



# Pinning down the primordial black hole formation mechanism with *gamma-rays* and *gravitational waves*

Ke-Pan Xie (谢柯盼)

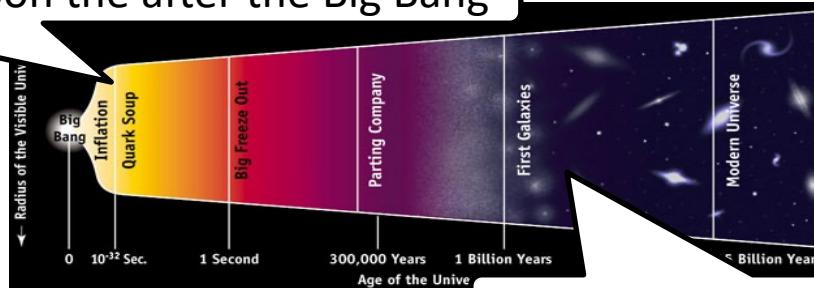
Beihang University

2022.11.9 @第十六届TeV物理工作组学术研讨会

With Tao Xu (U of Oklahoma), 2211.xxxxx

# Primordial black holes (PBHs)

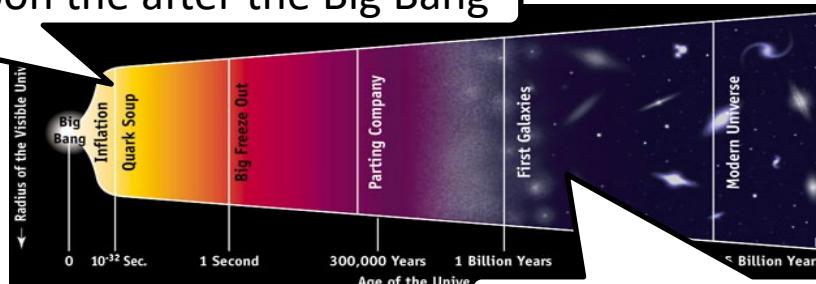
*Primordial*: soon the after the Big Bang



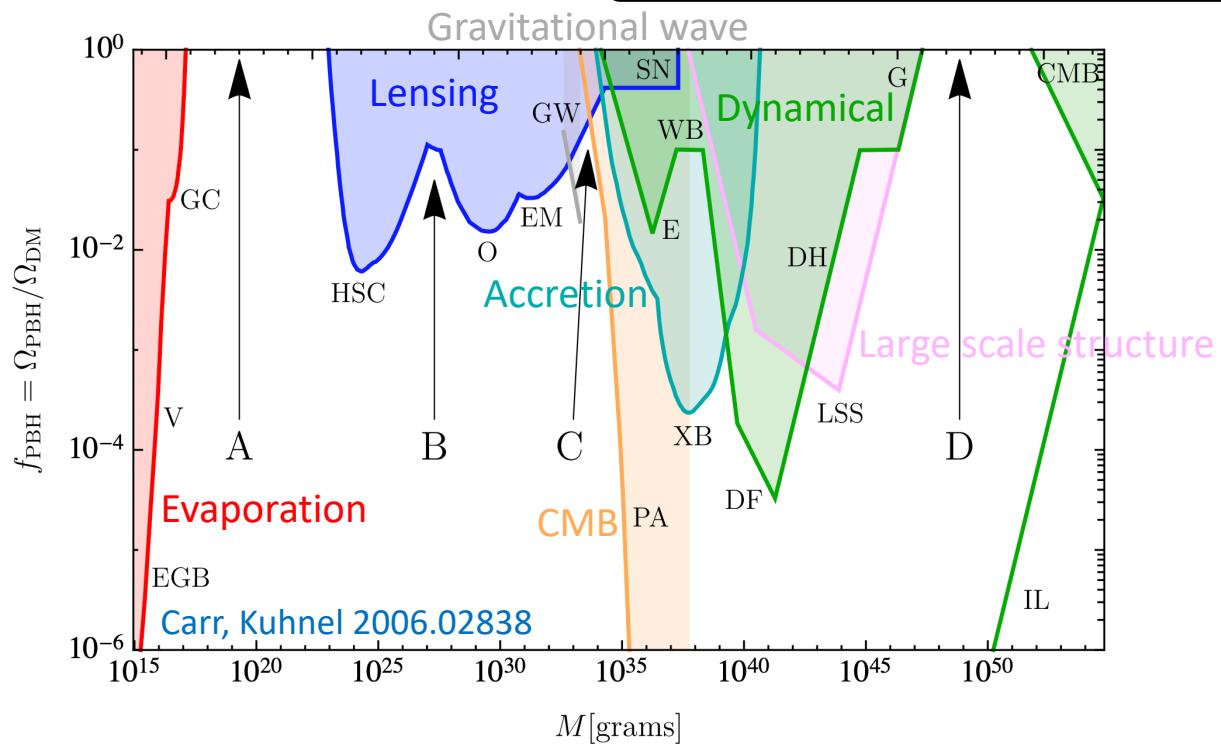
"Normal": from stellar collapse

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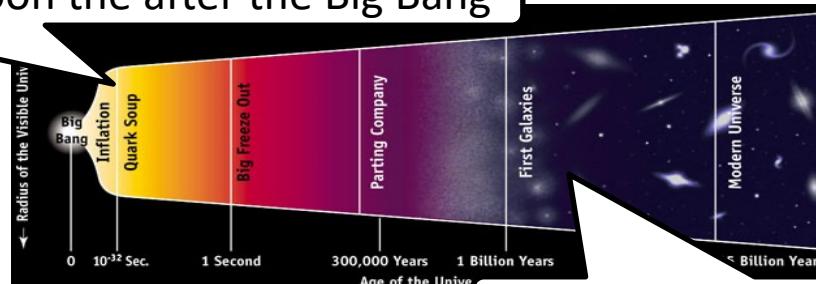


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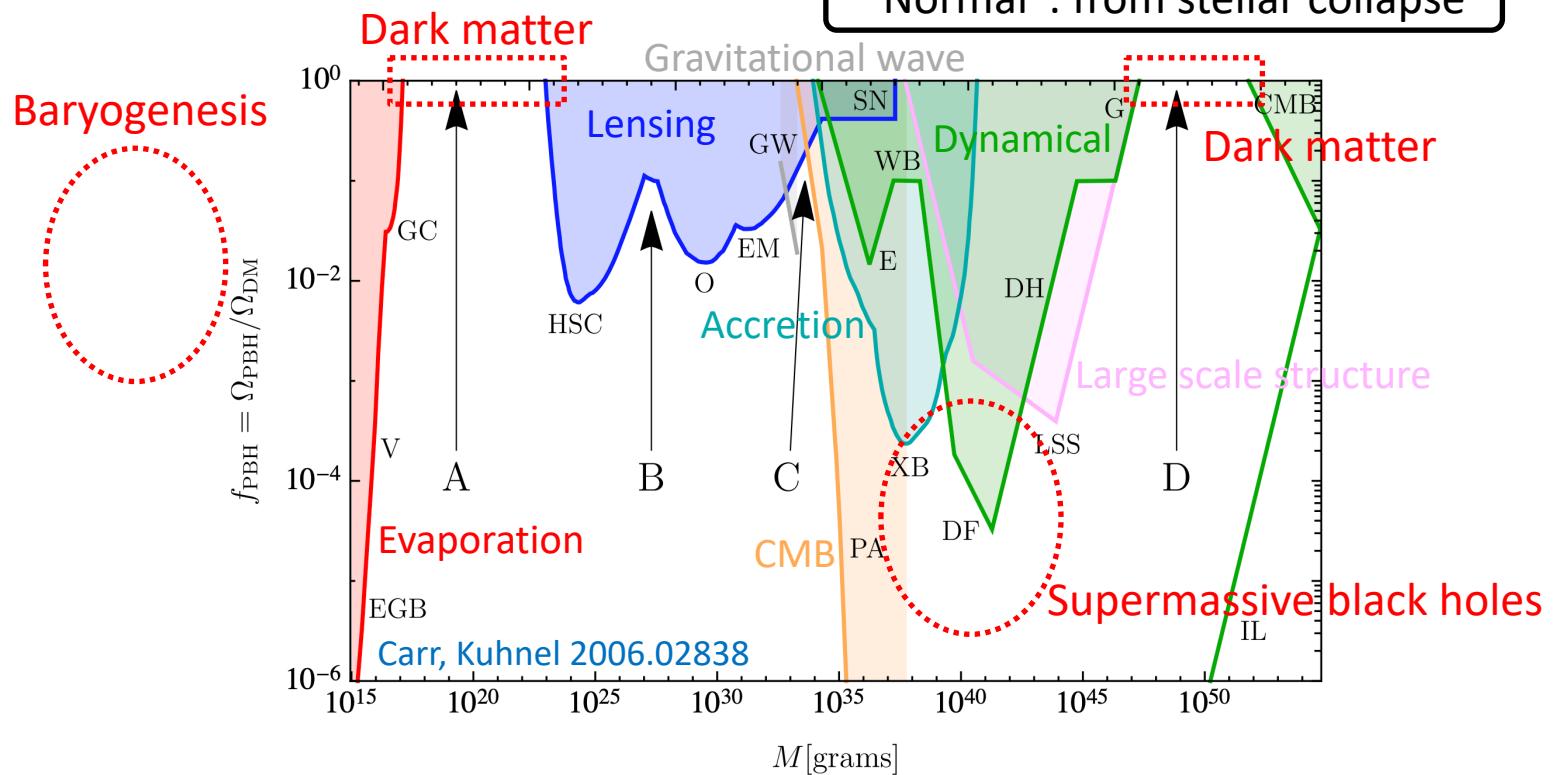


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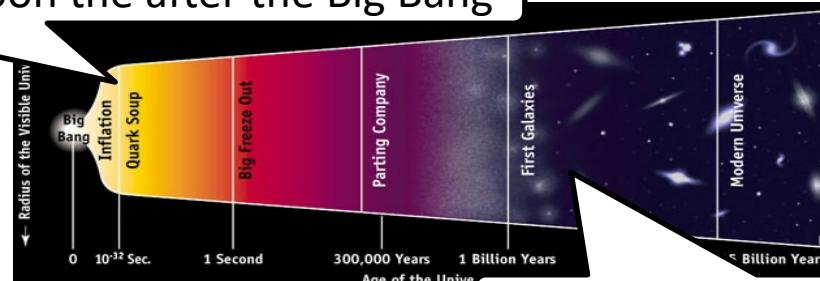


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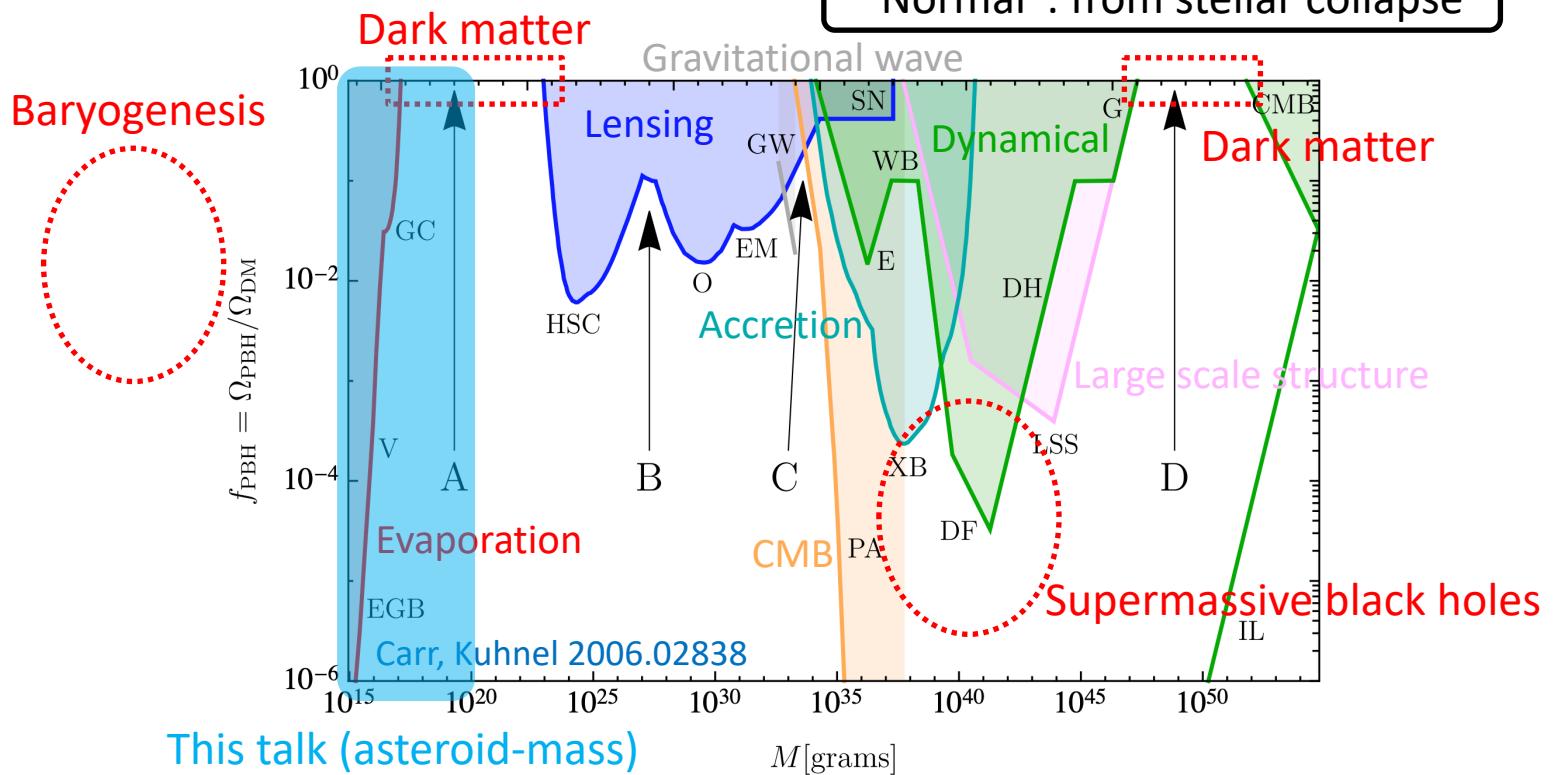


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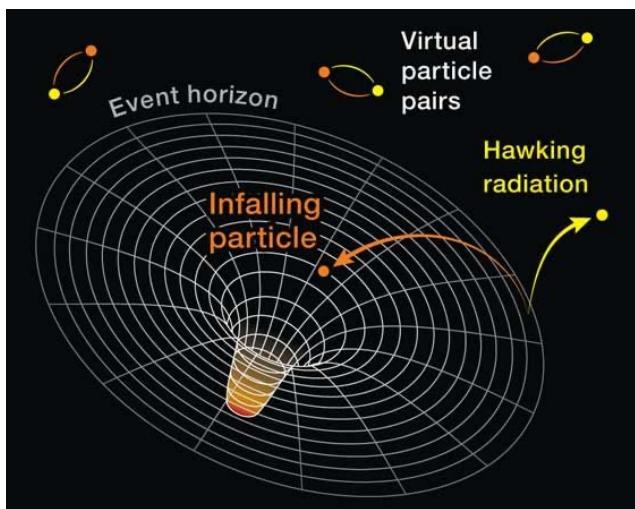
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# Asteroid-mass PBHs ( $10^{15}$ g to $10^{20}$ g)



Hawking radiation [Nature 248 (1974) 30–31]

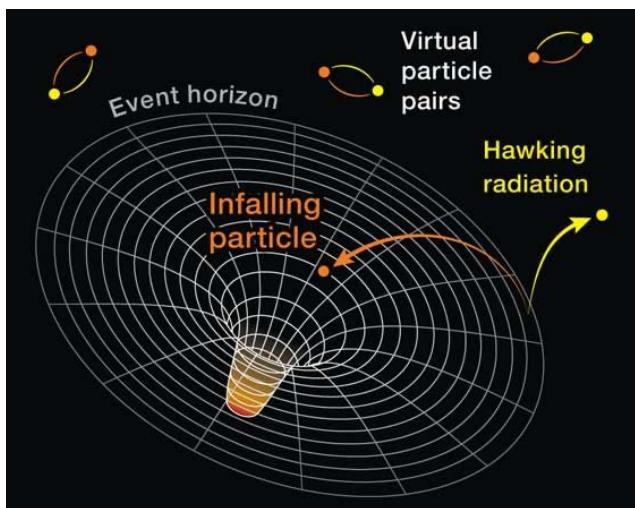
$$T_{\text{BH}} = \frac{M_{\text{Pl}}^2}{8\pi M} = 10.5 \text{ MeV} \times \left( \frac{10^{15} \text{ g}}{M} \right)$$

Evaporation: a kinematic effect

Lifetime of a black hole

$$\tau \approx 12.7 \times 10^9 \text{ yr} \times \left( \frac{M}{10^{15} \text{ g}} \right)^3$$

# Asteroid-mass PBHs ( $10^{15}$ g to $10^{20}$ g)



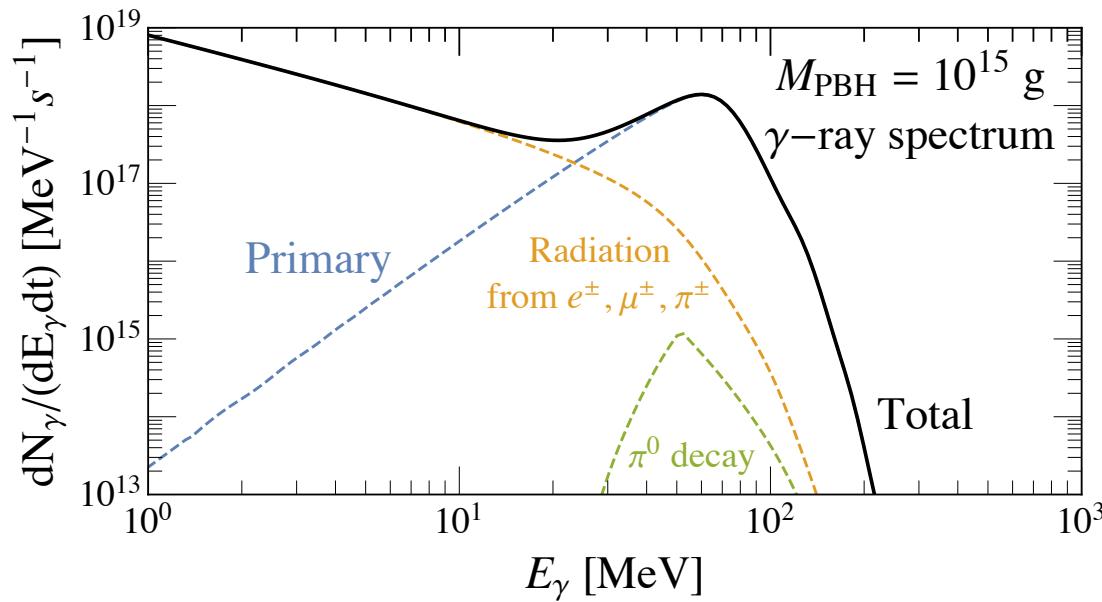
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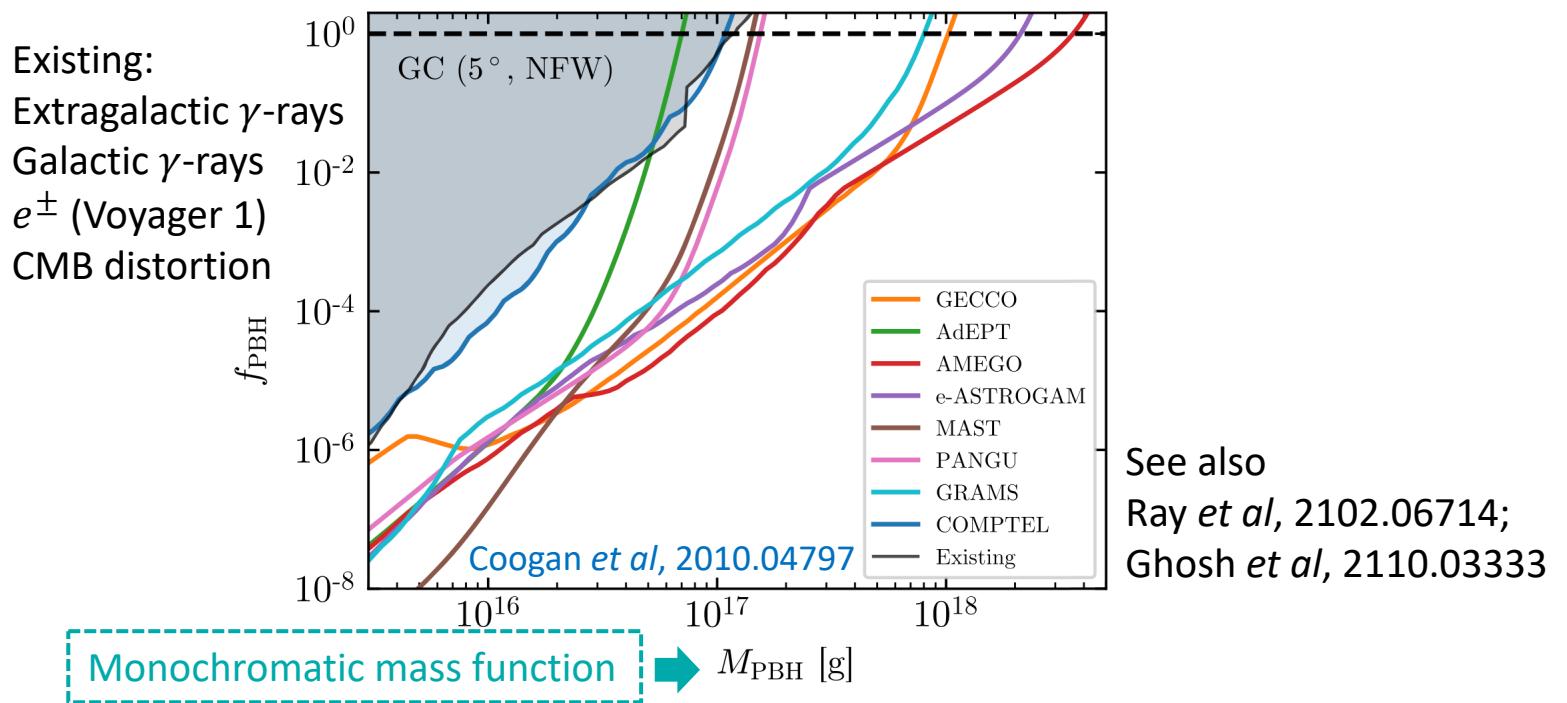
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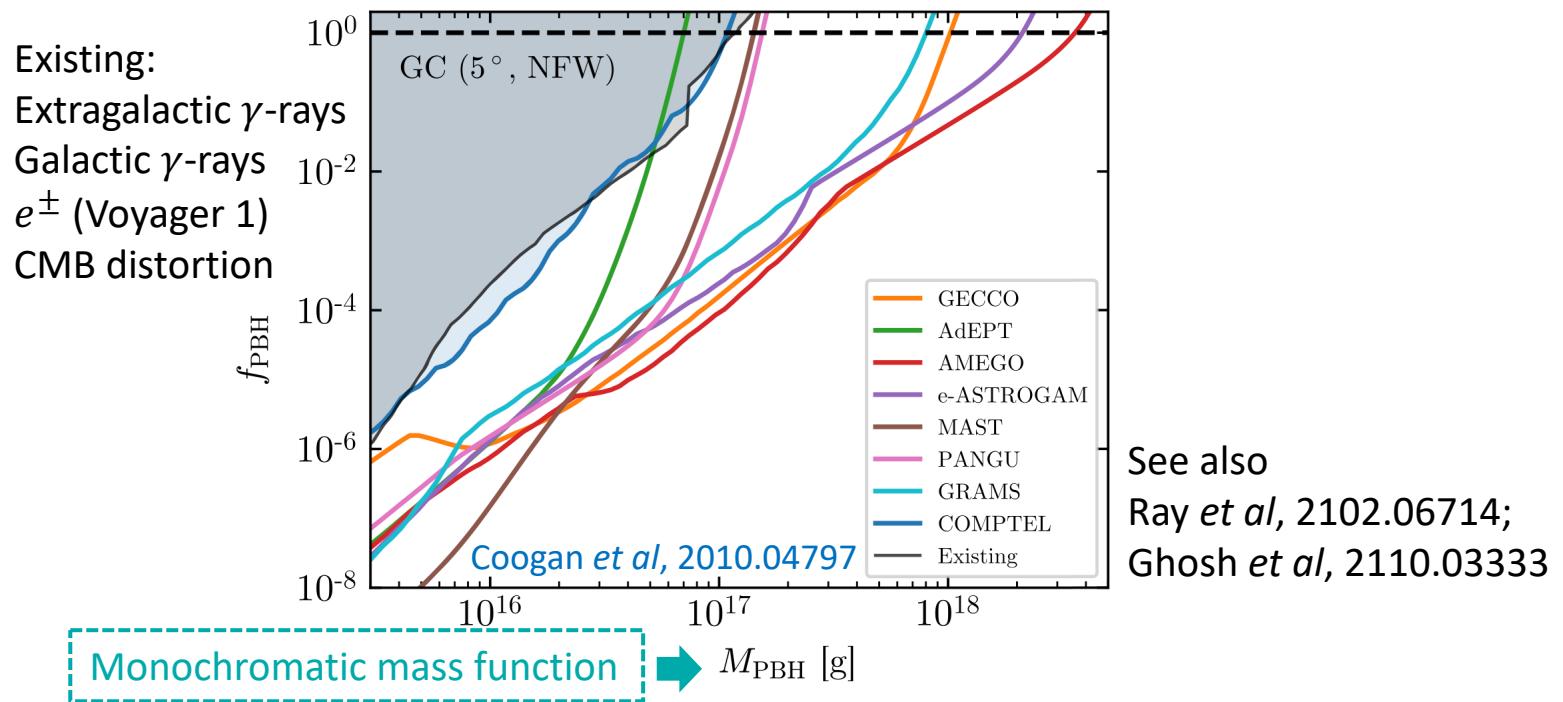
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# Probing asteroid-mass PBHs ( $10^{15}$ g to $10^{20}$ g)



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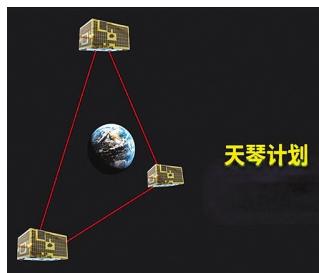
## This talk:

- Concrete formation mechanisms;
- Extended mass function, and hence more realistic;
- Combining the stochastic gravitational waves signals;
- Can identify the origin of PBHs!

# The novelty of our work



AMEGO-X (2028)  
e-ASTROGAM (2029)  
XGIS-THESEUS (2032)



LISA (2030s)  
TianQin, Taiji (2030s)



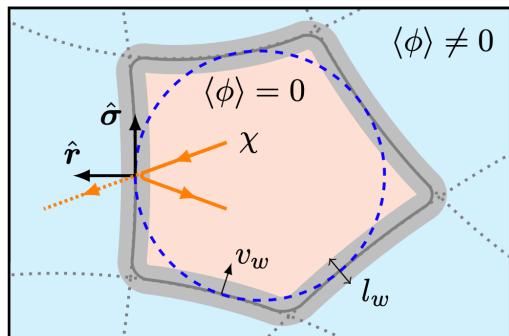
Combination!



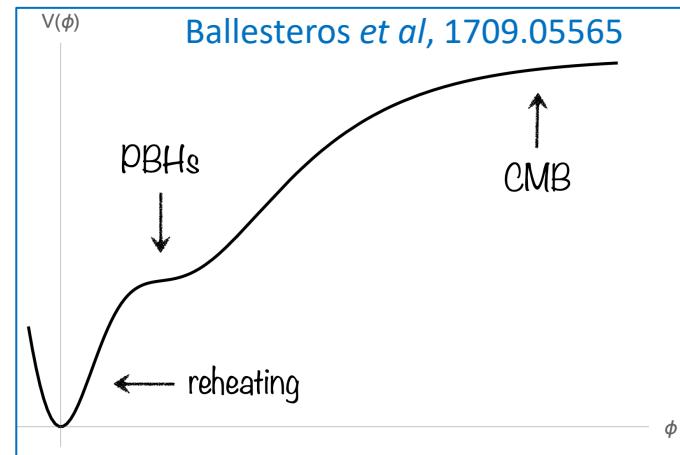
Not only detect PBHs,  
but also identify the origin!

# The PBH formation mechanisms

- Density perturbation during inflation;
- Direct collapse from FOPT;

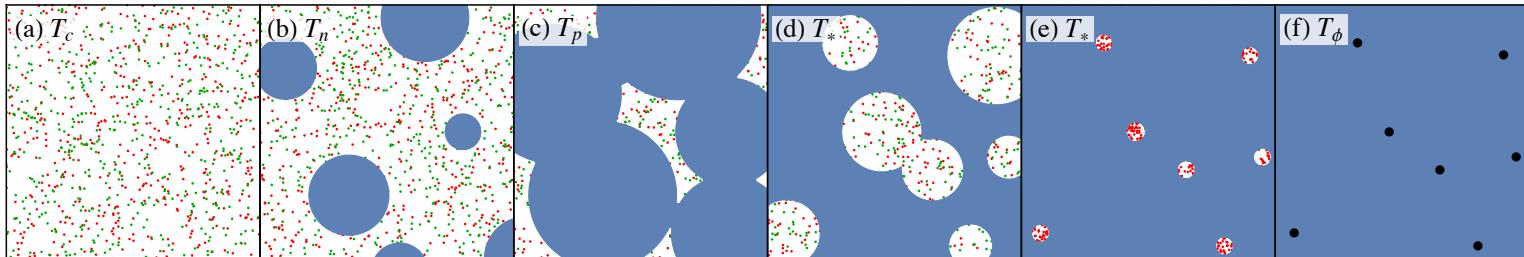


Baker et al, 2105.07481

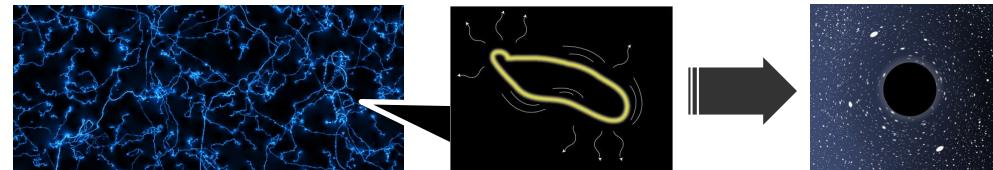


Ballesteros et al, 1709.05565

- Collapse of solitons from FOPT;

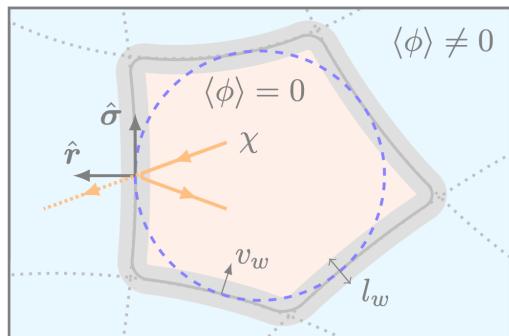


- Cosmic strings

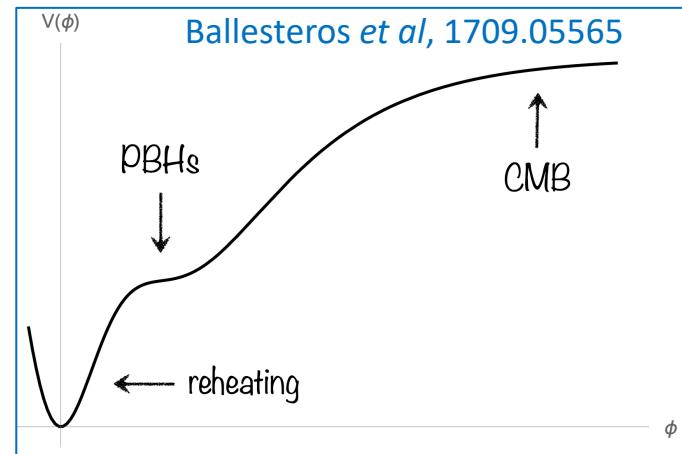


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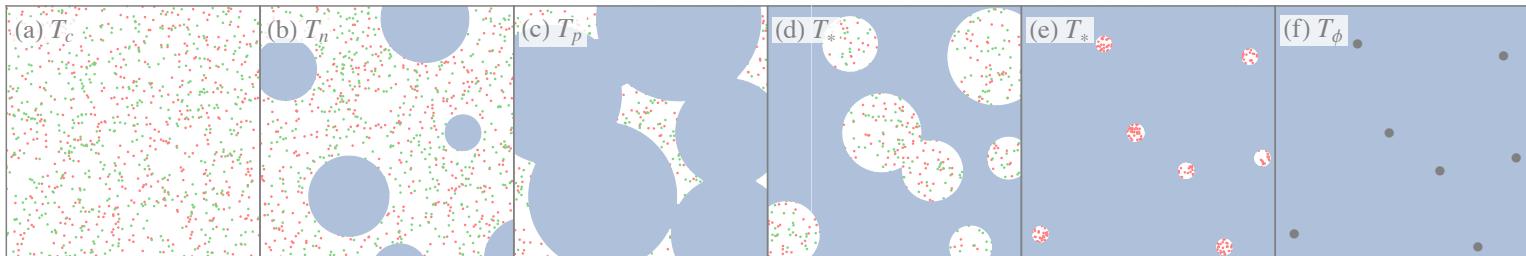


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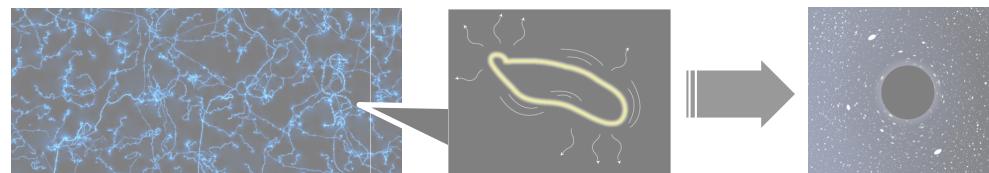


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Kawana and KPX, 2106.00111



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# PBHs from density perturbation during inflation

Carr *et al*, Mon. Not. Roy. Astron. Soc. 168, 399 (1974)

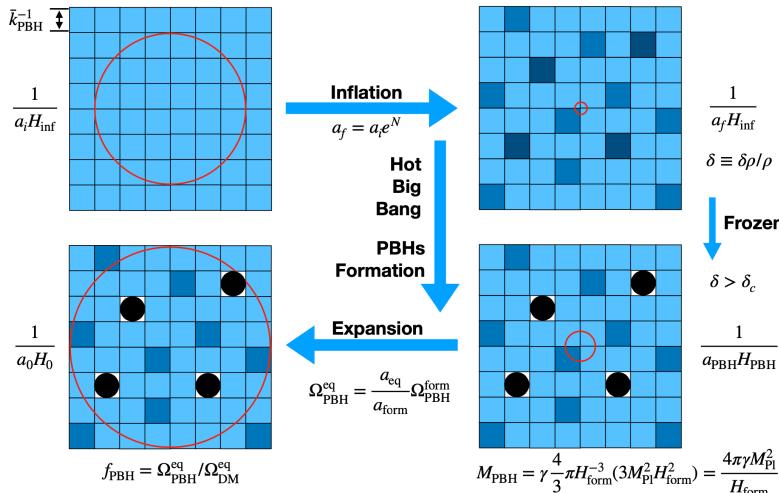


Figure from talk of Dr. Shao-Jiang Wang

The curvature perturbation power spectrum

$$P_\zeta(k) \approx \frac{A}{\sqrt{2\pi\sigma^2}} \exp\left(\frac{\log^2(k/k_p)}{2\sigma^2}\right)$$

PBH mass peak

$$M_{\text{PBH}}^{\text{peak}} \sim 10^{15} \text{ g} \times \left(\frac{k_p}{10^{15} \text{ Mpc}^{-1}}\right)^{-2}$$

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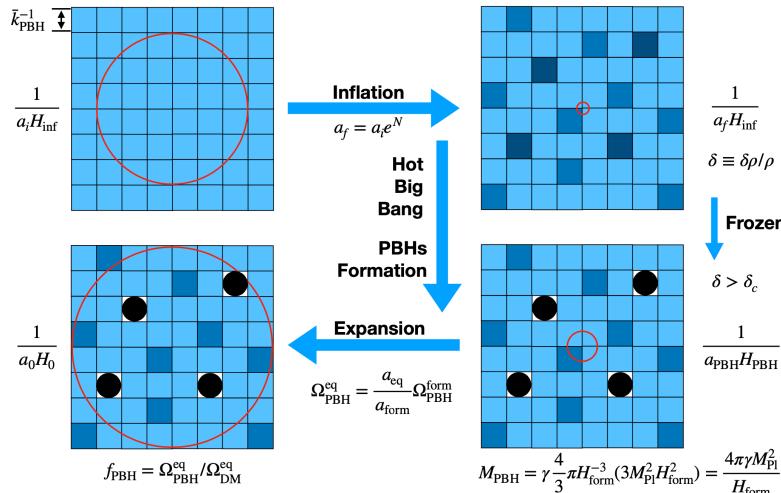
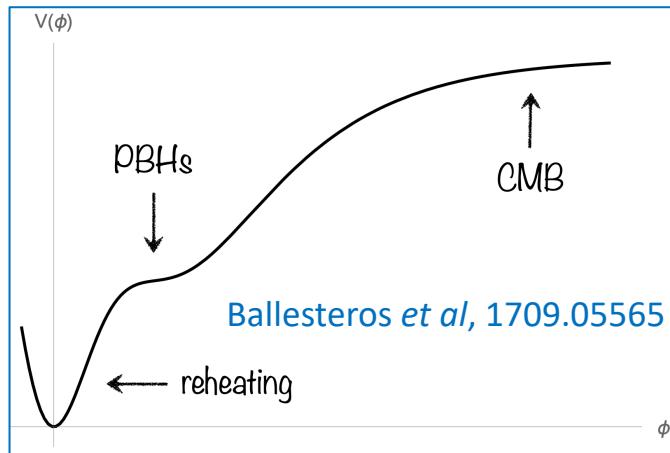


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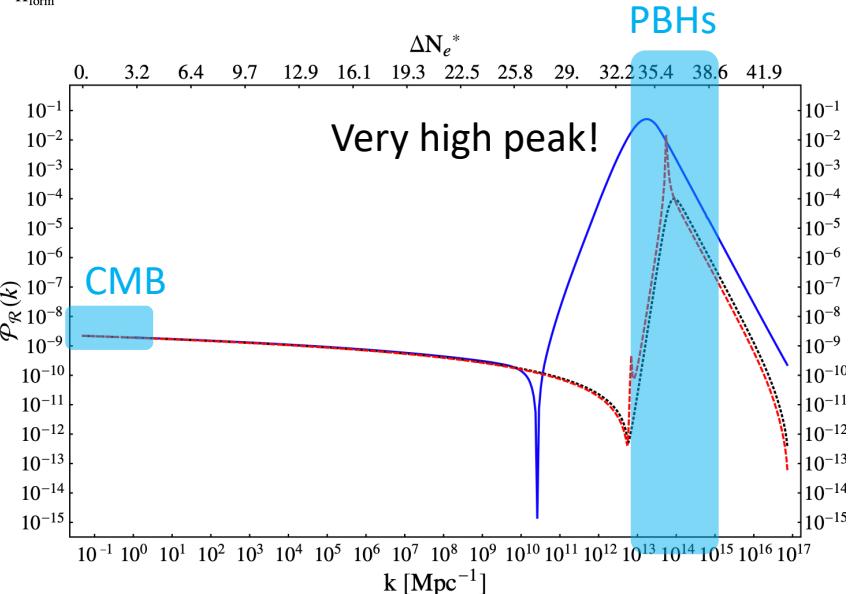


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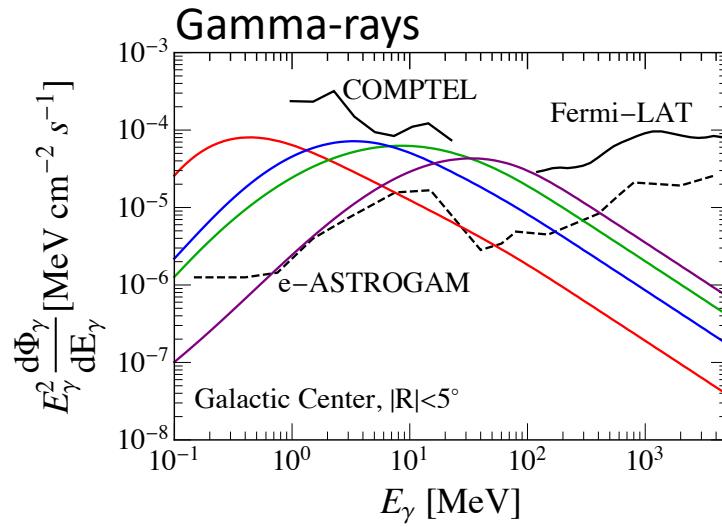
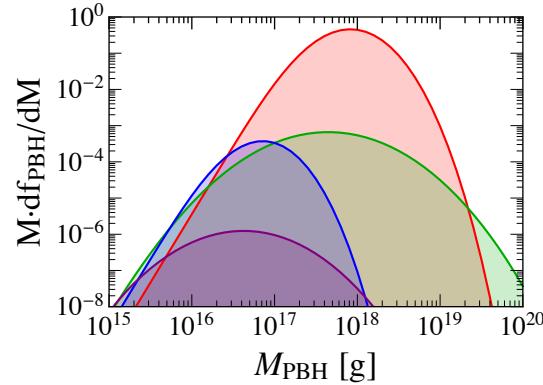
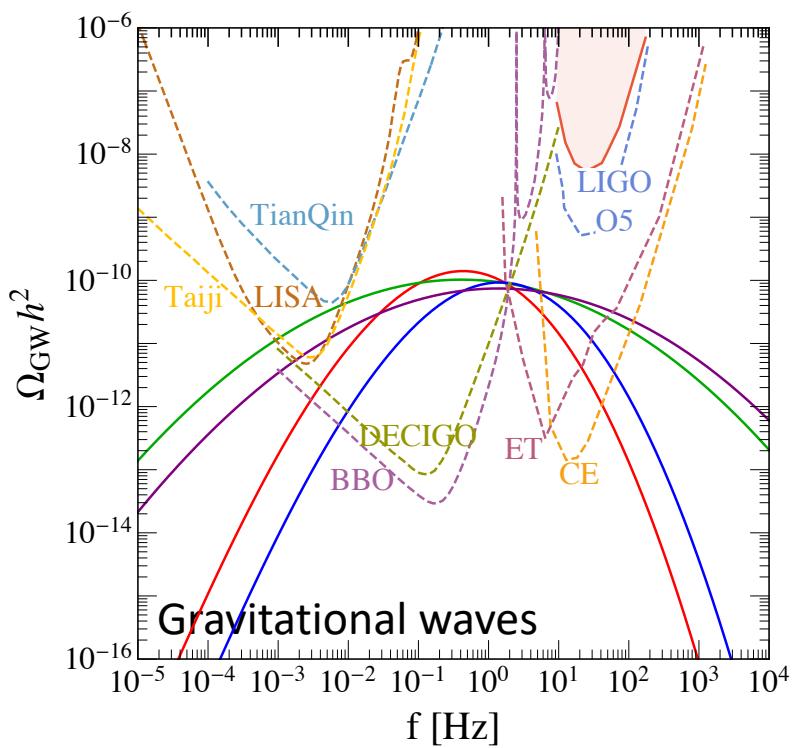
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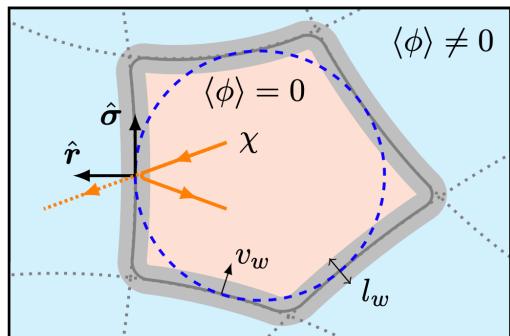
# PBHs from density perturbation during inflation

$k_p$	$A$	$\sigma$
$3 \times 10^{14} \text{ Mpc}^{-1}$	$10^{-1.94}$	2
$3 \times 10^{14} \text{ Mpc}^{-1}$	$10^{-1.72}$	4
$10^{15} \text{ Mpc}^{-1}$	$10^{-2.03}$	2
$10^{15} \text{ Mpc}^{-1}$	$10^{-1.79}$	4

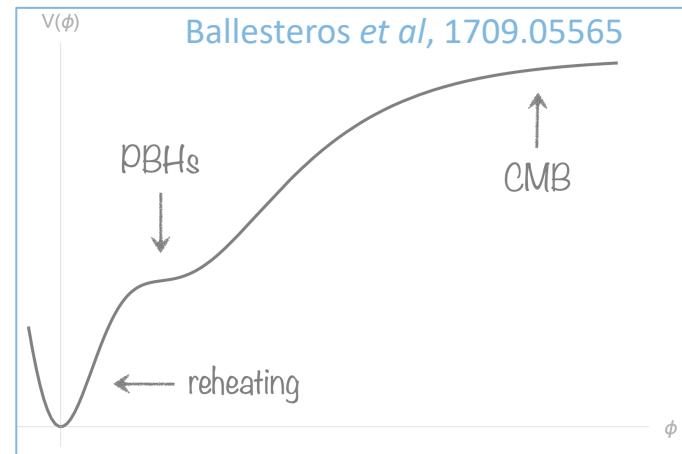


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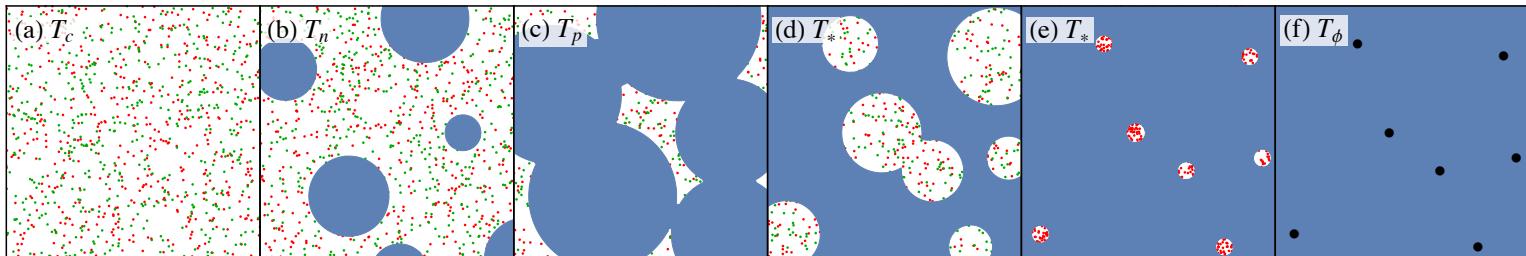


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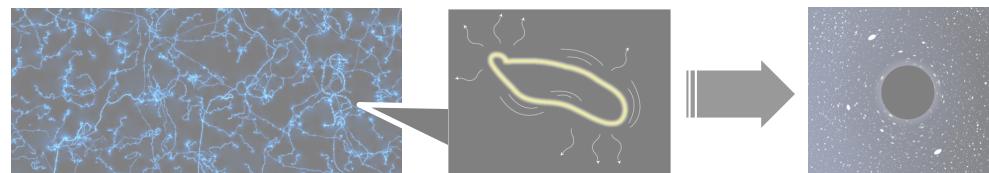


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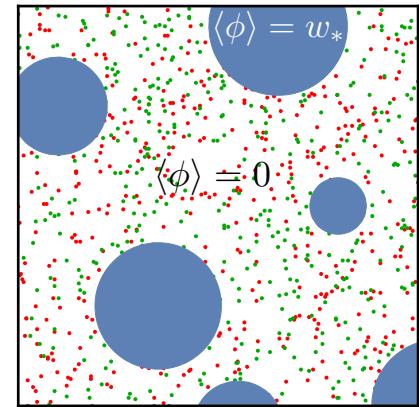
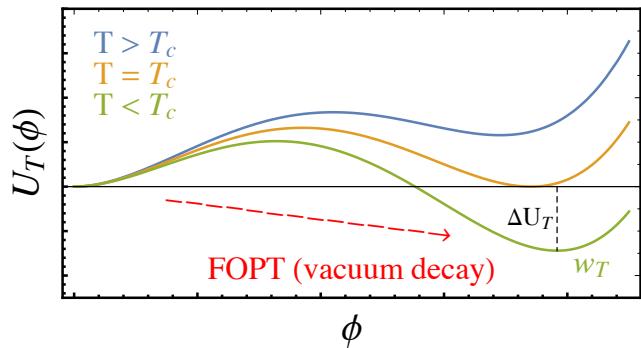
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# PBHs from a FOPT

The minimal Lagrangian

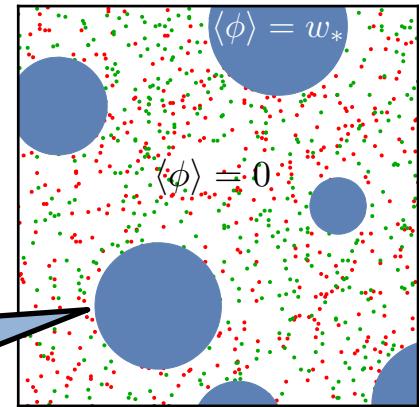
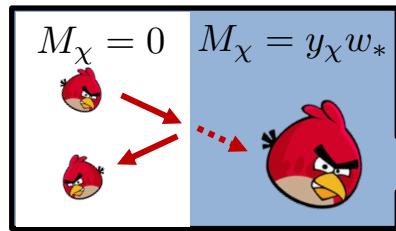
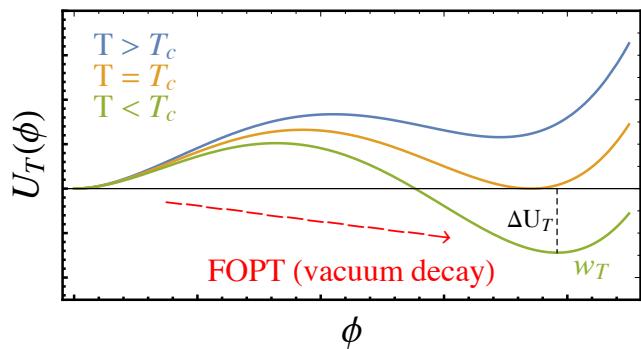
$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - U(\phi) + \bar{\chi}i\gamma^\mu\partial_\mu\chi - y_\chi\phi\bar{\chi}\chi$$



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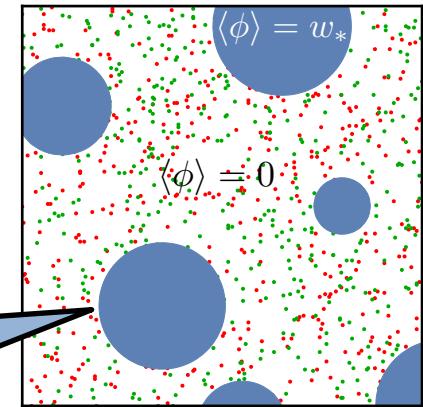
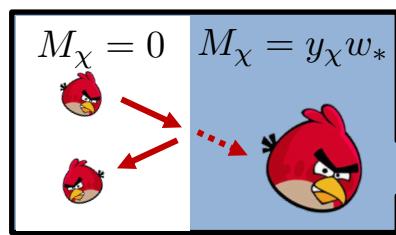
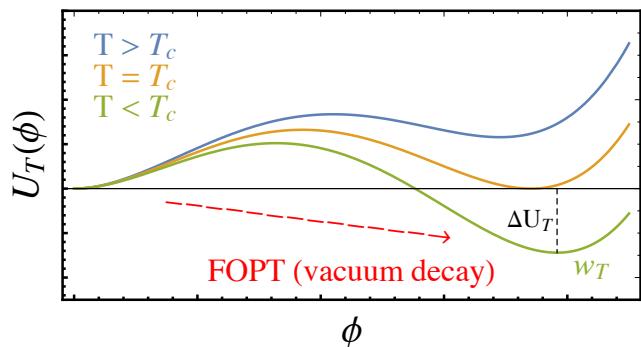


When  $M_\chi \gg T_*$ , particles are reflected!

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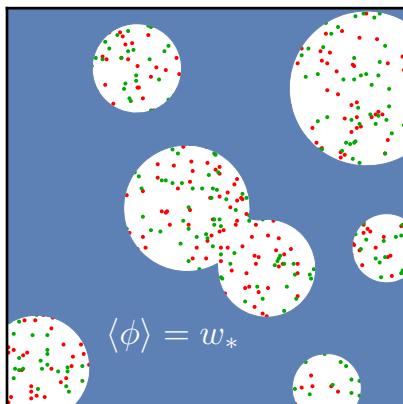
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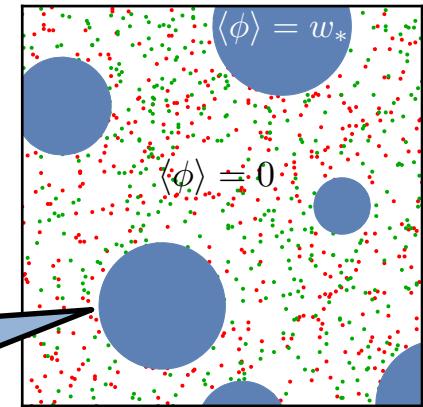
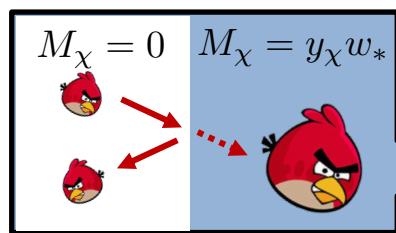
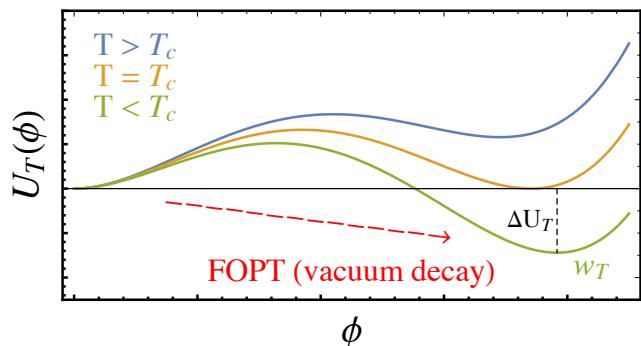
Fermions get trapped and squeezed in the false vacuum



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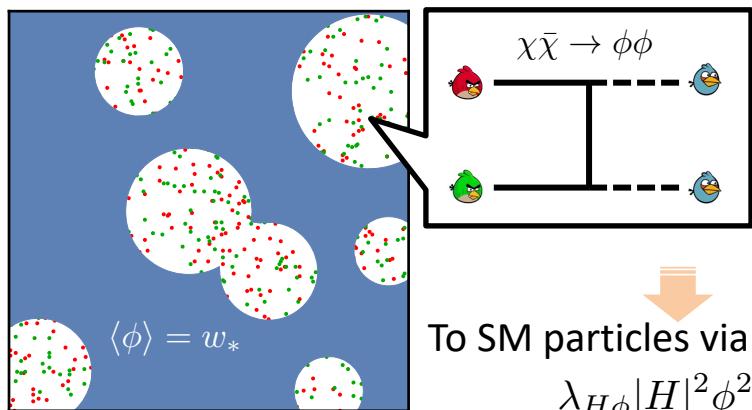
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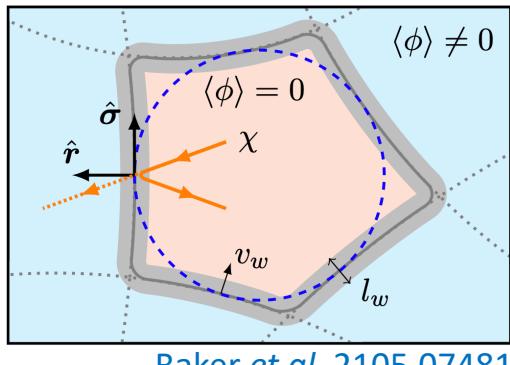


Two scenarios:

1. Annihilation is suppressed by taking  $y_\chi \lesssim 10^{-4} / \sqrt{\frac{T_*}{10^6 \text{ GeV}}}$ ;
2. There is a  $\chi$ -asymmetry (i.e. asymmetric dark matter)

# PBHs from a FOPT: scenario 1

The annihilation is suppressed:  $y_\chi \lesssim 10^{-4}/\sqrt{T_*/\text{PeV}}$



$$\rho(t) \sim \frac{7}{8} \frac{\pi^2}{30} g_\chi T_*^4 \left( \frac{r_w(0)}{r_w(t)} \right)^4$$

Size of the false vacuum remnant

Collapse happens when

$$r_c \equiv \frac{2}{M_{\text{Pl}}^2} \frac{4\pi}{3} r_w^3(t) \rho(t) > r_w(t)$$

Schwarzschild radius

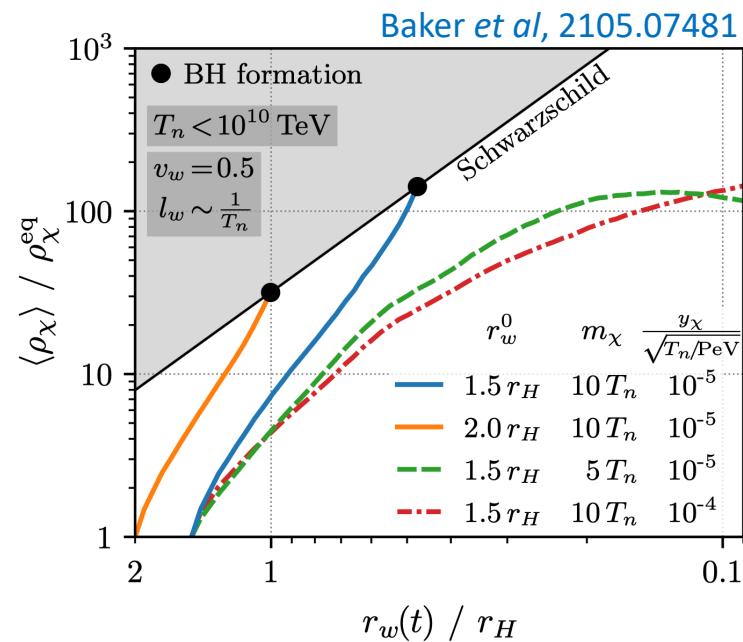
Approximate collapse condition

$$\frac{r_w(t)}{r_w(0)} \lesssim \frac{r_w(0)}{1/H(T_*)}$$

Needs a very large “false vacuum pocket” radius  $r_w(0)$

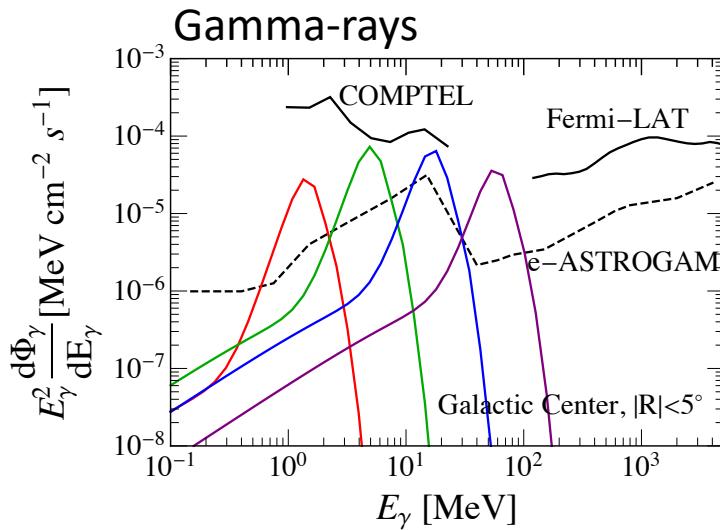
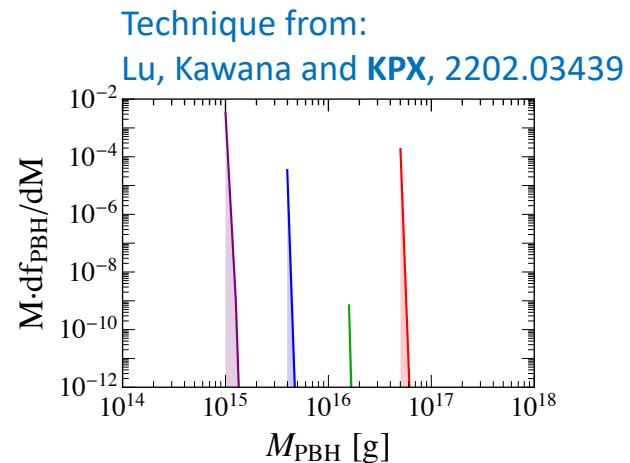
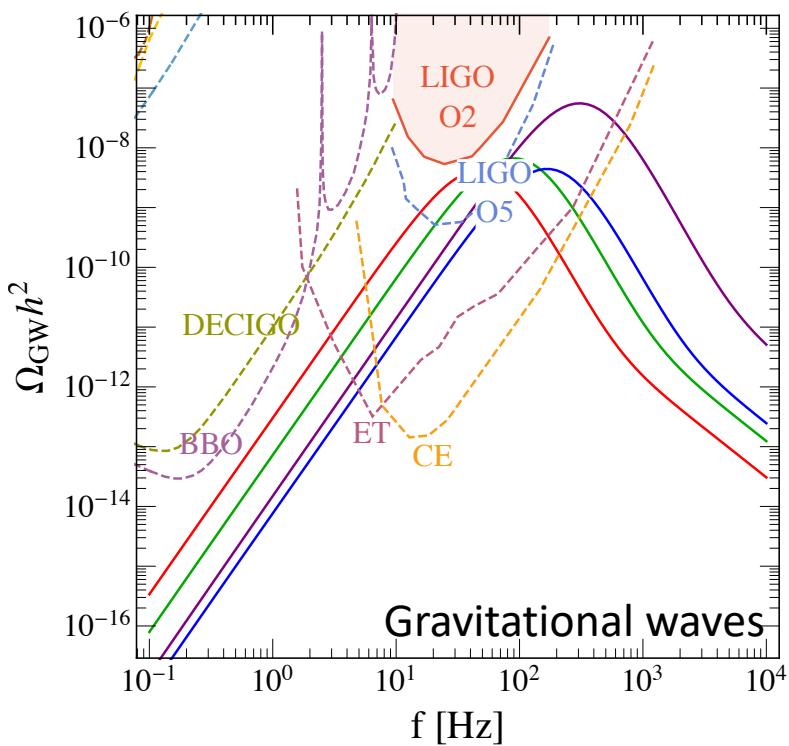
$$M_{\text{PBH}} \sim \frac{4\pi}{3} r_w^3(t) \rho_R \sim \frac{M_{\text{Pl}}^2}{H}$$

$$\sim 10^{16} \text{ g} \times \left( \frac{10^8 \text{ GeV}}{T_*} \right)^2$$



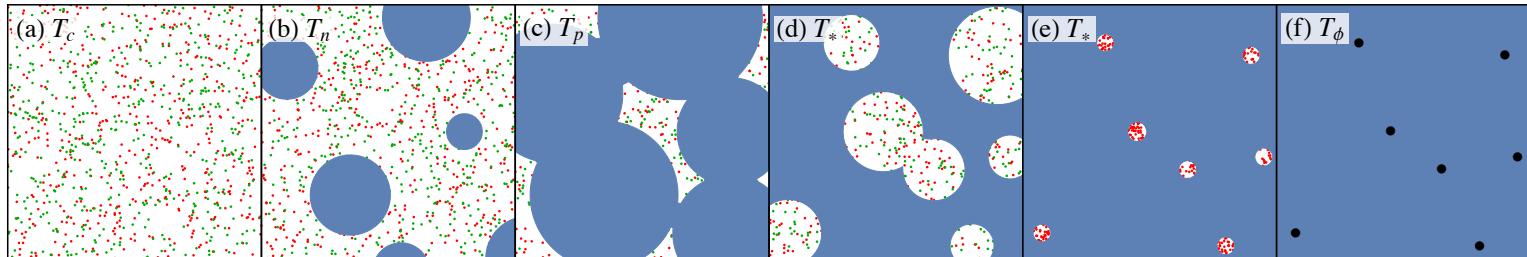
# PBHs from a FOPT: scenario 1

$\alpha$	$\beta/H_*$	$T_*$	$v_w$
0.25	1.7	$6.4 \times 10^7$ GeV	0.44
0.24	2.3	$1.2 \times 10^8$ GeV	0.59
0.21	2.3	$2.2 \times 10^8$ GeV	0.57
0.63	2.8	$4.1 \times 10^8$ GeV	0.72



# PBHs from a FOPT: scenario 2

There is a  $\chi$ -asymmetry: only  $\chi$  survives the annihilation

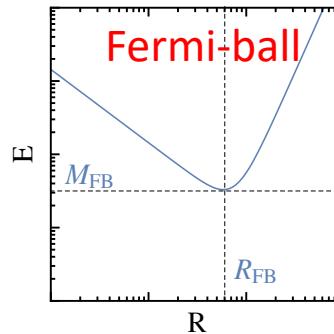


Surface tension (negligible)

$$E = \frac{3\pi}{4} \left( \frac{3}{2\pi} \right)^{2/3} \frac{Q_{FB}^{4/3}}{R} + 4\pi\sigma_0 R^2 + \frac{4\pi}{3} U_0 R^3$$

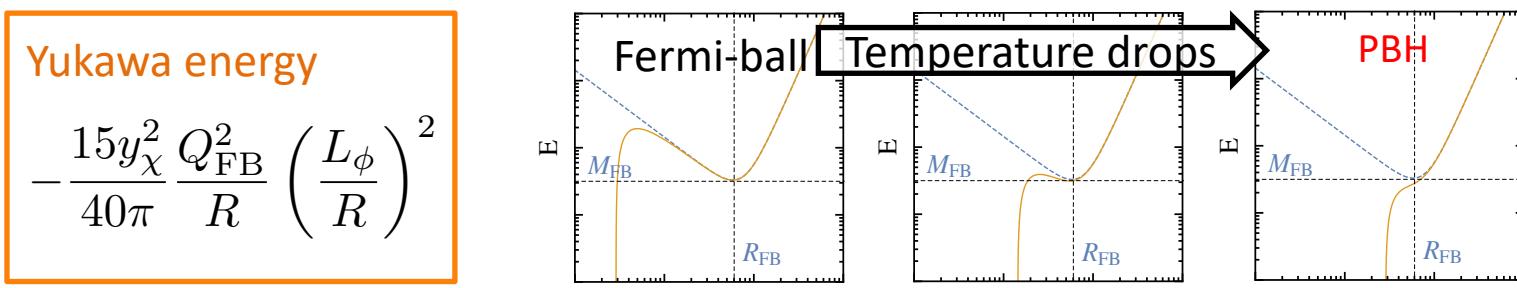
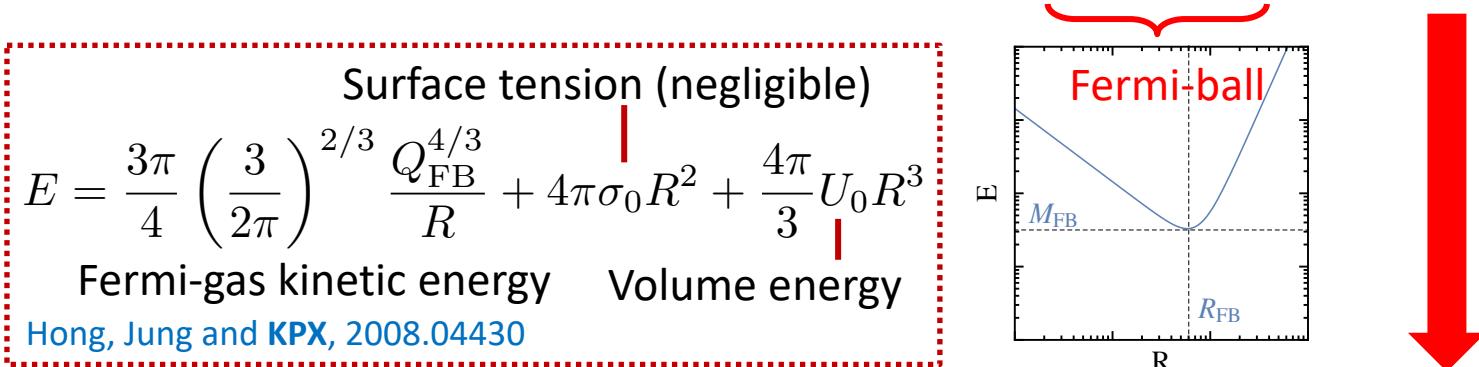
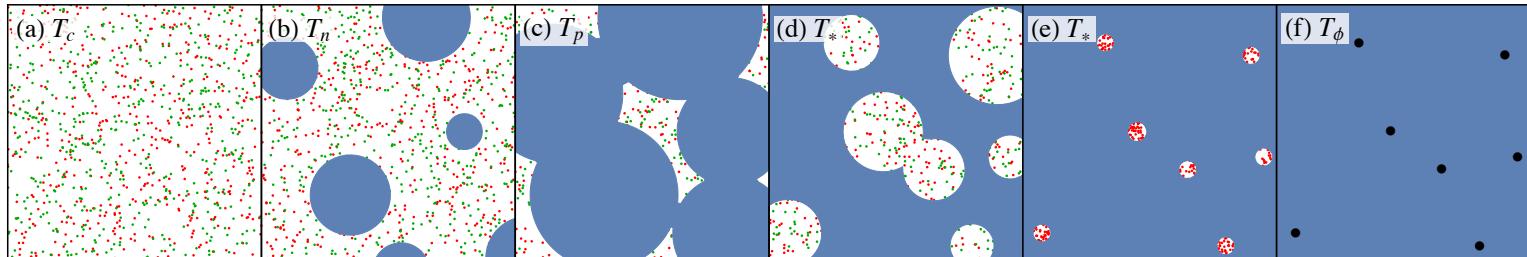
Fermi-gas kinetic energy      Volume energy

Hong, Jung and KPX, 2008.04430



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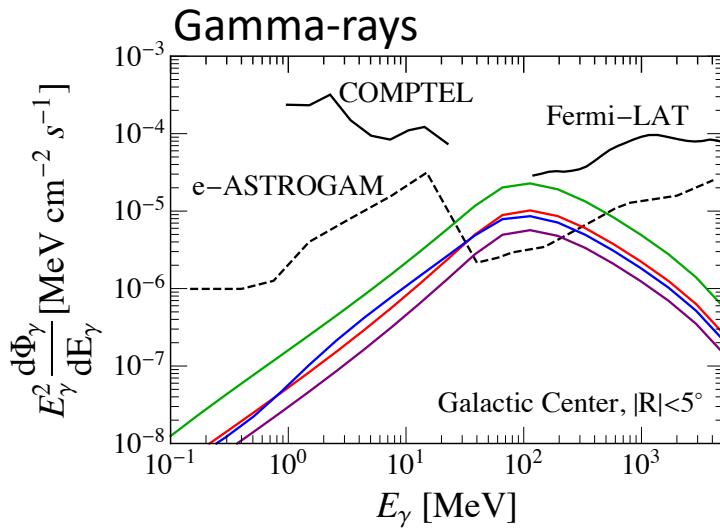
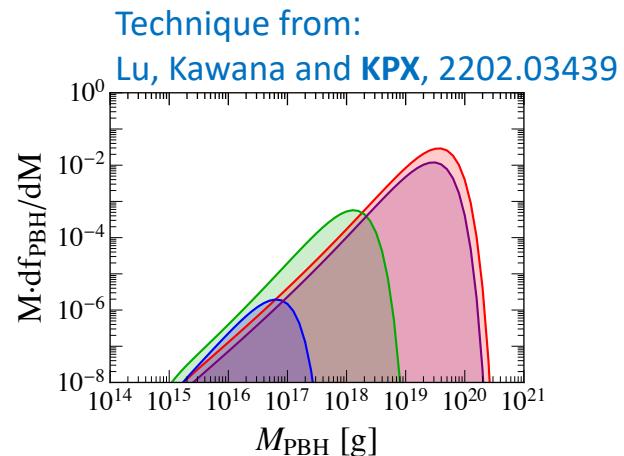
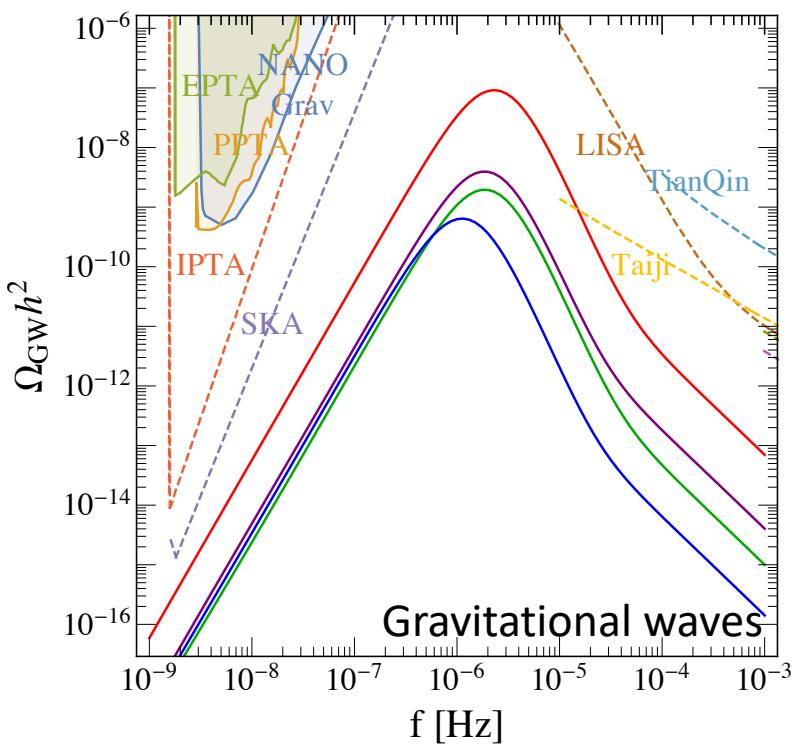
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Fermi-ball's collapse:  $M_{PBH} \approx 1.4 \times 10^{18} \text{ g} \times v_w^3 \left( \frac{\eta_\chi}{10^{-10}} \right) \left( \frac{\text{GeV}}{T_*} \right)^2 \left( \frac{100}{\beta/H_*} \right)^3 \alpha^{1/4}$

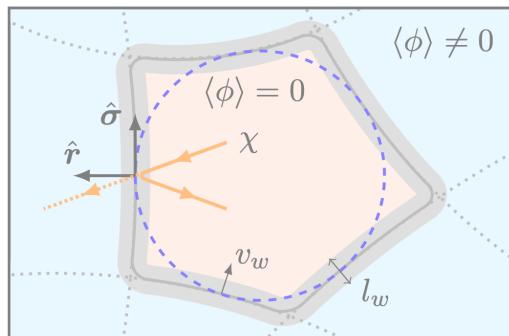
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$\alpha$	$\beta/H_*$	$T_*$	$v_w$	$\eta_\chi$
0.99	3.9	2.5 GeV	0.78	$1.5 \times 10^{-12}$
0.75	25	0.33 GeV	0.80	$2.4 \times 10^{-13}$
0.32	3.9	0.41 GeV	0.25	$2.6 \times 10^{-15}$
0.20	4.3	1.8 GeV	0.75	$1.3 \times 10^{-12}$

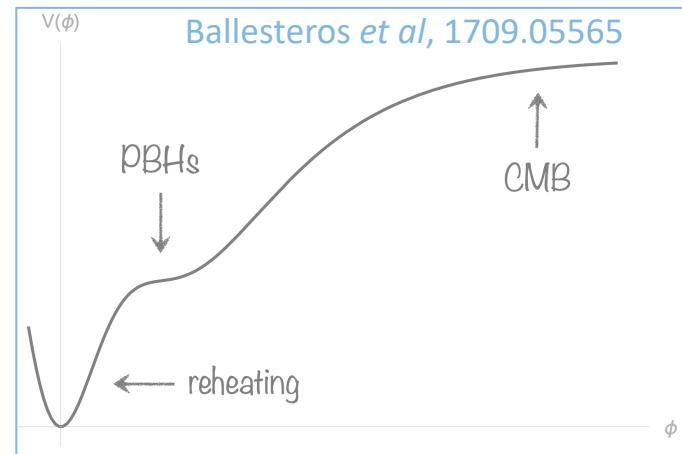


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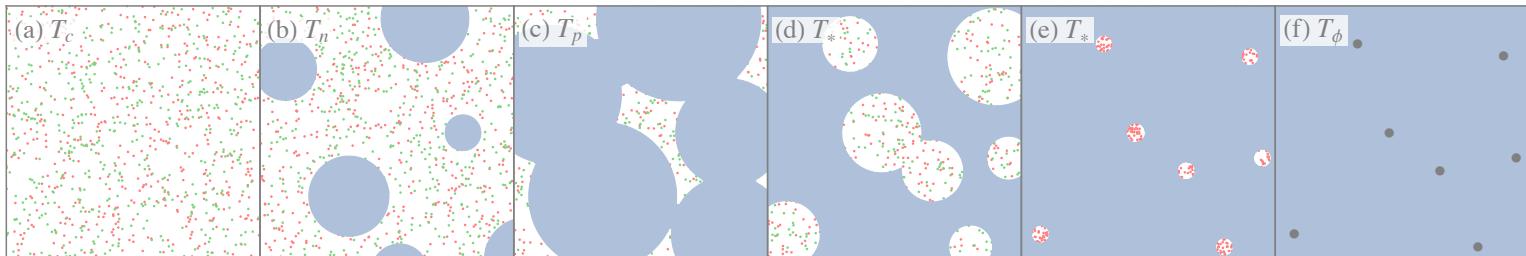


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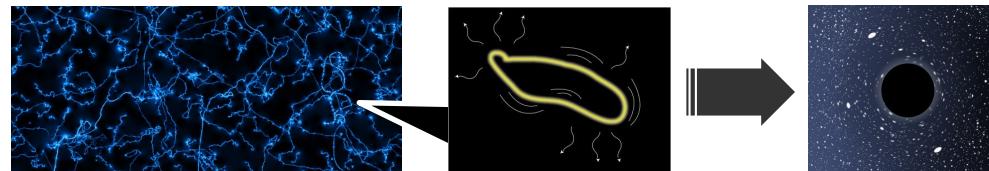


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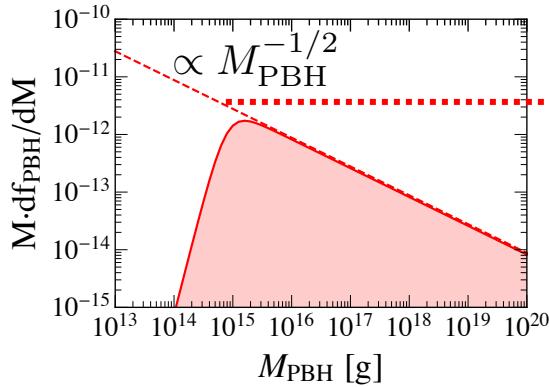
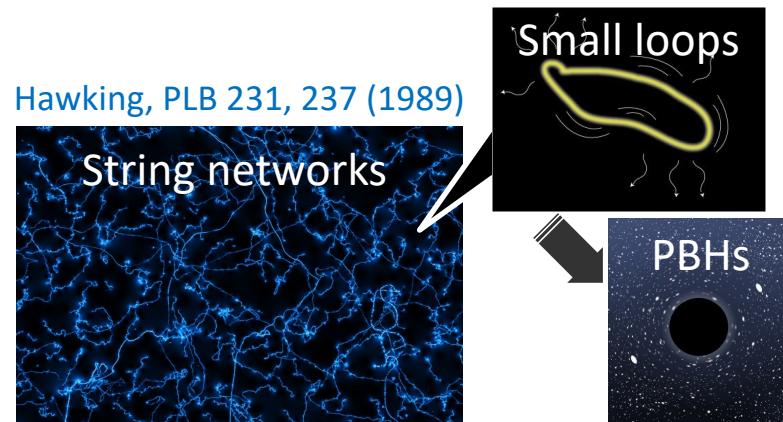
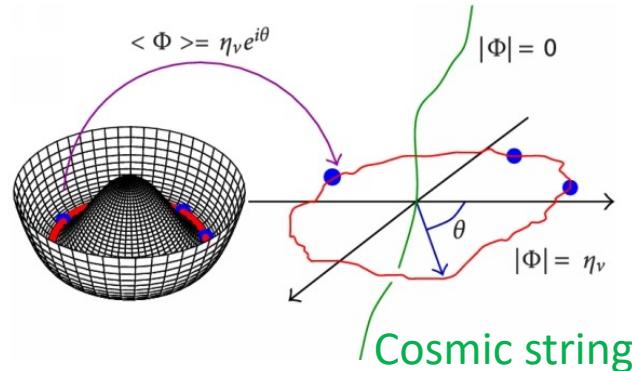
Kawana and KPX, 2106.00111



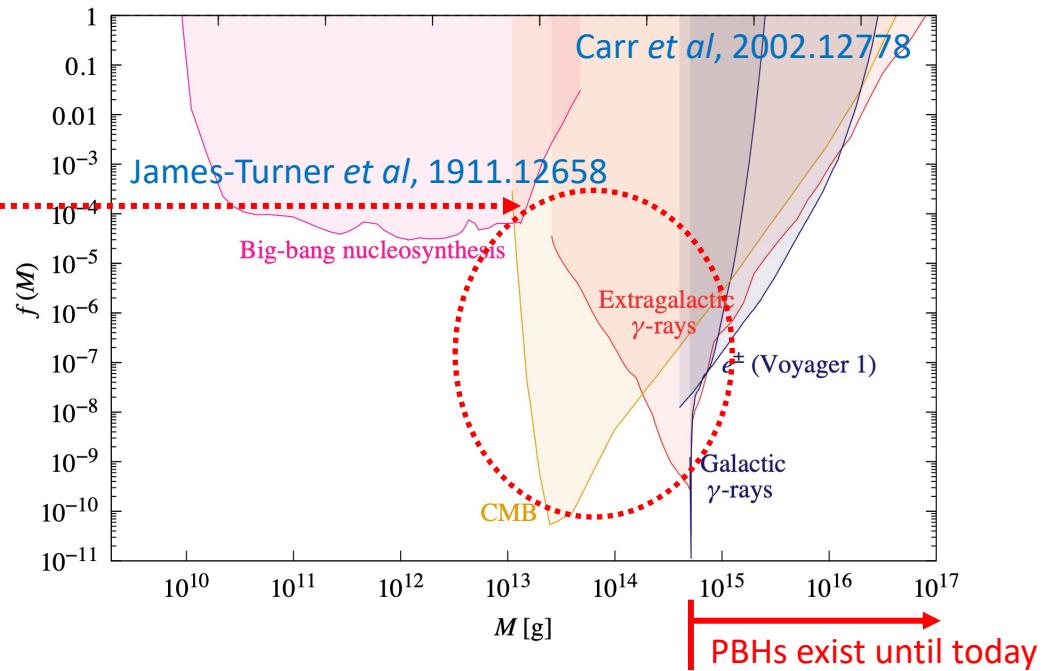
- Cosmic strings



# PBHs from cosmic string collapse



No hope to detect 😅



# Summary & Thank you!

1. Inflation-induced PBHs
2. FOPT-induced PBHs (1): direct collapse
3. FOPT-induced PBHs (2): soliton collapse
4. Cosmic string

