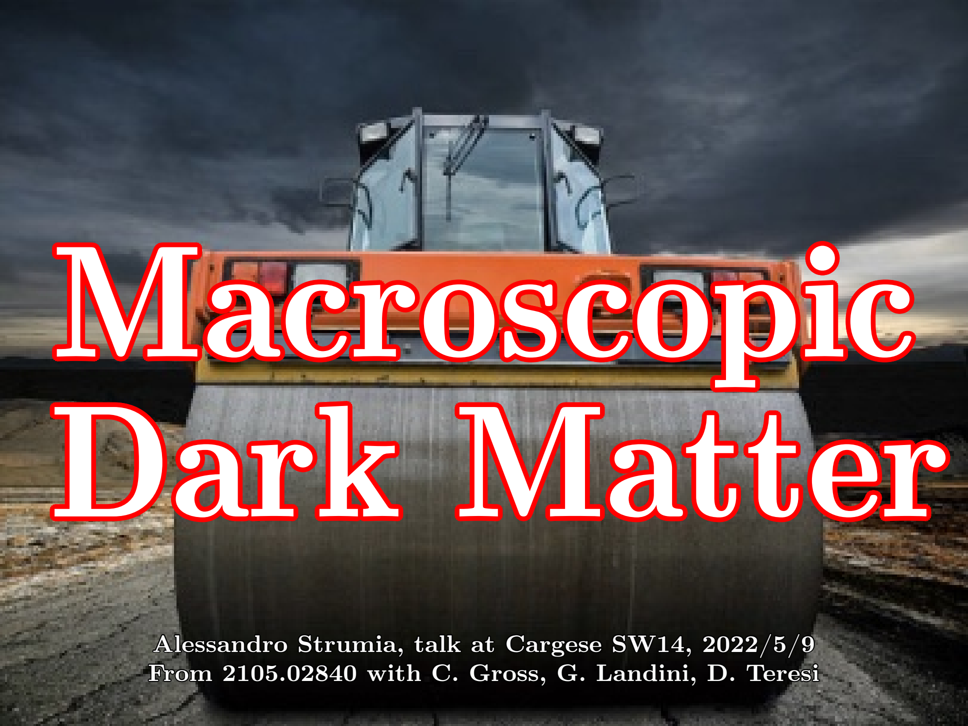
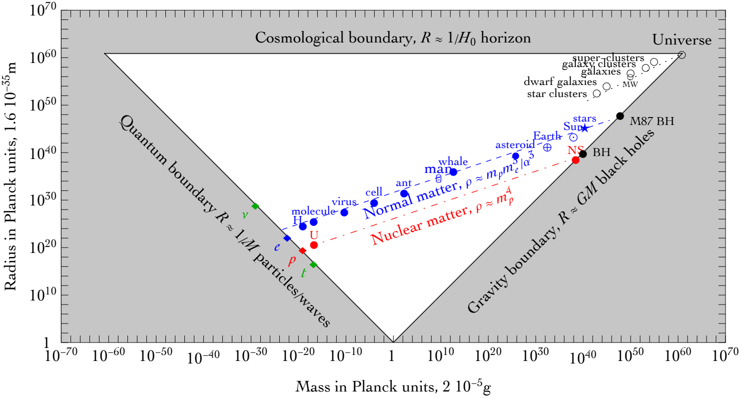


Macroscopic Dark Matter

Alessandro Strumia, talk at Cargese SW14, 2022/5/9
From 2105.02840 with C. Gross, G. Landini, D. Teresi

Catalogue of the Universe

Mass M? Size R? Particle? Light particle i.e. wave? Black hole? Object?



- Normal matter forms objects with any R and density $\rho \sim M/R^3 \sim \alpha^3 m_p m_e^3$.
- Nuclear matter with density $\rho \sim m_n^4$ only forms ~ 100 nuclei (nn repel, np attract, pp repel) and next gravitational neutrons stars, almost BH.
- Observed DM structures seem gas-like with different ρ, same a.

Are DM macroscopic objects possible? Can they from cosmologically?

Existence: possible macroscopic objects

A non-relativistic ball with $Q \gg 1$ nearly-conserved particles is stable if pressures $\wp = \partial U_i / \partial V$ balance, i.e. if its energy U is minimal at some radius R:

$$U = U_{\text{Yukawa}}^{\text{Coulomb}} + U_{\text{quantum}} + U_{\text{gravity}} + U_{\text{volume}} + U_{\text{surface}} + \cdots$$

Usual matter: $U_{\text{Coulomb}} \sim \pm \alpha Q^2 / R$ (attractive, needs e, p) and repulsive U_{quantum}

$$U_{\text{quantum}} = \frac{9}{20} \left(\frac{3\pi^2}{2} \right)^{1/3} \frac{Q^p}{mR^2} \quad \text{with } p = 5/3 \text{ for free non-relativistic fermion}$$

($\wp_{\text{quantum}} \sim nK$ with number density $n \sim Q/R^3$ fills up to Fermi momentum $k \sim n^{1/3}$ i.e. energy $K = k^2/2m$). (Bosons have $k \sim 1/R$, non-intensive $p = 1$). (Relativistic particles have $K = k$, so $U_{\text{quantum}} \sim Q^{4/3,1}/R$, bad).

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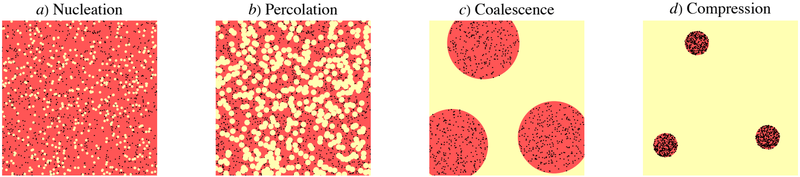
To get more, consider two different phases or vacua:

$$U_{\text{volume}} = \Delta V\, \frac{4\pi R^3}{3}, \qquad U_{\text{surface}} = \sigma\, 4\pi R^2.$$

Cosmological formation of macroscopic objects

Idea: new phase appears via a 1st order phase transition. Its bubbles expand.



DM gets compressed, forming pockets of false vacuum with dense DM if

- DM particles cannot enter bubbles. For example, DM tends to remain trapped if it's lighter inside $m_{\rm in} \ll m_{\rm out}$. Or because confinement.
- Bubbles expand slow, like a steam-roller.
- Compressed DM don't annihilate or start other bad particle processes.

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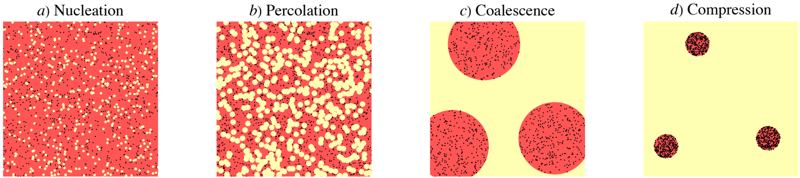

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Models with scalars + fermions + Yukawas + 1st order phase transition.

In the multiverse other vacua have different light particles. DM could be residual pockets of such particles (conditions on steam-roller ... decay... met).

I will compute one specific simple theory...

Theory

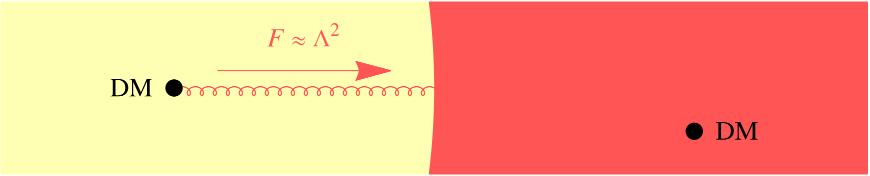
Dark QCD-like confinement at Λ

$$\mathscr{L} = \mathscr{L}_{\rm SM} - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + \bar{q}(i\not{D} - m)q$$

Phase transition to confinement is 1st order if the number of light quarks is

$$N_f = 0 \qquad \text{or (maybe)} \qquad 3 \le N_f \lesssim 3N.$$

If $N_f > 0$: quarks lighter than hadrons tend staying in pockets. But really 1st?
Focus on $N_f = 0$: heavy q cannot enter confined regions, as strings push back.



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Strong phase transition to confinement is steamroller-like: **thin-wall bubbles**

$$\gamma \approx T_{\rm cr}^4 \exp\left[-\frac{\kappa}{\delta^2}\right] \qquad \text{where} \qquad \delta = 1 - \frac{T_{\rm dark}}{T_{\rm cr}}, \qquad \kappa = \frac{16\pi}{3} \frac{\sigma^3}{\mathcal{L}^2 T_{\rm cr}} \sim 10^{-4}$$

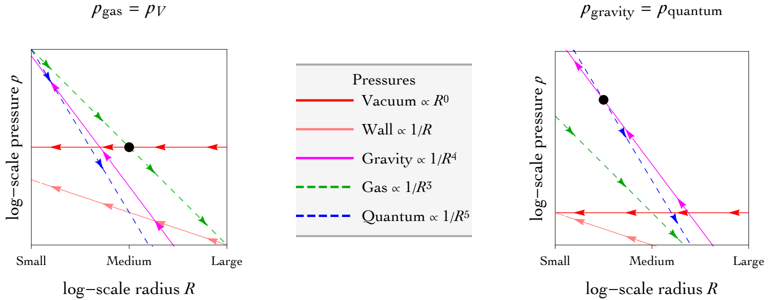
that nucleate fast at small $\delta \sim \sqrt{\kappa}$ (i.e. at $T_{\rm dark}$ just below $T_{\rm cr} \approx \Lambda$; $\mathcal{L} \approx 1.4 T_{\rm cr}^4$ is the latent heat, $\sigma \approx 0.02 T_{\rm cr}^3$ the surface tension) **and expand slowly**, $v \approx \delta$, limited by the fact that expansion releases big latent heat $\mathcal{L}$ that would de-confine, unless it's Hubbled away. **So no cooling until bubbles slowly compress all**.

This allows to compute how many bubbles/pockets form per Hubble volume, and so the number Q of dark quarks in each pocket, assuming $\Omega = \Omega_{\rm DM}$ abundance.

Compression

Vacuum energy initially stabilised by gas pressure. Cooling gives slow pocket compression, until various particle physics phenomena can start being relevant.

- q can annihilate with $\bar{q}$, leaving nothing.
  Avoid assuming a baryon asymmetry or statistical fluctuations $Q \pm \sqrt{Q}$.
- Heavy q tend to form baryons and exit, leaving nothing.
- Light q tend to remain forming Fermi or Bose balls with $\wp_{\text{quantum}} = \wp_{\text{vacuum}}$ or Color Superconductivity phase $\langle qq \rangle$ (not studied yet).



- Heavy enough q that $\wp_{\text{gravity}} > \wp_{\text{quantum}}$: pockets gravitationally collapse...

Gravitational collapse

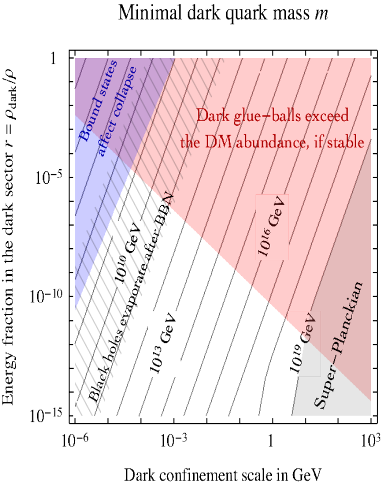
Gravitational collapse happens if heavy q

$$m \gtrsim m_{\rm cr} \approx \min\left(\frac{10^7 T_{\rm cr}^{3/2}}{{\rm eV}^{1/2} r^{3/8}}, \frac{300 T_{\rm cr}}{r^{1/8}}\sqrt{\frac{M_{\rm Pl}}{\rm eV}}\right).$$

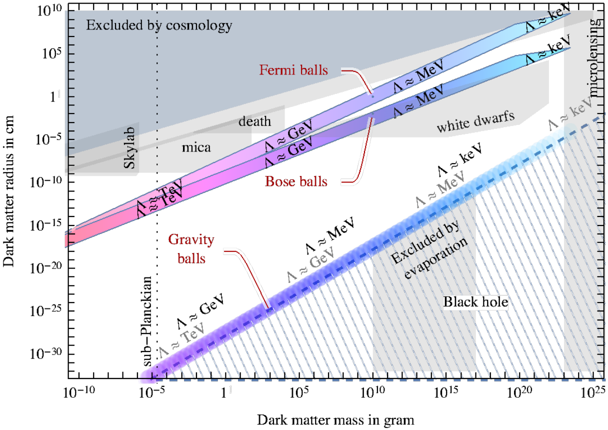
Baryon formation is energetically relevant if $\alpha_{\rm dark} \gtrsim (m/M_{\rm Pl})^{1/6}$ (in the blue region) and makes a nuclear-like bang and...? Otherwise sure collapse to black holes or to dark dwarfs

$$R_{\rm dwarf} \approx \left(\frac{81\pi^2}{16N^2}\right)^{1/3} \frac{M_{\rm Pl}^2}{m^3 Q^{2-p}} \sim \frac{M_{\rm Pl}^2}{m^{1+p} M^{2-p}}$$

($p = 5/3$ for a fermion, $p = 1$ for a boson). They are parametrically similar, so we solved TOV to verify that $\mathcal{O}(1)$ factors allow dwarfs.



Final objects



Qualitative difference: small BH evaporate, small dwarfs remain.

Signals? Small dwarfs with gravitational interactions only can accrete into BH and evaporate now, or pass through matter and melt and crack it. Too low rates.

Gravitational Dark Matter

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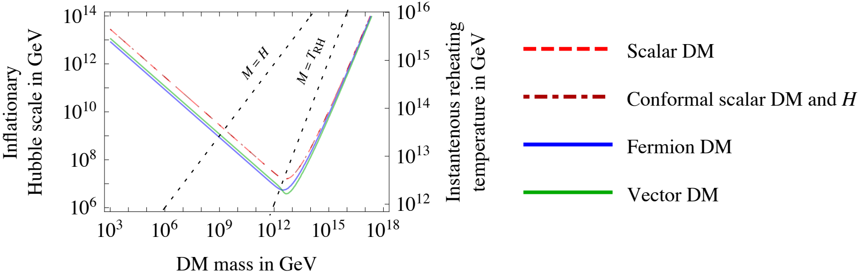
Sloth et al. assumed a stable scalar or fermion or massive vector that only has gravitational interactions, and found that it can be a DM candidate cosmologically produced via freeze-in or inflation:



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Sloth et al. assumed a stable scalar or fermion or massive vector that only has gravitational interactions, and found that it can be a DM candidate cosmologically produced via freeze-in or inflation. Can we get a plausible theory?

- × Scalar S can have renormalizable quartic $|H|^2|S|^2$.
- × Same problem for vectors that get mass from $\langle S \rangle$.
- × Abelian vectors can mix with hypercharge, $F^Y_{\mu\nu}F^{\rm dark}_{\mu\nu}$.
- × Singlet fermions N can have renormalizable Yukawa LNH. Forbid with $\mathbb{Z}_2$?

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- A non-abelian group G with no scalars (and no fermions, for simplicity)

$$\mathscr{L}_{\rm DM} = -\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu a} + \theta_{\rm DM}\frac{g^2_{\rm DM}}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{\mu\nu a}$$

confines at Λ and has no renormalizable coupling to SM:

$$S = \int d^4x \sqrt{|\det g|}\left[-\frac{1}{2}\bar{M}^2_{\rm Pl}R + \mathscr{L}_{\rm SM} + \mathscr{L}_{\rm DM} + \mathscr{L}_{\rm NRO}\right]$$

Simple, so predictive. DM can be dark glue-balls, if long lived enough.

Glue-balls and accidental symmetries

The lightest glue-ball is Tr $\mathcal{G}^2$ with $J^{PC} = 0^{++}$ and $M \sim \Lambda$.
It decays gravitationally $\Gamma \sim M^5/M_{\rm Pl}^4$, so $\tau > 10^{26}\,$sec needs $M \lesssim 100\,$TeV.

Other glue-balls with similar mass are co-stable.

Some glue-balls are special, protected by accidental symmetries of $\mathscr{L}_{\rm DM}$:

- $G = {\rm SU}(N)$ has charge conjugation, a **C-odd glue-ball** exists

$$\mathcal{O}_{\rm C-odd} = {\rm Tr}\; \mathcal{G}_{\mu\mu'}\{\mathcal{G}_{\nu\nu'}, \mathcal{G}_{\rho\rho'}\} \propto d^{abc} G^a_{\mu\mu'} G^b_{\nu\nu'} G^c_{\rho\rho'}$$

  Stable without NRO. Otherwise $\Gamma_{\rm C-odd} \sim \Lambda^9/M_{\rm Pl}^8$, stable enough if $\Lambda \lesssim 10^{11}\,$GeV (mostly excluded by decays of less stable C-even).

- $G = {\rm SO}(N)$ has group parity $\mathbb{Z}_2 = {\rm O}(N)/{\rm SO}(N)$ (non-trivial, e.g. reflection of the 1st component of the anti-symmetric vector matrix $\mathcal{G}_{ij} = G^a T^a_{ij}$).
  A **P-odd glue ball** exists for even N and is stable without NRO

$$\mathcal{O}_{\rm P-odd} = {\rm Pf}\,\mathcal{G} \sim \epsilon_{i_1\cdots i_N} \mathcal{G}_{i_1 i_2} \cdots \mathcal{G}_{i_{N-1} i_N}$$

  Otherwise $\Gamma_{\rm P-odd} \sim \Lambda(\Lambda/M_{\rm Pl})^{2N-4}$: very stable for large N e.g. SO(10).

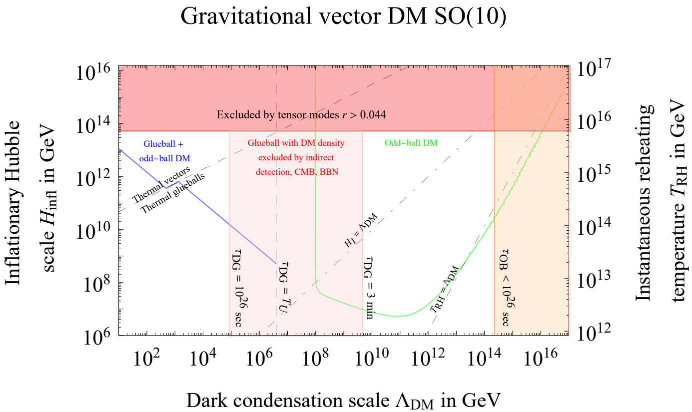
- Similar P-odd state exists for $G = F_4 \subset {\rm SO}(26)$ and E_8 like SO(248)?

Freeze-in abundance

Gravitational decays and scatterings are precisely computable if $\mathscr{L}_{\rm NRO} = 0$. Planck-suppressed NRO compatible with symmetries of other interactions are unavoidably generated (RG) and correct gravitational processes by order-one factors.

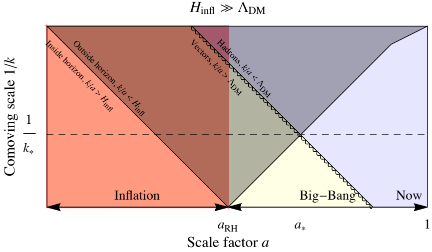
SM SM $\to \mathcal{G}\mathcal{G}$ that hadronize give $N_{\rm DG}(E) \sim \exp\left(\sqrt{\frac{48}{11}\ln\frac{E}{\Lambda}}\right)$ glue-balls.

Odd-ball fraction: $\sim 0.76^N$ from naive combinatorial MC.
Condensation. Decay of short-lived glue-balls and reheating, details, details...



Minimal inflationary abundance: negligible

FRW is conformally flat. Classical massless vectors are conformal. Quantum running of $g_{\rm DM}$ and finally Λ break conformality. Try expanding in comoving modes that transition from vector to bound states:



$$S_{\rm eff} = \int d^4x\,\sqrt{-\det g}\left\{\begin{array}{ll} -\hat{G}^{a\mu\nu}\hat{G}_{a\mu\nu}/4g^2_{\rm DM} & \text{at } k/a \gtrsim \Lambda \\ \sum_X [(\partial X)^2 - (m_X^2 + \xi_X R)X^2]/2 & \text{at } k/a \lesssim \Lambda \end{array}\right.$$

Bound states X (ξ?)

$$\ddot{X}_k + \omega_k^2 X_k = 0, \qquad \omega_k^2 = \frac{k^2}{a^2} + H^2_{\rm infl}\mu^2, \qquad \mu^2 \equiv -\frac{1}{4} + \frac{m^2}{H^2_{\rm infl}} + 12\left(\xi - \frac{1}{6}\right).$$

Vectors:

$$\ddot{G}_k + \omega_k^2 G_k = 0, \qquad \mu^2 \equiv -\frac{1}{4} + \frac{\epsilon}{2} \qquad \epsilon \equiv \frac{d\ln g^2_{\rm DM}}{d\ln a} = \frac{11C_G}{3}\frac{g^2_{\rm DM}}{8\pi^2} > 0.$$

Final result: $T \sim H_{\rm infl}$, negligible abundance.

Signals?

DM is less testable if heavy and weakly coupled.
Worst of the worst: heavy and gravitationally coupled.

Still:

1. Sub-leading inflationary production can give iso-curvature inhomogeneities.
2. Slow gravitational decays of heavy DM give showers containing all SM particles and gravitons.
3. Dyson: are gravitons not observable *in principle*? Decays can produce energetic gravitons detectable with planet-size detectors, $\sigma \sim e^2/M_{\rm Pl}^2$.
4. $\sigma(\text{odd-ball} + \text{odd-ball} \to \text{glue-ball} + \text{glue-ball}) \sim 1/\Lambda^2$.
   Glue-balls quickly decay gravitationally. Flux small because DM is heavy: $\Phi \sim R_\odot(\rho_\odot/\Lambda)^2\sigma \sim (10^{10}\,\text{GeV}/\Lambda)^4 10^{-18}/\text{km}^2\,\text{yr}$.