DARK MATTER
VIA INVERSE PHASE TRANSITION

SABIR RAMAZANOV (CEICO, PRAGUE)
IN COLLABORATION WITH E. BABICHEV, D. GORBUNOV, F. URBAN, A. VIKMAN

COPERNICUS WEBINAR

06.04.2021

INTRODUCTION

WHAT IS DARK MATTER?

(Nearly) pressureless fluid $\mathcal{P}_{DM} \approx 0 \Longrightarrow \rho_{DM} \propto \frac{1}{a^3(t)}$

Stable on cosmological scales

Weakly/feebly interacting with other matter fields

Only gravitational manifestations of Dark Matter are known

Zoo of Dark Matter models:

10^{-21} eV $\lesssim M \lesssim$ (tens of) M_{Sun}

Ultralight axions, axions (or ALPs),
WIMPS,
superheavy Dark Matter (WIMPZILLAs), primordial black holes

Mechanisms of Dark Matter production

- Freeze-out: relatively large Dark Matter couplings to maintain early time thermal equilibrium.

- Freeze-in: feebly coupled Dark Matter.

  No equilibrium at any time. McDonald’02, Hall et al’10

- Gravitational production: typically superheavy Dark Matter.

  Chung, Kolb, and Riotto’98 Tkachev and Kuzmin’98

- Collapse of large curvature perturbations: primordial black holes.

  Zel’dovich and Novikov’67, Carr and Hawking’74

- Misalignment mechanism (axions, ALPs).

INVERSE PHASE TRANSITION

$$V_{eff} = \frac{M^2 \cdot \chi^2}{2} + \frac{\lambda \cdot \chi^4}{4} - \frac{\chi^2 \mu^2(t, \mathbf{x})}{2}$$

The field χ is not in thermal equilibrium with plasma.

Variety of possible $\mu^2(t, \mathbf{x}) \Longrightarrow$ class of models

$$\mu^2(t, \mathbf{x}) \propto R,\ \mathbf{B^2}, \dots$$

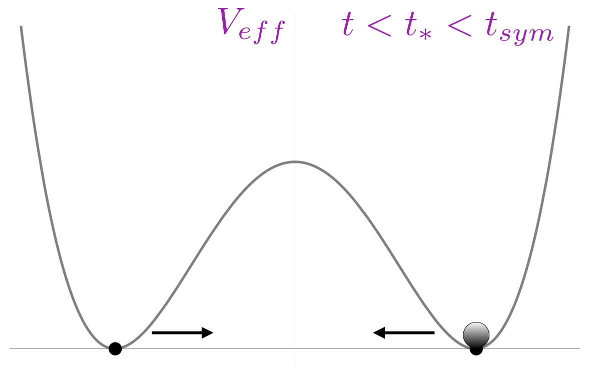
———————————————————————————-

Dynamics is largely independent of choice of $\mu^2(t)$

$$\mu^2(t) \propto \frac{1}{a^n(t)}$$

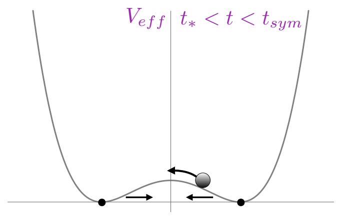
Large $\mu^2(t)$ at early times $\Longrightarrow$ spontaneous symmetry breaking

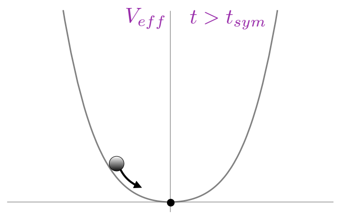
$\mu^2(t) \ll M^2$ at late times $\Longrightarrow$ symmetry is restored



$$\langle\chi\rangle = \sqrt{\frac{\mu^2(t) - M^2}{\lambda}} \Longrightarrow$$

$$\frac{d\langle\chi\rangle}{dt} \propto \frac{1}{\sqrt{\mu^2(t) - M^2}} \to \infty \qquad \text{as} \qquad \mu^2(t) \to M^2$$





$$\chi(t) \simeq \frac{M^{2/3} \cdot H_*^{1/3}}{\sqrt{\lambda}} \cdot \left(\frac{a_*}{a(t)}\right)^{3/2} \qquad \rho_{DM} \simeq \frac{M^2 \chi^2(t)}{2} \simeq \frac{M^{10/3} \cdot H_*^{2/3}}{\lambda} \cdot \left(\frac{a_*}{a(t)}\right)^3$$

$$\frac{\dot{\mu}(t_*)}{\mu(t_*)} \simeq H_* \qquad M \gtrsim H_*$$

Three faces of inverse phase transition

THREE FACES OF INVERSE PHASE TRANSITION

- Gravitational face: $\mu^2 \propto R$

  E. Babichev, D. Gorbunov, S. R.'20

- Magnetic face $\mu^2 \propto \mathbf{B}^2$

  S. R., F. Urban, A. Vikman'20

- Thermal face (work in progress): $\mu^2 \propto T^2$

  S. R., E. Babichev, D. Gorbunov, A. Vikman-work in progress

GRAVITATIONAL FACE: $\mu^2 = -\xi R$

$$V_{eff} = \frac{(M^2 + \xi R) \cdot \chi^2}{2} + \frac{\lambda \chi^4}{4} \qquad \xi \gg 1$$

$$M^2 \approx -\xi R_* \approx 12 \xi H_*^2$$

$$M \approx 10^{15}\ \text{GeV} \qquad H_* \approx 10^{13}\ \text{GeV} \qquad \xi \approx 10^3$$

One can create a huge amount of Dark Matter during inflation.

If Dark Matter is created $15 - 20$ e-folds before the end of inflation, it can get diluted down to the observed value.

MAGNETIC FACE: $\mu^2 \propto \mathbf{B}^2$

$$V_{eff} = \frac{M^2 \cdot \chi^2}{2} + \frac{\lambda \cdot \chi^4}{4} - \frac{\chi^2 \cdot F^{\mu\nu} \cdot F_{\mu\nu}}{4\Lambda^2}$$

Rayleigh operator $\frac{\chi^2 \cdot F^{\mu\nu} \cdot F_{\mu\nu}}{4\Lambda^2} \Longrightarrow \frac{\chi^2 \cdot \mathbf{B}^2}{2\Lambda^2}$

$$F^{\mu\nu} F_{\mu\nu} = 2(\mathbf{B}^2 - \mathbf{E}^2) \qquad \mathbf{E} \to 0$$

$$V_{eff} = \frac{[M^2 - \mathbf{B}^2/\Lambda^2] \cdot \chi^2}{2} + \frac{\lambda \cdot \chi^4}{4}$$

Spontaneous symmetry breaking for large **B**

Recall that $B \propto 1/a^2$

One needs seeds for magnetic fields in galaxies.

Non-observation of gamma-rays from TeV blazars

Neronov and Vovk'10

$B \gtrsim 10^{-7}$ nG (or 10^{-16} G)   1 G(auss) $= 1.95 \cdot 10^{-20}$ GeV^2

Magnetic fields $B \sim 0.05$ nG relieve Hubble tension

Jedamzik and Pogosian'20

CMB limit: $B \lesssim 0.01 - 0.05$ nG   Jedamzik and Saveliev'18

Planck'15 limit: $B \lesssim 1$ nG

Rotation measures: $B \lesssim 1$ nG   Pshirkov, Tinyakov, Urban'15

LONG STORY SHORT

There are good reasons to expect that magnetic fields had primordial origin

$$10^{-7}\ \mathrm{nG} \lesssim B \lesssim 5 \cdot 10^{-2}\ \mathrm{nG}$$

One could probe this region from the studies of first star formation, reionization etc.

Our way: amplify magnetic fields effects through interactions with beyond the Standard Model sector.

$$V_{eff} = \frac{[M^2 - \mathbf{B}^2/\Lambda^2]\cdot\chi^2}{2} + \frac{\lambda\cdot\chi^4}{4}$$

Primordial magnetic fields are inhomogeneous! $\Longrightarrow$ time, when oscillations start t_*, is inhomogeneous $\Longrightarrow$ source of non-trivial phenomenology

$$\delta\mathbf{B}(t_*, \mathbf{x}) \to \delta t_*(\mathbf{x}) \to \delta\chi(t_*, \mathbf{x}) \to \delta\rho_\chi(t_*, \mathbf{x})$$

Assume a homogeneous background $\mathbf{B}(t,\mathbf{x}) = \mathbf{B}(t) + \delta\mathbf{B}(t,\mathbf{x})$

$$|\delta\mathbf{B}(t,\mathbf{x})| \ll |\mathbf{B}(t)|$$

Discussed in inflationary context.

Turner and Widrow’88   Issues: Demozzi, Mukhanov, Rubinstein’09

Not applicable to magnetic fields from phase transitions.

Vachaspati’91   Durrer and Caprini’03

Typically large isocurvature perturbations!

$$\frac{\delta\rho_\chi(\mathbf{x})}{\rho_\chi} = \frac{5}{6}\cdot\frac{\mathbf{B}_*\delta\mathbf{B}_*(\mathbf{x})}{B_*^2} \qquad \left(\text{normally } \frac{\delta\rho_{DM}(\mathbf{x})}{\rho_{DM}} \propto \frac{\delta T(\mathbf{x})}{T}\right)$$

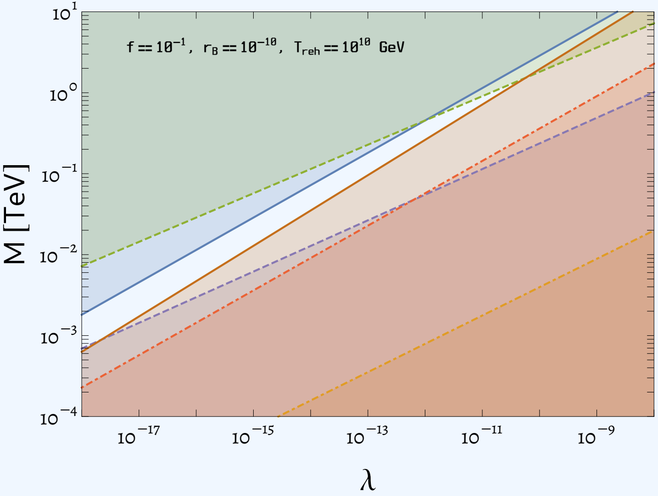
Generally, the field χ should constitute only a fraction of DM.

$$P_{\mathcal{S}_{DM}(k)}/P_\zeta(k) < 0.038 \;\; \text{(Planck'18)} \Longrightarrow f \equiv \frac{\rho_\chi}{\rho_{DM}} \ll 1$$

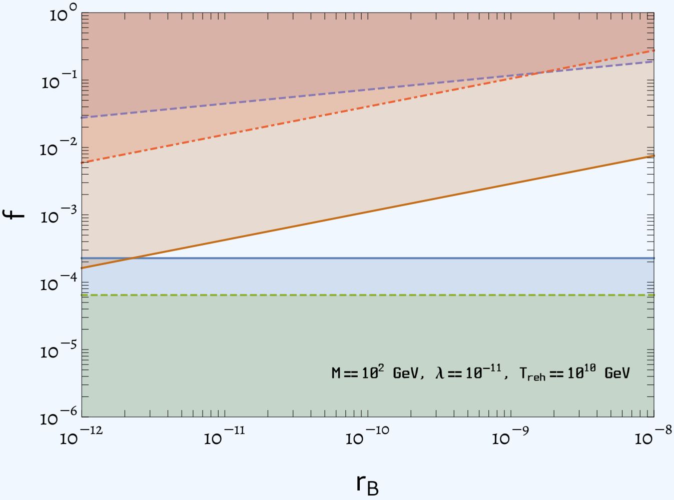
Isocurvature perturbations are direction-dependent:

$$P_{\mathcal{S}_{DM}}(\mathbf{k}) = \frac{25\cdot f^2}{36}\cdot\frac{P_B(k)}{B^2}\cdot(\hat{\mathbf{B}}\times\hat{\mathbf{k}})^2$$

Pretty rare prediction, which hints at non-trivial interactions of DM with long range vectors, cf. Nakayama'2019



The main constraint comes from freeze-in: $\gamma + \gamma \to \chi + \chi$. One should not overproduce DM!



$$r_B \simeq \frac{\rho_B}{\rho_{rad}} \simeq 10^{-12} \Longrightarrow B \simeq 10^{-3}\ \text{nG}$$

THERMAL FACE: $\mu^2 \propto T^2$

$$V_{eff} = \frac{M^2 \cdot \chi^2}{2} + \frac{\lambda \cdot \chi^4}{4} - \frac{g^2 \chi^2 \phi^\dagger \phi}{2} \, .$$

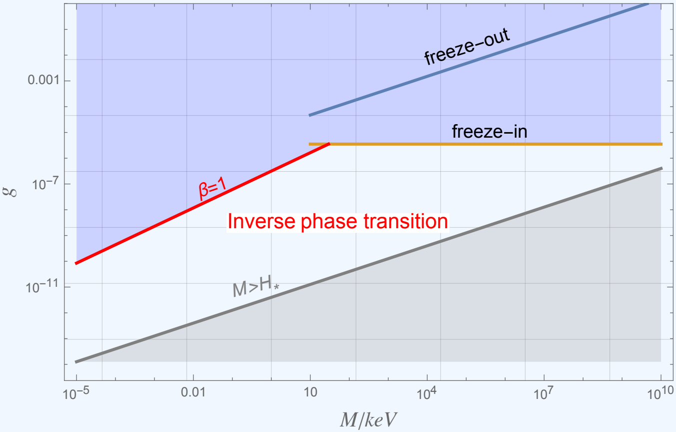
Assume that ϕ is in thermal equilibrium with hot plasma.
Could be Higgs field.

$$\langle \phi^\dagger \phi \rangle_T = \frac{T^2 N}{12} \qquad T \propto \frac{1}{a(t)}$$

- $|g^2| \simeq 0.1 - 0.01 \Longrightarrow$ freeze-out
- $|g^2| \simeq 10^{-11} \Longrightarrow$ freeze-in

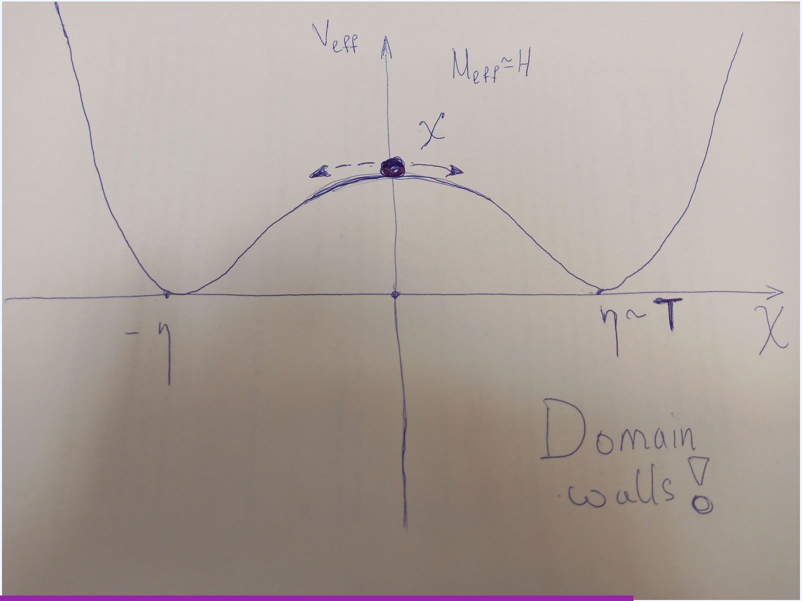
  Chu, Hambye, Tytgat'11, Yaguna'11, Lebedev and Toma'19
- $|g^2| \lesssim 10^{-11} \Longrightarrow$ inverse phase transition

IS THERE LIFE BEYOND FREEZE-IN?



$$\beta \equiv \frac{\lambda}{g^4} > \frac{1}{\lambda_\phi}$$

LONG TIME BEFORE: DOMAIN WALLS



DOMAIN WALLS ARE MELTING

Domain walls are harmless, because their tension decreases as the cube of the temperature.

$$\sigma_{wall} \propto \sqrt{\lambda}\eta^3 \propto T^3$$

$$\rho_{wall} \simeq \sigma_{wall} H \propto T^5 \qquad (\rho_{rad} \propto T^4)$$

MORE WEAKLY COUPLED MEANS MORE VISIBLE!

Domain walls emit gravitational waves!
See the analysis in Hiramatsu, Kawasaki, Saikawa’2013

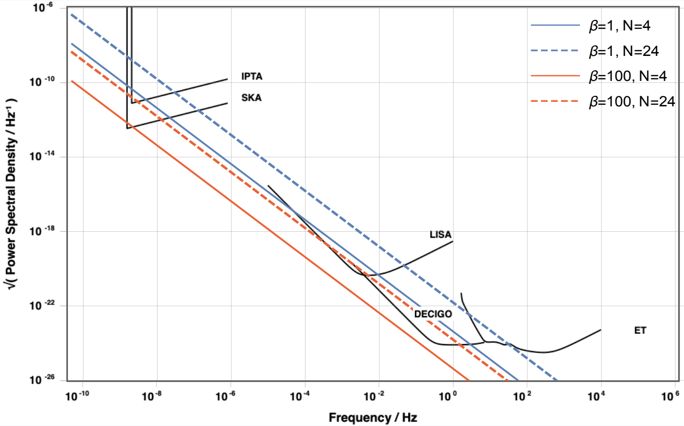
$$f_{gw} \simeq 60\ \mathrm{Hz} \cdot N^{1/2} \cdot \left(\frac{g}{10^{-8}}\right) \cdot \left(\frac{100}{g_*(T)}\right)^{1/3}$$

$$\Omega_{gw} \cdot h^2(t_0) \approx \frac{4 \cdot 10^{-14} \cdot N^4}{\beta^2} \cdot \left(\frac{100}{g_*(T)}\right)^{7/3}$$

Vanilla region:

$$\beta \equiv \frac{\lambda}{g^4} \simeq 1 \qquad N \gg 1$$

GRAVITATIONAL WAVES



gwplotter.com Moore, Cole, and Berry'14

SUMMARY

- Dark Matter can be produced through inverse phase transition.

- Gravitational version: Dark Matter already during inflation.

- Magnetic version: statistically anisotropic isocurvature perturbation.

- Thermal version: thawing domain walls and gravitational waves.

To be continued.

Thanks for listening!!!