Alternative Models of Dark Matter

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Stellar Halos Across the Cosmos
Heidelberg, July 4th 2018
Why alternative models?
(astro/cosmo vs. particle physics views)

Generic constraints

Selected examples
(SIDM, ULA, PBHs, etc.)
Alternative to what?

To Cold DM: DM that collapses on subgalactic scales and makes cusps in Dwarf Galaxies

→ Highly non-relativistic at matter-radiation equality
Why alternative models? (astro/cosmo)

Small-Scale Challenges to the ΛCDM Paradigm

arXiv:1707.04256

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Core/cusp+diversity problems or regularity vs. diversity problems. Maybe baryonic effects, but clear statistical answer needed. Does same feedback recipe solve all problems at once?
LIGO+VIRGO '16

Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess

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arXiv:1603.00464 (PRL)
Why alternative models? (particle physics)

Two main approaches

* Top-down
  “DM is a consequence”

* Bottom-up
  “DM is a requirement”
Why alternative models? (particle physics)

Two main approaches

* Top-down
  “DM is a consequence”

* Motivated by “defects” in SM
  - Asymmetry matter-antimatter not achieved
  - Strong CP pb
  - Stability of the Higgs sector (hierarchy pb)
  - Metastability of EW vacuum
  - Flavor hierarchy
  - Gauge unification
  - Quantum gravity (strings)
  - etc.

+++ may solve several issues + DM candidates
- - - DM “solution” potentially embedded in large parameter space (tricky phenomenology)

* Bottom-up
  “DM is a requirement”

* Consistent QFT
  +++ DM phenomenology with a minimal set of parameters => predictive
  - - - built on purpose (ad hoc)
Two main approaches

**Top-down**
“DM is a consequence”

* Might be cured by adding canceling terms
  * e.g. **Supersymmetry** => bosons ↔ fermions cancel in loops
* want to **forbid new interactions, like:**
  → discrete symmetry (parity, Z2, etc.)
  => proton does not decay
  => lightest particle stable

DM: neutralino, sneutrino, gravitino, etc.

**Bottom-up**
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The **hierarchy pb** (Higgs stability), aka the theoretical particle physicist crisis

\[ \delta m_H^2 = \frac{\Lambda^2}{32\pi^2} \left[ 6\lambda + \frac{1}{4} (9g^2 + 3g'^2) - y_i^2 \right] \]

(e.g. Csaki & Tanedo '16)

Higgs mass receives quantum corrections
→ very sensitive to any new heavy scale (fine tuning)

++QCD Axion DM, “string-inspired” axions (eg ULA)
+(Sterile) right-handed neutrino DM
+Others (e.g. relaxions …)
Two main approaches

* **Top-down**
  “DM is a consequence”

* **Bottom-up**
  “DM is a requirement”

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The hierarchy pb (Higgs stability), aka the theoretical particle physicist crisis

\[ \delta m^2_{4l} = \frac{\Lambda^2}{32\pi^2} \left[ 6\lambda + \frac{1}{4} \left( 9g^2 + 3g'^2 \right) - \gamma_i^2 \right] \]

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=> CDM, WDM, SIDM, Wh(atever)DM
**Top-down approaches**

→ Solutions to Higgs “hierarchy” problem strongly challenged by LHC: Supersymmetry (SUSY), extra-dimensions, composite models (to a less extent) => either accept fine-tuning or find other ways.

!!!! Does not mean SUSY is dead (could still be realized in Nature at the price of fine-tuning)!!!!

→ **WIMPs a generic prediction** (weak-scale physics, e.g. neutralinos) !!!! WIMPs are not excluded: still strongly motivated candidates from simplicity in production mechanism.

=> **Dark matter to the rescue**: initially a by-product → now a goal/justification for particle model building.

=> **Bottom-up approaches** (banished before LHC) a new playground for particle physicists: WIMPs, SIDM, WISPs (ALPs/ULA/etc).

NB: still top-bottom candidates: WIMPs, QCD axions, sterile neutrinos, primordial black holes

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**Why alternative models? (particle physics)**

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**Prospects for SUSY WIMP direct searches**

**Prospects for SUSY WIMP gamma-ray searches**
Generic constraints on DM particles

→ Constraints assuming a single DM species:

* Massive

* **Cold or close to cold** (or cold-warm):
  
  CMB peaks + Ly-alpha + structure formation + dwarf galaxy phase space

  => For **DM produced thermally** in the early universe: \( m > 1-5 \text{ keV} \) (bosons or fermions)
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* Fermions: the Tremaine-Gunn limit ('78) => use dwarf galaxies as test systems!

Liouville's theorem for non-interacting fermions, assuming they were close to FD distribution in early universe

\[
f_\nu(p, T) = \frac{g_\nu}{(2\pi)^3} \frac{1}{e^{E/T} + 1} \geq \frac{\rho(r)}{m_\nu} \times \left\{ f(p) = \frac{e^{-\frac{p^2}{2 m_\nu^2 \sigma_v^2}}}{(2\pi m_\nu^2 \sigma_v^2)^{3/2}} \right\}
\]

\[
\rho(r) = \frac{9 \sigma_v^2}{4 \pi G (r + r_0)^2}
\]
Cored-isothermal sphere

\[
m_\nu \gtrsim \left\{ \frac{9 \sqrt{2\pi} M_P^2}{g_\nu \sigma_v r_0^2} \right\}^{1/4} = 0.1 \text{ keV} \left\{ \frac{r_0}{1 \text{ kpc}} \right\}^{-1/2} \left\{ \frac{\sigma_v}{30 \text{ km/s}} \right\}^{-1/4}
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Pauli exclusion principle (no assumption on initial phase space): cannot exceed density of degenerate Fermi gas!

\[
E_F = \left( \frac{\hbar^2}{2m} \right) \left( 3 \pi^2 n \right)^{2/3} \quad \Rightarrow \quad v_{F,\nu} \equiv \sqrt{\frac{2E_F,\nu}{m_\nu}} = \left( 3 \pi^2 \frac{\rho}{m_\nu^4} \right)^{1/3} \leq v_{\text{esc}}
\]

\[
m_\nu > \left\{ 3 \pi^2 \frac{\rho}{v_{\text{esc}}^3} \right\}^{1/4} \approx 0.1 \text{ keV} \left\{ \frac{r_0}{1 \text{ kpc}} \right\}^{-1/2} \left\{ \frac{\sigma_v}{30 \text{ km/s}} \right\}^{-1/4}
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  → Updated by Boyarsky+09: \( m > 0.5 \text{ keV} \)
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  * Bosons: de Broglie wavelength > size of system => $m > 10^{-22}$ eV

  → see review in e.g. Marsh '15 (axion-like particles)
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Lower mass bounds only!
(except for unitarity constraints – thermal case)
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* Interactions?
  → Electrically neutral (or charge << 1: milli-charged – except in secluded dark sector)
  → If thermally produced => (weak) couplings to SM particles
  → No prejudice on asymmetry dark matter/antimatter
  → Self-interactions and/or annihilations allowed
    => self-interaction cross section bounded
  → Possibility of entire dark sector(s)

  \[ 2 \text{ cm}^2/\text{g} \simeq 4 \text{ b/GeV} \leq \frac{\sigma_{\text{self}}}{m_\chi} \leq 0.4 \text{ b/GeV} \]

Original proposal by Carlson+'92
Cure small-scale crisis
(e.g. Spergel+'00, Calabrese+'16)
Dynamics of clusters
(Kaplinghat+'15)
Self-interacting Dark Matter (SIDM)

Combine constraints on small/large scales
=> velocity-dependent cross section
Self-interacting Dark Matter (SIDM)

Creasey+’17
→ diversity of v-curves reproduced

Cluster A2537

IC2574
Production of SIDM in the Early Universe

Master equation: Boltzmann equation (e.g. Lee & Weinberg '77, Bernstein+ '85-88)

\[
\frac{d f(x^\mu, p^\mu)}{d\lambda} = \hat{C}[f]
\]

\[
\frac{dY_\chi}{dx} \propto g_\chi^{1/2}(x) x^2 \langle \sigma v \rangle \left\{ \frac{Y_\chi^2}{Y_{\chi, eq}} - Y_\chi^2 \right\}
\]

Could be very similar to WIMPs or FIMPs

- Thermal production
- Very light mediator to get correct \( \nu \)-dependence
- or strong cannibalizing 3\( \rightarrow \)2

SIDM configs (how to get large \( \sigma/m \)?)

- Light DM (eg Heikinheimo+16, Chu+16)
- Strong dark sector (eg Kaplan+10, Hochberg+14, Kamada+16)
- Light mediators (eg Feng+09, Buckley+09, Bringmann+15)

Freeze-in mechanism:

- Dodelson & Widrow '94
- McDonald '02
- Hall+ 10

Hall+ 10

Could be very similar to WIMPs or FIMPs

- Thermal production
- Very light mediator to get correct \( \nu \)-dependence
- or strong cannibalizing 3\( \rightarrow \)2

\( \Omega_\chi \propto Y_\chi(x_0) \)

\( \Omega_{\text{WIMP}} \approx \frac{1}{g_*^{1/2}(x_{\text{dec}}) \langle \sigma v \rangle} \)

\( \Omega_{\text{FIMP}} \approx g_*^{1/2}(x_{\text{dec}}) \langle \sigma v \rangle \)

\( \langle \sigma v \rangle_{\text{FIMP}} \ll \langle \sigma v \rangle_{\text{WIMP}} \)
Production of SIDM in the Early Universe

Master equation: Boltzmann equation (e.g. Lee & Weinberg '77, Bernstein+'85-88)

\[ \frac{df(x^\mu, p^\mu)}{d\lambda} = \hat{C}[f] \]

\[ \frac{dY_\chi}{dx} \propto \frac{g^{1/2}_*(x)}{x^2} \langle \sigma v \rangle \left\{ \frac{Y^2_{\chi,eq}}{m_\chi} - Y^2_\chi \right\} \]

\[ \Omega_\chi \propto Y_\chi(x_0) \]

SIDM configs (how to get large \( \sigma/m \)?):
* Light DM (eg Heikinheimo+16, Chu+16)
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Could be very similar to WIMPs or FIMPs

\[ \Rightarrow \text{Thermal production} \]

+ very light mediator to get correct \( v \)-dependence
  / or strong cannibalizing \( 3 \rightarrow 2 \)

\[ \Rightarrow \text{Both DM and mediator constrained} \]

Freeze-in mechanism:
Dodelson & Widrow '94
McDonald '02
Hall+ 10

\[ \Omega_{\text{WIMP}} \sim \frac{1}{g^{1/2}_*(x_{\text{dec}}) \langle \sigma v \rangle} \]

\[ \Omega_{\text{FIMP}} \sim g^{1/2}_*(x_{\text{dec}}) \langle \sigma v \rangle \]

\[ \langle \sigma_{\chi\chi} v \rangle_{\text{FIMP}} \ll \langle \sigma_{\chi\chi} v \rangle_{\text{WIMP}} \]

Production line:
- DM self-interactions
- DM annihilation

\[ Y \]

\[ \Gamma_\chi = \langle \sigma v \rangle n_\chi > H \]

Heikinheimo+17

\[ \Omega_x \propto Y_x = \frac{m_x}{m_\chi} Y_\chi \]

Hall+ 10

\[ x_{\text{dec}} \approx 20, \quad x = m/T \]
**SIDM: potential signatures**

Same as WIMPs! + Mediator searches

Particle searches (e.g. Tulin+18):
Indirect searches + direct searches + collider searches

**SIDM structure formation summary:**
- induces *cores* in LSS down to dwarf galaxy scale
- *subhalos* still present! (but could be heated in their host – e.g. Kummer+18)
... unless significant interactions with dark radiation induce collisional damping (e.g. Boehm+02).
(QCD) axions

Peccei-Quinn, Wilczek, Weinberg, Kim, Shifman, Vainshtein, Zakharov, Dine, Fishler, Srednicki, Sikivie – 70'-80'

\[ V(\phi) \]

\[ V(\phi) \]

\[ V(\phi) \]

Pecccei-Quinn (PQ) symmetry unbroken
Very high T

PQ symmetry broken
\@ T ~ f_a \sim 10^{10} \text{ GeV}

The axion picks up a mass
T~T_{QCD} \sim 150 \text{ MeV}

\[ \mathcal{L}_{\theta_{QCD}} = \frac{\theta_{QCD}}{32\pi^2} \text{Tr} \, G_{\mu\nu} \tilde{G}^{\mu\nu} \]

NB: QCD axion needs physics beyond standard model
Production mechanism (relevant to DM axions):
* Misalignment mechanism (generic)
* Decay of topological defects (if PQ broken after inflation)
→ compact axion asteroids! (f~0.5) – Tkachev’86
* \( m \ll eV \Rightarrow \text{large occupation \#} \Rightarrow \text{classical field} \)
* QCD axions = CDM \Rightarrow \text{searches through EM couplings!} 

\[ \Omega_\alpha h^2 \sim 2 \times 10^4 \left( \frac{f_\alpha}{10^{16} \text{ GeV}} \right)^{7/6} \langle \theta_{\alpha,i}^2 \rangle \]

\[ m_a^2 = \frac{m_\pi^2 f_\pi^2 m_u m_d}{(f_a/N_{DW})^2 (m_u + m_d)^2} \]

Axion cosmology
(review)
Marsh’15
Non-QCD ultra-light axions (ULA = fuzzy DM)

Hu+00, Peebles’00, Marsh+15, Hui+16, Schive+14, Du+18, etc.

Same production mechanisms as axions but not meant to solve the strong CP (QCD) pb
\Rightarrow PQ breaking + axion mass free parameters (cosmological constraints) \Rightarrow EM couplings optional

Main properties:
* Suppression of small-scale perturbations
* incoherent interference pattern and granularity on scales ~ 1-100 kpc
* formation of solitonic cores at halo centers
* core/cusp solved in galaxies if m\sim 10^{-22} eV

\begin{align*}
    i\hbar \left( \frac{\psi}{2} H \psi \right) &= \left( -\frac{\hbar^2}{2mR^2} \nabla^2 + m\Phi \right) \psi \\
    \nabla^2 \Phi &= 4\pi G m_a |\psi|^2
\end{align*}

Bozek+15
Halo mass function

Schive+14
Solitonic cores in Fuzzy DM simulations

Veltmaat+18
Evolution of solitonic cores
**ULA probes**

Tidal disruption of subhalo solitonic cores

**Other effects:**
- Sizable oscillations of the core density (Veltmaat+18)
- $\rho_c = f(r_c)$ (Deng+18)
- Abundance of ultra-faint lenses HFF@z=6 (Menci+17)
- Probe incoherent zone (talk by N. Amorisco)
- Ly-alpha => A catch-22 scenario? (like Maccio+12 for WDM)
- 21cm? (See Schneider’18)
Primordial black holes

**Generic idea (Zel’dovich&Novikov, Hawking, Carr&Hawking’70’s):**
- Very large density fluctuations may collapse directly into Bhs in the radiation era
- $M_{\text{pbh}} \sim$ mass within horizon
- Fluctuation amplitude $\sim 10^{-5}$ at CMB scales
- $\sim 0.01$ needed $\Rightarrow$ more power (e.g. non gaussianity) needed on very small scales
- Production enhanced at phase transitions (e.g. QCD $\leftrightarrow$ Mh~1 Msun)
- A potentially macroscopic CDM candidate

**Review in Carr+16**

\[ \frac{\delta}{\delta_c} \geq w = \frac{p}{\rho} = \frac{1}{3} \]

\[ M_H \sim 10^{15} \text{ g} \left( \frac{t}{10^{-23} \text{s}} \right) \]

\[ \beta(M) \sim \int_{\delta_c}^{\infty} P(\delta(M_H)) \, d\delta(M_H) \]

Gaussian spectrum

\[ \beta(M) = \text{erfc} \left( \frac{\delta_c}{\sqrt{2} \sigma(M_H)} \right) \]

\[ \sigma(M_H) \sim 10^{-5} \]

CMB scale

\[ \sim 10^5 \exp \left[ -\left(10^5 \right)^2 \right] \]

Mass fraction in PBHs strongly suppressed in standard inflation.
$\Rightarrow$ Fine-tuned inflation models

\[ \text{Courtesy Anne Green} \]
**Primordial black holes**

* Most (past) constraints based on assuming peak mass function
* Huge effort to reconsider them (e.g. Green+, Kamionkowski+, Carr+, Garcia-Bellido+)
* Typically two windows: below and above microlensing constraints.
* If mass function extended enough, PBHs could be ~100% of DM

→ if 1-100 Msun, might solve core/cusp
→ GW with < 1 Msun a specific signature

\[ M = k M_H (\delta - \delta_c) \gamma \]

Byrnes+18 – impact of QCD PT
Extended mass function (logN)
(also Choptuik; Niemeyer & Jedamzik; Musco+)

Caveat:
potentially strong constraints from lensing of SNe Ia for \( M_{pbh} > 1 M_{\odot} \)
→ see Zumalacarregui & Seljak ‘17 (PBHs < 0.4 CDM)
Summary

* CDM have several motivated particle candidates, e.g.: WIMPs, QCD axions
  → Clarify whether baryonic physics could solve observational issues with “realistic” implementation.

* Several motivations to explore beyond vanilla CDM:
  - small-scale issues
  - absence of new physics at LHC: challenges previous theoretical guiding principles
  - WIMPs not detected so far (but not excluded – observational window closed in ~10 yrs)
  - Gravitational waves as a new window on the universe

* Dark matter: a new playground to test ideas in particle physics/cosmology
  → Production mechanisms vs. observational features

* Some scenarios provide new features on small scales, e.g.:
  - SIDM (could be detected as particles)
  - Ultra-light bosons (e.g. axion-like): solitonic cores (also superfluidity features – see Khoury+)
  → Important to exclude / confirm existence of DM subhalos + probe small scales (streams, Ly-alpha, 21 cm).

* Modified gravity as new degrees of freedom (scalar/vector fields) still a possibility (provided CMB and structure formation OK – no compelling model so far).

* What if only gravitational (non-GW) signatures?
Backup
Non-QCD Ultra-light axions (ULA) 
(+ axion-like particles + dark/hidden photons = WISPs)

(Very) weakly interacting slim particles
→ solves the strong CP problem (BSM physics required)
→ CDM candidate (not necessarily all DM!)
→ µeV-meV mass range

Aspects relevant to cosmology:
* non-thermal remnants => expected ultra-cold DM
→ minimal mass scale \( \sim 10^{-12} \) Msun subhalos
→ detailed structure formation under study

Detection (main):
* from interactions with photons: conversion
→ e.g. ADMX (ongoing): conversion of DM axions into photons

Extra:
* Axion-like particles (ALPs), arising in string-inspired theories => relaxed axion mass range
* Hidden photons: kinetic mixing with photons from broken U(1) in some BSM extensions
Constraints on ultra-light bosonic DM

See also:
Irsic+’17 m22>20 (Ly-alpha)
Calabrese+’16: m22<5 (from dwarf spheroidals)
Menci+’17: m22>8 (from abundance of ultra-faint lensed galaxies @ z=6 in the HFF)

→ Scenario under strong pressure

$m_a > 2.0 \times 10^{-21} \text{ eV}$
Axion searches

TeV blazar gamma-ray conversion to axions
e.g. HESS-CTA

“Light shining through a wall”
(laser + B-field + wall)
e.g. ALPS@DESY

Not sensitive to DM

Sensitive to DM axions
(irrespective of local DM density)

Needs that local DM density is made of axions

Helioscopes
CAST + IAXO @ CERN
B-field + micromegas

Haloscopes
Microwave cavities / dish antennae
B-field + detector (~GHz)
WIMP searches

Relic abundance and indirect detection (cosmic-rays)

Arrow of time

Any theory you like

WIMP

Anti-SM

anti-WIMP

SM

Direct detection (scattering)

LUX, Xenon-1t, etc.

Searches at colliders
Astro/particle complementarity

Direct detection rate – WIMP-matter scattering

\[
\frac{d\Gamma_{\chi-N}}{dE_r}(E_r, t) = \frac{\sigma_{\chi-N} F^2(E_r)}{2 \mu_r^2 m_\chi} \int_{v>v_{\text{min}}} d^3 \vec{v} f(\vec{v}, t)
\]

Scattering

(→ kinetic decoupling in early universe + subhalo mass cutoff)

WIMP

WIMP

SM

SM

Annihilation vs. scattering

=> constraints from cosmological abundance + minimal scale for DM structures (subhalos)

Annihilation

(→ chemical decoupling in early universe)

WIMP

SM

WIMP

SM

Indirect detection rate (e.g. gamma rays) – WIMP annihilation

\[
\frac{d\phi_{\gamma}^{\text{ann.}}}{dE} = \frac{\delta \langle \sigma v \rangle}{4 \pi} \frac{dN_\gamma}{dE} \int_{\text{res.}} d\Omega \int_{1.0.s} dl \left[ \frac{\rho(r)}{m_\chi} \right]^2
\]

Dark matter profile + phase space (+ cosmic-ray transport)

=> constrained by Milky Way-mass model (full gravitational potential DM + baryons)

\(\Gamma_{\text{scat}} = \langle \sigma_{\text{scat}} v \rangle n_{\text{plasma}}\)
Direct DM searches: recent results

XENON-1t results:
=> the sub-zepto-barn era!

Billard+ 13
**Up to the skies!**

- **Galactic Center**
  - Closest/Largest expected annihilation rate
  - Large theoretical uncertainties (background not controlled)

- **Diffuse gamma-ray emission**
  - Check spectral/spatial properties wrt background

- **Big DM subhalos**
  - Dwarf Spheroidal Galaxies (~40) – no other HE astrophysical processes expected there.

- **Requirements (and/or):**
  - Clean signal (spectral lines or features)
  - Large signal/noise ratio
  - Control astrophysical backgrounds

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**Cosmic-ray transport**

**Pieri, JL+ '11**

**Mertsch PhD thesis '10**
Satellite dwarf galaxies in gamma rays

Individual J-factors+errors:
* Careful Jeans analysis from velocity dispersion measures
* Systematics from mock data

=> Segue I overestimated
=> Fermi limit likely affected

\[
\frac{d\phi_{\gamma}^{\text{ann.}}}{dE} = \frac{\delta \langle \sigma v \rangle}{4 \pi} \frac{dN_\gamma}{dE} \int_{\text{res.}} d\Omega \int_{\text{1.o.s.}} dl \left( \frac{\rho(r)}{m_\chi} \right)^2
\]

Bonnivard+15

Hayashi+ '16
Down to MeV DM with cosmic rays

Voyager 1 has passed the heliopause in 2012!

=> cosmic rays no longer shielded by solar magnetic fields

=> use MeV e+e- data on tape + AMS-02 beyond

=> Constraints on annihilating MeV dark matter as stringent as those obtained with CMB.

Boudaud, JL, Salati – to appear in PRL.
Sterile neutrino (W/C)DM

e.g. Dodelson & Widrow '94, Shi & Fuller '99, Asaka, Shaposhnikov, Boyarsky '06-16

→ Neutrino masses (see-saw)
→ Leptogenesis
→ DM candidates (more or less warm)
→ keV mass range (≠ thermal mass)

Aspects relevant to cosmology:
* suppress power on small scales
  (free-streaming scale larger than CDM)
  → viable? (e.g. Schneider 15)
* current limits on thermal masses > 1.7 keV

Detection (main):
* neutrino experiments (double β decay)
* decays to \textbf{X-ray line: hints @ 3.5 keV} (Bulbul+14, Boyarsky+14)
  → 7 keV consistent with thermal mass of 2 keV (e.g. Abazajian 14)
  → hot debate, could be systematics (cf. Jeltema & Profumo)

Constraints: Resonant-production mechanism almost excluded →
(Modified gravity?)

MOND (Milgrom+’83) works on small scales but fails on large scales + CMB + structure formation => covariant forms challenging

Dark Matter via Massive (bi-)Gravity
Luc Blanchet\textsuperscript{1,*} and Lavinia Heisenberg\textsuperscript{2,3,†}

Dipolar Dark Matter
Luc Blanchet\textsuperscript{a} and Lavinia Heisenberg\textsuperscript{b,c}

\[ \mathcal{L} = \sqrt{-g} \left( \frac{M_p^2}{2} R_g - \rho_{\text{bar}} - \rho_g \right) + \sqrt{-f} \left( \frac{M_{f}^2}{2} R_f - \rho_f \right) + \sqrt{-g_{\text{eff}}} \left[ m^2 M_{\text{eff}}^2 + M_\mu \left( j_\mu \right) \right] + \lambda M_{\text{eff}}^2 \mathcal{W}(\lambda) \]

++ Reproduces LCDM in the linear regime
++ Reproduces MOND at the scale of galaxies

… BUT actually involves DM

Not only based on modified gravity, but also on 2 new types of dark matter … (a generic issue in modified gravity models is the unsustainable need of DM). Origin of matter fields???

=> Modified gravity more popular in the Dark Energy community.

Mass-discrepancy acceleration relation (MDAR)