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

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In collaboration with B. Dutta, P. Huang, A. Thompson

Primordial Black Hole (PBH) Formation Mechanism

Particle Model

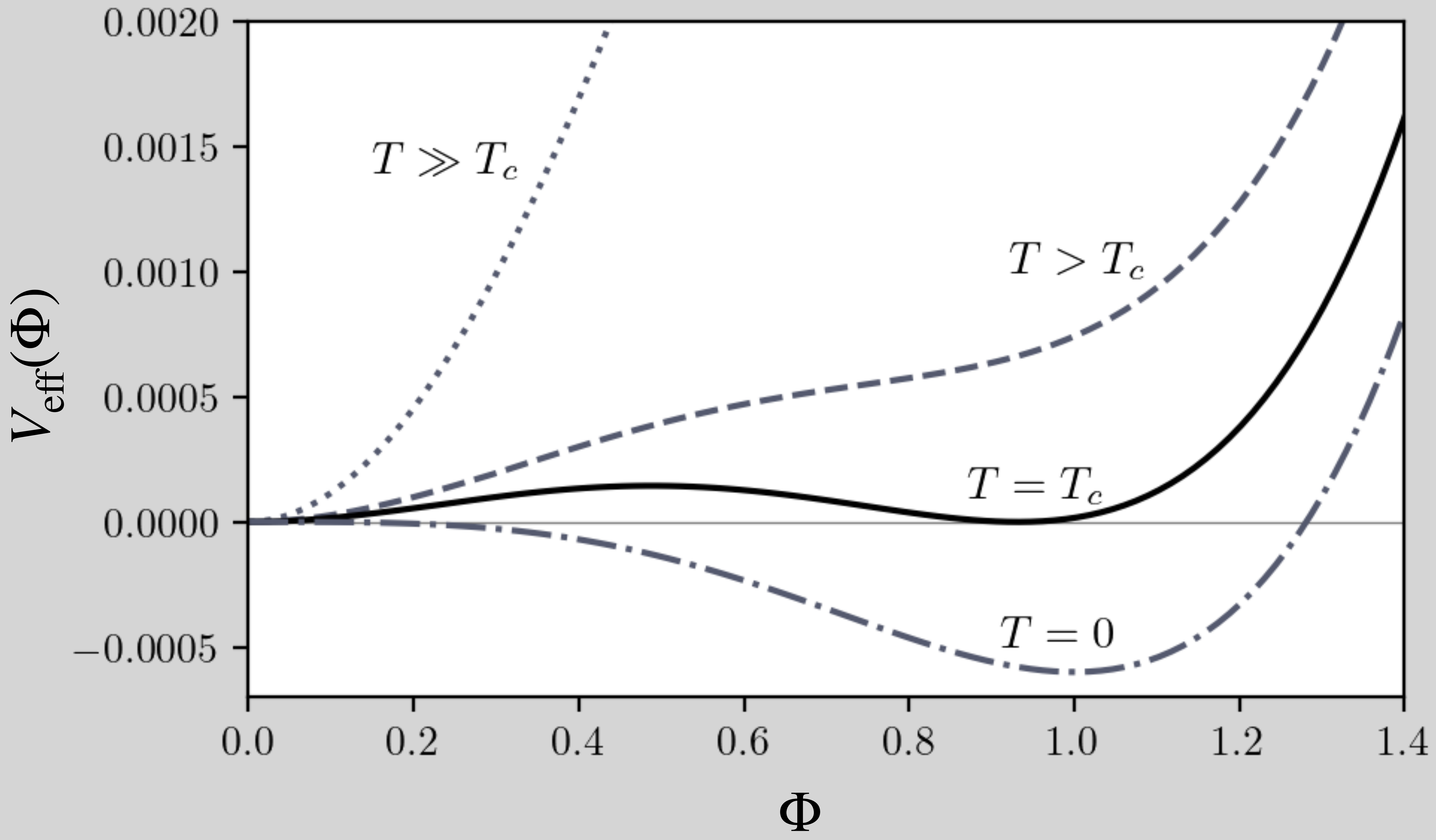
Symmetry-breaking scalar + Yukawa fermion

- 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

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Primordial Black Hole (PBH) Formation

in first-order phase transitions (FOPTs)

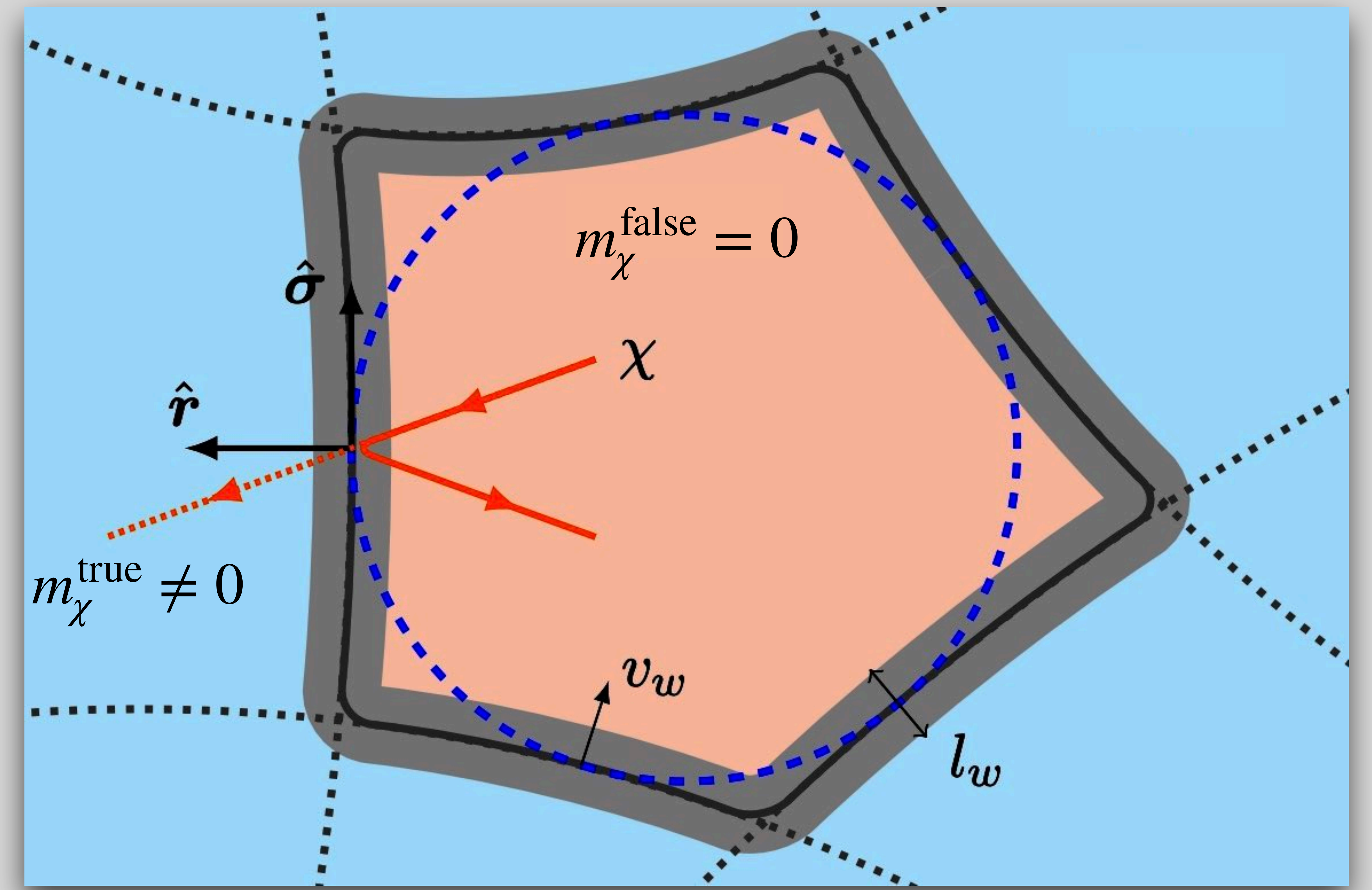
- In FOPTs, stochastic quantum tunneling is responsible for $\langle\Phi\rangle = 0 \to \langle\Phi\rangle \neq 0$
- When tunneling occurs, bubbles of the *new, "true" vacuum nucleate and expand*
- Particles may be unable to penetrate bubble walls into the true vacuum
- As the FOPT completes, trapped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

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]

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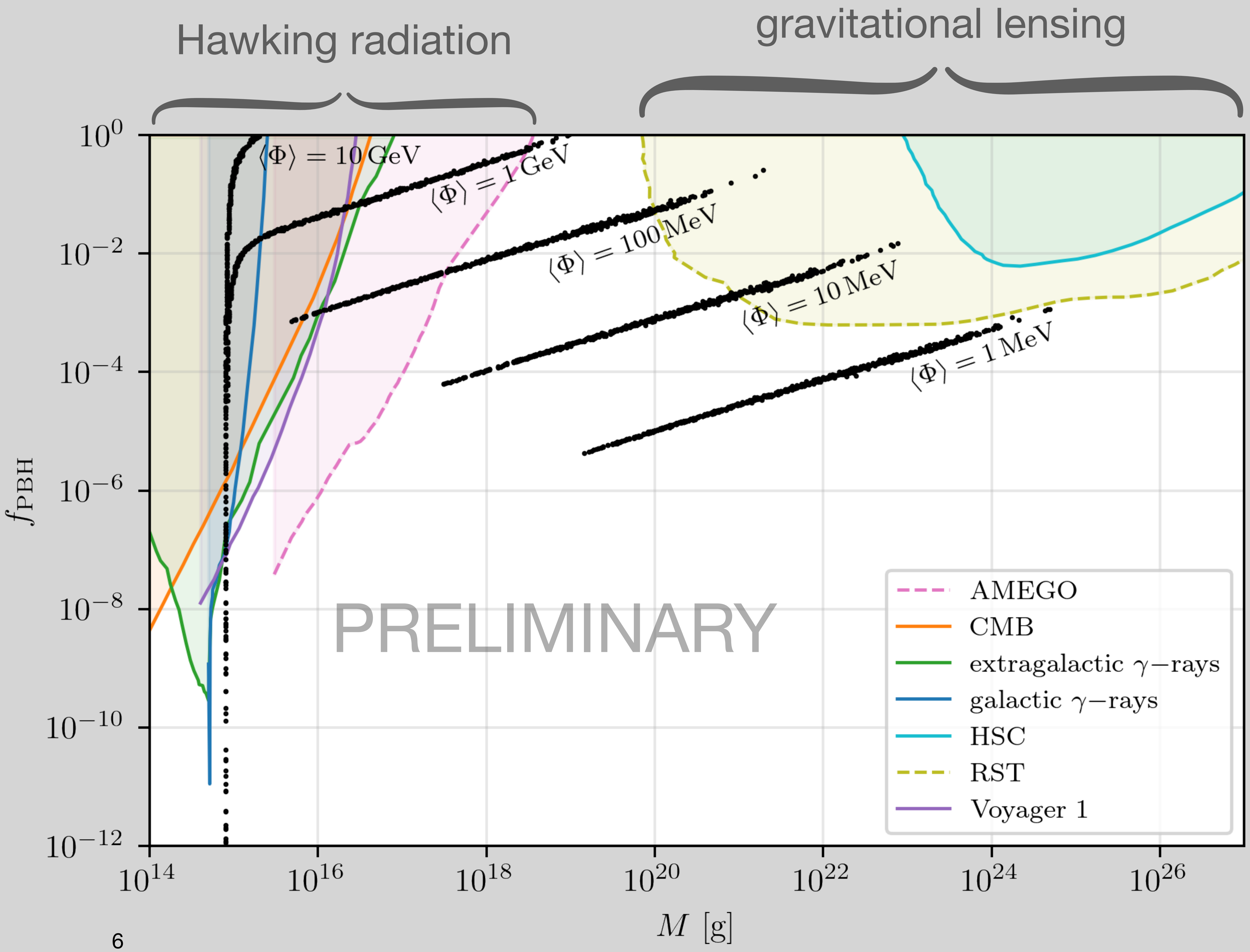
f_{PBH}

Fraction of dark matter comprised of compact objects

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



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Gravitational Waves (GW)

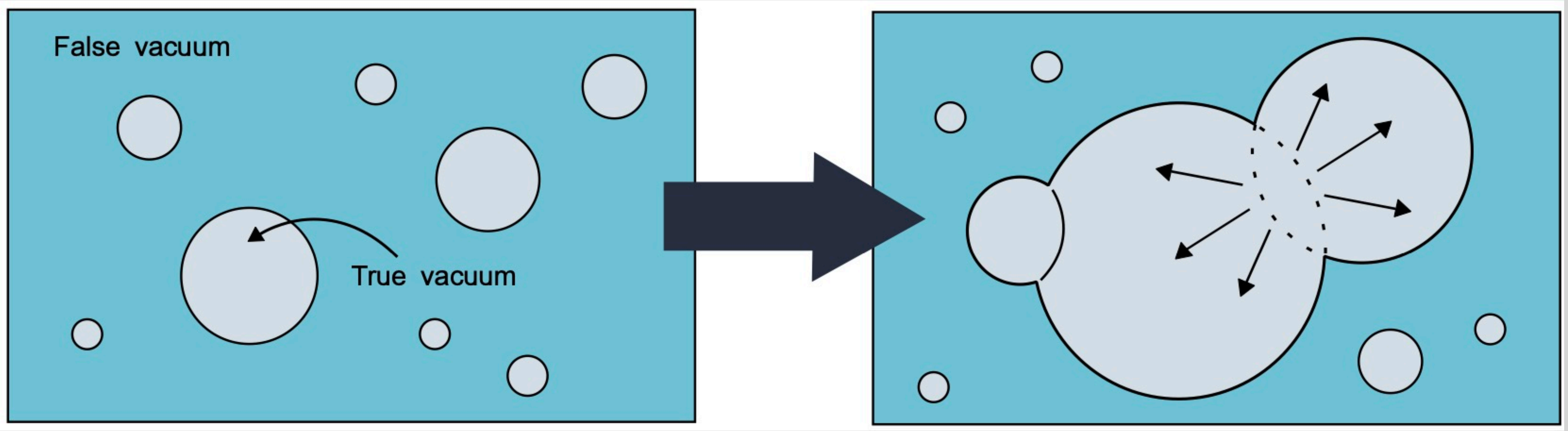
Gravitational Waves (GW) Production

- FOPTs produce **stochastic GW backgrounds** mainly due to

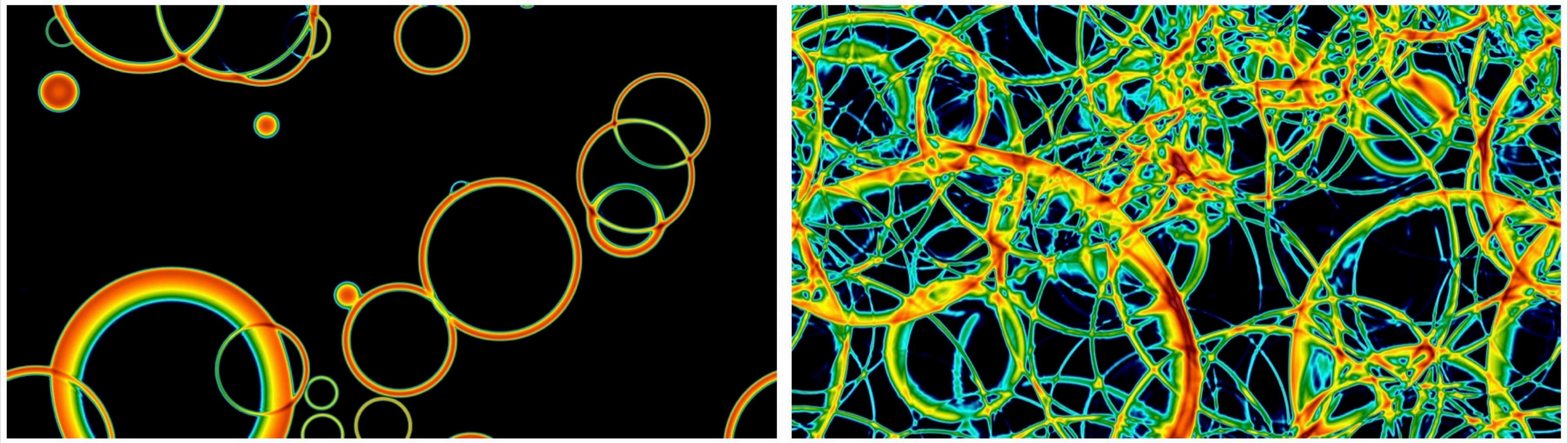
  1. sound waves in the plasma
  2. bubble wall collisions
  3. magnetohydrodynamic turbulence

- 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]

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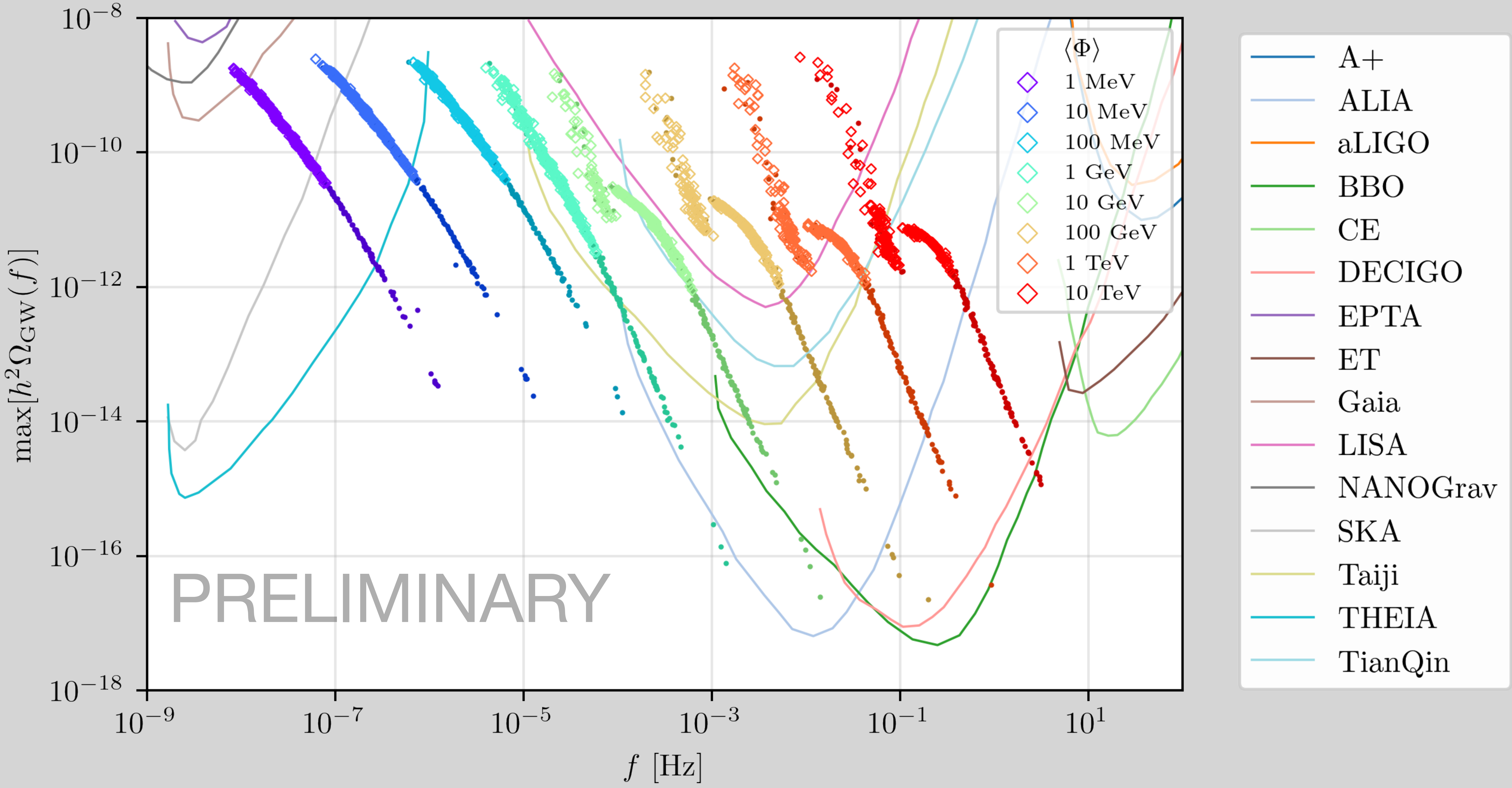
Gravitational Waves (GW) Signal

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**

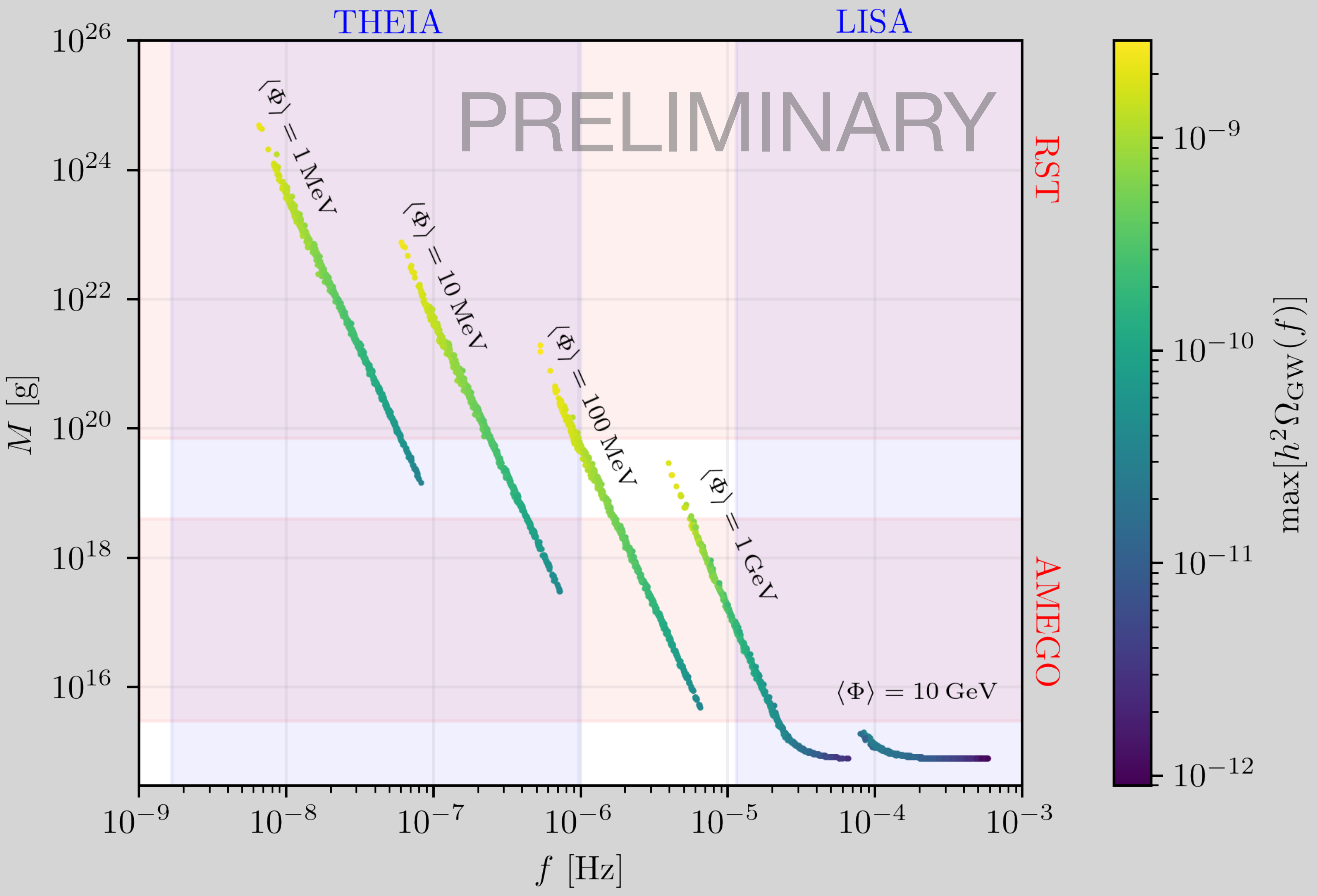
diamonds: $m_\chi > T_{\rm PT}$

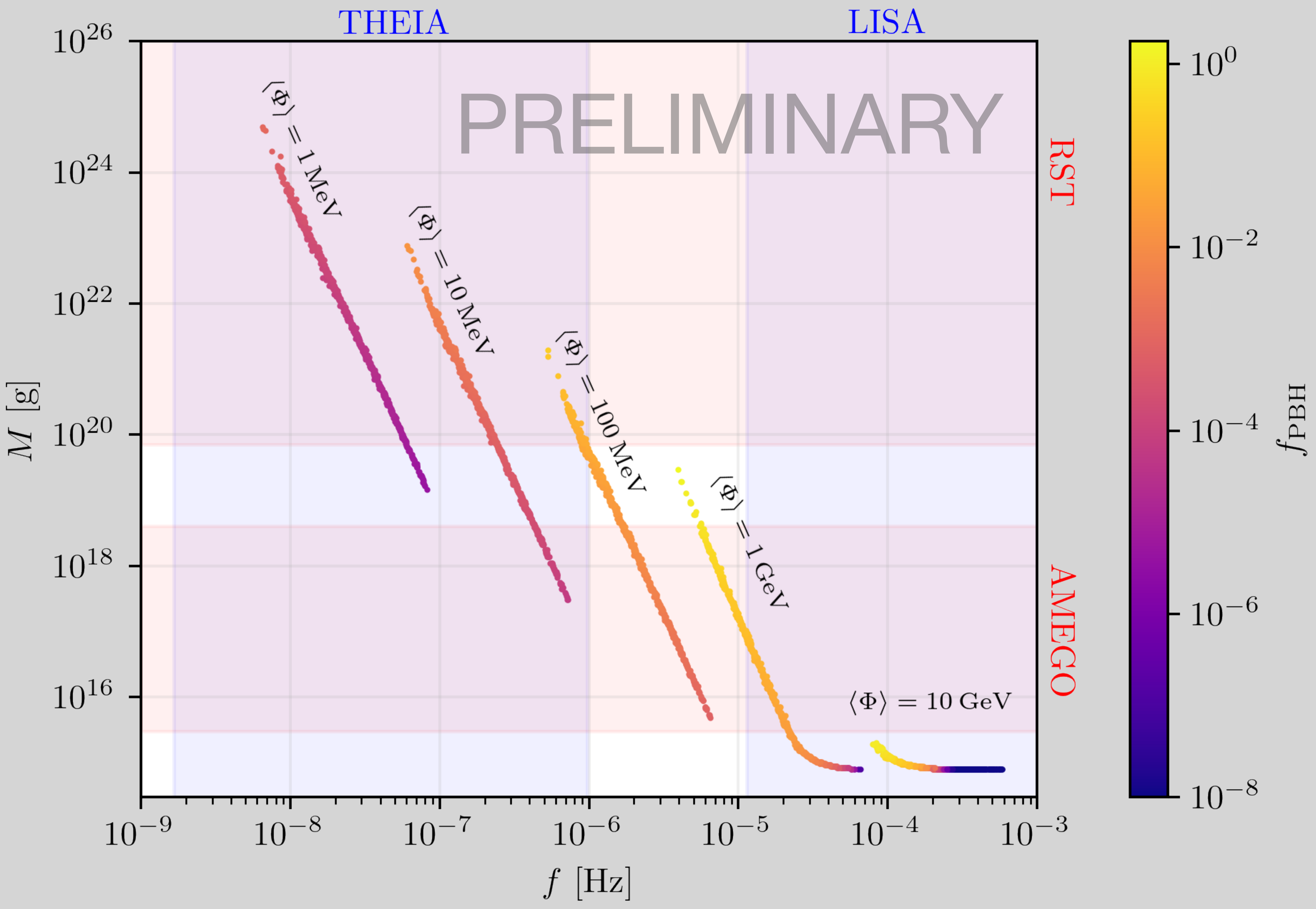


Multi-Messenger Probes

Multi-Messenger Probes

Mixed parameter space



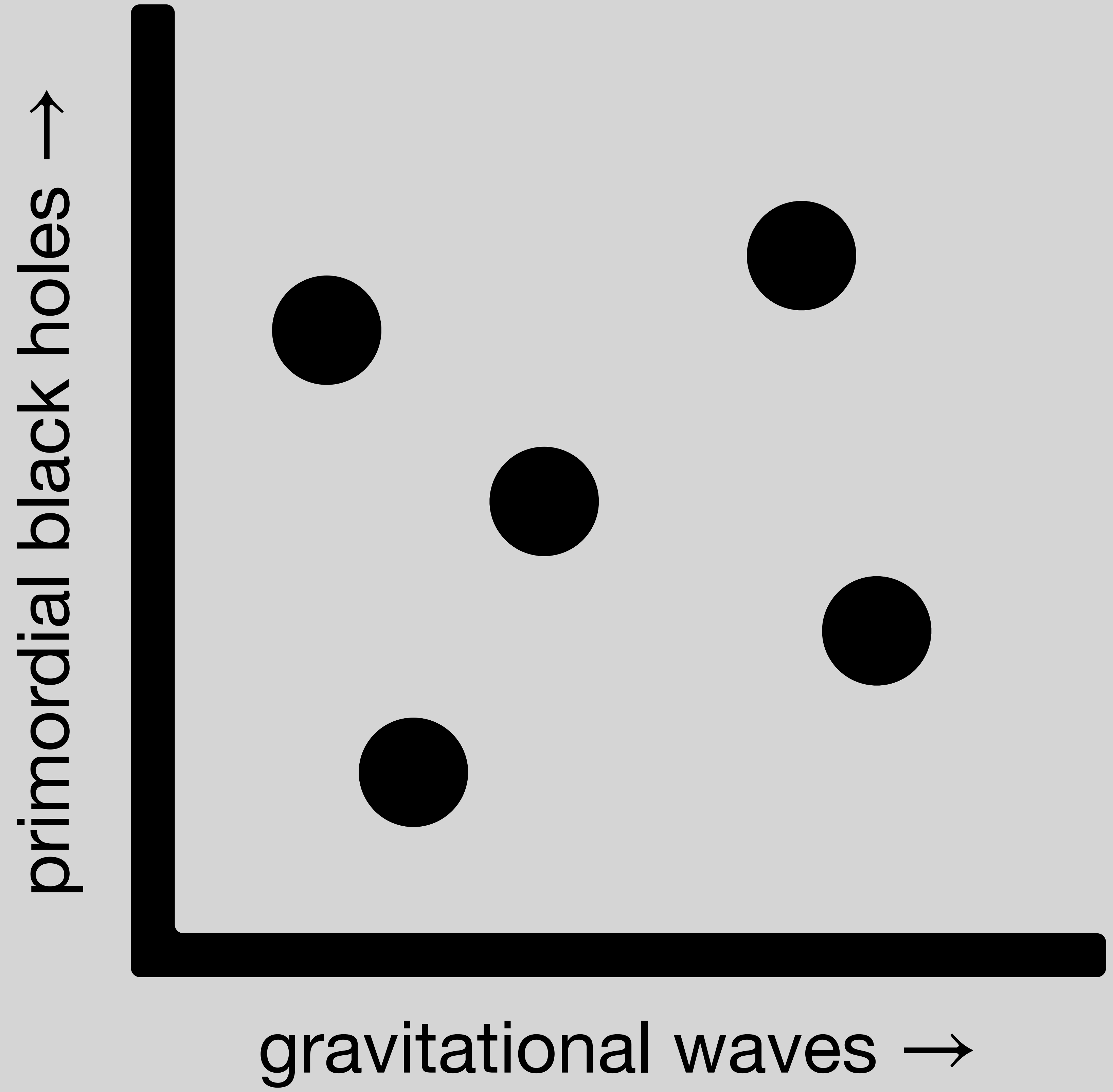


Similar studies:
Marfatia, Tseng 2022
Xie 2023

Summary

Multi-messenger probes of 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 interactions

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

$$D_\mu = \partial_\mu - \underbrace{ig_s\lambda_\alpha G_\mu^\alpha}_{\mathrm{SU(3)}_c} - \underbrace{ig\sigma_j W_\mu^j - ig'YB_\mu}_{\mathrm{SU(2)}_L \times \mathrm{U(1)}_Y} - \underbrace{ig_{B-L}Q_{B-L}Z'_\mu}_{\mathrm{U(1)}_{B-L}}$$

- 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:

$$\mathscr{L} \supset -\overline{\nu_R^c} Y \nu_R \phi/2$$

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

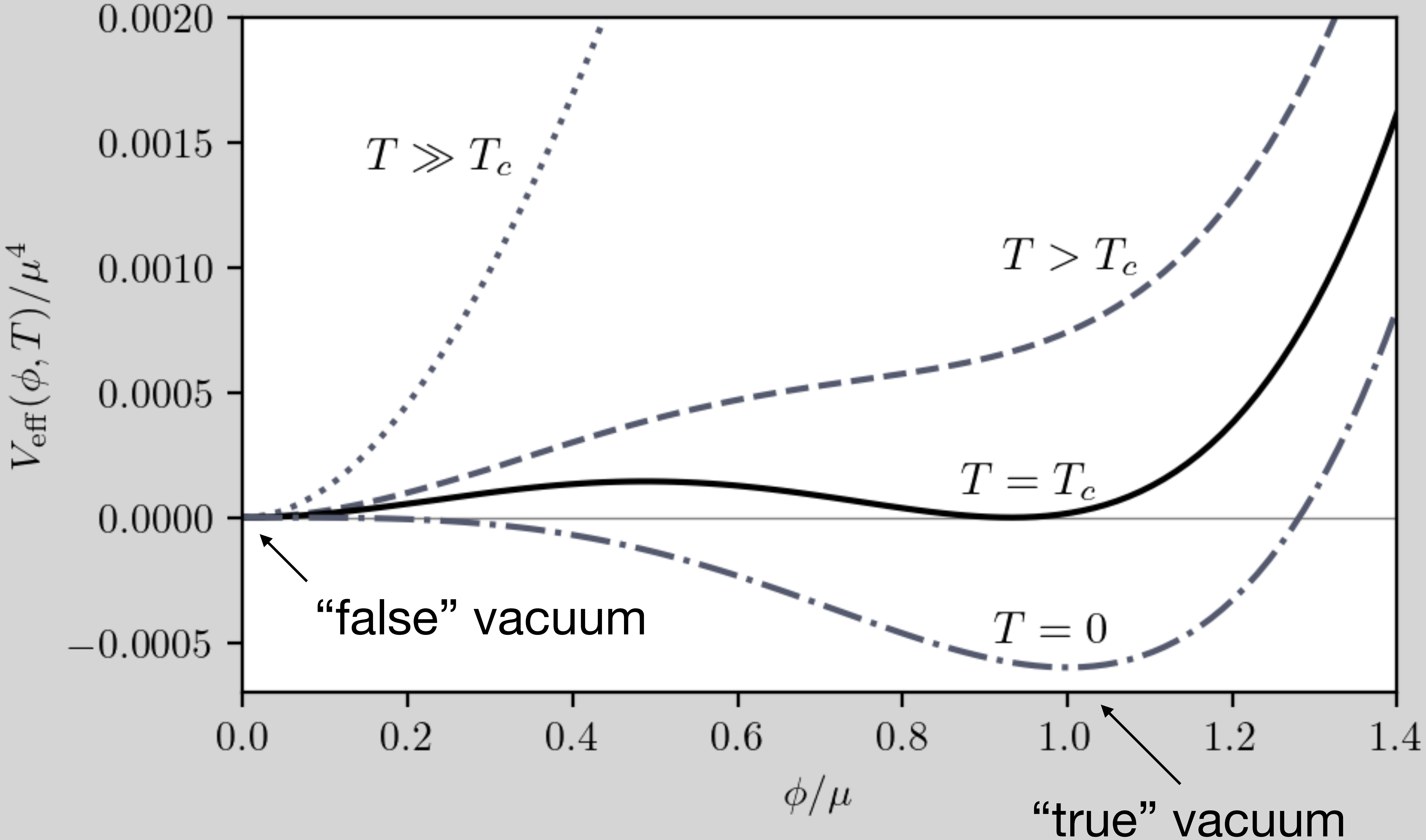
- Solving the RG equations (and therefore the potential) only requires **"two" input parameters** for our theory:

$$\underset{\substack{B-L\text{ coupling}\\ \text{strength}}}{\alpha_{B-L}(0)}, \qquad \underset{\substack{\text{right-handed}\\ \text{neutrino mass}}}{\alpha_Y(0)}$$

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



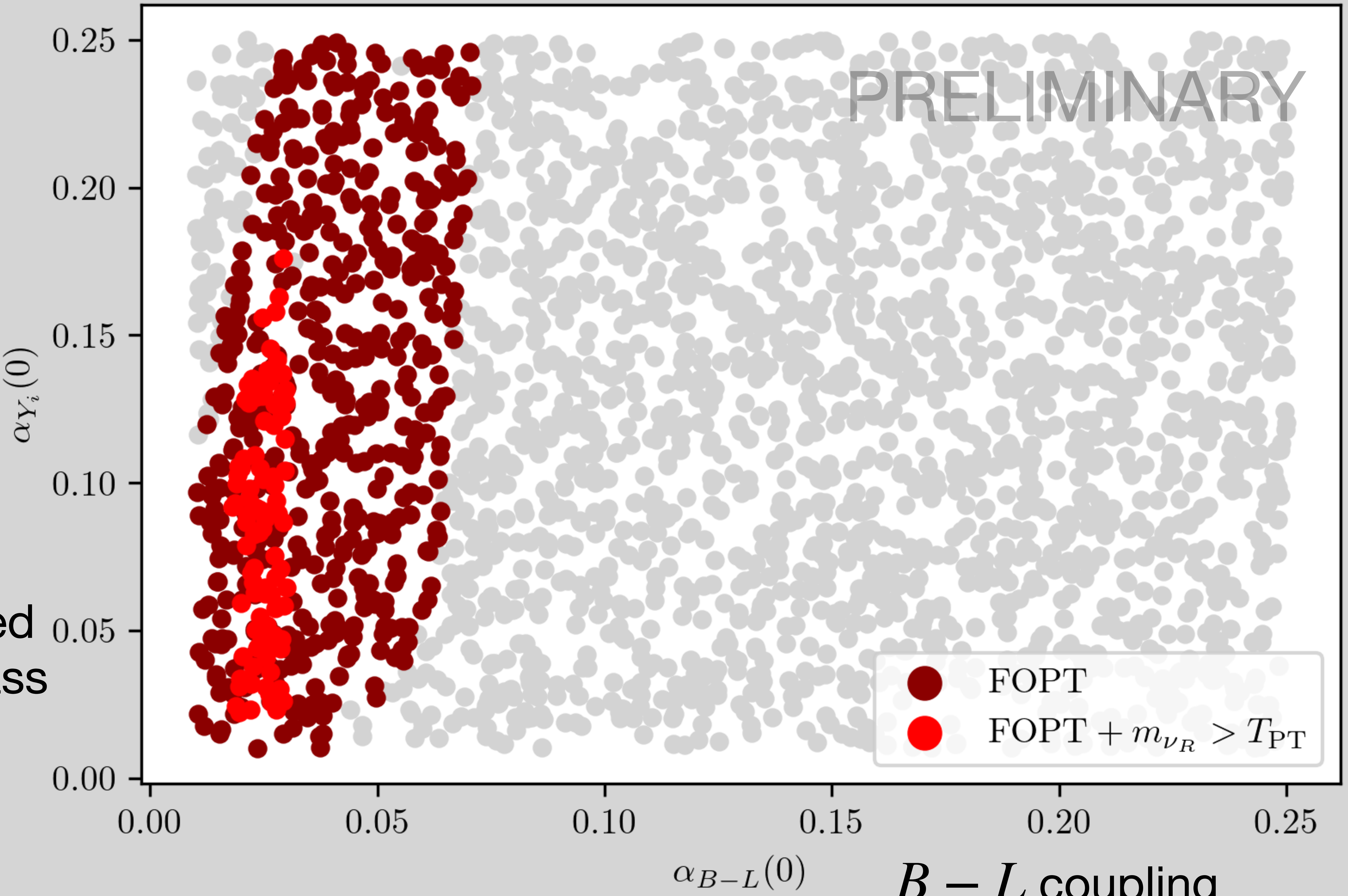
“false” vacuum

“true” vacuum

Minimal $B - L$ Model

First-order phase transition scan

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



right-handed neutrino mass

$B - L$ coupling strength

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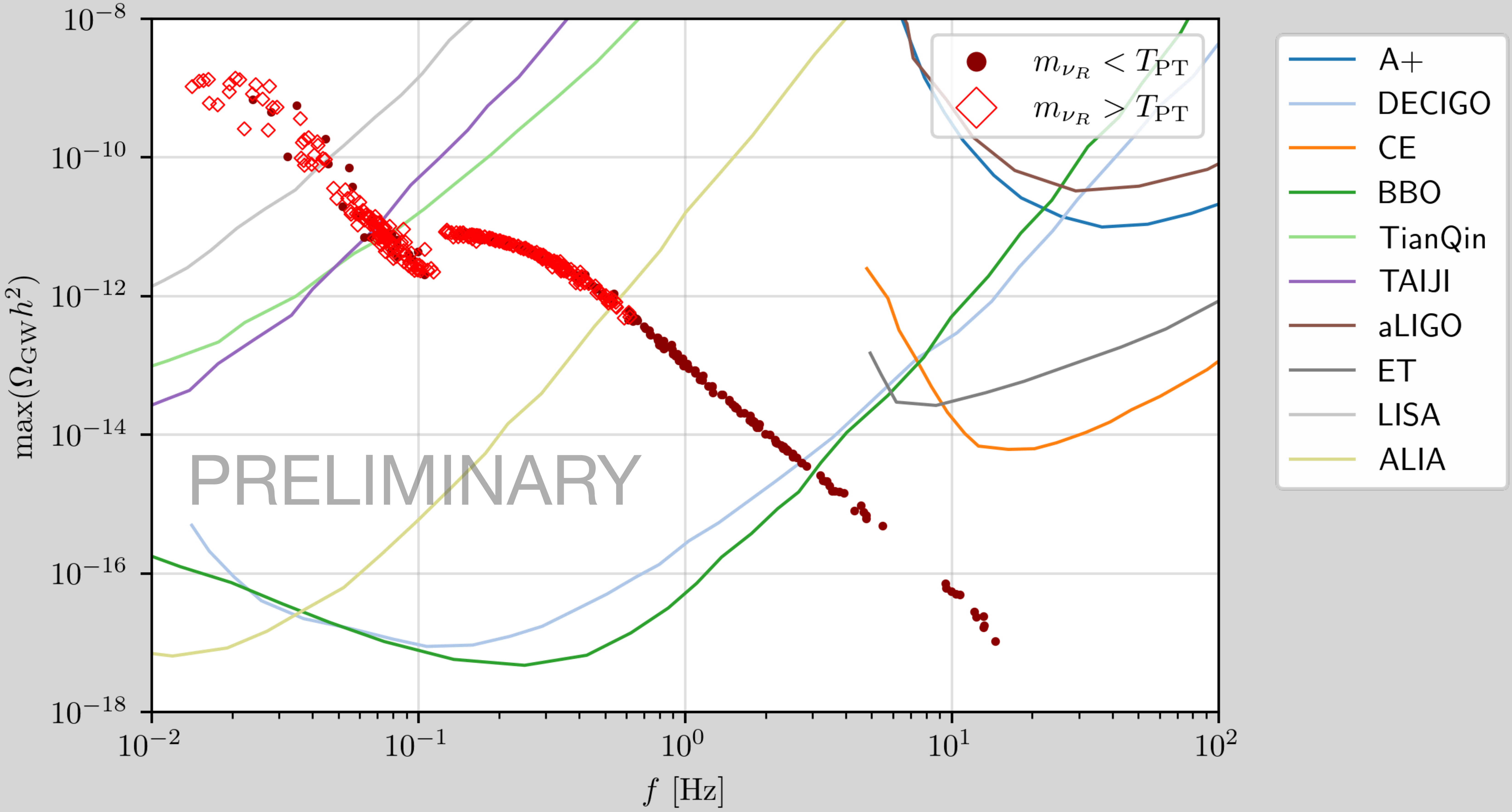
Gravitational Waves Signal

Peaks of GW energy

- <u>Red</u>: successful FOPT
- <u>Light red</u>: favorable for PBH formation
- <u>Colored lines</u>: *projected* experimental sensitivities
- **Discontinuity is not physical**

$\langle\Phi\rangle$ = 10 TeV



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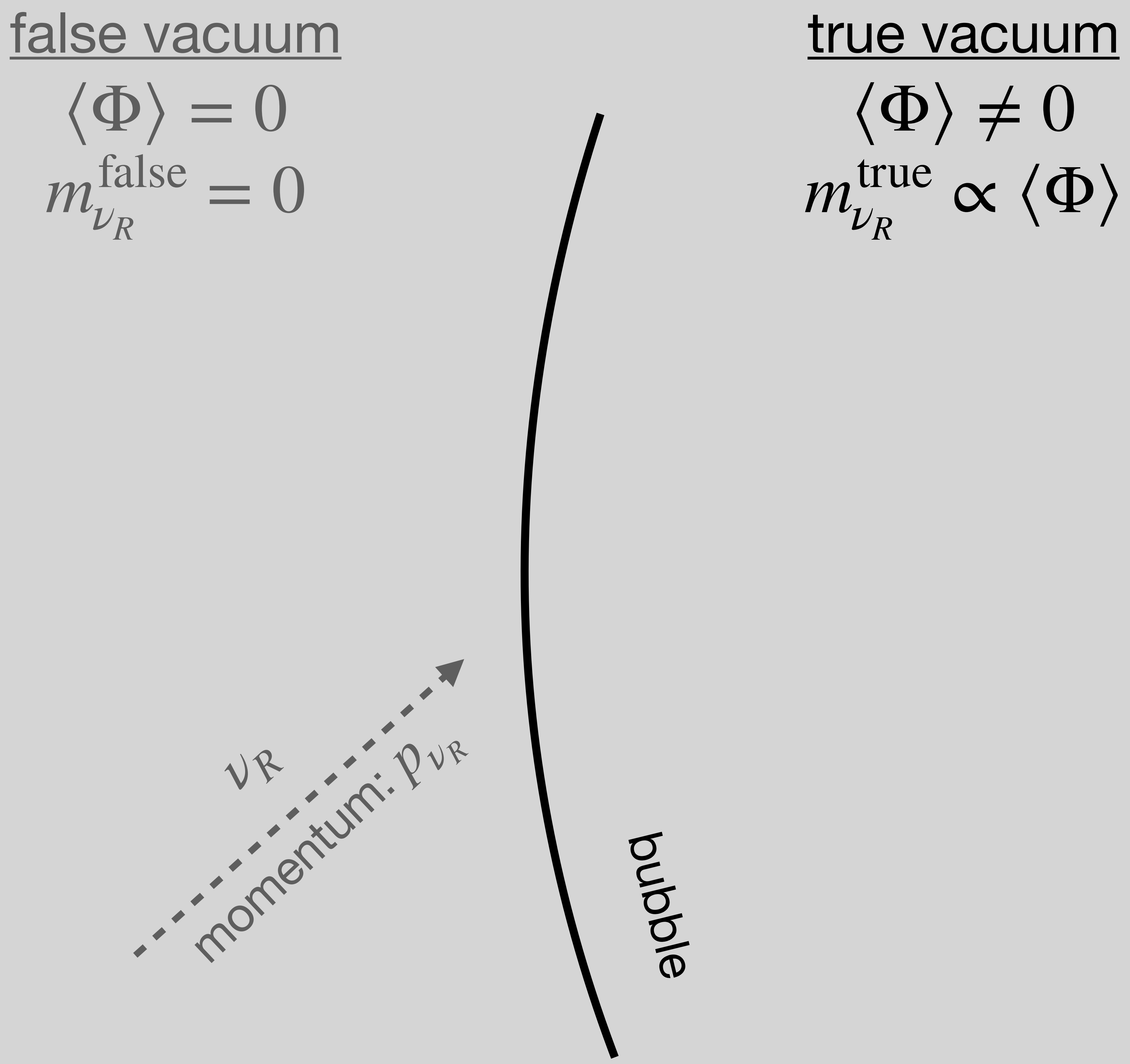
Challenges of PBH Formation

Trapping particles

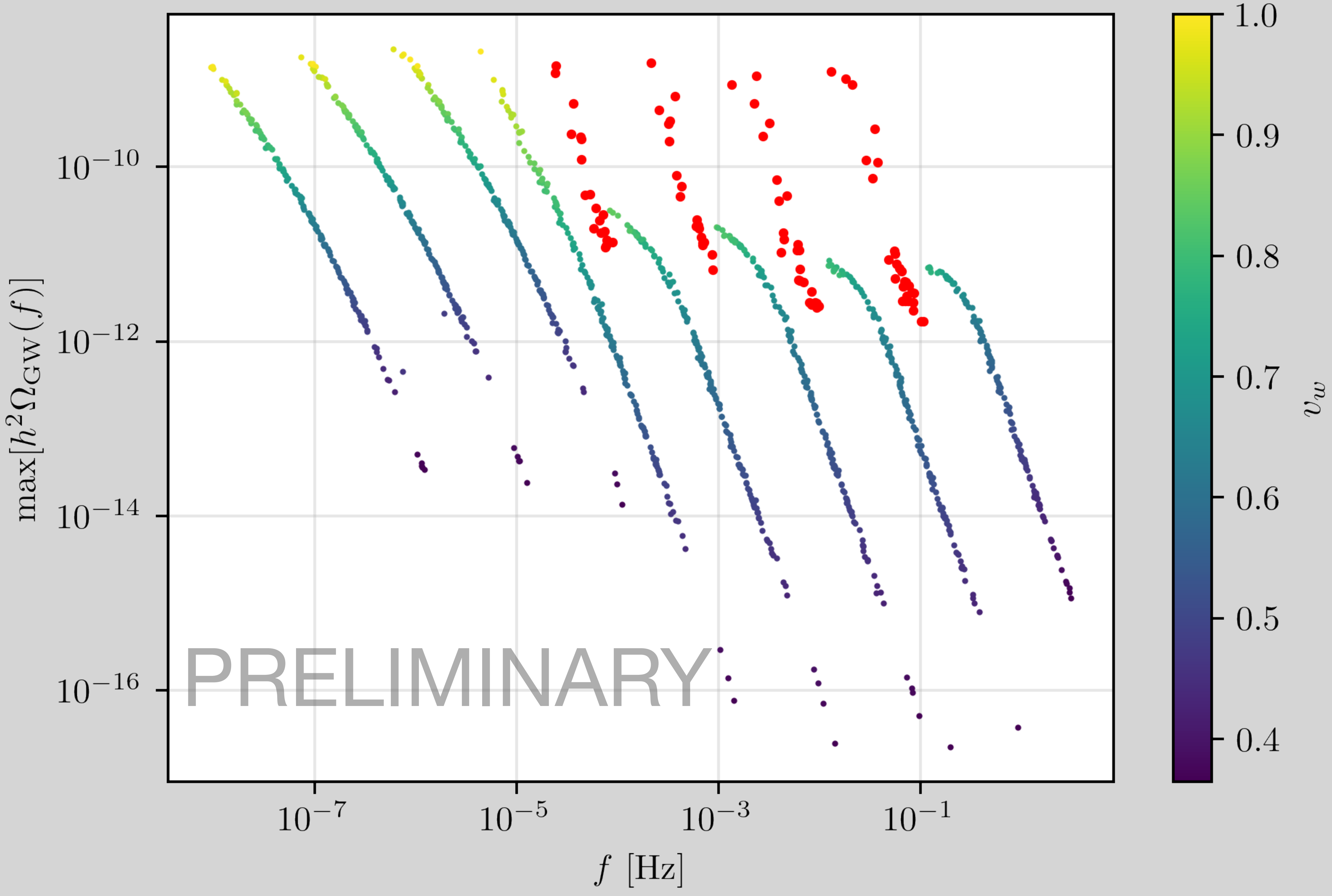
- Suppose Φ develops a nonzero VEV $\langle\Phi\rangle$
- Suppose fermions ν_R acquire mass from Φ interactions via Higgs mechanism
- Energy conservation: particles can cross bubble walls if they have sufficient momentum to overcome the mass gap.
- To trap enough particles for PBH formation, $m_{\nu_R}^{\text{true}} > p_{\nu_R}$
  - **Or,** $m_{\nu_R}^{\text{true}} \gtrsim T_{\text{PT}}$



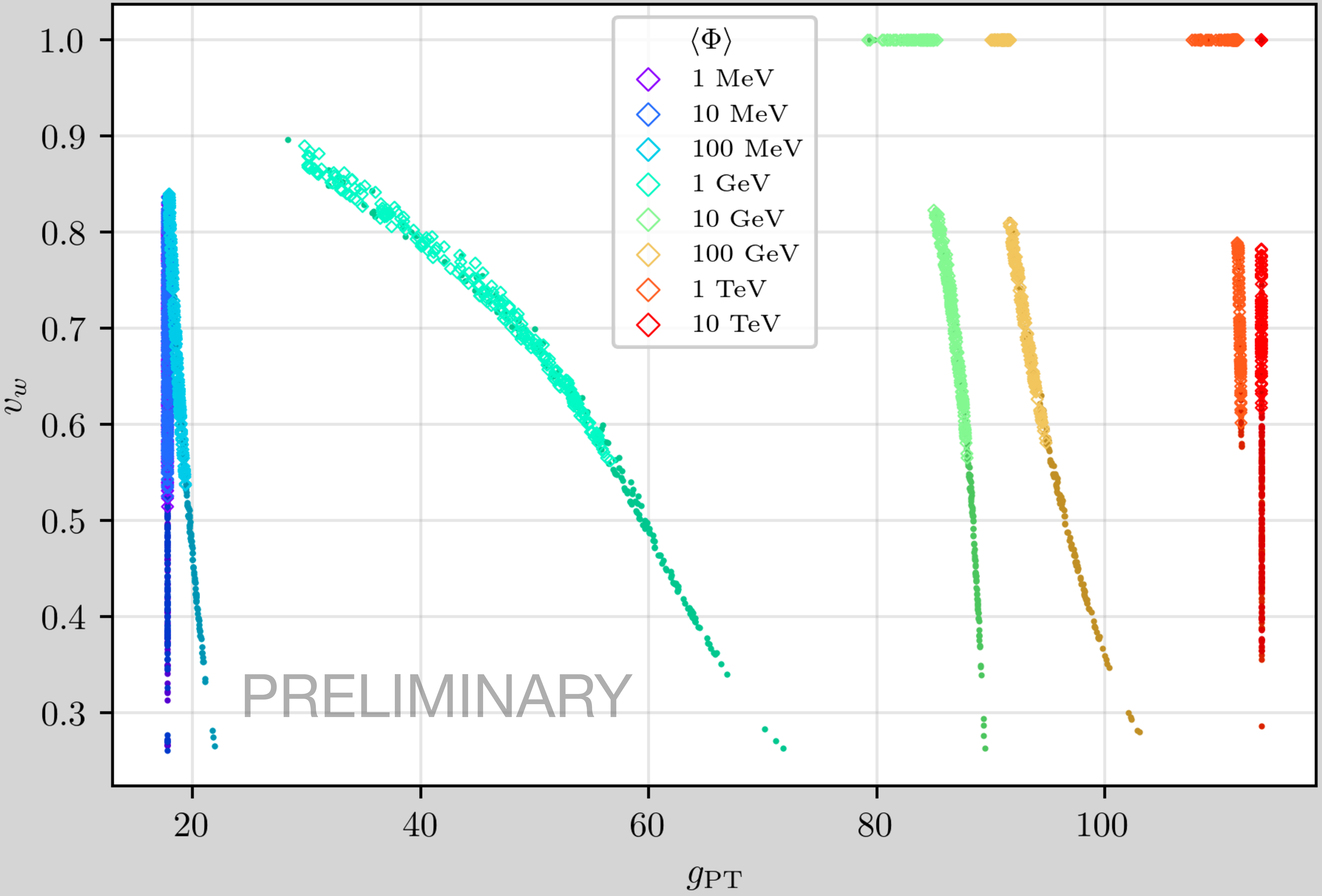
discontinuity

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

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

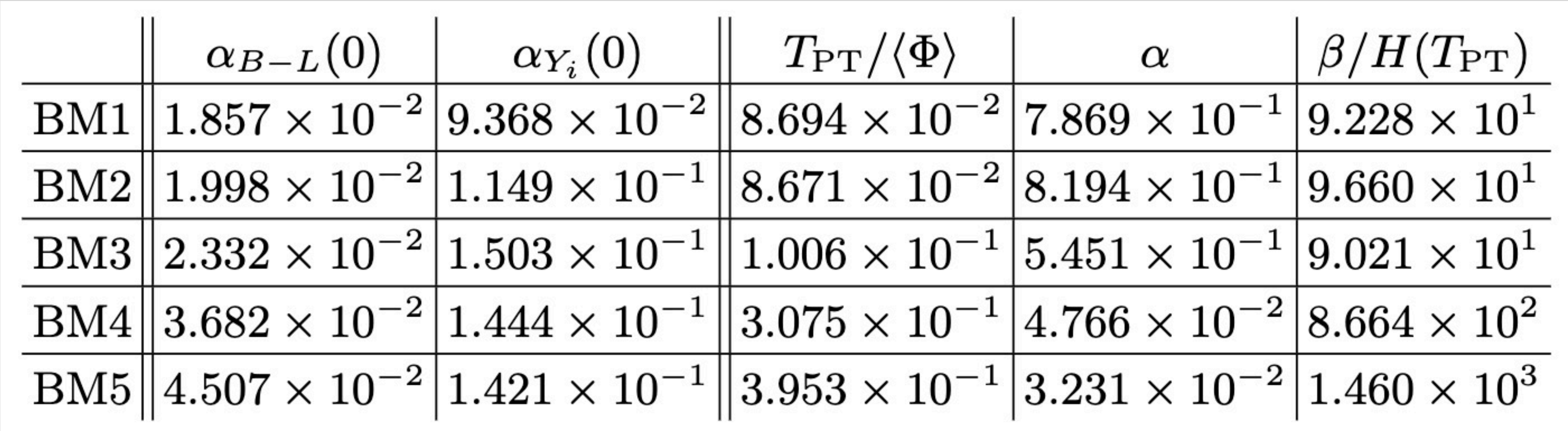


discontinuity

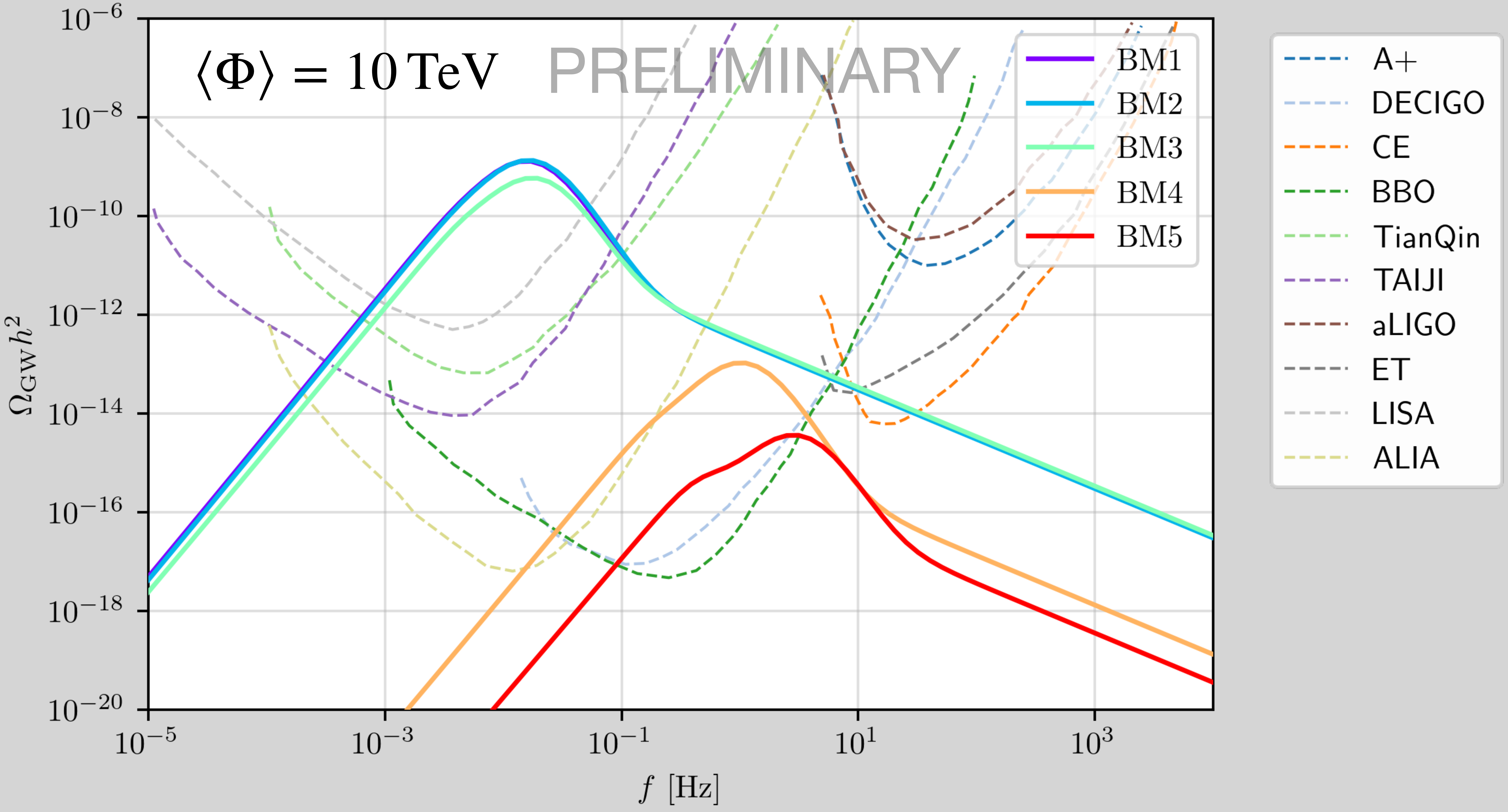


Benchmarks

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}



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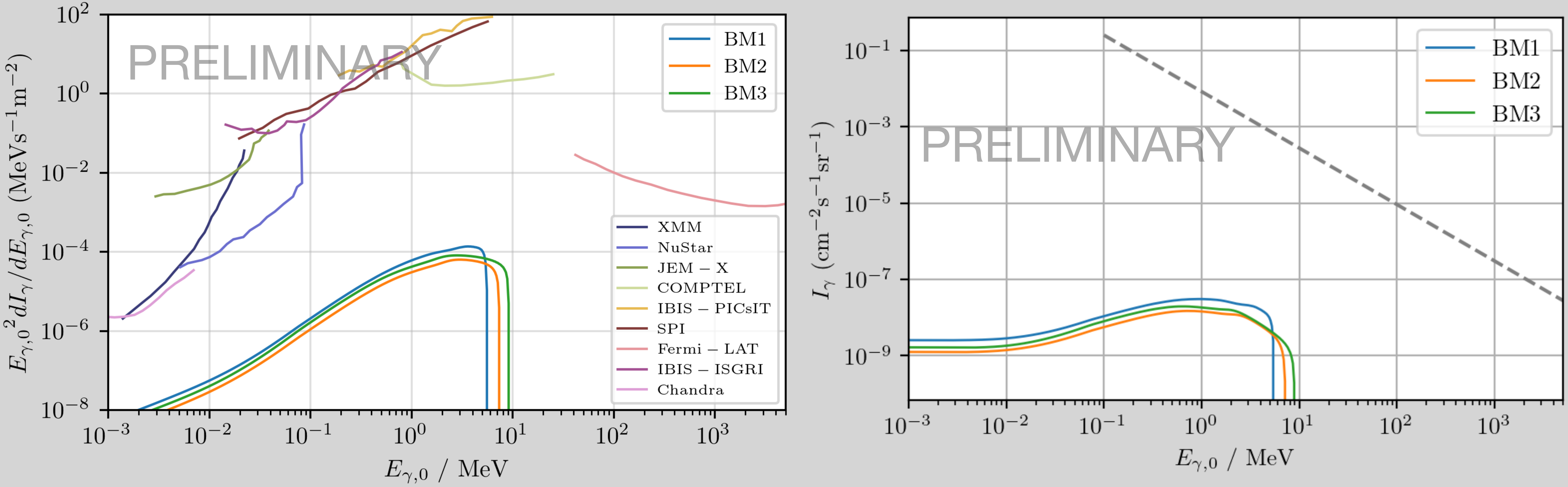
Benchmarks

Hawking radiation



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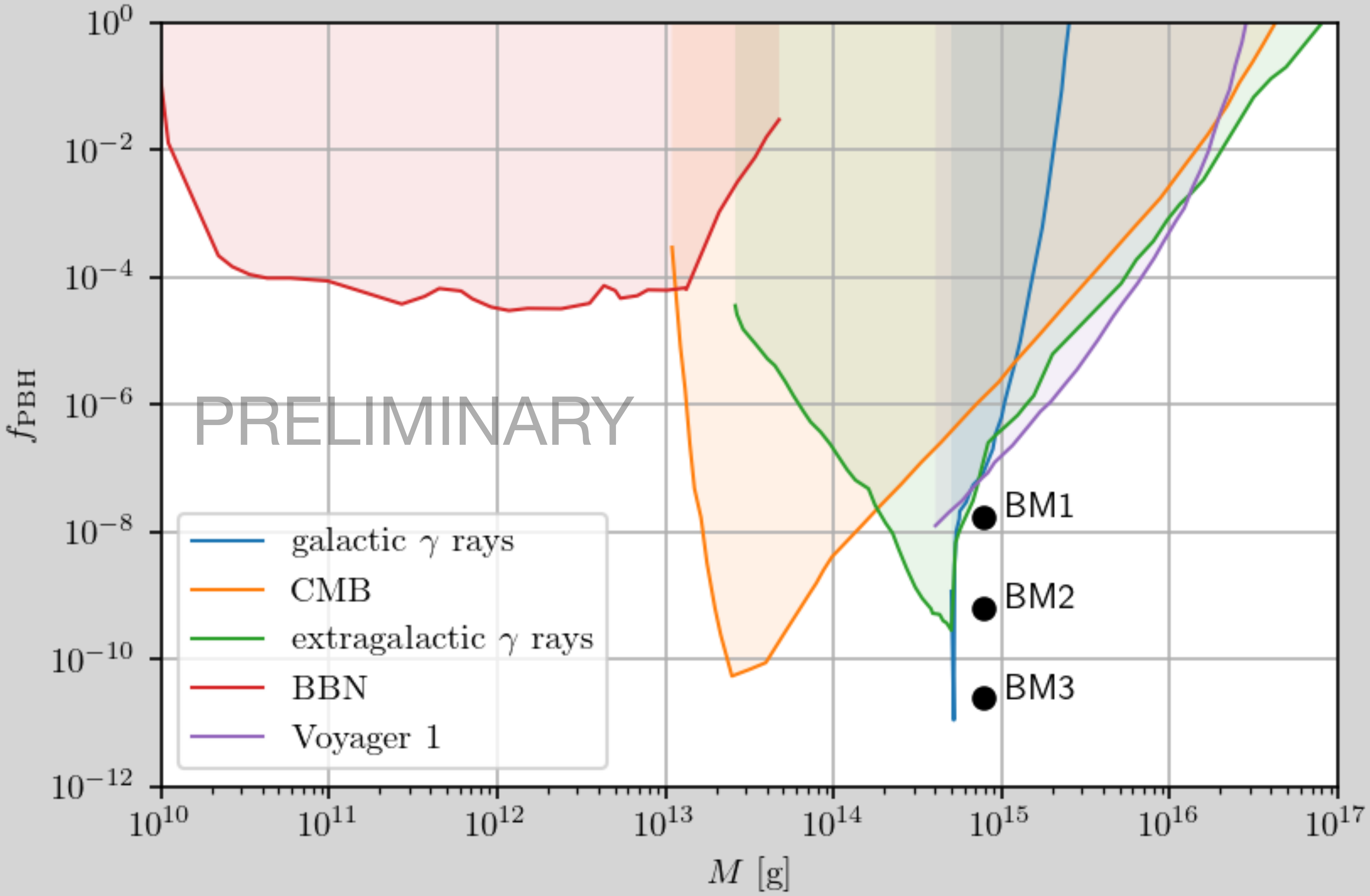
Benchmarks

f_{PBH}



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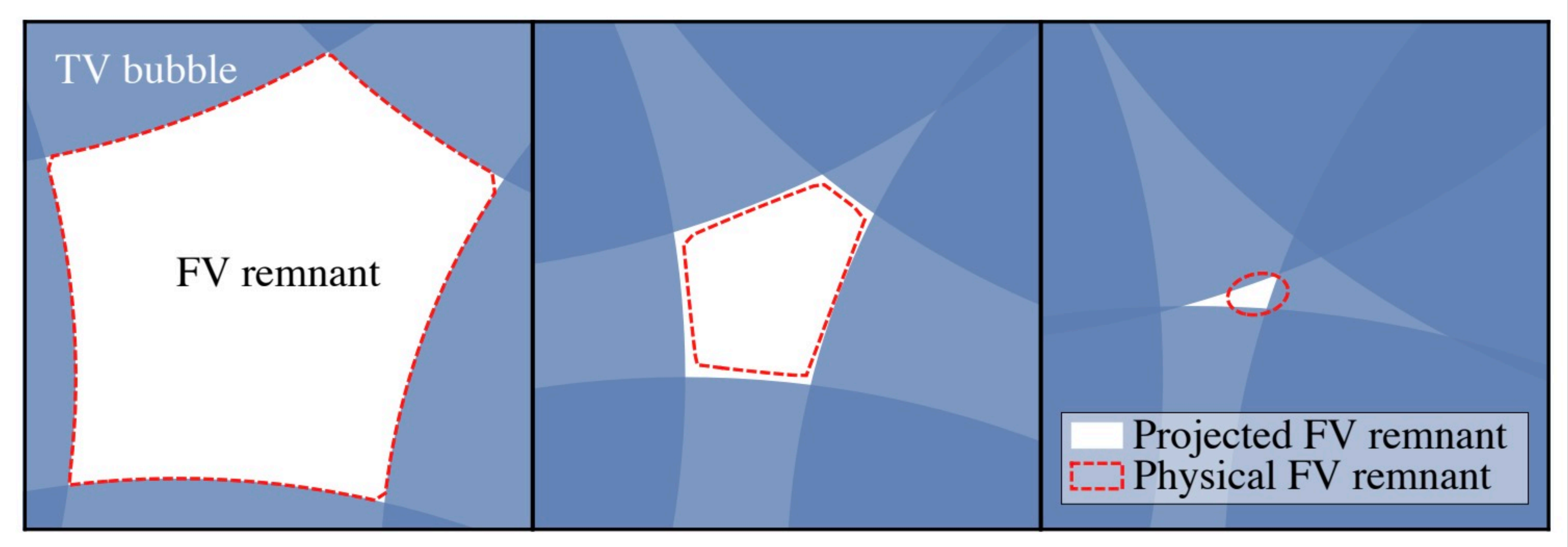
PBH Distribution

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.

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

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

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

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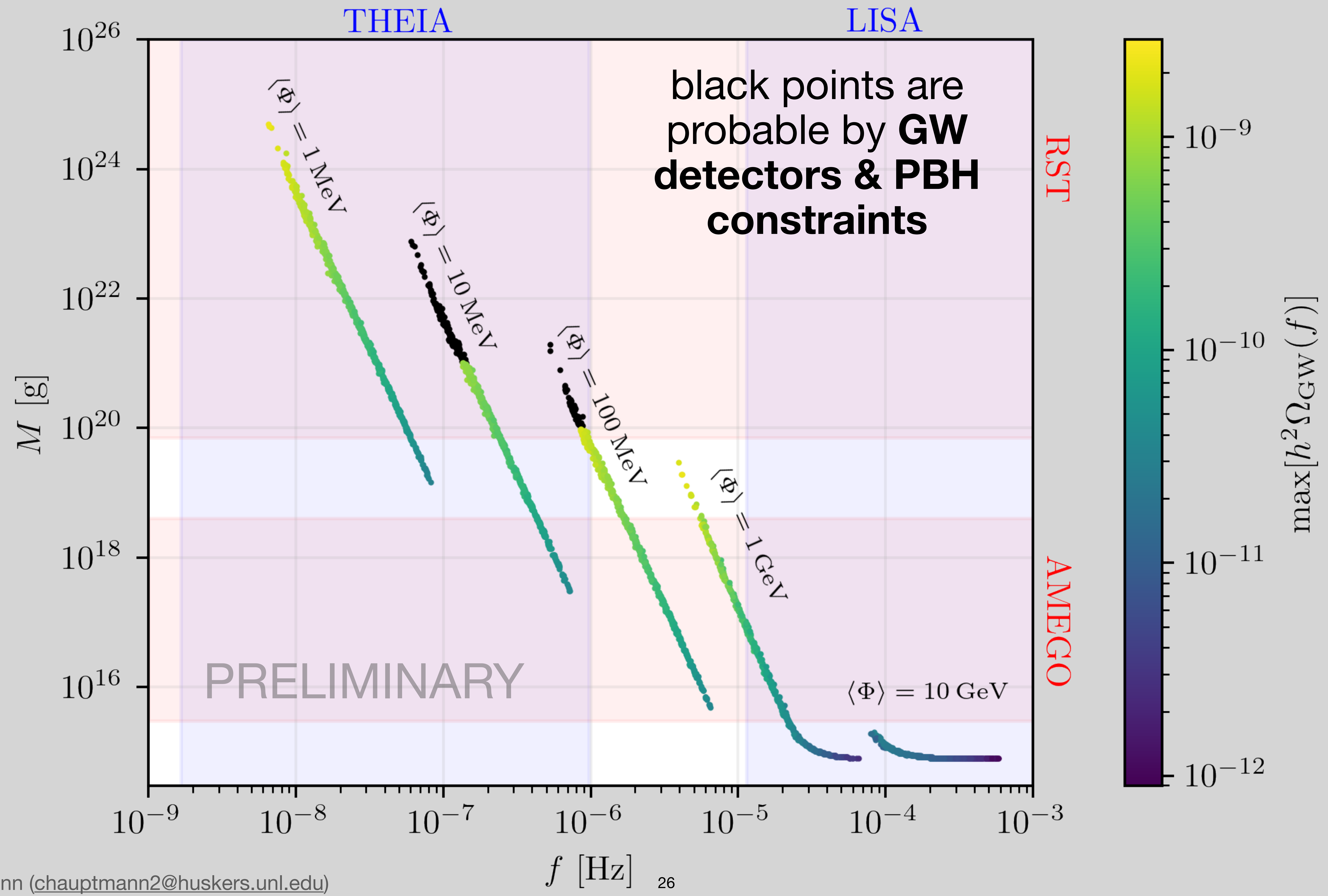
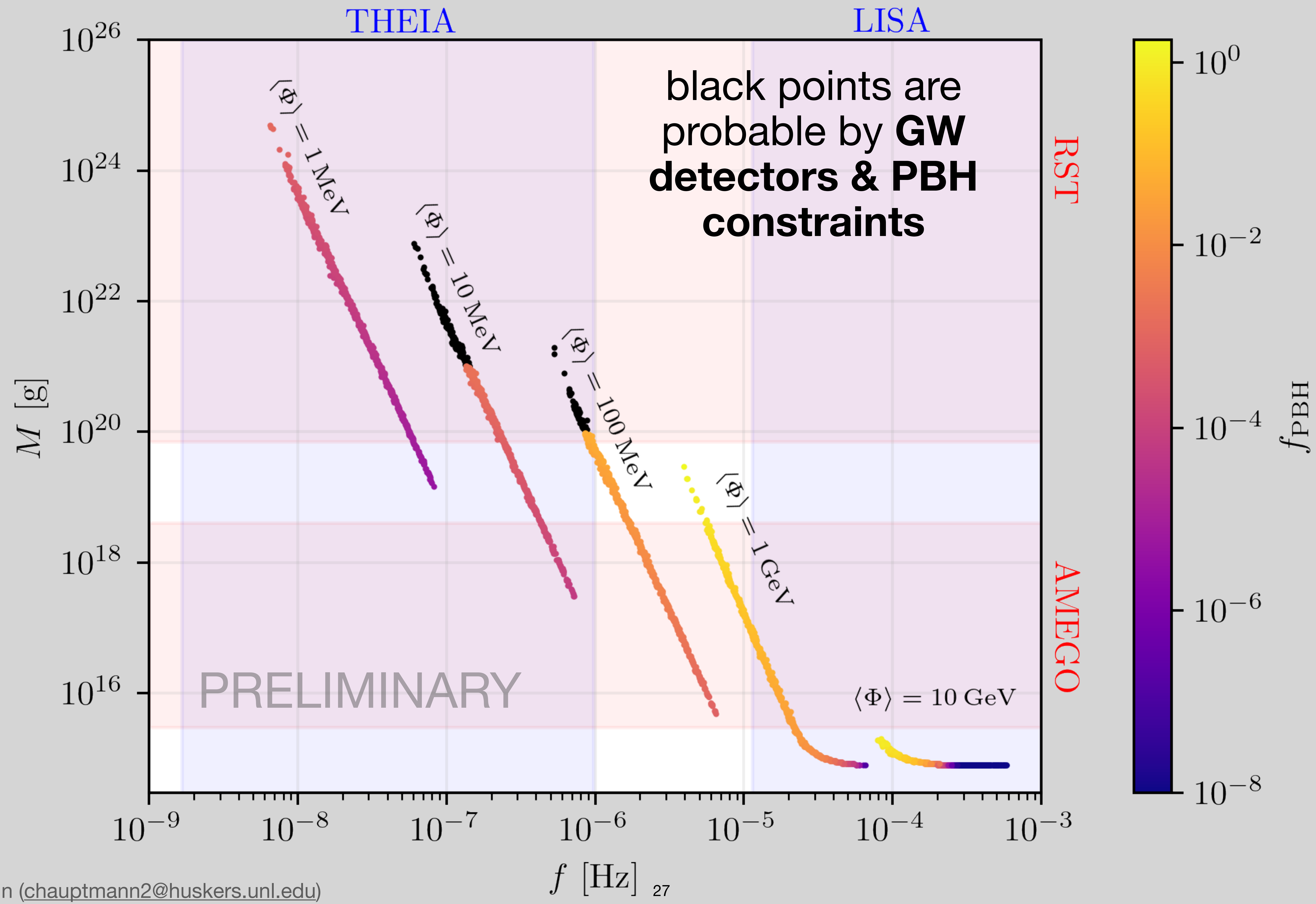


black points are probable by **GW detectors & PBH constraints**



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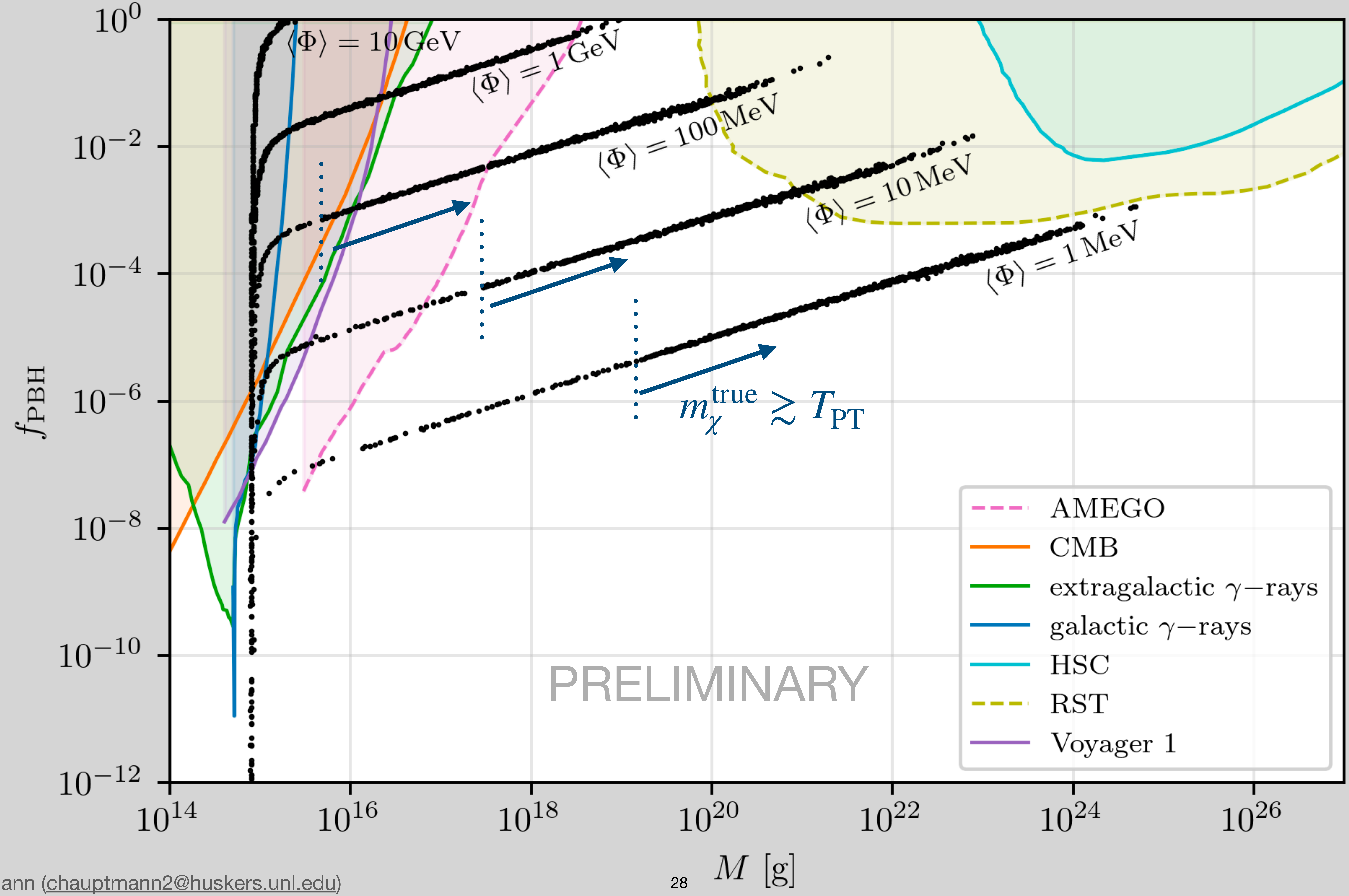

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