# 宇宙学一级相变与物质、暗物质和原初黑洞的起源

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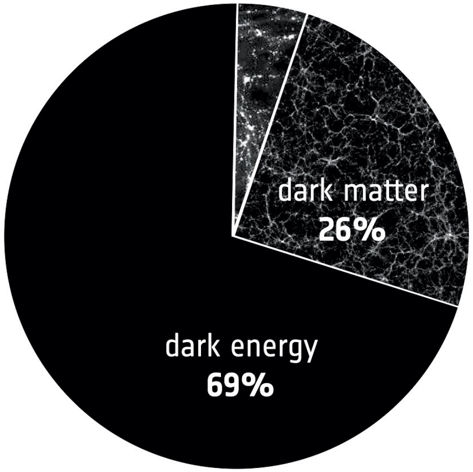
2023.4.26 @中科院高能所

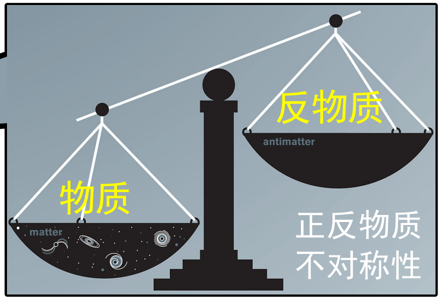
# 我们生活的宇宙，充满了谜团

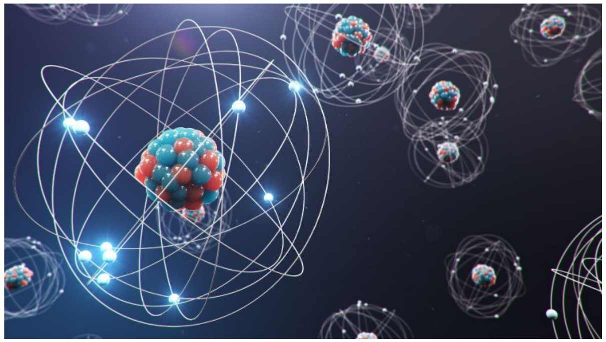
当今宇宙的
能量分布



可见物质 5%

反物质失踪了！





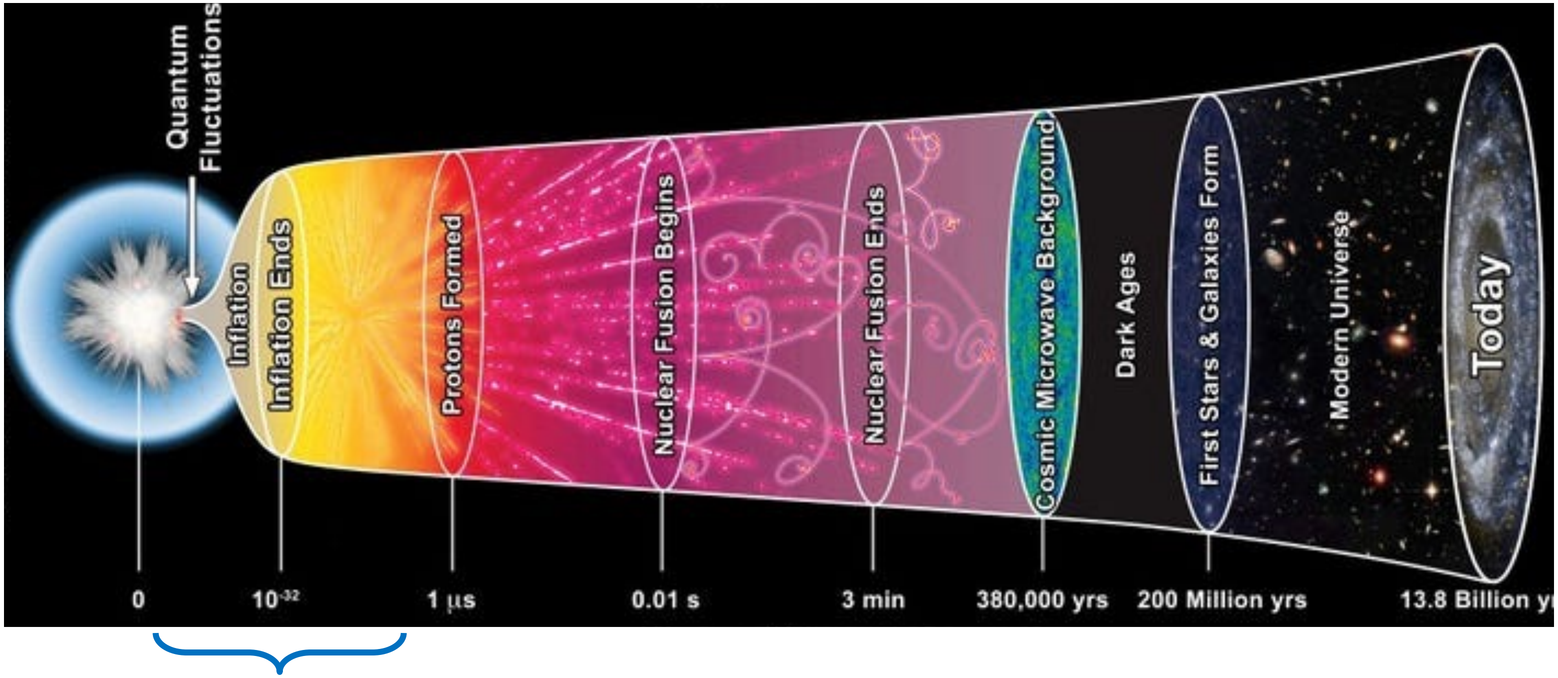
粒子物理标准模型——“已知的宇宙”

暗物质 26% [???]

暗能量 69% [???]

未知的宇宙……

# 这些谜团存在已久



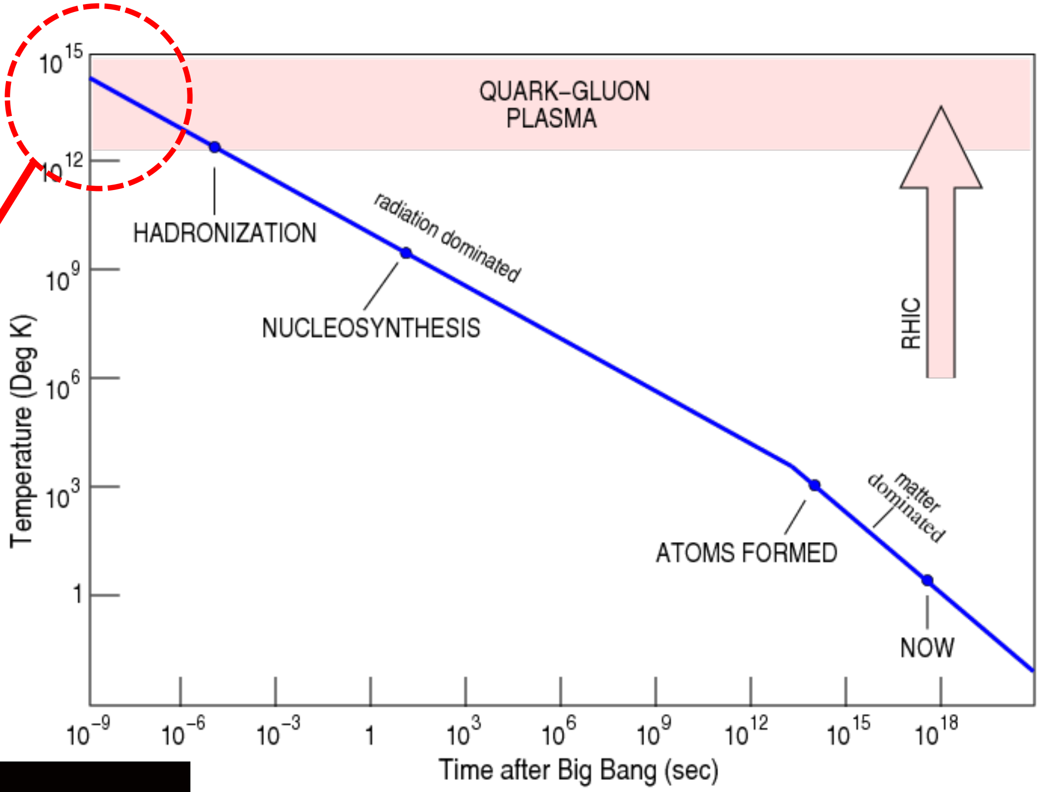
大爆炸后约0.1纳秒~1秒内，**正反物质不对称性**就已经产生，**暗物质**已经形成

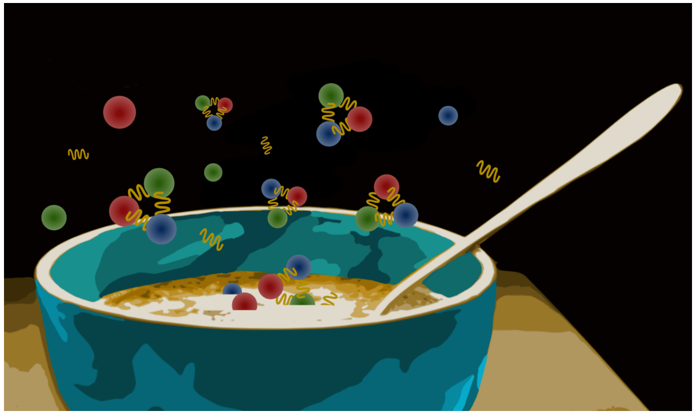
- 1920年代起，就陆续有暗物质存在的证据；至1970年代，暗物质成为被广泛承认的未解之谜，持续至今
- 正反物质不对称性于1960年代被注意到，一直没有妥善的解答

# 追溯早期宇宙的历史

早期宇宙的显著特点：

**粒子宇宙学**





基本粒子（电子、中微子、夸克……）以等离子体的形式存在

宇宙像一锅炽热的汤

# Solving the puzzles with a first-order phase transition

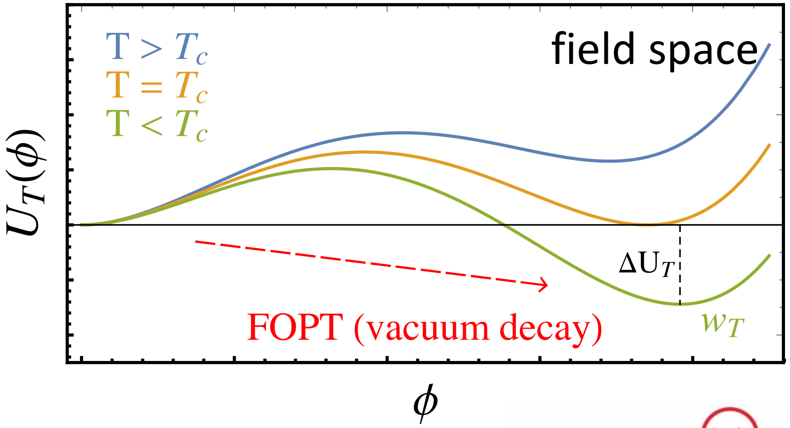
Vacuum decay

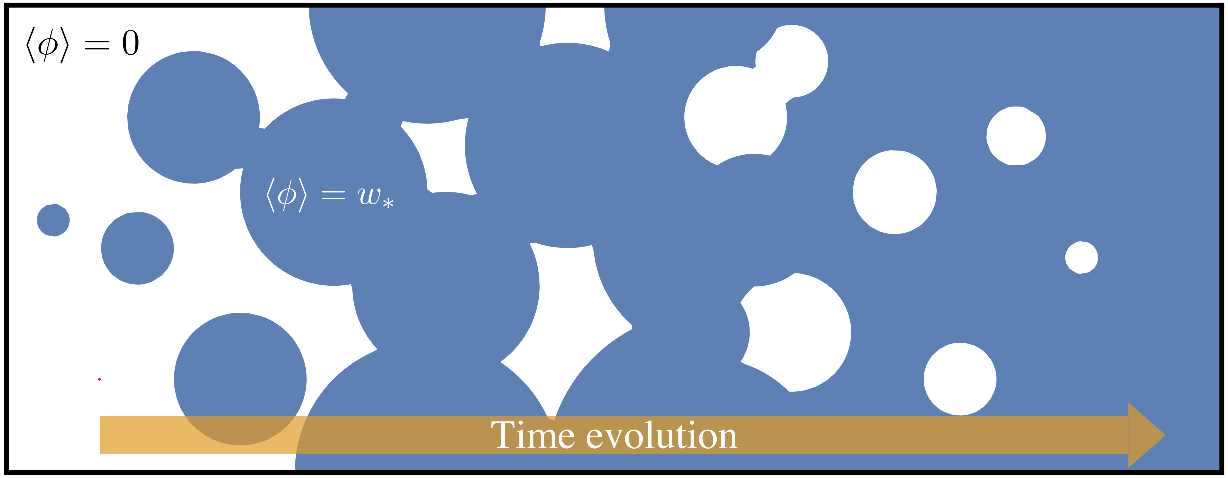
$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - U(\phi)$$

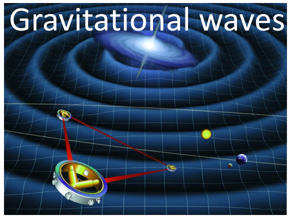
↑

Thermal corrections

$U(\phi) \Rightarrow U_T(\phi, T)$







Boiling of the Universe, vacuum bubble nucleation and expansion

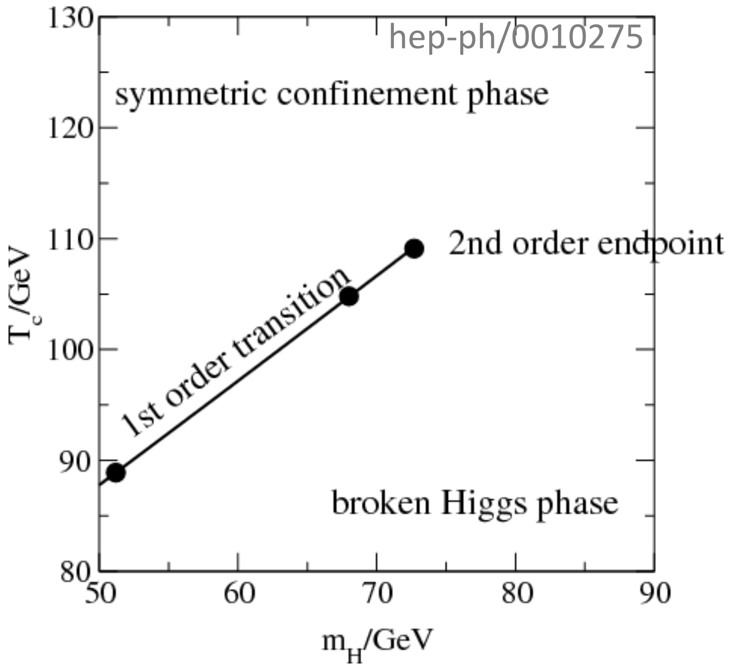
If $\phi = h$ (SM Higgs) – first-order electroweak phase transition

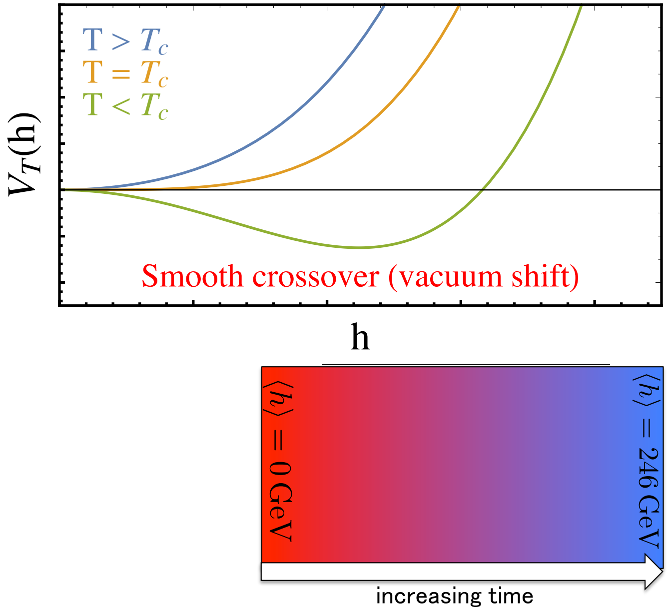
If $\phi =$ new physics field – general FOPT

# 3 main directions of research on a boiling Universe

1. The dynamics of FOPT;
2. FOPTs in new physics models;
3. New physics mechanisms based on FOPTs

There is NO FOPT in the Standard Model



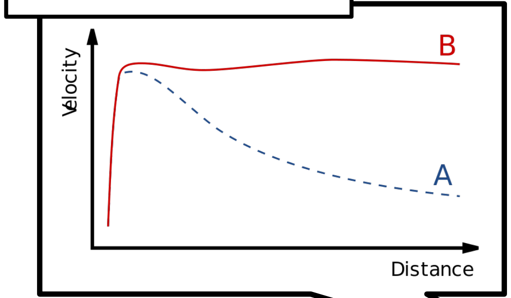


FOPT ⇒ new physics

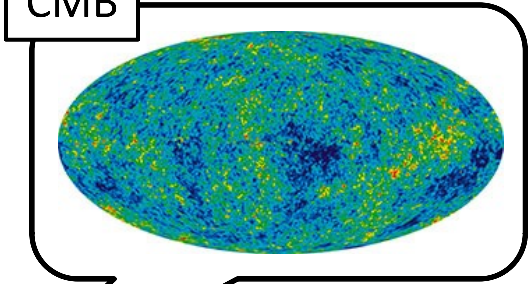
First-order EW phase transition of $h$, or FOPT of a new field $\phi$

# The mystery of dark matter

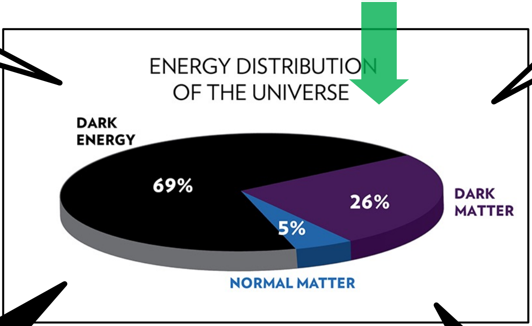
Rotation curves



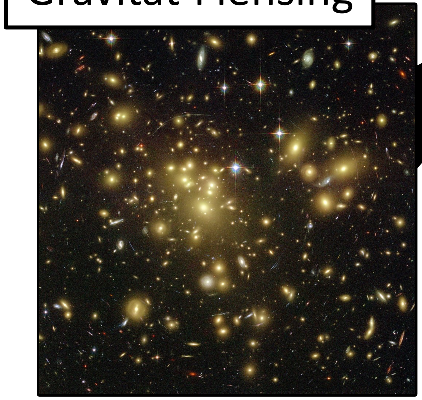
CMB



$$\Omega_{\mathrm{DM}} h^2 \approx 0.12$$

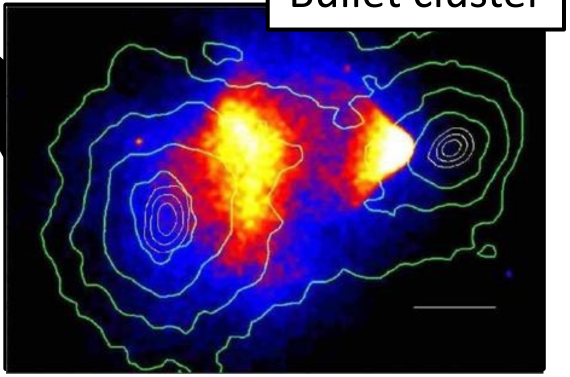


Gravitat’l lensing



*It is there!*

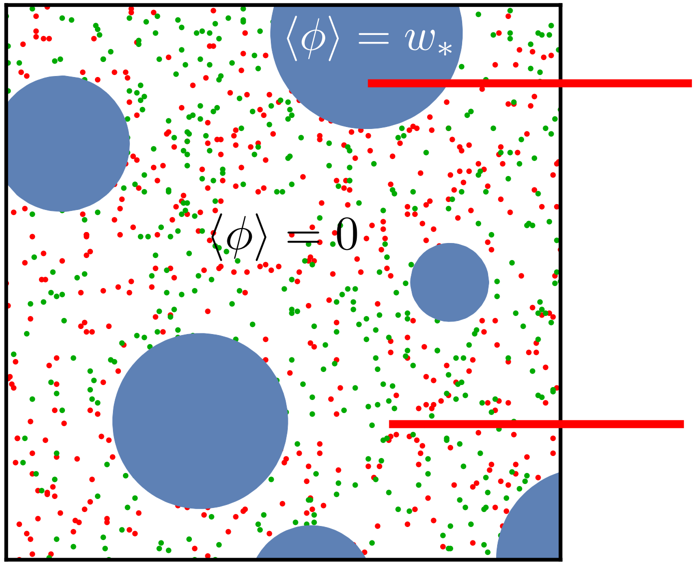
Bullet cluster



# Dark matter & FOPTs

Relevant Lagrangian

$$\mathcal{L} \supset \underbrace{\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - U(\phi)}_{\text{FOPT Lagrangian}} + \bar{\chi}\left(i\gamma^\mu\partial_\mu - m_0\right)\underset{\substack{\uparrow \\ \text{Dark fermion}}}{\chi} - \overbrace{y_\chi\phi\bar{\chi}\chi}^{\text{Portal coupling}}$$



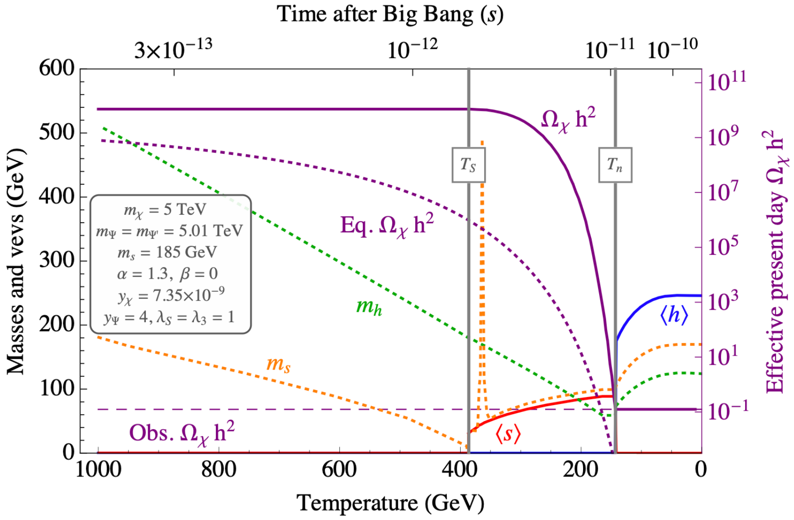
Inside the bubble:
$m_\chi = m_0 + y_\chi w_*$

Outside the bubble:
$m_\chi = m_0$

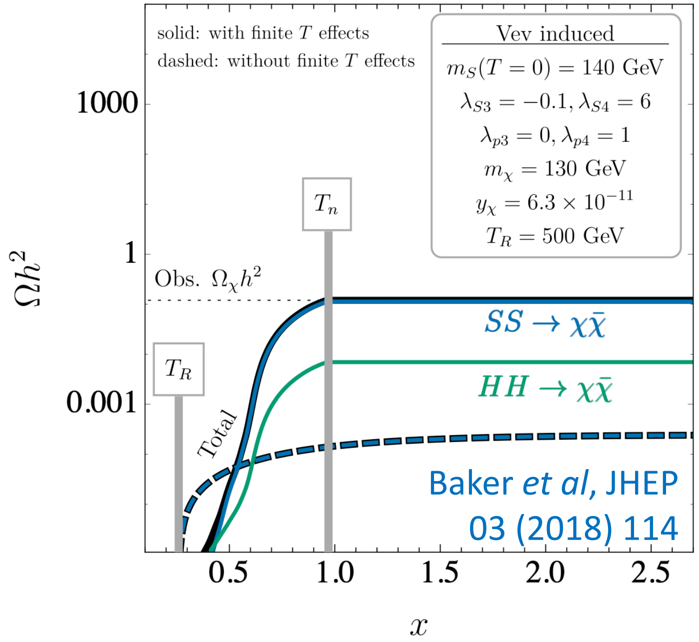
Novel!!

Mass discontinuity between two sides of the bubble wall

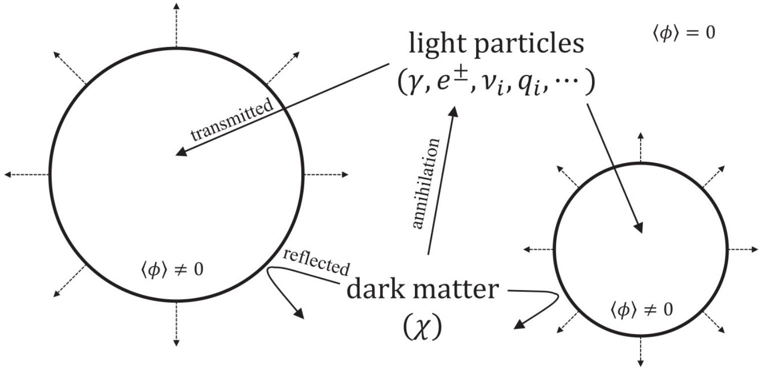
# Dark matter mechanisms based on a FOPT



Baker *et al*, PRL 119 (2017) 6, 061801

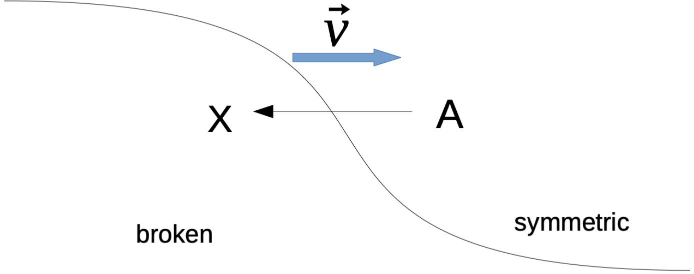


Baker *et al*, JHEP 03 (2018) 114



Baker *et al*, PRL 125 (2020) 15, 151102
Chway *et al*, PRD 101 (2020) 9, 095019

Azatov *et al*, JCAP 01 (2021) 058;
JHEP 03 (2021) 288



# The fermion soliton dark matter from a FOPT

FOPT Scalar

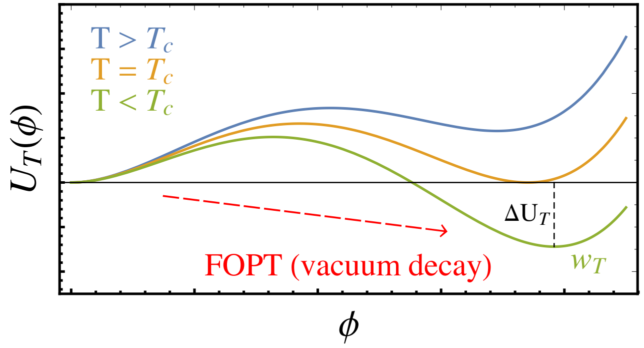
Fermion

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

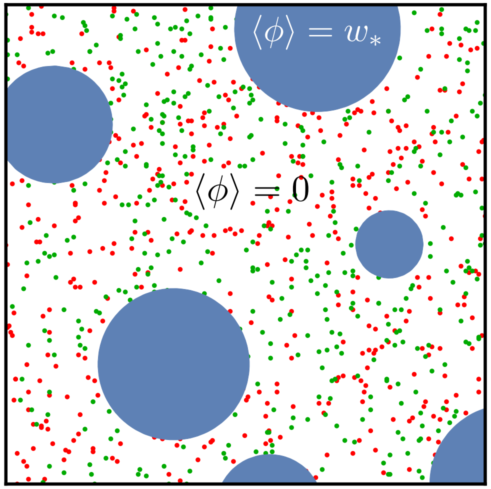
Potential for phase transition

Yukawa vertex

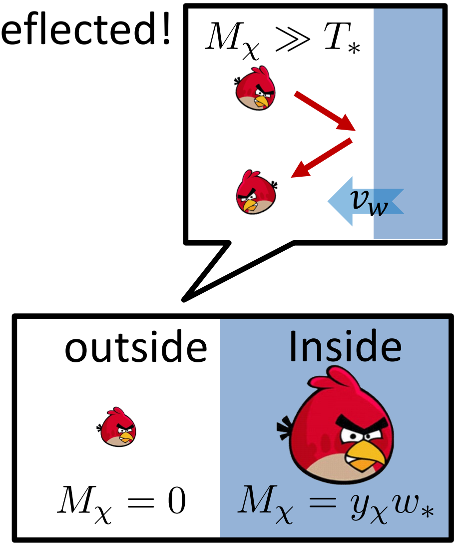
The interaction between bubble and fermion!



Bubble nucleation

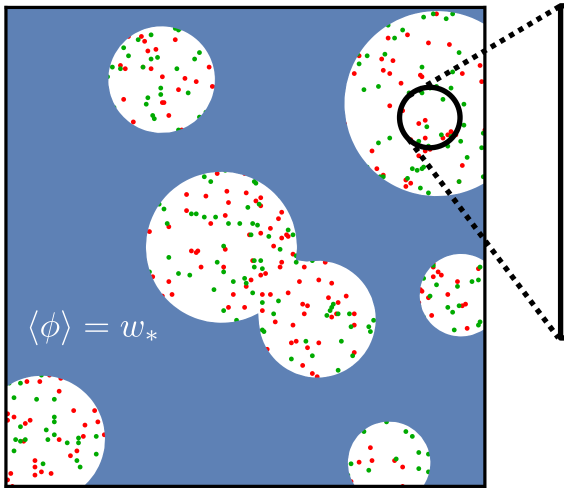


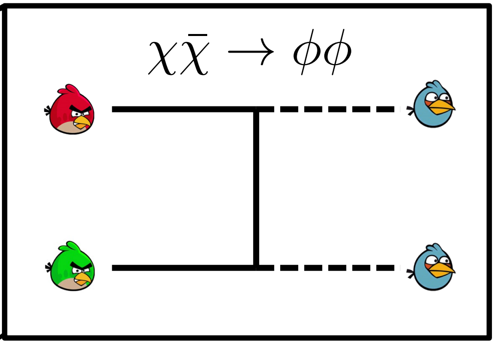
Reflected!



Example: trapping fraction = 98% for $M_\chi/T_* = 12$ and $v_w = 0.6$

# What happens for the trapped fermions?



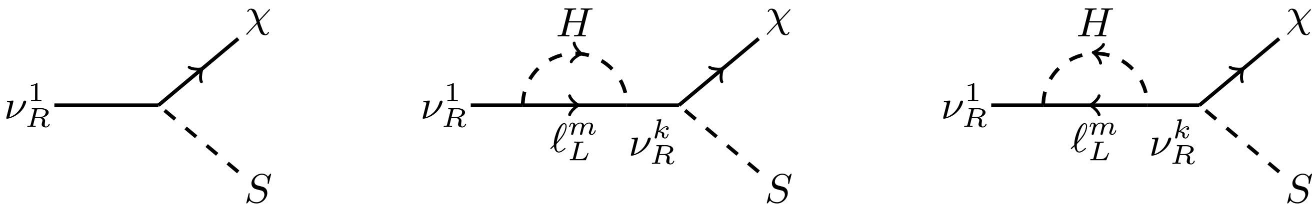


$-\,y_\chi \phi \bar{\chi}\chi$

Eventually to SM particles via portal coupling $\lambda_{H\phi}|H|^2\phi^2$

To have a nontrivial result, there should be $N(\chi) \neq N(\bar{\chi})$

1. Thermal fluctuation;[Asadi *et al*, PRL 127 (2021) 21, 211101]
2. A baryogenesis-like asymmetry;[Shelton *et al*, PRD 82 (2010) 123512]

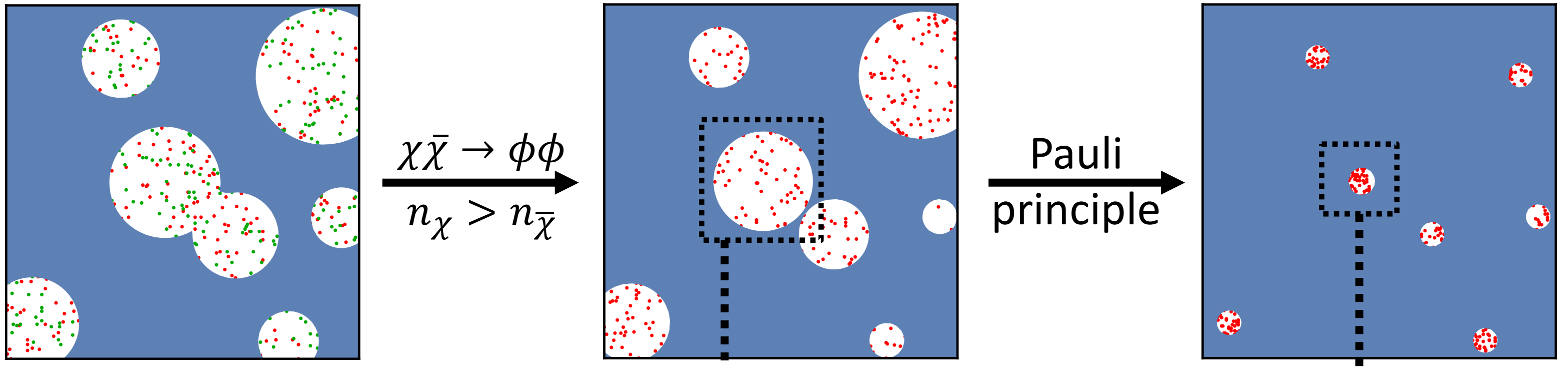


$$\Gamma(\nu_R^1 \to \chi S) > \Gamma(\nu_R^1 \to \bar{\chi} S)$$

$$\eta_\chi \equiv \frac{n_\chi - n_{\bar{\chi}}}{s}$$

Similar to baryon asymmetry of the Universe

# Formation of Fermi-ball solitons



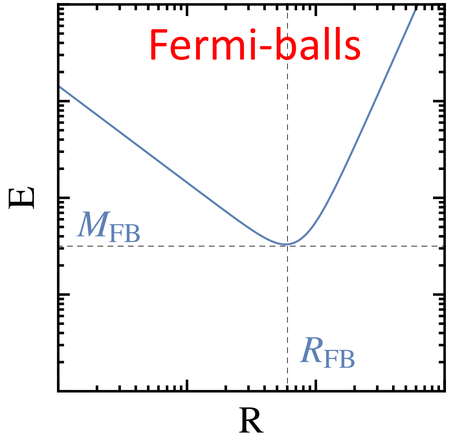
$\chi\bar{\chi} \rightarrow \phi\phi$

$n_\chi > n_{\bar{\chi}}$

Pauli principle

Charge trapped: $Q_{\rm FB} \approx \eta_\chi s_* V_*$ ← Remnant volume

Fermion asymmetry $\eta_\chi = \frac{n_\chi - n_{\bar{\chi}}}{s}$



$$E = \underbrace{\frac{3\pi}{4}\left(\frac{3}{2\pi}\right)^{2/3}\frac{Q_{\rm FB}^{4/3}}{R}}_{\text{Fermi-gas energy}} + \underbrace{\frac{4\pi}{3}R^3 U_0}_{\text{Volume energy}}$$

$$M_{\rm FB} = Q_{\rm FB}(12\pi^2 U_0)^{1/4};$$

$$R_{\rm FB} = Q_{\rm FB}^{1/3}\left[\frac{3}{16}\left(\frac{3}{2\pi}\right)^{2/3}\frac{1}{U_0}\right]^{1/4}$$

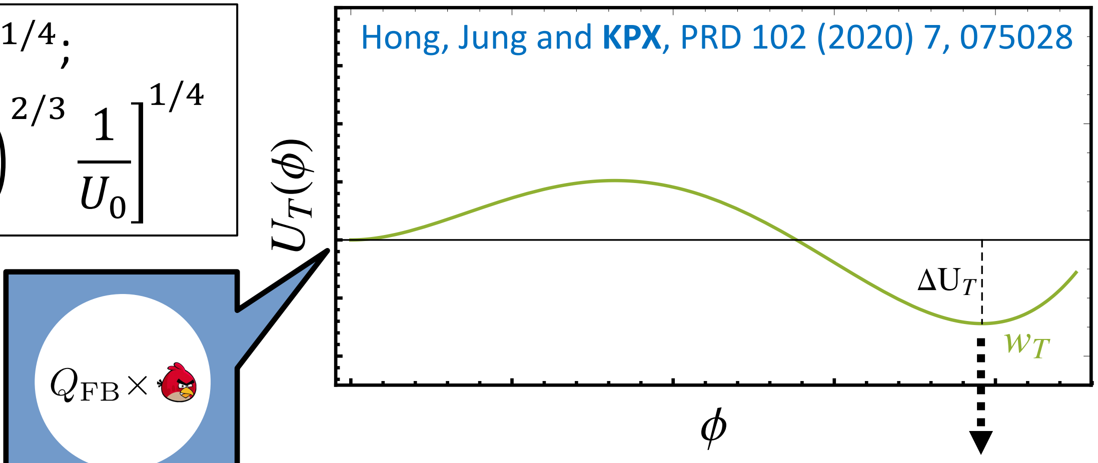
Hong, Jung and **KPX**, PRD 102 (2020) 7, 075028

# The Fermi-ball profile

$$M_{\rm FB}=Q_{\rm FB}(12\pi^2U_0)^{1/4};$$

$$R_{\rm FB}=Q_{\rm FB}^{1/3}\left[\frac{3}{16}\left(\frac{3}{2\pi}\right)^{2/3}\frac{1}{U_0}\right]^{1/4}$$

Effective $\chi$-mass inside the ball: $M_{\rm eff}=(12\pi^2U_0)^{1/4}$



Hong, Jung and **KPX**, PRD 102 (2020) 7, 075028

Mass at true vacuum $M_\chi=y_\chi w$

$$\text{Stability condition: }\frac{{\rm d}M_{\rm FB}}{{\rm d}Q_{\rm FB}}=M_{\rm eff}<M_\chi$$

*Fission stability ${\rm d}^2M_{\rm FB}/{\rm d}Q_{\rm FB}^2<0$ always satisfied with surface term $\propto Q_{\rm FB}^{2/3}$

## Estimates

$$Q_{\rm FB}\approx10^{42}\times v_w^3\left(\frac{\eta_\chi}{10^{-3}}\right)\left(\frac{100}{g_*}\right)^{1/2}\left(\frac{100\ \rm GeV}{T_*}\right)^3\left(\frac{100}{\beta/H_*}\right)^3$$

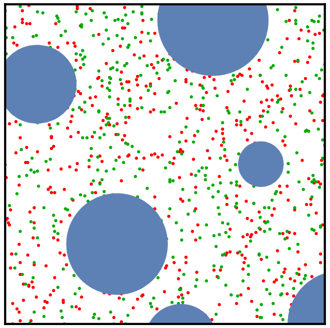
$$M_{\rm FB}\approx1.4\times10^{21}\ {\rm g}\times v_w^3\left(\frac{\eta_\chi}{10^{-3}}\right)\left(\frac{100}{g_*}\right)^{1/4}\left(\frac{100\ \rm GeV}{T_*}\right)^2\left(\frac{100}{\beta/H_*}\right)^3\alpha^{1/4}$$

$$R_{\rm FB}\approx4.8\times10^{-3}\ {\rm cm}\times v_w\left(\frac{\eta_\chi}{10^{-3}}\right)^{1/3}\left(\frac{100}{g_*}\right)^{5/12}\left(\frac{100\ \rm GeV}{T_*}\right)^2\left(\frac{100}{\beta/H_*}\right)\alpha^{-1/4}$$

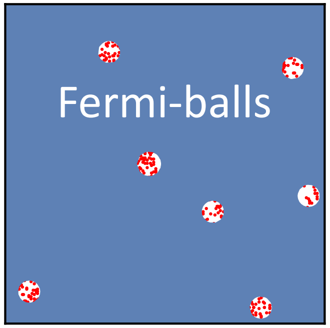
**Macroscopic Dark Matter!**

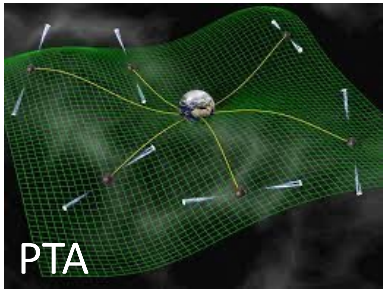
# An example of phenomenology

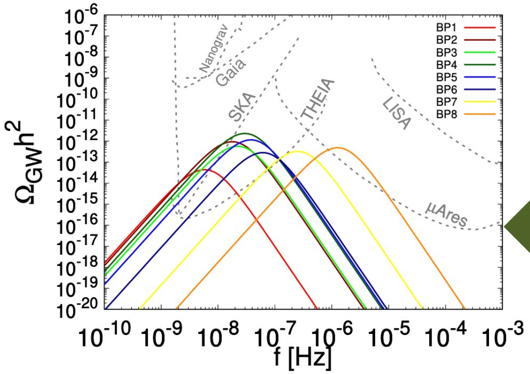
Marfatia *et al*, JHEP 11 (2021) 068



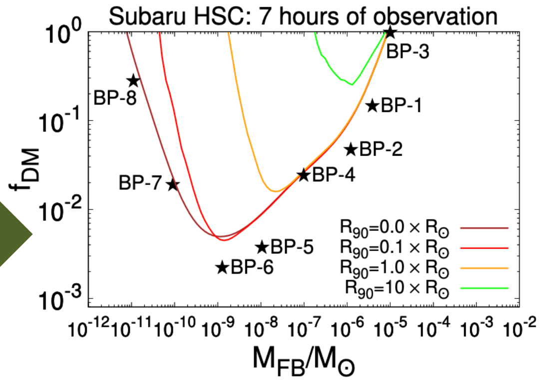
Forming



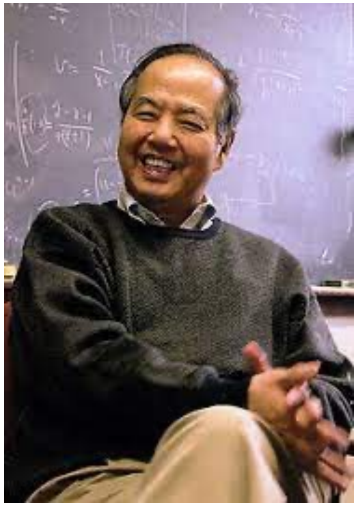




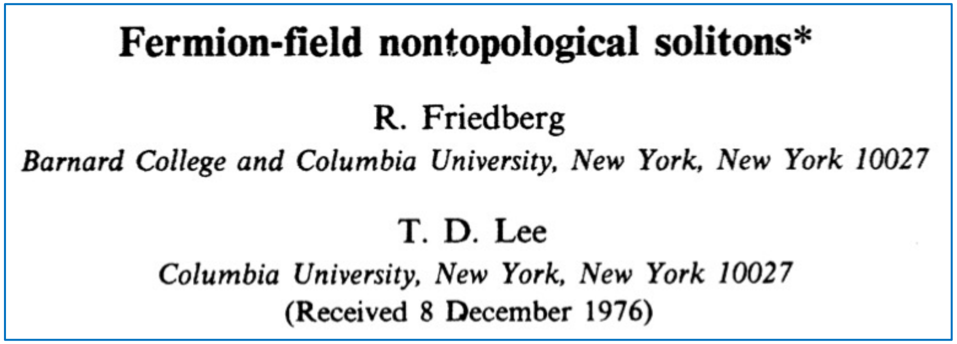
Correlation!



# Big picture: fermion-type solitons



Proposed by T. D. Lee.[PRD.15.1694, PRD.16.1096]

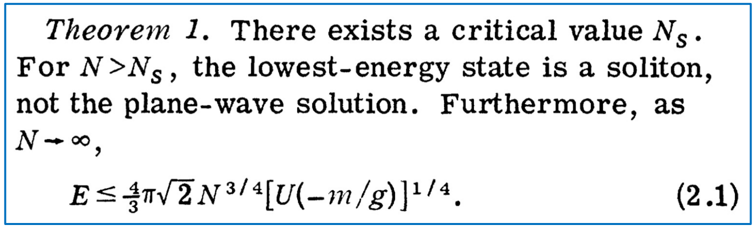


**Fermion-field nontopological solitons***

R. Friedberg
*Barnard College and Columbia University, New York, New York 10027*

T. D. Lee
*Columbia University, New York, New York 10027*
(Received 8 December 1976)

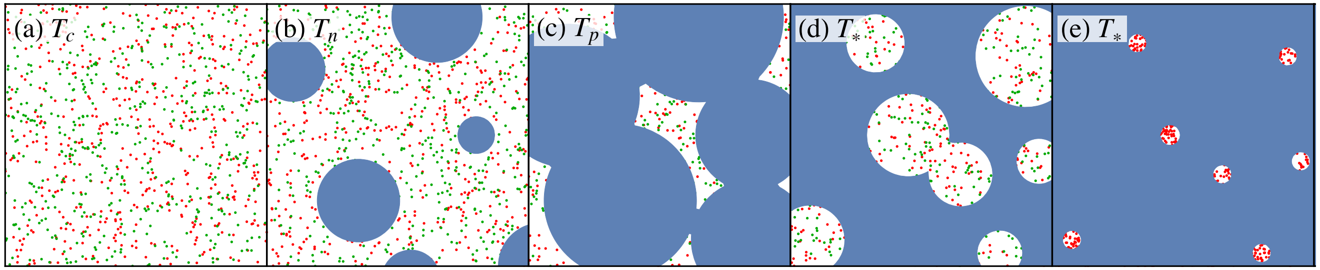
Fermion-soliton is possible with a scalar



*Theorem 1.* There exists a critical value $N_S$. For $N>N_S$, the lowest-energy state is a soliton, not the plane-wave solution. Furthermore, as $N\to\infty$,

$$E \le \tfrac{4}{3}\pi\sqrt{2}\,N^{3/4}[U(-m/g)]^{1/4}. \qquad (2.1)$$

Our work provides a dynamical mechanism to form such solitons

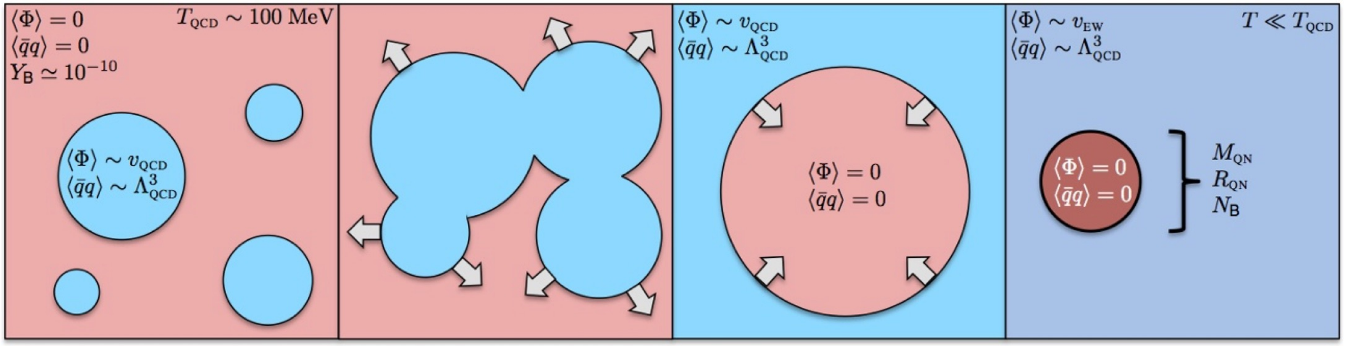


Hong, Jung and **KPX**, PRD 102 (2020) 7, 075028

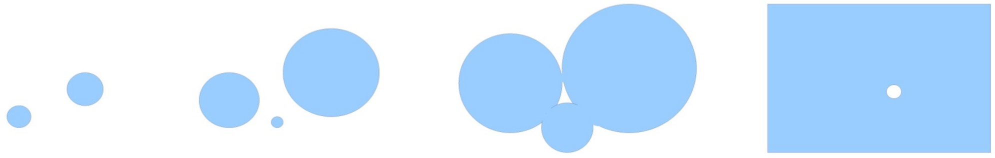
# Big picture: solitons formation during a FOPT

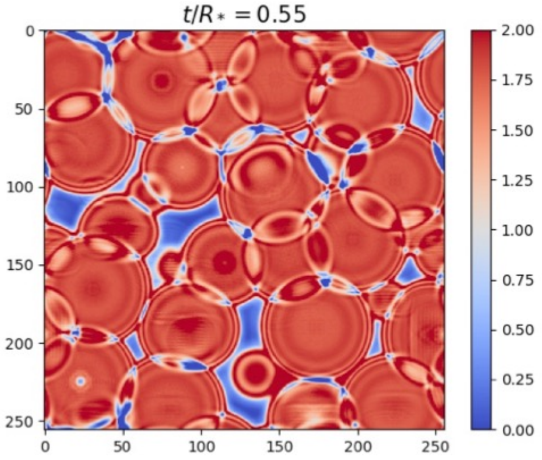
Fermions trapped to form dark dwarfs[Gross *et al*, JHEP 09 (2021) 033]

Quark-nuggets in a QCD FOPT[Bai *et al*, JHEP 06 (2018) 072; PRD 99 (2019) 5, 055047]



Scalar Q-balls[Krylov *et al*, PRD 87 (2013) 8, 083528; Huang *et al*, PRD 96 (2017) 9, 095028]



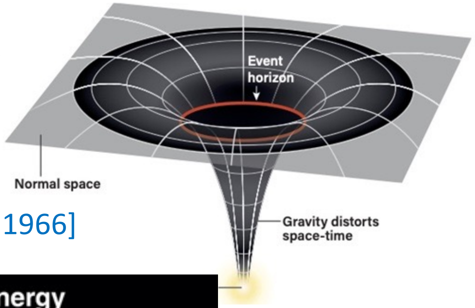


Topological solitons—

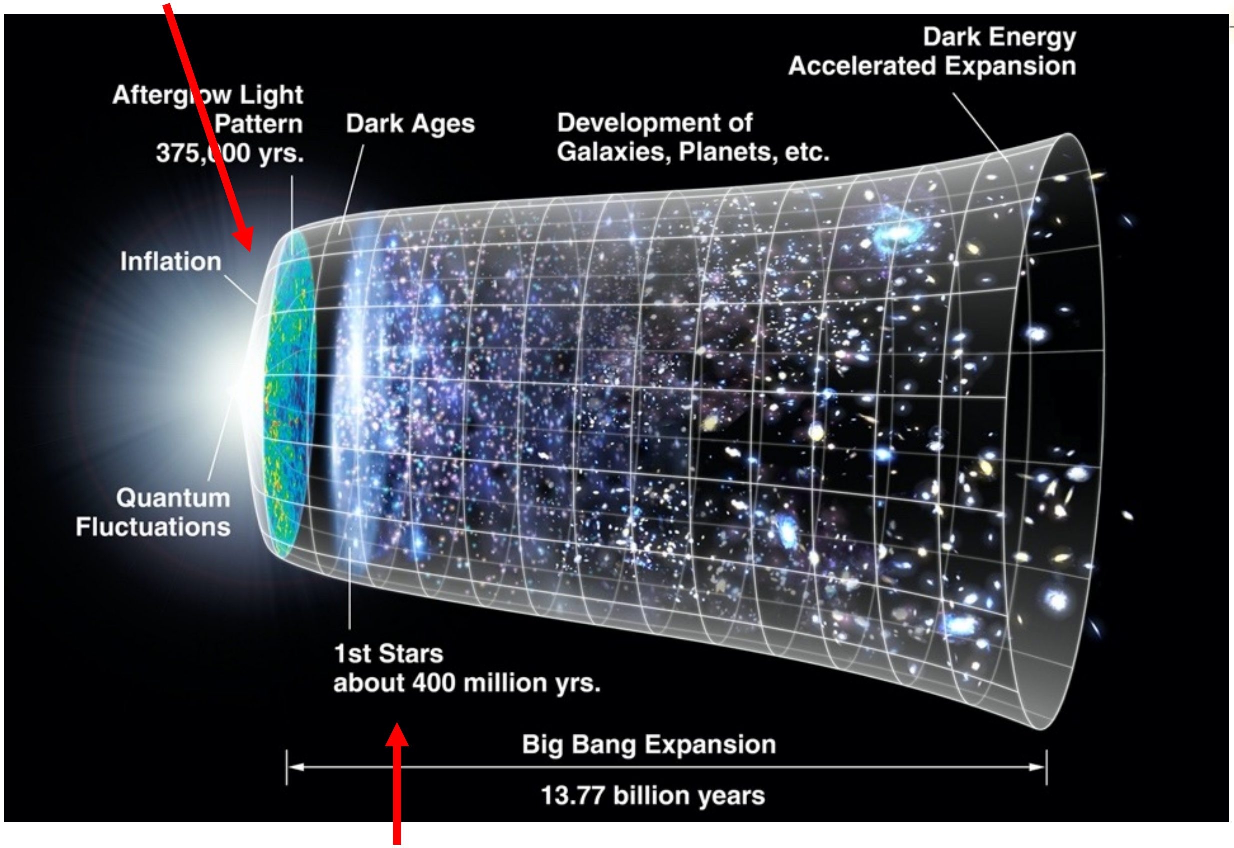
- Monopoles[Bian *et al*, PLB 839 (2023) 137822]
- Cosmic strings[Bian, Cai *et al*, 2204.04427]
- Domain walls[Jiang *et al*, 2208.07186]

# From solitons to black holes

Almost all kinds of solitons have the possibility of **collapsing into black holes**



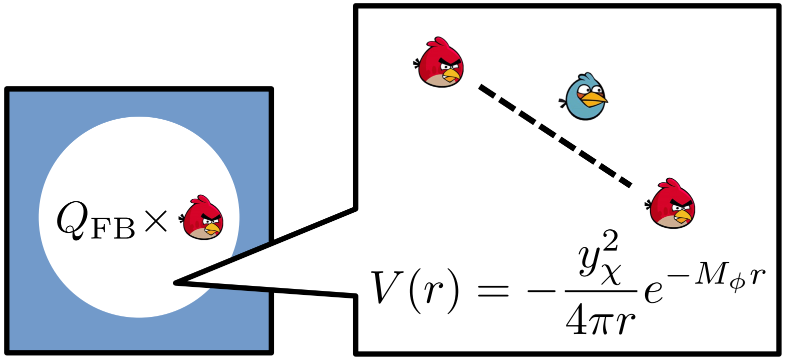
**Primordial** black holes (soon after Big Bang);[Zel'dovitch *et al*, 1966]



Astrophysical black holes (from stellar collapse)

# Attractive force inside a soliton

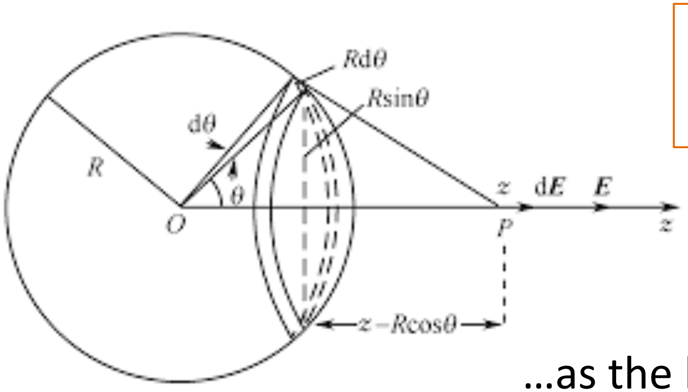
Yukawa force *inside* a Fermi-ball



$$V(r) = -\frac{y_\chi^2}{4\pi r}e^{-M_\phi r}$$

Originates from
$\mathcal{L} \supset -y_\chi \phi \bar{\chi}\chi$

A “textbook exercise” calculation…



$$\boxed{E_{\rm Yuk} \approx -\frac{15y_\chi^2}{40\pi}\frac{Q_{\rm FB}^2}{R}\left(\frac{L_\phi}{R}\right)^2}$$

$L_\phi = M_\phi^{-1}$: range of force

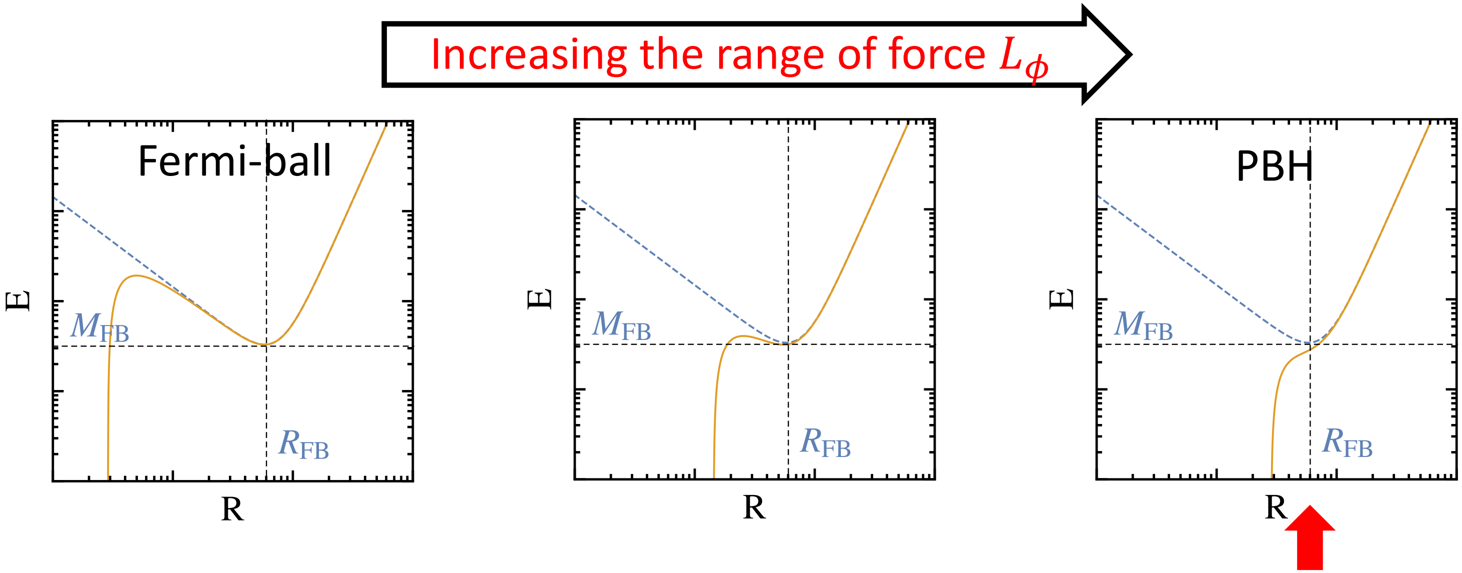
…as the leading-order approximation

# The complete energy profile

The improved energy profile (when $L_\phi = M_\phi^{-1} \ll R$)

$$\boxed{E \approx \frac{3\pi}{4}\left(\frac{3}{2\pi}\right)^{2/3}\frac{Q_{\mathrm{FB}}^{4/3}}{R} + \frac{4\pi}{3}R^3 U_0 - \frac{15 y_\chi^2}{40\pi}\frac{Q_{\mathrm{FB}}^2}{R}\left(\frac{L_\phi}{R}\right)^2}$$

What if the Yukawa energy dominates?



Increasing the range of force $L_\phi$

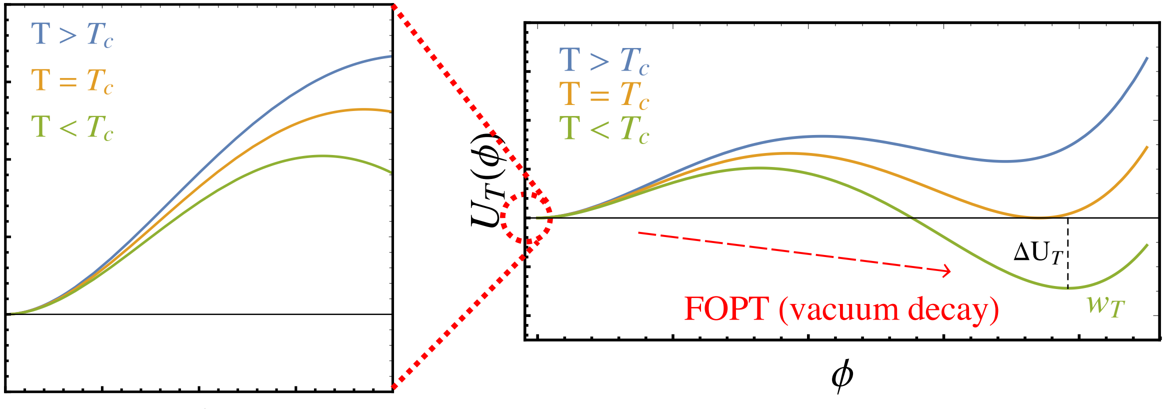
A Fermi-ball collapses in to a black hole!

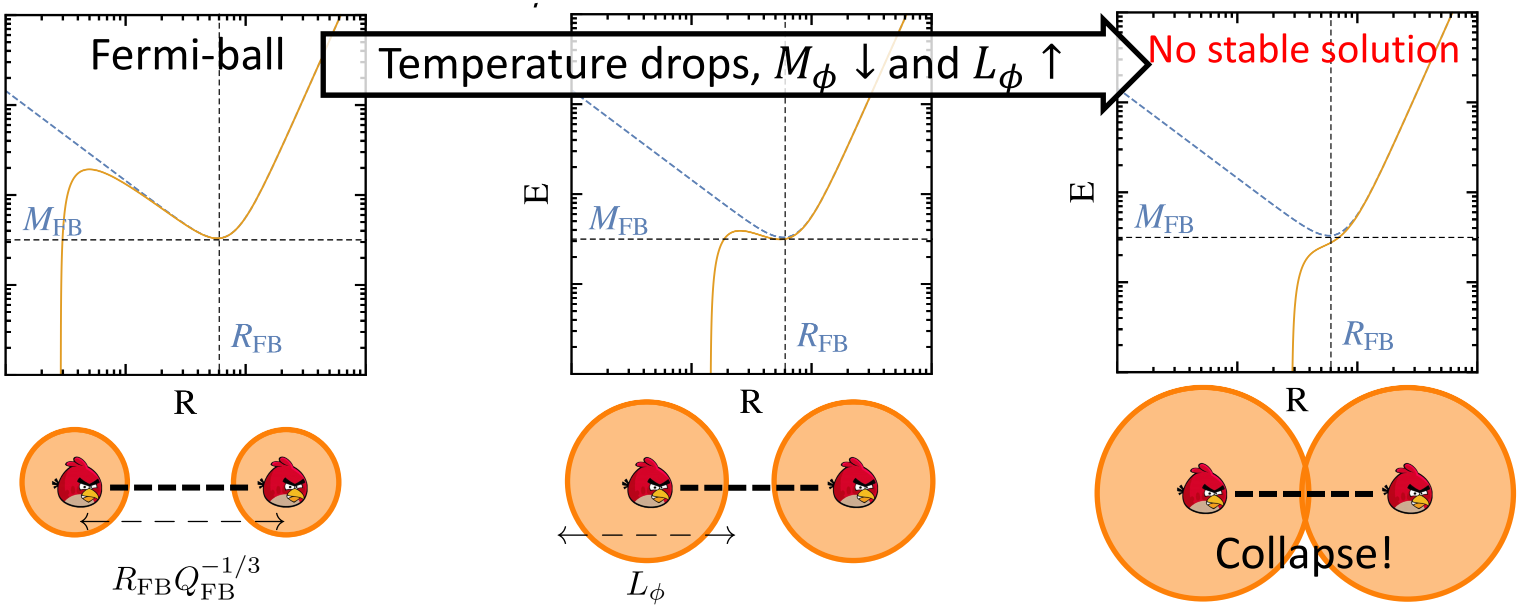
$L_\phi \sim R_{\mathrm{FB}} Q_{\mathrm{FB}}^{-1/3}$

# Fermi-balls may collapse when they cool down

The range of force increases as temperature drops!

$M_\phi = \sqrt{\mu^2 + cT^2}$




Temperature drops, $M_\phi \downarrow$ and $L_\phi \uparrow$

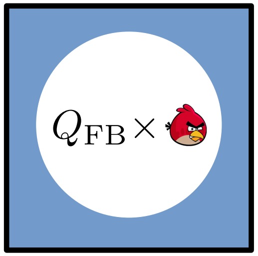
No stable solution

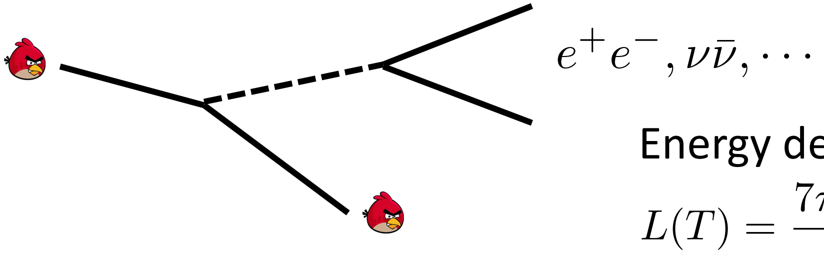
Collapse!

Kawana and **KPX**, PLB 824 (2022) 136791

# The cooling of Fermi-balls

Emitting SM light particles (black body radiation[Witten, PRD1984]);





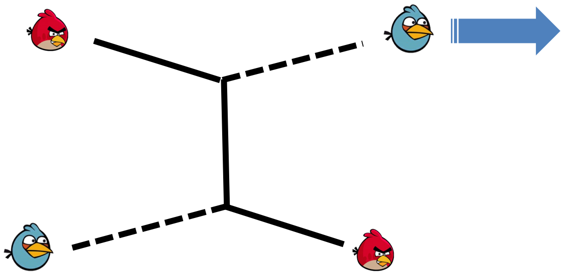
Energy decreasing rate

$$L(T)=\frac{7\pi^3 N_f}{240}R_{\rm FB}^2 T^4$$

$$\tau_{\rm cool}=\frac{240}{7\pi^2}\left(\frac{2\pi}{3}\right)^{1/3}\frac{Q_{\rm FB}^{1/3}(12\pi^2 U_0)^{1/4}}{N_f T^2}.$$

Radiation cooling is very efficient: $\tau_{\rm cool}\ll 1/H$

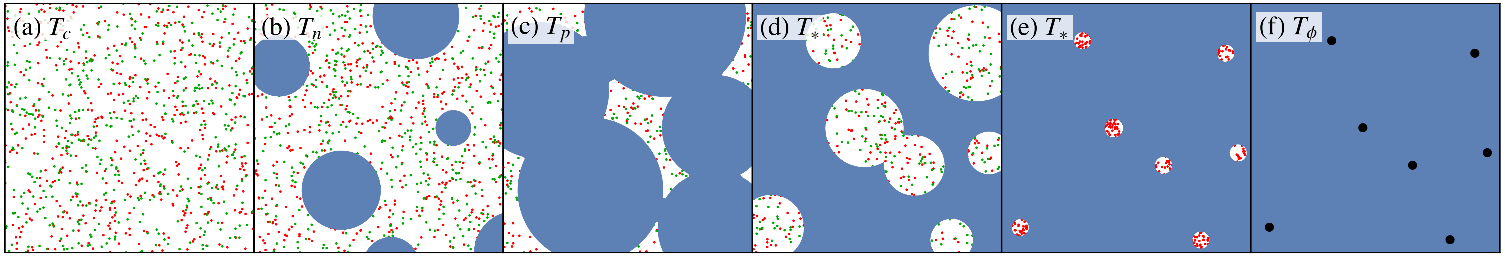
Scattering cooling:[Kawana, Lu and **KPX**, JCAP 10 (2022) 030]



In thermal bath via
$\lambda_{H\phi}|H|^2\phi^2$

In short: Fermi-balls can cool down!

# PBHs from Fermi-ball collapse from a FOPT



**Kawana and KPX, PLB 824 (2022) 136791**

Mechanism

- Mass discrtibution: Lu, Kawana and KPX, PRD 105 (2022) 12, 123503
- New soliton & PBH solutions: Kawana, Lu and KPX, JCAP 10 (2022) 030

Application

- EWPT & PBH DM: Huang and KPX, PRD 105 (2022) 11, 115033
- PBH & gamma-rays: Marfatia et al, JHEP 08 (2022) 001
- 511 keV galactic line: Tseng et al, 2209.01552
- PBHs after the CMB: Lu et al, 2210.16462
- Boosted DM: Marfatia et al, JHEP 04 (2023) 006
- Distinguishing different mechanisms: KPX, 2301.02352
- GWs at PTA: Tseng et al, 2304.10084

Advantages:

- Friendly to particle physicists;
- Can control the formation time of PBHs

# Big picture: primordial black holes from FOPTs

- Bubble collisions

Hawking *et al*, PRD 26 (1982) 2681

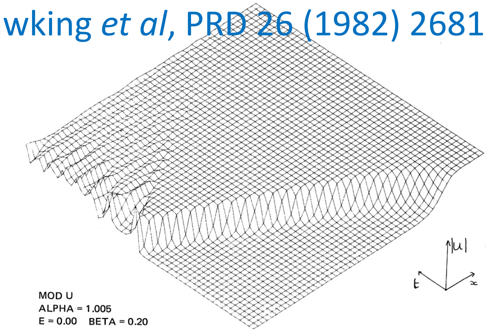
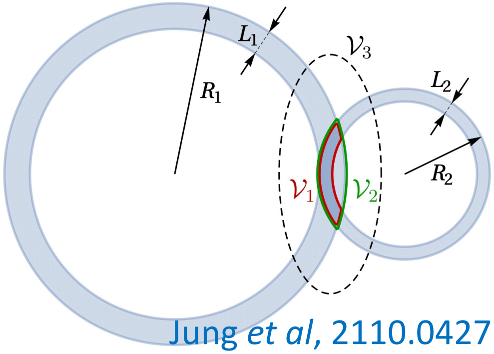


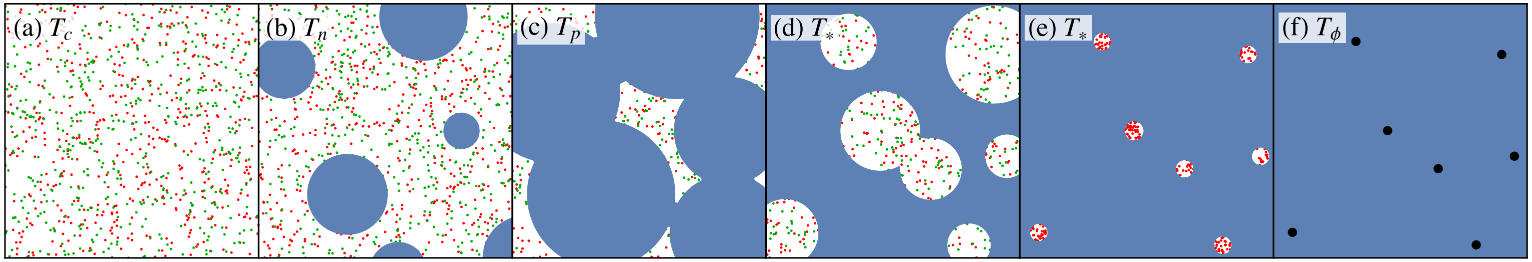
FIG. 5. The modulus of $u$ when the phase difference $\alpha \approx 1$.

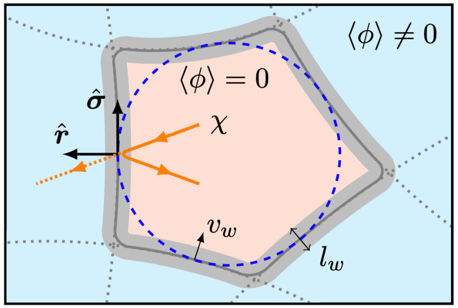


Jung *et al*, 2110.04271

- Particle trapping

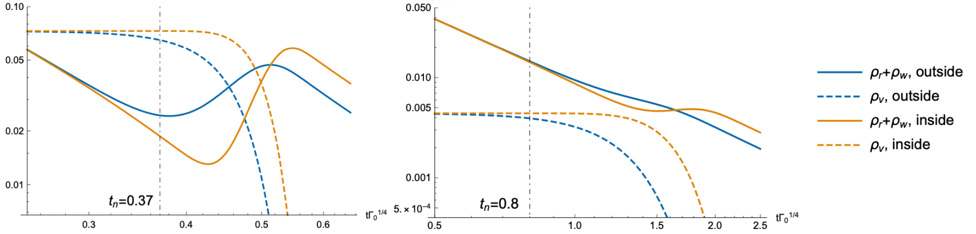
Kawana and **KPX**, PLB 824 (2022) 136791





Baker *et al*, 2105.07481

- Vacuum delayed decay



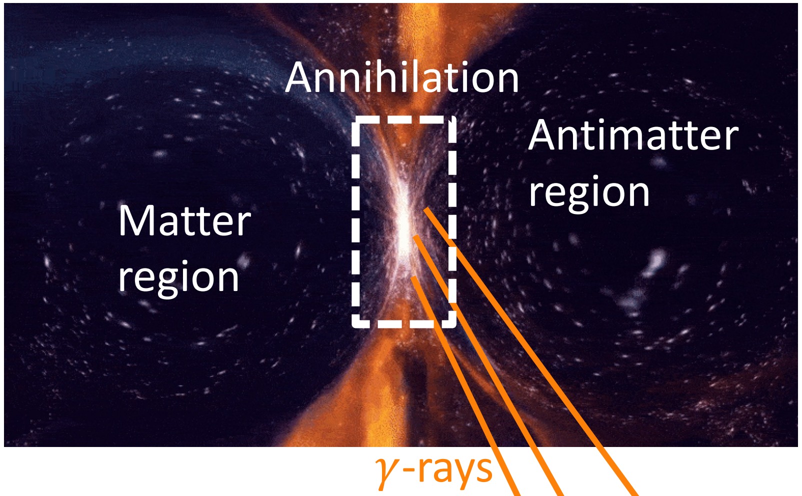
Liu, Bian, Cai, Guo and Wang PRD 105, L021303

# The matter-antimatter asymmetry

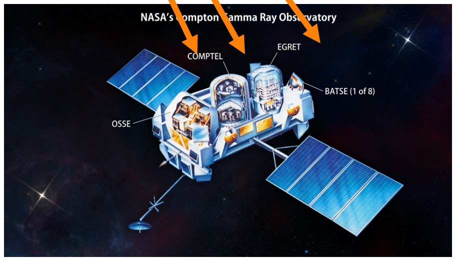
Also known as the *baryon asymmetry*

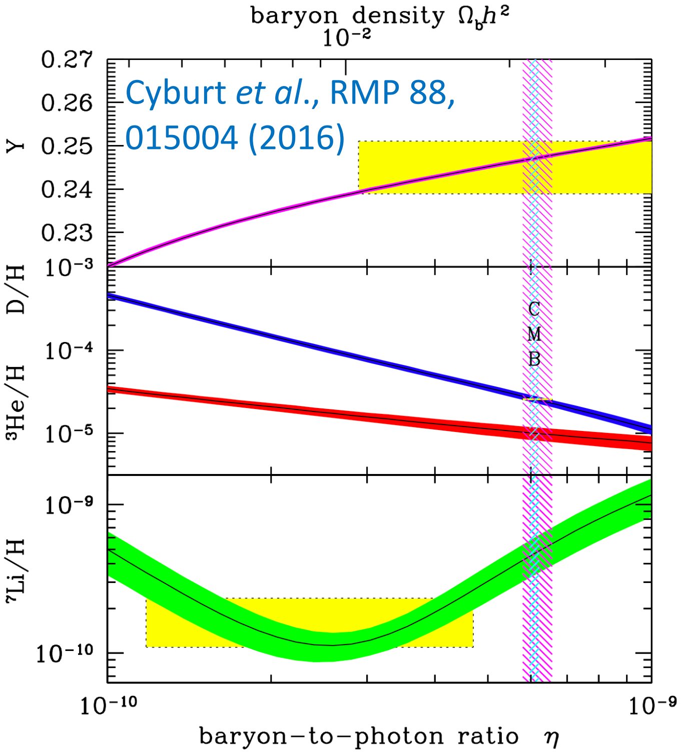
$$Y_B = \frac{n_B - n_{\bar{B}}}{s} \approx 10^{-10}$$

Two evidences:



Cohen *et al*, Astrophys. J. 495, 539 (1998)





Cyburt *et al.*, RMP 88, 015004 (2016)

# Generating the matter-antimatter asymmetry

A.Sakharov (1921-1989)

Baryogenesis between inflationary reheating & BBN

**Three conditions** for baryogenesis:[Sakharov,1967]

1. Baryon number violation;
2. C/CP violation;
3. Departure from equilibrium.

SM cannot satisfy

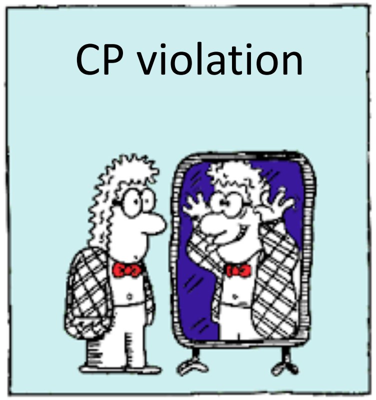
C&CP violation: To avoid

*N*(matter) = *N*(antimatter)

*N*(left-handed matter) = *N*(right-handed antimatter)
*N*(right-handed matter) = *N*(left-handed antimatter)

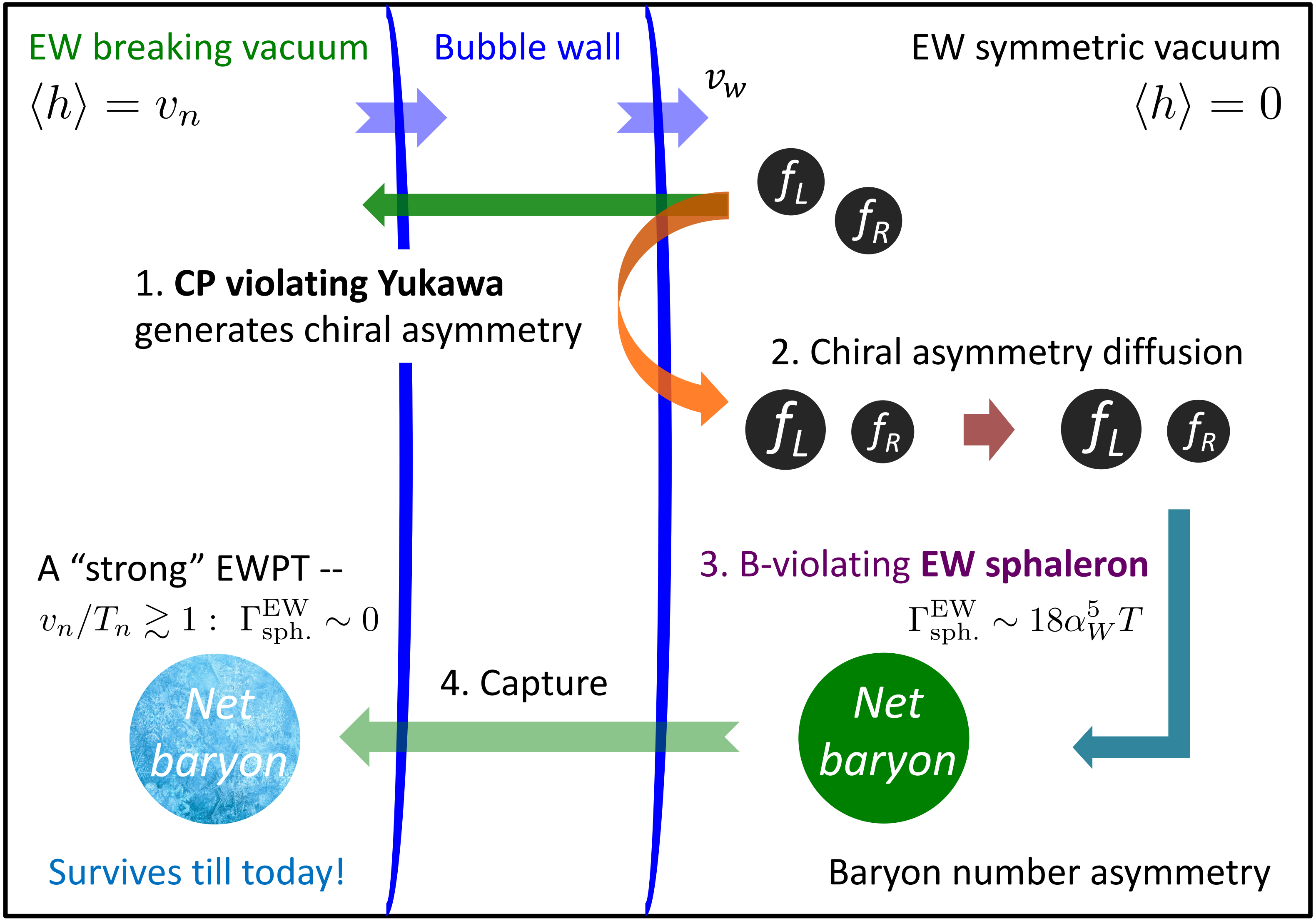
Why departure from equilibrium:

$$\langle B\rangle = \mathrm{tr}\left[Be^{-H/T}\right]$$
$$= \mathrm{tr}\left[(CPT)^{-1}Be^{-H/T}(CPT)\right] = -\mathrm{tr}\left[Be^{-H/T}\right]$$
$$= -\langle B\rangle = 0$$



# Electroweak baryogenesis

Joyce *et al*, PRL 75 (1995) 1695–1698



EW breaking vacuum

$\langle h \rangle = v_n$

Bubble wall

$v_w$

EW symmetric vacuum

$\langle h \rangle = 0$

1. **CP violating Yukawa** generates chiral asymmetry

2. Chiral asymmetry diffusion

3. B-violating **EW sphaleron**

$\Gamma^{\rm EW}_{\rm sph.} \sim 18\alpha_W^5 T$

A “strong” EWPT --

$v_n/T_n \gtrsim 1: \;\; \Gamma^{\rm EW}_{\rm sph.} \sim 0$

4. Capture

*Net baryon*

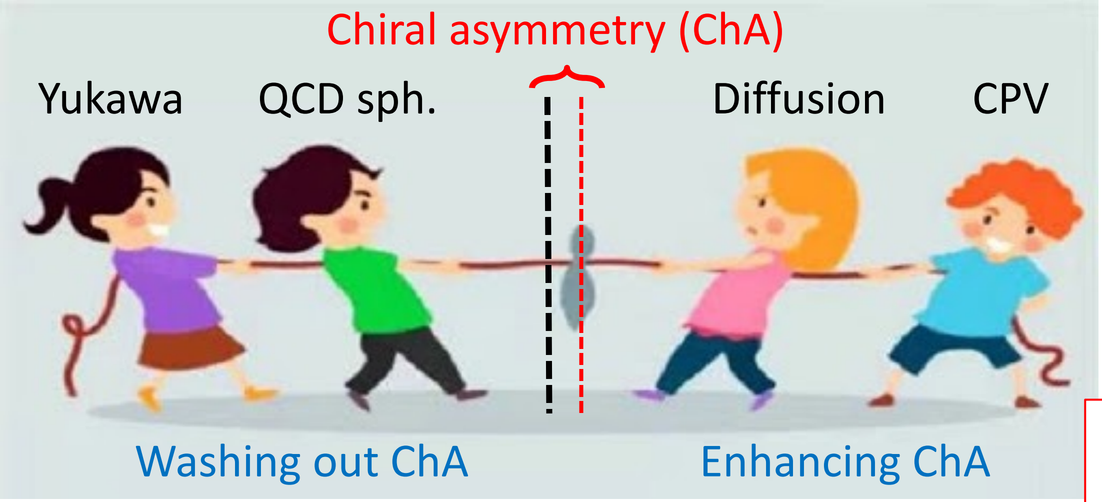
*Net baryon*

Survives till today!

Baryon number asymmetry

[Review] Morrissey *et al*, New J.Phys. 14 (2012) 125003

# Which fermion?



Most popular choice

$f = t$ $y_t \approx 1$ Large $D_q \approx 6/T$ $y_t \approx 1$

Strong washout v.s. Strong source

$f = \tau$ $y_\tau \approx 0.01$ Absent $D_\ell \approx 100/T$ $y_\tau \approx 0.01$

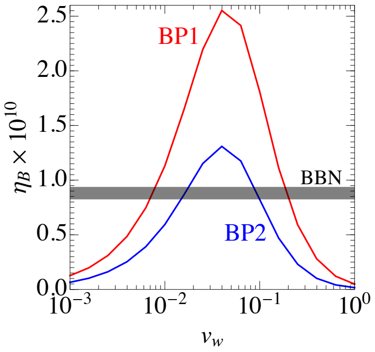
Small washout v.s. Small source

$\tau$-mediated Chung *et al*, PRL 102 (2009) 061301; Guo, Li, Liu, Ramsey-Musolf and Shu, PRD 96 (2017) 115034; De Vries *et al*, JHEP 04 (2019) 024; **KPX**, JHEP 02 (2021) 090

$b$-mediated[Modak *et al*, PRD 99 (2019) 115022]

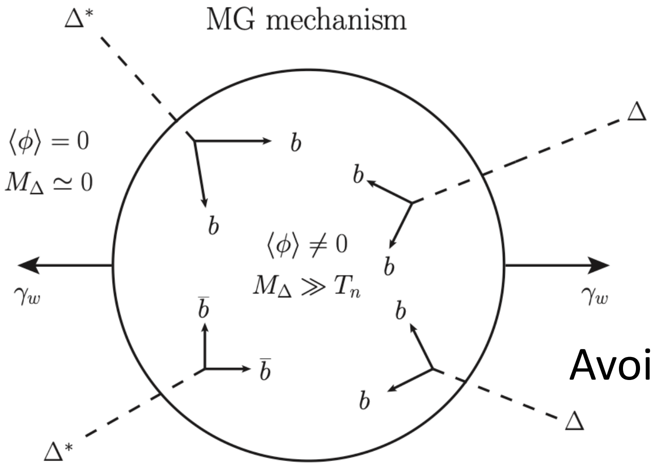
$\mu$-mediated[Fuchs *et al*, PRL 124 (2020) 181801]

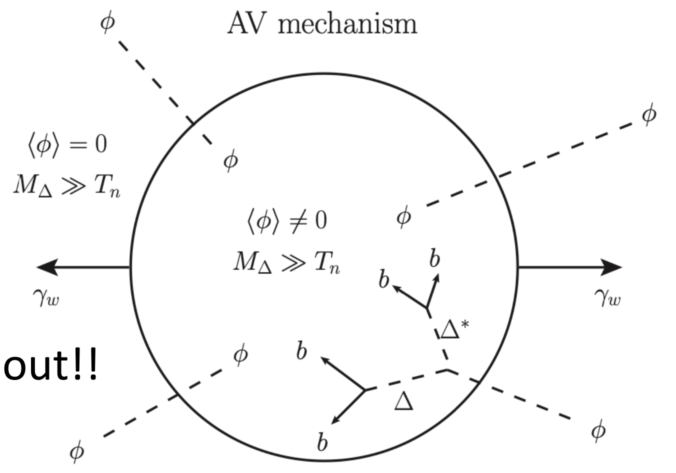
$\nu$-mediated[Fernandez-Martinez *et al*, JHEP 10 (2020) 063]



# Baryogenesis triggered by a FOPT

Relativistic bubbles[Baldes *et al*, PRD 104 (2021) 115029; Azatov *et al*, JHEP 10 (2021) 043]





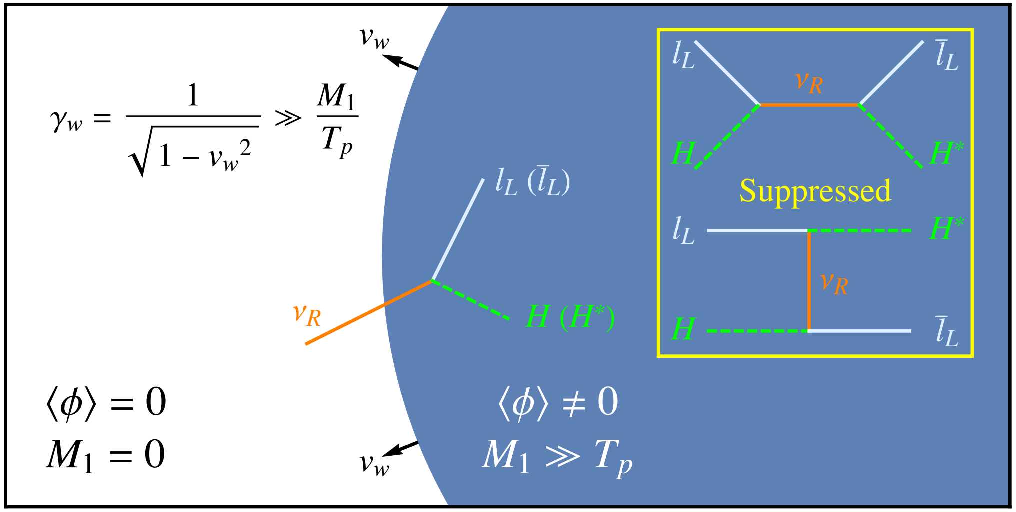
Avoiding washout!!

Apply to leptogenesis

- $\nu_R \rightarrow \ell_L H$
- $\epsilon_1 = \frac{\Gamma_{\ell H} - \Gamma_{\bar{\ell} H^*}}{\Gamma_{\ell H} + \Gamma_{\bar{\ell} H^*}}$
- $Y_B \approx \epsilon_1 \frac{n_{\nu_R}}{s}$

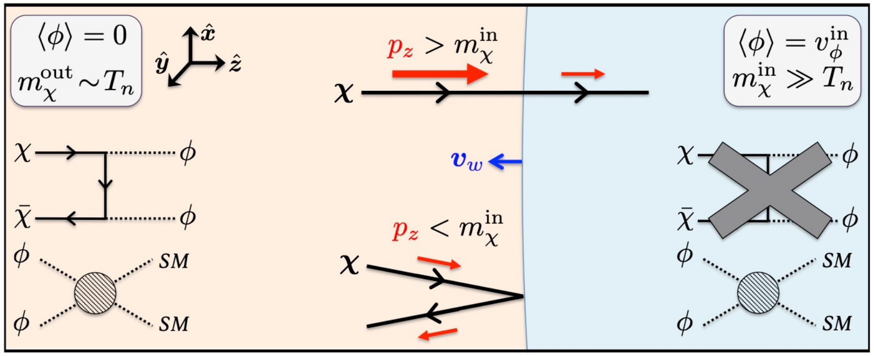
No washout at all

Huang and **KPX**, JHEP 09 (2022) 052

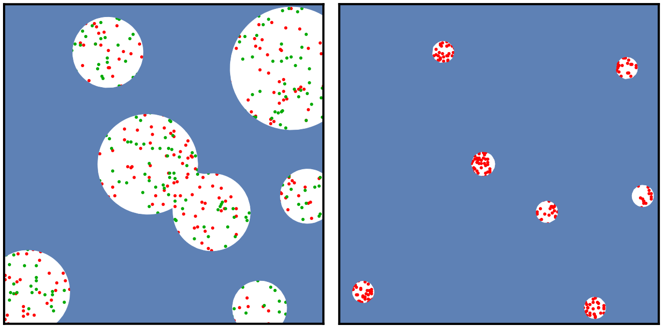


# A short summary on new physics mechanisms (1)

<u>Slow-moving bubble walls</u> ($v_w < 1$): particle filtering or trapping; diffusion; change of kinetic space, etc

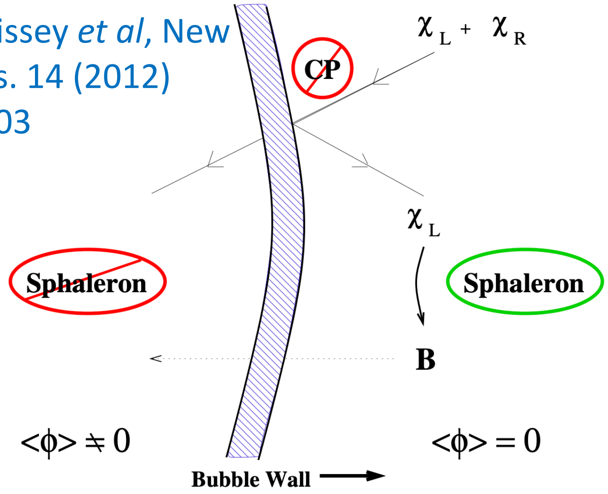


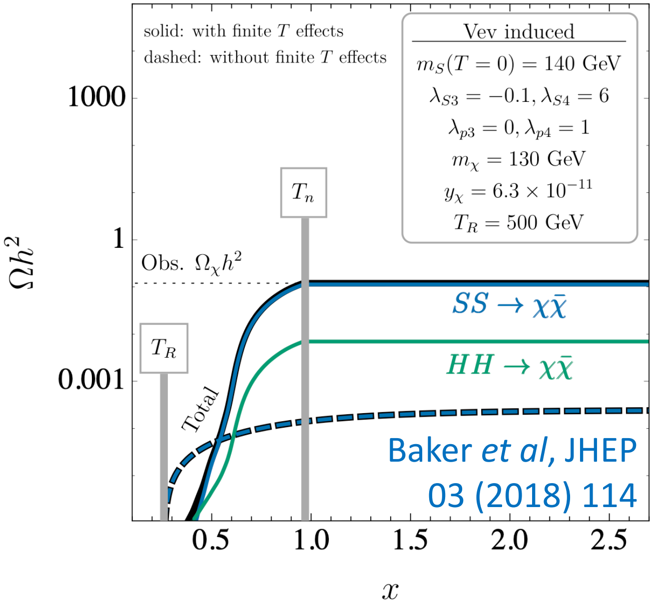
Baker *et al*, PRL 125 (2020) 15, 151102;
Chao *et al*, JCAP 06 (2021) 038



Hong, Jung and **KPX**, PRD 102 (2020) 7, 075028

Morrissey *et al*, New J.Phys. 14 (2012) 125003



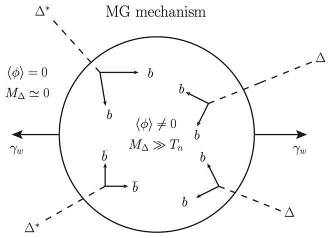


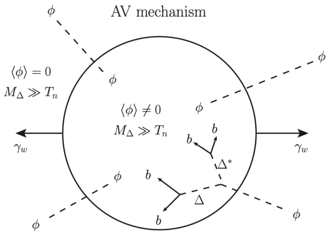
Baker *et al*, JHEP 03 (2018) 114

# A short summary on new physics mechanisms (2)

Relativistic bubble walls ($v_w \approx 1$): heavy particle production; entropy injection, etc

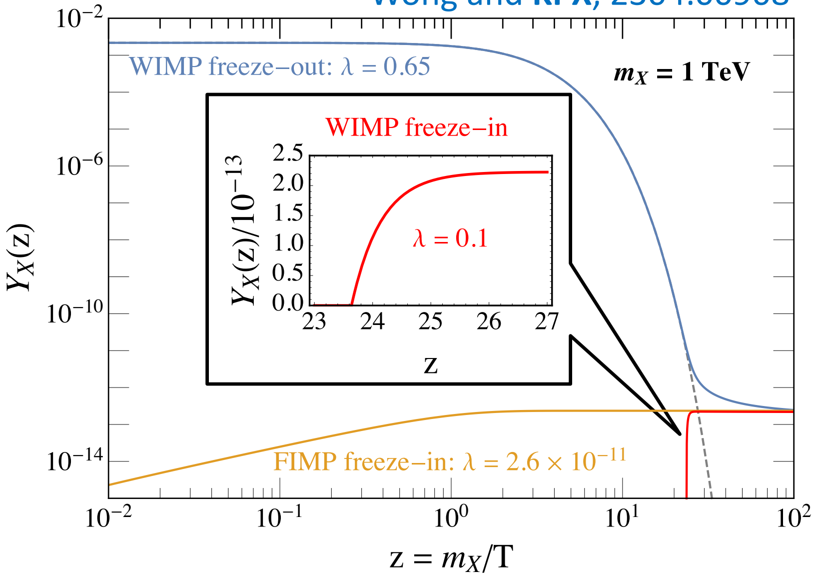
Baldes *et al*, PRD 104 (2021) 115029
Azatov *et al*, JHEP 10 (2021) 043
Huang and **KPX**, JHEP 09 (2022) 052



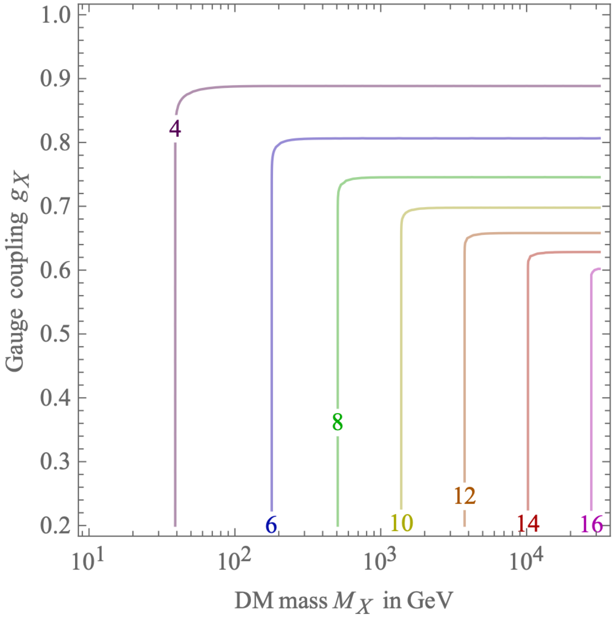


Hambye *et al*, JHEP 08 (2018) 188;
Baldes *et al*, JHEP 07, 084 (2022)

Wong and **KPX**, 2304.00908



Number of $e$–folds $N$



# Models that can have FOPTs

## SM + singlet scalar (xSM or cxSM)

Cline *et al*, JCAP 01 (2013) 012; Alanne et al, NPB 889 (2014) 692; Chiang *et al*, PLB 789 (2019) 154; Jiang, Bian, Huang and Shu, PRD 93 (2016) 6, 065032; Alves *et al*, JHEP 04 (2019) 052, JHEP 12 (2018) 070, JHEP 03 (2020) 053, PLB 818 (2021) 136377; Carena *et al*, JHEP 08 (2020) 107; Liu and **KPX**, JHEP 04 (2021) 015; Huang and **KPX**, PRD 105 (2022) 11, 115033, Liu *et al*, PRD 105 (2022) 11, 115040; etc

## Two-Higgs-doublet model

Cline *et al*, JHEP 11 (2011) 089; Dorsch *et al*, JHEP 10 (2013) 029; Basler *et al*, JHEP 02 (2017) 121; Dorsch *et al*, JHEP 12 (2017) 086; Bian, Jiang *et al*, JHEP 05 (2018) 151; Wang, Yang, Zhang and Zhang, PLB 788 (2019) 519; Wang, Huang, Zhang, PRD 101 (2020) 015015; Su *et al*, JHEP 04 (2021) 219; etc

## Left-right model

Brdar, Graf and Xu, JCAP 12 (2019) 027; Li, Yan, Zhang, Zhao, JHEP 03 (2021) 267; etc

## Georgi-Machacek model

Zhou, Cheng, Deng, Bian and Wu, JHEP 01 (2019) 216; etc

## Supersymmetric model

Lee *et al*, PRD 71 (2005) 075010; Balazs *et al*, PRD 71 (2005) 075002; Huang, Kang, Shu, Wu and Yang, PRD 91 (2015) 2, 025006; Bi, Bian, Huang, Shu and Yin, PRD 92 (2015) 023507; Bian, Guo, Shu, CPC 42 (2018) 9, 093106; Athron *et al*, JHEP 11 (2019) 151; Wang, **KPX**, Wu and Yang, EPJC 82 (2022) 12, 1120; etc

## Composite Higgs model

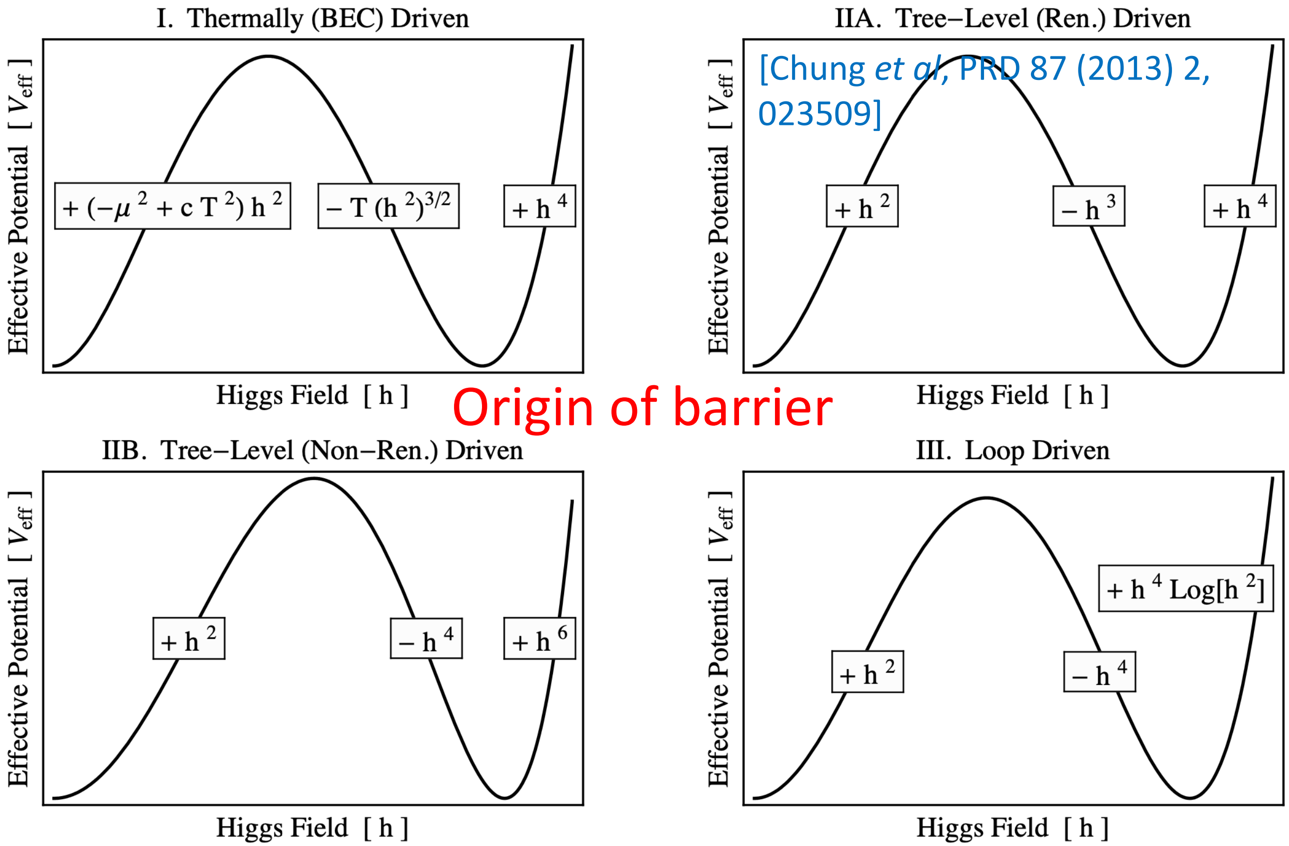
Espinosa *et al*, JCAP 01 (2012) 012; Bian, Wu and **KPX**, JHEP 12 (2019) 028, JHEP 12 (2020) 047; De Curtis *et al*, JHEP 12 (2019) 149; Angelescu *et al*, JHEP 10 (2022) 019; etc

# Calculating the FOPTs (1): potential

The finite temperature potential[Quiros, hep-ph/9901312]

$$U_T(\phi, T) = U_0(\phi) + U_1(\phi) + U_{1,T}(\phi, T) + U_{\text{daisy}}(\phi, T)$$

Tree level　1-loop CW　1-loop thermal　Daisy resummation



[Chung *et al*, PRD 87 (2013) 2, 023509]

Origin of barrier

IIA & III: Hot now

# Calculating the FOPTs (2): dynamics

Vacuum decay rate[Coleman *et al*, PRD 15 (1977) 2929-2936; PRD 16 (1977) 1762-1768]

At finite temperature[Linde, NPB 216 (1983) 421] $\Gamma(T) \sim \left(\frac{S_3}{2\pi T}\right) T^4 e^{-S_3/T}$

$S_3$ -- Action of $O(3)$-symmetric bounce solution

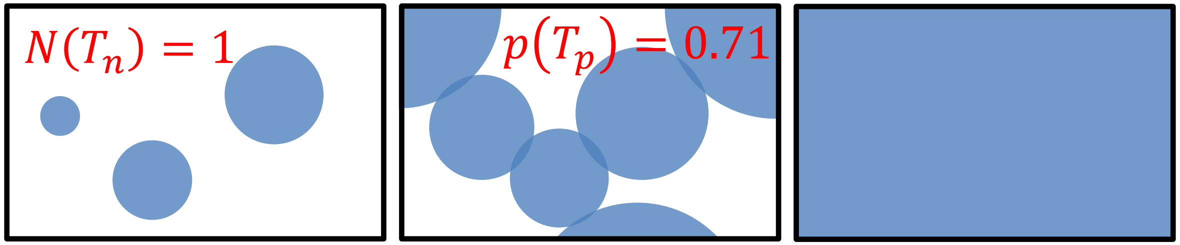
Bounce solution

$$S_3 = \int_0^\infty 4\pi r^2 \mathrm{d}r \left[\frac{1}{2}\left(\frac{\mathrm{d}\hat{\phi}}{\mathrm{d}r}\right)^2 + U_T\left(\hat{\phi}, T\right)\right]$$

Nucleation rate $N(T) = \int_T^{T_c} \frac{\mathrm{d}T'}{T'} \frac{\Gamma(T')}{H^4(T')}$

False vacuum fraction[Guth *et al*, PRD23 (1981) 876] $p(T) = e^{-I(T)}$;

$$I(T) = \frac{4\pi}{3} \int_T^{T_c} \mathrm{d}T' \frac{\Gamma(T')}{T'^4 H(T')} \left(\int_T^{T'} \frac{v_w \mathrm{d}\tilde{T}}{H(\tilde{T})}\right)^3$$



1. Nucleation $T_n$ 2. Percolation $T_p$ 3. Completed

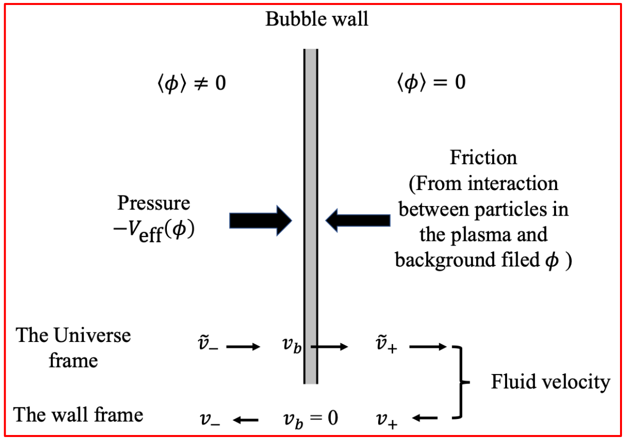
FOPT criterion

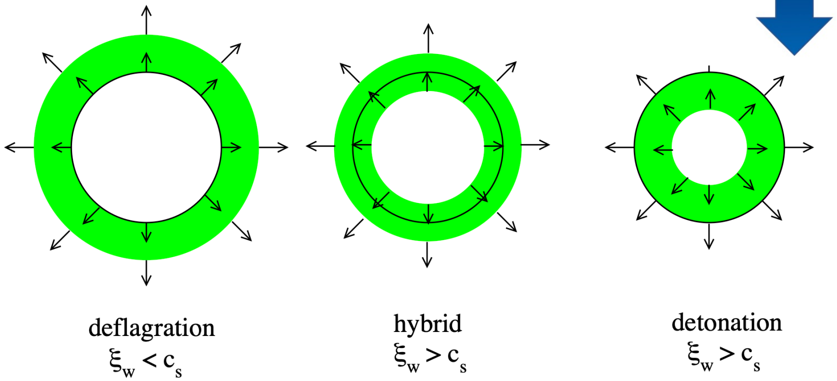
Very rough: $\frac{S_3}{T} \sim 4 \ln \frac{M_{\mathrm{Pl}}}{T}$

Strict: $3 + T_p \frac{\mathrm{d}I}{\mathrm{d}T}\Big|_{T_p} < 0$

# Dynamics of the FOPT

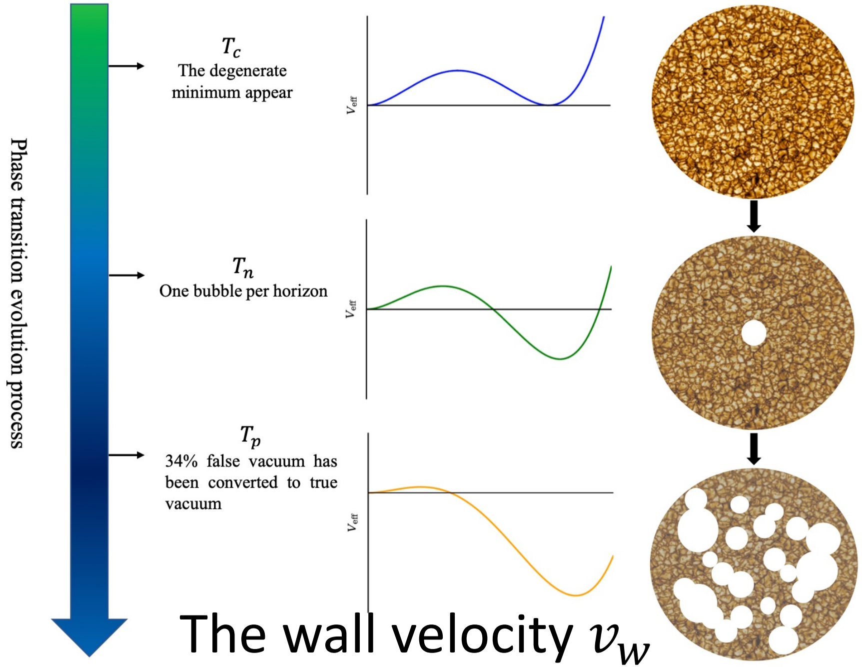
Energy budget: how much energy is devoted into wall or plasma motion?





Espinosa *et al*, JCAP 1006 (2010) 028;
Ellis *et al*, JCAP 06 (2019) 024, JCAP 11 (2020) 020

Wang, Huang and Zhang, JCAP 05 (2020) 045



## The wall velocity $v_w$

Konstandin *et al*, JCAP 09 (2014) 028; Bodeker *et al*, JCAP 0905 (2009) 009, JCAP 05 (2017) 025; Höche *et al*, JCAP 03 (2021) 009; Cai and Wang, JCAP 03 (2021) 096; Lewicki *et al*, JHEP 02 (2022) 017; Ai *et al*, JCAP 03 (2022) 03, 015; Gouttenoire(DESY and Tel Aviv U.), Ryusuke Jinno *et al*, JHEP 05 (2022) 004; Wang *et al*, PRD 107 (2023) 2, 023501

# Gravitational waves & lattice simulation

Sources: [Caprini *et al*, JCAP 1604 (2016) 001]

1. Bubble collision;
2. Sound waves;
3. Turbulence

Normally, sound wave dominates

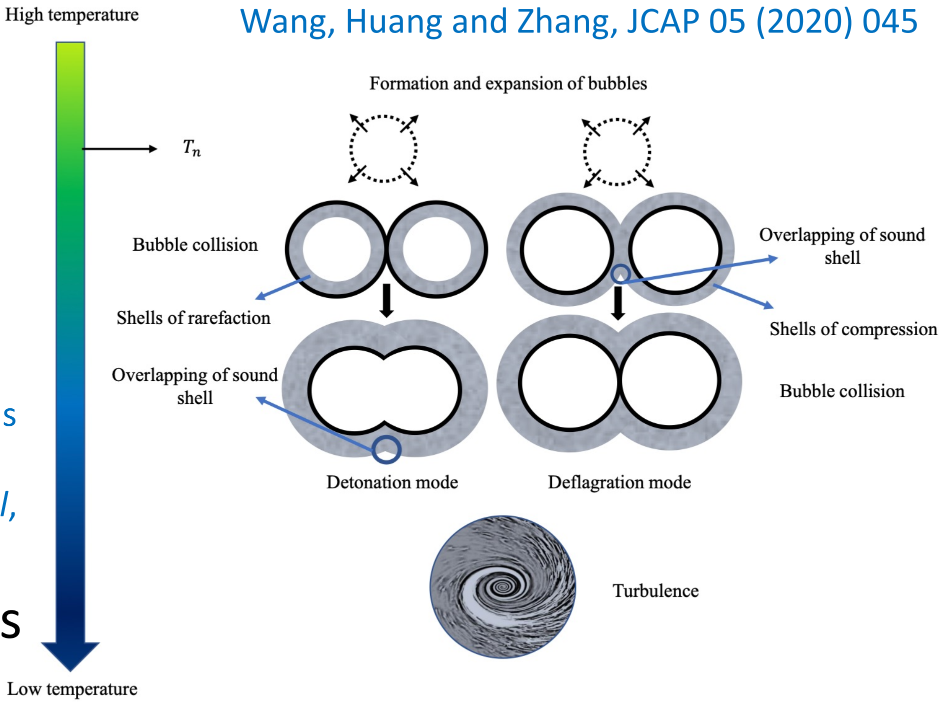
Espinosa *et al*, JCAP 1006 (2010) 028; Ellis *et al*, JCAP 04 (2019) 003; Wang, Huang and Zhang, JCAP 05 (2020) 045; Guo *et al*, JCAP 01 (2021) 001; etc

Bubble collision dominates for relativistic bubbles

Ellis *et al*, JCAP 06 (2019) 024, JCAP 11 (2020) 020; etc

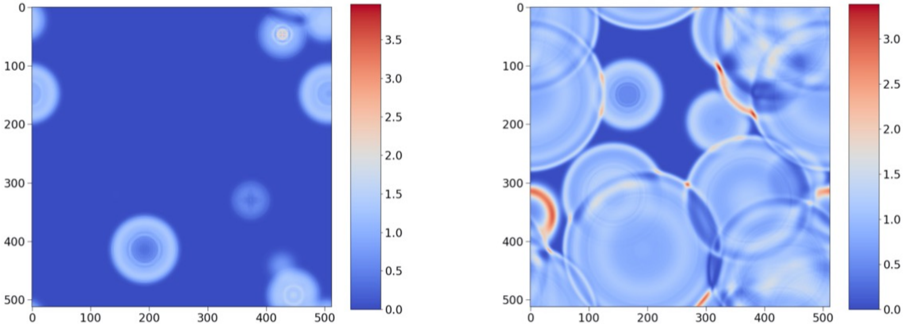
Lattice simulations

Di, Wang, Zhou, Bian, Cai and Liu, PRL 126 (2021) 25, 251102; Zhao, Di, Bian and Cai, 2204.04427; Li, Bian and Jia, 2304.05220; etc



Wang, Huang and Zhang, JCAP 05 (2020) 045

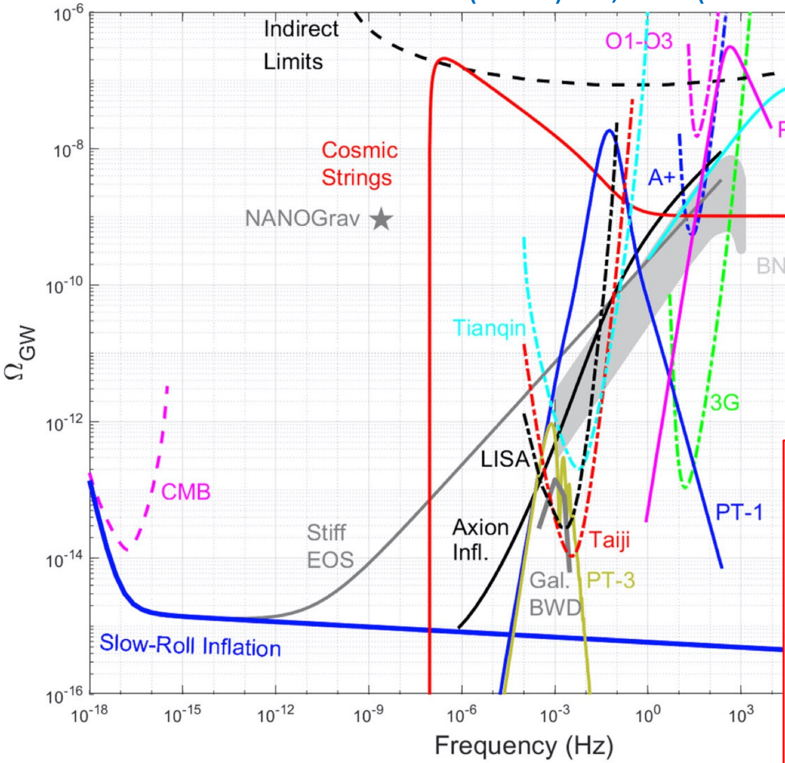
Di *et al*, PRL 126 (2021) 25, 251102

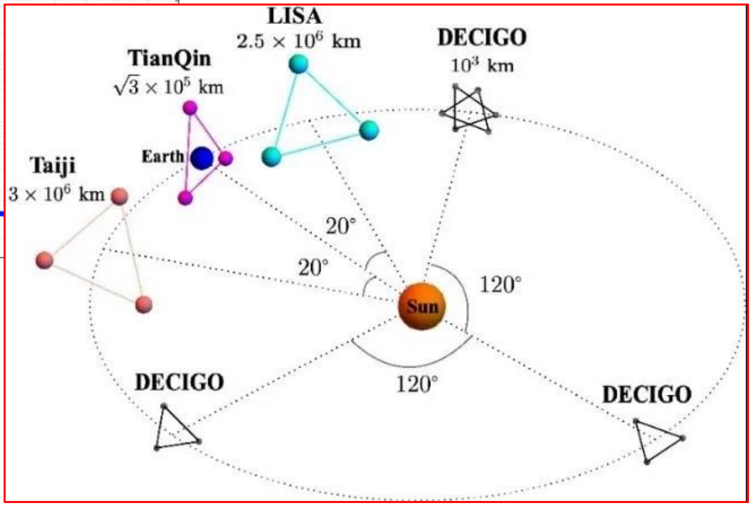


# Detecting FOPTs (1)

## Current and future GW detectors

Gen.Rel.Grav. 54 (2022) 12, 156 (Snowmass 2021)

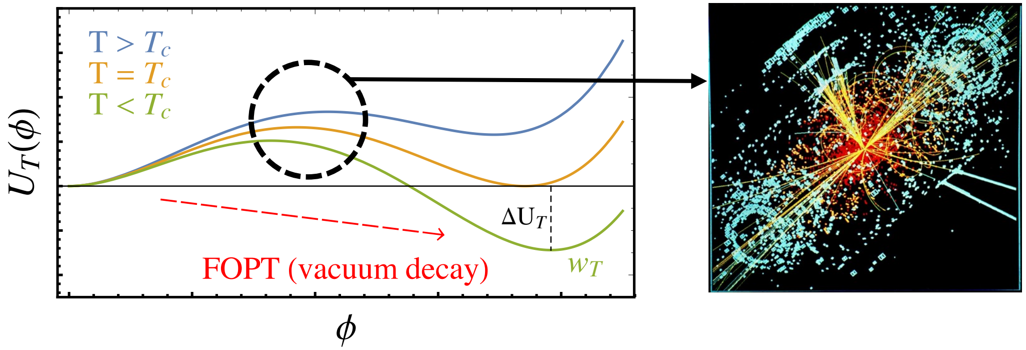




LIGO constraints PRL 126 (2021) 15, 151301;
PTA constraints PRL 127 (2021) 25, 251303

# Detecting FOPTs (2)

## Collider experiments complementarity



LHC → HL-LHC
HE-LHC? LHeC?
CEPC? ILC? FCC?
Muon collider?

## Di-Higgs production

Huang, Gu, Yu and Zhang, PRD 93 (2016) 10, 103515; Alves, Guo, *et al*, JHEP 04 (2019) 052, JHEP 12 (2018) 070, JHEP 03 (2020) 053, PLB 818 (2021) 136377; Liu and **KPX**, JHEP 04 (2021) 015; etc

## Exotic Higgs decay

Kozaczuk *et al*, PRD 101 (2020) no. 11, 115035; Carena, **KPX** *et al*, 2203.08206 (Snowmass 2021); Liu *et al*, PRD 105 (2022) 11, 115040; etc

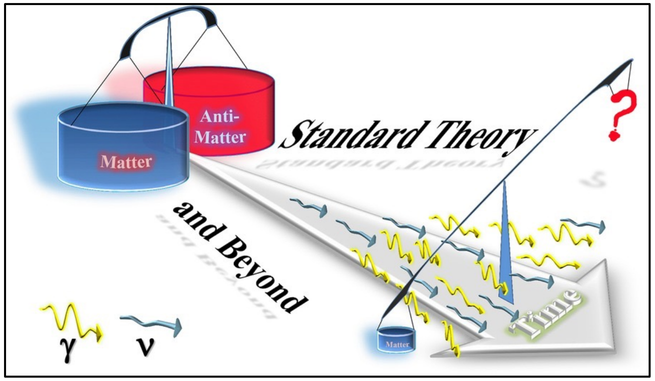
## Higgs triple coupling, EW precision measurements

Huang, Gu, Yu and Zhang, PRD 93 (2016) 10, 103515; Cao, Huang, **KPX** and Zhang, CPC 42 (2018) 2, 023103; Su, Williams and Zhang, JHEP 04 (2021) 219; Song, Su and Zhang, JHEP 10 (2022) 048; etc

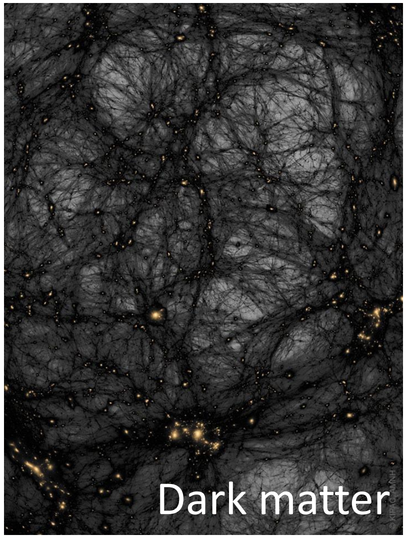
## And other signals (very model-dependent)

# Closing remarks

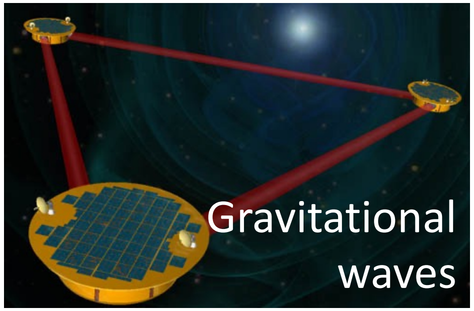
A lot of fun in a boiling Universe!



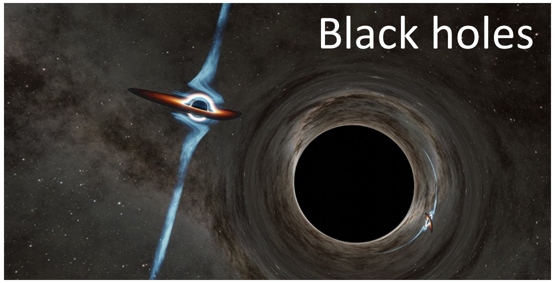
Matter-antimatter asymmetry



Dark matter



Gravitational waves



Black holes

**Thank you!**