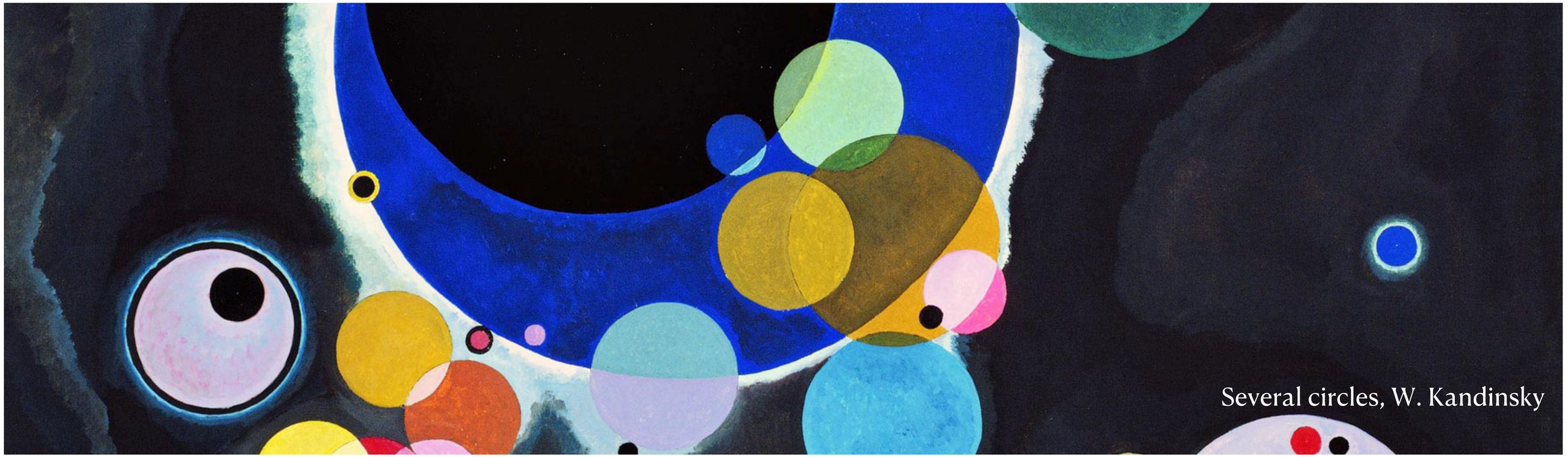
Magnetogenesis with gravitational waves and primordial black hole dark matter



based on Phys.Rev.D 109 (2024) 7, 075048 (2402.05179)

María Olalla Olea Romacho

King's College London

in collaboration with S. Balaji and M. Fairbairn

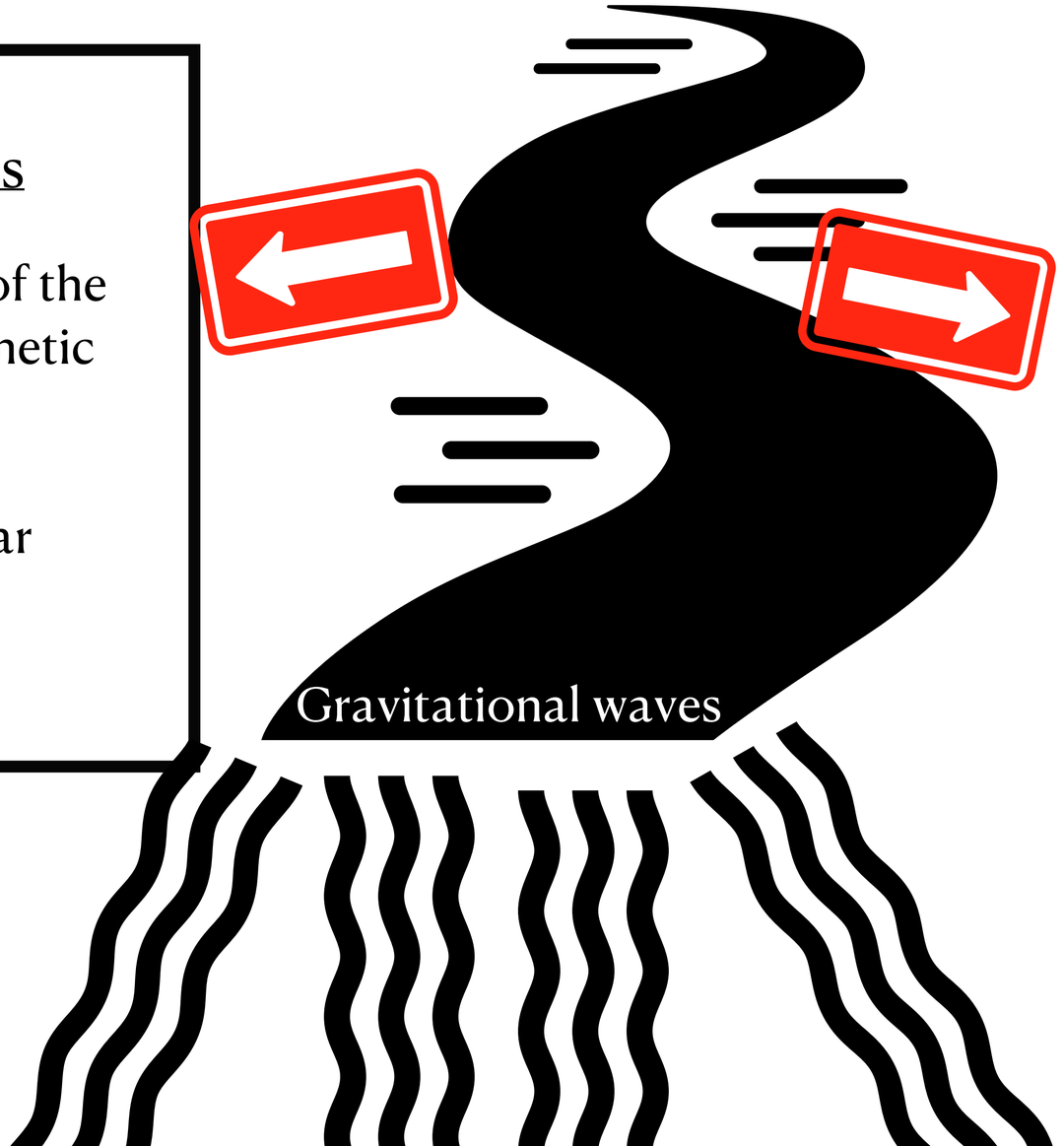
Cosmological phase transitions:

as a common origin for

Intergalactic magnetic fields

What's the origin of the intergalactic magnetic fields?

Evidence: blazar observations



Primordial black hole dark matter

What's dark matter?
Evidence: galaxy rotation curves, Bullet cluster, CMB...

Maybe it's made out of primordial black holes (?)

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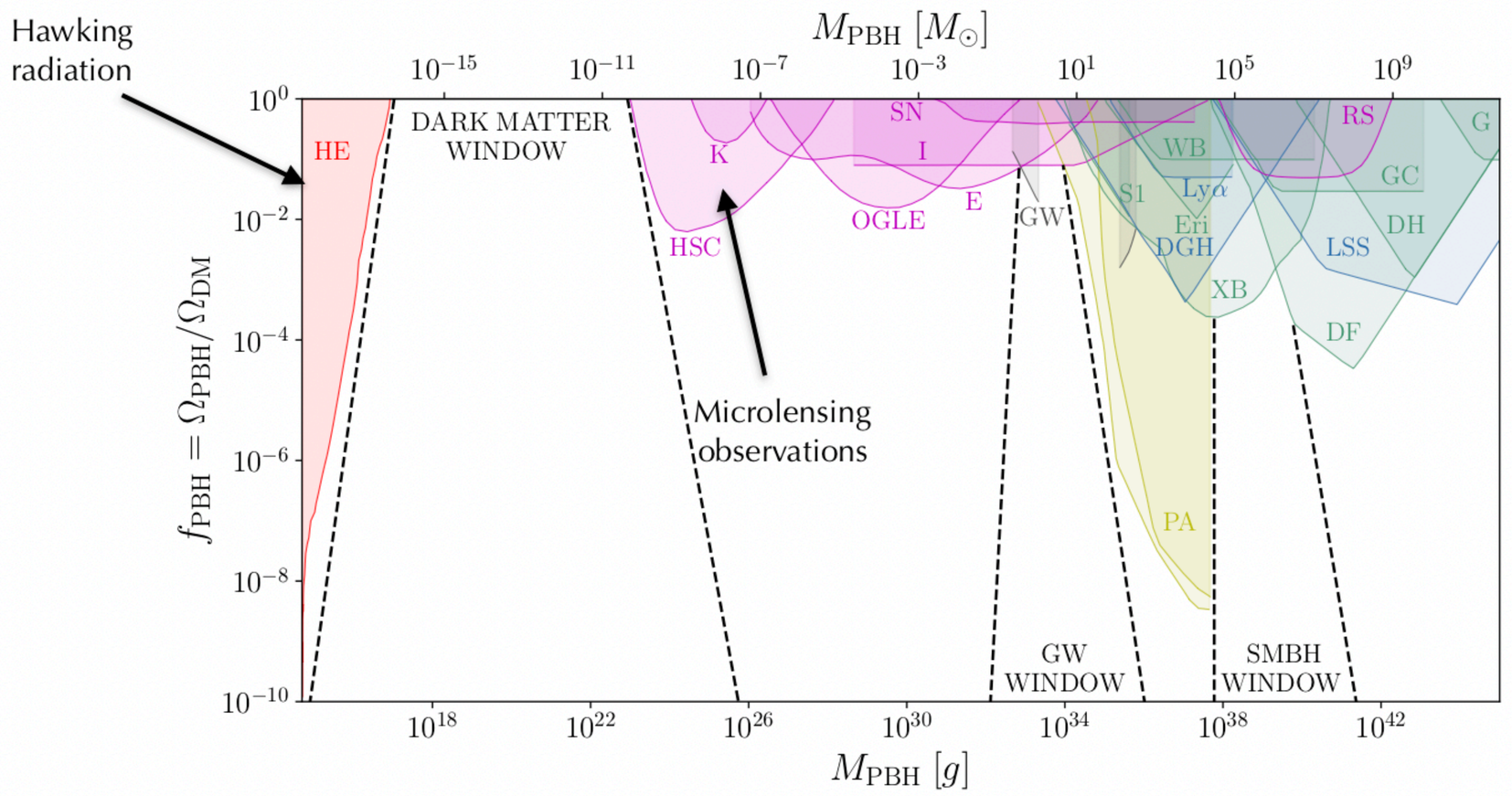
Primordial black holes (PBHs) as dark matter



- Black holes formed in the early universe, so different from stellar black holes.
- Interact through gravity.
- Cold dark matter.

[Credits: Marcos Flores]

$$f_{\rm pbh} \equiv \frac{\rho_{\rm pbh}}{\rho_{\rm DM}} = 1$$

$$10^{-16} M_\odot \lesssim M_{\rm PBH} \lesssim 10^{-10} M_\odot$$

They can constitute all dark matter if their masses fall in this range

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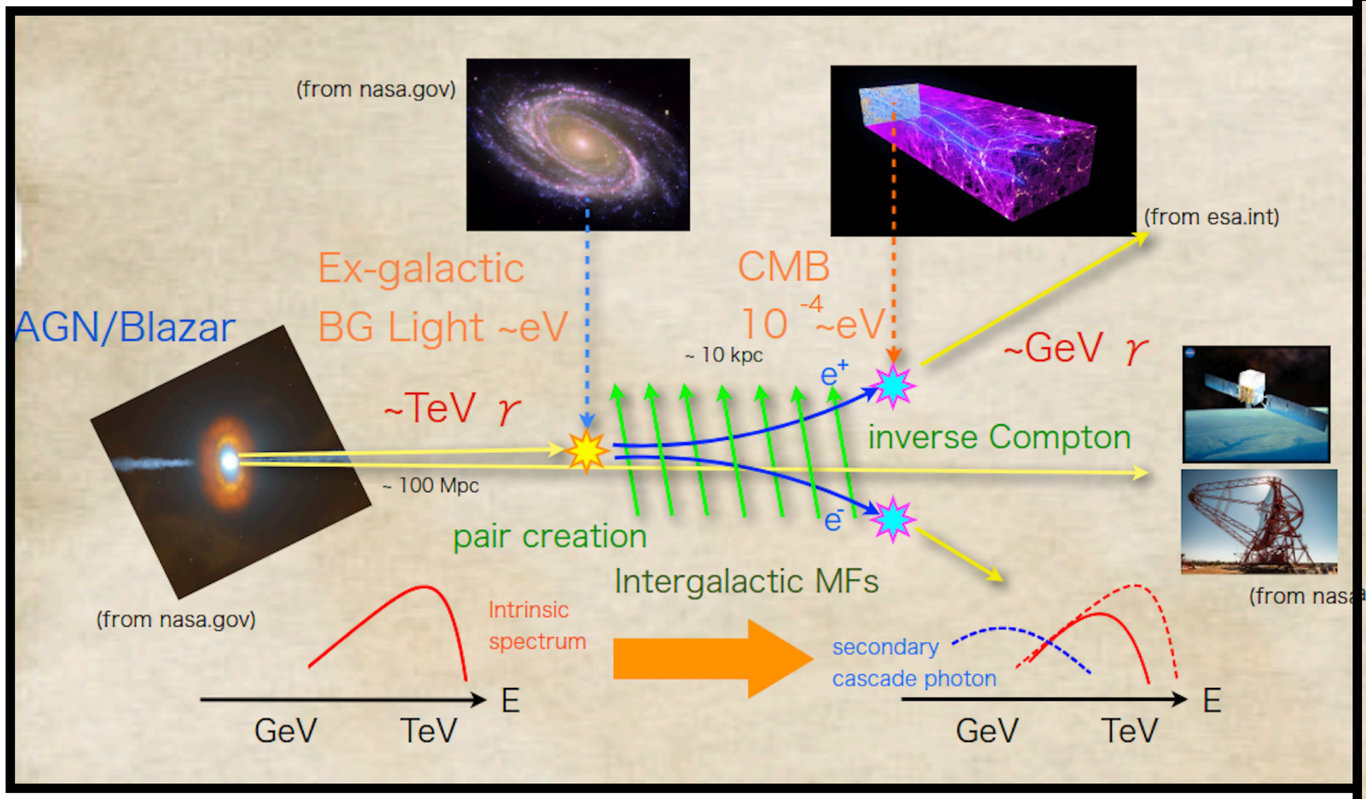
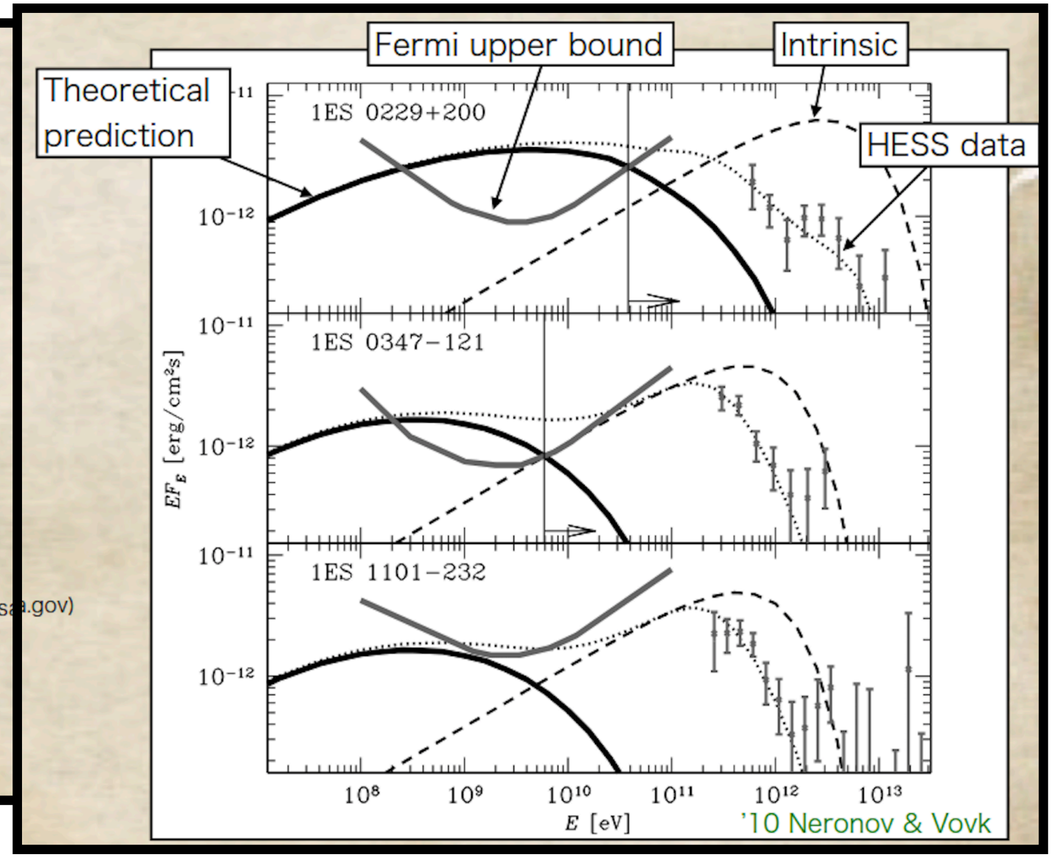
Primordial magnetic fields (PMFs)

Pictures, credits: Kohei Kamada





Non-observation of secondary photon cascades suggests the existence of intergalactic magnetic fields and sets a lower strength limit

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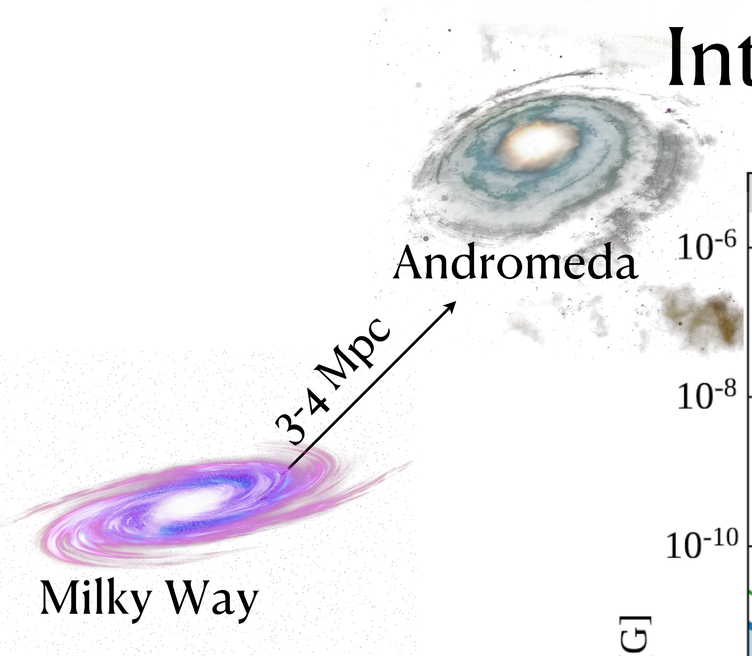
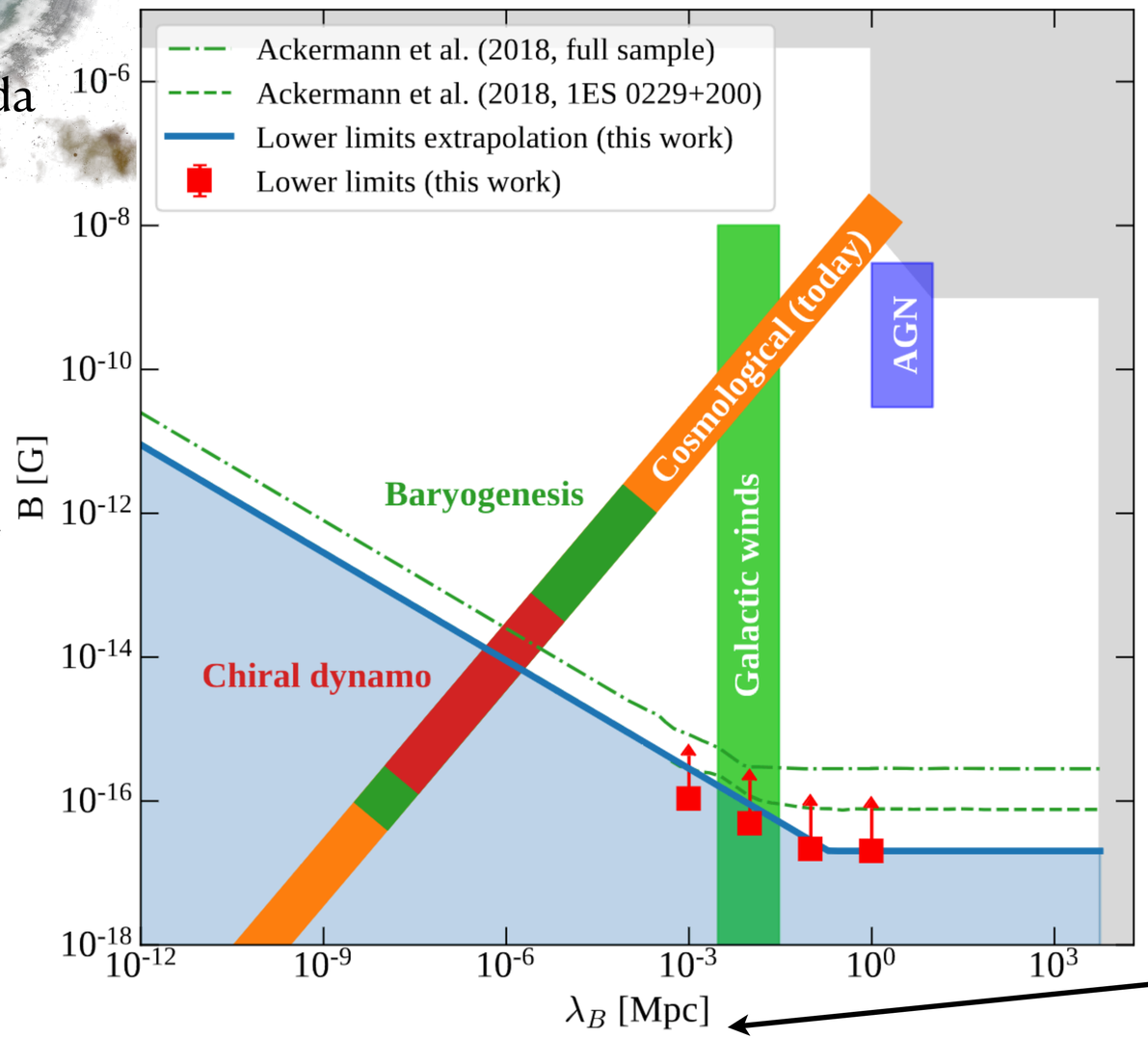
Intergalactic magnetic fields: limits





Strength of the magnetic field

Even magnetic fields are not as directly observed as CMB photons or gravitational waves, they can be important relics from the early universe...(if cosmological)

2210.03321:
MAGIC, Fermi/LAT collaborations

Coherence length of the magnetic field: distance over which it maintains a consistent direction and can be considered uniform.

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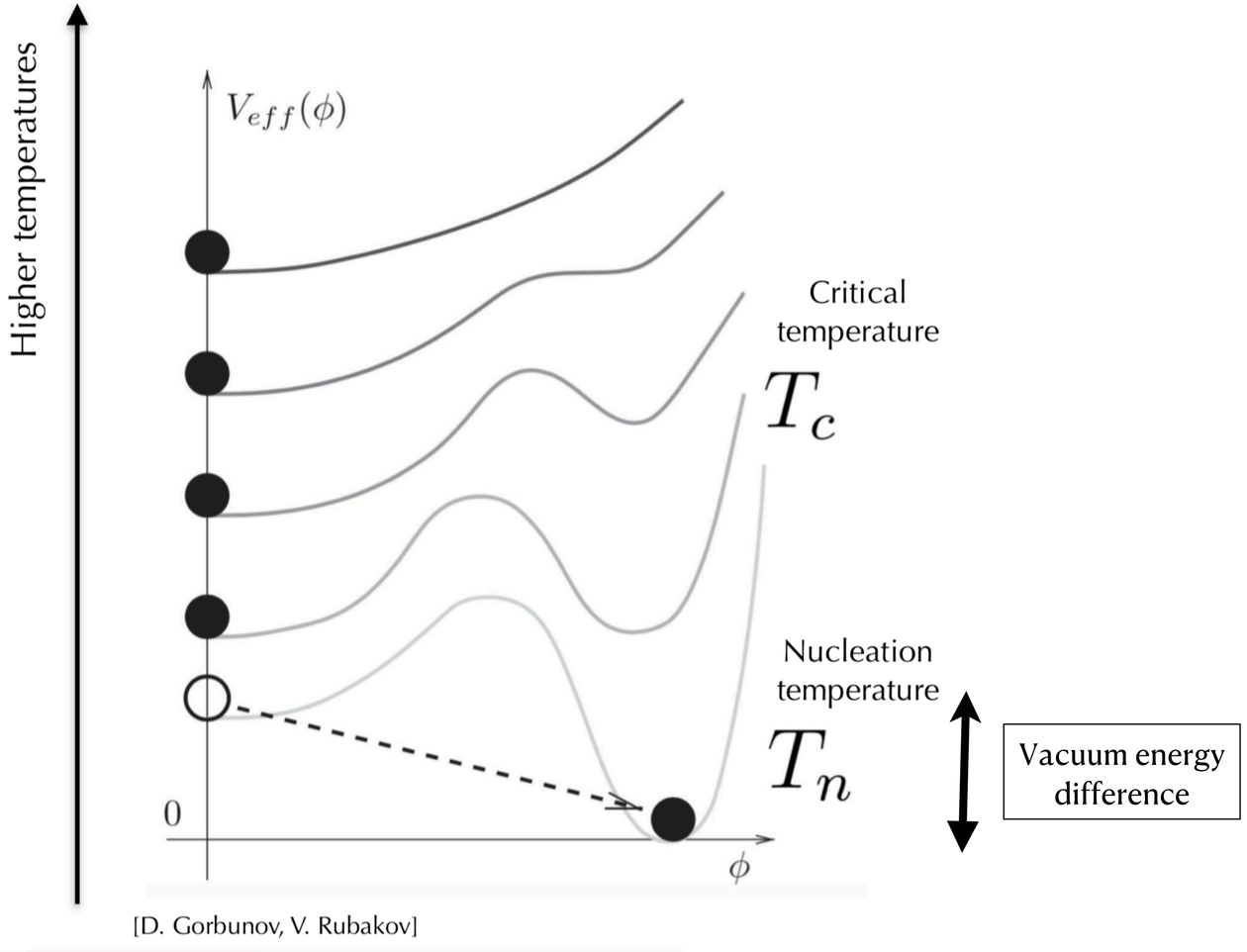
Cosmological phase transitions

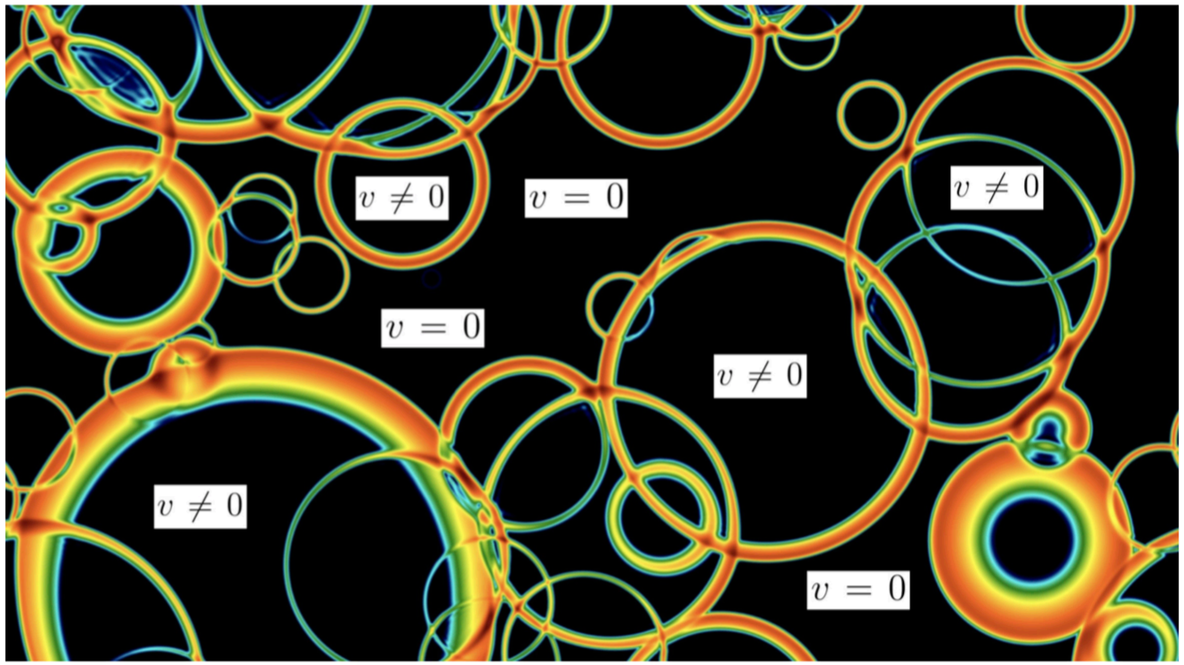


[D. Gorbunov, V. Rubakov]

Transition rate: (S_3: *bounce action*)

$$\Gamma \sim \exp\left(-S_3(T)/T\right)$$

[Image by D. Weir]



Bounce action minimized by a field configuration with **spherical symmetry**, so the transition occurs by creating spherical bubbles of the new phase inside the old phase

$$\Gamma_{\rm bub} = H^4$$

Nucleation temperature

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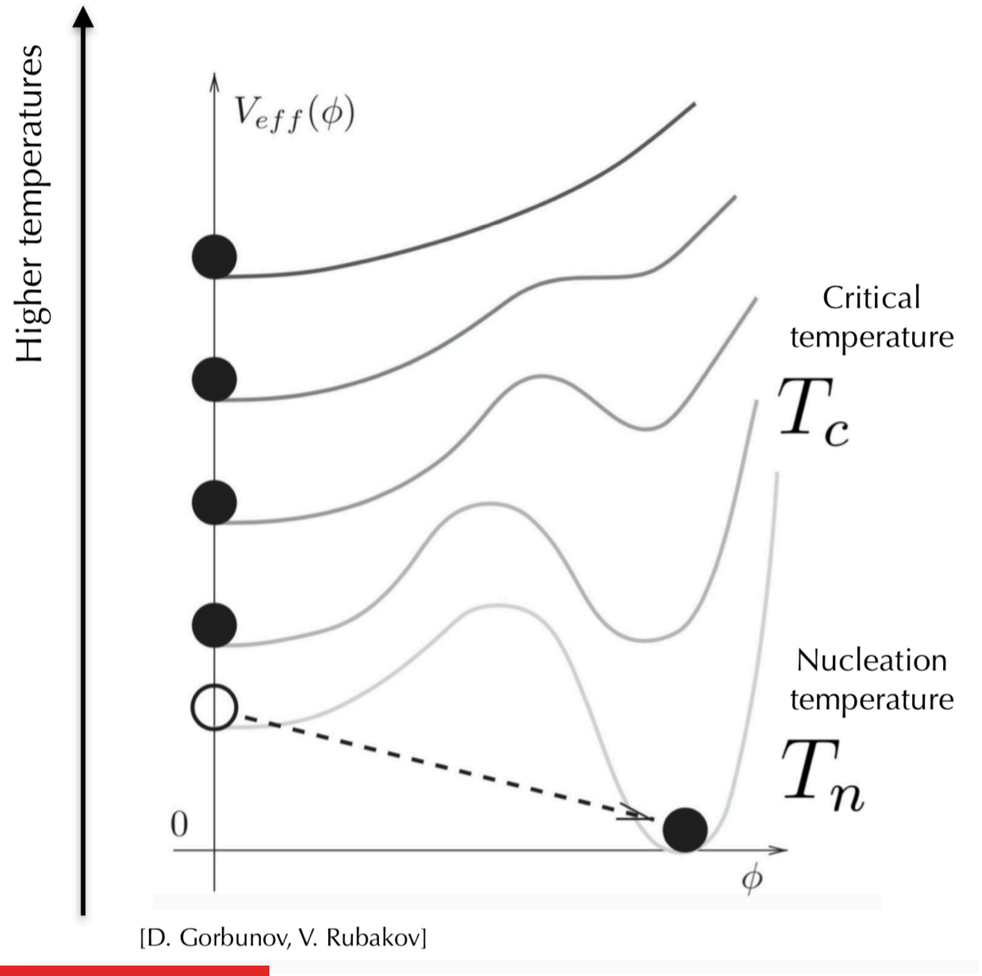
Cosmological phase transitions



[D. Gorbunov, V. Rubakov]

Vacuum energy

- Kinetic energy of bubble walls:
  accelerating bubble walls
- Thermal energy:
  shock waves,
  turbulence
- Particle production:
  interactions between the plasma
  and the bubble walls
- Magnetic fields and MHD turbulence

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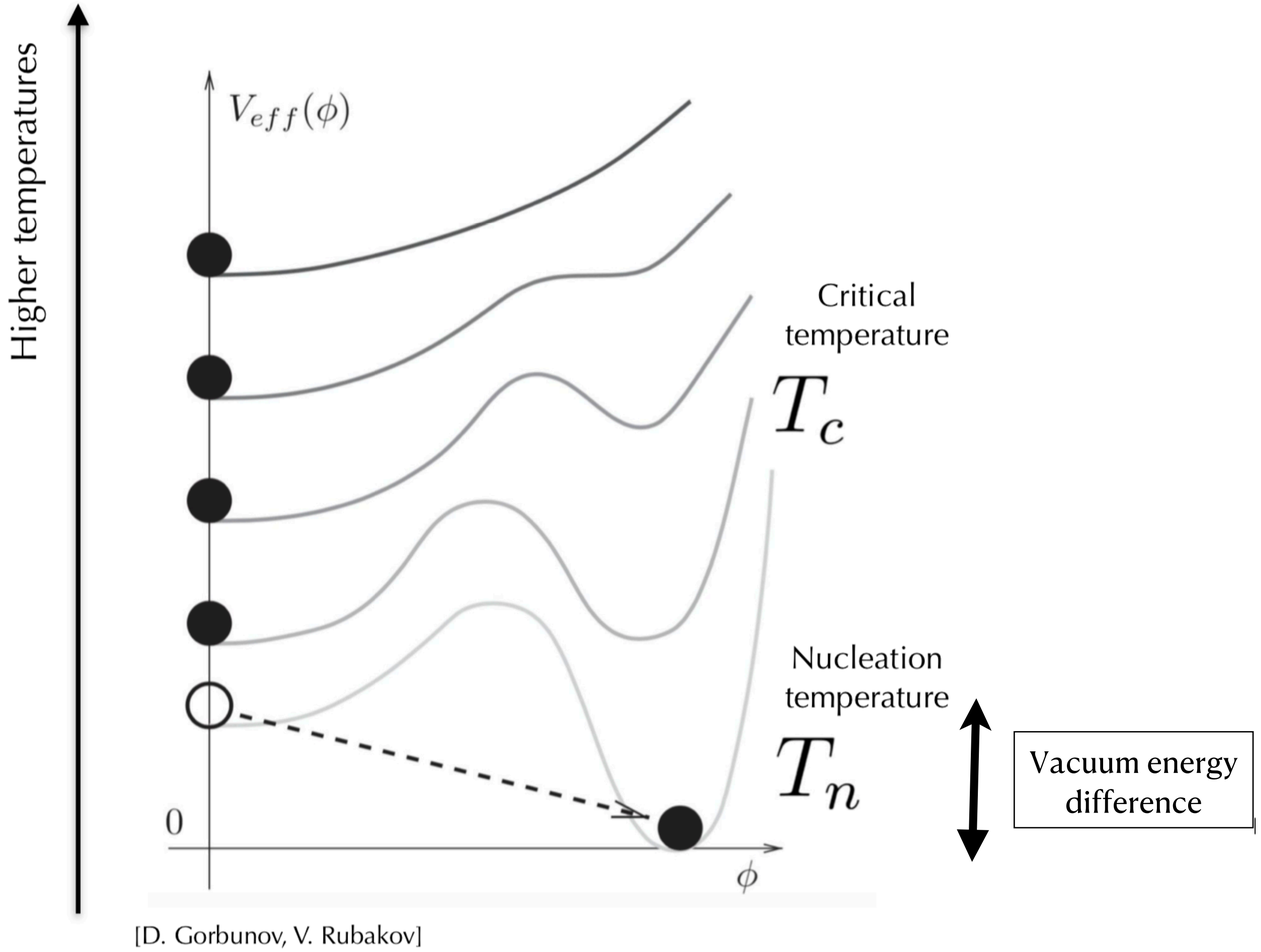
Cosmological phase transitions



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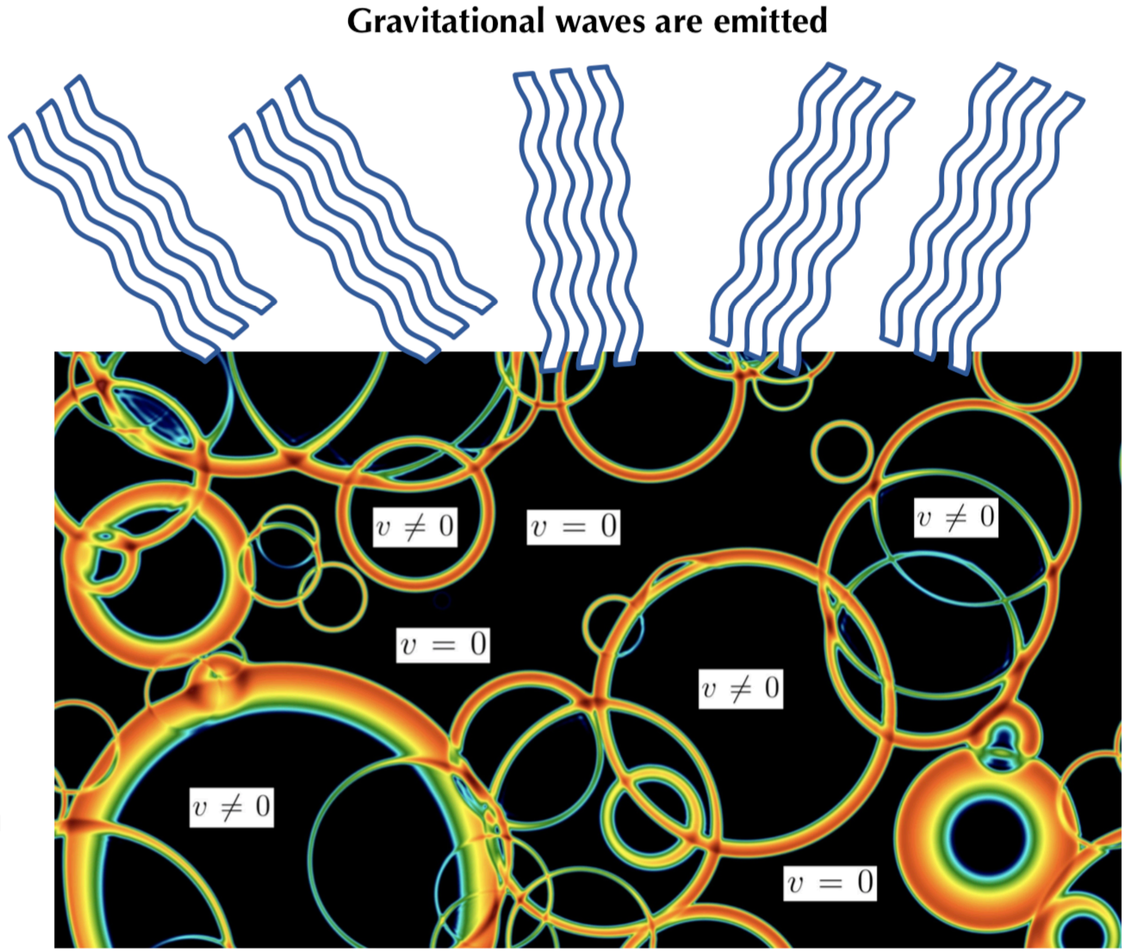

$$\Gamma_{\text{bub}} = H^4$$

Nucleation temperature

The lowest order contribution from the expansion of gravitational waves in spherical harmonics is the quadrupole moment
Gravitational radiation is mainly generated after the bubbles collide and the spherical symmetry is broken

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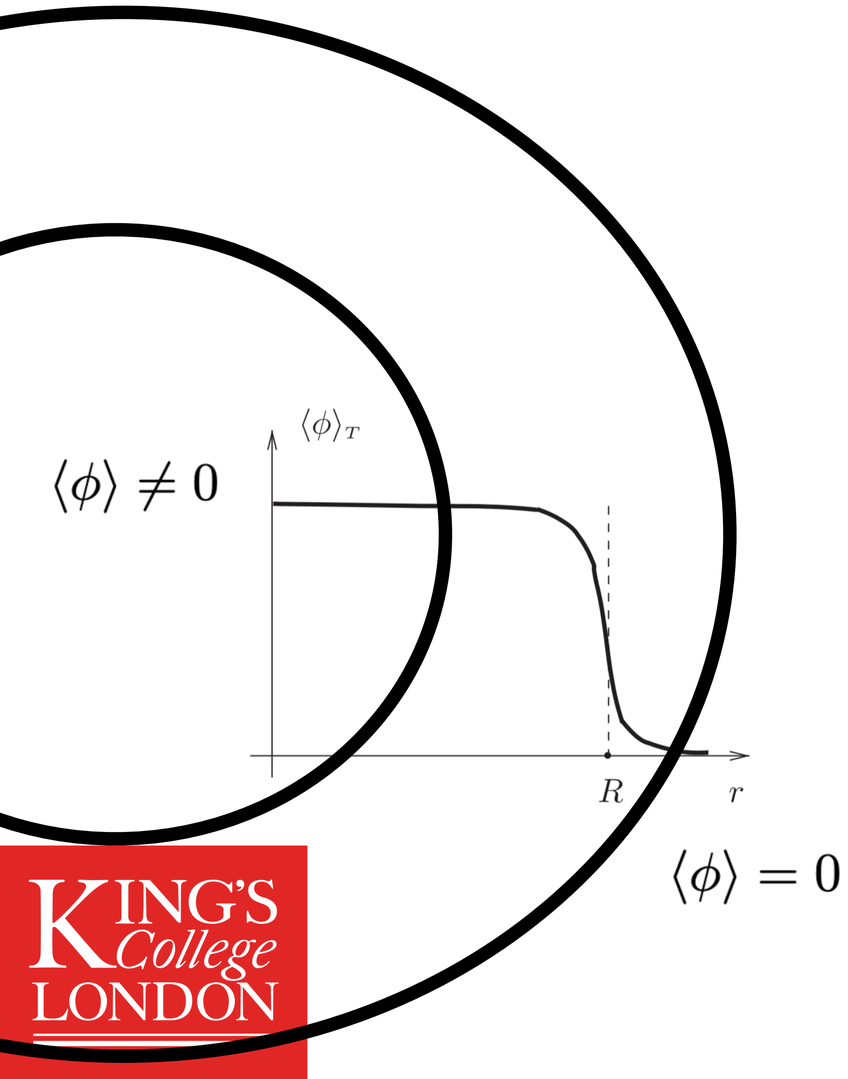
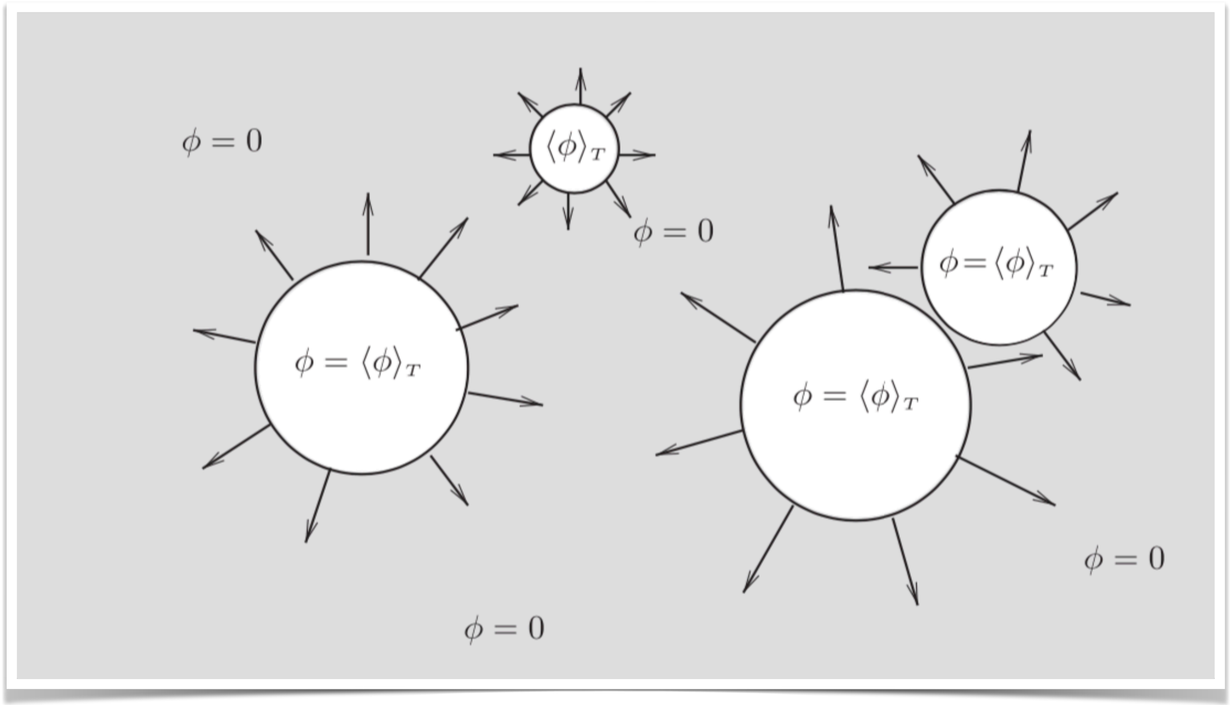
Cosmological phase transitions: PMFs

$$F^{em}_{\mu\nu} \equiv \sin(\theta_W) n^a F^a_{\mu\nu} + \cos(\theta_W) F^Y_{\mu\nu}$$

$$-i4g^{-1}\eta^{-2}\sin(\theta_W)[(D_\mu\phi)^\dagger D_\nu\phi - (D_\nu\phi)^\dagger D_\mu\phi]$$

Electromagnetic tensor





Picture, credits: Gorbunov, Rubakov

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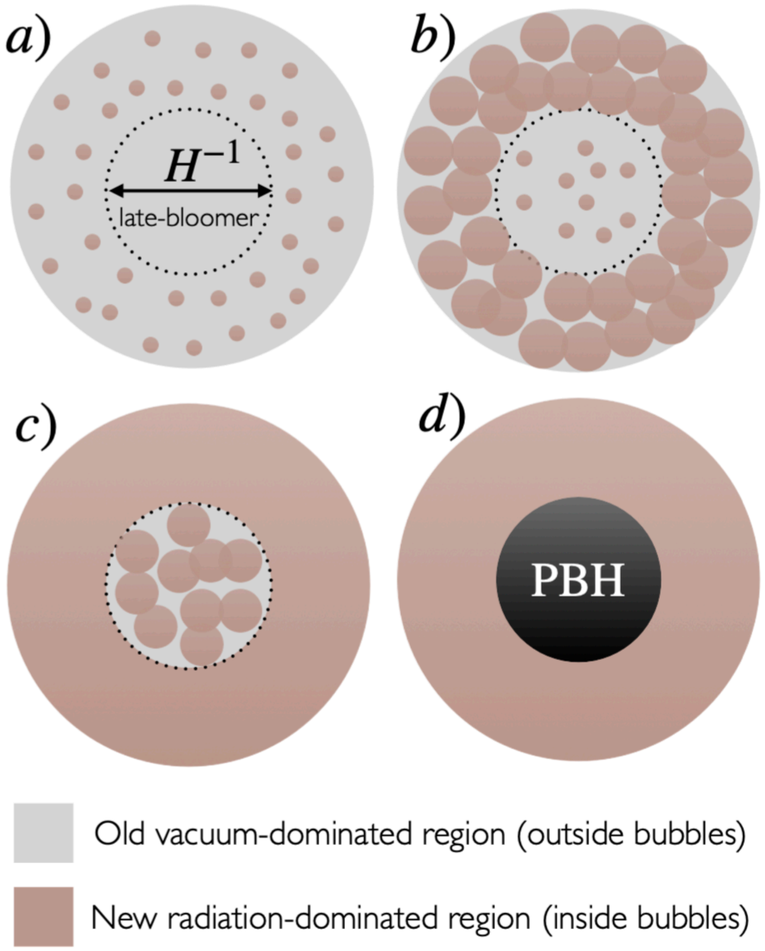
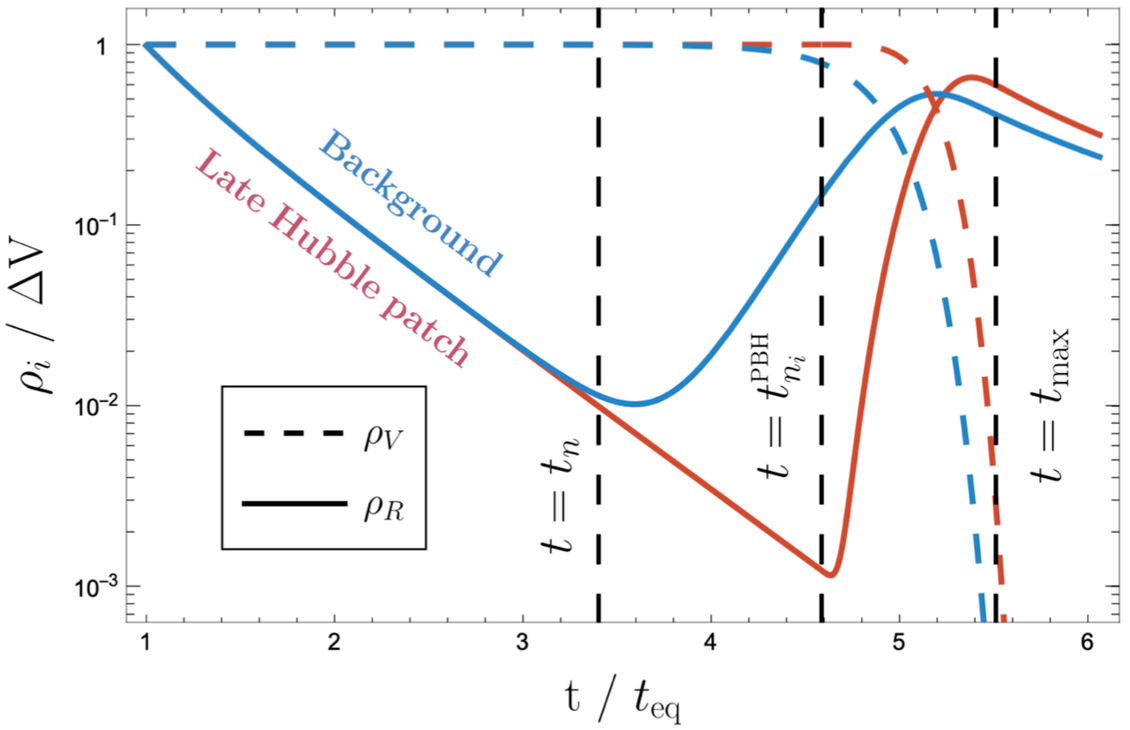
Cosmological phase transitions: PBHs



[Images: Y. Gouttenoire, T. Volansky, 2023]



$$\delta(T) \equiv \frac{\rho_{\rm radlate} - \rho_{\rm rad}}{\rho_{\rm rad}} = \delta_c = 0.45$$

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Requirements to produce black holes as all dark matter

Four parameters characterise first-order phase transitions:

$$T, \quad \beta/H, \quad \alpha \quad v_w$$

T, fixed by requiring mass of black holes in the asteroid-mass window:

$$M_{\rm PBH}\left(T_{\rm reh}\right) = M_\odot \left(\frac{20}{g_r(T_{\rm reh})}\right)^{1/2} \left(\frac{140\,{\rm MeV}}{T_{\rm reh}}\right)^2$$

$$\downarrow$$

$$10\,{\rm TeV} \lesssim T_{\rm reh} \lesssim 10^4\,{\rm TeV}$$

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$$f_{\rm PBH} = 1$$

β/H fixed by requiring all the dark matter to be primordial black holes:

$$(\beta/H)_* = \frac{a_2 W_0\left[\frac{a_3}{a_2}\left(\frac{19.5983+\log T_{\rm reh}}{a_1}\right)^{\frac{1}{a_2}}\log(1+\delta_c)\right]}{a_3\log(1+\delta_c)},$$

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In supercooled (really strong) first-order phase transitions, we have:

$$v_w \approx 1, \quad \alpha \to \infty$$

$$f_{\rm PBH} = 1$$

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Magnetic field production and evolution

simulations
[1711.03804]
[0907.0197]
[1303.7121]

Production

$$\rho_{B,*} = 0.1 \frac{\kappa_{\rm col}\alpha}{1+\alpha}\rho_* \approx \frac{\pi^2}{3} T_{\rm reh}^4 \approx 0.1\,\rho_{\rm vac}$$

Here, $\rho_* = \frac{3M_{\rm Pl}^2}{8\pi} H_*^2 = \frac{g_r(T_{\rm reh})\pi^2}{30} T_{\rm reh}^4 \approx \rho_{\rm vac}$ is the total energy density at the percolation temperature.

$$B_* = \sqrt{2\rho_*}$$

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$$B_* = \sqrt{2\rho_*}$$

Evolution

$$q_b = \frac{2}{b+3} \quad \text{and} \quad p_b = \frac{2}{b+3}(b+1)\,,$$

$$B \sim a^{-p_b/2}, \quad \lambda \sim a^{q_b}$$

$$b = 0 \text{ and } b = 1$$

non-helical evolution

maximally helical evolution

Inverse cascade of magnetic energy

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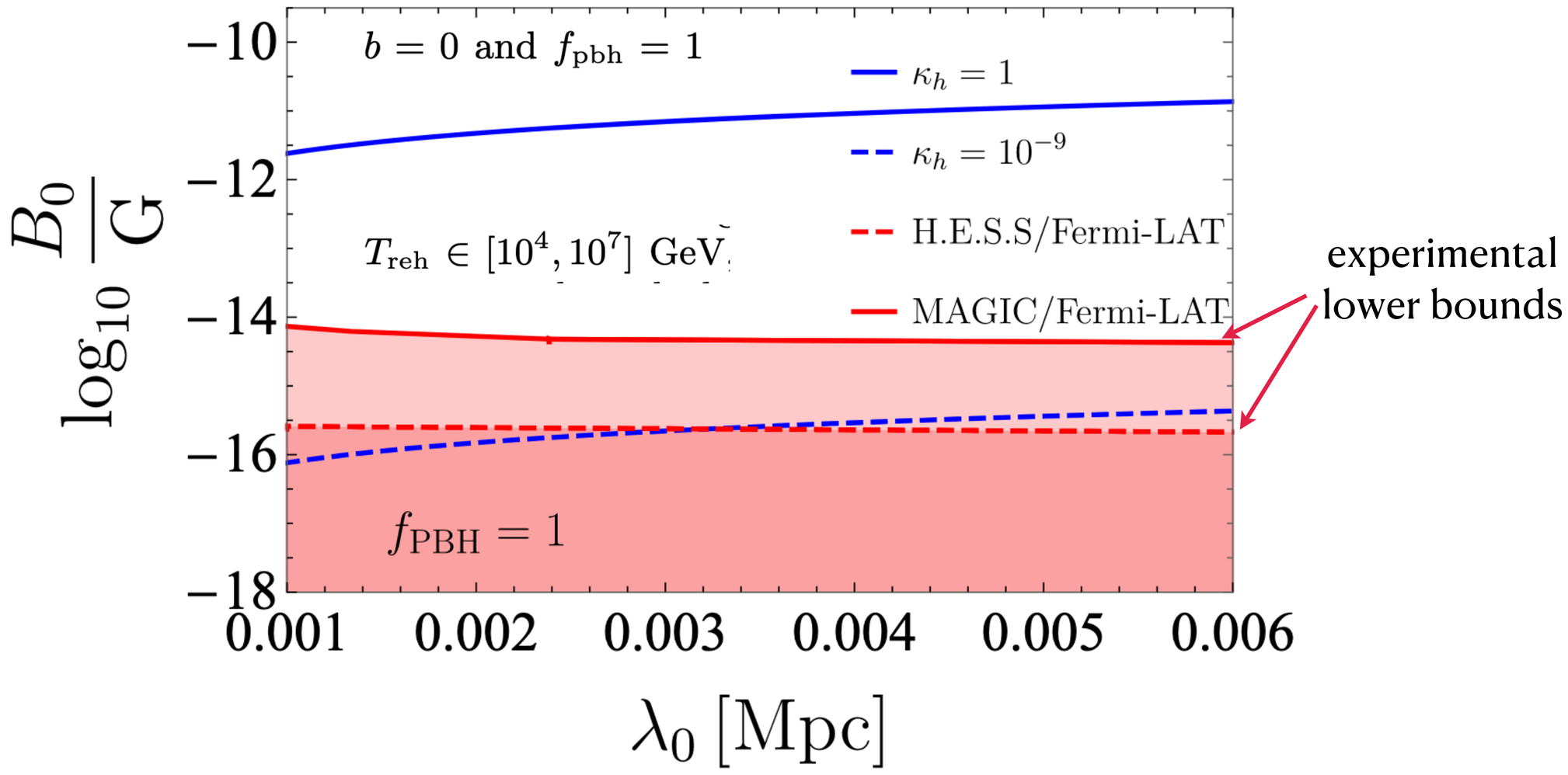
Results



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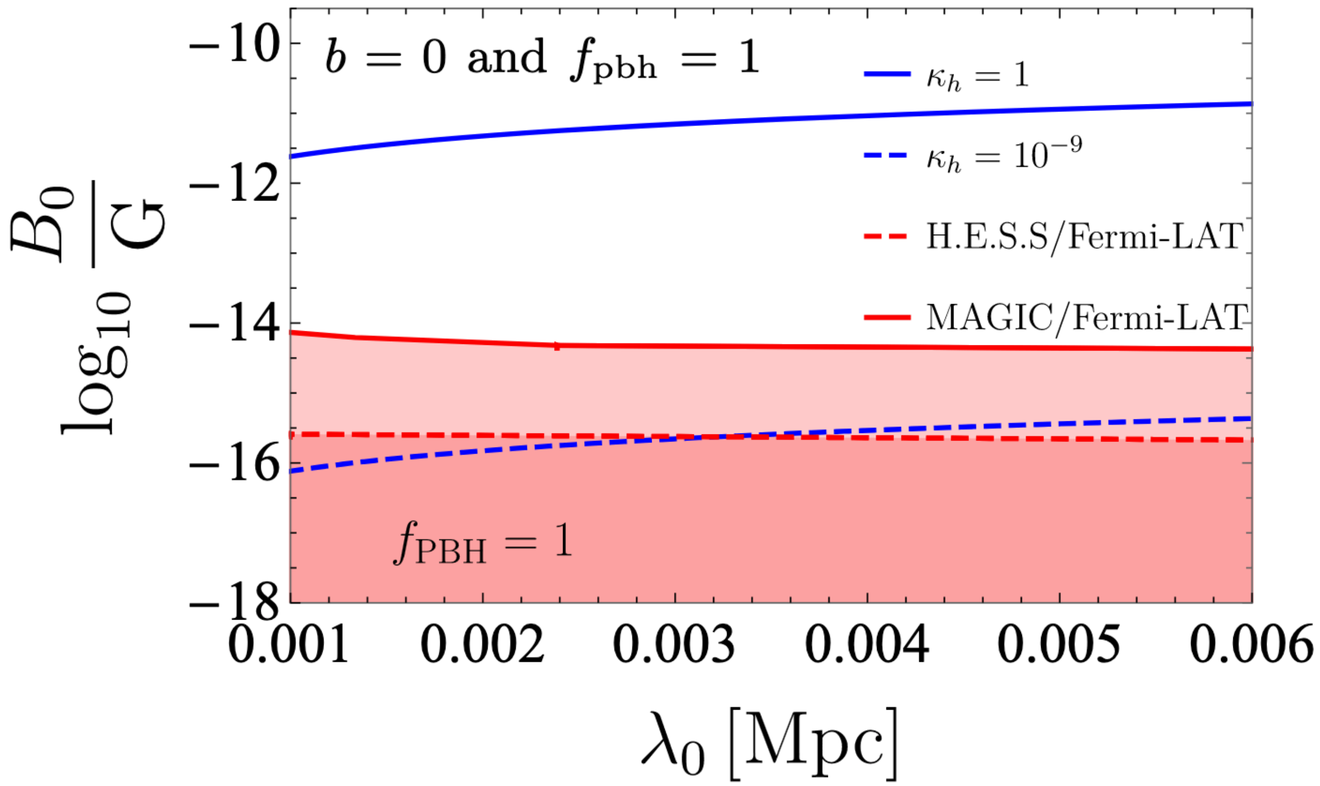
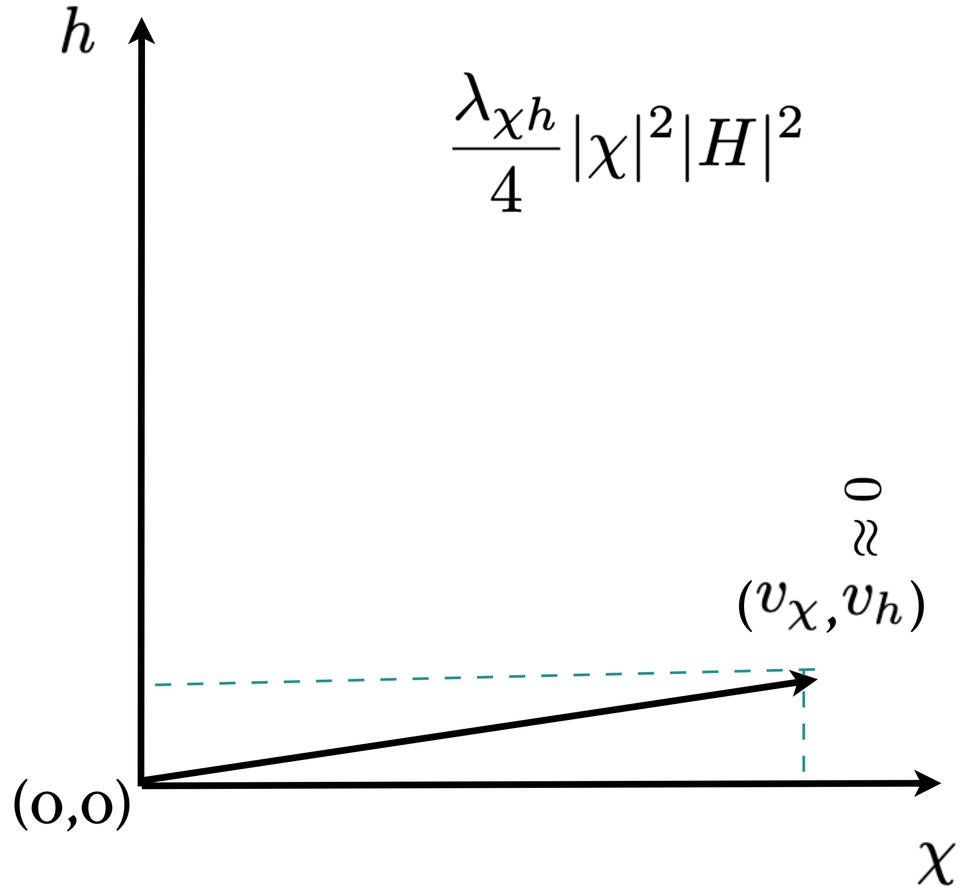
Results

$$B \approx \sqrt{2\kappa_h \rho_B}$$





We need a dark scalar and the transfer to the Standard Model sector is small for benchmark models...

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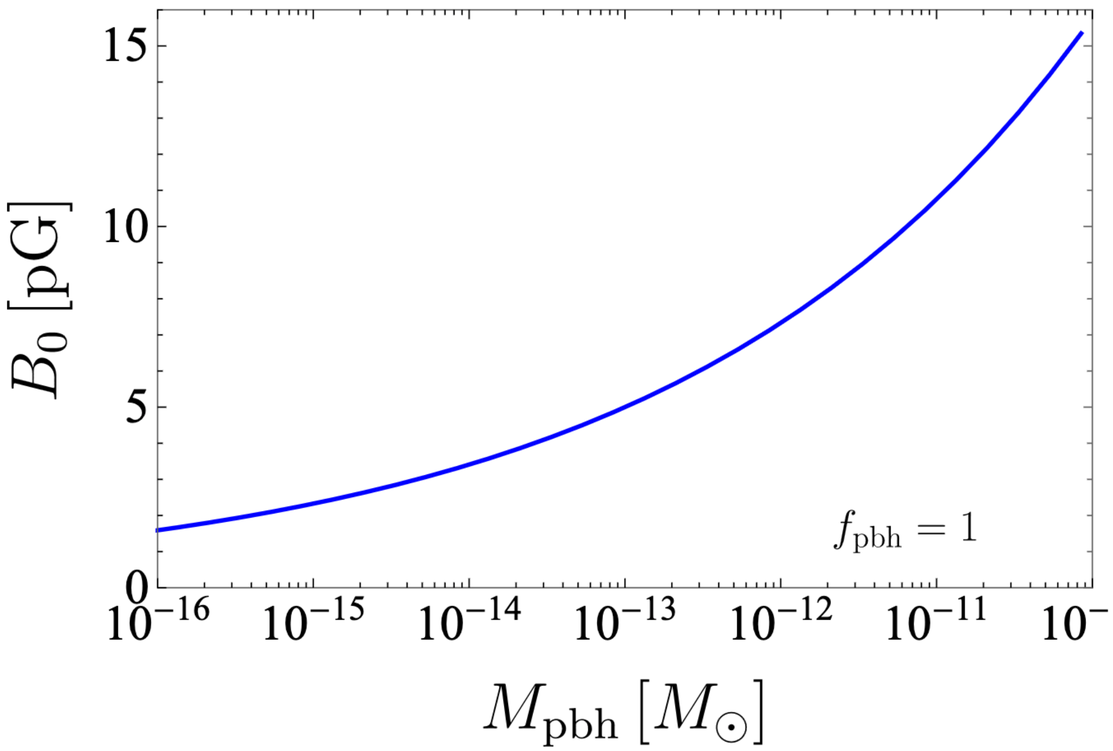
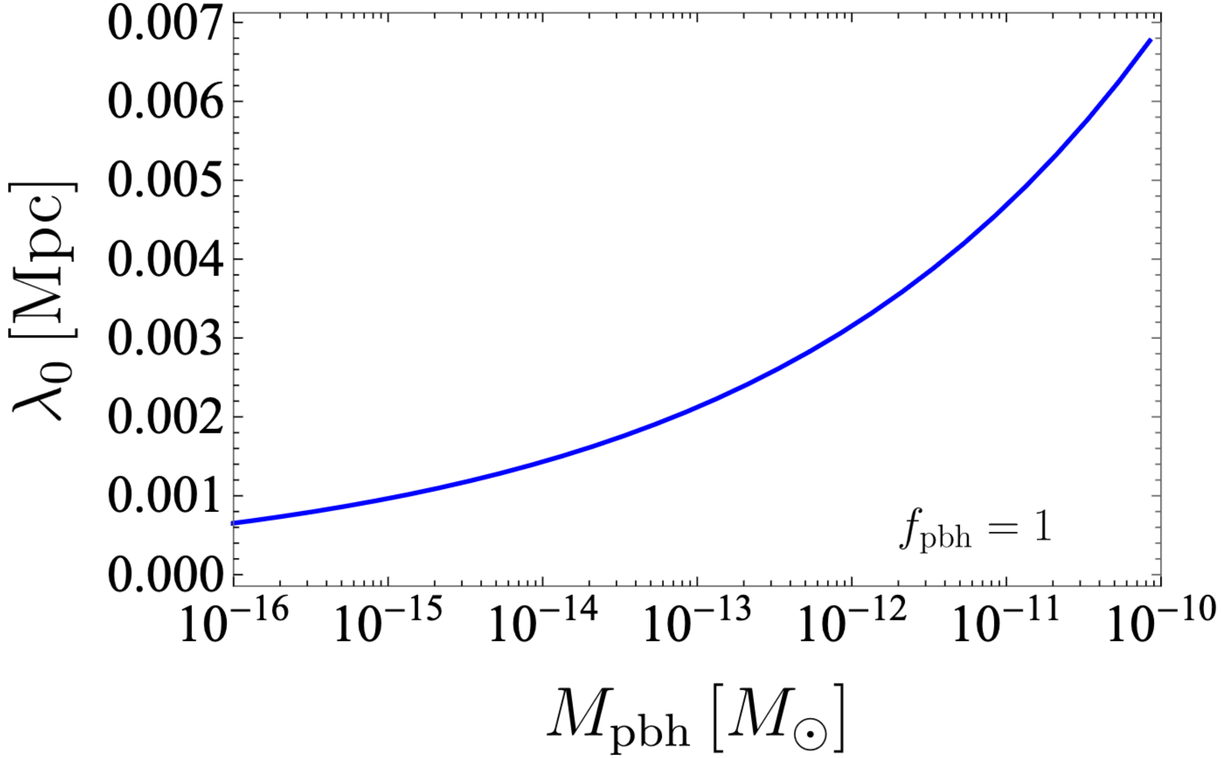
Results





We can relate the value of the magnetic field and the coherence length to the PBH mass

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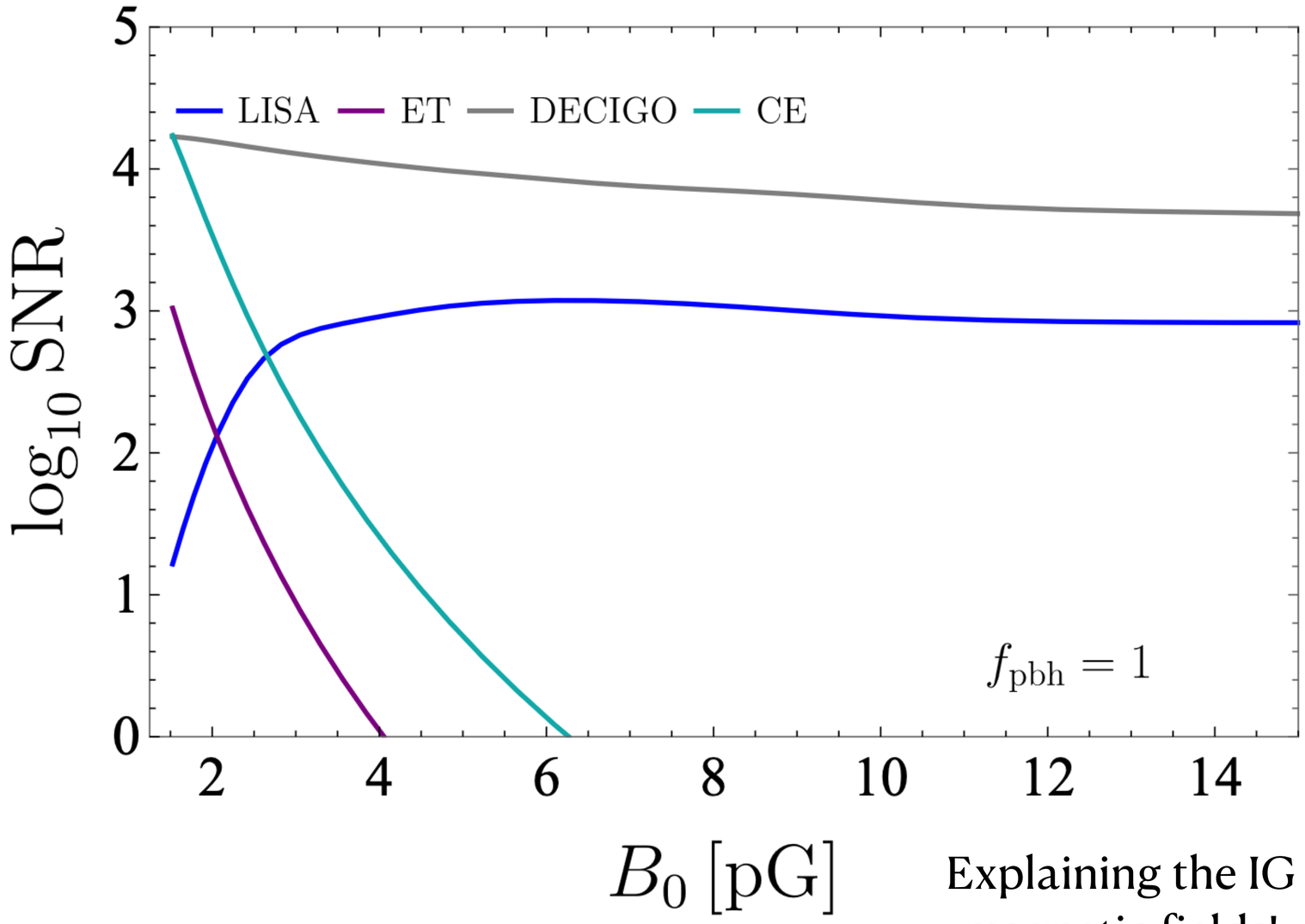
Results

Detectable GWs!



Explaining the IG magnetic fields!

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Conclusions

- We investigated slow first-order phase transitions as a source of dark matter primordial black holes and primordial magnetic fields.
- We explain blazar observations and dark matter.
- This process also generates strong gravitational wave (GW) signals.
- Multimessenger probles: GWs (large SNRs) and gamma-ray telescopes (proposals for probing asteroid-mass dark matter).

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Thank you!

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