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Namur Center for Complex Systems (naXys), Namur University

Primordial Black Holes Dark Matter

*based on arXiv:1711.10458, 1710.04694, 1707.04206, 1610.08479, 1603.05234, 1501.00460
(work with J. García-Bellido, P. Serpico, V. Poulin, F. Calore,...)
or (if lazy) review article in the Scientific American, July 2017*

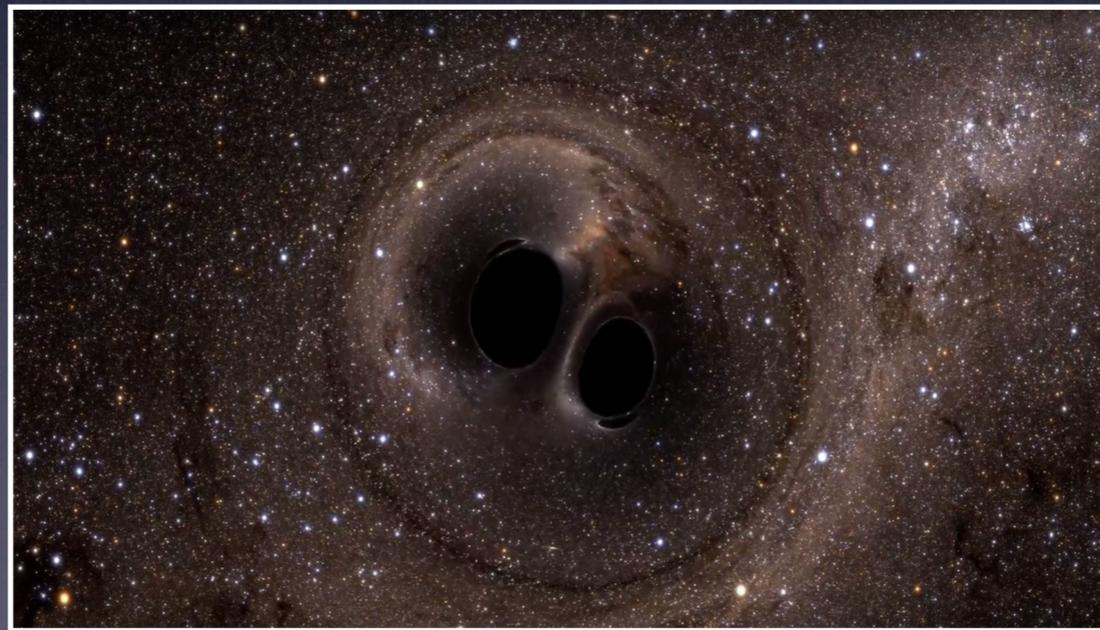


Dark Matter Workshop @CP3
December 7th, 2017, Université Catholique de Louvain

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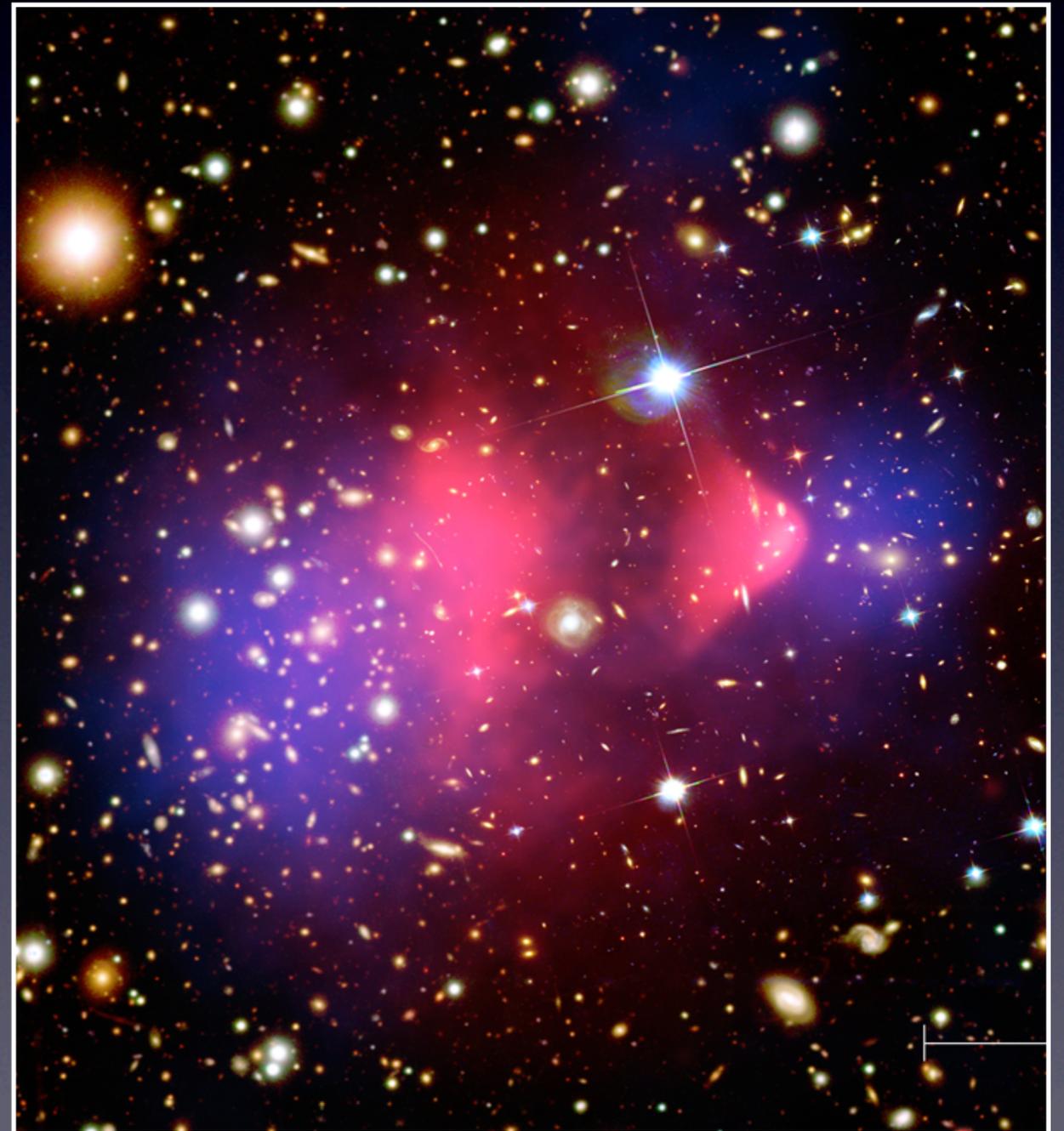


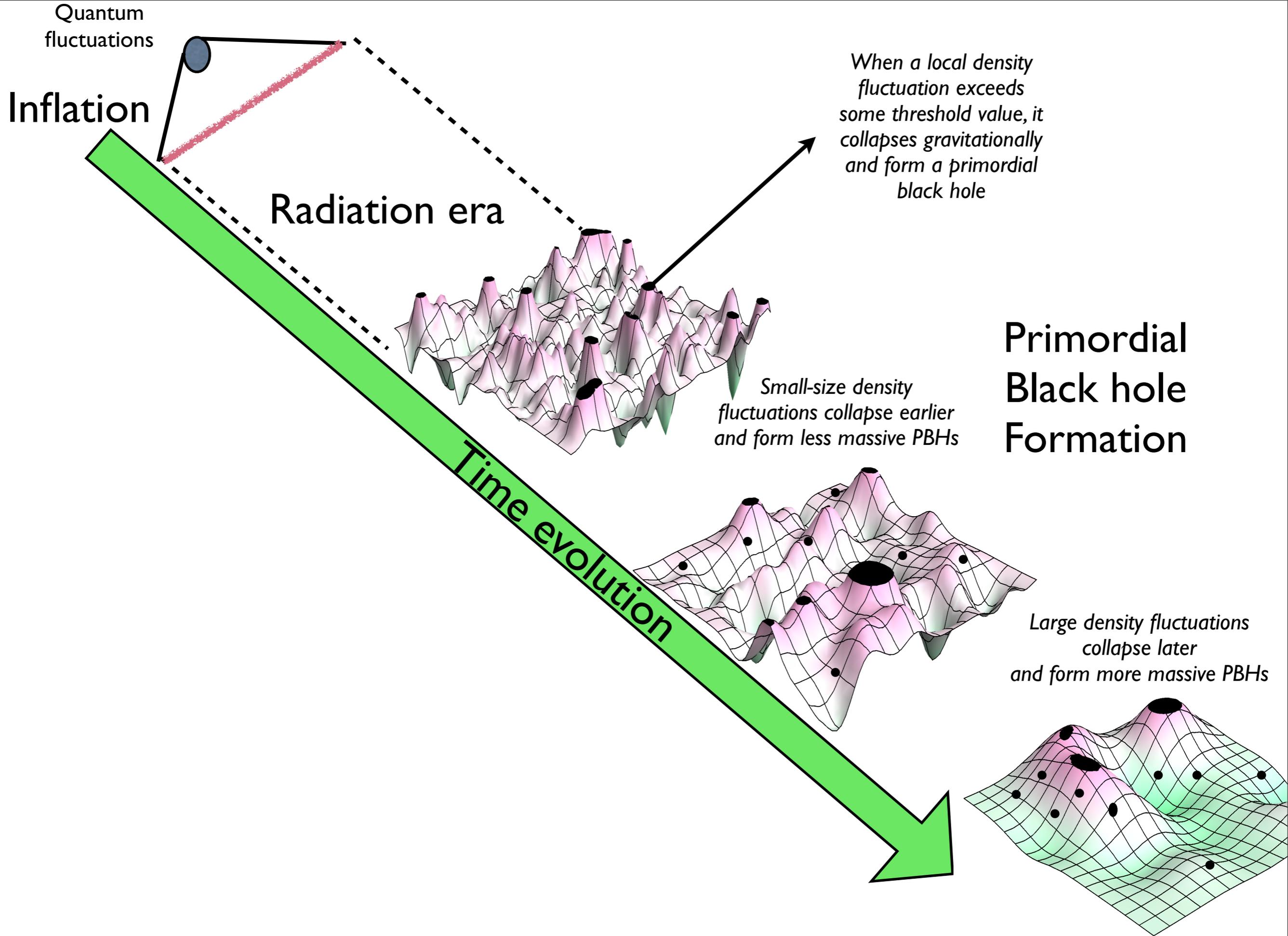
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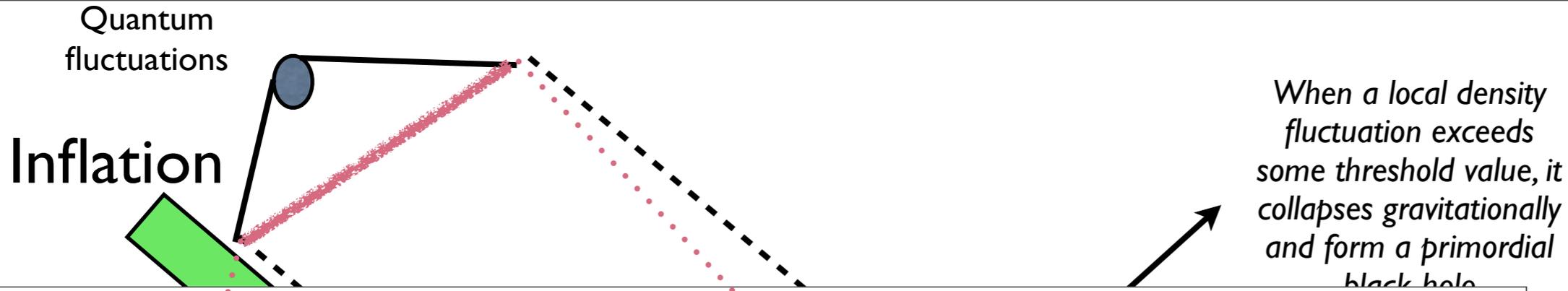
Part I: Reviving PBH Dark Matter

A good Dark Matter candidate

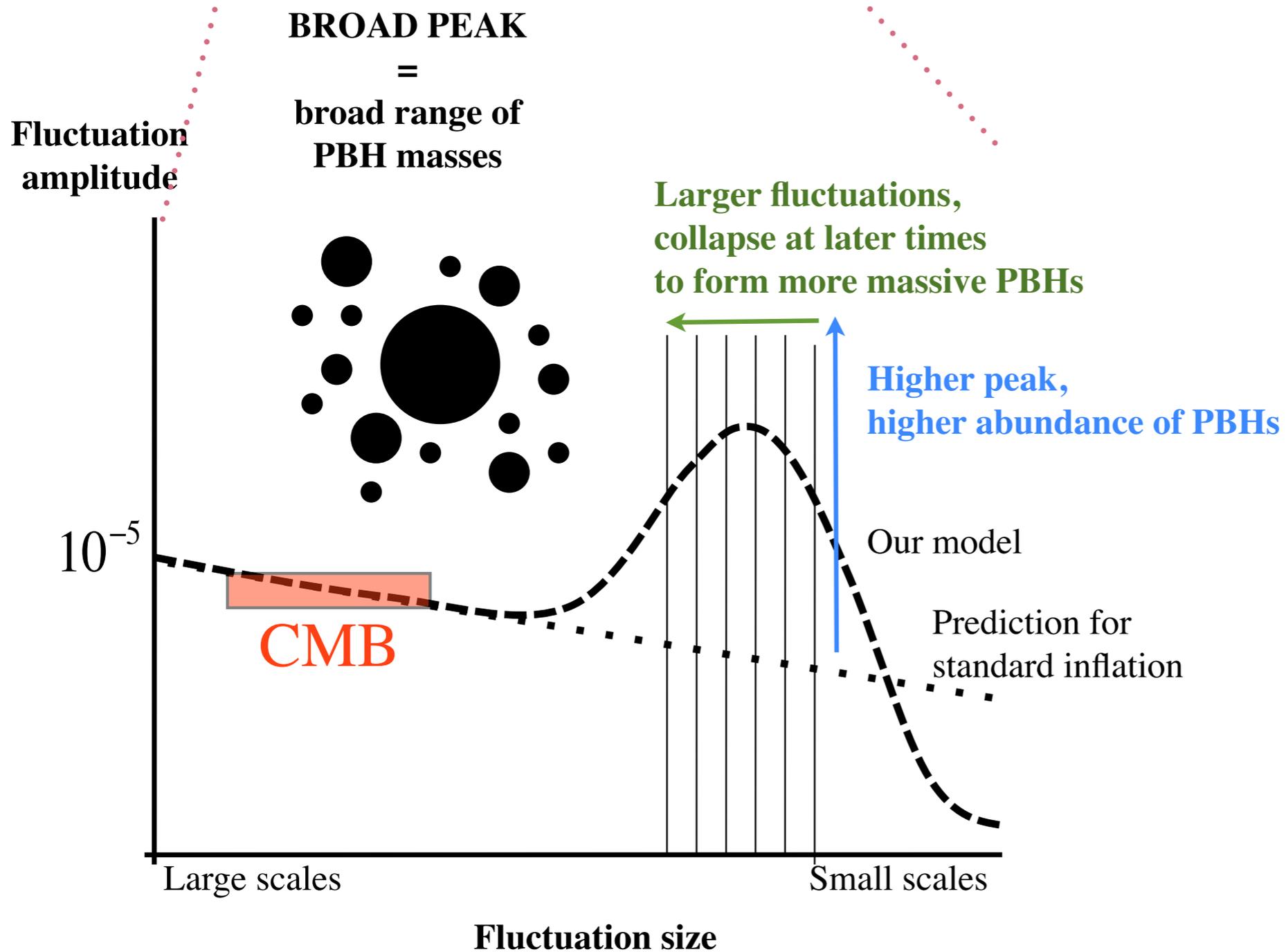
- Do not emit light by nature
- Non-relativistic
- Nearly collisionless
- Formed in the early Universe





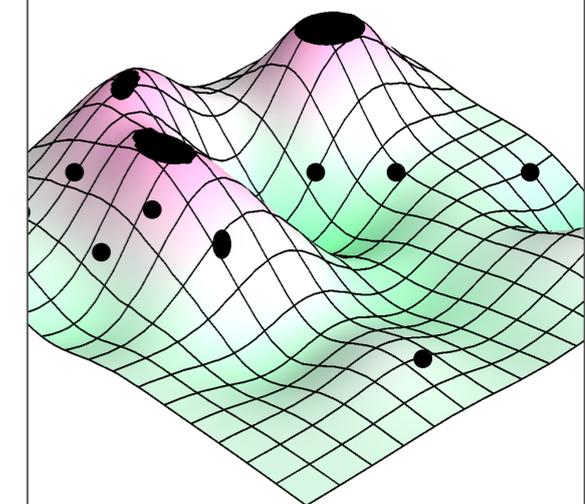


Spectrum of density fluctuations after inflation



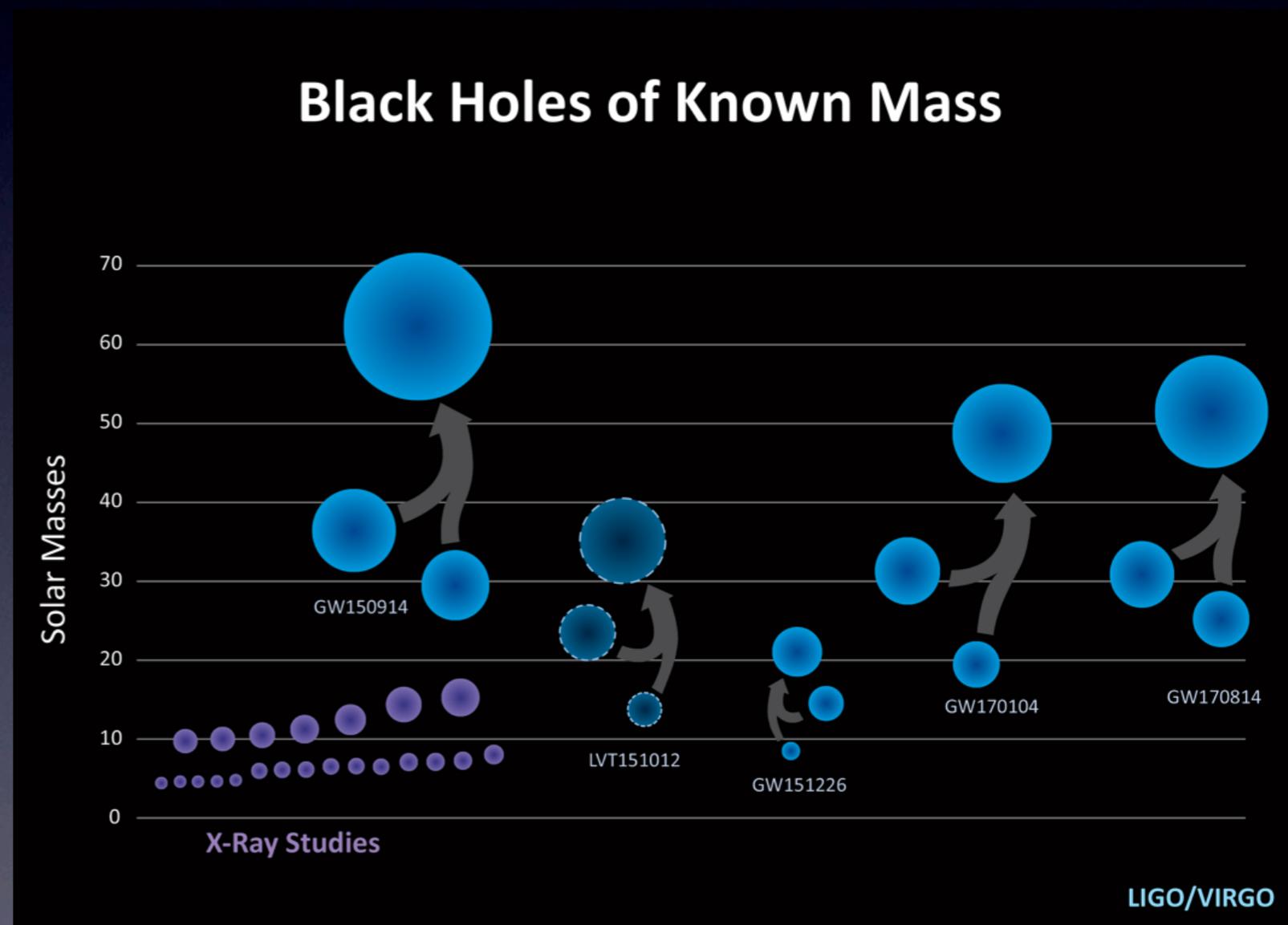
Primordial Black hole formation

Large density fluctuations collapse later and form more massive PBHs



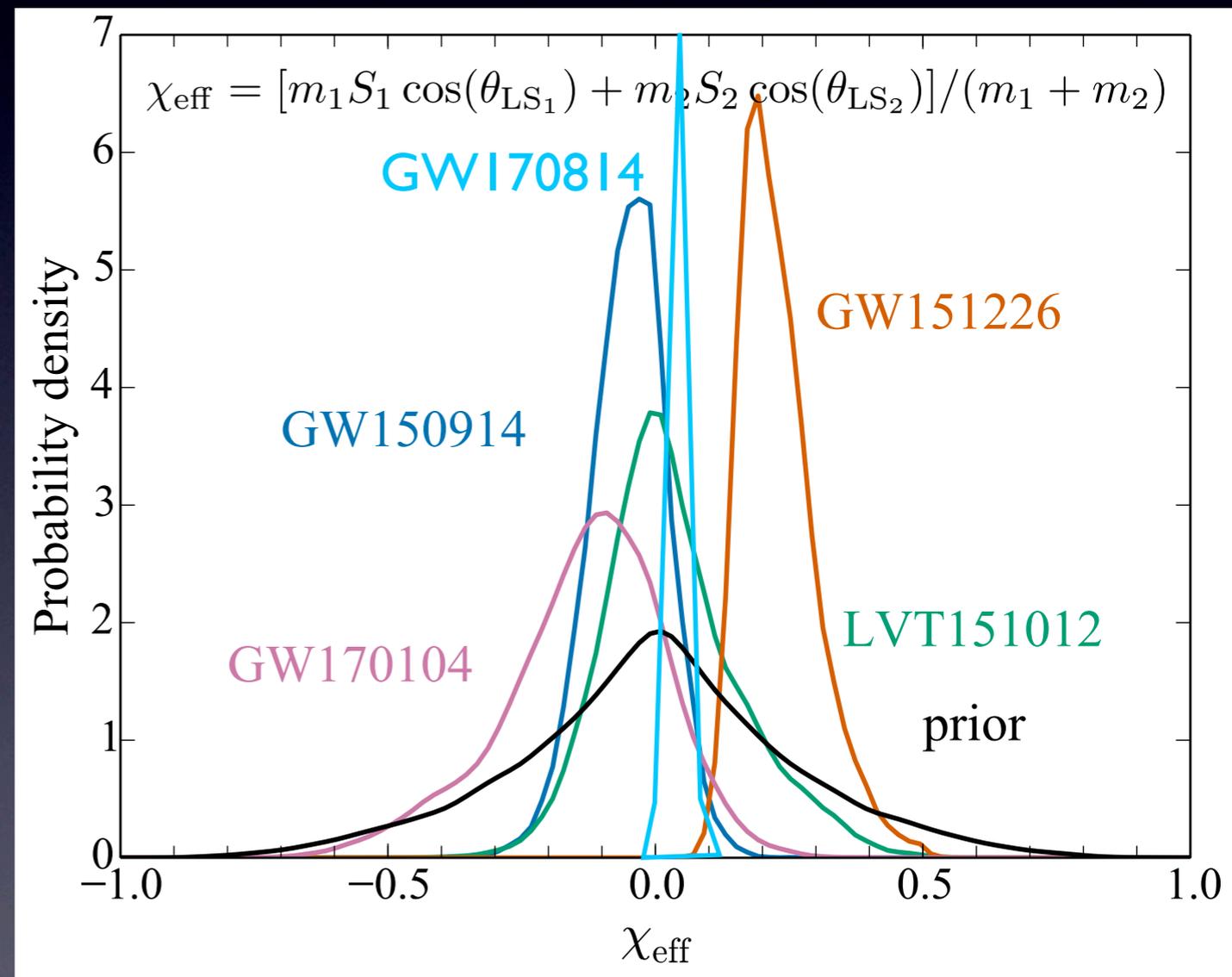
LIGO and the strange BH mergers

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



LIGO and the strange BH mergers

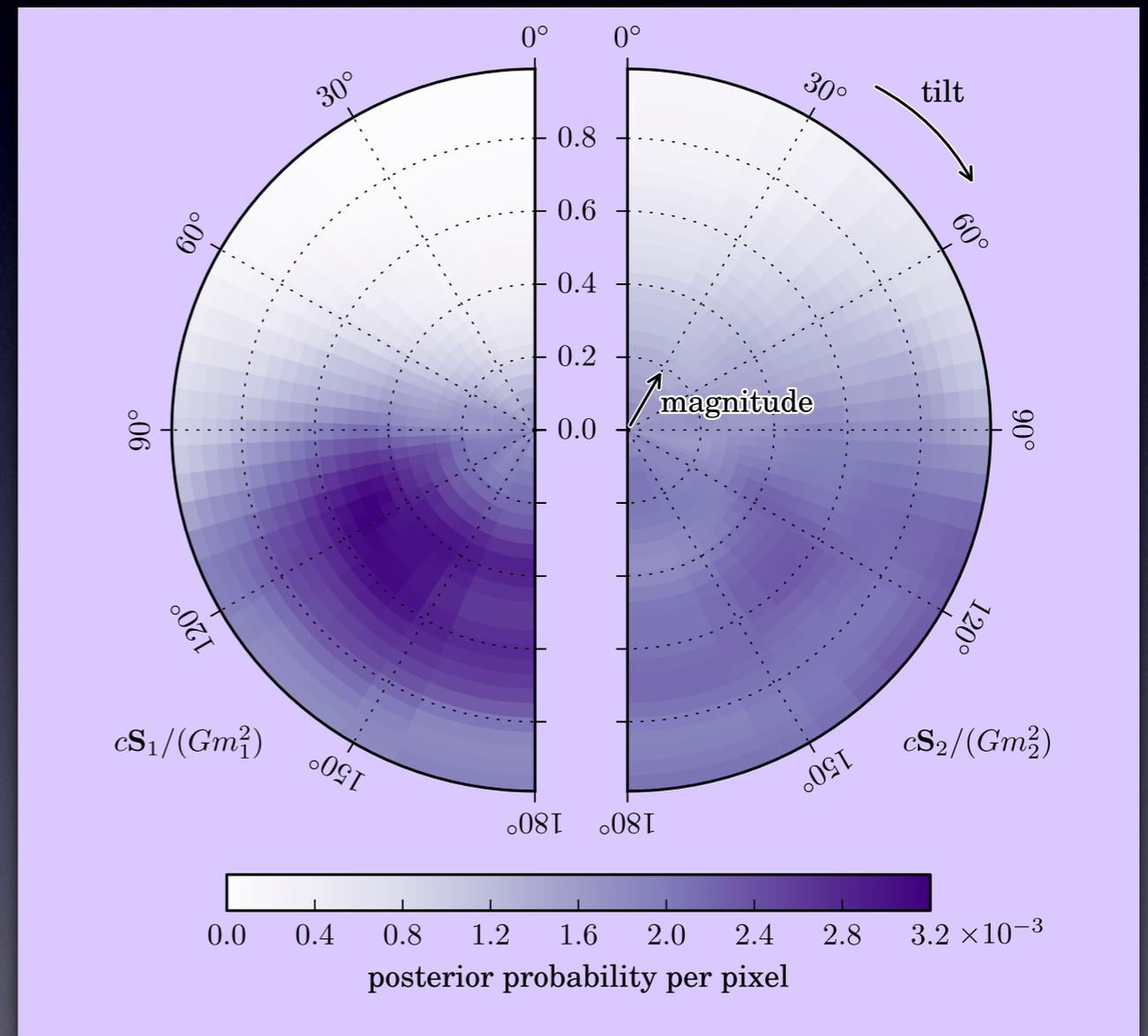
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Adapted from Adv.LIGO/VIRGO June release (supl. material)

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

Confirmation of « a new population of black holes »

In March 2016...

- S. Bird et al., 1603.00464

Monochromatic spectrum, extended halo mass function

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

**Most mergings
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- S.C., J. García-Bellido, 1603.05234

Broad mass spectrum, natural clustering scale

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

**Faint Dwarf Galaxies
or Globular Clusters**

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**Faint Dwarf Galaxies
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- M. Sasaki et al., 1603.08338

Monochromatic spectrum, BH binaries from Early Universe

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

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

LIGO and the strange BH mergers

LIGO and the strange BH mergers

The bright scenario

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

LIGO and the strange BH mergers

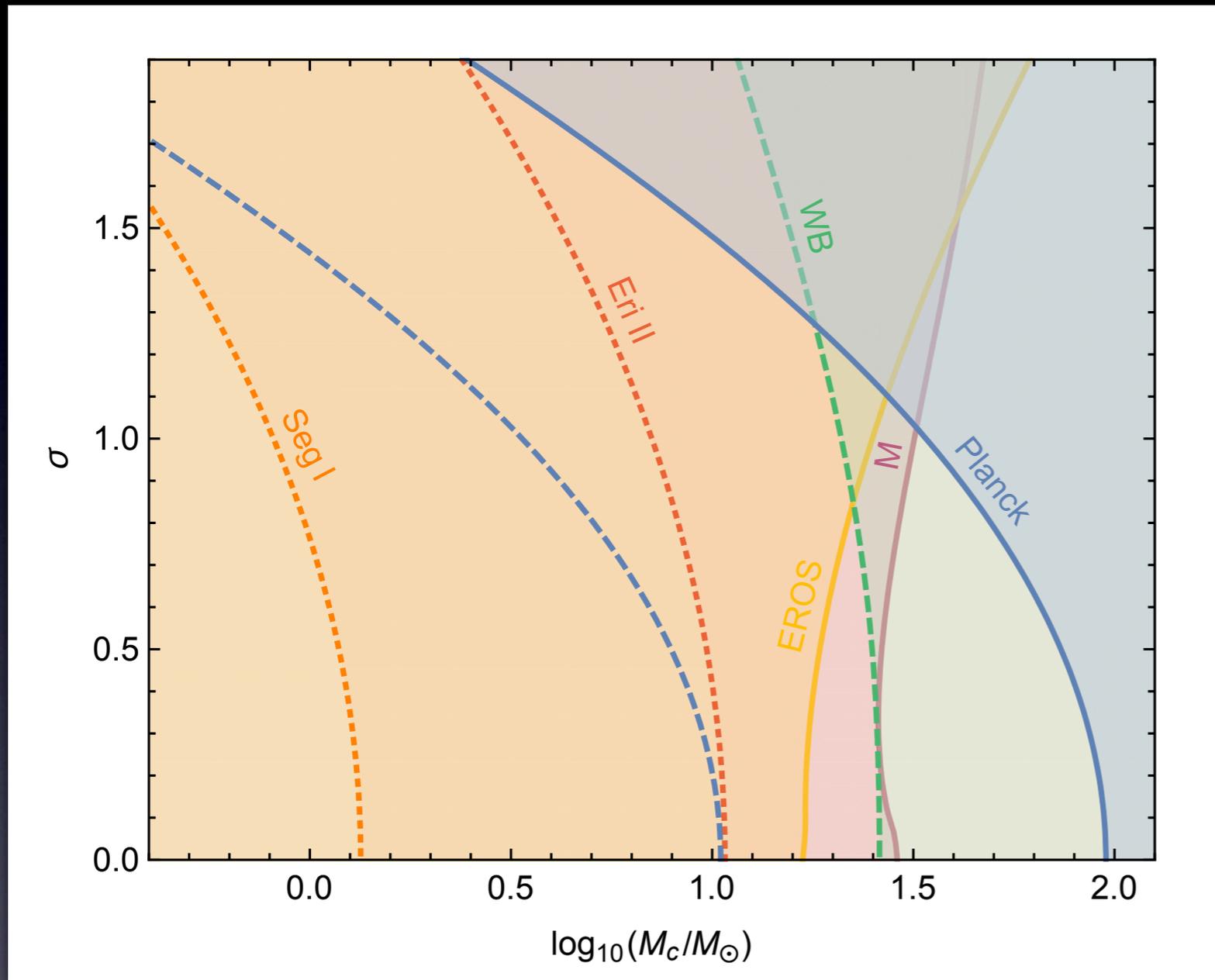
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The dark scenario

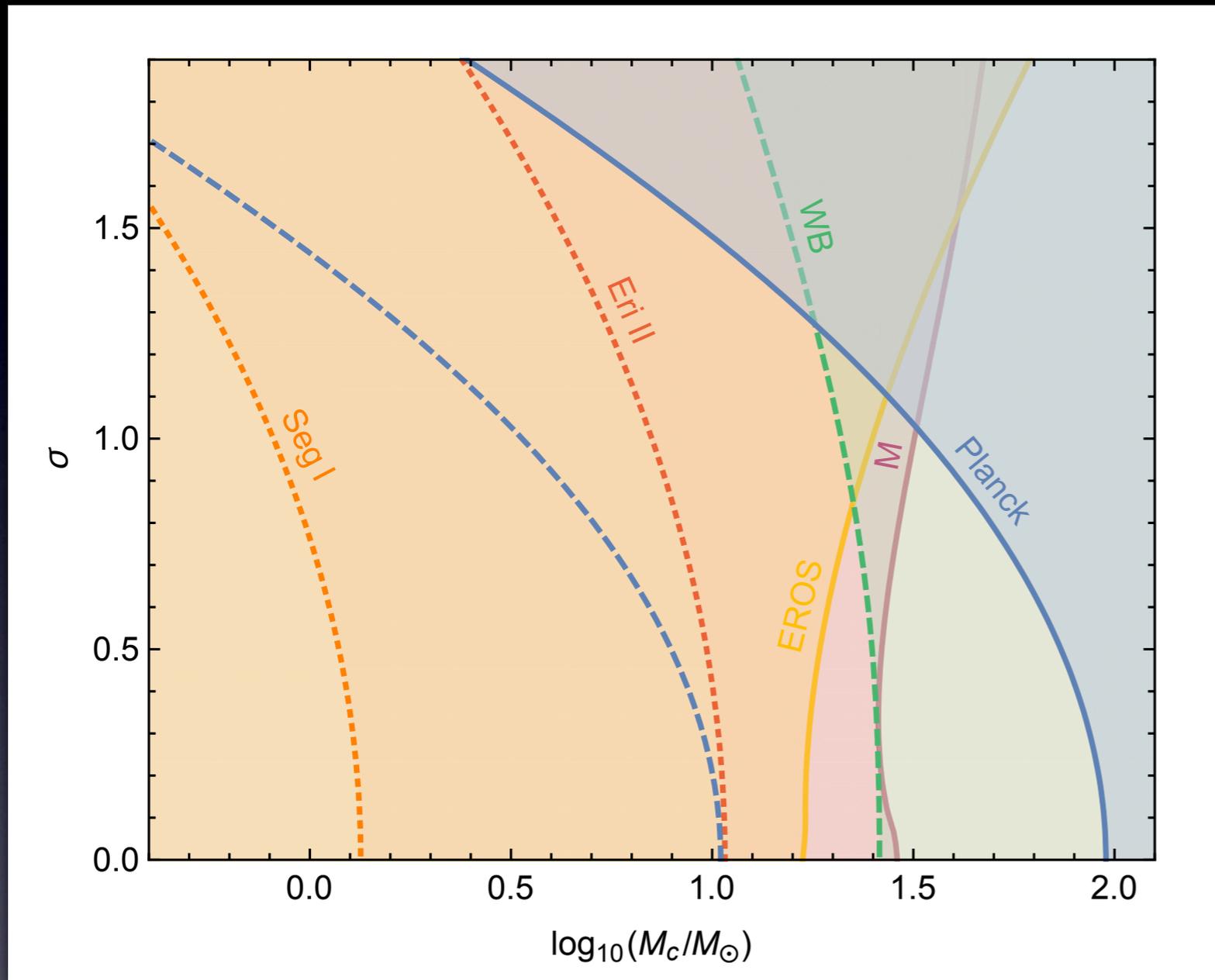
- Primordial
- Merging rates compatible with Dark-Matter-like abundance
- Low, non-aligned spins expected
- BUT: very stringent observational constraints

Constraints on PBH abundances



B. Carr et al., 1705.05567

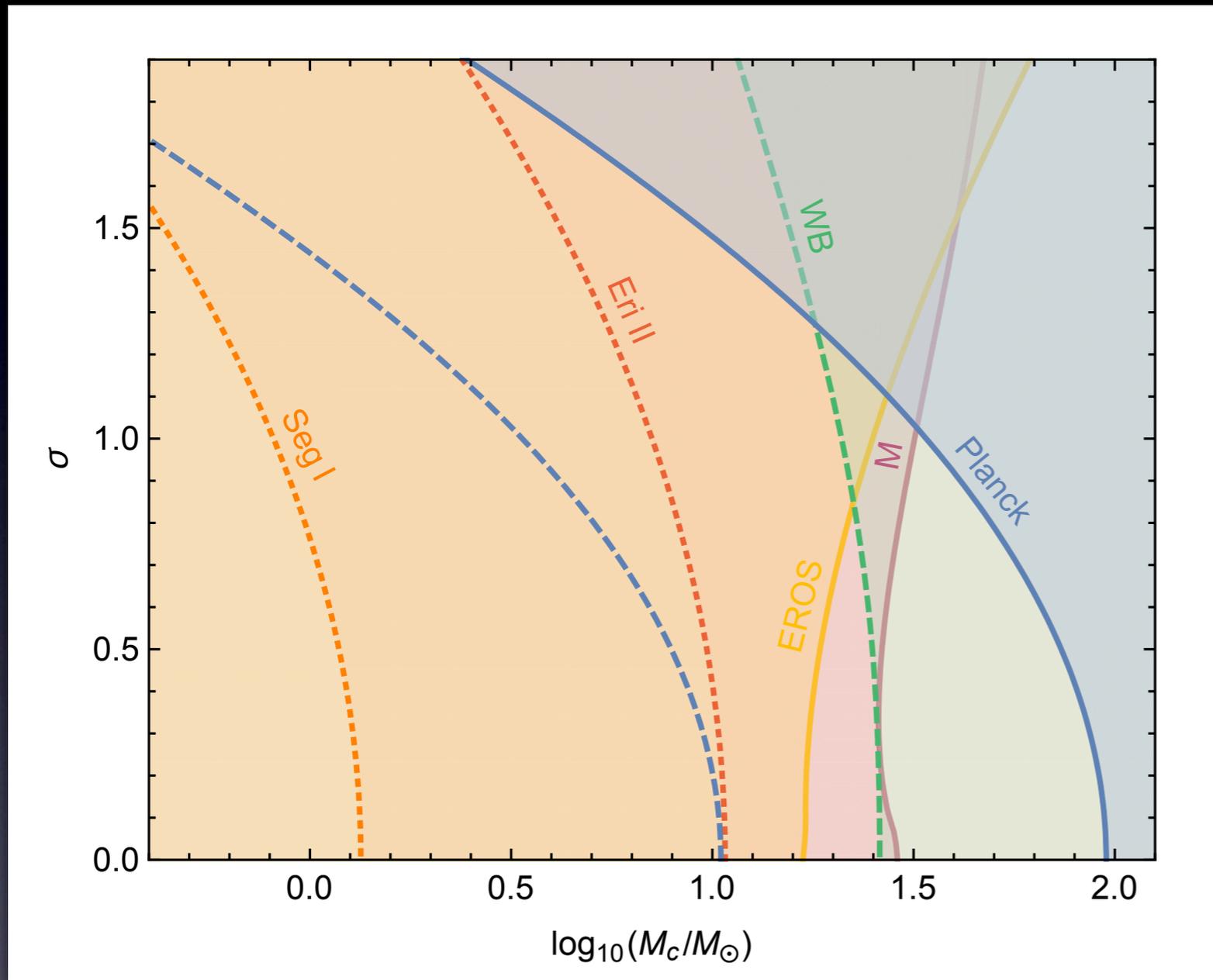
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Broad spectrum
(log-normal dist):
PBH-DM looks excluded
in the whole parameter
range

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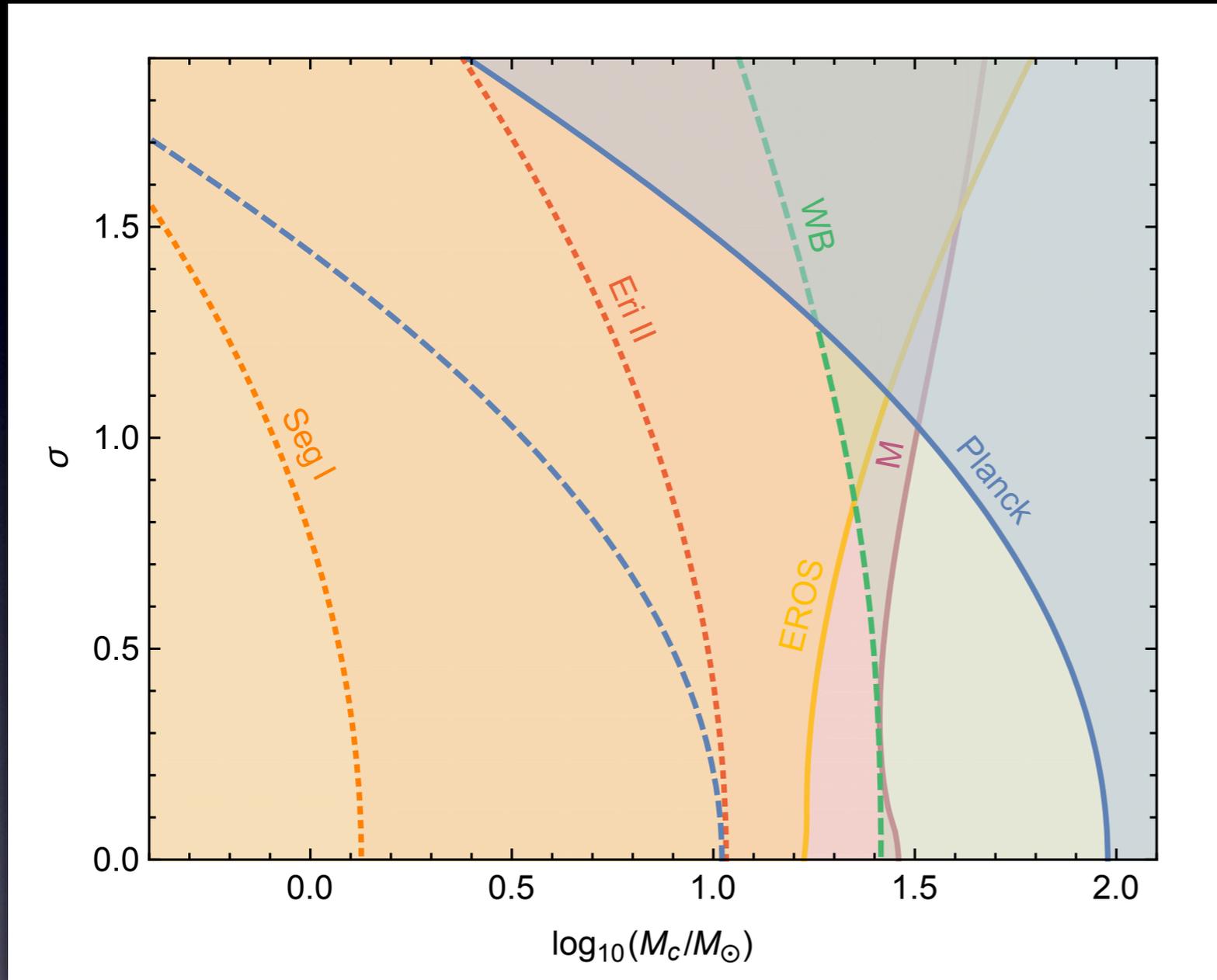


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controversial and evaded
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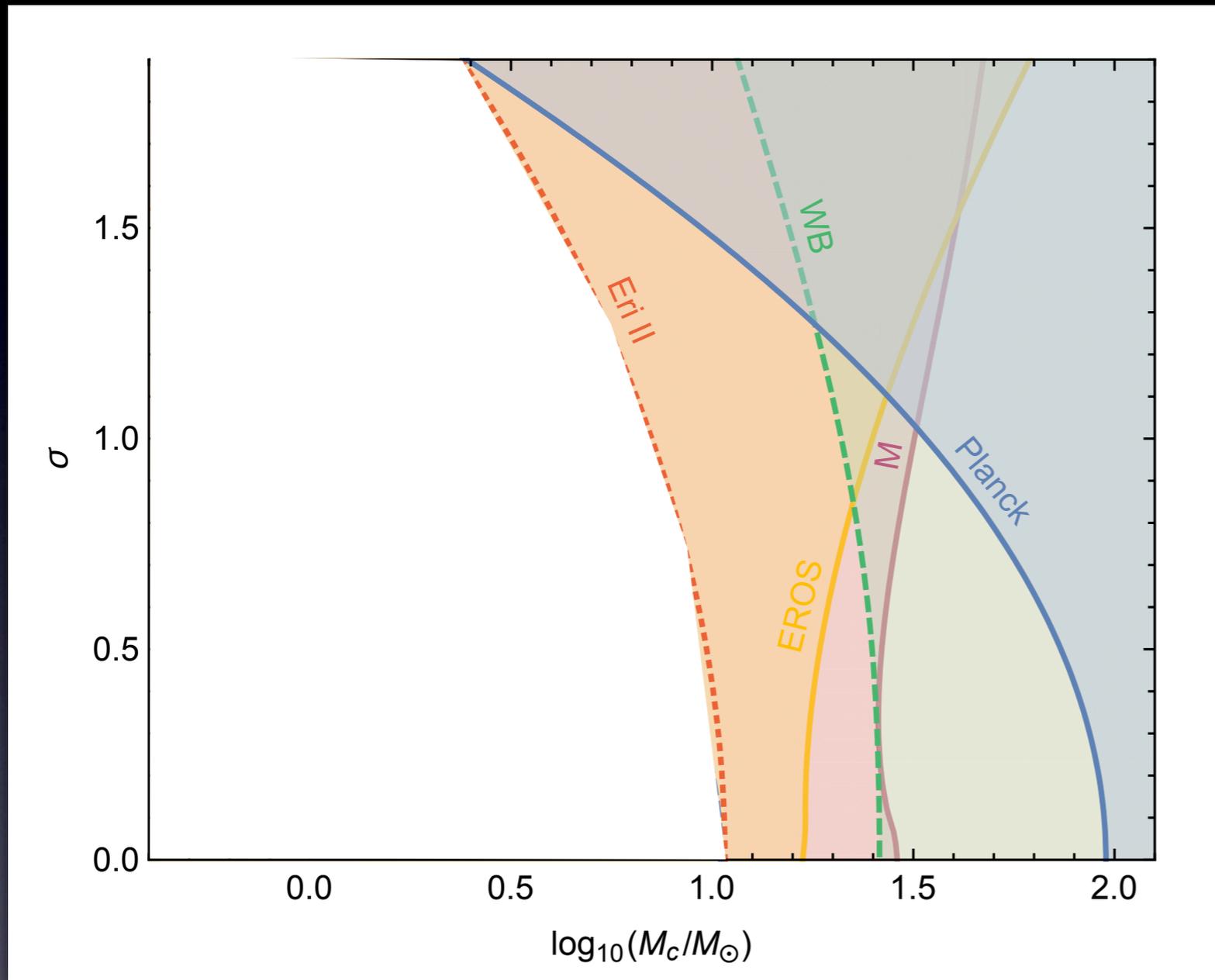
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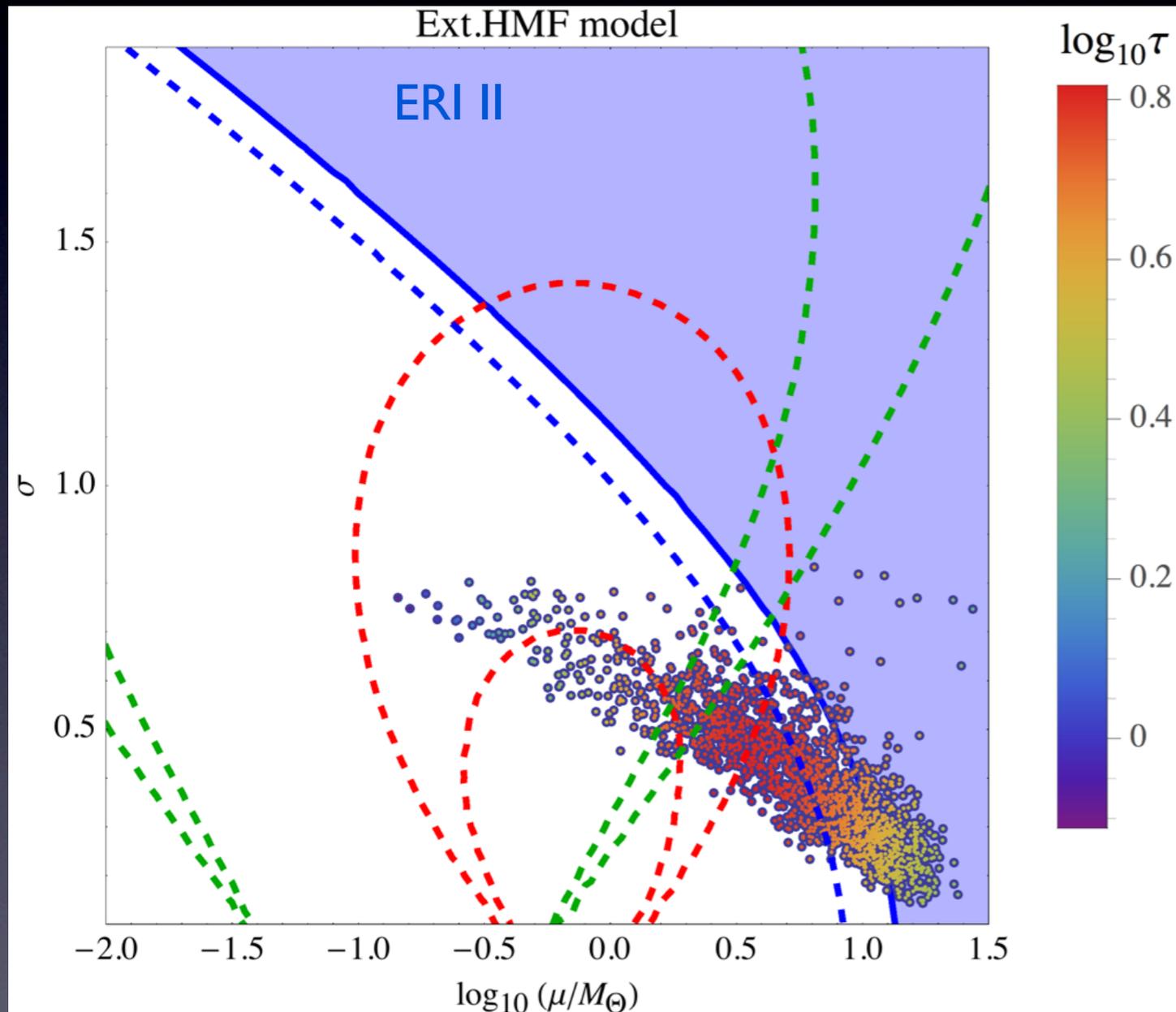
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Part II: Seven hints (clues) for PBH Dark Matter

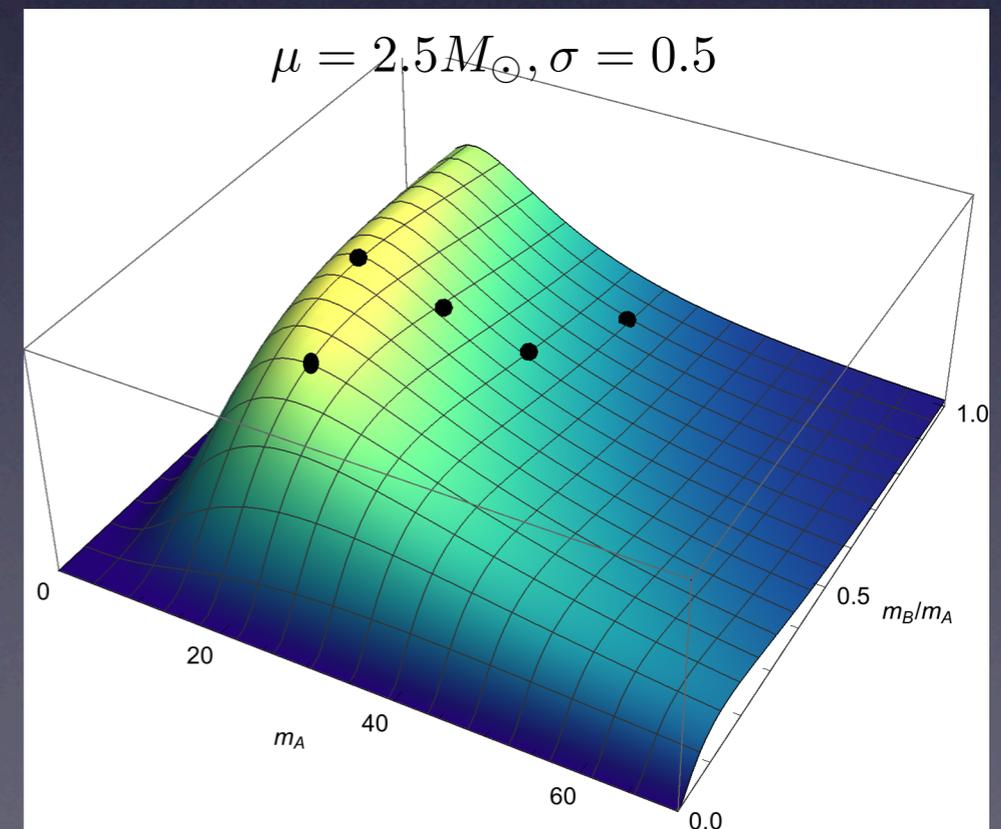
S.C., J. Garcia-Bellido, arXiv:1711.10458

Seven hints for PBH-DM

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

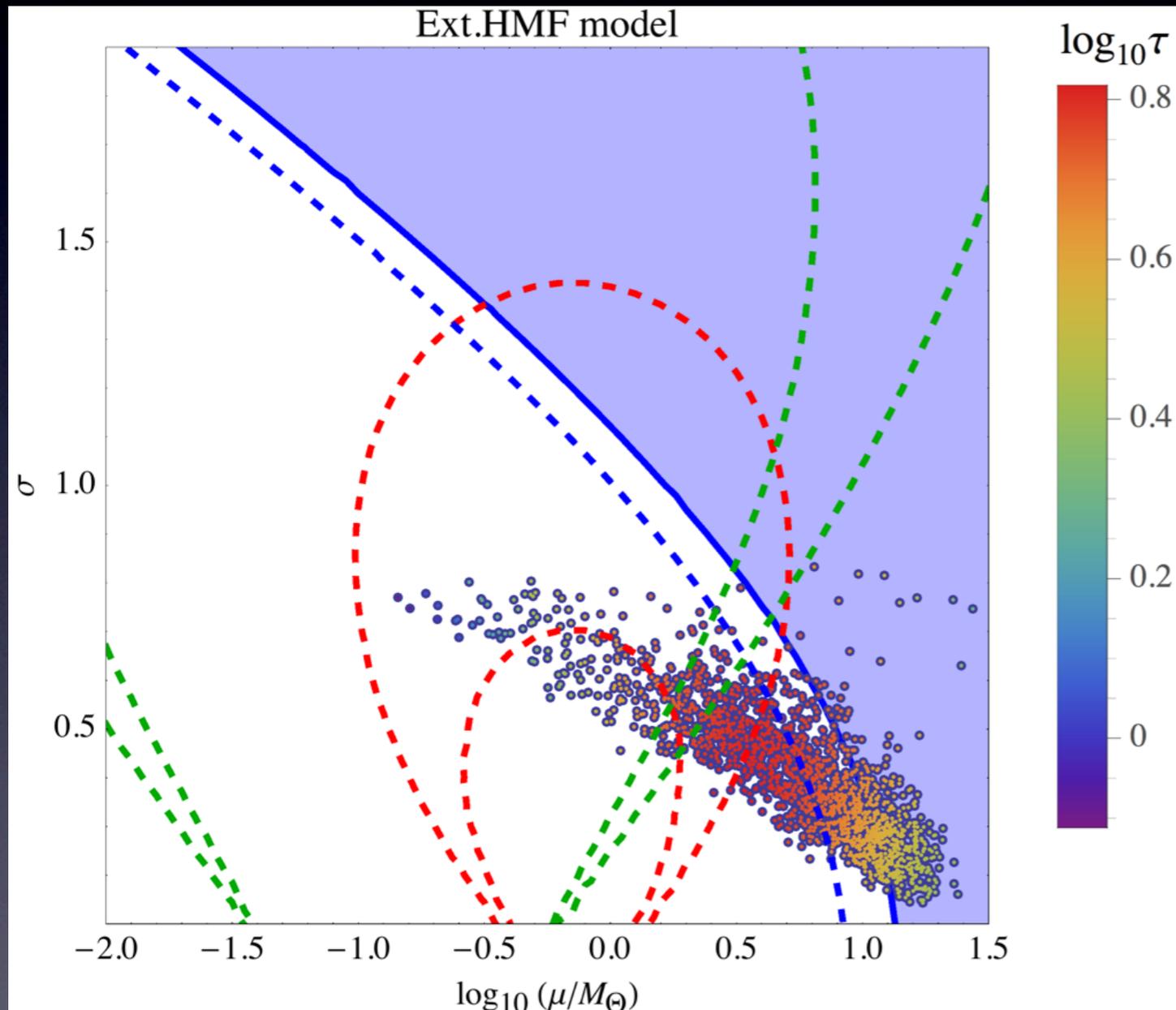


- MCMC mass spectrum reconstruction from LIGO events and rates
- Event likelihood peaks on large masses: LIGO detectability scales like inverse distance



Seven hints for PBH-DM

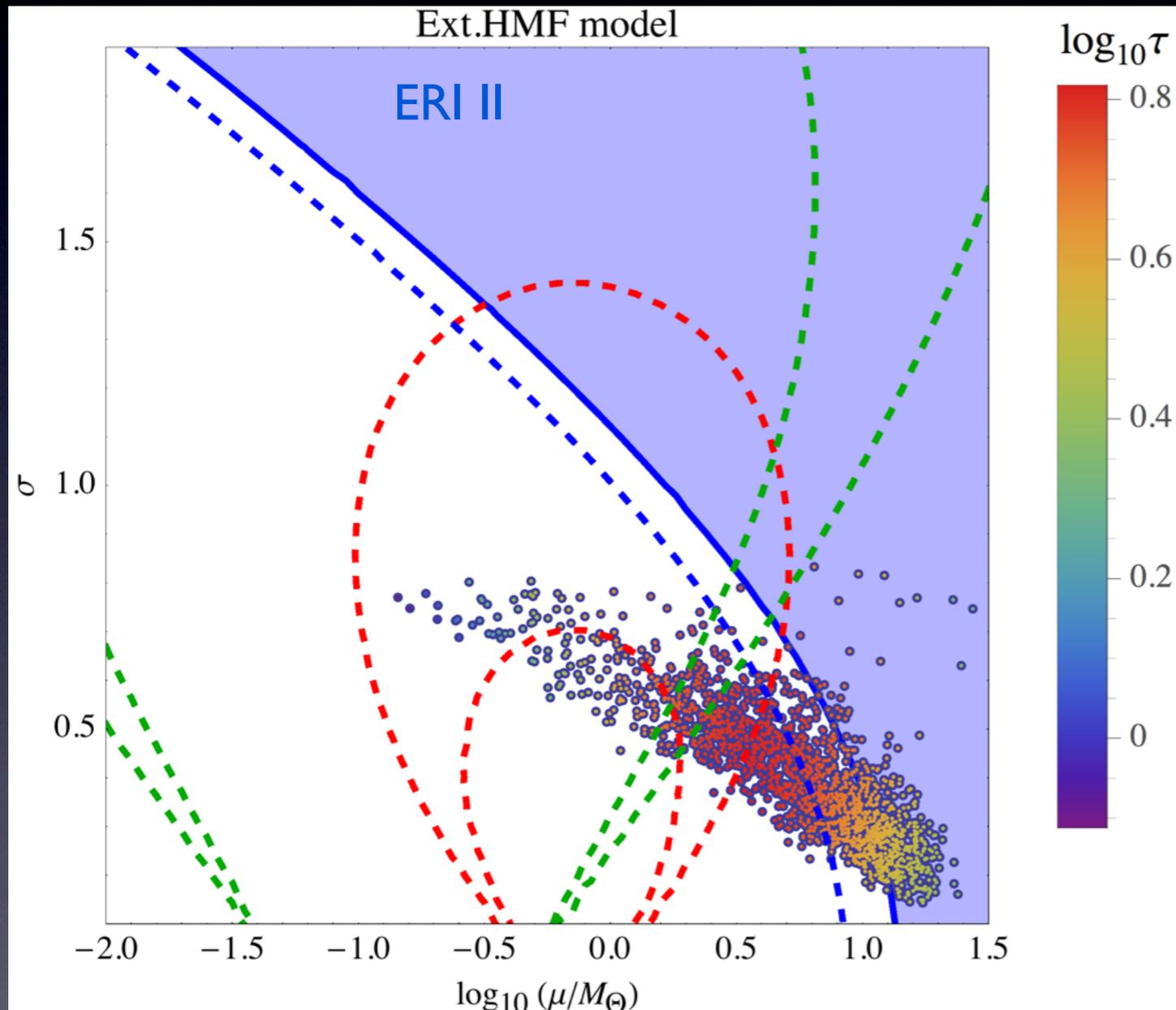
Hint 3: Microlensing of M31 and quasars



- 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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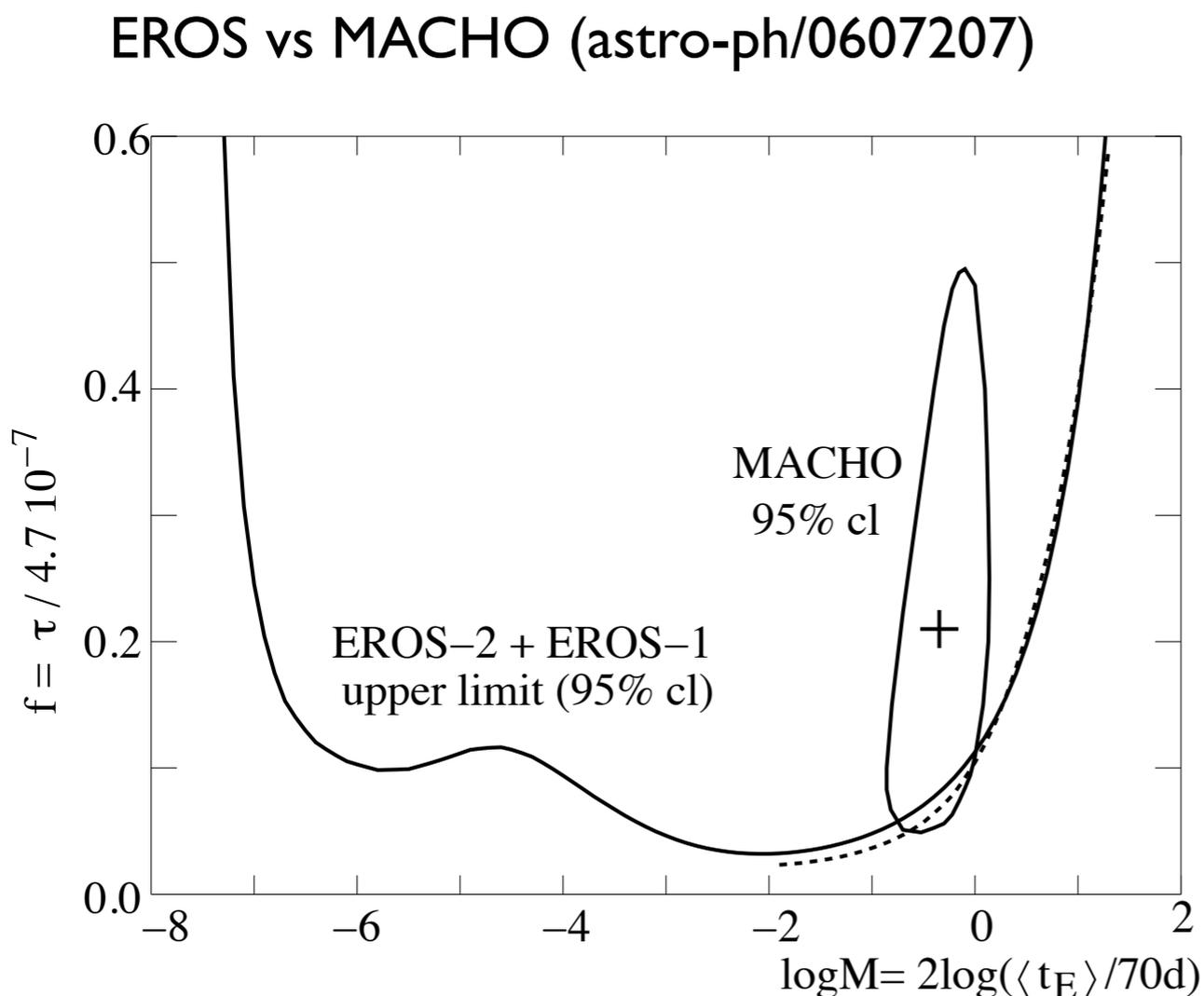


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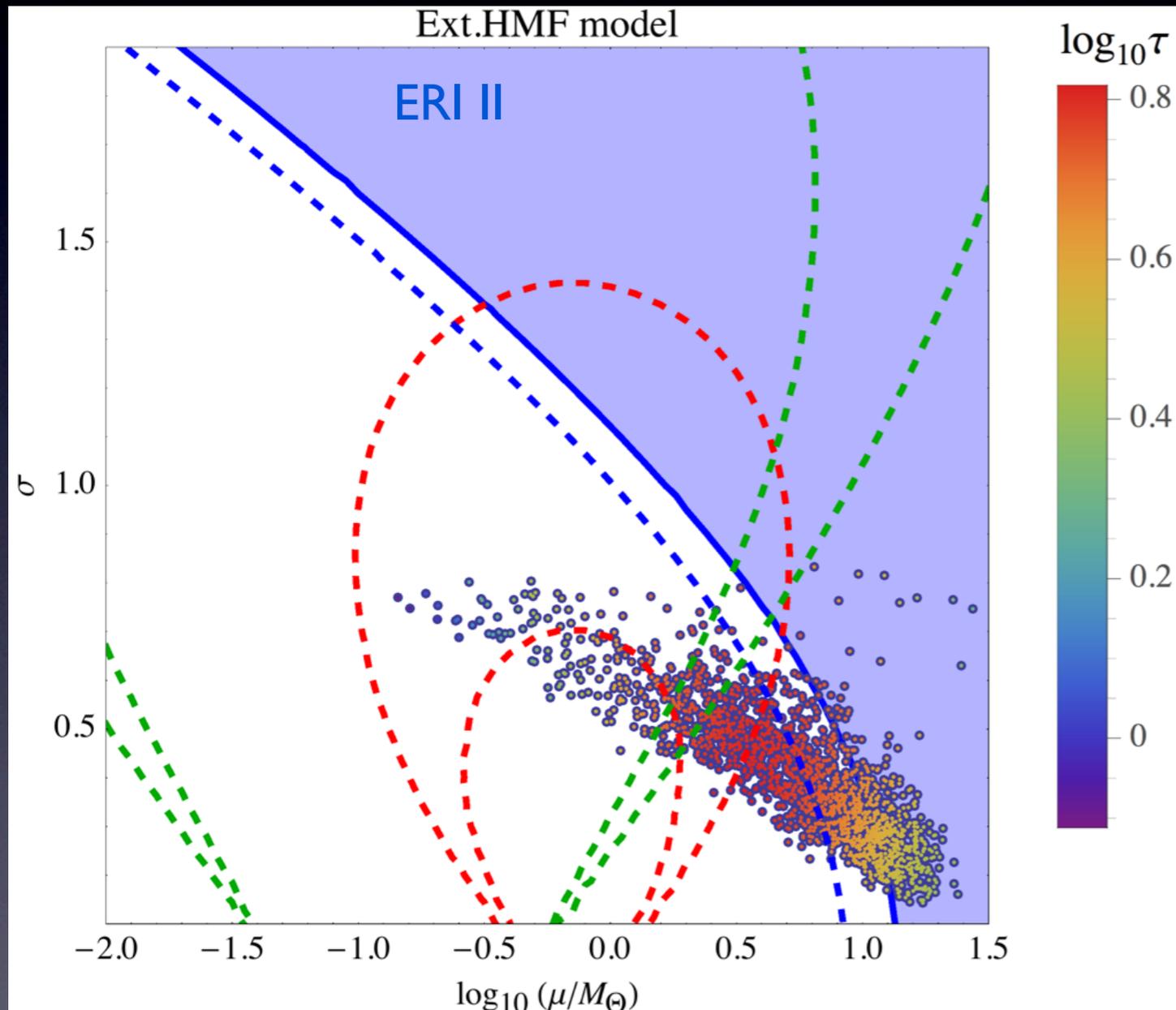
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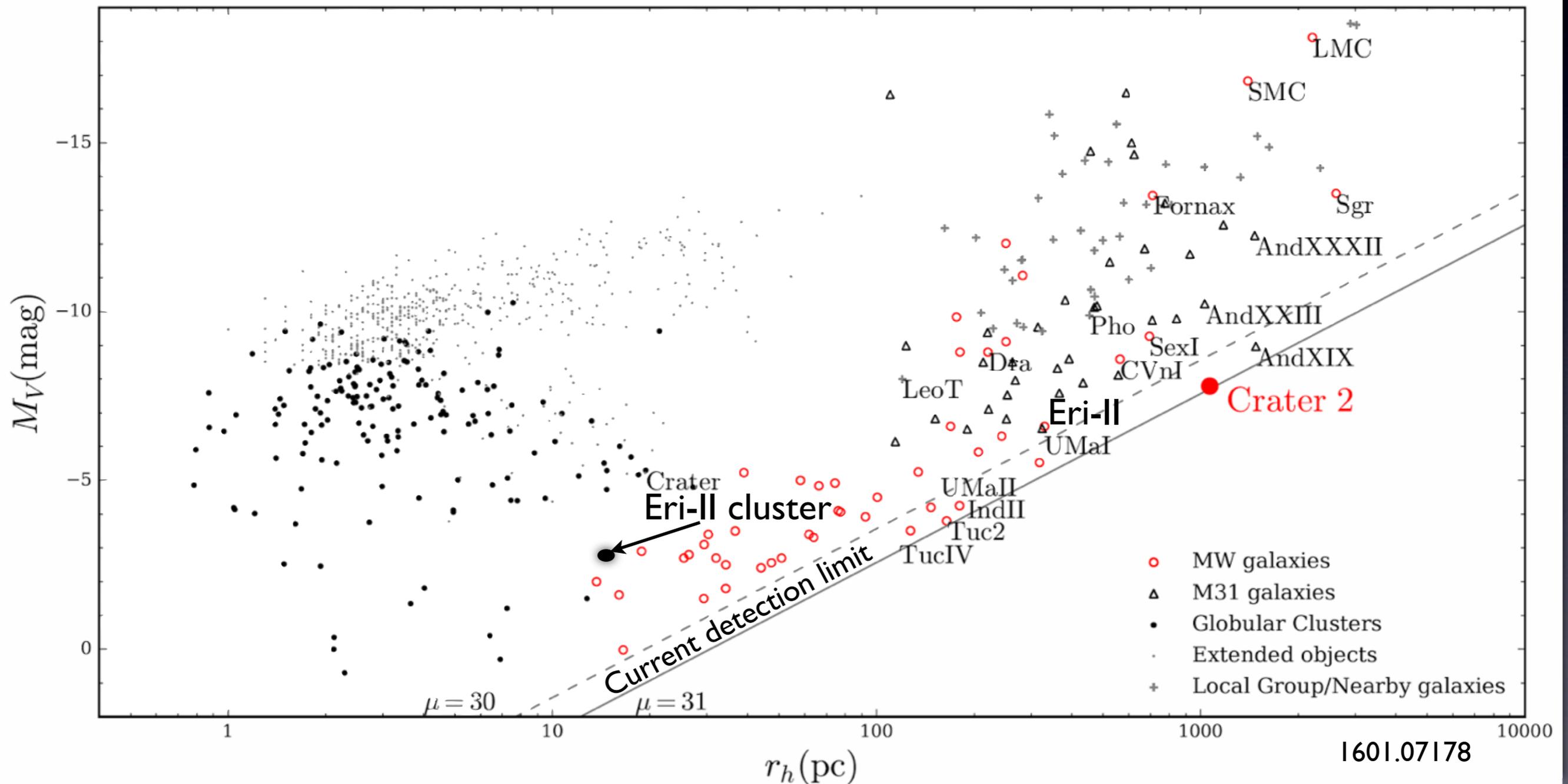
Hint 4: Star clusters and dynamics of faint dwarf galaxies



- 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

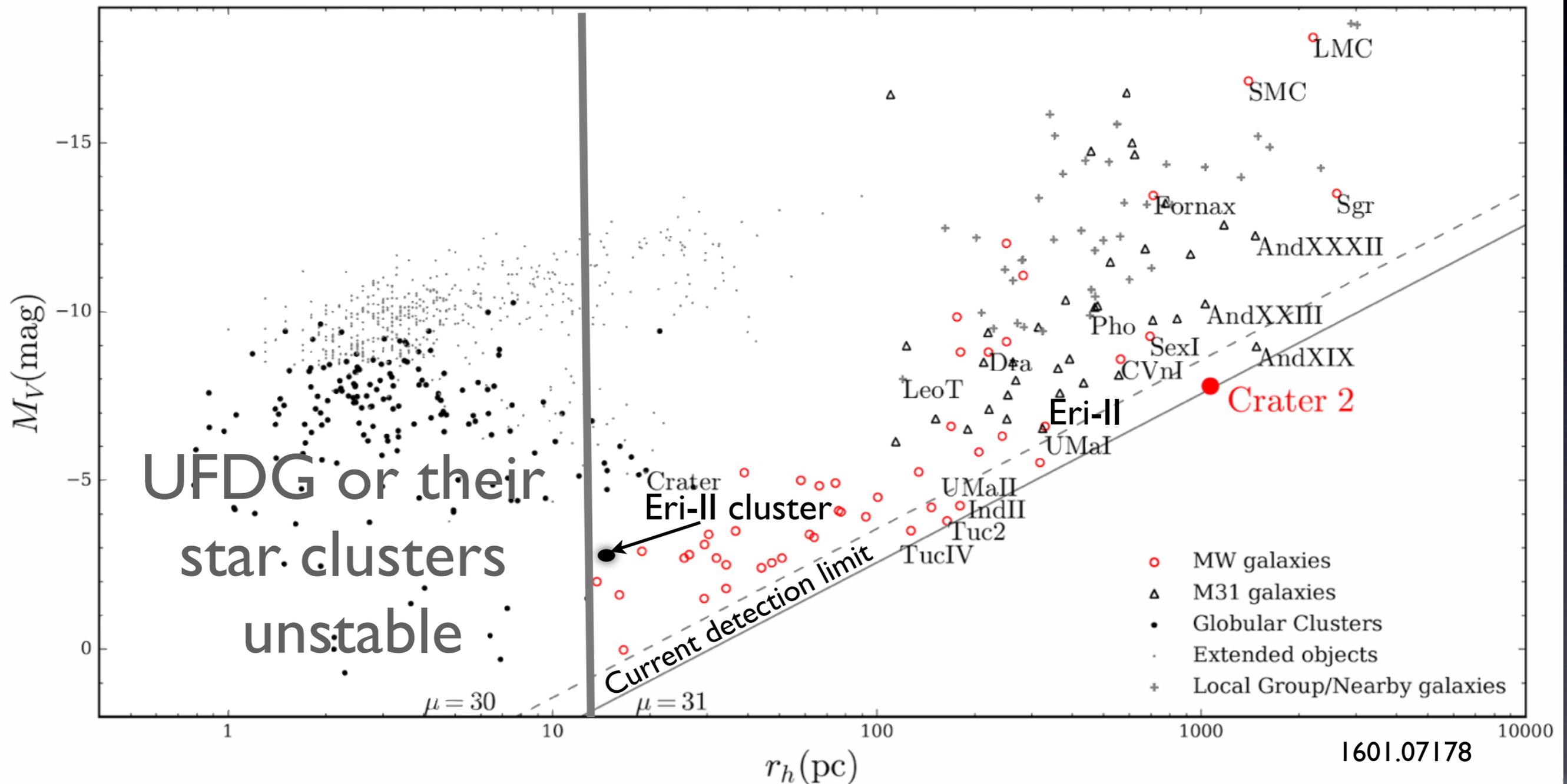
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1601.07178

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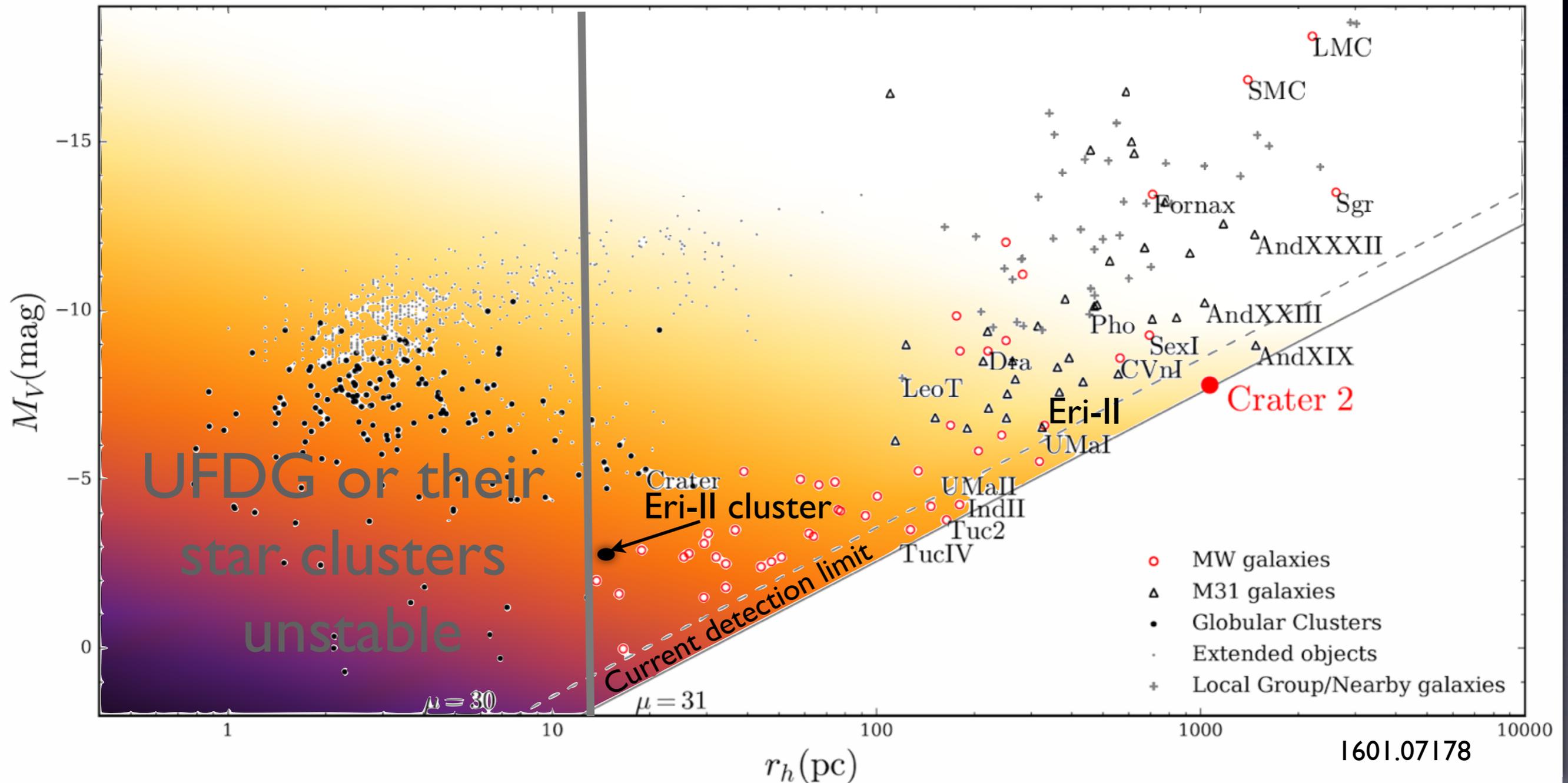
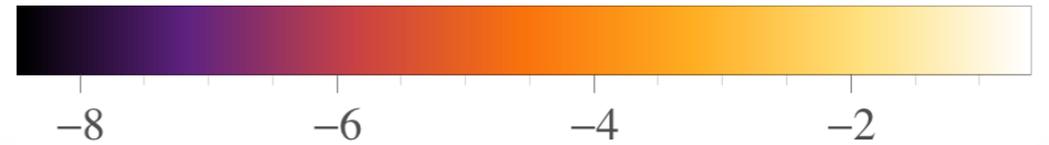
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Seven hints for PBH-DM

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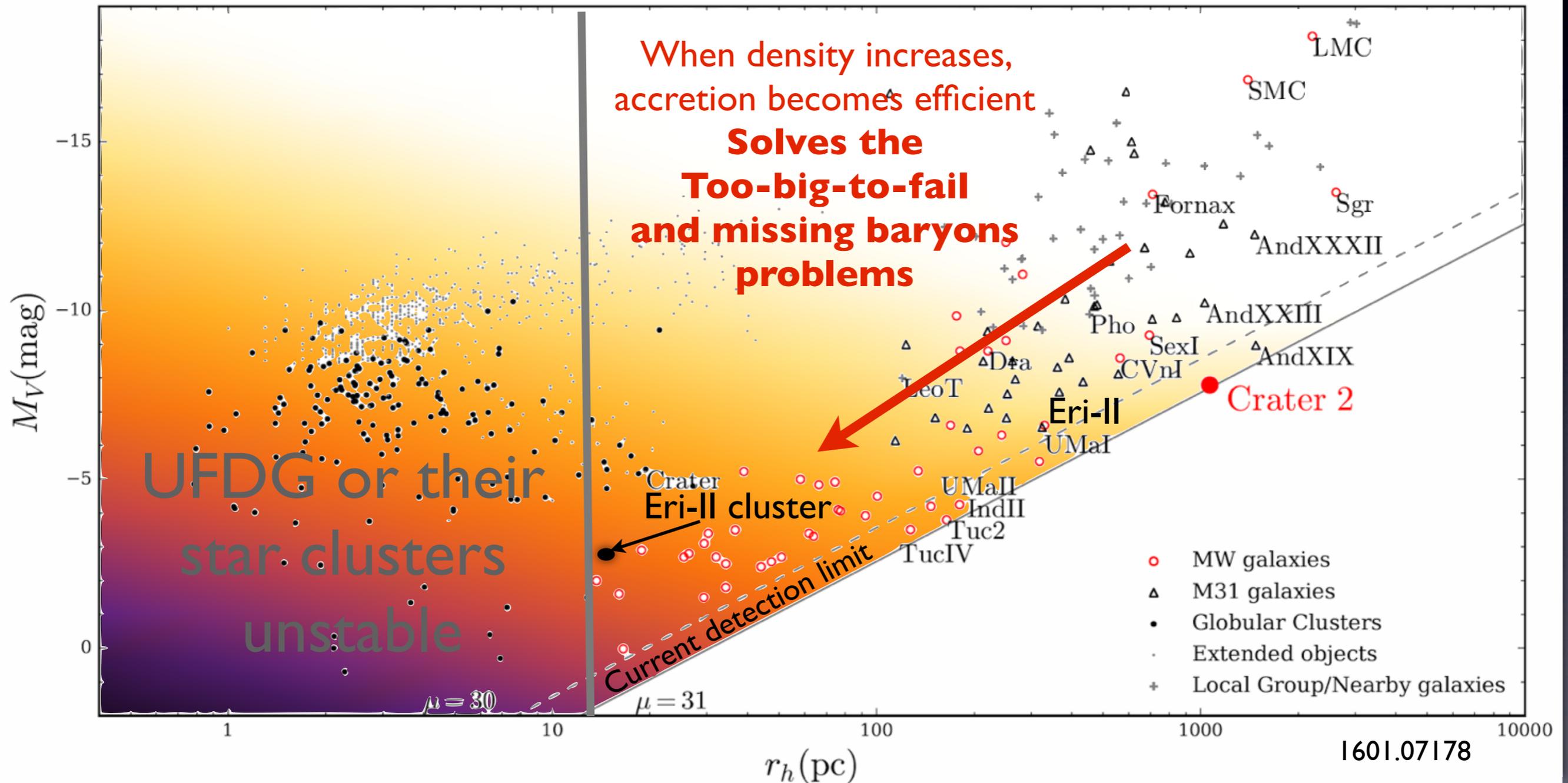
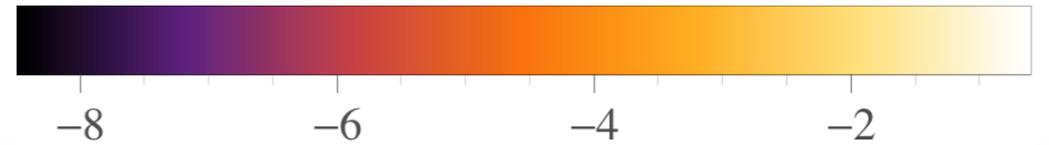
Log_{10} (Baryon fraction)



Seven hints for PBH-DM

Hint 4: Star clusters and dynamics of faint dwarf galaxies

Log_{10} (Baryon fraction)



Seven hints for PBH-DM

Hint 5: Core DM density profiles

- Gravitational scattering between PBH:

$$\frac{\sigma}{m_{\text{PBH}}} \sim 0.1 - 1 \text{ cm}^2/\text{g}$$

- Dynamical heating of cusps due to two-body interactions
- Relaxation time scale:

$$t_{\text{rel}} \approx \frac{r}{v} \frac{N_{\text{PBH}}}{8 \ln N_{\text{PBH}}}$$

- **Cusps homogenized in ~ 10 Gyrs up to a radius ~ 1 kpc**
- 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-IR cosmic infrared background anisotropies

A. Kashlinsky¹,

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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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

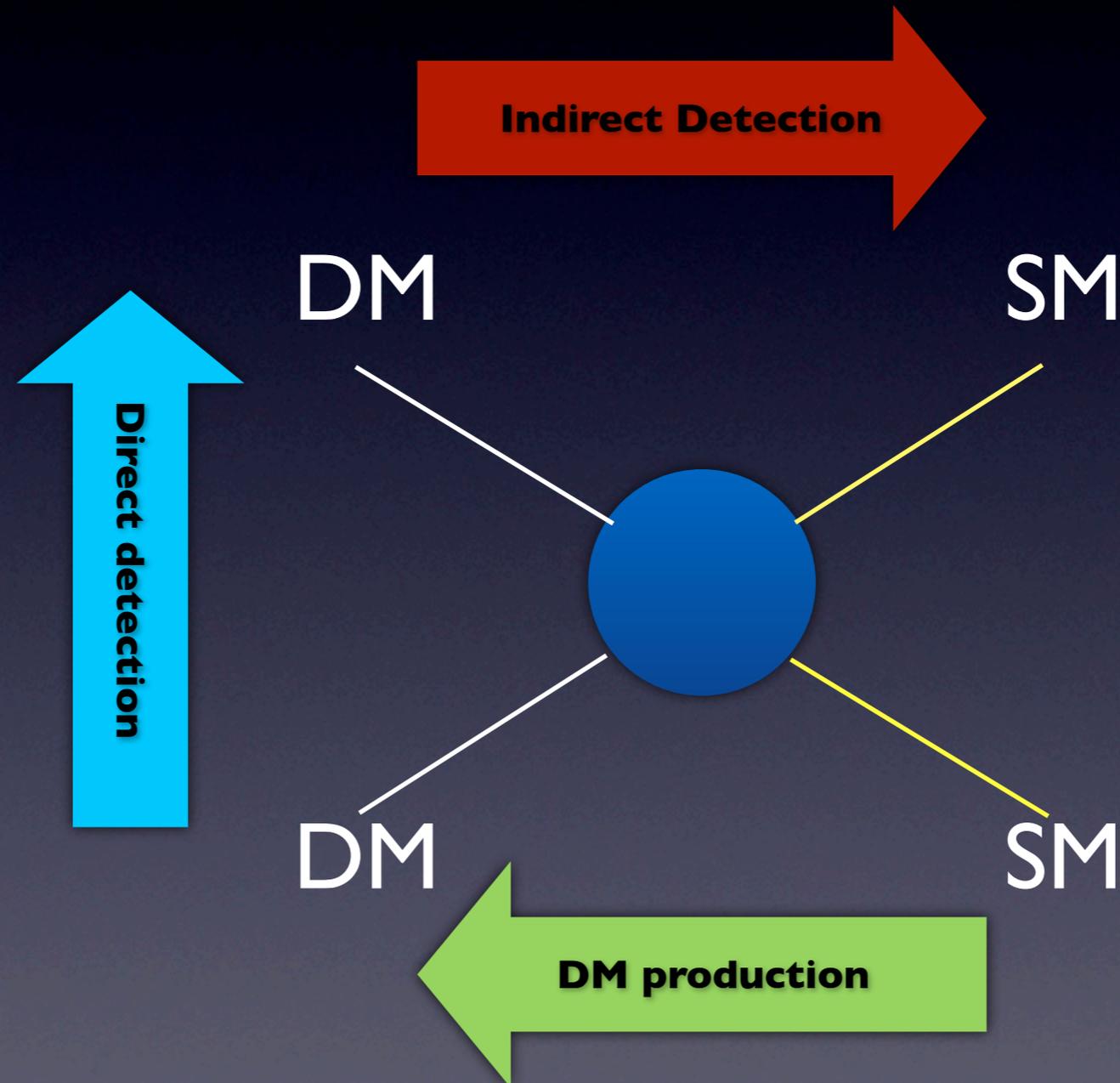
Nature
doi:10.1038/nature25180
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Received: 29 June 2017
Accepted: 28 November 2017
Published online: 06 December 2017

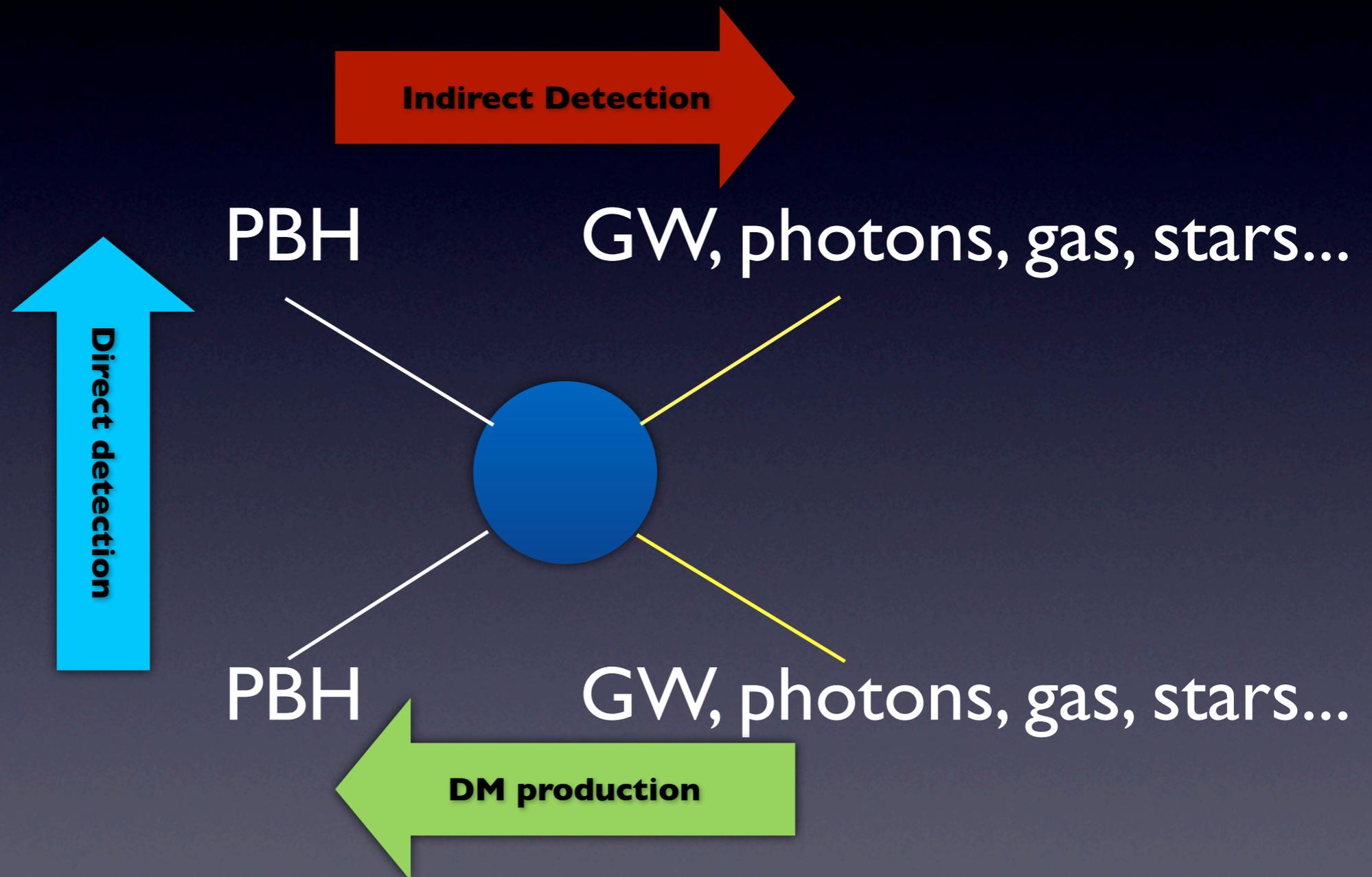
1712.01870

PBH provide the right
number of seeds for SMBH

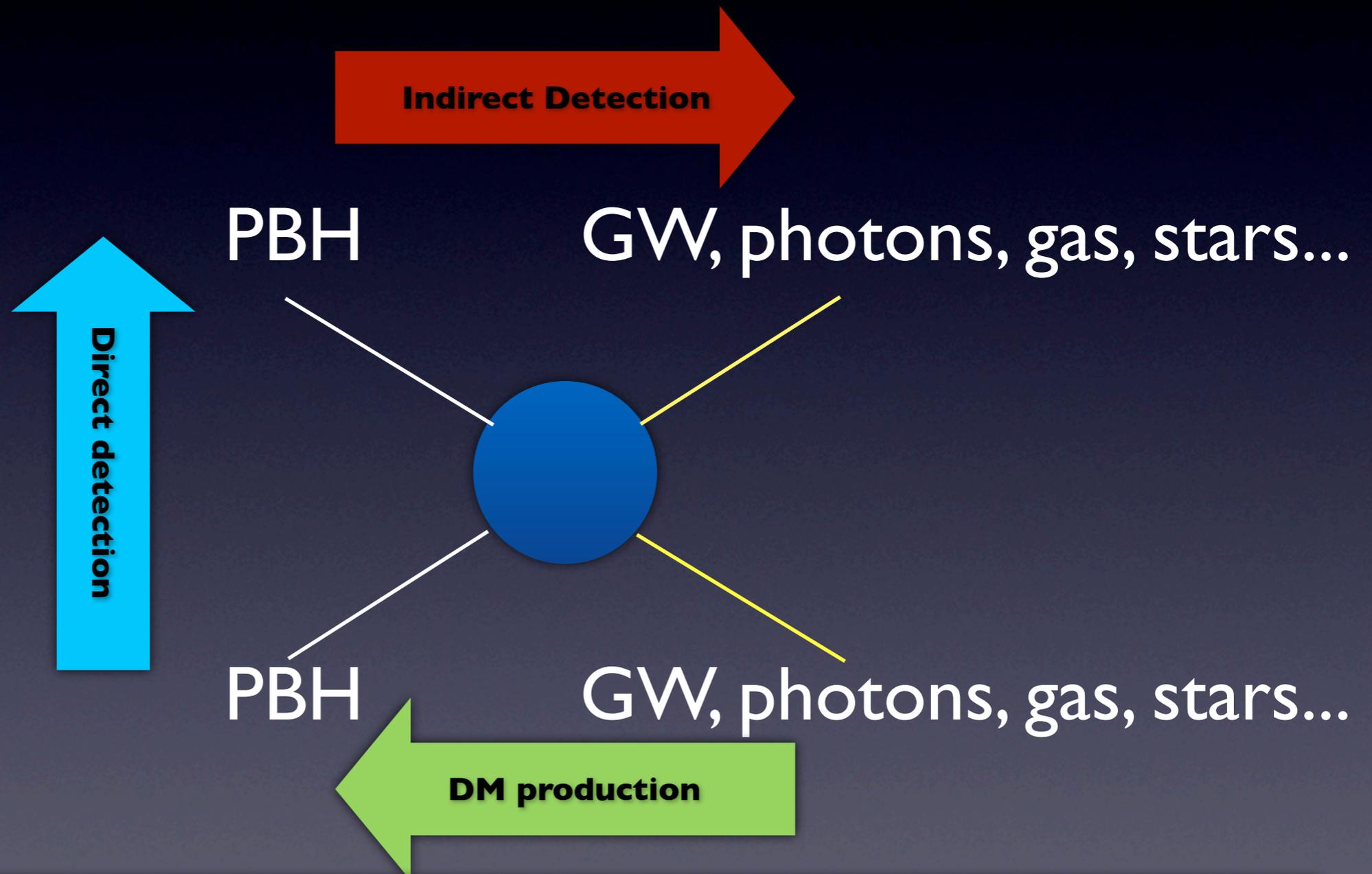
Rethinking DM interactions



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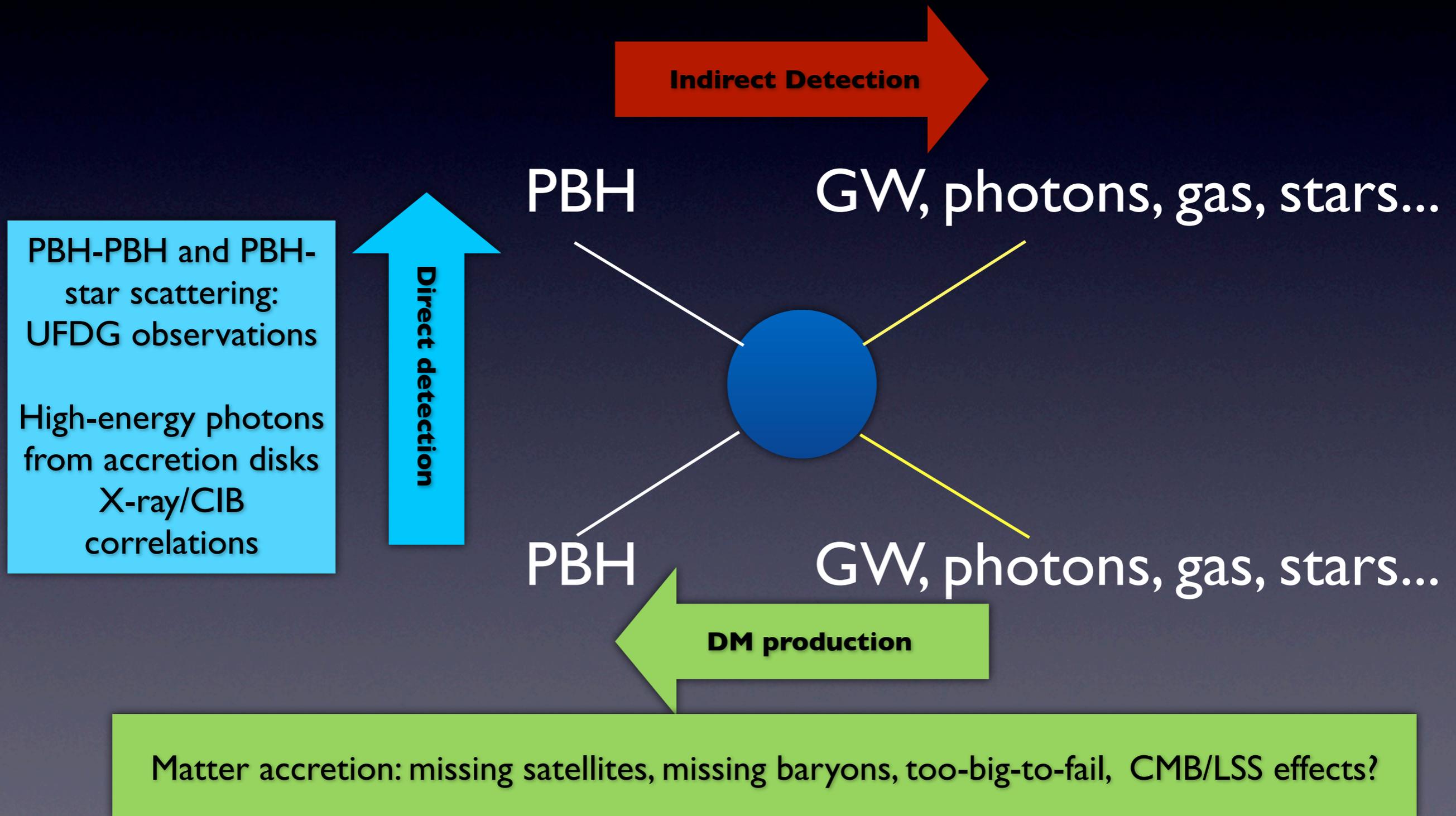


Rethinking DM interactions

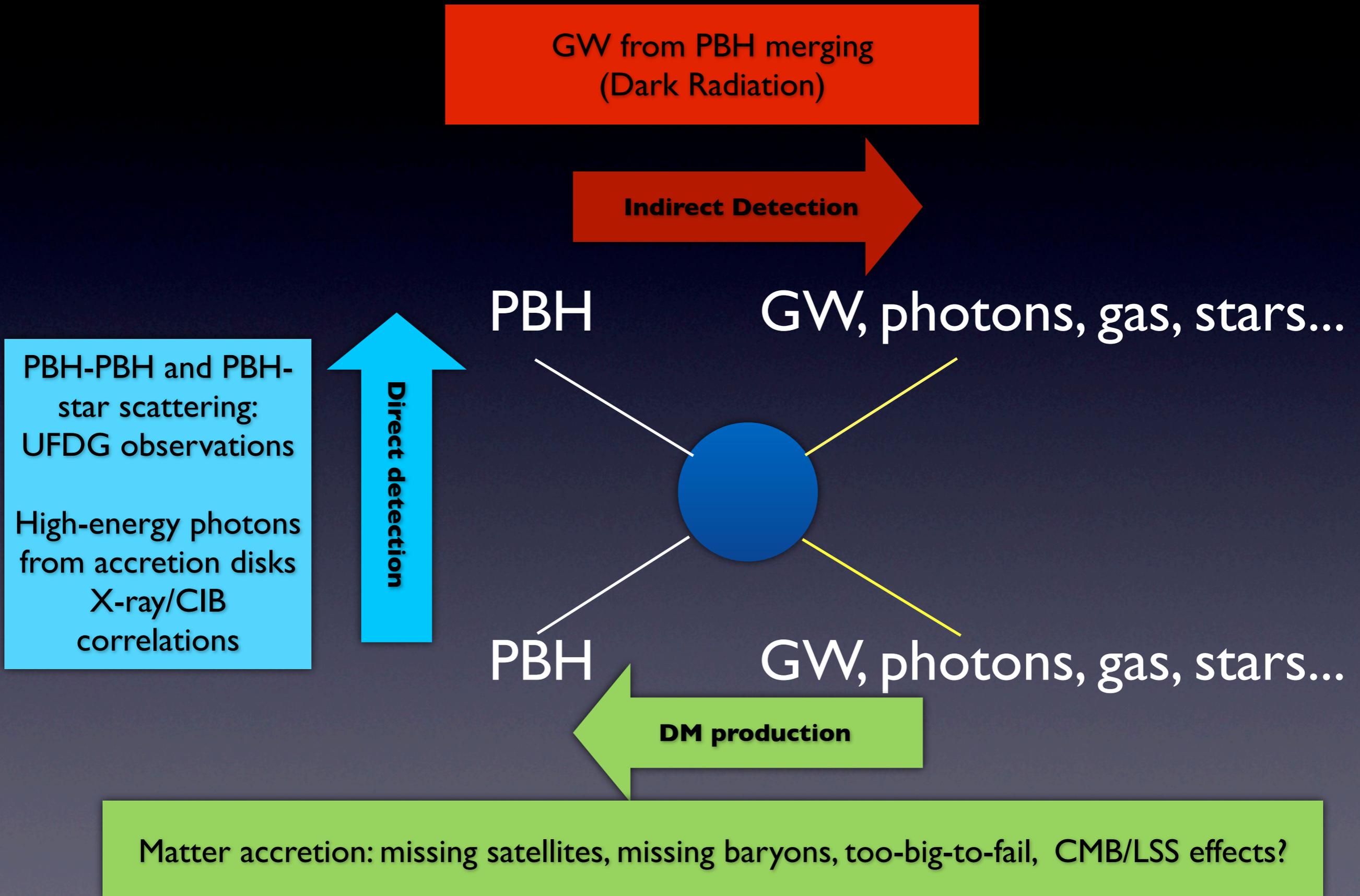


Matter accretion: missing satellites, missing baryons, too-big-to-fail, CMB/LSS effects?

Rethinking DM interactions



Rethinking DM interactions



...and future prospects

- Detecting a BH below the Chandrasekar 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)
- 21 cm signal (SKA)
- CMB (Planck, S4, LiteBird)
- Star position and velocities (GAIA), LMXB, PS in GC



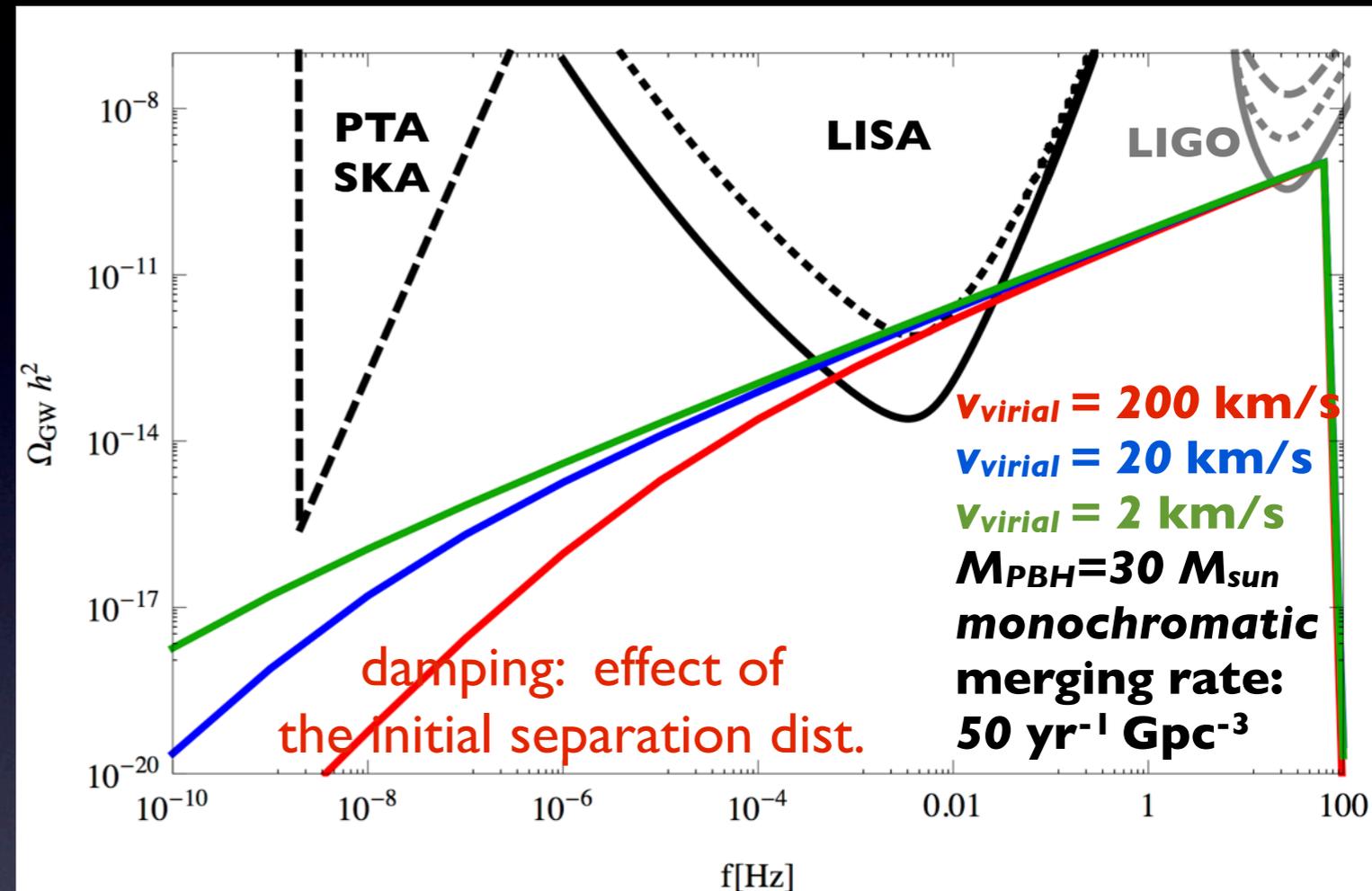
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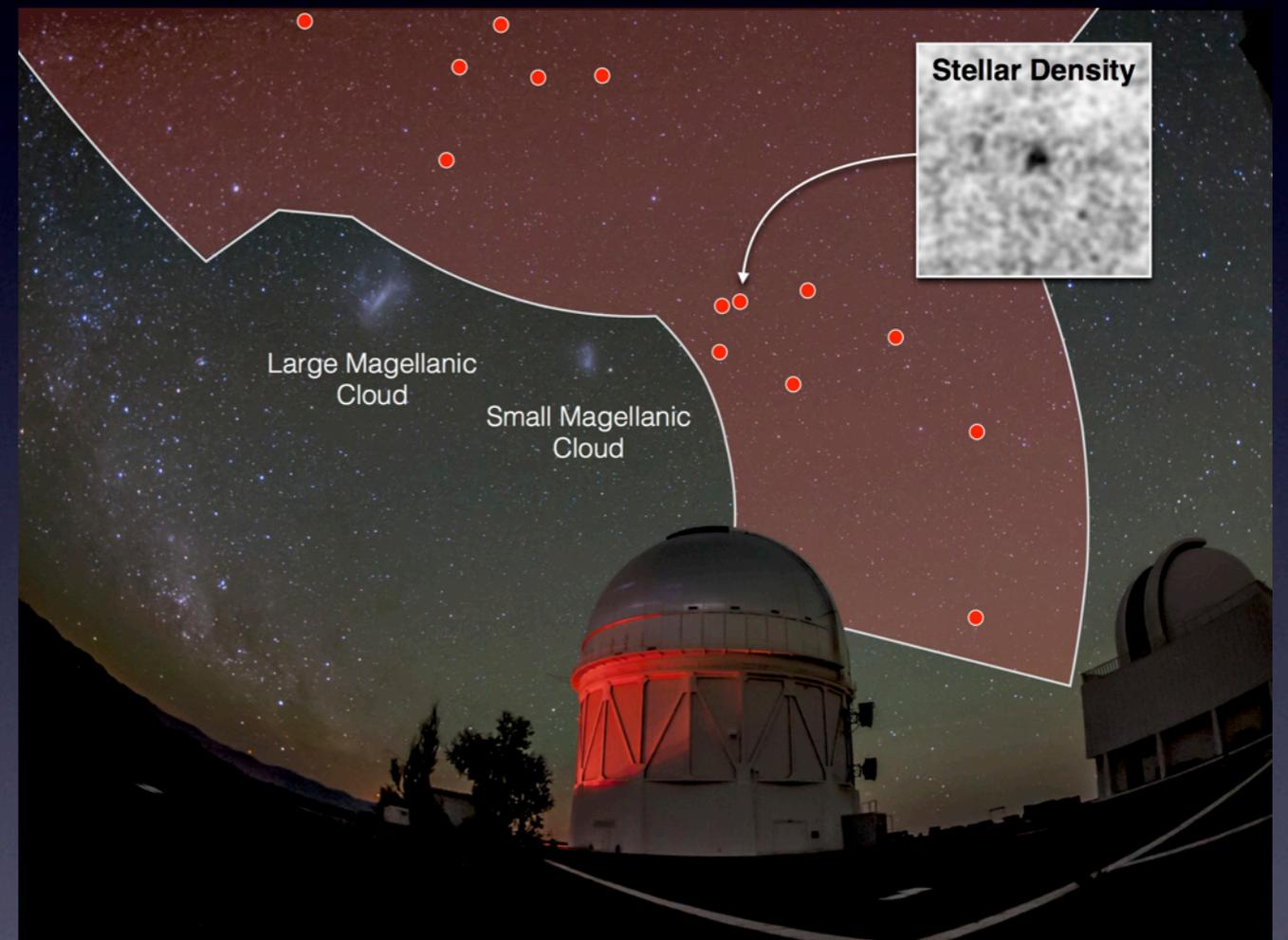
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Clustering allows to distinguish stellar and primordial origins
SC, JGB, 1610.08479

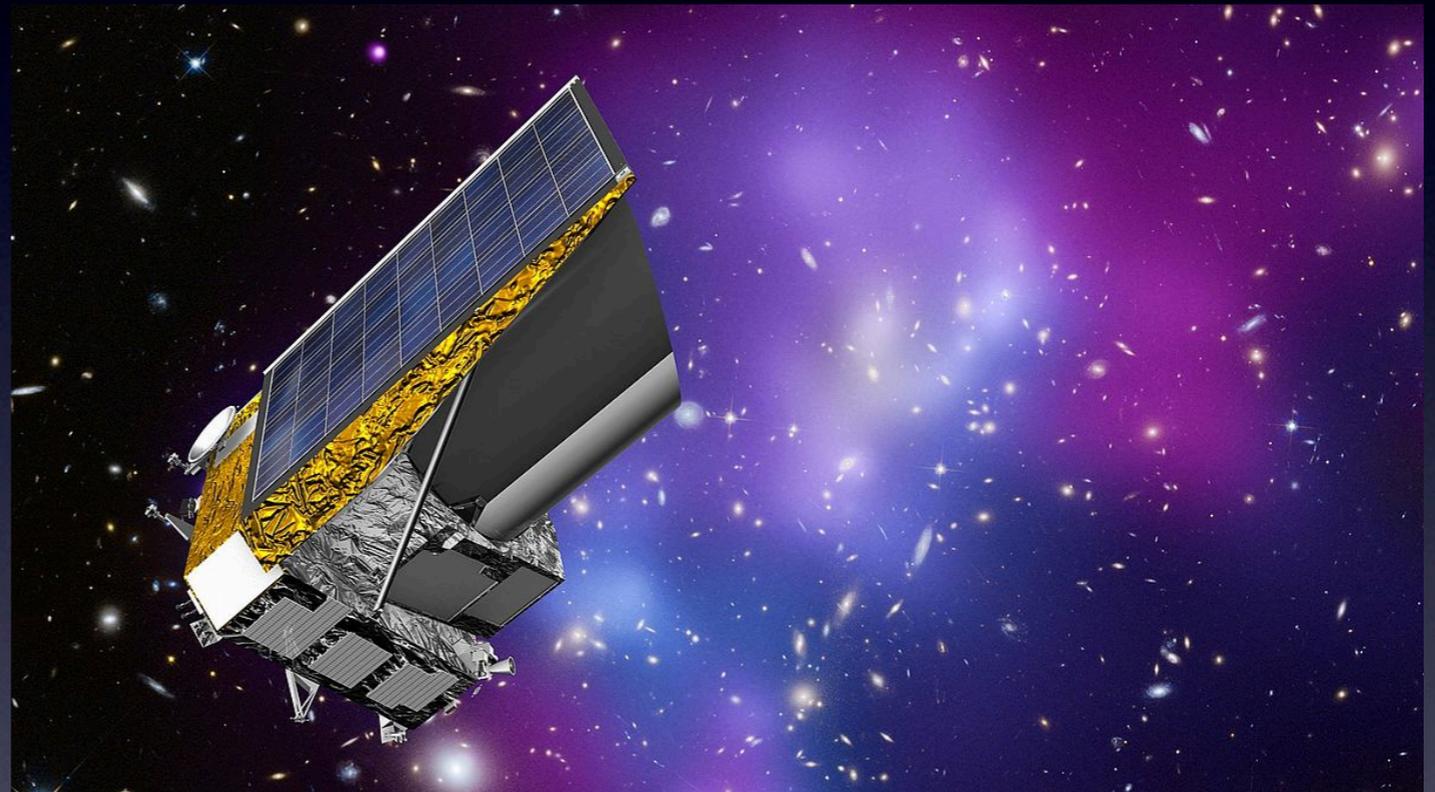
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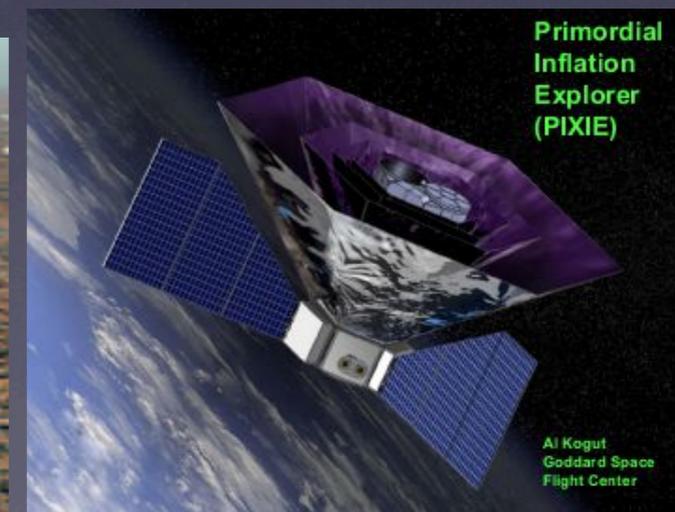
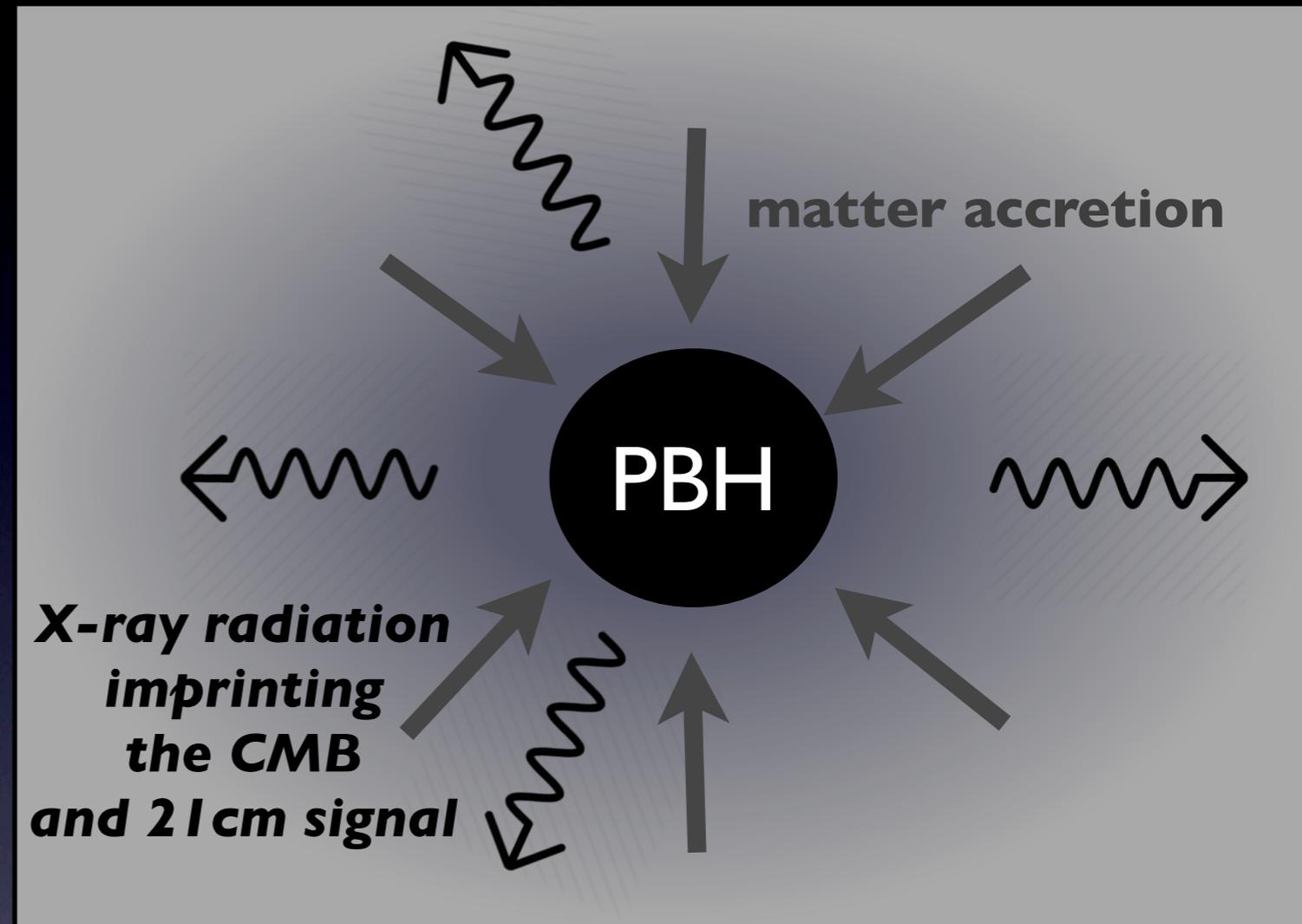
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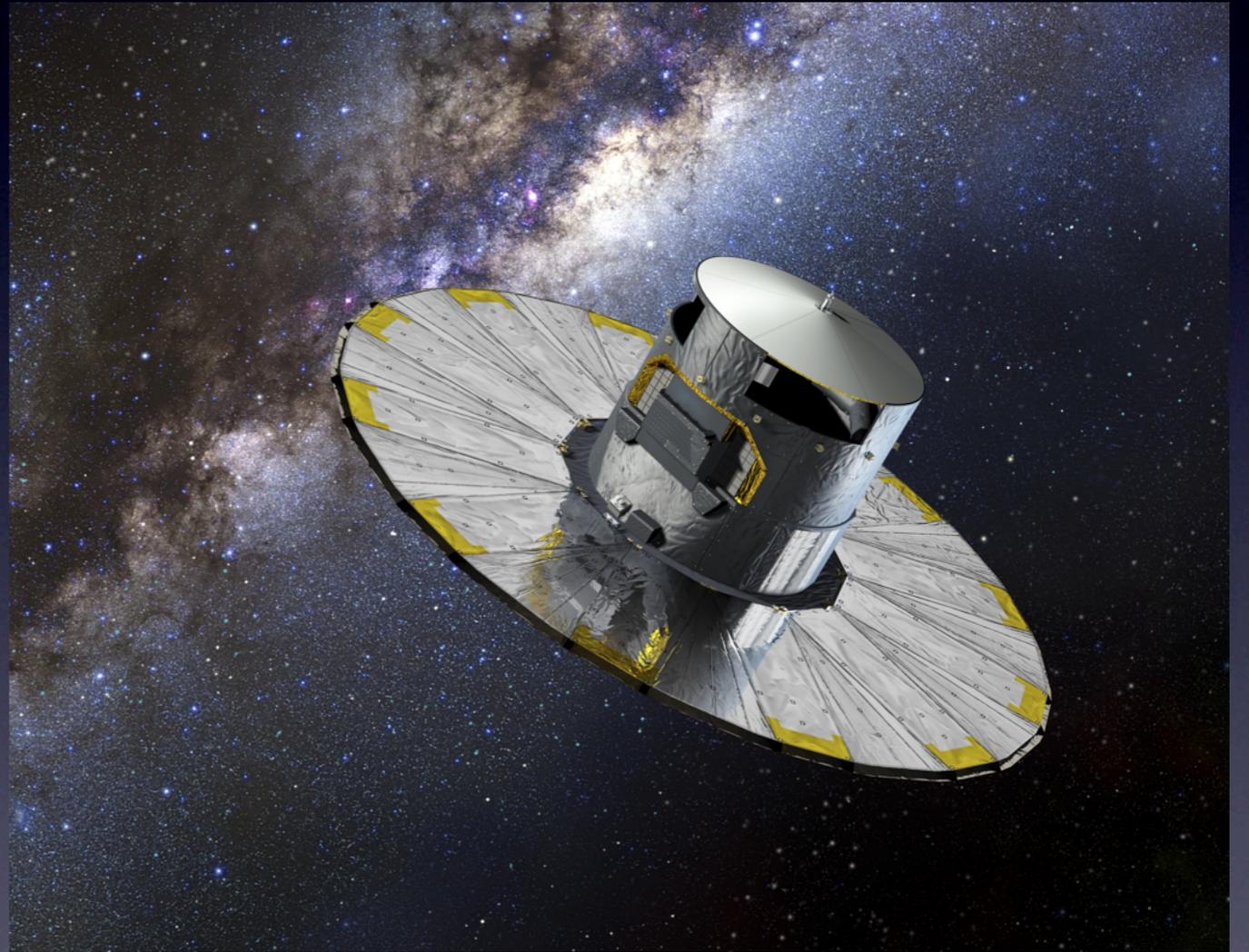
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Thank you
for your attention

LIGO and the strange

PBH Dark Matter interaction I

Gravitational waves from BH mergers

Dark Matter decay
in «Dark Radiation» (GW)

CMB: No more than $\sim 3.8\%$ of the DM

Poulin et al., 1606.02073

Constraints the PBH merging history

- Need a new model...

observational constraints

Four clues for PBH-DM

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

PBH Dark Matter interaction II

X-rays from matter accretion

Dark Matter decay
in electromagnetic channels

Spatial correlations
in X-ray and infrared backgrounds

1605.04
1709.02

Constraints on PBH abundances

Disk accretion at high redshifts

PBH Dark Matter interaction II

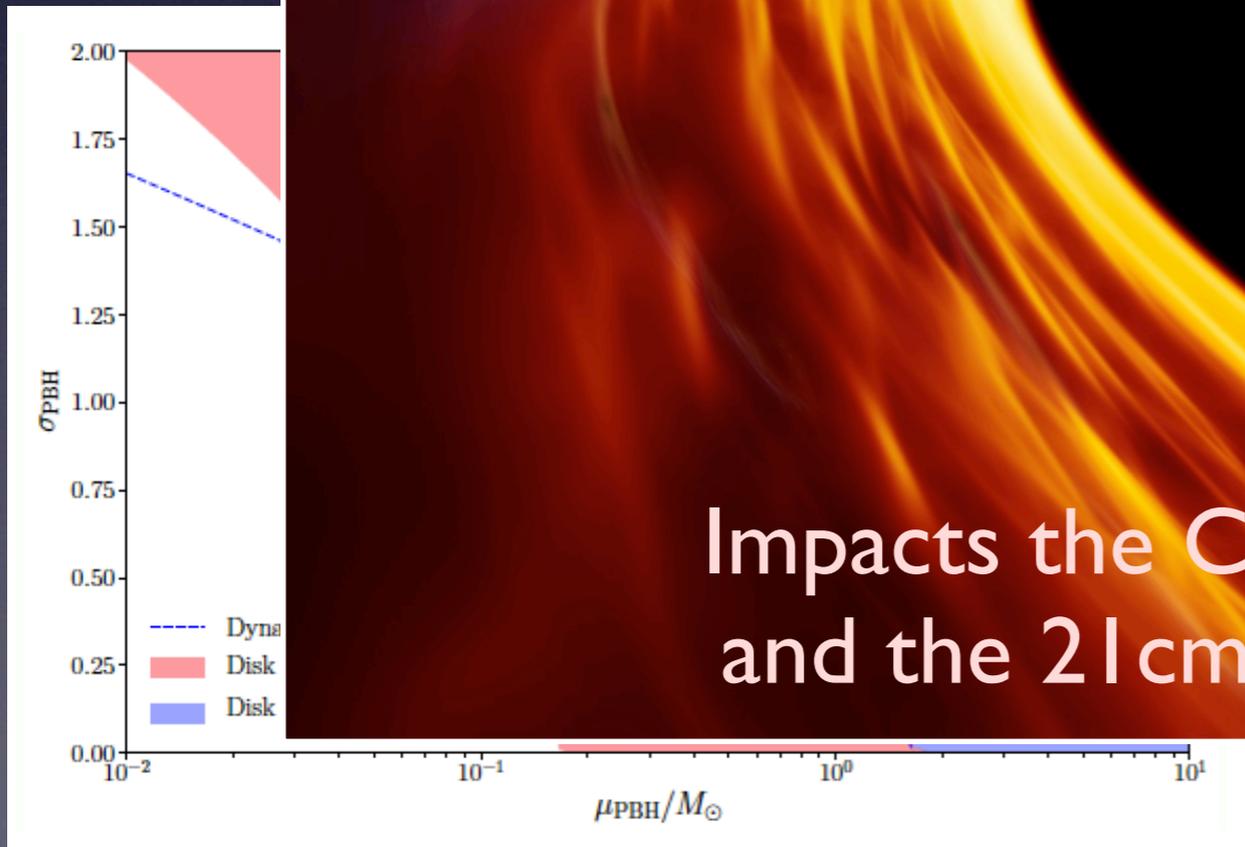
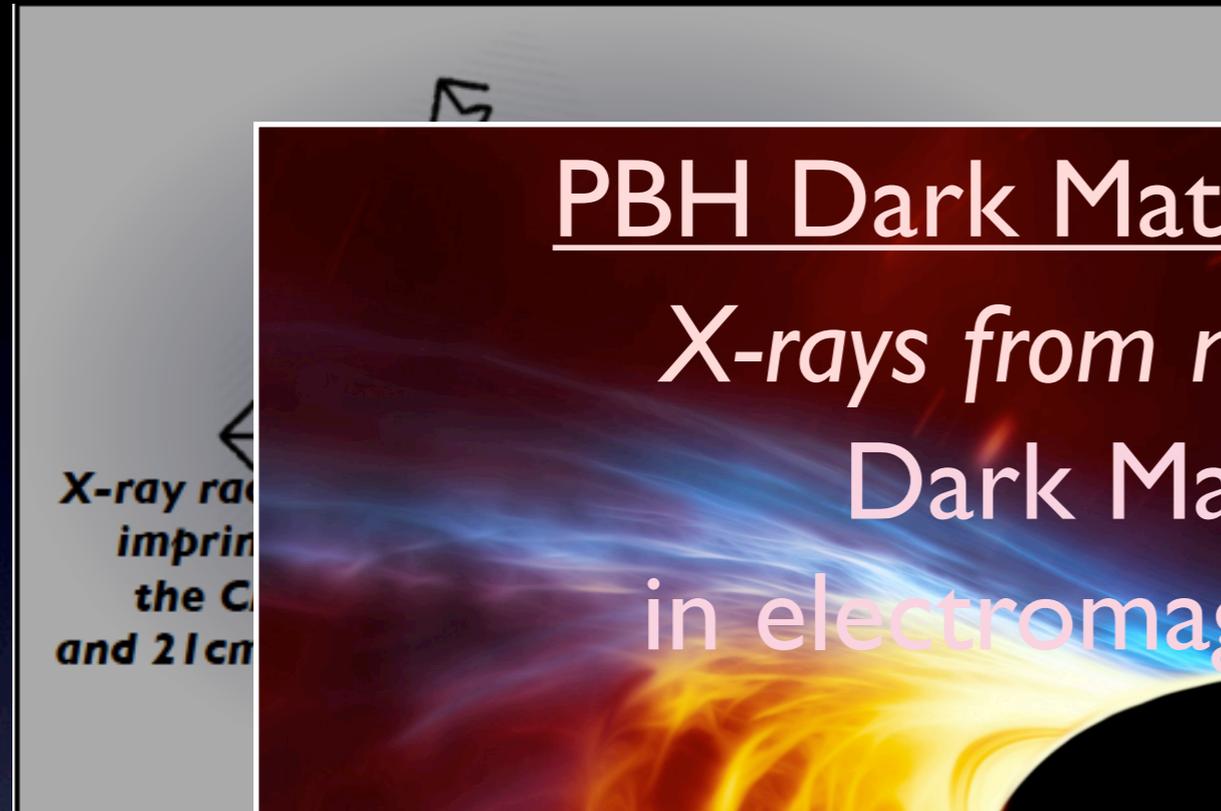
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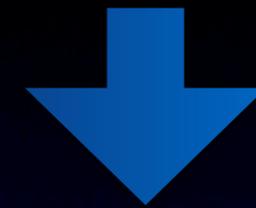
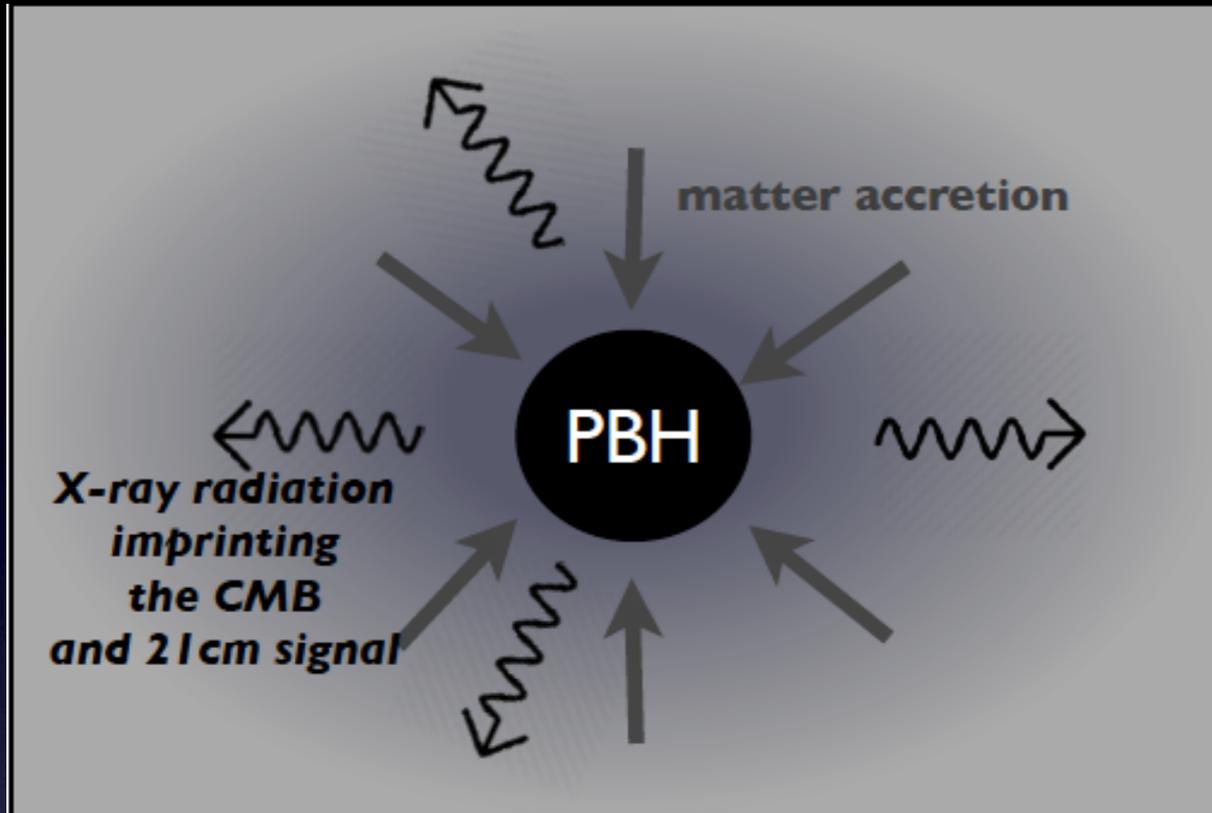
Impacts the CMB (e.g. 1610.10051)
and the 21cm signal (Laura's talk)

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

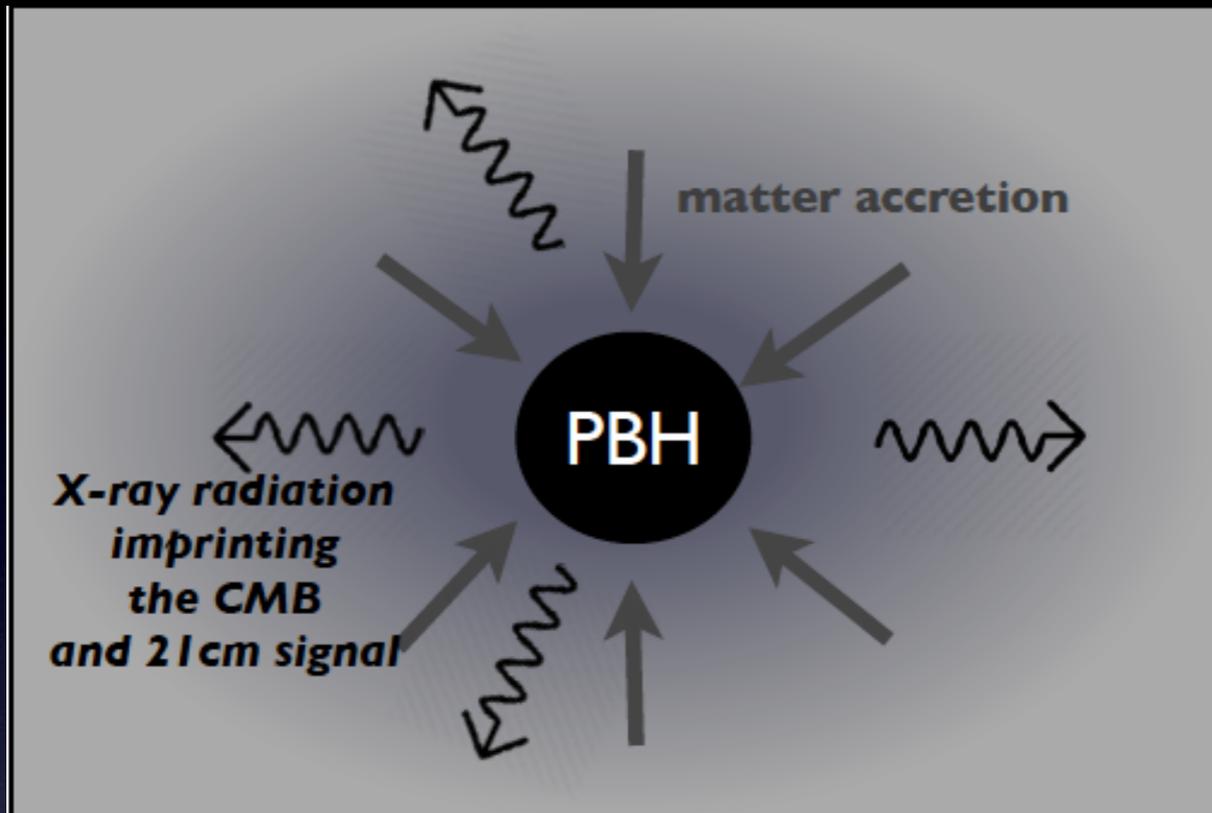
Poulin et al., 1707.04296



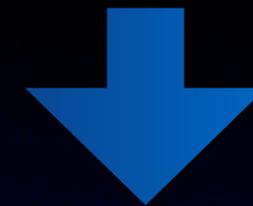
Constraints on PBH abundances



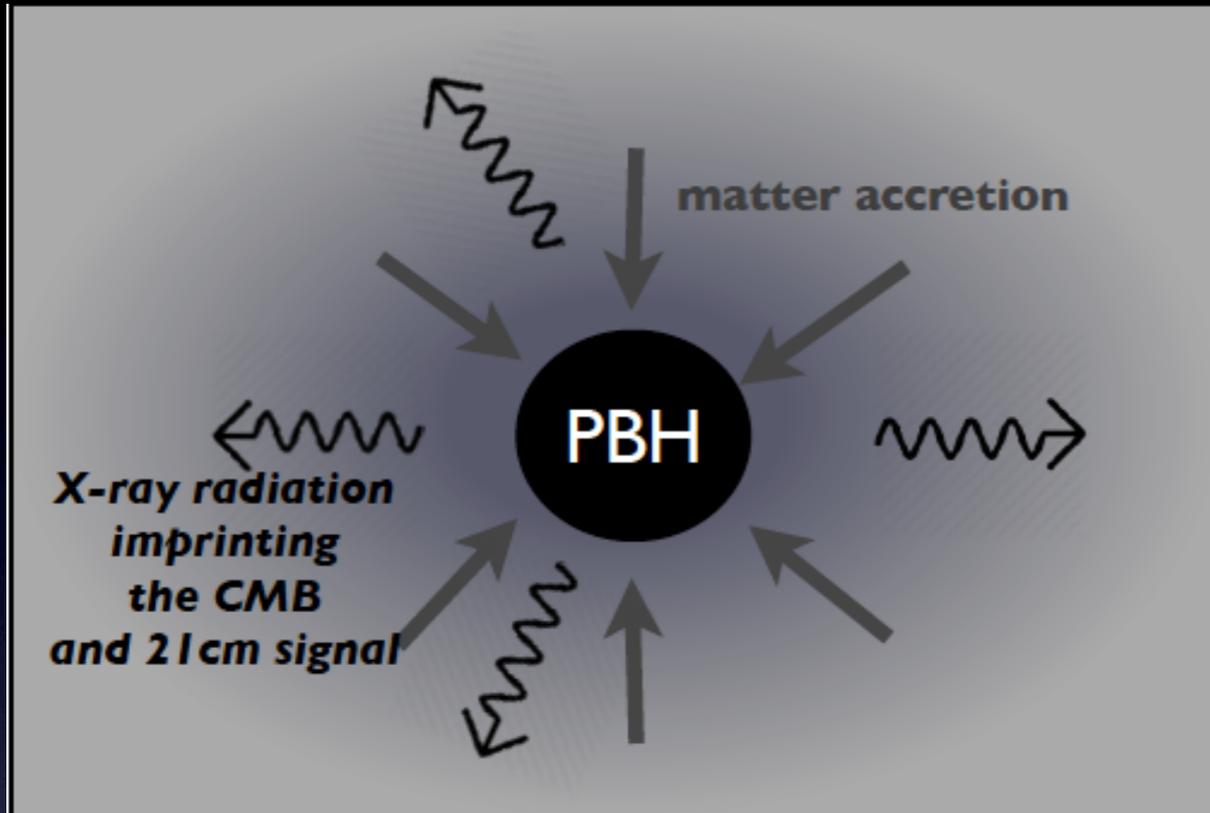
Constraints on PBH abundances



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



Constraints on PBH abundances

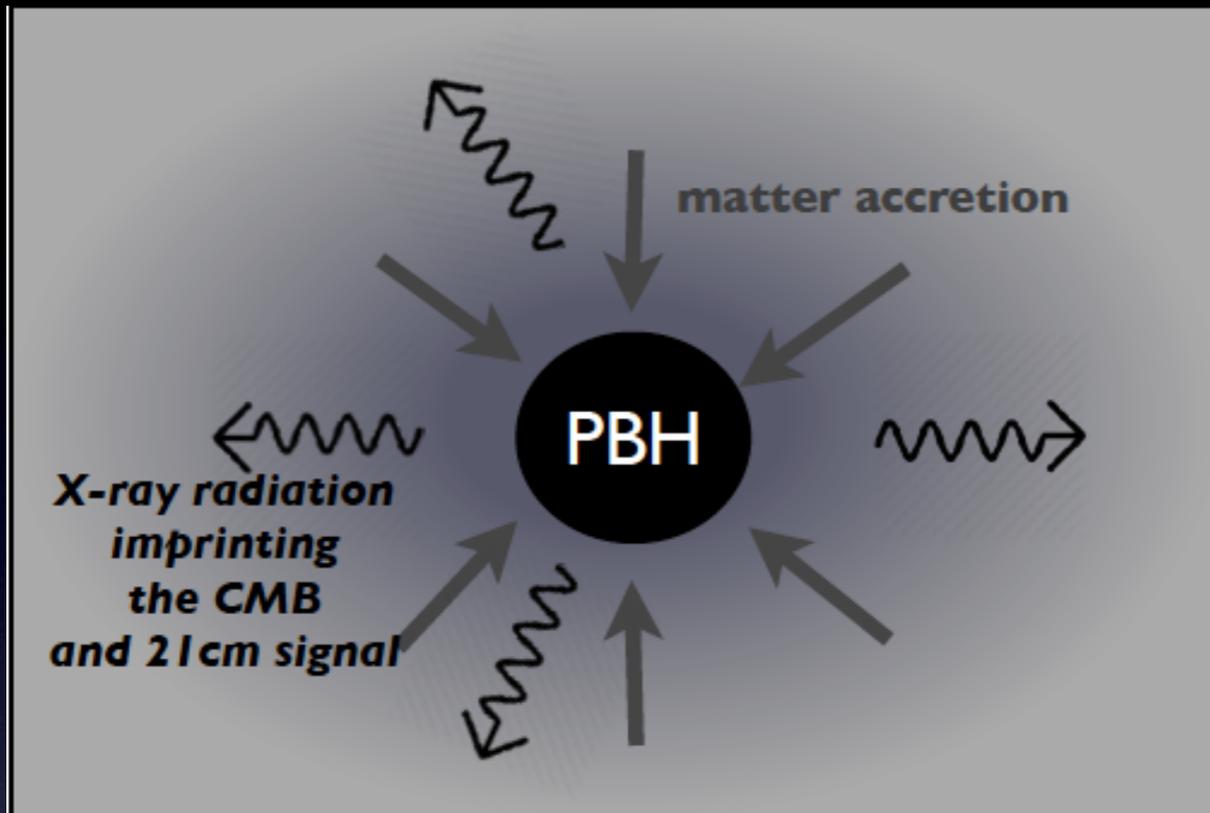


Disk accretion at high redshifts
 $100 < z < 10\,000$

↓
Accretion Luminosity



Constraints on PBH abundances

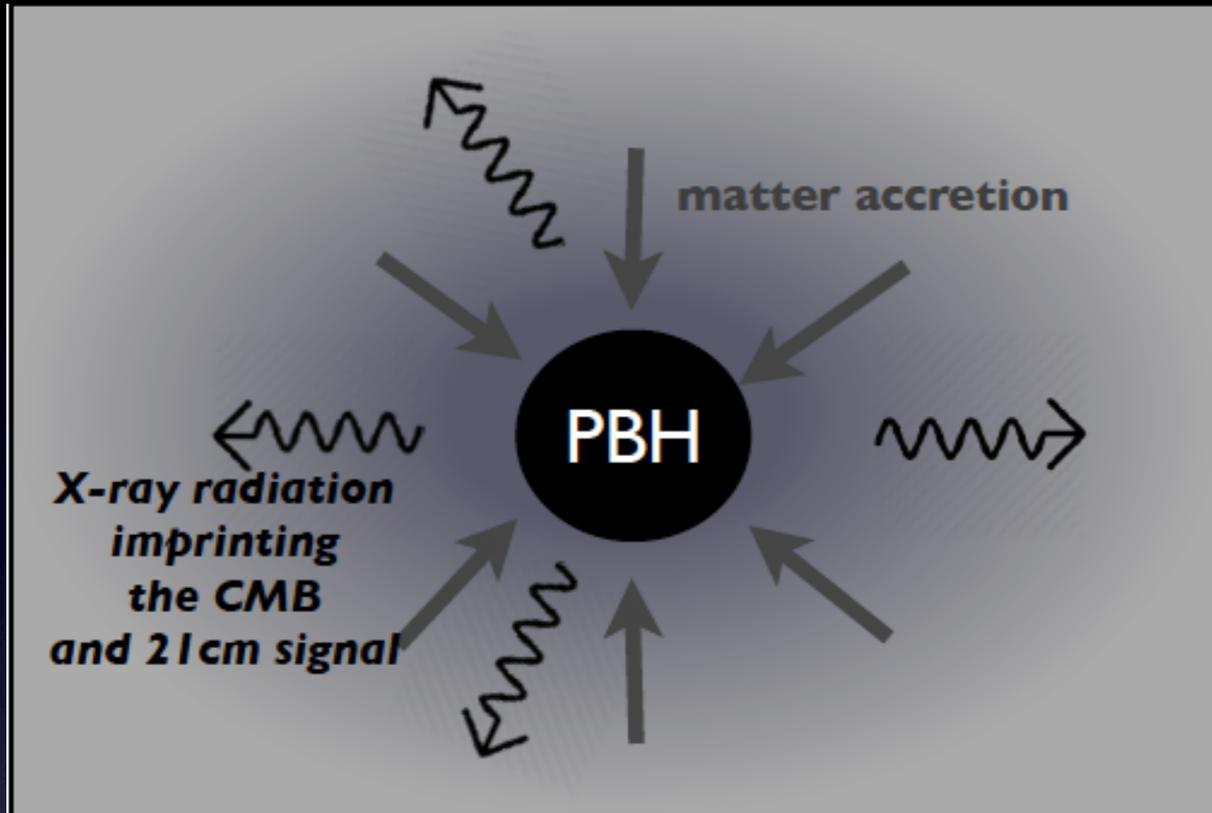


Disk accretion at high redshifts
 $100 < z < 10\,000$

↓
Accretion Luminosity

↓
Energy deposition

Constraints on PBH abundances



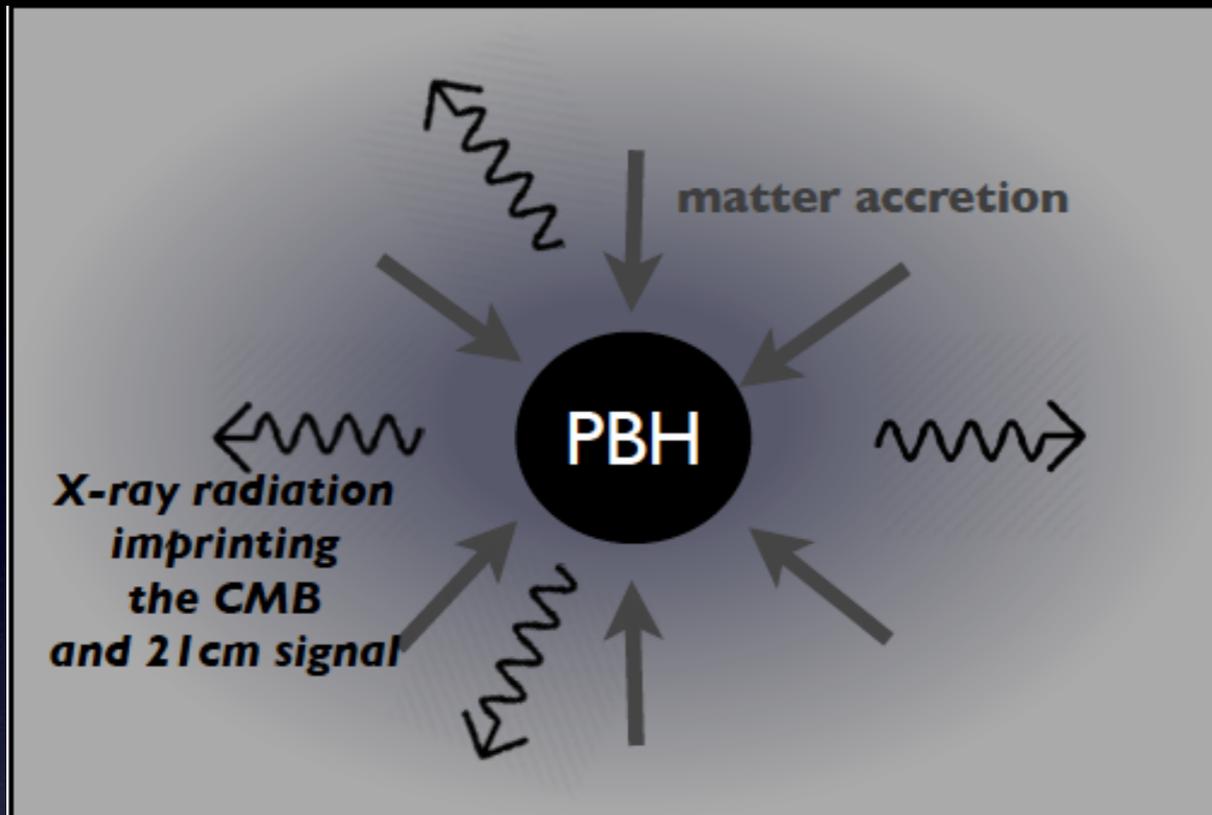
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↓
Accretion Luminosity

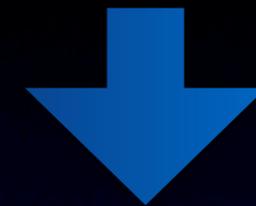
↓
Energy deposition

↓
Thermal History of the Universe
and effects on the CMB

Constraints on PBH abundances



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



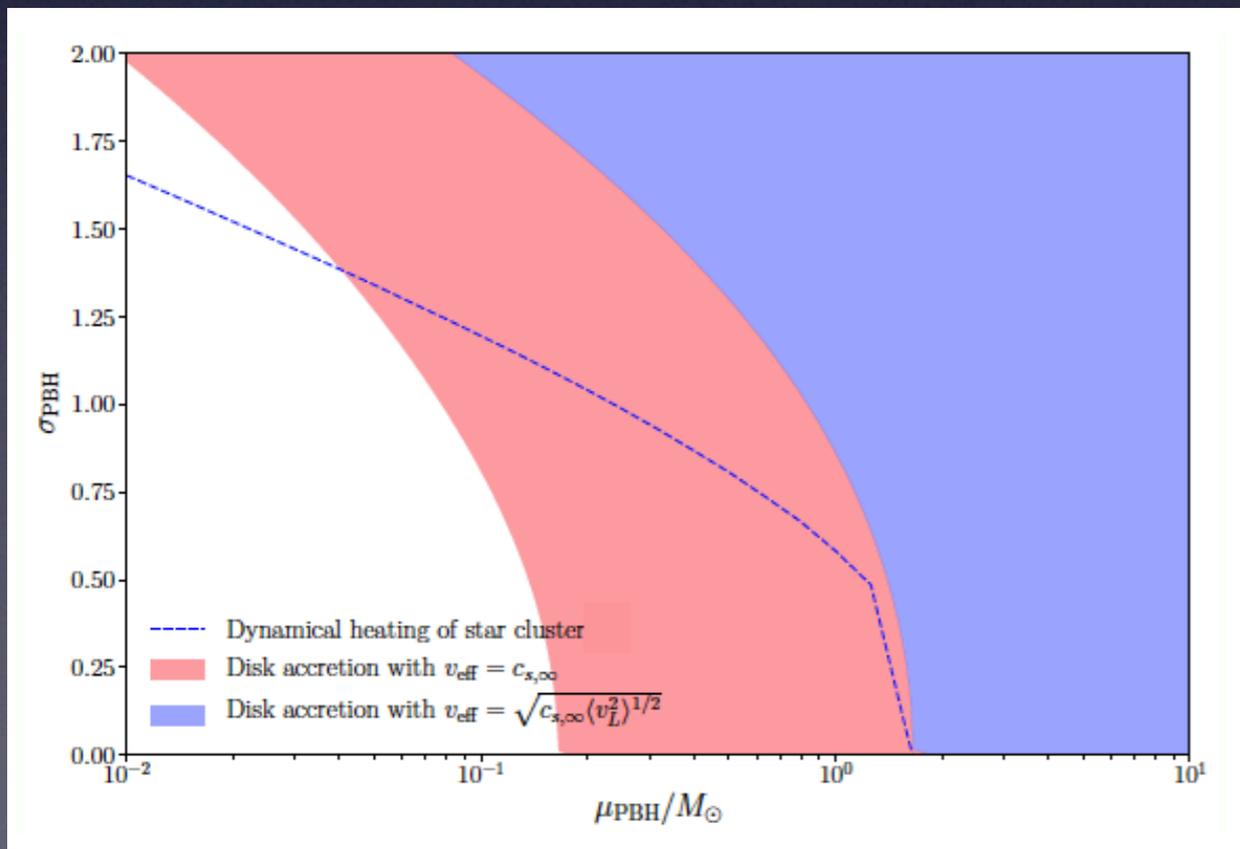
Accretion Luminosity



Energy deposition

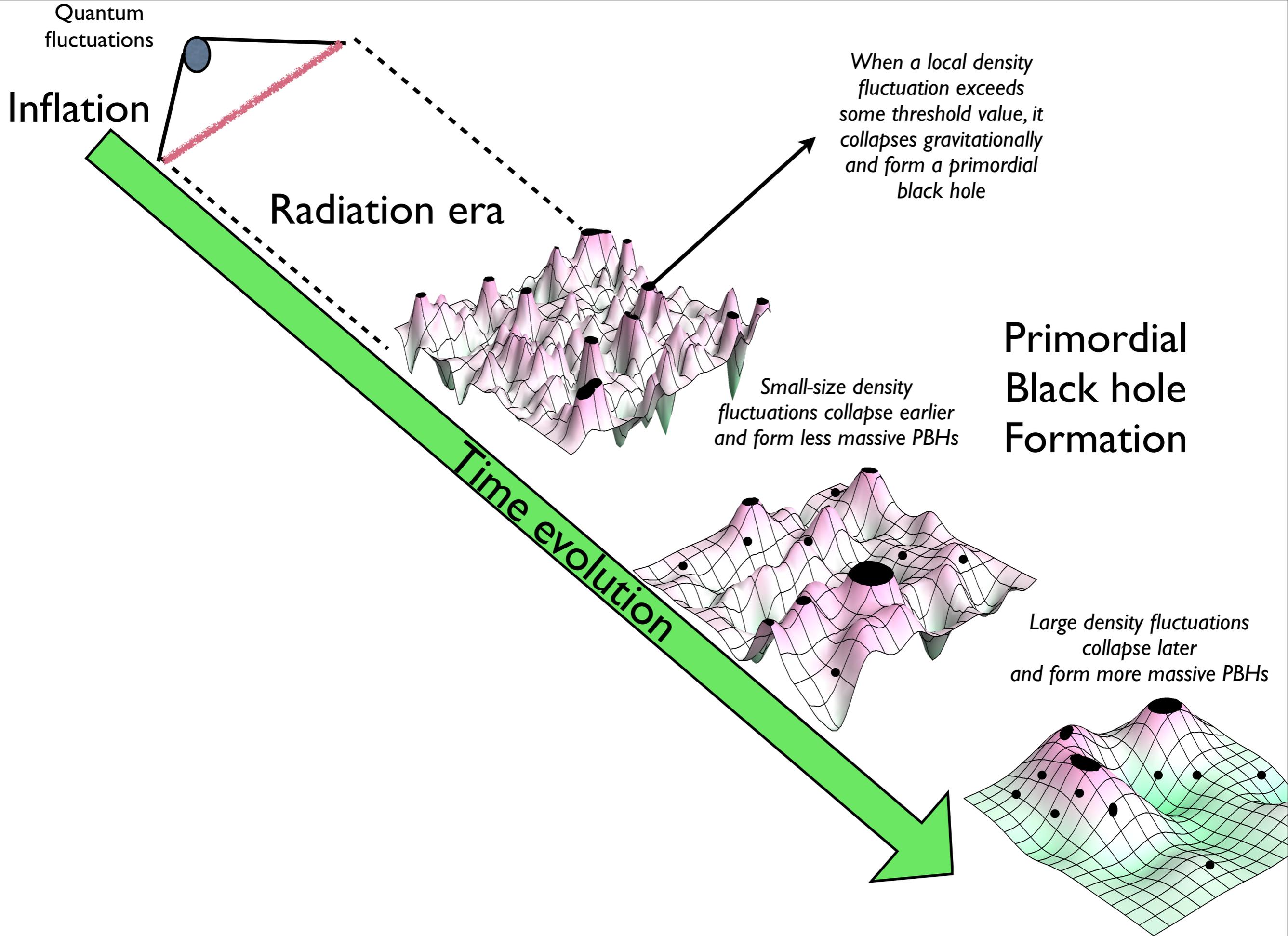


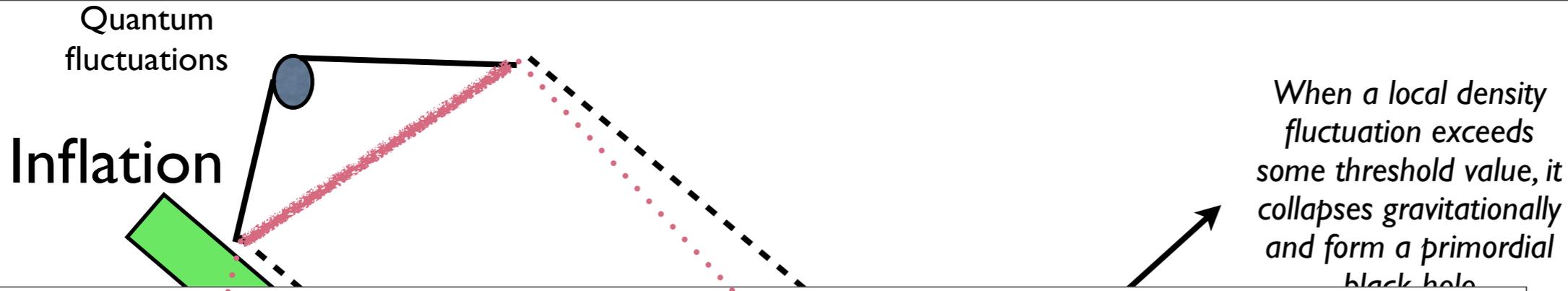
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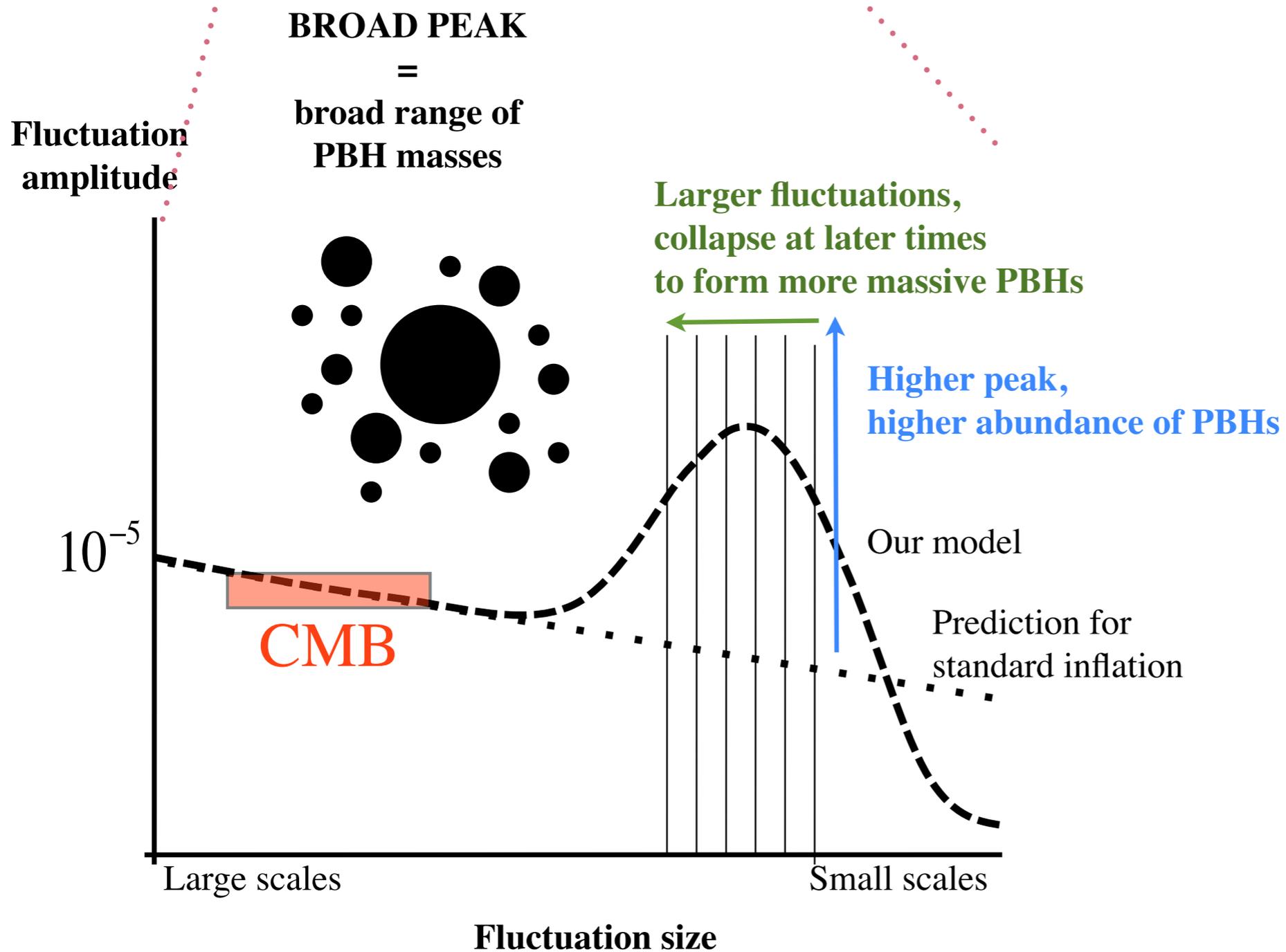
$$f_{\text{PBH}} < \left(\frac{4 M_{\odot}}{M} \right)^{1.6} \left(\frac{v_{\text{eff}}}{10 \text{ km/s}} \right)^{4.8} \left(\frac{0.01}{\lambda} \right)^{1.6}$$

Poulin et al., 1707.04296



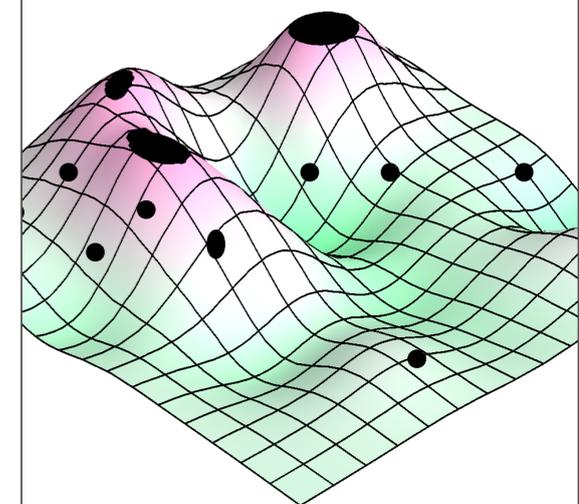


Spectrum of density fluctuations after inflation



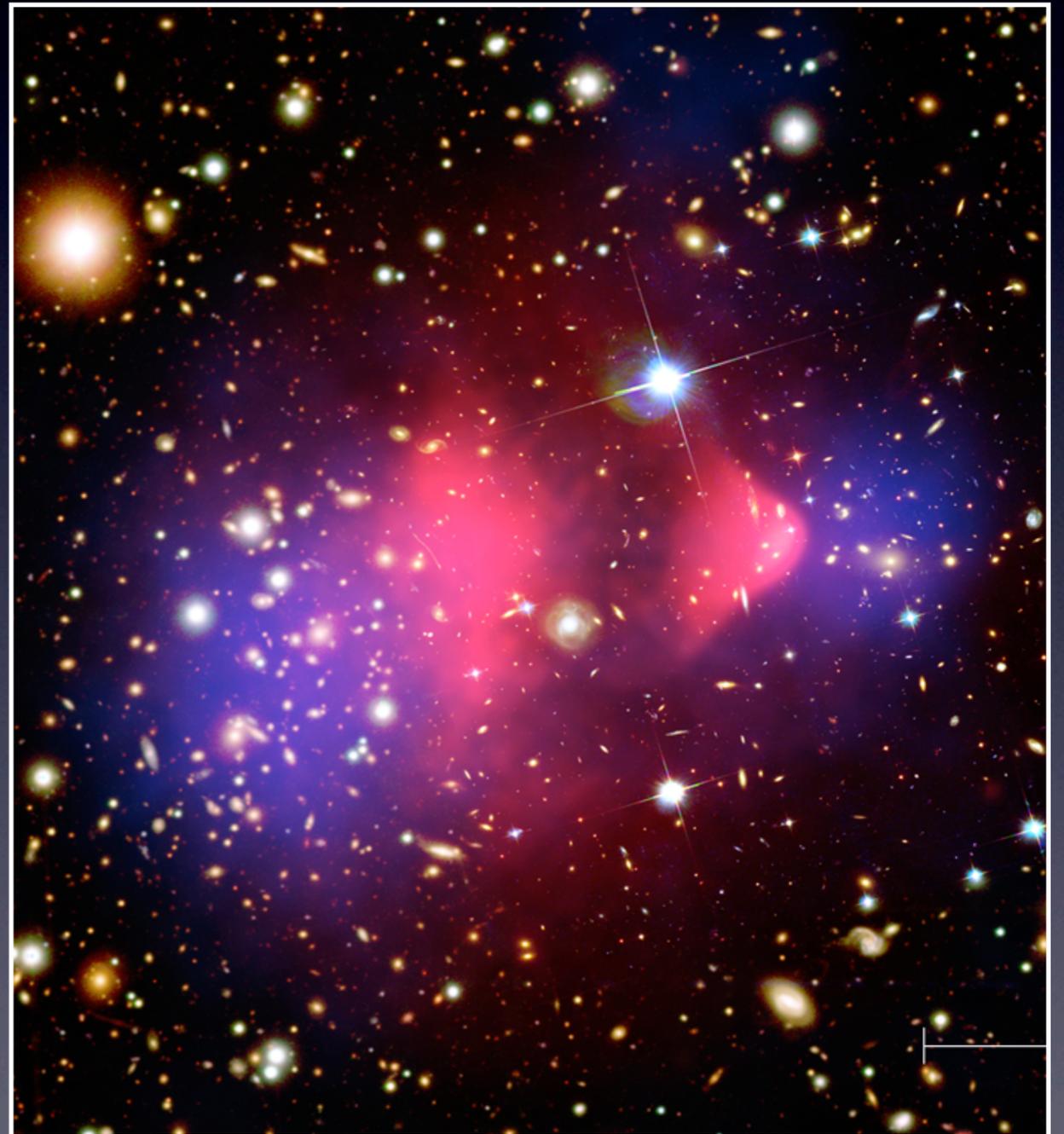
Primordial Black hole formation

Large density fluctuations collapse later and 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

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

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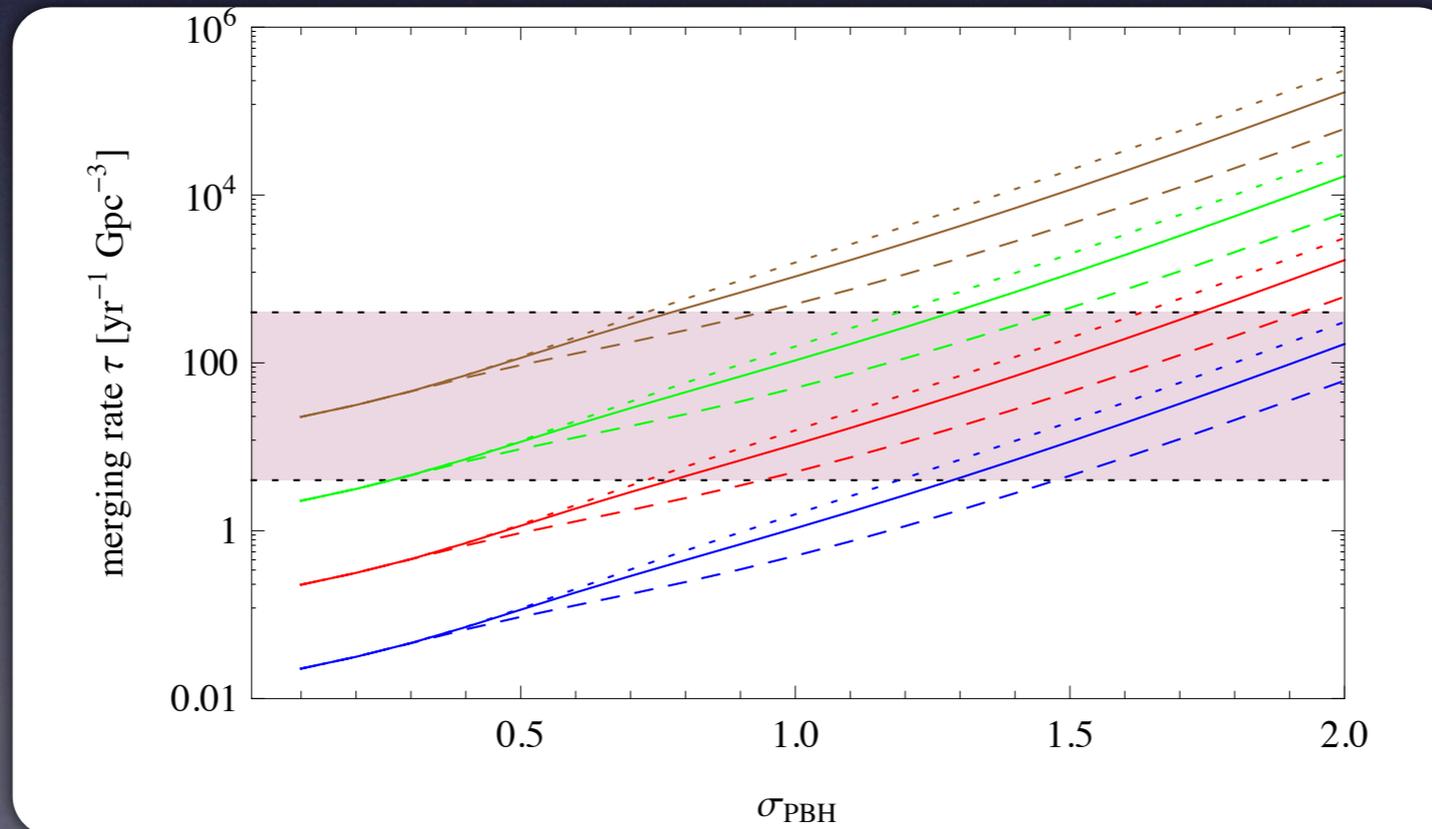
Most mergings
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- S.C., J. García-Bellido, 1603.05234

Broad mass spectrum, natural clustering scale

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

Faint Dwarf Galaxies
or Globular Clusters



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- M. Sasaki et al., 1603.08338

Monochromatic spectrum, BH binaries from Early Universe

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

**cannot be the
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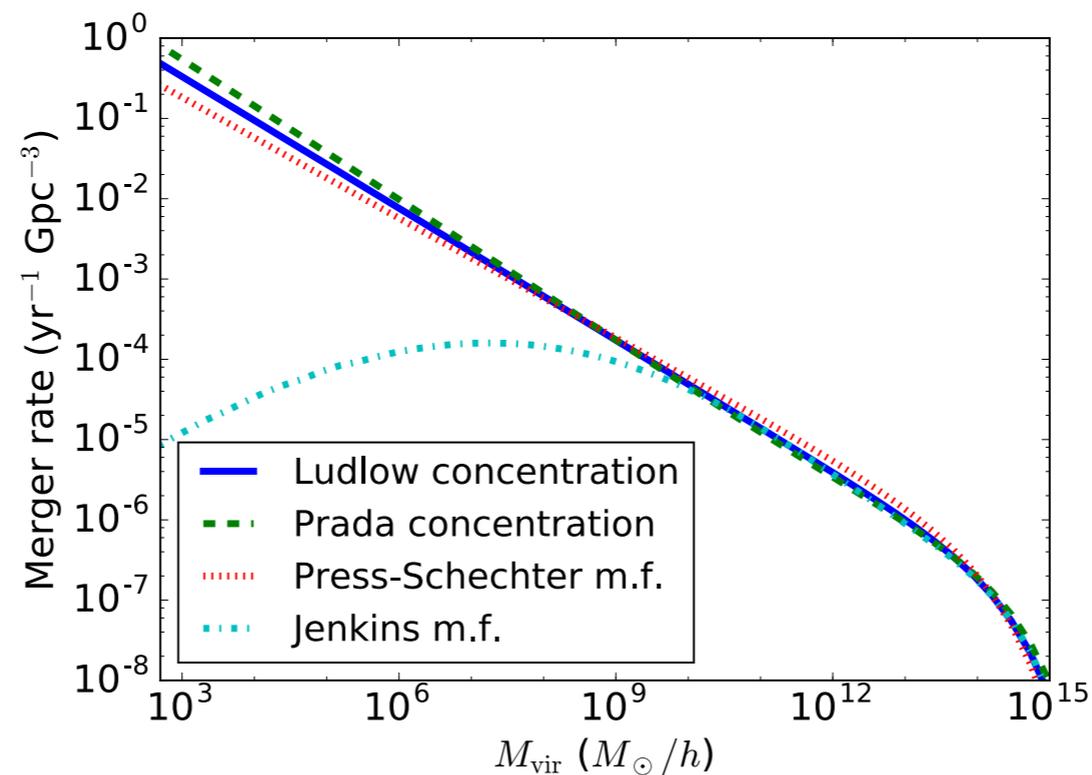
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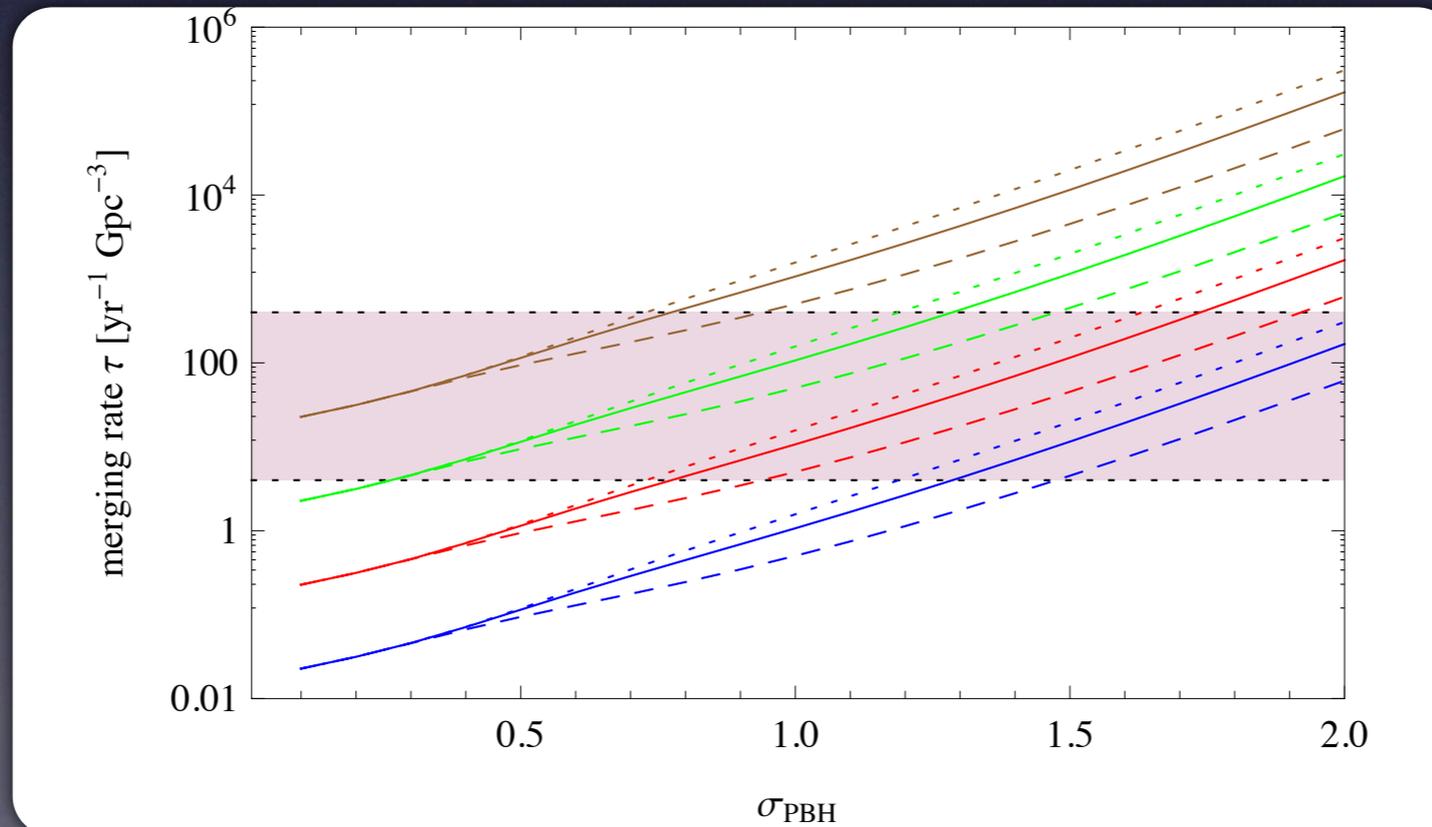
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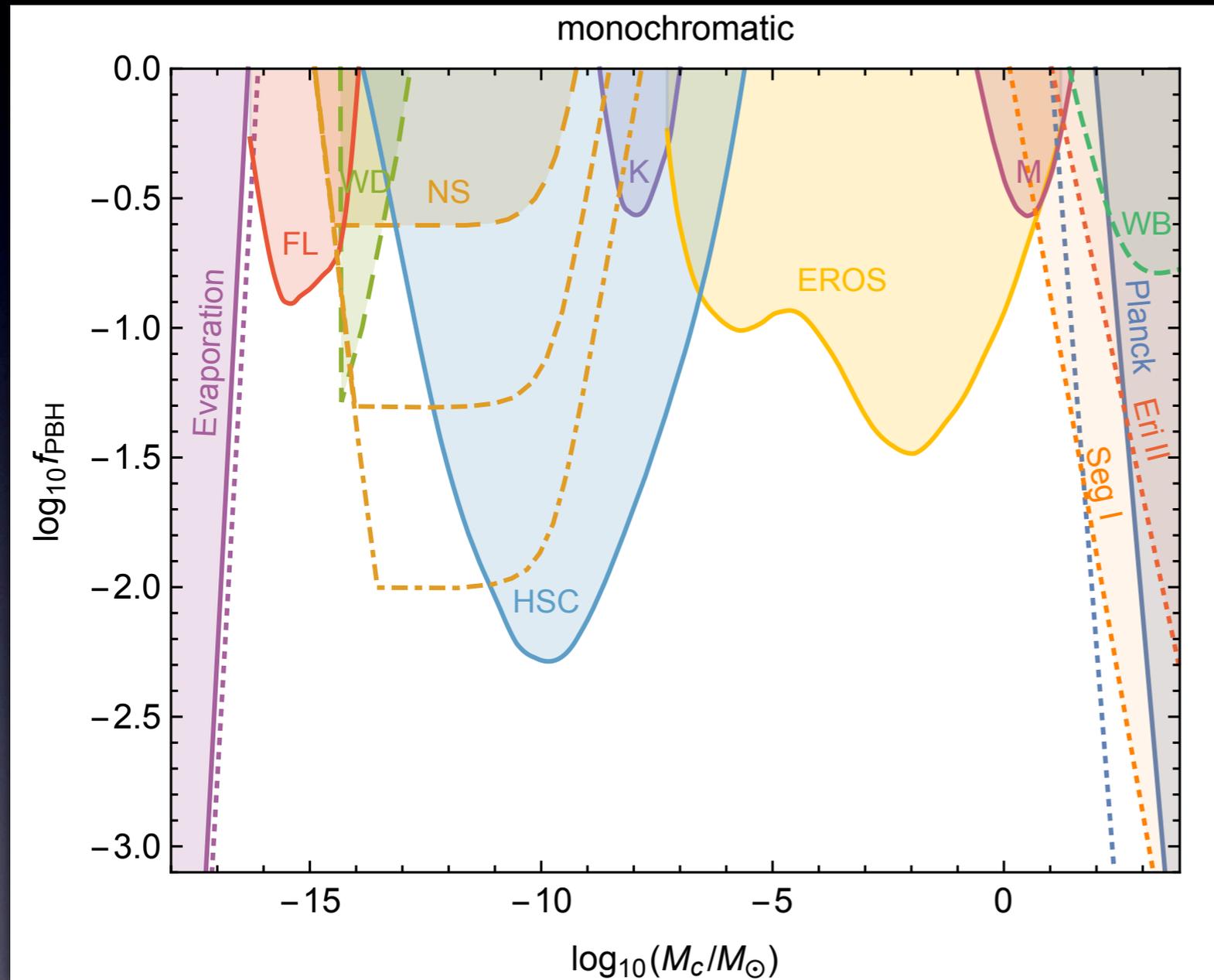
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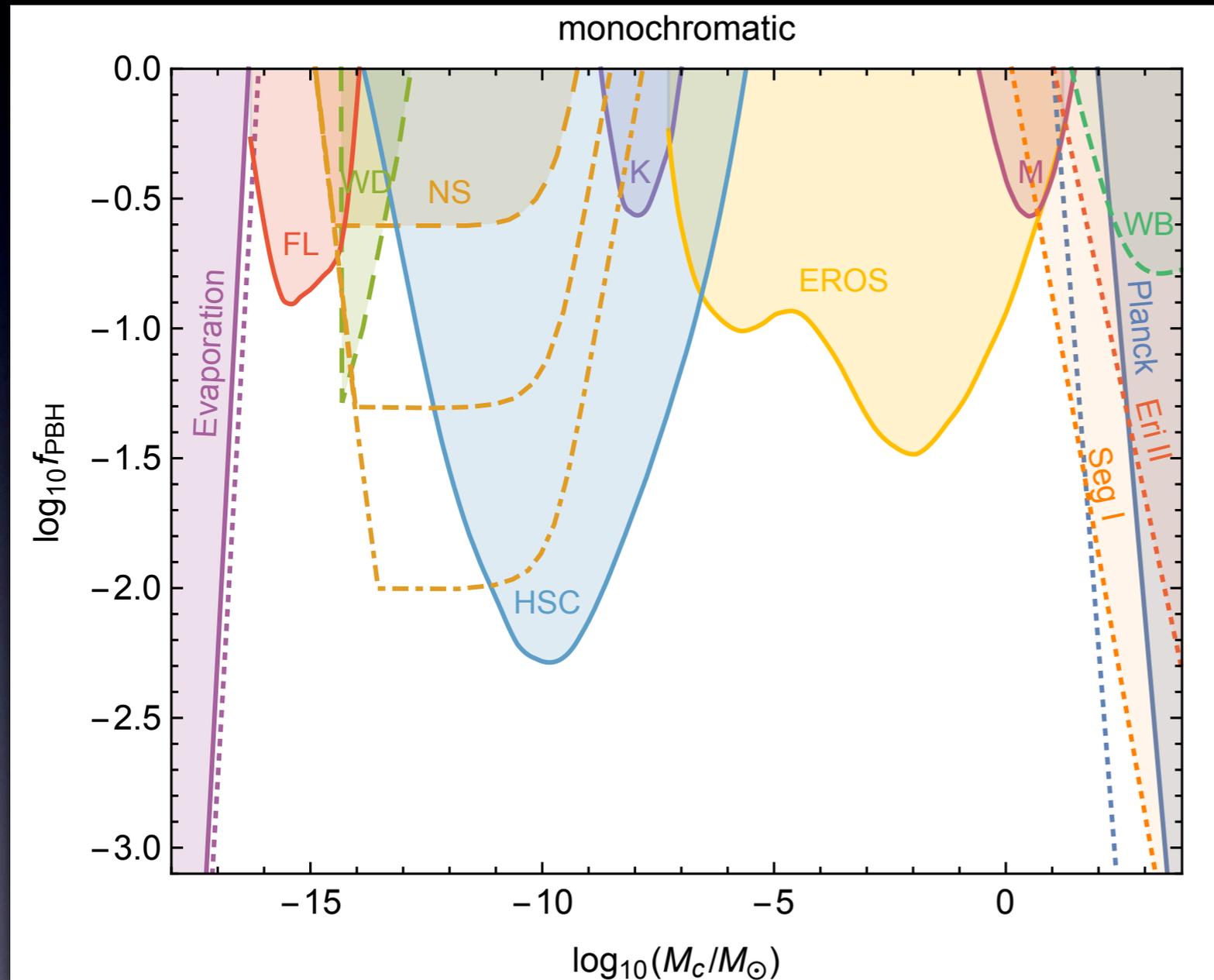
**cannot be the
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Constraints on PBH abundances



B. Carr et al., 1705.05567

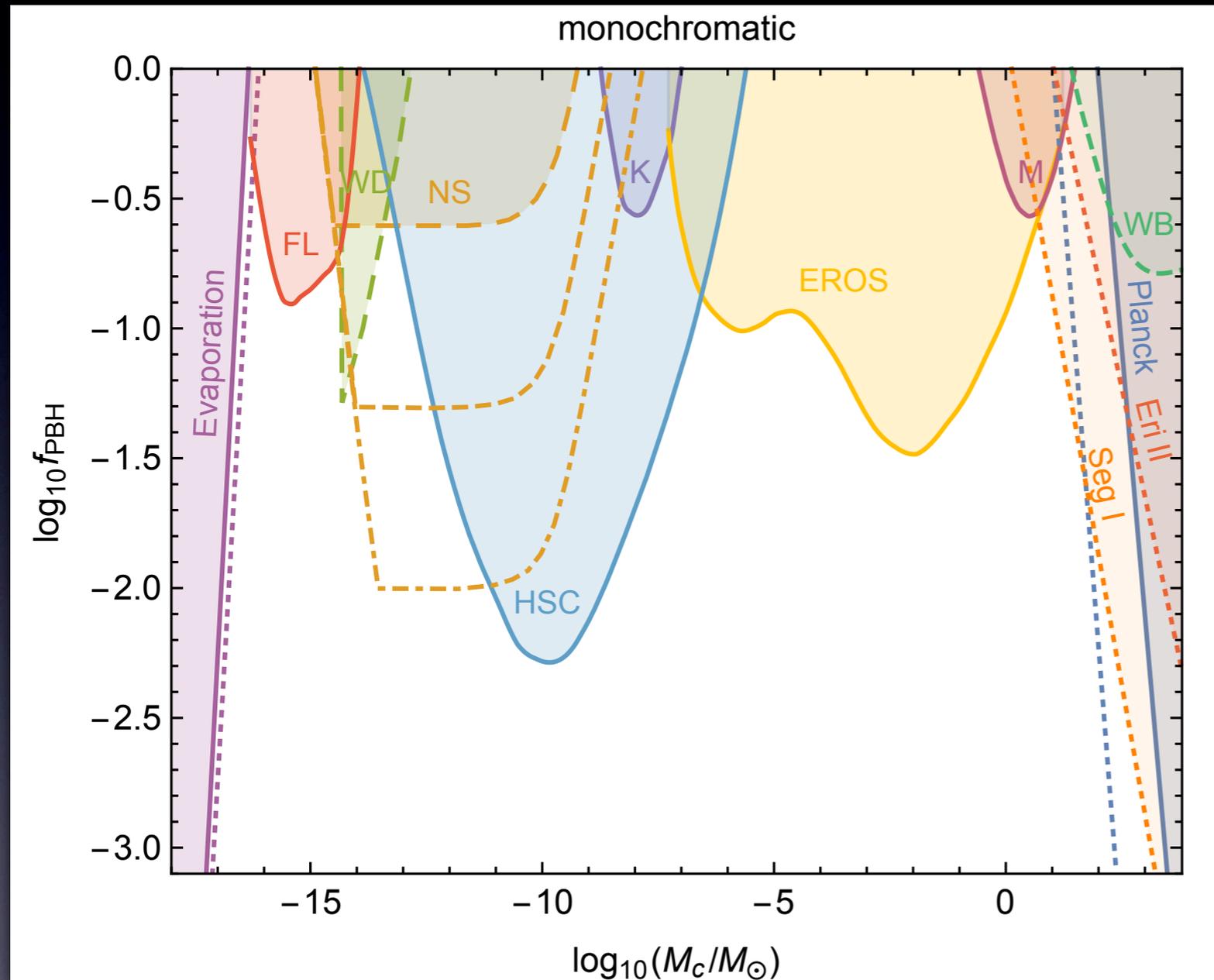
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Monochromatic
spectrum:
PBH-DM looks excluded
in the whole mass range

B. Carr et al., 1705.05567

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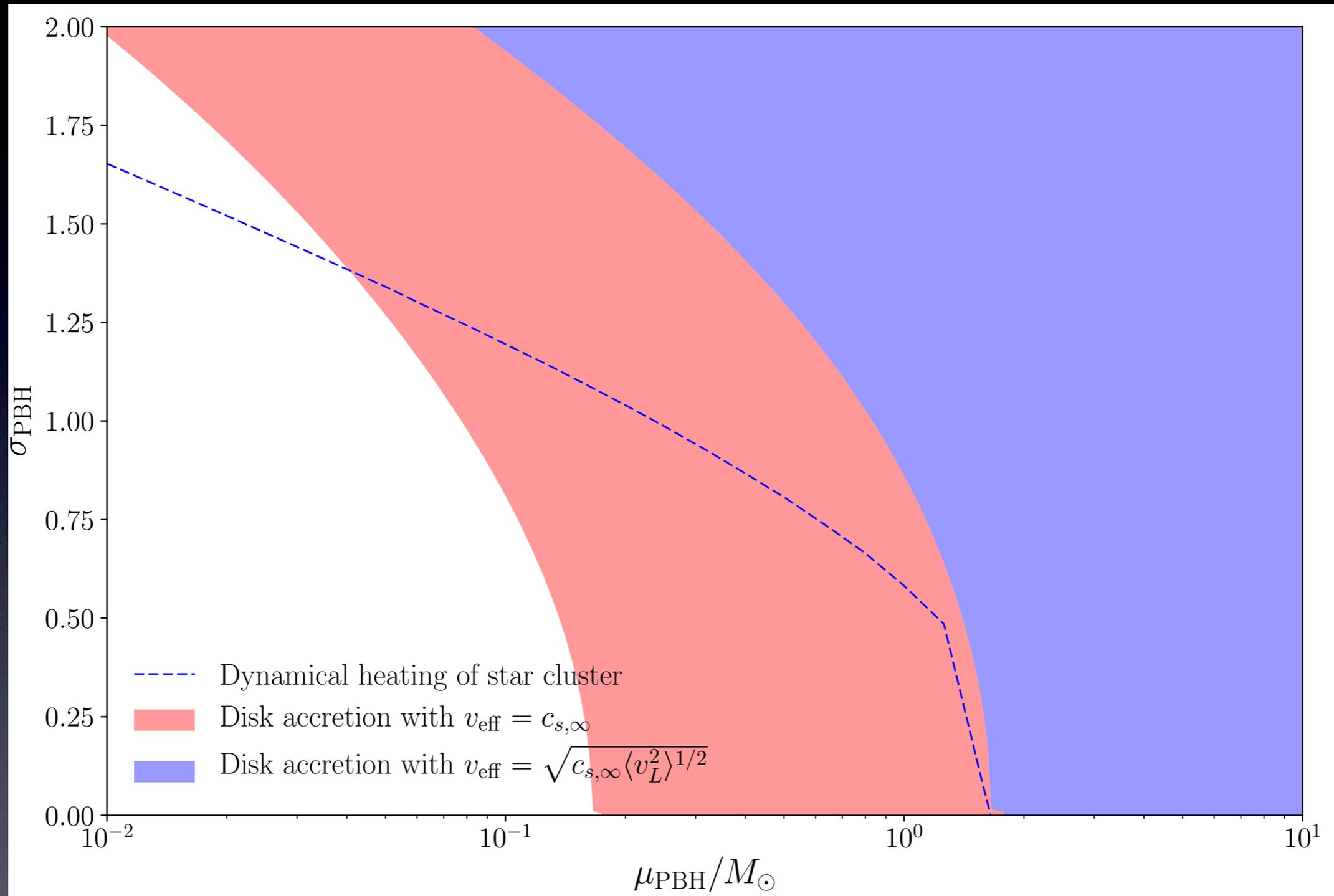
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Microlensing constraints
are controversial
and change if
PBH are clustered!
(SC., JGB, 1501.07565
A. Green, 1705.10818)!

B. Carr et al., 1705.05567

Constraints on PBH abundances

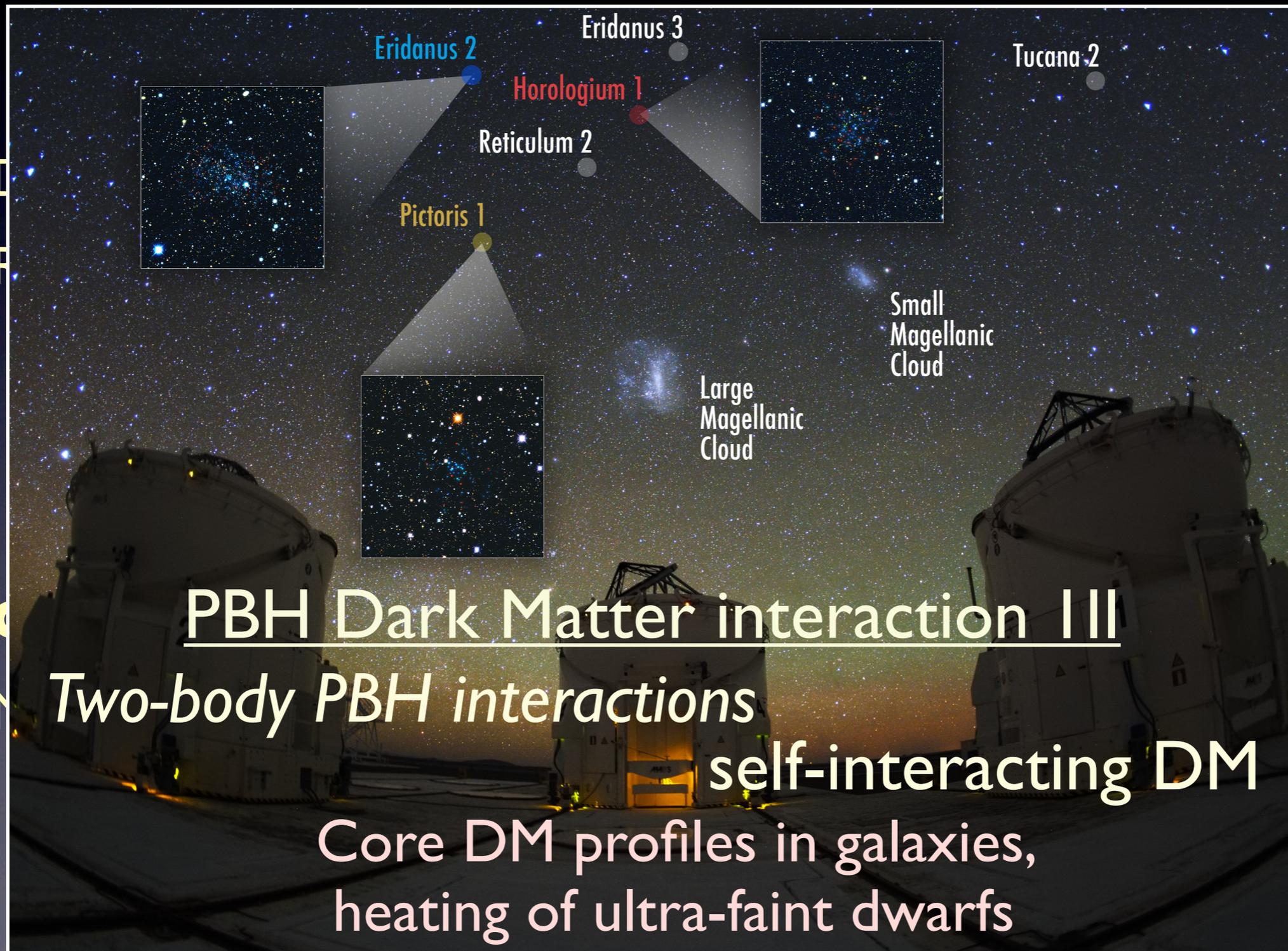


Poulin, Serpico, Calore, SC, Kohry 170704206

CMB very sensitive to the relative PBH/baryon velocity

Seven hints for PBH-DM

Hint 2: Star clusters and dynamics of faint dwarf galaxies



Seven hints for PBH-DM

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PBH Dark Matter interaction IV

- Dy
- Re
- C
- Na

Accretion of baryonic matter

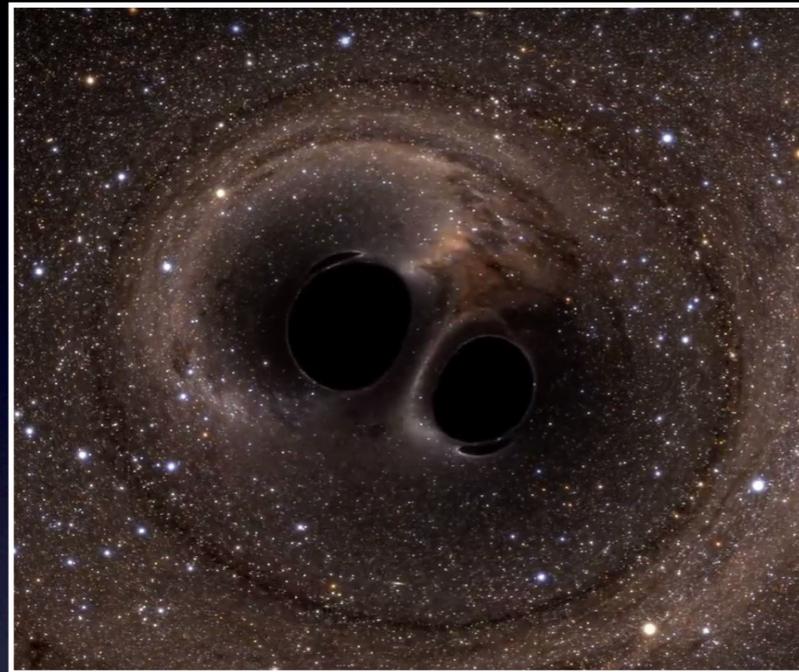
Baryon decay in DM

Missing satellites, missing baryons

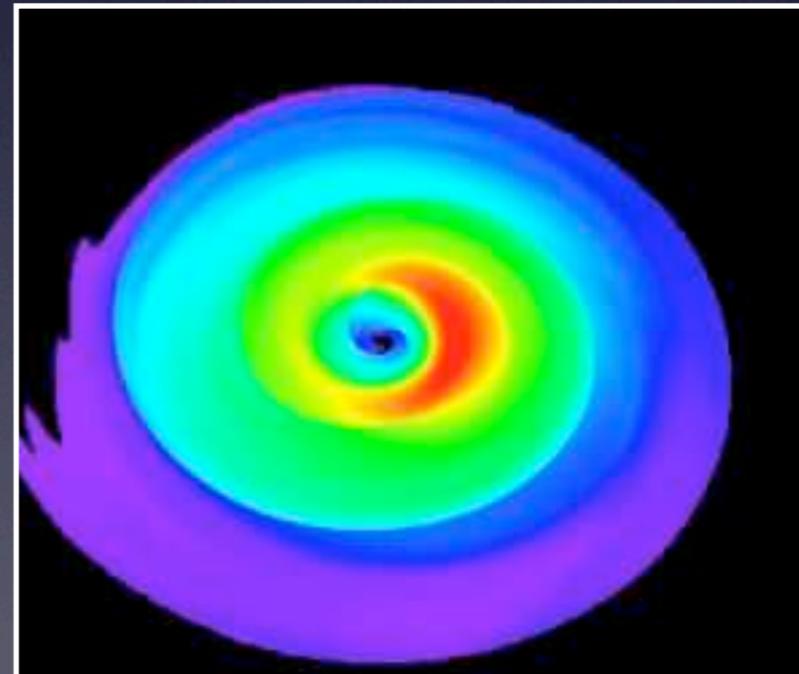
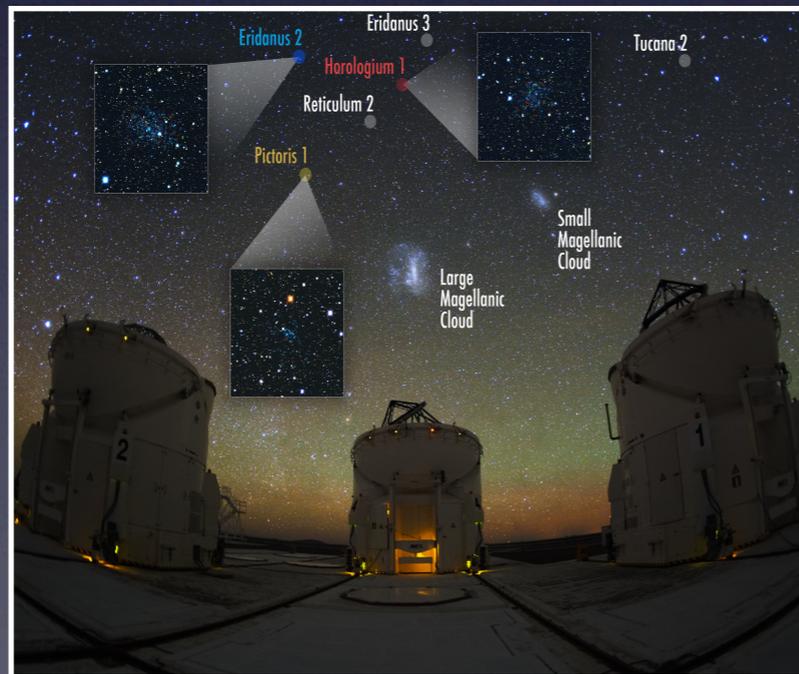
Evolution of
cosmological perturbations?
(CMB, matter power spectrum)

Rethinking DM interactions

DM decay in dark radiation



DM decay to photons



Self-interacting dark matter

DM production