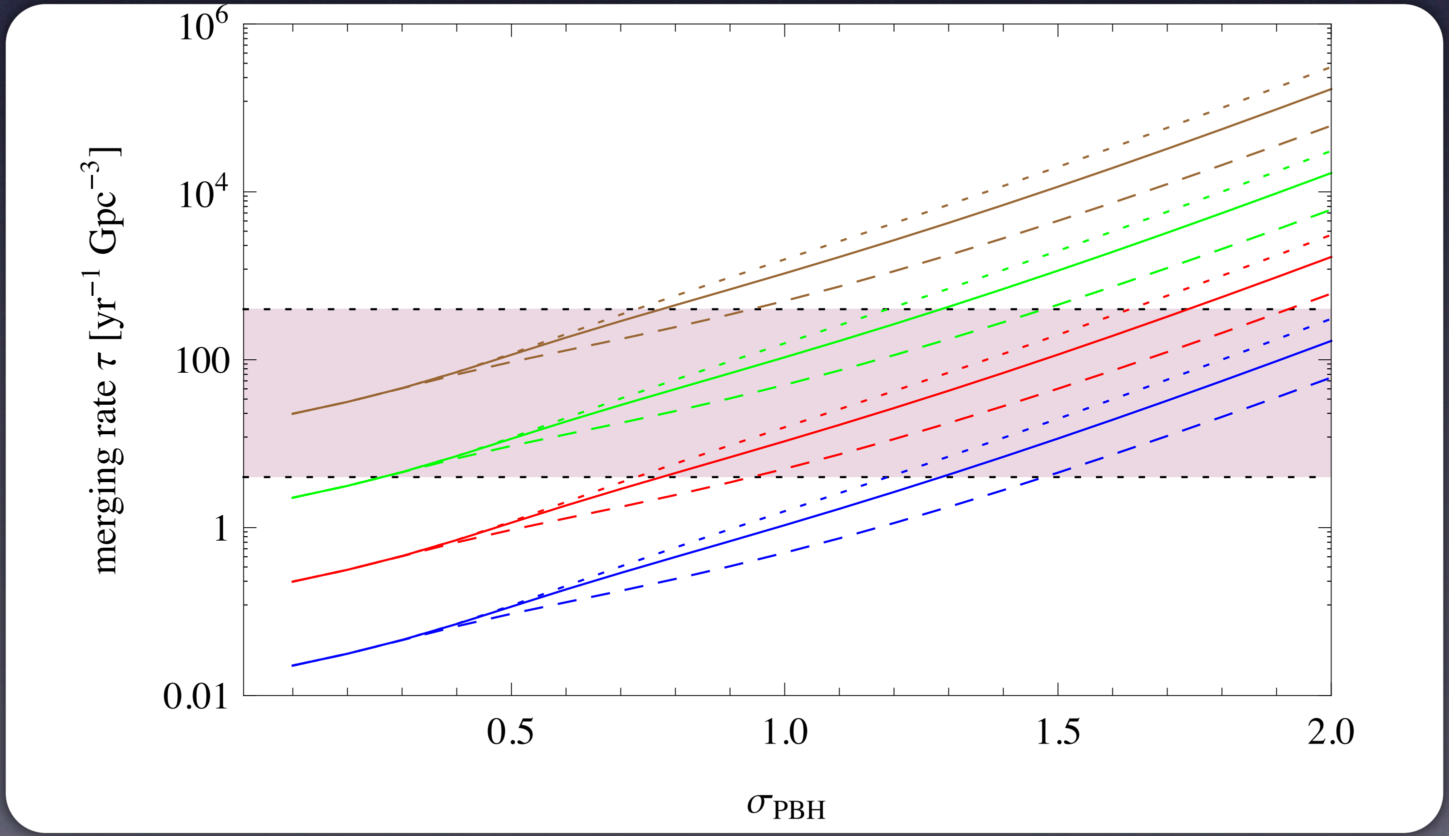
Most mergings come from mini-halos

- S.C., J. Garcìa-Bellido, 1603.05234
  Broad mass spectrum, natural clustering scale

$$\tau_{\rm merg} \sim f_{\rm DM} 10^{-8} \delta_{\rm PBH}^{\rm loc.} {\rm Gpc}^{-3} {\rm yr}^{-1}$$

Faint Dwarf Galaxies or Globular Clusters



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- S.C., J. Garcìa-Bellido, 1603.05234
  Broad mass spectrum, natural clustering scale

$$\tau_{\rm merg} \sim f_{\rm DM} 10^{-8} \delta_{\rm PBH}^{\rm loc.} {\rm Gpc}^{-3}{\rm yr}^{-1}$$

Faint Dwarf Galaxies or Globular Clusters

- M. Sasaki et al., 1603.08338
  Monochromatic spectrum, BH binaries from Early Universe

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cannot be the Dark Matter except if PBHs are initially clustered

In March 2016...

- S. Bird et al., 1603.00464
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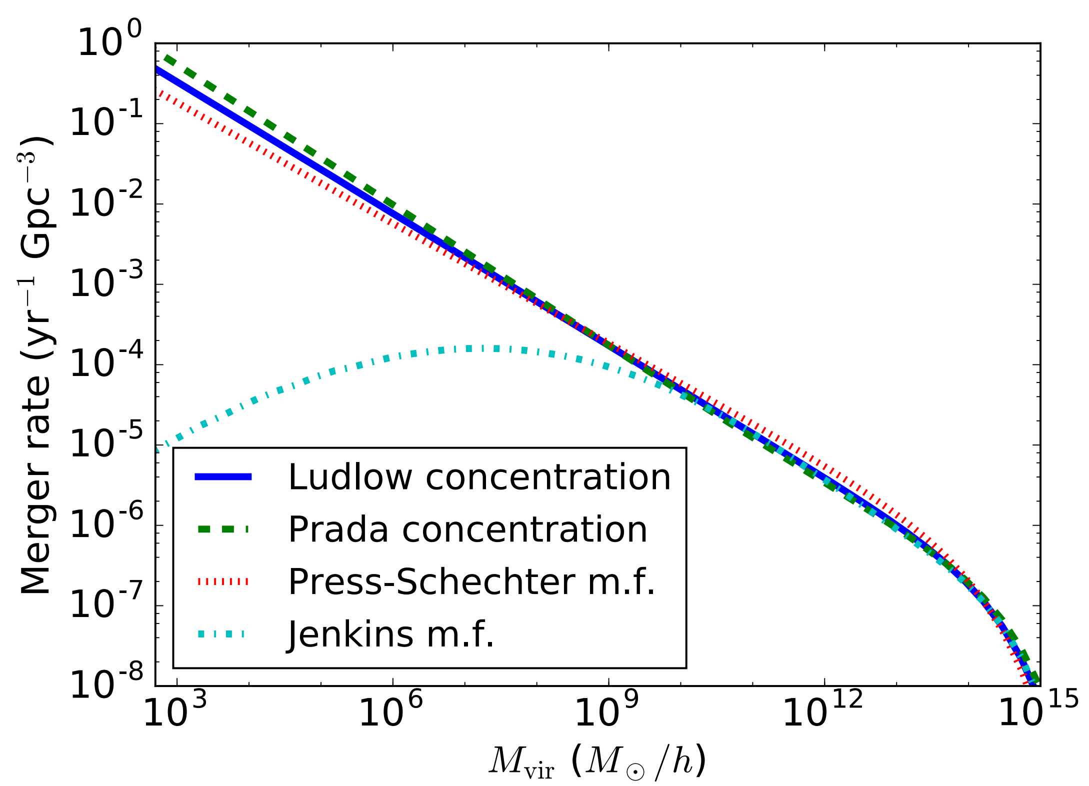

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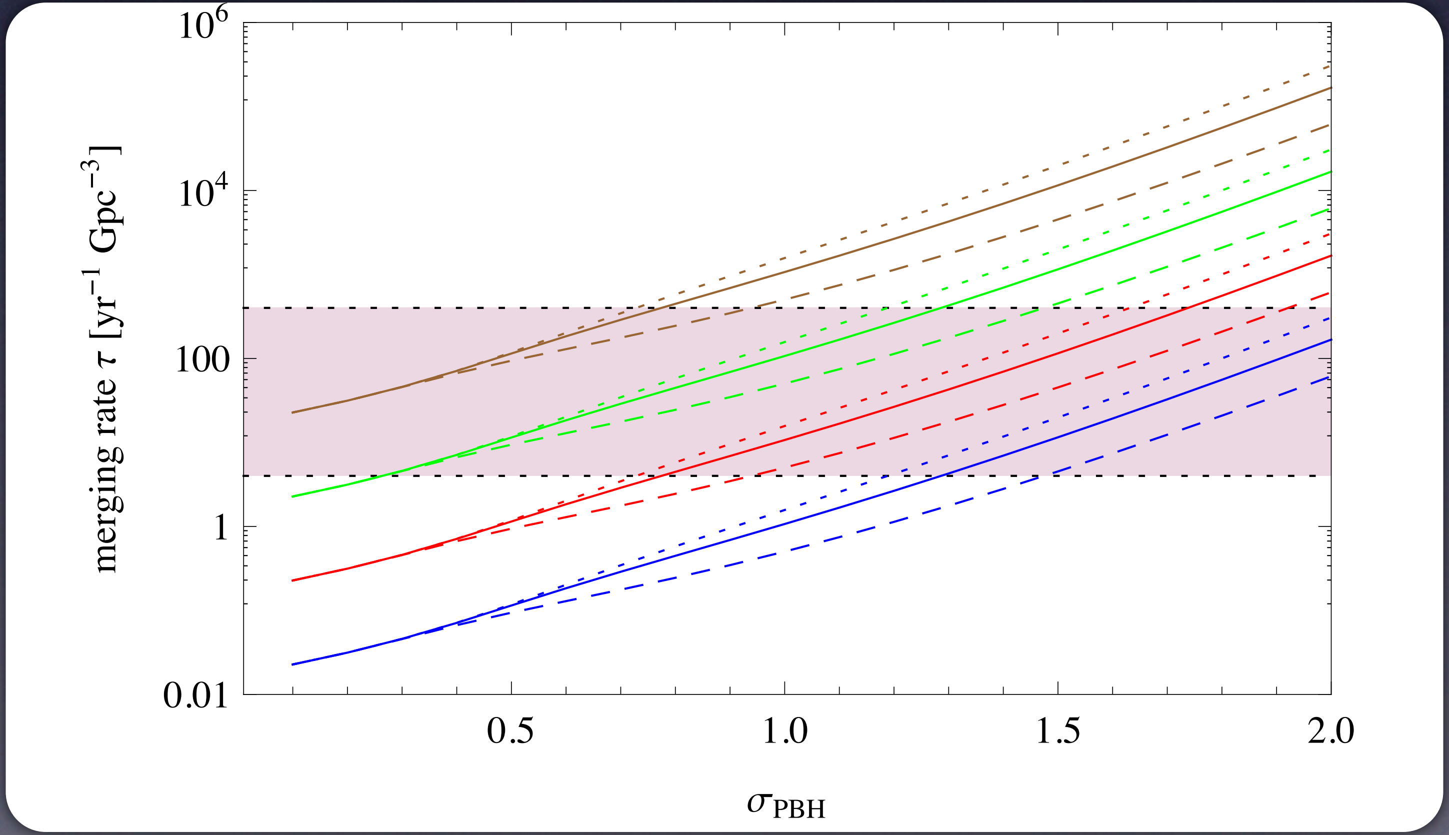

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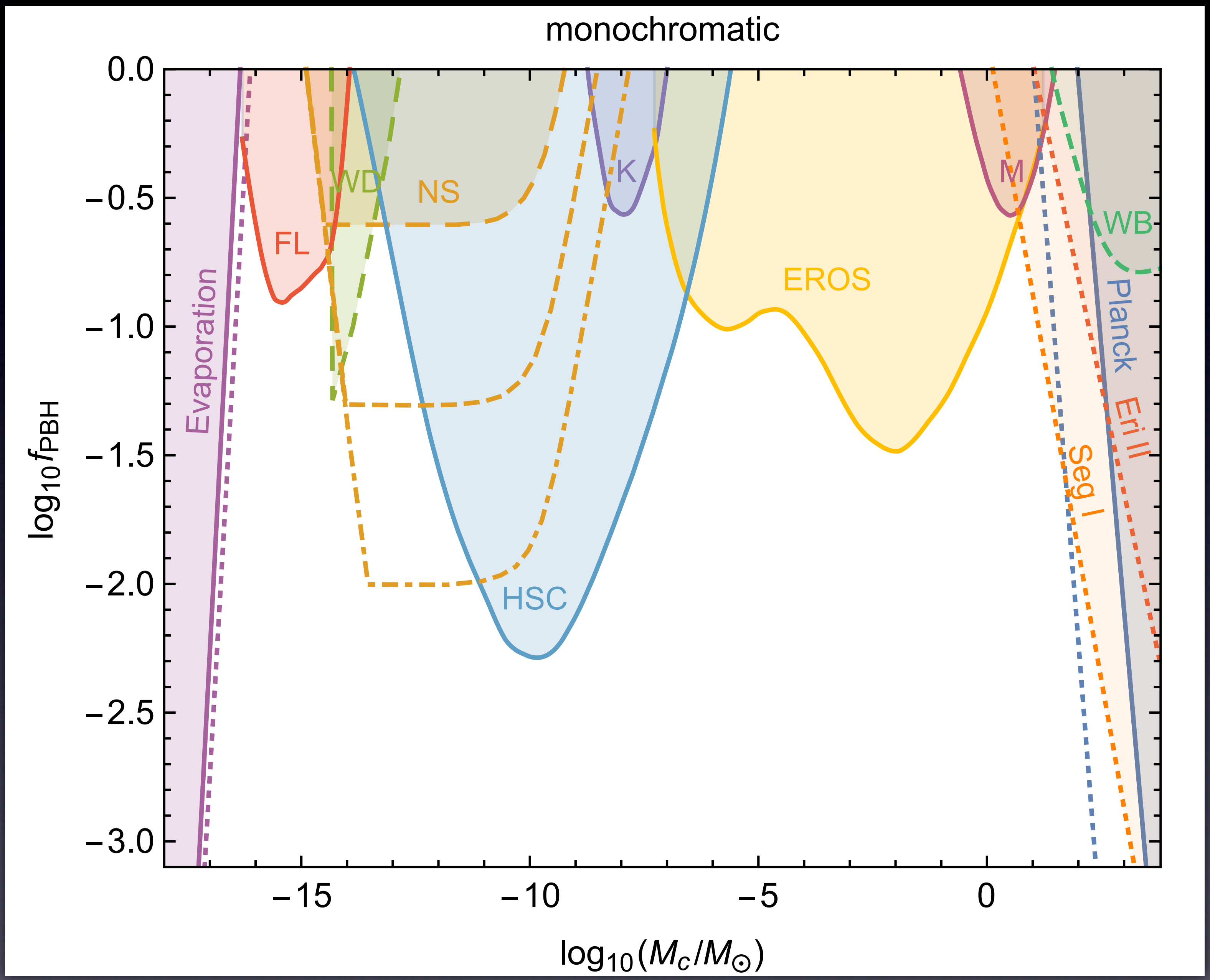
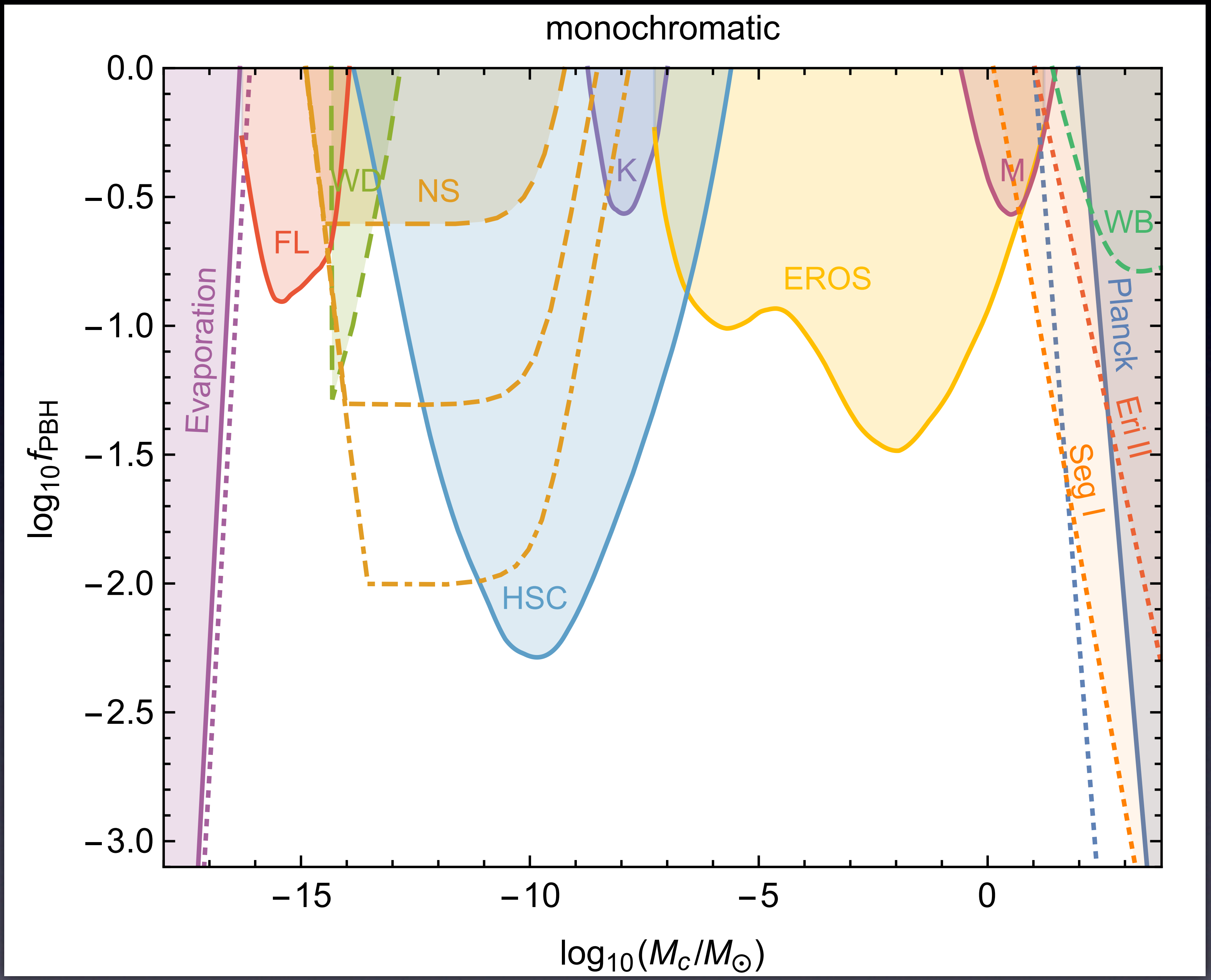
Constraints on PBH abundances



B. Carr et al., 1705.05567

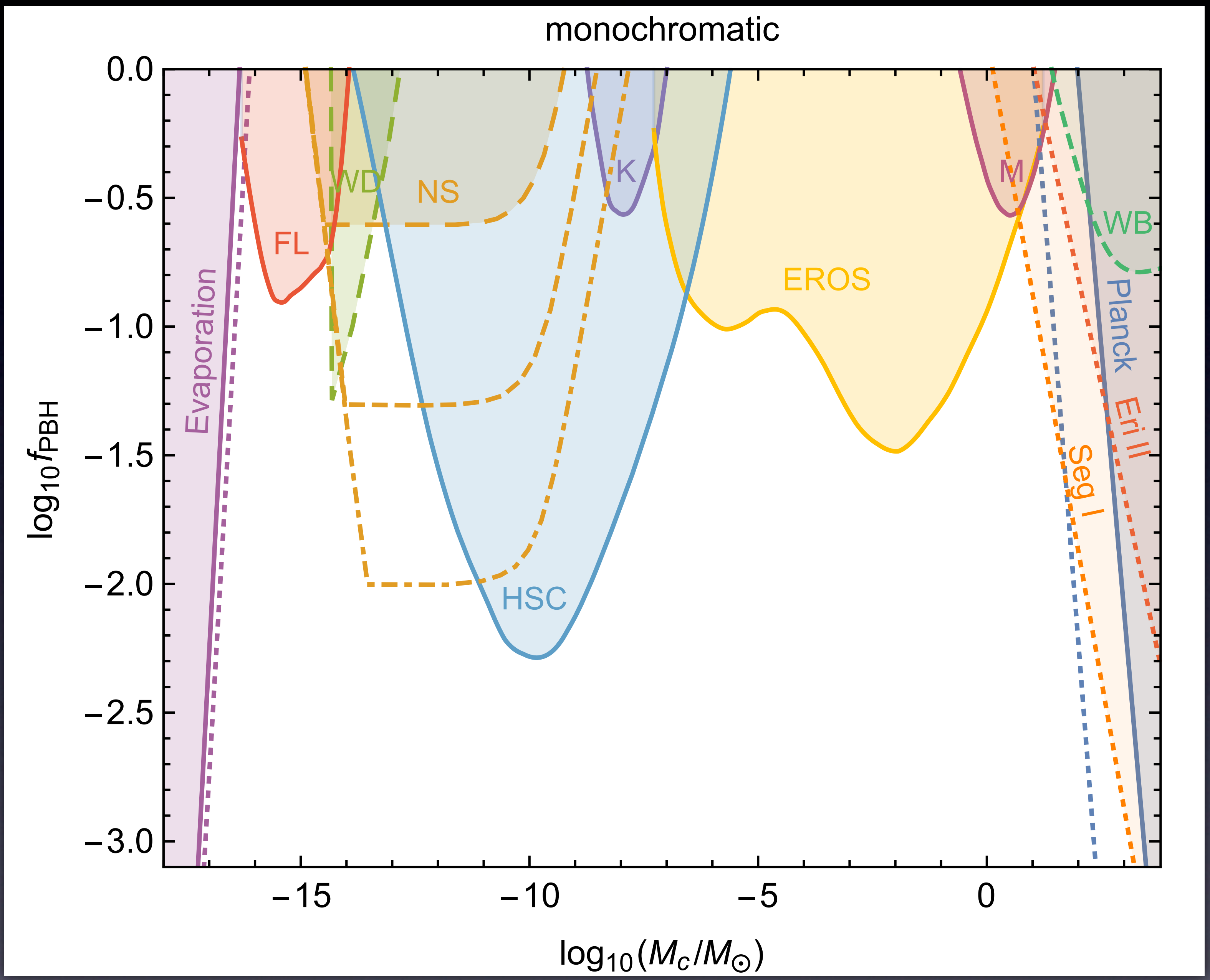
Constraints on PBH abundances



Monochromatic spectrum:
PBH-DM looks excluded in the whole mass range

B. Carr et al., 1705.05567

Constraints on PBH abundances

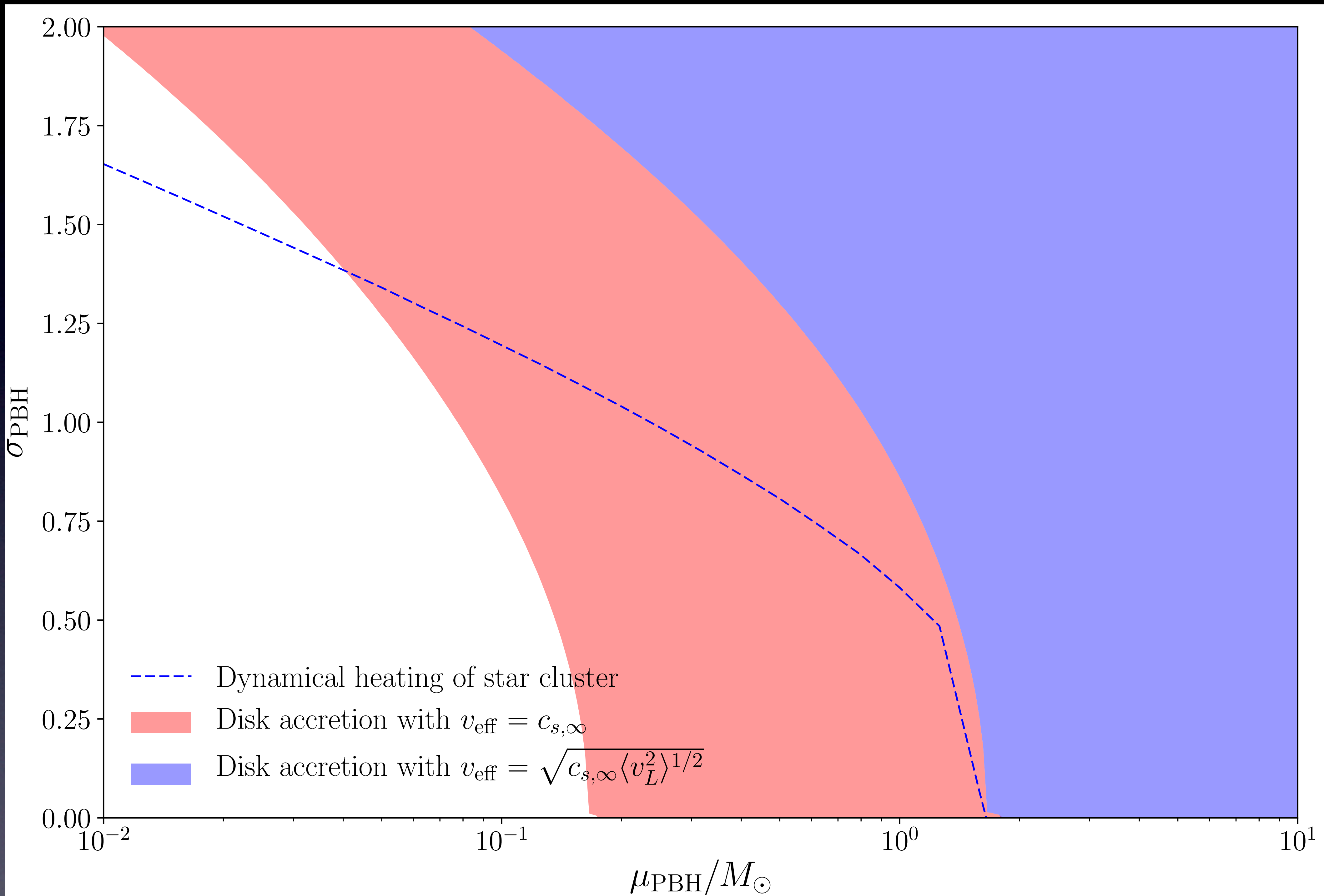


B. Carr et al., 1705.05567

Monochromatic spectrum:
PBH-DM looks excluded in the whole mass range

Microlensing constraints are controversial and change if PBH are clustered!
(SC., JGB, 1501.07565
A. Green, 1705.10818)!

Constraints on PBH abundances

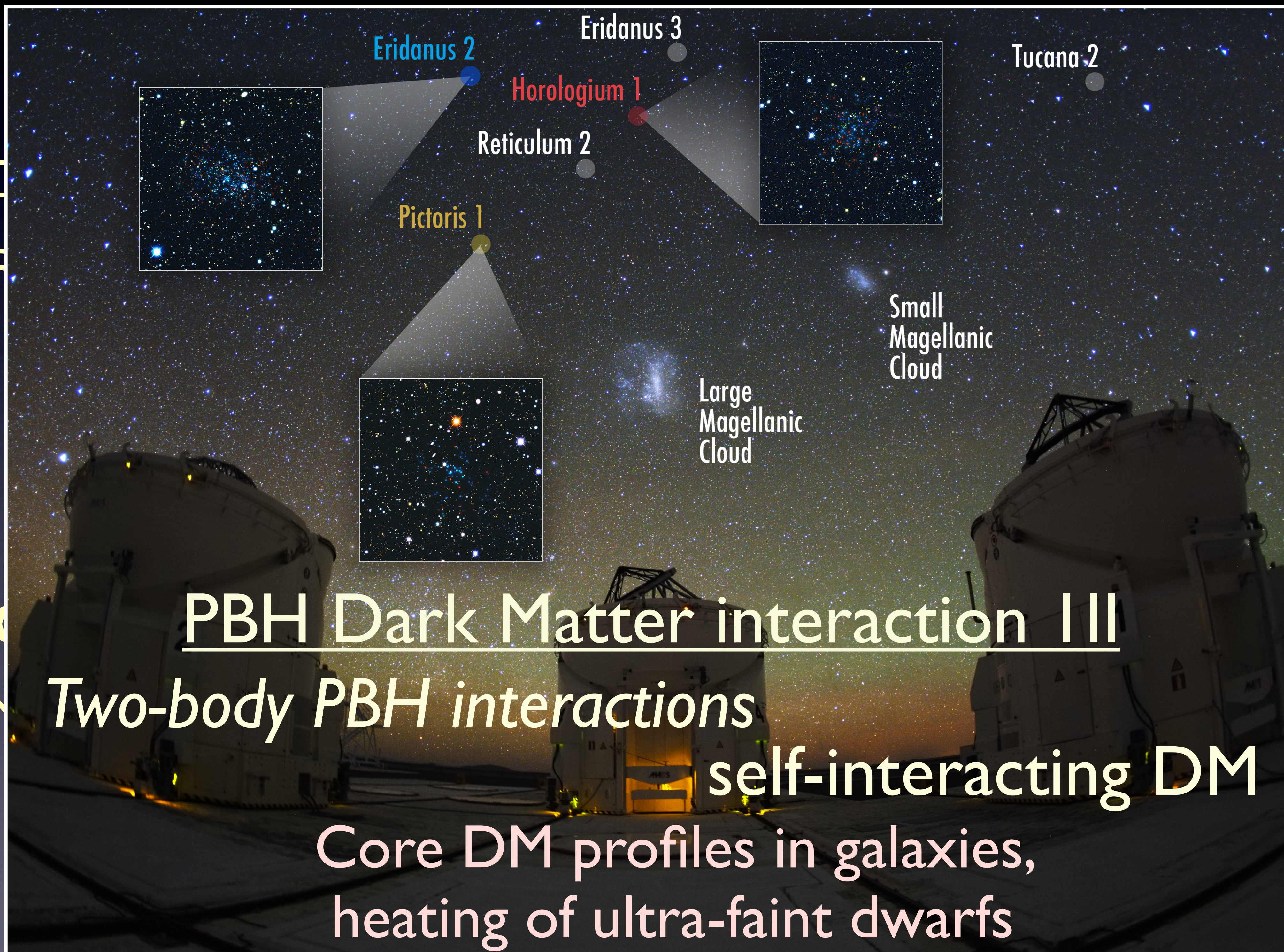


Poulin, Serpico, Calore, SC, Kohry 170704206

CMB very sensitive to the relative PBH/baryon velocity

Seven hints for PBH-DM

Hint 2: Star clusters and dynamics of faint dwarf galaxies



PBH Dark Matter interaction III

Two-body PBH interactions

self-interacting DM

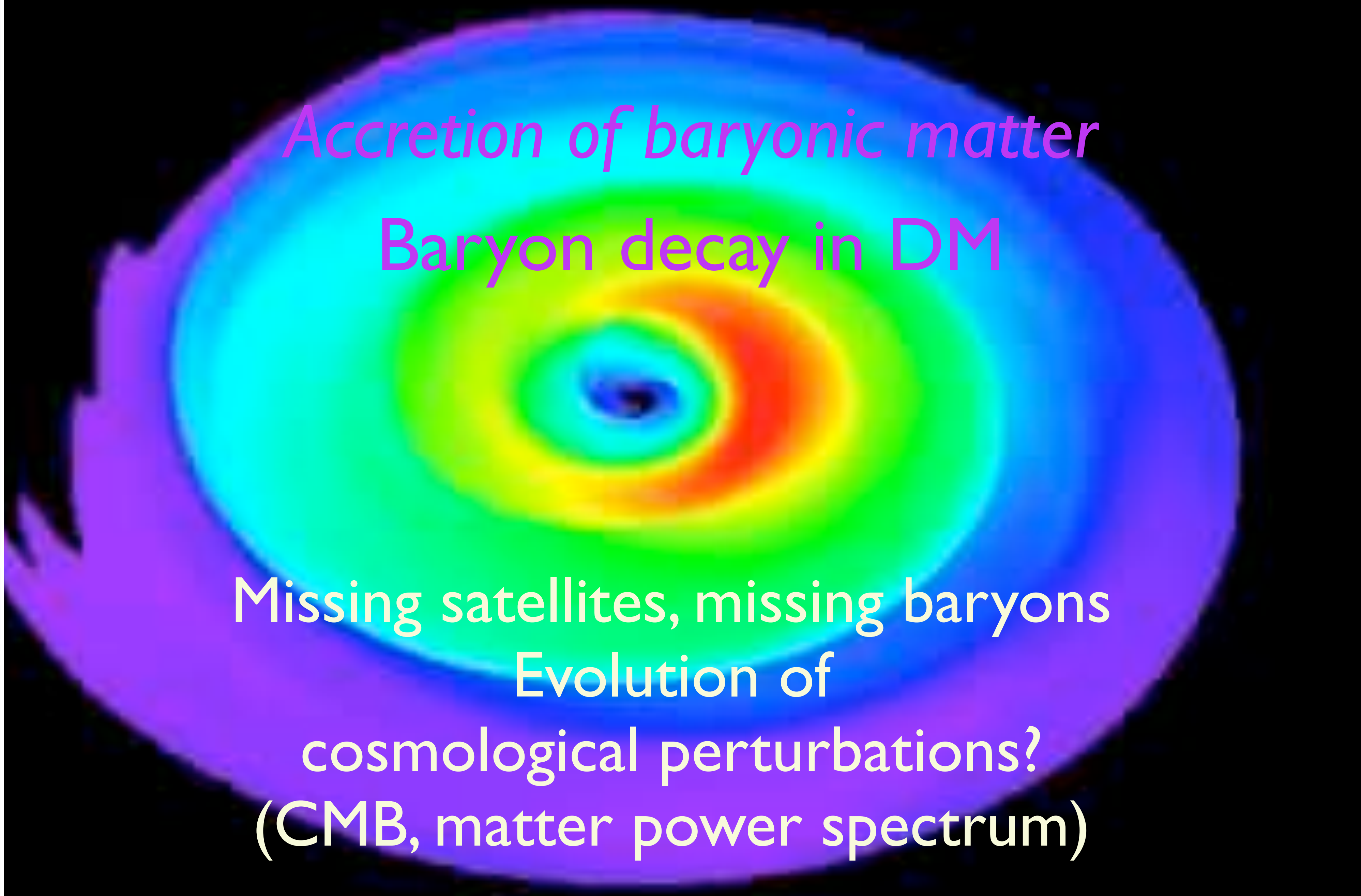
Core DM profiles in galaxies,
heating of ultra-faint dwarfs

Seven hints for PBH-DM

Hint 2: Star clusters and dynamics of faint dwarf galaxies

- Dy
- Re
- **Cu**
- Na

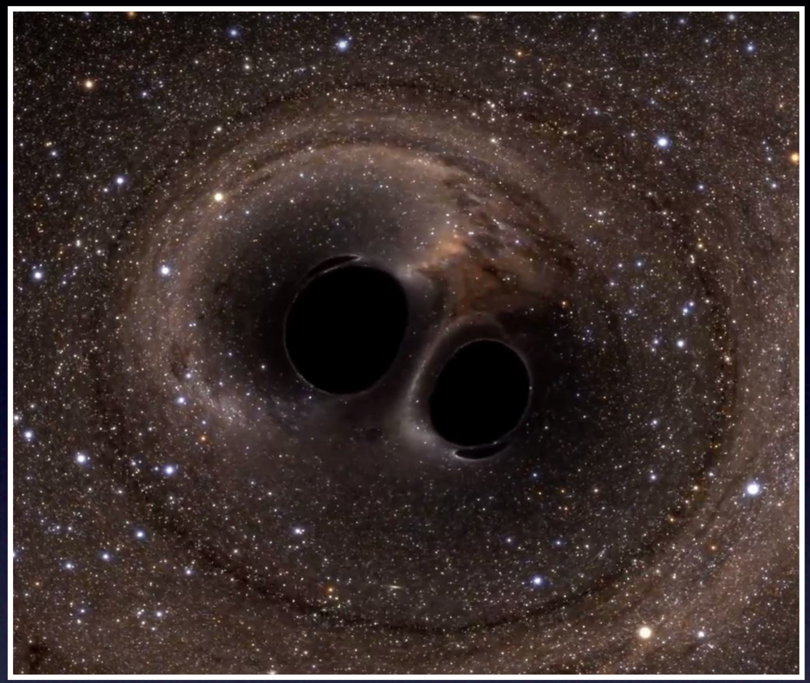
PBH Dark Matter interaction IV

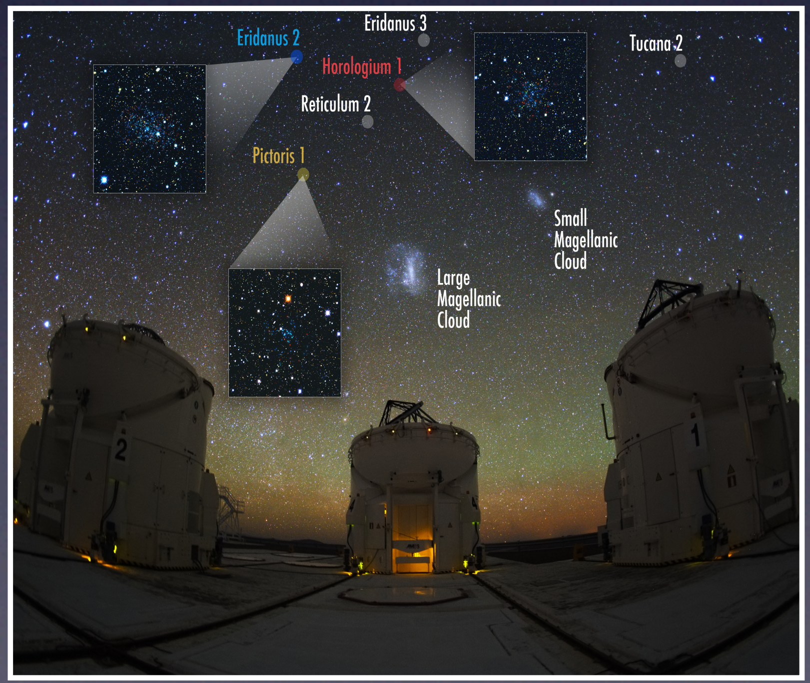


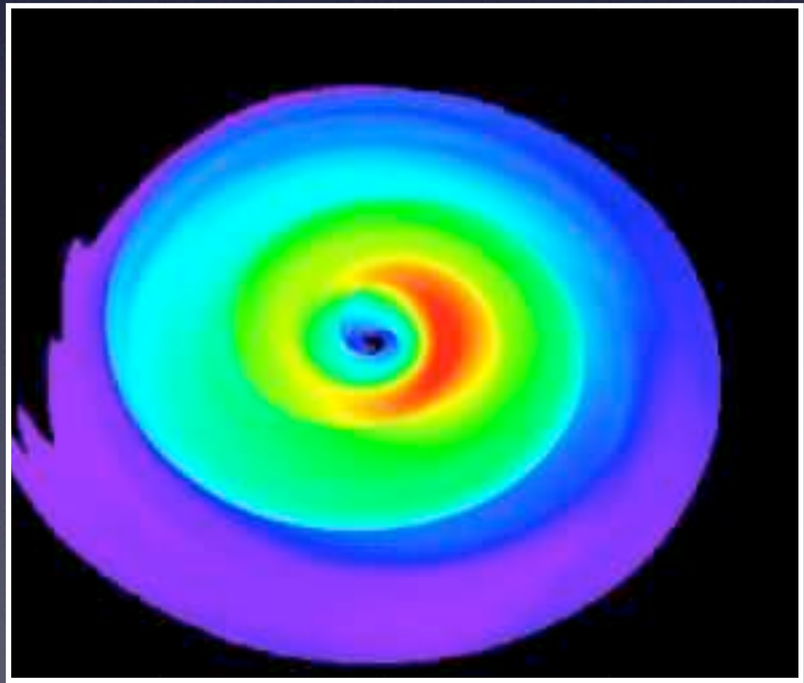
Rethinking DM interactions

DM decay in dark radiation

DM decay to photons

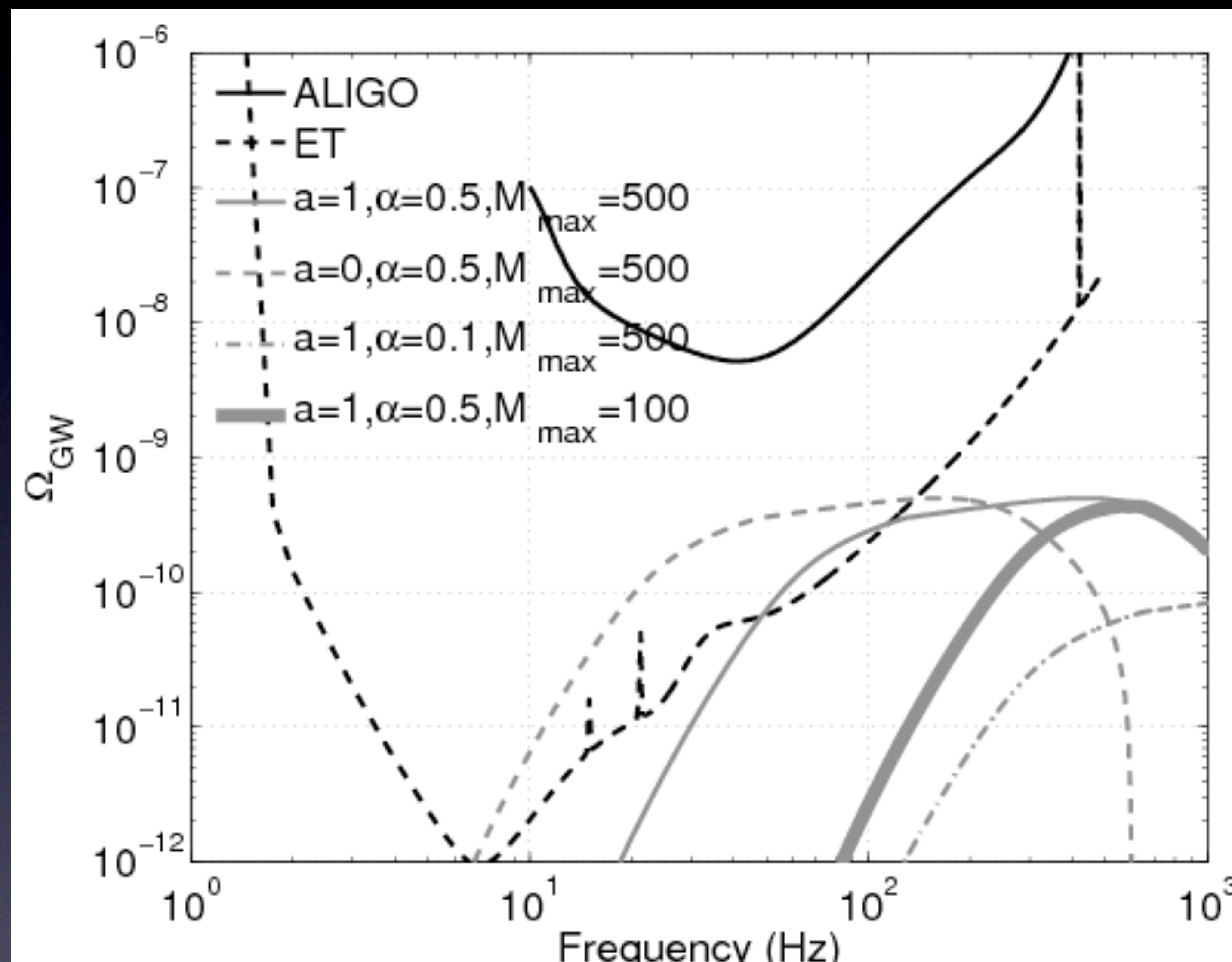






Self-interacting dark matter

DM production



ALIGO
ET
a=1,α=0.5,M max =500
a=0,α=0.5,M max =500
a=1,α=0.1,M max =500
a=1,α=0.5,M max =100
Ω GW
Frequency (Hz)