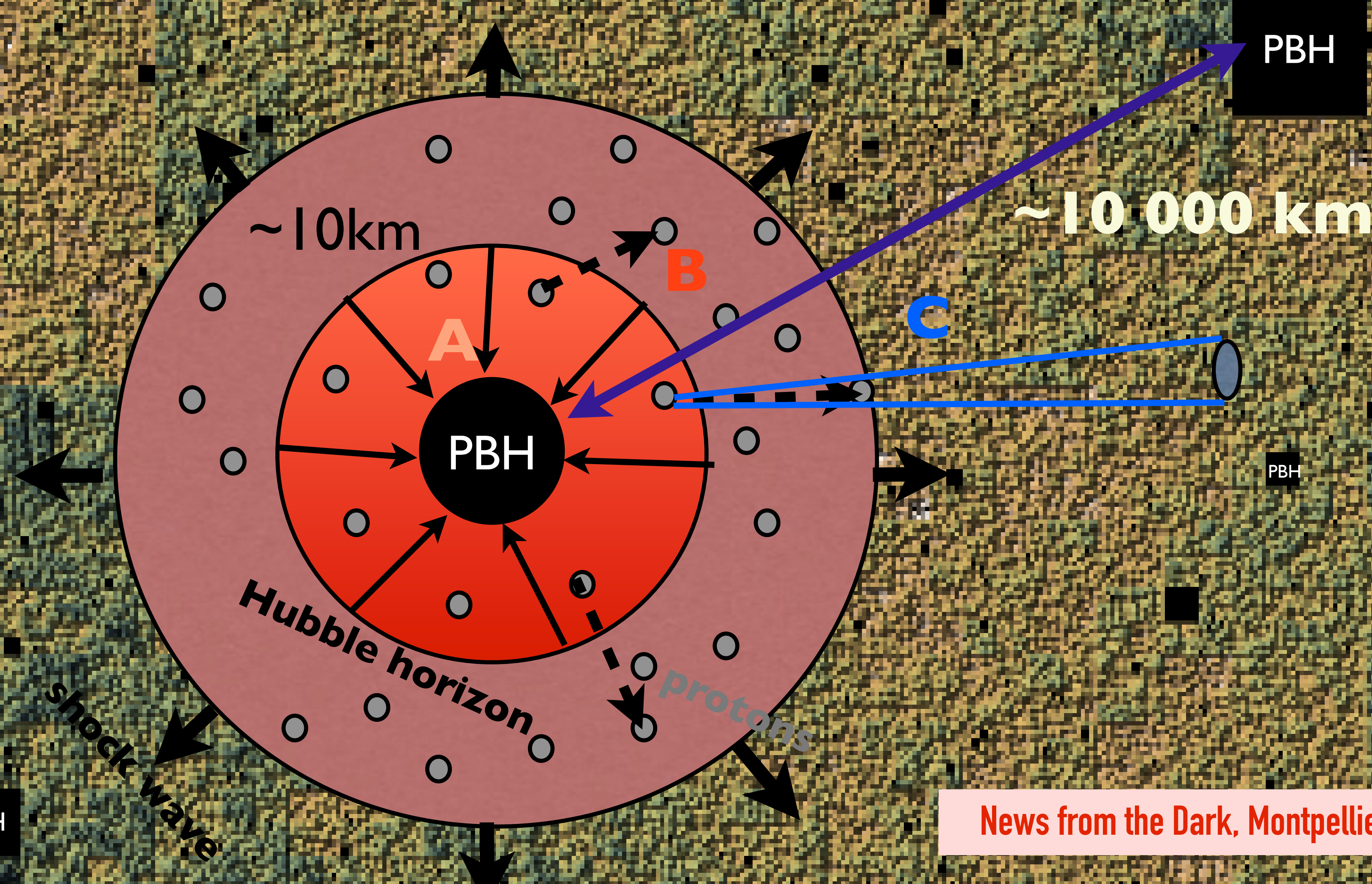
A common origin for Baryons and Dark Matter?

Sébastien Clesse, Louvain (CURL) & Namur (naXys) University

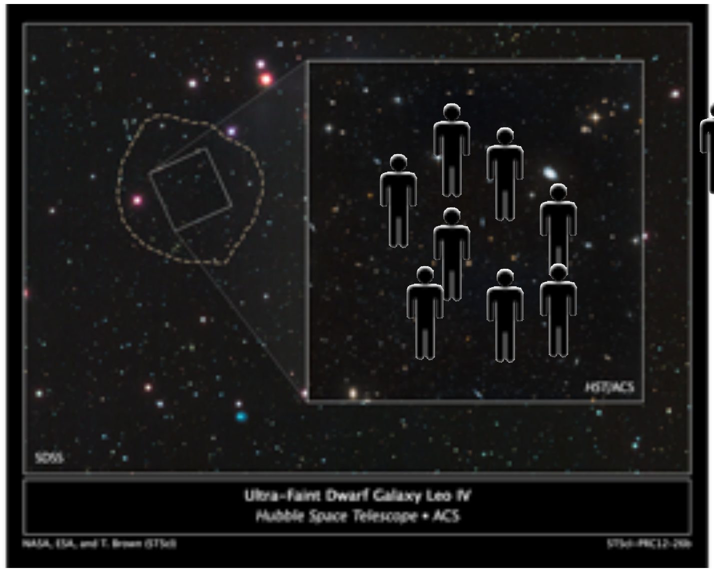


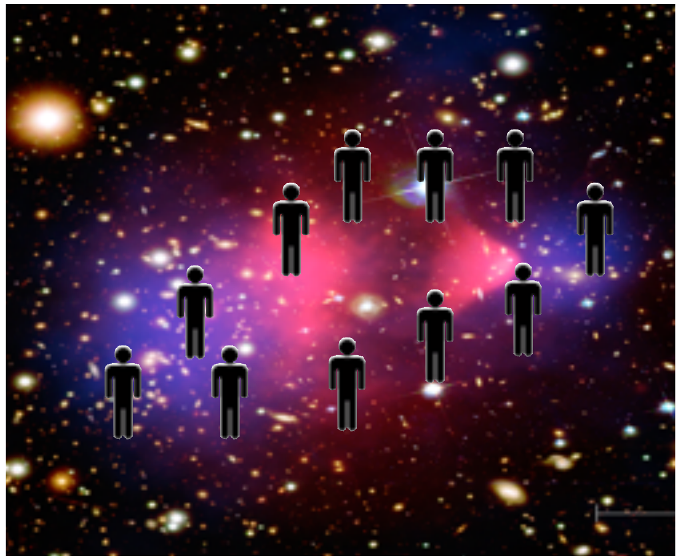
News from the Dark, Montpellier, 20th.-22nd. May 2019

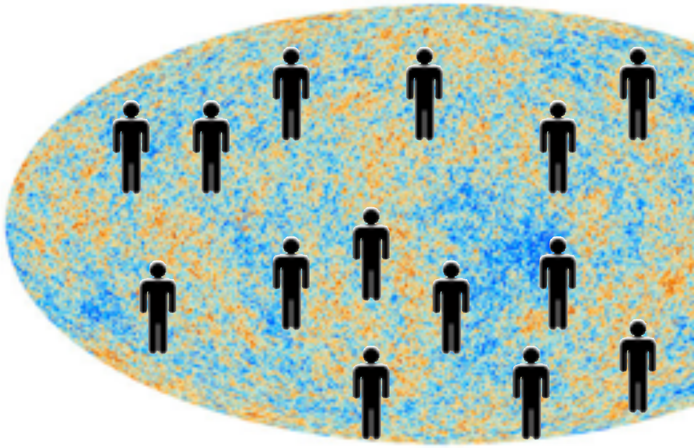
Dark Matter

is made of very strange guys. They

- dont’ interact with normal guys, except gravitationally
- don’t emit light
- move slowly
- don’t interact with themselves, or only slighly (core-cusp)
- are born in the early Universe
- don’t like to live with normal guys in overcrowded flats (dwarf sph.)
- In total, they weight five times normal guys, $\Omega_{DM} = 5.5\ \Omega_b$
- When they form structures, the expansion of the Universe accelerates (Dark Energy)







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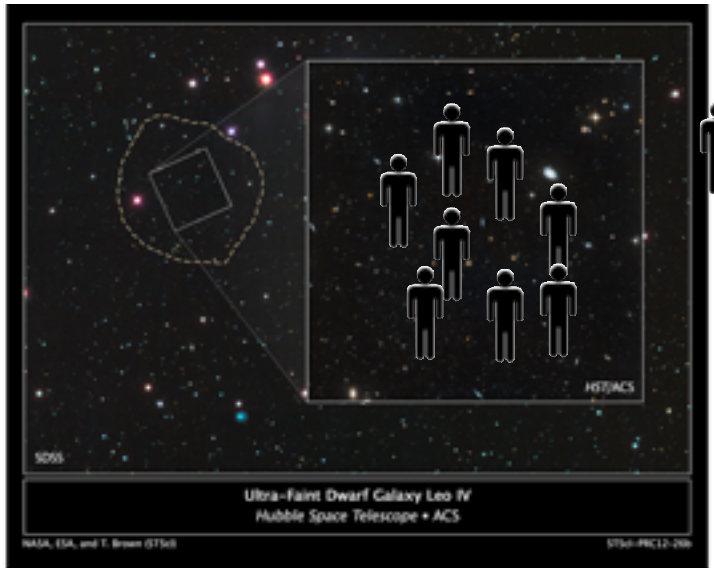

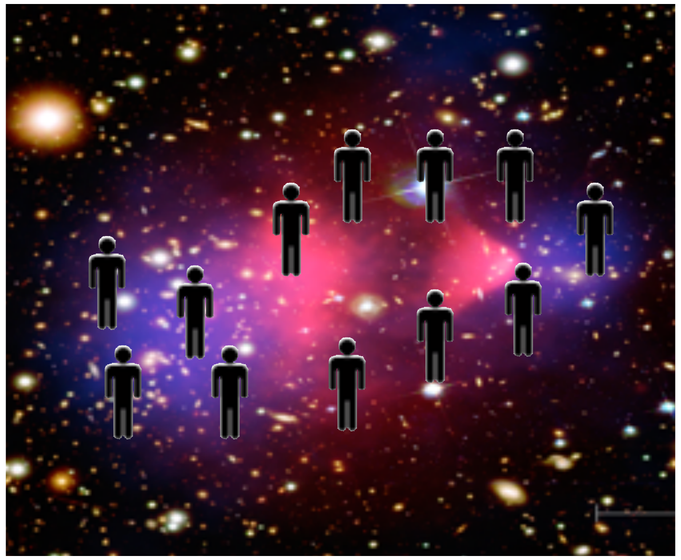

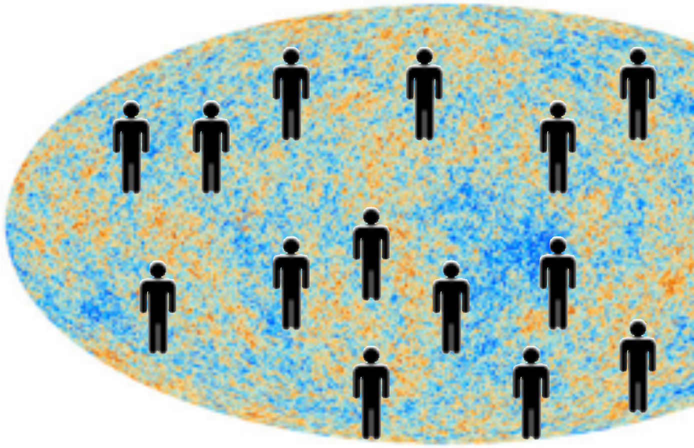

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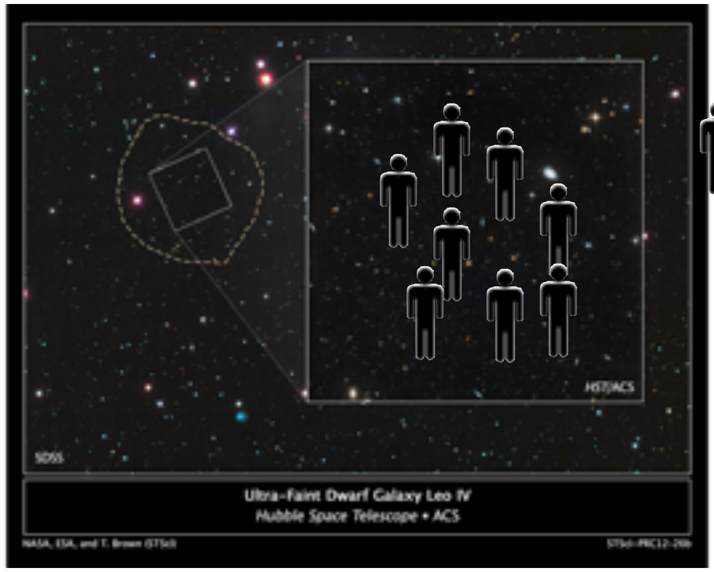

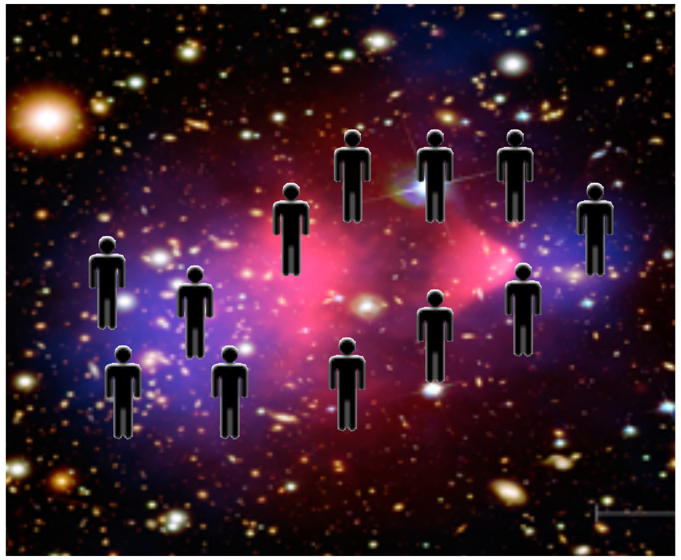

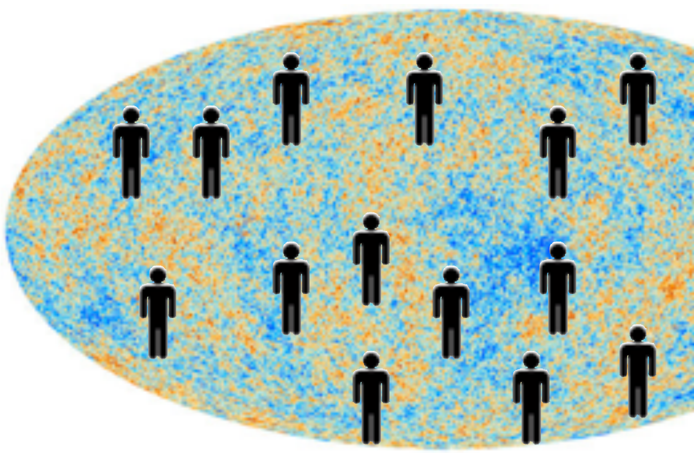

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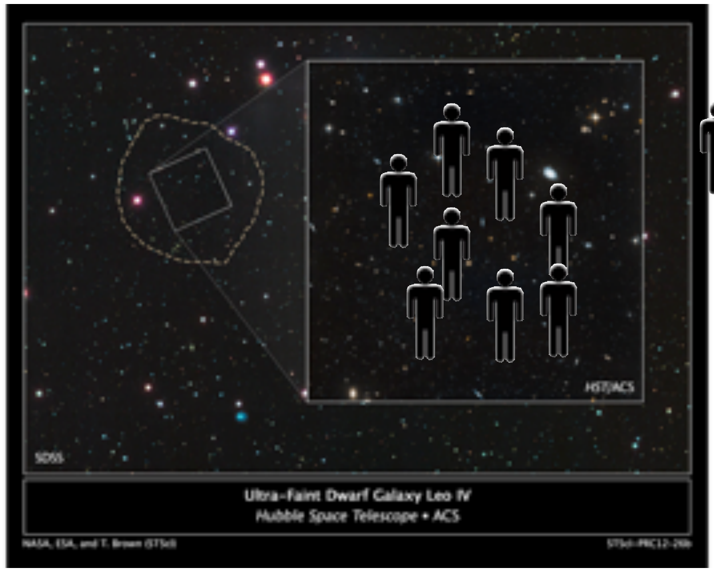


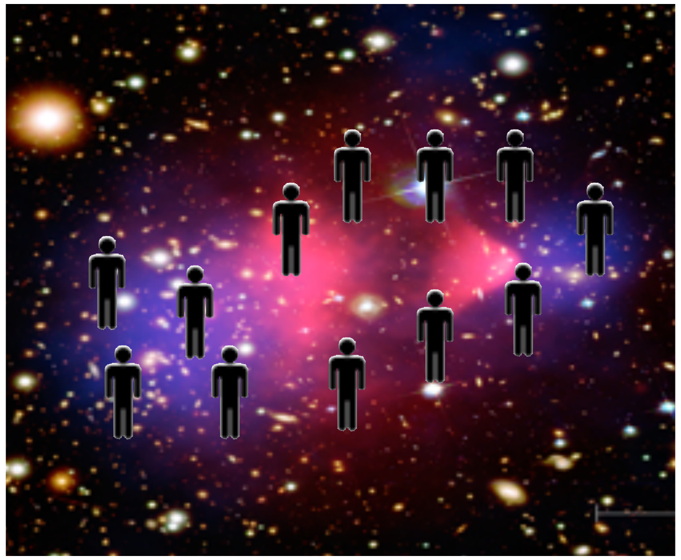
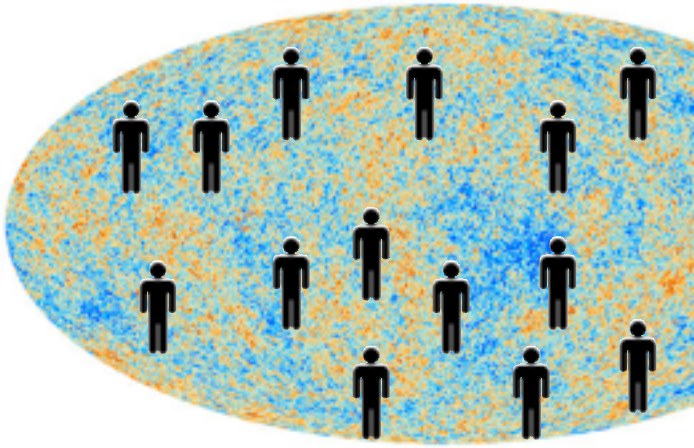

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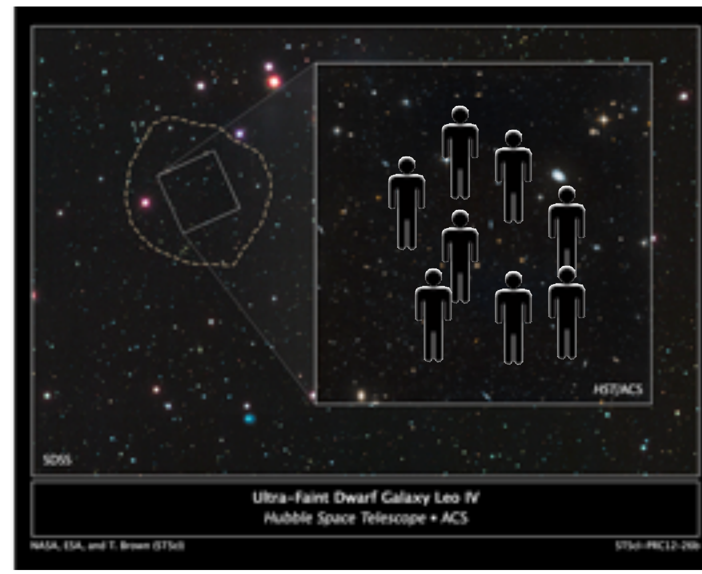


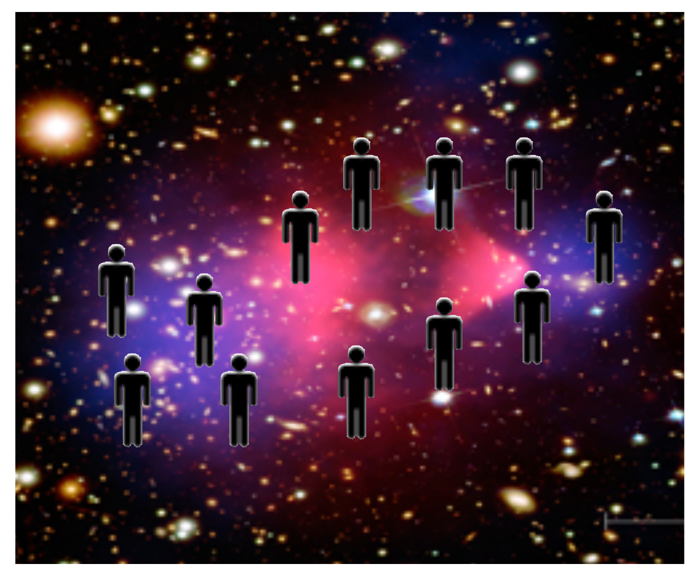
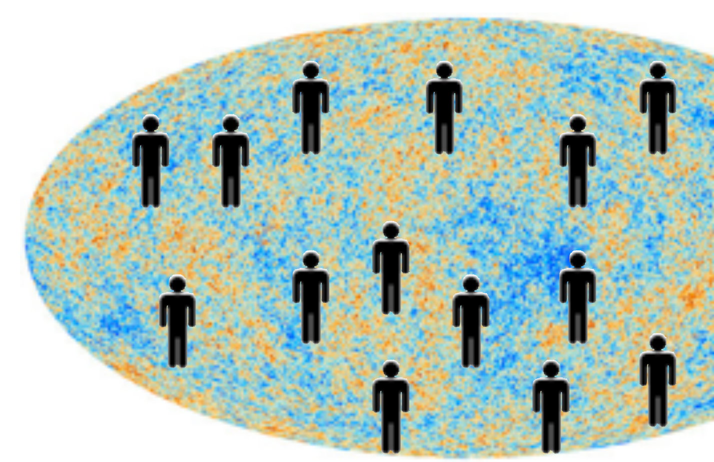

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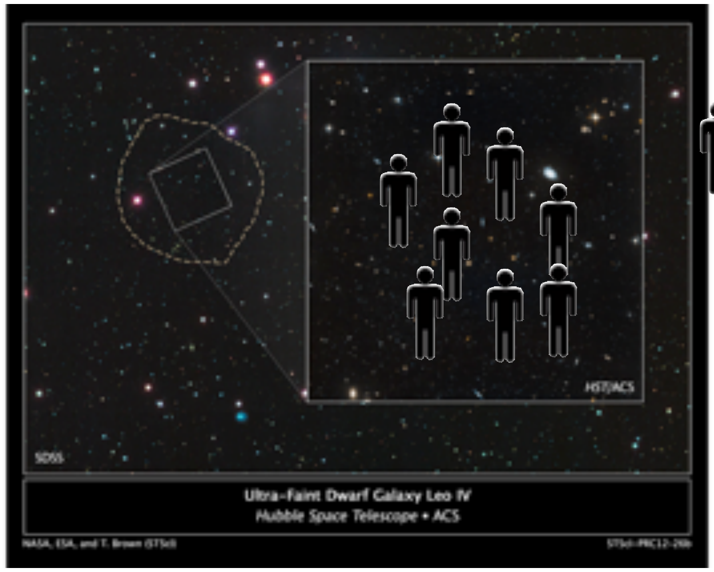

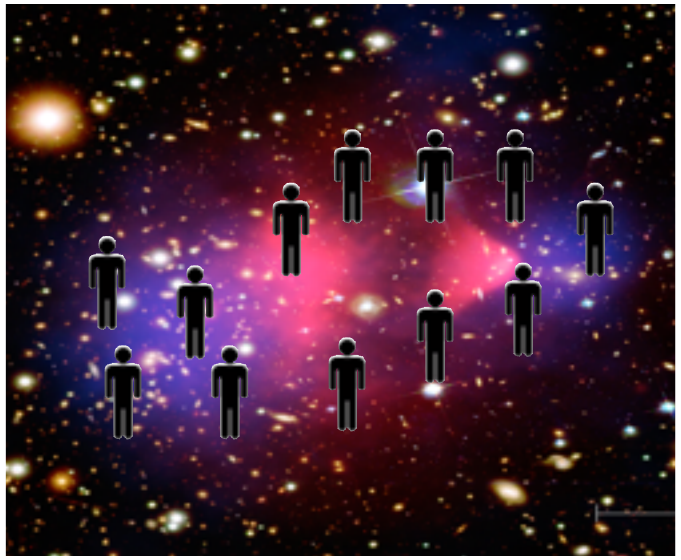

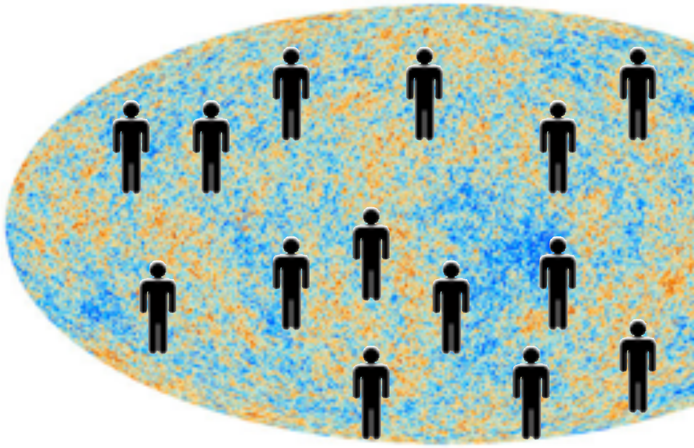

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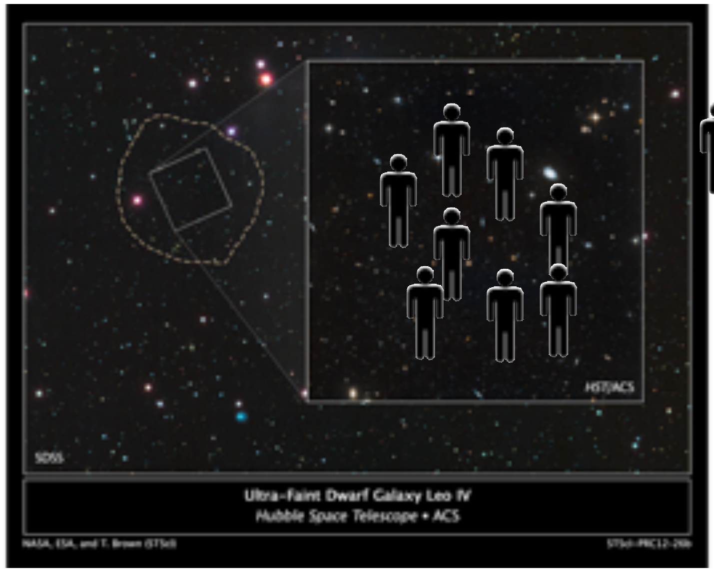

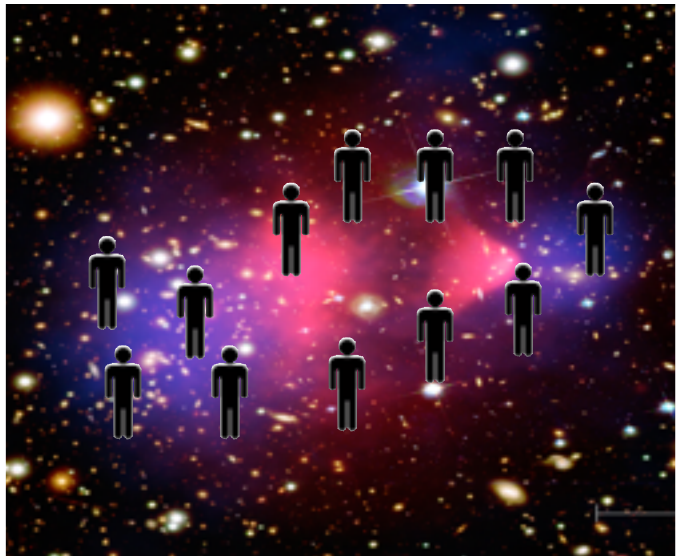

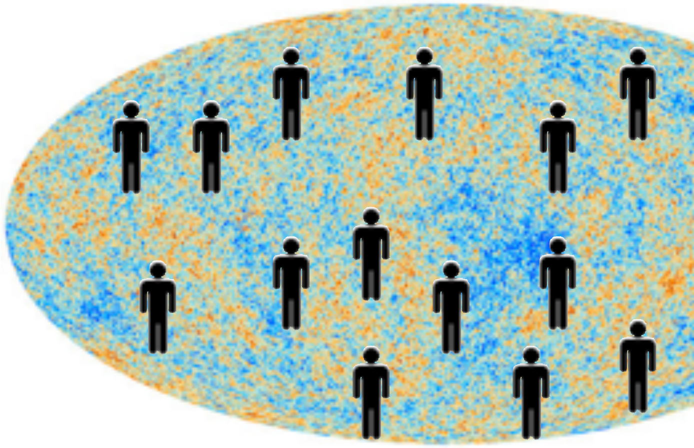

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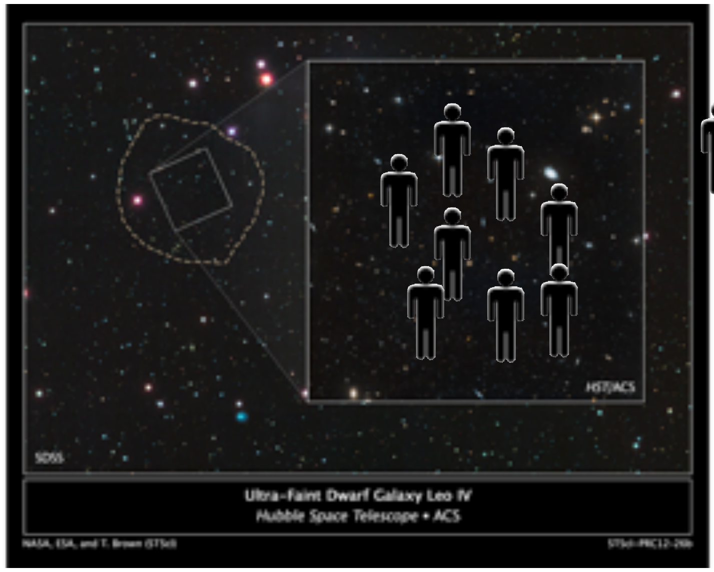

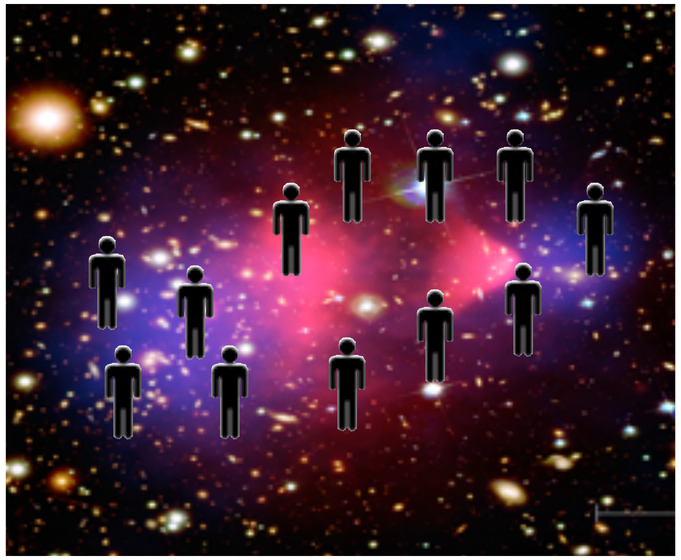

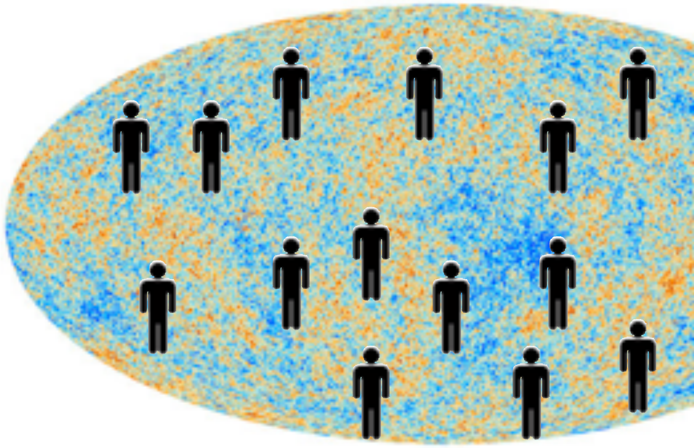

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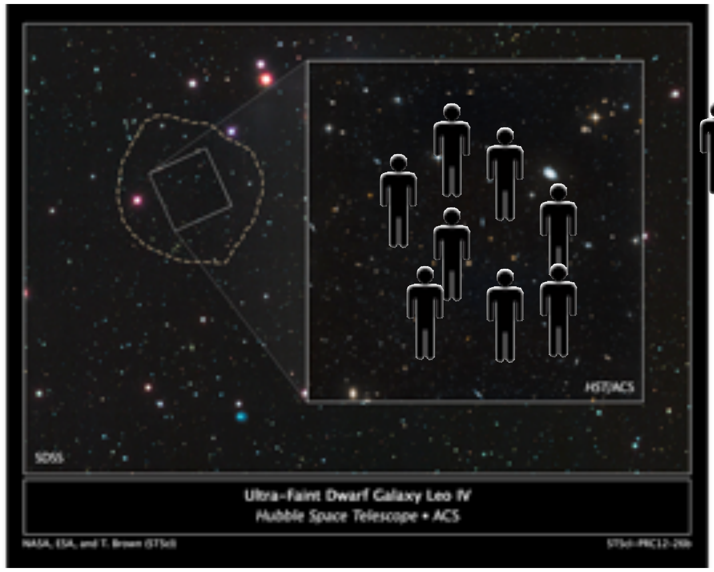

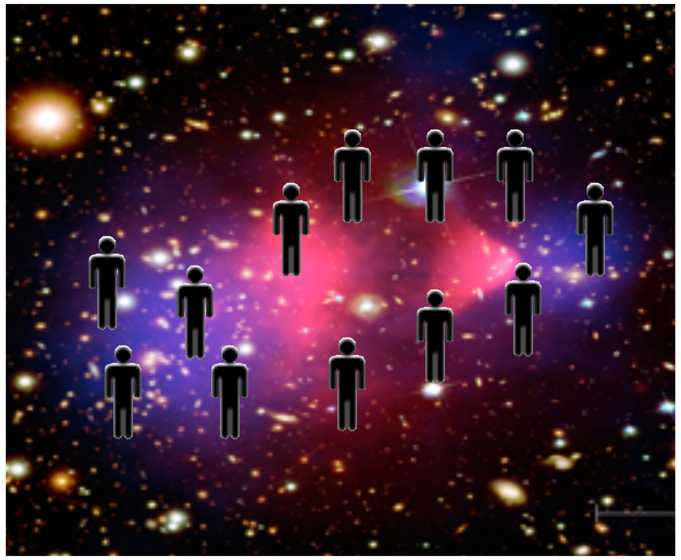

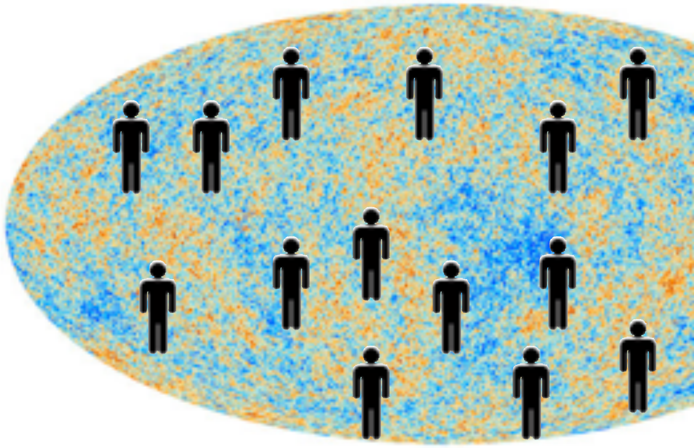

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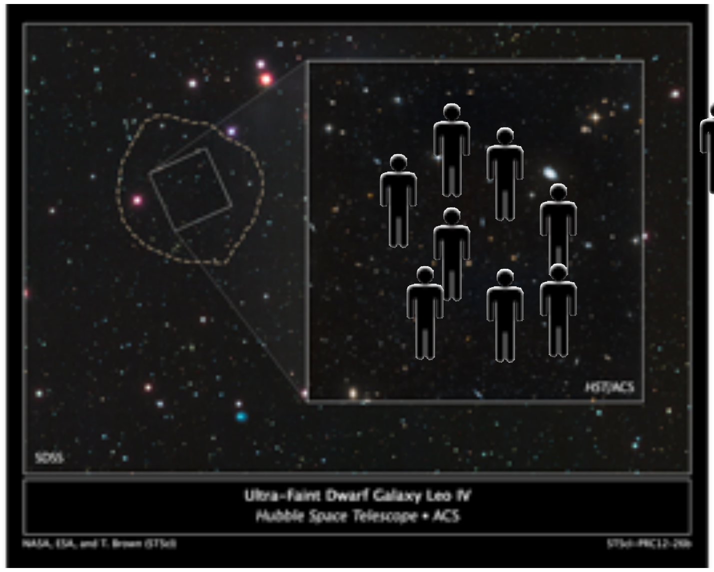
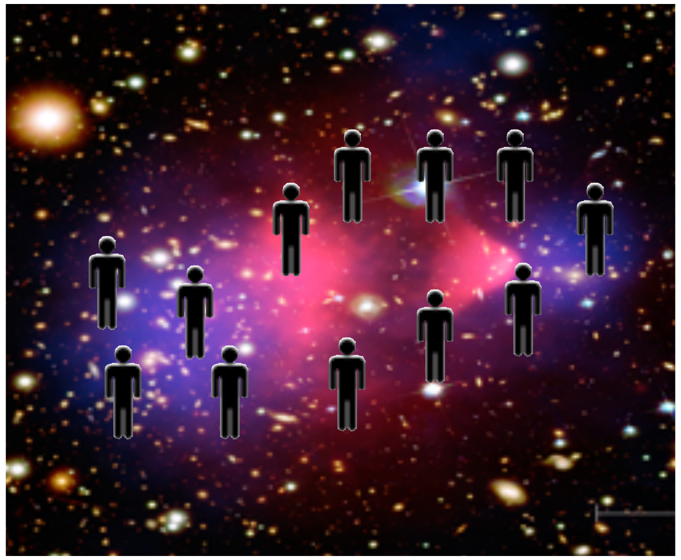
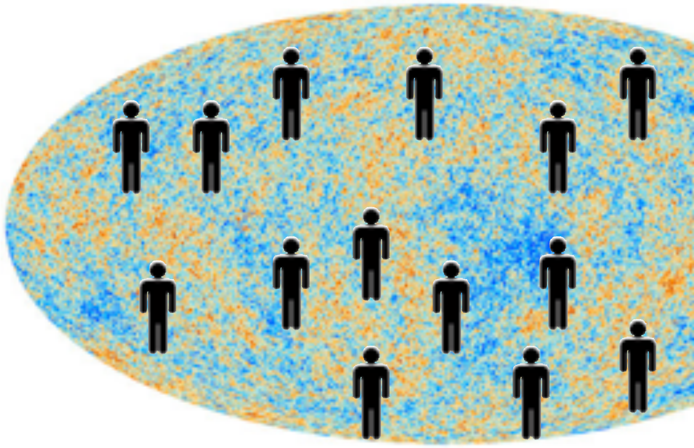
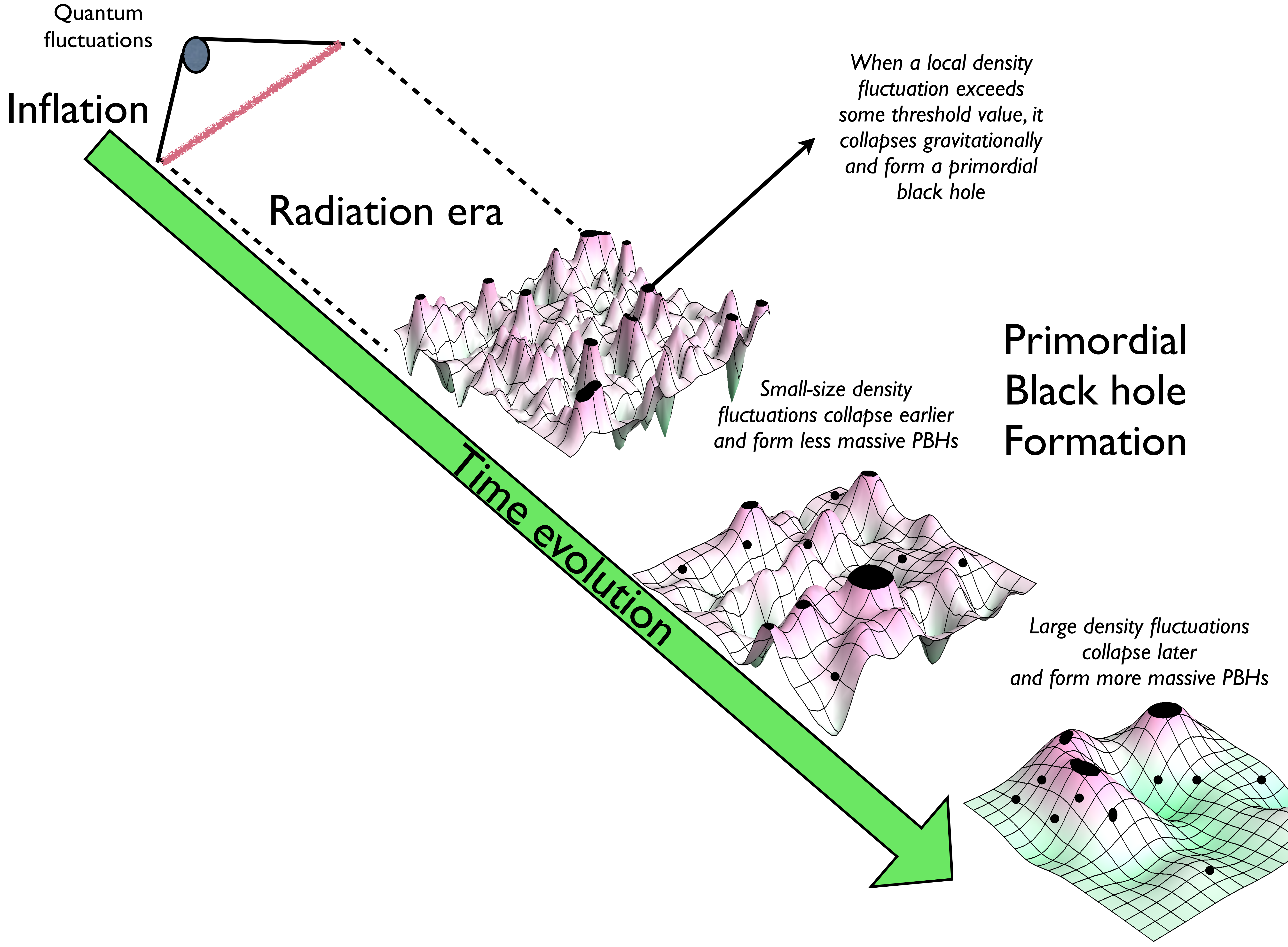


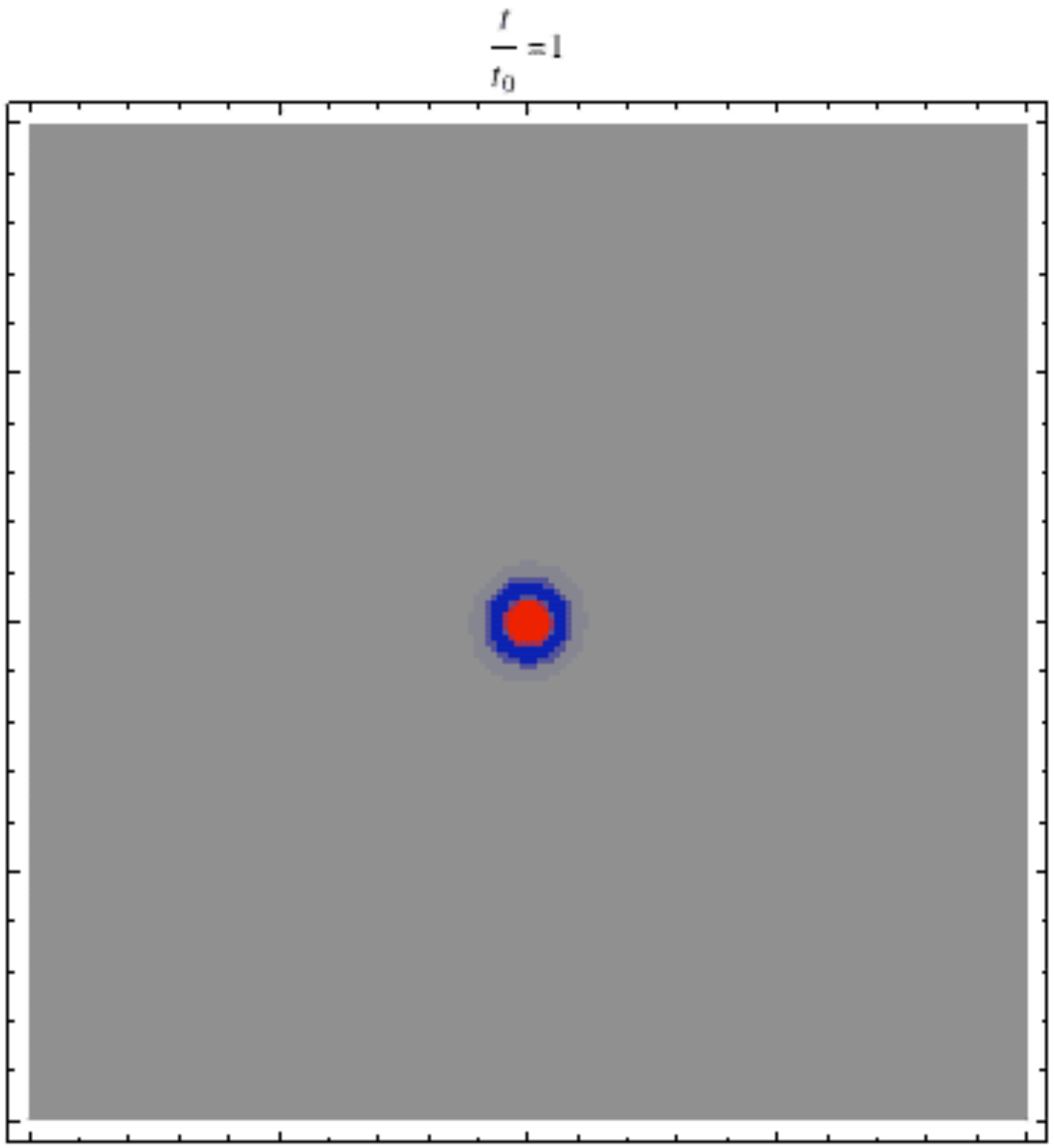


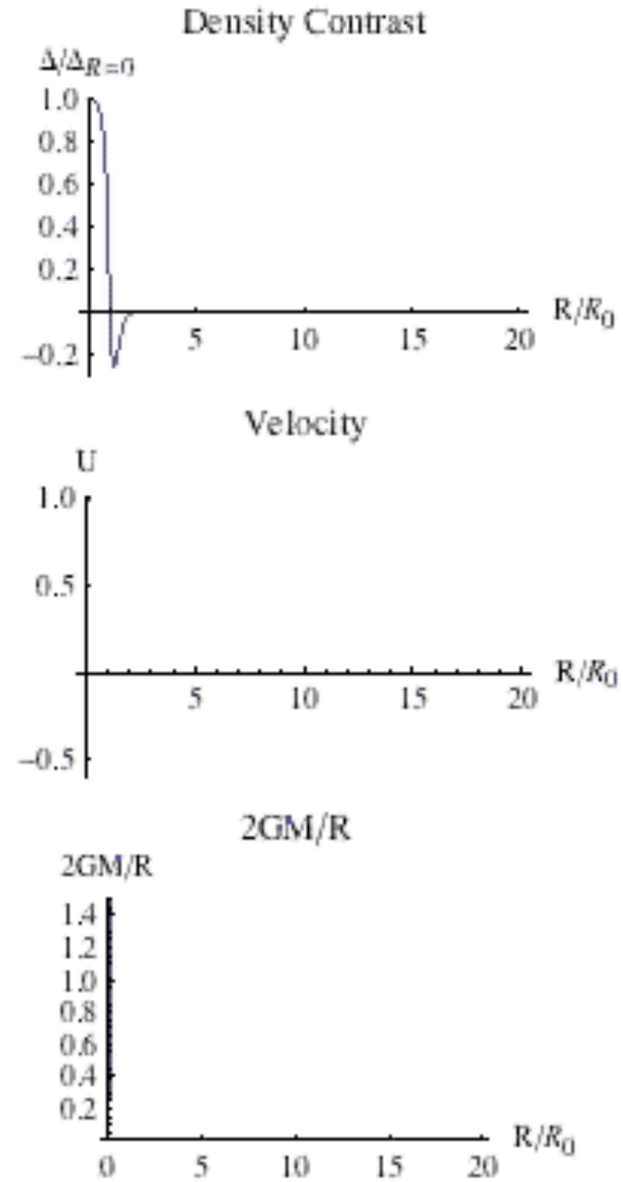


Fine-tuning problem?
Do they pass astro/cosmo constraints?


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

Credit: Ilia Musco and Samuel Young





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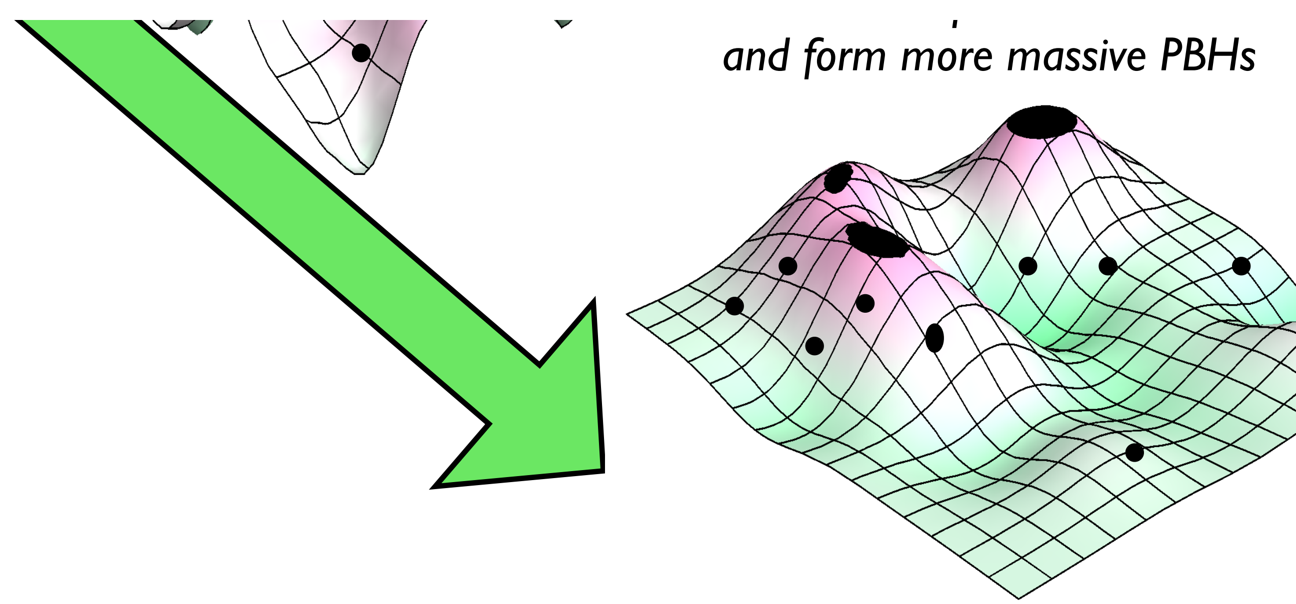

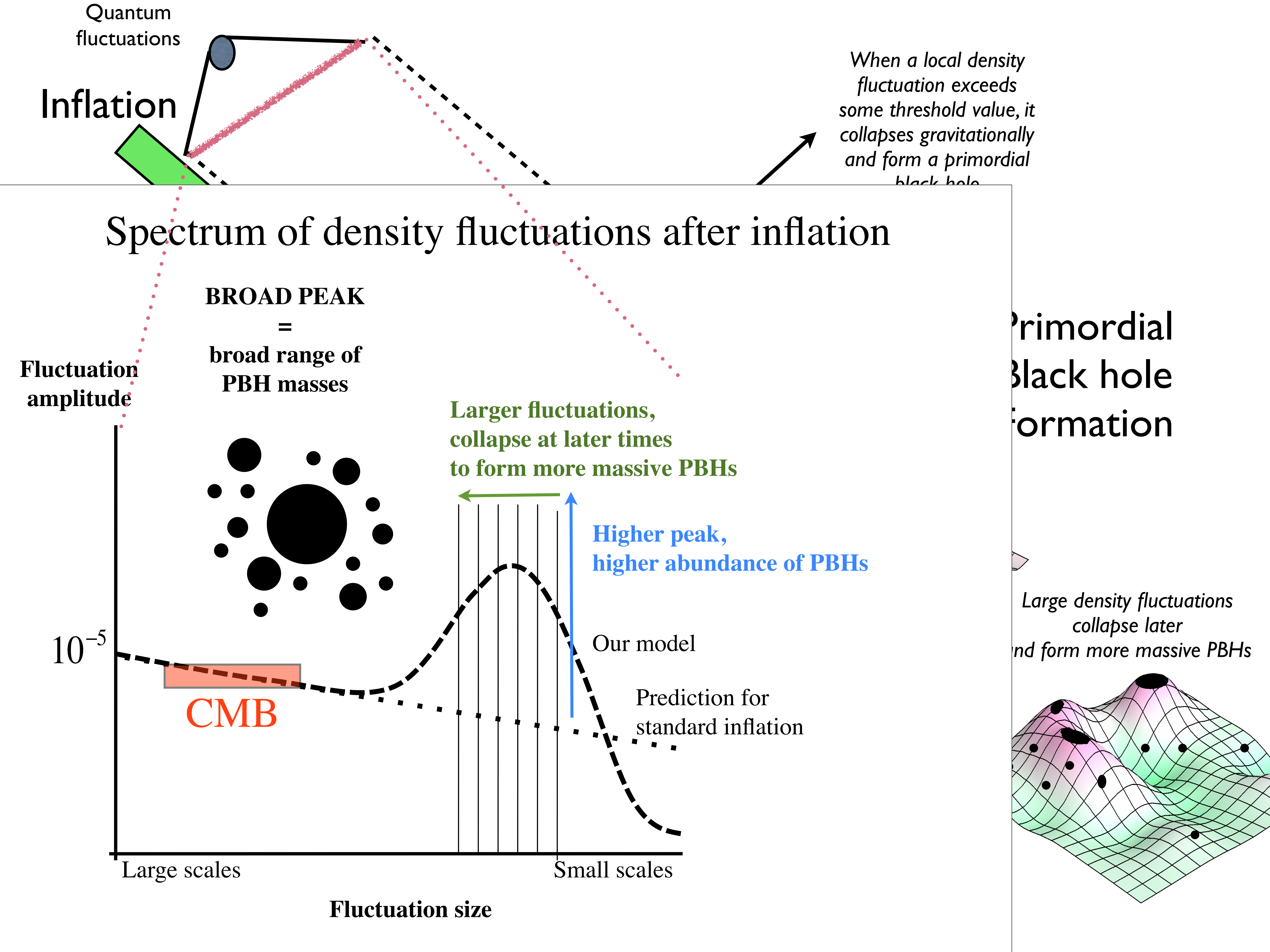
Quantum fluctuations
Inflation
When a local density fluctuation exceeds some threshold value, it collapses gravitationally and form a primordial
Spectrum of density fluctuations after inflation
BROAD PEAK = broad range of PBH masses
Fluctuation amplitude
Larger fluctuations, collapse at later times to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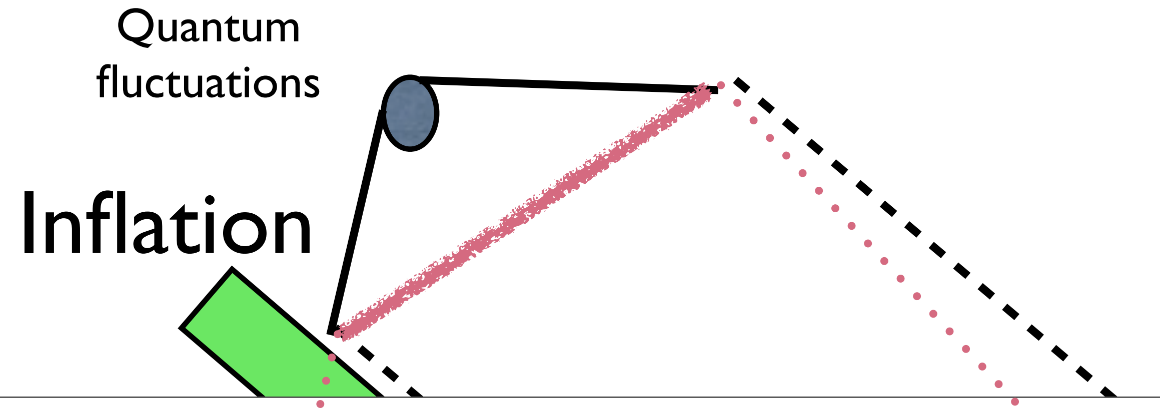

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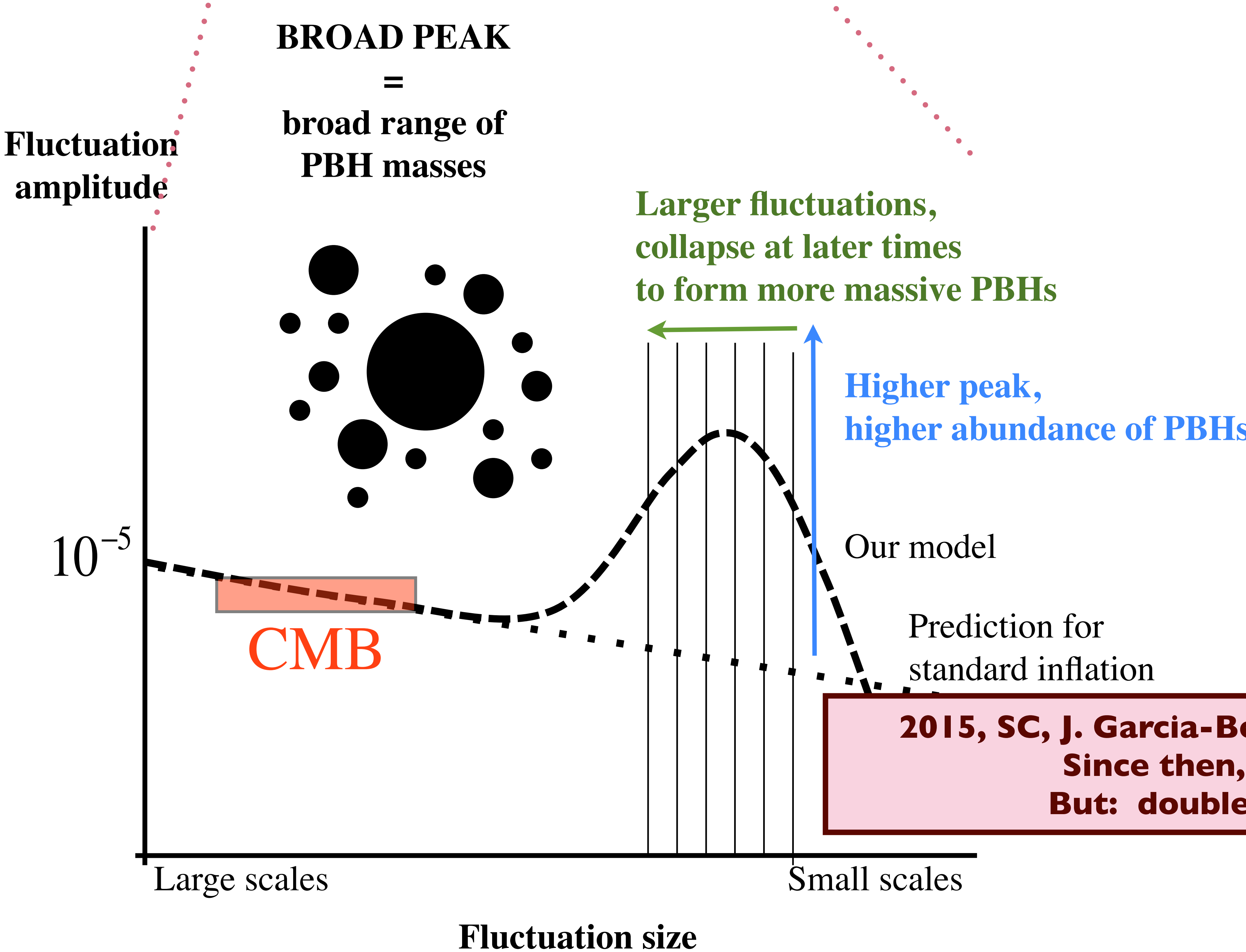

rimordial
lack hole
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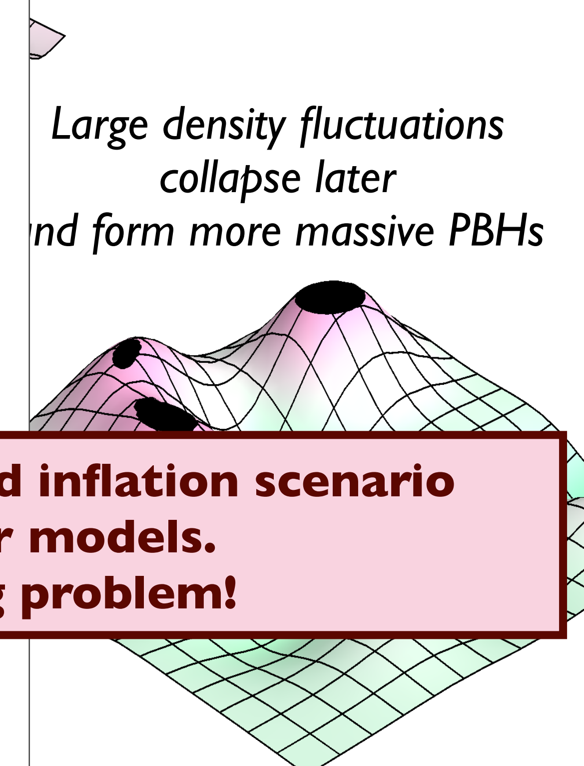
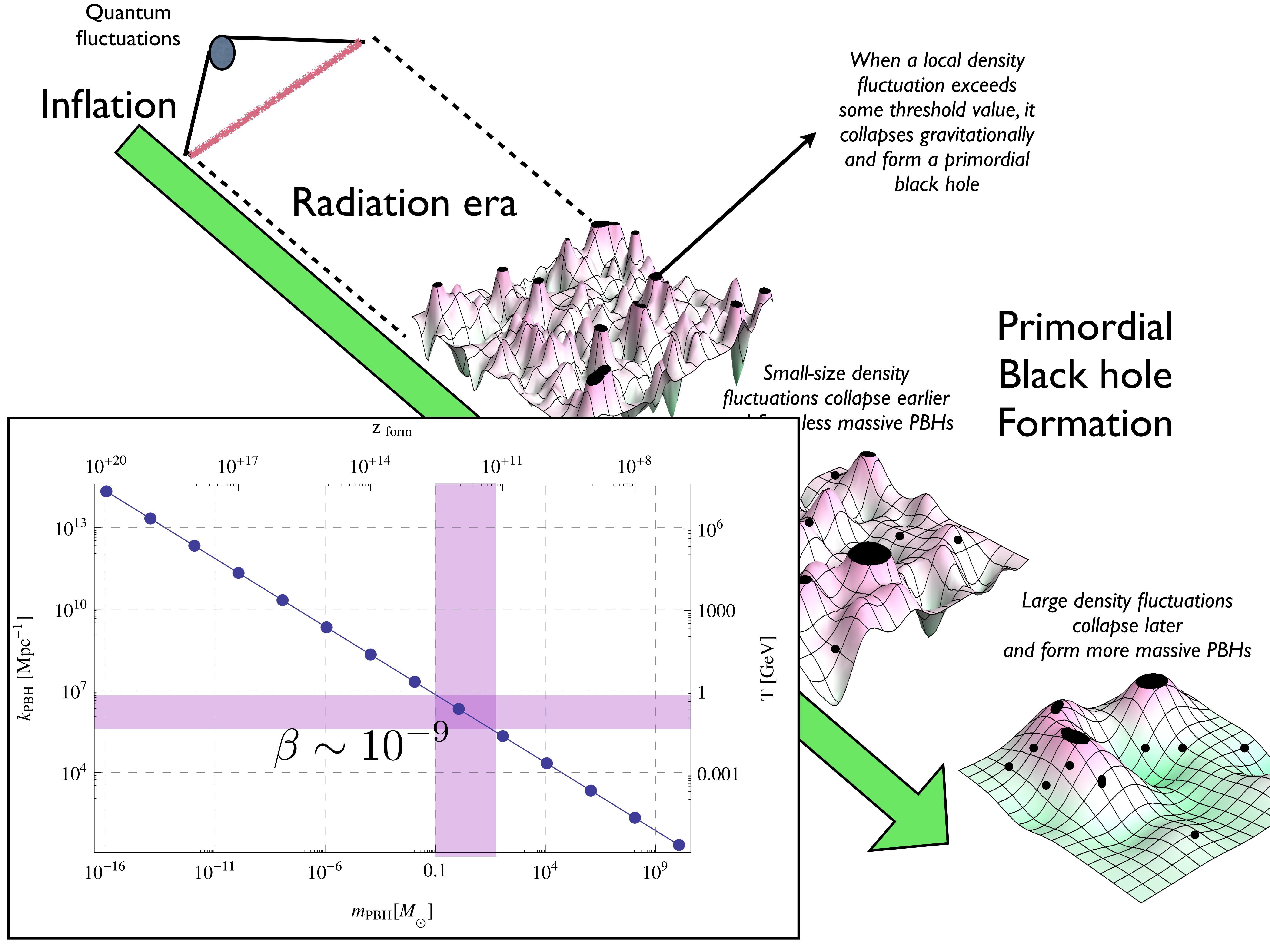


Large density fluctuations collapse later
nd form more massive PBHs

2015, SC, J. Garcia-Bellido: hybrid inflation scenario
Since then, many other models.
But: double fine-tuning problem!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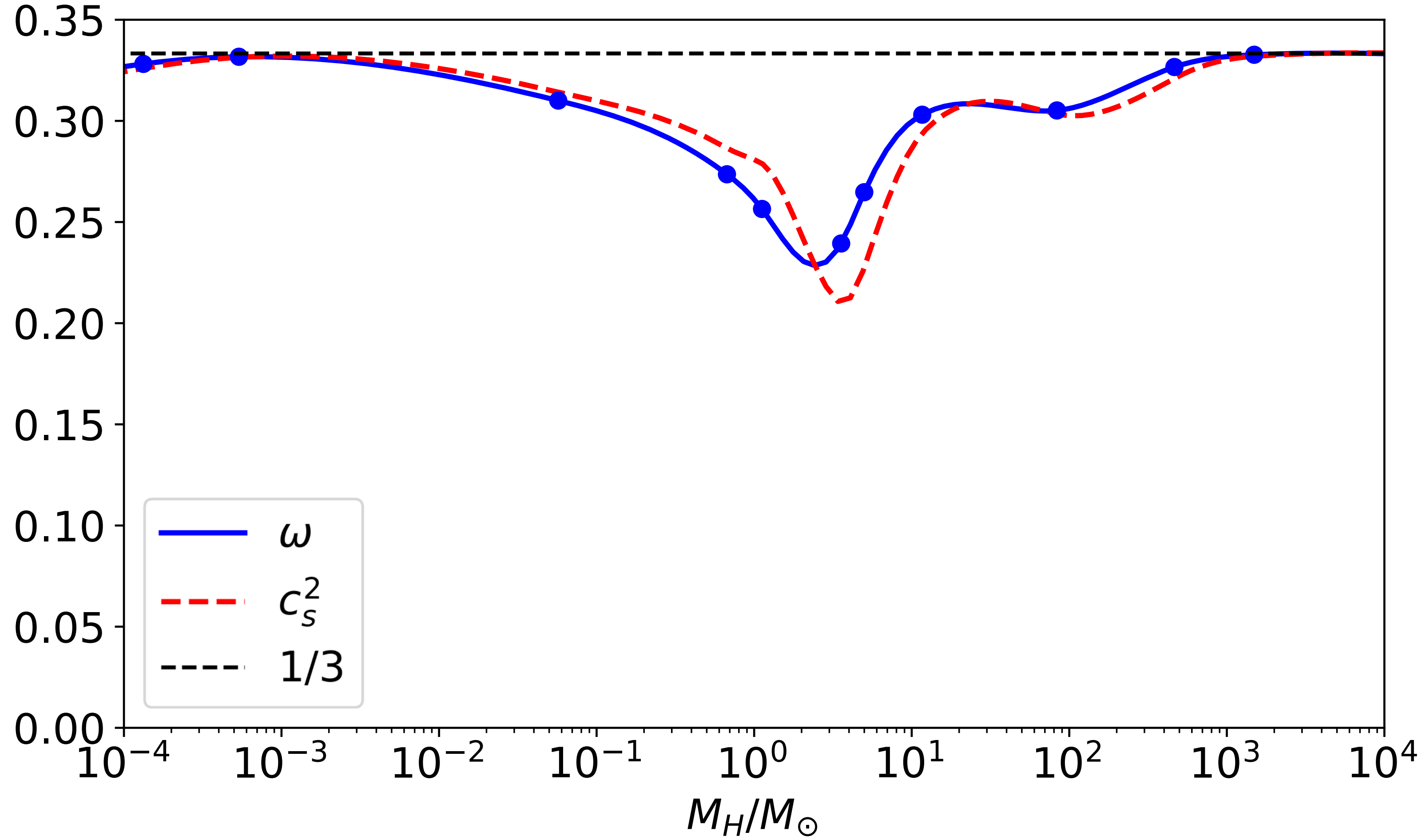
z form
10+20
10+17
10+14
10+11
10+8
10^13
10^10
10^7
10^4
10^6
1000
1
0.001
k_PBH [Mpc^-1]
T [GeV]
β ~ 10^-9
10^-16
10^-11
10^-6
0.1
10^4
10^9
m_PBH[M_⊙]

PBH formation at QCD phase transition

- Sound speed/equation of state reduction during QCD (cross-over) transition
- Boosted PBH formation in the range 0.1-5 msun (assuming a nearly flat power spectrum)
- Second peak at 5-30 Msun



K. Jedamzik, astro-ph/9605152
Cardal & Fuller, astro-ph/9801103
Byrnes et al., 1801.06138
Carr, SC, Garcia-Bellido, Kuhnel, in preparation

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- Sound speed/equation of state reduction during QCD (cross-over) transition
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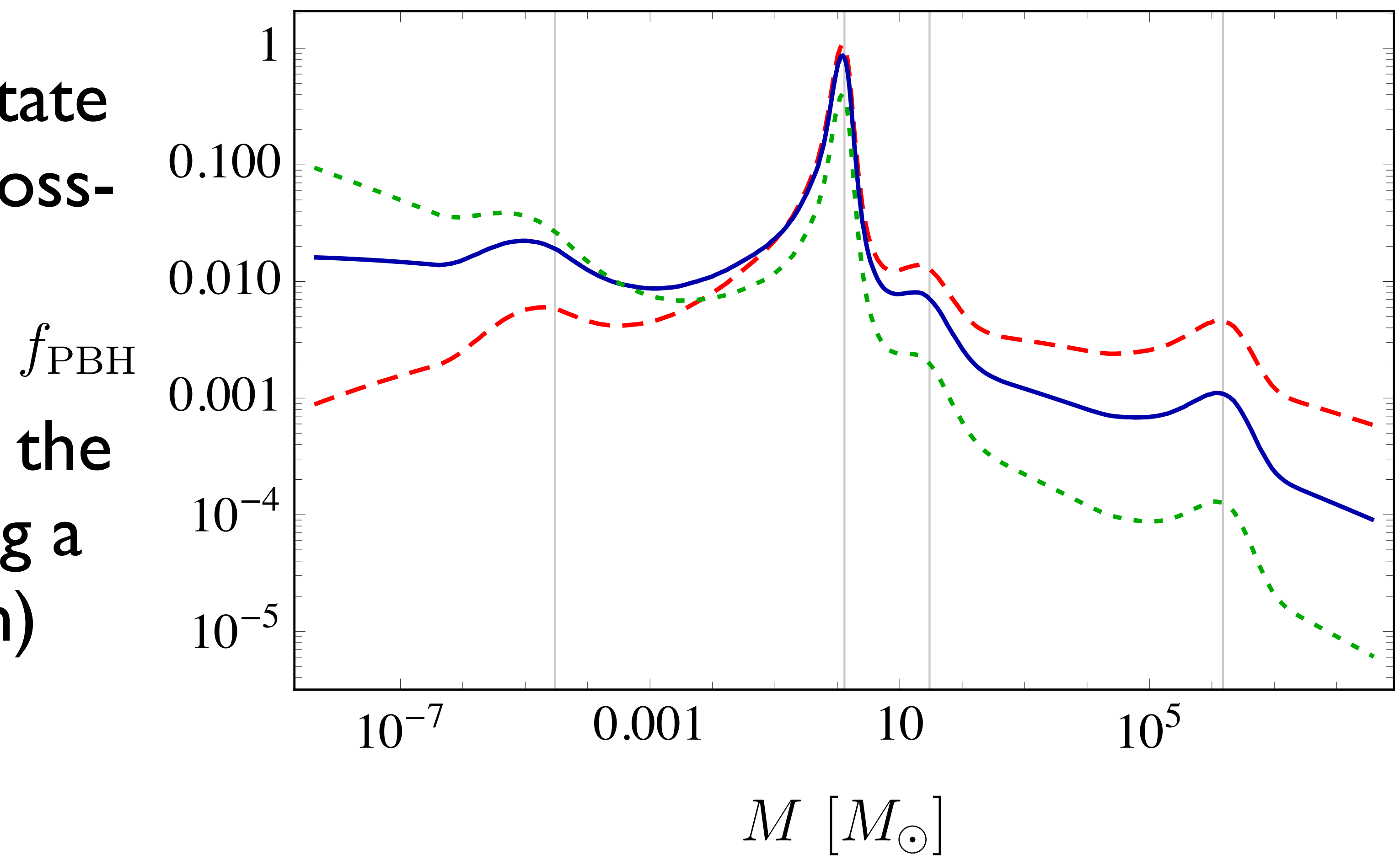
- Second peak at 5-30 Msun
- nearly scale-invariant spectrum with n_s = 0.97 works fine



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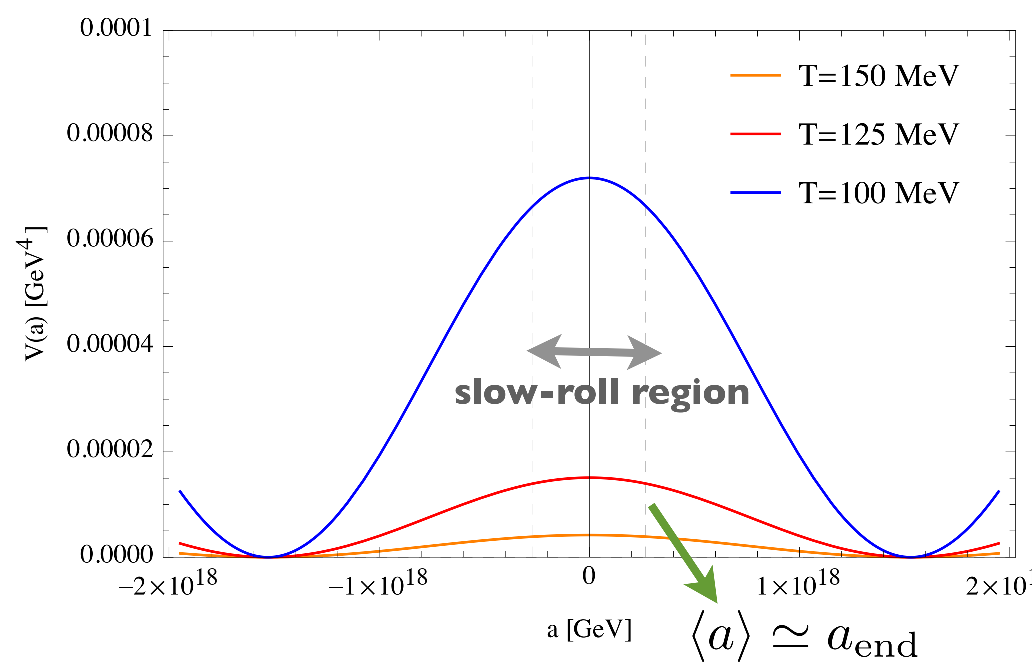
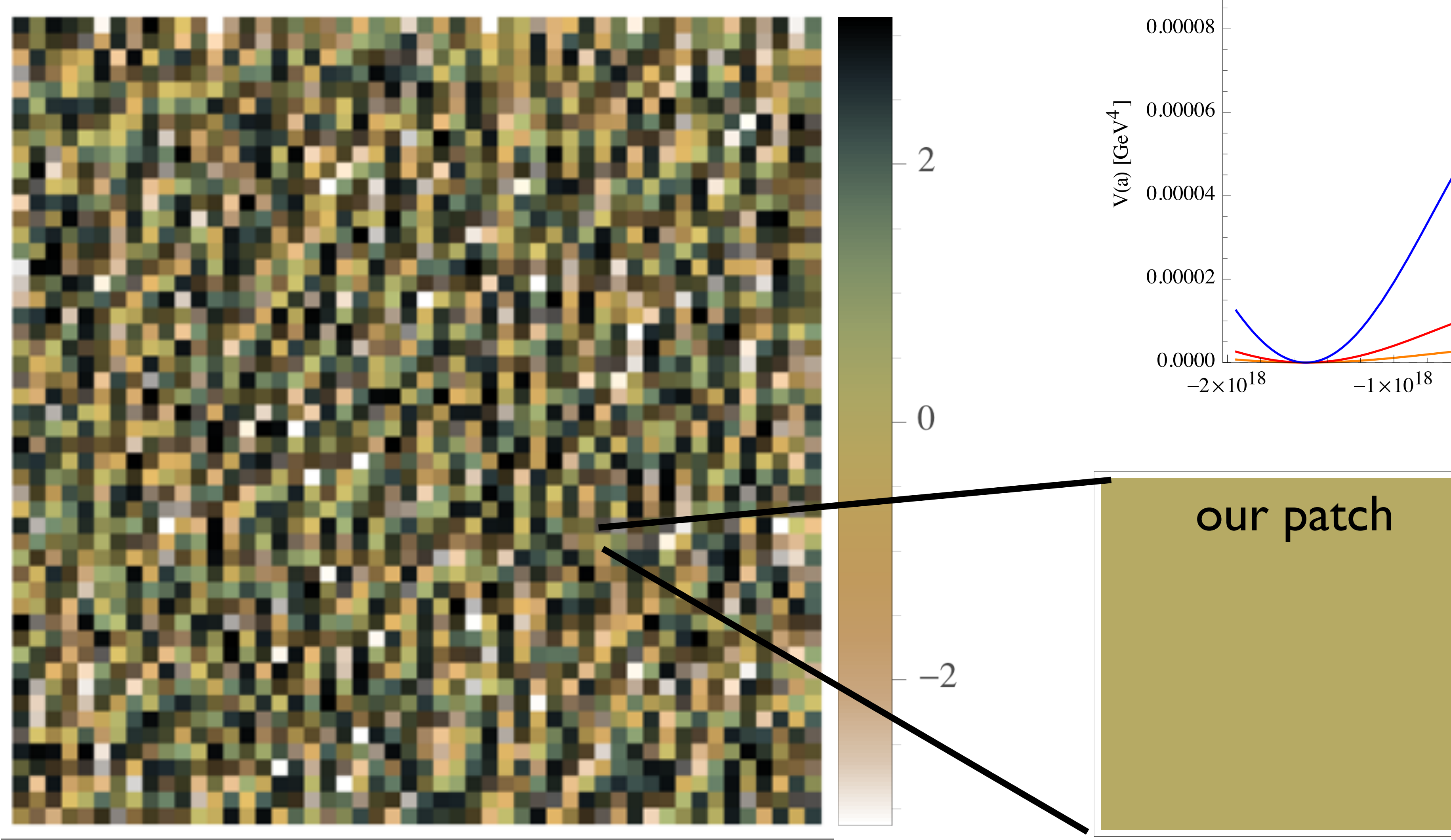
Let's take a light spectator field during inflation (like the QCD axion)...

Stochastic quantum fluctuations $\Delta a_{\rm qu} \simeq H_{\rm inf}/2\pi$ dominate over the classical dynamics and do not affect the expansion.

N>60 e-folds before the end of inflation: **Coarse-grained multiverse**





$\langle a \rangle \simeq a_{\rm end}$

...and see how this field evolves in our Universe patch during inflation

$a(x) - \langle a \rangle$

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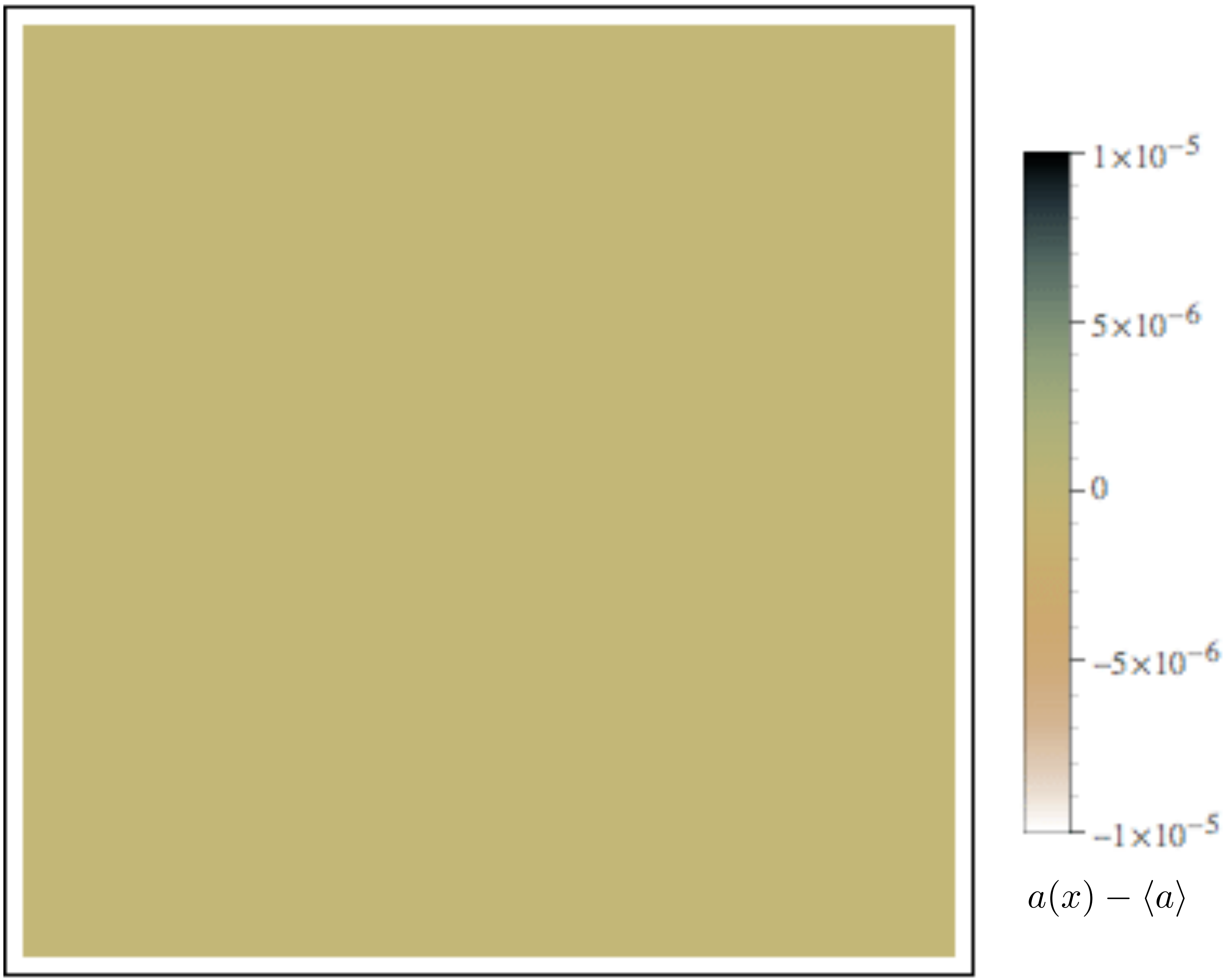

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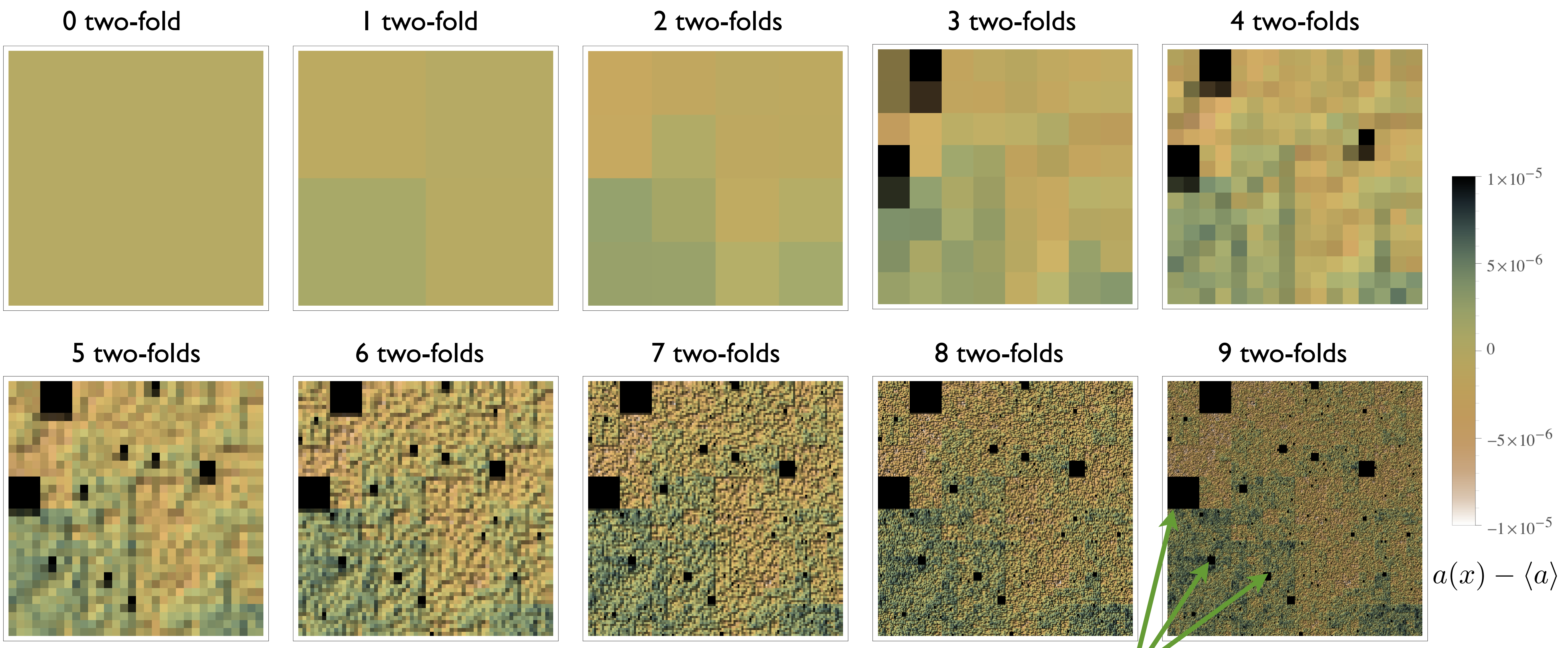


These regions will generate curvature fluctuation <u>after inflation</u> and form PBH with different masses

Stochastic spectator landscape after inflation....

slow-roll
$\delta N \sim 1$

$\delta N \sim 1$

Fast roll,
$\delta N \sim 0$
no additional curvature fluctaution

$\delta N \sim 1$

$\delta N \sim 1$

Super-horizon fluctuation of the stochastic spectator above threashold

slow-roll
$\delta N \sim 1$

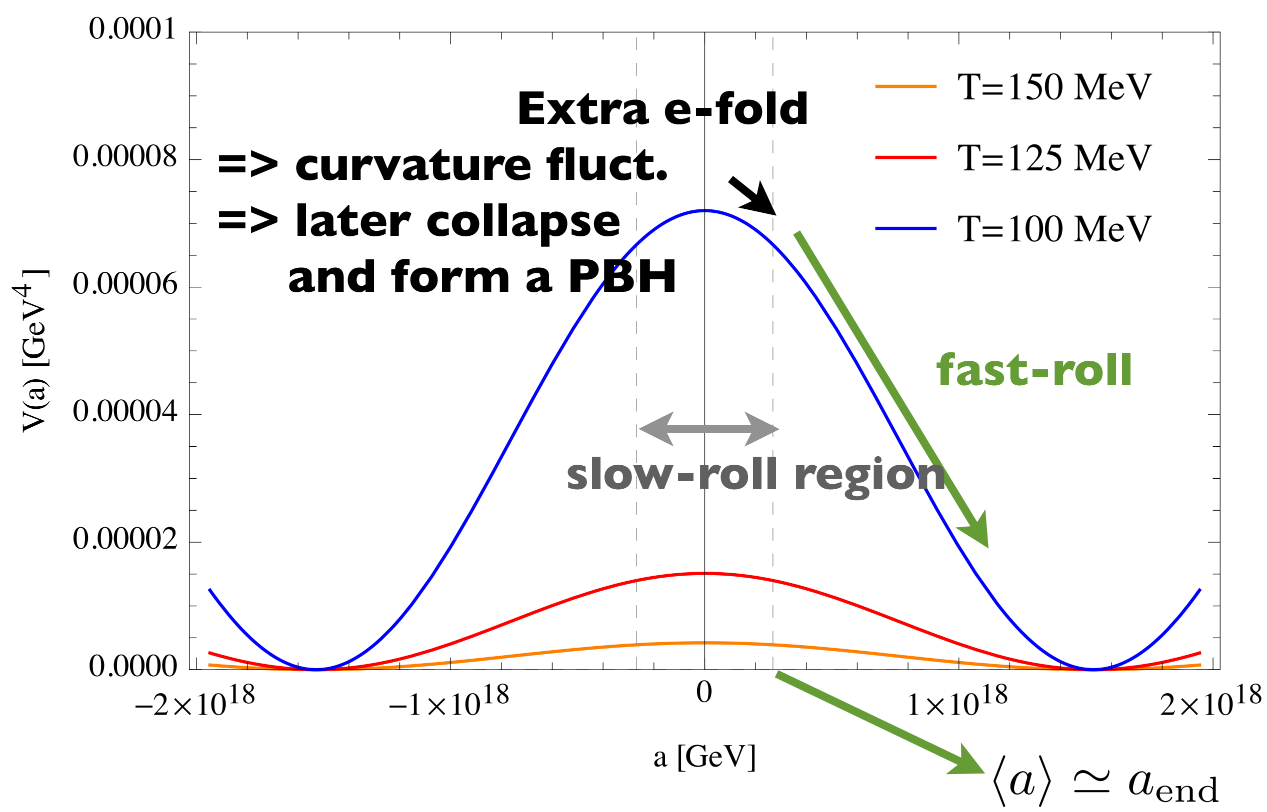
slow-roll
$\delta N \sim 1$

$\delta N \sim 1$

These regions will collapse and form PBHs of different masses

$\delta N \sim 1$

During radiation era, <u>when field density dominates</u>:



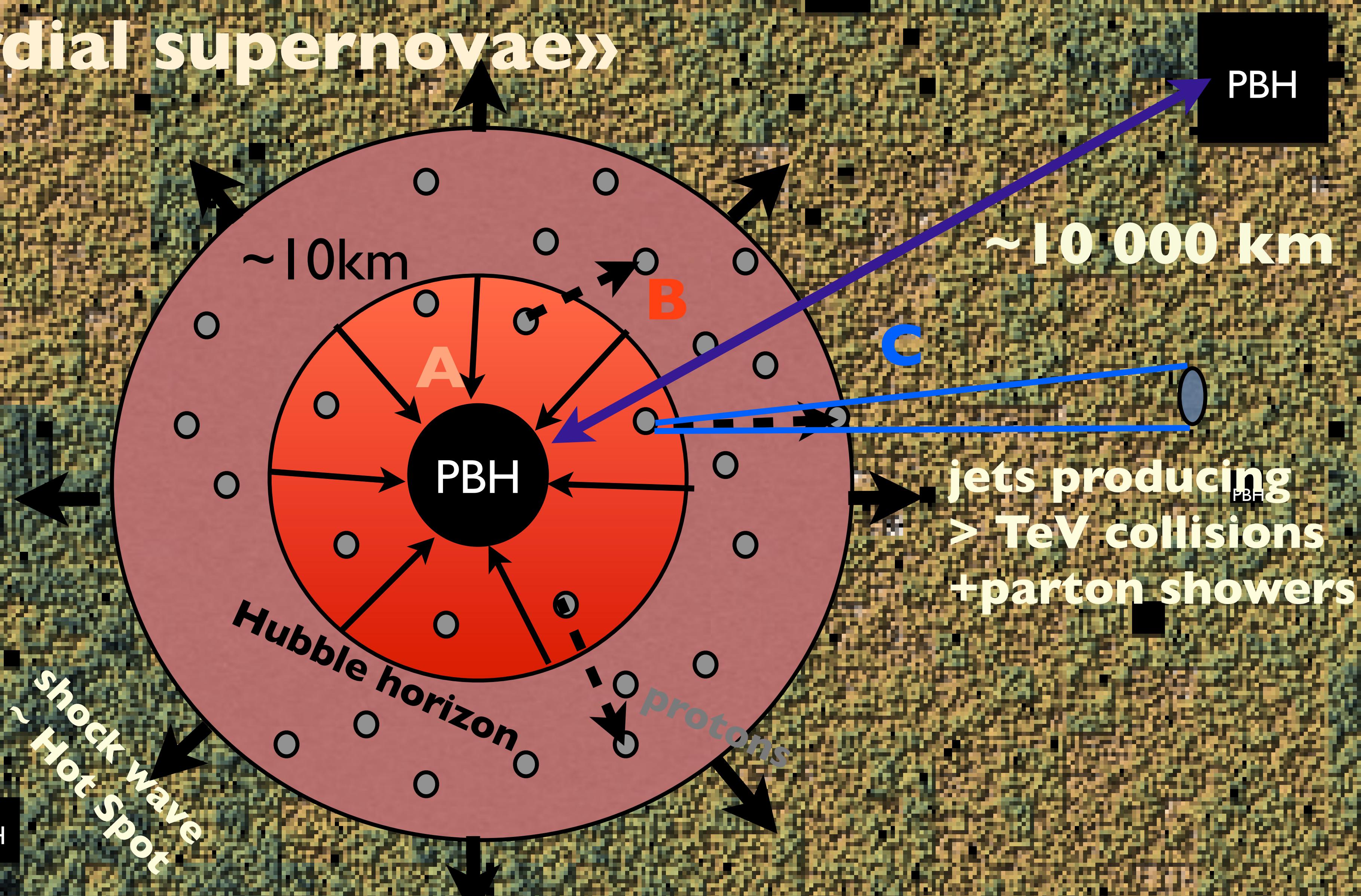
At horizon re-entry (quark-hadron epoch) these fluctautions collapse into PBH

A. Gravitational collapse of a curvature fluctuation at horizon re-entry

B. Around collapsing regions, shock waves lead to Hot-Spot EW Baryogenesis with $n_b/n_\gamma > 1$

C. After radiating at speed of light, baryon asymetry $n_b/n_\gamma = 6 \times 10^{-10}$

which produces sort of «primordial supernovae»



All the (Sakharov) conditions are met for Hot-Spot Electroweak Baryogenesis around PBH!

Carr, SC, Garcia-Bellido, 1904.02129
Garcia-Bellido, Carr, SC, 1904.11482

- C and CP violation (the one in the standard model - CKM matrix)
- Baryon number violation (sphaleron transitions, from >TeV collisions)
- interactions out of thermal equilibrium (PBH collapse)

Eletroweak baryogenesis: need of exotic physics.

Hot-spot Electroweak Baryogenesis: PBH provide the ingredients and one naturally has the correct baryon-to-photon ratio if PBH are the DM

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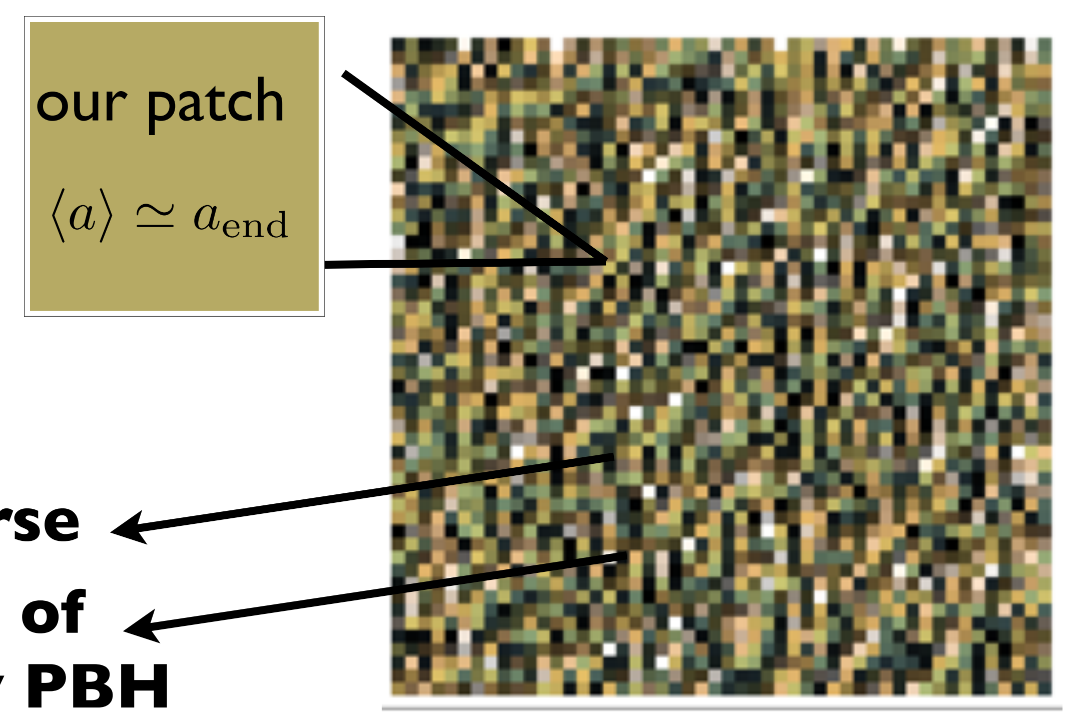
Works for any PBH-DM model!!!

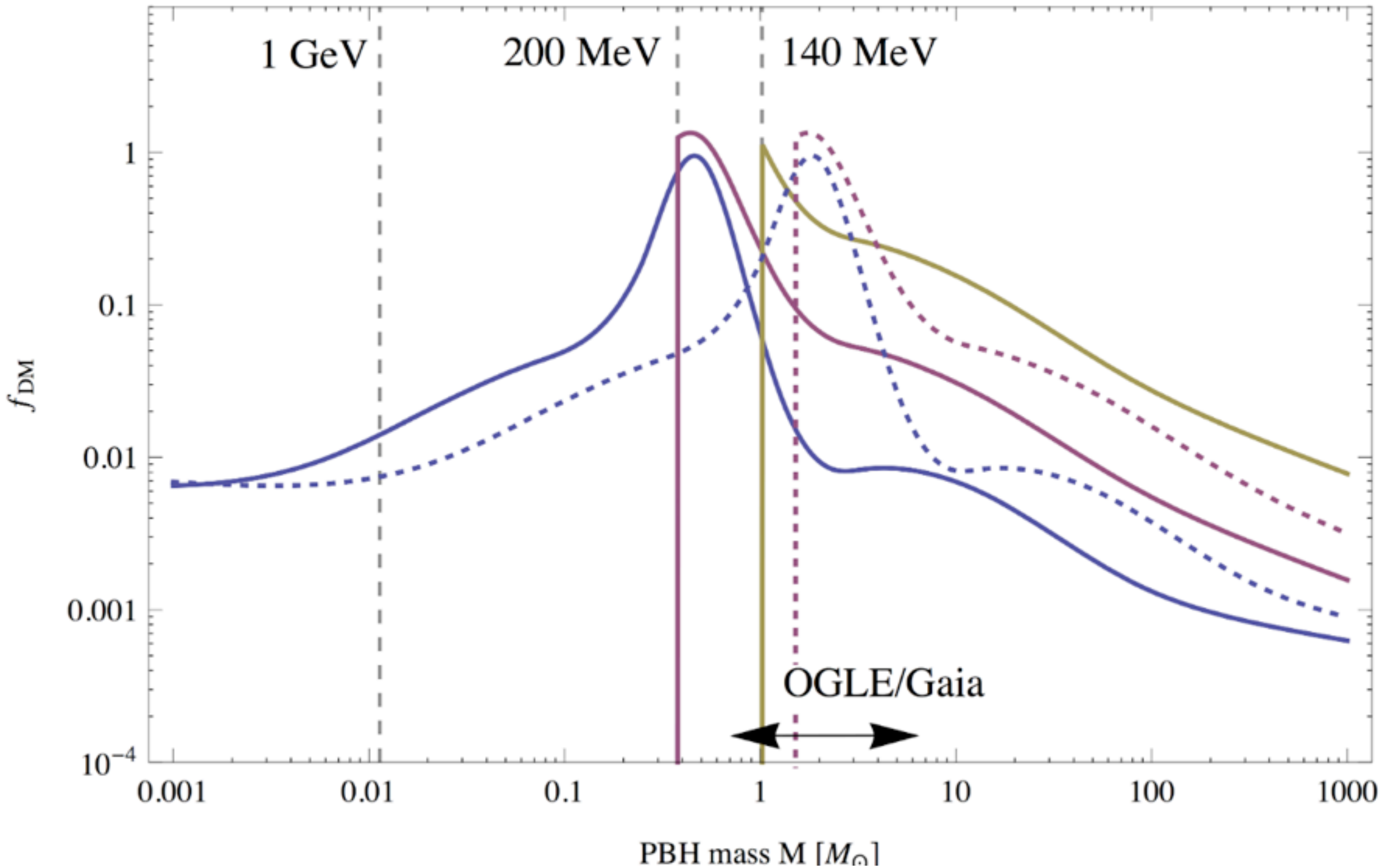
In the stochastic spectator scenario:
no parameter tuning,
but anthropic selection argument



radiation dominated Universe

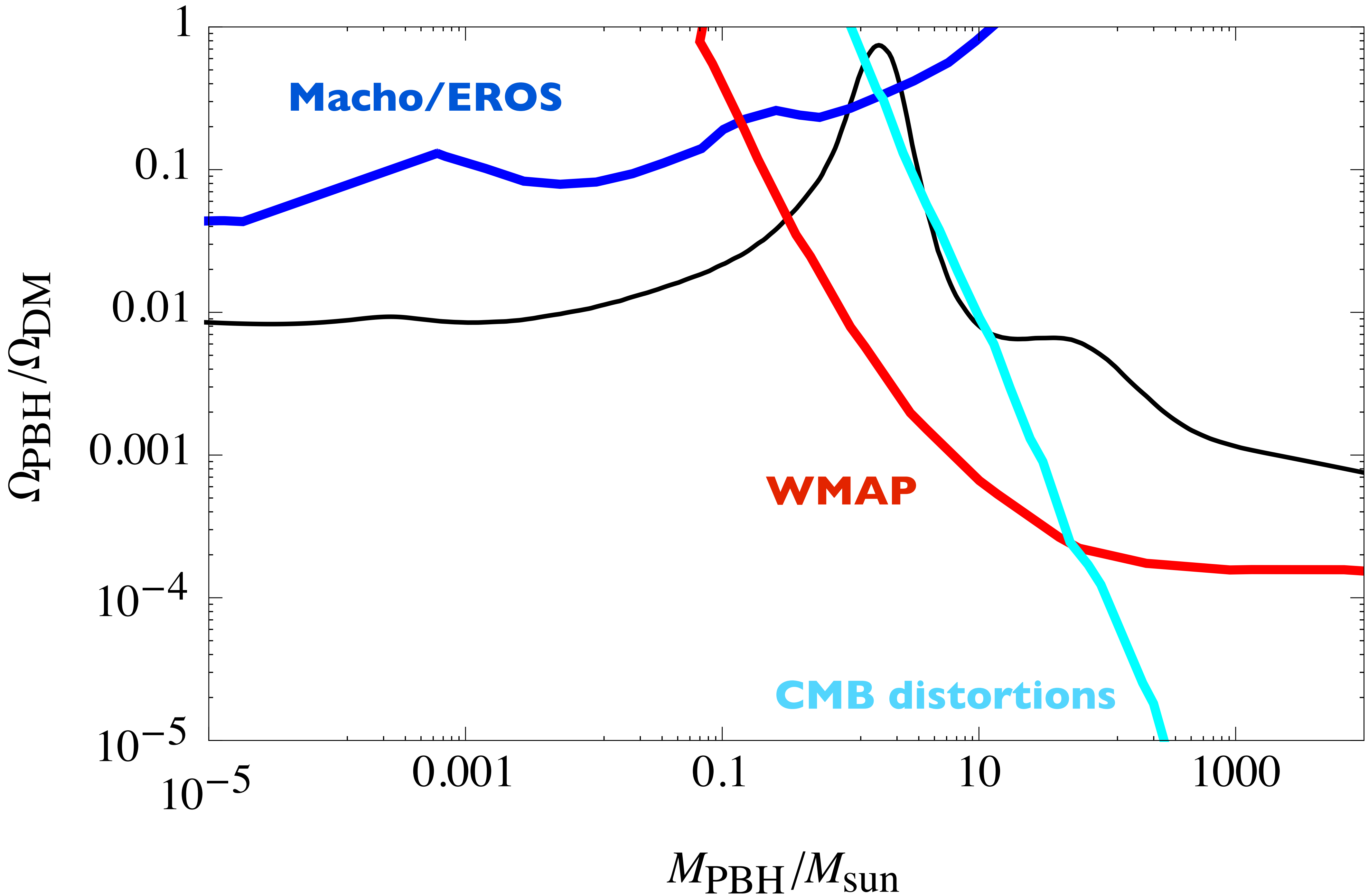
Shorter Silk damping scale, overabundance of DM subhaloes, all the baryons are accreted by PBH

And here is the expected mass function:



Does our preferred PBH model pass the current astro/cosmo limits?

Before 2016, it did not...

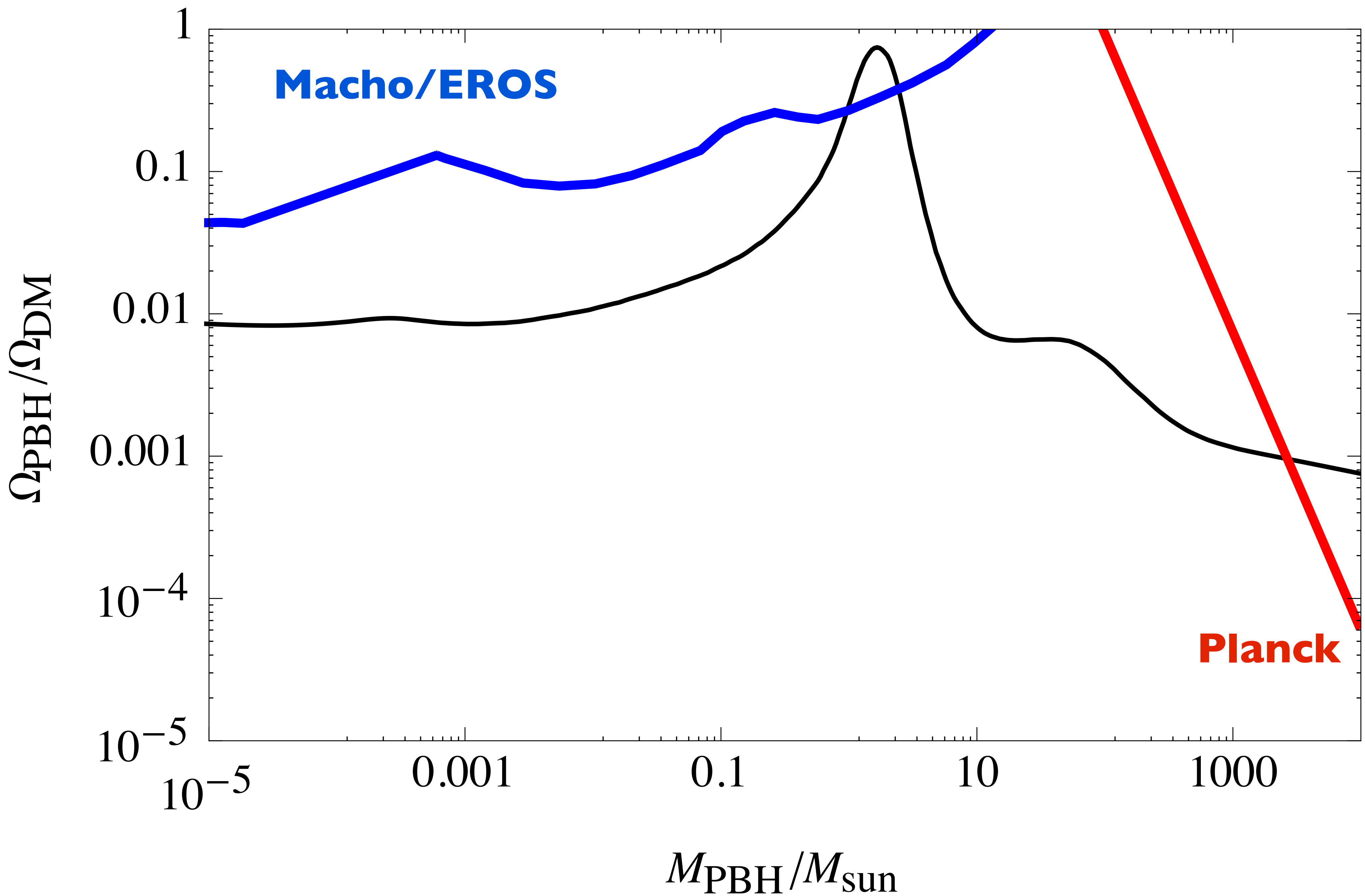


Limits for for a monochromatic mass function!

Does our preferred PBH model pass the current astro/cosmo limits?

However, the status today has changed!

Ali-Haimoud & Kamionkowski
1612.05644

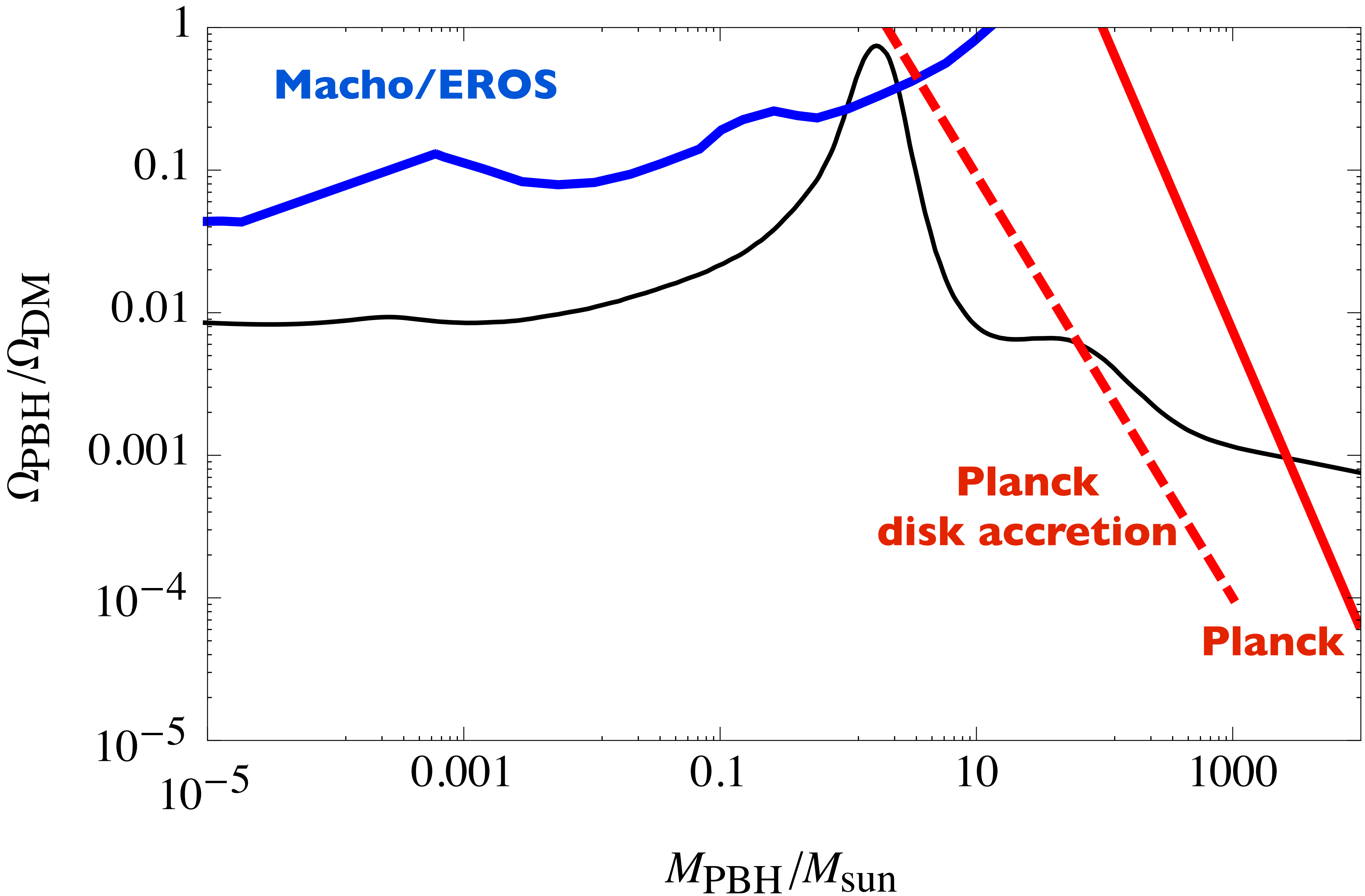


Limits for for a monochromatic mass function!

Does our preferred PBH model pass the current astro/cosmo limits?

However, the status today has changed!

Poulin, Serpico, Calore, SC, Kohri
1707.04206



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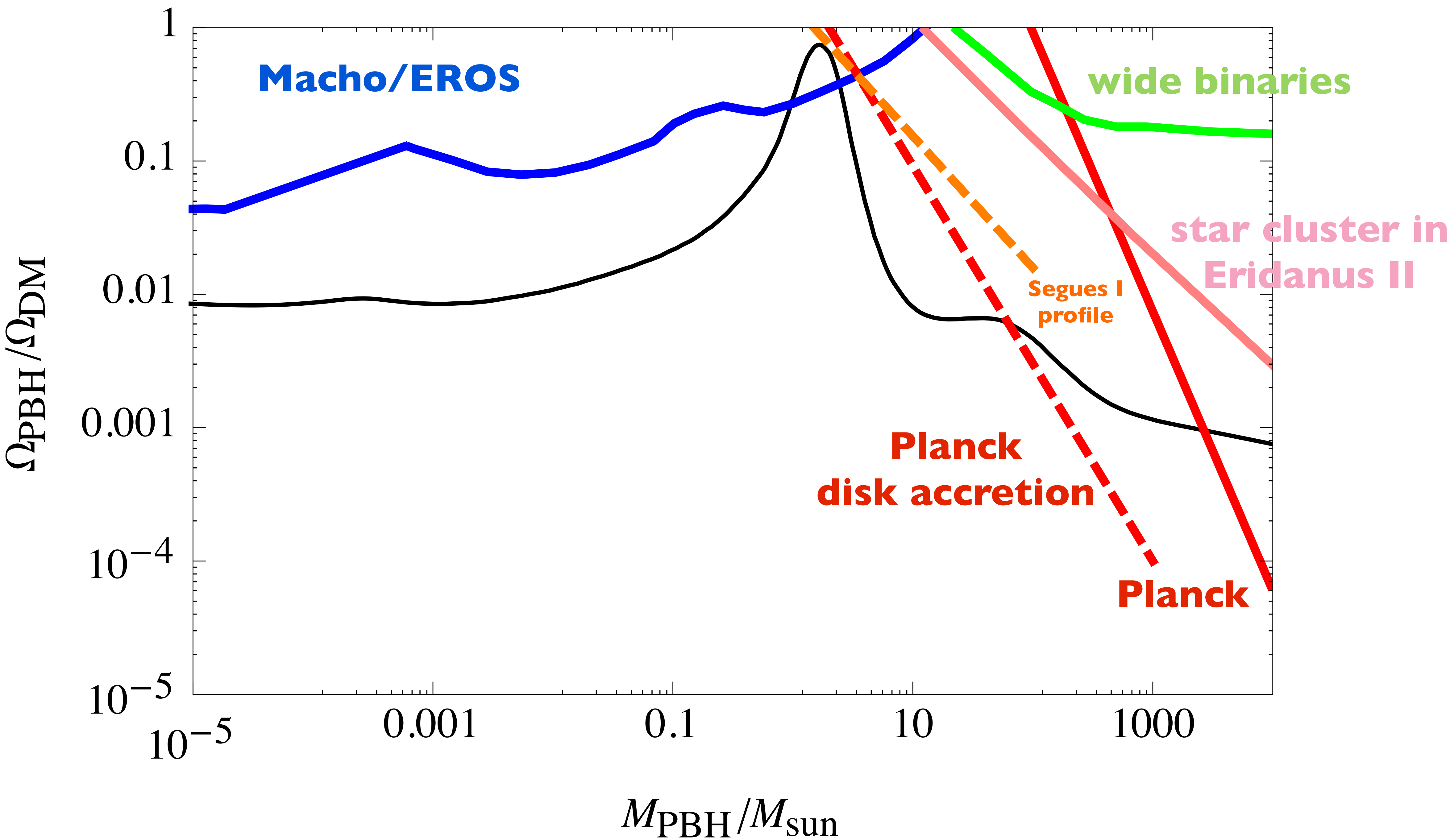
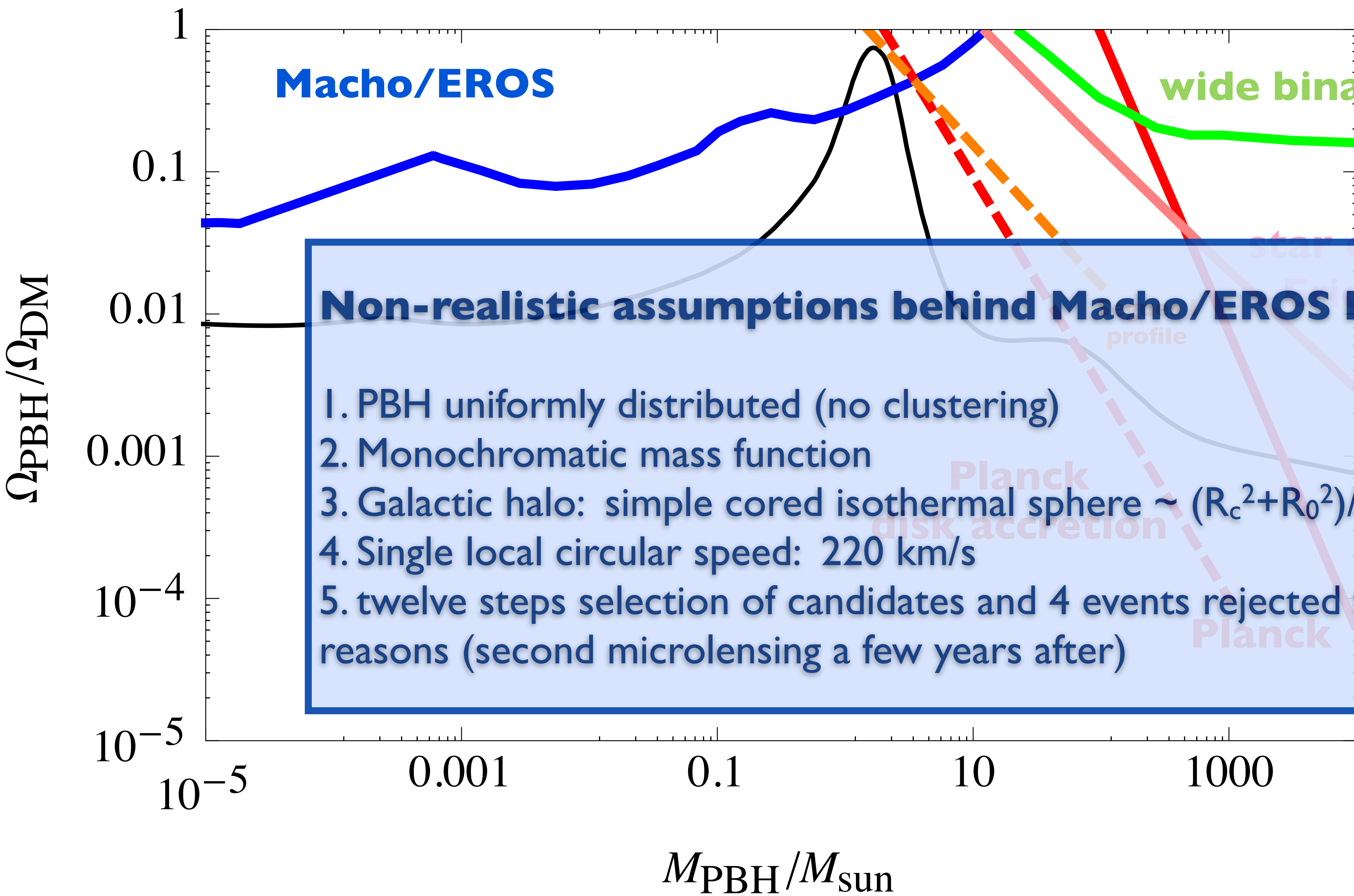


Limits for for a monochromatic mass function!

Does our preferred PBH model pass the current astro/cosmo limits?

However, the status today has changed!

A. Green, 1705.10818
1707.04206



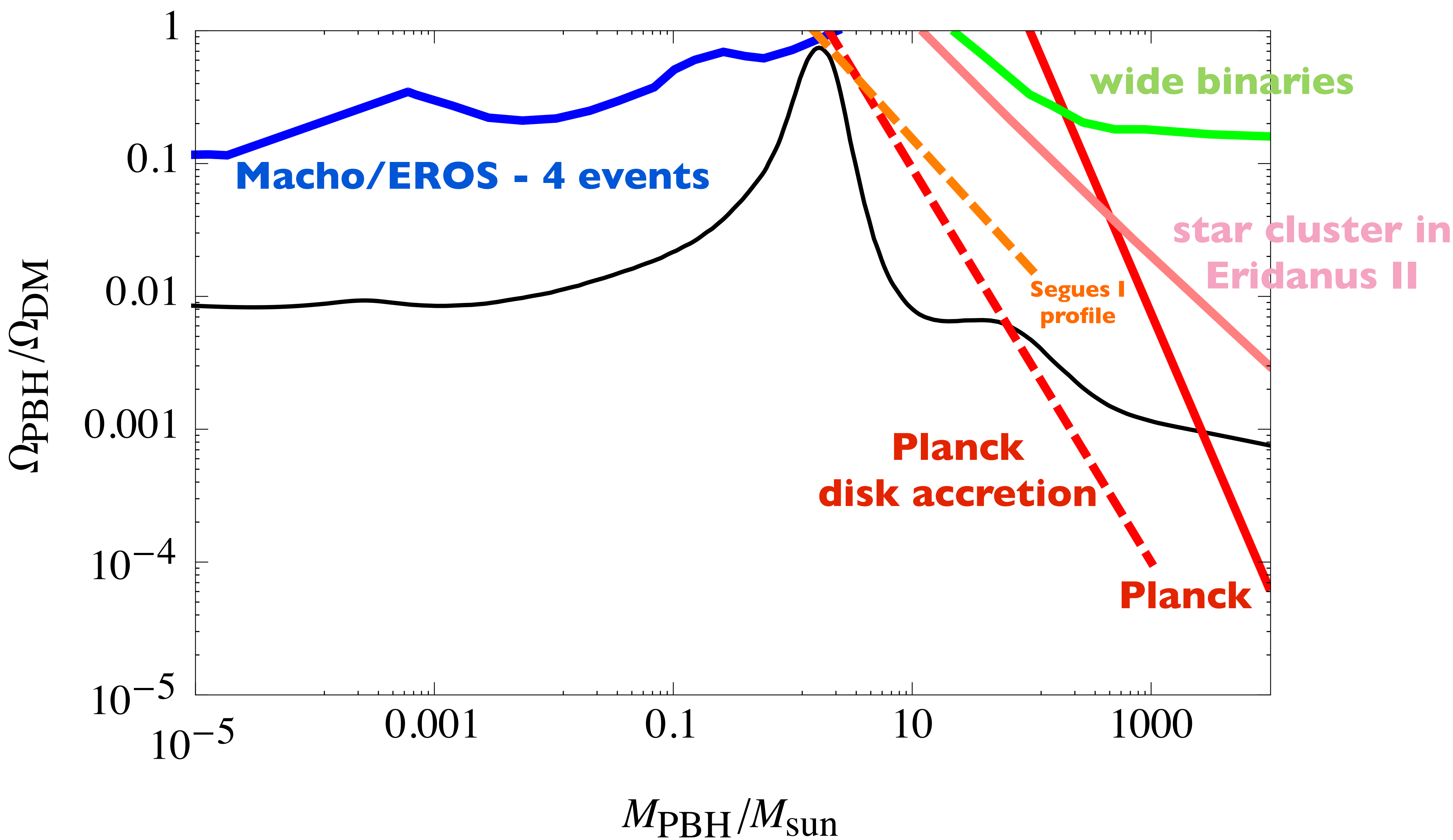
Non-realistic assumptions behind Macho/EROS limits:

1. PBH uniformly distributed (no clustering)
2. Monochromatic mass function
3. Galactic halo: simple cored isothermal sphere ~ $(R_c^2+R_0^2)/(R_c^2+R^2)$
4. Single local circular speed: 220 km/s
5. twelve steps selection of candidates and 4 events rejected for bad reasons (second microlensing a few years after)

Limits for for a monochromatic mass function!

Does our preferred PBH model pass the current astro/cosmo limits?

However, the status today has changed!



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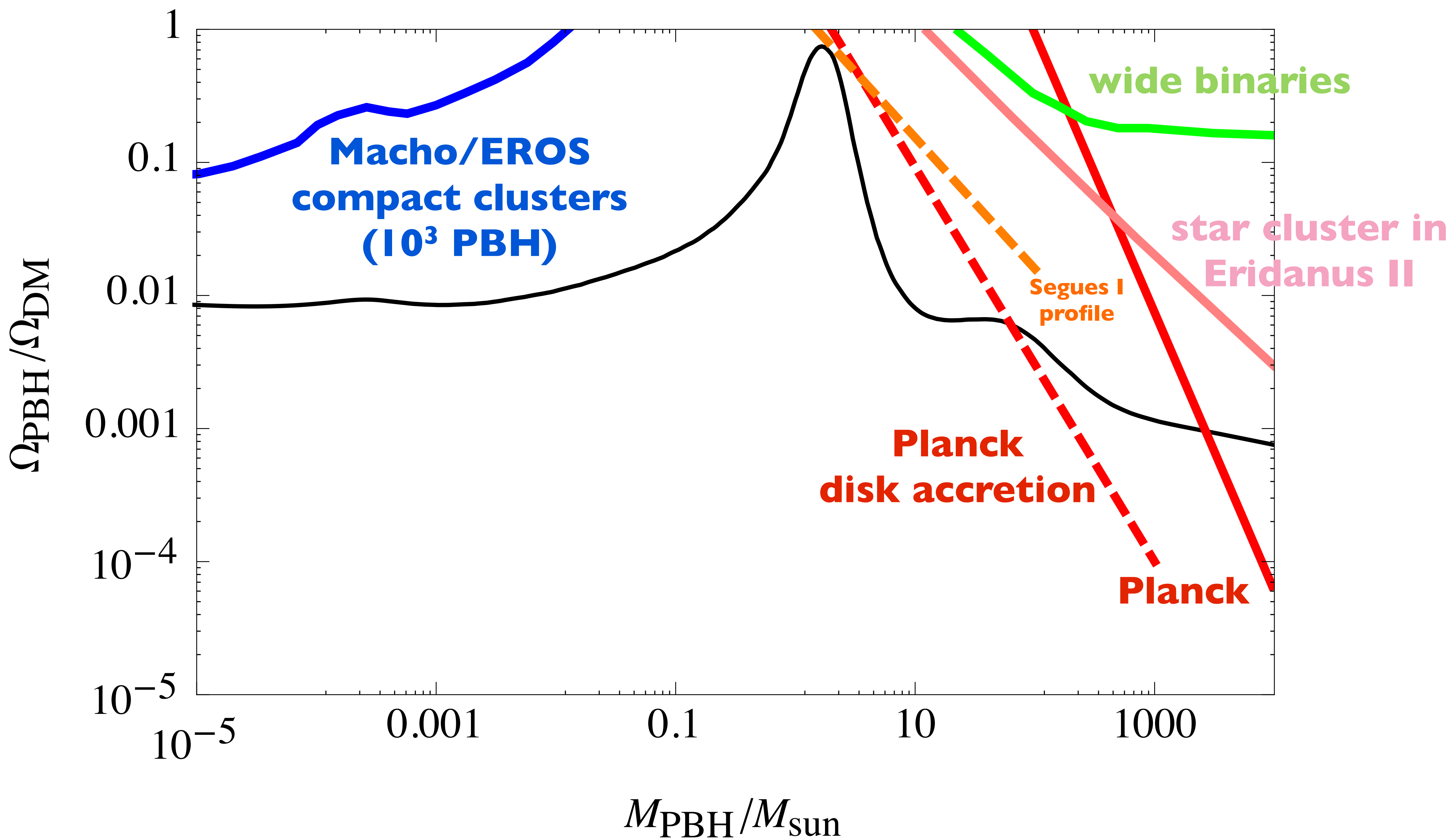

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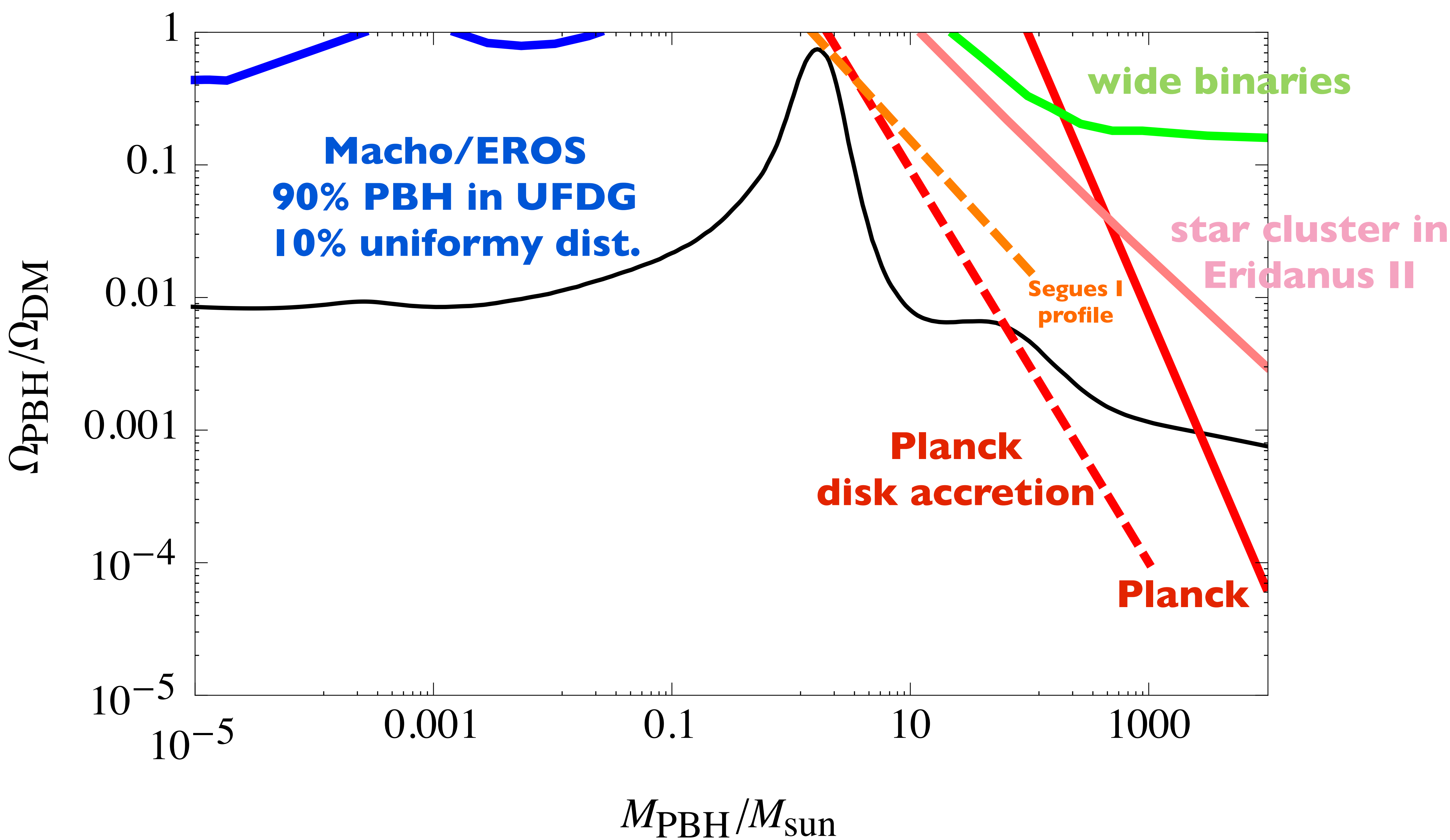

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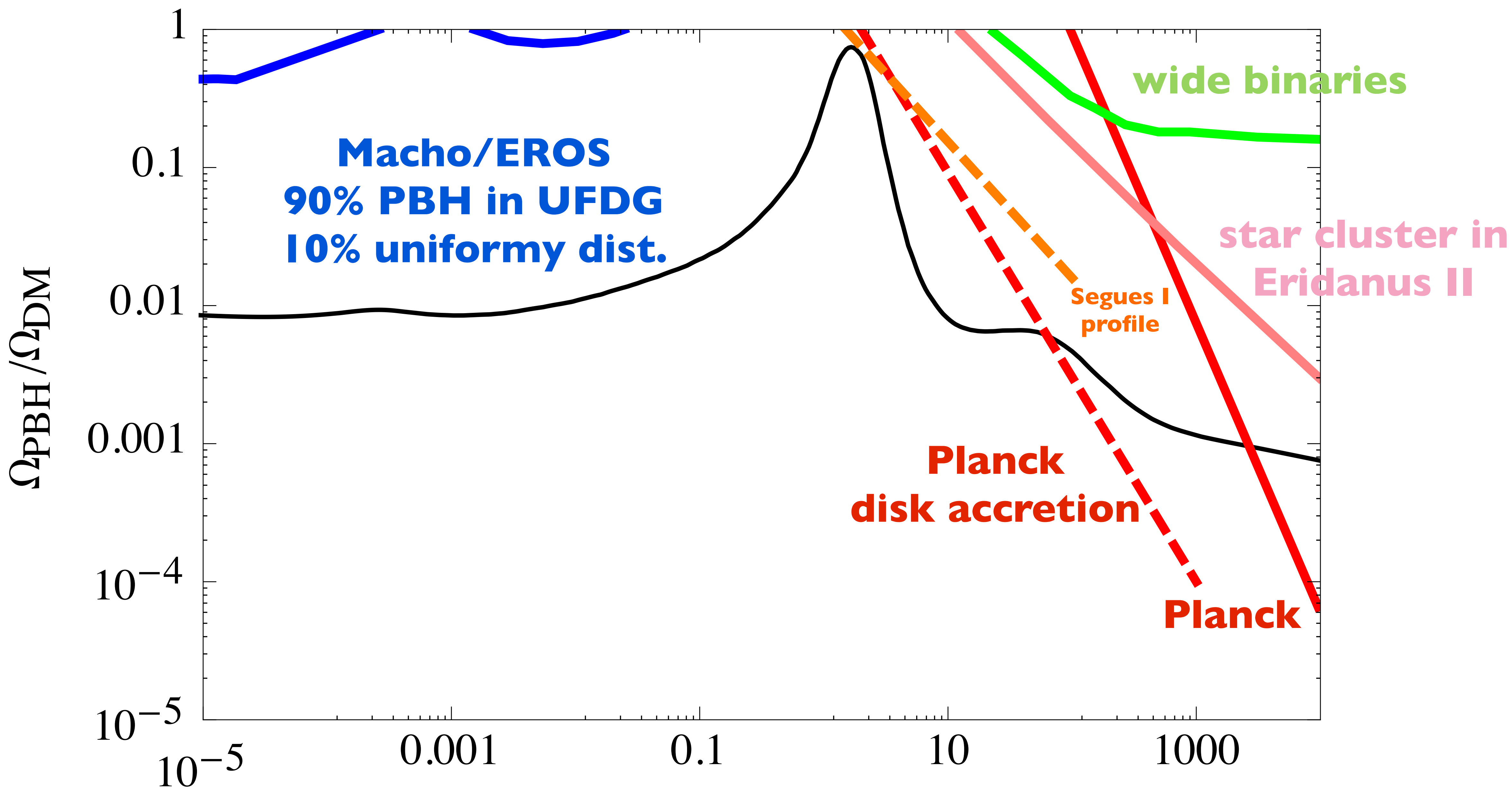
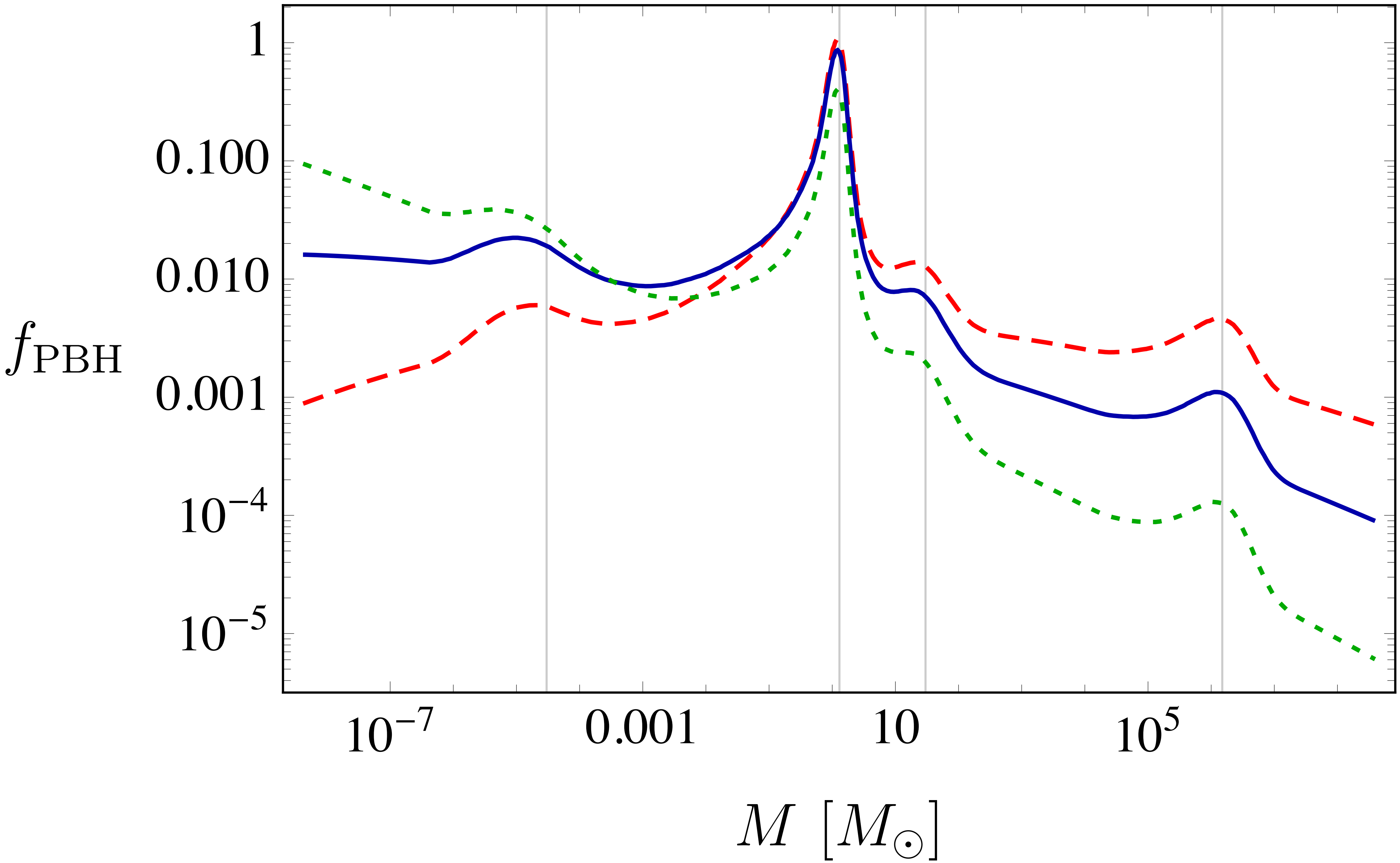


For an extended mass function, one needs to find the equivalent mass for each probe and compare to the monochromatic limit (Bellomo et al, 1709.07467)

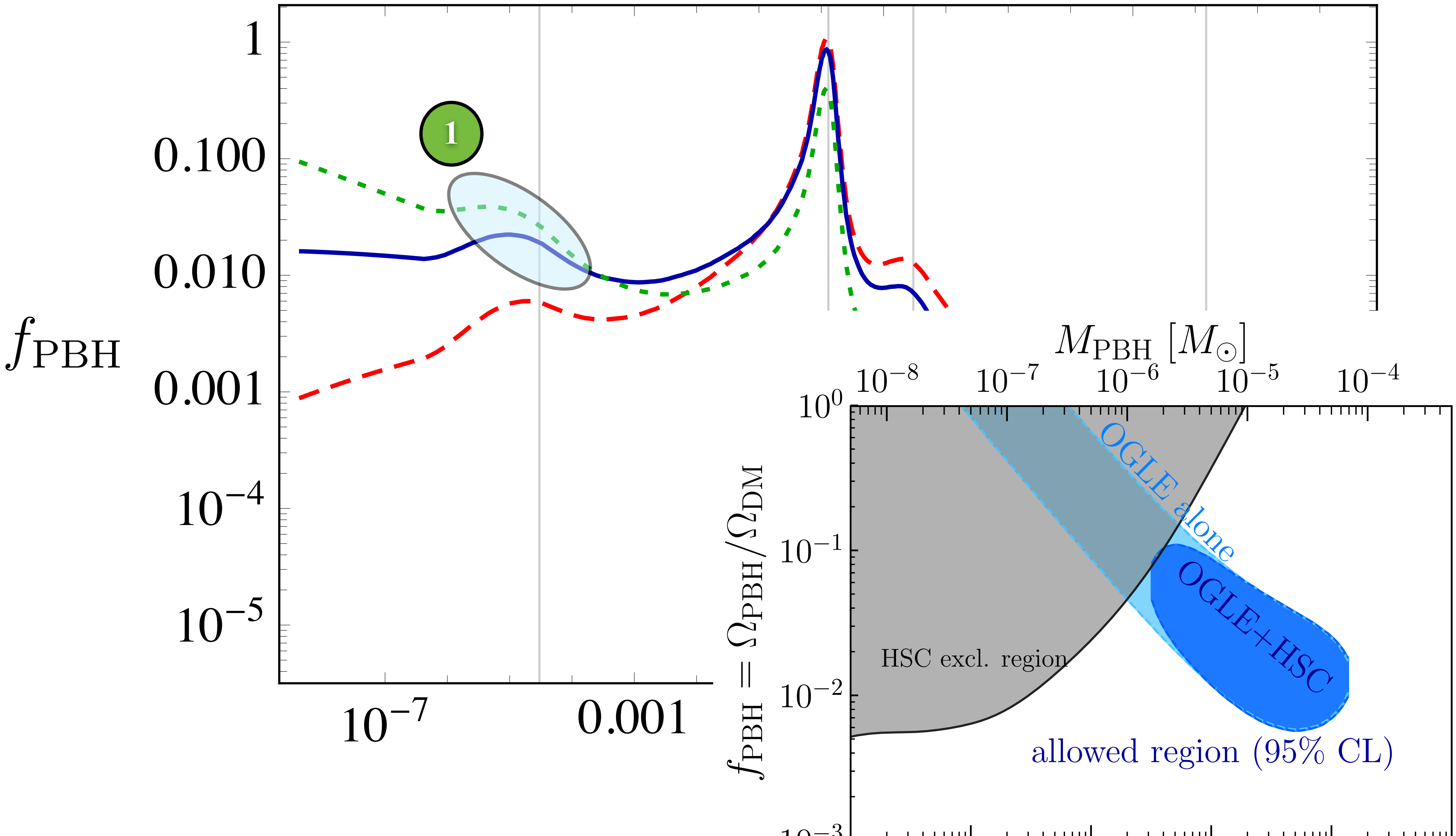
BUT: this approach neglects backreactions from PBH of different masses !!!

Does our preferred PBH model is supported by some observations?



Does our preferred PBH model is supported by some observations?

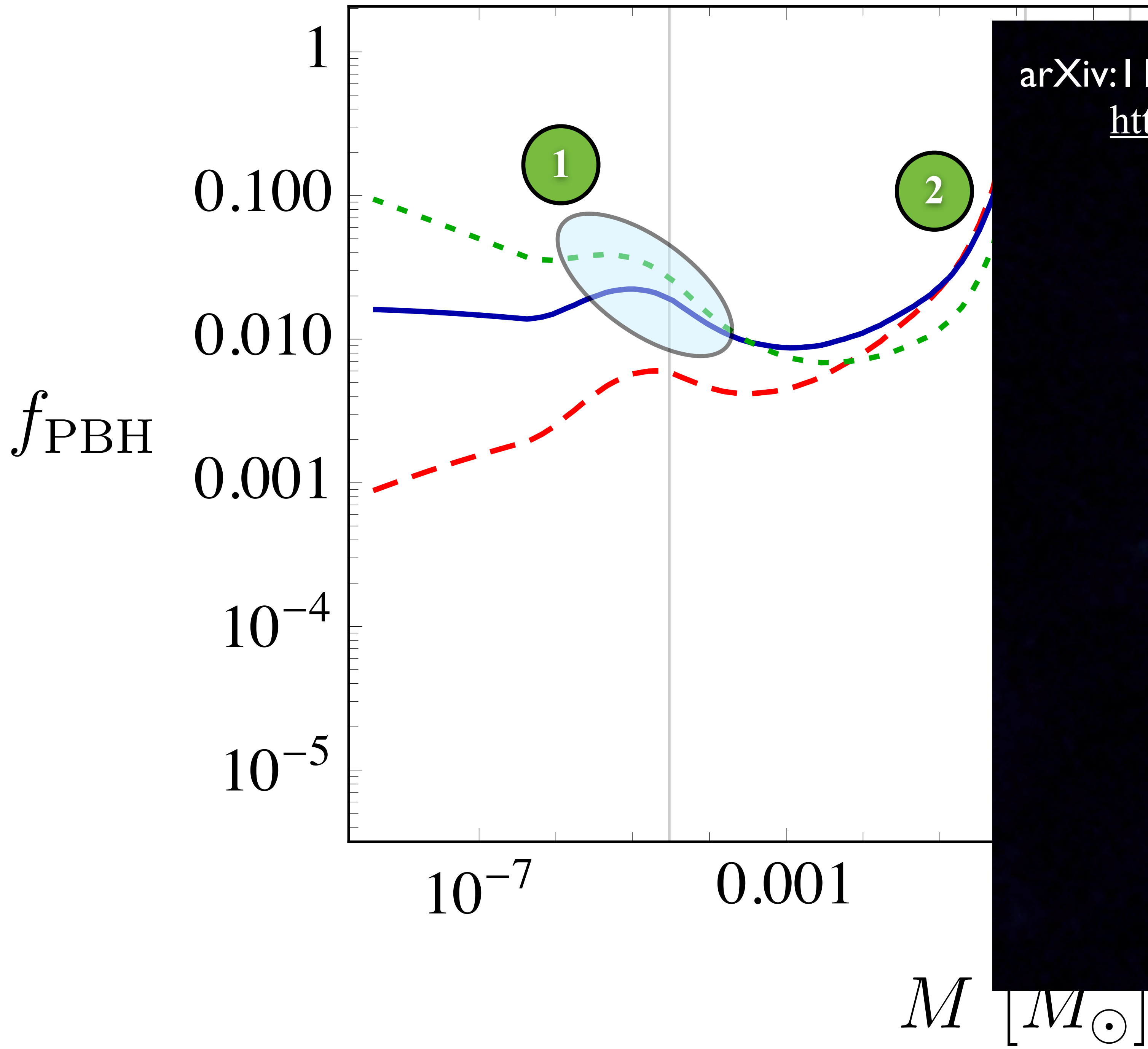
Niikura et al., 1901.07120

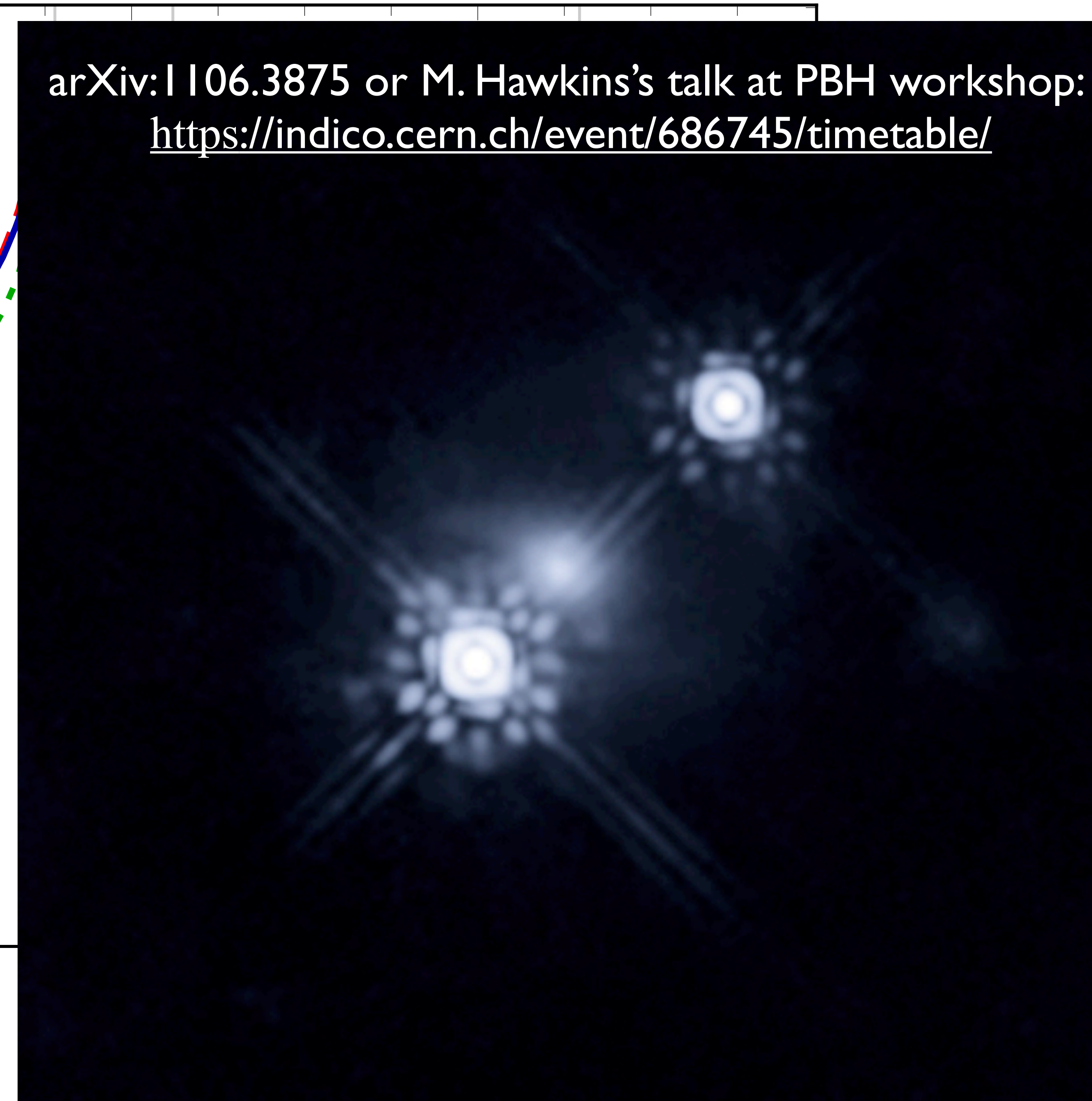


1 6 ultra-short microlensing events in OGLE data

Above expectations for floating planets!

Does our preferred PBH model is supported by some observations?

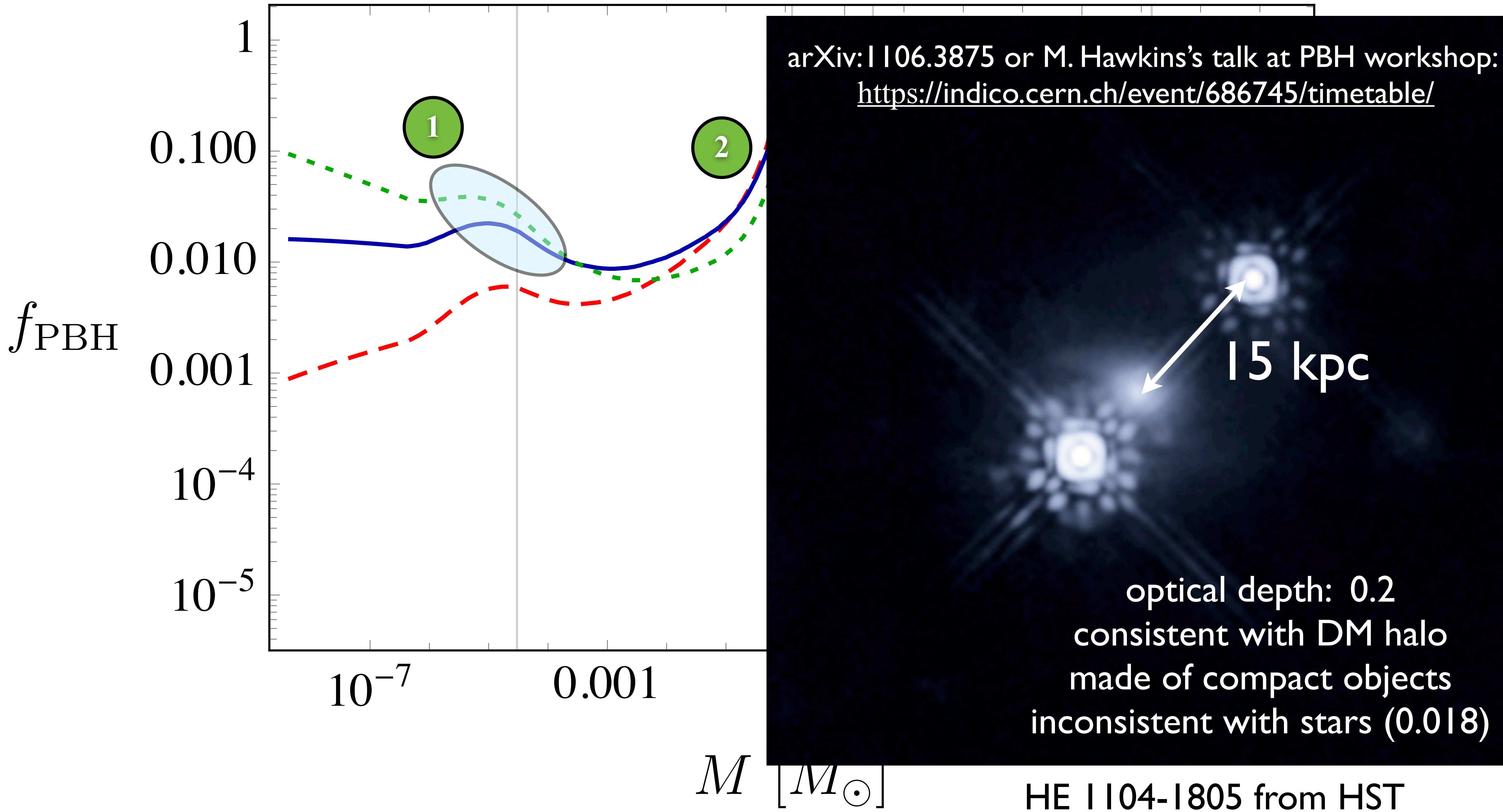




HE 1104-1805 from HST

2 Microlensing of quasars (24) with misaligned galaxy (a few)
+ 56 microlensing events in M31

Does our preferred PBH model is supported by some observations?



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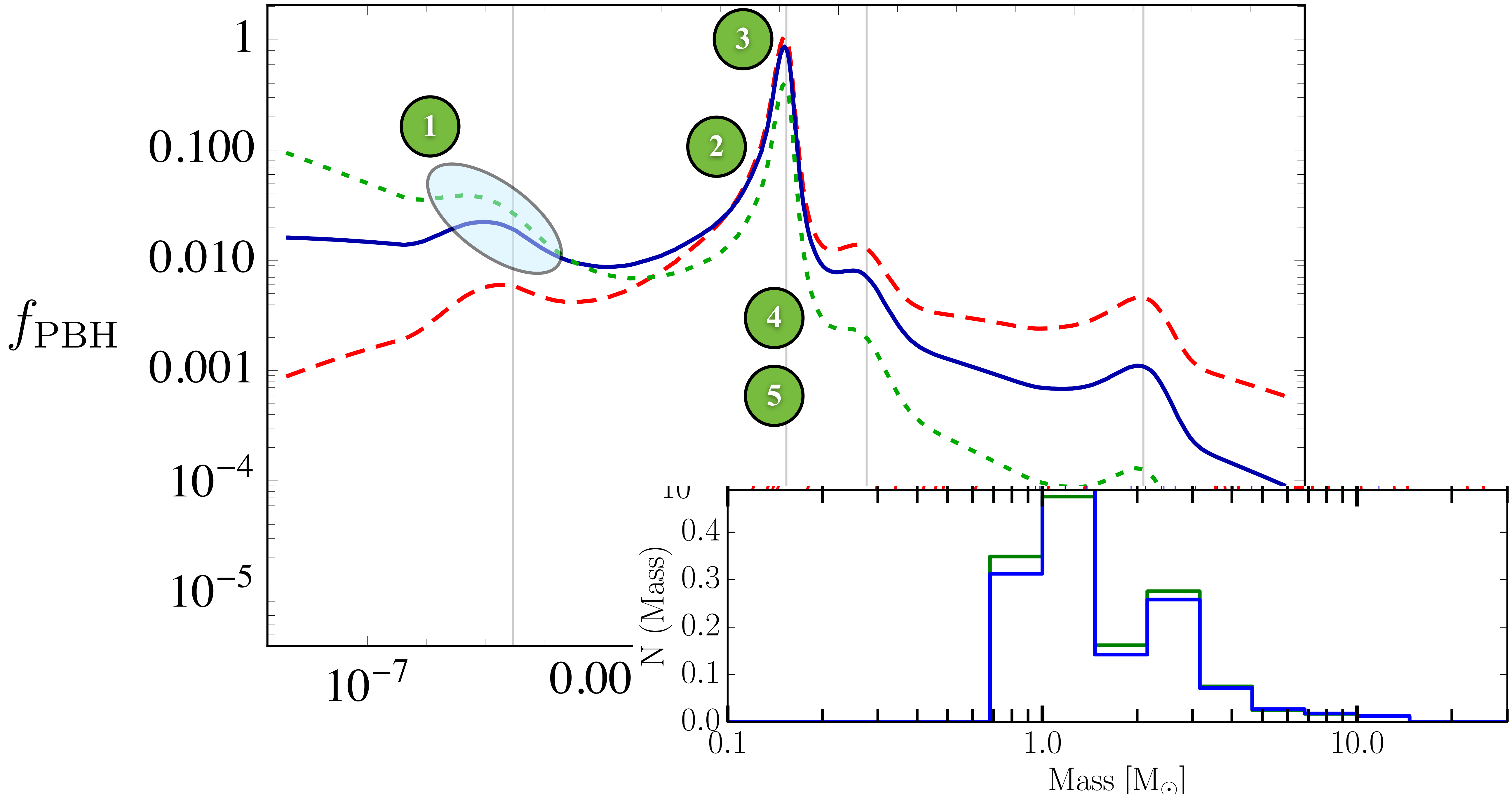
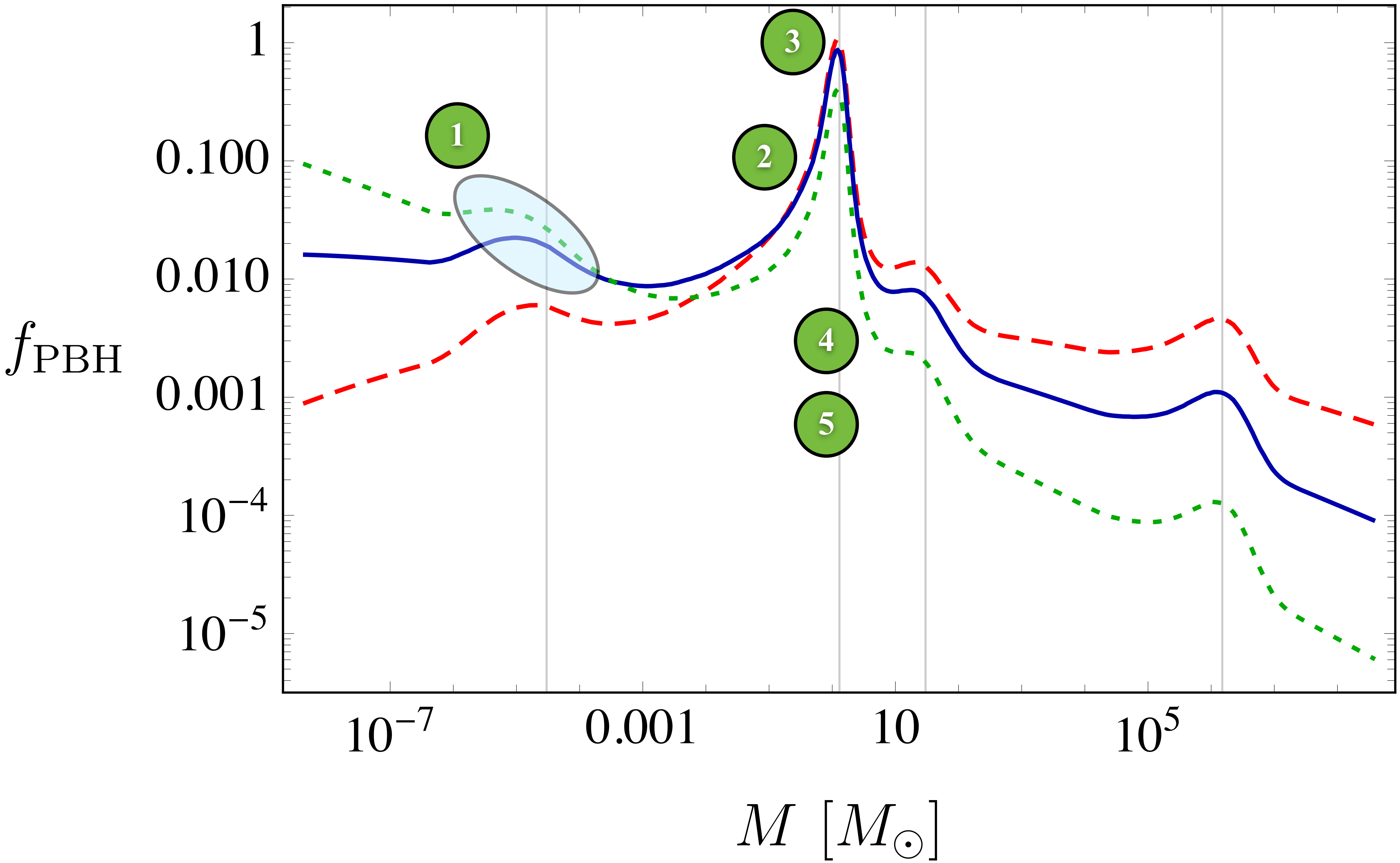
Niikura et al., 1904.07789



3 OGLE/Gaia microlensing events in the galactic bulge
Dark lenses: BH in the mass gap

Does our preferred PBH model is supported by some observations?

Niikura et al., 1904.07789



4 Spatial correlations in CIB and X-ray background

Spatial correlations in CIB and X-ray background

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

A. Kashlinsky[1],

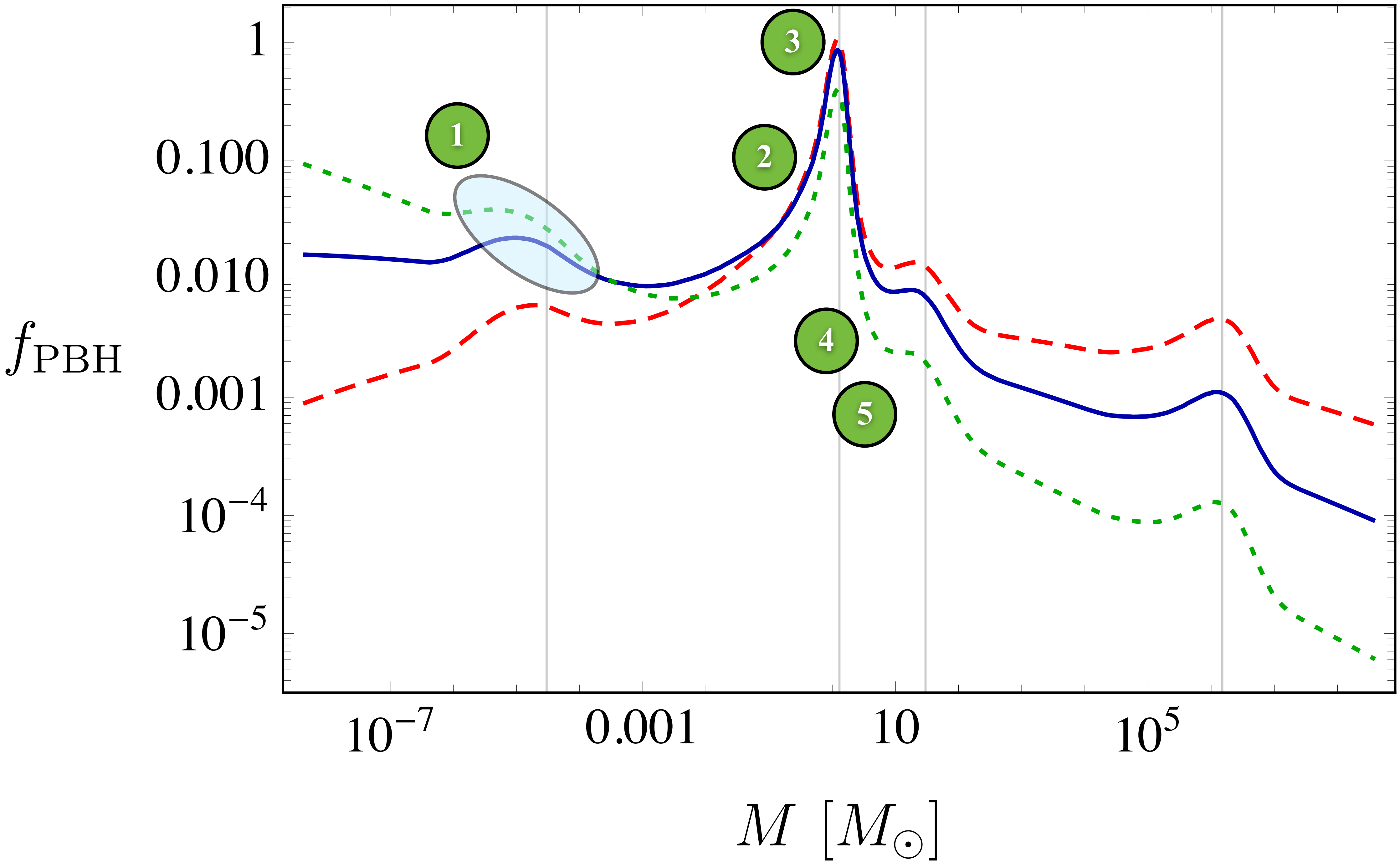
ABSTRACT

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
5-sigma detection

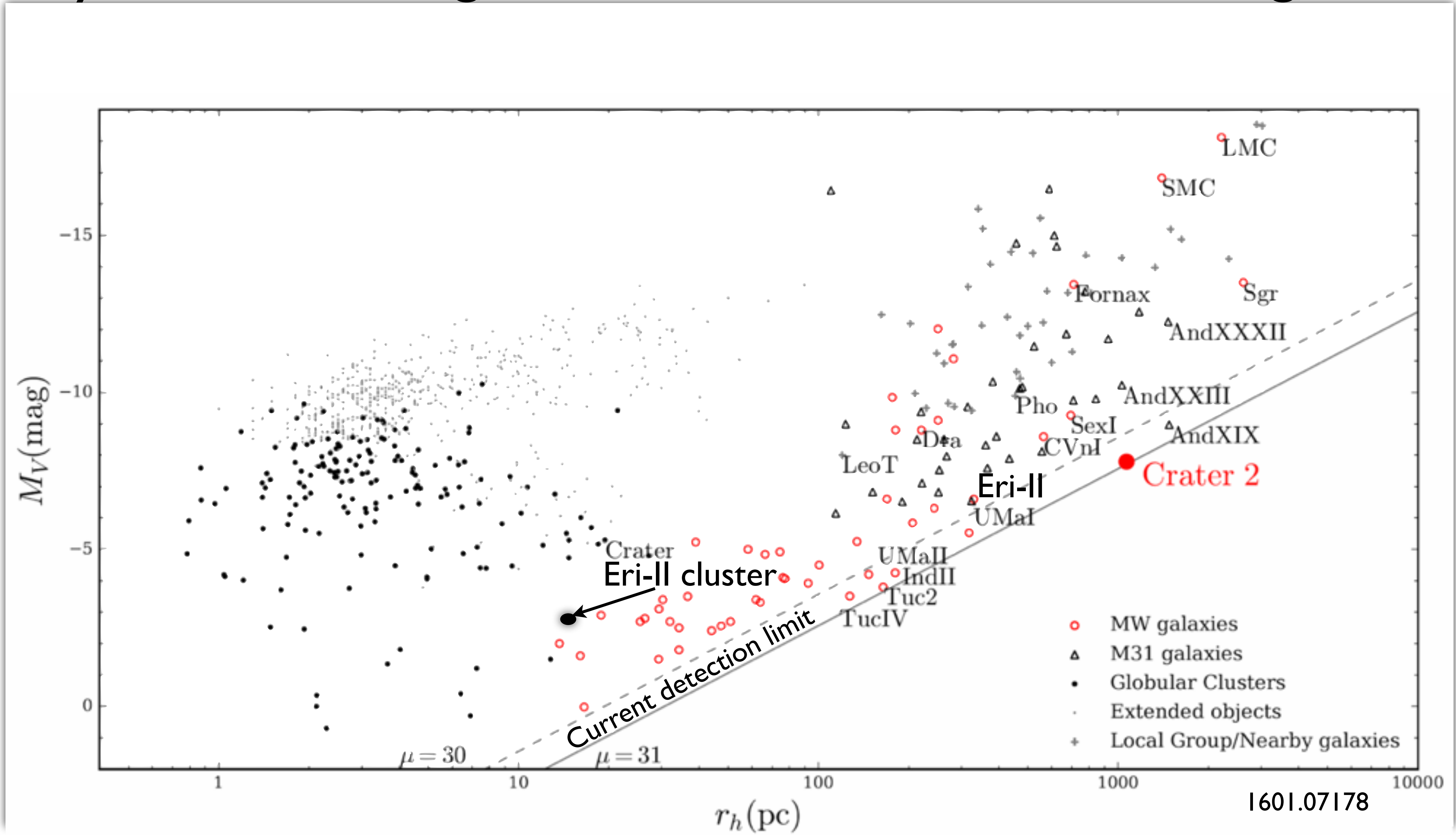
Does our preferred PBH model is supported by some observations?

Niikura et al., 1904.07789

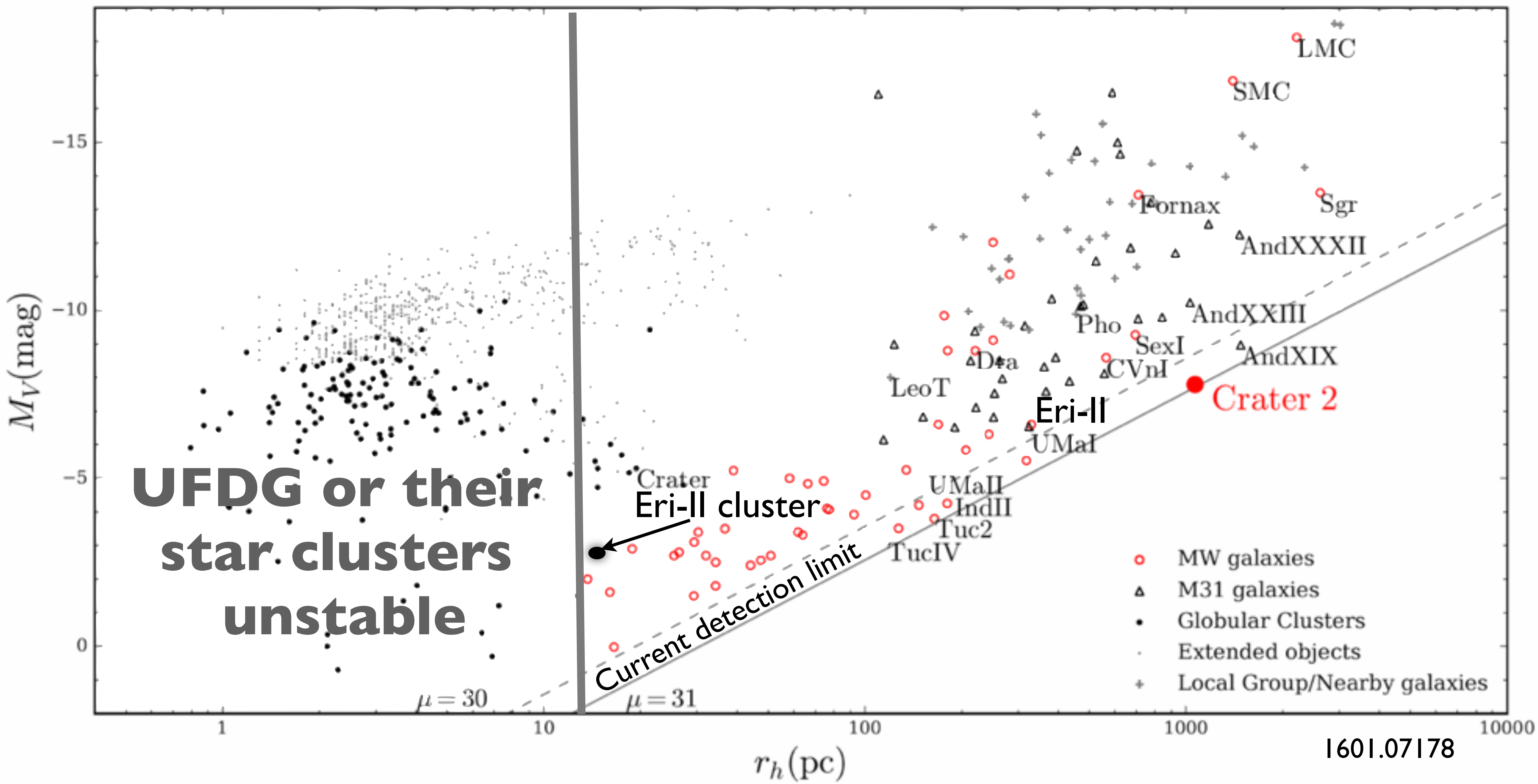


5 Critical radius of ultra-faint dwarf galaxies

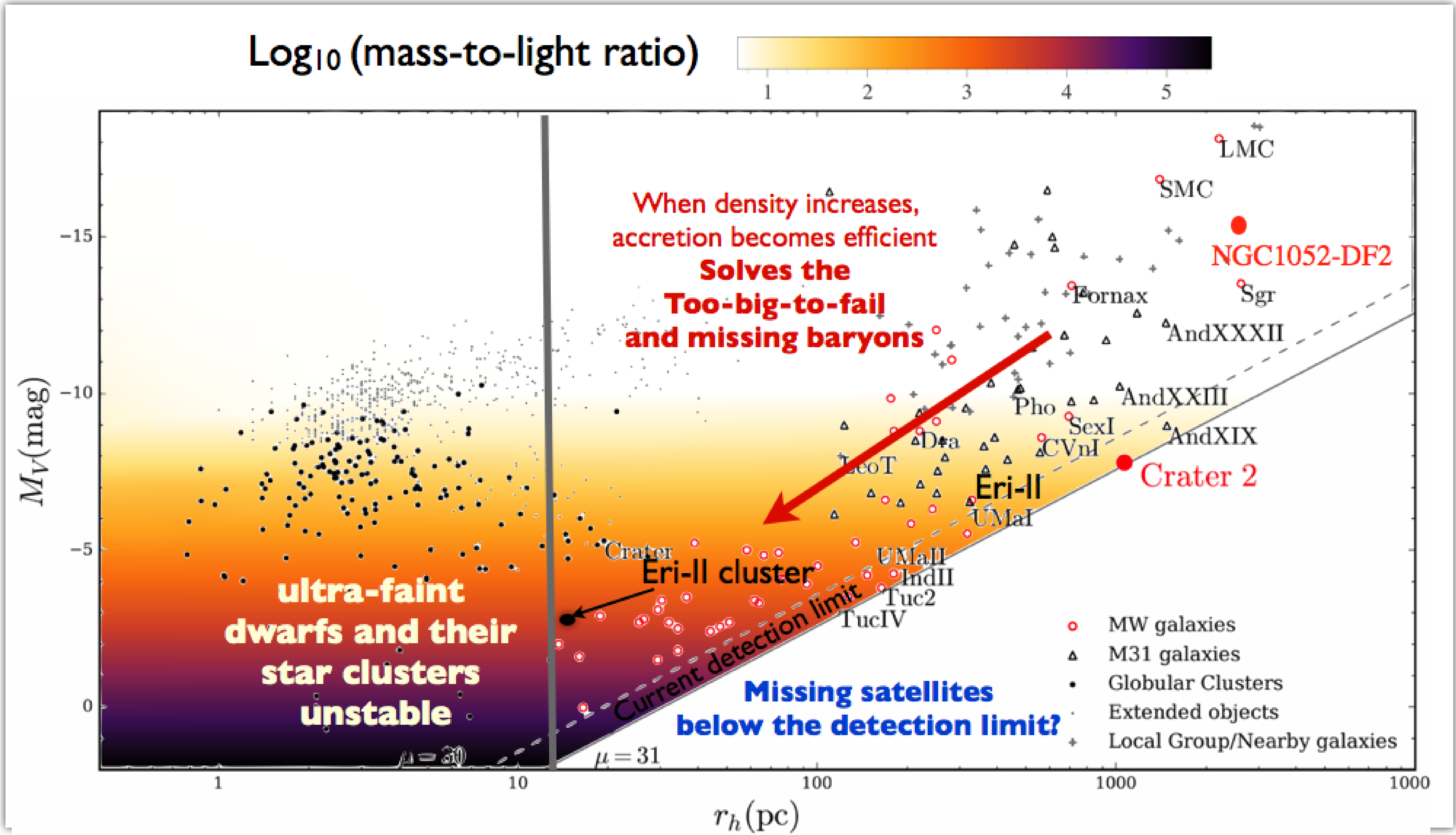
Dynamical heating of star clusters and faint dwarf galaxies



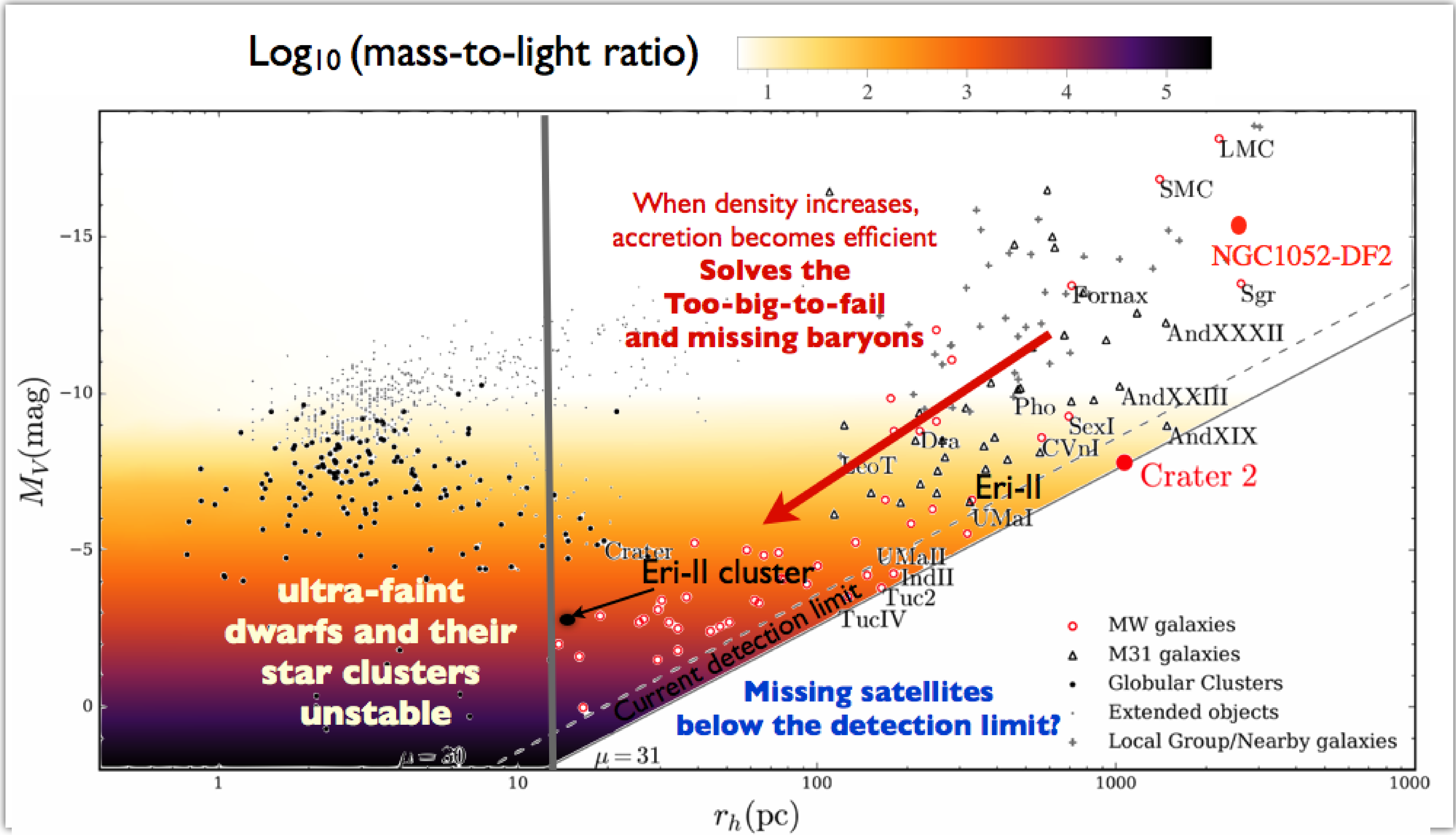
Dynamical heating of star clusters and faint dwarf galaxies



Dynamical heating of star clusters and faint dwarf galaxies



Dynamical heating of star clusters and faint dwarf galaxies



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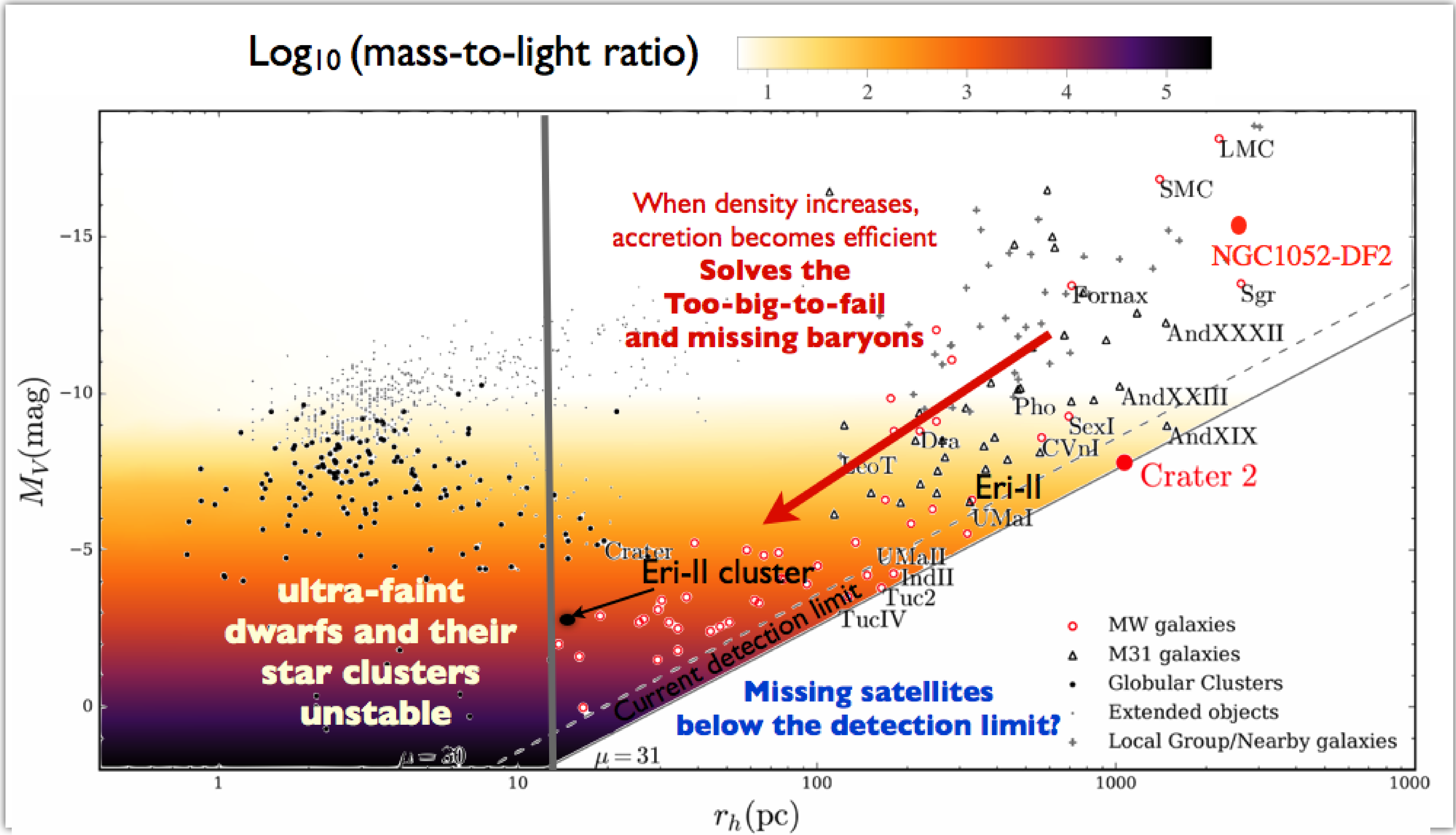
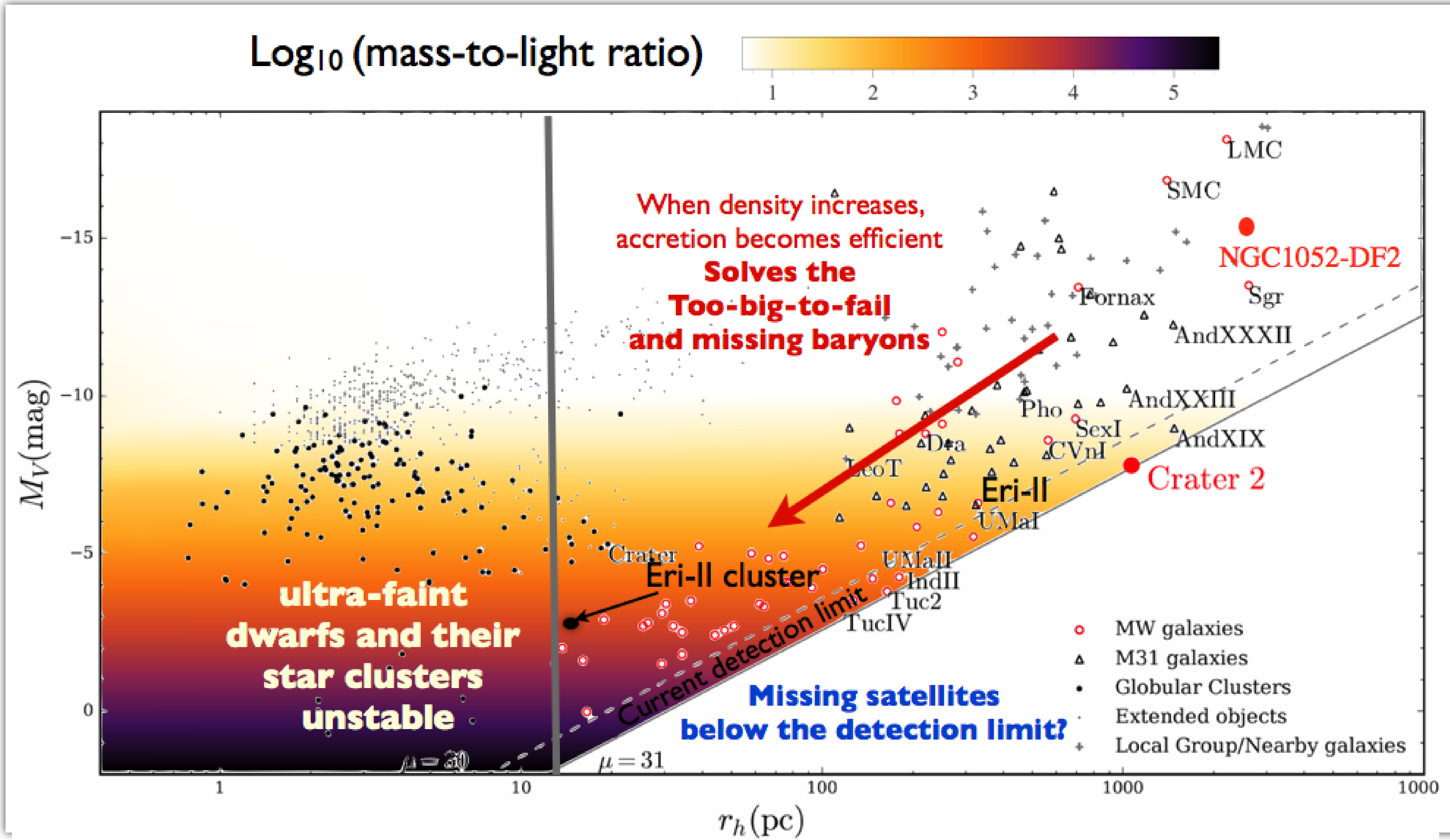


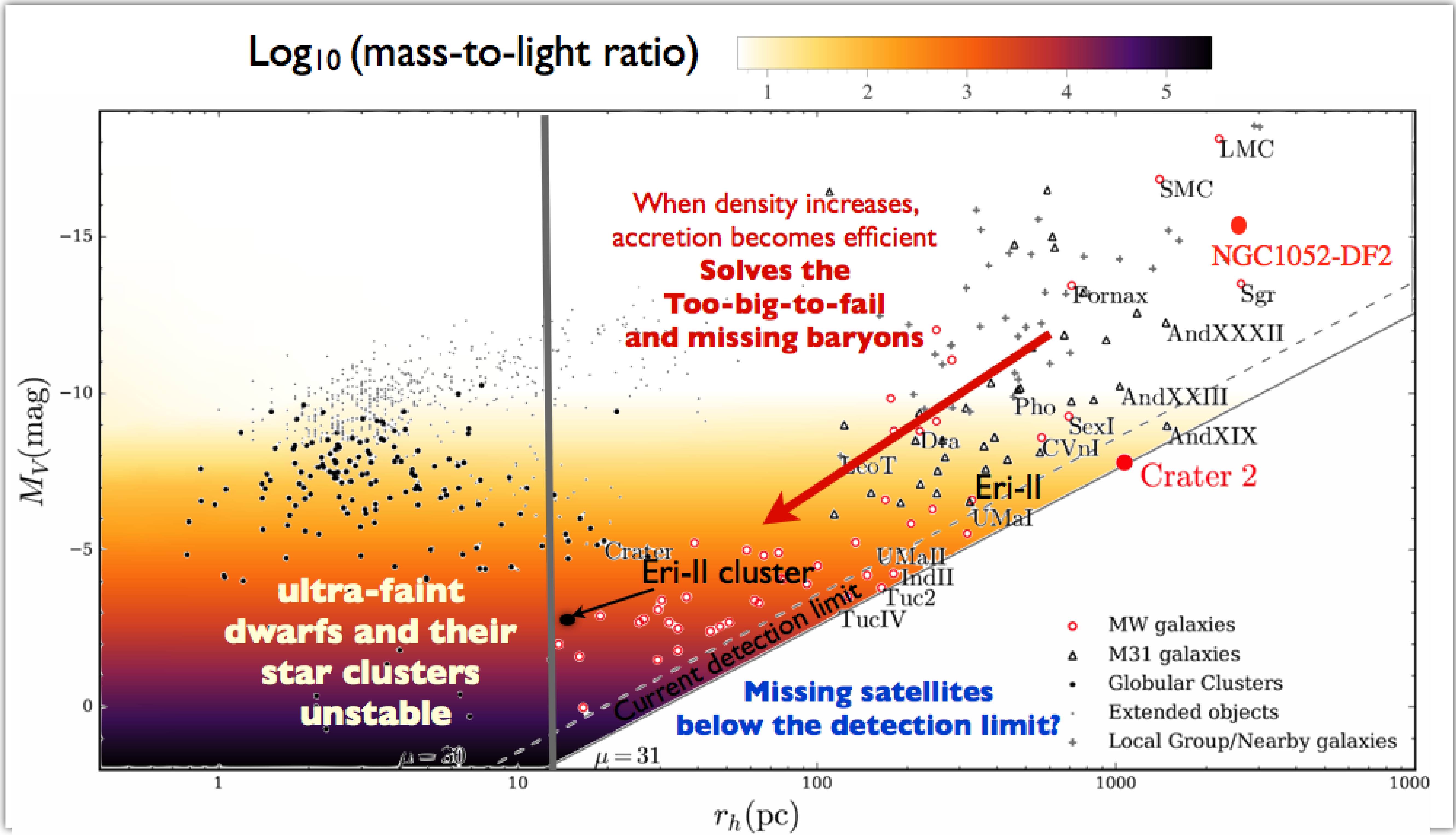
Dynamical heating of star clusters and faint dwarf galaxies



And solve the Core-Cusp problem (including for UFDG) for free: PBH behave like a self-interacting DM model

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

Dynamical heating of star clusters and faint dwarf galaxies



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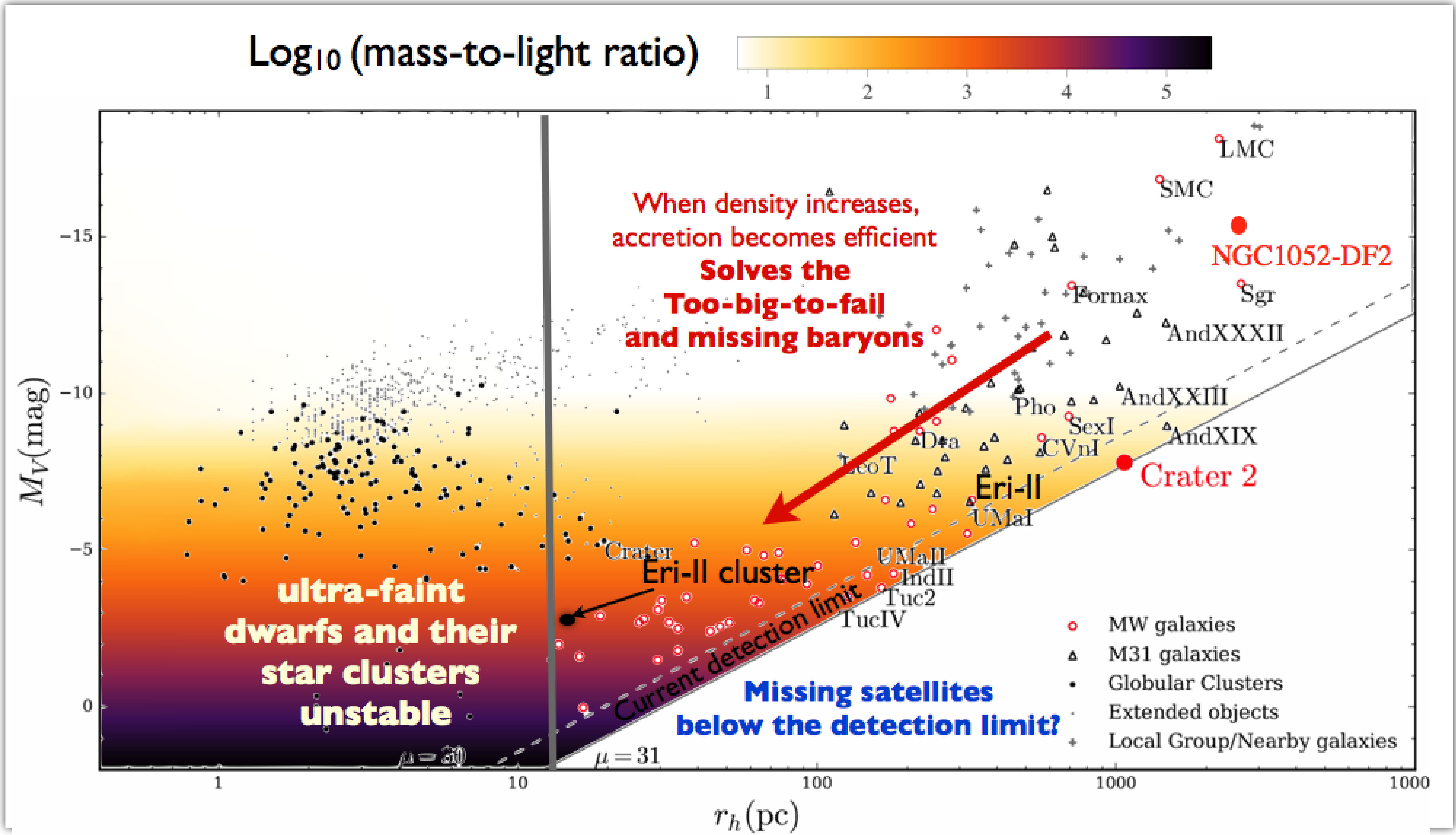

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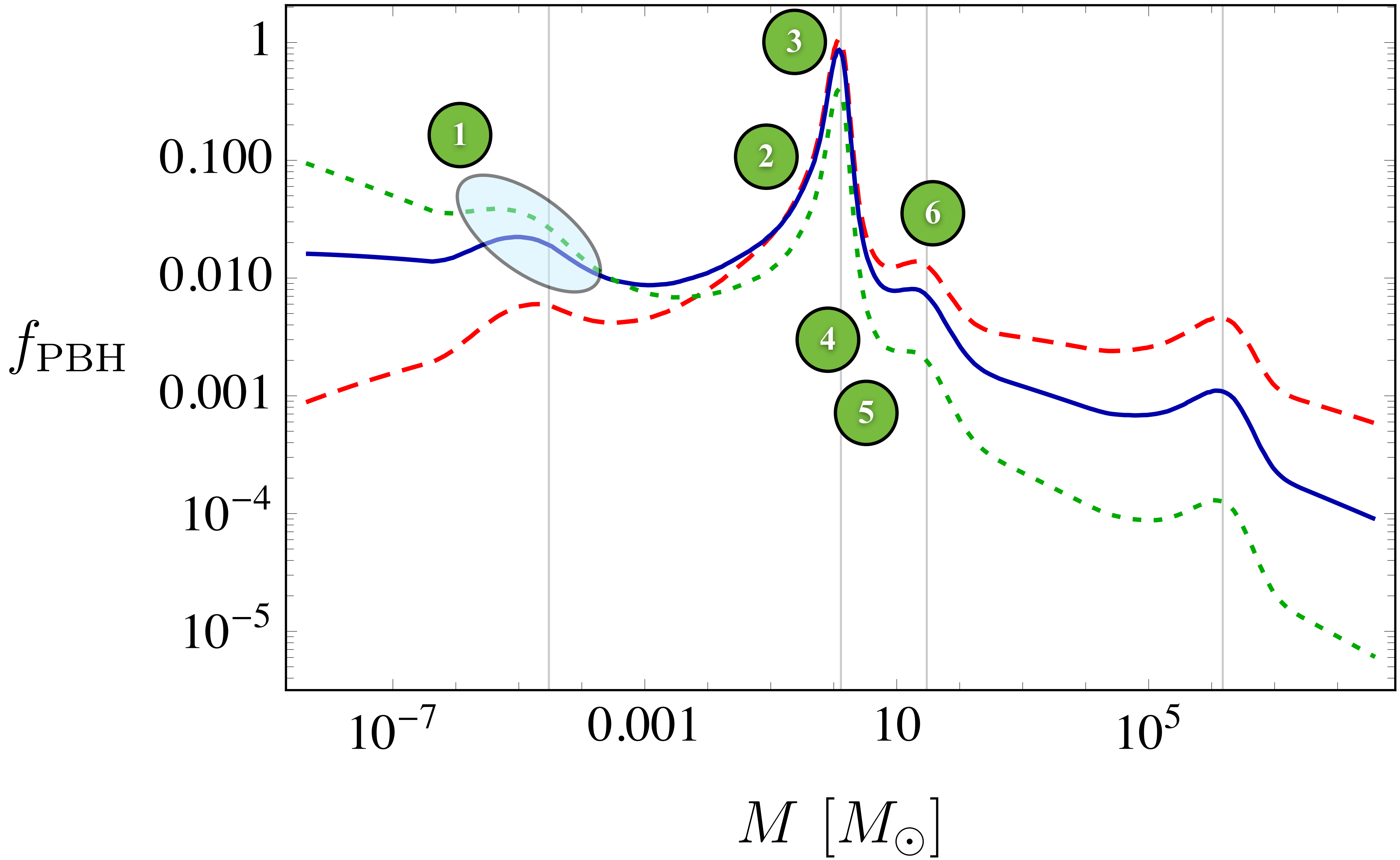

6 Explain the masses, rates and eff. spins of LIGO/Virgo BH

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

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e.g. Ultra-Faint Dwarf Galaxies

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e.g. Ultra-Faint Dwarf Galaxies

- 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

BUT:
(recent developments: Raidal et al, 1812.01930)

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

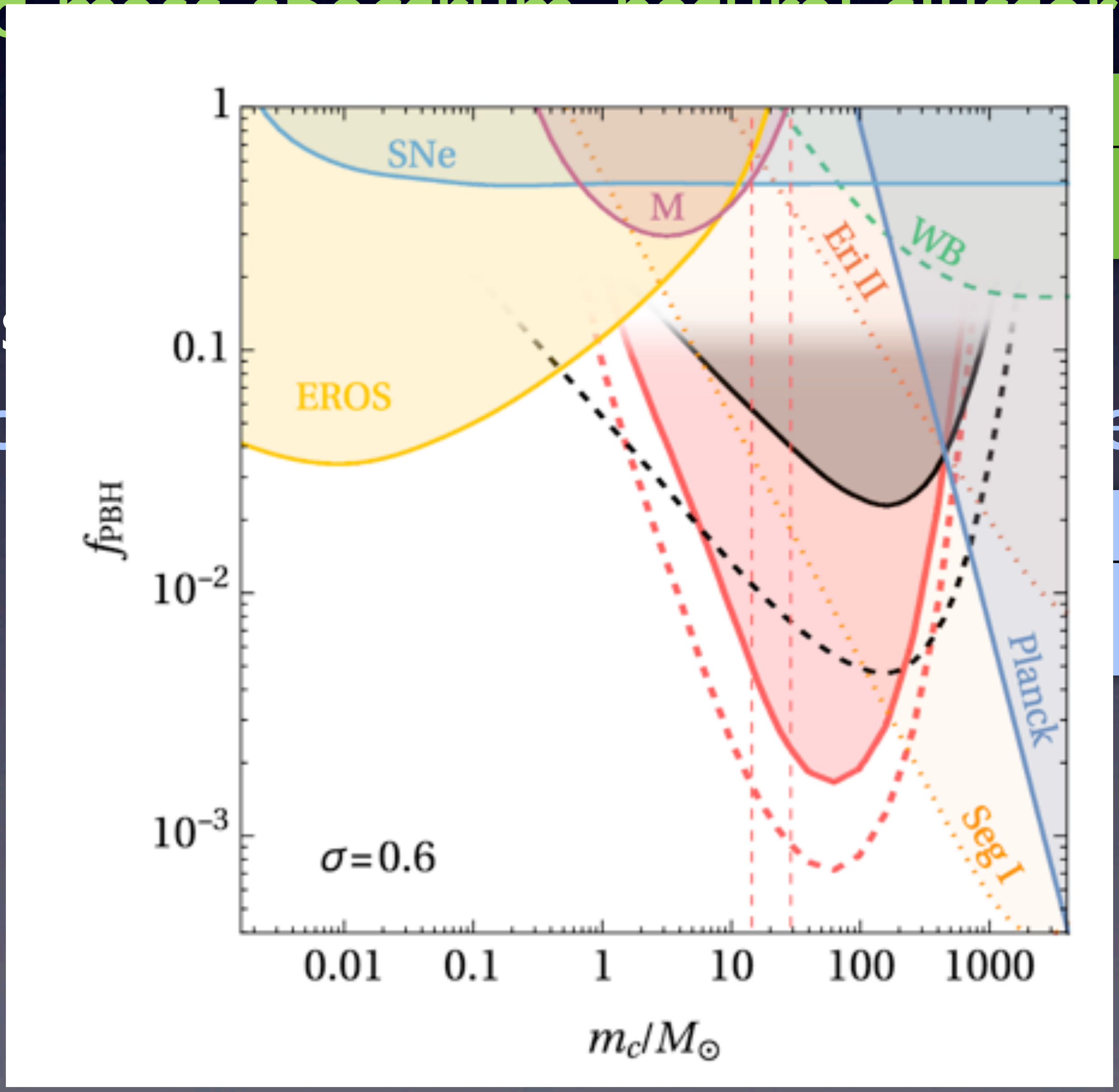
- S.C., J. Garcìa-Bellido, 1603.05234
  Broad ... ing scale

-3 yr^{-1}

e.g. Ultra-Faint Dwarf Galaxies

- M. Sa...
  Mon... es from Early Universe

-1



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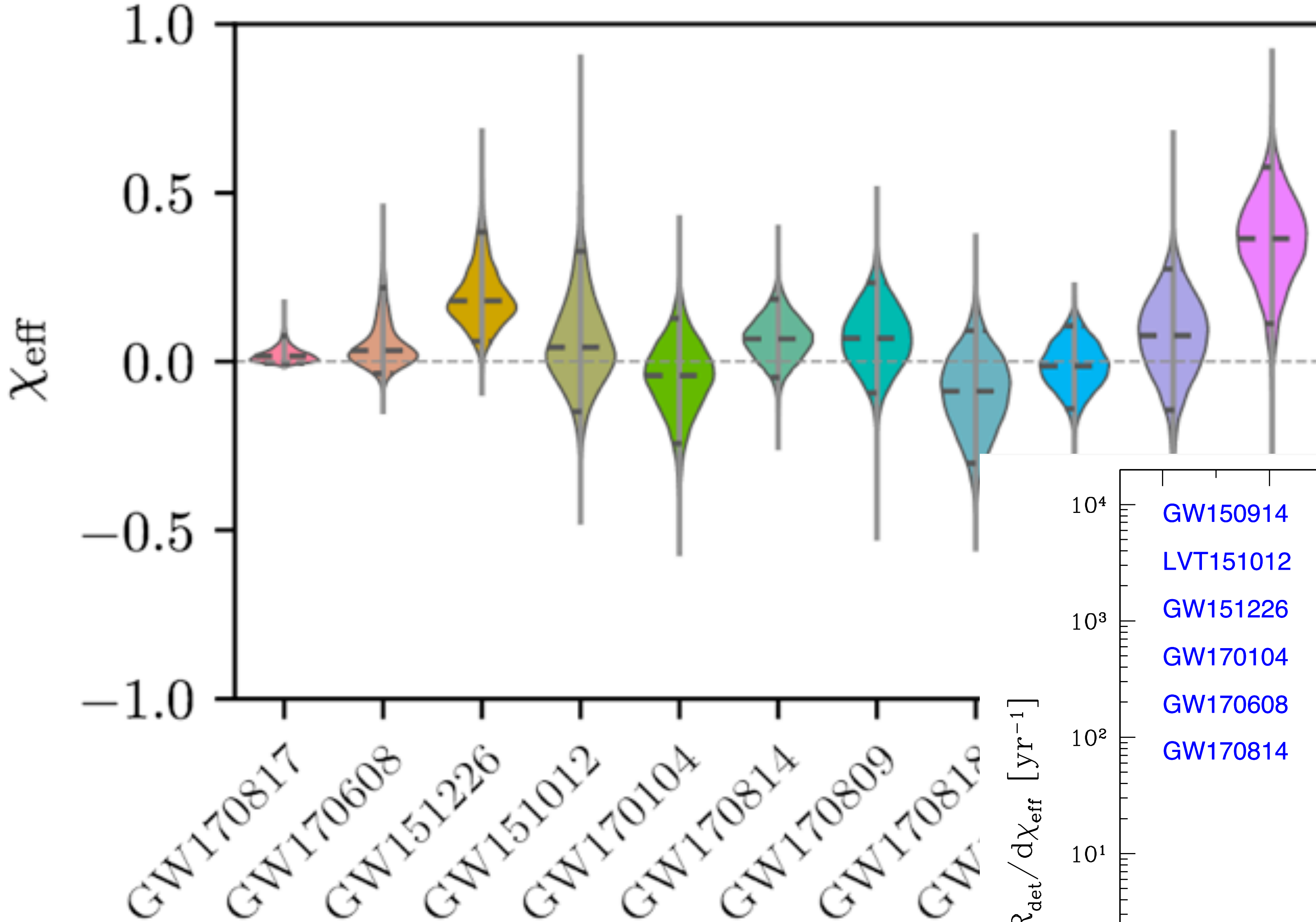
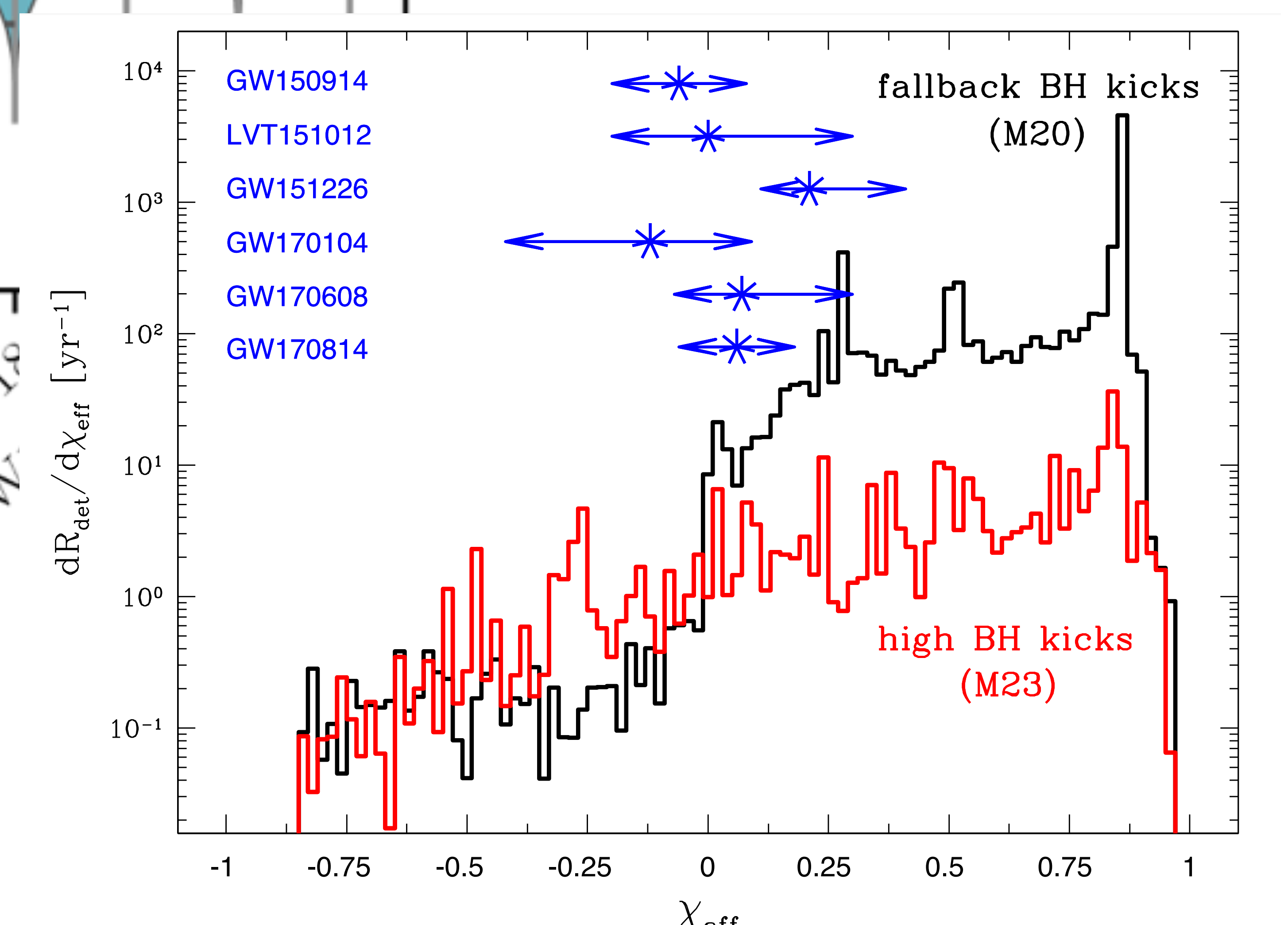
(recent developments: Raidal et al, 1812.01930)

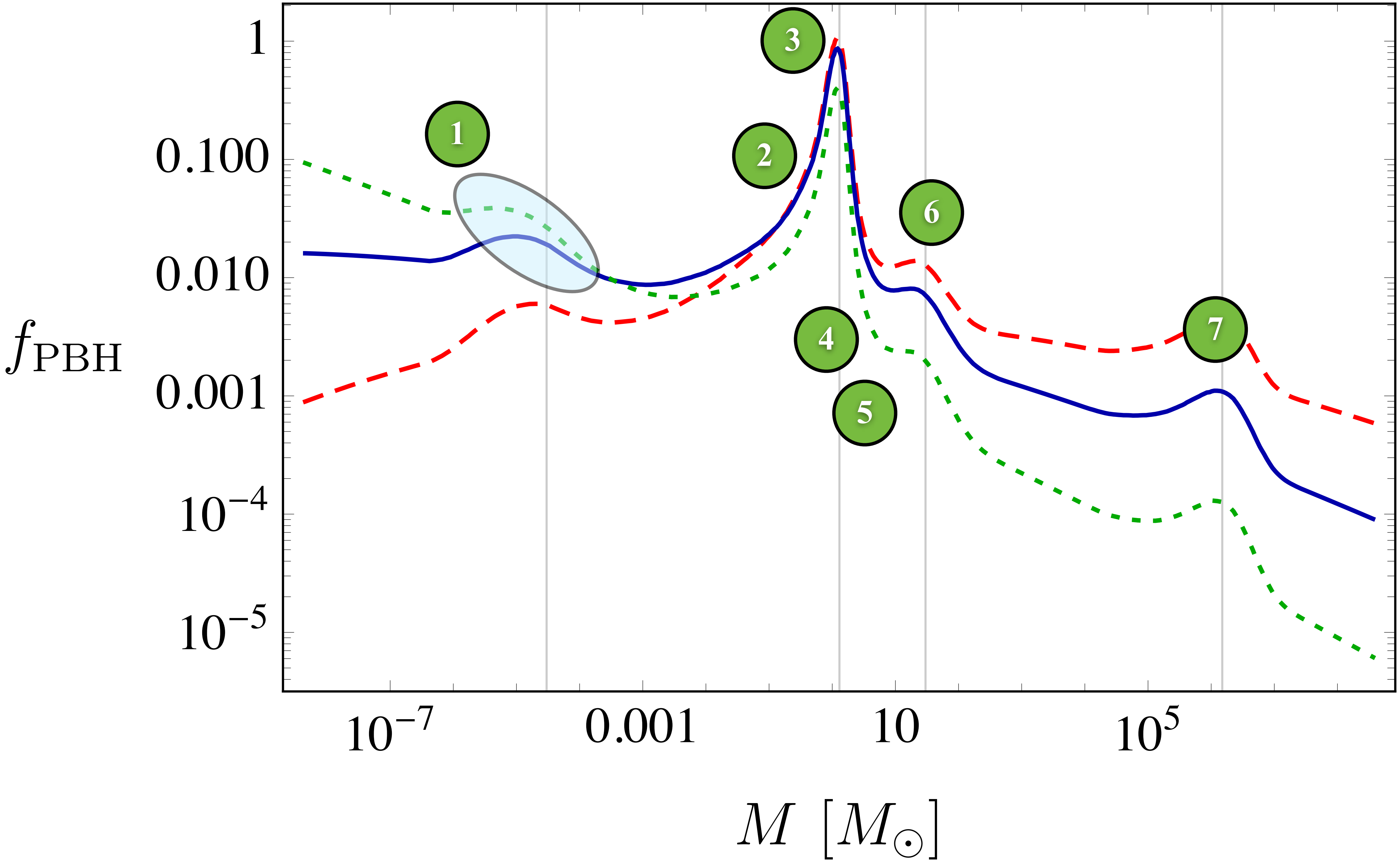




Expected effective spin distribution…
The best that stellar models can do!
from C. Belcynski's talk at 2018 CERN workshop on PBH

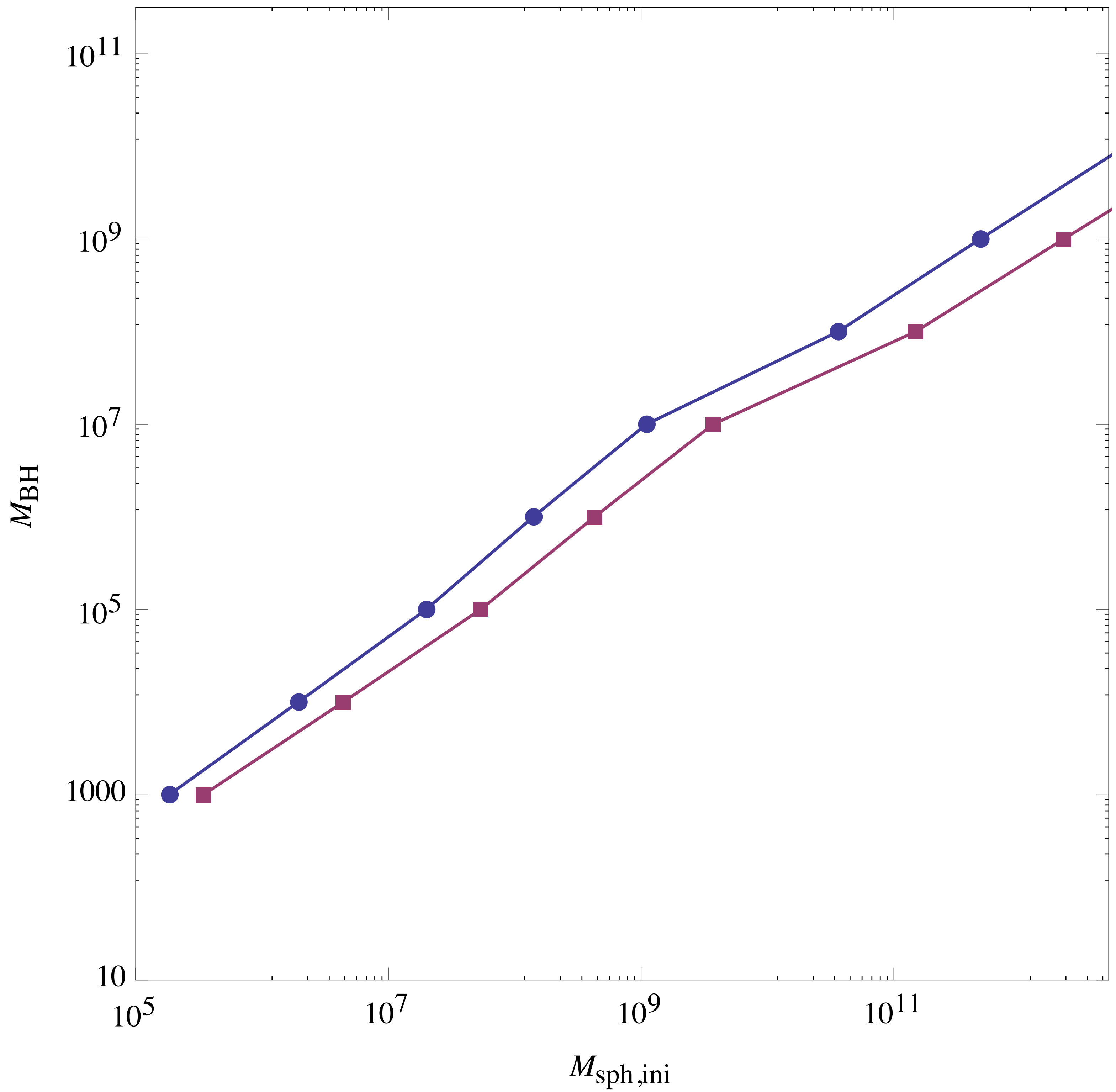
Does our preferred PBH model is supported by some observations?

Niikura et al., 1904.07789



7 Origin of IMBH and SMBH

Origin of IMBH and SMBH ?

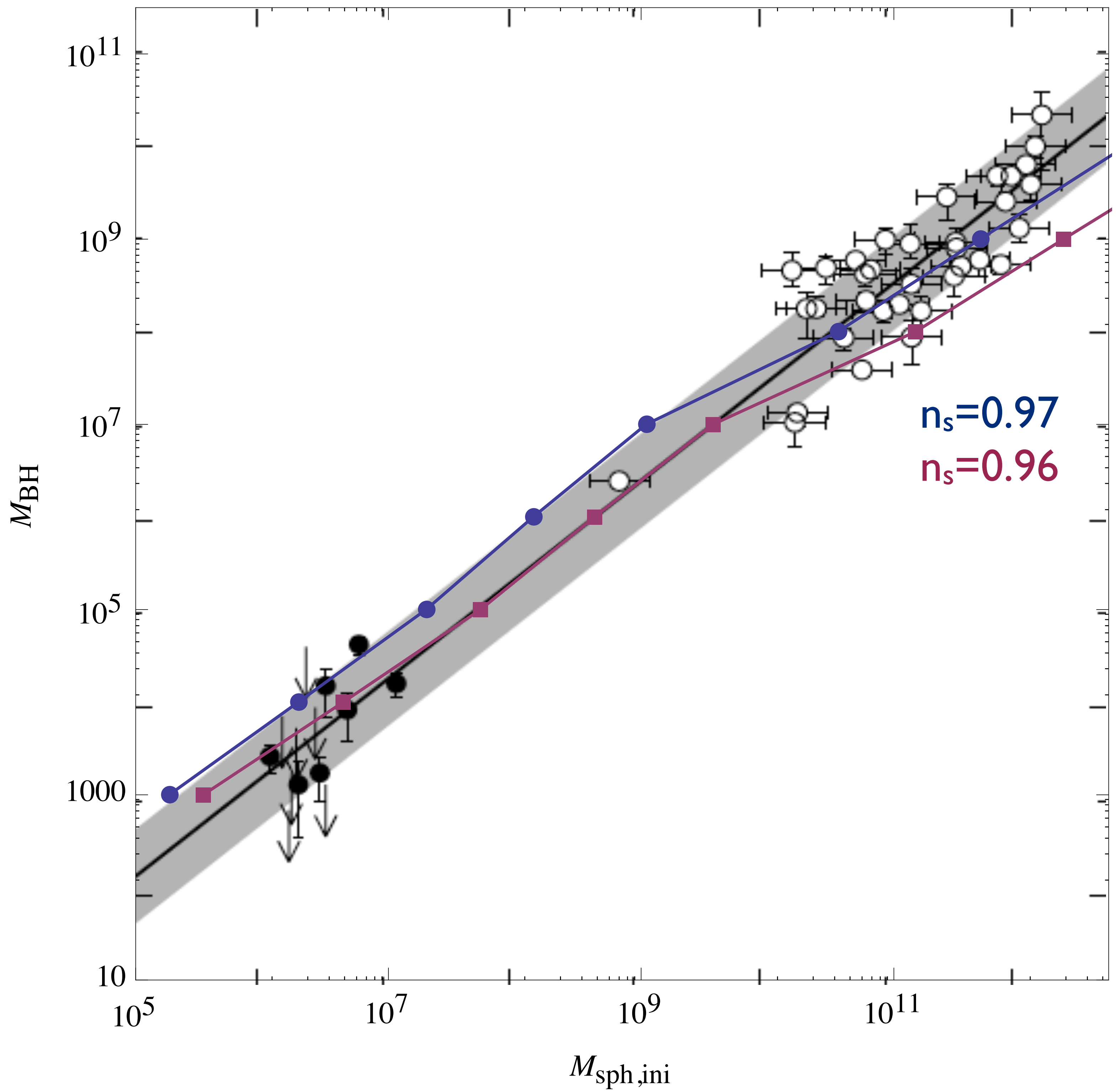


Carr, SC, Garcia-Bellido, Kuhnel, *in preparation*

adapted from **arXiv:1306.0561**

PBH could explain the relation between IMBH/SMBH mass and the mass of the host haloes

Origin of IMBH and SMBH ?



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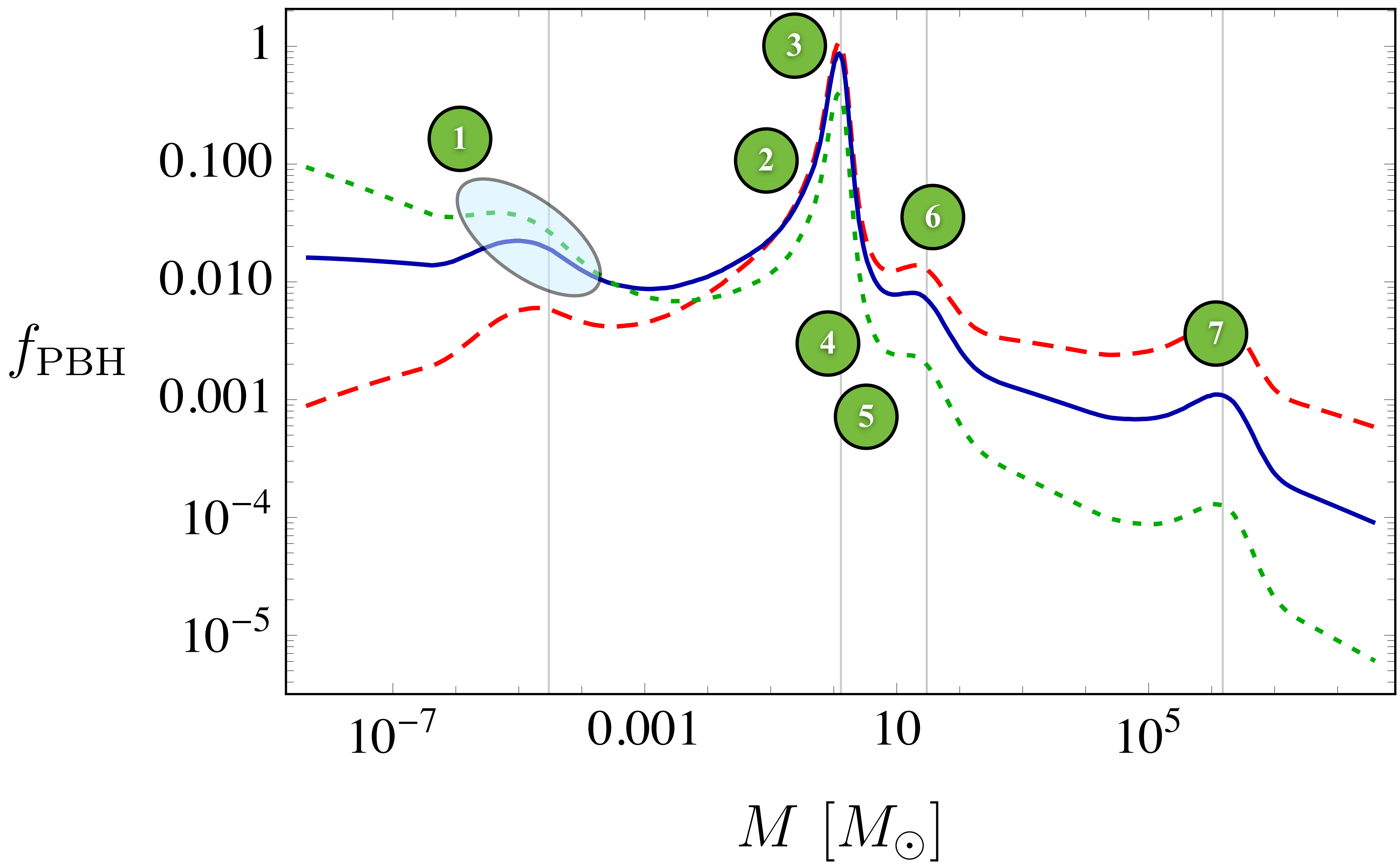
Niikura et al., 1904.07789

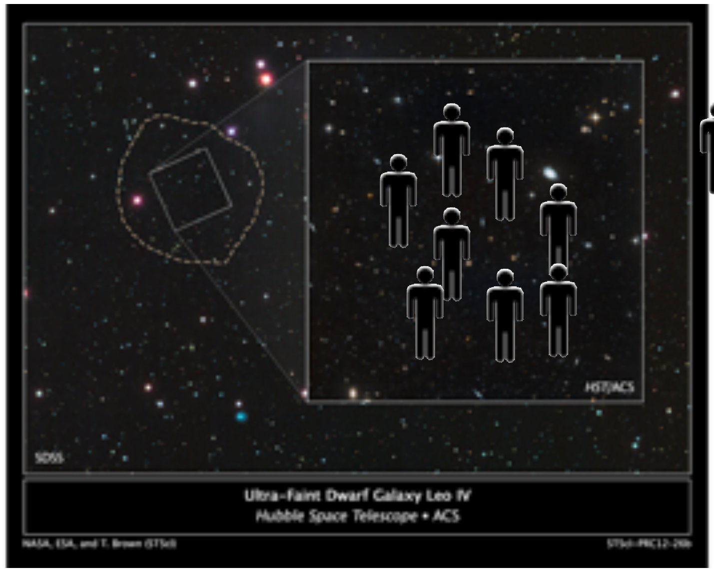


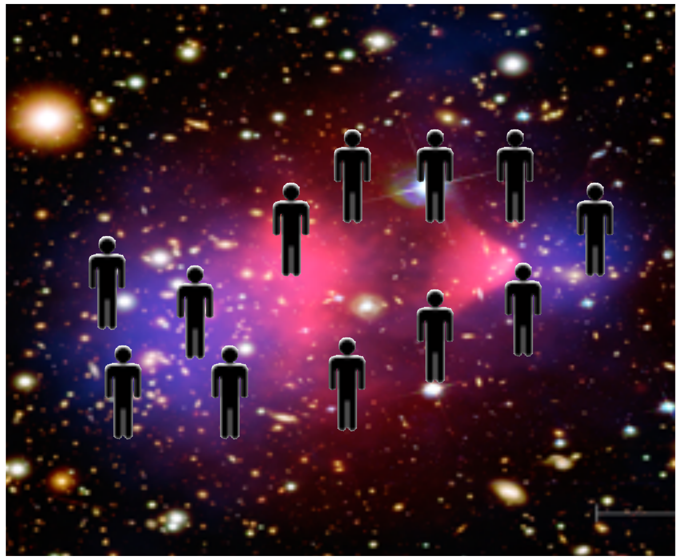
7 Origin of IMBH and SMBH

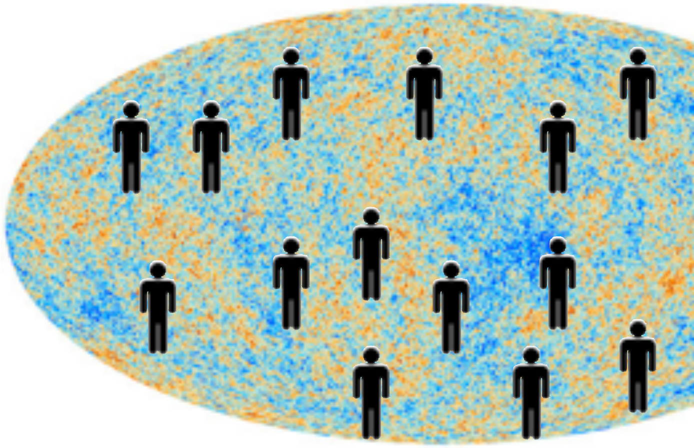
Could they be black holes? Yes !!!

First, they exist!

- dont' interact with normal guys, except gravitationally
OK
- don't emit light
OK
- move slowly
OK
- don't interact with themselves, or only slighly (core-cusp)
OK
- are born in the early Universe
primordial (PBH)
- don't like to live with normal guys in overcrowded flats (dwarf sph.)
OK
- In total, they weight five times normal guys, $\Omega_{DM} = 5.5\ \Omega_b$
OK, + matter-antimatter asymetry
- When they form structures, the expansion of the Universe accelerates (Dark Energy)
?







Fine-tuning problem? No

Do they pass astro/cosmo constraints? Yes

Could they be black holes? *Yes !!!*

First, they exist!

- dont' interact with normal guys, except gravitationally *OK*

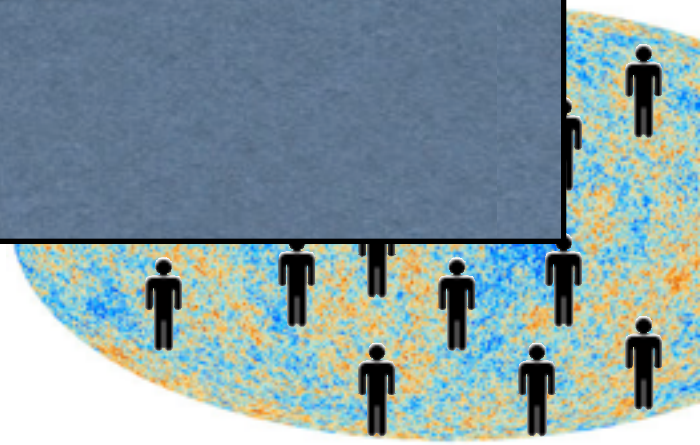
OK

OK

OK

- in overcrowded flats (dwarf sph.) *OK*
- In total, they weight five times normal guys, $\Omega_{DM} = 5.5\ \Omega_b$ *OK, + matter-antimatter asymetry*
- When they form structures, the expansion of the Universe accelerates (Dark Energy) *?*



Fine-tuning problem? No

Do they pass astro/cosmo constraints? Yes

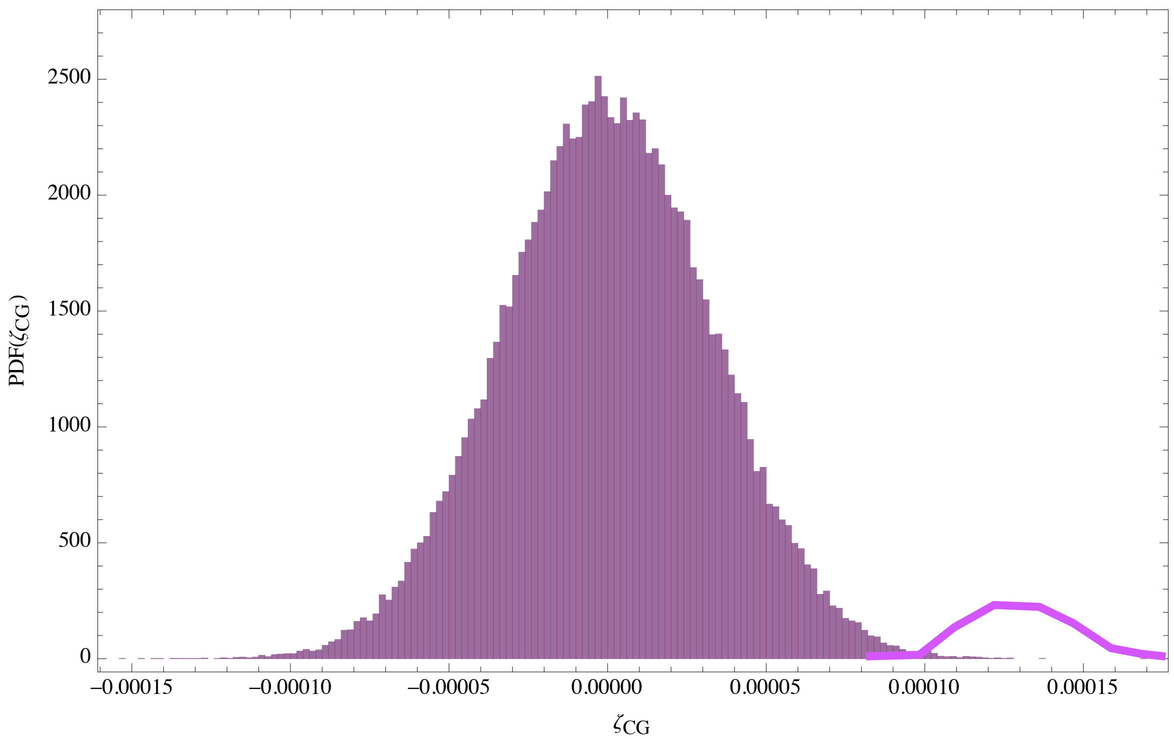
Conclusion: PBH might be the best motivated (both theoretically and observationally) Dark Matter model on the market!
Don't forget them!

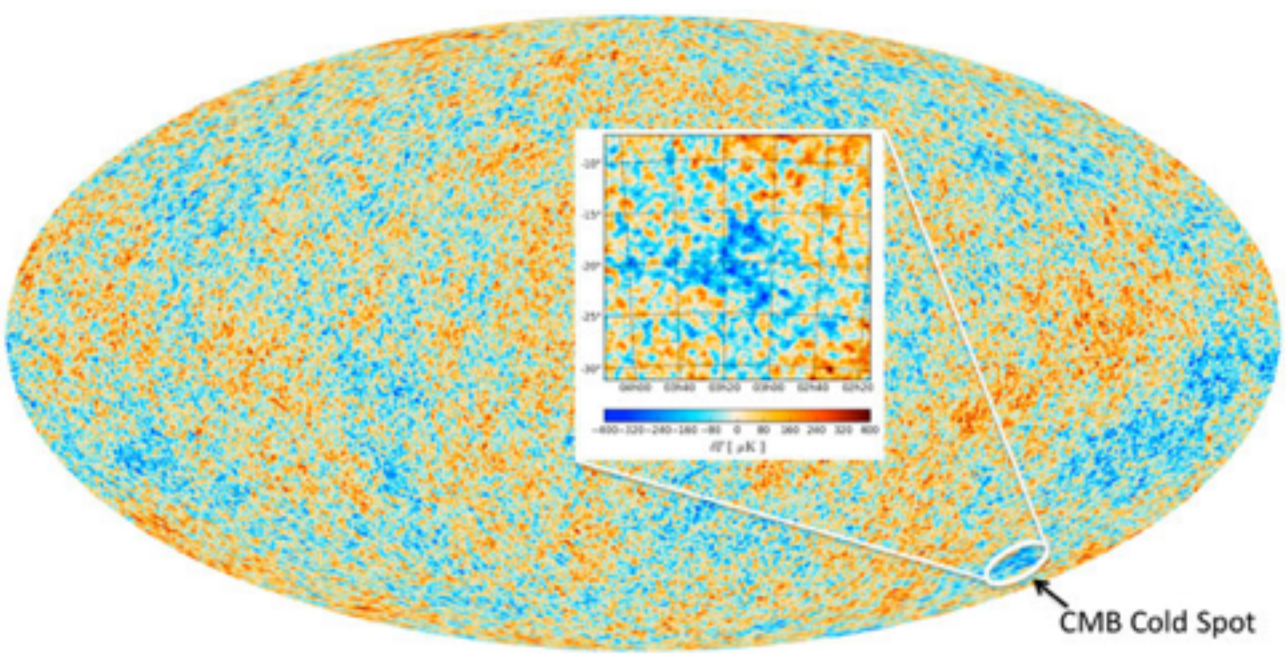
And Dark Energy????

Very crazy idea: There exists a long-standing natural explaination to this coincidence problem: backreactions!

Can gravitational backreactions from non-linear structures mimic Dark Energy?

- in LCDM: impossible due to CMB constraints on the power spectrum (Gaussian perturbations)
- in PBH-DM: a stochastic spectator generates a double peak in the statistical distribution of curvature perturbations.
  Rare large fluctuations exist! (without spoiling CMB)

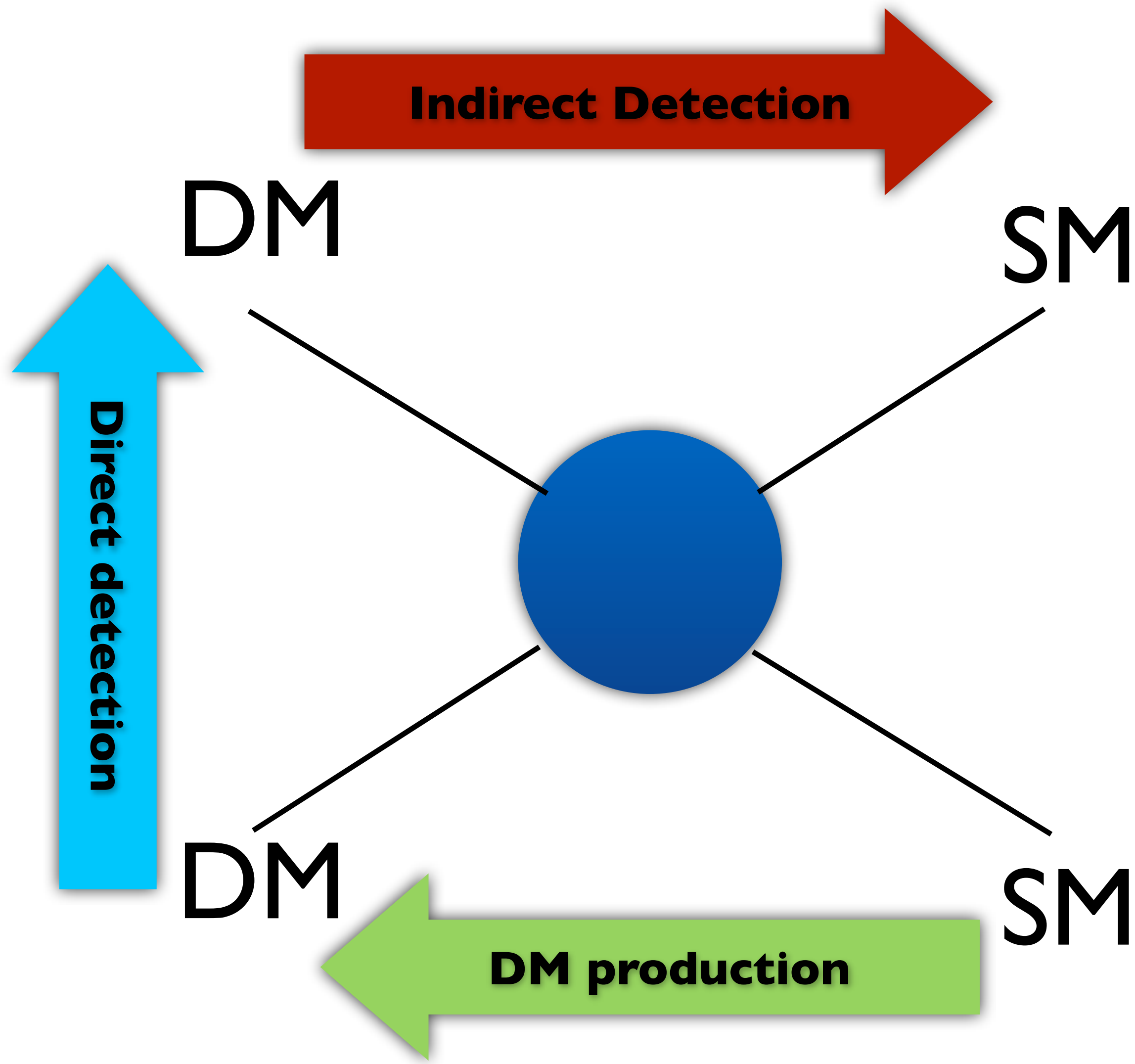




Thank you!

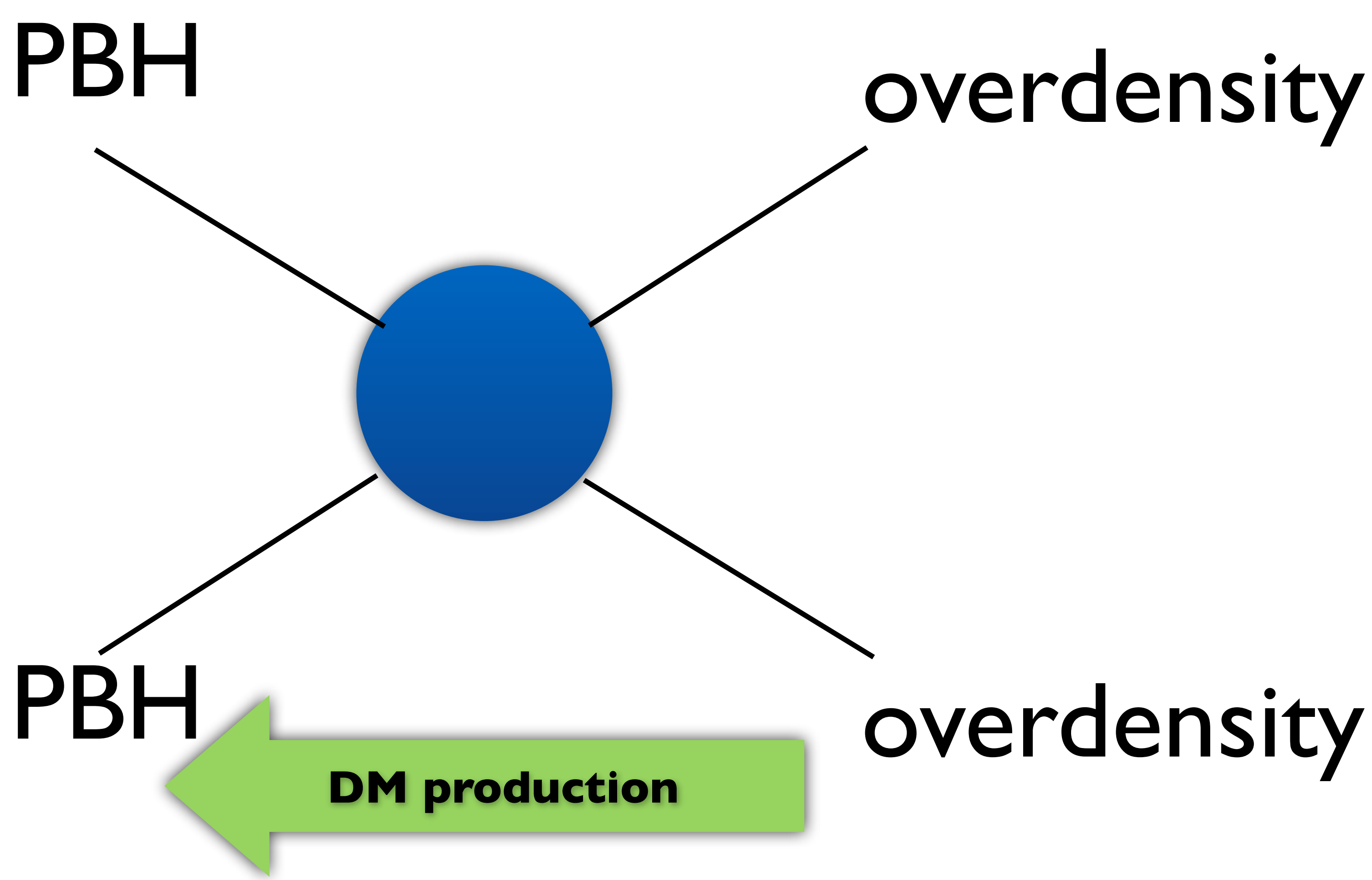
Primordial Black Holes

Rethinking Dark Matter interactions:



Primordial Black Holes

Rethinking Dark Matter interactions: PBH formation

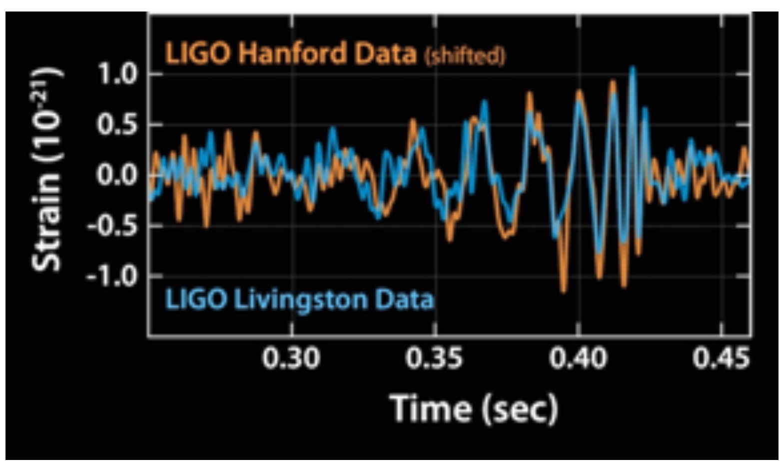


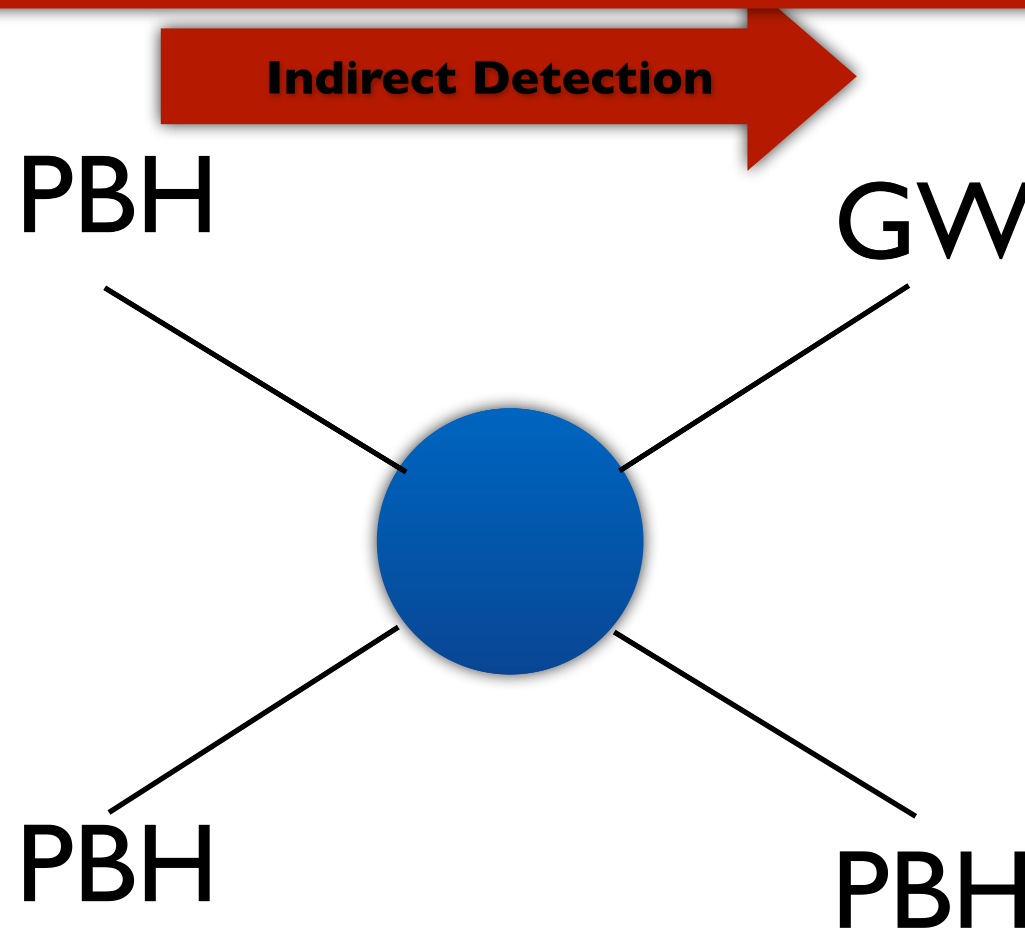
CMB distortions, ultra-compact mini halos
Detectable GW background by Pulsar Timing Arrays (SKA) / **LISA**

Primordial Black Holes

Rethinking Dark Matter interactions: merging of PBH

GW from BH mergers detected by LIGO,
constraints from Dark Radiation, detectable SGWB by LISA





Clue I: LIGO merger rates compatible with PBH-DM

Bird et al ; S.C., J. Garcia-Bellido ; M. Sasaki, T. Suyama, S. Yokoyama, March 2016

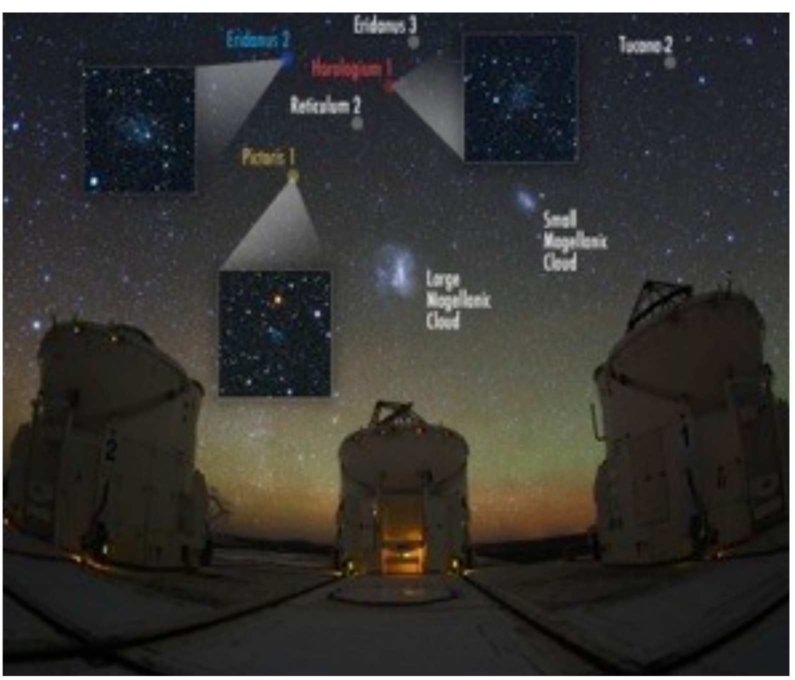
Clue II: Low spin and mass of black hole progenitors

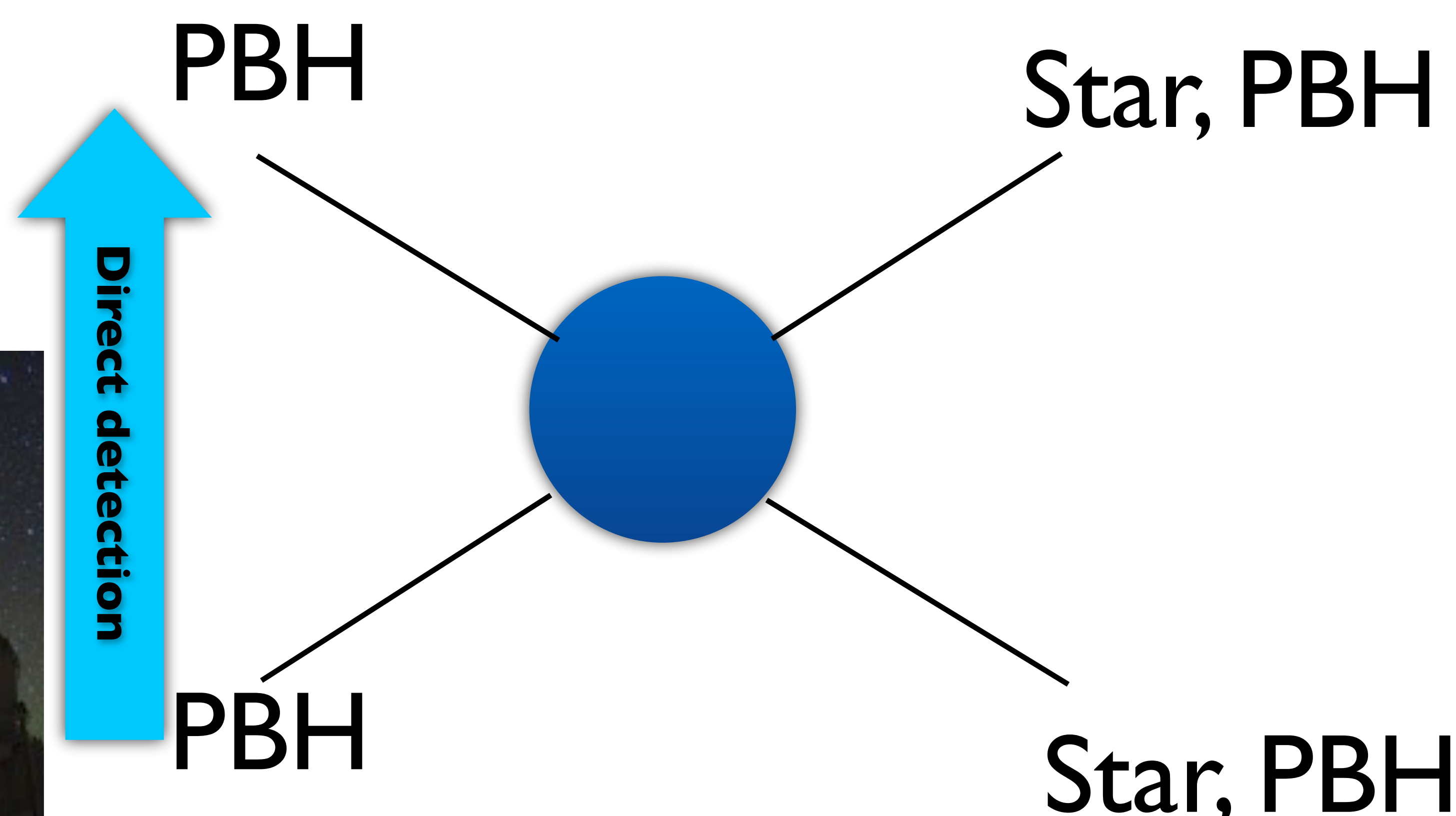
Next step: Black hole below Chandrasekhar mass (ET), SGWB

Primordial Black Holes

Rethinking Dark Matter interactions: Gravitational scattering

Ultra-faint
dwarf galaxies,
core/cusp problem





Clue 3: observations of faint dwarf galaxies and their star clusters

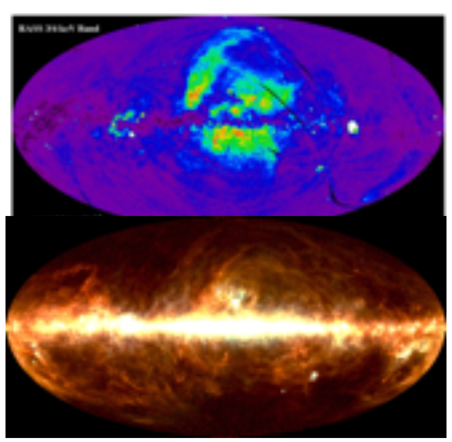
Primordial Black Holes

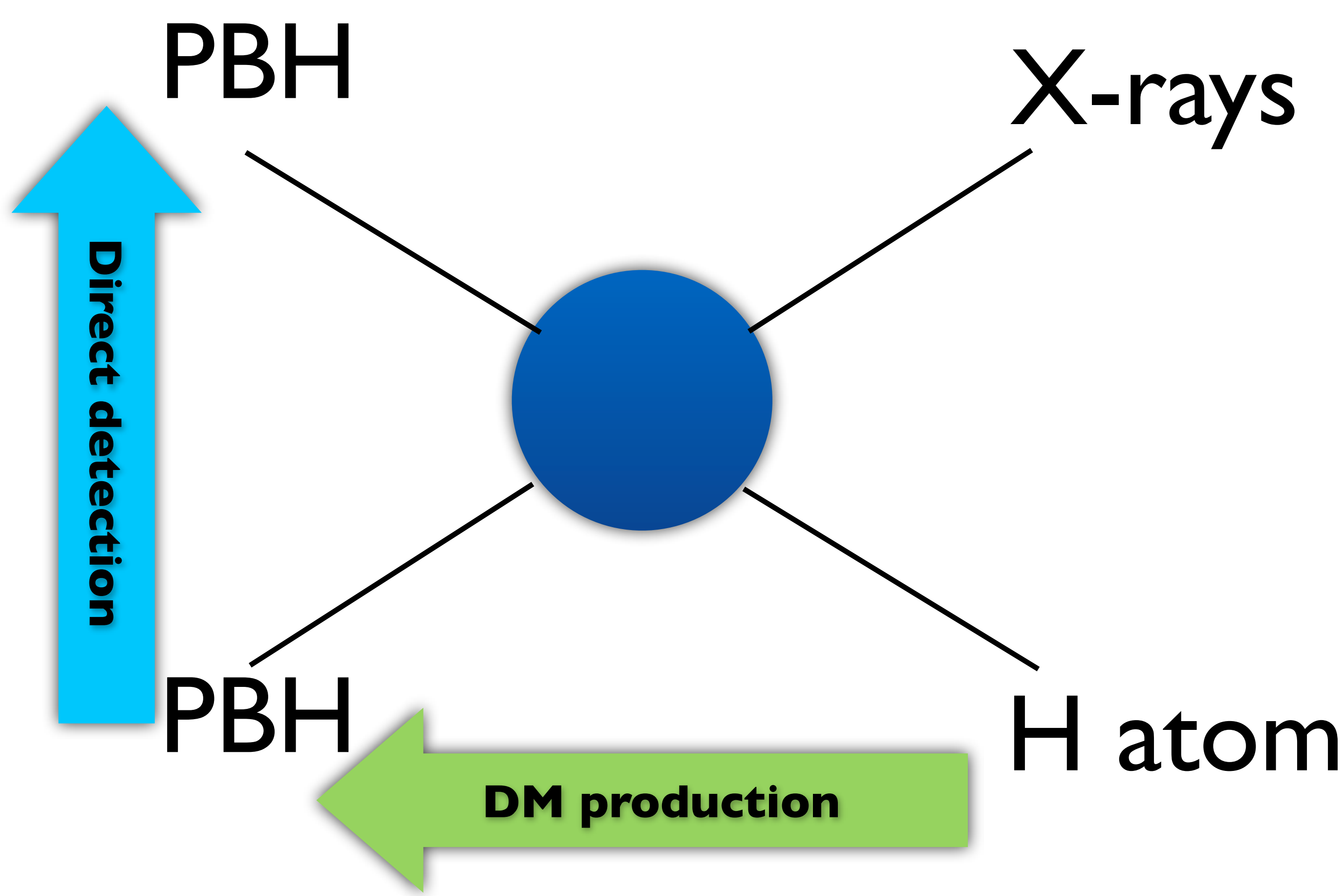
Rethinking Dark Matter interactions: accretion onto PBH

Clue 5: Correlations between X-ray and infrared backgrounds

Clue 6: Observations of early super-massive BH

X-ray background radiation,
CMB signatures,
21cm signal (SKA)



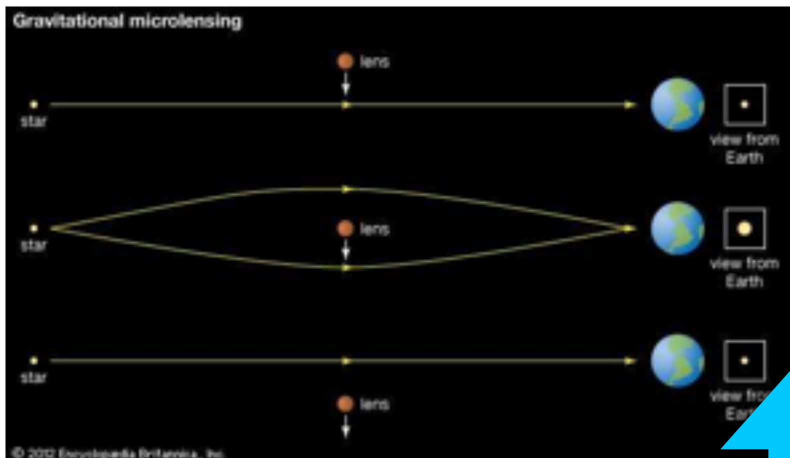


Could explains the mass-to-light ratios in dwarf galaxies, missing stellites, super-massive black holes...

Primordial Black Holes

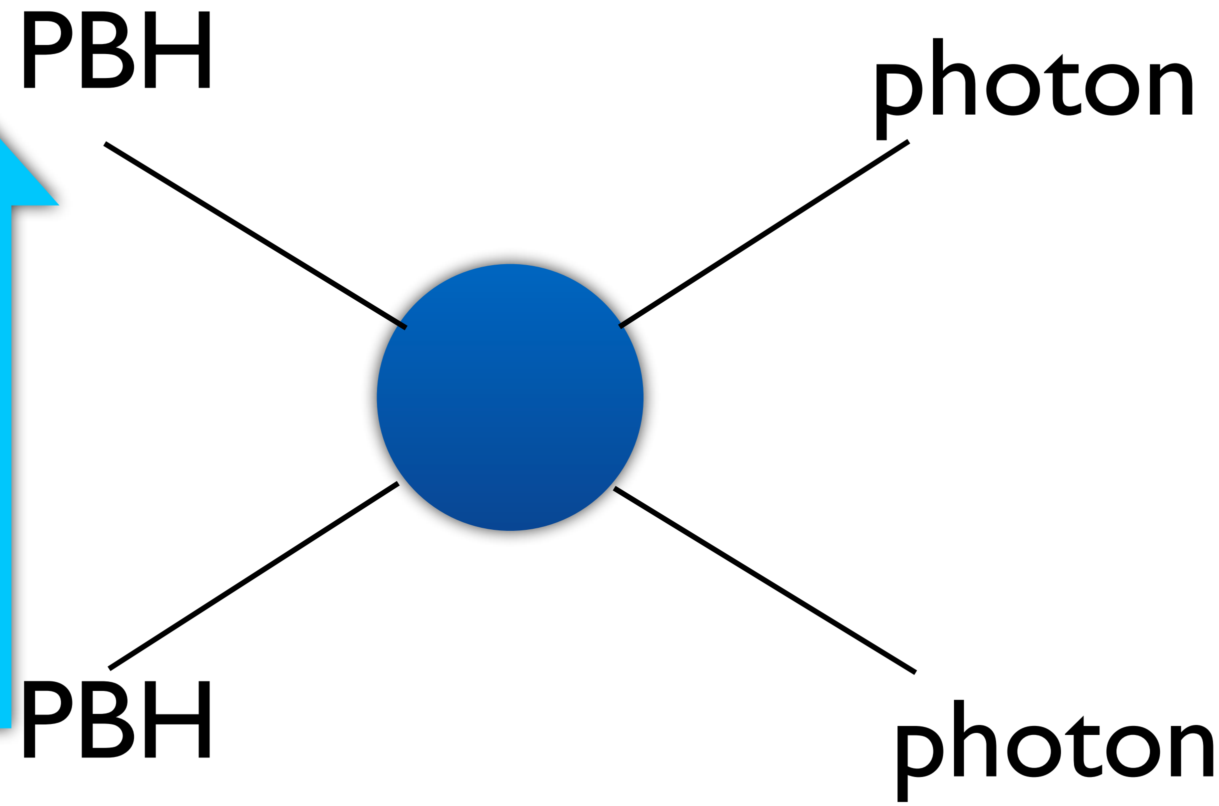
S.C., J. Garcia-Bellido, 1711.10458; ***SciAm****, July 2017*

Rethinking Dark Matter interactions: microlensing surveys



Microlensing
of stars in Andromeda
and distant quasars,
lensing of supernovae

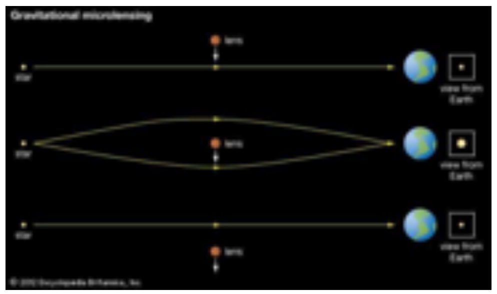
Direct detection

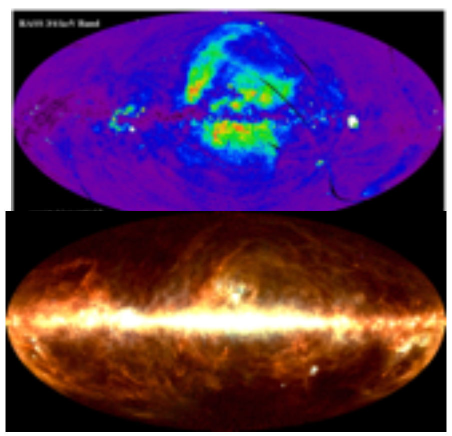


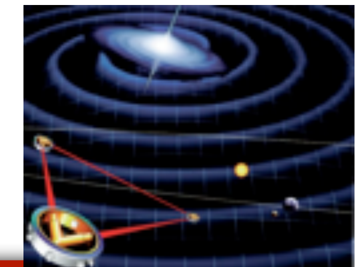
Clue 7: between 15% and 35% of sub-solar compact objects in galactic halos

Primordial Black Holes

Exciting times, multiple probes, some clues in observations, upcoming experiments will challenge the scenario...







PBH

Indirect Detection

photon, H, star, PBH, GW, overdensity

Direct detection

PBH

DM production

photon, H, star, PBH, GW, overdensity