北京航空航天大學
BEIHANG UNIVERSITY

Solitons and **Primordial black holes** from a cosmic phase transition

Ke-Pan Xie

Beihang University

2022.10.19 @King's College London (online)

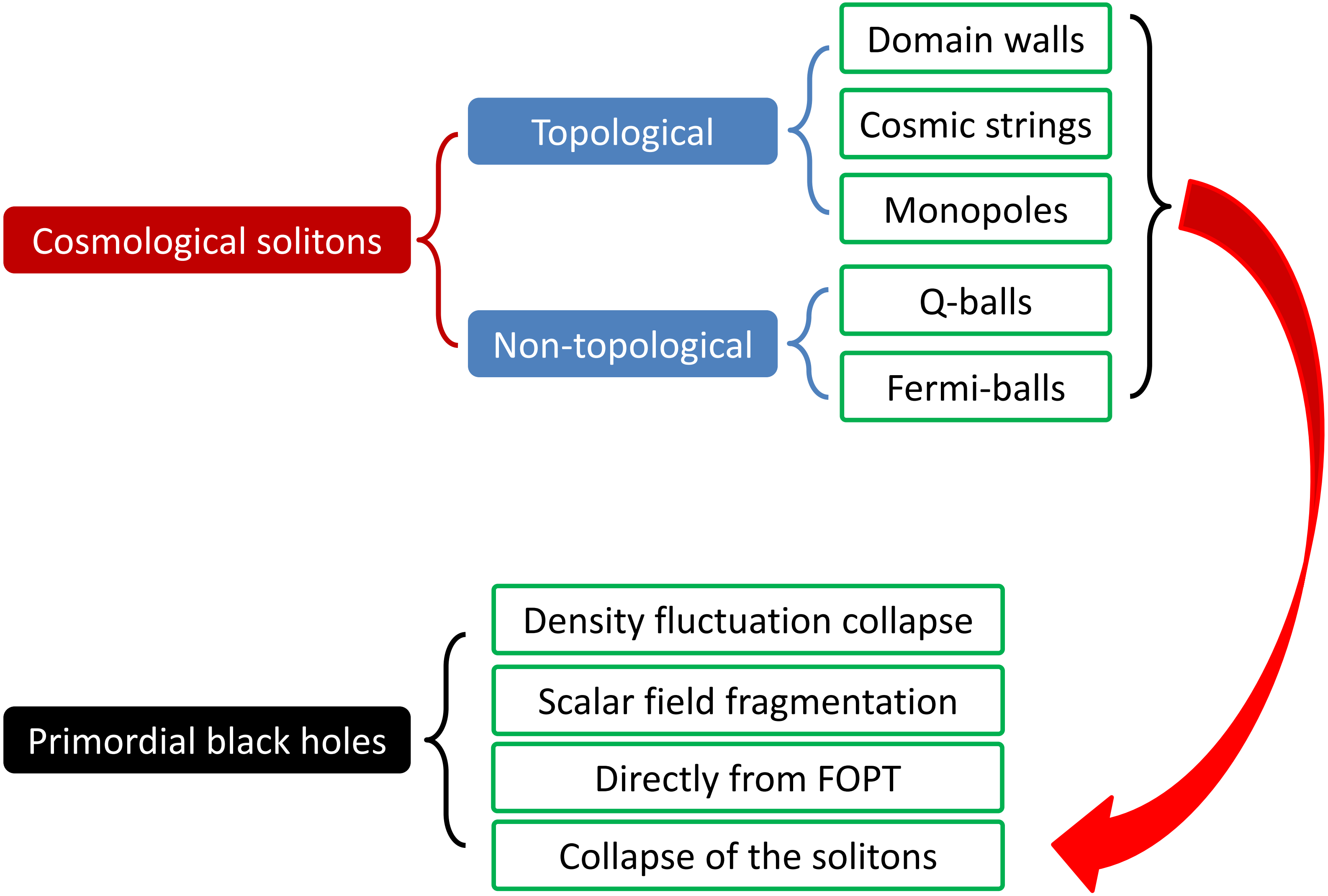
2008.04430 (PRD), 2106.00111 (PLB) and 2201.07243 (PRD);
With Sunghoon Jung, Jeong-Pyong Hong, Kiyoharu Kawana and Peisi Huang

Global picture

- Cosmological solitons
  - Topological
    - Domain walls
    - Cosmic strings
    - Monopoles
  - Non-topological
    - Q-balls
    - Fermi-balls

- Primordial black holes
  - Density fluctuation collapse
  - Scalar field fragmentation
  - Directly from FOPT

Global picture



Cosmological solitons

Topological

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Fermi-balls

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Density fluctuation collapse

Scalar field fragmentation

Directly from FOPT

Collapse of the solitons

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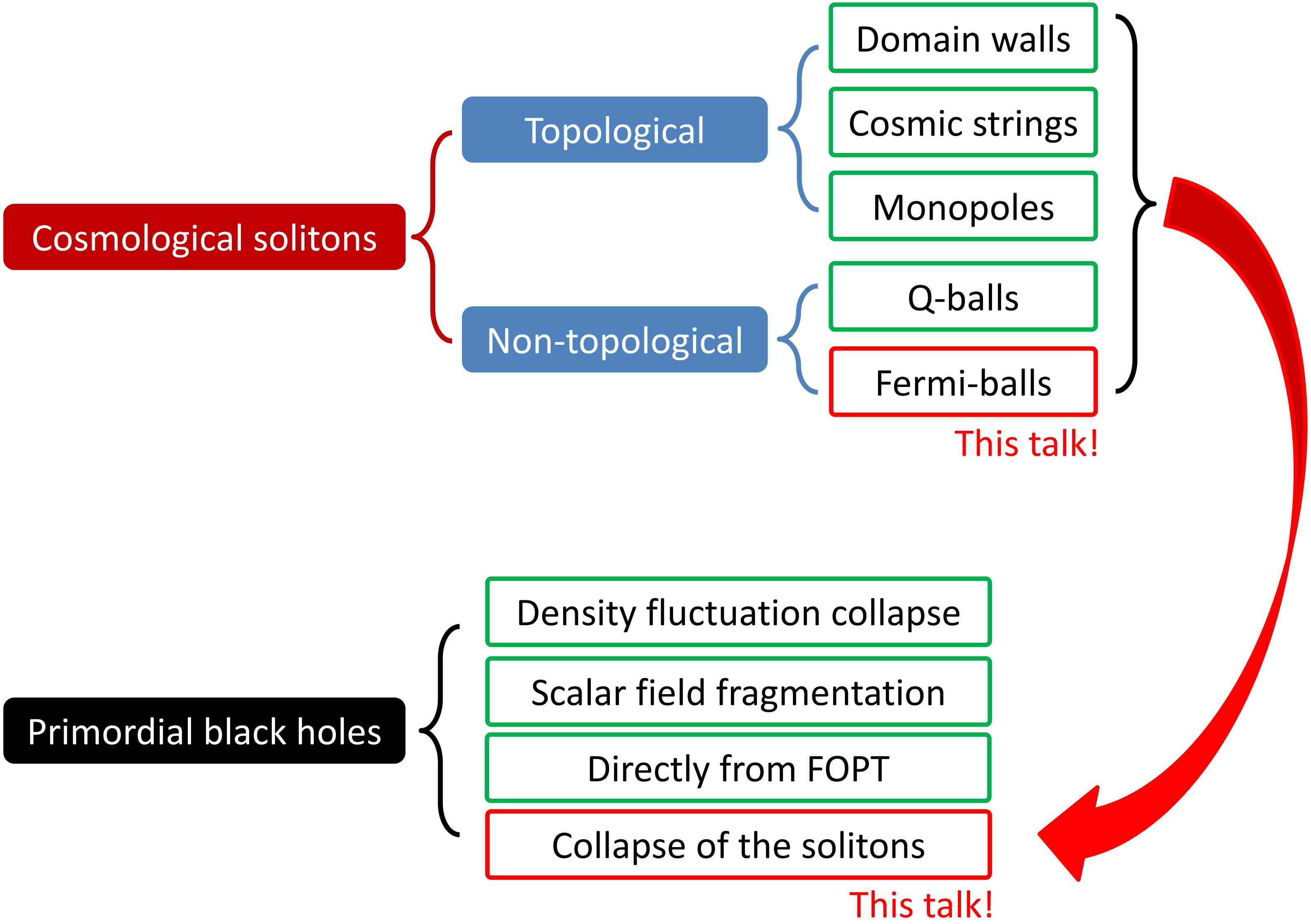

Cosmological solitons

Topological

- Domain walls
- Cosmic strings
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Non-topological

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- Fermi-balls

This talk!

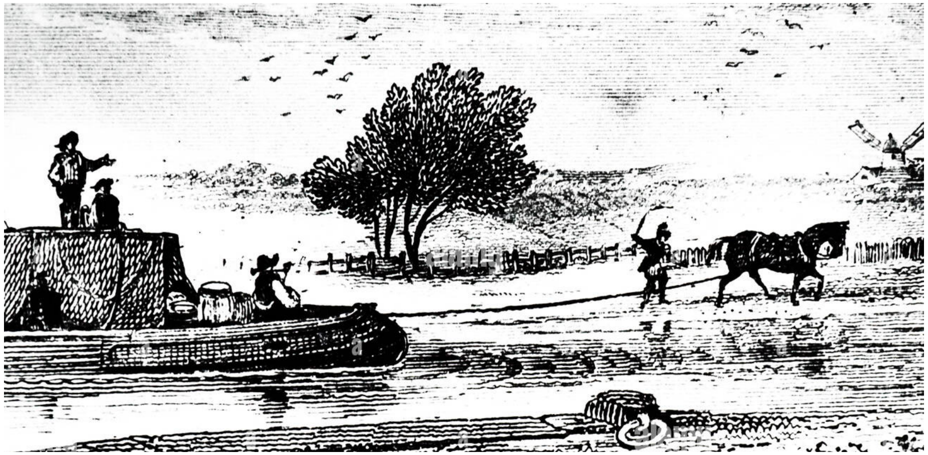
Primordial black holes

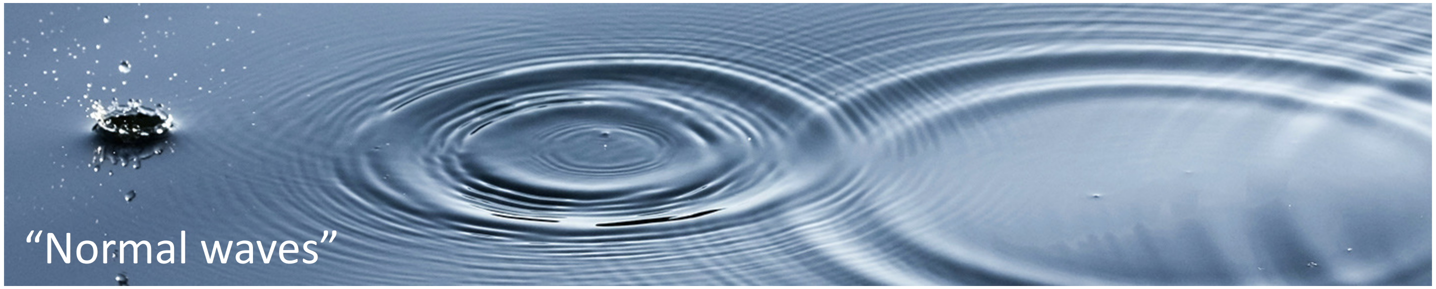
- Density fluctuation collapse
- Scalar field fragmentation
- Directly from FOPT
- Collapse of the solitons

This talk!

Solitons (solitary waves)

First discovered by John Scott Russell at 1834





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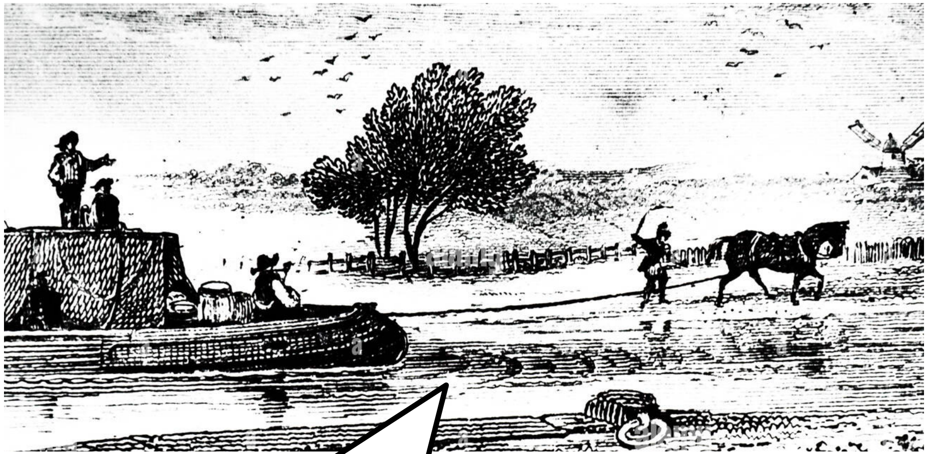
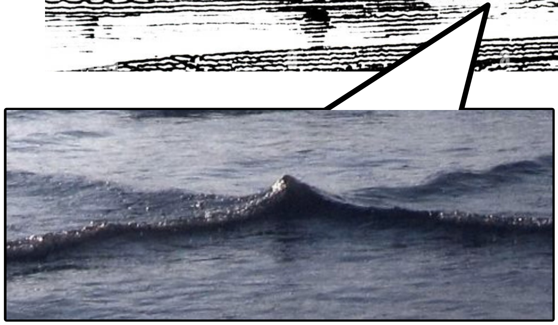


1808-1882



… preserving its original figure … after a chase of one or two miles I lost it in the windings of the channel…

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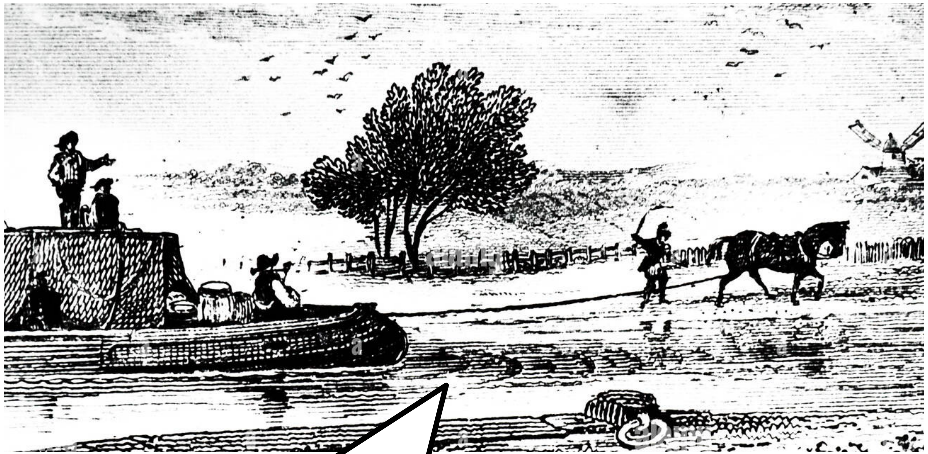

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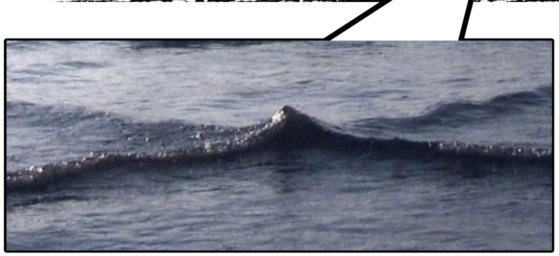

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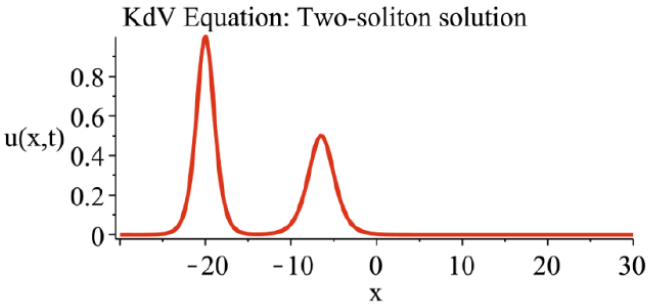
1895

Diederik Korteweg & Gustav de Vries

KdV equation



Solitons exist everywhere!

A conventional definition (Drazin & Johnson, 1989):

1. Of permanent form;
2. Localized within a region;
3. Can interact with other solitons, and emerge from the collision unchanged, except for a phase shift.

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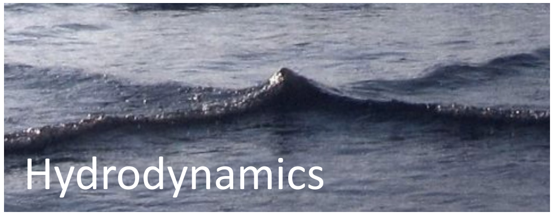
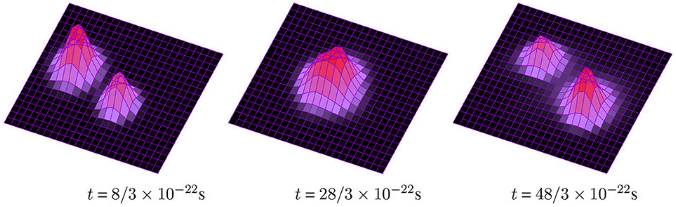
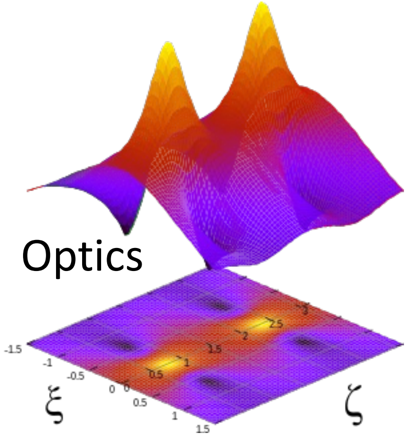


Hydrodynamics

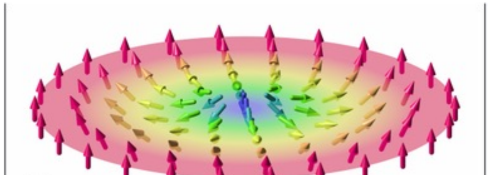
Nuclear physics



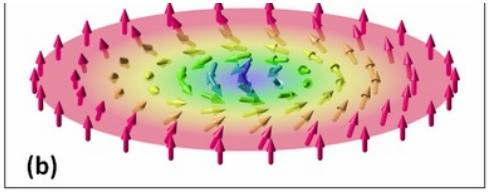
$t = 8/3 \times 10^{-22}$s $t = 28/3 \times 10^{-22}$s $t = 48/3 \times 10^{-22}$s



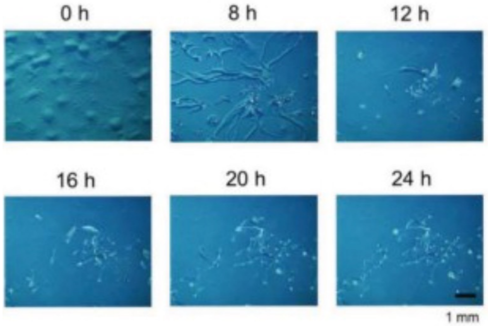
Optics



Condensed matter physics



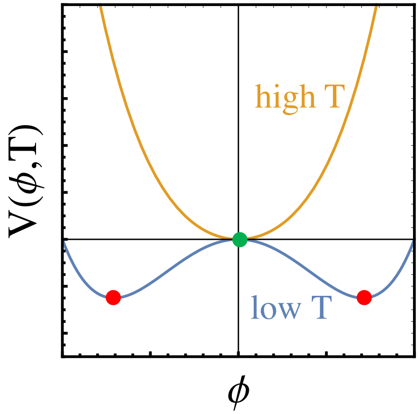
Biology

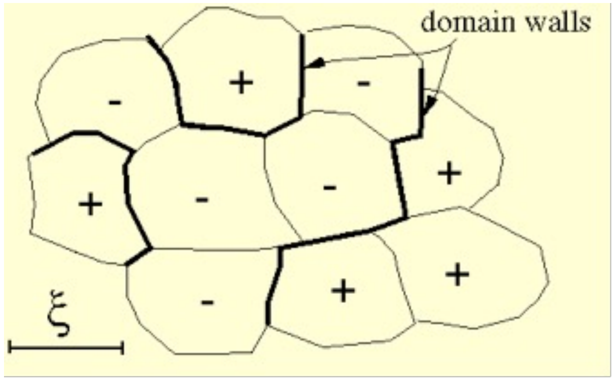


Topological solitons (defects) in cosmology

Domain walls: spontaneous breaking of discrete symmetries

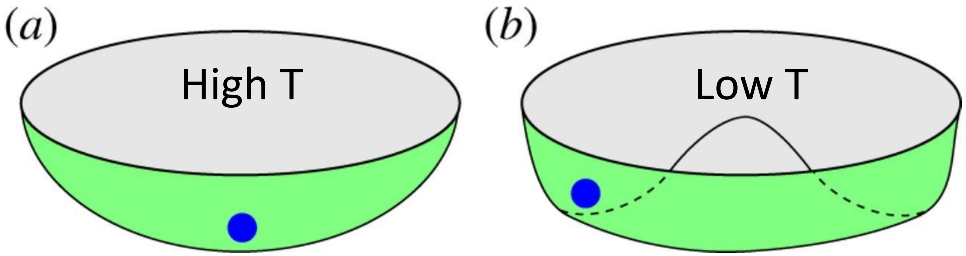
A Z_2 example:

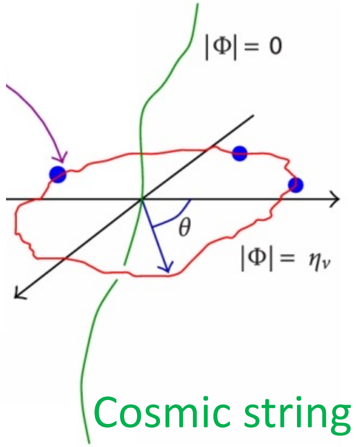




Cosmic strings: spontaneous breaking of continuous symmetries

A U(1) example:





Stabilized by their topological nature.

Non-topological solitons in cosmology

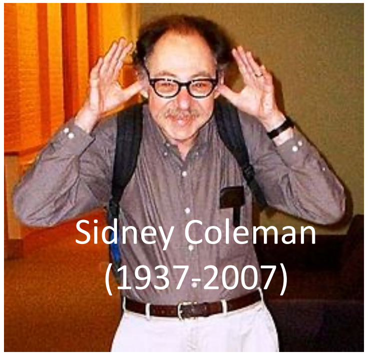
Stabilized by a conserved charge Q via Noether theorem

Most famous example: Q-balls[NPB 262 (1985) 263]

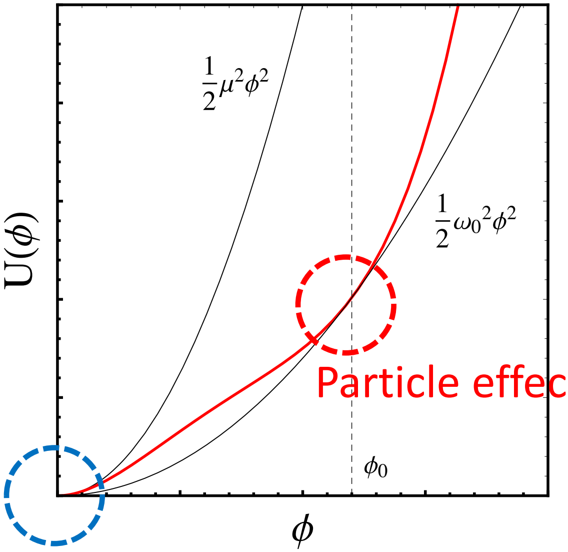
Complex scalar

$$\mathcal{L} = \partial_\mu \Phi^\dagger \partial^\mu \Phi - U(\Phi)$$

Preserves a U(1) symmetry



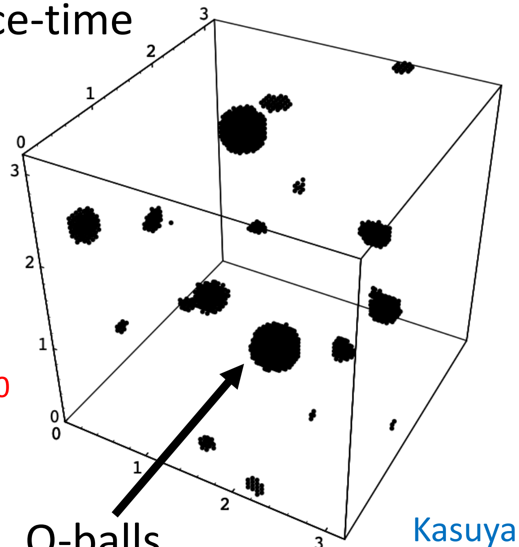
Sidney Coleman (1937-2007)



Particle effective mass: ω_0

Particle effective mass: μ

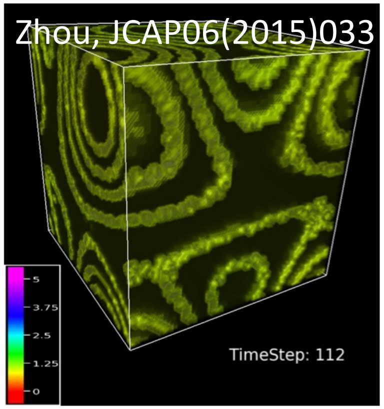
$\omega_0 < \mu$



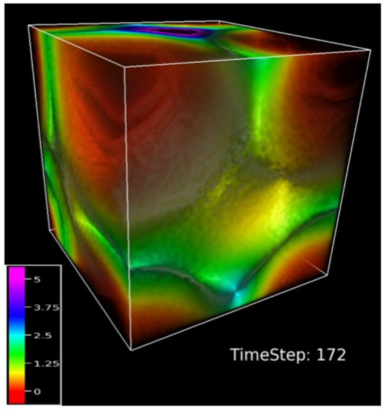
Kasuya *et al*, PRD62 (2000) 023512

How to form Q-balls?

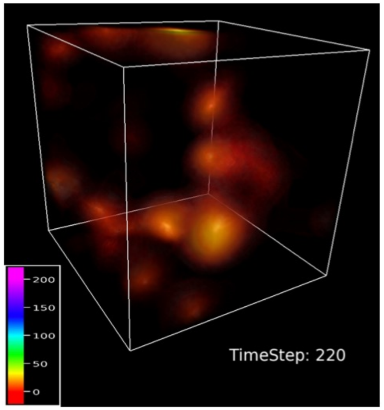
Nontrivial: formation of Q-balls[PLB 418 (1998) 46-54, PLB 425 (1998) 309-321]


Zhou, JCAP06(2015)033

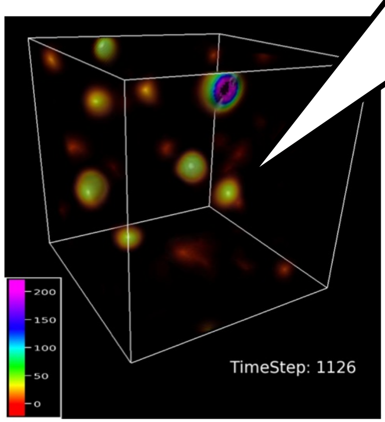
(a) Linear perturbation



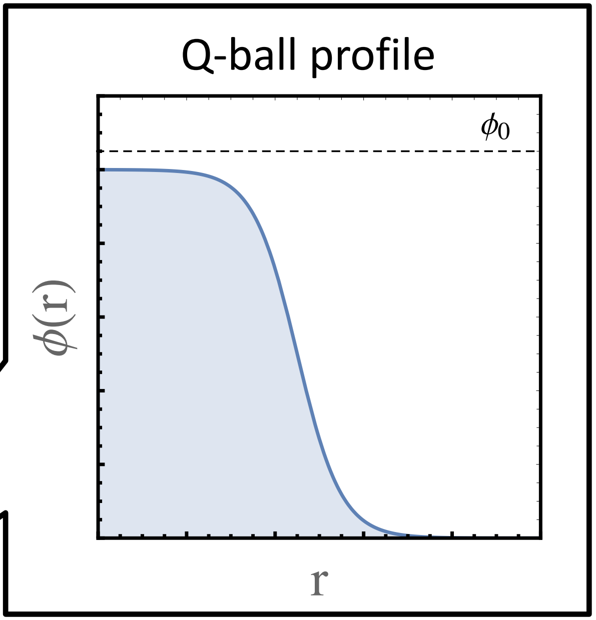
(b) Fragmentation



(c) Emerging Q-balls



(d) Properly formed Q-balls

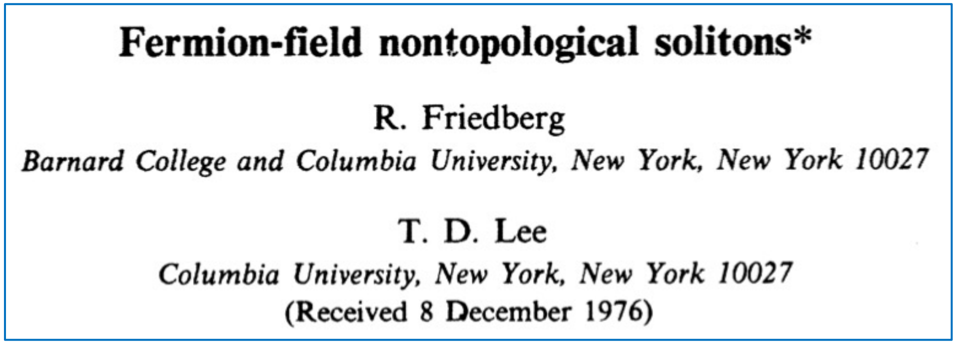

Q-ball profile

Cosmological implications

- Macroscopic dark matter;
- Saving baryon number for baryogenesis;
- Gravitational waves;

Can we have fermion-type solitons?

First studied by T. D. Lee.[PRD.15.1694, PRD.16.1096]



Fermion-field nontopological solitons*

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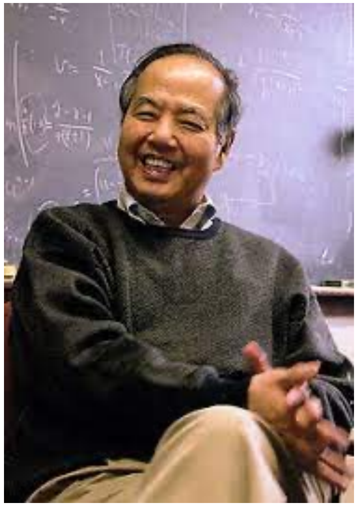
Barnard College and Columbia University, New York, New York 10027

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



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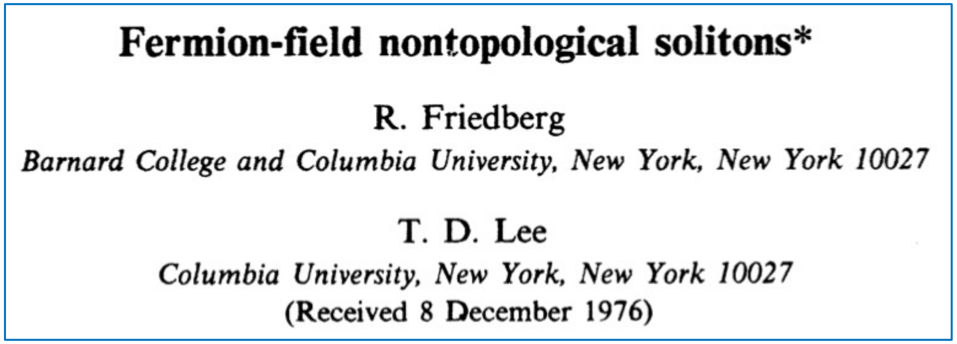

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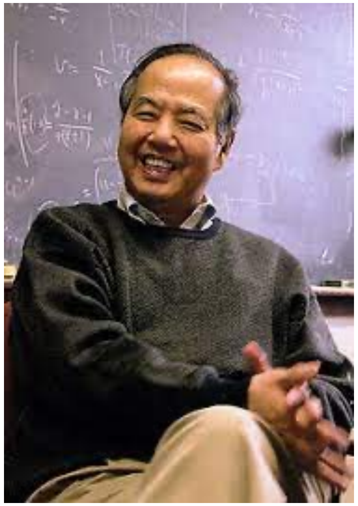

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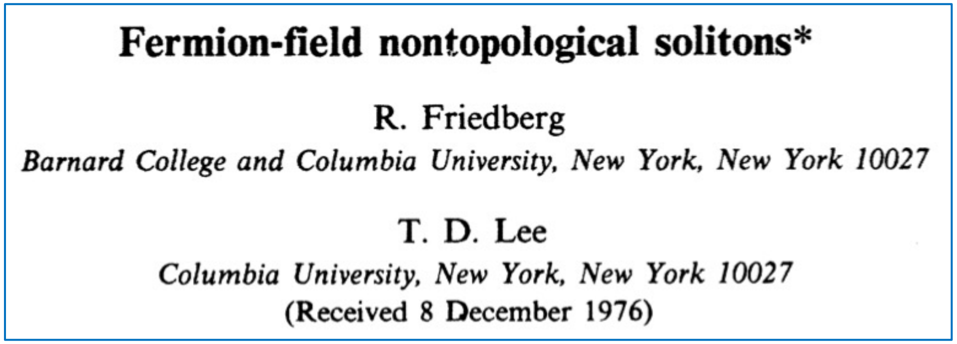

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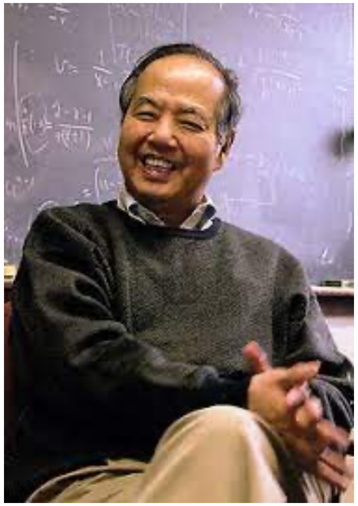
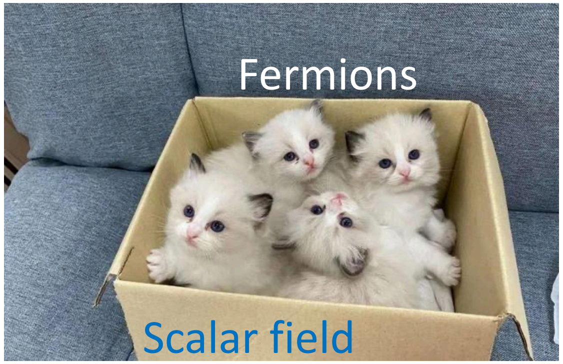
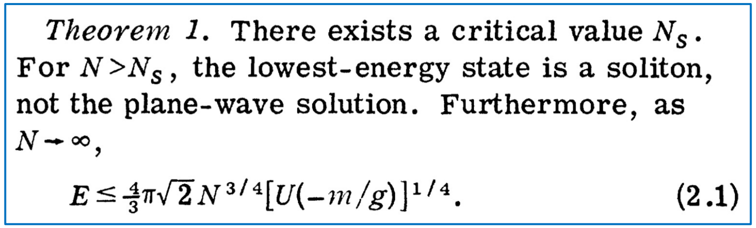




With a scalar field, fermions can be collected to form a soliton!



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

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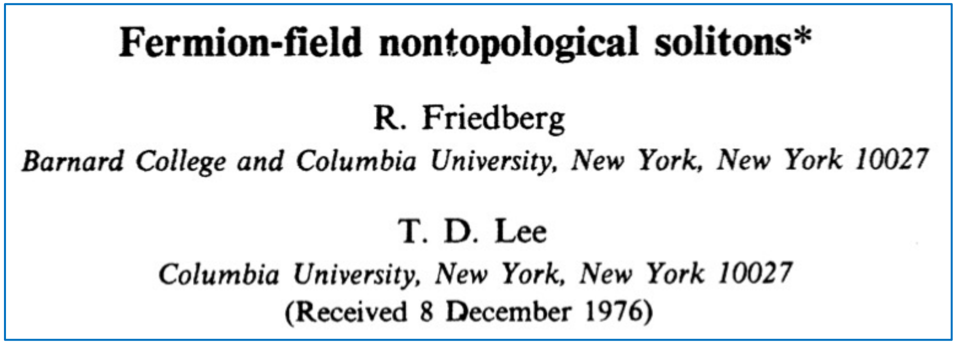

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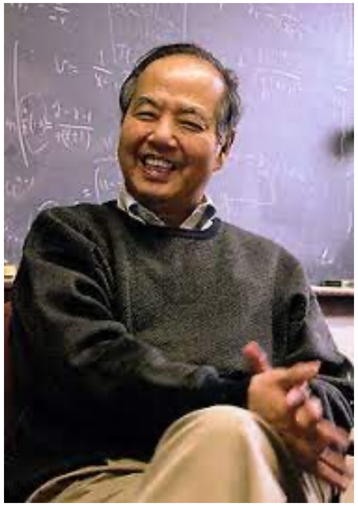

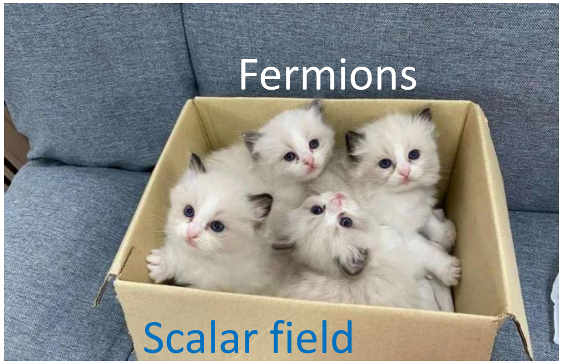

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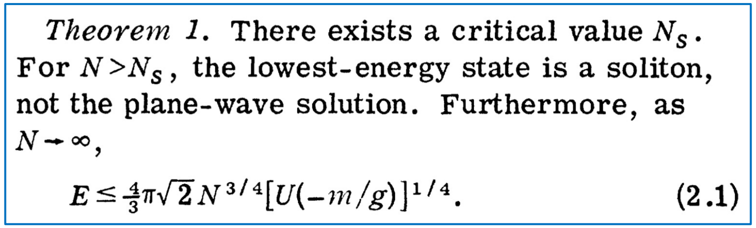

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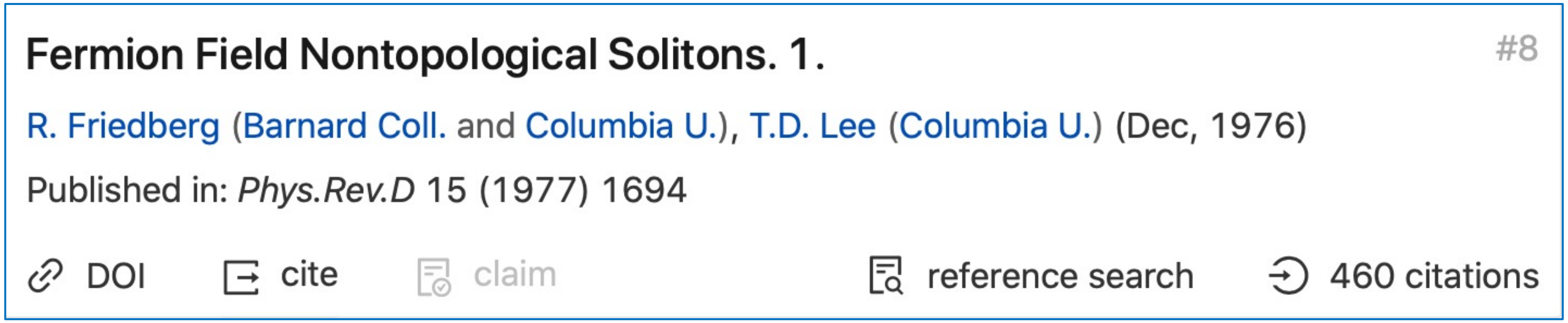
- Macroscopic dark matter;
- Soliton stars;
- Hadron states;

How to form fermion-type solitons?



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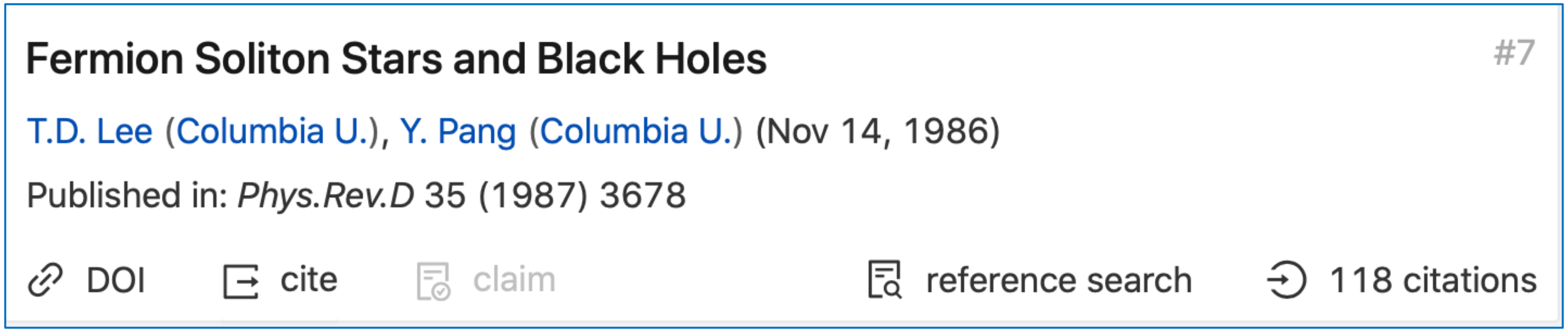

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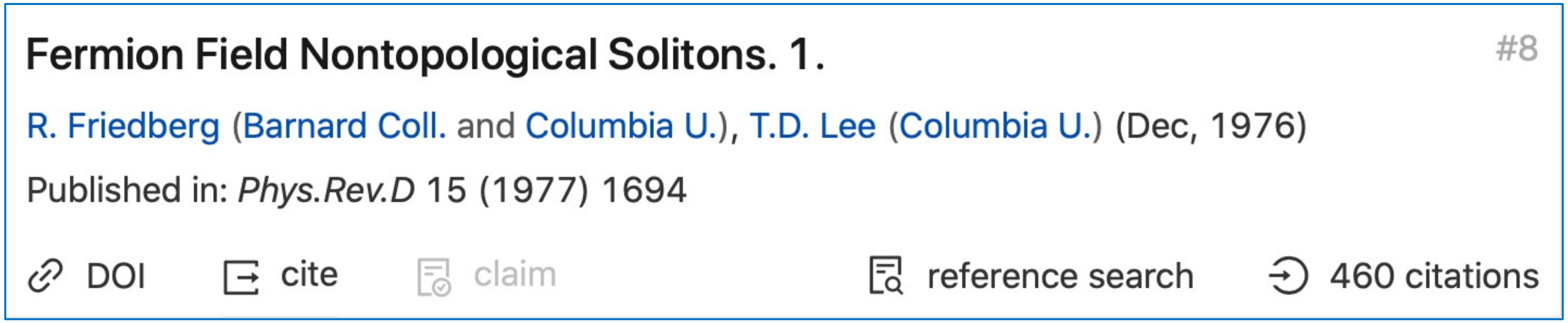

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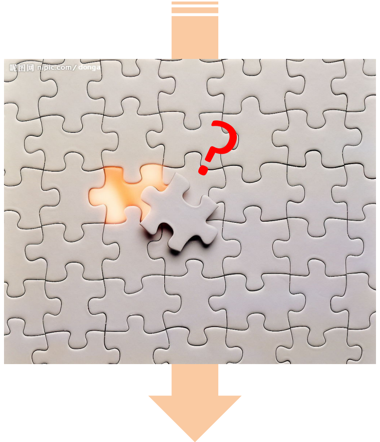
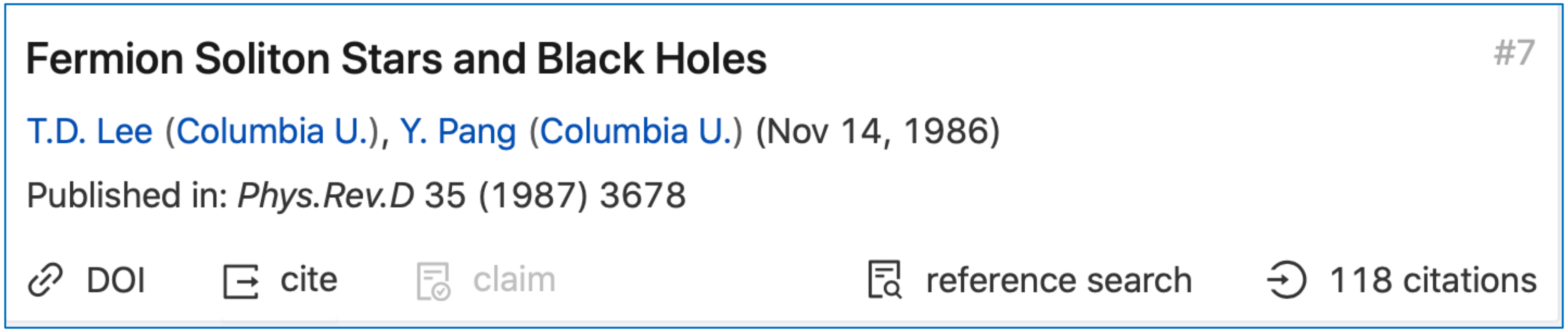


Can exist ≠ must exist!!!

Need a mechanism to form such solitons



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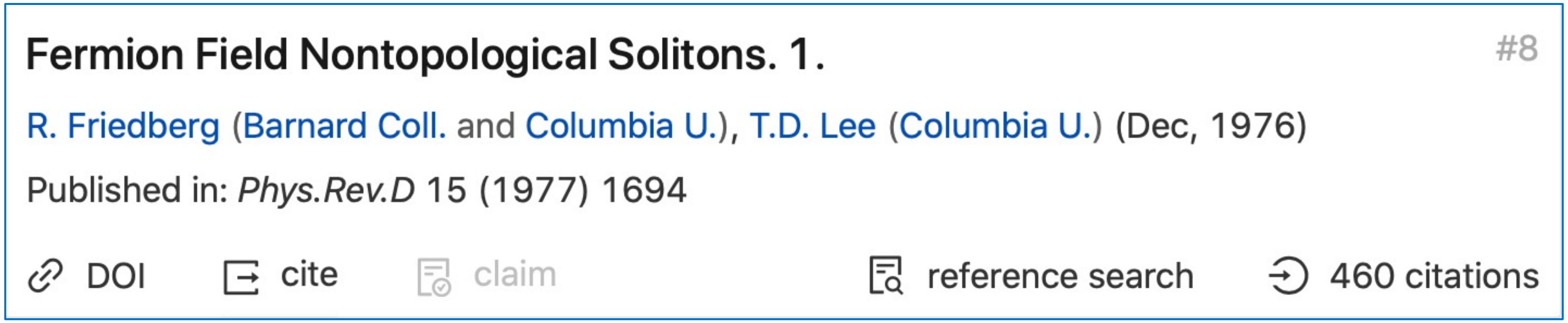

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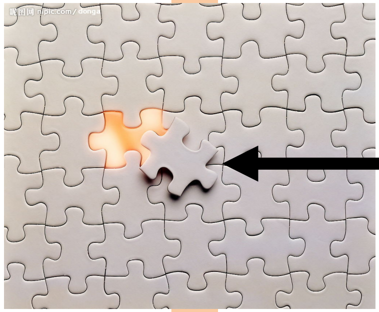
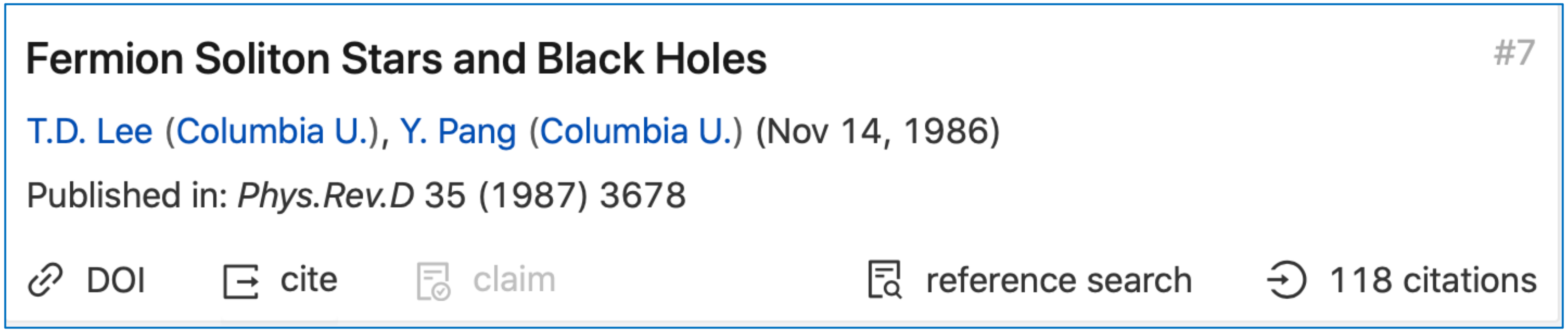


Hong, Jung and **KPX**,
Phys.Rev.D 102 (2020) 7, 075028
arXiv: 2008.04430



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Our mechanism

The simplest Lagrangian for the mechanism

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!

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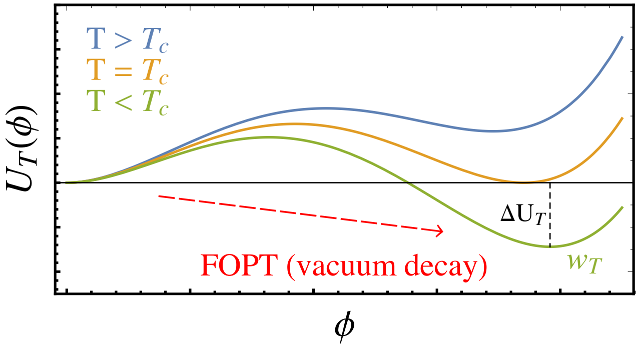

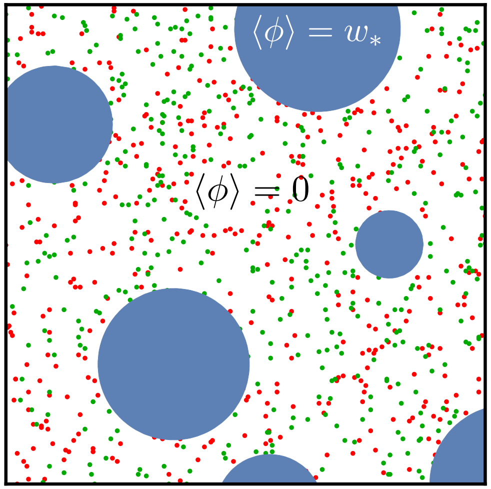

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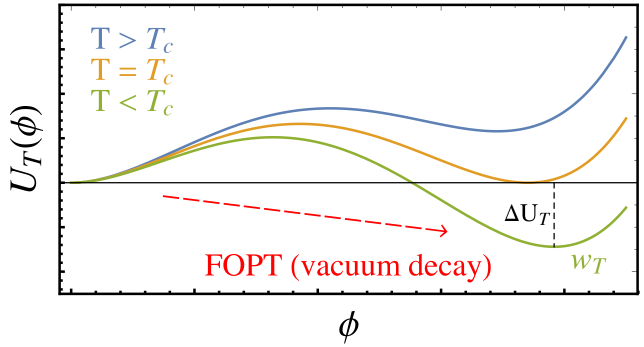

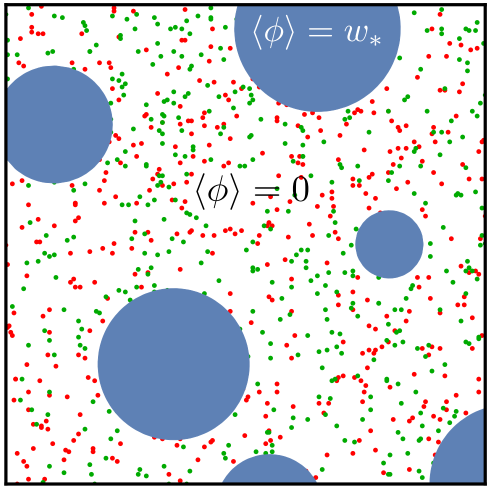

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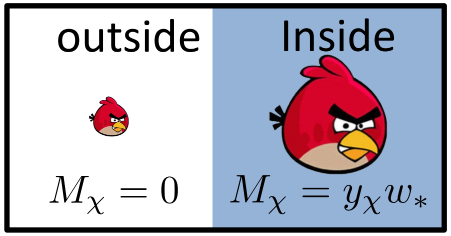

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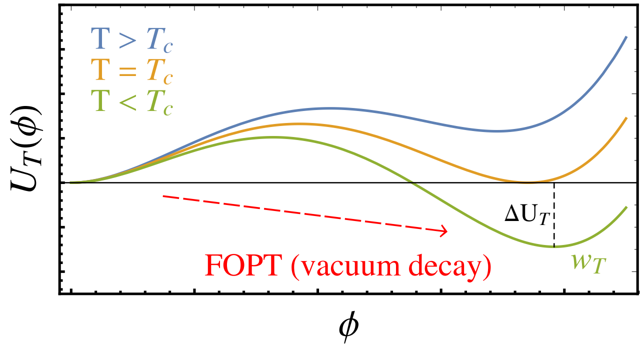
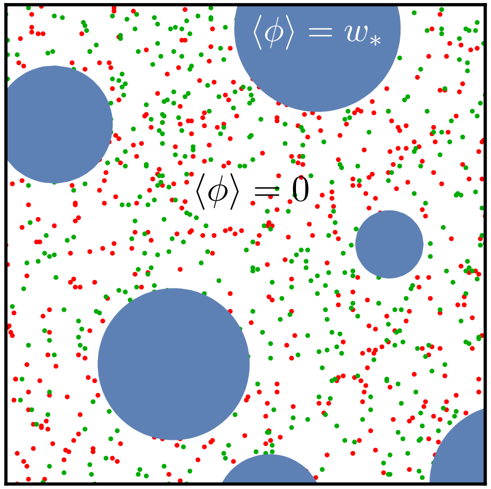
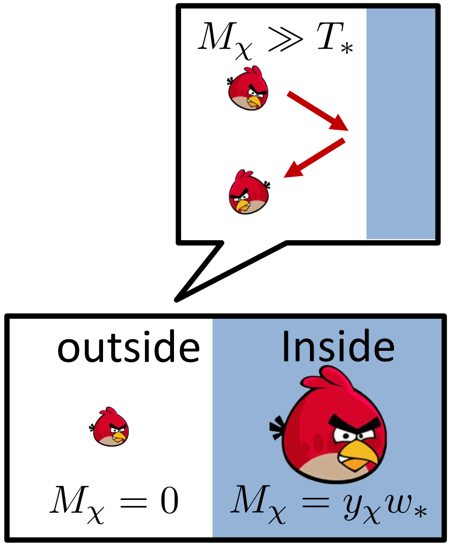


Bubble nucleation



Reflected!



Calculation of the trapping fraction

A simplified calculation: [Chway *et al*, PRD 101 (2020) 9, 095019]

1) In wall frame: χ in equilibrium

$$\tilde{f}_\chi^{\rm f.v.}(\mathbf{p}) = \frac{1}{e^{(\gamma_b|\mathbf{p}|+\gamma_b v_b p_z-\mu_\chi)/T_*}+1}$$

2) Particle current in wall frame

$$\tilde{J}_\chi = 2\int\frac{d^3\mathbf{p}}{(2\pi)^3}\frac{p_z}{|\mathbf{p}|}\tilde{f}_\chi^{\rm f.v.}(\mathbf{p})\Theta(p_z-M_\chi)$$

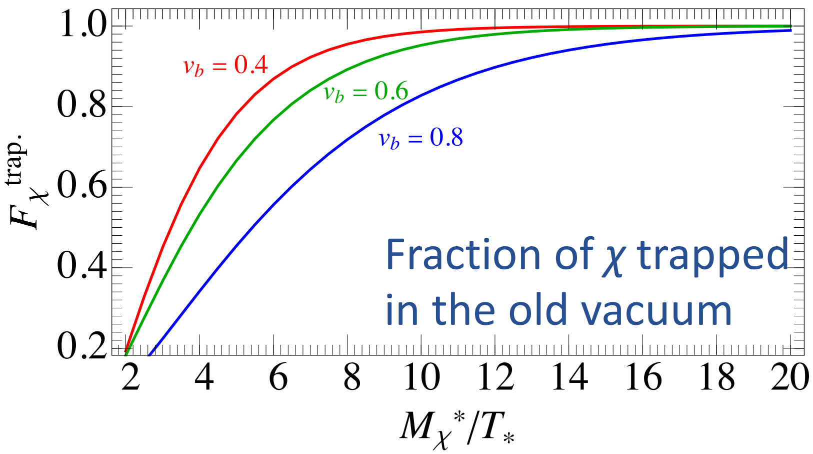
3) Back to plasma frame

$$J_\chi = \tilde{J}_\chi(1-v_b^2)^{1/2},$$

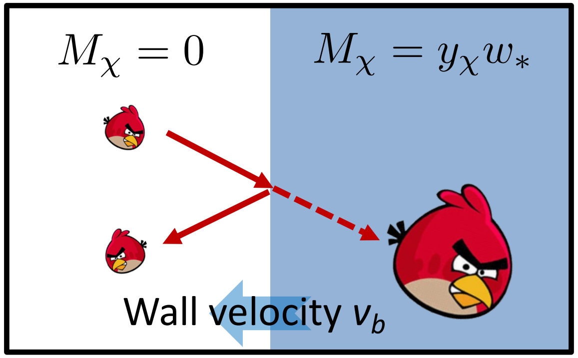
$$n_\chi^{\rm pene.} = J_\chi/v_b,$$

$$F_\chi^{\rm trap.} = 1-\frac{n_\chi^{\rm pene.}}{n_\chi^{\rm f.v.}}$$

For a more detailed calculation see Ref. [Baker *et al*, PRL 125 (2020) 15, 151102]

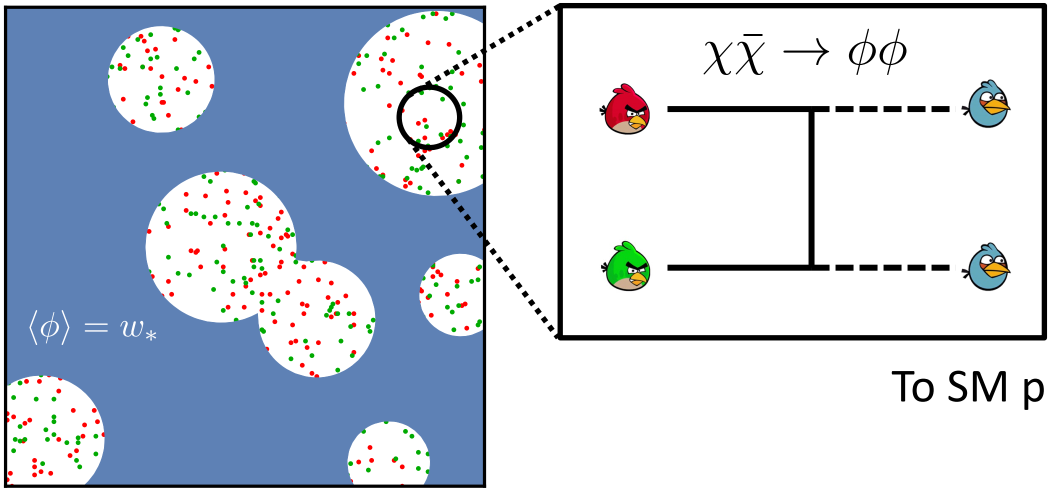


Fraction of χ trapped in the old vacuum



What happens for the trapped fermions?

Fermions annihilate with antifermions



To SM particles via
$\lambda_{H\phi}|H|^2\phi^2$

To have a nontrivial result, *N*(fermion) ≠ *N*(antifermion)

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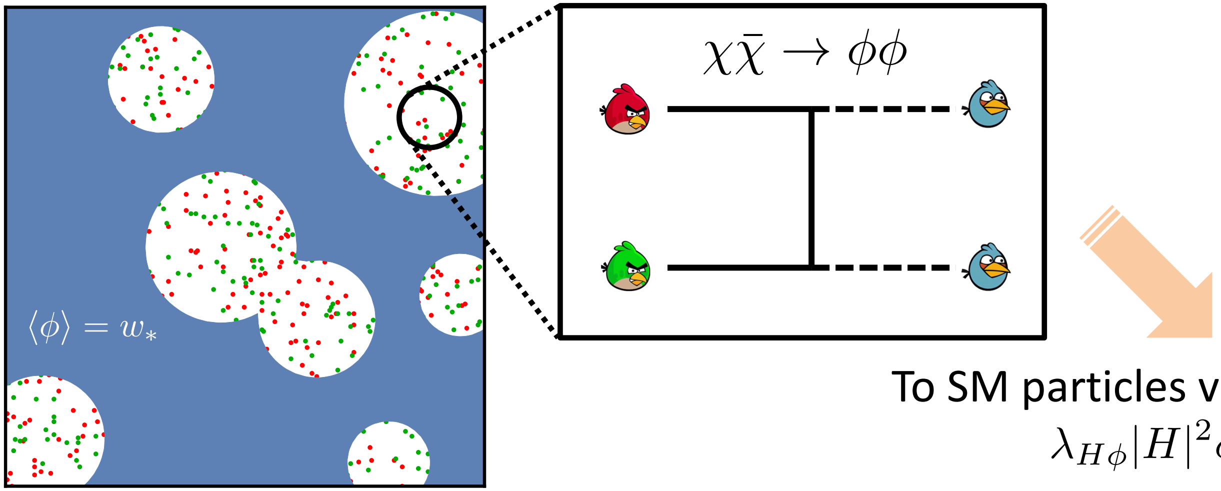

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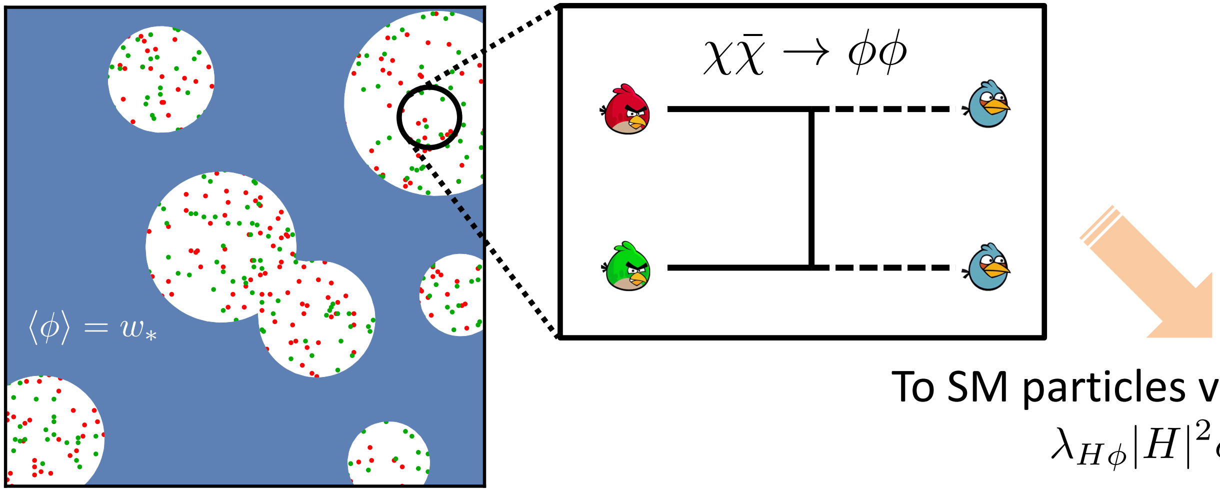

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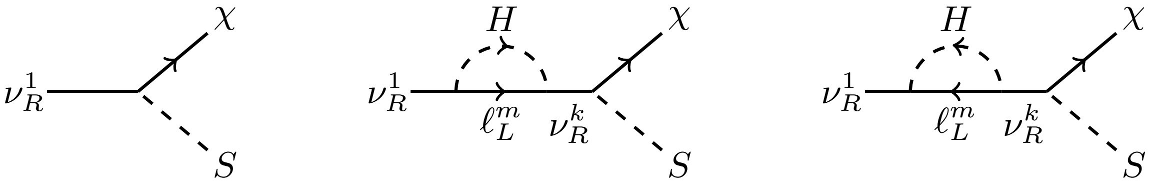

$$\Gamma(\nu_R^1 \to \chi S) > \Gamma(\nu_R^1 \to \bar{\chi} S)$$

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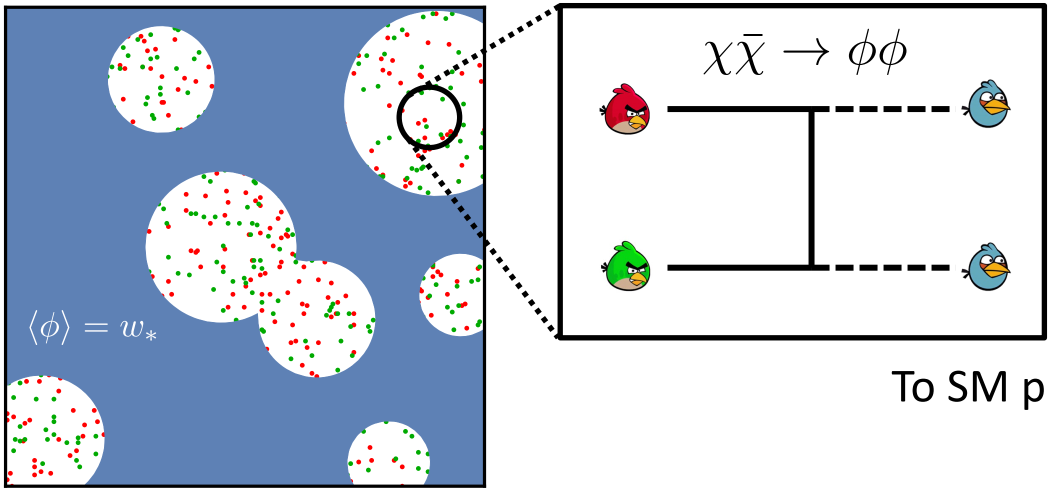

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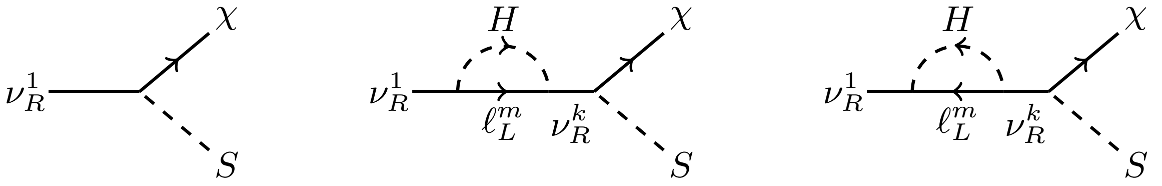


$\Gamma(\nu_R^1 \to \chi S) > \Gamma(\nu_R^1 \to \bar{\chi} S)$

Phenomenologically we set $\boxed{\eta_\chi \equiv \frac{n_\chi - n_{\bar{\chi}}}{s}}$

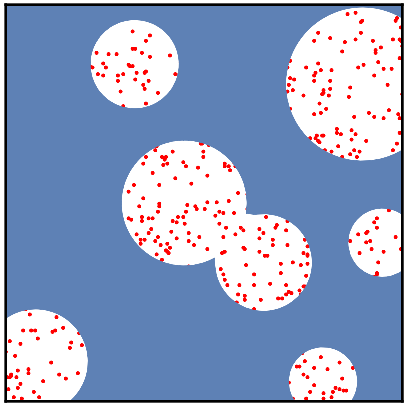
Formation of Fermi-ball solitons

The trapped fermions

$$Q_{\rm FB} = F_\chi^{\rm trap}\eta_\chi s_* V_* \leftarrow$$

Volume of the remnant

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



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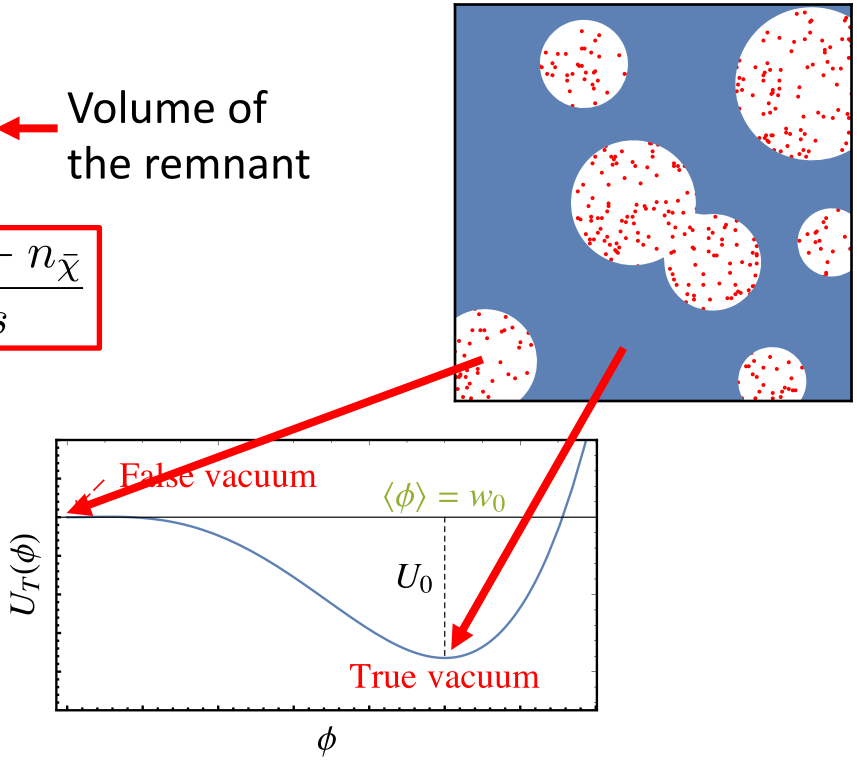

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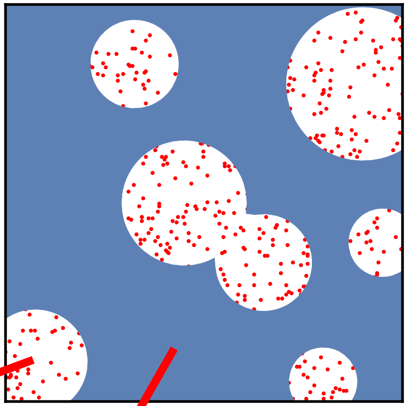

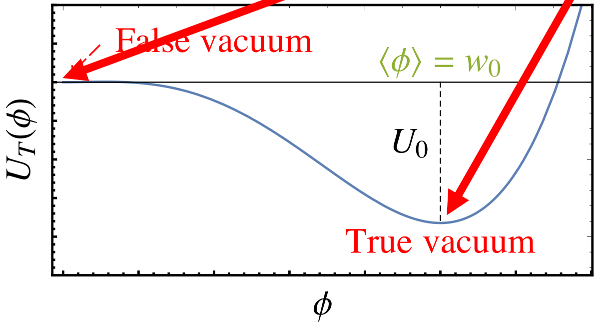

$$E = \underset{\text{Fermi-gas kinetic energy}}{\frac{3\pi}{4}\left(\frac{3}{2\pi}\right)^{2/3}\frac{Q_{\rm FB}^{4/3}}{R}} + \overset{\text{Surface tension (negligible)}}{4\pi\sigma_0 R^2} + \underset{\text{Volume energy}}{\frac{4\pi}{3}U_0 R^3}$$

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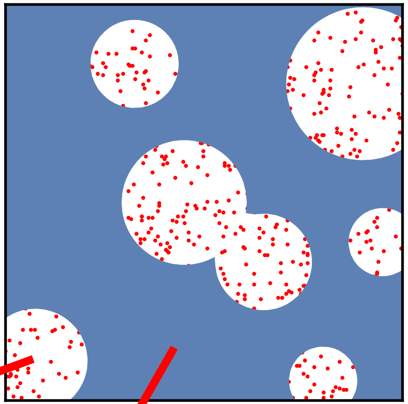

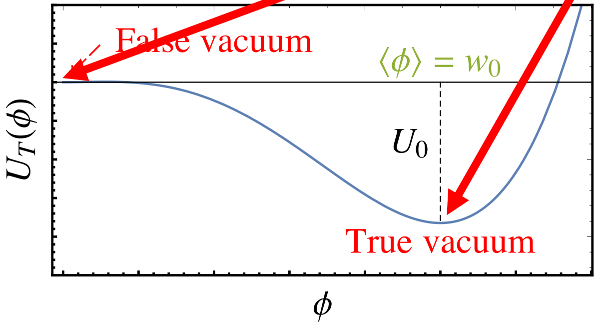

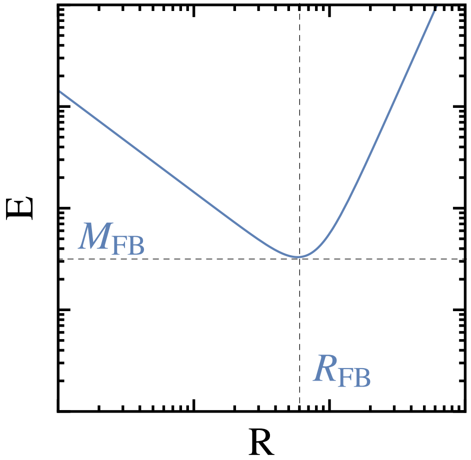

Surface tension (negligible)

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Fermi-gas kinetic energy

Volume energy

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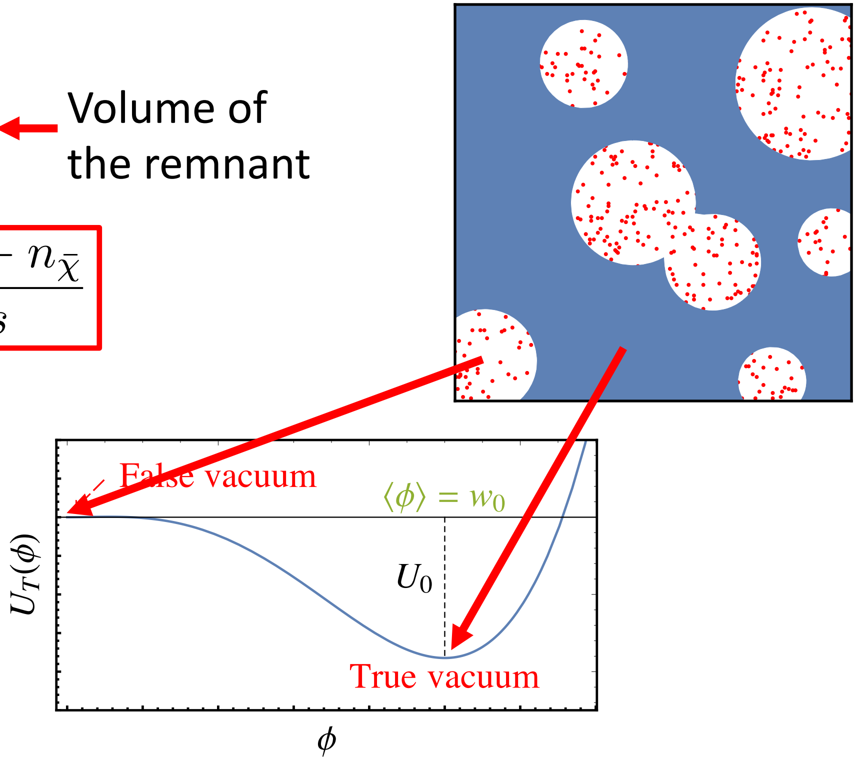

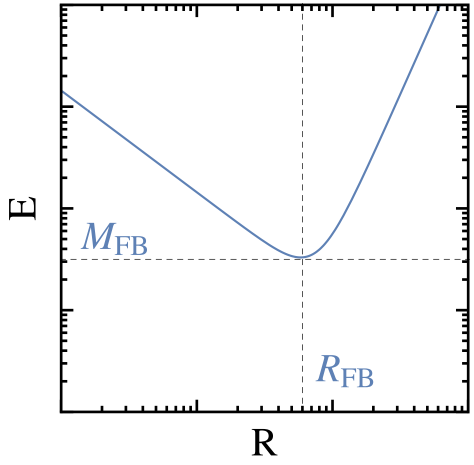

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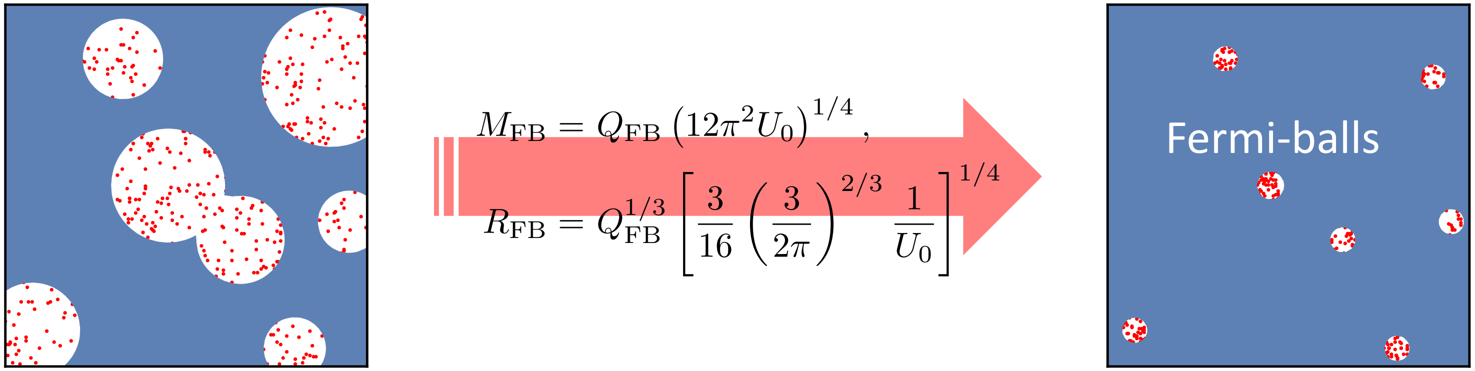
Fermi-gas kinetic energy

Volume energy

How many fermions survive?

Charge $Q_{\rm FB} = F_\chi^{\rm trap} \eta_\chi s_* V_*$ ← Volume of the remnant: crucial information!



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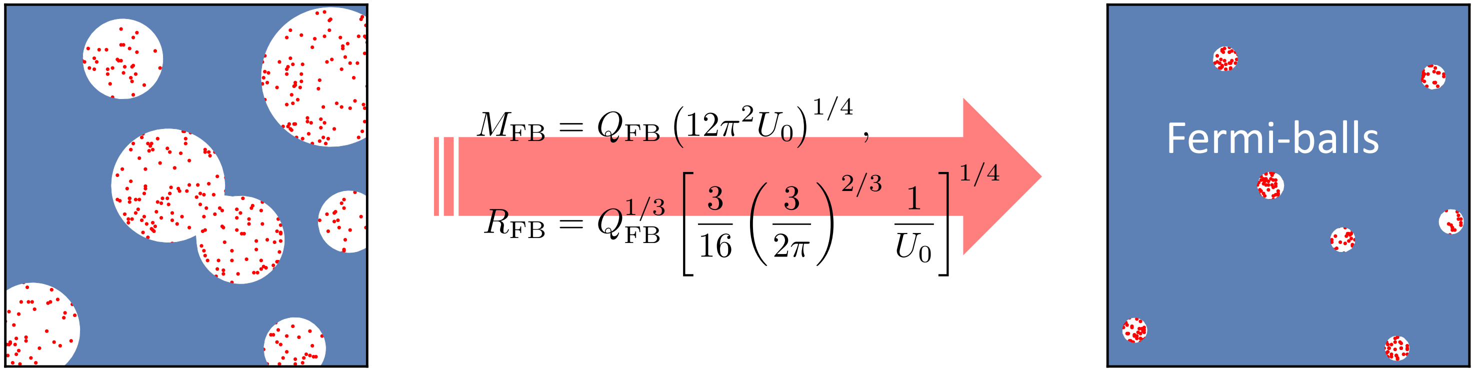

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A detailed treatment see Ref. [P.Lu, K.Kawana and **KPX**, PRD 105 (2022) 12, 123503]

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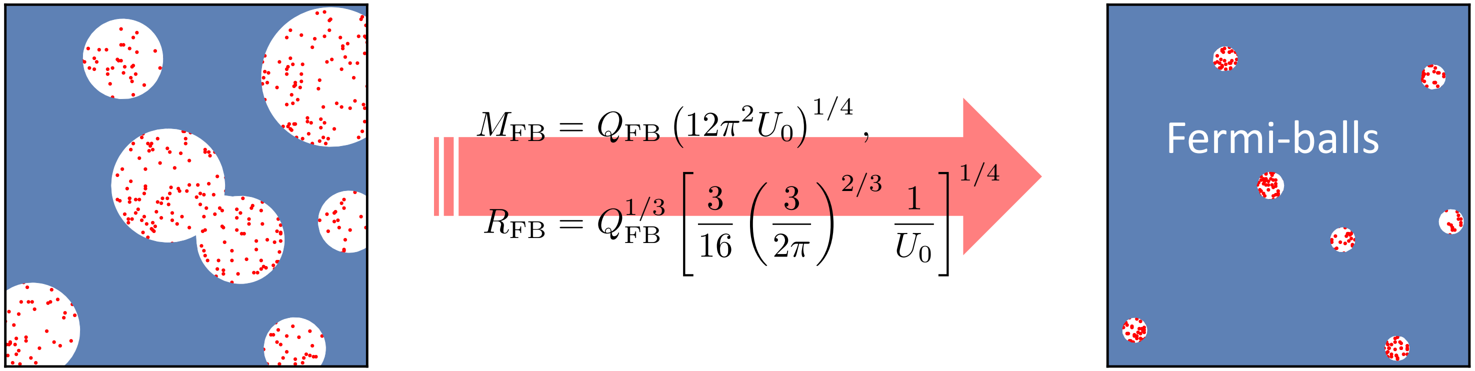

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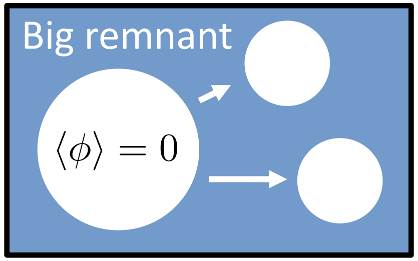
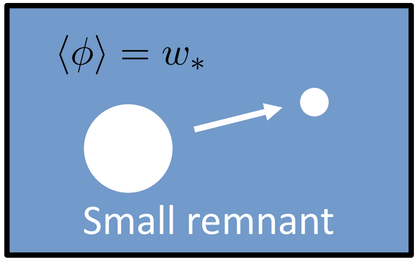
This talk just estimates





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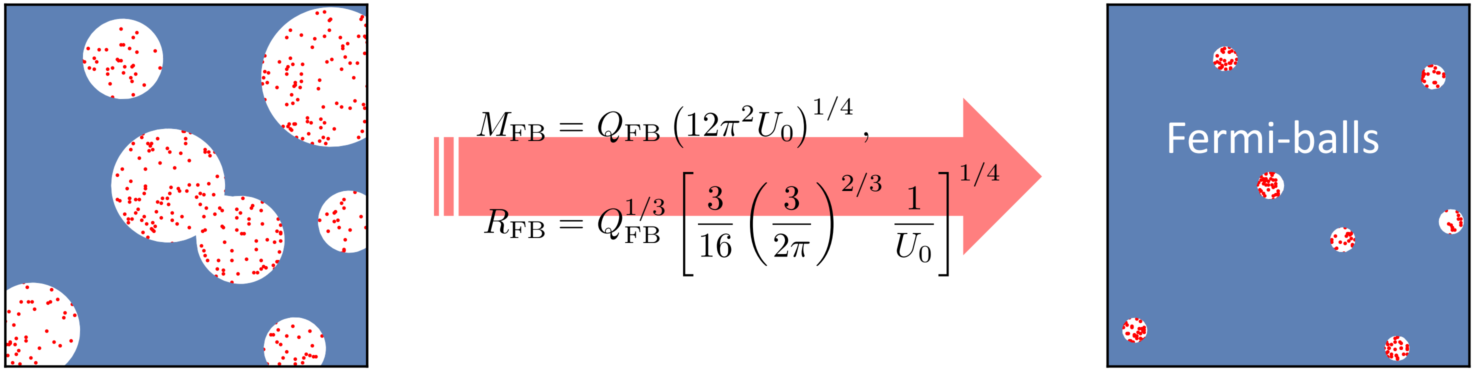

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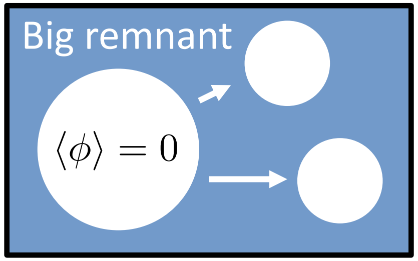
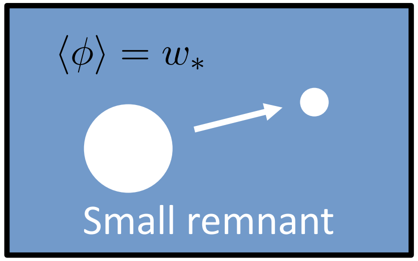




Critical size $\Gamma(T_*) V_* \Delta t \sim 1, \quad V_* = \dfrac{4\pi}{3} R_*^3, \quad \Delta t = \dfrac{R_*}{v_b}$ $\quad n_{\text{FB}}^* \approx 0.29 \times V_*^{-1}$

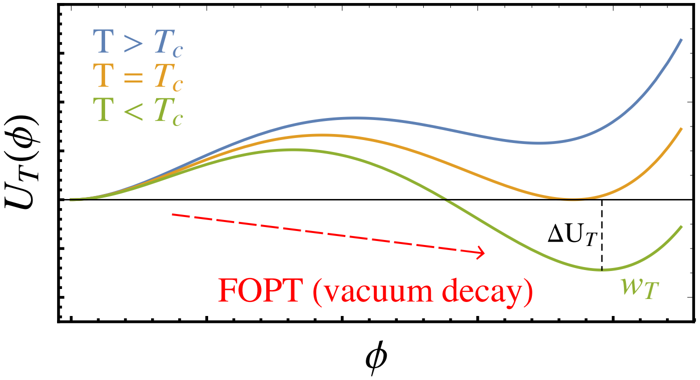
Bubble nucleation rate

The phase transition rate

The decay rate of vacuum per unit volume[Linde, NPB1983]

$$\boxed{\Gamma(T) \sim T^4 \exp\{-\underbrace{S_3}_{\text{Classical action [model-dependent]}}(T)/T\}}$$

Classical action [model-dependent]



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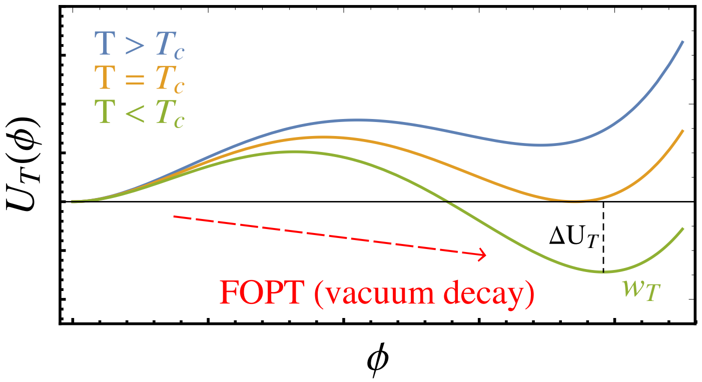
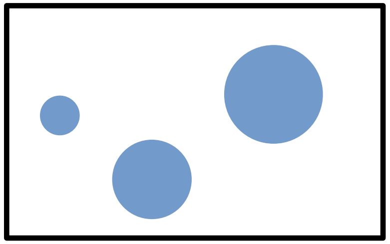


The fraction of false vacuum in the Universe[Guth *et al* PRD1981]

$$p(T) = e^{-I(T)}, \quad I(T) = \frac{4\pi}{3}\int_T^{T_c} dT' \frac{\Gamma(T')}{T'^4 H(T')}\left[\int_T^{T'} d\tilde{T}\frac{v_b}{H(\tilde{T})}\right]^3$$



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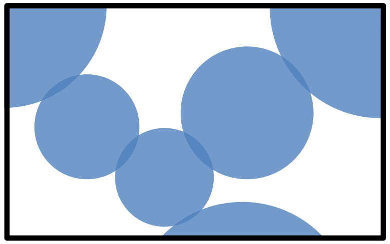
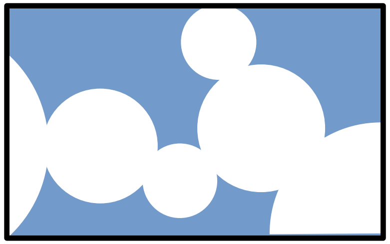
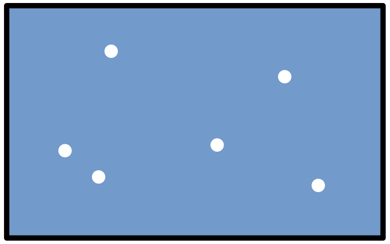


2. Percolation



3. Fermi-ball formation



4. Today

Percolation: $p(T_p) = 0.71$;

Fermi-ball formation: $p(T_*) = 1 - 0.71 = 0.29$;

The Fermi-ball profile

$$M_{\rm FB} = Q_{\rm FB}\left(12\pi^2 U_0\right)^{1/4}, \quad R_{\rm FB} = Q_{\rm FB}^{1/3}\left[\frac{3}{16}\left(\frac{3}{2\pi}\right)^{2/3}\frac{1}{U_0}\right]^{1/4}$$

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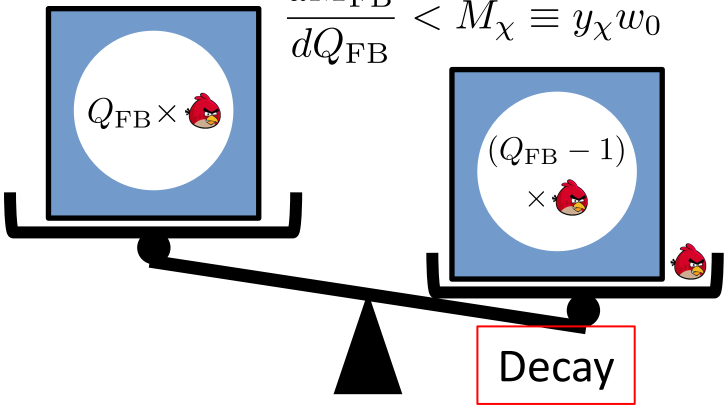
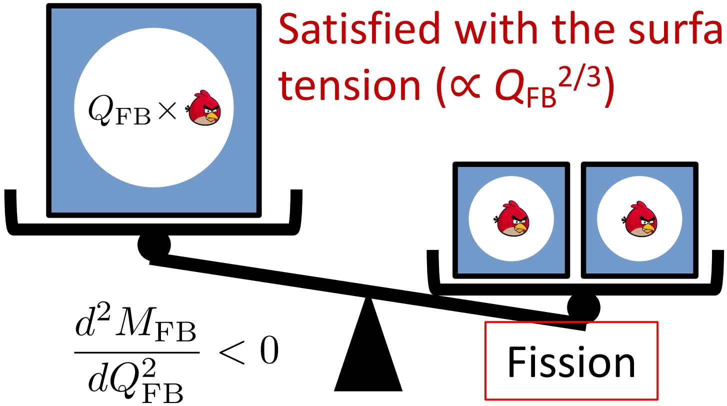
The stability conditions



$$\frac{dM_{\rm FB}}{dQ_{\rm FB}} < M_\chi \equiv y_\chi w_0$$



$$\frac{d^2 M_{\rm FB}}{dQ_{\rm FB}^2} < 0$$

Satisfied with the surface tension ($\propto Q_{\rm FB}^{2/3}$)

The Fermi-ball profile

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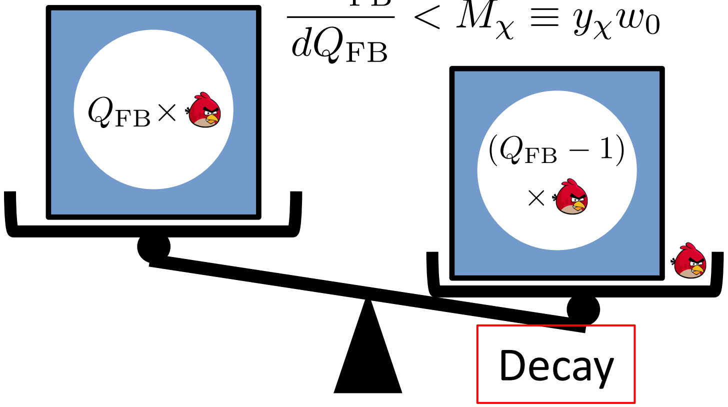

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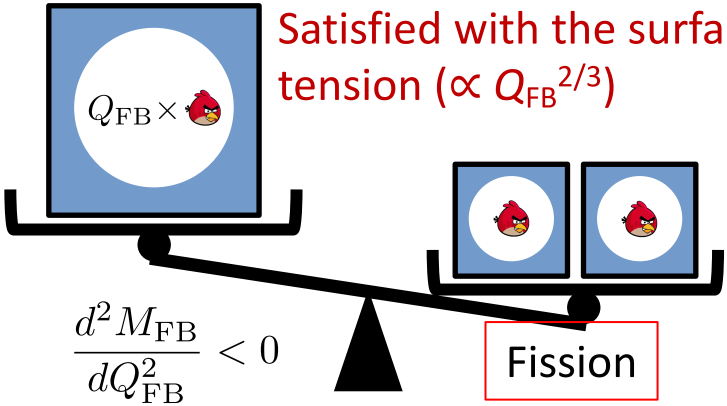

$$\frac{d^2M_{\rm FB}}{dQ_{\rm FB}^2}<0$$

Satisfied with the surface tension ($\propto Q_{\rm FB}^{2/3}$)

Very dense object

$$\frac{M_{\rm FB}}{4\pi R_{\rm FB}^3/3}=9.15\times10^{28}\ {\rm kg/m^3}\left(\frac{U_0^{1/4}}{100\ {\rm GeV}}\right)^4$$

Even denser than a neutron star $\rho_{\rm NS}\approx10^{17}$ kg/m^3

The Fermi-ball profile estimation

The first-order phase transition (FOPT) parameters

- *α*: FOPT latent heat over the radiation energy density;
- *β/H*: inverse ratio of FOPT duration to the Hubble time scale

$$\begin{aligned} Q_{\rm FB} &\approx 1.0 \times 10^{42} \times v_b^3 \left(\frac{\eta_\chi}{10^{-3}}\right) \times \left(\frac{100}{g_*}\right)^{1/2} \left(\frac{100~{\rm GeV}}{T_*}\right)^3 \left(\frac{100}{\beta/H}\right)^3, \\ R_{\rm FB} &\approx 4.8 \times 10^{-3}~{\rm cm} \times v_b \left(\frac{\eta_\chi}{10^{-3}}\right)^{1/3} \times \left(\frac{100}{g_*}\right)^{5/12} \left(\frac{100~{\rm GeV}}{T_*}\right)^2 \left(\frac{100}{\beta/H}\right) \alpha^{-1/4}, \\ M_{\rm FB} &\approx 1.4 \times 10^{21}~{\rm g} \times v_b^3 \left(\frac{\eta_\chi}{10^{-3}}\right) \times \left(\frac{100}{g_*}\right)^{1/4} \left(\frac{100~{\rm GeV}}{T_*}\right)^2 \left(\frac{100}{\beta/H}\right)^3 \alpha^{1/4}, \end{aligned}$$

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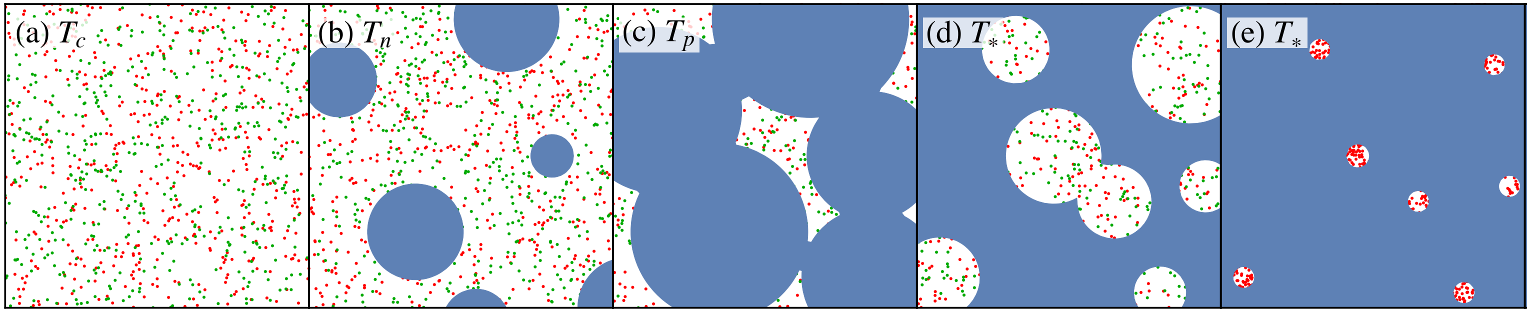
Fermi-balls[Hong, Jung and **KPX**, Phys.Rev.D 102 (2020) 7, 075028, arXiv:2008.04430]



Further remarks for Fermi-balls

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

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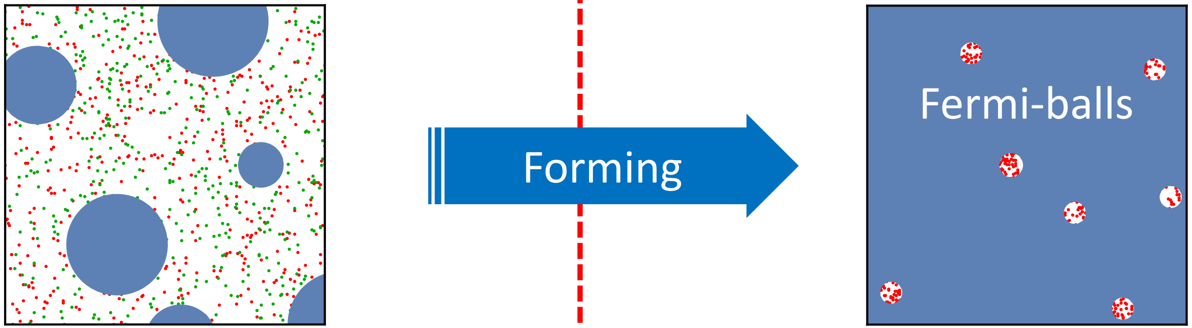
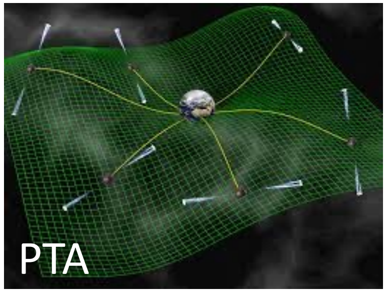
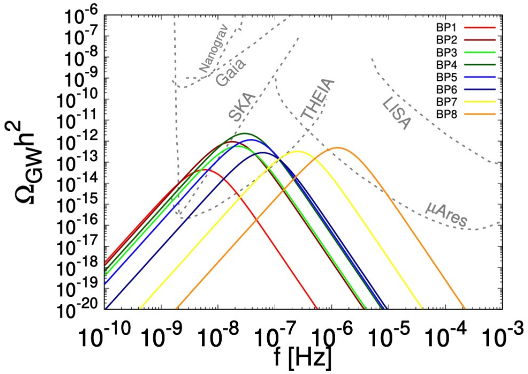
[Marfatia *et al*, JHEP 11 (2021) 068]

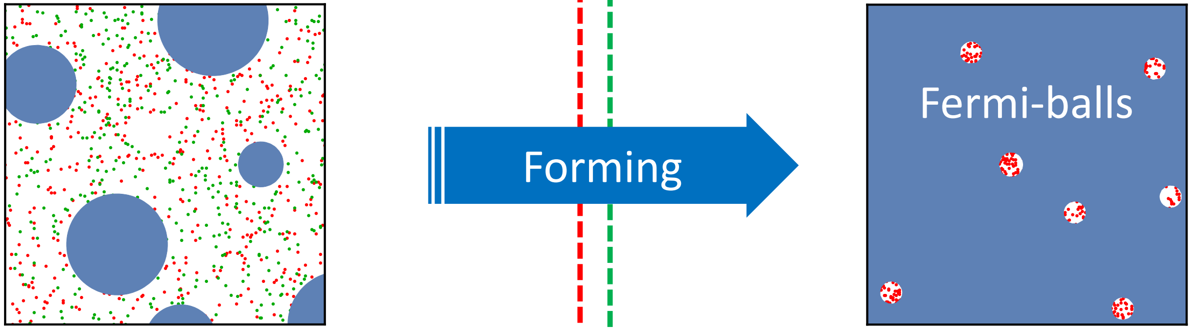


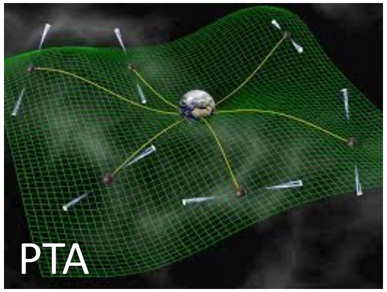


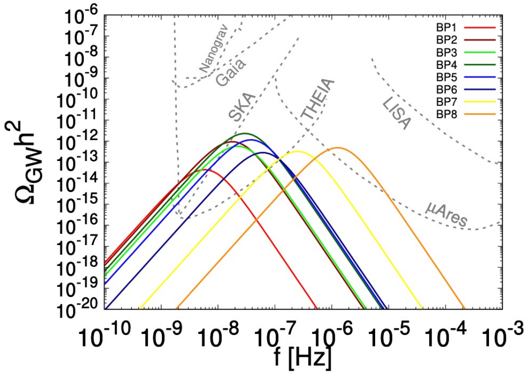


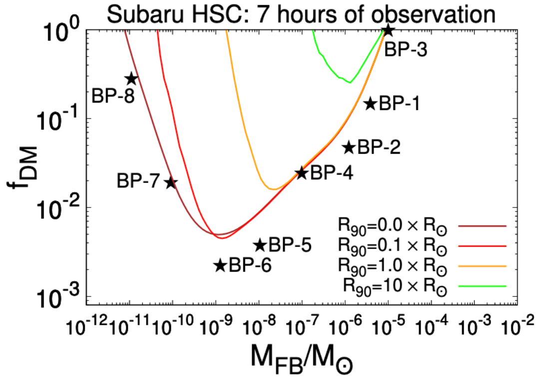
Further remarks for Fermi-balls

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









Further remarks for Fermi-balls

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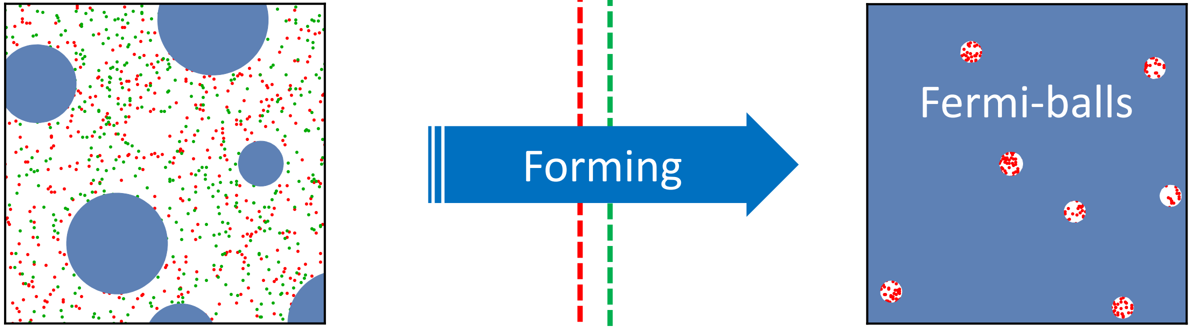
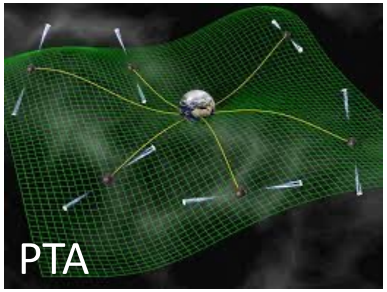
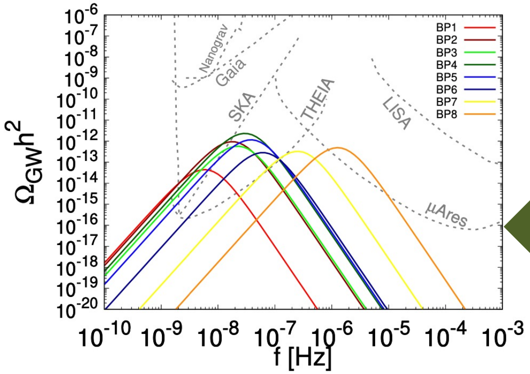
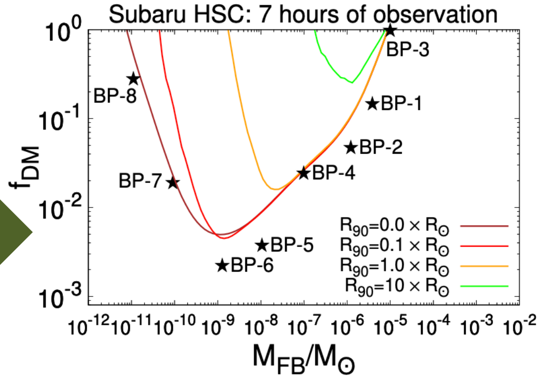


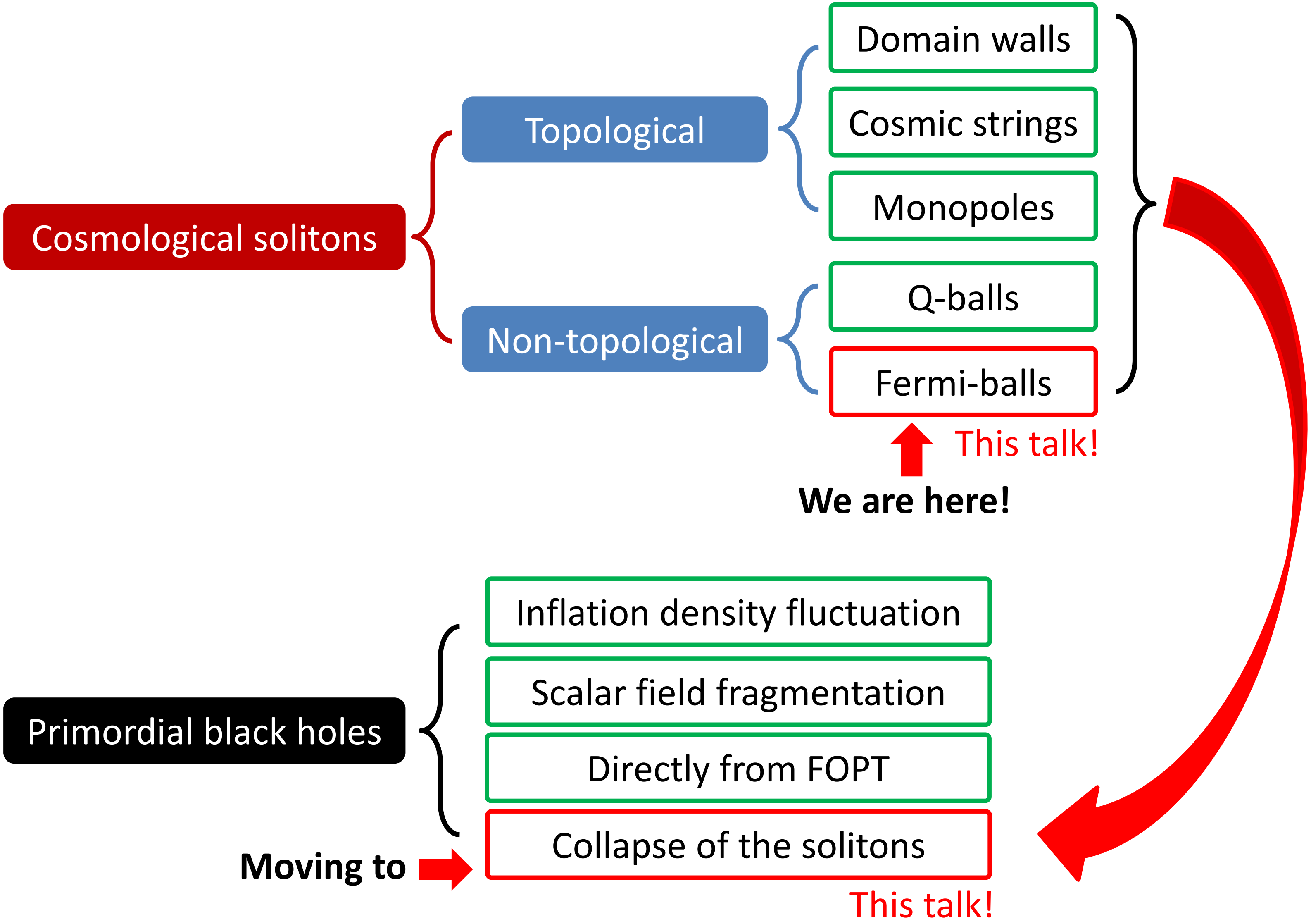




Correlation!



Outline



Cosmological solitons

- Topological
  - Domain walls
  - Cosmic strings
  - Monopoles
- Non-topological
  - Q-balls
  - Fermi-balls

This talk!

We are here!

Primordial black holes

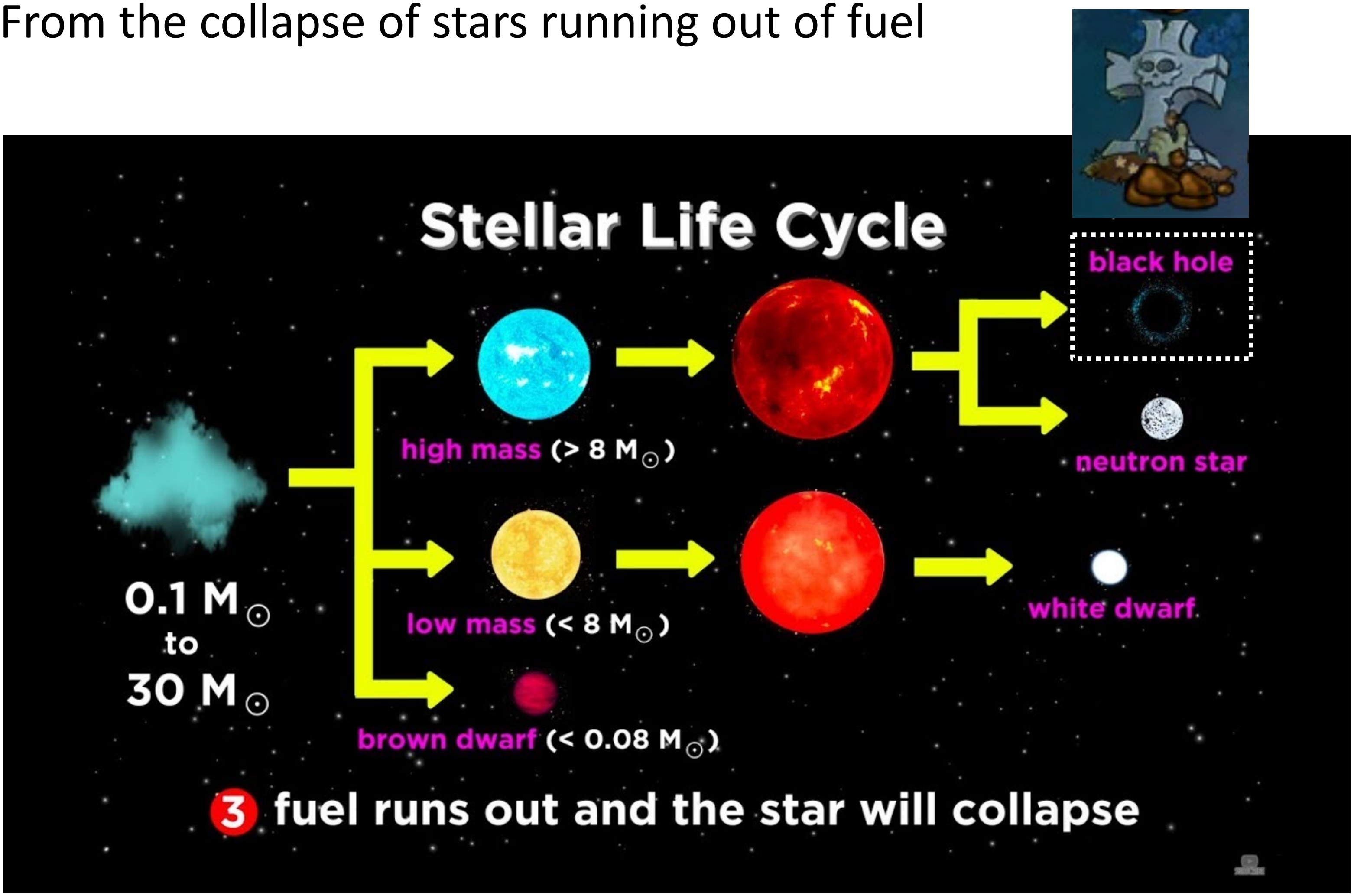
- Inflation density fluctuation
- Scalar field fragmentation
- Directly from FOPT
- Collapse of the solitons

Moving to

This talk!

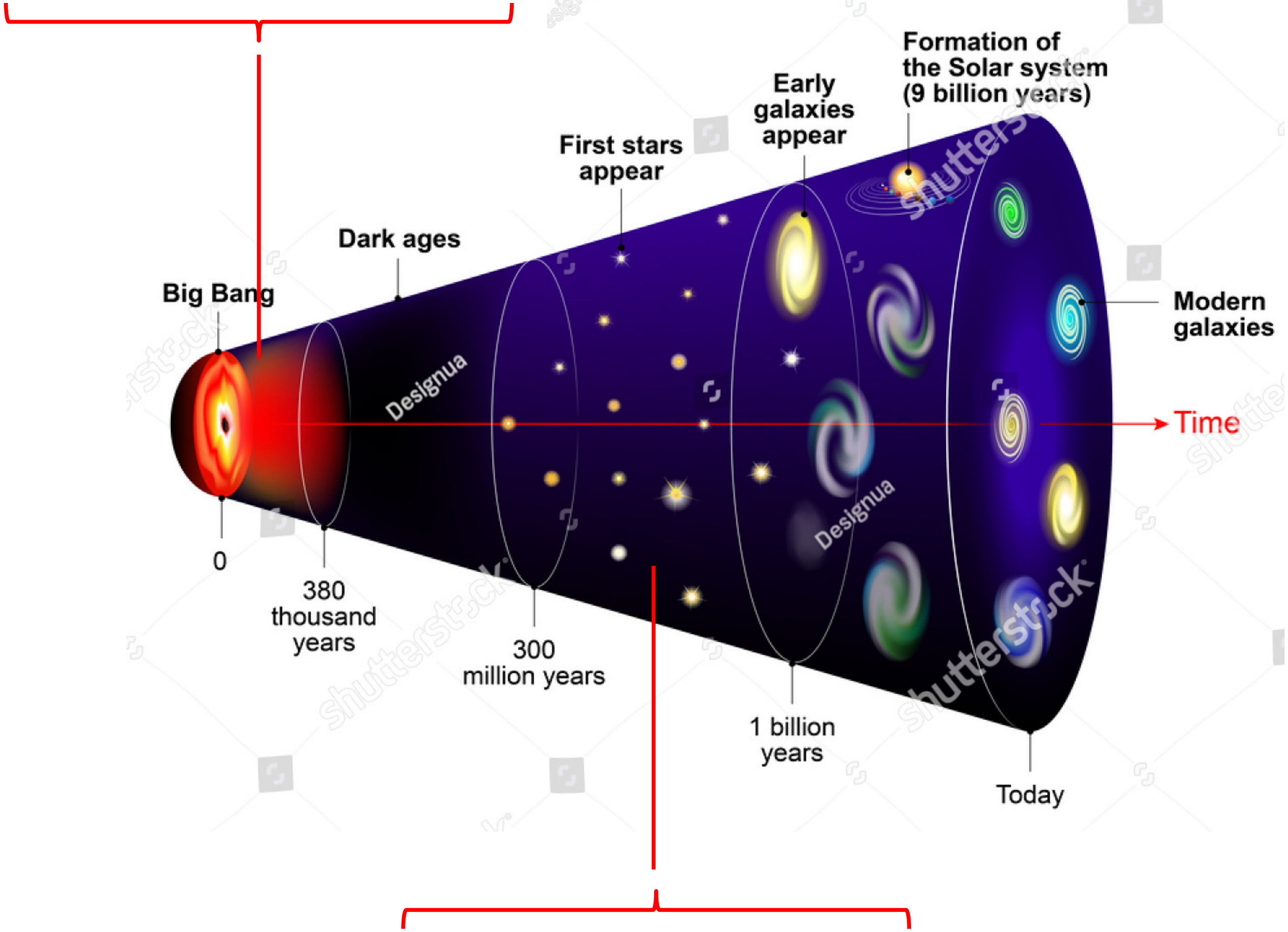
“Normal ”black holes

From the collapse of stars running out of fuel



Primordial black holes (PBHs)

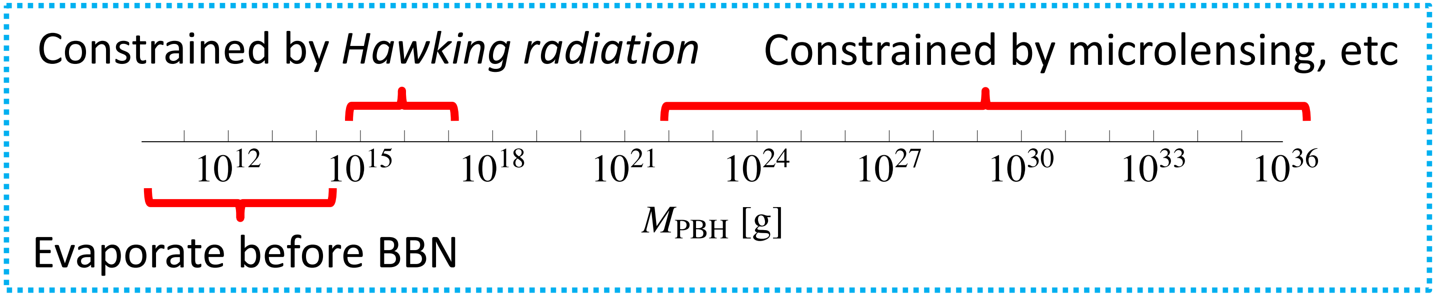
Hypothetical black holes (soon after Big Bang);[Zel'dovitch *et al*, 1966]



“Normal” black holes (from stellar collapse)

Primordial black holes (PBHs)

Mass lies in a vast region, depending on the formation mechanism.



Constrained by *Hawking radiation*

Constrained by microlensing, etc

Evaporate before BBN

Primordial black holes (PBHs)

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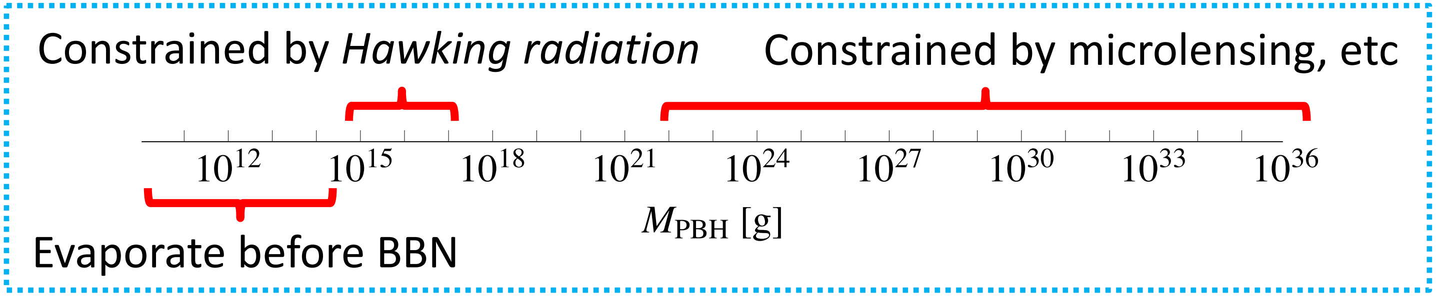
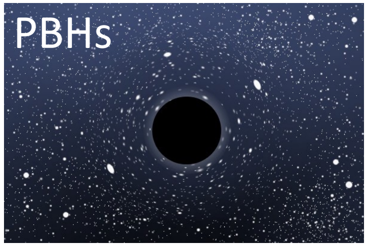


Constrained by *Hawking radiation*

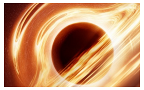
Constrained by microlensing, etc

Evaporate before BBN

What can PBHs do?

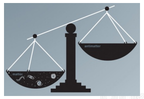


A natural **dark matter** candidate;



Seeds of the supermassive black holes;

Explaining LIGO/Virgo observations;



Origin of the matter-antimatter asymmetry;

Formation of the primordial black holes

Collapse of the overdense region during inflation;[Carr *et al*, MNRAS1974]

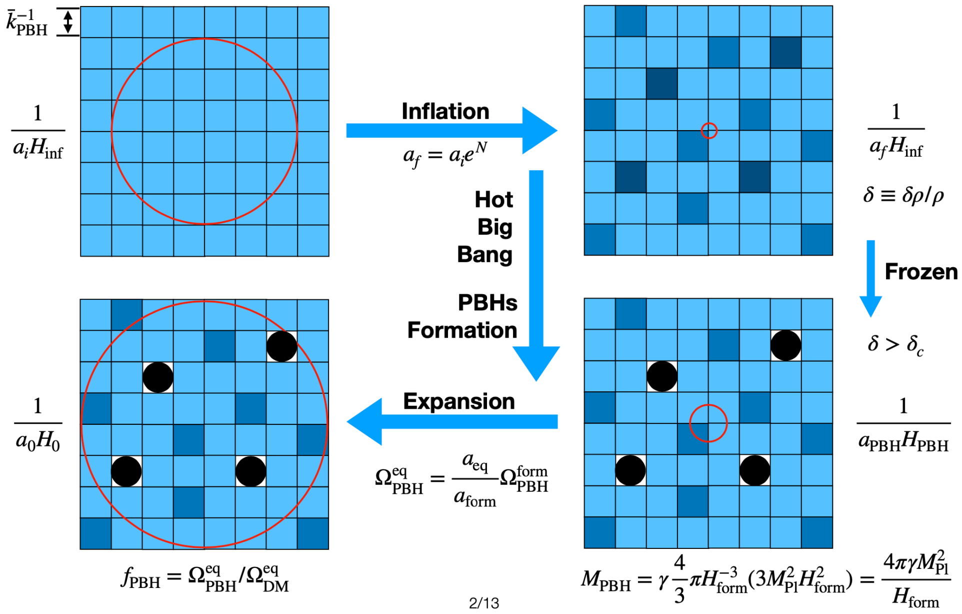


Figure from talk of Dr. Shao-Jiang Wang

Scalar field fragmentation;[Cotner *et al*, PRL 119 (2017) 3, 031103]

Directly from a FOPT;[Hawking *et al*, Phys.Rev.D 26 (1982) 2681; Baker *et al*, 2105.07481]

……

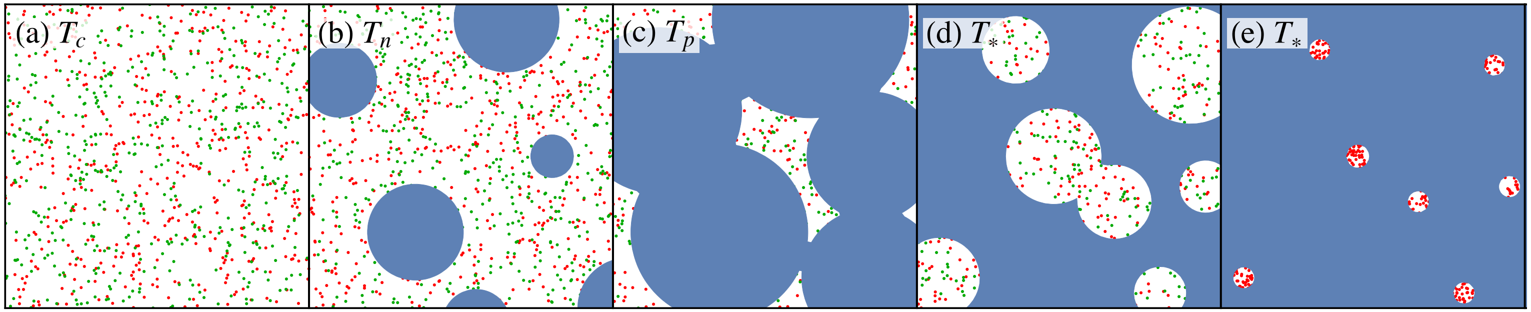
Collapse from the topological defects (e.g. cosmic strings, domain walls);[Hawking, PLB 231 (1989) 237-239]

Collapse from fermion non-topological solitons [this talk].

Recall the Fermi-ball scenario

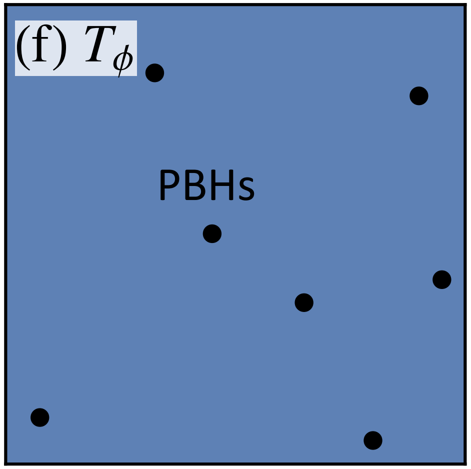
The Fermi-balls:

1. Non-topological solitons;
2. Dark matter candidate.



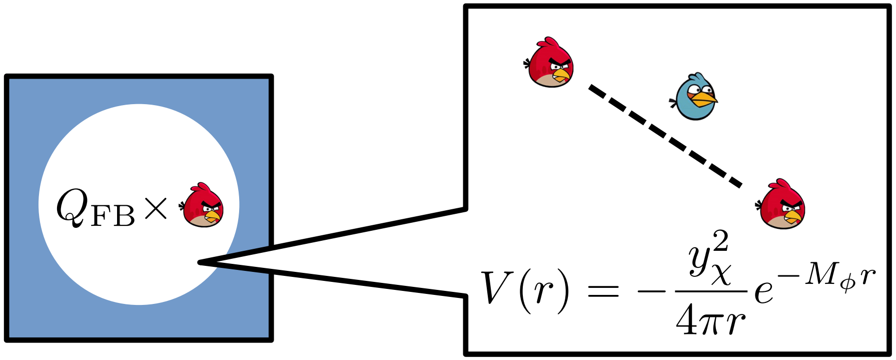
Is that the whole story?

Something is missed!



We have missed the Yukawa force!

Yukawa force *inside* a Fermi-ball



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

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

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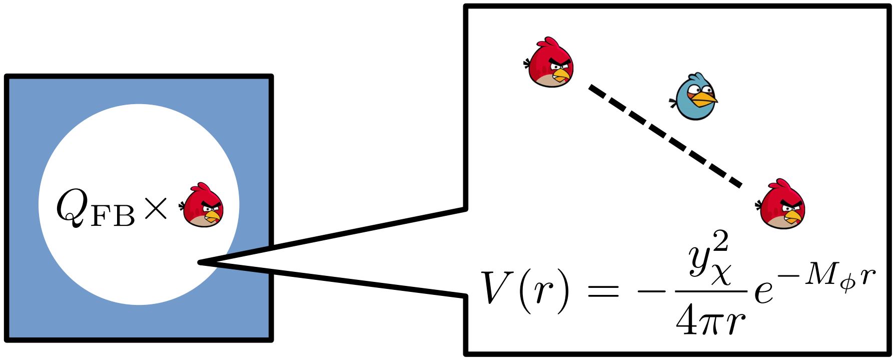

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Originated from $\mathcal{L}\supset -y_\chi\phi\bar{\chi}\chi$

The modified energy profile

Surface tension (negligible)

$$E=\frac{3\pi}{4}\left(\frac{3}{2\pi}\right)^{2/3}\frac{Q_{\rm FB}^{4/3}}{R}+4\pi\sigma_0R^2+\frac{4\pi}{3}U_0R^3$$

Fermi-gas kinetic energy

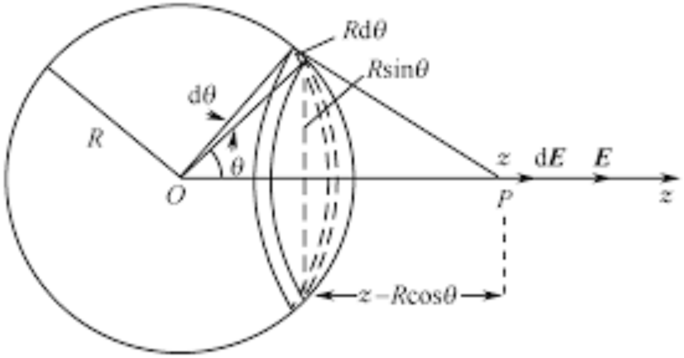
Volume energy

+ Yukawa energy

Calculating the Yukawa energy

A very simplified model: uniform distribution of the χ-fermions

A “textbook exercise” calculation…



…as the leading-order approximation

Calculating the Yukawa energy

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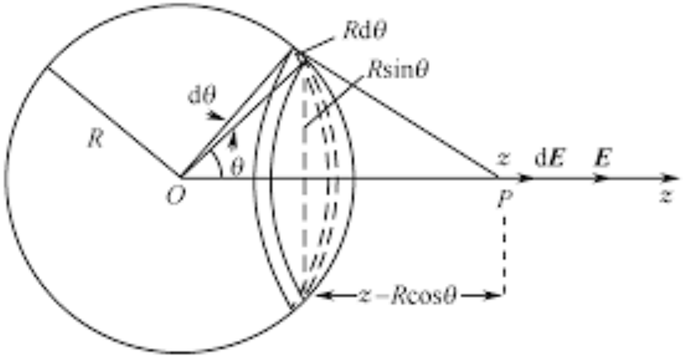

…as the leading-order approximation

$$E_{\rm Yuk} = -\frac{3y_\chi^2}{20\pi}\frac{Q_{\rm FB}^2}{R}f\left(\frac{L_\phi}{R}\right); \quad f(\xi) = \frac{5}{2}\xi^2\left[1+\frac{3}{2}\xi(\xi^2-1)-\frac{3}{2}\xi(\xi+1)^2e^{-2/\xi}\right]$$

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

* $f(0) = 0$ and $f(\infty) = 1$

Calculating the Yukawa energy

<u>A very simplified model</u>: uniform distribution of the χ-fermions

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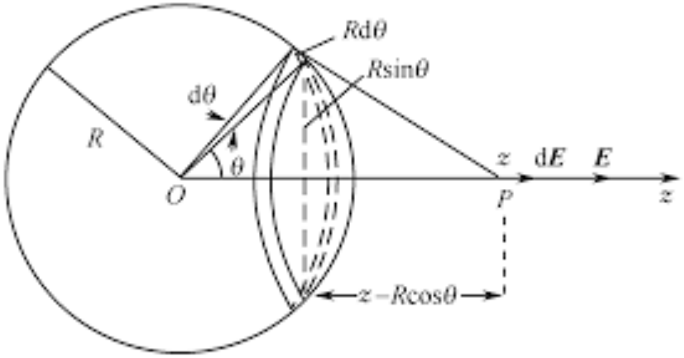

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Range of force $L_\phi = M_\phi^{-1}$

* $f(0) = 0$ and $f(\infty) = 1$

1. Always negative (attractive force);
2. Vanishes if mediator scalar is heavy;

Recall the Fermi-ball profile

The improved energy profile (when L_φ << R)

Surface tension (negligible)

$$E=\frac{3\pi}{4}\left(\frac{3}{2\pi}\right)^{2/3}\frac{Q_{\rm FB}^{4/3}}{R}+4\pi\sigma_0R^2+\frac{4\pi}{3}U_0R^3$$

Fermi-gas kinetic energy

Volume energy

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

What if the Yukawa energy dominates?

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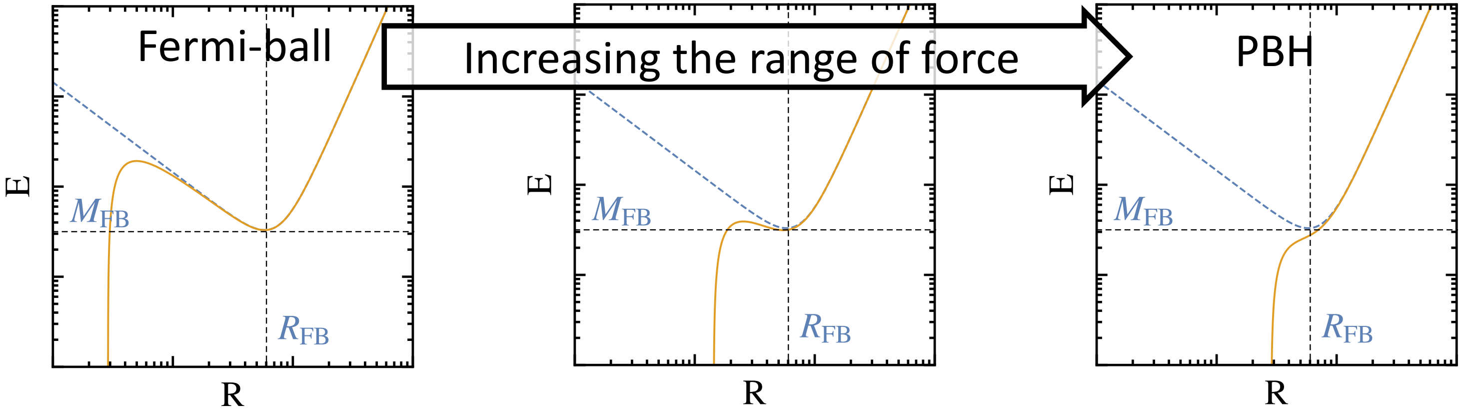

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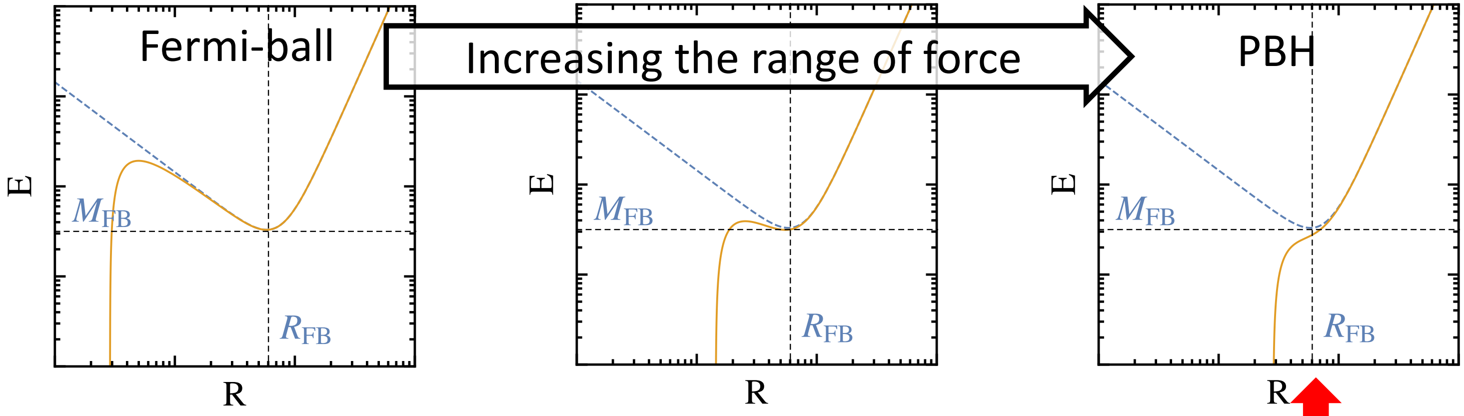


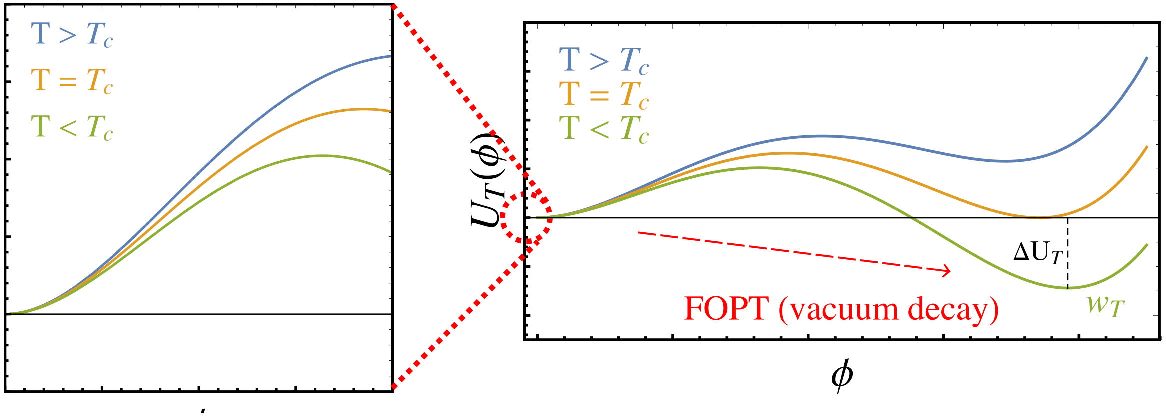
$$L_\phi \sim R_{\rm FB} Q_{\rm FB}^{-1/3}$$

Range of force reaches the <u>mean separation</u> of fermions in the Fermi-ball: collapse!

Evolution of range of force

The range of force increases as T drops!

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



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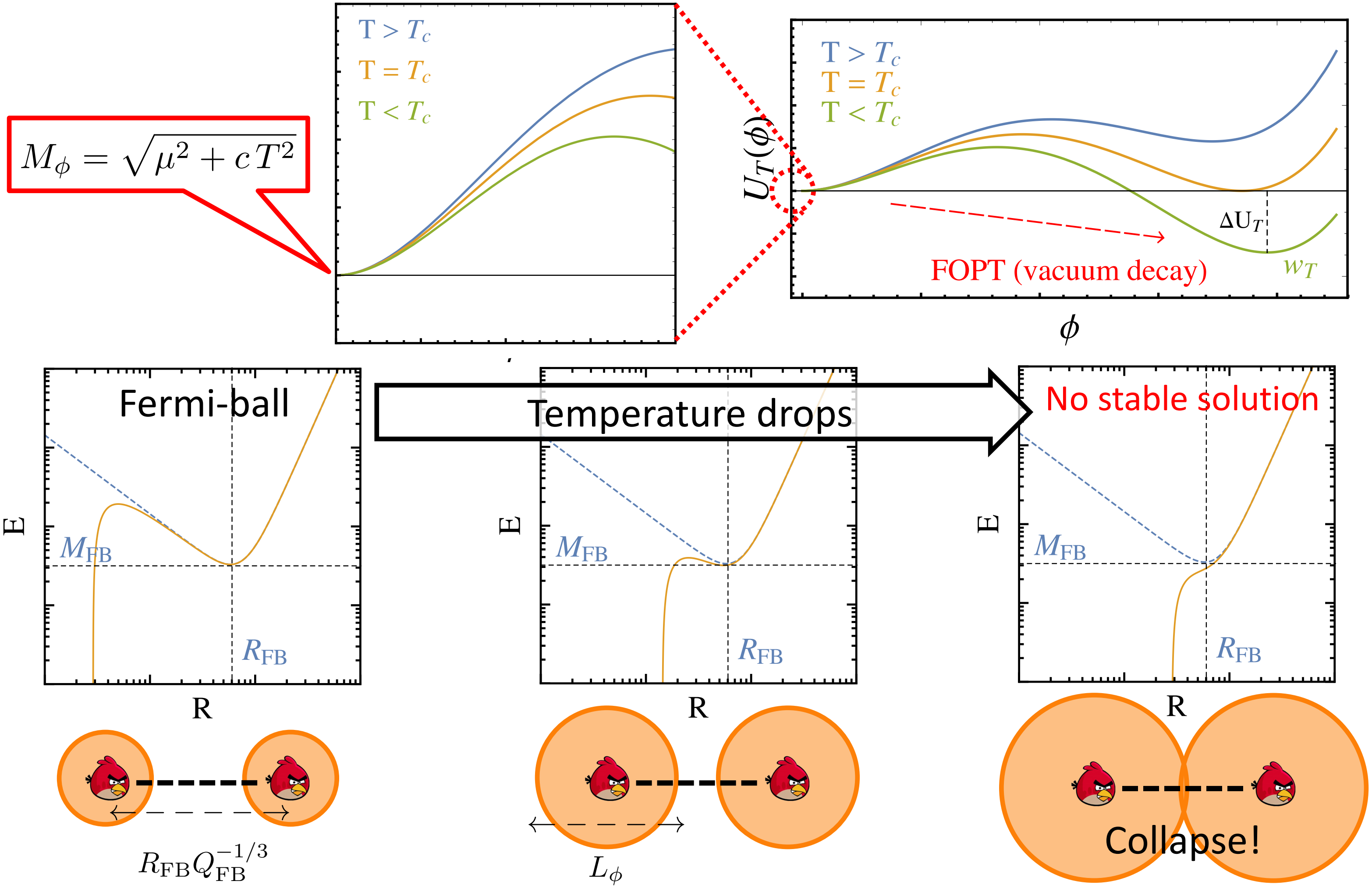

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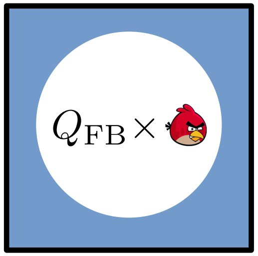
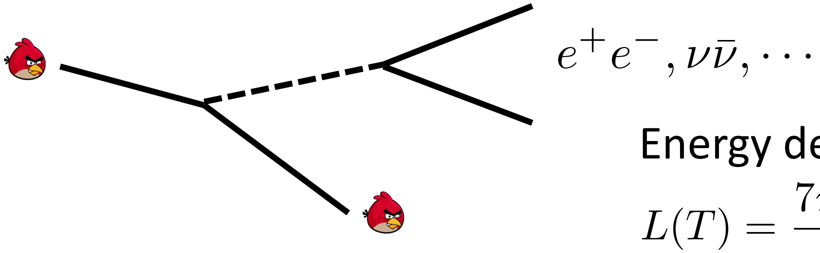
[Kawana and **KPX**, PLB 824 (2022) 136791, arXiv:2106.00111]

Wait, can a Fermi-ball cool down?

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! $\tau_{\rm cool} \ll 1/H$

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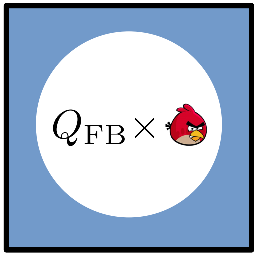

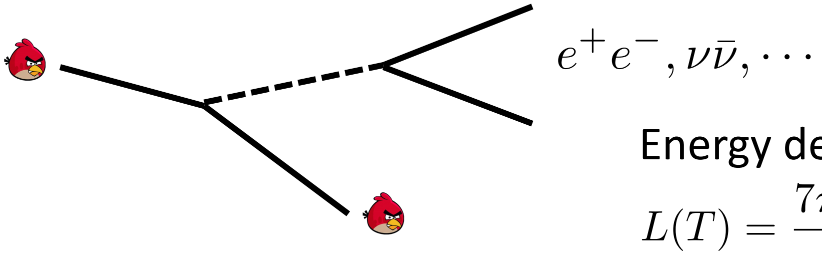

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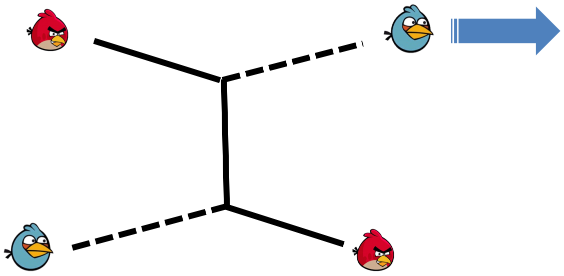
Scattering cooling:[Kawana, Lu and **KPX**, JCAP 10 (2022) 030, arXiv:2206.09923]



In thermal bath via

$\lambda_{H\phi}|H|^2\phi^2$

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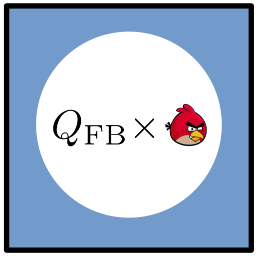

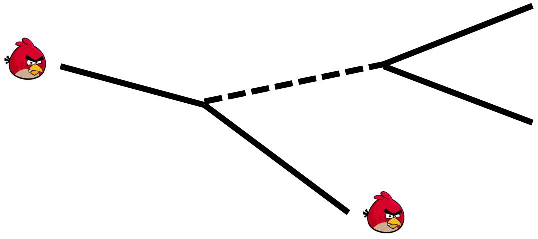

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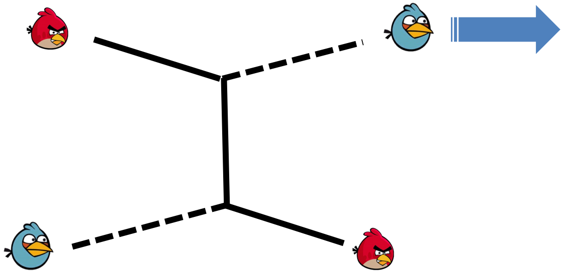


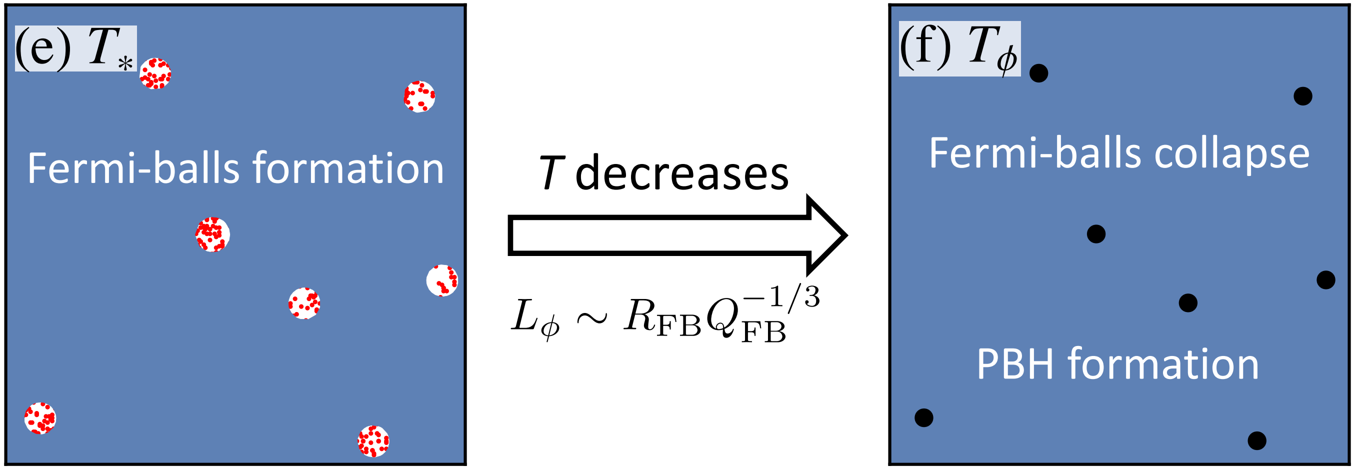
In thermal bath via

$\lambda_{H\phi}|H|^2\phi^2$

In short: Fermi-balls can cool down!

From Fermi-balls to primordial black holes

The Fermi-balls collapse to **primordial black holes** at T_φ when



Mass inherits from the mother Fermi-ball; number density

$$M_{\rm PBH} \approx M_{\rm FB} = Q_{\rm FB} \left(12\pi^2 U_0\right)^{1/4}$$

$$n_{\rm PBH} = s \times \frac{n_{\rm FB}^*}{s_*}$$

Recall the formulae

$$\Gamma(T_*) V_* \Delta t \sim 1, \quad V_* = \frac{4\pi}{3} R_*^3, \quad \Delta t = \frac{R_*}{v_b}$$

$$n_{\rm FB}^* \approx 0.29 \times V_*^{-1}$$

$$\Gamma(T) \sim T^4 \exp\left\{-S_3(T)/T\right\}$$

A quick estimate for the profile

The action is approximately[Huber *et al* JCAP2008]

The ratio of Hubble time to phase transition duration

$$\frac{S_3(T_*)}{T_*} \approx 131 - 4\ln\left(\frac{T_*}{100\ \mathrm{GeV}}\right) - 4\ln\left(\frac{\beta/H}{100}\right) + 3\ln v_b - 2\ln\left(\frac{g_*}{100}\right)\ ,$$

Vacuum energy $\boxed{U_0(T_*) \approx \alpha \times \frac{\pi^2}{30} g_* T_*^4}$

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Vacuum energy $U_0(T_*) \approx \alpha \times \frac{\pi^2}{30} g_* T_*^4$

$$\begin{aligned}
Q_{\rm FB} &\approx 1.0 \times 10^{42} \times v_b^3 \left(\frac{\eta_\chi}{10^{-3}}\right) \times \left(\frac{100}{g_*}\right)^{1/2} \left(\frac{100\text{ GeV}}{T_*}\right)^3 \left(\frac{100}{\beta/H}\right)^3 ,\\
R_{\rm FB} &\approx 4.8 \times 10^{-3}\text{ cm} \times v_b \left(\frac{\eta_\chi}{10^{-3}}\right)^{1/3} \times \left(\frac{100}{g_*}\right)^{5/12} \left(\frac{100\text{ GeV}}{T_*}\right)^2 \left(\frac{100}{\beta/H}\right) \alpha^{-1/4},\\
M_{\rm FB} &\approx M_{\rm PBH} \approx 1.4 \times 10^{21}\text{ g} \times v_b^3 \left(\frac{\eta_\chi}{10^{-3}}\right) \times \left(\frac{100}{g_*}\right)^{1/4} \left(\frac{100\text{ GeV}}{T_*}\right)^2 \left(\frac{100}{\beta/H}\right)^3 \alpha^{1/4},\\
f_{\rm PBH} &\approx 1.3 \times 10^3 \times v_b^{-3} \left(\frac{g_*}{100}\right)^{1/2} \left(\frac{T_*}{100\text{ GeV}}\right)^3 \times \left(\frac{\beta/H}{100}\right)^3 \left(\frac{M_{\rm PBH}}{10^{15}\text{ g}}\right);
\end{aligned}$$

The DM fraction today

Need further dilution mechanism if $f_{\rm PBH} > 1$.

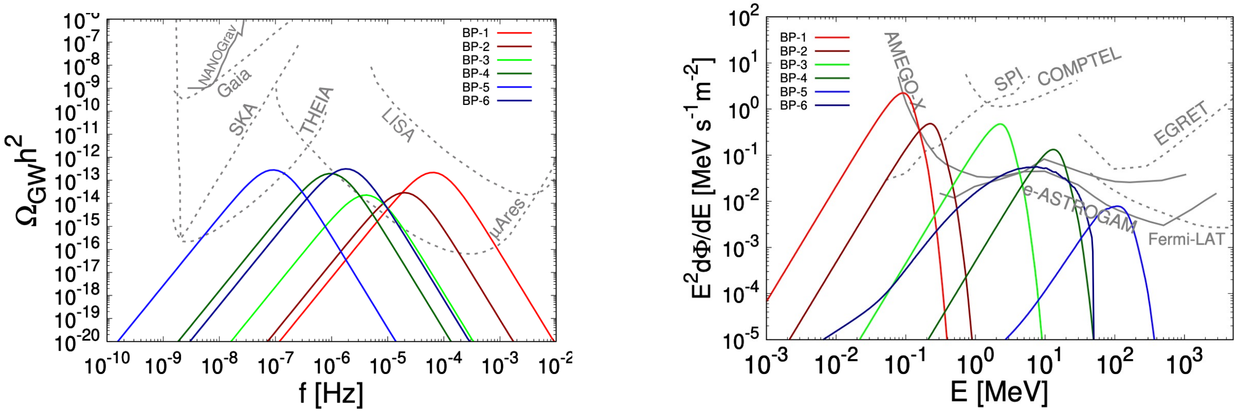
Correlation between FOPT and gamma-rays

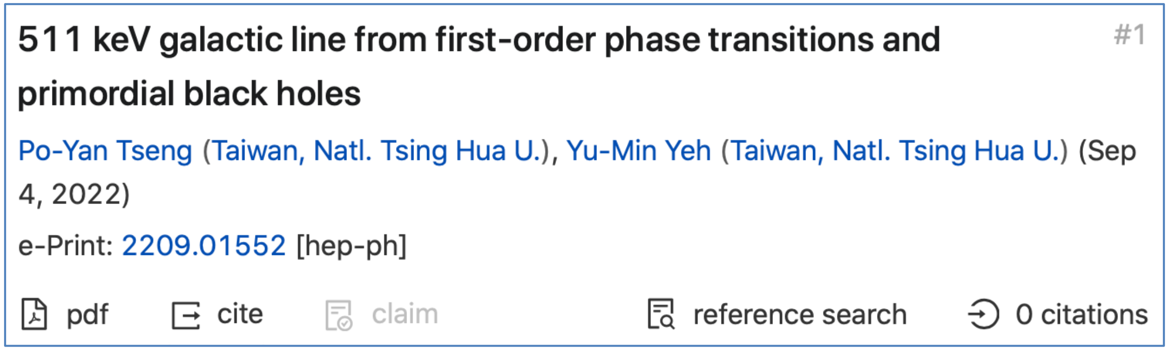
Correlated signals of first-order phase transitions and primordial black hole evaporation #1

Danny Marfatia (Hawaii U.), Po-Yan Tseng (Taiwan, Natl. Tsing Hua U.) (Dec 29, 2021)

Published in: *JHEP* 08 (2022) 001, *JHEP* 08 (2022) 249 (erratum) • e-Print: 2112.14588 [hep-ph], 2112.14588

pdf DOI cite claim reference search 9 citations





511 keV galactic line from first-order phase transitions and primordial black holes #1

Po-Yan Tseng (Taiwan, Natl. Tsing Hua U.), Yu-Min Yeh (Taiwan, Natl. Tsing Hua U.) (Sep 4, 2022)

e-Print: 2209.01552 [hep-ph]

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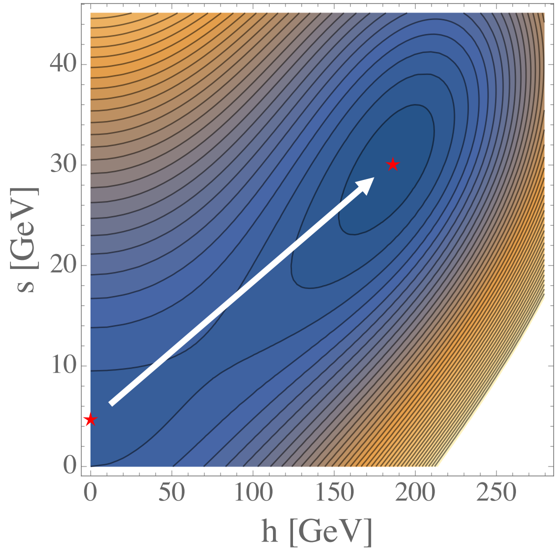
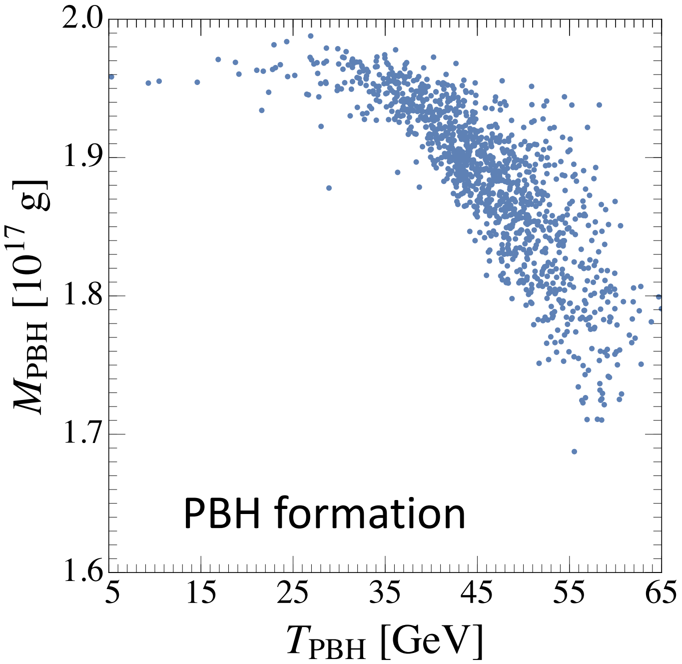
An application of this mechanism

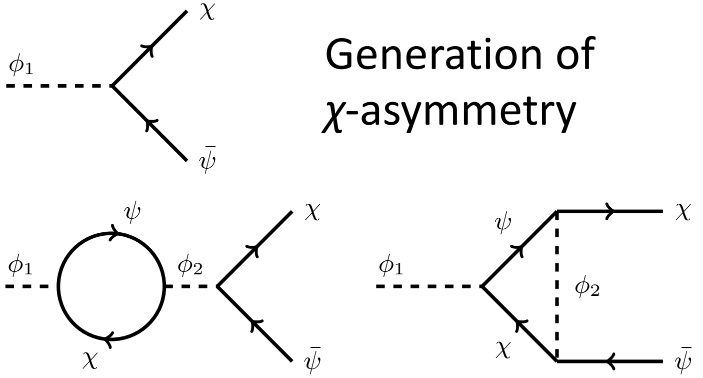
Primordial black holes from an first-order electroweak phase transition! [Huang and **KPX**, PRD 105 (2022) 11, 115033, arXiv:2201.07243]

$$\begin{aligned}\mathcal{L} \supset\ & \bar{\chi}\gamma^\mu i\partial_\mu\chi - g_\chi S\bar{\chi}\chi \\ & + D_\mu H^\dagger D^\mu H + \frac{1}{2}\partial_\mu S\partial^\mu S - V(H,S)\end{aligned}$$



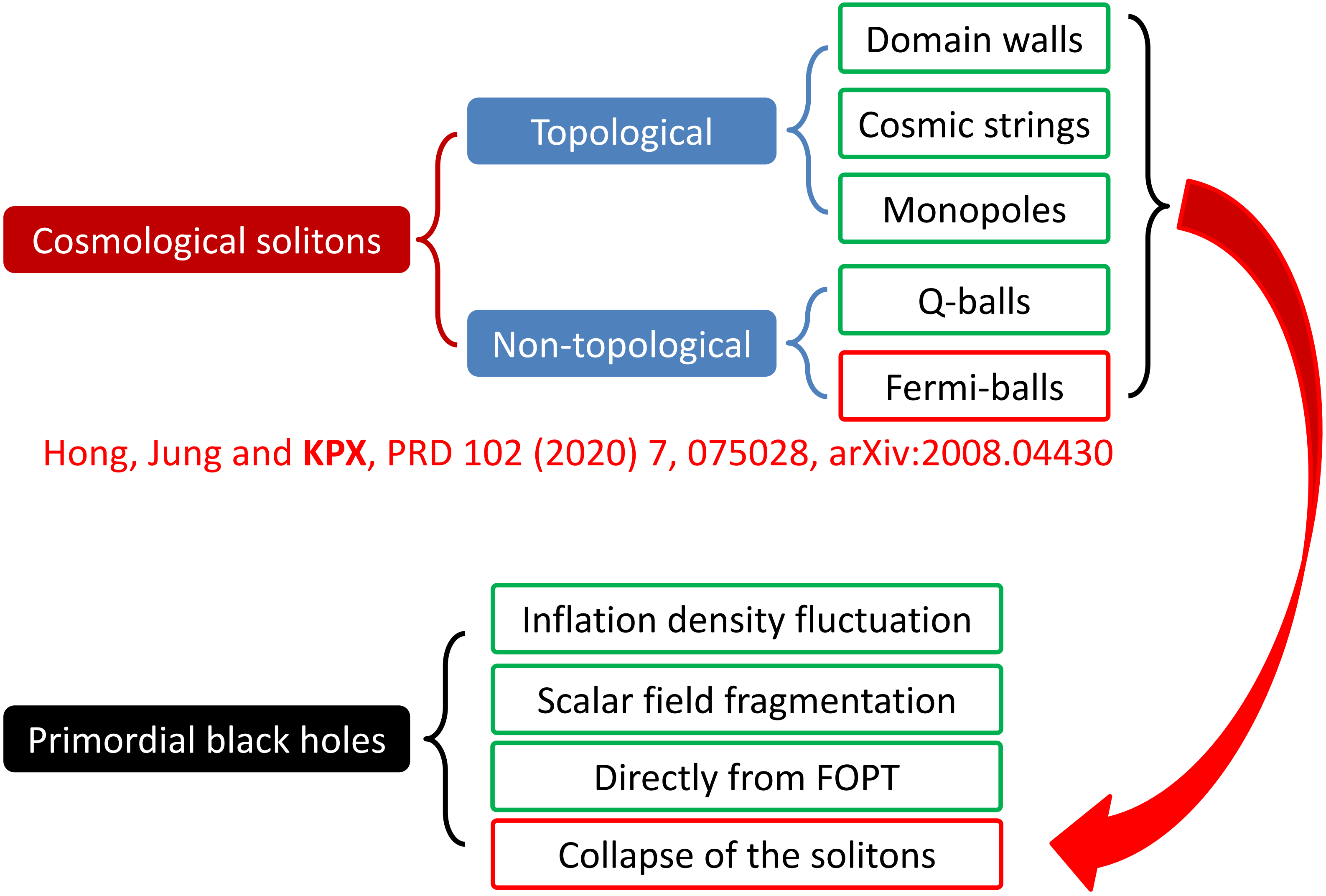


PBH formation



Generation of χ-asymmetry

Conclusion



Cosmological solitons

- Topological
  - Domain walls
  - Cosmic strings
  - Monopoles
- Non-topological
  - Q-balls
  - Fermi-balls

Hong, Jung and **KPX**, PRD 102 (2020) 7, 075028, arXiv:2008.04430

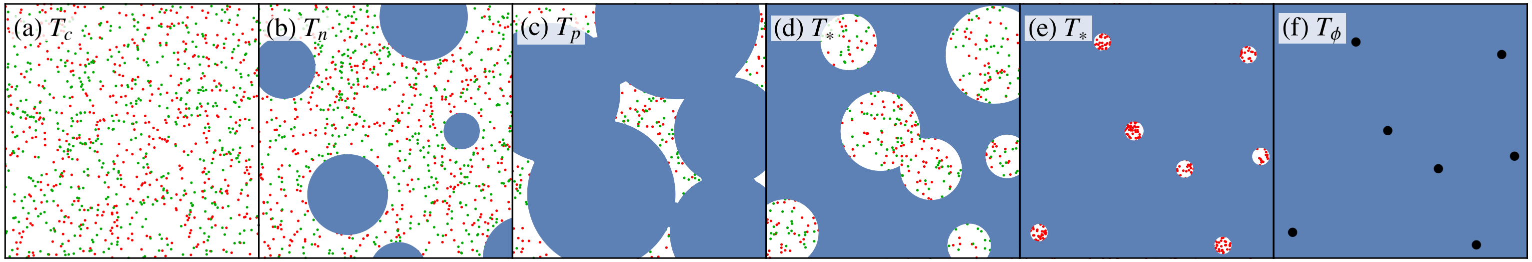
Primordial black holes

- Inflation density fluctuation
- Scalar field fragmentation
- Directly from FOPT
- Collapse of the solitons

Kawana and **KPX**, PLB 824 (2022) 136791, arXiv:2106.00111

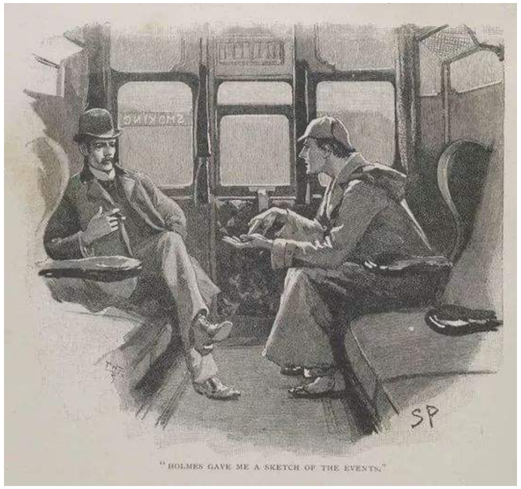
Conclusion

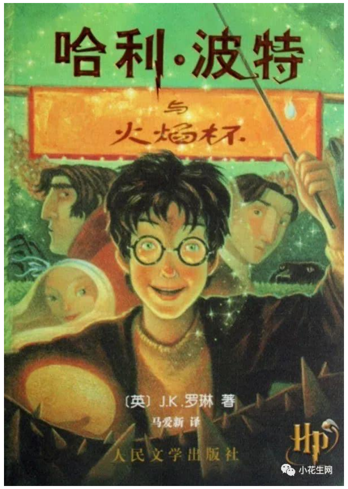
Our work!



Hong, Jung and **KPX**, PRD 102 (2020) 7, 075028, arXiv:2008.04430

Kawana and **KPX**, PLB 824 (2022) 136791, arXiv:2106.00111





Thank you!