Sebastien Clesse
Service de physique Théorique, University of Brussels (ULB)

Primordial Black Holes

Gravitational-wave signatures and contribution to the Dark Matter

GW Primordial Cosmology Workshop - Paris - May 17-19, 2021

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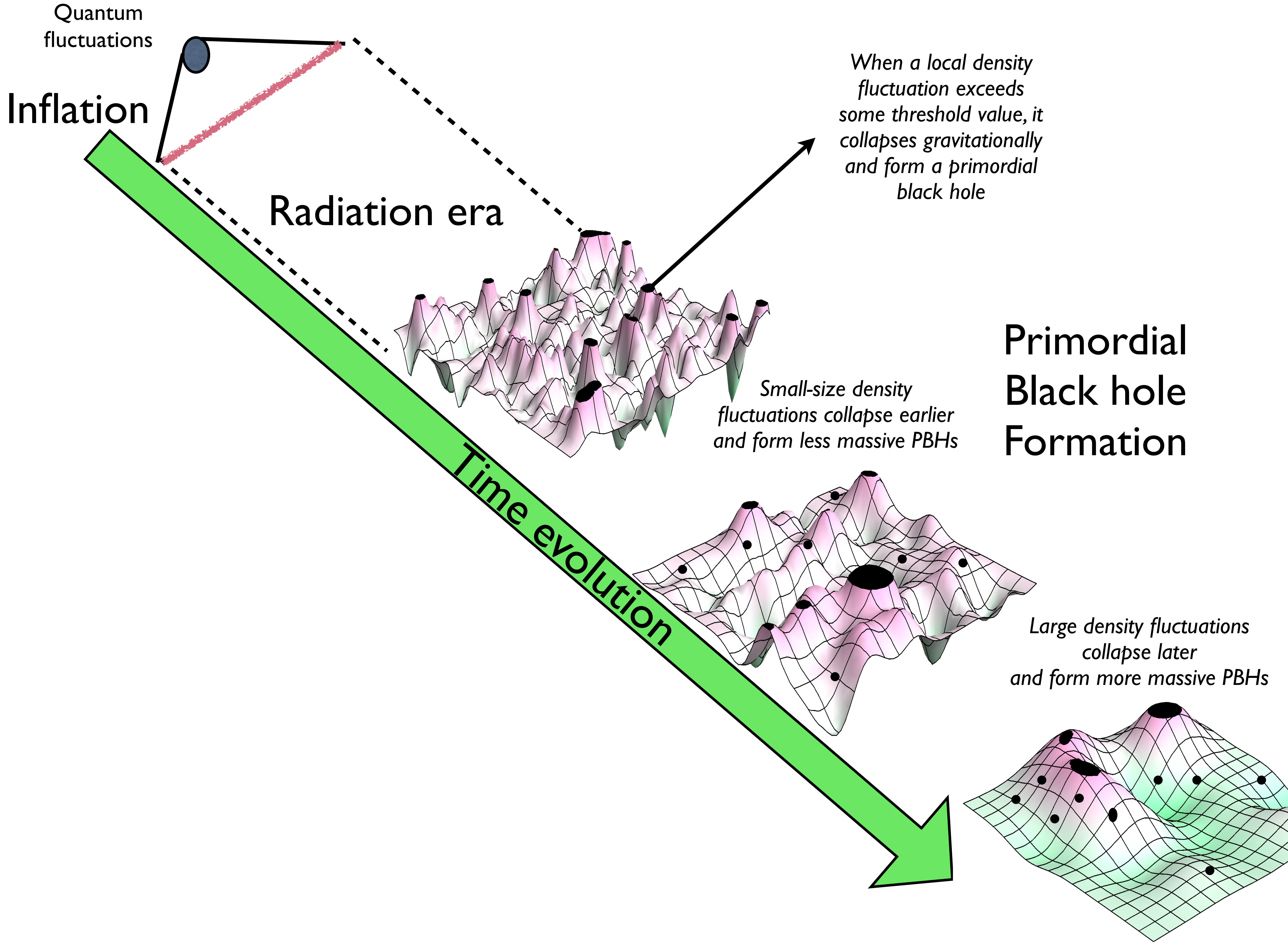
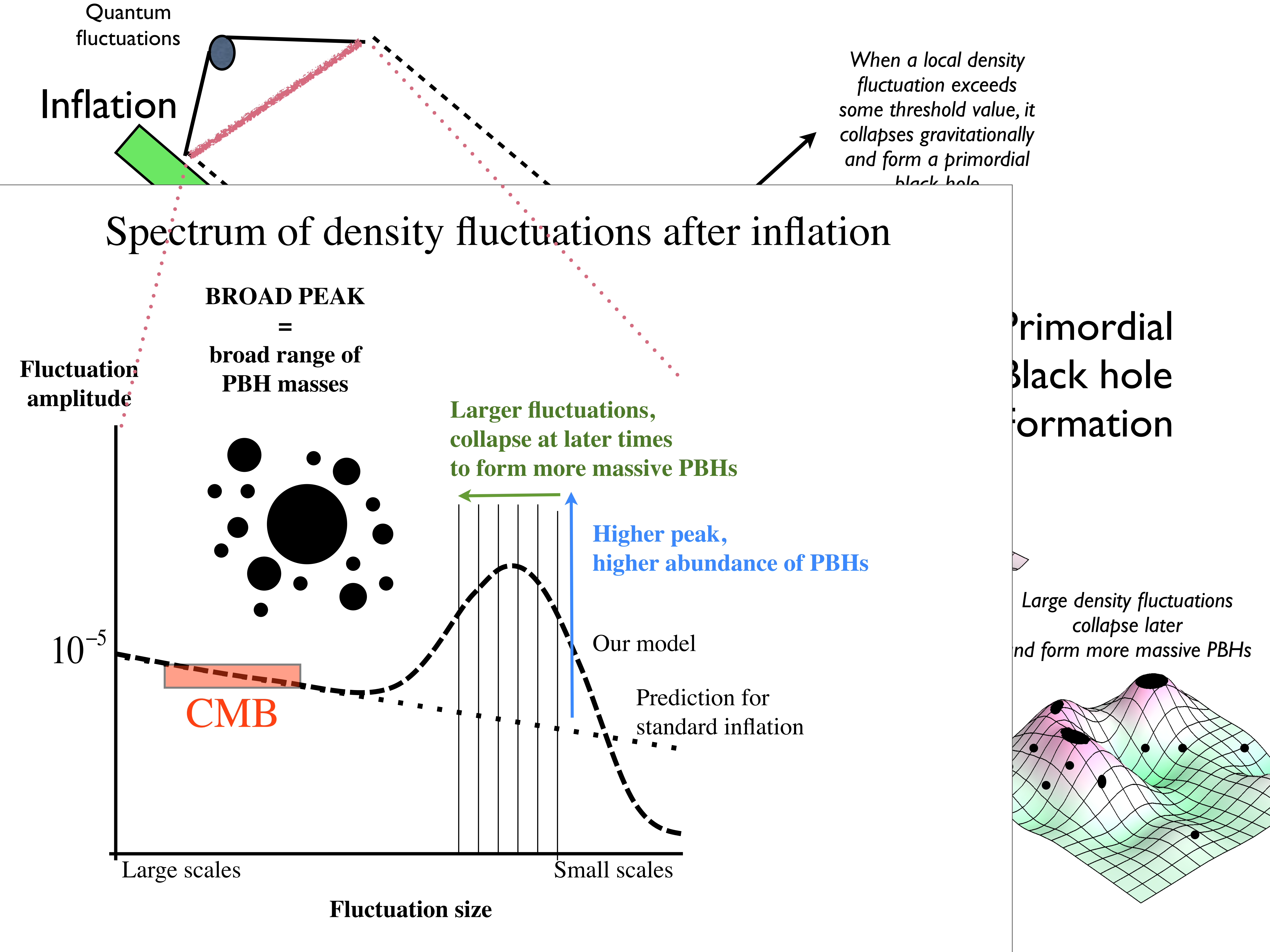
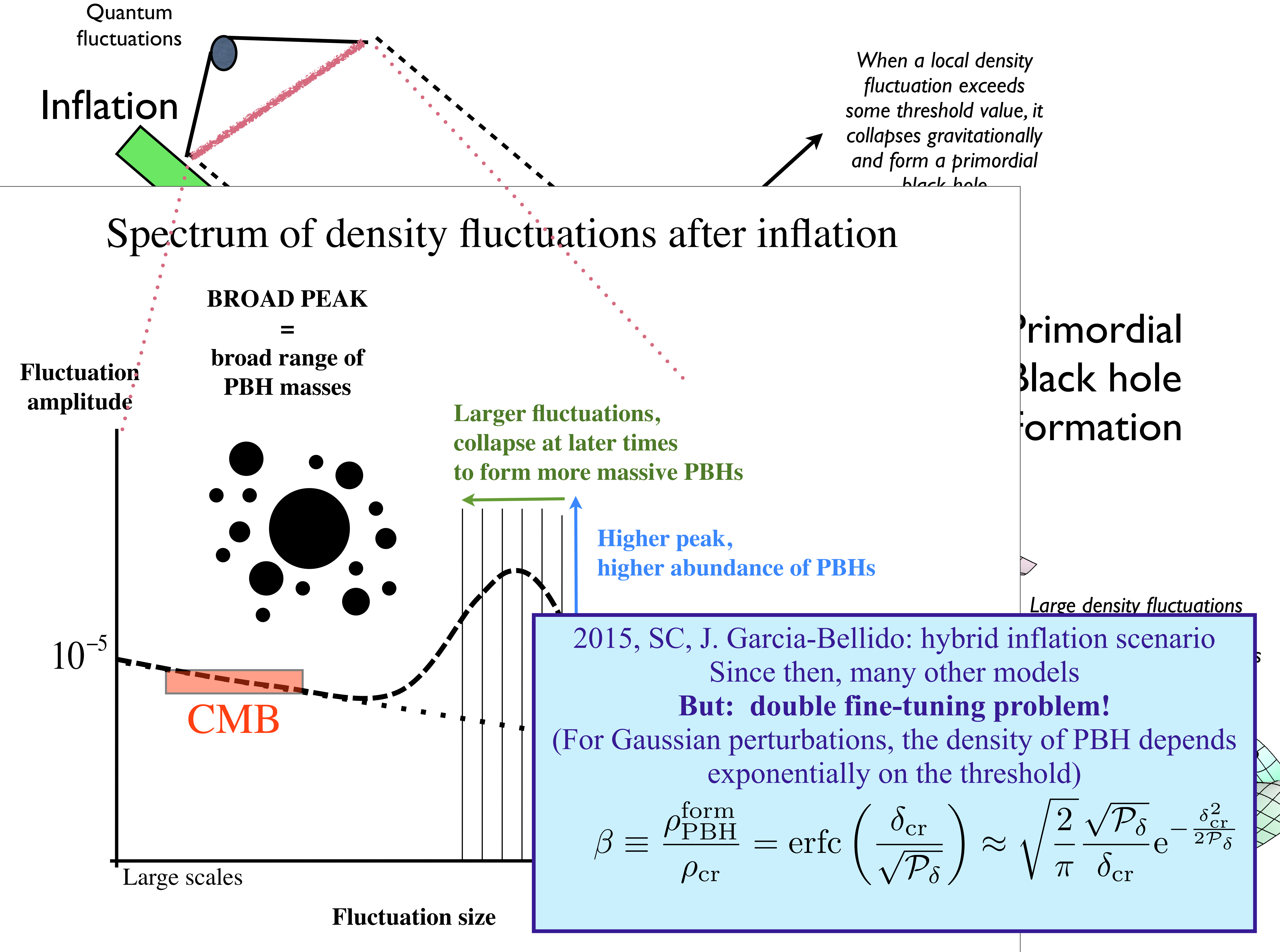

Quantum fluctuations
Inflation
Radiation era
When a local density fluctuation exceeds some threshold value, it collapses gravitationally and form a primordial black hole
Primordial Black hole Formation
Small-size density fluctuations collapse earlier and form less massive PBHs
Time evolution
Large density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

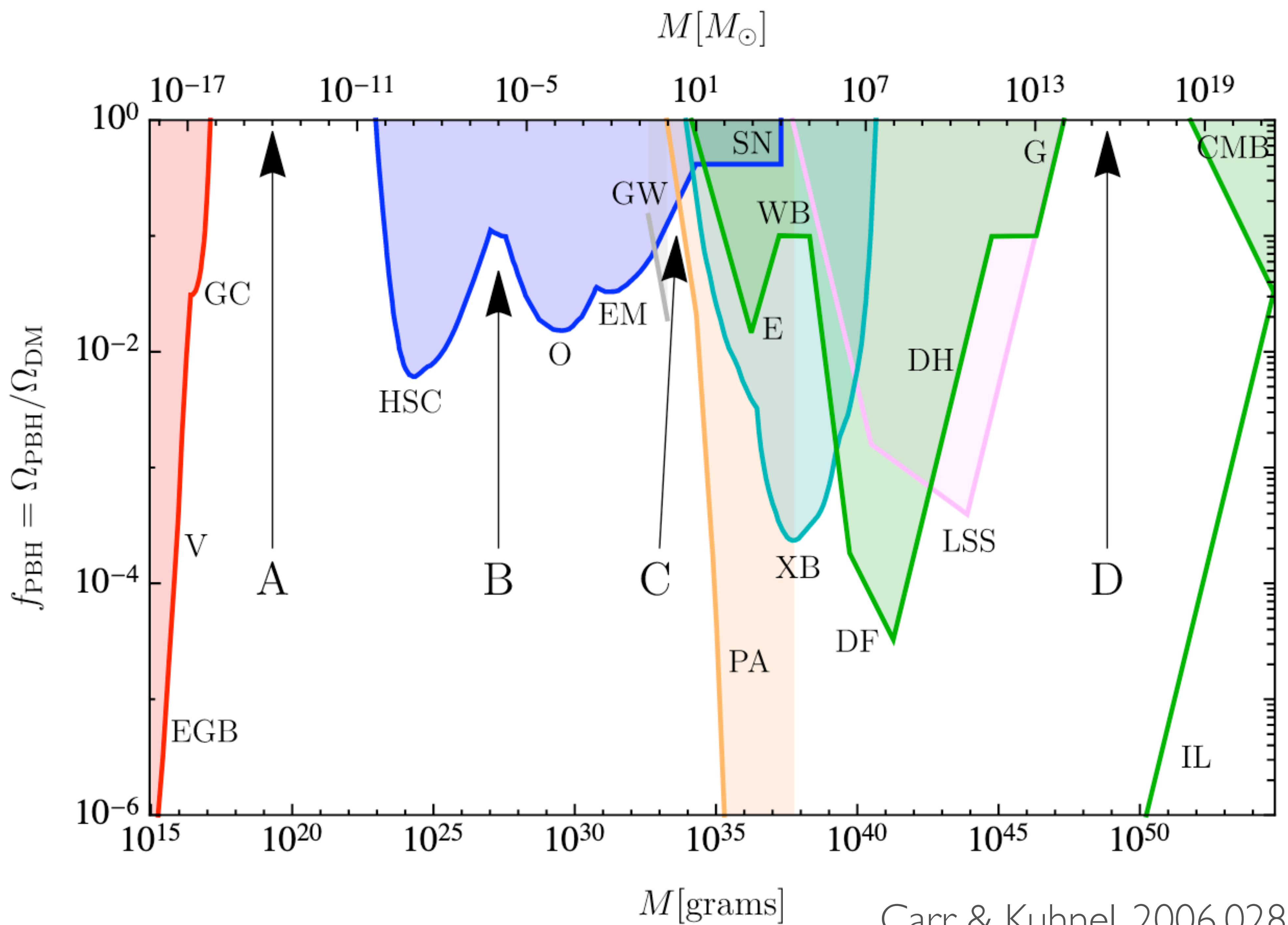
Spectrum of density fluctuations after inflation



2015, SC, J. Garcia-Bellido: hybrid inflation scenario
Since then, many other models
But: double fine-tuning problem!
(For Gaussian perturbations, the density of PBH depends exponentially on the threshold)

$$\beta \equiv \frac{\rho_{\rm PBH}^{\rm form}}{\rho_{\rm cr}} = {\rm erfc}\left(\frac{\delta_{\rm cr}}{\sqrt{\mathcal{P}_\delta}}\right) \approx \sqrt{\frac{2}{\pi}}\frac{\sqrt{\mathcal{P}_\delta}}{\delta_{\rm cr}} {\rm e}^{-\frac{\delta_{\rm cr}^2}{2\mathcal{P}_\delta}}$$

Astro/cosmo limits

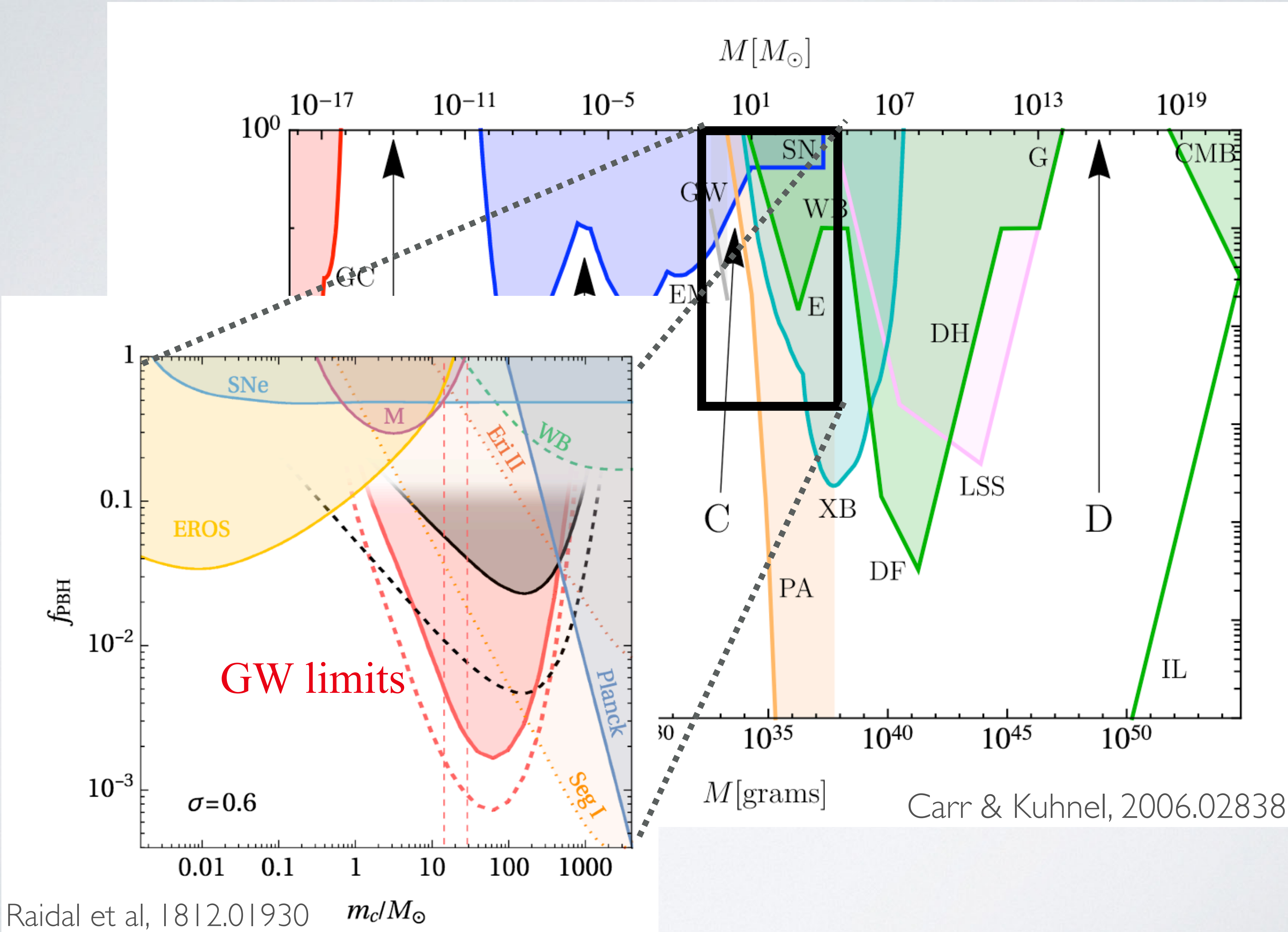


Carr & Kuhnel, 2006.02838

Hawking radiation | Microlensing | Dynamical effects

LIGO-Virgo / PTAs | Accretion | Large scale structures

Astro/cosmo limits



Carr & Kuhnel, 2006.02838

Raidal et al, 1812.01930

Conclusion

- PBHs need **O(1) density fluctuations**. CMB observations: $O(10^{-5})$
- Their amplitude to get $\Omega_{PBH} \sim \Omega_{DM}$ must be **fine-tuned**
- No reason for $\mathbf{m_{PBH}}$ **~ stellar-mass** (or any other specific mass)
- Need of an **exotic**, peaky, double-fine-tuned (inflation) model
- Very strong **astrophysical/cosmological limits** on the PBH abundance at (almost) all mass scales, hardly to evade…

Therefore, PBHs are not a natural dark matter candidate. Very likely they do not exist…

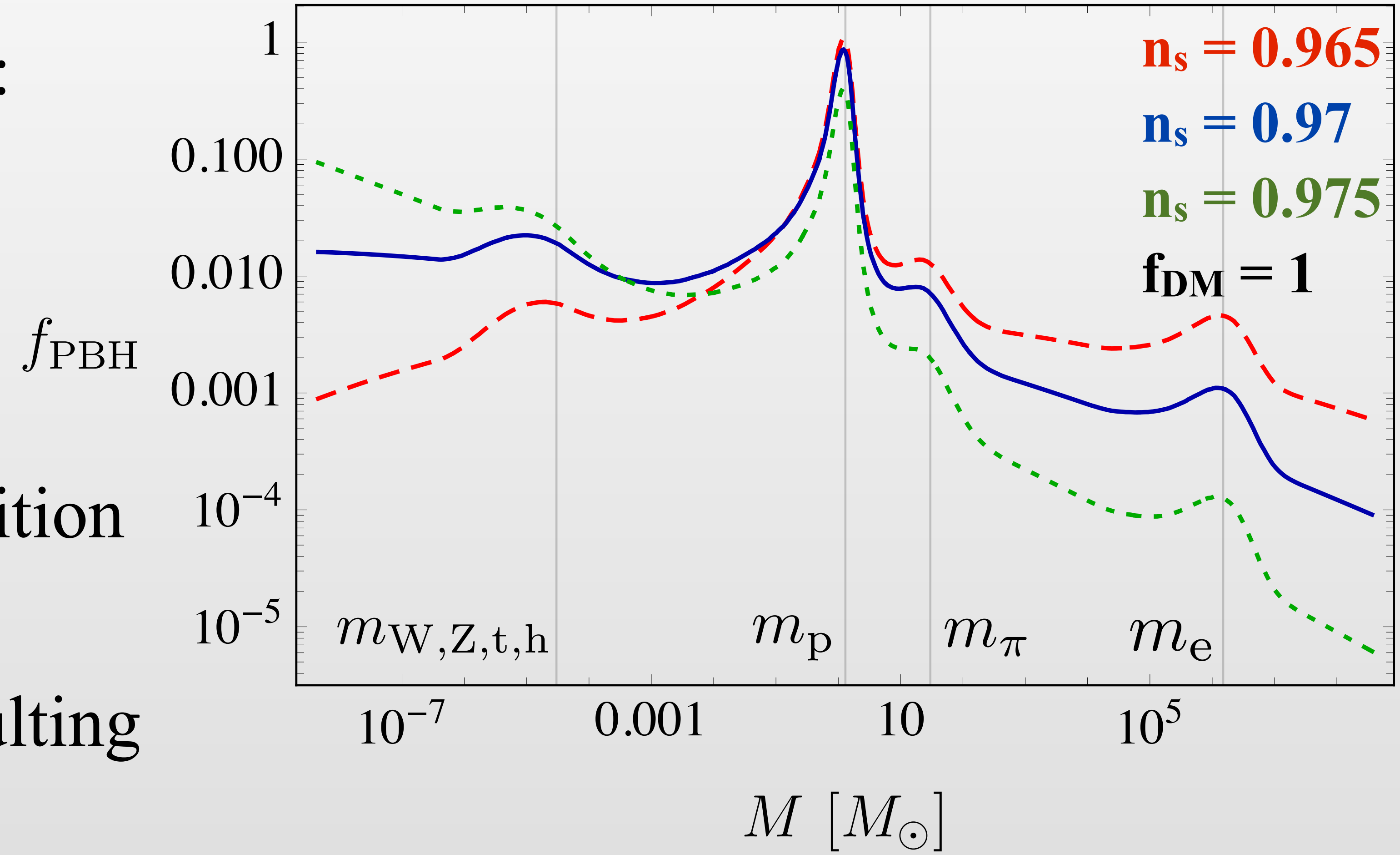
…so my talk is done and I stop working on PBHs?

PBH formation

at the QCD phase transition

From *known* thermal history:

- Change in the relativistic degrees of freedom
- Equation of state reduction, particularly at the QCD transition
- Critical threshold is reduced
- Boosted PBH formation, resulting in a bumpy mass function



Jedamzik, astro-ph/9605152
Cardal & Fuller, astro-ph/9801103
Byrnes et al., 1801.06138

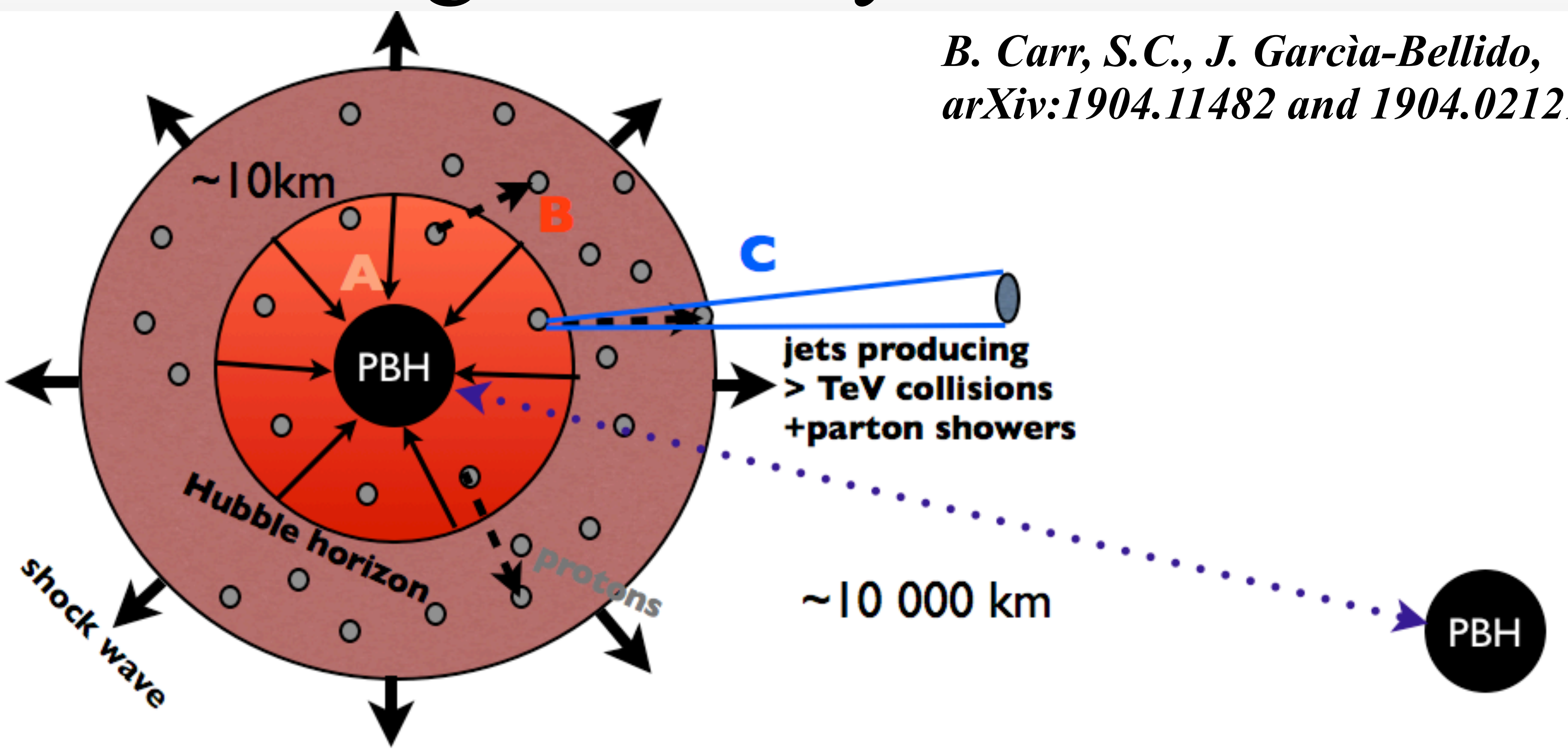
B. Carr, S.C., J. Garcìa-Bellido, F. Kühnel
arXiv:1906.08217

- **Nearly scale-invariant spectrum**
- **Spectral index: $n_s = 0.97$**
- **Peak at ~[2-3] $M_\odot$**
- **Second peak at ~30 $M_\odot$**
- **Two bumps at 10^{-6} and 10^6 $M_\odot$**

Primordial Black Holes

as a common origin of baryons and dark matter

B. Carr, S.C., J. Garcìa-Bellido,
arXiv:1904.11482 and 1904.02129



<u>*Sakharov's Conditions:*</u>

- C and CP violation: of the standard model
- Baryon number violation: sphaleron transitions from >TeV collisions
- Interactions out of thermal equilibrium: PBH collapse/shock wave

Eletroweak baryogenesis: need of exotic physics.

Hot-spot Electroweak Baryogenesis: <u>Gravitation</u>

<u>Explains the abondance of DM/baryon and baryon/photon ratios!</u>

Primordial Black Holes

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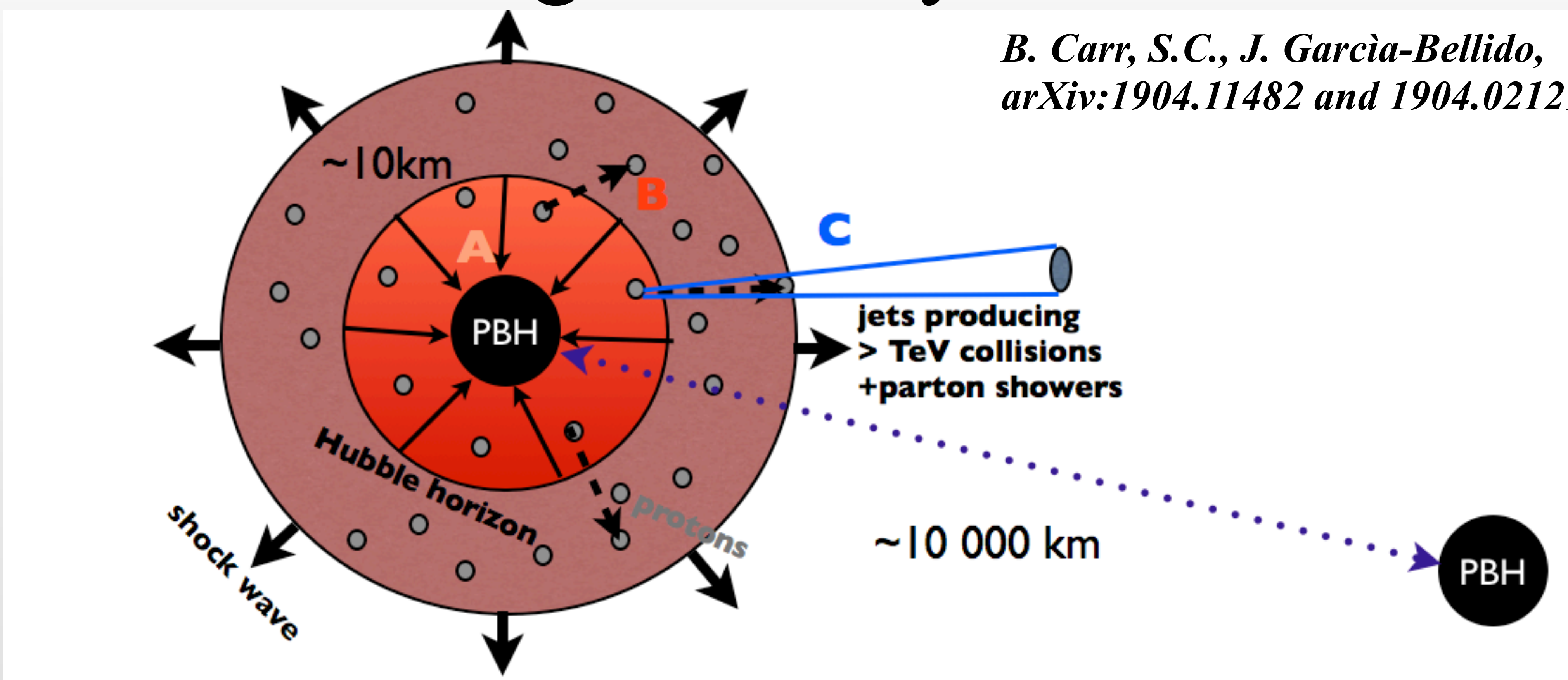


see also (in another context): Asaka, Shaposhnikov et al., *PRL 2004, hep-ph/0310100*

Proton number density: $n_{\rm p}(x) \approx 10^{40}{\rm cm}^{-3}$

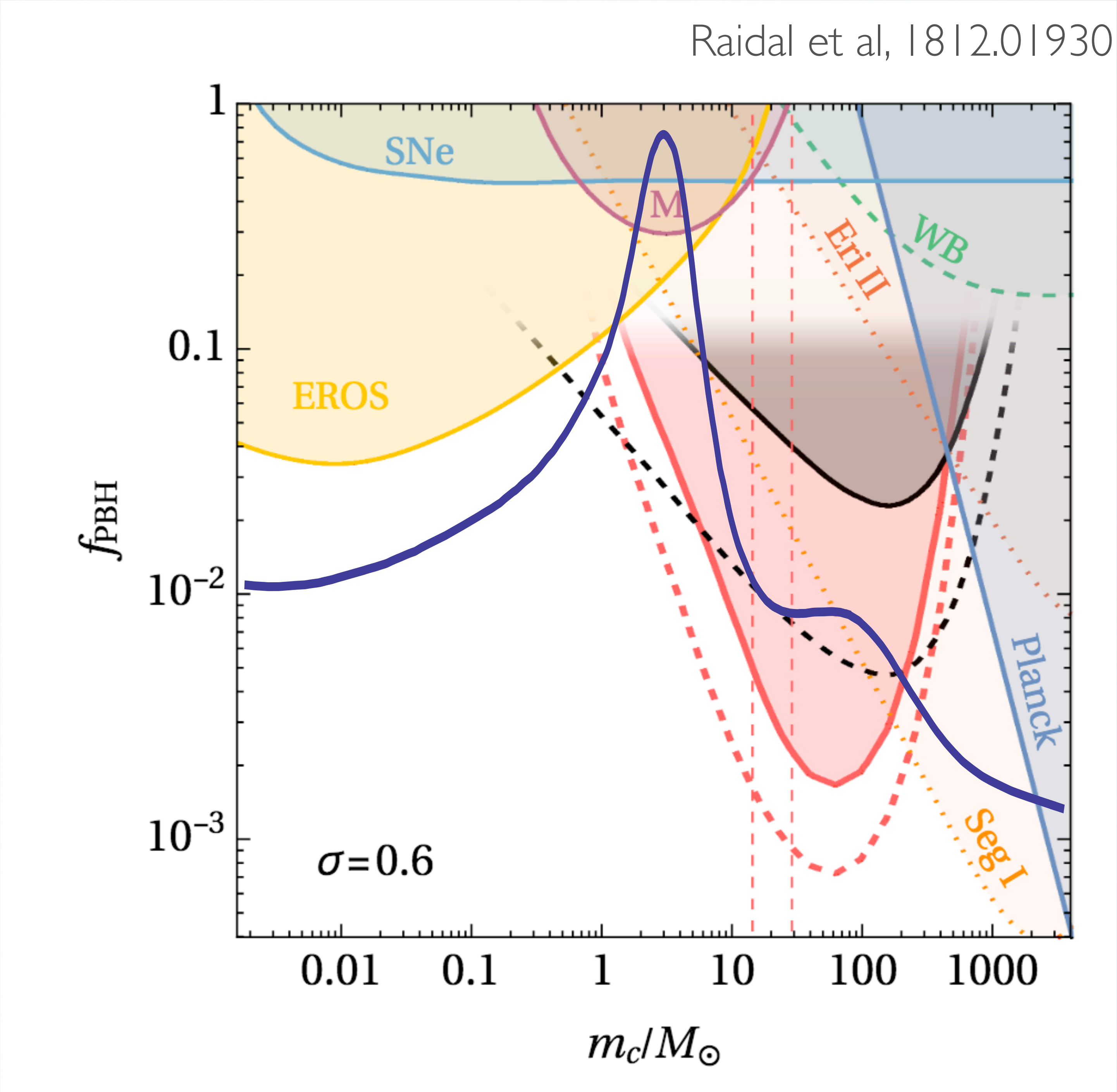
Energy per proton: $E_0 = \frac{\Delta K}{n_{\rm p}\Delta V} > 10\,{\rm TeV}$ **above sphaleron barrier**

Maximal-local baryon asymmetry: $\eta \equiv n_{\rm b}/n_\gamma \sim \delta_{\rm CP}(T) \gg 1$

$\delta_{\rm CP}(T) = 3\times 10^{-5}\,(20.4\,{\rm GeV}/T)^{12}$

Total baryon asymmetry: $\beta \equiv \frac{\rho_{\rm PBH}^{\rm form}}{\rho_{\rm cr}} \approx 10^{-9} \approx \eta_{\rm \,obs}$ **Horizon-PBH mass ratio:** $\frac{\Omega_{\rm DM}}{\Omega_{\rm b}} \approx \frac{\gamma}{1-\gamma} \simeq 5$

Astro/cosmo limits



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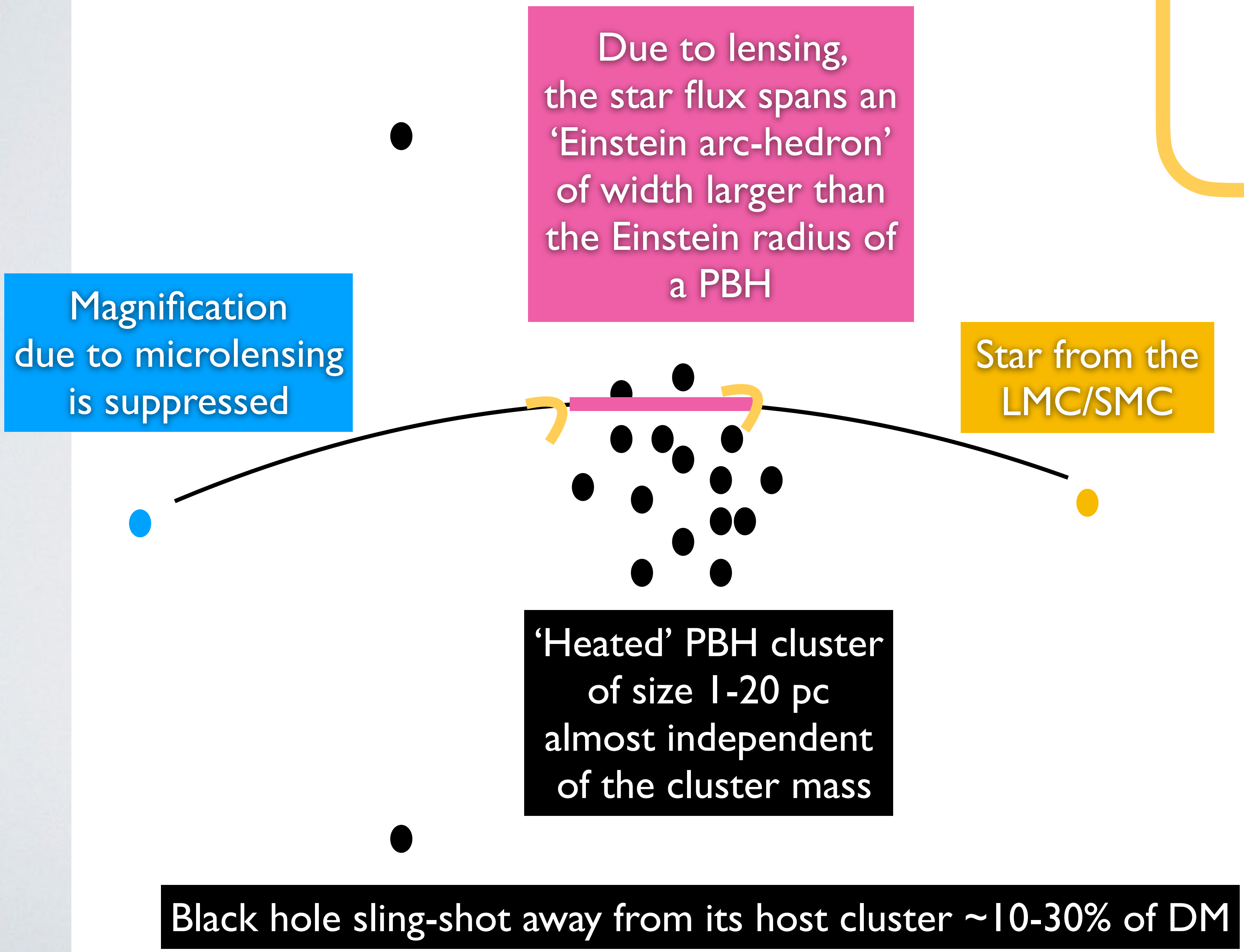
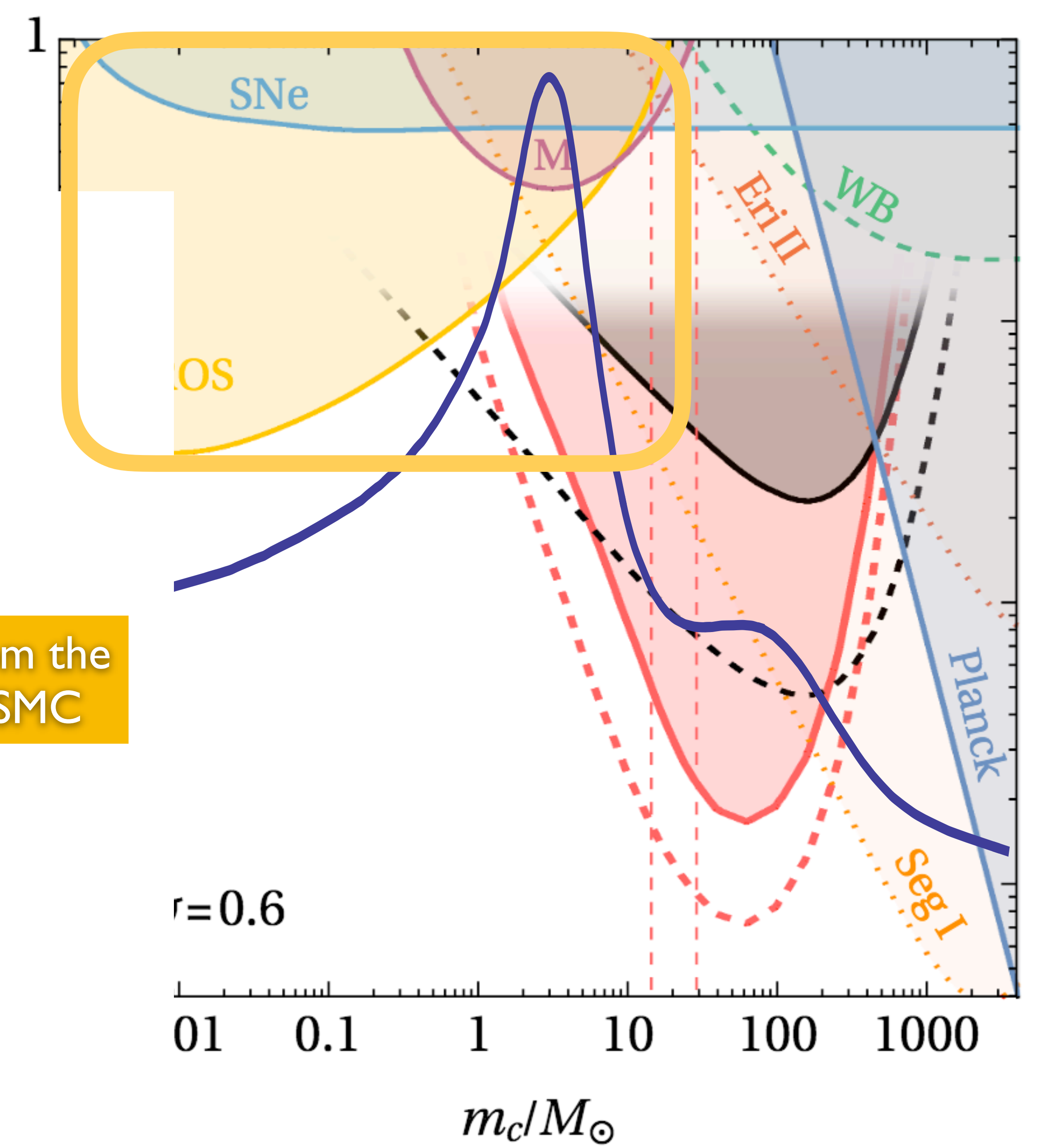
Astro/cosmo limits

Microlensing limits evaded if 80% PBHs are regrouped in clusters



Raidal et al, 1812.01930



B. Carr, S.C., J. Garcìa-Bellido, F. Kühnel
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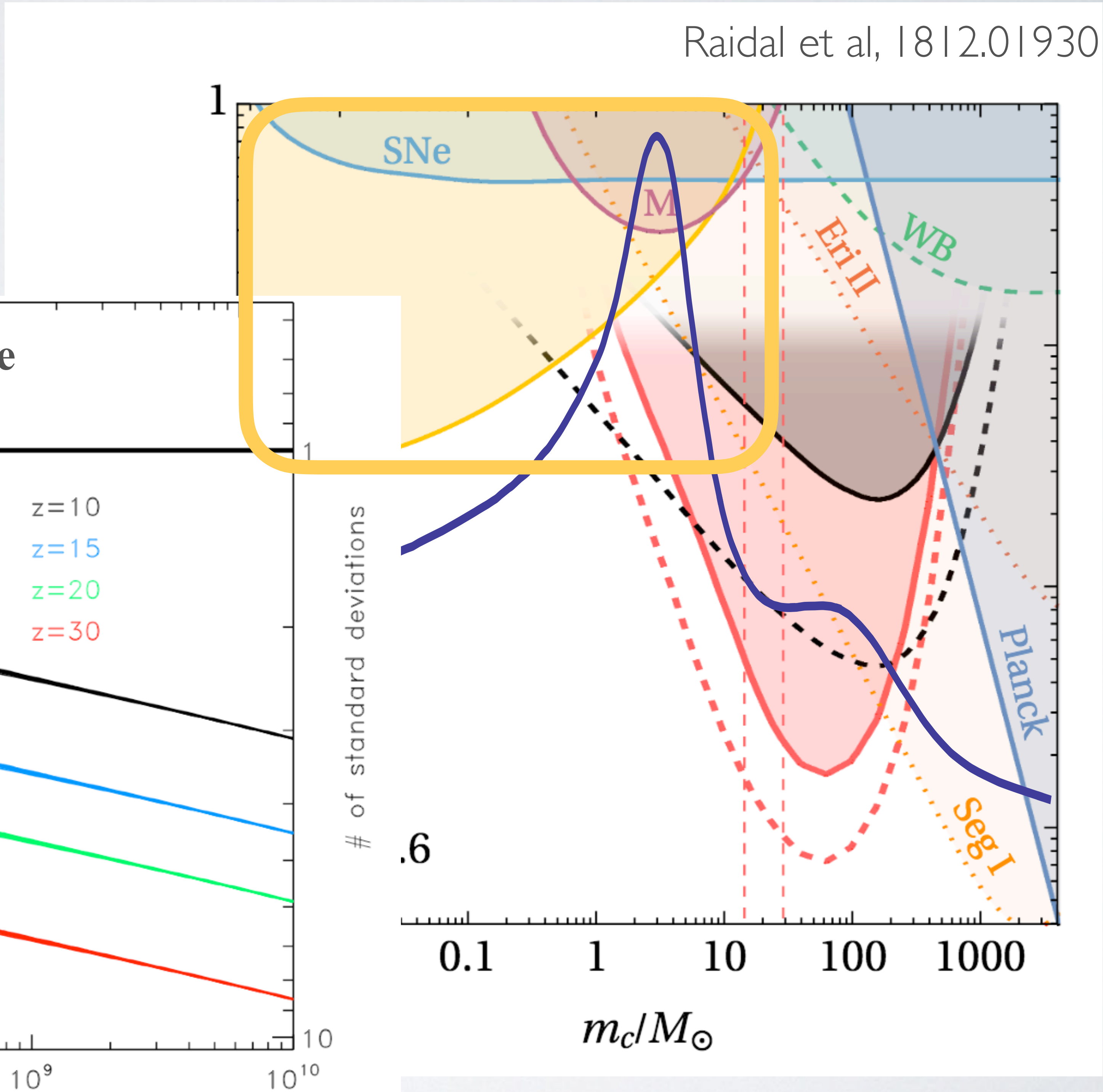
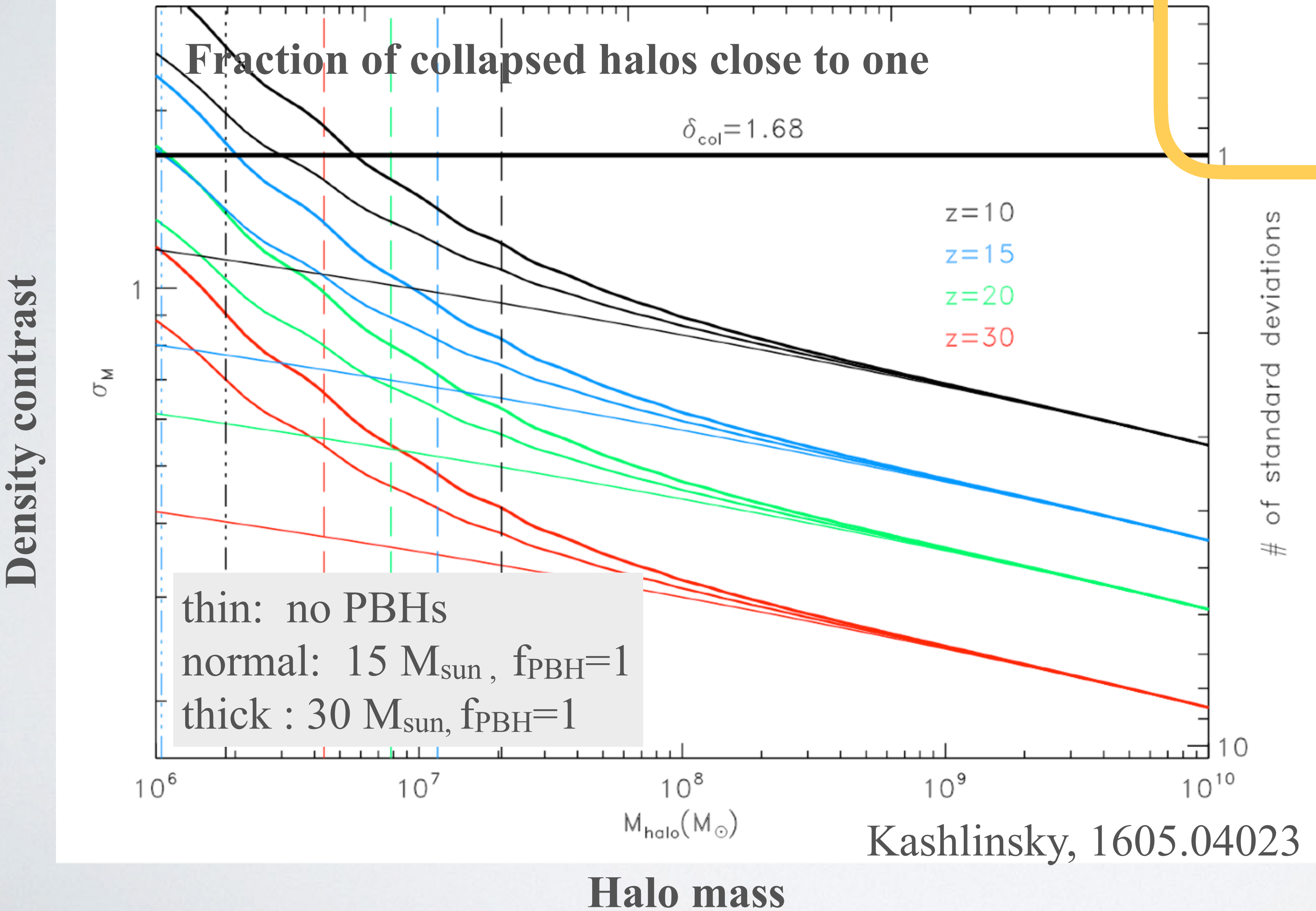
Astro/cosmo limits

Clusters due to
Poisson fluctuations
in the PBH distribution

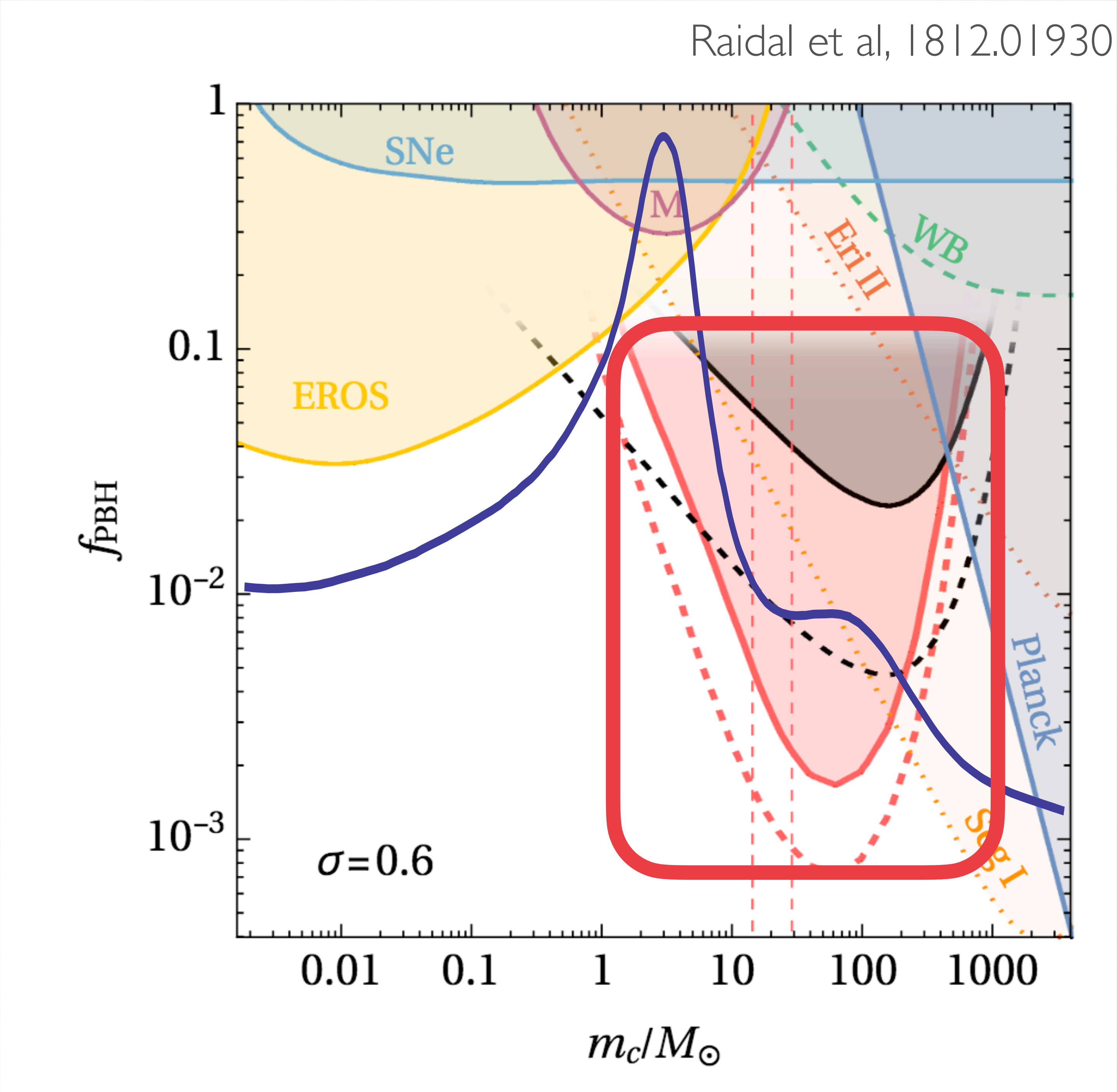




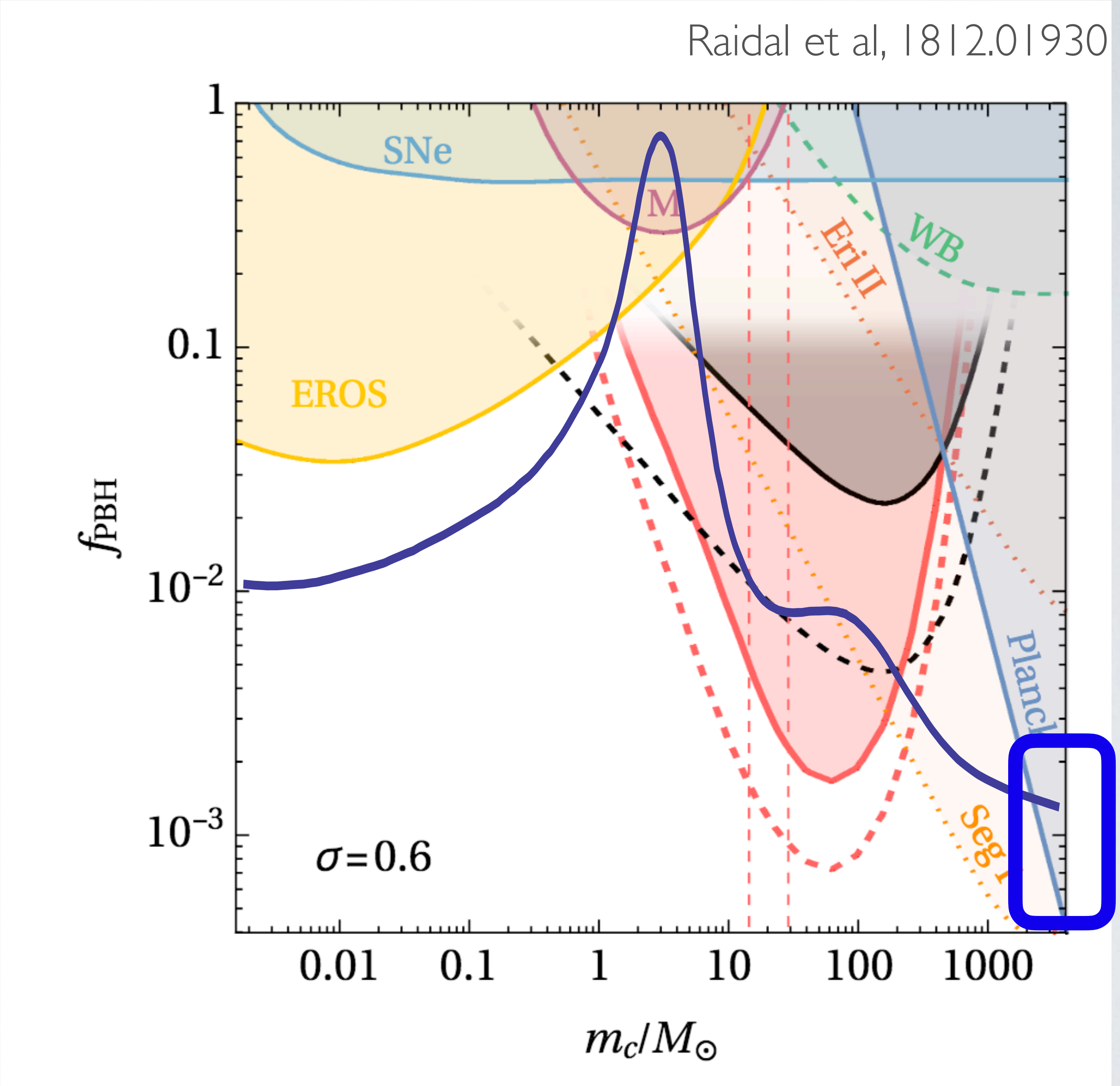
Astro/cosmo limits

Gravitational-wave limits from the merging of primordial binaries

Evaded due to the effect of early clusters and nearby PBHs on the binary lifetime…



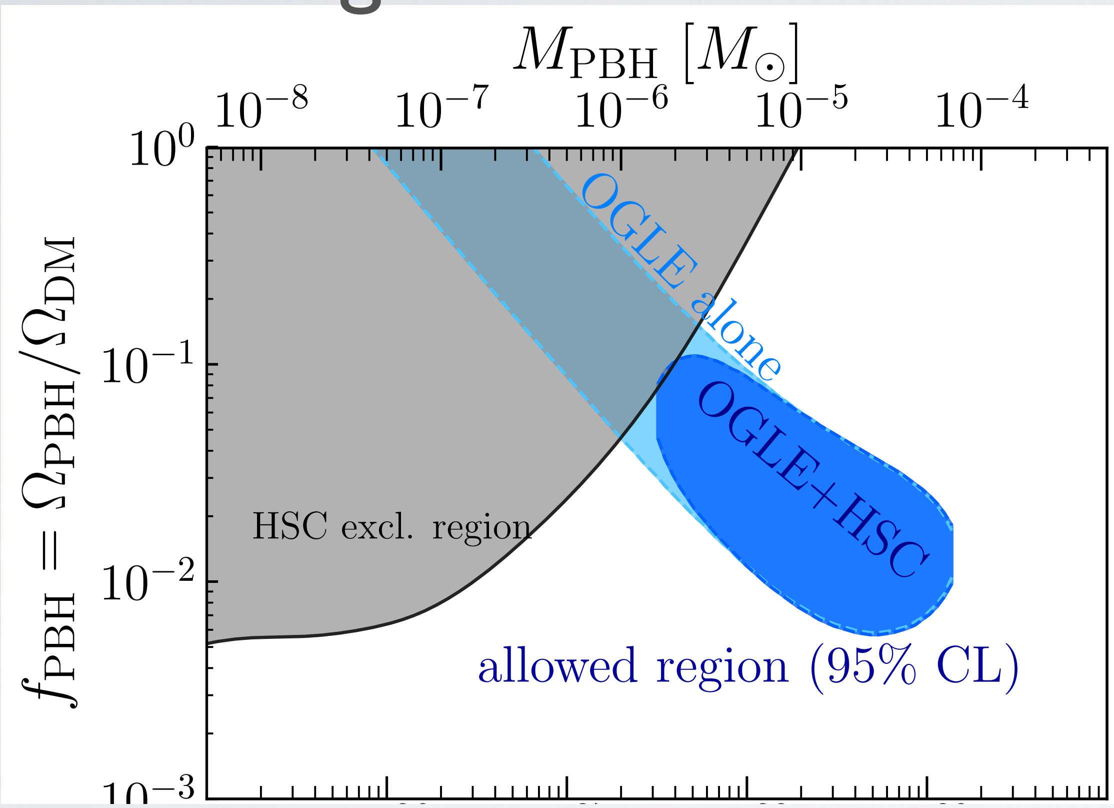
Astro/cosmo limits



issue
with Planck limits ?

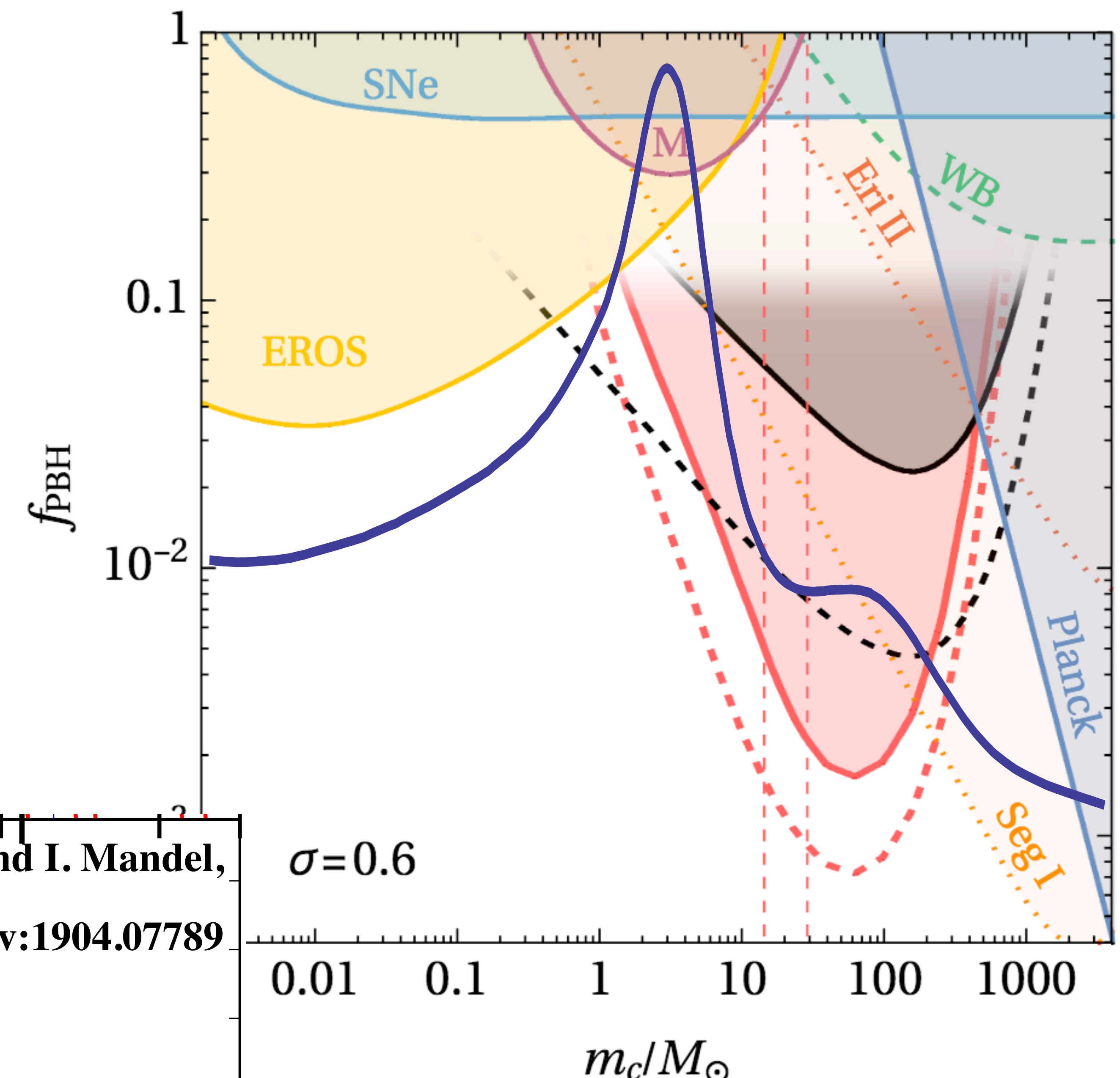
Astro/cosmo hints

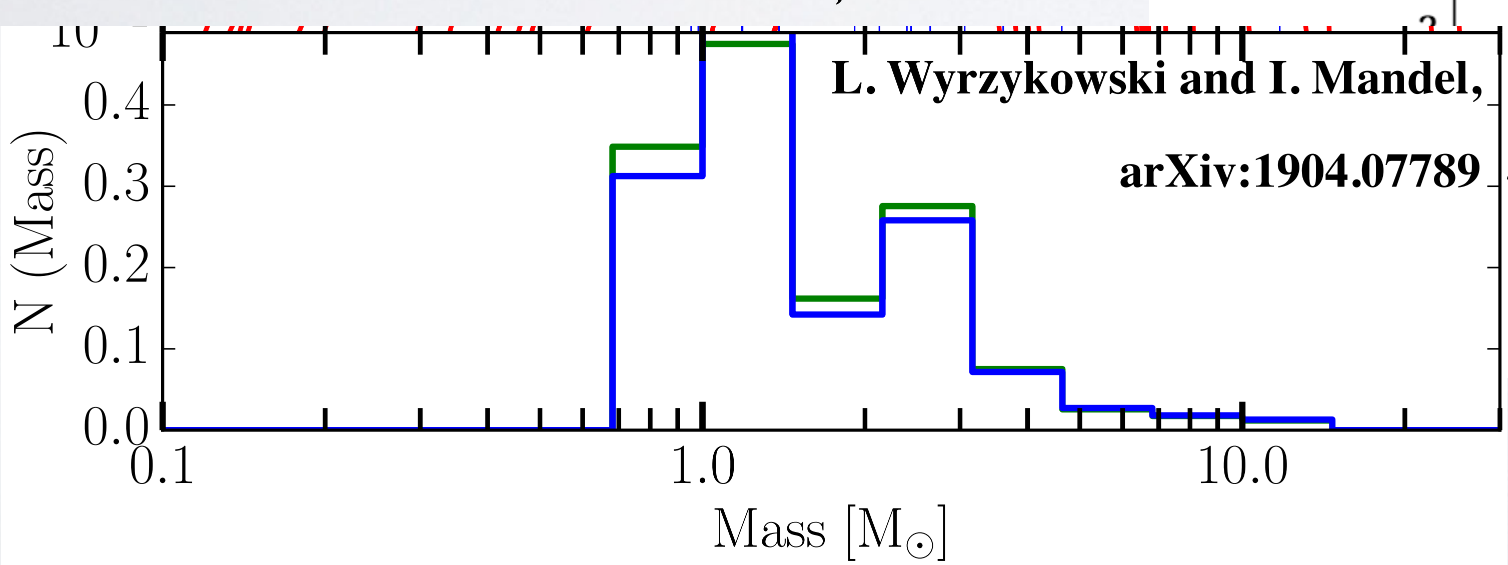
microlensing towards the galactic center



Niikura et al., 1901.07120

Raidal et al, 1812.01930

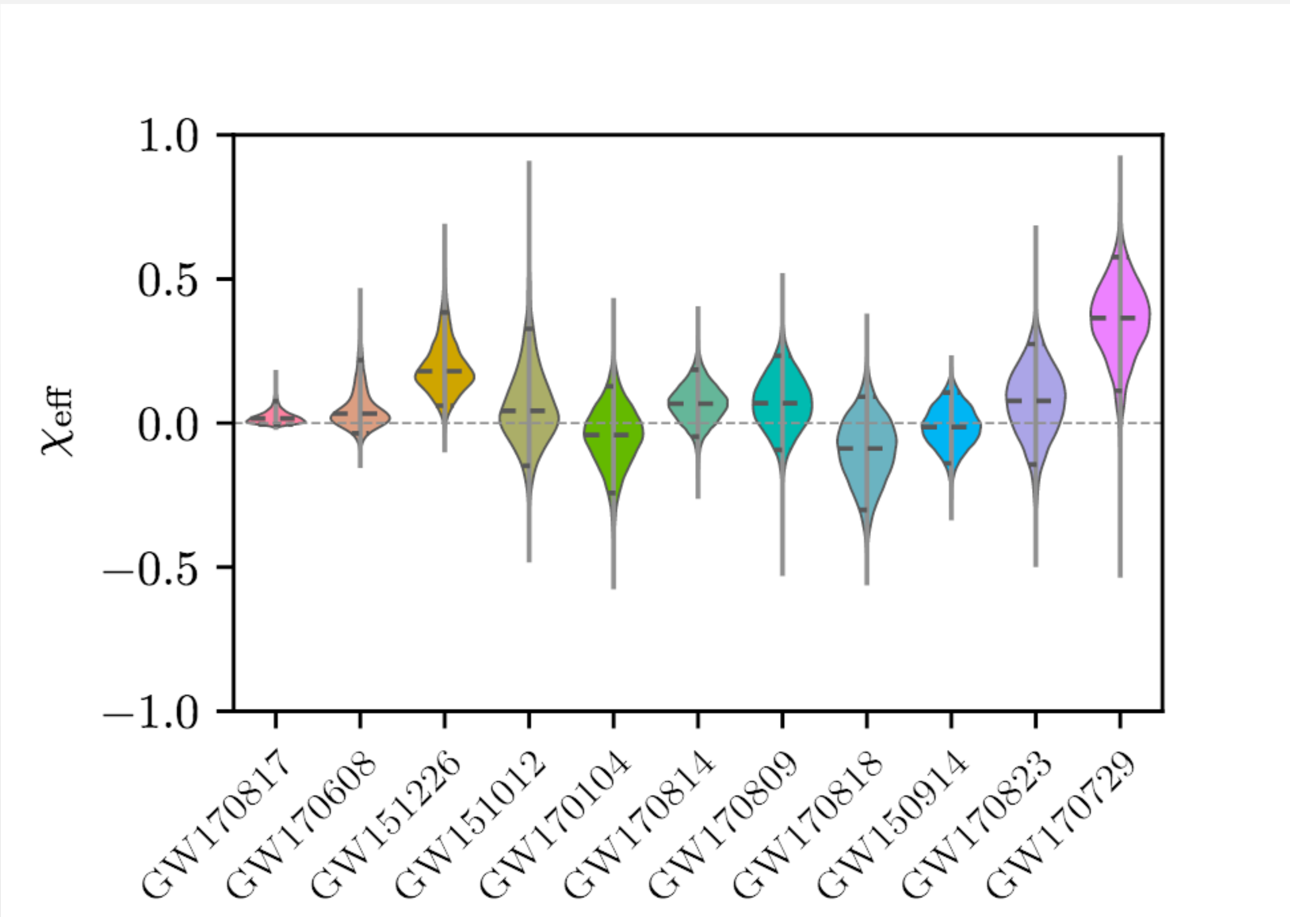




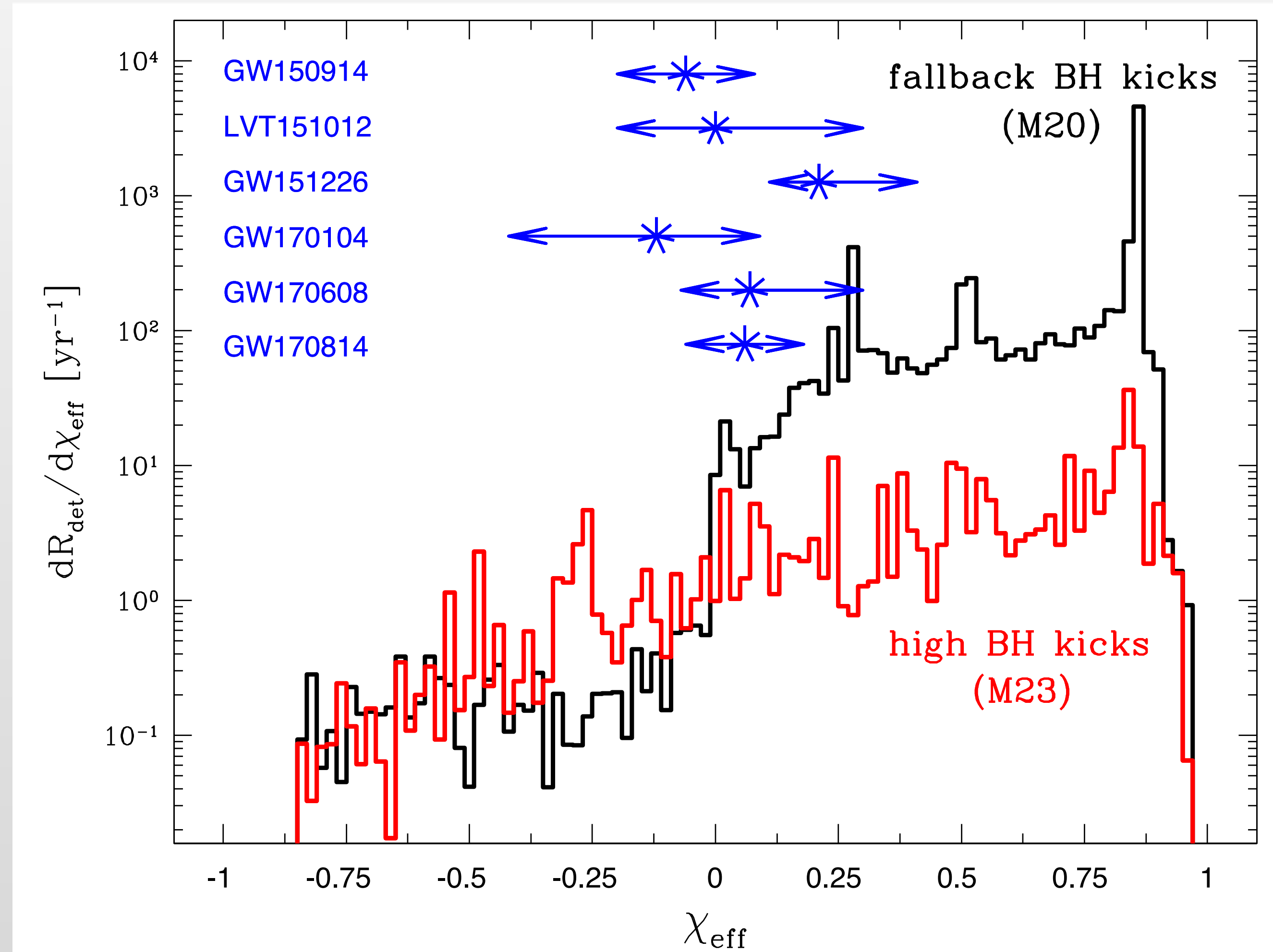
Gravitational Waves

Black Hole effective spins

$$\chi_{\rm eff} = [m_1 S_1 \cos(\theta_{\rm LS_1}) + m_2 S_2 \cos(\theta_{\rm LS_2})]/(m_1 + m_2)$$



Geneva model



Stellar-origin predictions
from C. Belczynski's talk at 2018 CERN workshop on PBH

PBH at formation have zero spins

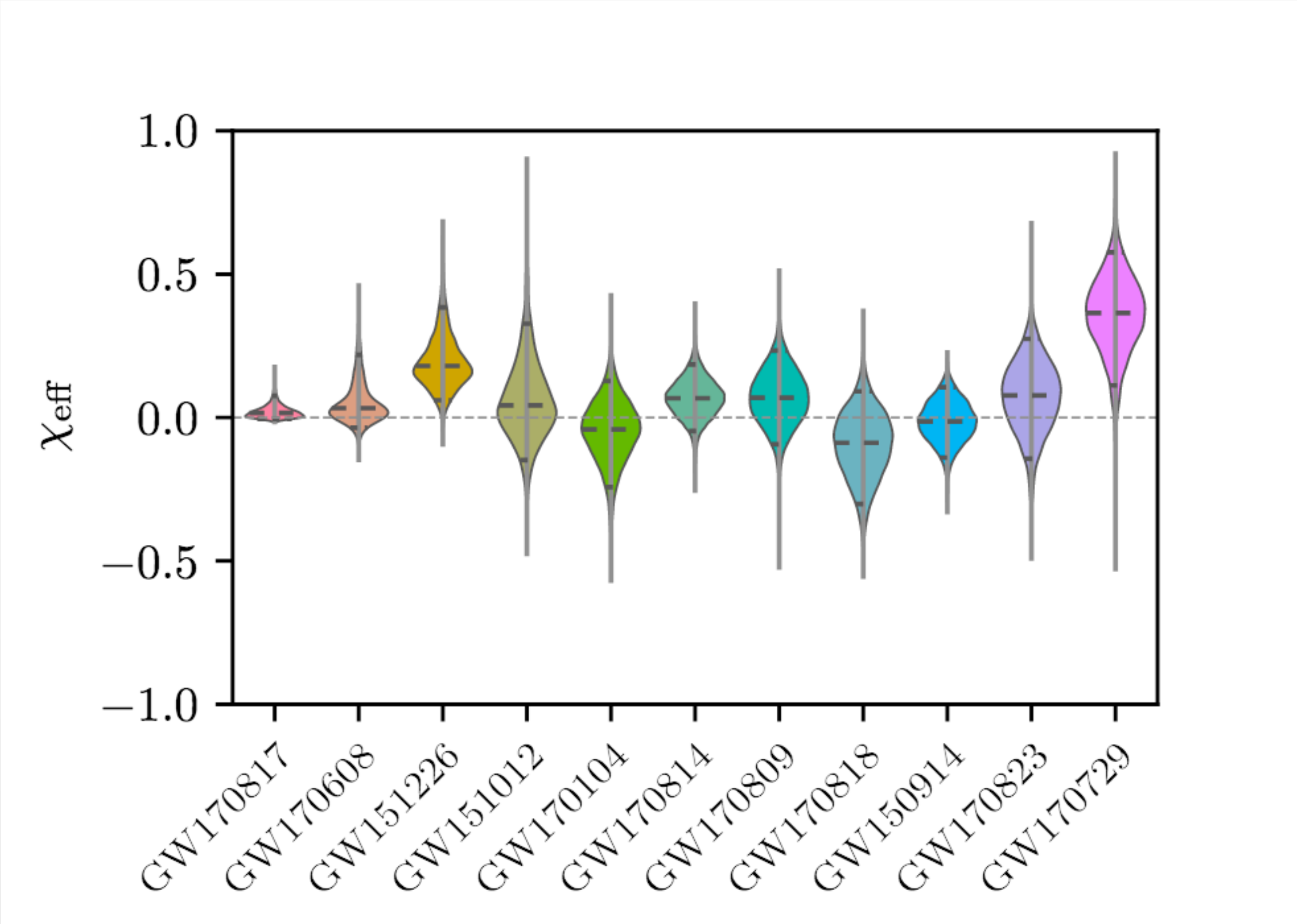
Open question: impact of secondary mergers? of accretion?

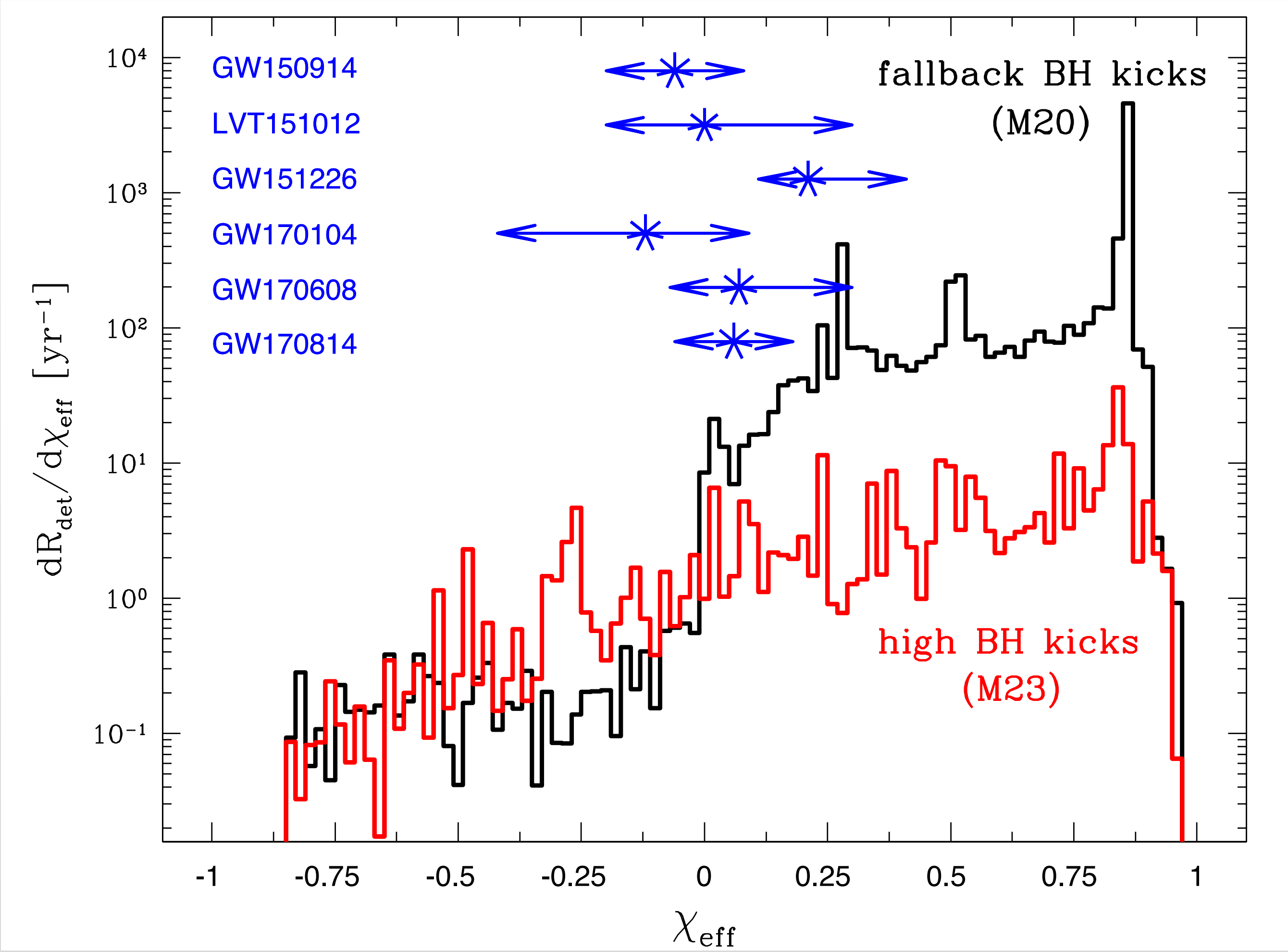
Gravitational Waves

Black Hole effective spins

$$\chi_{\rm eff} = [m_1 S_1 \cos(\theta_{\rm LS_1}) + m_2 S_2 \cos(\theta_{\rm LS_2})]/(m_1 + m_2)$$

Geneva model





Stellar-origin predictions
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Gravitational Waves

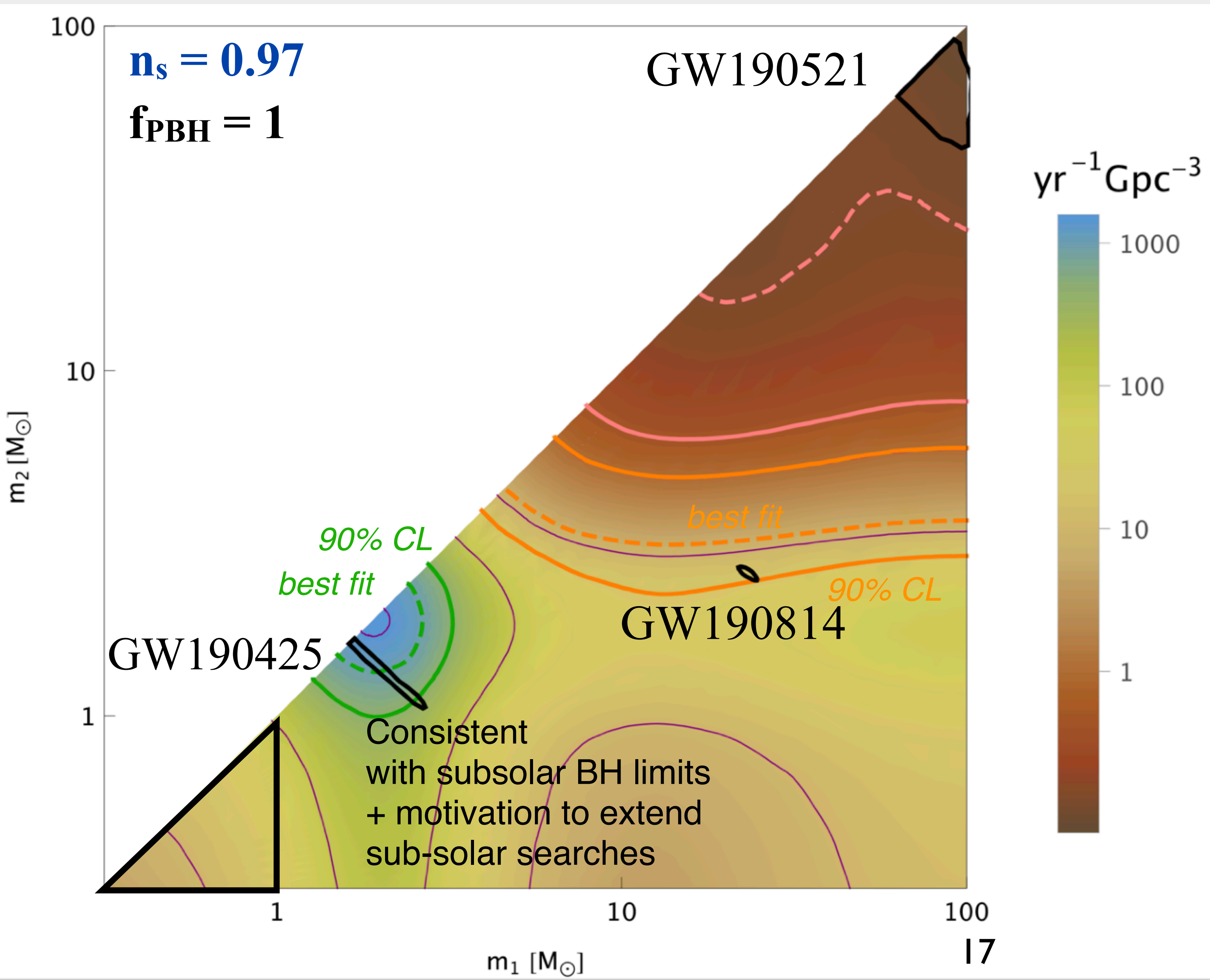
BH merger rate distribution

Agnostic about the abundance of PBH

Binaries formed by **capture in clusters**:

must be ~ 400

$$\frac{d\tau}{\mathrm{d}\ln m_1 \mathrm{d}\ln m_2} = R_{\mathrm{clust.}} \times f(m_1) f(m_2) \times \frac{(m_1+m_2)^{10/7}}{(m_1 m_2)^{5/7}} \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$$



Explains the masses and rates of GW190425, GW190814 and GW190521 in a unified way…

Consistency with O3?

GW190814:

- primary component: **very low spin (< 0.07)**
- secondary component: in the low mass gap
- rates as high as for equal-mass mergers

Gravitational Waves

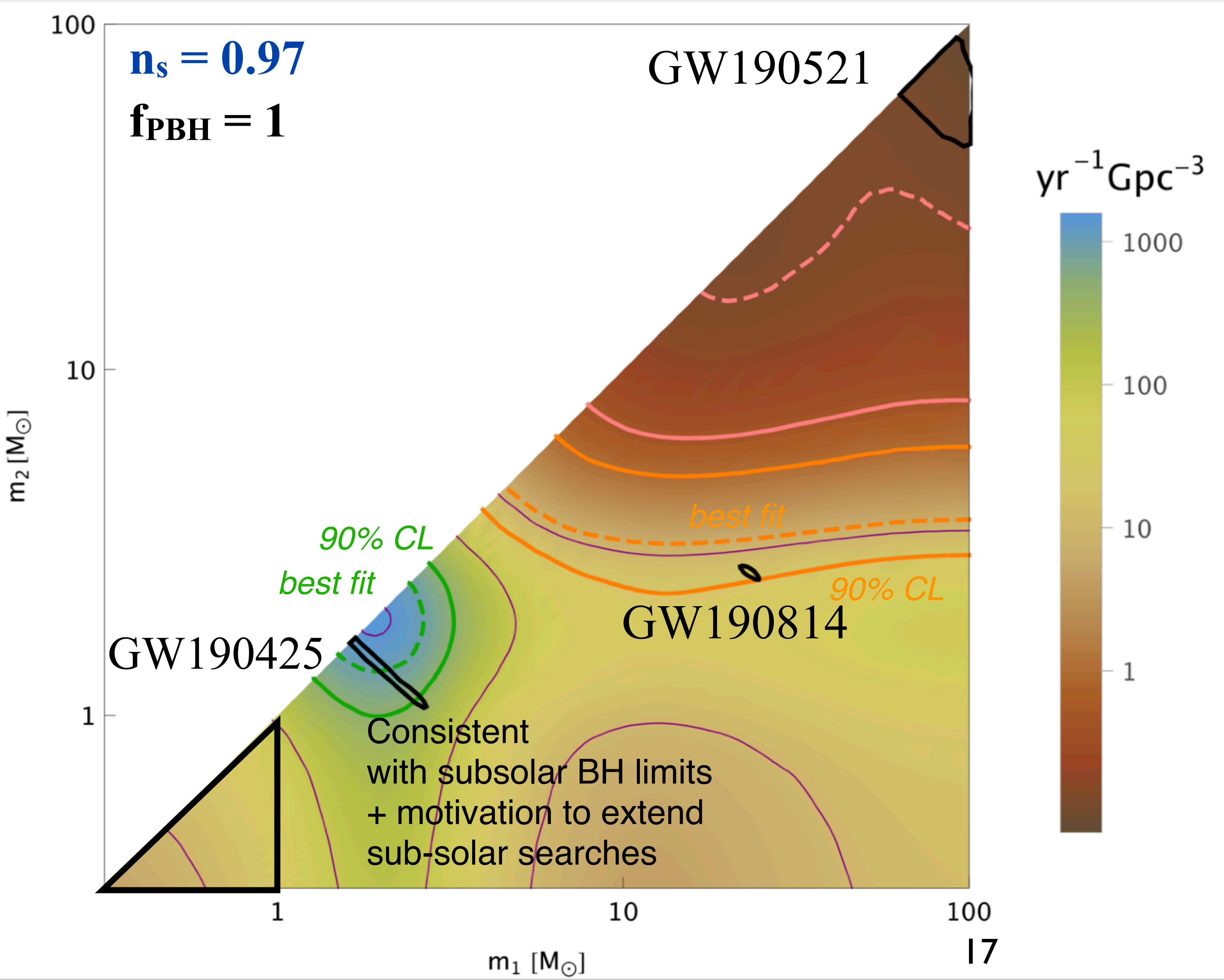
BH merger rate distribution

Agnostic about the abundance of PBH

Binaries formed by **capture in clusters**:

must be ~ 400

$$\frac{d\tau}{\mathrm{d}\ln m_1 \mathrm{d}\ln m_2} = R_{\mathrm{clust.}} \times f(m_1) f(m_2) \times \frac{(m_1 + m_2)^{10/7}}{(m_1 m_2)^{5/7}} \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$$



Explains the masses and rates of GW190425, GW190814 and GW190521 in a unified way…

Consistency with O3?

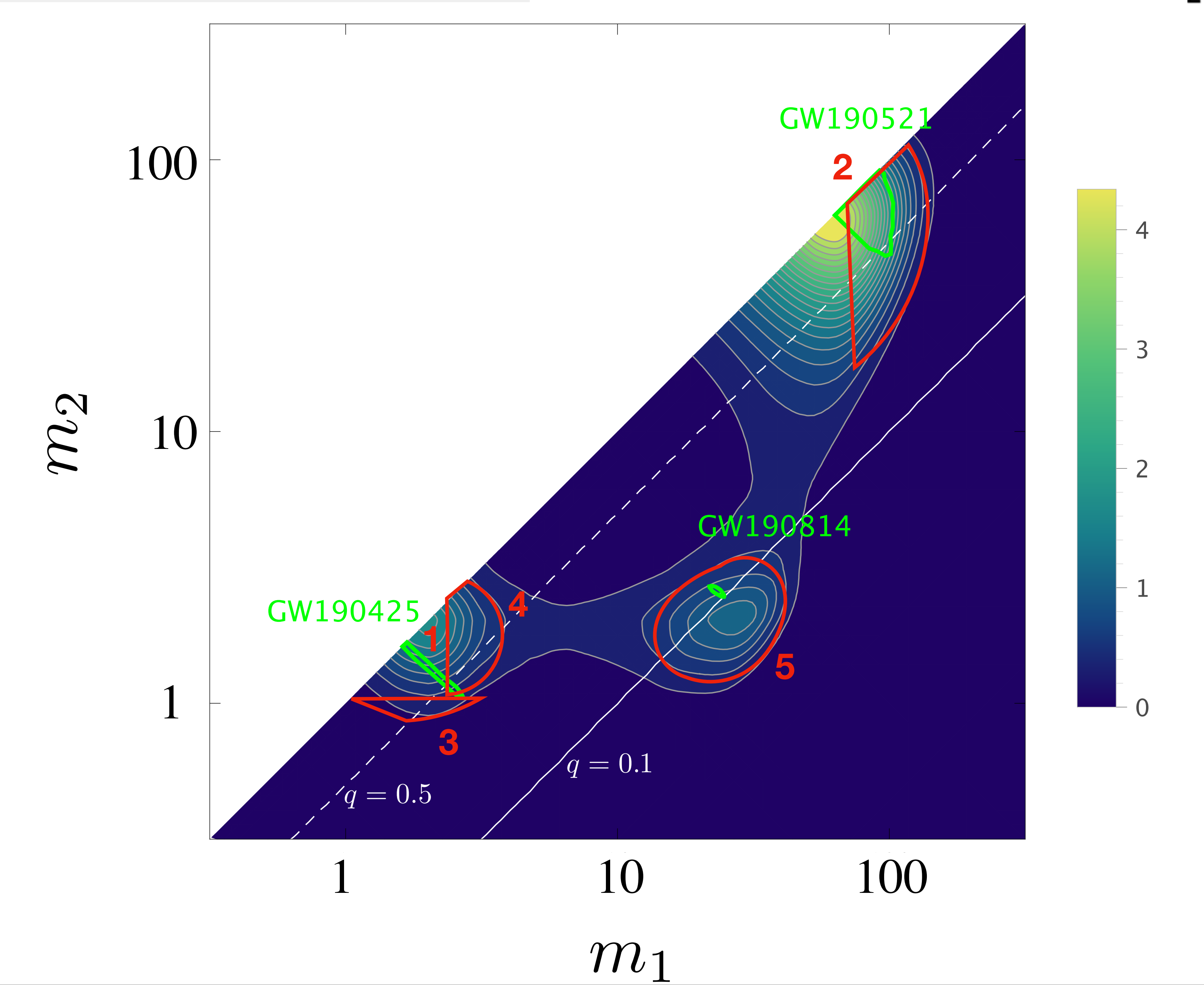
GW190814:

« the combination of mass ratio, component masses, and the inferred merger rate for this event challenges all current models of the formation and mass distribution of compact-object binaries. »

Gravitational Waves

PDF of detections

Astrophysical range: $R_{\rm det} = \frac{\sqrt{5}}{24}\frac{(G\mathcal{M}c^3)^{5/6}}{\pi^{2/3}} \times \frac{1}{2.26}\left[\int_{f_{\rm min}}^{f_{\rm max}} {\rm d}f \, \frac{f^{-\alpha}}{S_h(f)}\right]^{1/2}$



Expected distribution of GW events with O2 LIGO (L1) sensitivity

B. Carr, S.C., J. Garcia-Bellido, F. Kühnel, 19’

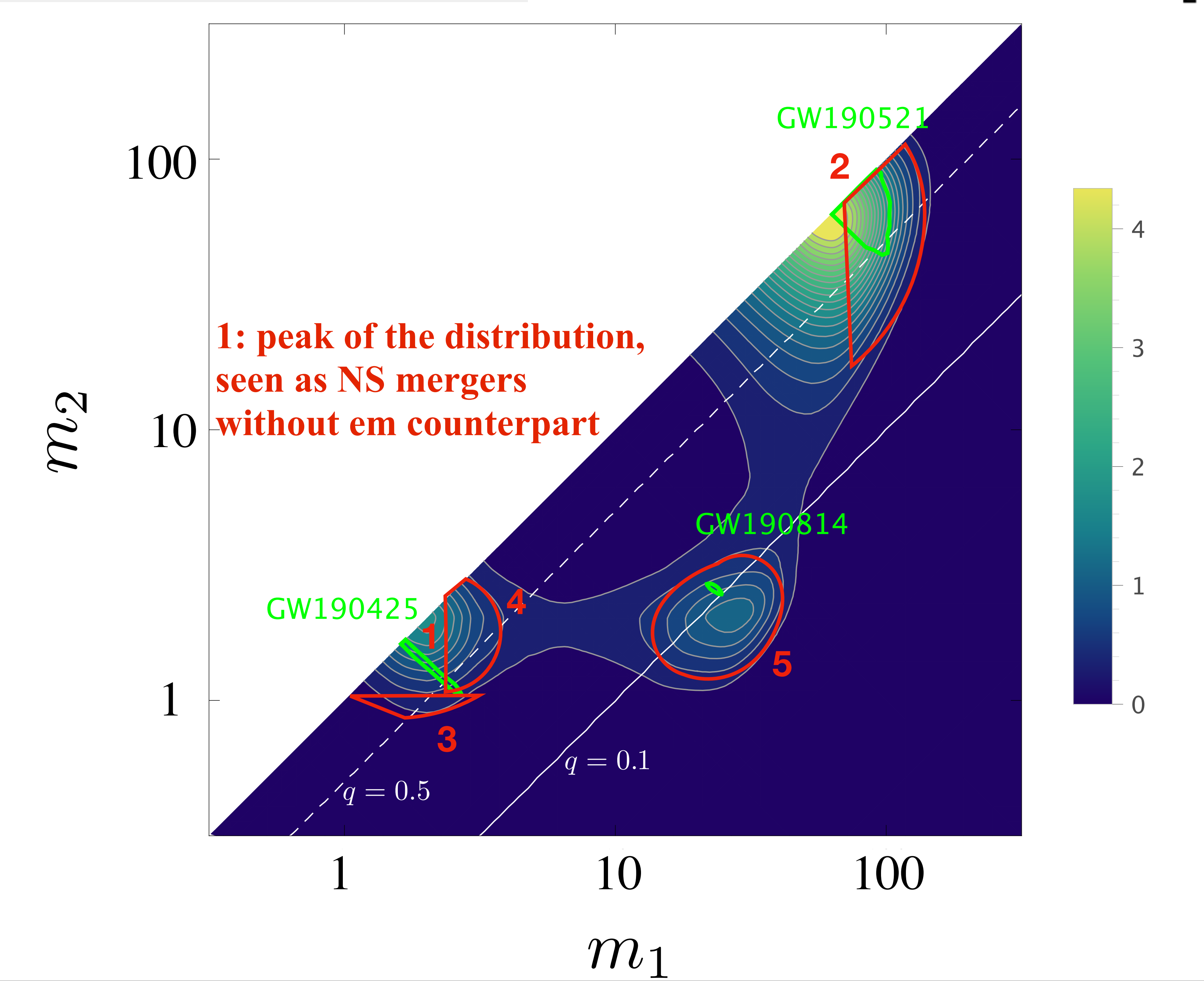
Similar distributions for primordial binaries, but less mergers above ~20 solar mass

Gravitational Waves

PDF of detections

Astrophysical range:

$$R_{\rm det} = \frac{\sqrt{5}}{24}\frac{(G\mathcal{M}c^3)^{5/6}}{\pi^{2/3}} \times \frac{1}{2.26}\left[\int_{f_{\rm min}}^{f_{\rm max}} {\rm d}f\, \frac{f^{-\alpha}}{S_h(f)}\right]^{1/2}$$



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Similar distributions for primordial binaries, but less mergers above ~20 solar mass

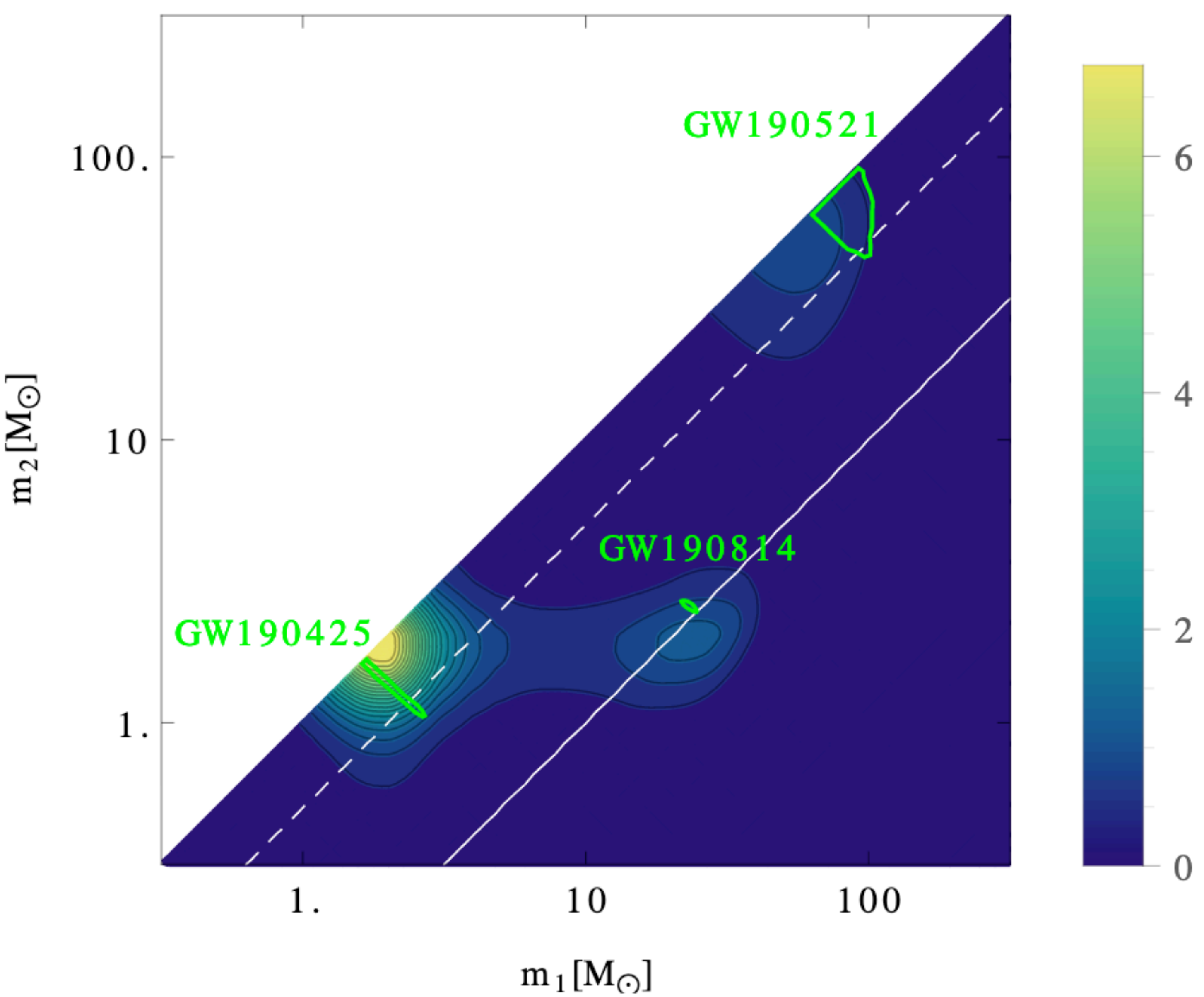
Gravitational Waves

PDF of detections

must be ~ 0.002

Primordial binaries:

$$\frac{d\tau}{d\ln m_1 d\ln m_2} \approx 1.6 \times 10^6\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1} f(m_1) f(m_2) f_{\rm sup} \times \left(\frac{m_1+m_2}{M_\odot}\right)^{-\frac{32}{37}} \left[\frac{m_1 m_2}{(m_1+m_2)^2}\right]^{-\frac{34}{37}} \quad (2)$$



Expected distribution of GW events with O2 LIGO (L1) sensitivity

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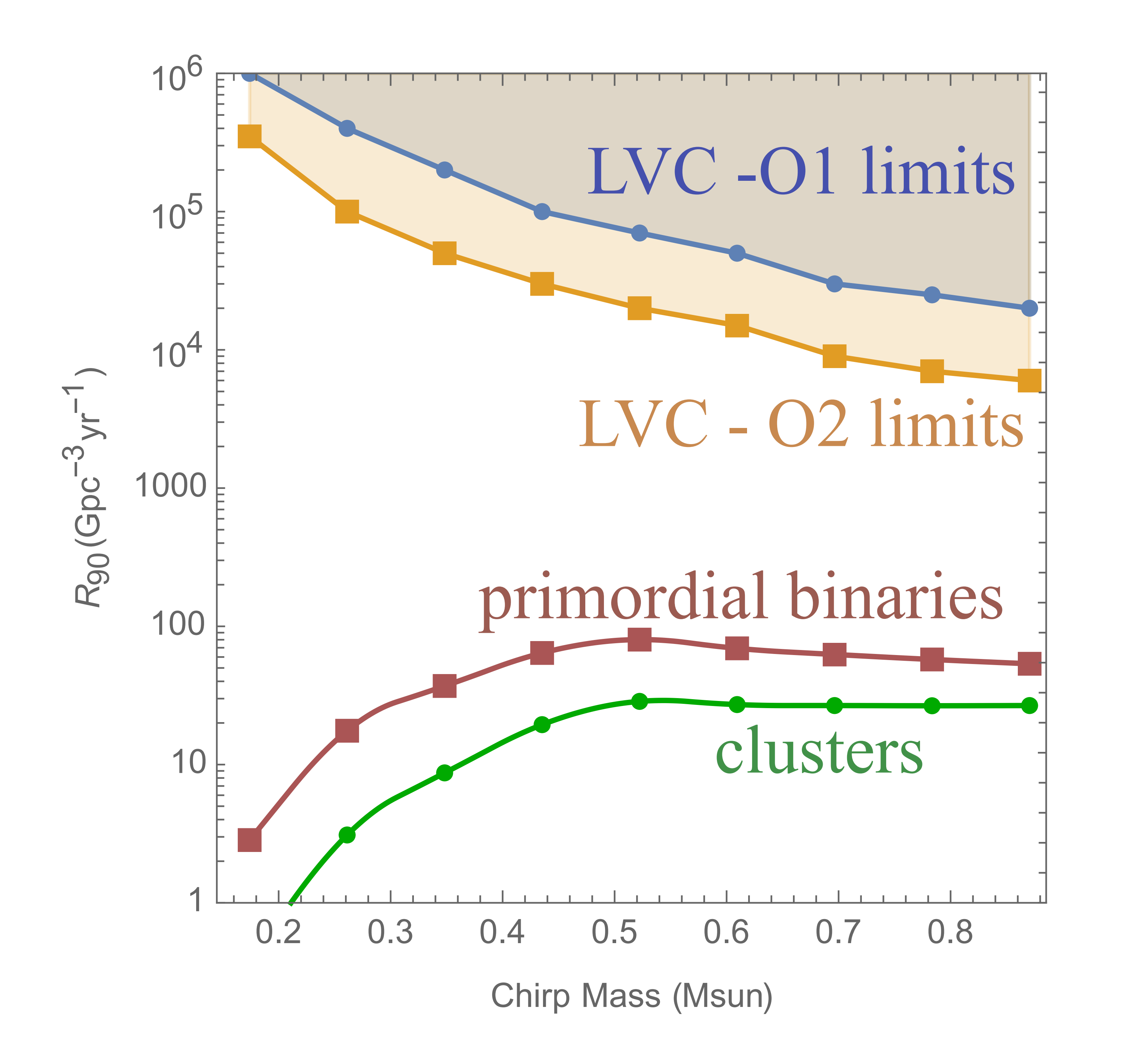
Similar distributions for primordial binaries, but less mergers above ~20 solar mass

Gravitational Waves

from subsolar black holes



Previous searches limited to < 2 M_{sun} for the primary component

Ongoing search (with Utrecht group) 2 $M_{sun} < m_1 < 10\ M_{sun}$

Stay tuned !

Gravitational Waves

Stochastic background from PBH binaries

preliminary, with Eleni Bagui

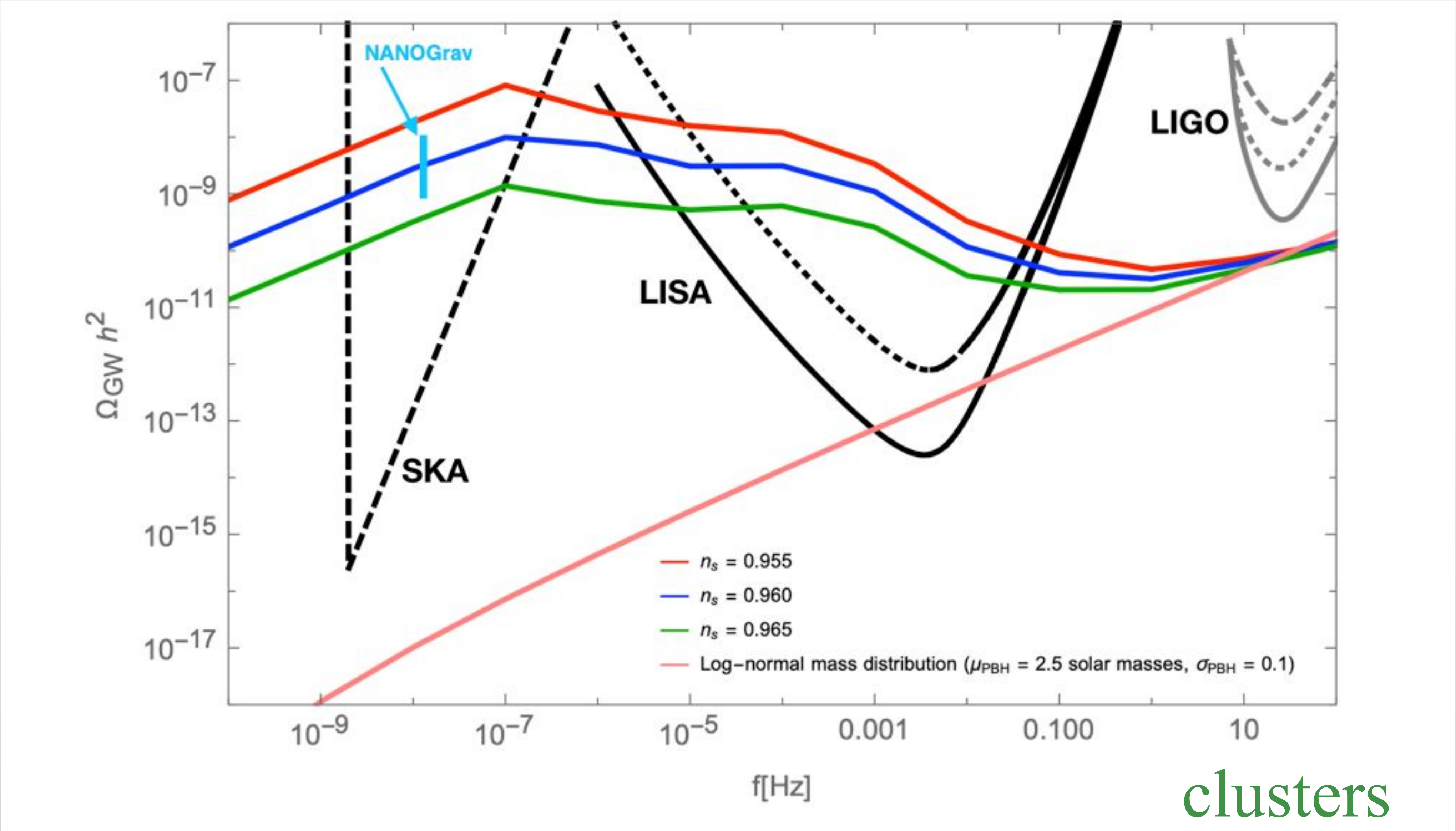
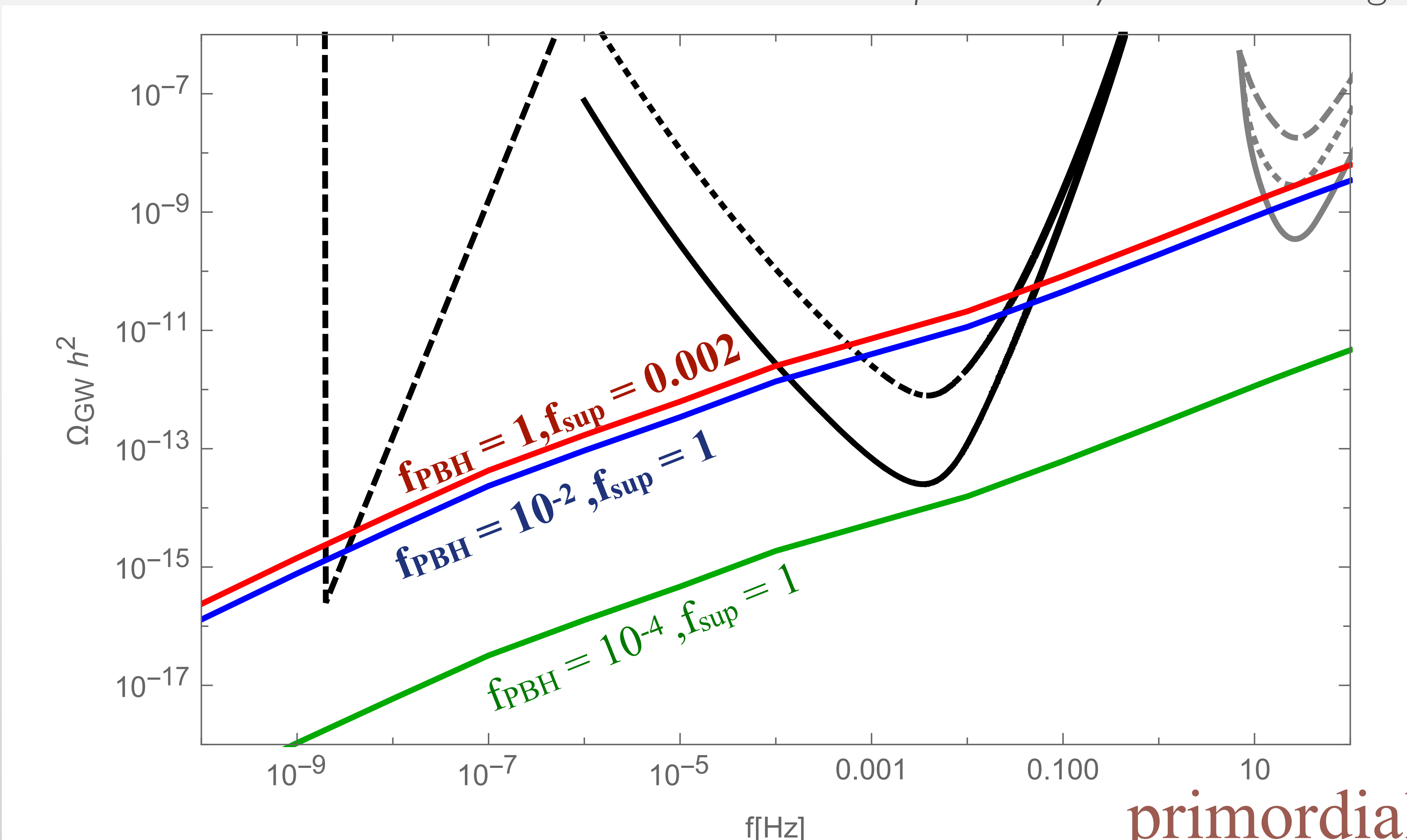


Figure 1: (Preliminary) SGWB induced by PBH binaries formed by **tidal capture in clusters** for wide mass distributions imprinted by the effects of the varying equation of state at the QCD transition. The three curves (red, dark blue, green) correspond to different spectral indices n_s . The results obtained for a log-normal mass distribution are shown for comparison (pink). The expected sensitivity for SKA pulsar timing arrays, for LISA and for LIGO (O1, O2, O5) are also shown. The location of the possible detection by NANOGrav is indicated in light blue.

Gravitational Waves

Stochastic background from PBH binaries

preliminary, with Eleni Bagui

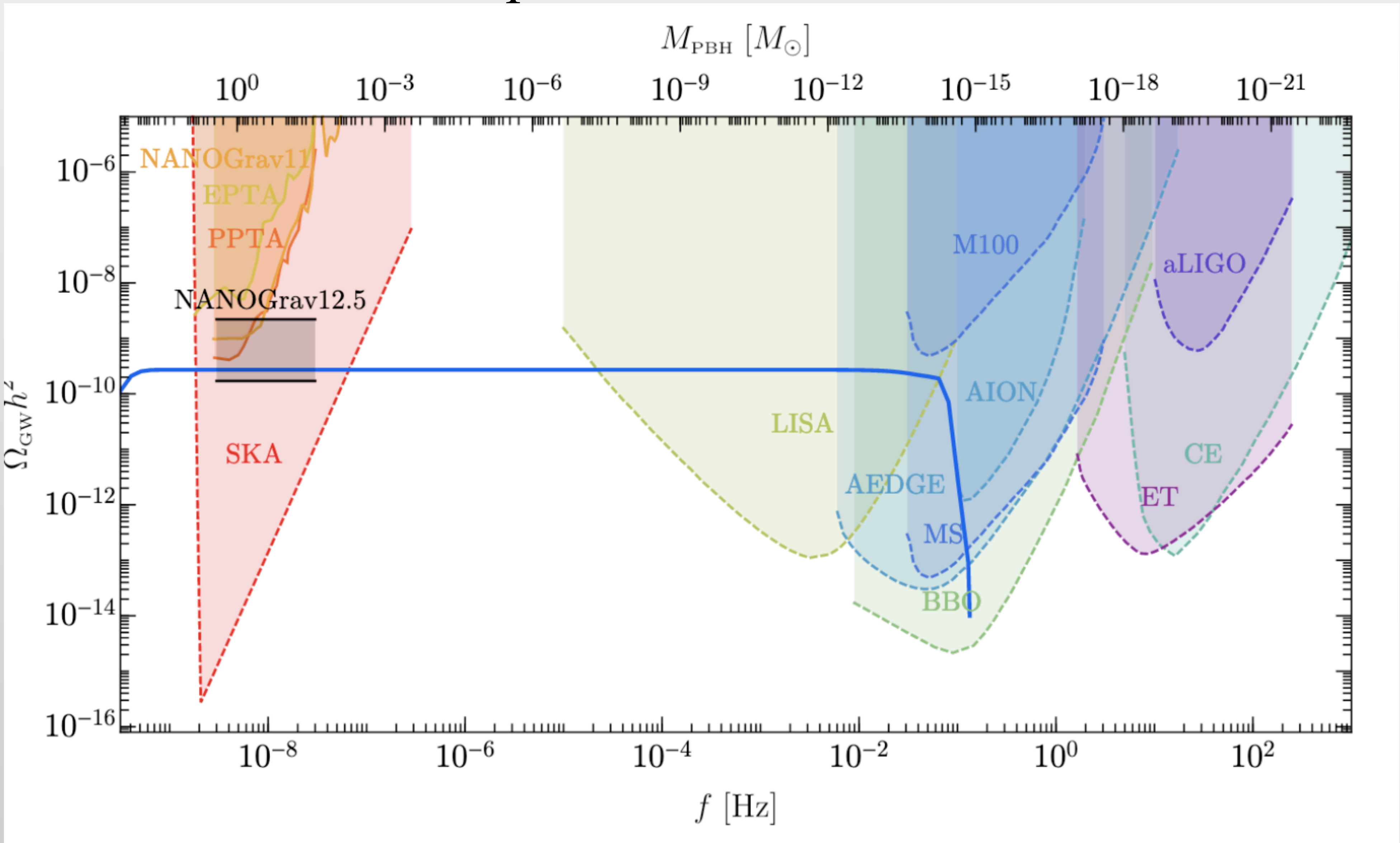


primordial binaries

Gravitational Waves

from density perturbations leading to PBHs

GWs sourced at second order by density perturbations
in the linear perturbation theory
=> SGWB compatible with NANOGrav 12.5 hint



De Luca et al, arXiv:2009.08268

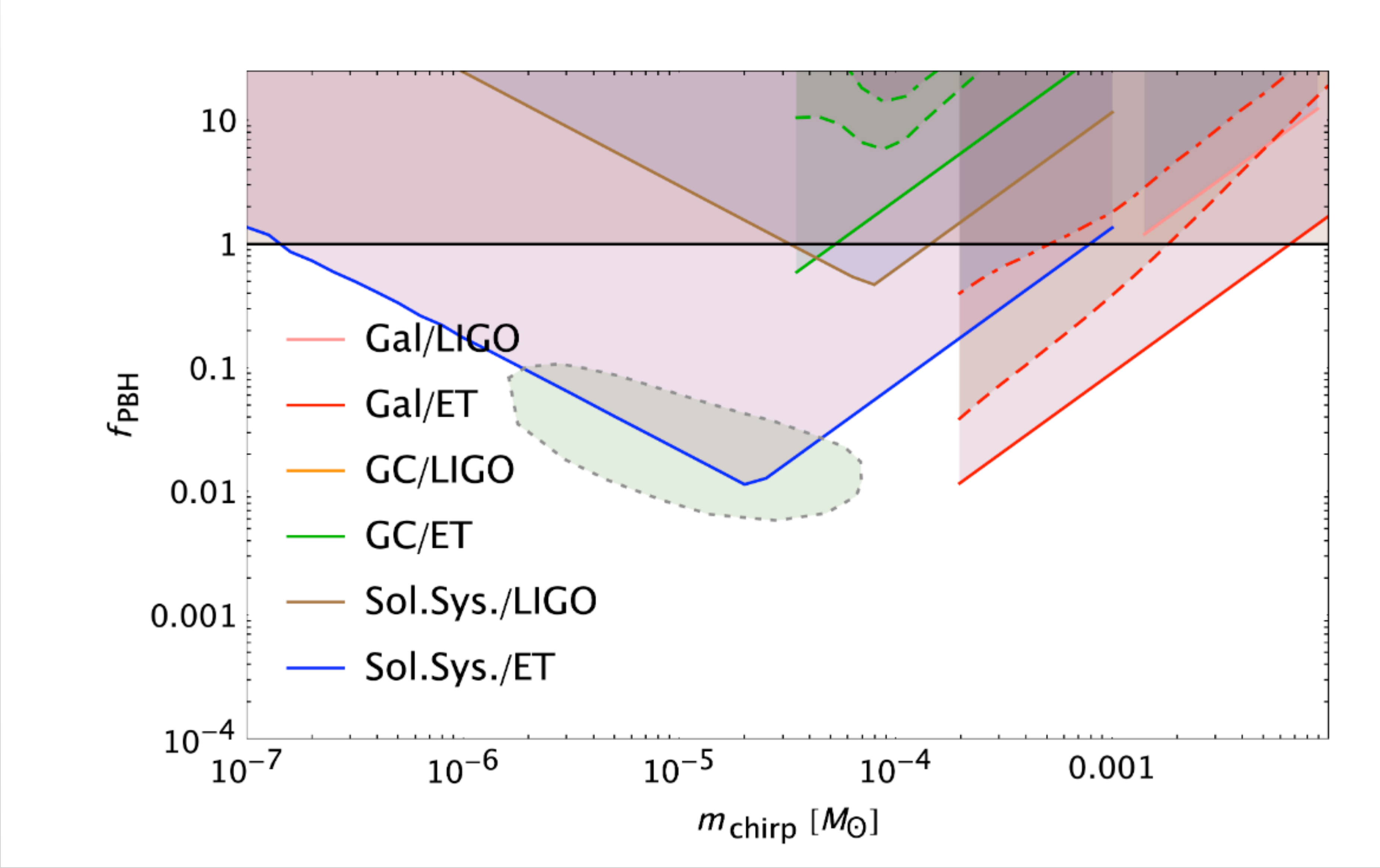
Gravitational Waves

from planetary-mass PBHs

With LIGO/Virgo or Einstein Telescope using continuous-wave methods

A. Miller, S.C., F. De Lillo et al., arXiv:2012.12983

Planetary-mass PBHs emit GWs at LIGO/Virgo frequencies during thousands-millions years



Gravitational Waves

from planetary-mass PBHs

With high-frequency electromagnetic GW detectors

N. Herman, A. Füzfa, S. Clesse, L. Lehoucq, arXiv:2012.12189

Based on inverse Gertzenstein effect:
GW interaction with a static magnetic field

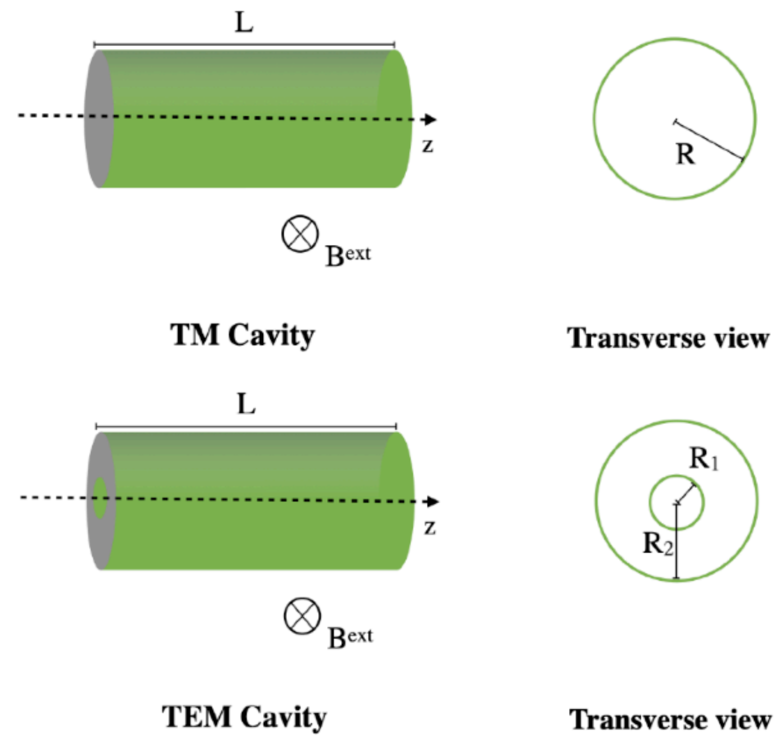
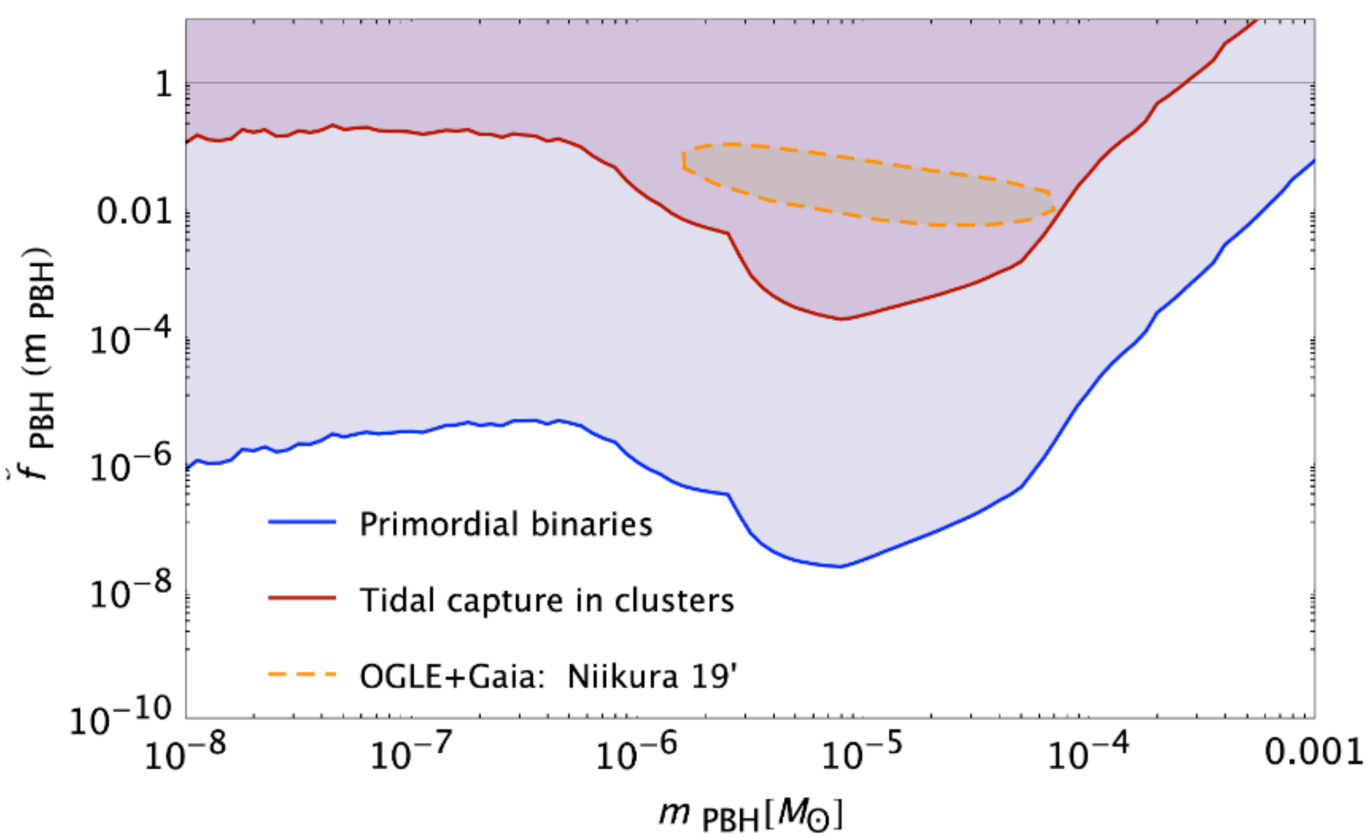


FIG. 1. Schematic representation of the experimental designs a cylindrical TM cavity (top) and TEM waveguide (bottom), into an external static and transverse magnetic field.

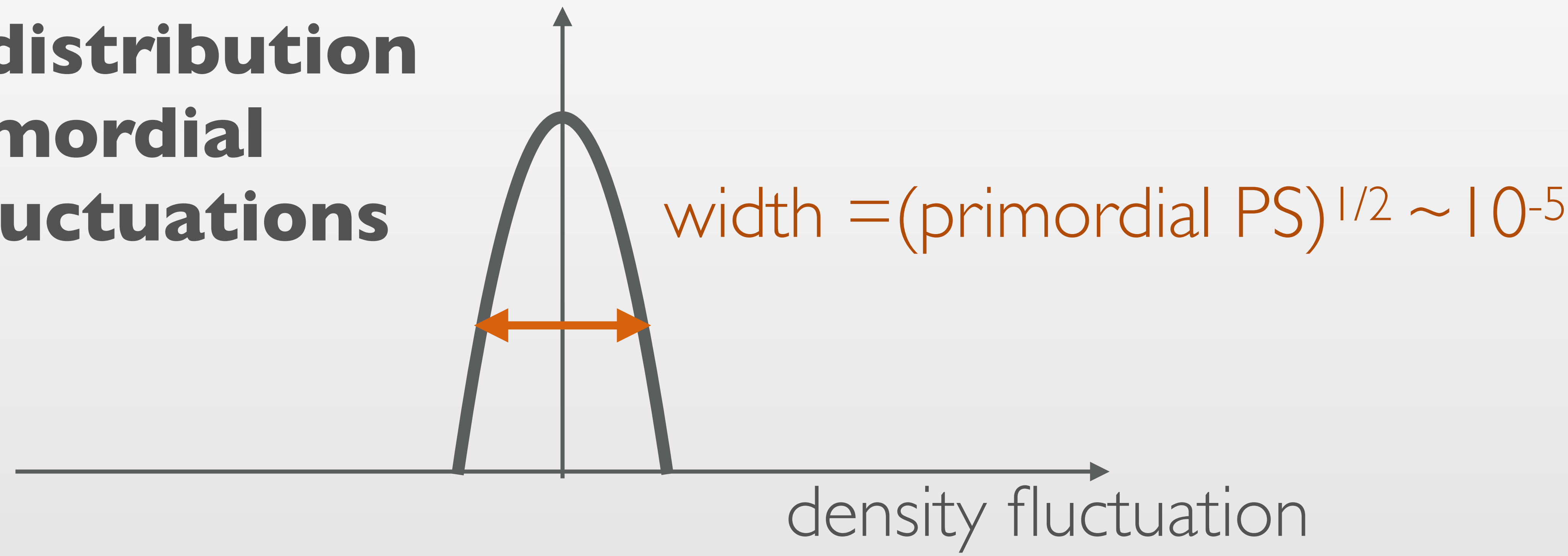
Projected limits on PBHs
for a power sensitivity of 10^{-10} W



Brainstorming

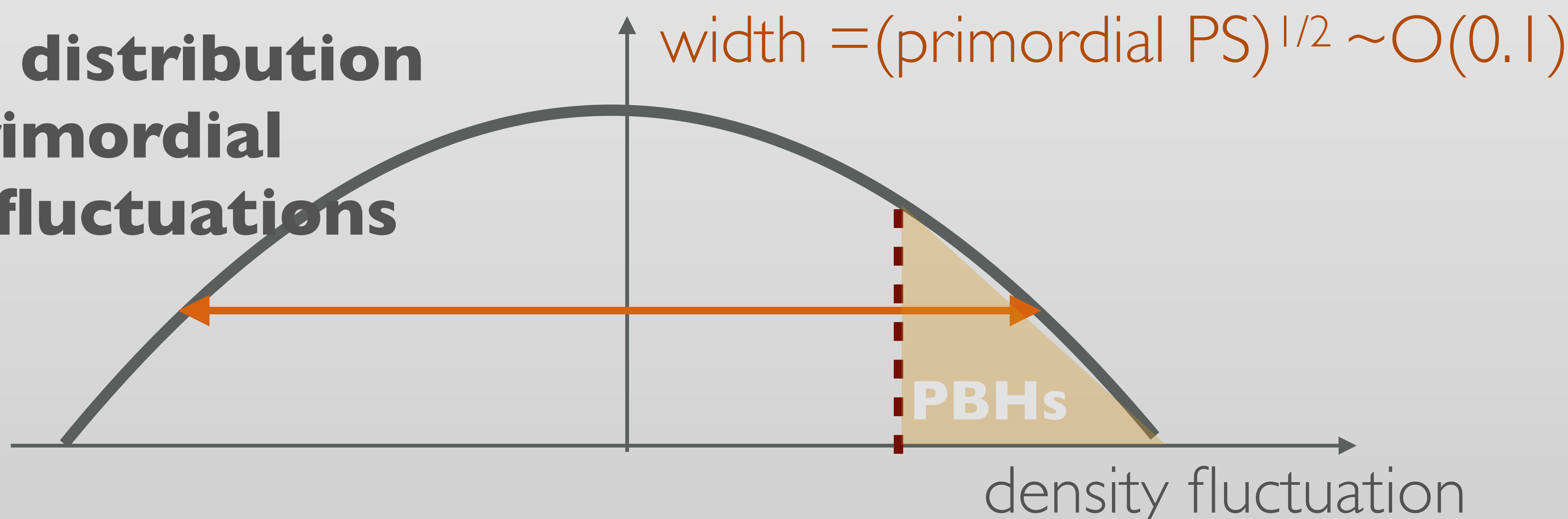
On CMB scales...

Gaussian distribution of primordial density fluctuations



On PBH scales...

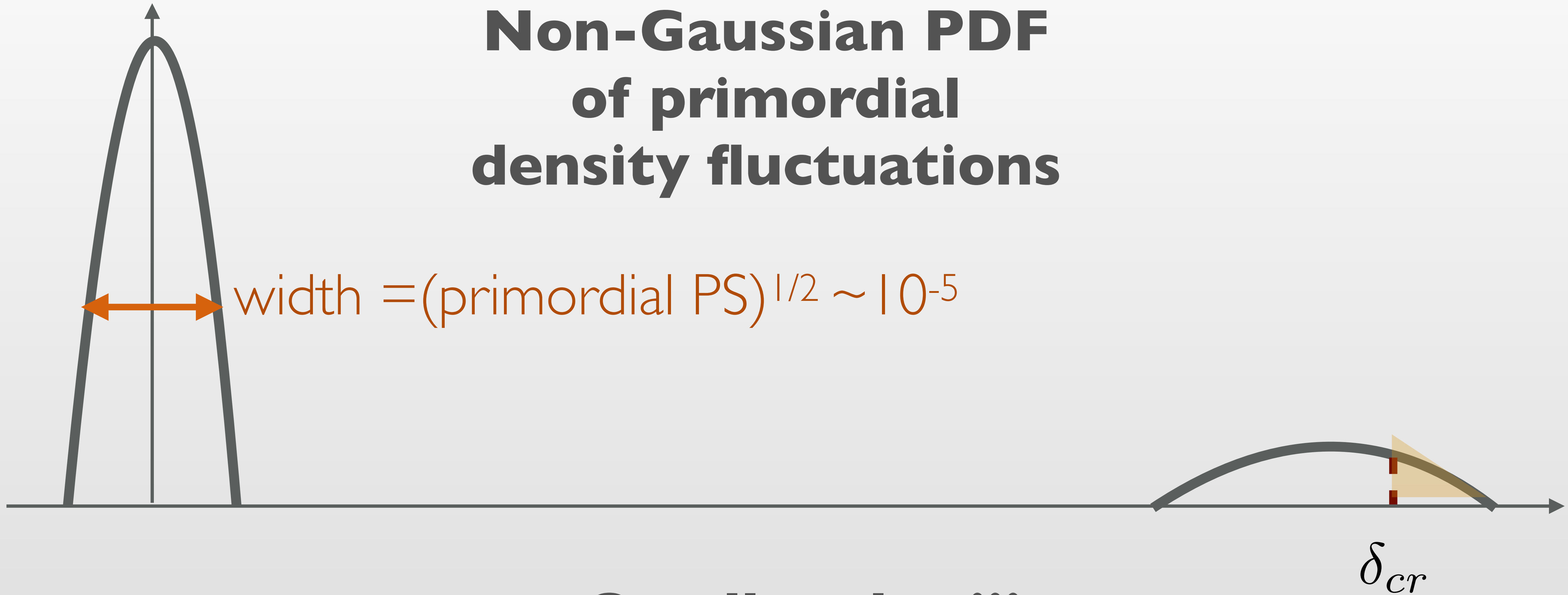
Gaussian distribution of primordial density fluctuations



Brainstorming

Crazy idea?

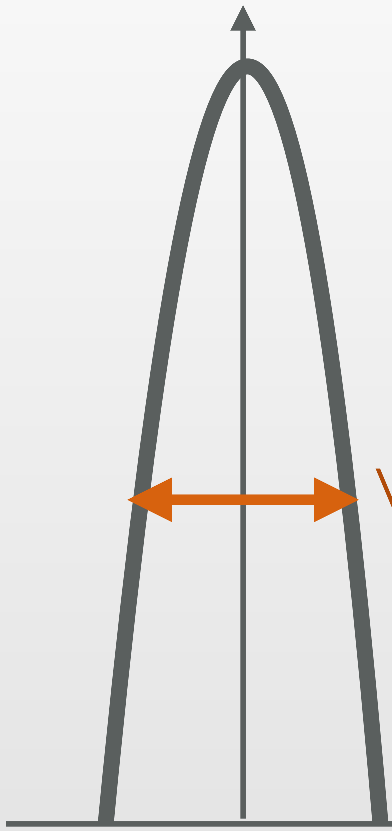
Non-Gaussian PDF of primordial density fluctuations



On all scales !!!

Brainstorming

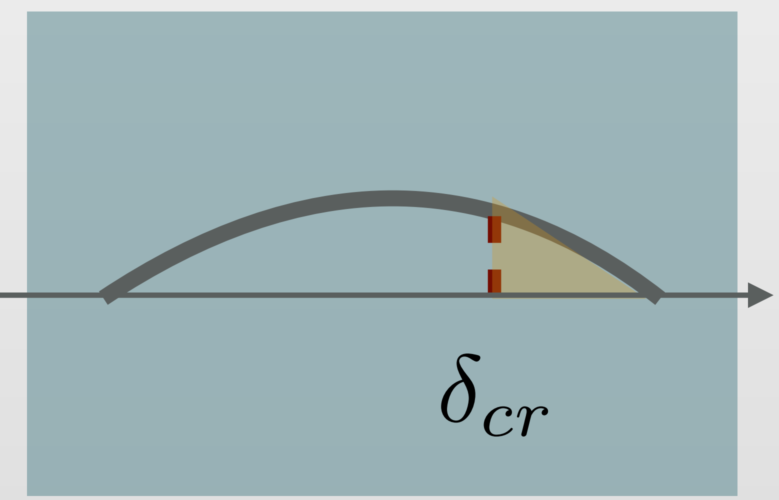
Crazy idea?



Non-Gaussian PDF of primordial density fluctuations

width =(primordial PS)$^{1/2}$ ~ 10^{-5}

Stochastic process (quantum fluctuations ?)



On all scales !!!

PBHs = Dark Matter due to anthropic <u>selection</u>

<u>Solution:</u>

Light stochastic spectator field during inflation

Carr, Clesse, Garcia-Bellido, arXiv:1904.02129

Conclusion

- Sound speed reduction at **QCD transition**: **m_{PBH} ~ stellar-mass**
- **QCD epoch and electroweak baryogengesis**:
  naturally: $n_b / n_\gamma \sim ß_{PBH} \sim 10^{-9}$ and $\Omega_{PBH} \sim \Omega_b$
- Rare **O(1) density fluctuations** may co-habit with $O(10^{-5})$ fluctuations
- Mass function in (almost) agreement with **astrophysical/cosmological limits <u>because</u> PBHs formed clusters**
- **Hints** in several observations and **testable GW signatures**
- Explanation of **GW190525, GW190814 and GW190521** with a single model
- SGWB from density fluctuations: possible hint from **NANOGrav**
- Ultimate discriminator: **detecting a subsolar black hole !**
- Most exciting prediction: **small PBHs in the solar system**

Therefore, PBHs <u>are</u> a natural, well-motivated and testable
dark matter & baryogenesis candidate. Possibly they <u>do</u> exist…

… so they deserve to be investigated further!