Multi-Messenger Probes of Primordial Black Holes formed in First-Order Phase Transitions

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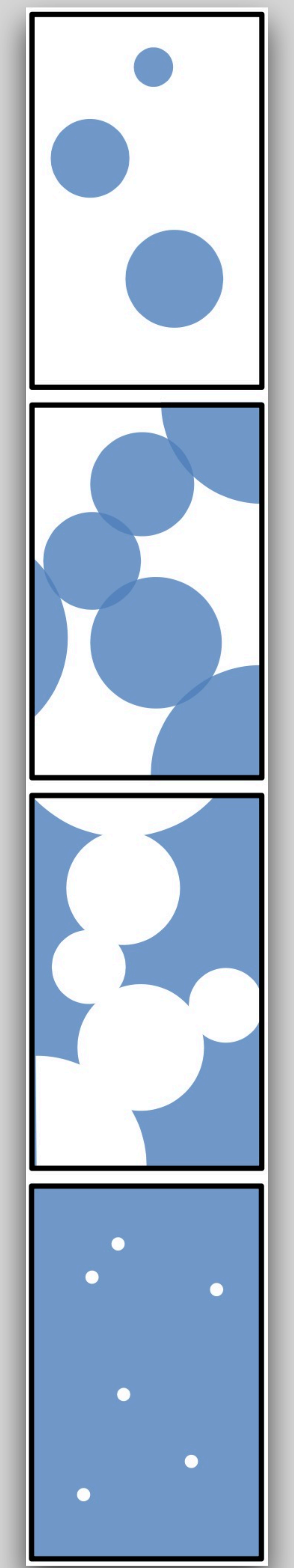


Hong, Jung, Xie
[2008.04430]

Particle Model

Particle Model Requirements

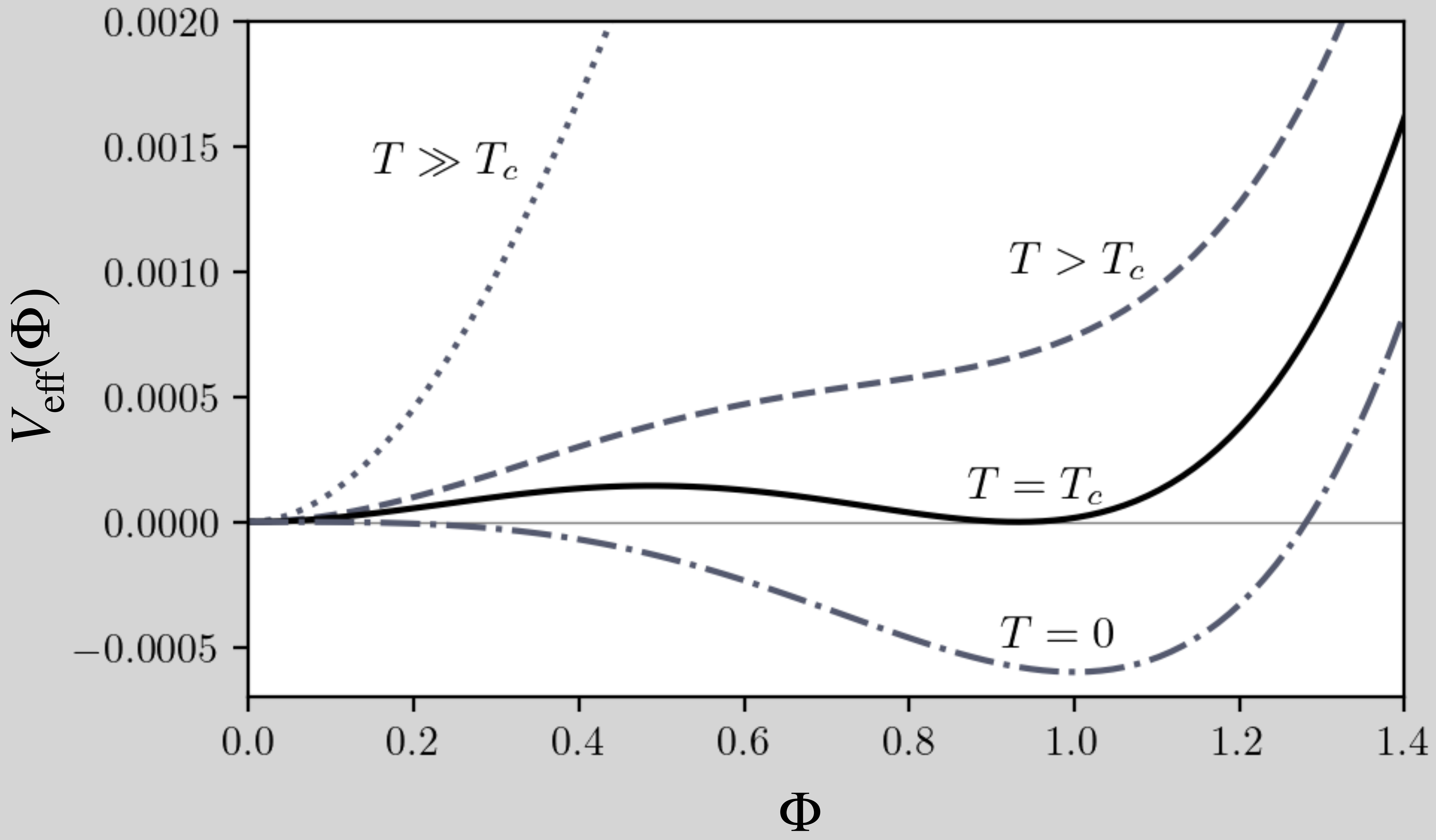
Symmetry-breaking scalar + Yukawa fermion

- A scalar field Φ acquires some nonzero vacuum expectation value $\langle\Phi\rangle$ through thermal and radiative effects

$$V_{\text{eff}}(\Phi) = \lambda\Phi^4 + V(\Phi, T)$$

- A fermionic field χ gains mass through a Yukawa interaction with Φ

$$\mathscr{L} \supset -Y\Phi\bar{\chi}\chi$$



➡ This talk uses conformal $B - L$ models

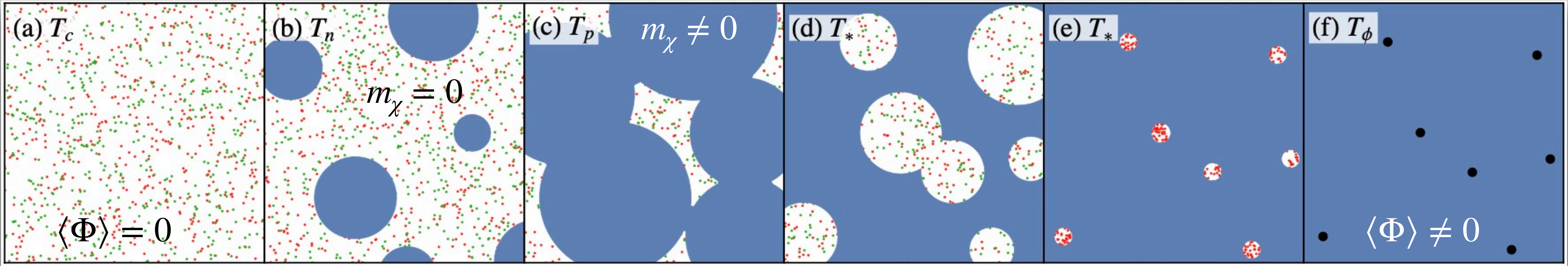
Primordial Black Hole (PBH) Formation Mechanism

Primordial Black Hole (PBH) Formation

in first-order phase transitions (FOPTs)

- In FOPTs, stochastic quantum tunneling is responsible for $\langle\Phi\rangle = 0 \rightarrow \langle\Phi\rangle \neq 0$
- When tunneling occurs, bubbles of the *new, "true" vacuum nucleate and expand*
- Particles may be unable to penetrate bubble walls into the true vacuum
- As the FOPT completes, trapped particles may form PBHs

high T



low T

Kawana, Xie [2106.00111]

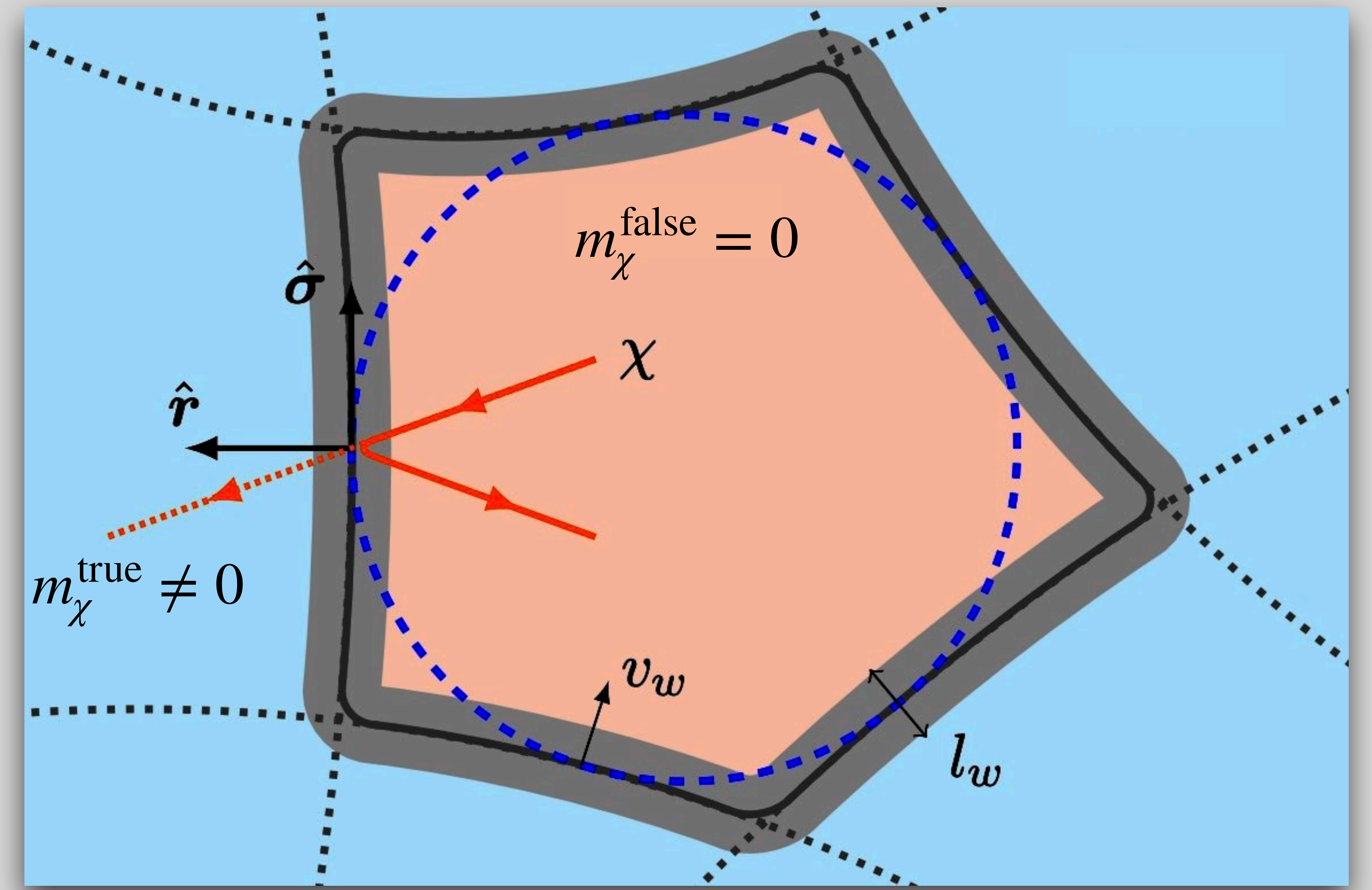
Primordial Black Hole (PBH) Formation

Trapping particles

- Energy conservation: particles can cross bubble walls if they have sufficient momentum to overcome their mass gap

- To trap enough massless particles for PBH formation, $m_\chi^{\text{true}} > p_\chi$

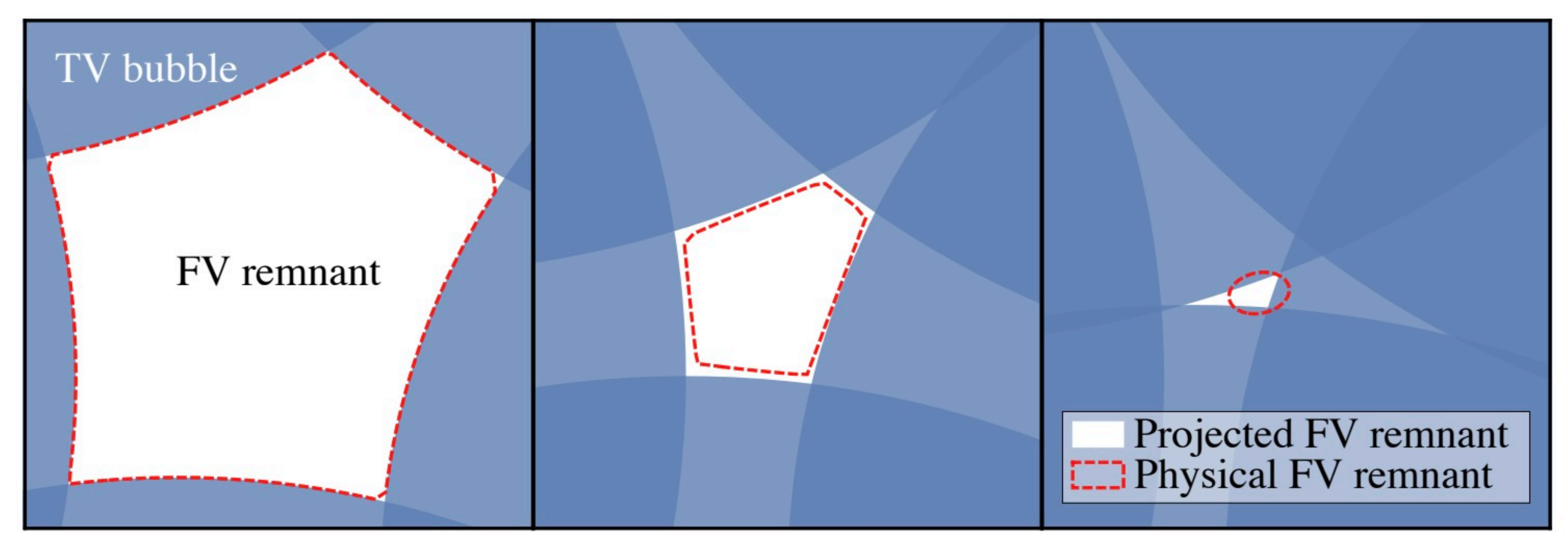
- Approximate trapping condition: $m_\chi^{\text{true}} \gtrsim T_{\text{PT}}$



Baker, Breitbach, Kopp, Mittnacht [2110.00005]

PBH Distribution

Collapsing false-vacuum remnants



Lu, Kawana, Xie [2202.03439]

- False-vacuum remnant distribution $\Longrightarrow$ **PBH distribution**

$$\rho_{\rm PBH} = \int {\rm d}M\, M \frac{{\rm d}n_{\rm PBH}}{{\rm d}M} = \int {\rm d}M\, M \frac{{\rm d}n_{\rm fv}}{{\rm d}R} \left(\frac{{\rm d}M}{{\rm d}R}\right)^{-1}$$

R is the remnant "radius" at $T_{\rm PT}$

false-vacuum remnants

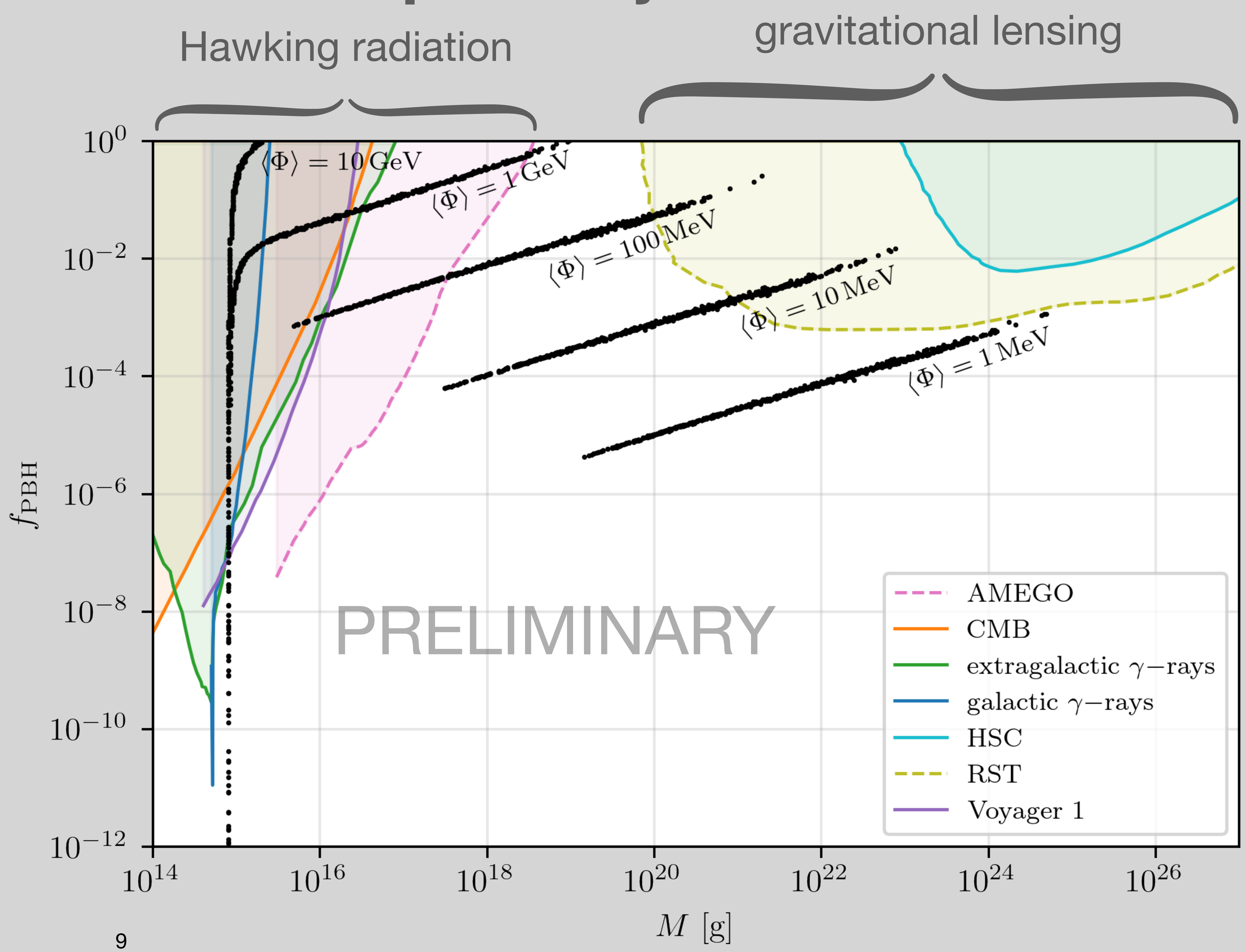
spherical PBH

- Models with $m_\chi^{\rm true} > T_{\rm PT}$ are assumed one PBH per false-vacuum remnant

f_{PBH}

Fraction of dark matter comprised of compact objects

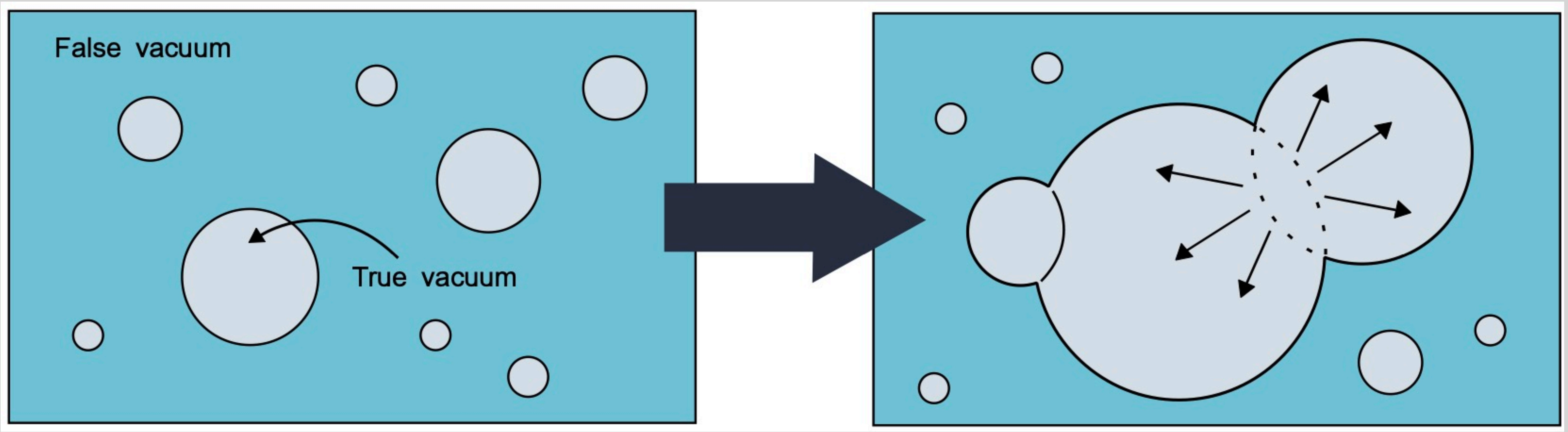
- PBH distributions from **conformal $B-L$ models**
- M = **initial PBH mass**
- $f_{\text{PBH}} \equiv \dfrac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}} = \dfrac{1}{\Omega_{\text{DM}}}\dfrac{\rho_{\text{PBH}}(t_0)}{\rho_c}$
- **Different f_{PBH} constraints can probe different energy scales**



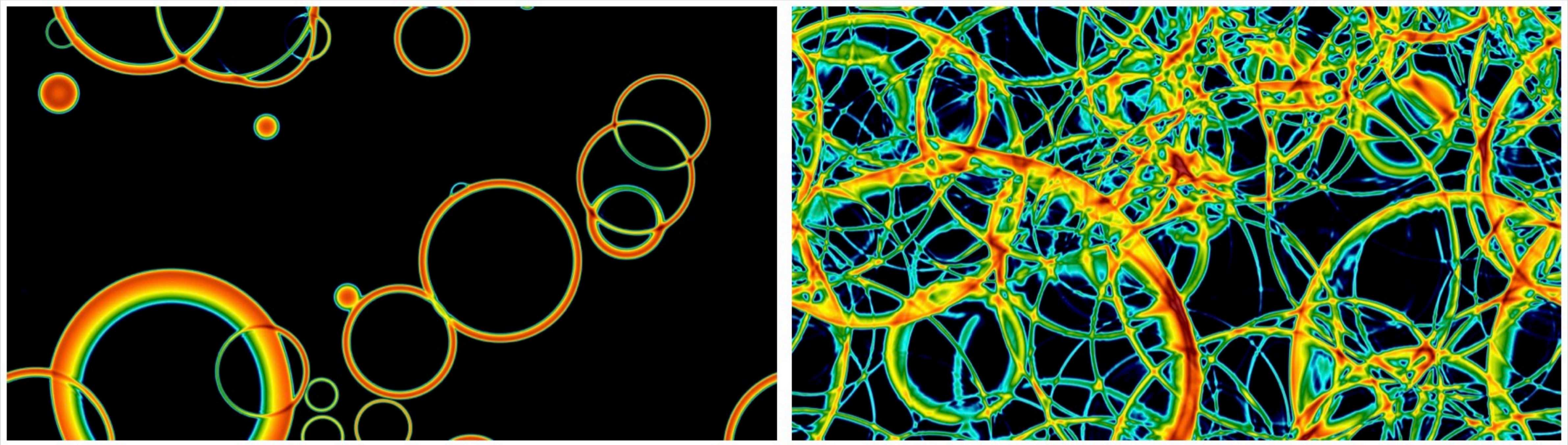
Gravitational Waves (GW)

Gravitational Waves (GW) Production

- FOPTs produce **stochastic GW backgrounds** mainly due to
  1. sound waves in the plasma
  2. bubble wall collisions
  3. magnetohydrodynamic turbulence
- Wave energies and frequencies are measured
- The next slide shows energies and frequencies of the **peak GW signal** from scanned FOPTs



Weir 2019

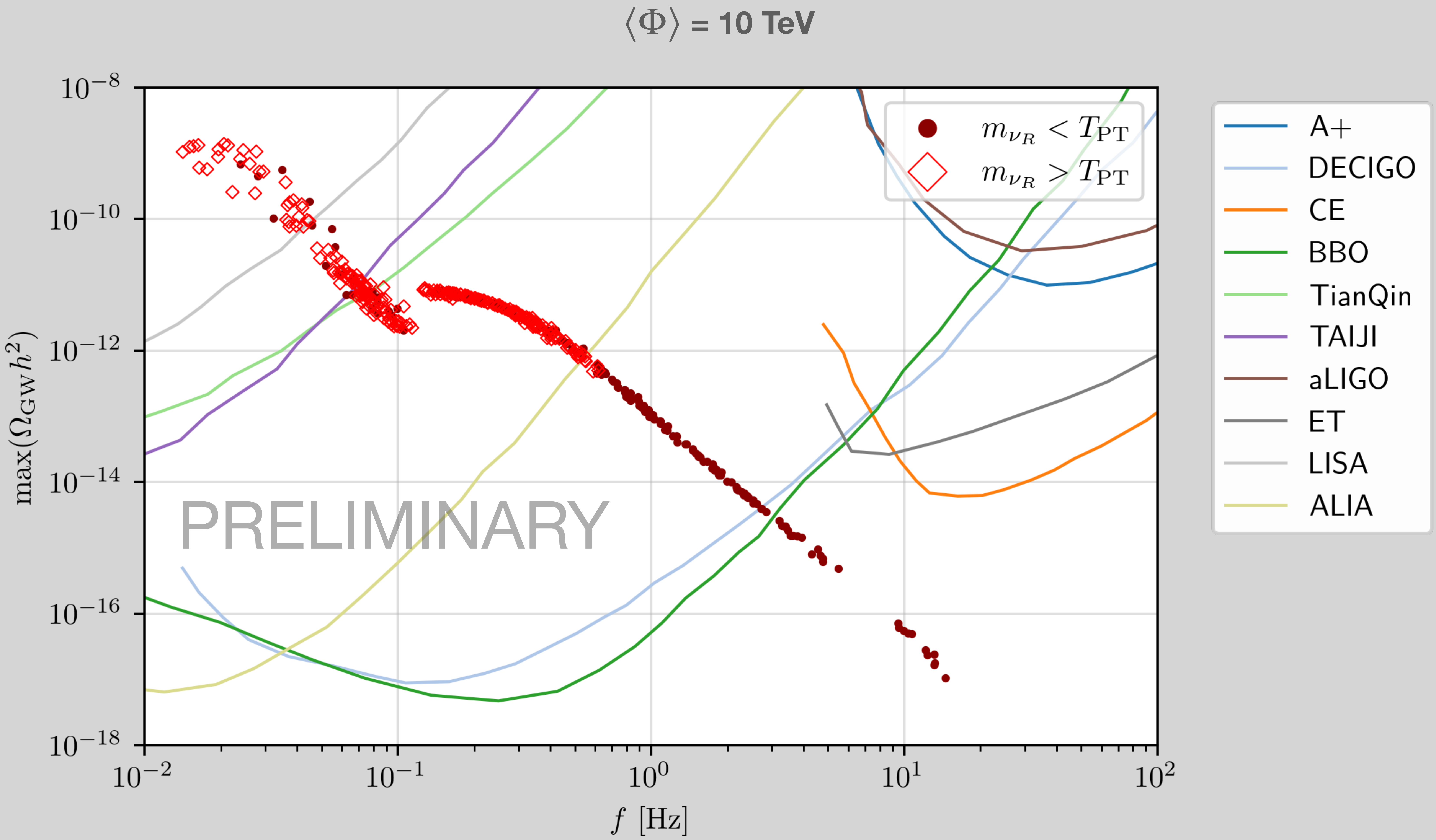


Weir [1705.01783]

Gravitational Waves Signal

Peaks of GW energy

- Red: successful FOPT
- Light red: $m_\chi > T_{\mathrm{PT}}$ (favorable for PBH formation)
- Colored lines: *projected* experimental sensitivities
- **Discontinuity is not physical**

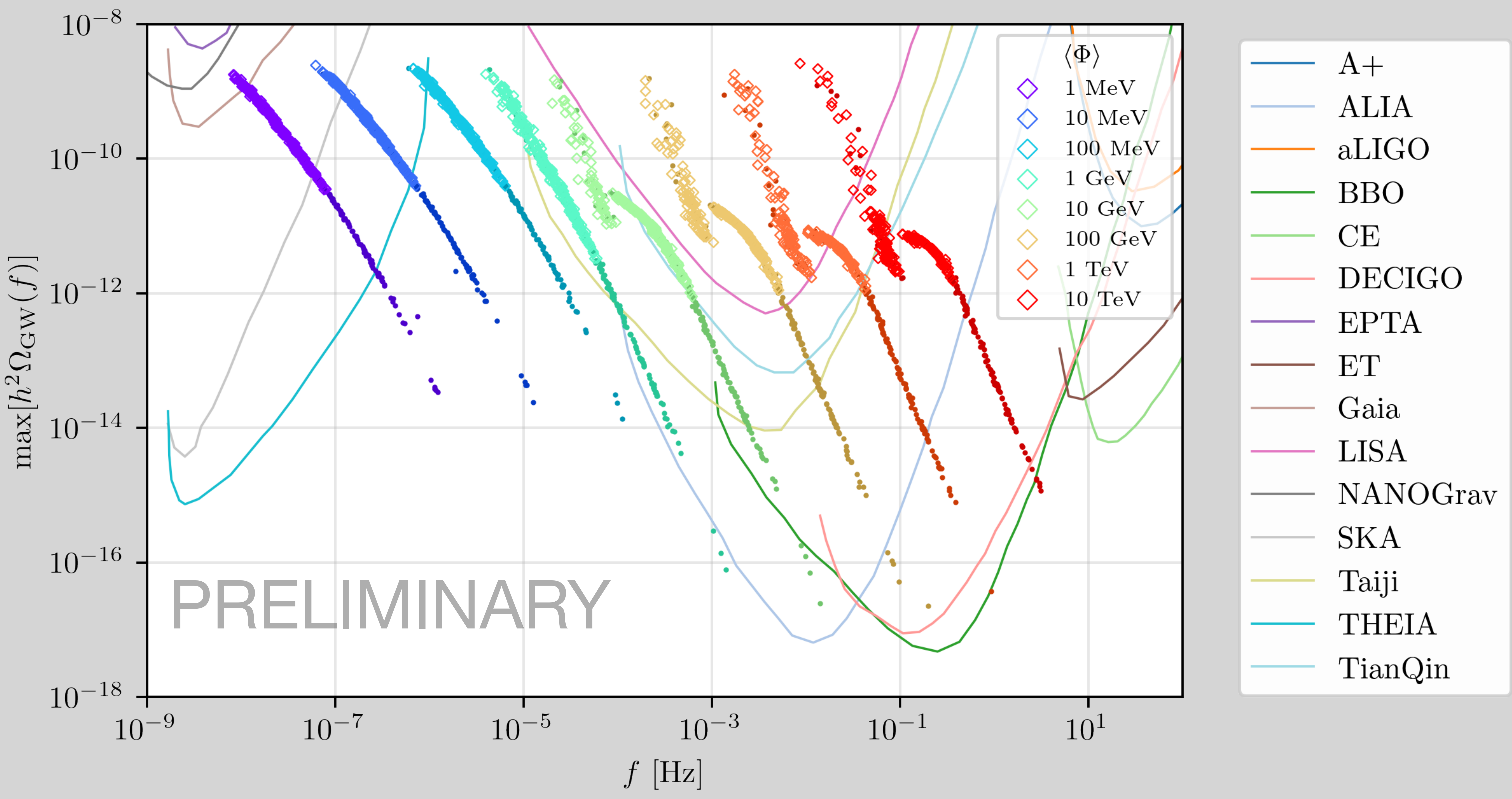


Gravitational Waves (GW) Signal

Peak GW signals

- <u>Point</u>: successful FOPT
- <u>Diamond</u>: favorable for PBH formation
- <u>Colored lines</u>: *projected* experimental sensitivities
- **Different GW experiments can probe different energy scales**

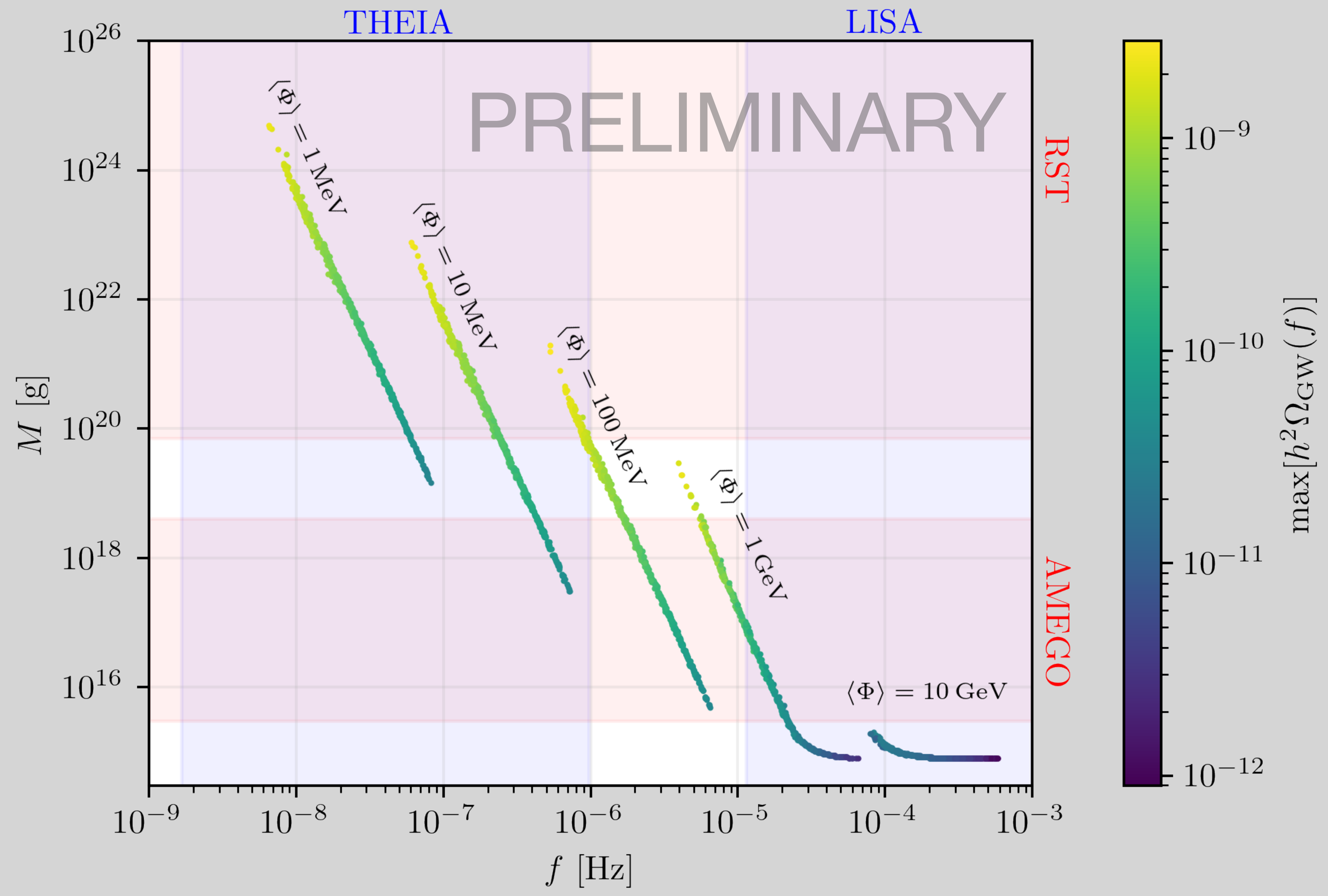
diamonds: $m_\chi > T_{\mathrm{PT}}$

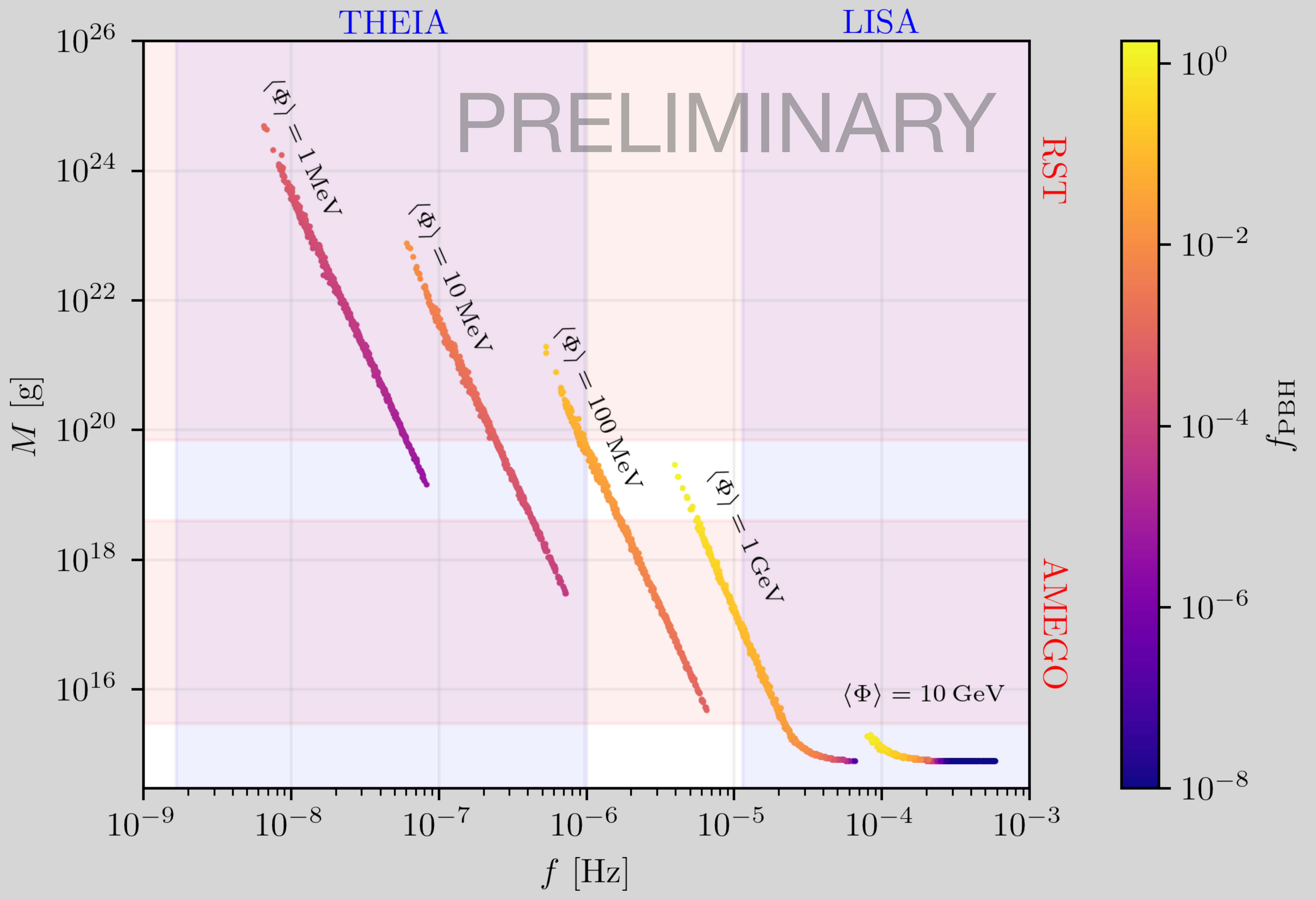


Multi-Messenger Probes

Multi-Messenger Probes

Mixed parameter space



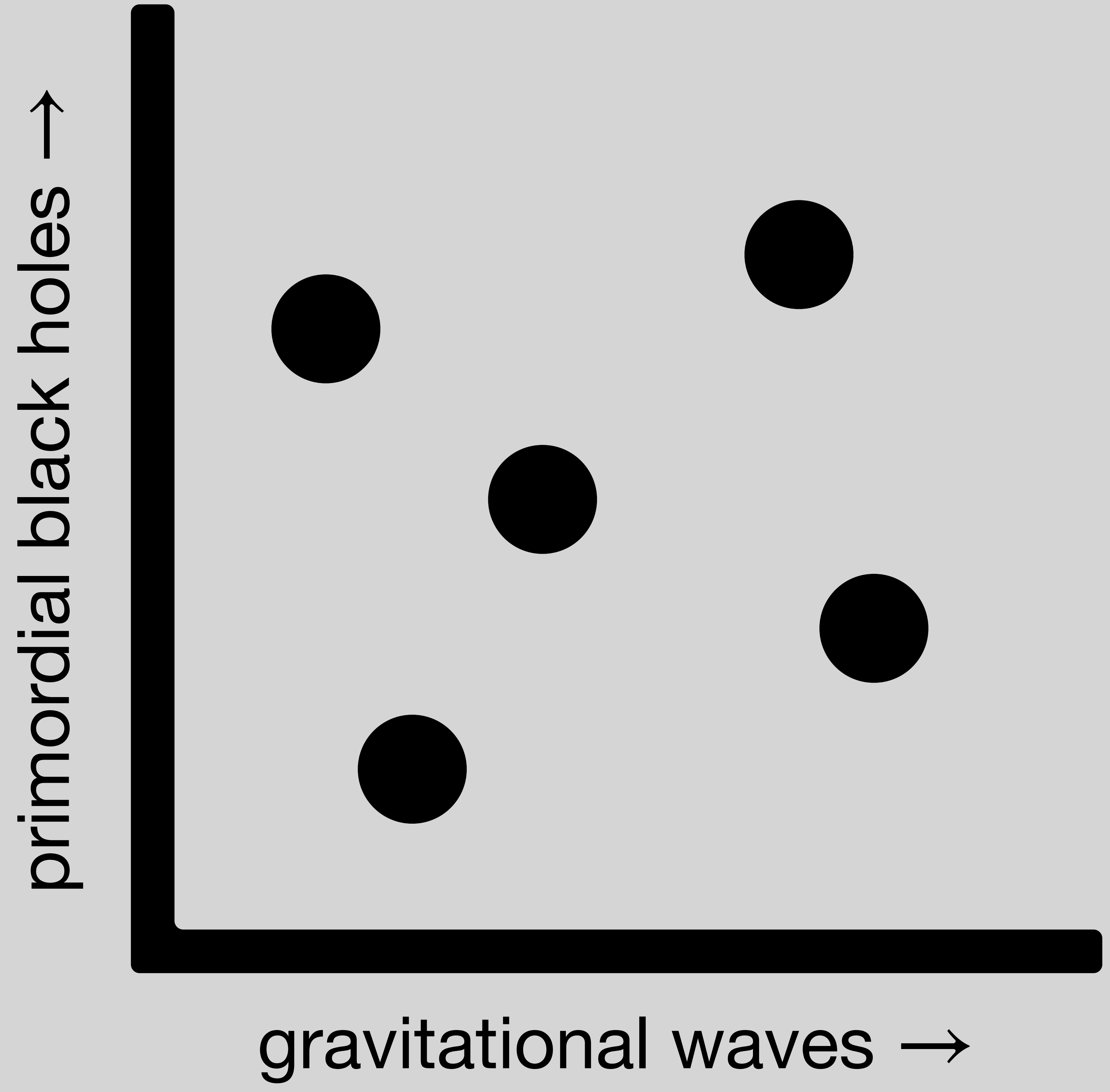


Similar studies:
Marfatia, Tseng [2112.14588]
Xie [2301.02352]

Summary

Multi-messenger probes of PBHs/FOPTs

- Phase transitions occur in any particle physics model with symmetry breaking
- FOPTs can be studied through their **GW production**
- Some models may **produce PBHs** at the end of their FOPT
- Models can be constrained by **GW + PBH probes** (multi-messenger astronomy)



more

Minimal $B - L$ Model

$B - L$: baryon number minus lepton number

- The SM "accidentally" conserves $B - L$ in perturbative interactions

- $B - L$ models make the symmetry explicit, introducing a **vector gauge boson**:

$$D_\mu = \partial_\mu - \underbrace{i g_s \lambda_\alpha G^\alpha_\mu}_{\mathrm{SU}(3)_c} - \underbrace{i g \sigma_j W^j_\mu - i g' Y B_\mu}_{\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y} - \underbrace{i g_{B-L} Q_{B-L} Z'_\mu}_{\mathrm{U}(1)_{B-L}}$$

- Symmetry breaking is done through a **scalar field** Φ

$$V_{\mathrm{eff}}(\Phi) = \lambda_\Phi \Phi^4 + V(\Phi, T)$$

- Anomalies are cancelled when **three right-handed neutrinos (RHNs)** are introduced:

$$\mathscr{L} \supset -\overline{\nu^c_R} Y \nu_R \Phi / 2$$

Minimal $B - L$ Parameter Space

- Redefine parameters for convenience:

$$\alpha_{B-L} \equiv \frac{g_{B-L}^2}{4\pi} \qquad \alpha_Y \equiv \frac{Y^2}{4\pi} \qquad \alpha_\lambda \equiv \frac{\lambda_\Phi}{4\pi}$$

- Renormalization requires these parameters to depend on a **renormalization scale** μ

$$\alpha_{B-L} = \alpha_{B-L}(t) \qquad \alpha_Y = \alpha_Y(t) \qquad \alpha_\lambda = \alpha_\lambda(t)$$

with $t \equiv \ln(\max[\Phi, T]/\mu)$.

- Solving the RG equations (and therefore the potential) only requires **"two" input parameters** for our theory:

$$\alpha_{B-L}(0), \qquad \alpha_Y(0)$$

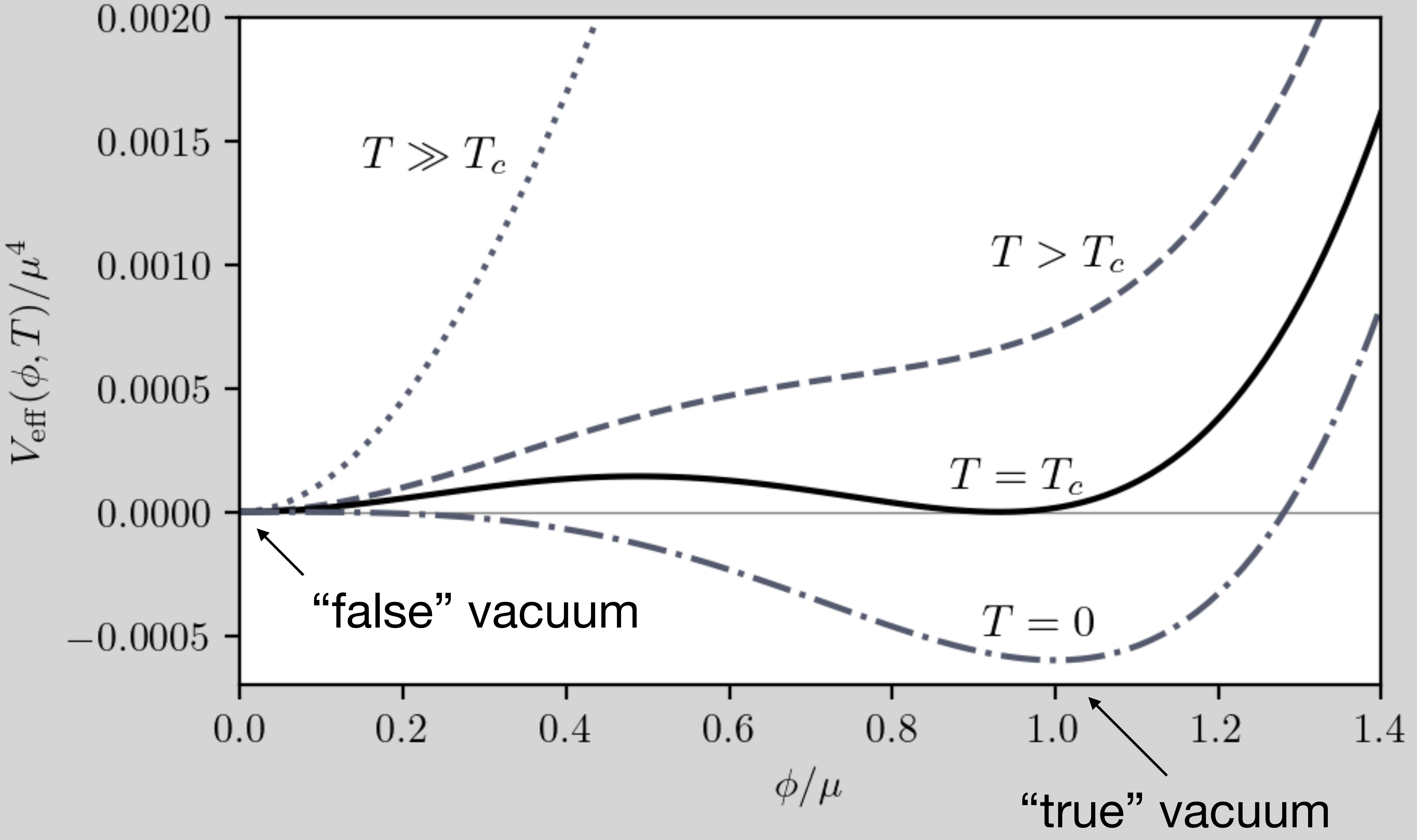
$B - L$ coupling strength → $\alpha_{B-L}(0)$

right-handed neutrino mass → $\alpha_Y(0)$

Minimal $B - L$ Model

First-order phase transitions

- V_{eff} has a global minimum at high T
- As T decreases, new local minima form
- All minima become degenerate at T_c
- **If a barrier in V_{eff} separates the minima, quantum tunneling can occur**
    - This is what makes the phase transition first-order

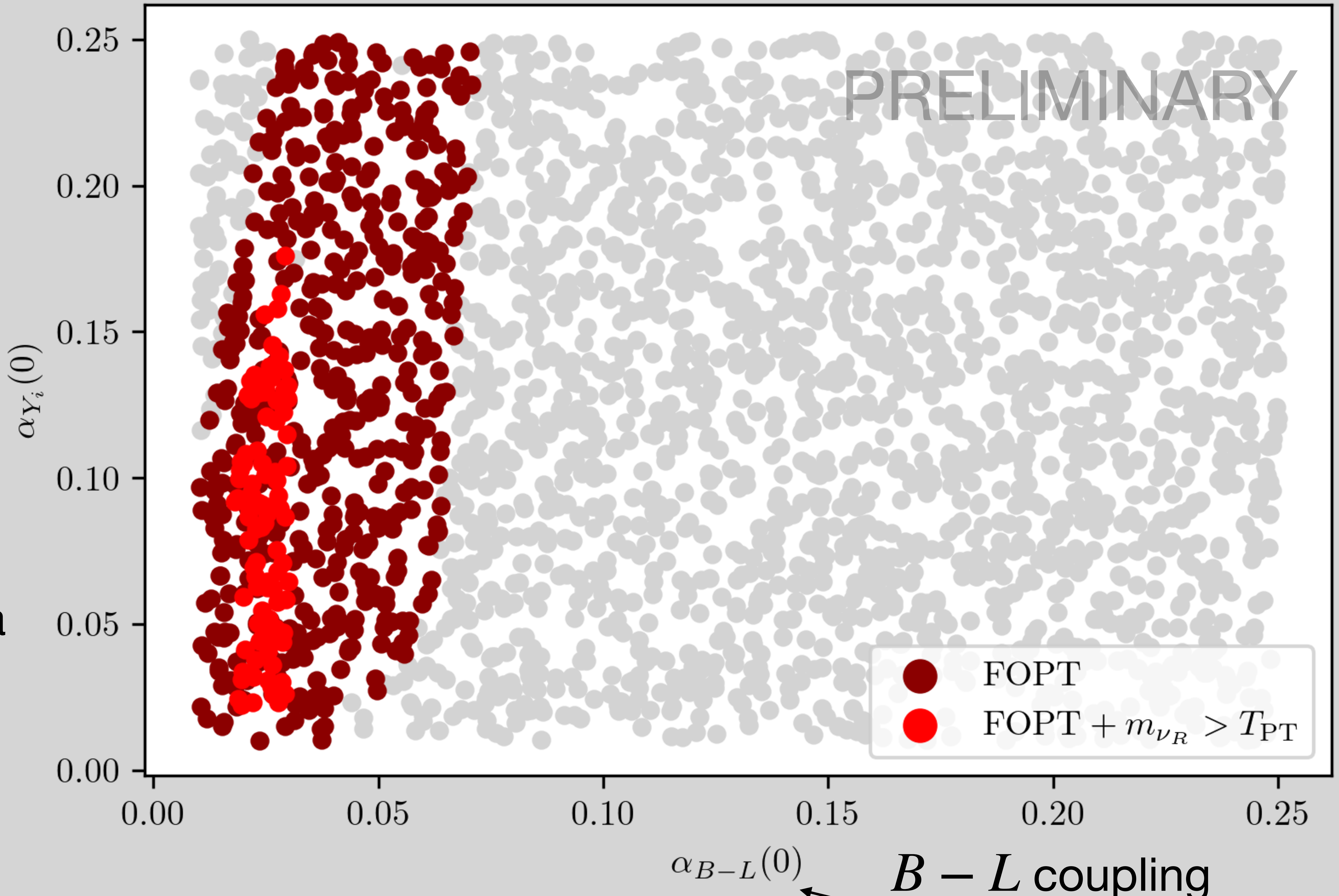


Minimal $B - L$ Model

First-order phase transition scan

- Red: successful FOPT
- Light red: χ mass gain is larger than the temperature
- **FOPTs favor small $B - L$ coupling, but are more agnostic to Yukawa coupling**

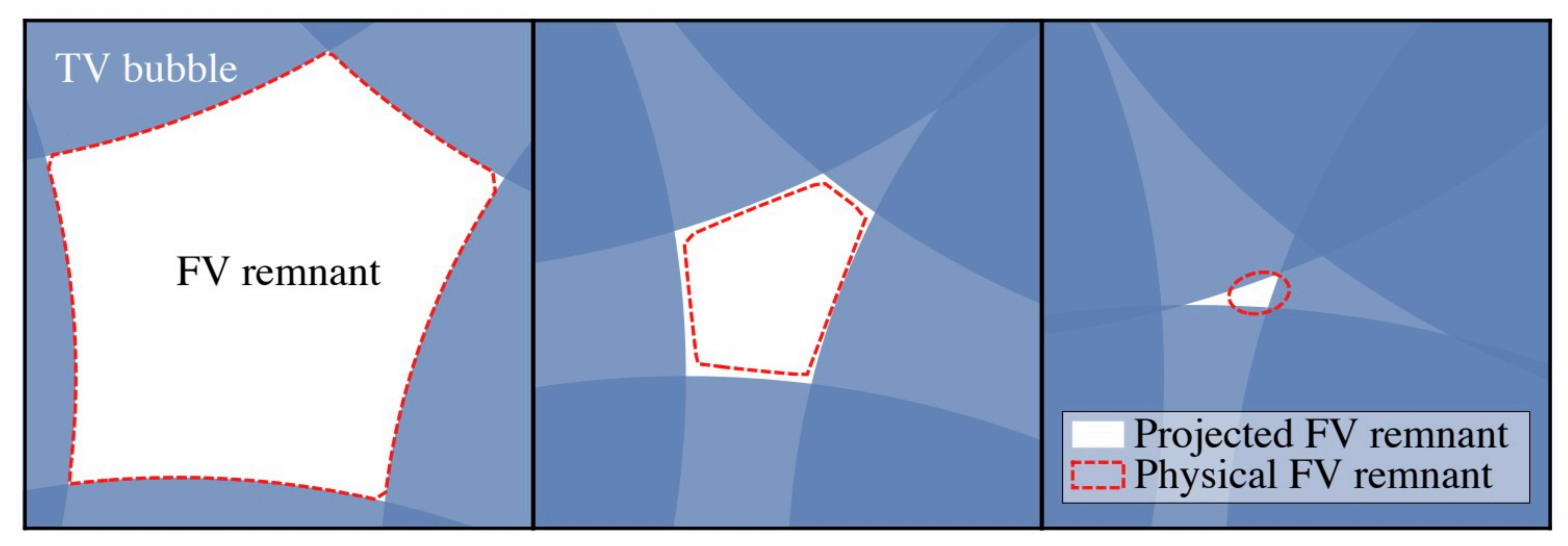
χ Yukawa coupling



$B - L$ coupling strength

PBH Distribution

Collapsing false-vacuum remnants



Lu, Kawana, Xie [2202.03439]

- Calculating the nucleation and expansion rates of true-vacuum bubbles allows you to find distribution statistics of false-vacuum remnants:

$$\frac{dn_{\mathrm{fv}}}{dR_0} \approx \frac{I_{\mathrm{PT}}^4 \beta^4}{192 v_w^3} e^{(4R_0\beta/v_w) - I_{\mathrm{PT}} e^{R_0\beta/v_w}} \left(1 - e^{-I_{\mathrm{PT}} e^{R_0\beta/v_w}}\right), \qquad \beta/H(T_{\mathrm{PT}}) \gg 1$$

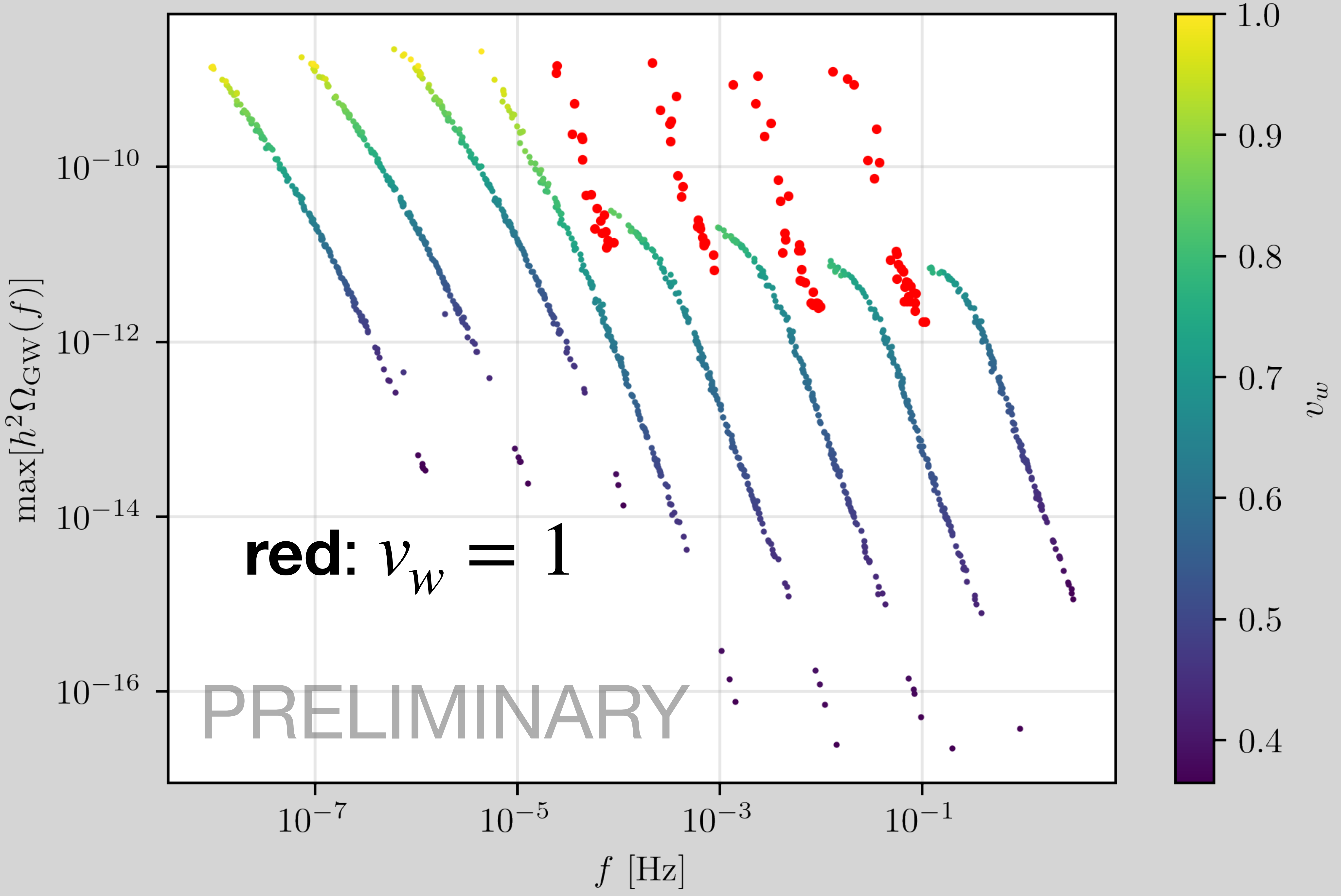
- Models with $m_\chi^{\mathrm{true}} > T_{\mathrm{PT}}$ are assumed to form one PBH per false-vacuum remnant.

- False-vacuum remnant distribution $\Longrightarrow$ **PBH distribution**

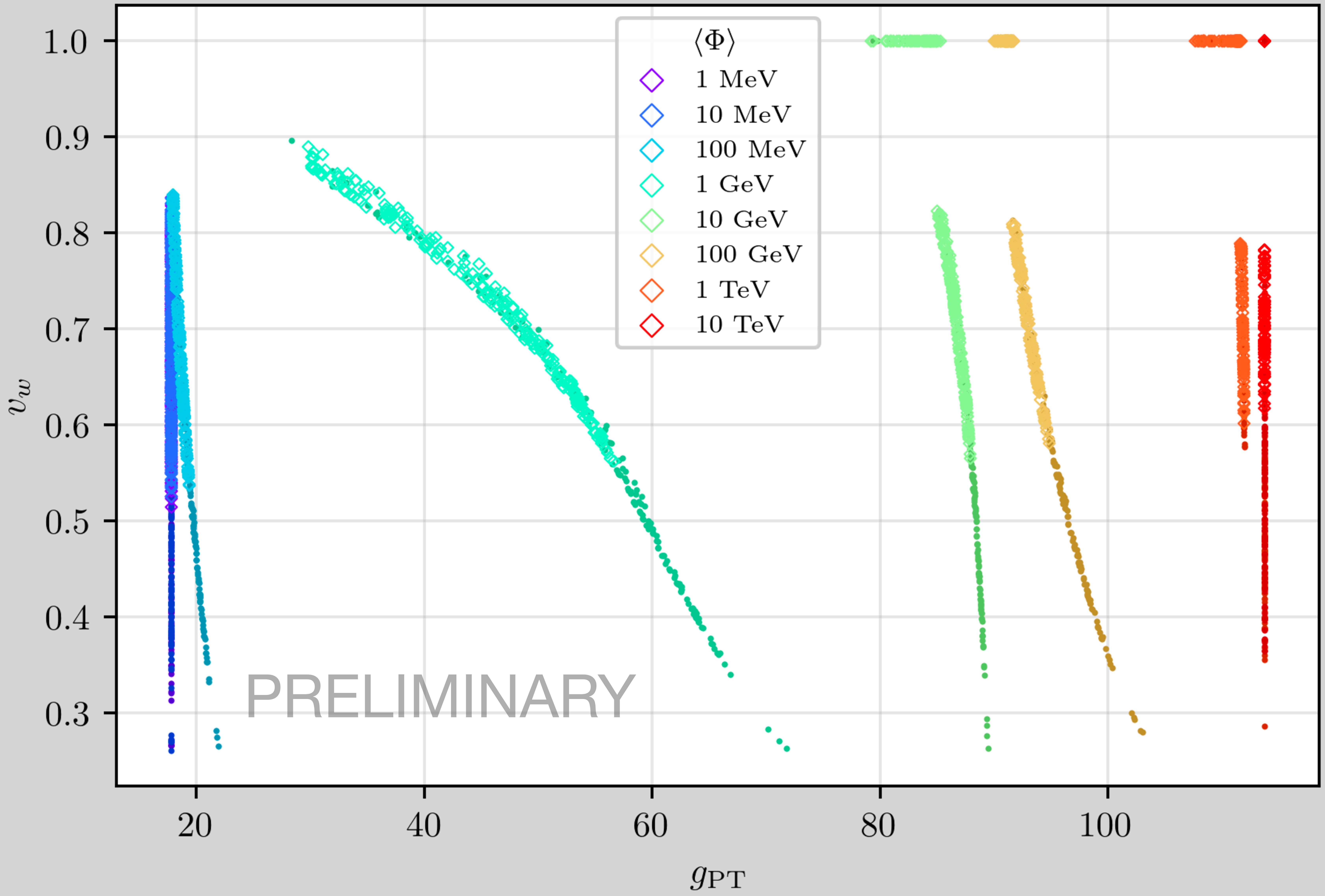
discontinuity

$$v_w = \begin{cases} \sqrt{\dfrac{\Delta V}{\alpha \rho_r}} & \text{for} \quad \sqrt{\dfrac{\Delta V}{\alpha \rho_r}} < v_J(\alpha) \\ 1 & \text{for} \quad \sqrt{\dfrac{\Delta V}{\alpha \rho_r}} \geq v_J(\alpha) \end{cases}$$

$$v_J(\alpha) = \frac{1 + \sqrt{3\alpha^2 + 2\alpha}}{\sqrt{3}(1 + \alpha)}$$



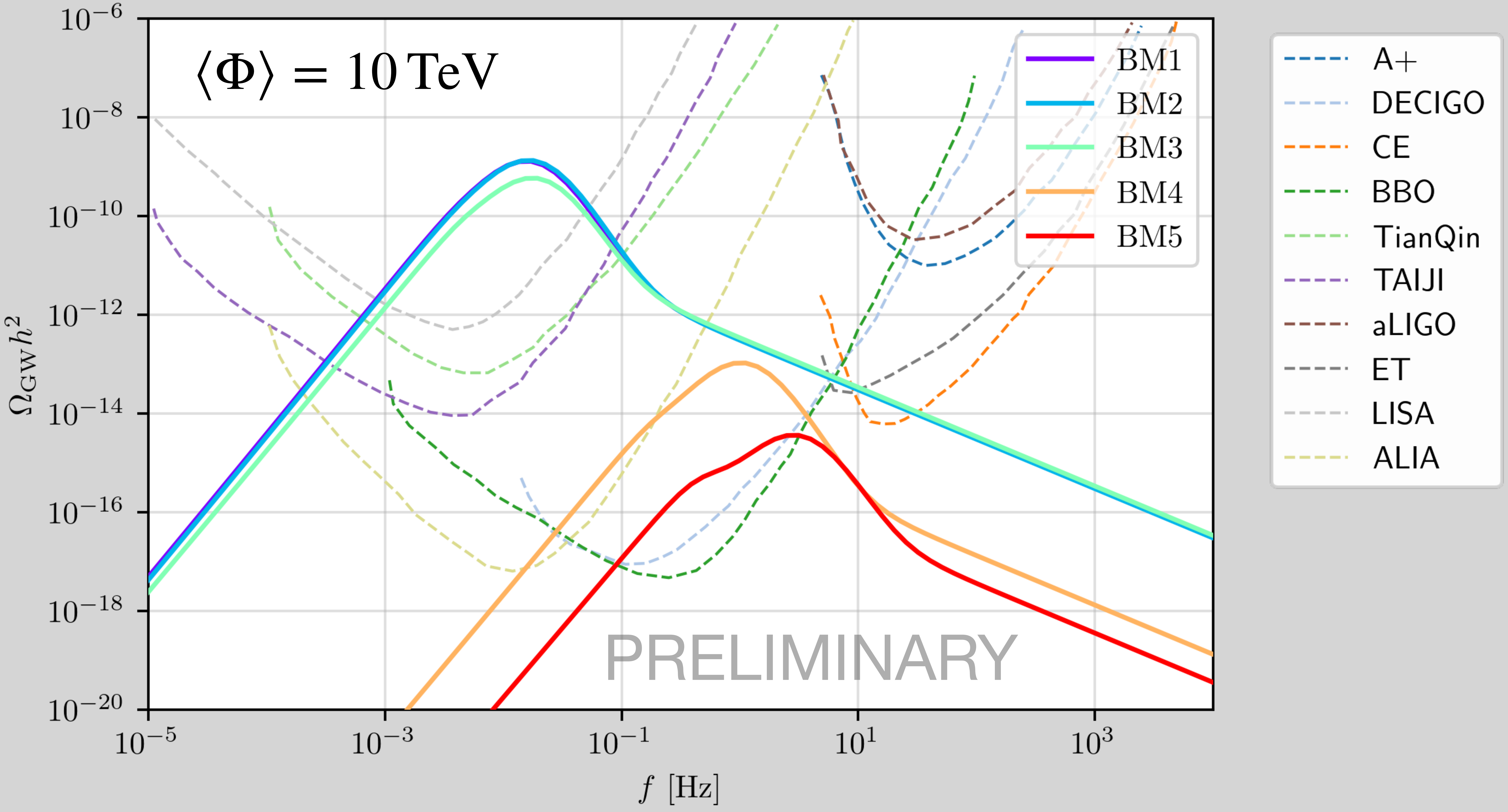
discontinuity



Benchmarks

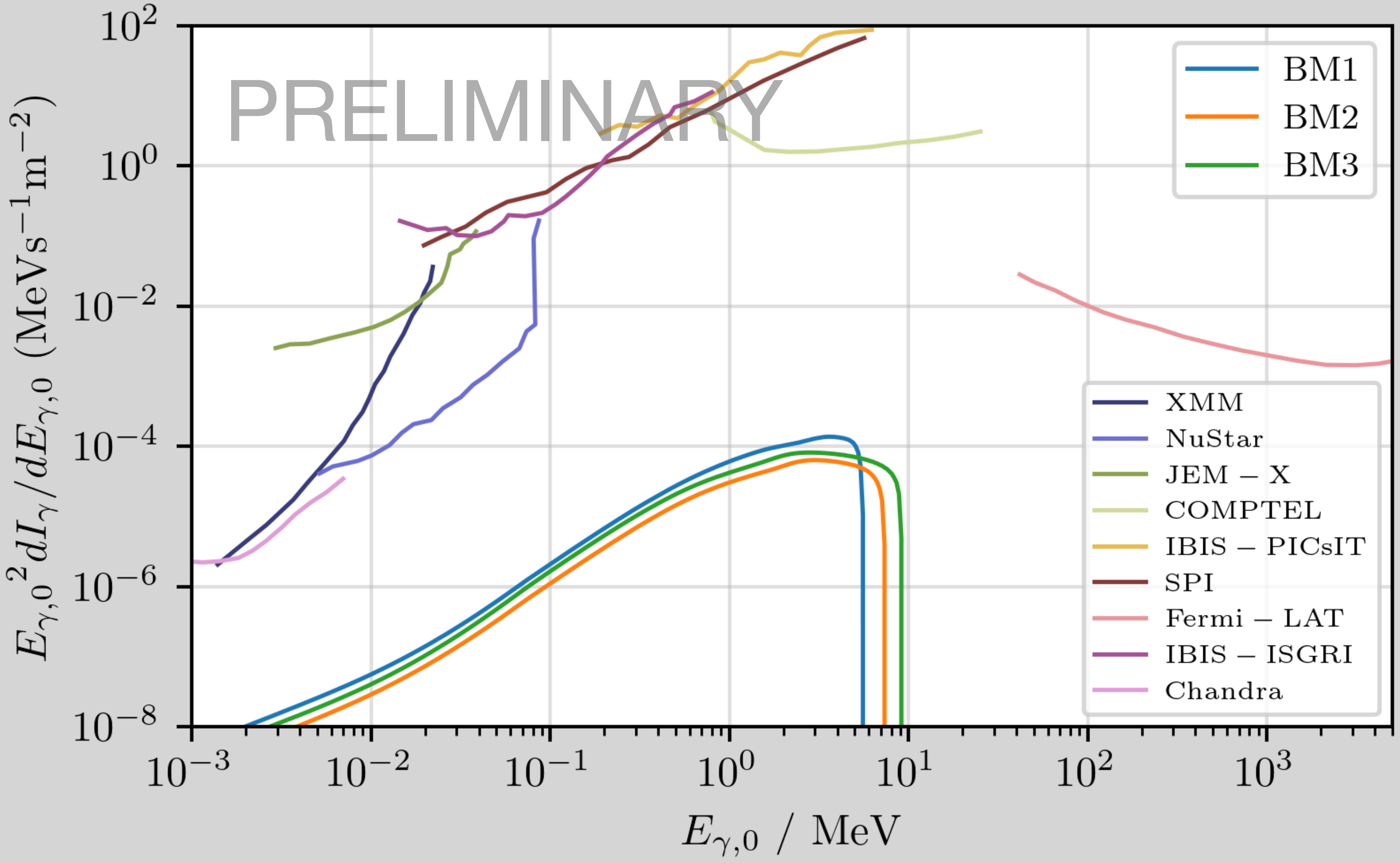
Gravitational waves

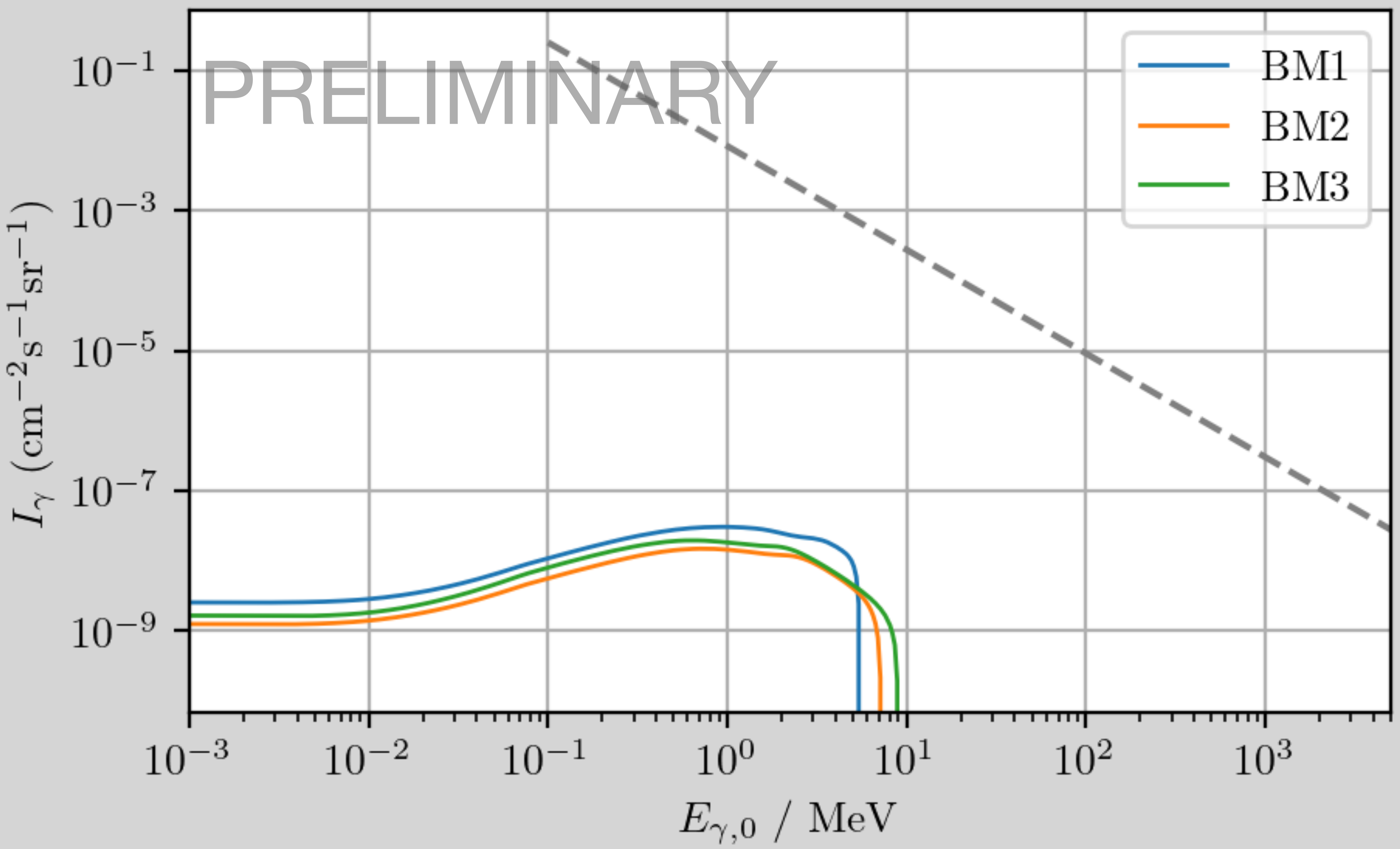
	$\alpha_{B-L}(0)$	$\alpha_{Y_i}(0)$	$T_{\rm PT}/\langle\Phi\rangle$	α	$\beta/H(T_{\rm PT})$
BM1	1.857×10^{-2}	9.368×10^{-2}	8.694×10^{-2}	7.869×10^{-1}	9.228×10^{1}
BM2	1.998×10^{-2}	1.149×10^{-1}	8.671×10^{-2}	8.194×10^{-1}	9.660×10^{1}
BM3	2.332×10^{-2}	1.503×10^{-1}	1.006×10^{-1}	5.451×10^{-1}	9.021×10^{1}
BM4	3.682×10^{-2}	1.444×10^{-1}	3.075×10^{-1}	4.766×10^{-2}	8.664×10^{2}
BM5	4.507×10^{-2}	1.421×10^{-1}	3.953×10^{-1}	3.231×10^{-2}	1.460×10^{3}



Benchmarks

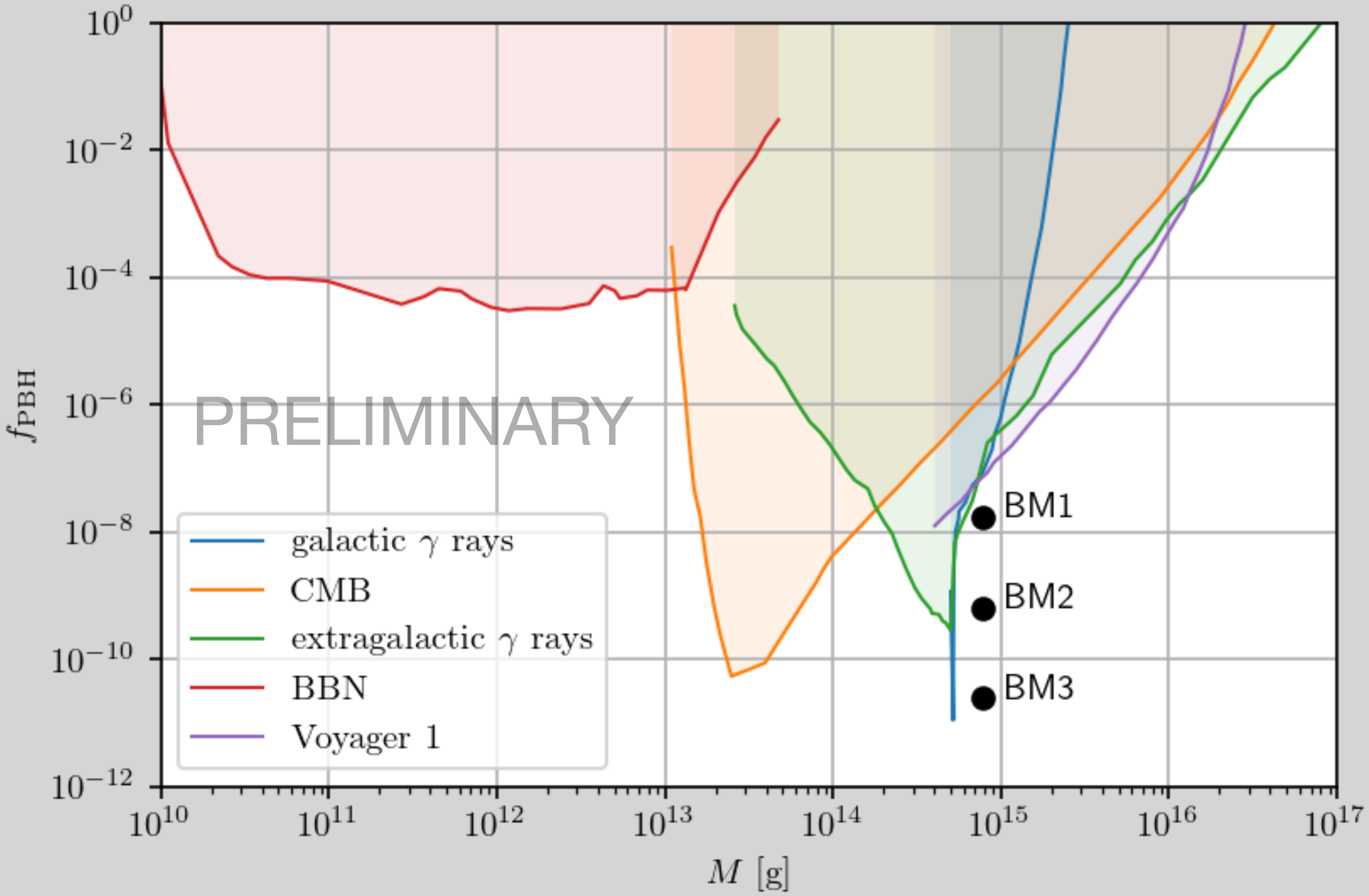
Hawking radiation

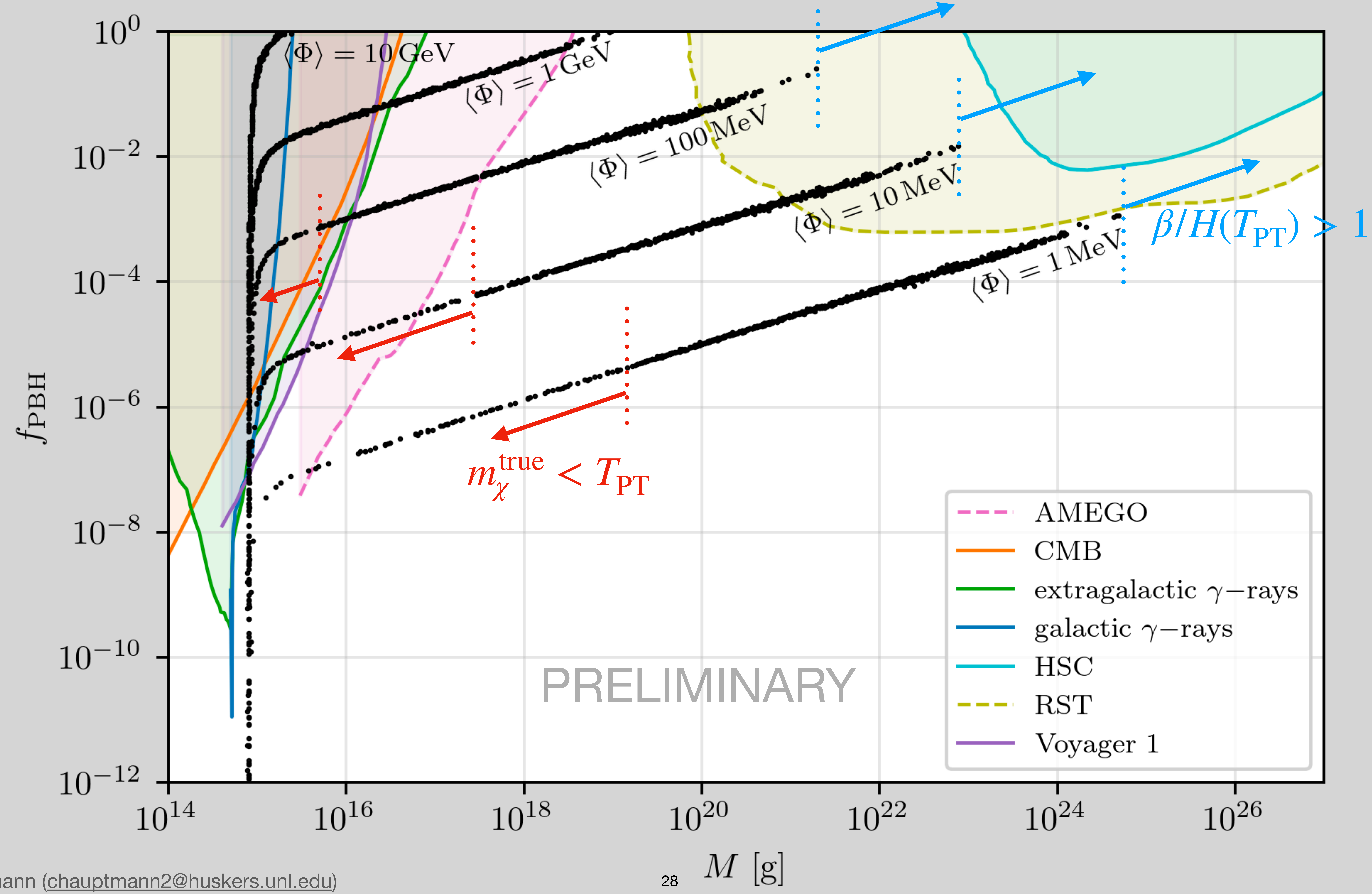


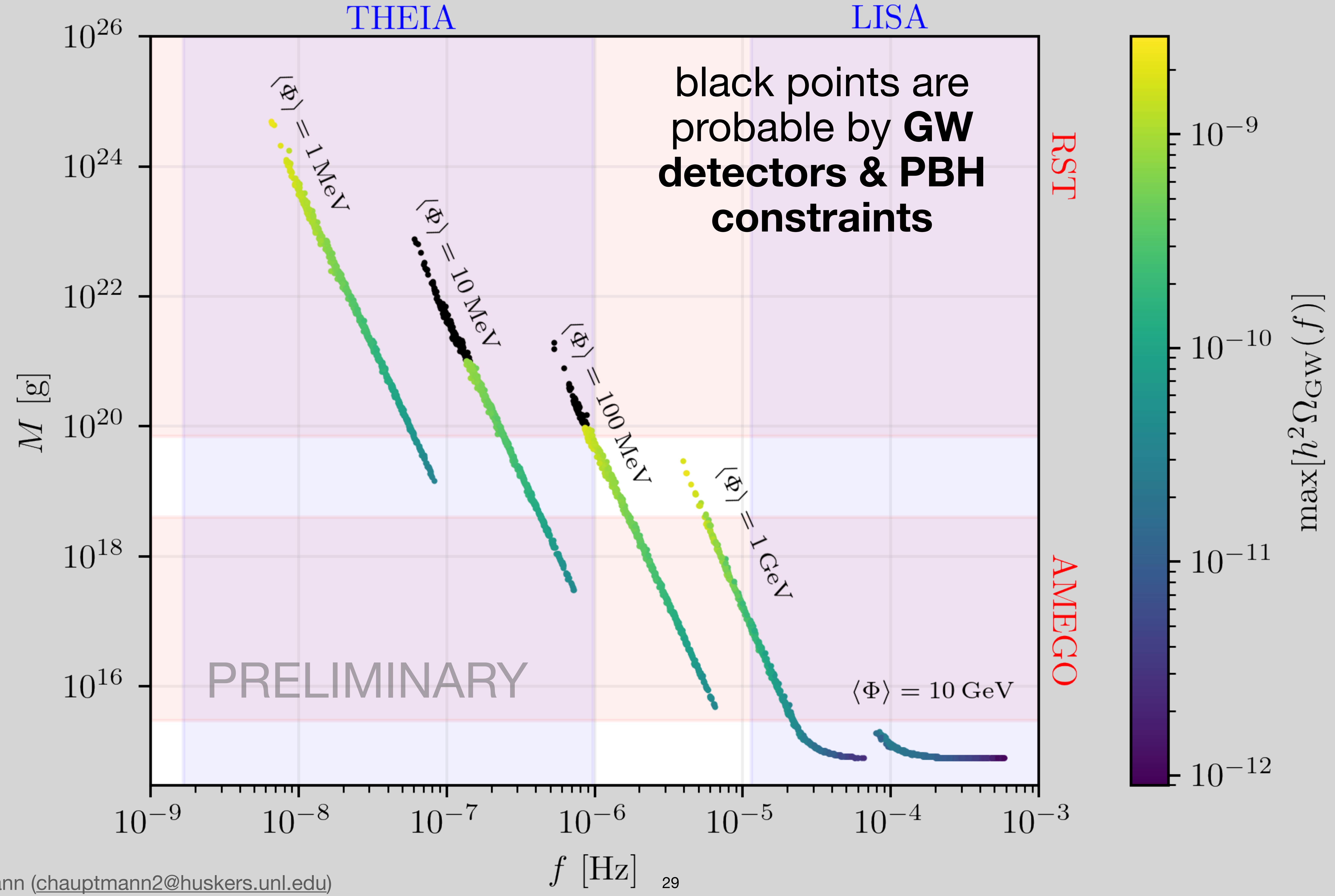


Benchmarks

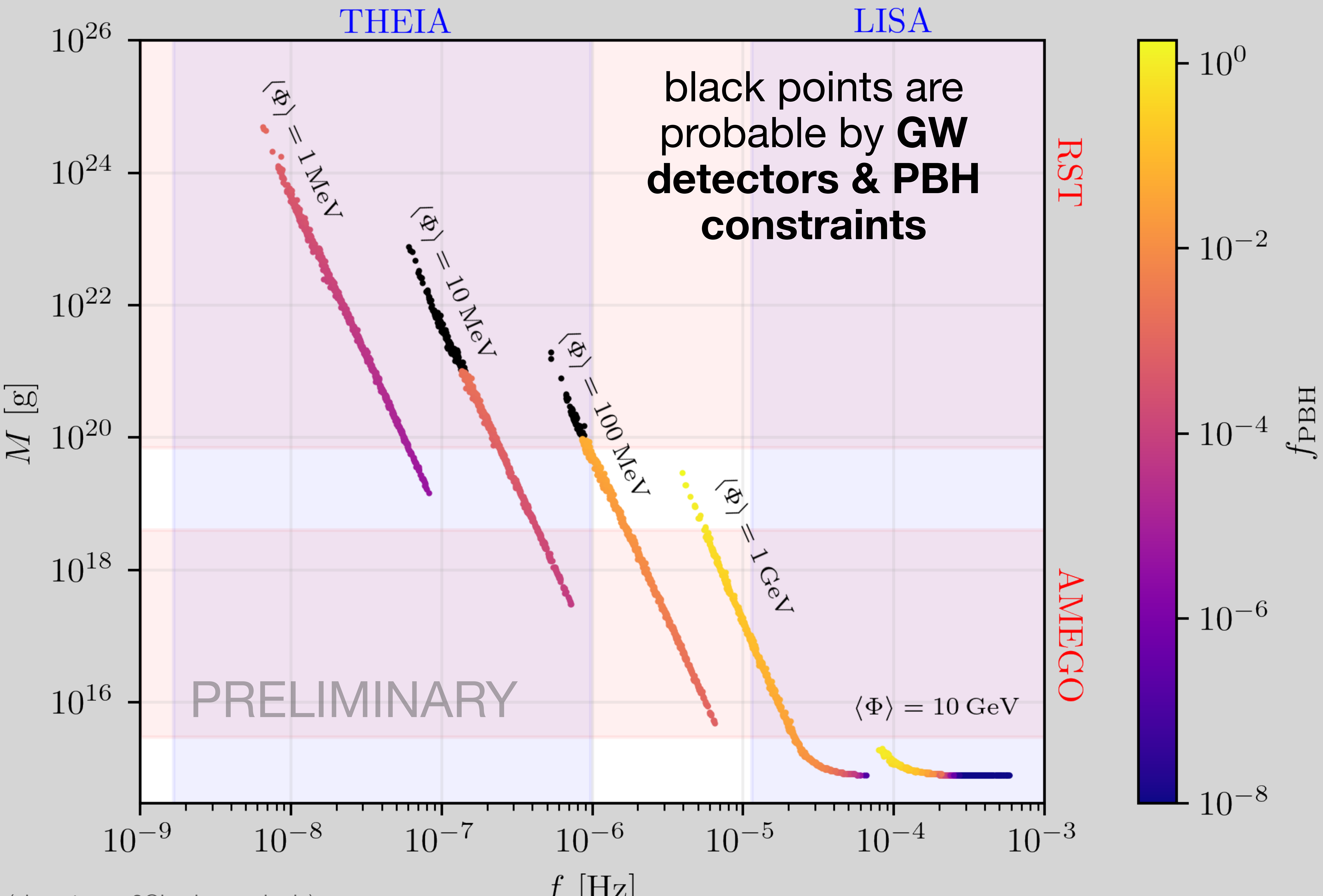
f_{PBH}




10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
f_{PBH}
10^{14}
10^{16}
10^{18}
10^{20}
10^{22}
10^{24}
10^{26}
M [g]
$\langle\Phi\rangle = 10\,\mathrm{GeV}$
$\langle\Phi\rangle = 1\,\mathrm{GeV}$
$\langle\Phi\rangle = 100\,\mathrm{MeV}$
$\langle\Phi\rangle = 10\,\mathrm{MeV}$
$\langle\Phi\rangle = 1\,\mathrm{MeV}$
$\beta/H(T_{PT}) > 1$
$m_\chi^{true} < T_{PT}$
PRELIMINARY
AMEGO
CMB
extragalactic γ−rays
galactic γ−rays
HSC
RST
Voyager 1



THEIA
LISA
RST
AMEGO
black points are probable by **GW detectors & PBH constraints**
$\langle\Phi\rangle = 1$ MeV
$\langle\Phi\rangle = 10$ MeV
$\langle\Phi\rangle = 100$ MeV
$\langle\Phi\rangle = 1$ GeV
$\langle\Phi\rangle = 10$ GeV
PRELIMINARY
M [g]
f [Hz]
$\max[h^2\Omega_{\rm GW}(f)]$


THEIA
LISA
black points are probable by **GW detectors & PBH constraints**
RST
AMEGO
$\langle\Phi\rangle = 1$ MeV
$\langle\Phi\rangle = 10$ MeV
$\langle\Phi\rangle = 100$ MeV
$\langle\Phi\rangle = 1$ GeV
$\langle\Phi\rangle = 10$ GeV
PRELIMINARY
M [g]
f [Hz]
$f_{\rm PBH}$
10^{26}
10^{24}
10^{22}
10^{20}
10^{18}
10^{16}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}