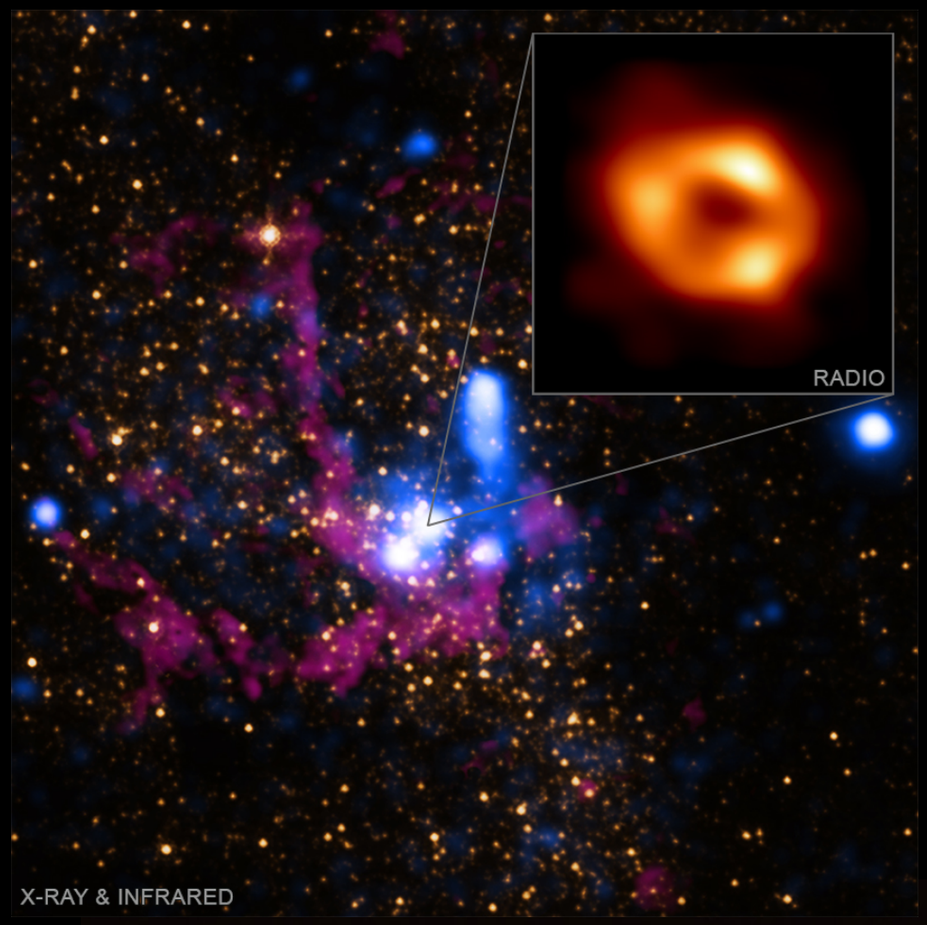
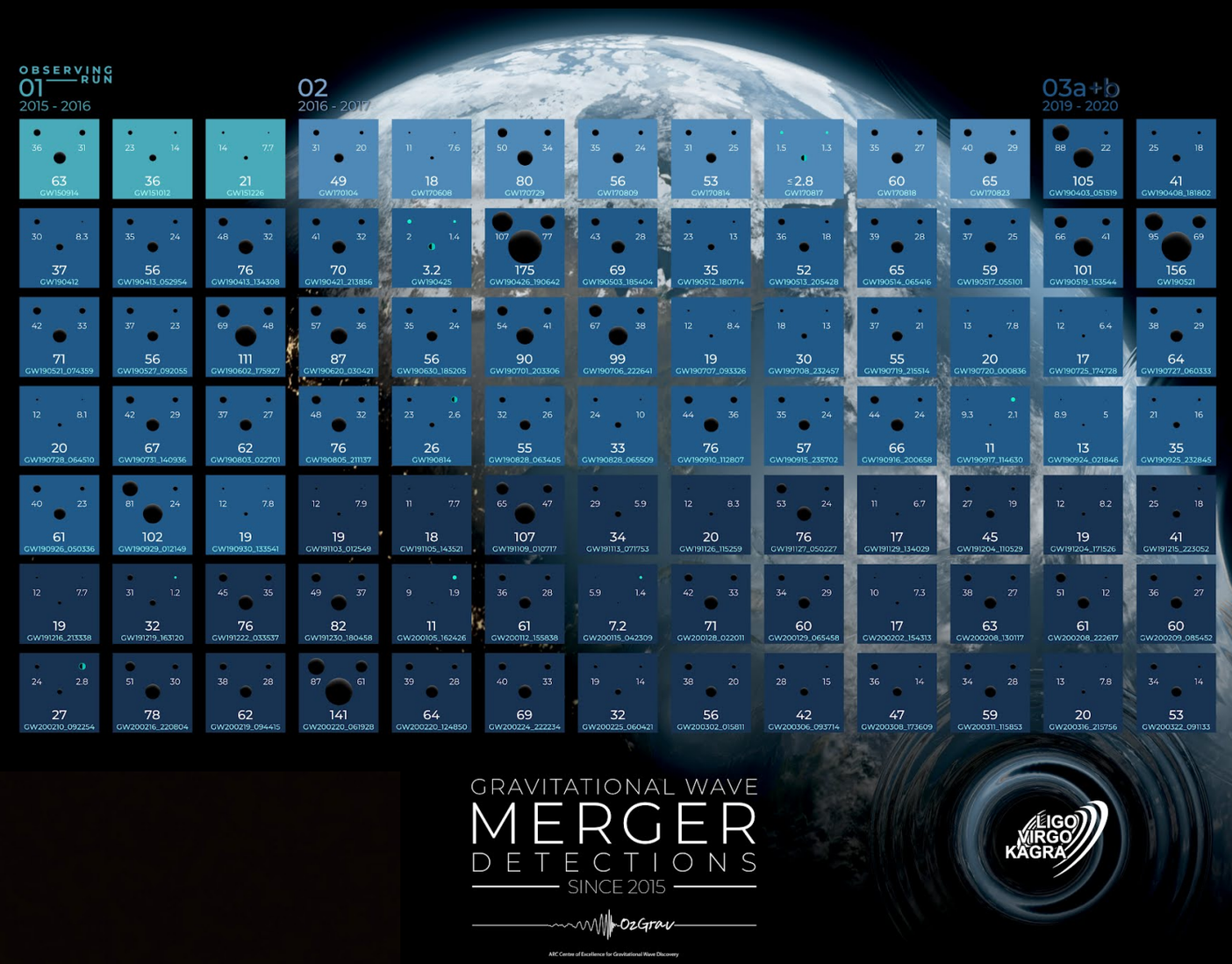
Constraining primordial black holes as a dark matter candidate

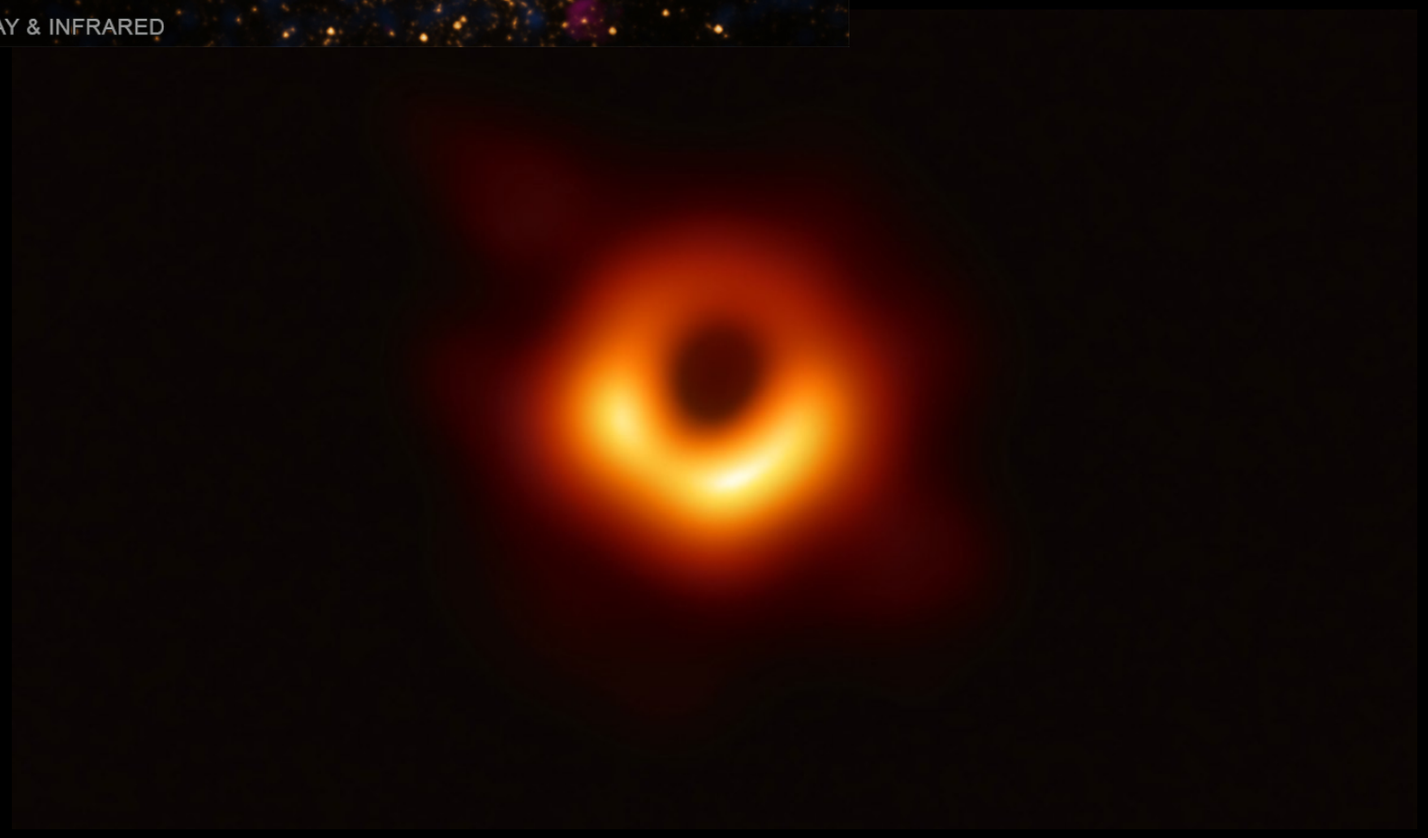
Gabriele Franciolini

14-12-2023 *Swiss CTA Observatory Days*

Black holes populate our universe







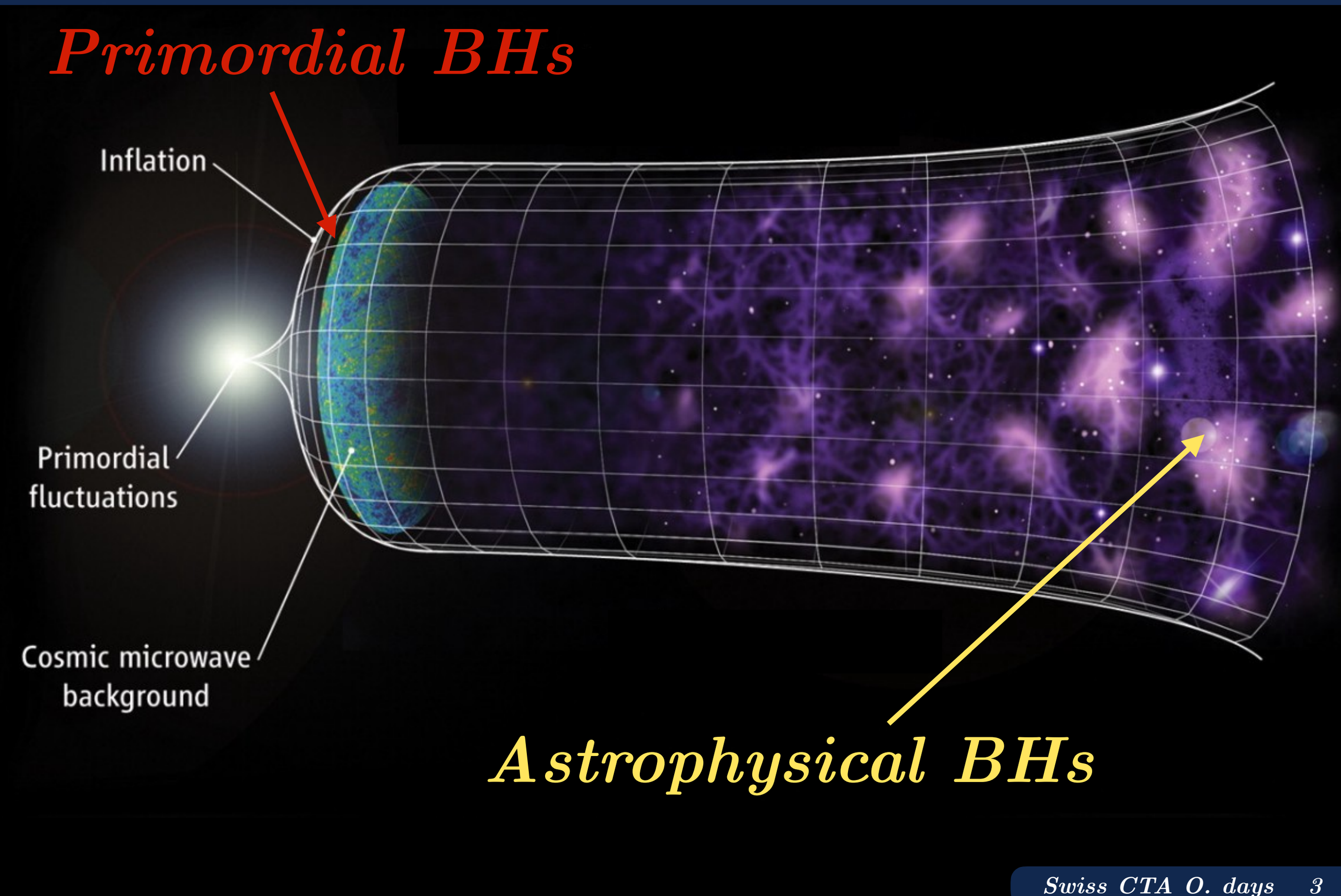
GRAVITATIONAL WAVE
MERGER
DETECTIONS
SINCE 2015

OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery

LIGO VIRGO KAGRA

[Credits: LIGO/Virgo/Kagra, EHT, ...]

Is it possible to form them in the early universe?

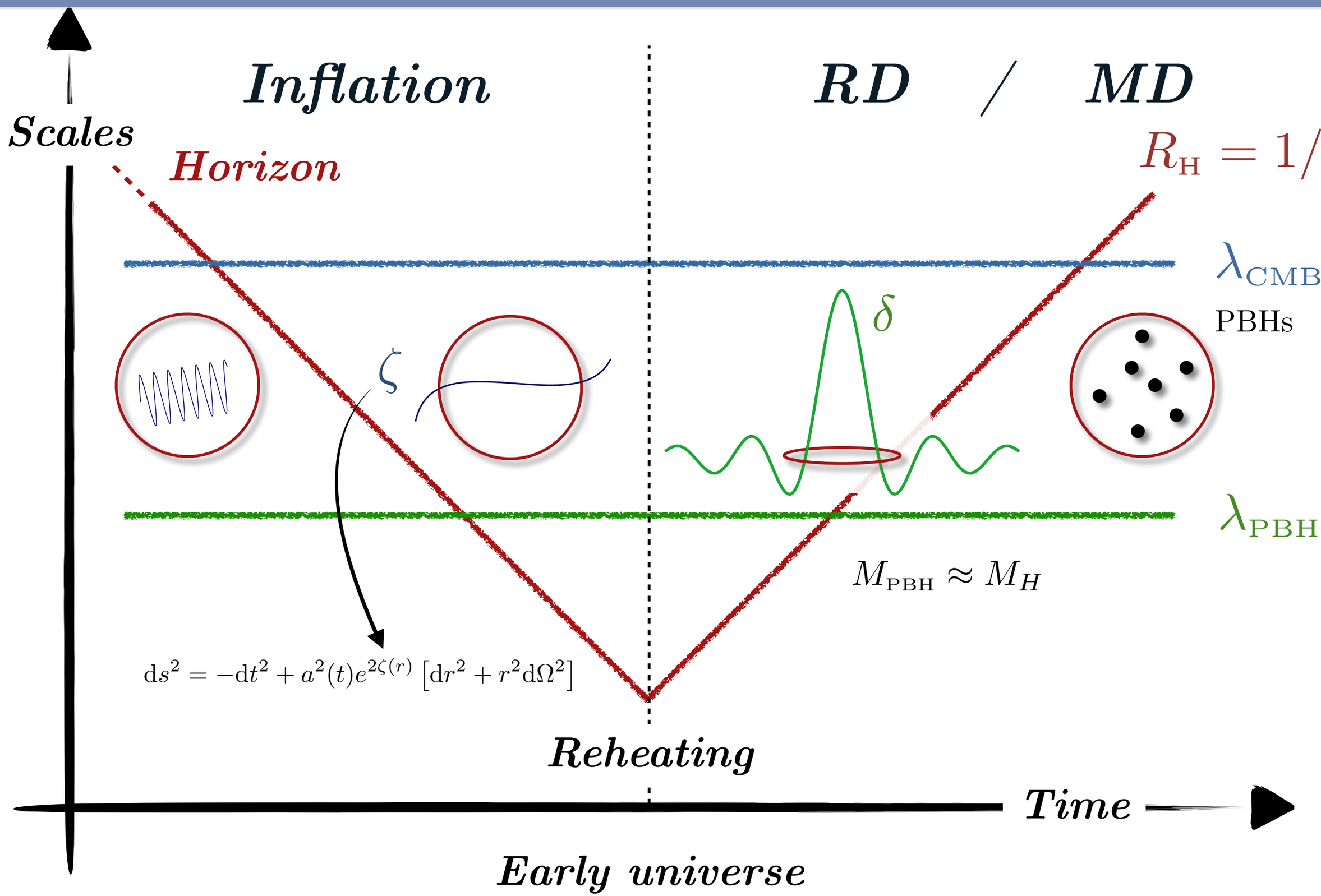


Outline

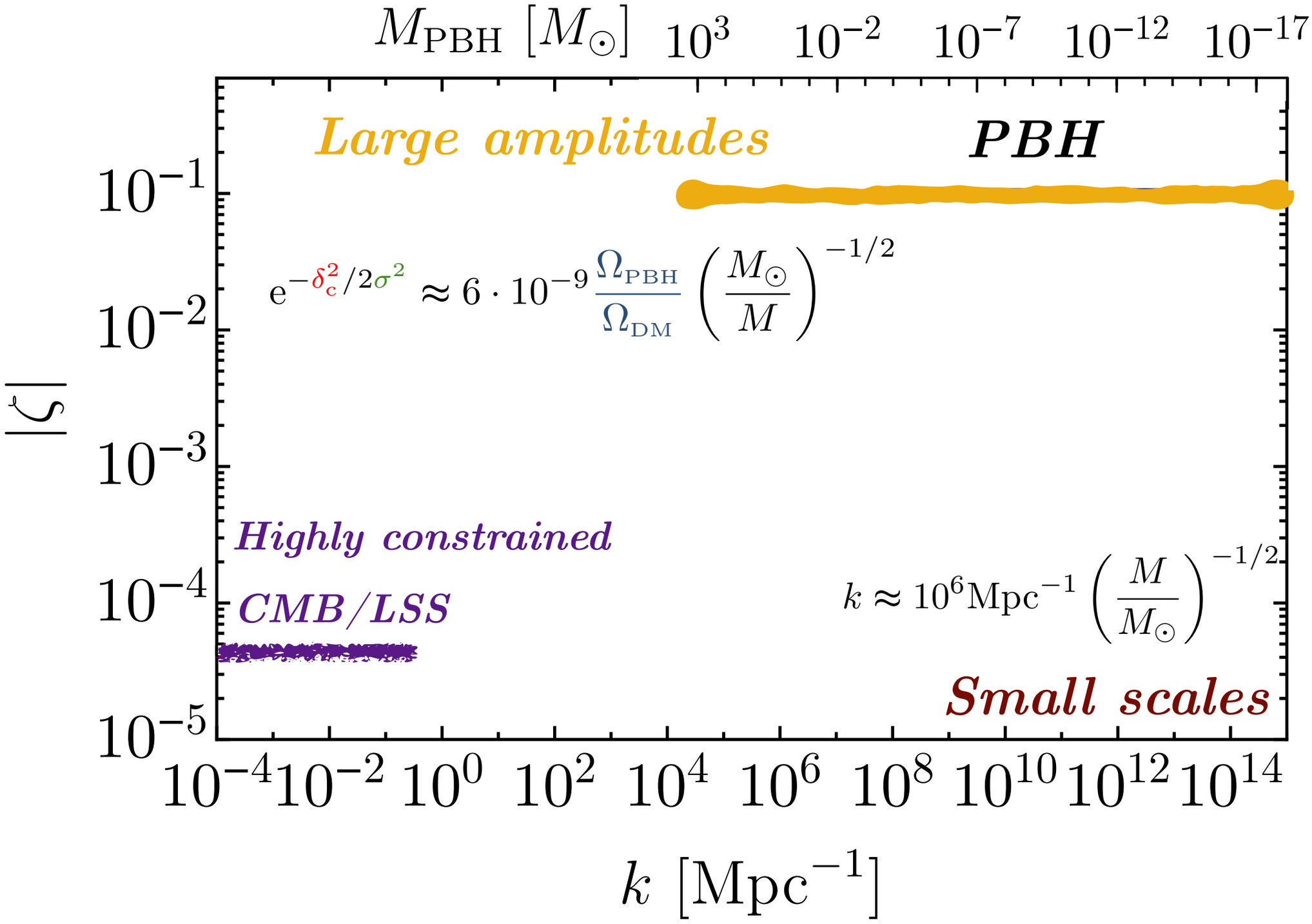
- *Introduction to Primordial Black Holes (PBHs)*
- *Review of main bounds on the abundance*
- *Current/future constraints with GWs*

Introduction

PBH formation timeline



Required Perturbations: mall scales - large amplitude



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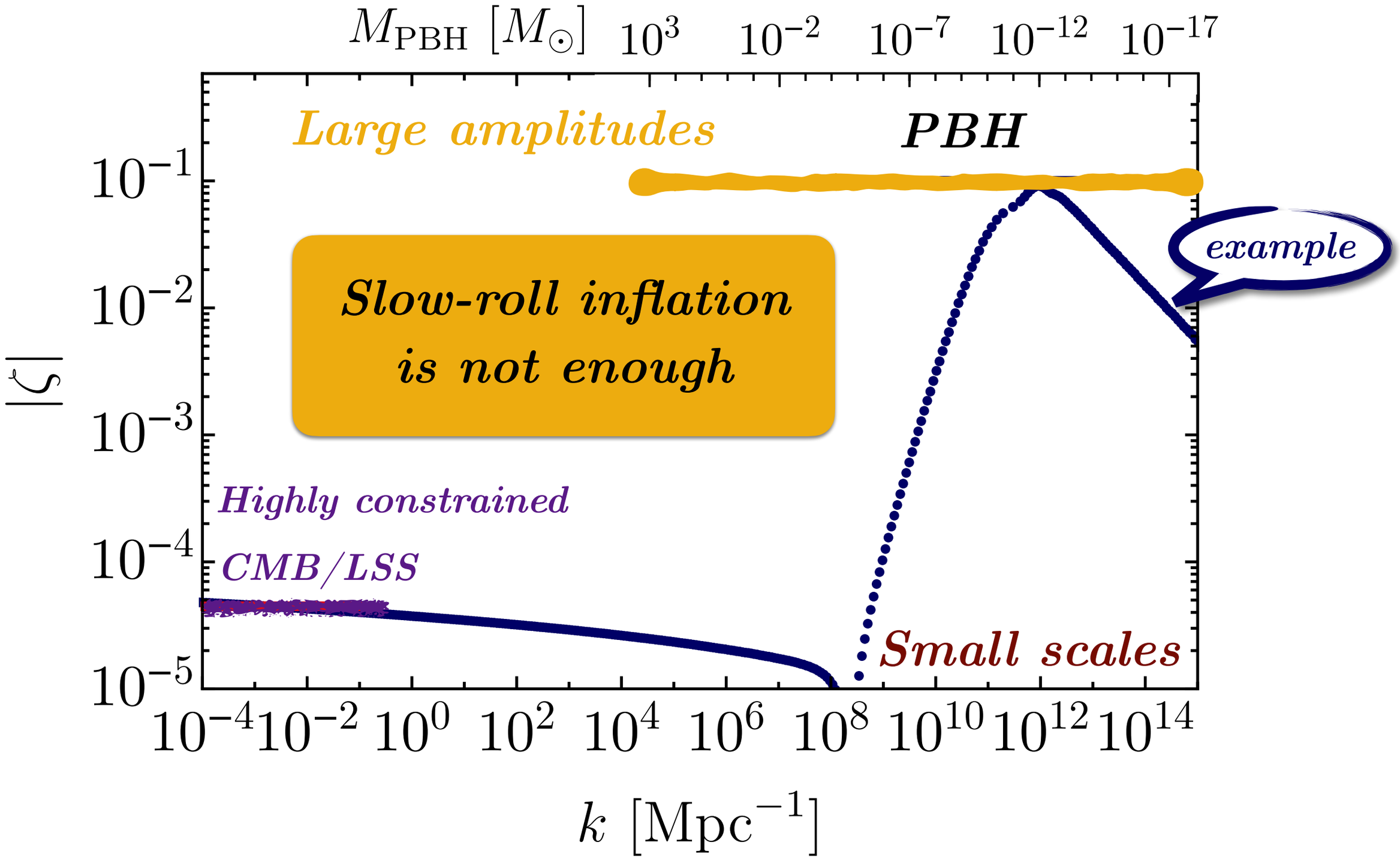
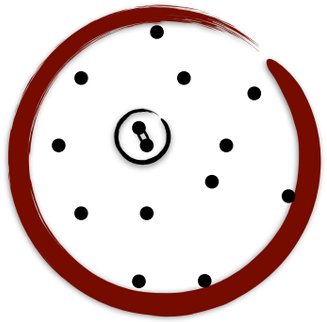


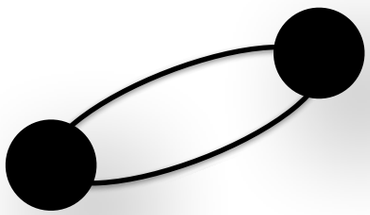
Searching for Primordial Black Holes

PBH Formation

Overdensity Collapse

PBH binaries Formation





Binary system can decouple from Hubble flow

Matter-radiation equality

Modify LambdaCDM cosmology at small scales

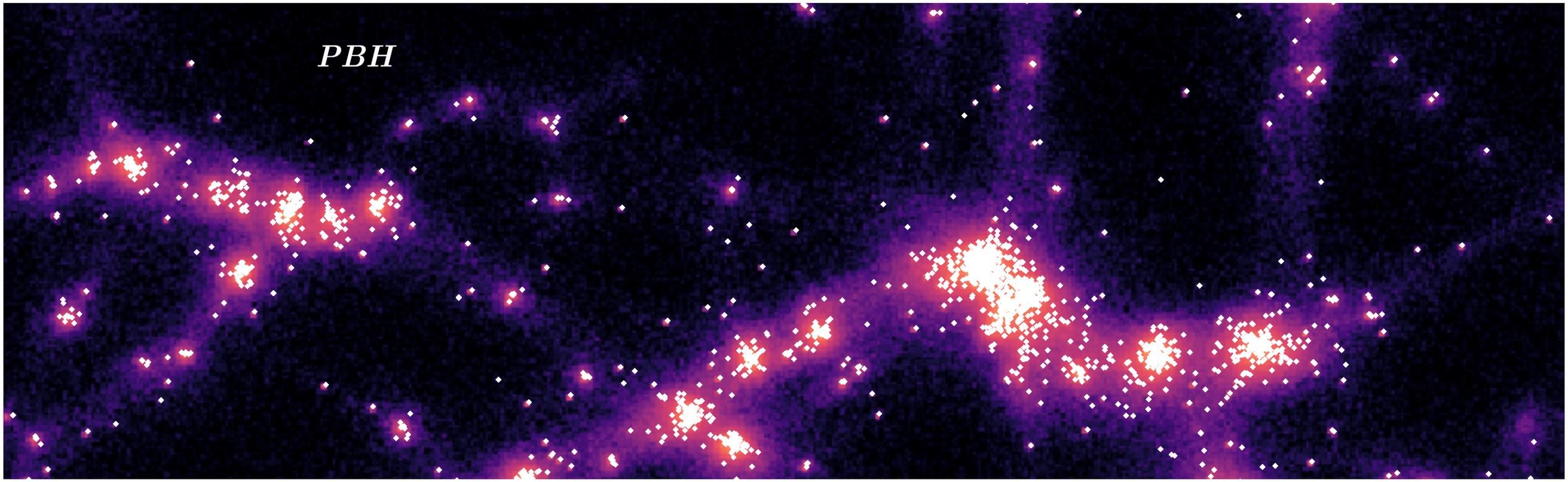
- *Hawking evaporation*
- *Small scale structure*
- *Accretion (EM emission)*
- *Mergers (GWs)*
- *Lensing*

Redshift →

$\approx 10^{10}$ $\approx 10^{3}$ ≈ 1 *Today*

Imprints of the formation mechanism

PBH dark matter



D. Inman and Y. Ali-Haïmoud, Phys. Rev. D **100**, no.8, 083528 (2019) [arXiv:1907.08129]

Primordial black holes on large scales behave as a cold and collisionless fluid

- ***PBH abundance expressed in terms of the dark matter***

$$f_{\rm PBH} \equiv \Omega_{\rm PBH}/\Omega_{\rm DM}$$

Are PBHs useful? YES

If they exist... $(f_{\mathrm{PBH}} \approx 1)$

- ***They could be a significant fraction of the dark matter in our universe***

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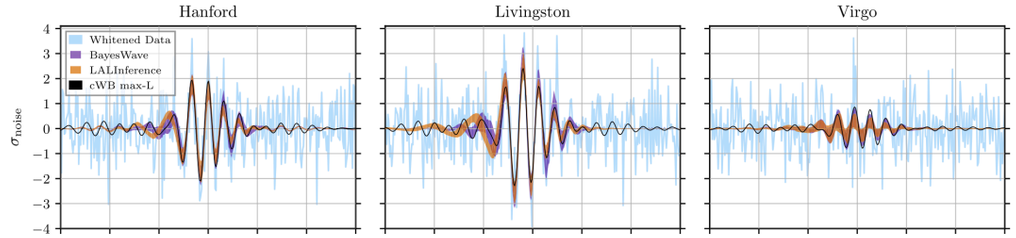
...if they are rare... $(f_{\rm PBH} < 1)$

- ***e.g. mass gap merger event GW190521, GW190814, ...***

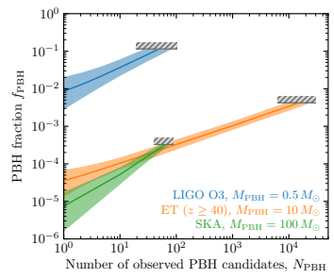
R. Abbott *et al.* [LIGO Scientific and Virgo], Phys. Rev. Lett. **125**, no.10, 101102 (2020) [arXiv:2009.01075]

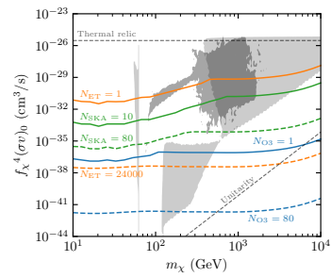
Interesting since they fall within the mass gaps



- ***They are largely incompatible with other particle DM candidates***

J. Adamek, C. T. Byrnes, M. Gosenca and S. Hotchkiss, Phys. Rev. D **100**, no.2, 023506 (2019) [arXiv:1901.08528]
G. Bertone, *et al.* Phys. Rev. D **100**, no.12, 123013 (2019) [arXiv:1905.01238],
....





- ***They could provide the SMBH seeds at high redshift***

M. Volonteri, M. Habouzit and M. Colpi, Nature Rev. Phys. **3** (2021) no.11, 732-743 [arXiv:2110.10175]
T. Nakama, B. Carr and J. Silk, Phys. Rev. D **97** (2018) no.4, 043525 [arXiv:1710.06945]
J. L. Bernal, A. Raccanelli, L. Verde and J. Silk, JCAP **05** (2018), 017 [arXiv:1712.01311], ...

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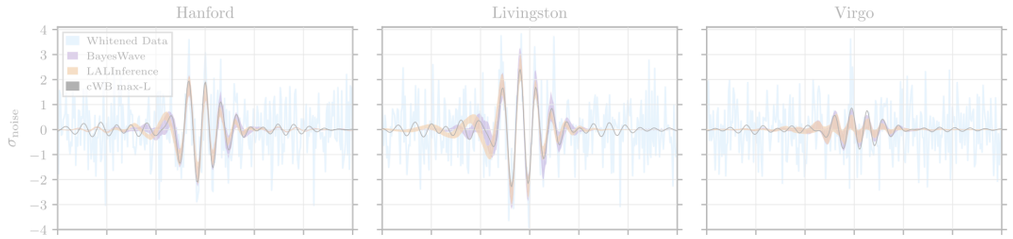

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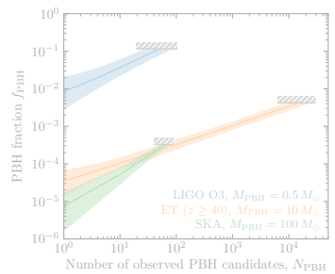

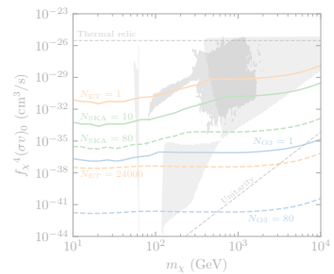

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J. L. Bernal, A. Raccanelli, L. Verde and J. Silk, JCAP **05** (2018), 017 [arXiv:1712.01311], ...

...and even if they didn't exist $(f_{\rm PBH} \approx 0)$

- ***They allow to set constraints on the early universe***

(just require no DM overproduction)

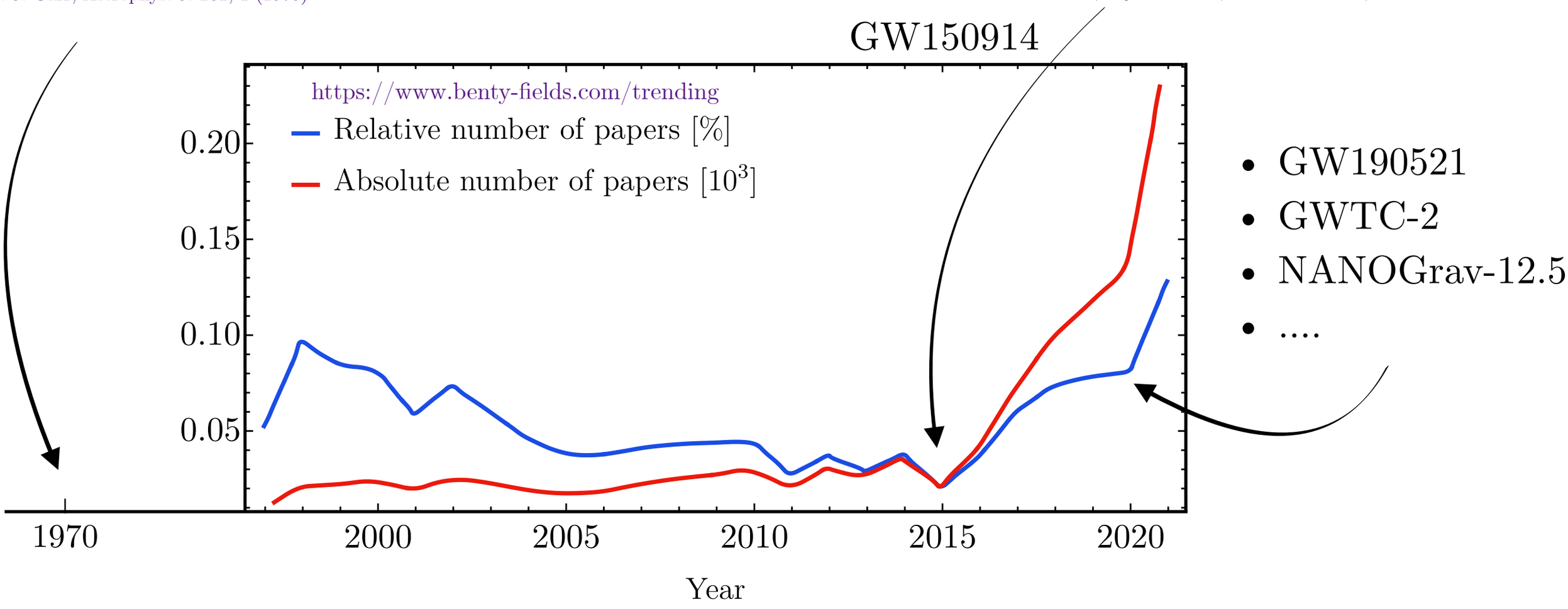
Why now?

Y. B. Zel'dovich and I. D. Novikov, ..., (1967)
S. W. Hawking, Nature 248, 30 (1974)
B. J. Carr and S. W. Hawking, ... , (1974)
G. F. Chapline, Nature 253, 251 (1975)
B. J. Carr, Astrophys. J. 201, 1 (1975)

S. Bird *et al* Phys. Rev. Lett. **116**, 201301 (2016), [arXiv:1603.00464]
M. Sasaki, *et al* Phys. Rev. Lett. **117**, 061101 (2016), [arXiv:1603.08338]
S. Clesse and J. Garcìa-Bellido, Phys. Dark Univ. **15** (2017), 142-147 [arXiv:1603.05234]
....

Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]



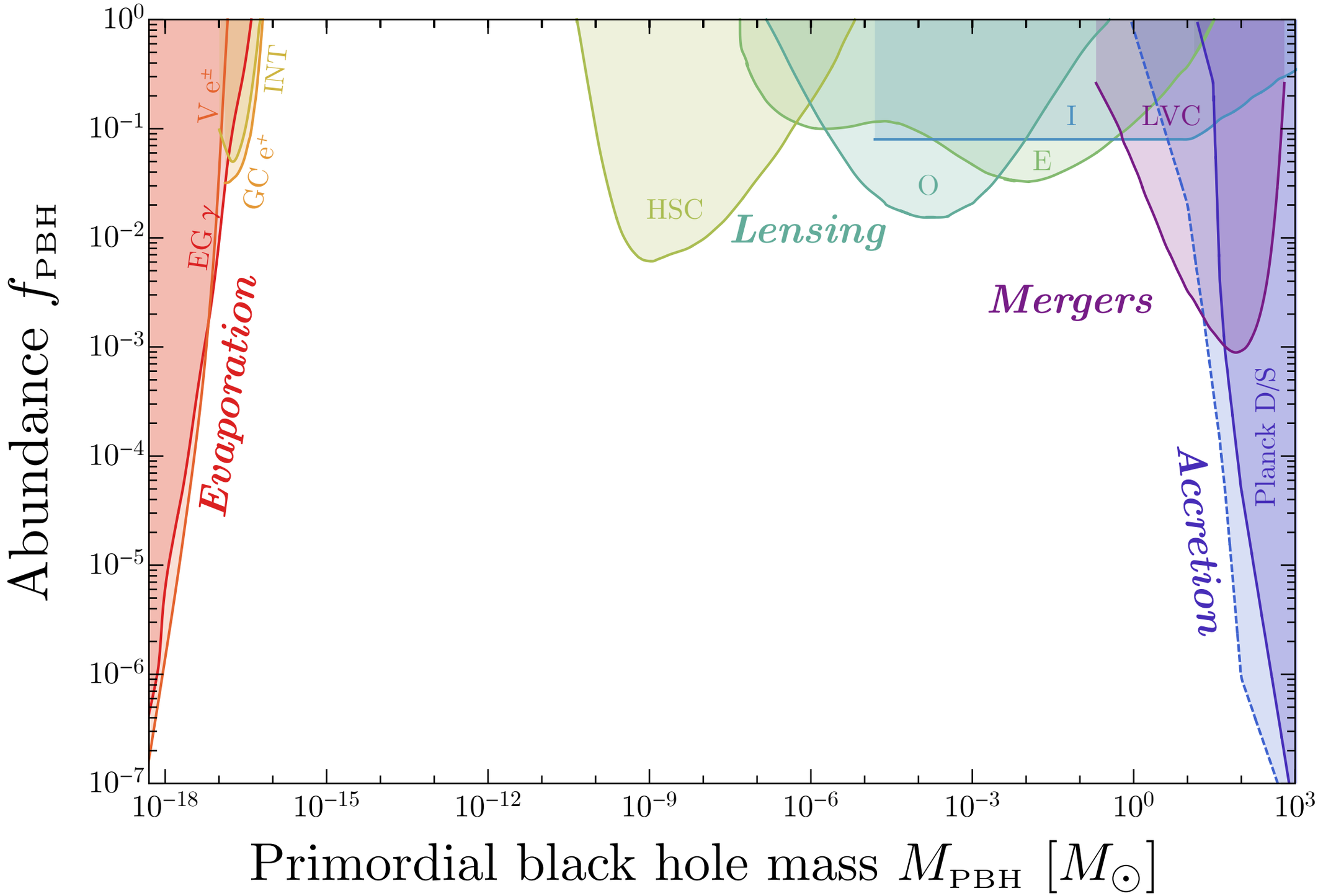
Gravitational Wave observations** will set important **constraints** on PBHs, or unprecedented **discoveries

Recent reviews: A. M. Green and B. J. Kavanagh, J. Phys. G **48** (2021) no.4, 043001 [arXiv:2007.10722]
B. Carr and F. Kuhnel, Ann. Rev. Nucl. Part. Sci. **70** (2020), 355-394 [arXiv:2006.02838]
...

Constraints on the PBH abundance

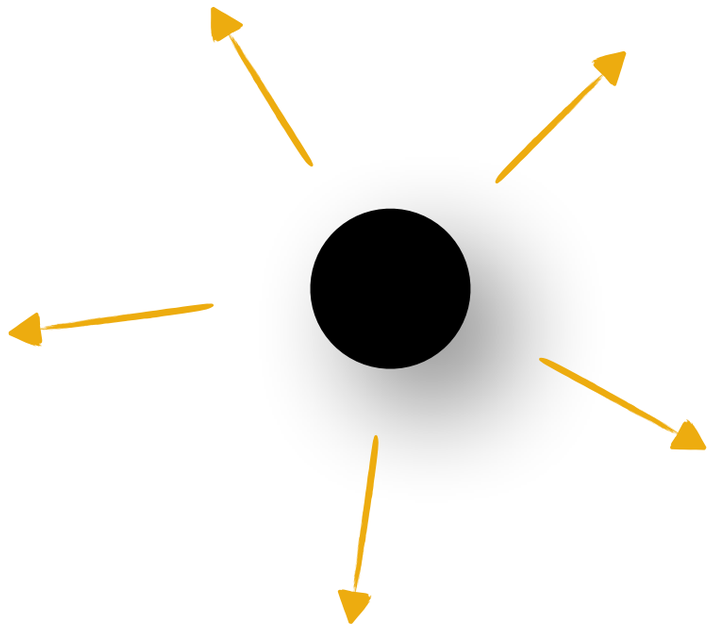
Constraints on the PBH DM abundance

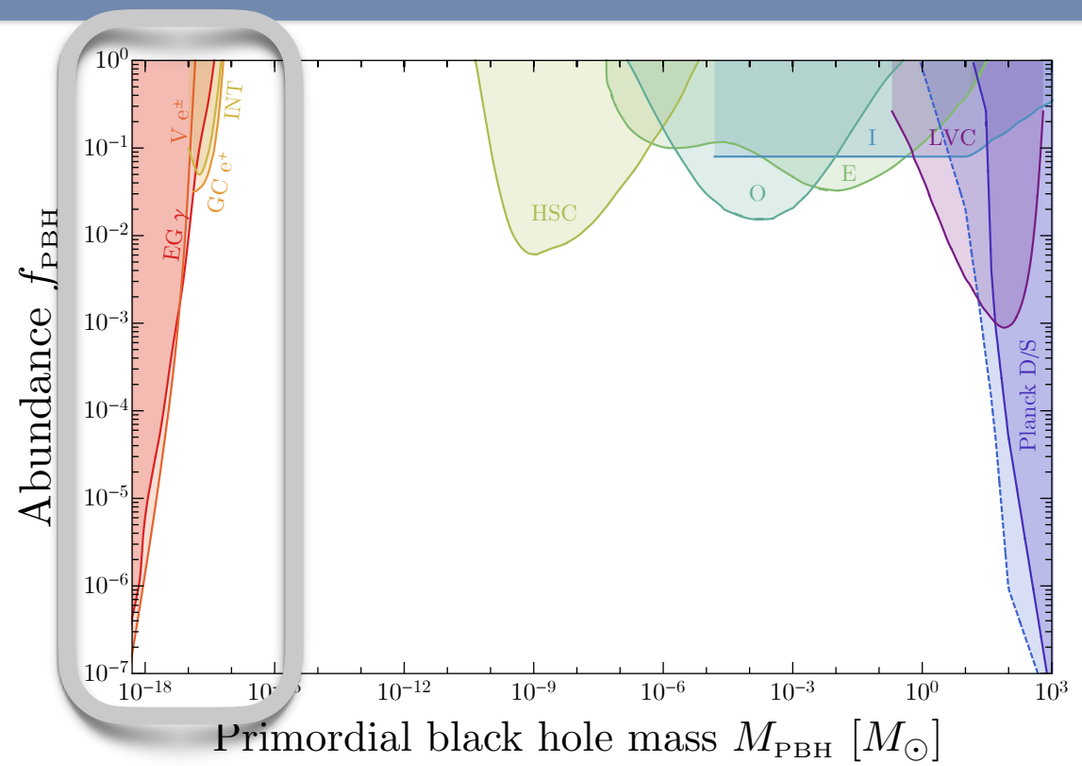
Review: B. Carr, K. Kohri, Y. Sendouda and J. Yokoyama, Rept. Prog. Phys. **84**, no.11, 116902 (2021) [arXiv:2002.12778]



****assuming narrow mass distribution***

PBH DM bounds: evaporation





PBHs evaporate with a temperature

$$T_{\rm PBH} = \frac{1}{8\pi G M_{\rm PBH}} = 53\,{\rm TeV}\left(\frac{M_{\rm PBH}}{10^{-25}M_\odot}\right)^{-1}$$

S. W. Hawking, Commun. Math. Phys. 43, 199 (1975)

PBH lifetime $$t_{\rm eva} \approx 3.4\times10^{-3}\,{\rm s}\left(\frac{g_{\rm H*}}{100}\right)^{-1}\left(\frac{M^i_{\rm PBH}}{10^{-25}M_\odot}\right)^{3}$$

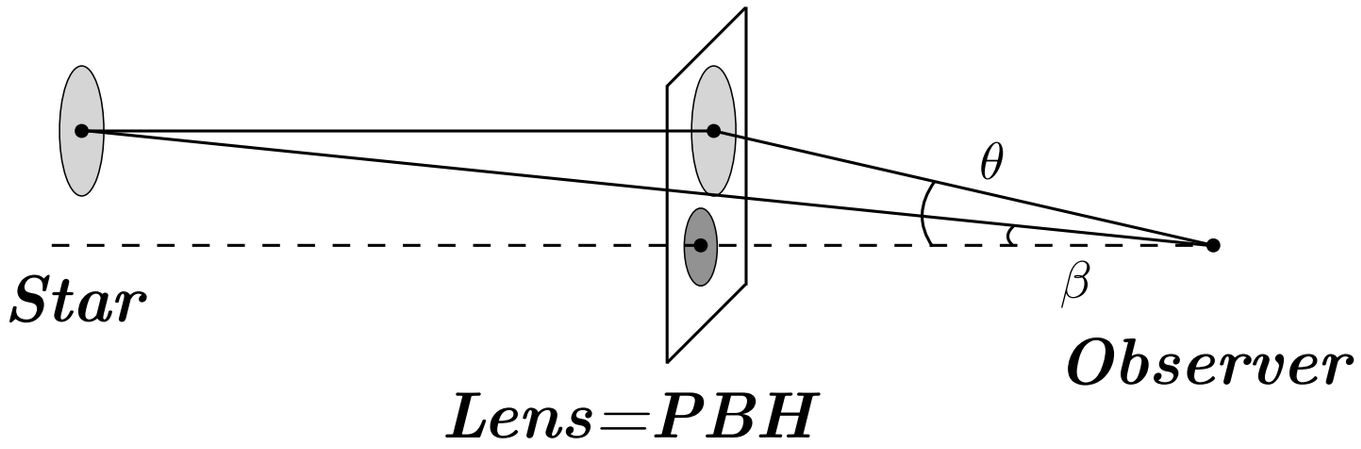
PBHs lighter than around $10^{-18}M_\odot$ ***evaporated by now***

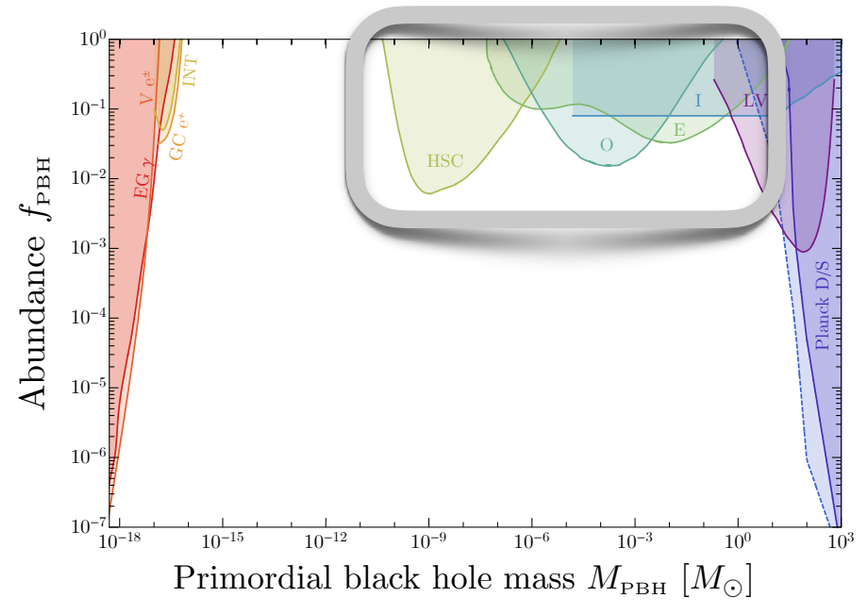
- ***BBN/CMB/21 cm/Gamma-ray backgrounds/Cosmic rays***

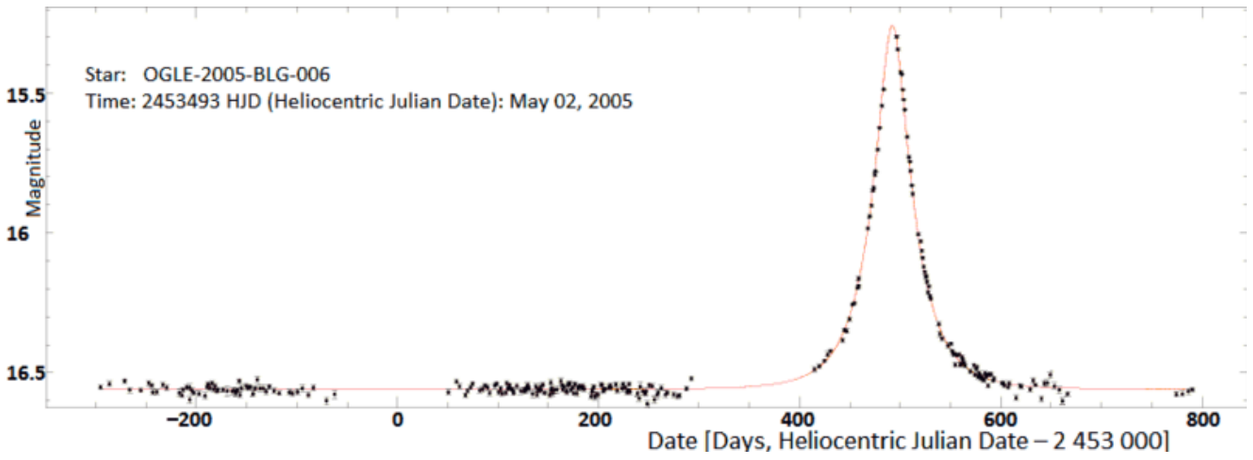
See review for (outdated) list of references: B. Carr, K. Kohri, Y. Sendouda and J. Yokoyama [arXiv:2002.12778]

Assumptions: Hawking evaporation and non-extremal spin

PBH DM bounds: (Micro-)lensing







HSC H. Niikura *et al.* [arXiv:1701.02151]

OGLE H. Niikura, *et al.* [arXiv:1901.07120]

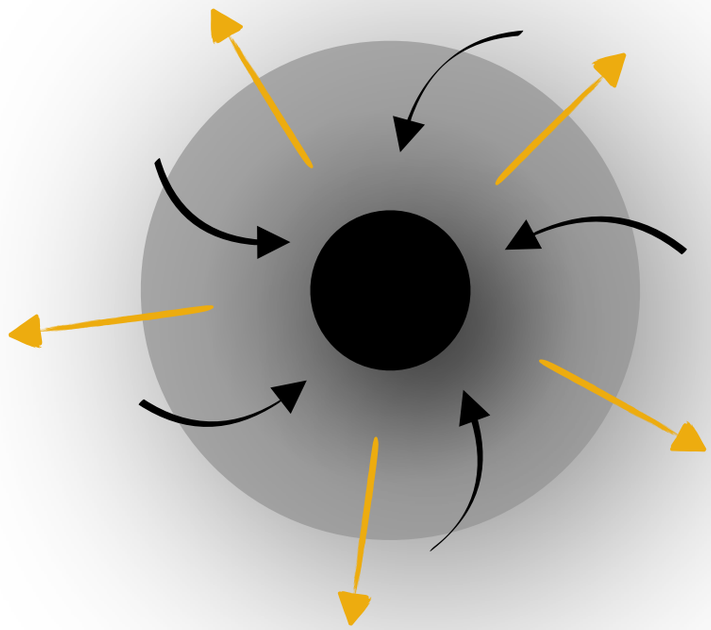
Eros&Macho R. A. Allsman *et al.* [arXiv:0011506]
P. Tisserand *et al.* [arXiv:0607207]

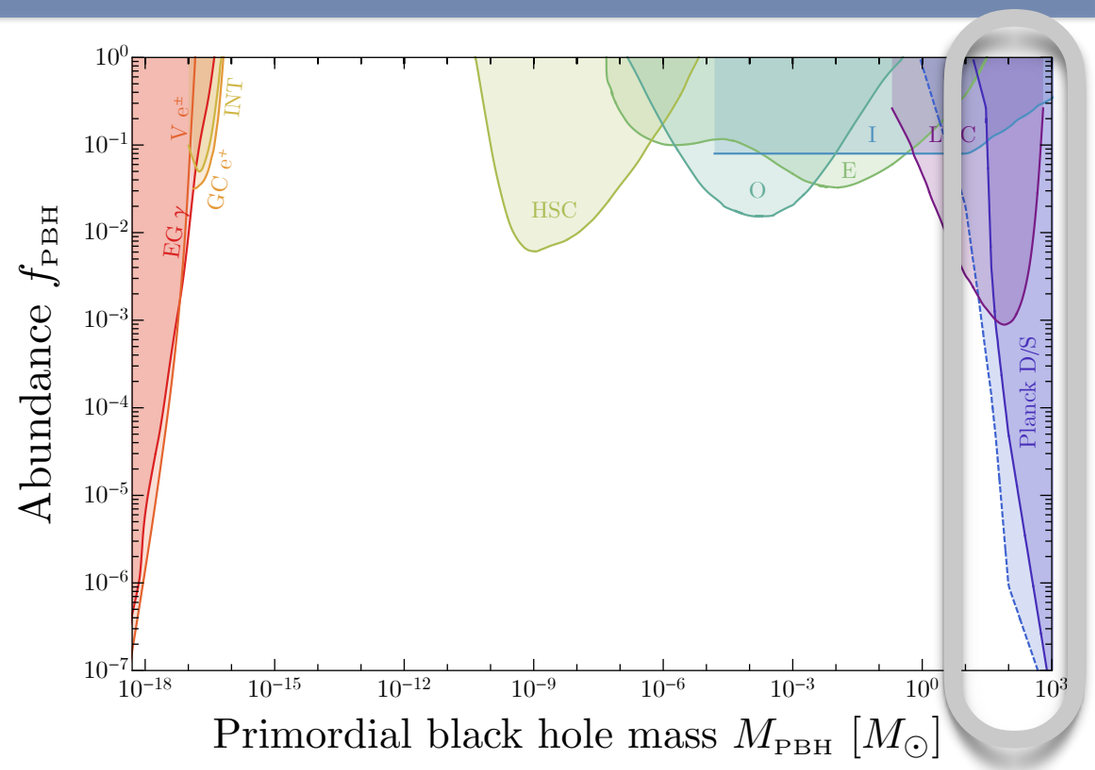
Constraints derived assuming isolated PBHs with a homogeneous distribution:

- ***Poisson induced PBH clustering in the late-time universe does not affect these constraints*** M. Petač, J. Lavalle, and K. Jedamzik, Phys. Rev. D **105**, 083520 (2022), [arXiv:2201.02521]
  M. Gorton and A. M. Green, JCAP **08**, 035 (2022), [arXiv:2203.04209]
- ***Secondary DM halo could strengthen these constraints***

  R. G. Cai, T. Chen, S. J. Wang and X. Y. Yang, JCAP **03** (2023), 043 [arXiv:2210.02078]

PBH DM bounds: accretion





Accreting PBH emits radiation with a luminosity $L = \epsilon \dot{M} c^2$

$$\dot{\rho}_{\rm inj} = n_{\rm PBH} L = f_{\rm PBH} \, \frac{\rho_{\rm DM}}{M} L$$

Uncertainties on L due to:

- ***Spherical vs disk accretion***
- ***Secondary DM halo***
- ***Outflows***
- ***...***

- ***CMB anisotropies***

M. Ricotti, J. P. Ostriker and K. J. Mack, Astrophys. J. **680** (2008), 829 [arXiv:0709.0524]
Y. Ali-Haïmoud and M. Kamionkowski, Phys. Rev. D **95** (2017) no.4, 043534 [arXiv:1612.05644]
V. Poulin, P. D. Serpico, F. Calore, S. Clesse and K. Kohri, Phys. Rev. D **96** (2017) no.8, 083524 [arXiv:1707.04206]
P. D. Serpico, V. Poulin, D. Inman and K. Kohri, Phys. Rev. Res. **2** (2020) no.2, 023204 [arXiv:2002.10771]
L.Piga, M.Lucca, N.Bellomo, V.Bosch-Ramon, S.Matarrese, A.Raccanelli and L.Verde, JCAP **12** (2022), 016 [arXiv:2210.14934]

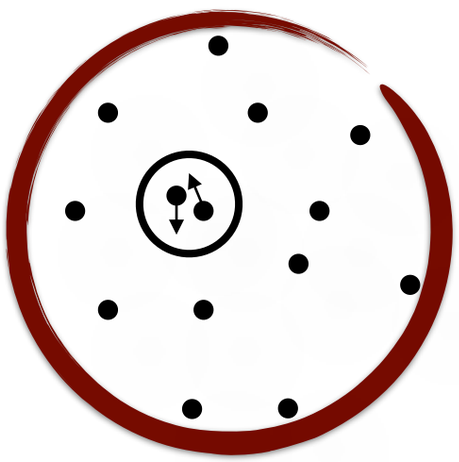
- ***X-ray and radio emission***

D. Gaggero, G. Bertone, F. Calore, R. M. T. Connors, M. Lovell, S. Markoff and E. Storm, Phys. Rev. Lett. 118 (2017) no.24, 241101 [arXiv:1612.00457]
Y. Inoue and A. Kusenko, JCAP 10 (2017), 034 [arXiv:1705.00791]
J. Manshanden, D. Gaggero, G. Bertone, R. M. T. Connors and M. Ricotti, JCAP **06** (2019), 026 [arXiv:1812.07967]
F. Ziparo, S. Gallerani, A. Ferrara and F. Vito, Mon. Not. Roy. Astron. Soc. **517** (2022) no.1, 1086-1097 [arXiv:2209.09907],
....

PBH DM bounds: LVK mass mergers

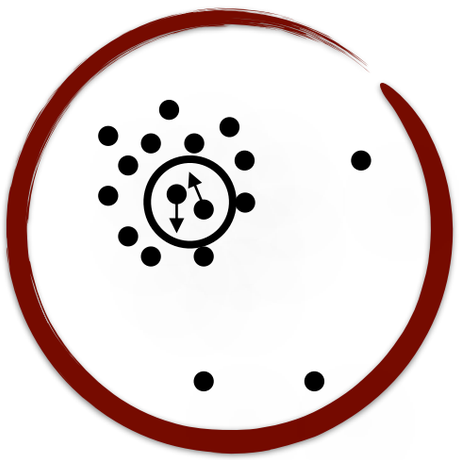
Within clusters seeded by Poisson initial conditions:

Early universe binaries

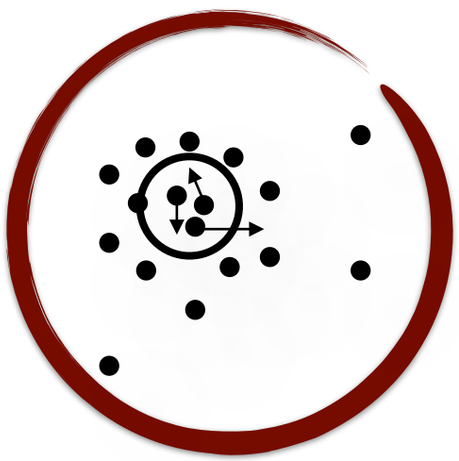


Dominant contribution even with suppressions

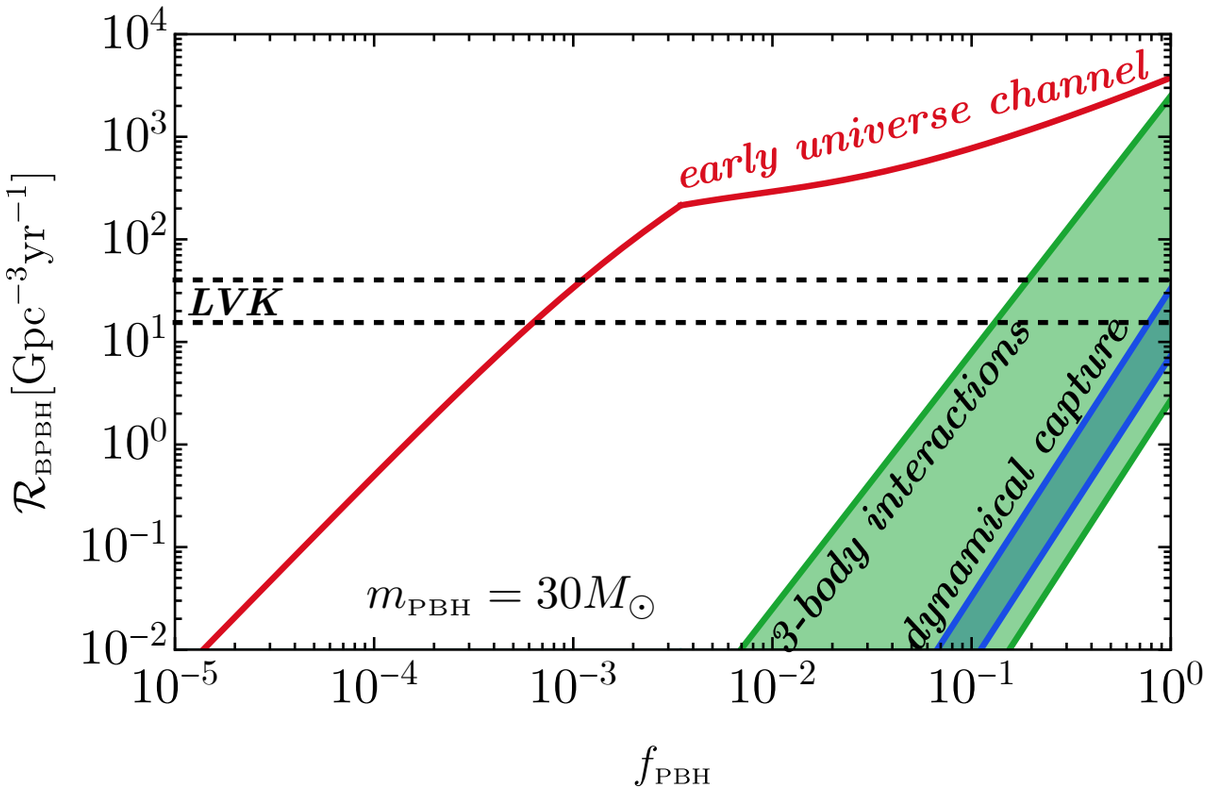
Dynamical capture
(adopted in Bird et al.)



3-b dynamical interaction

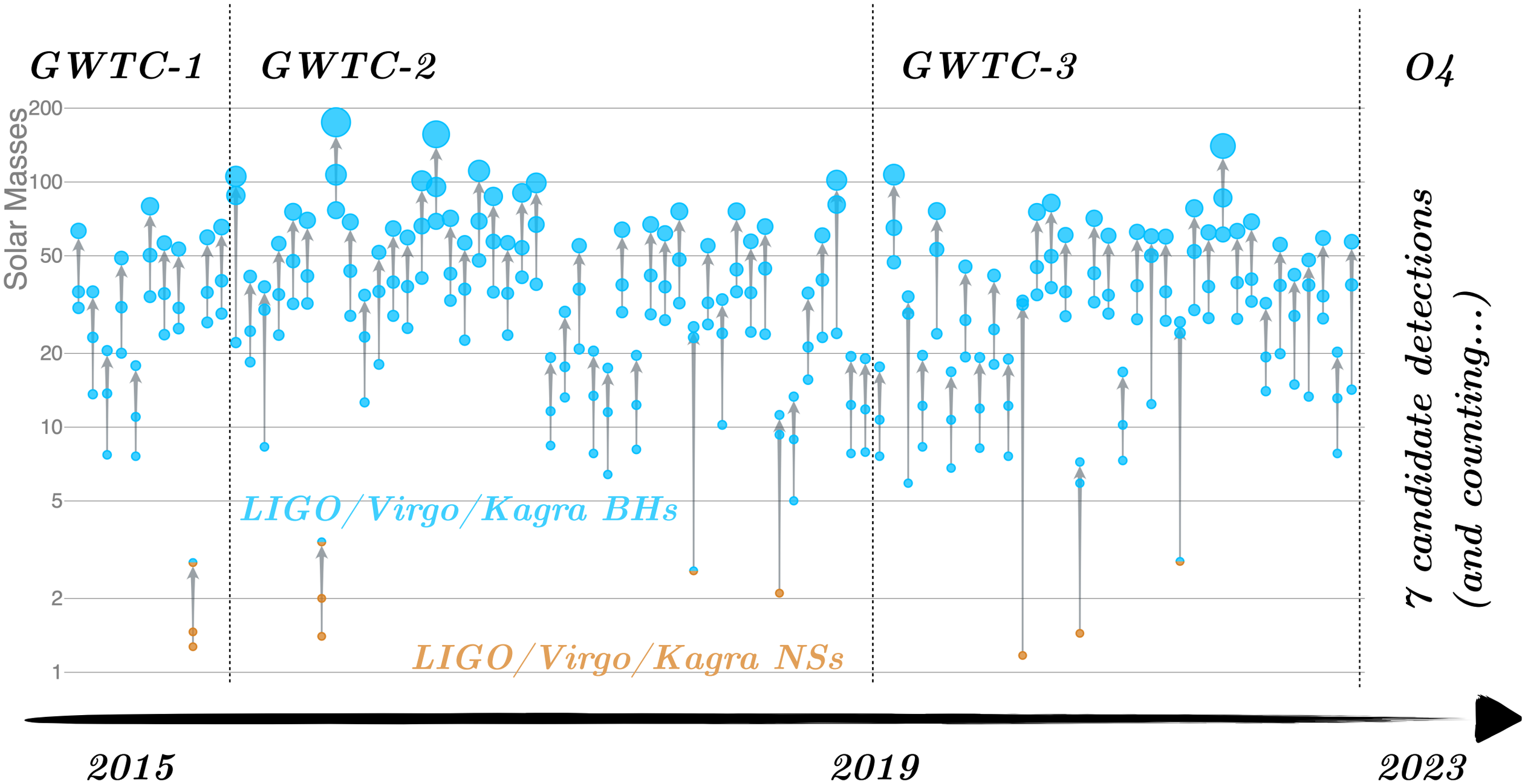


G. Franciolini, K. Kritos, E. Berti and J. Silk,
Phys. Rev. D **106** (2022) no.8, 083529 [arXiv:2205.15340]



- ***Dynamical channels largely subdominant in the standard scenario***
- ***Rate in the ballpark of LVK already with sub-percent DM abundance of PBHs***

LIGO/Virgo/Kagra growing number of detection

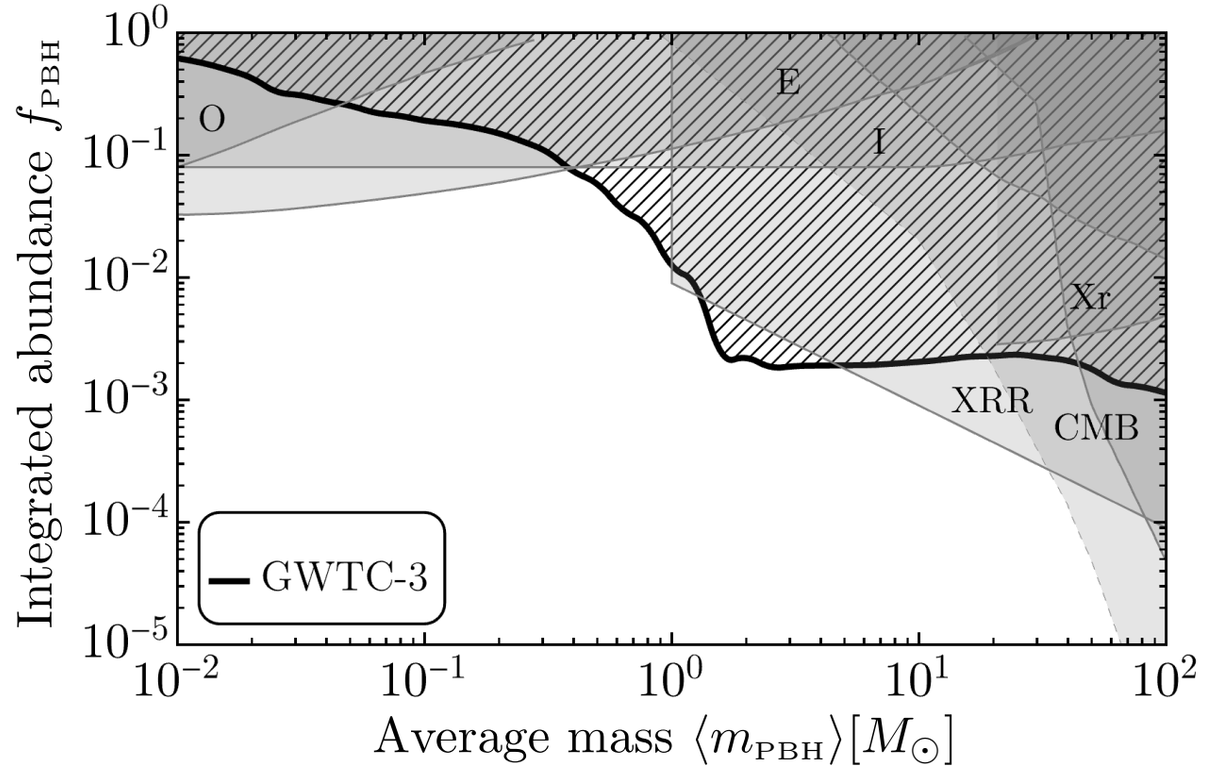


- Around 90 events, O4 observing run just started

LIGO-Virgo-KAGRA / Aaron Geller / Northwestern
R. Abbott *et al.* [LIGO Scientific, VIRGO and KAGRA], [arXiv:2111.03634]

Current LVK bounds on PBH mergers

G. Franciolini, I. Musco, P. Pani and A. Urbano, Phys. Rev. D **106** (2022) no.12, 123526 [arXiv:2209.05959]



PBH merger smoking gun signatures:

- ***Subsolar BBH masses: no detections*** A. H. Nitz and Y. F. Wang, Phys. Rev. D **106** (2022) no.2, 023024 [arXiv:2202.11024]
  R. Abbott *et al,* [LIGO Scientific, VIRGO and KAGRA], [arXiv:2212.01477]
- ***High redshift mergers: only accessible by next generation of detectors***
  (e.g. M. Branchesi, M. Maggiore, *et al.* [arXiv:2303.15923])

Population studies, subject to large uncertainties:

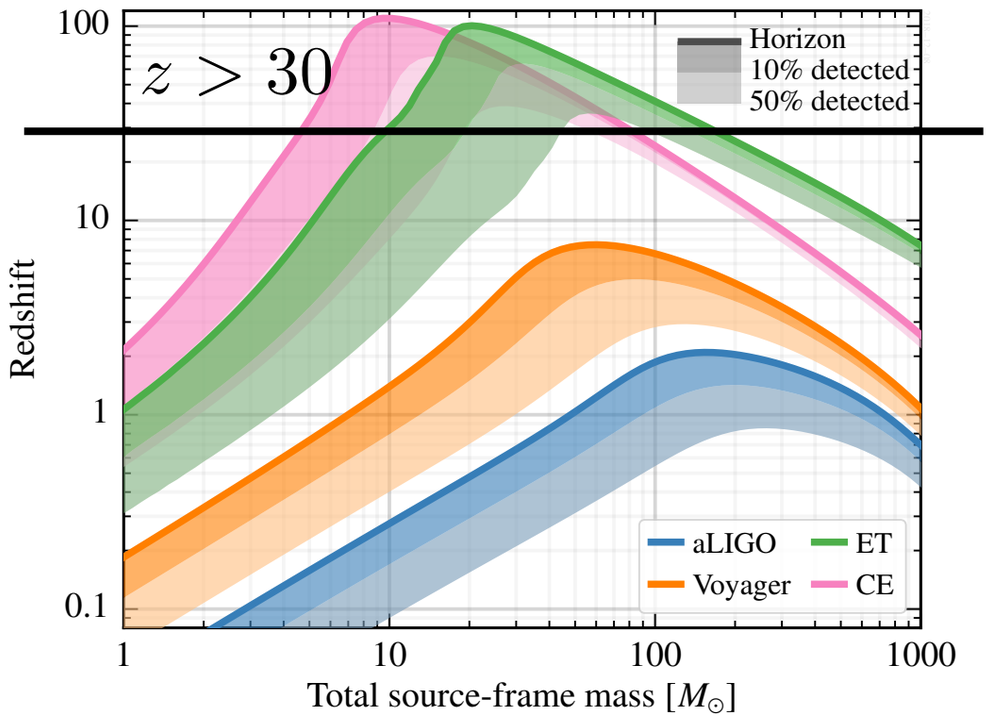
- ***Search for mass-spin correlations induced by PBH accretion***
  G. Franciolini and P. Pani, Phys. Rev. D **105** (2022) no.12, 123024 [arXiv:2201.13098]
- ***Full multi-pop inference with astro population synthesis models***
  M. Zevin *et al*, Astrophys. J. **910** (2021) no.2, 152 [arXiv:2011.10057]
  G. Franciolini *et al*, Phys. Rev. D **105** (2022) no.8, 083526 [arXiv:2105.03349]

Future constraints: 3G detectors

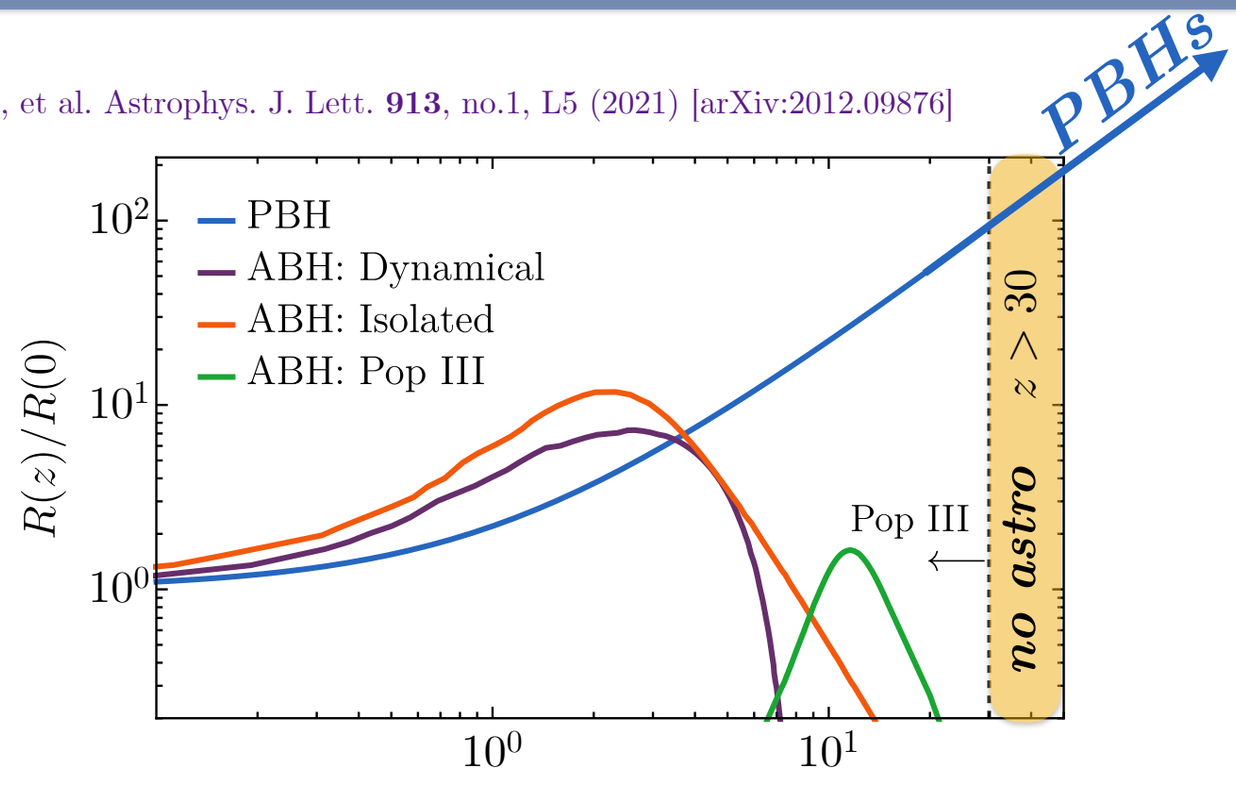
Monotonic growth up to $z \gtrsim 10^3$

$$R \approx t^{-34/37}$$

E.D.Hall and M.Evans, Class. Quant. Grav. **36**, 22, 225002 (2019) [arXiv:1902.09485]



K. Ng, et al. Astrophys. J. Lett. **913**, no.1, L5 (2021) [arXiv:2012.09876]



- ***No astro contamination above redshift*** $z \approx 30$

  T. Nakamura, *et al.* PTEP **2016**, no.9, 093E01 (2016) [arXiv:1607.00897]
  S. Koushiappas and A. Loeb, Phys. Rev. Lett. **119**, no.22, 221104 (2017) [arXiv:1708.07380]
  ....

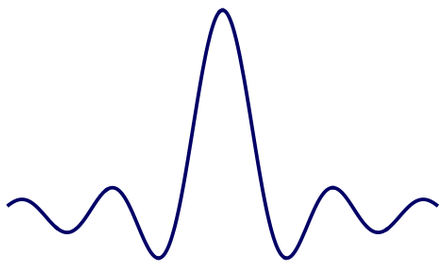
- ***3G detectors could observe these sources!***

If some PBH mergers in current GWTC-3: (10-100) detections/yr at z>30

G. Franciolini, F. Iacovelli, M. Mancarella, M. Maggiore, P. Pani and A. Riotto, [arXiv:2304.03160]

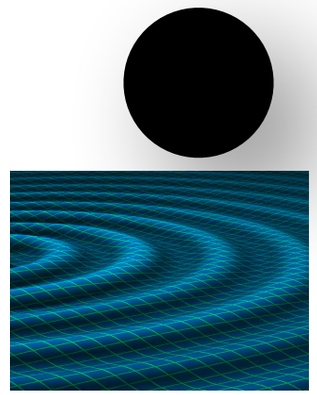
PBH DM bounds: induced GWs

Large curvature perturbations



PBH collapse

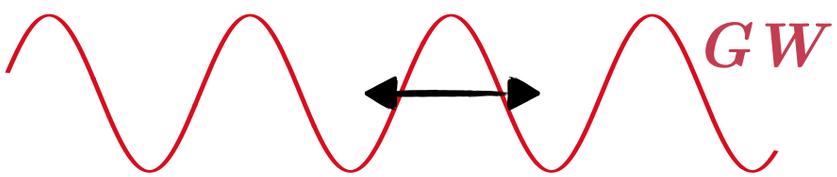
Emission of II order GWs



$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} \approx \mathcal{S}_{ij}\,(\zeta\zeta)$$

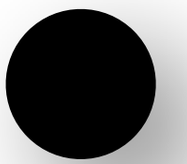
K. Tomita, Prog. Theor. Phys. 54, 730 (1975).
S. Matarrese, O. Pantano, and D. Saez, Phys. Rev. Lett. 72, 320 (1994), [arXiv:9310036].
V. Acquaviva, *et al.* Nucl. Phys. B 667, 119 (2003), [arXiv:0209156].
S. Mollerach, D. Harari, and S. Matarrese, Phys. Rev. D 69, 063002 (2004), [arXiv:0310711].
K. N. Ananda, C. Clarkson, and D. Wands, Phys. Rev. D 75, 123518 (2007), [arXiv:0612013].
...

Mass and frequency related by the Hubble horizon at formation



$$f_{\rm GW} \approx 3 \cdot 10^{-9}{\rm Hz} \left(\frac{m_{\rm PBH}}{M_\odot}\right)^{-1/2}$$

PBH

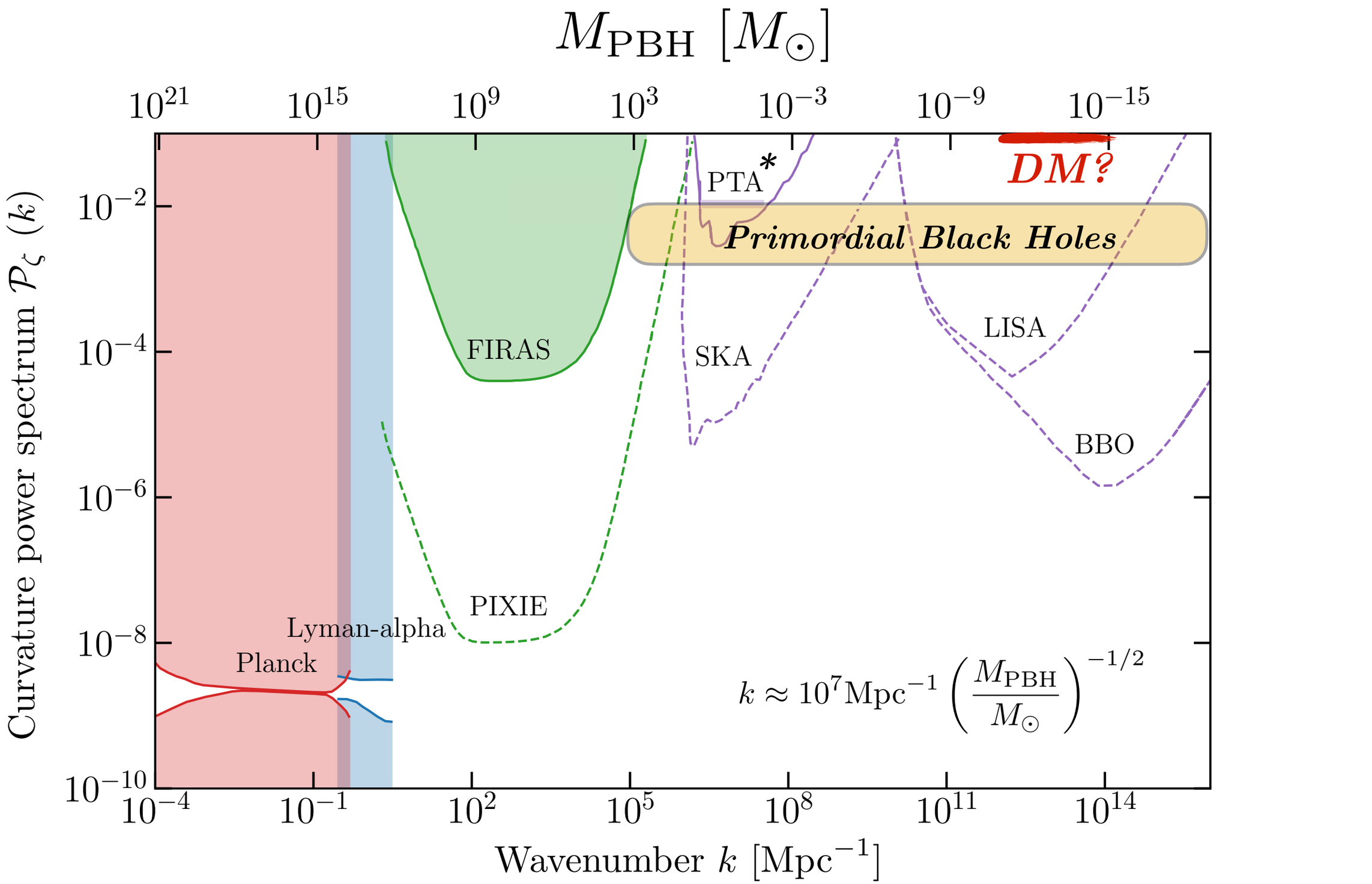


$\text{nHz} \leftrightarrow M_\odot$

$\text{mHz} \leftrightarrow 10^{-12} M_\odot$

$\text{kHz} \leftrightarrow 10^{-23} M_\odot$

Small scales constrained by no PBH overproduction



Conclusions

- ***Searching for PBHs in GW data is difficult, but provide a probe of the early universe***
- ***There still exist a window for PBHs to be the dark matter***
- ***Gravitational wave observations may close the window in the future, many constraints will improve***

What now?

- ***New GW data to be available in the short-term: LVK O4 run, PTA new data releases***
- ***Develop solid tests to distinguish primordial from astrophysical signals***
- ***If astro nature established, how far can we still constrain PBHs before foregrounds stop us?***

Thanks!