Sebastien Clesse

Service de physique Théorique, University of Brussels (ULB)

in collaboration with

B. Carr and J. Garcia-Bellido

Primordial Black Holes as a common origin of Baryons and Dark Matter ?

Conference: PONT-2020, December 7, 2020

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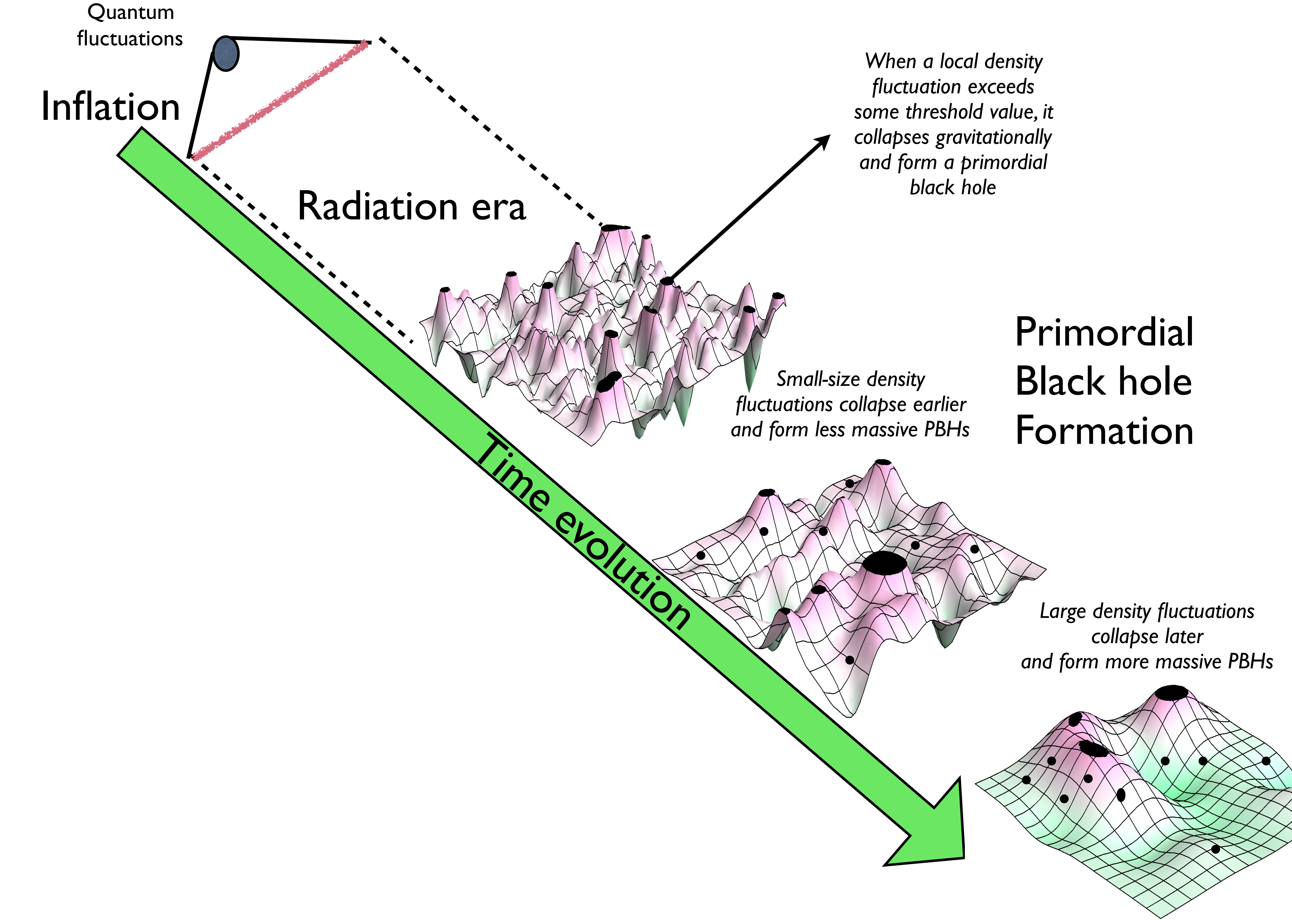
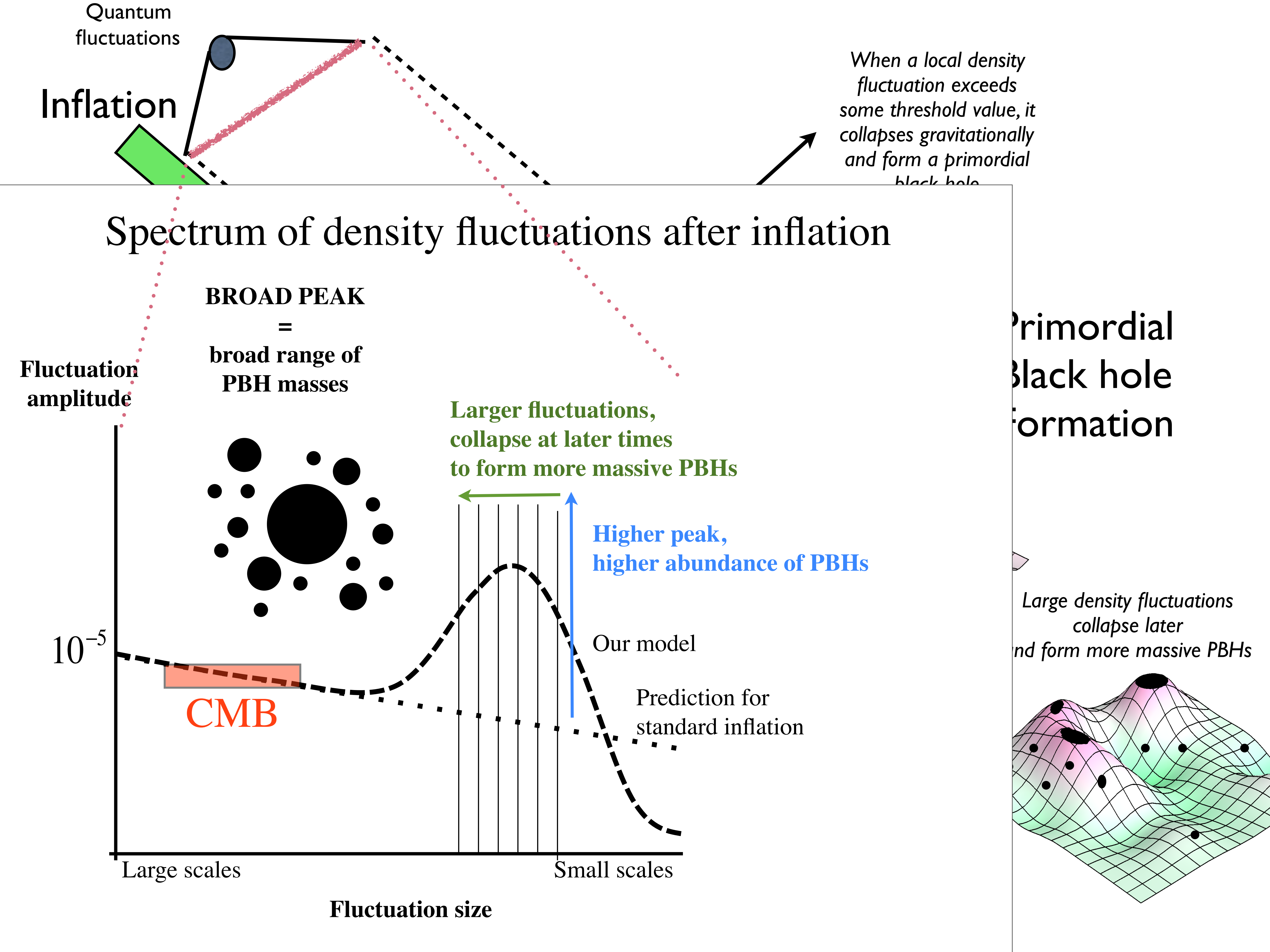

Quantum fluctuations
Inflation
Radiation era
When a local density fluctuation exceeds some threshold value, it collapses gravitationally and form a primordial black hole
Primordial Black hole Formation
Small-size density fluctuations collapse earlier and form less massive PBHs
Time evolution
Large density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


Quantum
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When a local density
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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
Our model
Prediction for
standard inflation
10^{-5}
CMB
Large scales
Small scales
Fluctuation size
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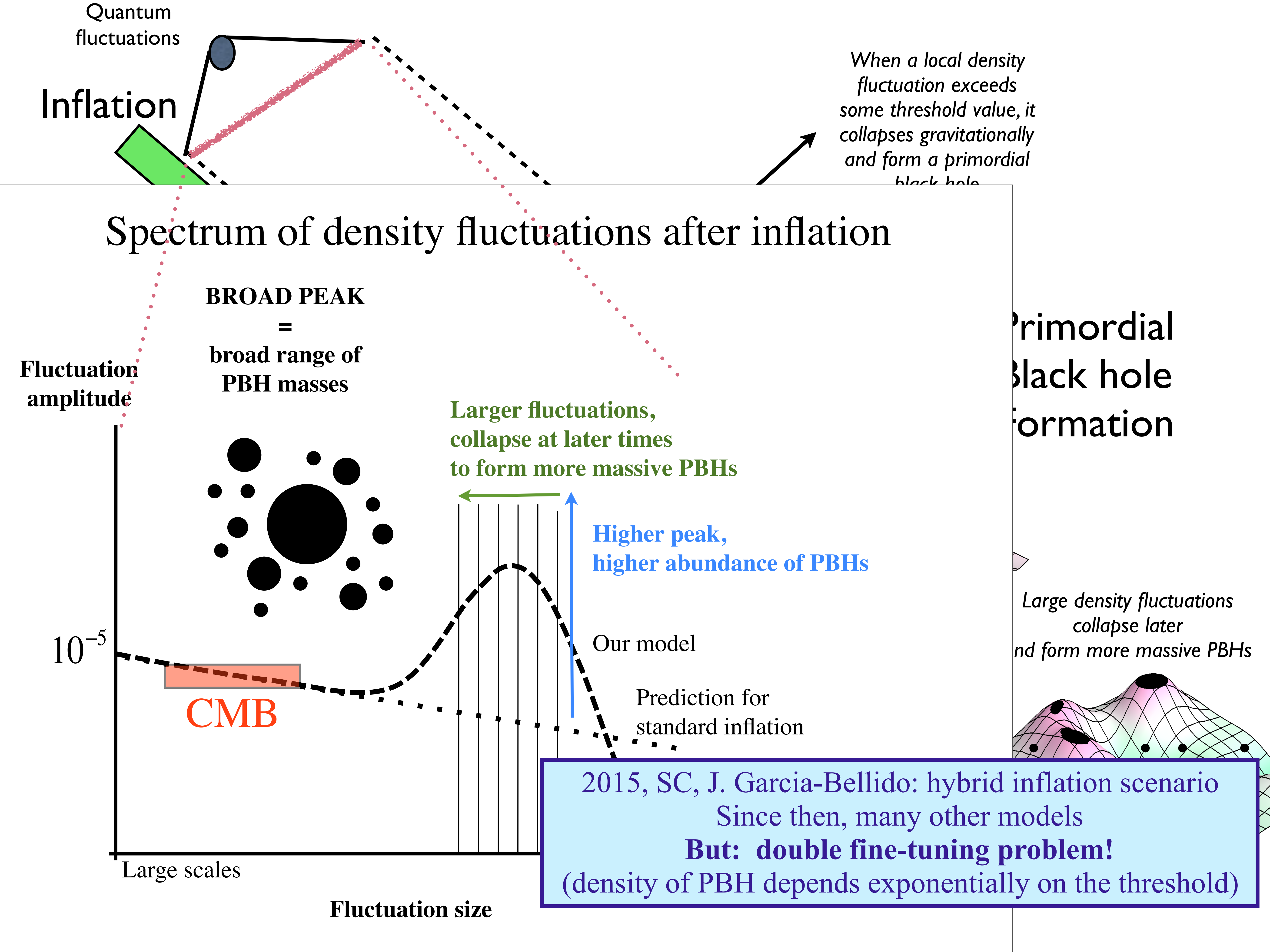
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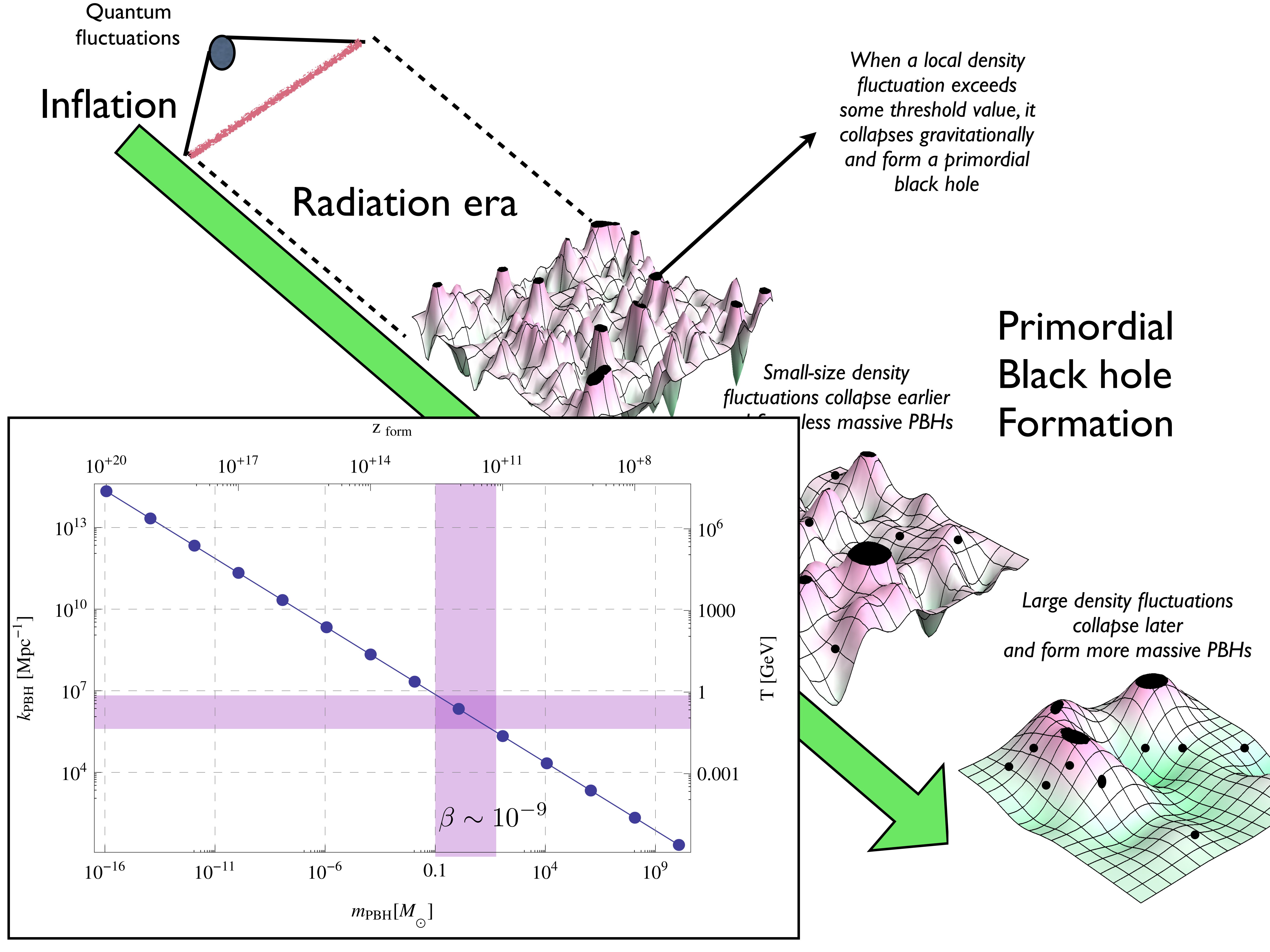
Large density fluctuations collapse later
nd form more massive PBHs
2015, SC, J. Garcia-Bellido: hybrid inflation scenario
Since then, many other models
But: double fine-tuning problem!
(density of PBH depends exponentially on the threshold)



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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
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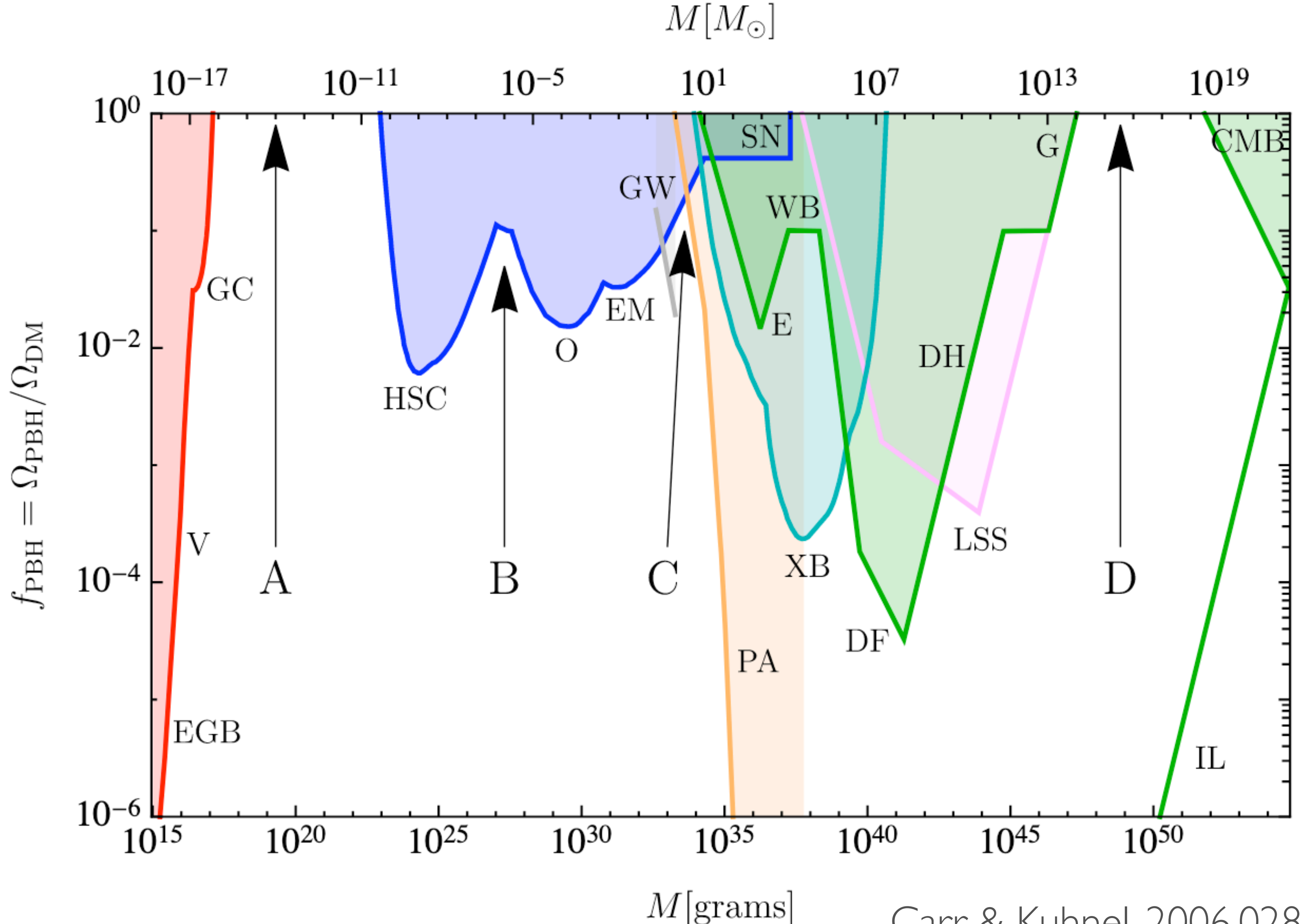
z form
10^+20
10^+17
10^+14
10^+11
10^+8
10^13
10^10
10^7
10^4
10^6
1000
1
0.001
k_PBH [Mpc^-1]
T [GeV]
β ~ 10^-9
10^-16
10^-11
10^-6
0.1
10^4
10^9
m_PBH[M_⊙]

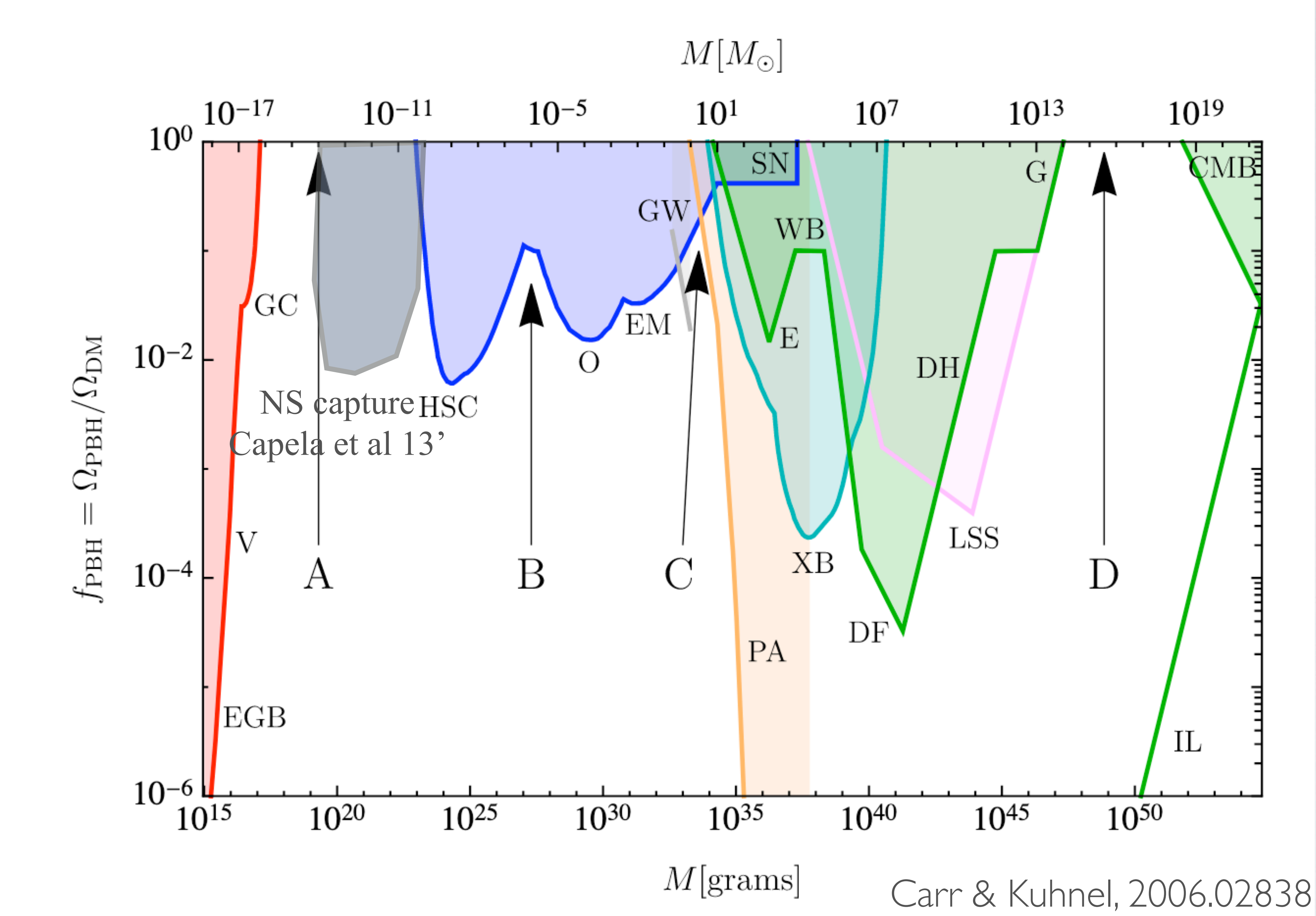
Astro/cosmo limits



Carr & Kuhnel, 2006.02838

Hawking radiation
Microlensing
Dynamical effects
CMB distortions
Accretion
Large scale structures

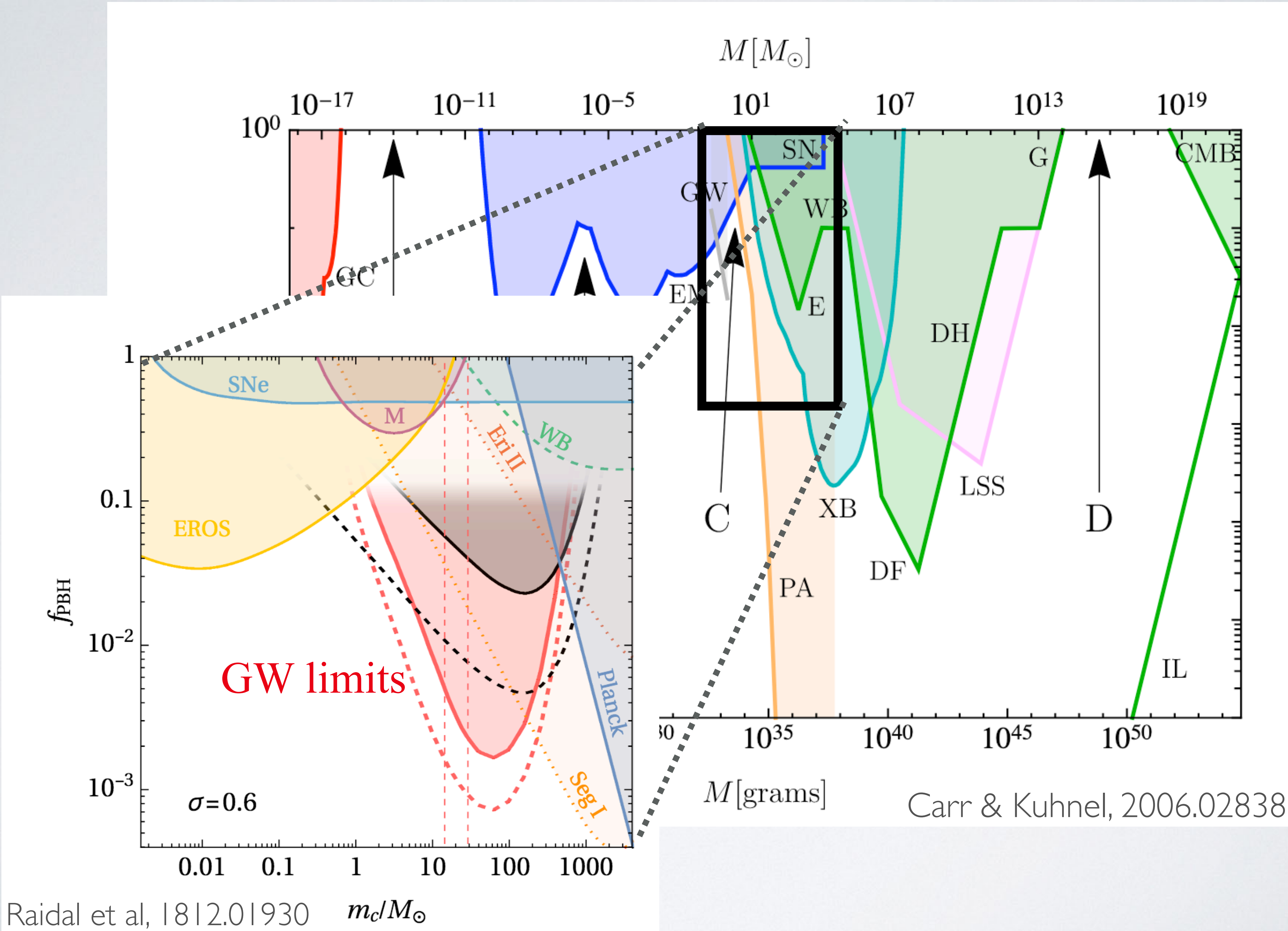
Astro/cosmo limits



Hawking radiation   Microlensing   Dynamical effects

CMB distortions   Accretion   Large scale structures

Astro/cosmo limits



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 **m_{PBH} ~ stellar-mass** (or any other specific mass)
- Need of an **exotic**, peaky and non-Gaussian, 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…

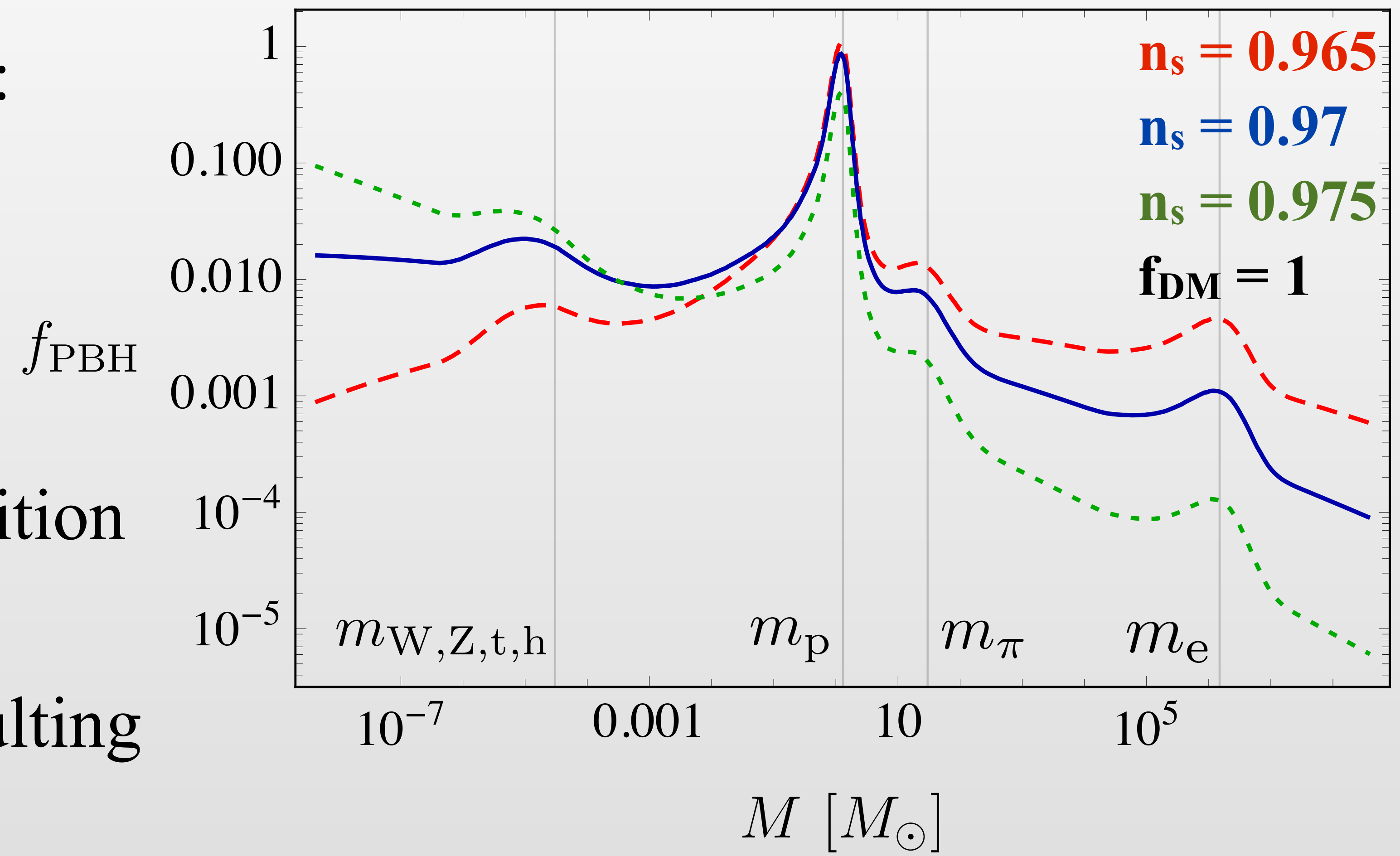
…so my talk is done and I stop working on PBHs?

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

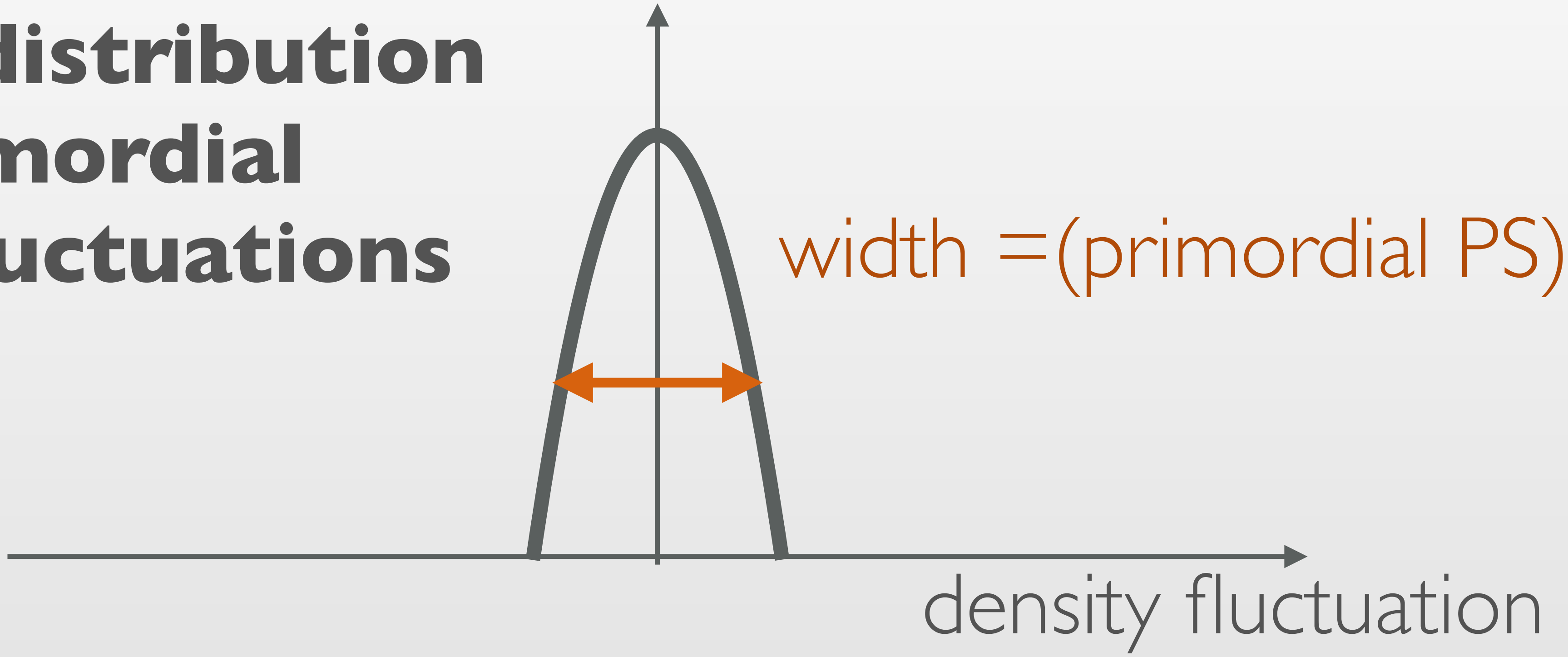
B. Carr, S.C., J. Garcìa-Bellido, F. Kühnel
arXiv:1906.08217

- **Nearly scale-invariant PS**
- **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} $M_\odot$**

Brainstorming

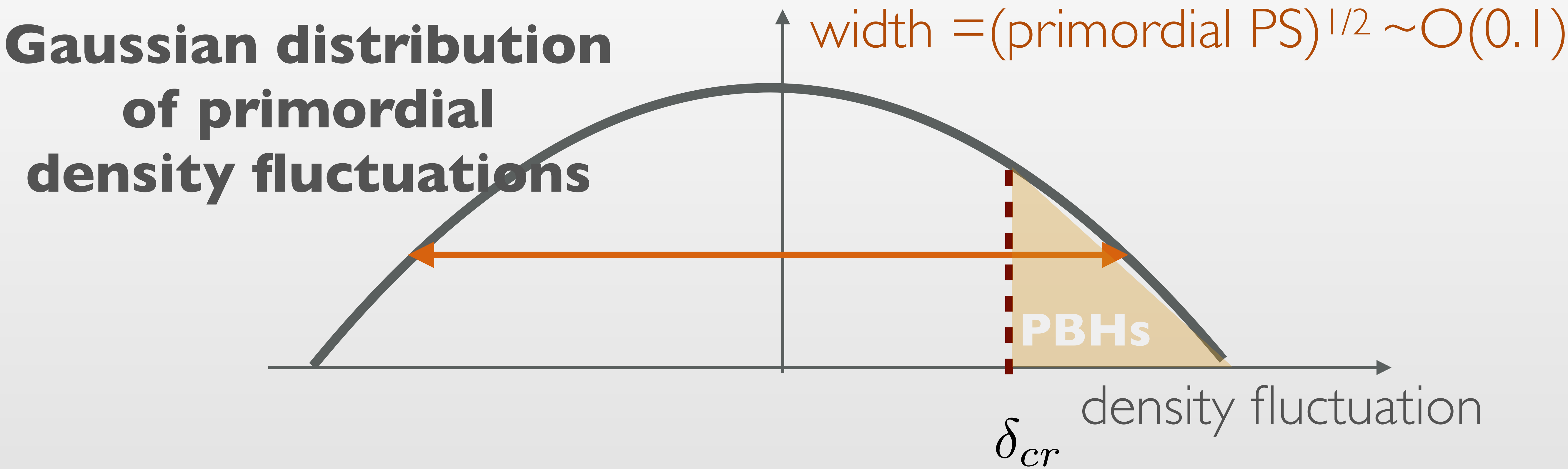
On CMB scales...

Gaussian distribution of primordial density fluctuations



Brainstorming

On PBH scales...



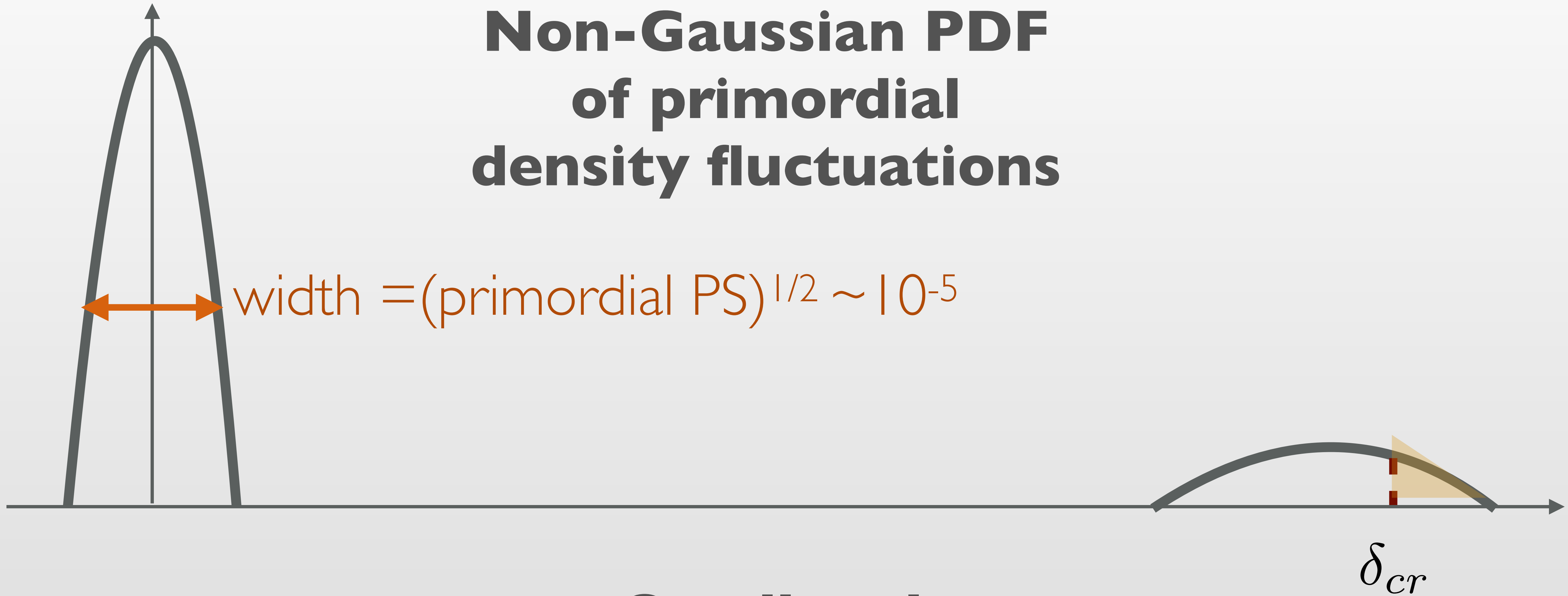
$$\beta \equiv \frac{\rho_{\rm PBH}^{\rm form}}{\rho_{\rm cr}} = {\rm erfc}\left(\frac{\delta_{\rm cr}}{\sqrt{\mathcal{P}_\delta}}\right) \approx \sqrt{\frac{2}{\pi}}\frac{\sqrt{\mathcal{P}_\delta}}{\delta_{\rm cr}}{\rm e}^{-\frac{\delta_{\rm cr}^2}{2\mathcal{P}_\delta}}$$

Origin of the fine-tuning !

Brainstorming

Crazy idea?

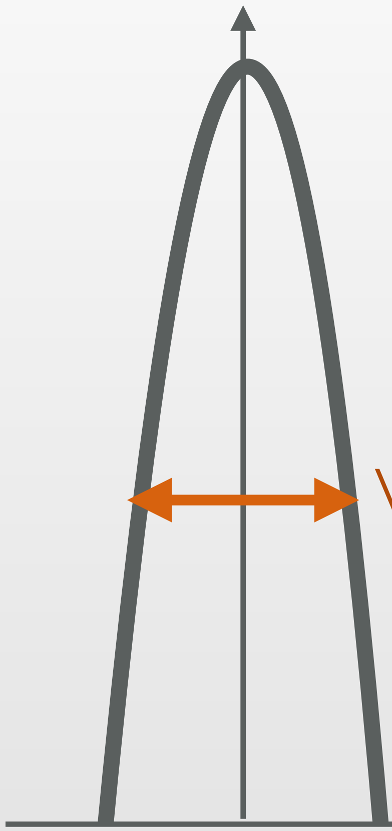
Non-Gaussian PDF of primordial density fluctuations



On all scales

Brainstorming

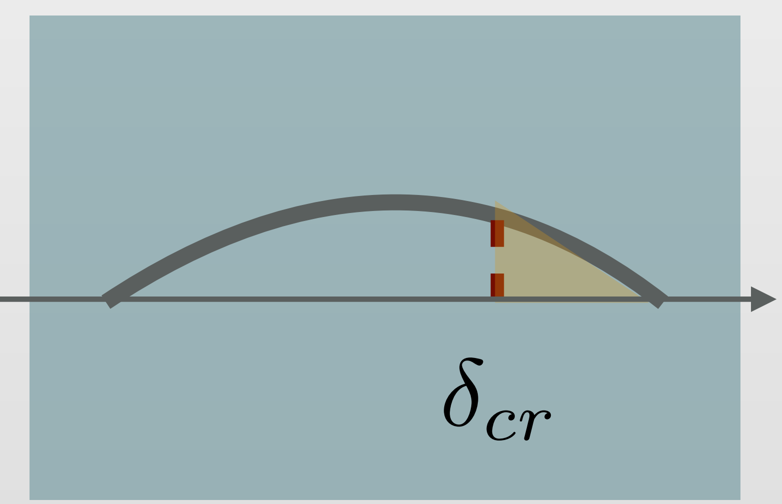
Crazy idea?



Non-Gaussian PDF of primordial density fluctuations

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

Stochastic process (quantum fluctuations ?)

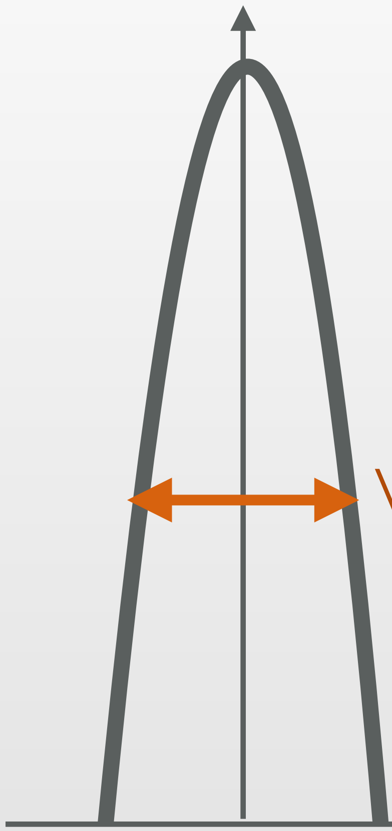


On all scales

PBHs = Dark Matter due to anthropic selection

Brainstorming

Crazy idea?



Non-Gaussian PDF of primordial density fluctuations

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

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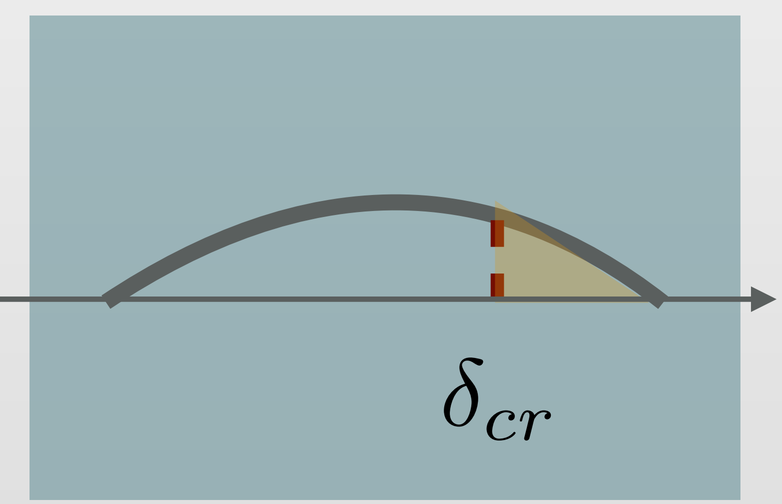


On all scales

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

Would work even better if PBHs could trigger the baryogengesis

Baryon-to-PBH ratio:

$$\Omega_{\rm PBH} \sim \Omega_{\rm b}$$

Baryon-to-photon ratio:

$$\beta_{\rm PBH} \sim \frac{n_{\rm b}}{n_\gamma} \sim 10^{-9}$$

Brainstorming

Crazy idea?

<u>Solution:</u>

1. **Hot-spot Electroweak Baryogenesis**

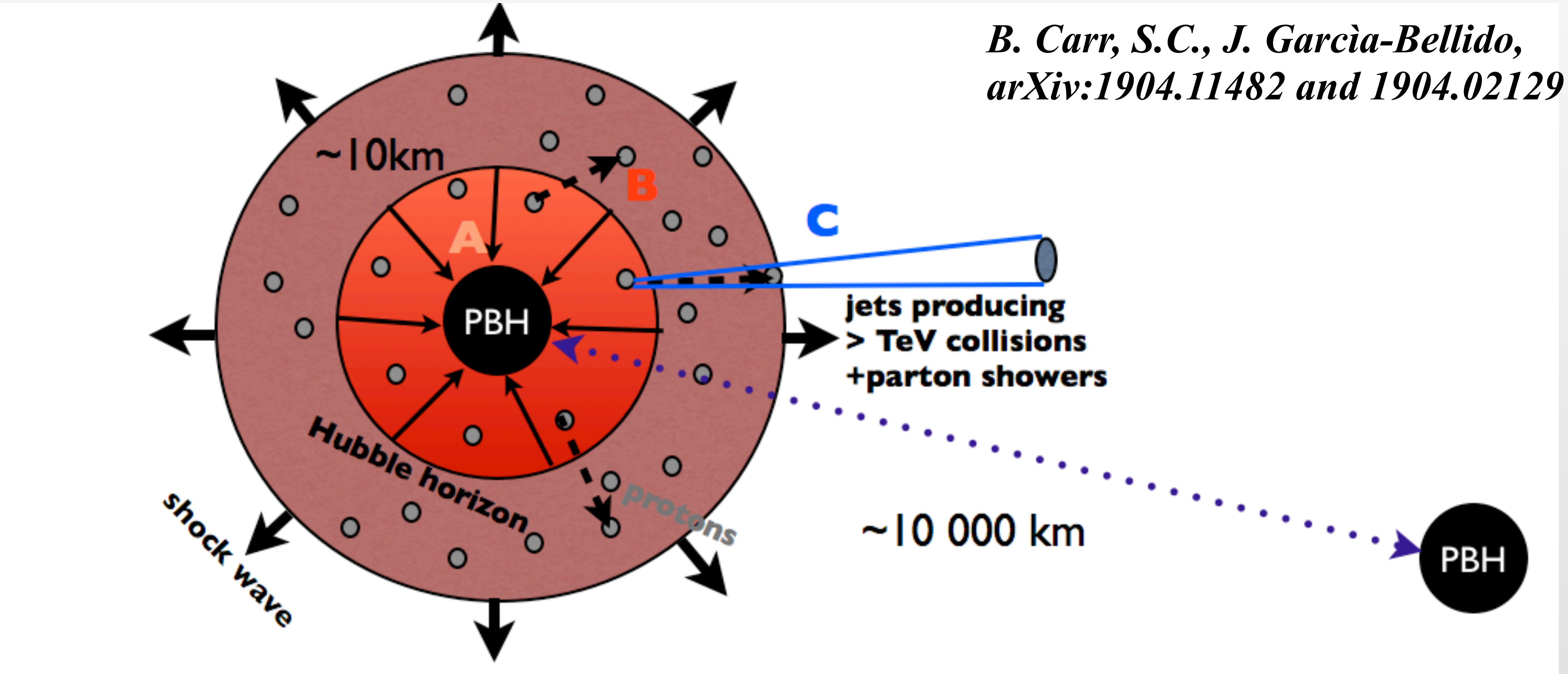
2. **Light stochastic spectator field during inflation**

Carr, Clesse, Garcia-Bellido
arXiv:1904.02129, arXiv:1904.1182

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 (CKM matrix)
- Baryon number violation: sphaleron transitions from >TeV collisions
- Interactions out of thermal equilibrium: PBH collapse/shock wave

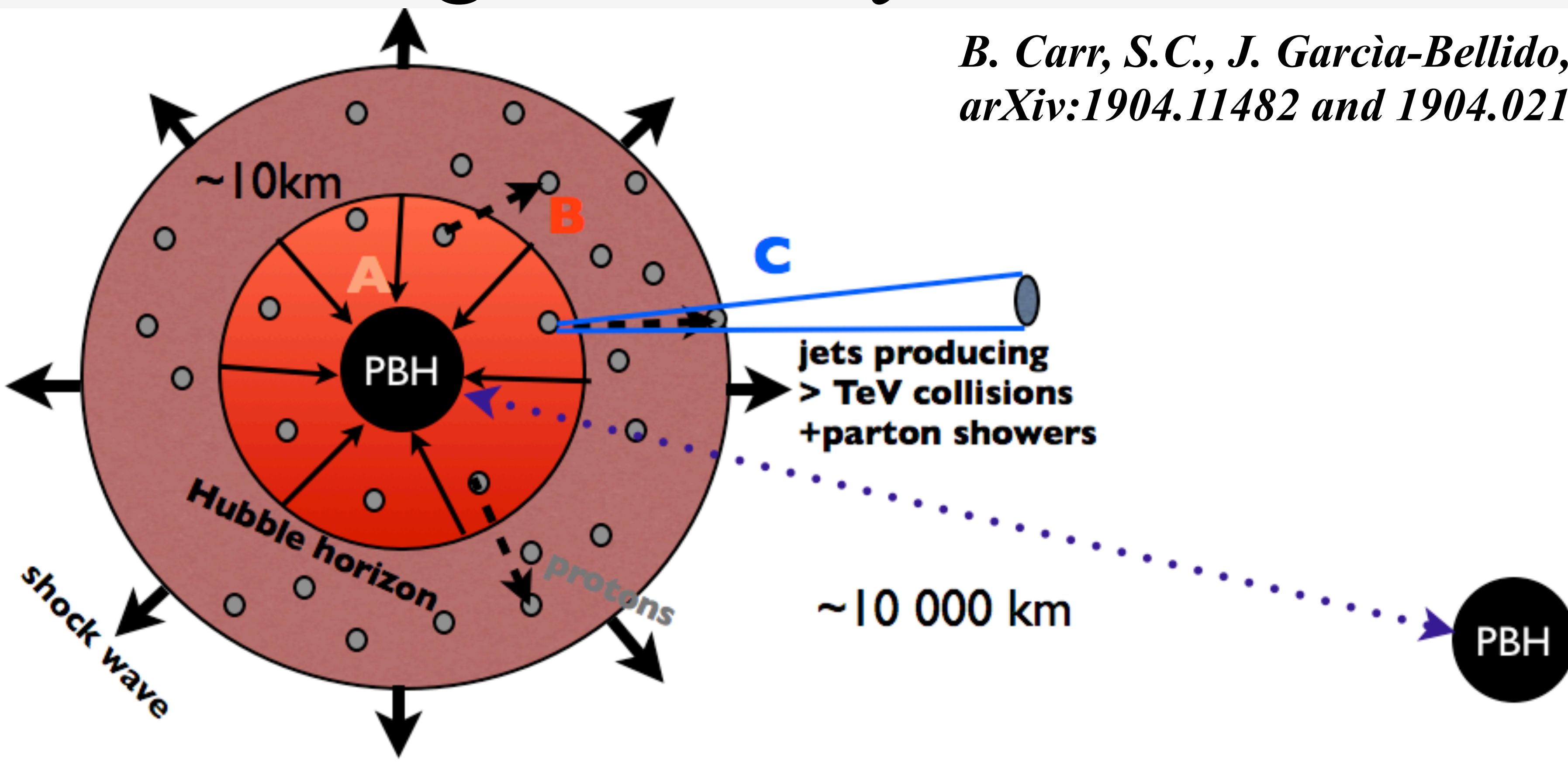
Eletroweak baryogenesis: need of exotic physics.

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

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

Primordial Black Holes

as a common origin of baryons and dark matter



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

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

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

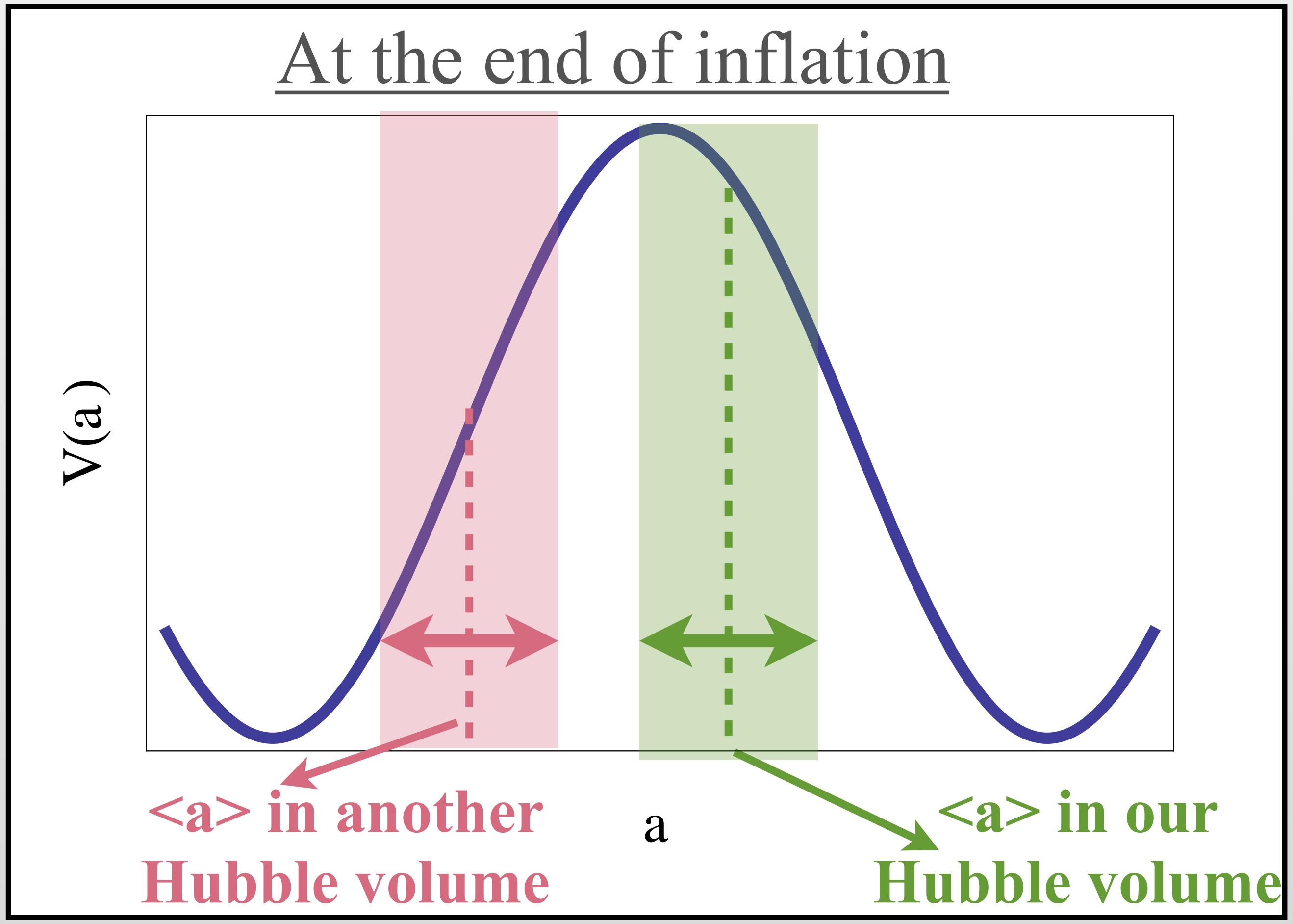
$$\delta_{\rm CP}(T) = 3\times 10^{-5}\,(20.4\,{\rm GeV}/T)^{12}$$

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

Primordial Black Holes

without power spectrum enhancement

- Step 1- During inflation: **Light stochastic spectator field** (*a*) with plateau or small-field potential : $\Delta a_{\rm qu} \simeq H_{\rm inf}/2\pi$

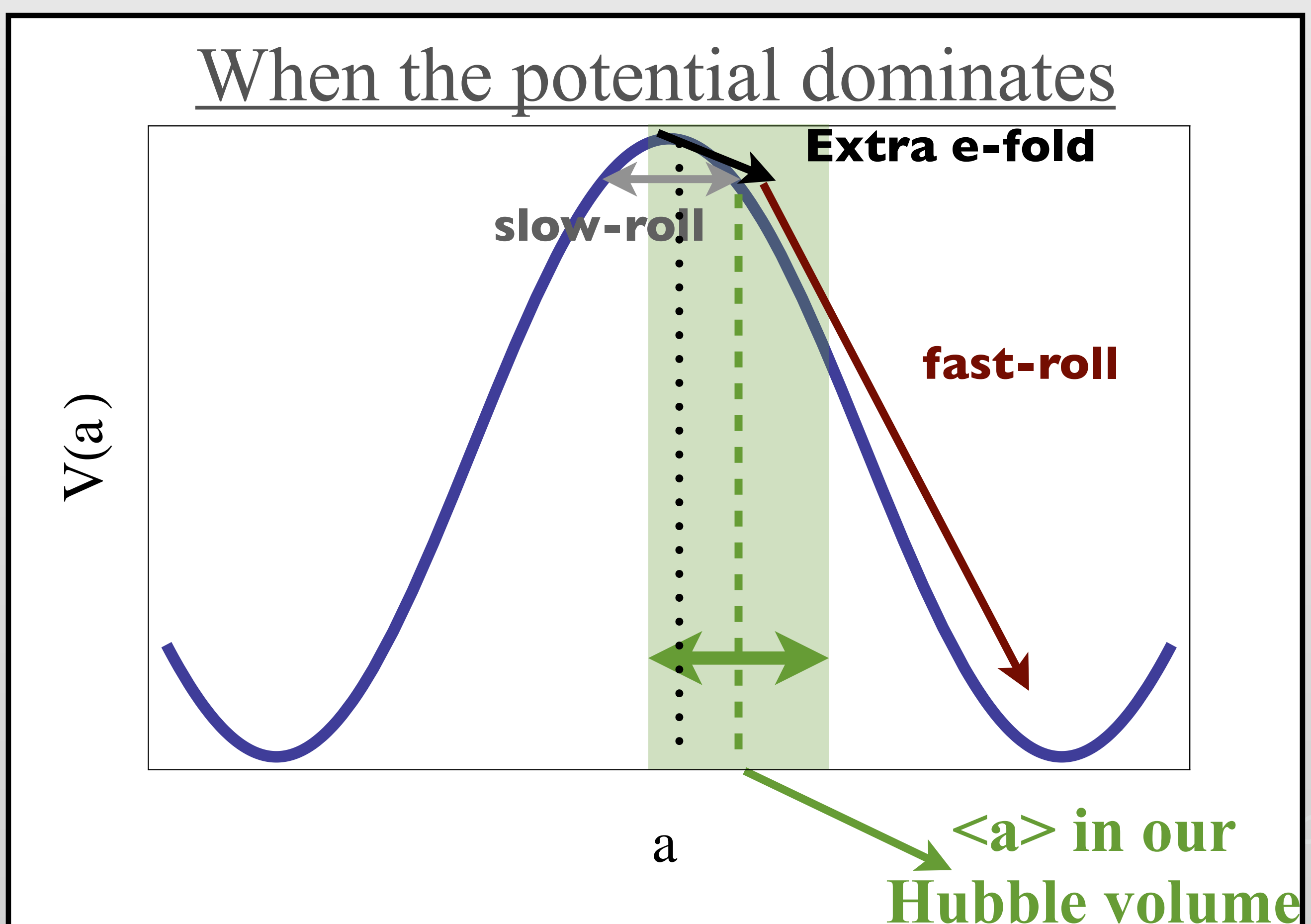


Due to quantum fluctuations, the field explores the whole potential

Primordial Black Holes

without power spectrum enhancement

- Step 1- During inflation: **Light stochastic spectator field** (*a)* with plateau or small-field potential : $\Delta a_{\rm qu} \simeq H_{\rm inf}/2\pi$
- Step 2 - In the radiation era: At some point, the potential starts to dominate the energy density. **Extra e-fold** of expansion **in regions** where the field lies **in the slow-roll part** of the potential => **Super-horizon O(1) curvature fluctuations are produced**



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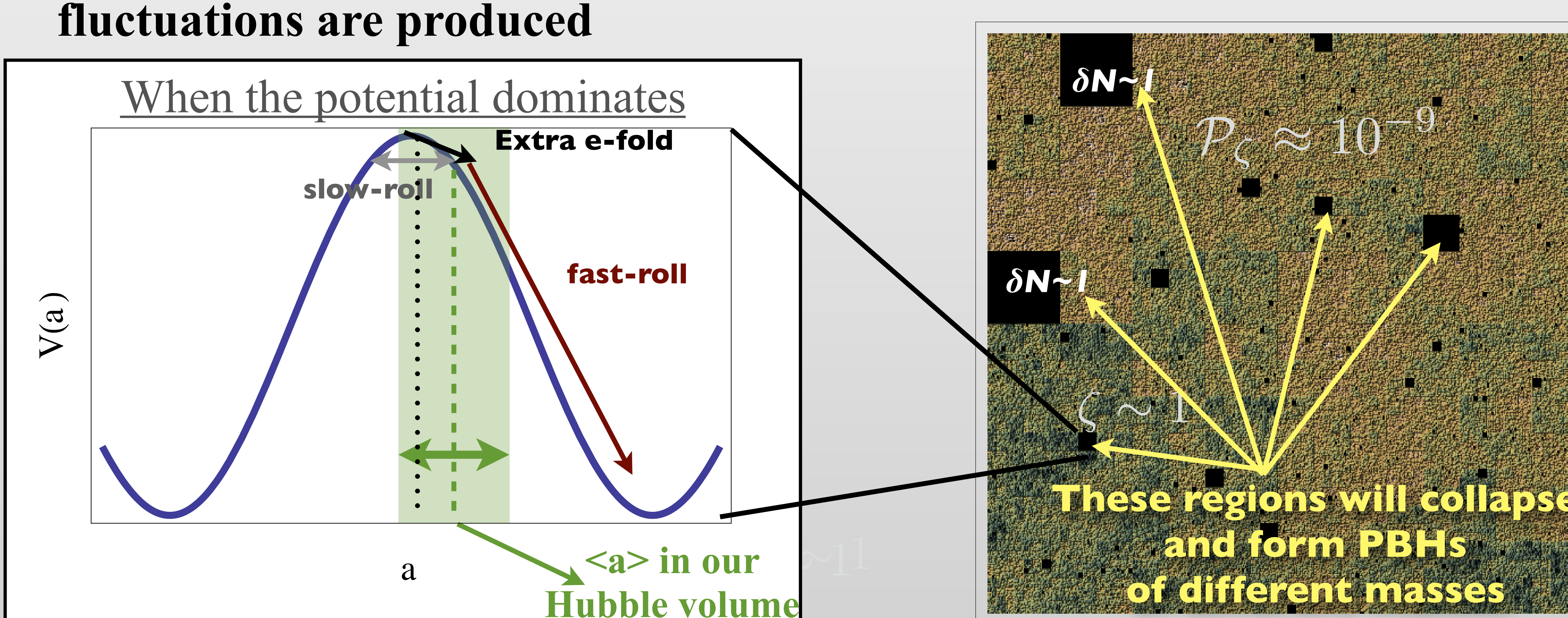

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- Step 3 - QCD transition: These curvature fluctuations enter inside the horizon and collapse to form PBHs

Primordial Black Holes

without parameter fine-tuning

Exploring the multiverse…

Primordial Black Holes

without parameter fine-tuning

Exploring the multiverse…

Primordial Black Holes

without parameter fine-tuning

Exploring the multiverse…

QCD transition:
$m_{PBH} \sim m_{chandra}$

Dark Universe

Primordial Black Holes

without parameter fine-tuning

Exploring the multiverse…

HSEWB:

$\Omega_b \sim \Omega_{PBH}$

$n_b / n_\gamma \sim \beta_{PBH}$

QCD transition:

$m_{PBH} \sim m_{chandra}$

Dark Universe

Primordial Black Holes

without parameter fine-tuning

Exploring the multiverse…

Stochastic spectator:
β_{PBH} linked to $\langle a \rangle$
no spectrum enhancement

HSEWB:
$\Omega_b \sim \Omega_{PBH}$
$n_b / n_\gamma \sim \beta_{PBH}$

QCD transition:
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Dark Universe

Primordial Black Holes

without parameter fine-tuning

Exploring the multiverse…

our <a>

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QCD transition:
$m_{PBH} \sim m_{chandra}$

Dark Universe

most <a>

Radiation Universe

no PBH
no baryons
no life

Primordial Black Holes

without parameter fine-tuning

Exploring the multiverse…

some <a> — our <a> — most <a> →

some <a>

Black Hole Universe

$\Omega_b \sim \Omega_{PBH}$
$\beta_{PBH} >> 10^{-9}$

Smaller Silk-damping scale

Boosted clustering
All baryons accreted by PBHs
no life

our <a>

Stochastic spectator:
β_{PBH} linked to <a>
no spectrum enhancement

HSEWB:
$\Omega_b \sim \Omega_{PBH}$
$n_b / n_\gamma \sim \beta_{PBH}$

QCD transition:
$m_{PBH} \sim m_{chandra}$

Dark Universe

most <a>

Radiation Universe

no PBH
no baryons
no life

Primordial Black Holes

without parameter fine-tuning

Exploring the multiverse…

some <a>

Black Hole Universe

$\Omega_b \sim \Omega_{PBH}$
$\beta_{PBH} >> 10^{-9}$

Smaller Silk-damping scale

Boosted clustering
All baryons accreted by PBHs
no life

our <a>

Stochastic spectator:
β_{PBH} linked to <a>
no spectrum enhancement

HSEWB:
$\Omega_b \sim \Omega_{PBH}$
$n_b / n_\gamma \sim \beta_{PBH}$

QCD transition:
$m_{PBH} \sim m_{chandra}$

Dark Universe

some <a>

Gas + PBH Universe

$\Omega_b \sim \Omega_{PBH}$
$\beta_{PBH} << 10^{-9}$

Larger Silk-damping scale

No galaxy
no stars
no life

most <a>

Radiation Universe

no PBH
no baryons
no life

Primordial Black Holes

without parameter fine-tuning

Exploring the multiverse…

some <a> | our <a> | some <a> | most <a>

All these universes exist and are unavoidable

Anthropic selection related to quantum fluctuations

some <a>:

Smaller Silk-damping scale

Boosted clustering
All baryons accreted by PBHs
no life

our <a>:

HSEWB:
$\Omega_b \sim \Omega_{PBH}$
$n_b / n_\gamma \sim \beta_{PBH}$

QCD transition:
$m_{PBH} \sim m_{chandra}$

Dark Universe

some <a>:

Larger Silk-damping scale

No galaxy
no stars
no life

most <a>:

no PBH
no baryons
no life

PBH mass function

- ‘Standard’ PBH formation scenario: $\beta \equiv \frac{\rho_{\rm PBH}^{\rm form}}{\rho_{\rm cr}} = {\rm erfc}\left(\frac{\delta_{\rm cr}}{\sqrt{\mathcal{P}_\delta}}\right) \approx \sqrt{\frac{2}{\pi}}\frac{\sqrt{\mathcal{P}_\delta}}{\delta_{\rm cr}}{\rm e}^{-\frac{\delta_{\rm cr}^2}{2\mathcal{P}_\delta}}$
- Light Stochastic Spectator: $m_\psi \ll H_{\rm inf}$ and $\Delta\psi^{\rm stoch} \sim H/2\pi$

$$\langle\delta\psi^2\rangle \simeq \int_0^N \frac{H(N')^2}{4\pi^2}{\rm d}N' \simeq \frac{H_{\rm CMB}^2}{8\pi^2\epsilon_1}\left(1-{\rm e}^{-2\epsilon_1 N}\right) \qquad P(\psi,N) = \frac{1}{\sqrt{2\pi\langle\delta\psi^2\rangle}}\exp\left[-\frac{(\psi-\langle\psi\rangle)^2}{2\langle\delta\psi^2\rangle}\right],$$

Probability of a local field fluctuation: $P(\Delta\psi, N) = \frac{1}{\sqrt{2\pi(H(N)^2/4\pi^2)}}\exp\left[-\frac{\Delta\psi^2}{2(H(N)^2/4\pi^2)}\right].$

Case 1: $\Delta\psi^{\rm sr} \gg \Delta\psi^{\rm stoch}$

Plateau pot.

Proba. that the field lies in the slow-roll region

$$P_{\rm PBH} = \frac{{\rm d}\beta(t)}{{\rm d}\ln M} = \frac{1}{4}{\rm erfc}\left[\frac{\psi_{\rm cr}-\langle\psi\rangle}{\sqrt{2\langle\delta\psi^2\rangle}}\right]{\rm erfc}\left[\frac{\Delta\psi_{\rm tr}}{\sqrt{2}H(N)/(2\pi)}\right]$$

Proba. of fluctuation leading to extra N~(1)

Case 2: $\Delta\psi^{\rm sr} \ll \Delta\psi^{\rm stoch}$

Small field pot.

Symmetric potential (for simplicity):

Potential dependent, fixed by field dynamics

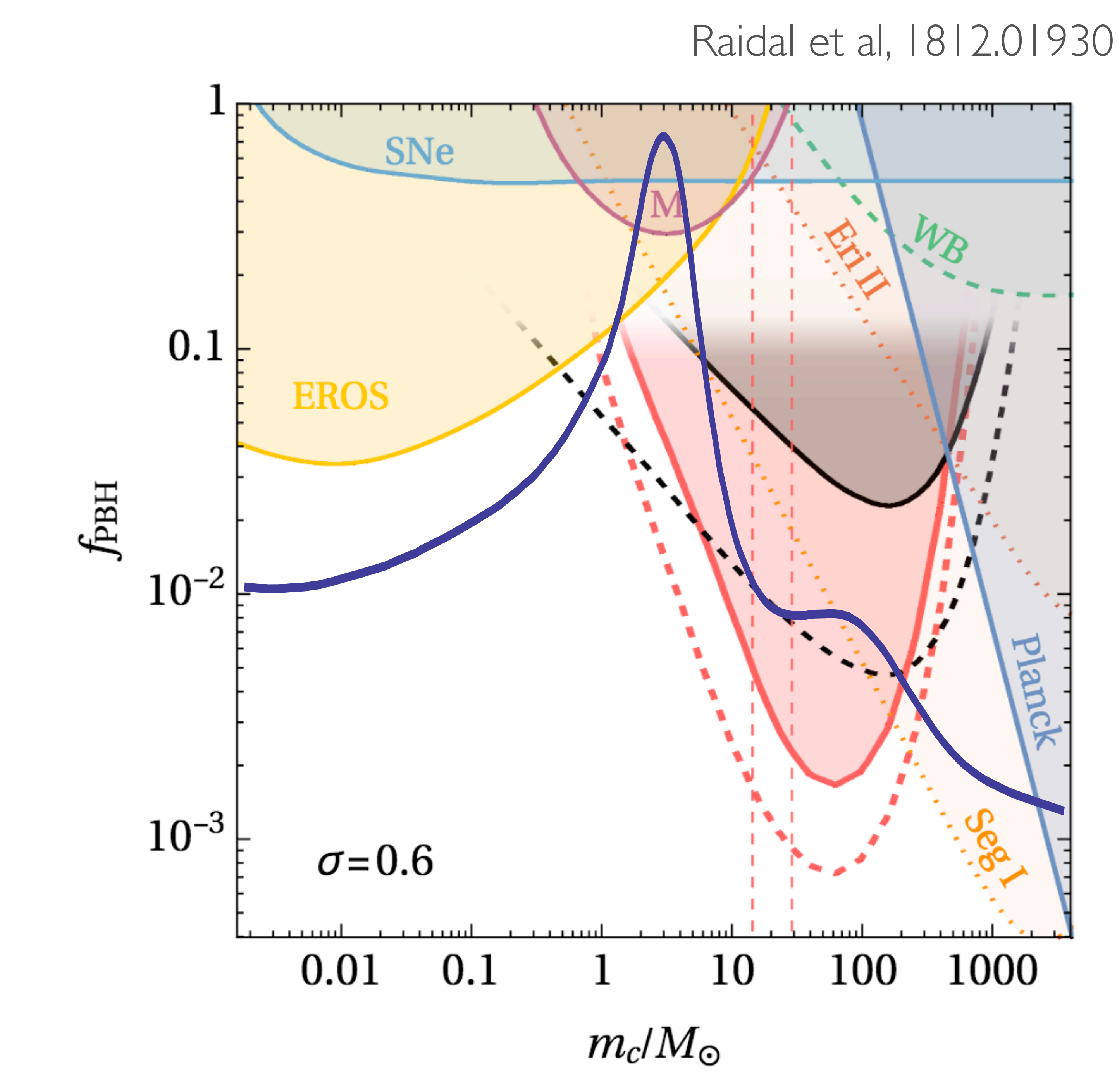
$$P_{\rm PBH} = \sqrt{\frac{2}{\pi}}\frac{\Delta\psi^{\rm sr}}{\sqrt{H_N^2/(4\pi^2)+\langle\delta\psi^2\rangle_{N-1}}}\exp\left[-\frac{\langle\psi\rangle^2}{2(H_N^2/4\pi^2+\langle\delta\psi^2\rangle_{N-1})}\right]$$

Proba. to get a field value leading to extra N~(1)

In both cases, the PBH mass function ‘mimics’ the standard scenario.

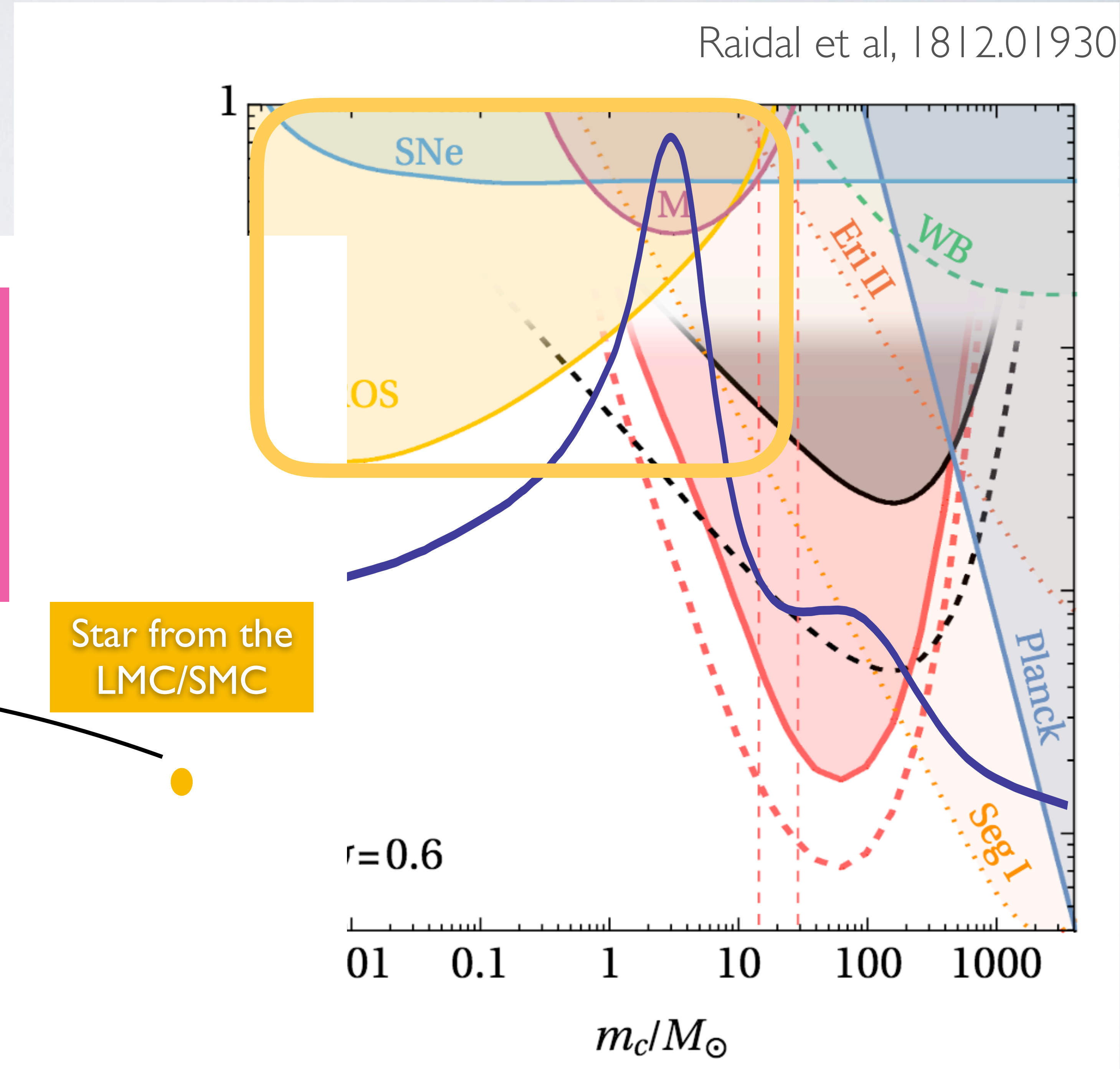
With anthropic selection of $\langle\psi\rangle$ one gets PBH-DM with $A_{\rm s} = 2.1\times10^{-9} \simeq \frac{H_*^2}{8\pi\epsilon_{1*}\bar{M}_{\rm P}^2}$

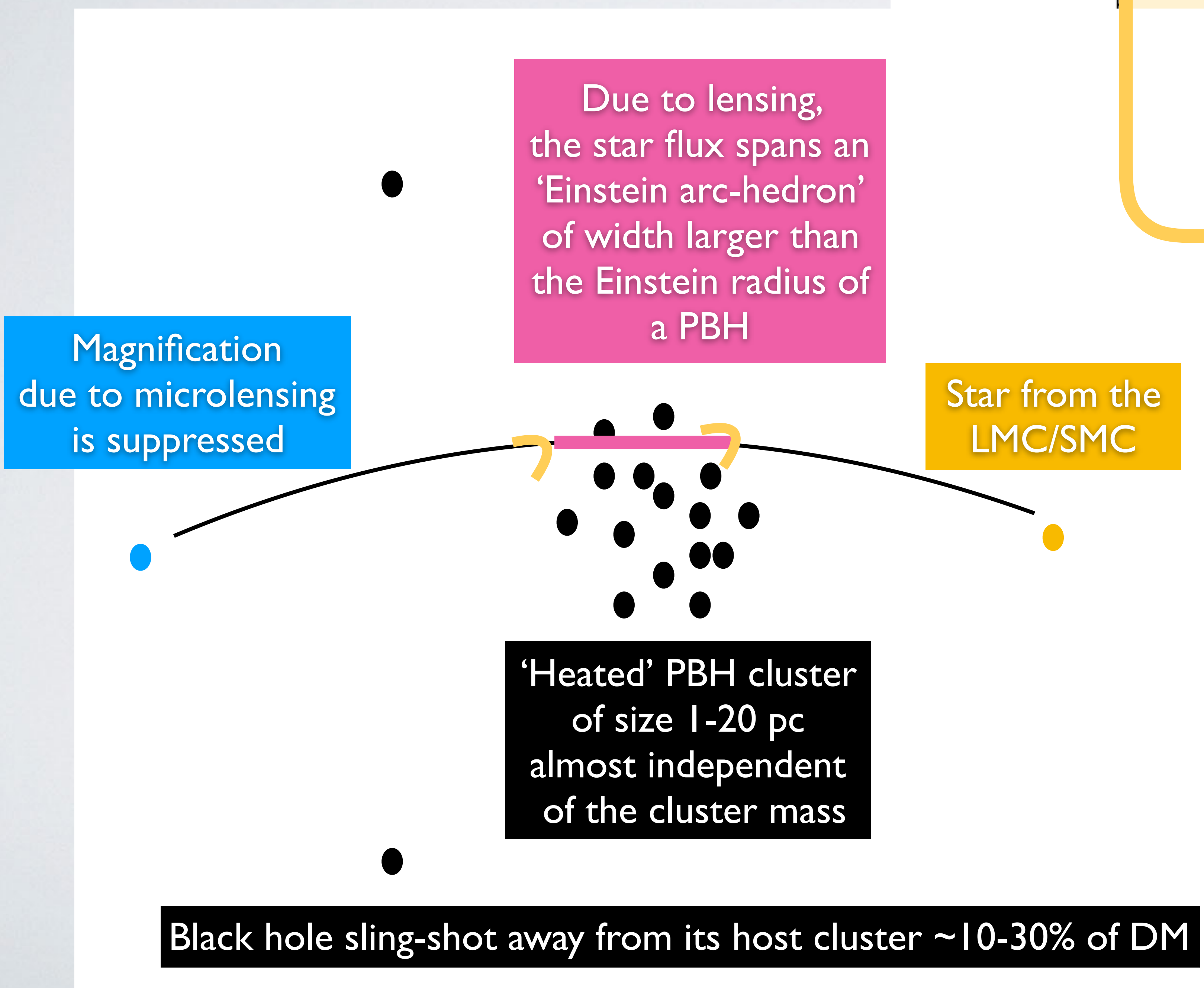
Astro/cosmo limits



Astro/cosmo limits

Microlensing limits evaded if 80% PBHs are regrouped in clusters



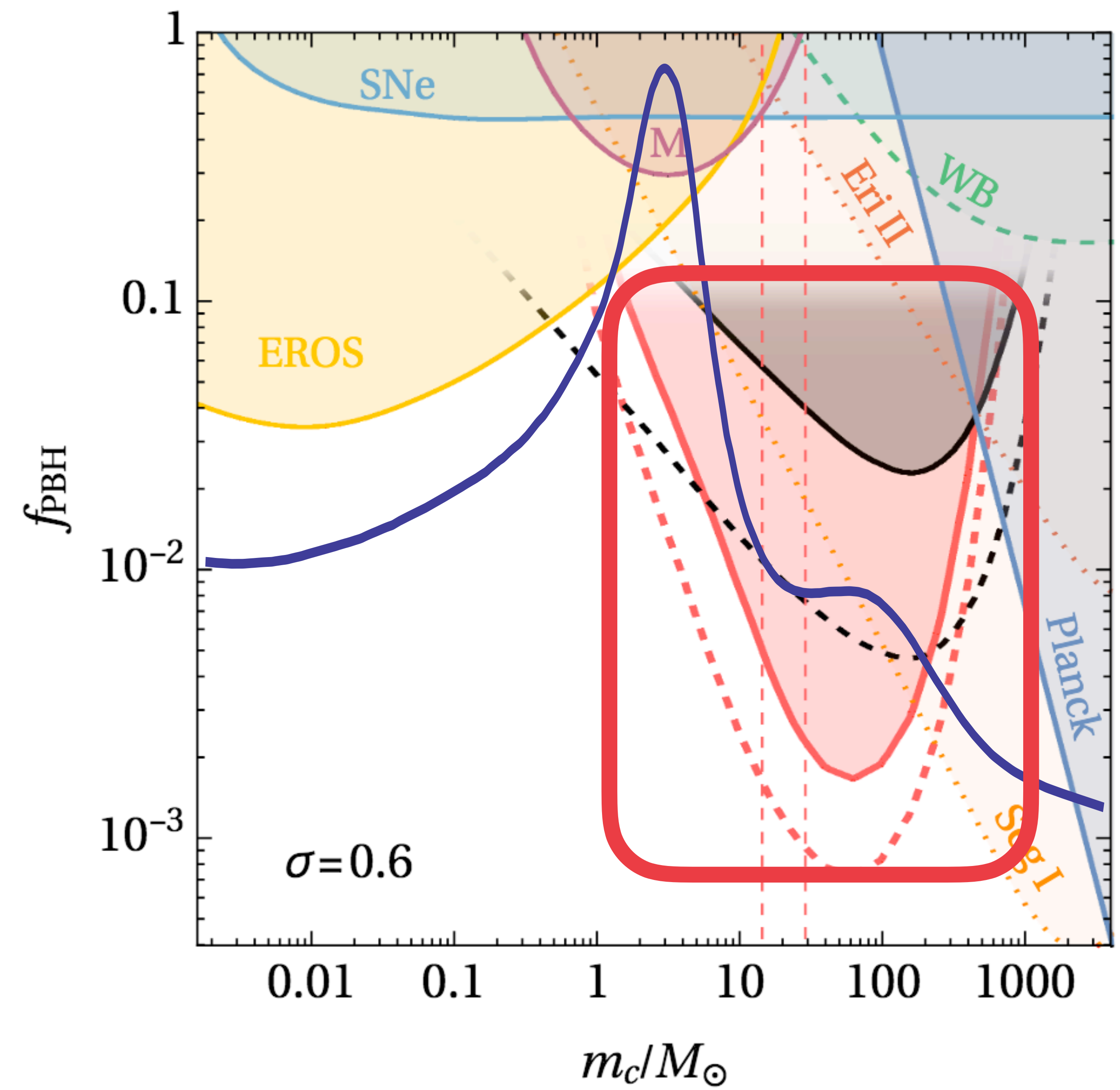


Astro/cosmo limits

Gravitational-wave limits from the merging of primordial binaries

Either evaded due to the effect of early clusters on the binary lifetime…

Raidal et al, 1812.01930

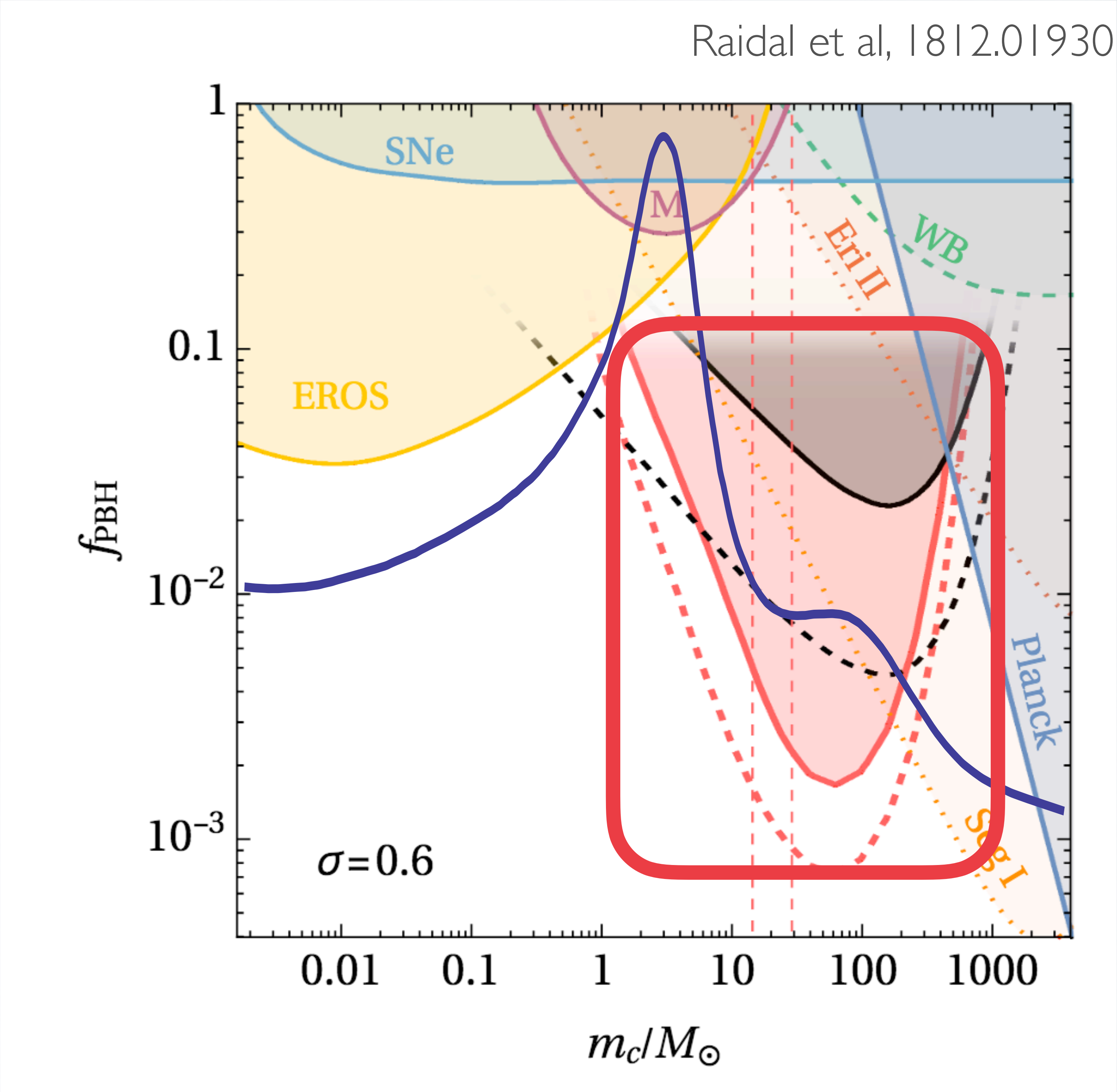


Astro/cosmo limits

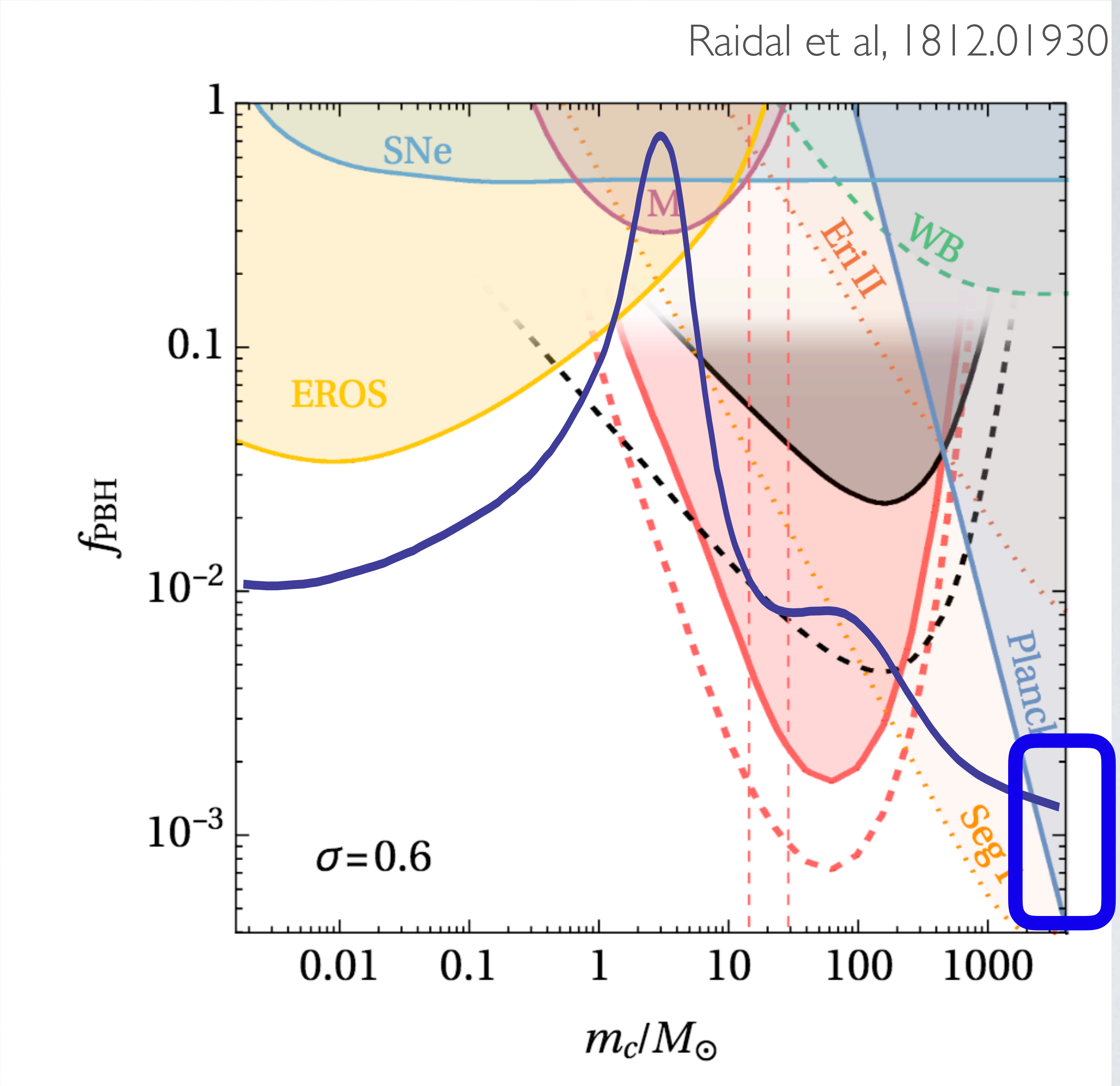
Gravitational-wave limits from the merging of primordial binaries

Either evaded due to the effect of early clusters on the binary lifetime…

… or totally suppressed according to Boehm et al 2008.10743 due to a subtle GR effect



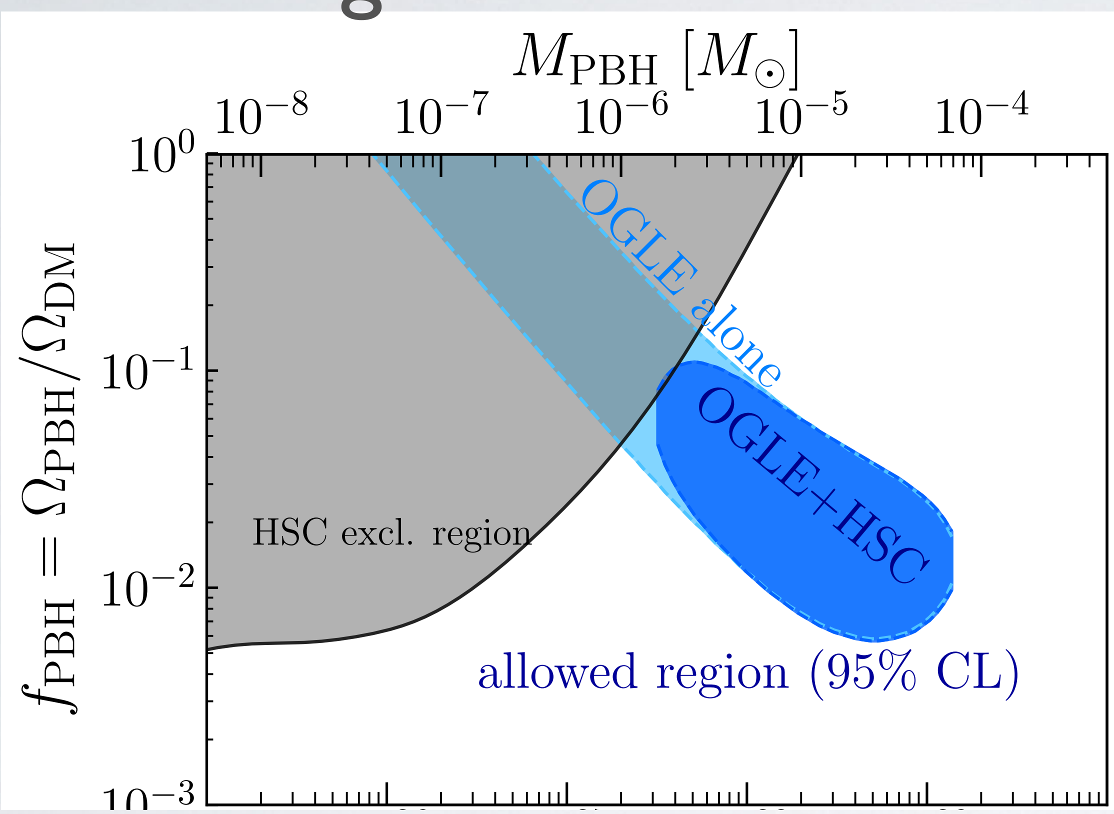
Astro/cosmo limits



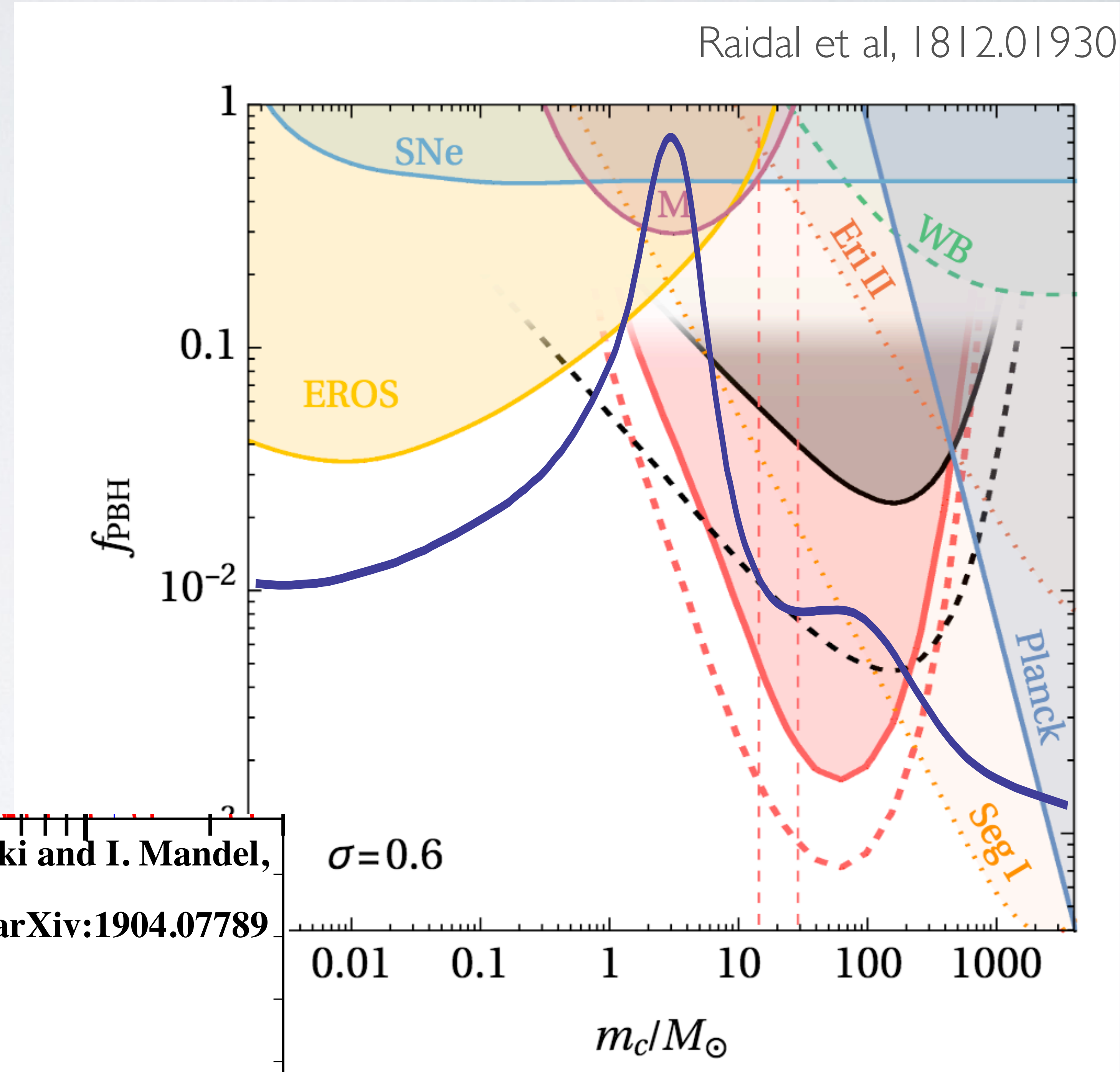
issue
with Planck limits ?

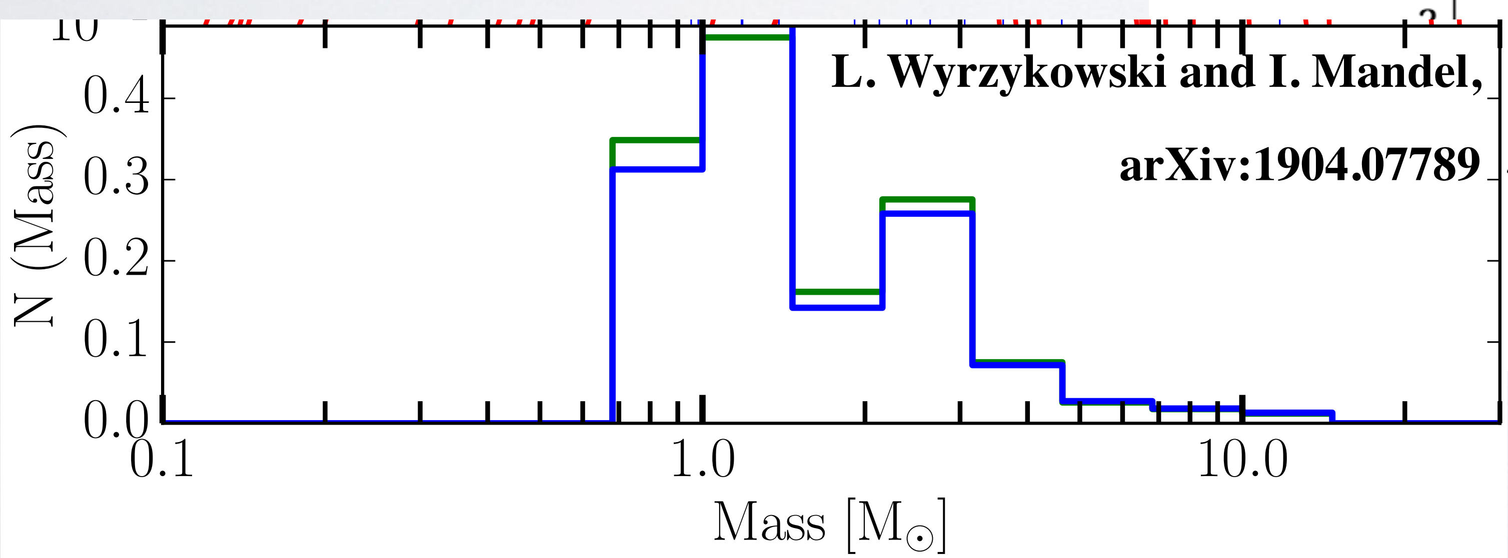
Astro/cosmo hints

microlensing towards the galactic center



Niikura et al., 1901.07120





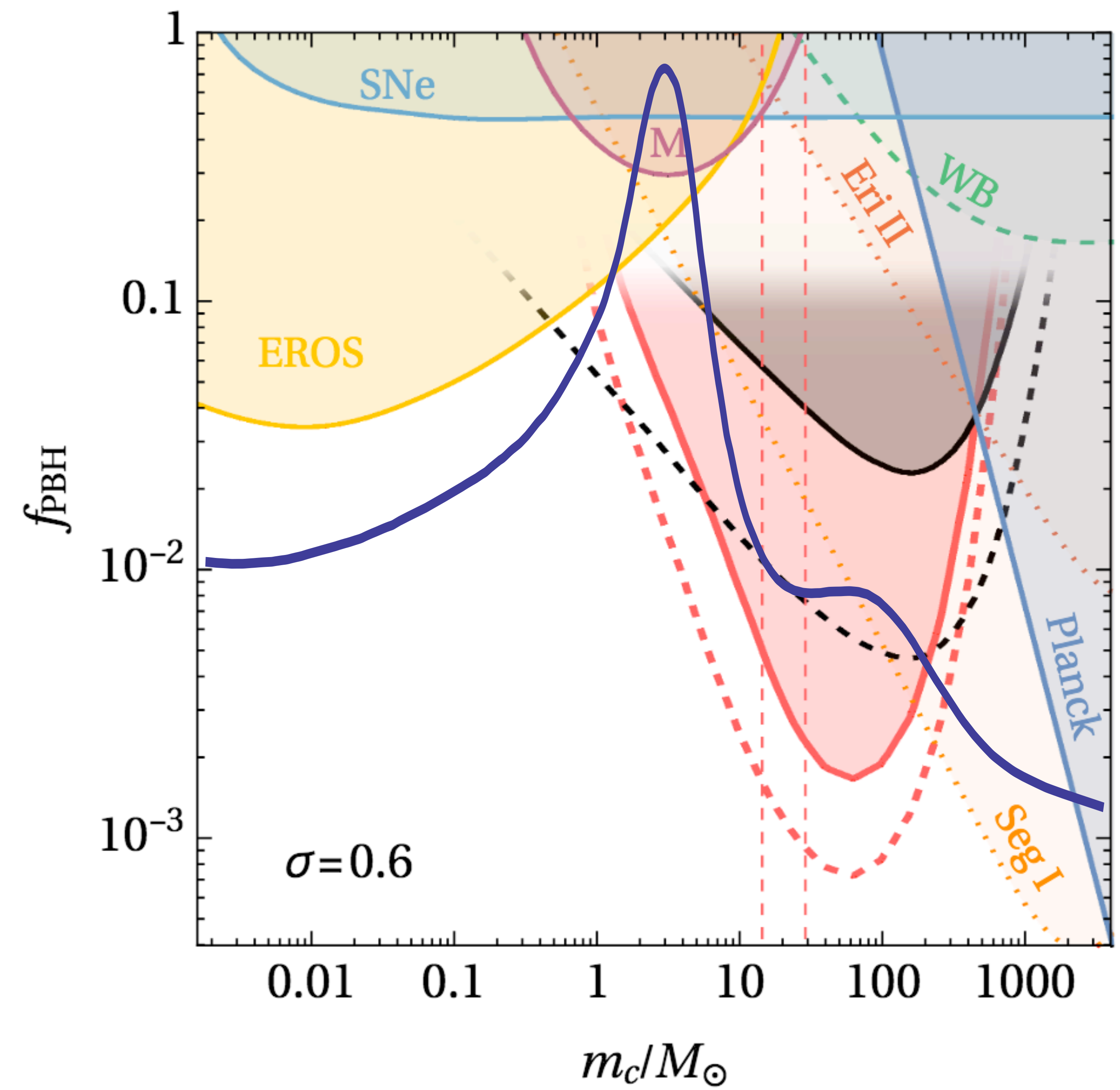
Astro/cosmo hints

- Critical size and mass-to-light ratios of ultra-faint dwarf galaxies
- Spatial correlations between infrared and source-subtracted X-ray backgrounds
- Quasar microlensing
- Number of SMBH seeds
- LIGO/Virgo black hole binary mergers
- NANOGrav

S.C., J. Garcìa-Bellido, 1711.

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

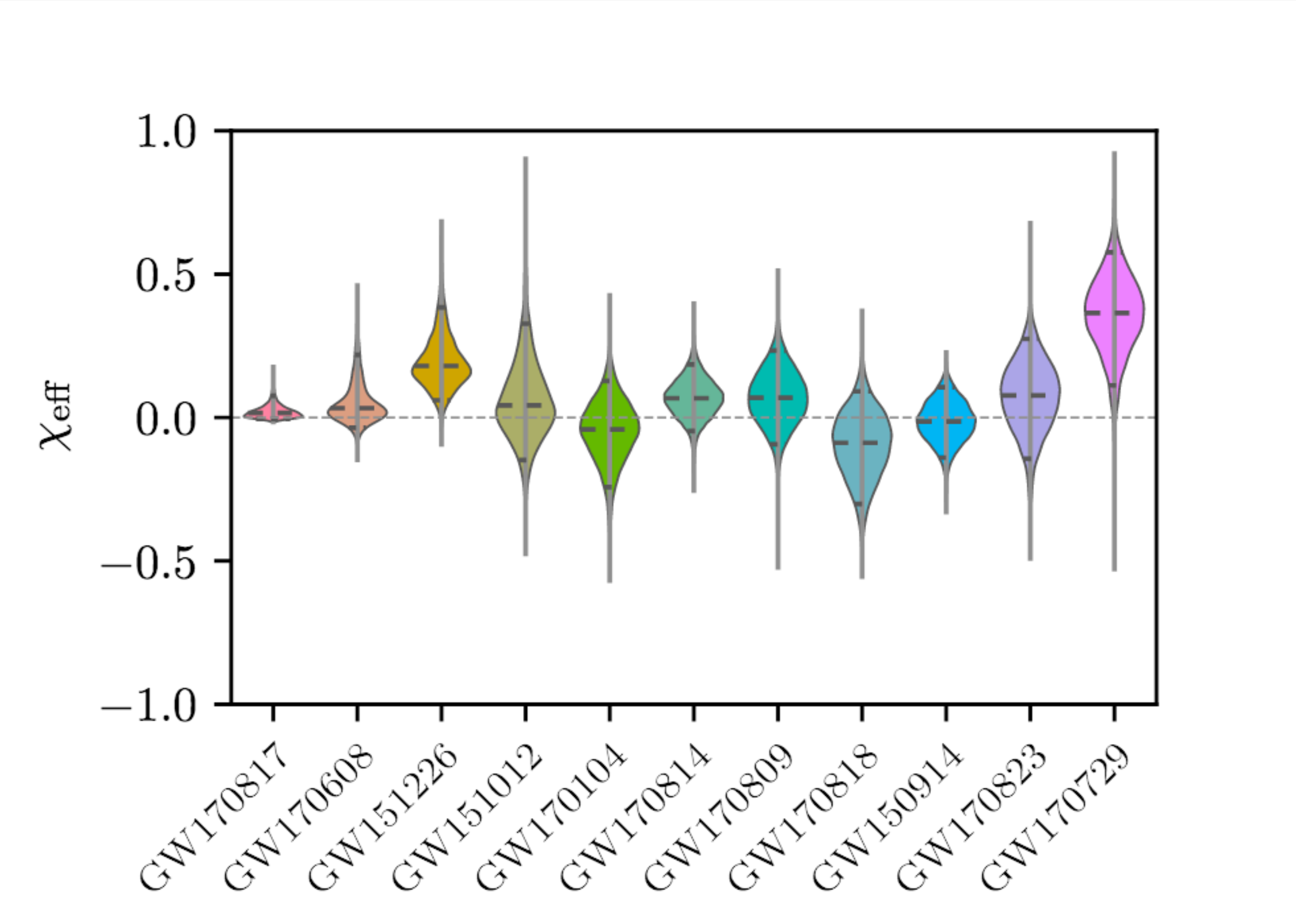
Raidal et al, 1812.01930



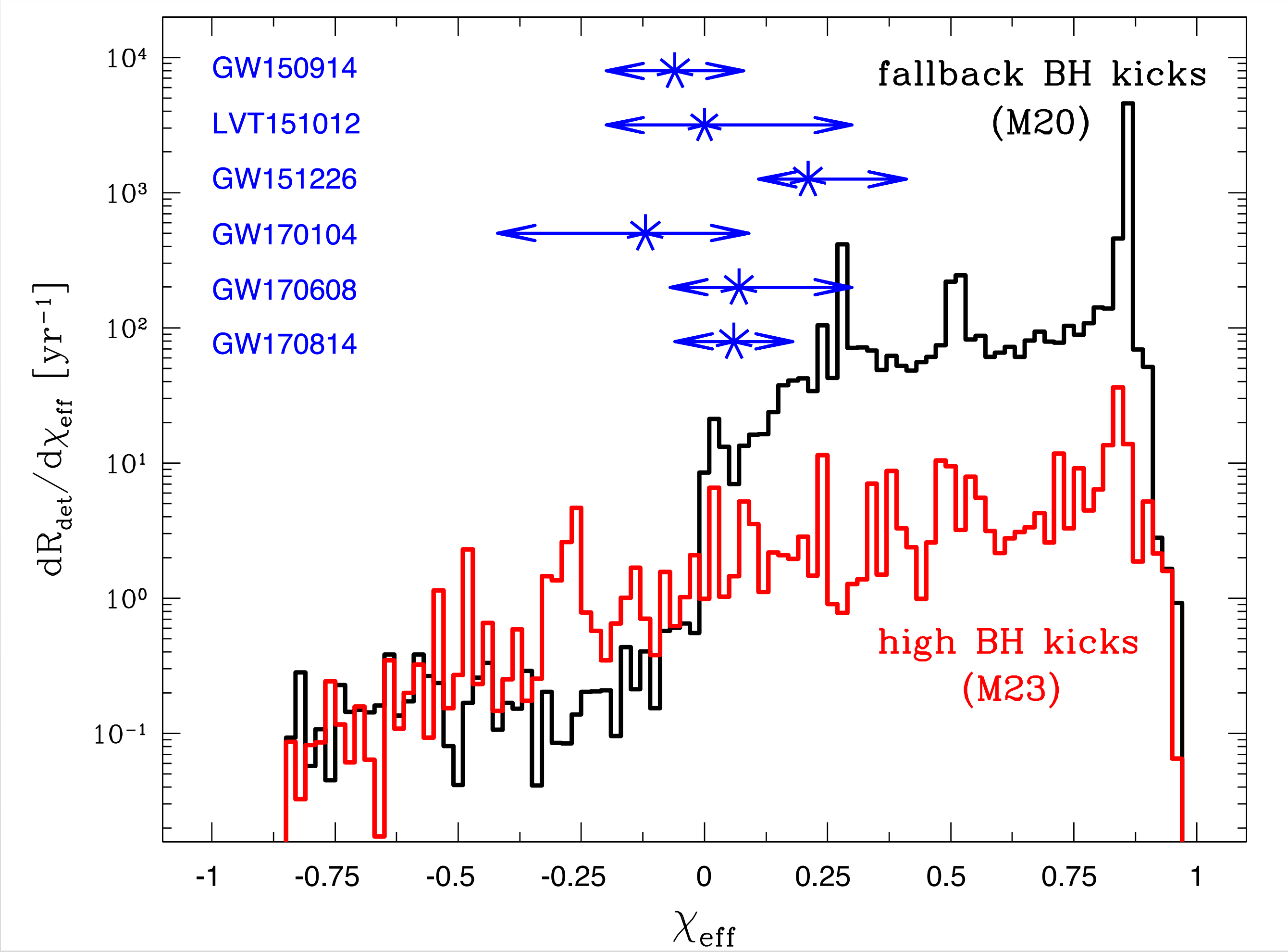
Gravitational Waves

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

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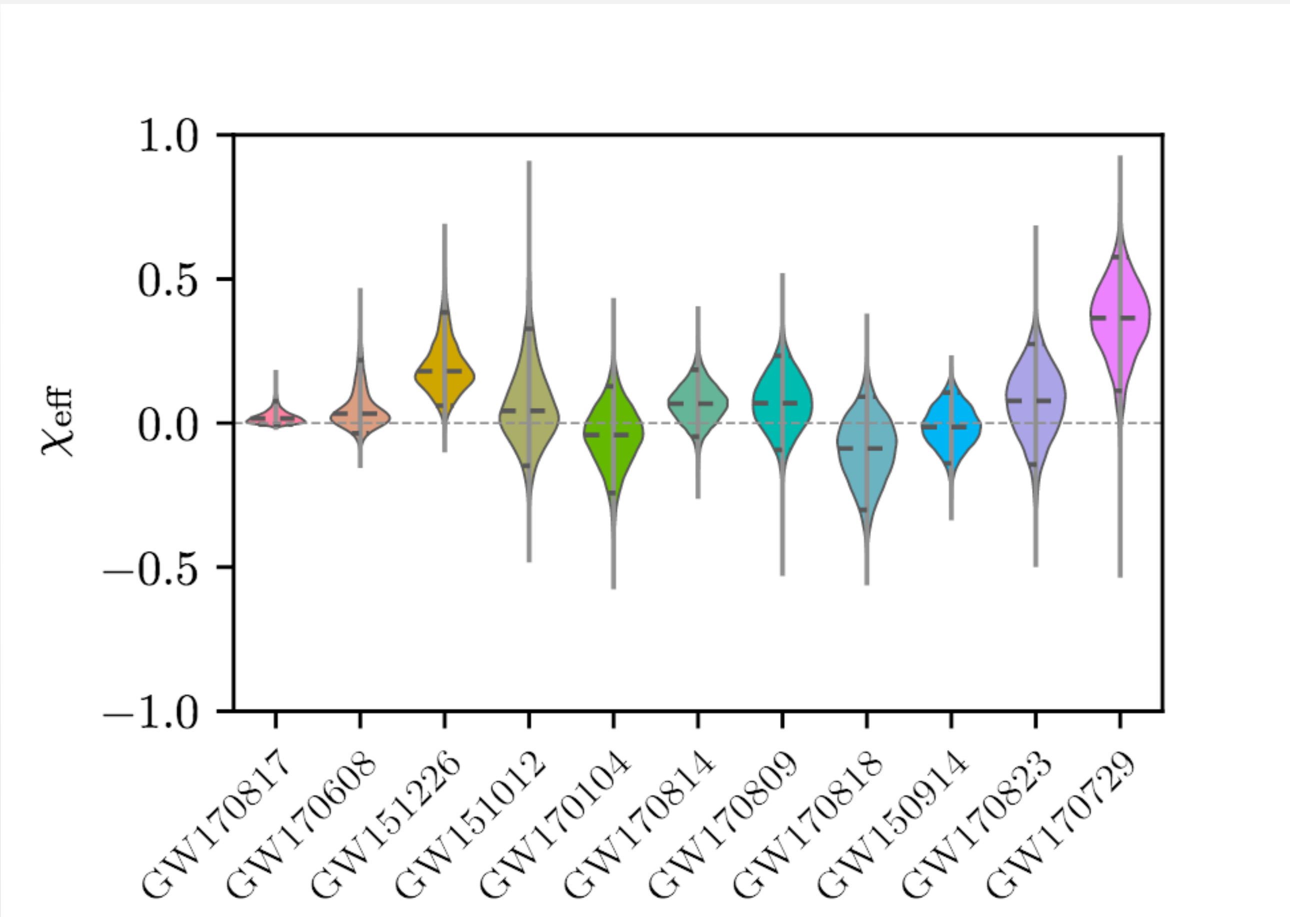

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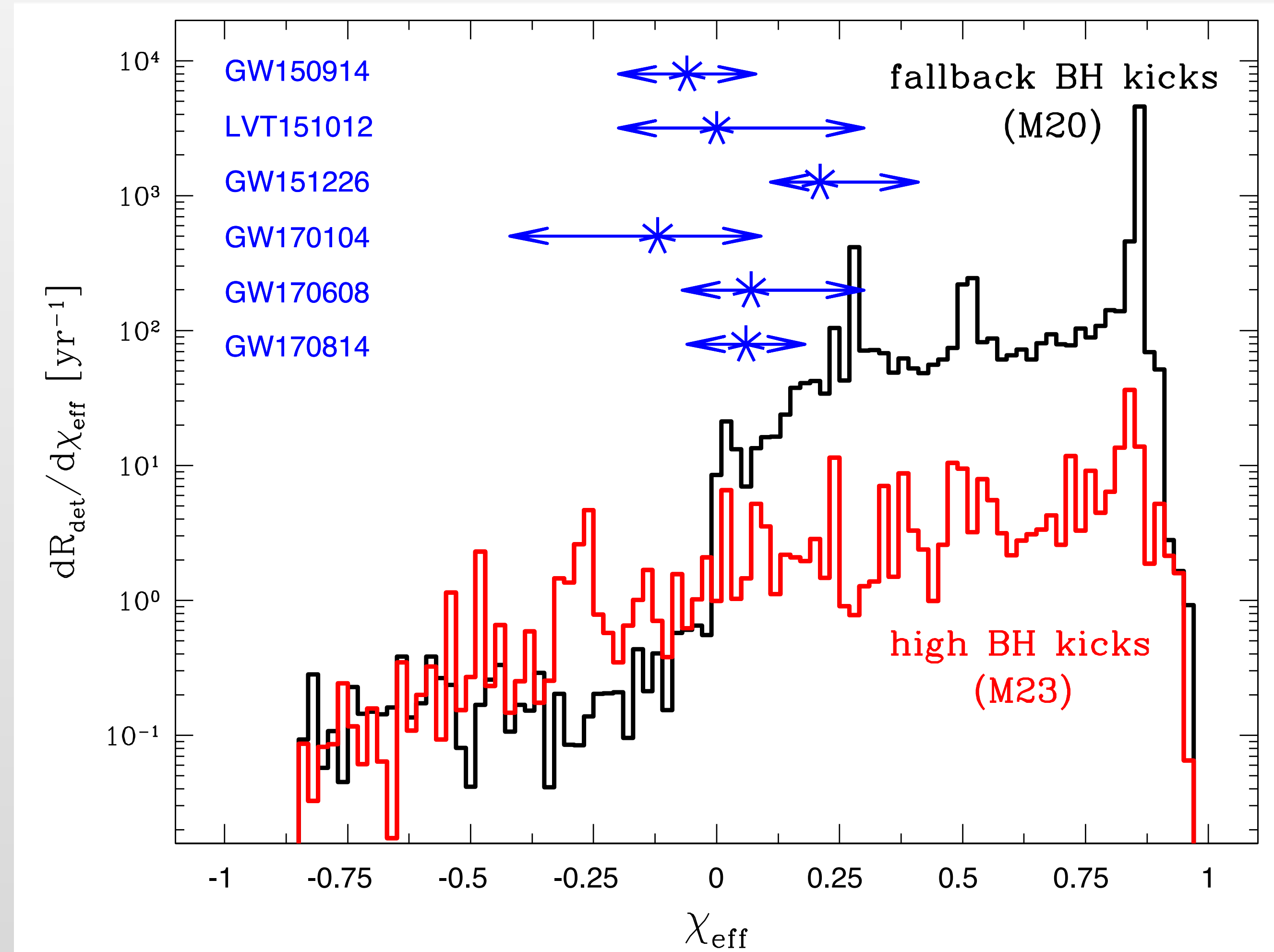

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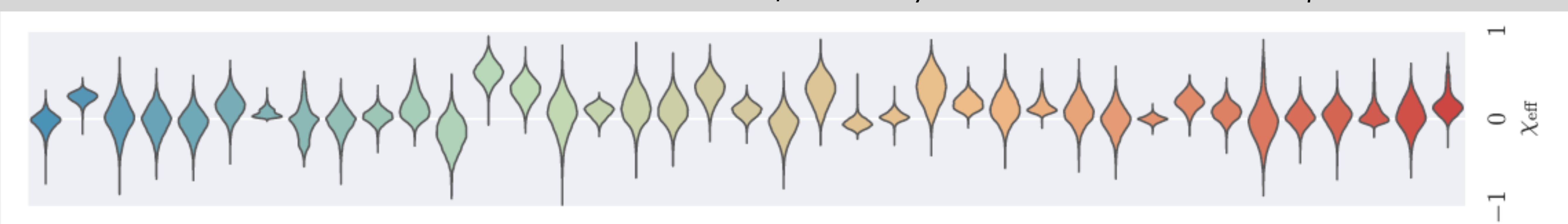


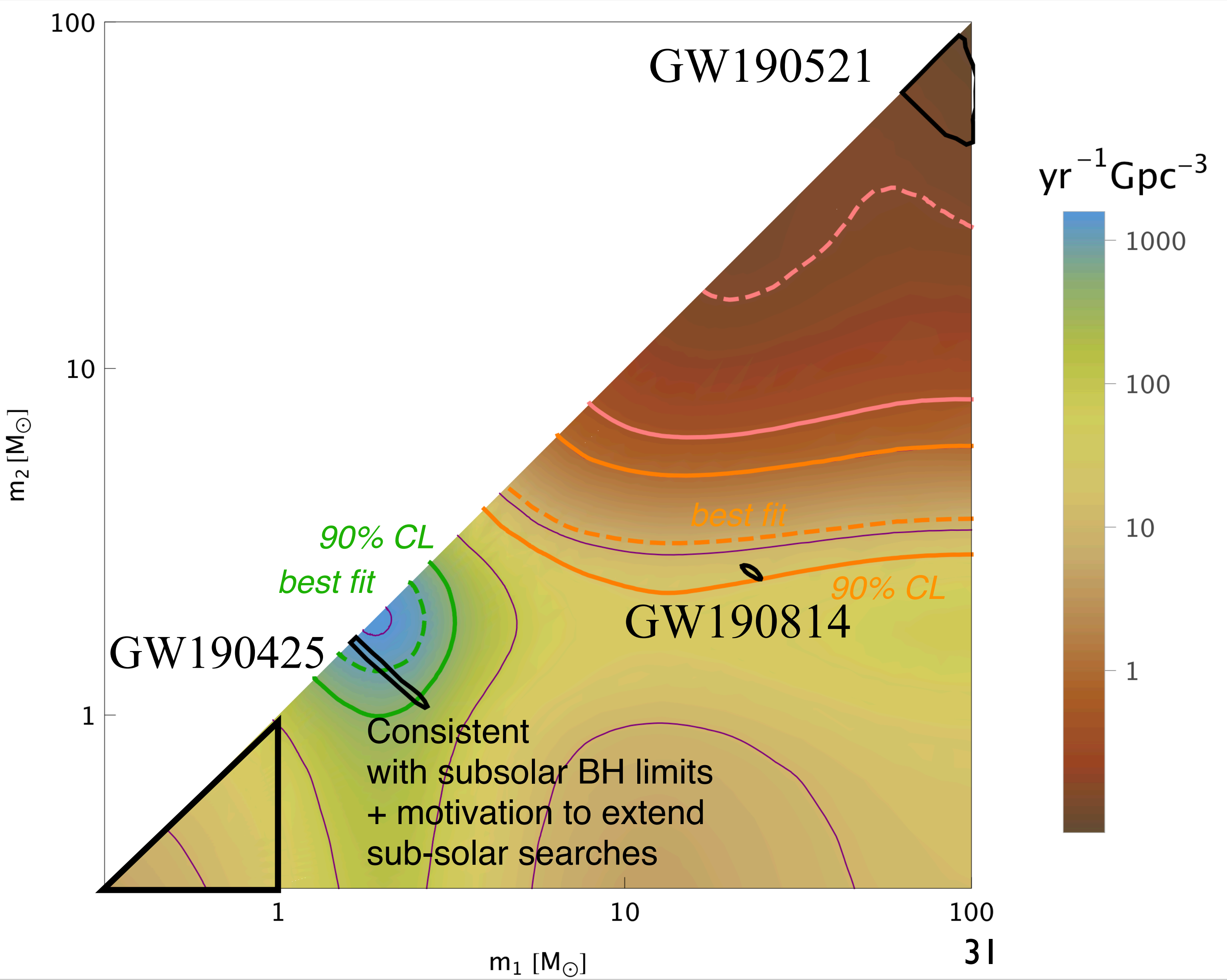
Gravitational Waves

BH merger rate distribution

To get 20 / yr /Gpc³ at large mass

Agnostic about the abundance of PBH

Binaries formed by **capture in clusters**: $\frac{d\tau}{\mathrm{d}\ln m_1 \mathrm{d}\ln m_2} = R_{\text{clust.}} \times f(m_1) f(m_2) \times \frac{(m_1+m_2)^{10/7}}{(m_1 m_2)^{5/7}} \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$

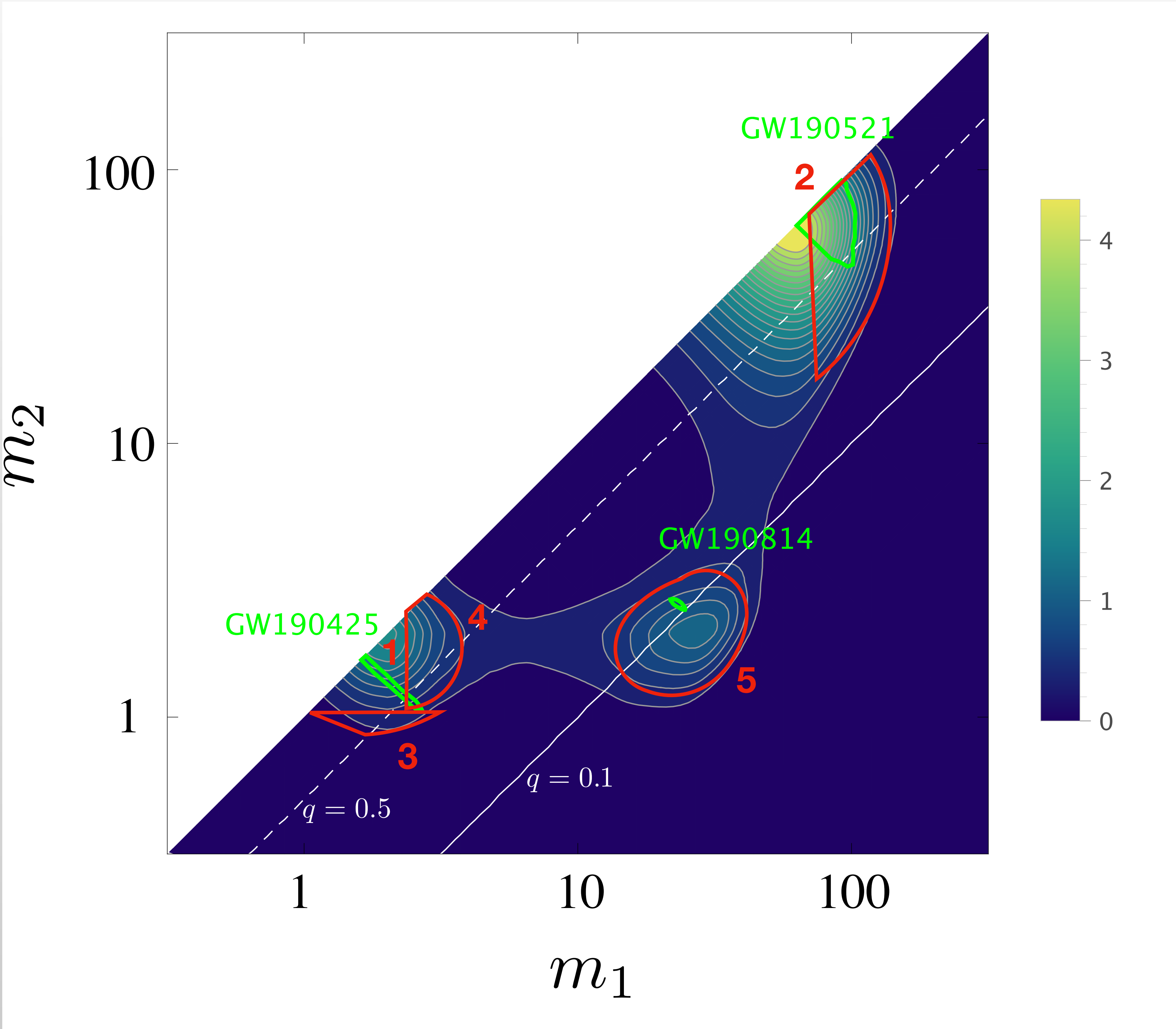


Explains the masses and rates of GW190425, GW190814 and of GW190521 in a unified way…

Consistency with O3?

Gravitational Waves

Distribution of detections



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

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

Gravitational Waves

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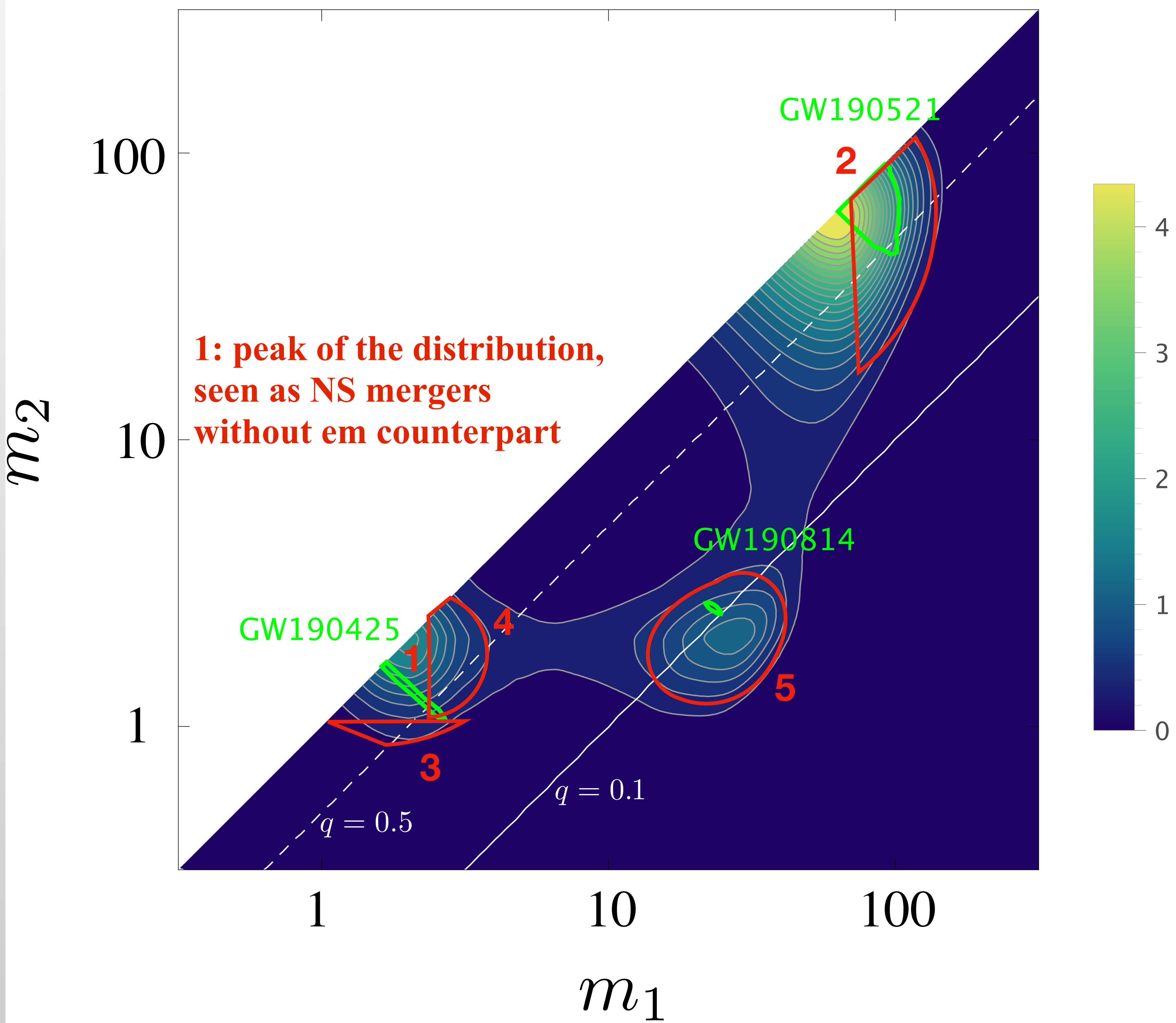

Expected distribution of GW events with O2 LIGO (L1) sensitivity

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

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 **m_{PBH} ~ stellar-mass** (or any other specific mass)
- Need of an **exotic**, peaky and non-Gaussian, 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?

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Therefore, PBHs are a natural, well-motivated and testable dark matter candidate.
Possibly they do exist…

… so they deserve to be investigated further!