Asteroid-mass soliton as the dark matter-baryon coincidence solution

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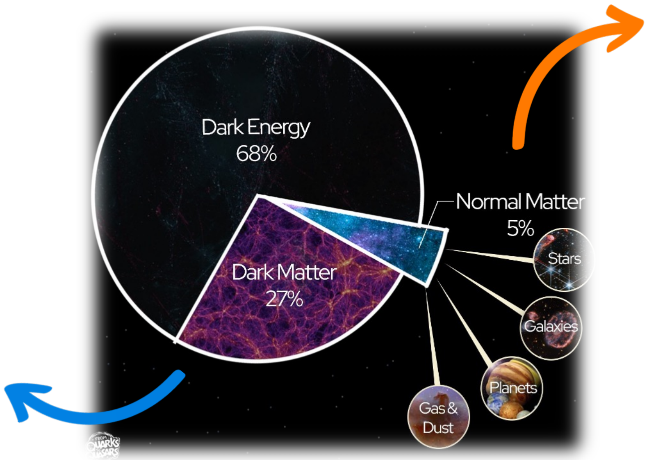
2025.7.16@The 6th Workshop on Frontiers of Particle Physics, Changchun

Based on 2504.08304, with Shinya Kanemura and Shao-Ping Li

Two longstanding mysteries

What is dark matter?

$\Omega_{\rm dm} \sim 0.27$



Where is antimatter?

$\Omega_{\rm B} \sim 0.05, \Omega_{\overline{\rm B}} \sim 0$

Two longstanding mysteries

What is dark matter?

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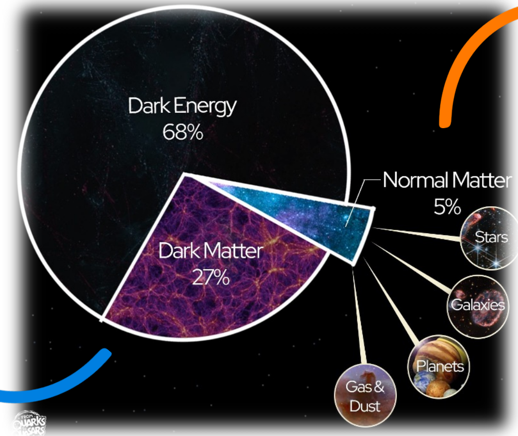


Where is antimatter?

$\Omega_{\mathrm{B}} \sim 0.05, \Omega_{\overline{\mathrm{B}}} \sim 0$

A ***third*** mystery ...

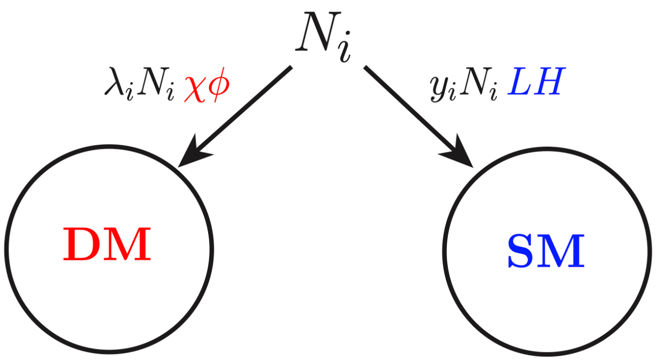
The cosmic **coincidence** problem: why is $\Omega_{\mathrm{dm}}/\Omega_{\mathrm{B}} \approx 5 \sim \mathcal{O}(1)$?

無 → Matter

→ Antimatter —Somehow→ Dark matter

Asymmetric dark matter

Previous: **particle** dark matter Zurek, 1308.0338 (review)



Leptogenesis, Falkowski et al, 1101.4936

General feature:

- $n_{\rm dm} \sim n_{\rm B}$, therefore $\Omega_{\rm dm} \sim 5\Omega_{\rm B} \Rightarrow m_{\rm dm} \sim \mathcal{O}(5~{\rm GeV})$

See also

Kaplan, PRL 68 (1992) 741-743; Barr, PRD 44 (1991) 3062–3066; Hooper *et al*, hep-ph/0410114; Kitano *et al*, hep-ph/0411133; Farrar *et al*, hep-ph/0510079; etc

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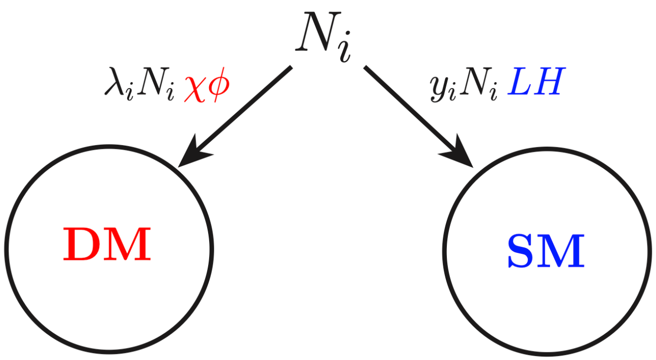

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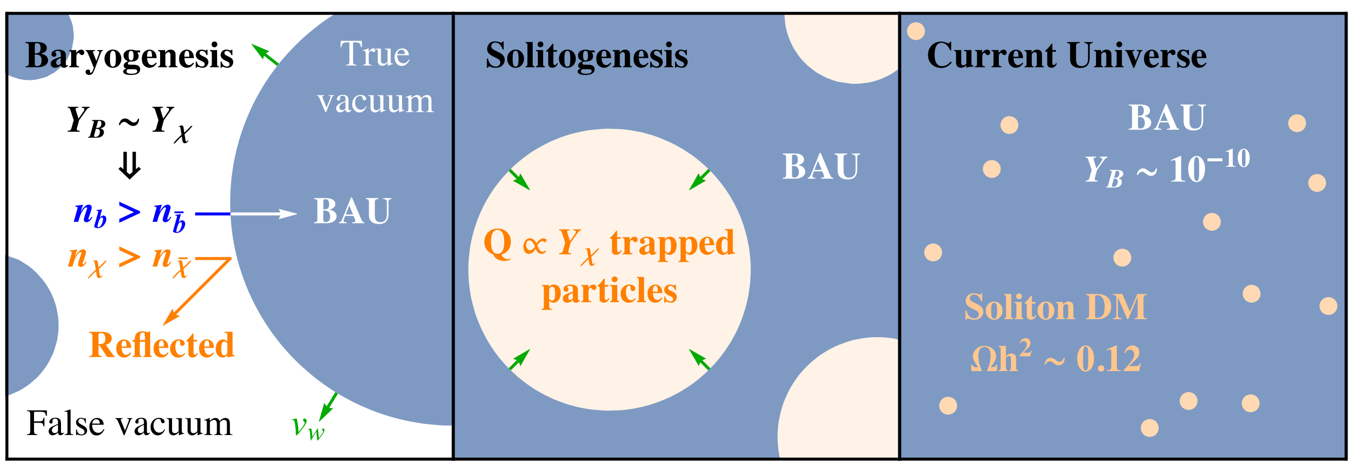
This talk: **macroscopic** dark matter Kanemura, Li, and **KPX**, 2504.08304

- Needs the assistance of the *cosmic bubbles*



An illustrative model

Dirac **type-I seesaw** Roncadelli *et al*, PLB 133 (1983) 325–329; Chuliá *et al*, 1606.04543

SM Higgs doublet

Right-handed SM neutrino

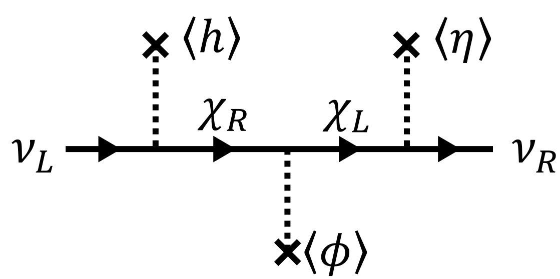
$$\mathcal{L} = -y_h \bar{\ell}_L \widetilde{H} \chi_R - y_\eta \bar{\chi}_L \eta \nu_R - y_\phi \bar{\chi}_L \phi \chi_R + \mathrm{h.c.}$$

SM lepton doublet

Sterile neutrino

ϕ & η: real singlet scalars

Sterile neutrino mass $m_\chi = y_\phi \langle \phi \rangle$



SM **Dirac neutrino** mass

$$m_\nu \approx \frac{y_h \langle h \rangle \cdot y_\eta \langle \eta \rangle}{y_\phi \langle \phi \rangle} \approx 17\ \mathrm{meV} \times \left(\frac{y_h}{10^{-6}}\right)\left(\frac{y_\eta}{10^{-4}}\right)\left(\frac{\langle \eta \rangle}{10^{-3} m_\chi}\right)$$

Overview of our mechanism

Yukawa couplings

$-y_h \bar{\ell}_L \widetilde{H} \chi_R$

$-y_\eta \bar{\chi}_L \eta \nu_R$

$-y_\phi \phi \bar{\chi}_L \chi_R$

$\bar{\ell}_L \widetilde{H} \chi_R$

CP-violating Higgs decay

Y_χ $\quad$ Y_L

$B - L$ conservation

$Y_\chi + Y_L = 0$

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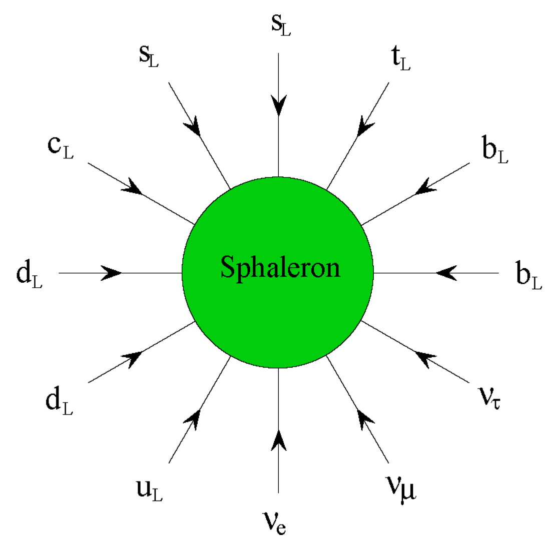
CP-violating Higgs decay

Y_χ Y_L → Sphaleron → Y_B converted (Baryon asymmetry)



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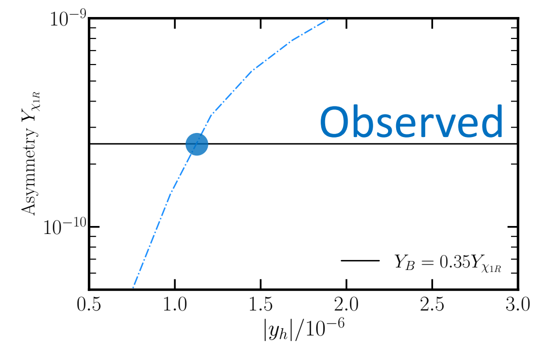
CP-violating Higgs decay

Y_χ Y_L

$Y_B \sim 0.9\times10^{-10}$

(Baryon asymmetry)



Thermalized via $\bar{\chi}_L \eta \nu_R$, $\bar{\ell}_L \tilde{H} \chi_R$

Asymmetric sterile neutrino $Y_\chi = 8Y_B/21$

$B-L$ conservation

$Y_\chi + Y_L = Y_B$

Frozen at $T < 132$ GeV

(Sphaleron decouples)

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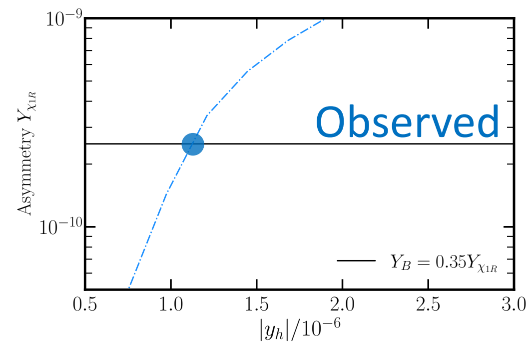

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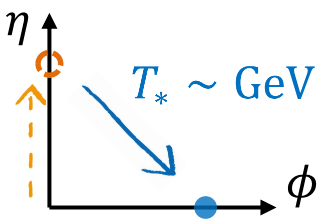
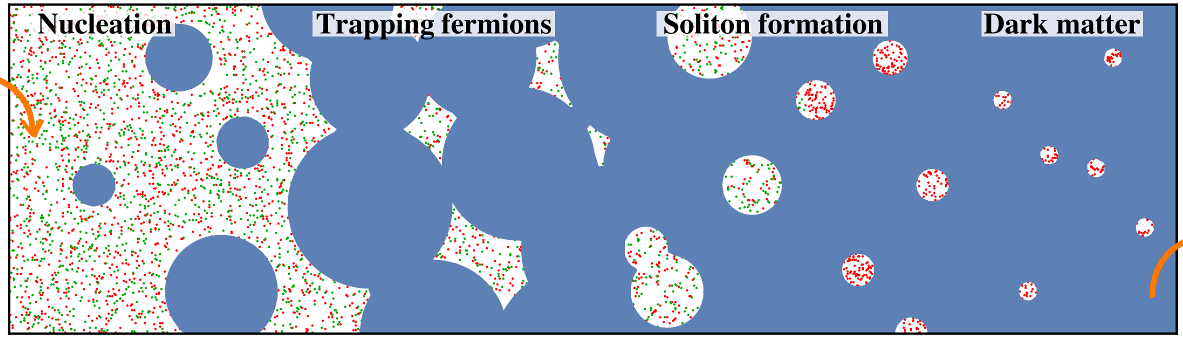


First-order phase transition

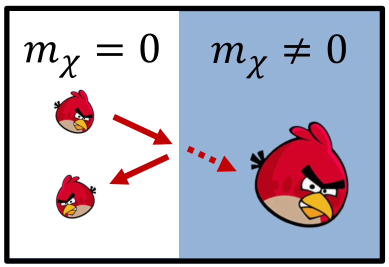
Forming macroscopic **neutrino-balls** via $\phi \bar{\chi}_L \chi_R$, dark matter candidate

Solitogenesis via bubbles

$\langle\phi\rangle = 0$
$m_\chi = 0$



$\langle\phi\rangle \neq 0$
$m_\chi = y_\phi\langle\phi\rangle$



Key Yukawa coupling: $-y_\phi\phi\bar{\chi}\chi$

Sterile neutrinos get **trapped** if $y_\phi\langle\phi\rangle_*/T_* \gg 1$

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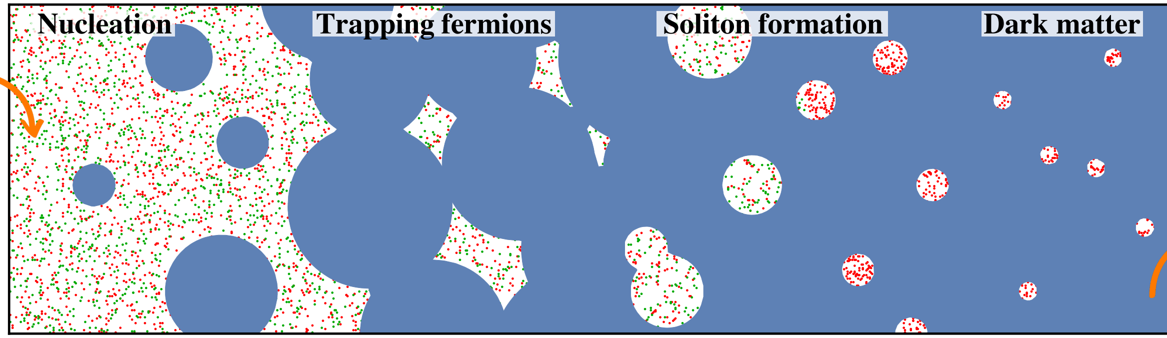

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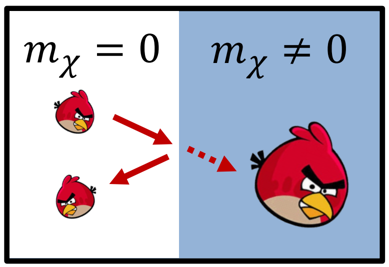

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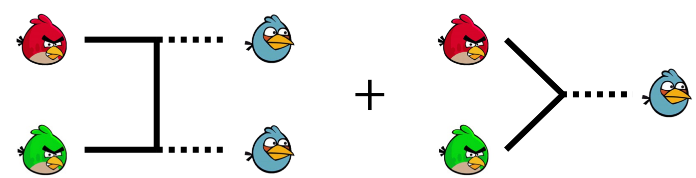
Asymmetry: $Y_\chi > 0, \Rightarrow n_\chi > n_{\bar{\chi}}$

$\bar{\chi}$ disappears, χ survives the annihilation

**Majorana particles always disappear!*



$\chi\bar{\chi} \to \phi\phi$ + $\chi\bar{\chi} \to \phi$

Solitogenesis via bubbles

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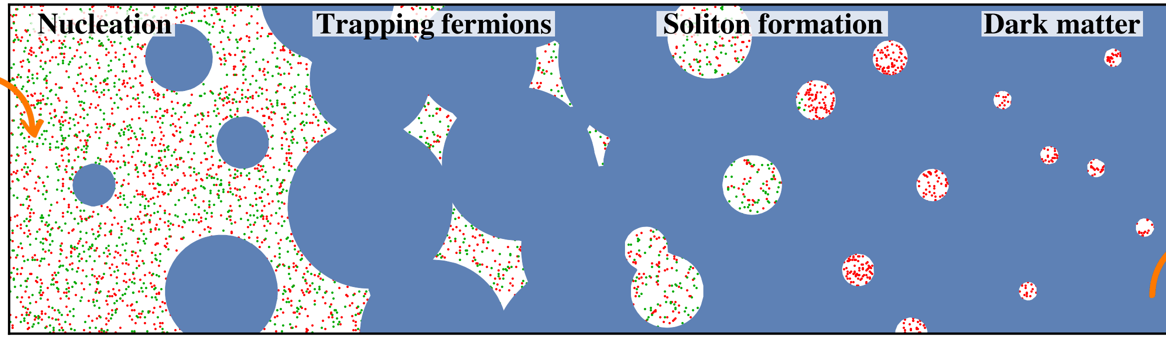

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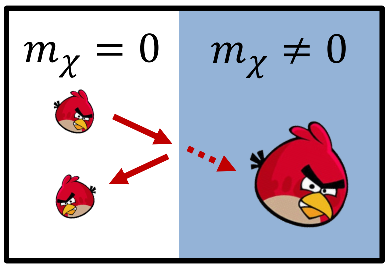

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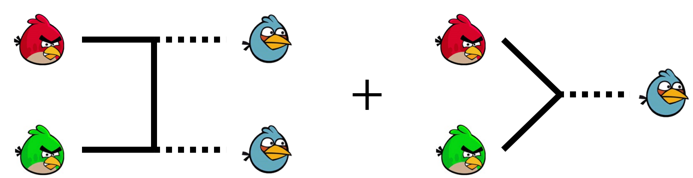

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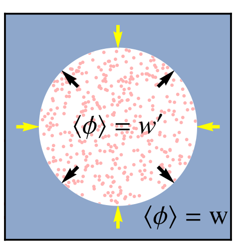
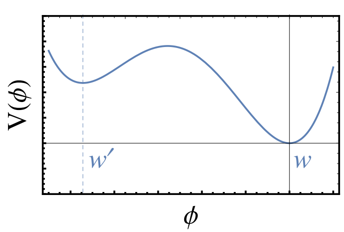


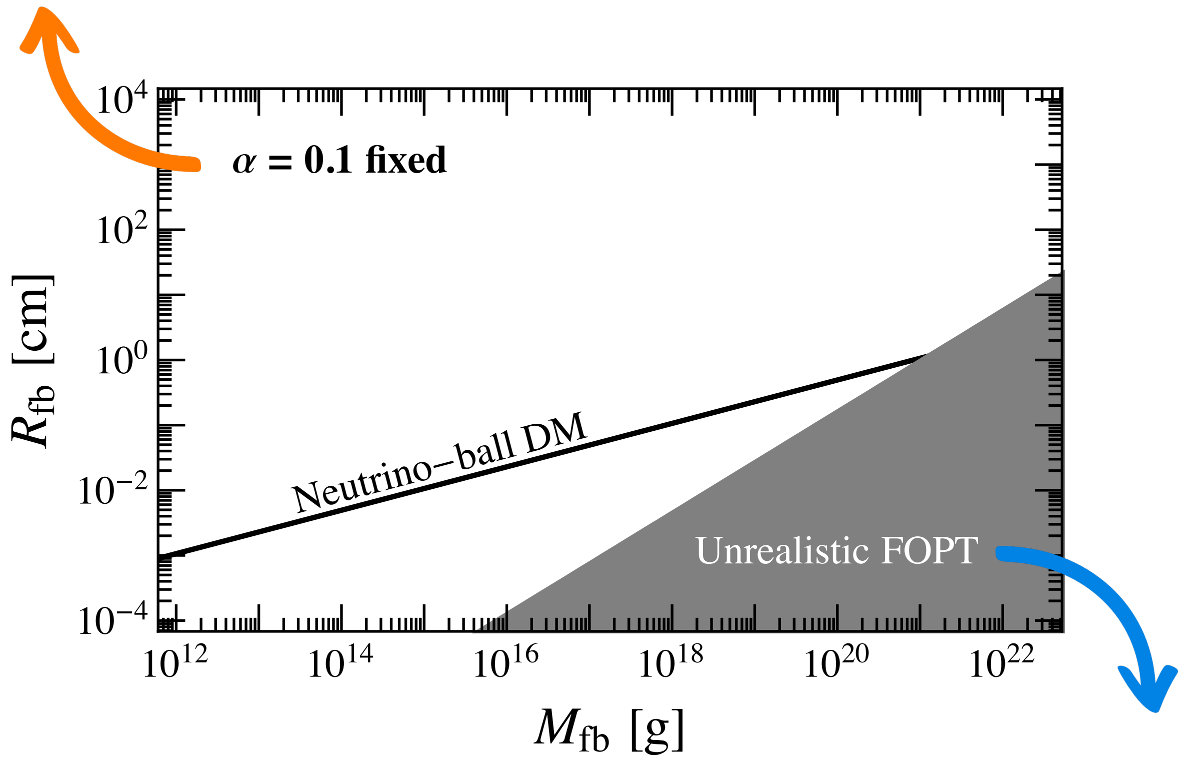


Balance between Fermi-gas pressure and vacuum pressure: a nontopological soliton

Hong, Jung, and **KPX**, 2008.04430; Kawana, Lu, and **KPX**, 2206.09923; **KPX**, 2405.01227

Mass and radius profiles

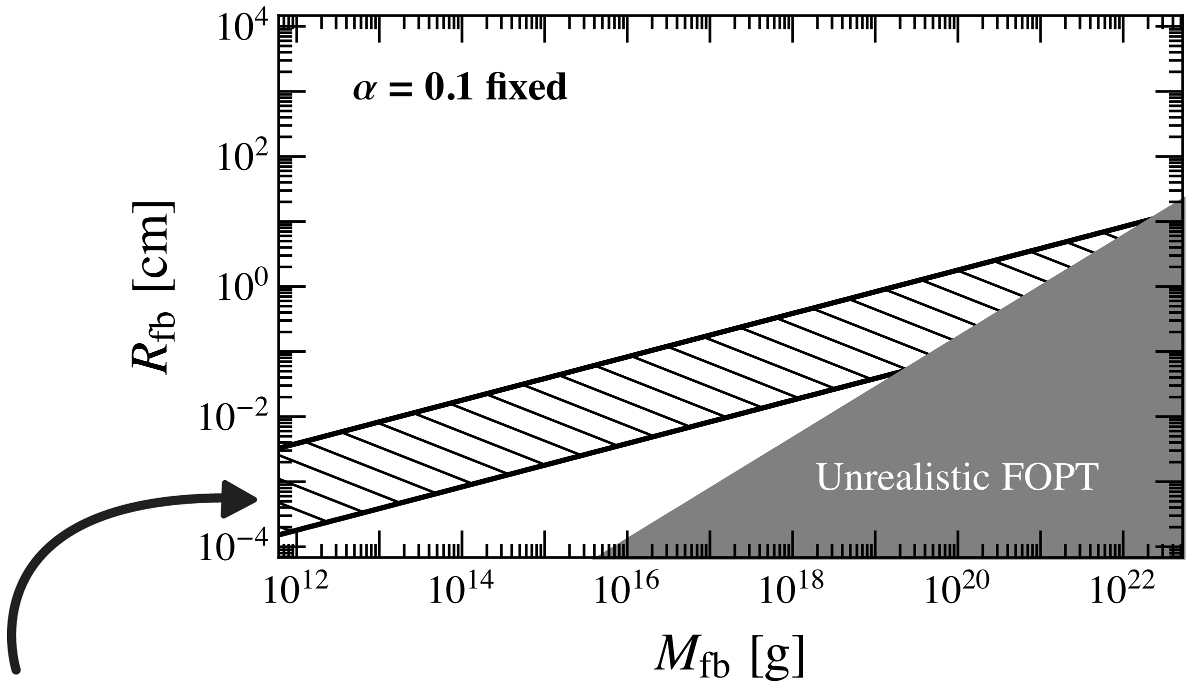
Phase transition Latent heat over radiation energy
Should be $\lesssim 1$ for soliton formation (to avoid *melting* the solitons)



Duration β^{-1} > Hubble time H_*^{-1}
Phase transition too slow; cannot complete

General mass and radius profiles

Not limited to a specific model: general ***fermionic soliton*** dark matter
e.g., quark nuggets, top-partner balls, heavy-lepton balls, *etc*



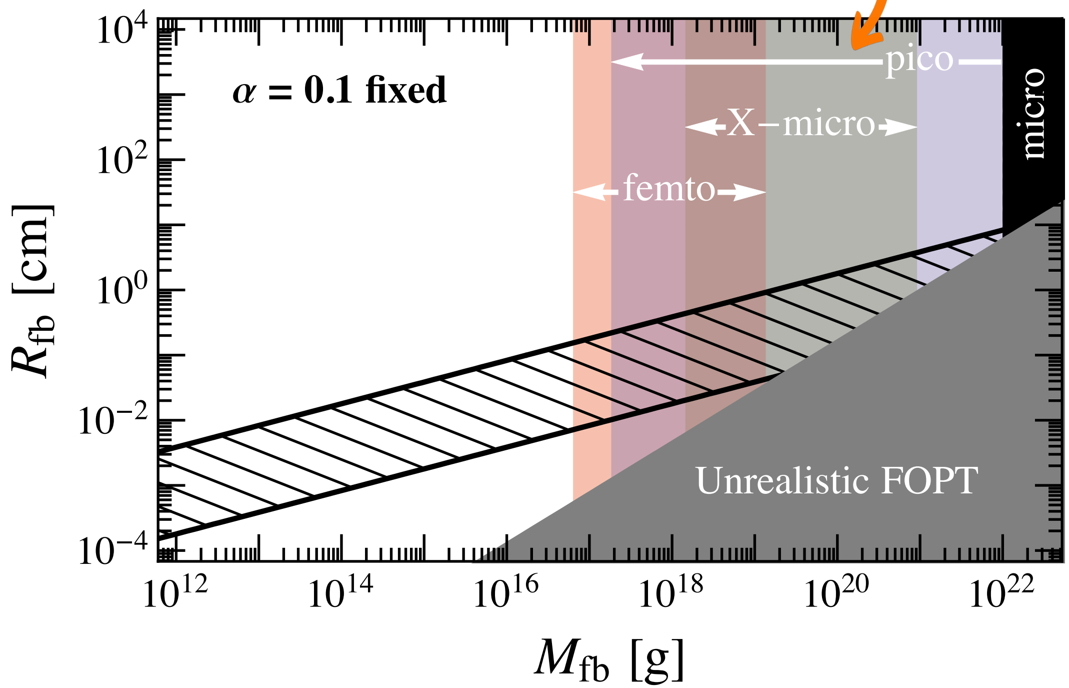
Solving the cosmic coincidence problem: $0.1 < Y_\chi / Y_B < 1$

Asteroid-mass dark matter

Asteroid-mass range – $\mathcal{O}(10^{17}\ \mathrm{g} - 10^{22}\ \mathrm{g})$: a ***hot*** window!

See Katz *et al*, 1807.11495; Bai *et al*, 1812.01427; Jung & Kim, 1908.00078; Gawade *et al*, 2308.01775; Kaplan *et al*, 2407.06262; Fedderke *et al*, 2411.12947; etc

Projections



Excluded

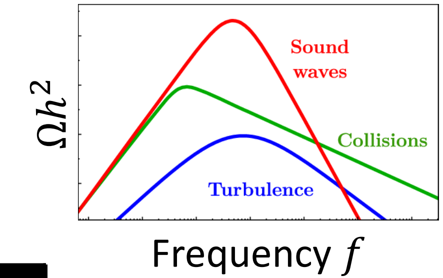
Previous: on *primordial black holes*, lacking theoretical motivations

This work: a novel **non-black-hole** asteroid-mass dark matter scenario ***well-motivated*** by the cosmic coincidence problem

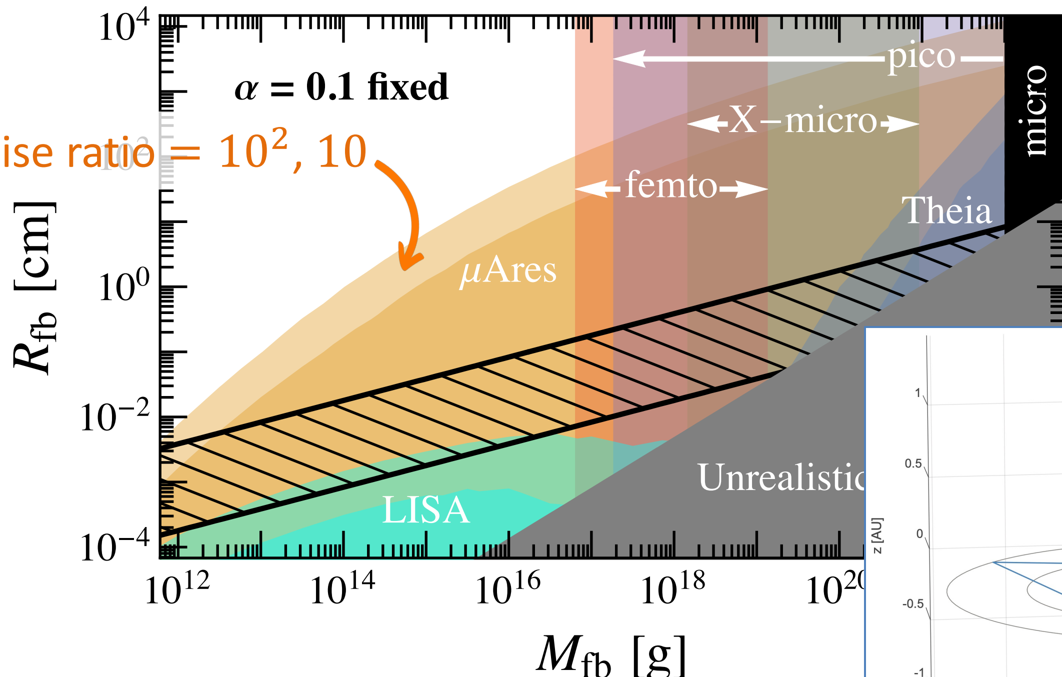
Byproduct: gravitational waves (GWs)

GWs from sound waves dominate

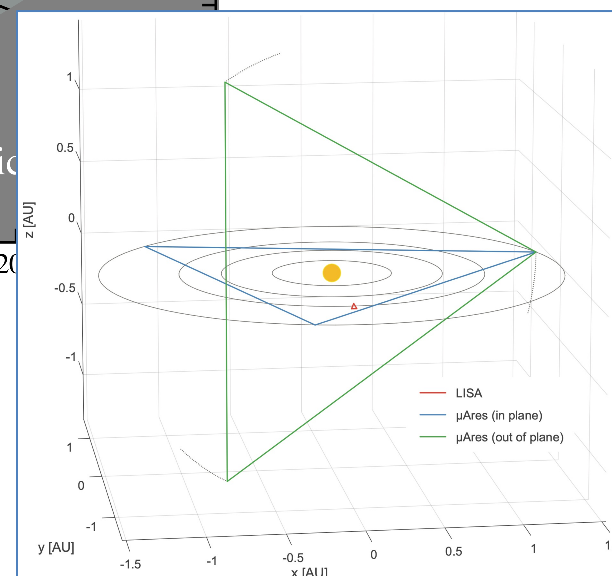
$$f_{\rm pk} \approx 38\ \mu{\rm Hz} \times \left(\frac{10^{17}\ {\rm g}}{M_{\rm fb}}\right)^{1/3}$$



Signal-to-noise ratio = 10^2, 10



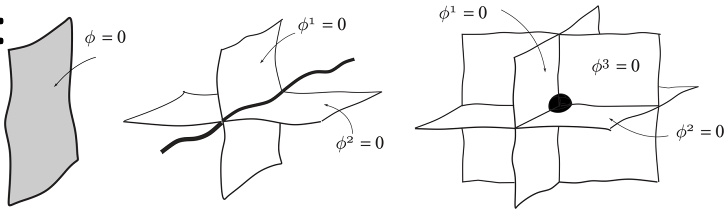
Voyage 2050 Whitepaper
1908.11391



Solitons as the solution to DM & BAU

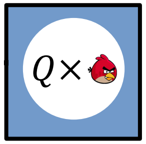
Domain walls, cosmic strings, monopoles: stabilized by vacuum topology

- Topological solitons



<u>Nontopological</u> solitons: stabilized by **conserved Noether charge**

Zhou, 2411.16604; Lee *et al*, Phys.Rept. 221 (1992) 251-350



- Requires a charge asymmetry in the dark sector
- Naturally connected to the baryon asymmetry in the visible sector

Solitons as the solution to DM & BAU

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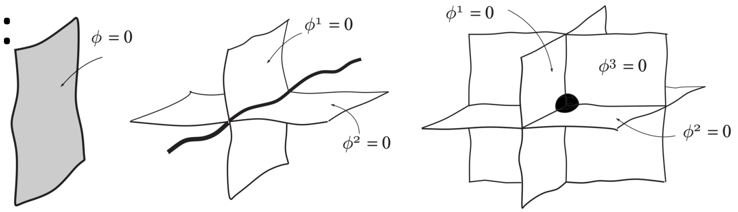

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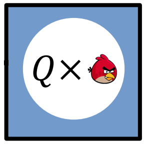

Zhou, 2411.16604; Lee *et al*, Phys.Rept. 221 (1992) 251-350

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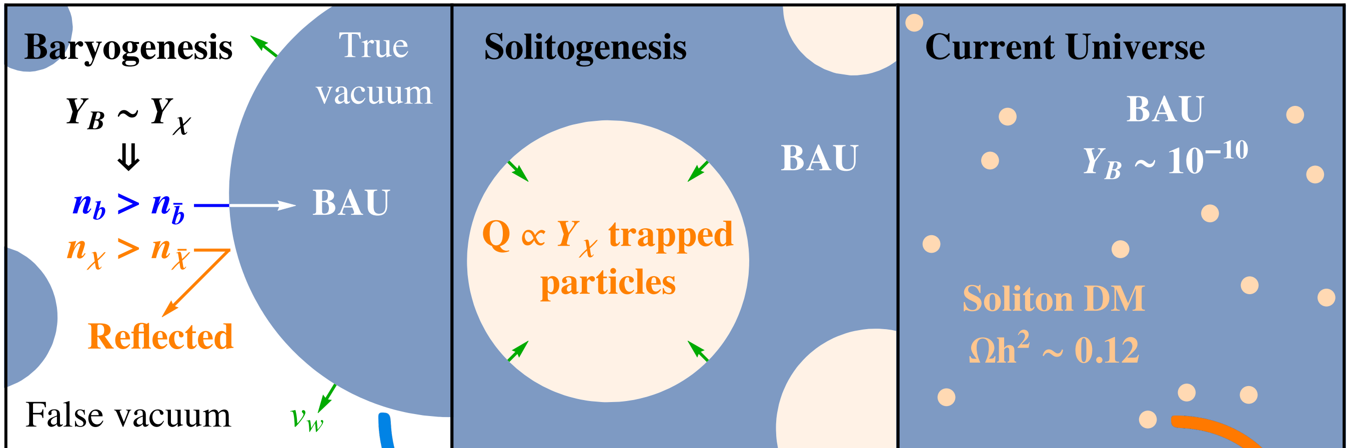
This work: a first quantitative study along this line

- Building a framework to describe this mechanism
- Deriving the general features, e.g. Fermi-ball profile, FOPT profile, phenomenological signals
- Revealing the relation between asteroid-mass DM & μHz GWs
- Providing a concrete particle model (i.e. Dirac seesaw), guiding the model-building

Conclusion and outlook

A general pattern to solve the *coincidence problem*



μHz gravitational waves

Asteroid-mass dark matter

Highly correlated

Not only neutrino-balls!

Applicable to other models:

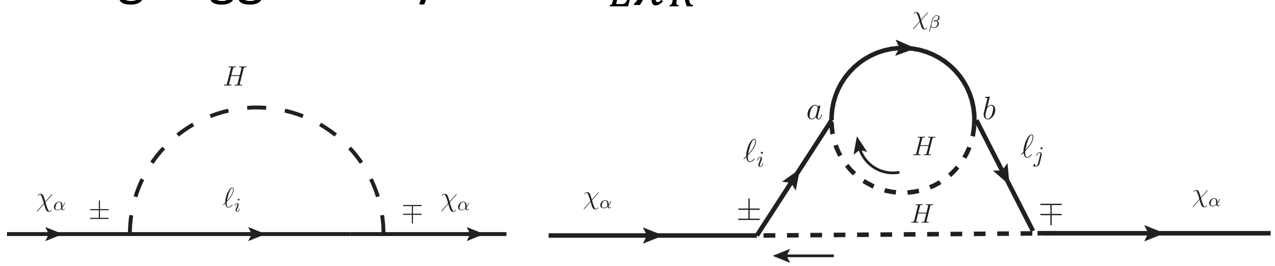
- Quark nuggets, top-partner balls, heavy-lepton balls, *etc*
- More model-dependent signals: capture, evaporation, collider, etc

Thank you!

Backup: leptogenesis via thermal mass (1)

Before the electroweak phase transition (EWPT): all particles massless

- CP-violating Higgs decay $H \to \overline{\ell}_L \chi_R$ via thermal mass



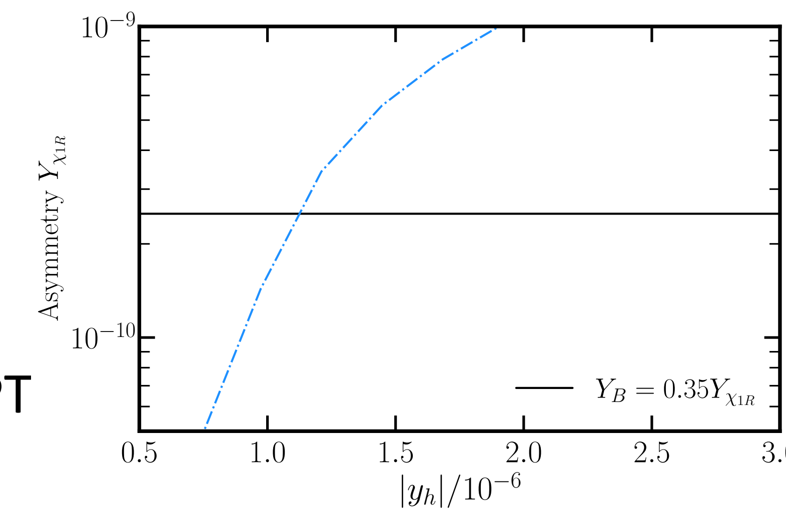
Schwinger-Keldysh closed-time-path formalism Kanemura & Li, 2408.06555

$$Y_\chi \propto \frac{m_h^2}{m_{\ell_j}^2 - m_{\ell_i}^2}$$

Enhanced by $\left(y_\mu^2 - y_e^2\right)^{-1} \sim 10^7$

$B - L$ conservation: $Y_L \equiv -Y_\chi$.

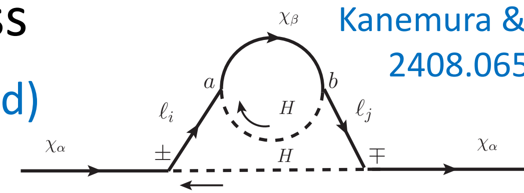
Sphaleron converts $Y_L \to Y_B$ until EWPT and $T_{\rm sph} \approx 132$ GeV



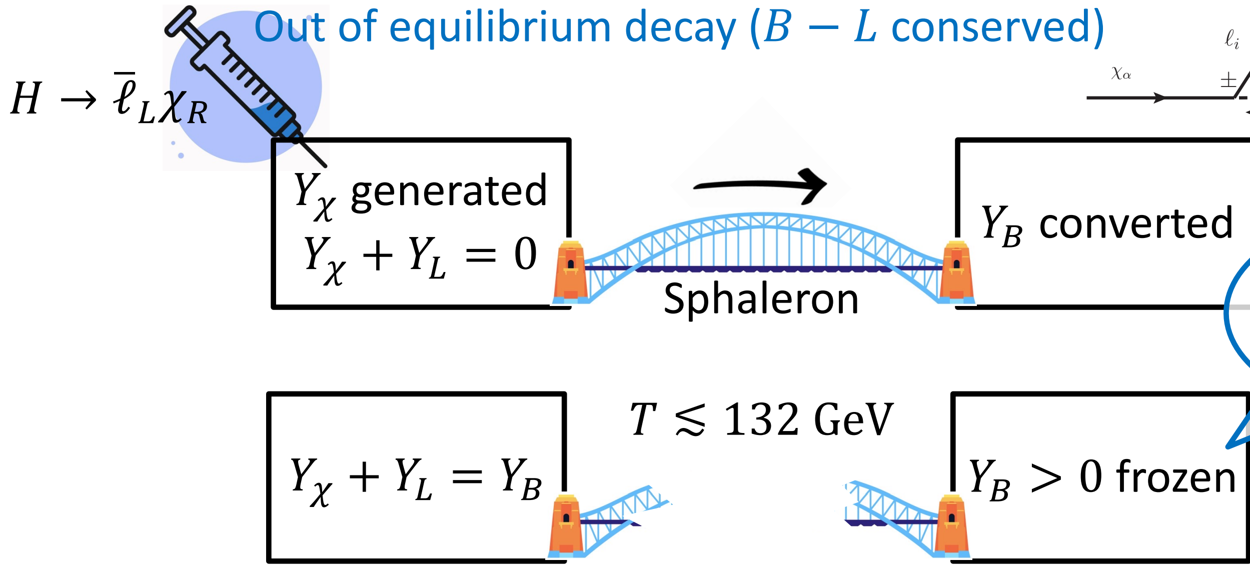
The observed **SM baryon asymmetry** requires $y_h \sim \mathcal{O}(10^{-6})$

Backup: leptogenesis via thermal mass (2)

Before EW phase transition: all particles massless



Kanemura & Li, 2408.06555



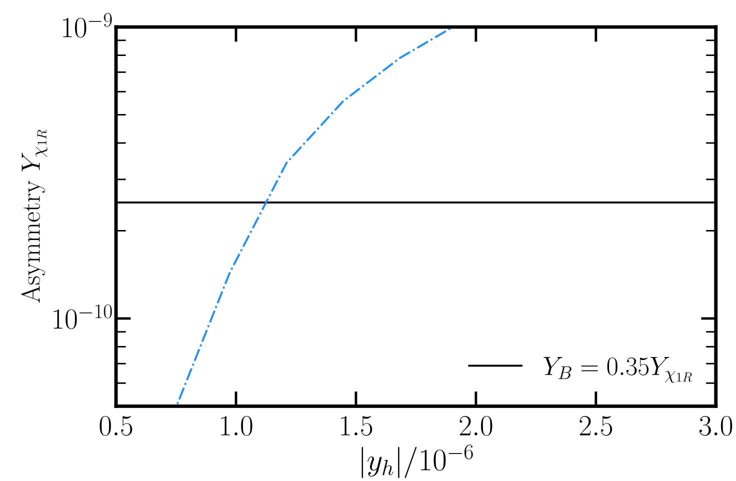
$\bar{\ell}_L \widetilde{H} \chi_R$ and $\bar{\chi}_L \eta \nu_R$ in equilibrium

After EW phase transition:

- $Y_B \approx 0.9\times10^{-10}$, observed BAU
- Lepton asymmetry <u>redistribution</u>:

$$Y_\chi \approx 8Y_B/21\, Y_B \approx 0.38 Y_B$$

Dark "lepton" asymmetry



Backup: early Universe potential

Finite temperature scalar potentials

The Higgs field

$$V_T(h,T)=\frac{\mu_h^2+c_hT^2}{2}h^2+\frac{\lambda_h}{4}h^4$$

With coefficient

$$c_h=\frac{3g^2+g'^2}{16}+\frac{y_t^2}{4}+\frac{\lambda_h}{2}\approx 0.4$$

The (ϕ,η)-system

$$V_T(\phi,\eta,T)=\frac{\mu_\phi^2+c_\phi T^2}{2}\phi^2+\frac{\mu_\eta^2+c_\eta T^2}{2}\eta^2+\frac{\lambda_\phi}{4}\phi^4+\frac{\lambda_{\phi\eta}}{4}\phi^4\eta^4+\frac{\lambda_\eta}{4}\eta^4$$

With coefficients

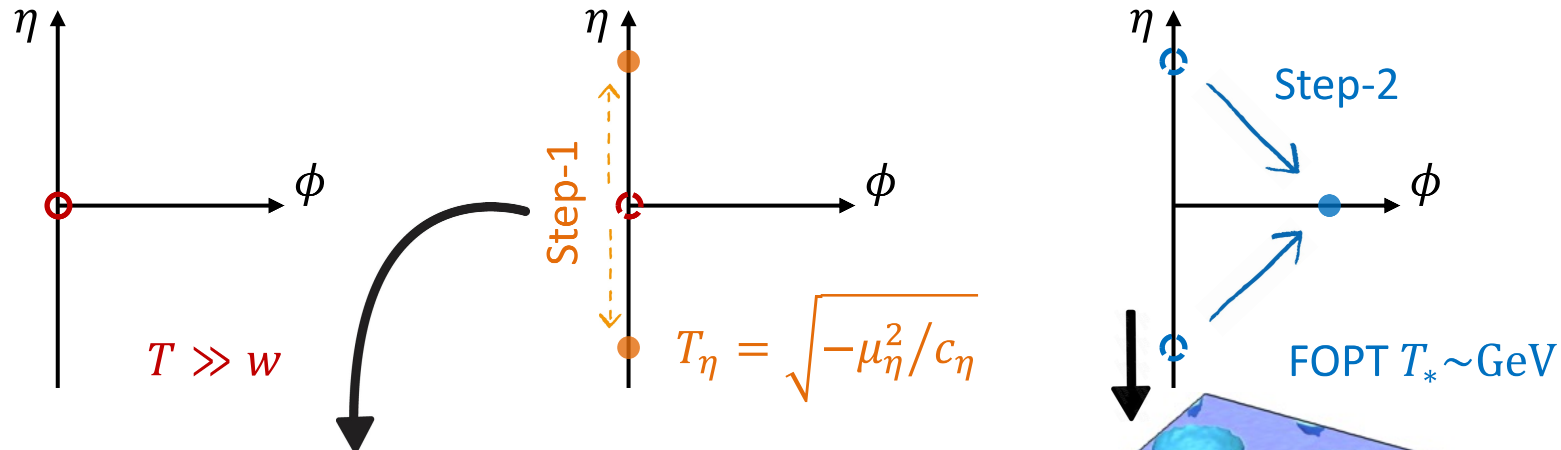
$$c_\phi=\frac{\lambda_\phi}{4}+\frac{\lambda_{\phi\eta}}{24}+\frac{y_\phi^2}{2},\qquad c_\eta=\frac{\lambda_\eta}{4}+\frac{\lambda_{\phi\eta}}{24}$$

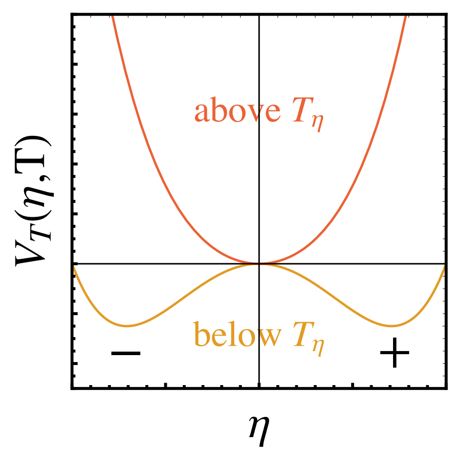
Small couplings between h-ϕ and h-η are assumed

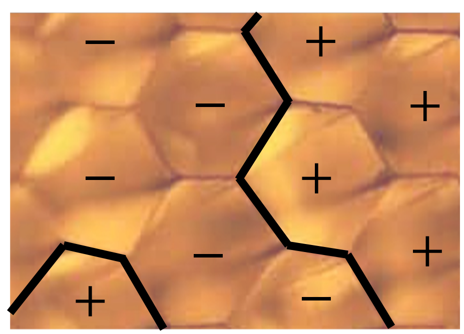
For sufficiently large T, symmetry is restored, i.e. $\langle h\rangle=\langle\phi\rangle=\langle\eta\rangle=0$

Backup: the phase transition pattern

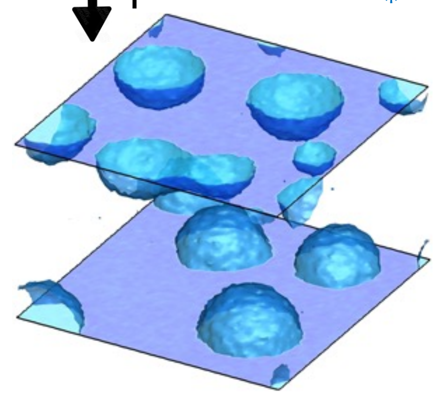
Evolution of the (ϕ, η) system: a two-step phase transition







Domain walls formation



Bubble nucleation on the wall
Domain-wall-catalyzed FOPT
Blasi *et al*, 2203.16450, 2302.06952

- $\mathbb{Z}_2$-odd η, to forbid $\bar{\ell}_L \widetilde{H} \nu_R$ Barman *et al*, 2205.03422
- Soft-breaking term (e.g. η^3), to have a small $\langle \eta \rangle$ for neutrino mass

Backup: a sketch of the wall-catalyzed FOPT

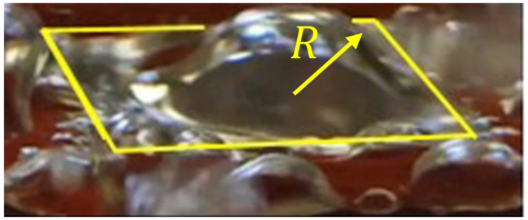
Vacuum decay rate per unit **area** $\Gamma_S(T) \sim \sigma_{\rm DW} e^{-S_{\rm inh}}$

Nucleation happens at

$$\int_{t_c}^{t_n} \frac{\Gamma_S}{H^2} \mathrm{d}t = \int_{T_n}^{T_c} \frac{\Gamma_S}{H^2} \frac{\mathrm{d}T}{HT} \sim 1$$

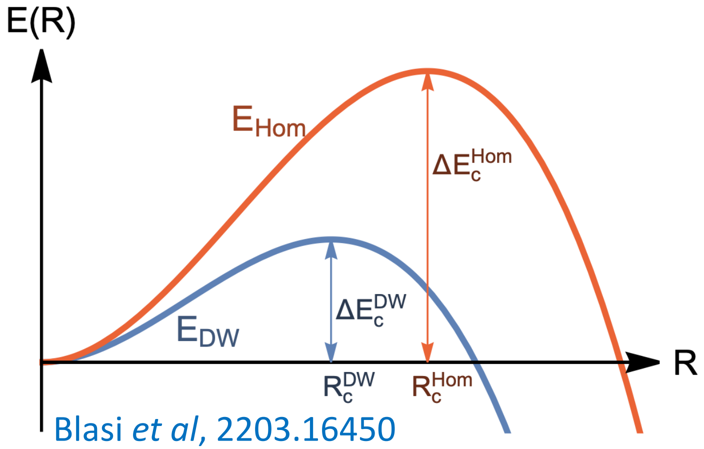
The most simple case: a spherical bubble nucleates on a domain wall

- Before, energy $\pi R^2 \sigma_{\rm DW}$
- After, energy $4\pi R^2 \sigma_B - (4\pi/3) R^3 \Delta V$



Therefore the total energy difference

$$E_R = 4\pi R^2 \left(\sigma_B - \frac{\sigma_{\rm DW}}{4}\right) - \frac{4\pi}{3} R^3 \Delta V$$



Blasi *et al*, 2203.16450

WKB approximation

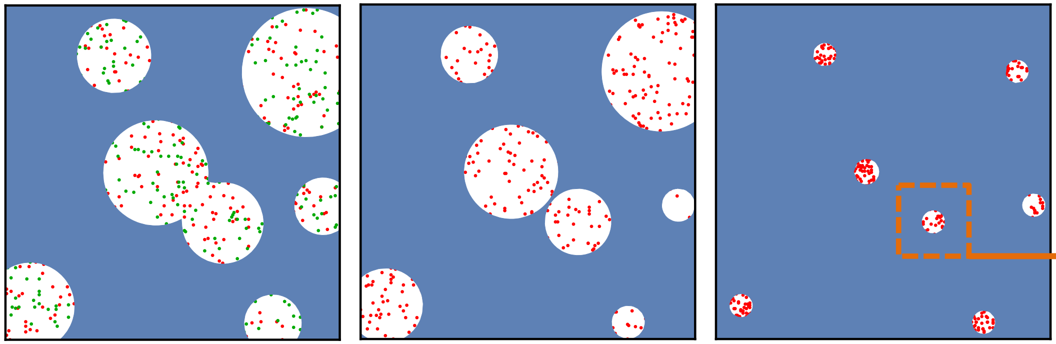
$$\Gamma_S(T) \sim \sigma_{\rm DW} e^{-\Delta E_c^{\rm DW}/T}$$

$\Delta E_c^{\rm DW}$ is the barrier height

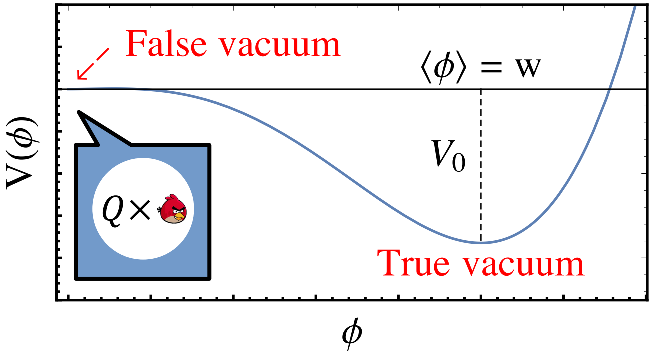
Usually **more efficient** than conventional homogeneous FOPT

Blasi *et al*, 2203.16450, 2302.06952

Backup: details of solitogenesis



A single remnant confines a number of Q fermions



Energy of such a "ball"

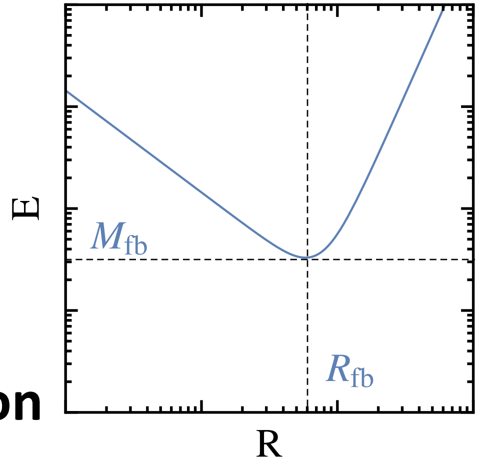
$$E = \frac{3\pi}{4}\left(\frac{3}{2\pi}\right)^{2/3}\frac{Q^{4/3}}{R} + \frac{4\pi}{3}R^3V_0$$

Fermi-gas kinetic energy + vacuum energy

Stable solution is reached at

$$M_{\rm fb} = Q(12\pi^2V_0)^{1/4}$$

$$R_{\rm fb} = Q^{1/3}\left[\frac{3}{16}\left(\frac{3}{2\pi}\right)^{2/3}\frac{1}{V_0}\right]^{1/4}$$



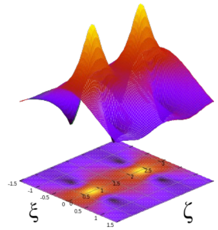
Called a **Fermi-ball**, which is a nontopological **soliton**

Hong, Jung, and **KPX**, 2008.04430; Kawana, Lu, and **KPX**, 2206.09923

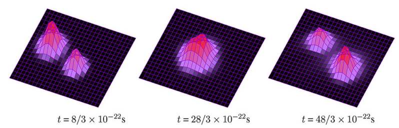
Backup: solitons

An extended and localized, stable or meta-stable "lump"

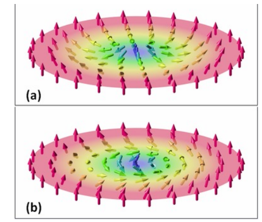
Optics



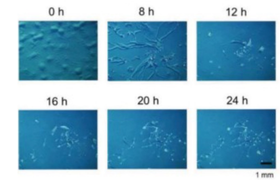
Nuclear physics



Condensed matter physics

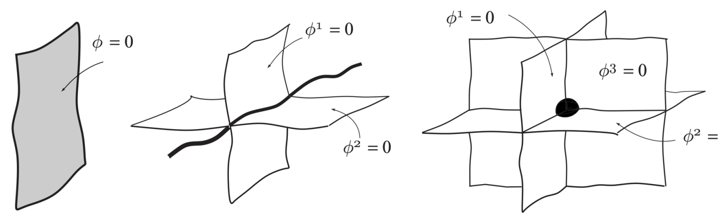


Biology

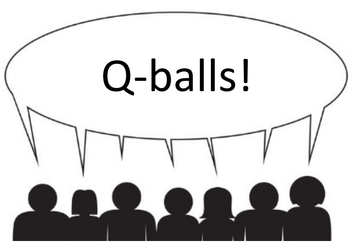


Solitons in quantum field theory

- Topological solitons: domain walls, cosmic strings, monopoles
- Nontopological solitons: stabilized by **conserved Noether charge**

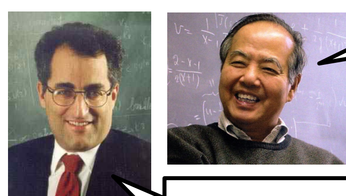


The scalar case



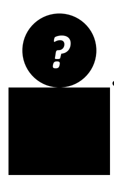
Friedberg, Lee, Sirlin, PRD 13 (1976) 2739–2761; Coleman, NPB 262 (1985) 2, 263

The fermion case

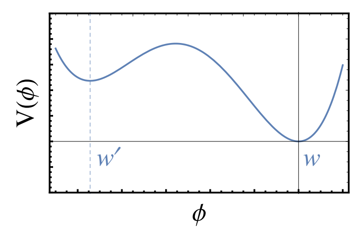


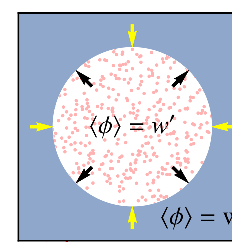
Fermion-field nontopological solitons
PRD 15 (1977) 1694, PRD 16 (1977) 1096

Quark nuggets
PRD 30 (1984) 272–285



Fermi-balls, plz…



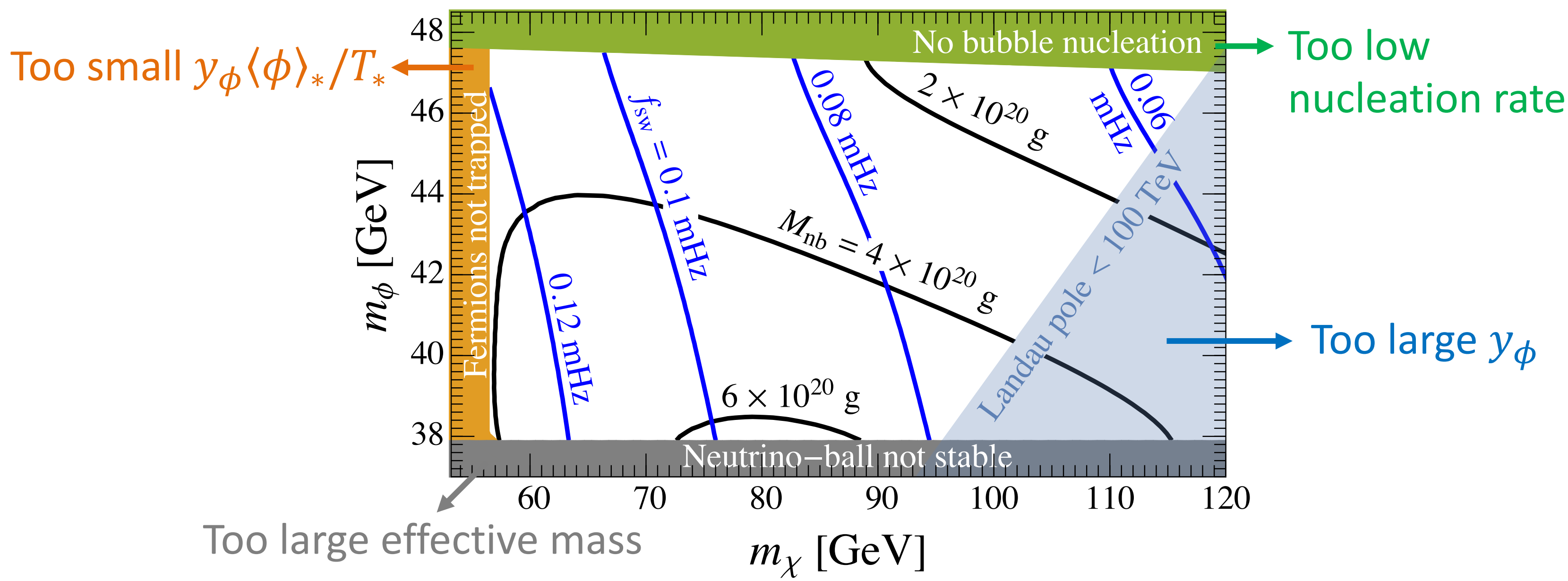


See also **KPX**, 2405.01227

Backup: an example of the parameter space

Fixing $\lambda_\phi = 0.18$, $\lambda_\eta = 0.30$, and $\lambda_{\phi\eta} = 1.2$ in

$$V(\phi,\eta) \approx \frac{\mu_\phi^2}{2}\phi^2 + \frac{\mu_\eta^2}{2}\eta^2 + \frac{\lambda_\phi}{4}\phi^4 + \frac{\lambda_{\phi\eta}}{4}\phi^4\eta^4 + \frac{\lambda_\eta}{4}\eta^4$$

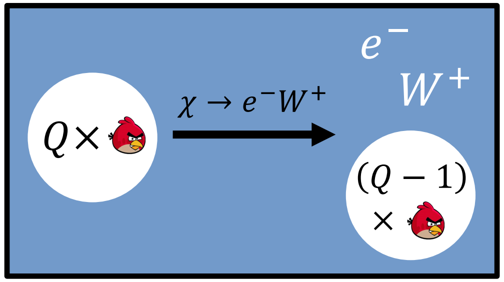


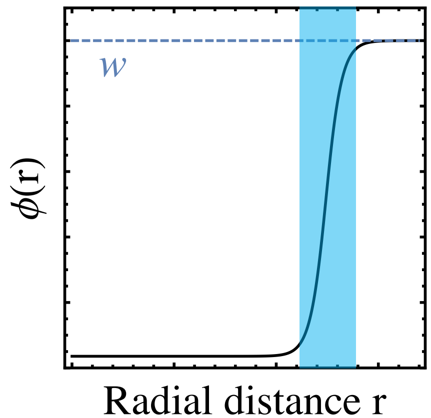
- Neutrino-ball mass $\sim 10^{20}$ g, asteroid-mass, detectable via lensing
- Phase transition gravitational waves $f \sim 10\ \mu\text{Hz}$
- Sterile neutrino χ mass ~ 100 GeV, available at colliders

Backup: lifetime

Leptogenesis vertex $-y_h\bar{\ell}_L\widetilde{H}\chi_R$ causes χ decay

The neutrino-ball is NOT stable!





χ mass $m_\chi(r)=y_\phi\phi(r)$

Deep inside the ball: $m_\chi\to 0$, no phase space

$\Rightarrow$ Decay only via **surface evaporation**

Neutrino-ball lifetime

$$\frac{\tau_{\rm nb}}{\tau_\chi}\gtrsim 10^{13}\times\left(\frac{m_\phi}{\rm GeV}\right)\left(\frac{M_{\rm nb}}{10^{17}\ {\rm g}}\right)^{1/3}$$

Free particle τ_χ

$\tau_{\rm nb}>H_0^{-1}\sim 1.4\times 10^{10}$ yr is required for dark matter candidate

3 generations of χ

- $y_h^{\ell 1}\sim 10^{-12}$ for neutrino-ball consisting of χ_1 (with $Y_{\chi_1}=Y_\chi/3$)
- $y_h^{\ell 2,\ell 3}\sim 10^{-6}$ for leptogenesis, then $\chi_{2,3}$ decays and disappear

Prediction: one generation of **SM neutrino mass** 10^{-5} meV

Backup: details of the mechanism

Yukaawa couplings

$-y_h \bar{\ell}_L \tilde{H} \chi_R$

$-y_\eta \bar{\chi}_L \eta \nu_R$

$-y_\phi \phi \bar{\chi}_L \chi_R$

$\bar{\ell}_L \tilde{H} \chi_R$

Higgs decay, $y_h^{\ell 2,\ell 3} \sim 10^{-6}$

$Y_{\chi_{2,3}}$ Y_L

Sphaleron → $Y_B \sim 0.9\times 10^{-10}$ (**observed BAU**)

Thermalized via $\bar{\chi}_L \eta \nu_R$, $\bar{\ell}_L \tilde{H} \chi_R$

$$Y_{\chi_1} \approx Y_{\chi_2} \approx Y_{\chi_3} \approx 0.13 Y_B$$

ϕ-η first-order phase transition at T_*
Forming macroscopic **neutrino-balls**
via $\phi \bar{\chi}_L \chi_R$

χ_1-based neutrino-balls long-lived due to $y_h^{\ell 1} \sim 10^{-12}$, **dark matter**