Part 1:
Regurgitated Dark Matter

Philip Lu
Korea Institute for Advanced Study
2024 Korea-France STAR Workshop
November 21, 2024

Phys.Rev.D 110 (2024) 5, L051702

arXiv:2309.05703

T. Kim, **P. Lu**, D. Marfatia, V. Takhistov

Weakly Interacting Massive Particles

WIMP Miracle

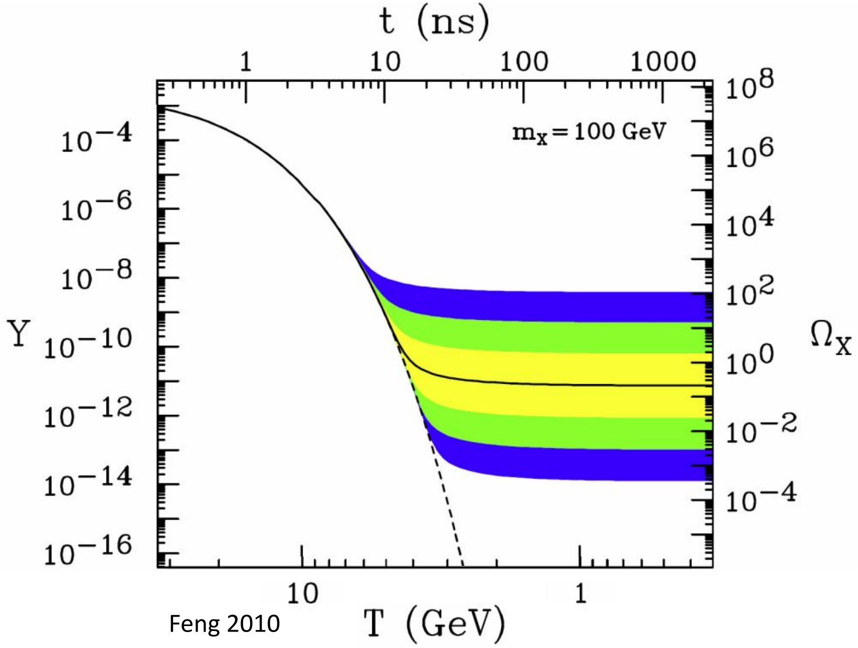
Can be produced by thermal freeze-out

Required cross-sections in the range of weak interactions

Lightest supersymmetric particle

Focus of large direct detection experiments

Not found



Feng 2010

Primordial Black Holes

Macroscopic dark matter candidate

Can comprise all of dark matter within the "mass window"

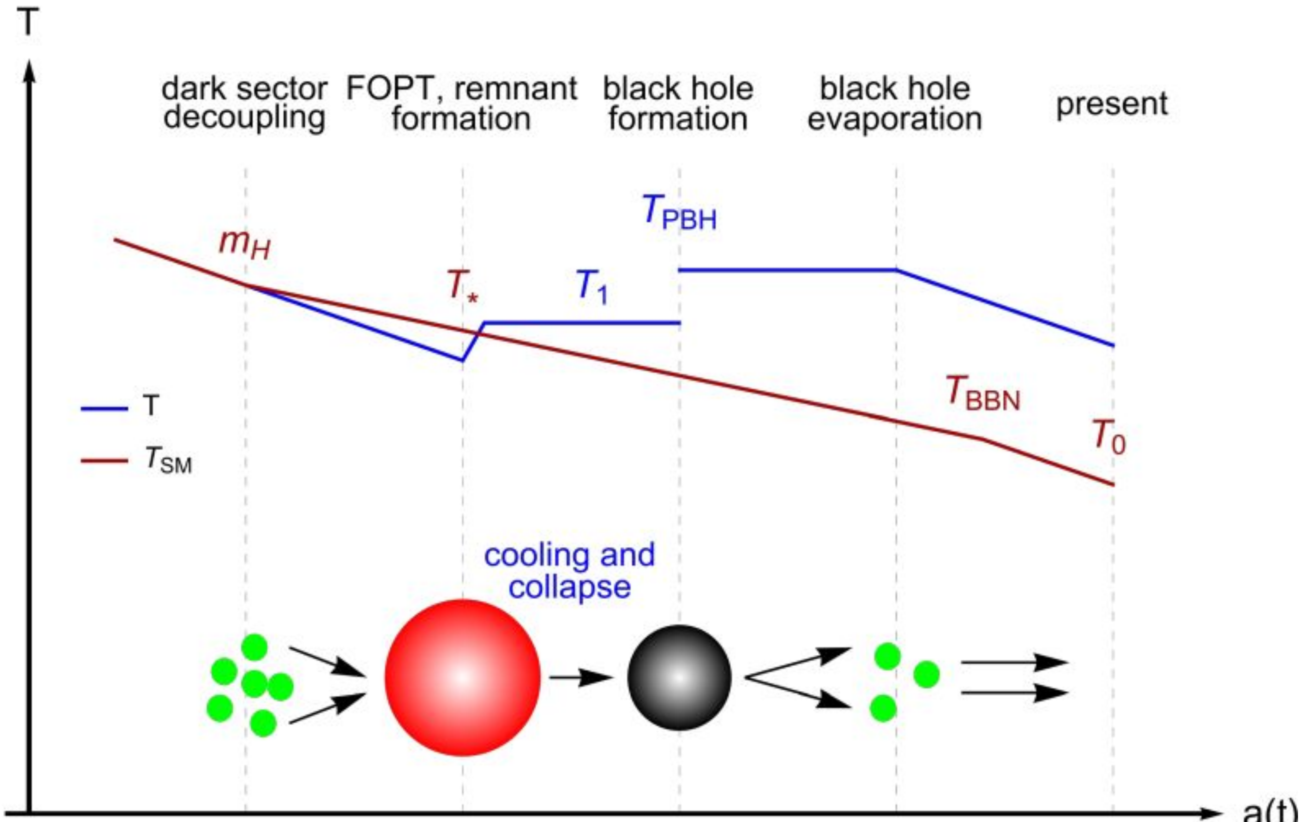
Natural consequence of inflation*

Formation scenarios usually result in gravitational waves (NanoGRAV?)

Emits Hawking Radiation

space.com

Timeline



T
dark sector decoupling
FOPT, remnant formation
black hole formation
black hole evaporation
present
T_{PBH}
m_H
T_*
T_1
T_{BBN}
T_0
T
T_{SM}
cooling and collapse
a(t)

Dark Sector Model

Simple model with (asymmetric) fermion and scalar

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{\mu^2}{2}\phi^2 - \frac{\kappa}{2}\phi^2(H^\dagger H) - V(\phi) + \bar{\chi}i\partial\!\!\!/\chi - y_\chi\phi\bar{\chi}\chi$$

Higgs portal and Yukawa terms

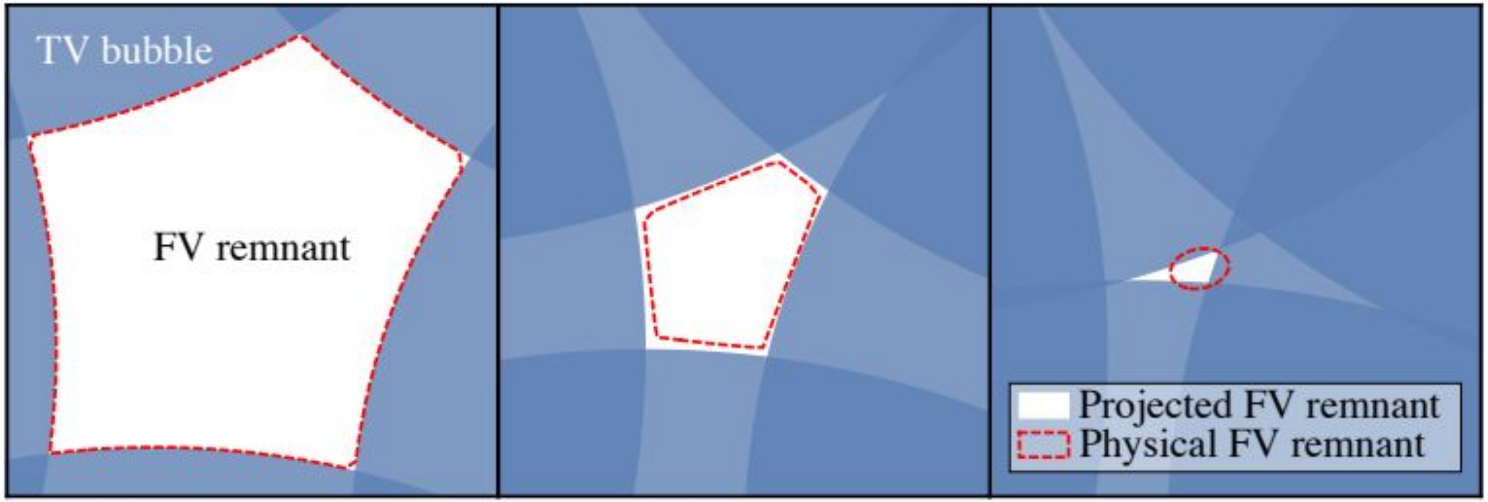
Particle trapping:

$$M_\chi^* \equiv y_\chi v_* \gg T_*, \quad M_\phi^* \equiv \left(\frac{\partial^2 V_{\rm eff}(\phi, T_*)}{\partial\phi^2}\right)^{1/2}\Big|_{\phi=v_*} \gg T_*$$

Initial Collapse

True bubble walls expand

Trapped particles confined to compact remnants



SM Portal Cooling

Thermal balls support by thermal pressure against vacuum pressure

Trapped φ particles annihilate through Higgs coupling

$$\dot{C} = n^2 \langle 2E \rangle \sigma v_{\rm rel} = \frac{0.051 \kappa^2 T_1^7 m_f^2}{m_H^4}$$

Cooling leads to thermal ball ->Fermi ball transition (Fermi Pressure)

$$T_{\rm SM}^{\rm tr} \simeq \ 10^4 \ {\rm GeV} \, \kappa \left(\frac{T_1}{1 \ {\rm GeV}} \right)^{3/2}$$

Cooling should end before BBN, lower bound on coupling

PBH Formation

Yukawa force becomes long range: $y_\chi \phi \bar{\chi} \chi$

$$L_\phi(T_D) = m_\phi(T_D)^{-1} = \frac{1}{\sqrt{\mu^2 + cT_D^2}}$$

Rapid collapse to PBH

Light average mass:

$$\overline{M}_{\text{PBH}} \sim 7 \times 10^6\ g\ \left(\frac{\beta/H}{10^4}\right)^{-3} \left(\frac{\eta_\chi}{10^{-15}}\right) \left(\frac{T_*}{1\ \text{GeV}}\right)^{-2}$$

Evaporating PBH

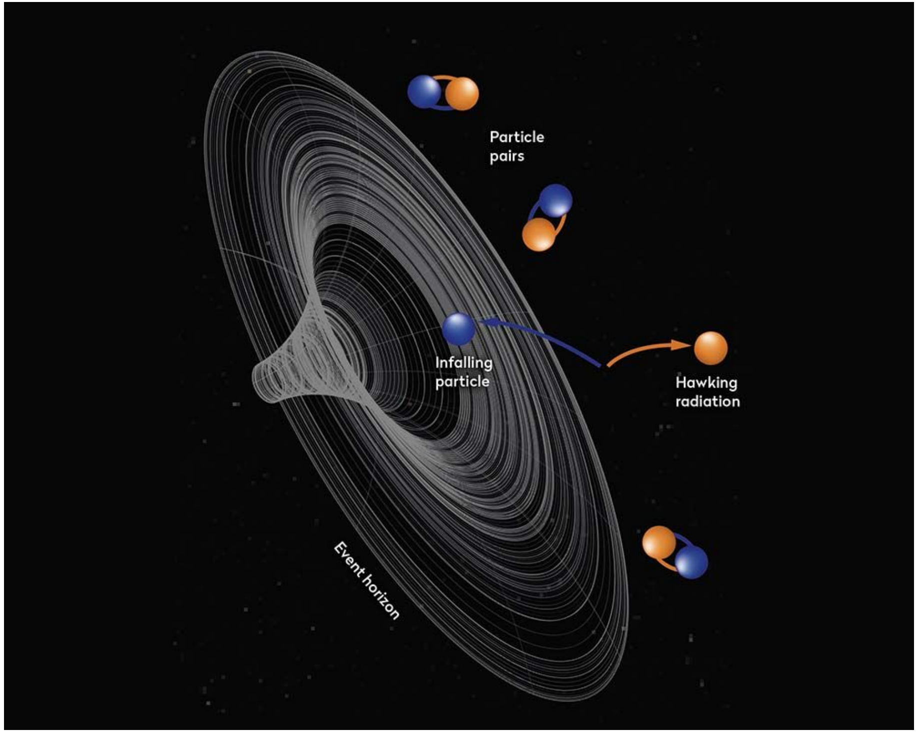
Recent interest on very light PBH

Hawking Temperature

$$T_{\text{PBH}} = 1.06 \times 10^5 \ \text{GeV} \left(\frac{M_{\text{PBH}}}{10^8 \text{g}} \right)^{-1}$$

Hawking evaporation emits particles based on mass-> DM emission

What if DM produced PBH that produced DM?



Getty Images

PBH Domination

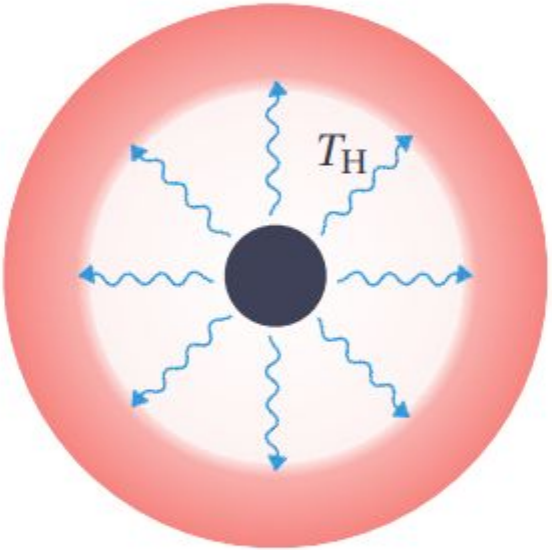
PBH density grows relative to plasma density

PBH domination before evaporation if

$$\beta \gtrsim 10^{-13} \left(\frac{M_{\mathrm{PBH}}}{10^8 g} \right)^{-1}$$

Reheating temperature

$$T_{\mathrm{RH}} = 50.5\mathrm{MeV} \left(\frac{10^8 \mathrm{g}}{M_{\mathrm{PBH}}} \right)^{3/2}$$



He et al. 2022

Dark Matter Density

Initial abundance: $$\frac{\rho_{\phi,\chi}}{\rho_{\rm SM}} = \frac{g_{H,(\phi,\chi)}}{g_{\rm H,SM}}$$

Non-relativistic emission:

Particles heavier than Hawking temperature

Suppressed by particle emission threshold

$$\frac{M_{\rm PBH}^{\rm em}}{M_{\rm PBH}} = \epsilon_{\rm em}\left(\frac{M_{\rm PBH}}{10^8 g}\right)^{-1}\left(\frac{m_{(\phi,\chi)}}{10^5\ {\rm GeV}}\right)^{-1}$$

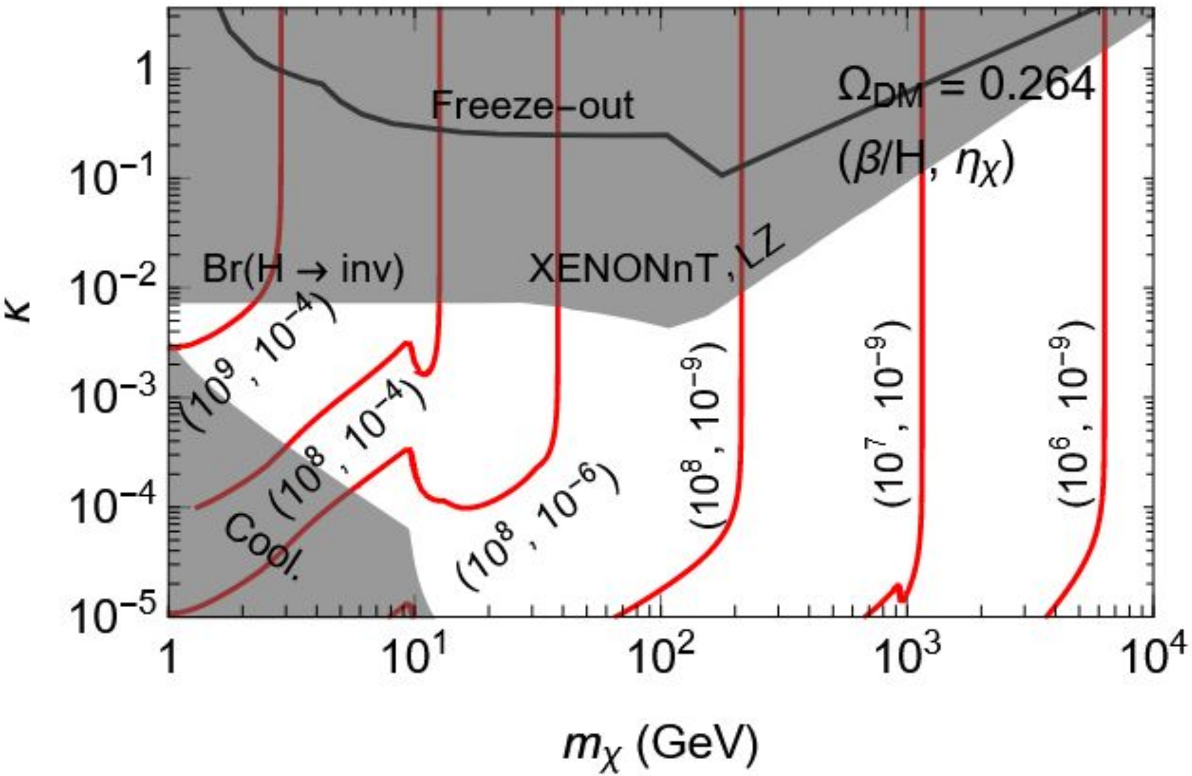
Relativistic emission:

Particles lighter than Hawking temperature

Suppressed by redshift after emission

$$\gamma \sim \frac{m_(\phi,\chi)}{\epsilon T_{\rm PBH}}$$

WIMP Regurgitation



Conclusions

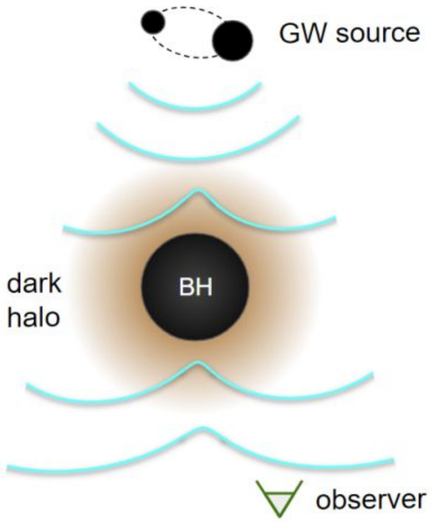
1. First order phase transition can trap particles and form compact remnants, which eventually collapse into PBH.

2. The three endpoints of this process, thermal balls, Fermi balls, and PBH can all be dark matter candidates.

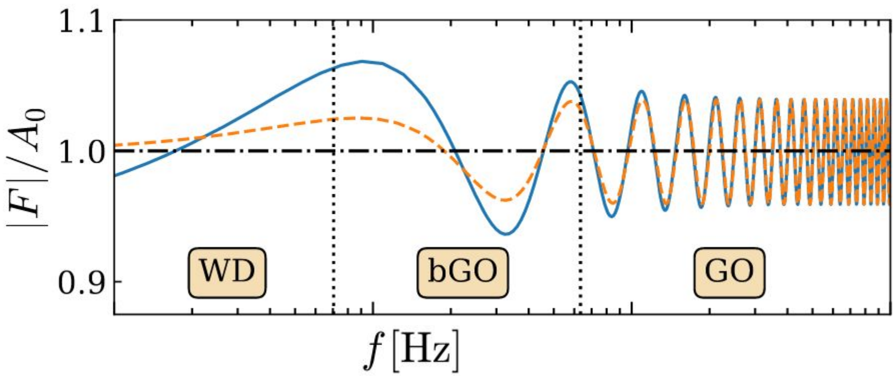
3. Regurgitated dark matter is a novel production mechanism in which dark matter particles form PBH which reemit dark matter particles.

4. Due to the disassociation of interaction strength and abundance, WIMP parameter space is increased.

GW Halo Lensing Constraint



- Binary black hole mergers produce reliable “chirp” signals
- Intervening PBH lens and amplify GW signals
- Dark halos around PBH improve constraints by ~O(10)
- Frequency scan can probe structure of dark halo



- Distinguishability of “dressed” and “bare” lens can imply the existence of PBH

Part 2: Q-balls in the Presence of Attractive Force

Philip Lu
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JHEP 08 (2024) 242
arXiv:2407.11115
Y. Hamada, K. Kawana, T. Kim, **P. Lu**

Q-Ball Models

Friedberg-Lee-Sirlin

- One complex + one real scalar
- Symmetric vacuum inside
- “Non-topological Solitons”

Coleman

- One complex scalar
- “Q-ball”

Both

- Conserved charge Q
- Evades Derrick’s Theorem with time-dependent phase
- Stable macroscopic objects

FLS Lagrangian w/ Yukawa Force

Complex scalar Φ with U(1) symmetry

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \chi)^2 + |\partial_\mu \Phi|^2 - V(\chi, \Phi)$$

Quartic interaction promotes stability, new Yukawa interaction destabilizes

$$V(\chi, \Phi) = U(\chi) + \boxed{\Lambda \chi |\Phi|^2} + \boxed{\kappa \chi^2 |\Phi|^2}$$

Real scalar X potential induces symmetry breaking

$$U(\chi) = \frac{\lambda}{4!}(\chi^2 - v^2)^2$$

Equations of Motion

Χ EOM enforces constant value inside Q-ball

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d\chi}{dr}\right) - \frac{dU(\chi)}{d\chi} - \frac{\Lambda}{2}\phi^2 - \kappa\phi^2\chi = 0$$

Φ sinc function satisfies Helmholtz equation

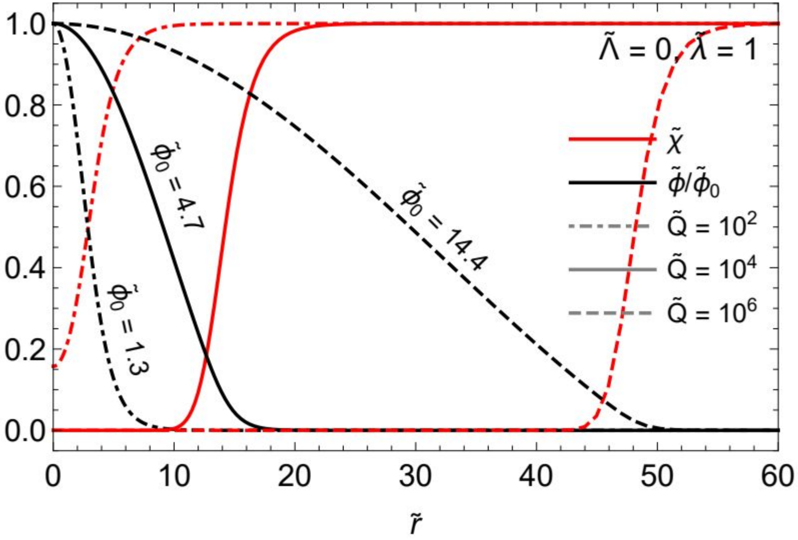
$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d\phi}{dr}\right) + \omega^2\phi - (\Lambda\chi + \kappa\chi^2)\phi = 0$$

Conserved charge ensures stability w.r.t. decays

$$Q = 4\pi\omega\int_0^\infty r^2 dr\,\phi^2(r)$$

Approximate Solution

$$\chi(r) \simeq \begin{cases} -\frac{\Lambda}{2\kappa} & r < R_\Lambda \\ -\frac{\Lambda}{2\kappa} + \left(v + \frac{\Lambda}{2\kappa}\right)\left[1 - e^{-m_\chi (r - R_\Lambda)}\right] & r > R_\Lambda \end{cases}, \qquad \phi(r) \simeq \begin{cases} \phi_0 \frac{\sin \omega_\Lambda r}{\omega_\Lambda r} & r < R_\Lambda \\ 0 & r > R_\Lambda \end{cases}$$



Effective radius:

$$\frac{\pi}{R_\Lambda} = \omega_\Lambda = \sqrt{\omega^2 + \Lambda^2/4\kappa}$$

Solving for ω

Total energy of the Q-ball:

$$E = \omega Q + \boxed{\frac{\lambda \pi^4}{18\omega_\Lambda^3}\left(\frac{\Lambda^2}{4\kappa^2} - v^2\right)^2} + \boxed{\frac{2\pi^3 v^2 m_\chi}{\omega_\Lambda^2} a_1 + \frac{4\pi^2 v^2}{\omega_\Lambda} a_2 + \frac{4\pi v^2}{m_\chi} a_3}$$

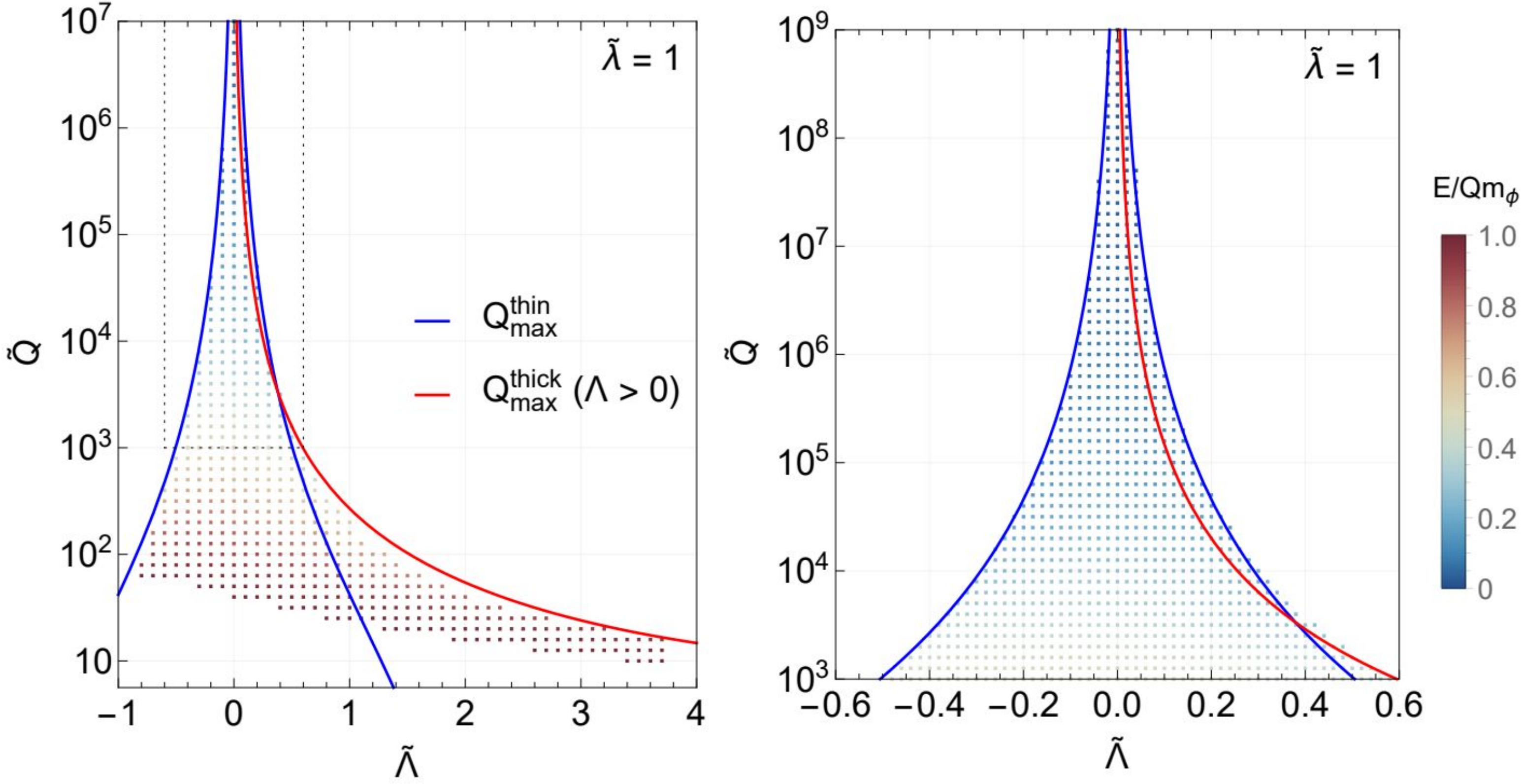
Thin wall approximation: drop surface terms

$$\frac{dE}{d\omega} = Q - \frac{\lambda \pi^4 \omega}{6\left(\omega^2 + \frac{\Lambda^2}{4\kappa}\right)^{5/2}}\left(\frac{\Lambda^2}{4\kappa^2} - v^2\right)^2 = 0$$

Thick wall approximation: drop volume term

$$\frac{dE}{d\omega} = Q - \frac{\lambda \pi^4 \omega}{6\omega_\Lambda^5}\left(\frac{\Lambda^2}{4\kappa^2} - v^2\right)^2 - \frac{4\pi^3 v^2 m_\chi \omega}{\omega_\Lambda^4} a_1 - \frac{4\pi^2 v^2 \omega}{\omega_\Lambda^3} a_2 = 0$$

Maximum Stable Charge



Implications of Instability (Preliminary)

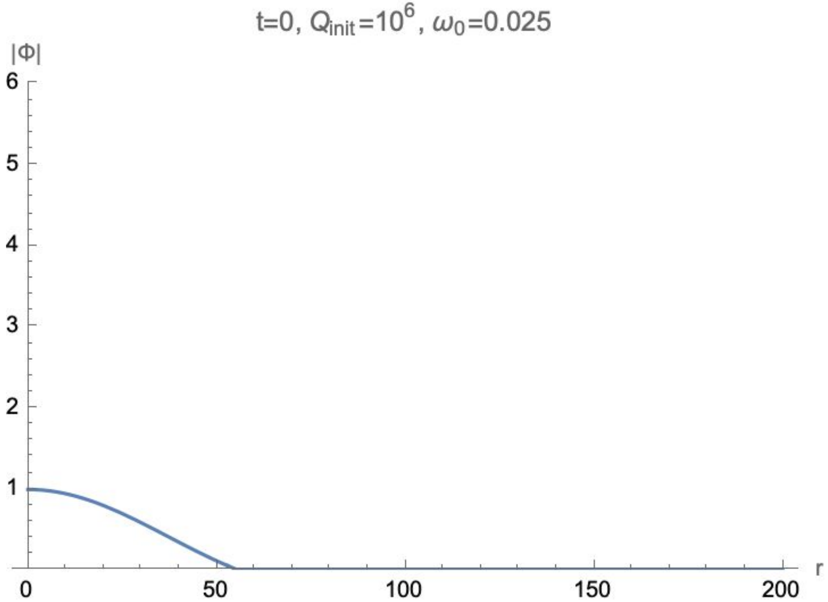
No stationary solution above the maximum charge

$\not\Rightarrow$Collapse into black hole

$\Rightarrow$Exponential Growth

Does growth continue?

Could unstable Q-balls cover the Universe?



Conclusions

1. The inclusion of the Yukawa interaction term alters the Q-ball profile

2. Even at low interaction strengths, a meaningful upper bound on the charge is imposed

3. Unstable Q-balls may not collapse into PBHs, as an attractive interaction would suggest, but could paradoxically expand and grow.