Alternative Models of Dark Matter

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CNRS
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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

$\rightarrow$ *Highly non-relativistic at matter-radiation equality*

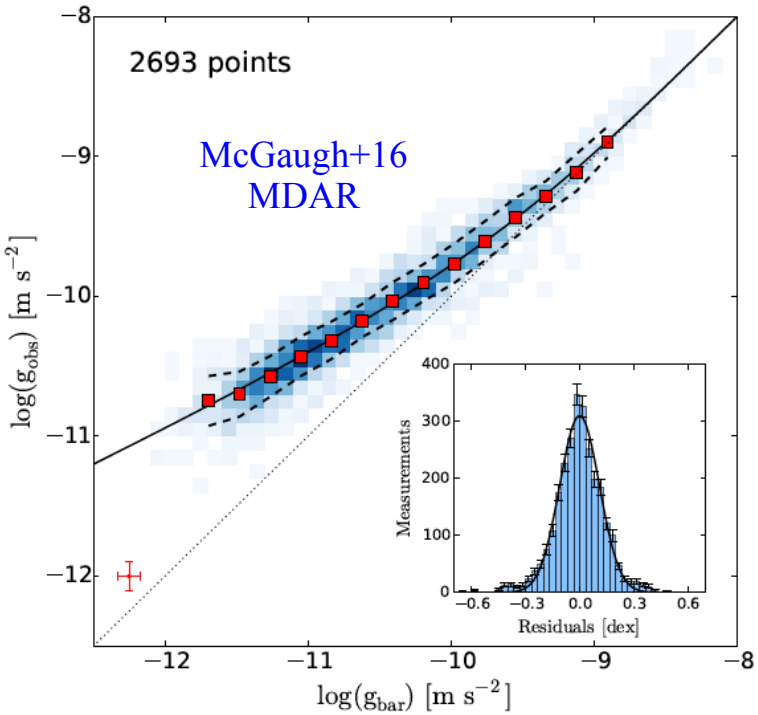
Why alternative models? (astro/cosmo)

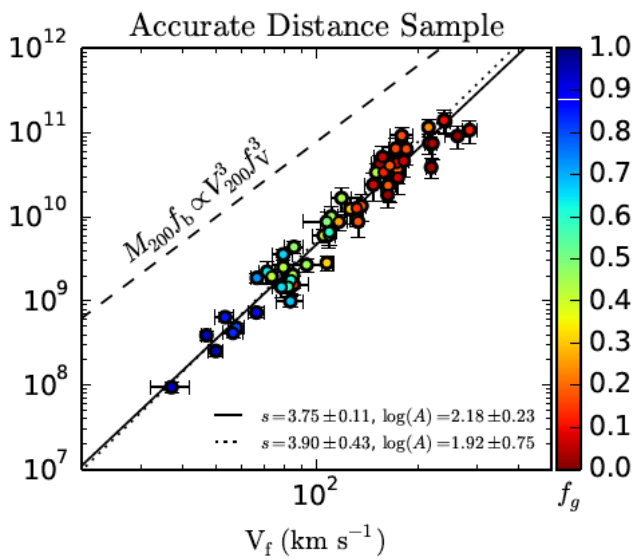
Small-Scale Challenges to the ΛCDM Paradigm

arXiv:1707.04256

James S. Bullock[1] and Michael Boylan-Kolchin[2]

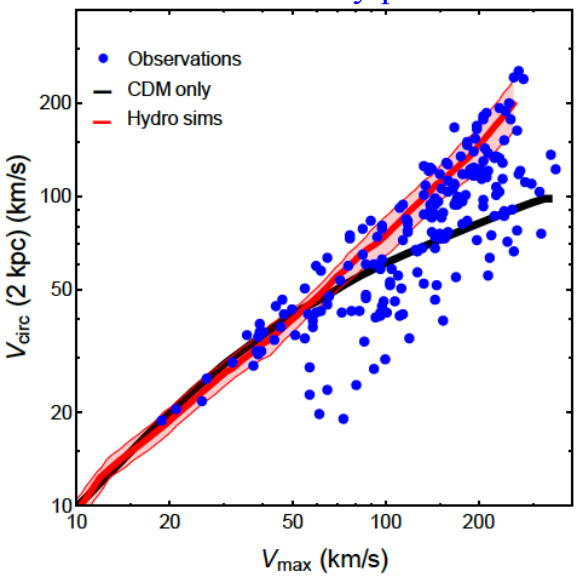
[1]Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA; email: bullock@uci.edu
[2]Department of Astronomy, The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, TX 78712, USA; email: mbk@astro.as.utexas.edu





Lelli+15, BTFR

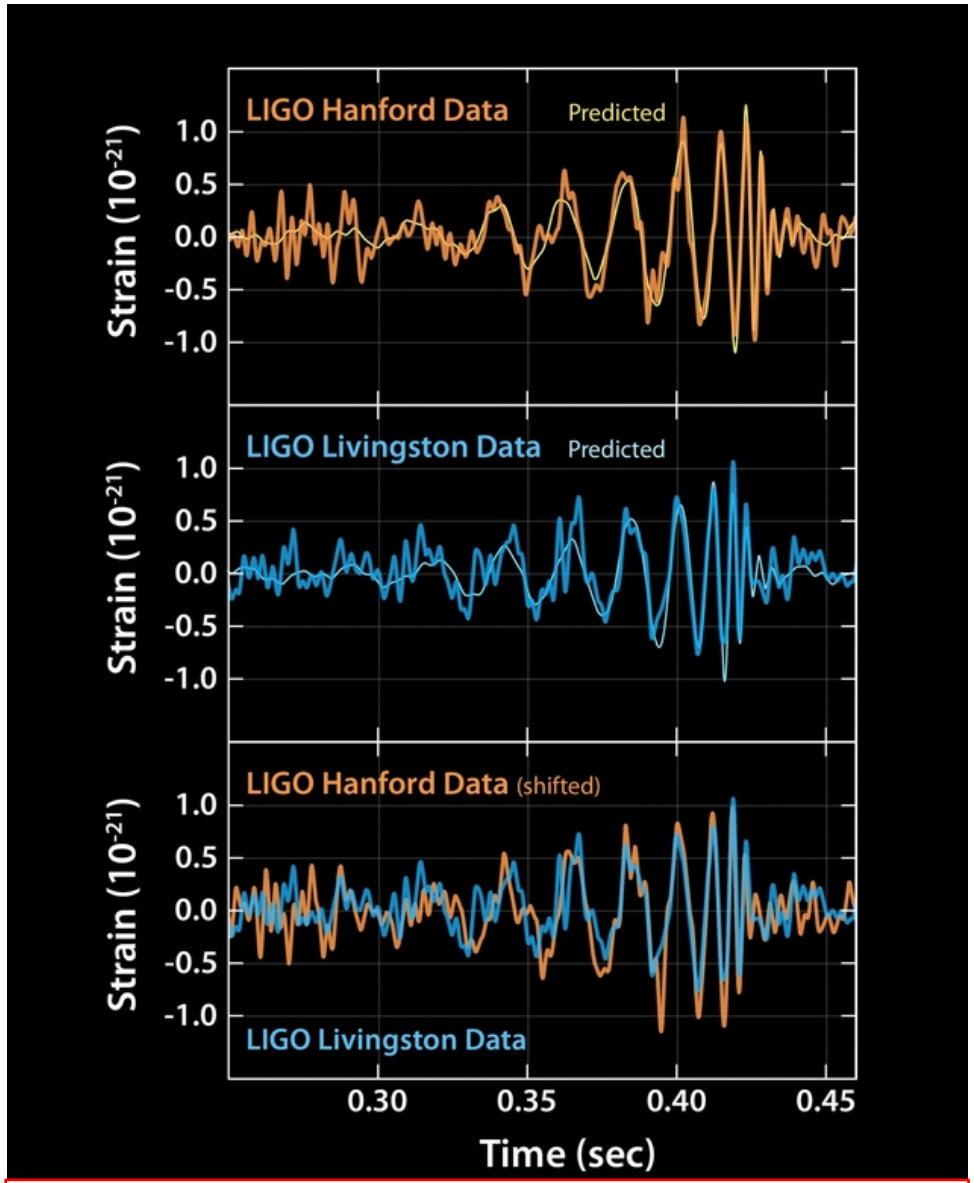
Tulin+18 after Oman+15
Diversity problem



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?

Why alternative models? (astro/cosmo)

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[1]

[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

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)

Why alternative models? (particle physics)

Two main approaches

*** Top-down**
"DM is a consequence"

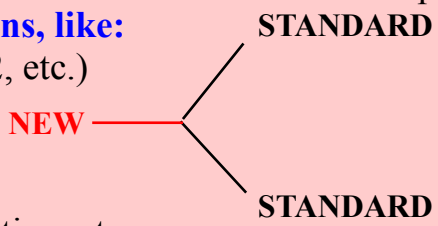
The **hierarchy pb** (Higgs stability),
aka the theoretical particle physicist crisis

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

(e.g. Csaki & Tanedo '16)

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

* 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.

+QCD Axion DM, "string-inspired" axions (eg ULA)
+(Sterile) right-handed neutrino DM
+Others (e.g. relaxions …)

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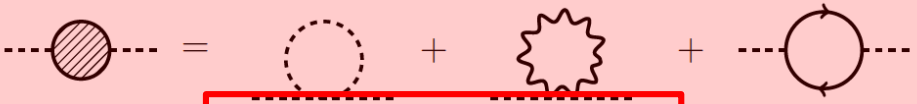

Challenged by LHC

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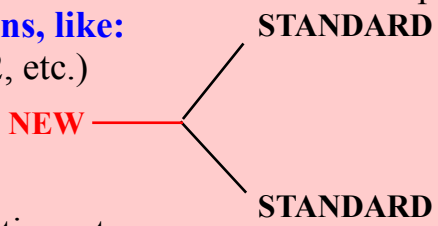

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=> CDM, WDM, SIDM, Wh(atever)DM

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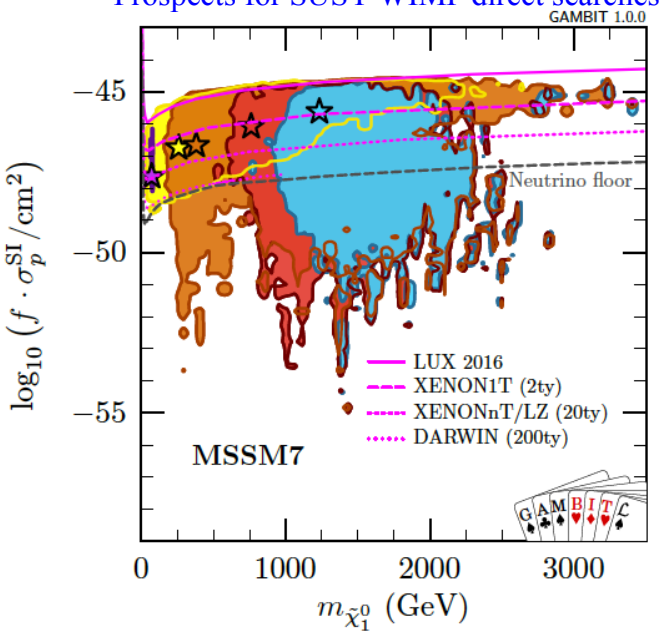
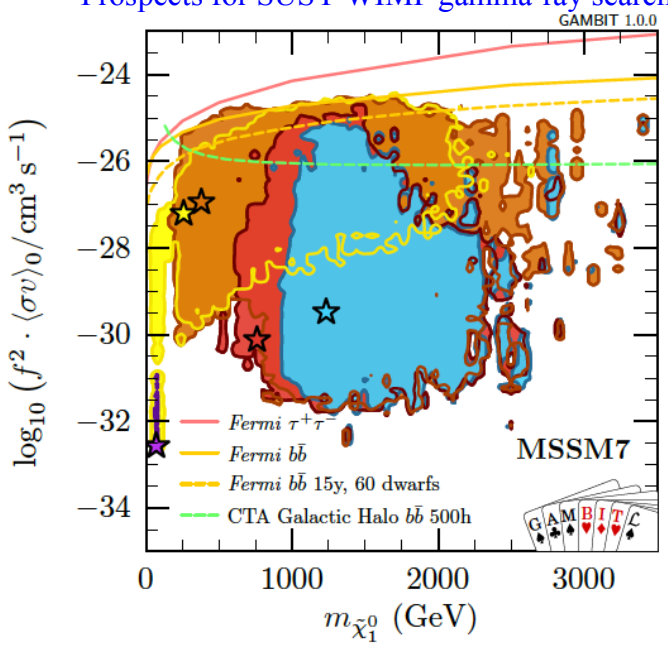
Prospects for SUSY WIMP direct searches



Prospects for SUSY WIMP gamma-ray searches



*** 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

Prospects for SUSY WIMP searches
P. Scott for GAMBIT, arXiv:1711.01973

$\tilde{t}_1$ co-annihilation | A/H funnel | $\tilde{\chi}_1^\pm$ co-annihilation | $\tilde{b}_1$ co-annihilation | h/Z funnel

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 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

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

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

$$m_\nu \gtrsim \left\{ \frac{9\,\sqrt{2\,\pi}\,M_P^2}{g_\nu\,\sigma_v\,r_0^2} \right\}^{1/4} = 0.1\,\mathrm{keV}\,\left\{ \frac{r_0}{1\,\mathrm{kpc}} \right\}^{-1/2} \left\{ \frac{\sigma_v}{30\,\mathrm{km/s}} \right\}^{-1/4}$$

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Pauli exclusion principle (no assumption on initial phase space): cannot exceed density of degenerate Fermi gas!

$$E_F = \left(\frac{\hbar^2}{2\,m}\right)\left(3\,\pi^2\,n\right)^{2/3} \longrightarrow v_{F,\nu} \equiv \sqrt{\frac{2\,E_{F,\nu}}{m_\nu}} = \left(3\,\pi^2\,\frac{\rho}{m_\nu^4}\right)^{1/3} \boxed{\leq v_{\rm esc}}$$

$$\boxed{m_\nu > \left\{3\,\pi^2\,\frac{\rho}{v_{\rm esc}^3}\right\}^{1/4} \approx 0.1\,{\rm keV}\,\left\{\frac{r_0}{1\,{\rm kpc}}\right\}^{-1/2}\left\{\frac{\sigma_v}{30\,{\rm km/s}}\right\}^{-1/4}}$$

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Lower mass bounds only!
(except for unitarity constraints – thermal case)

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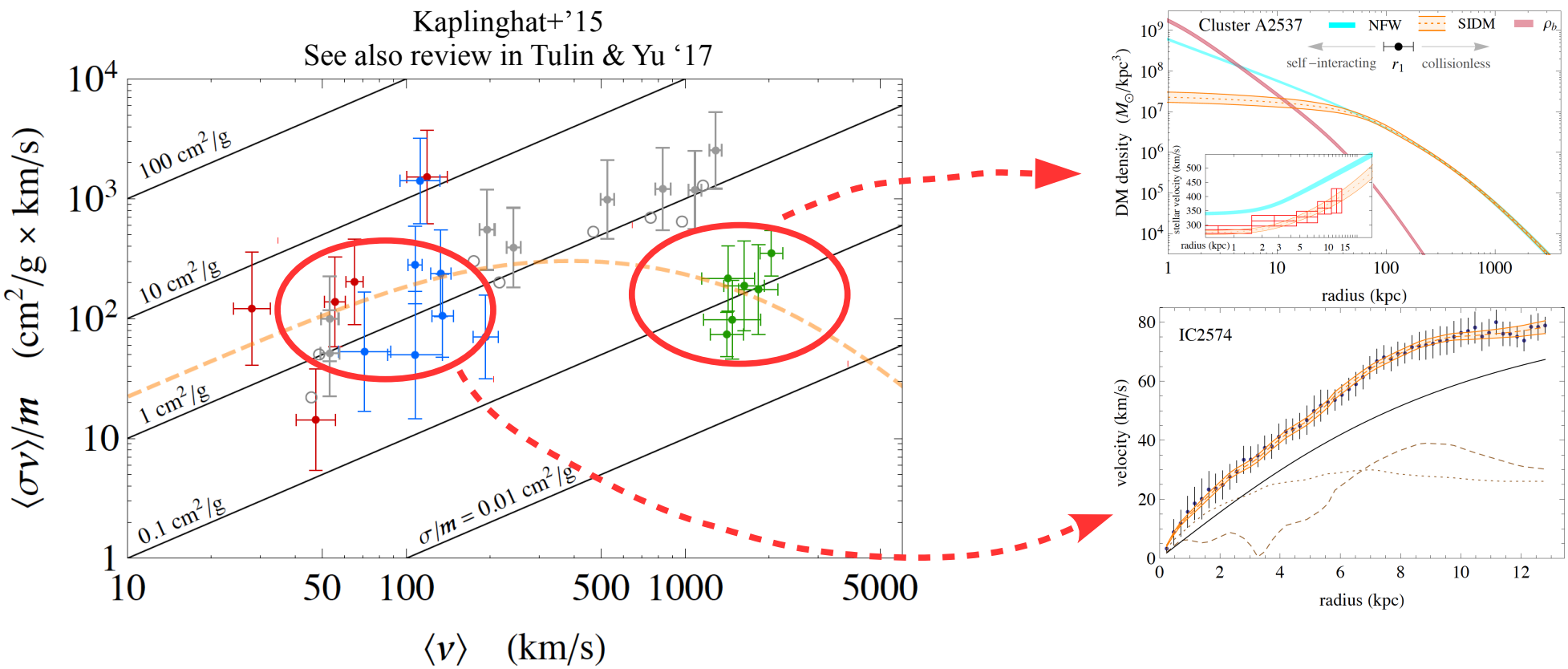
*** Interactions?**
→ Electrically neutral (or charge << 1: milli-charged – except in secluded dark sector)
→ If thermally produced => (weak) couplings to SM particles
→ No prejudice on asymmetry dark matter/antimatter
→ Self-interactions and/or annihilations allowed
=> self-interaction cross section bounded → $2\mathrm{cm}^2/\mathrm{g} \simeq 4\ \mathrm{b/GeV} \lesssim \frac{\sigma_{\mathrm{self}}}{m_\chi} \lesssim 0.4\ \mathrm{b/GeV}$
→ Possibility of entire dark sector(s)

Original proposal by Carlson+'92

Cure small-scale crisis (e.g. Spergel+'00, Calabrese+'16)

Dynamics of clusters (Kaplinghat+'15)

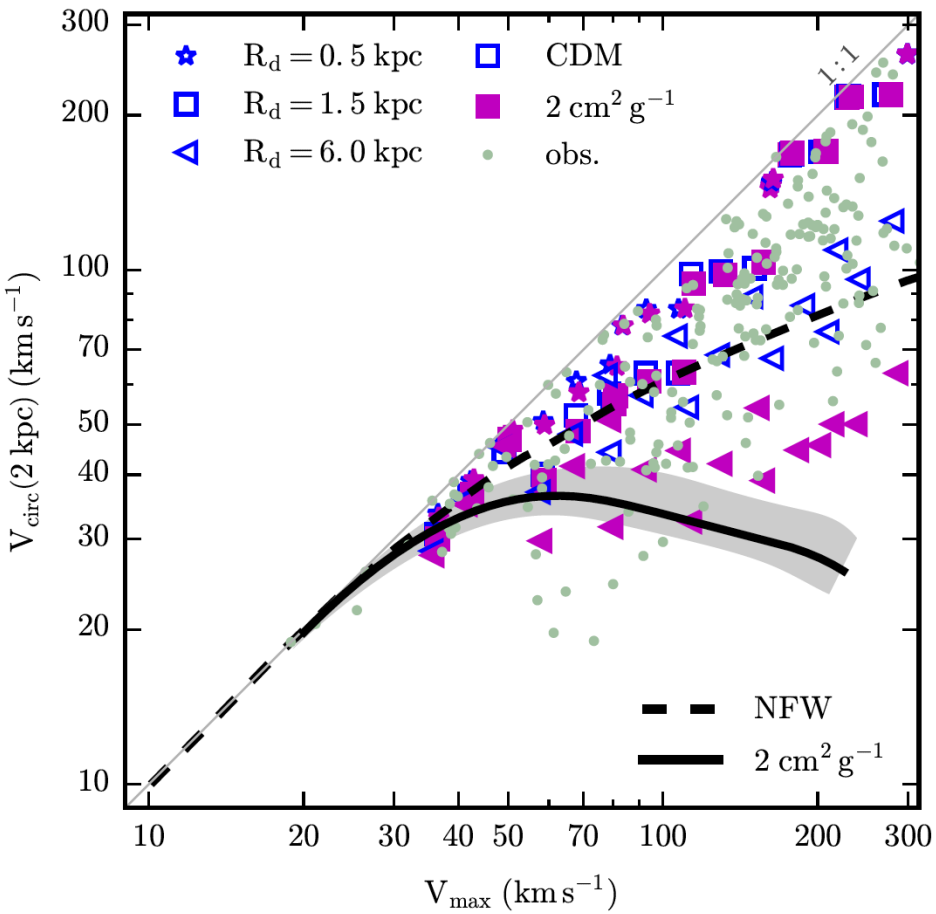
Self-interacting Dark Matter (SIDM)

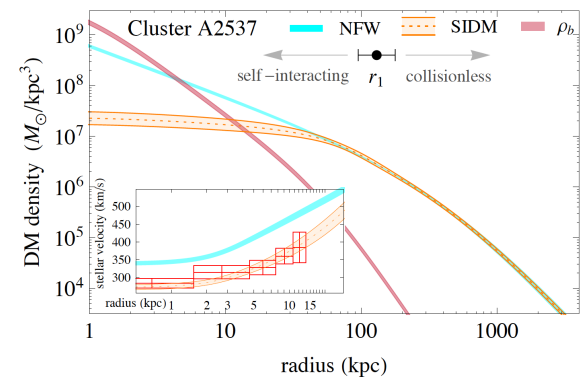


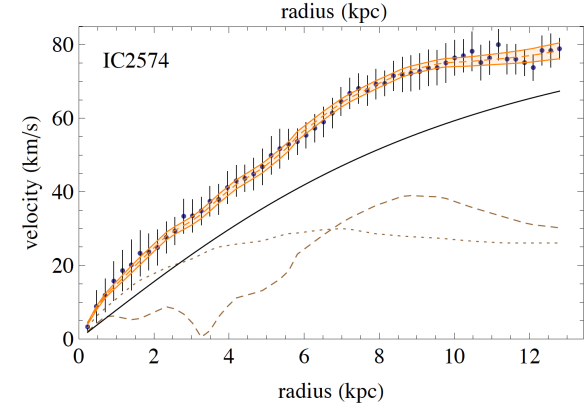
Combine constraints on small/large scales
=> velocity-dependent cross section

Self-interacting Dark Matter (SIDM)

Creasey+'17
→ diversity of v-curves reproduced



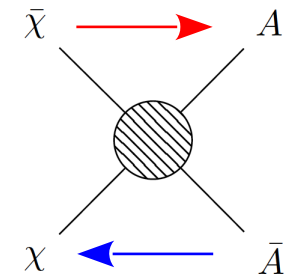


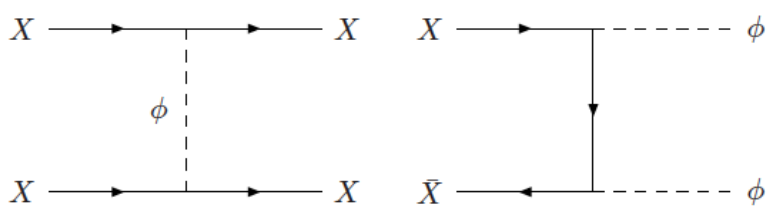


Production of SIDM in the Early Universe

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

$$\frac{d\,f(x^\mu, p^\mu)}{d\lambda} = \widehat{C}[f] \longrightarrow \frac{dY_\chi}{dx} \propto \frac{g_\star^{1/2}(x)}{x^2}\,\langle\sigma v\rangle\,\{Y_{\chi,\mathrm{eq}}^2 - Y_\chi^2\}$$



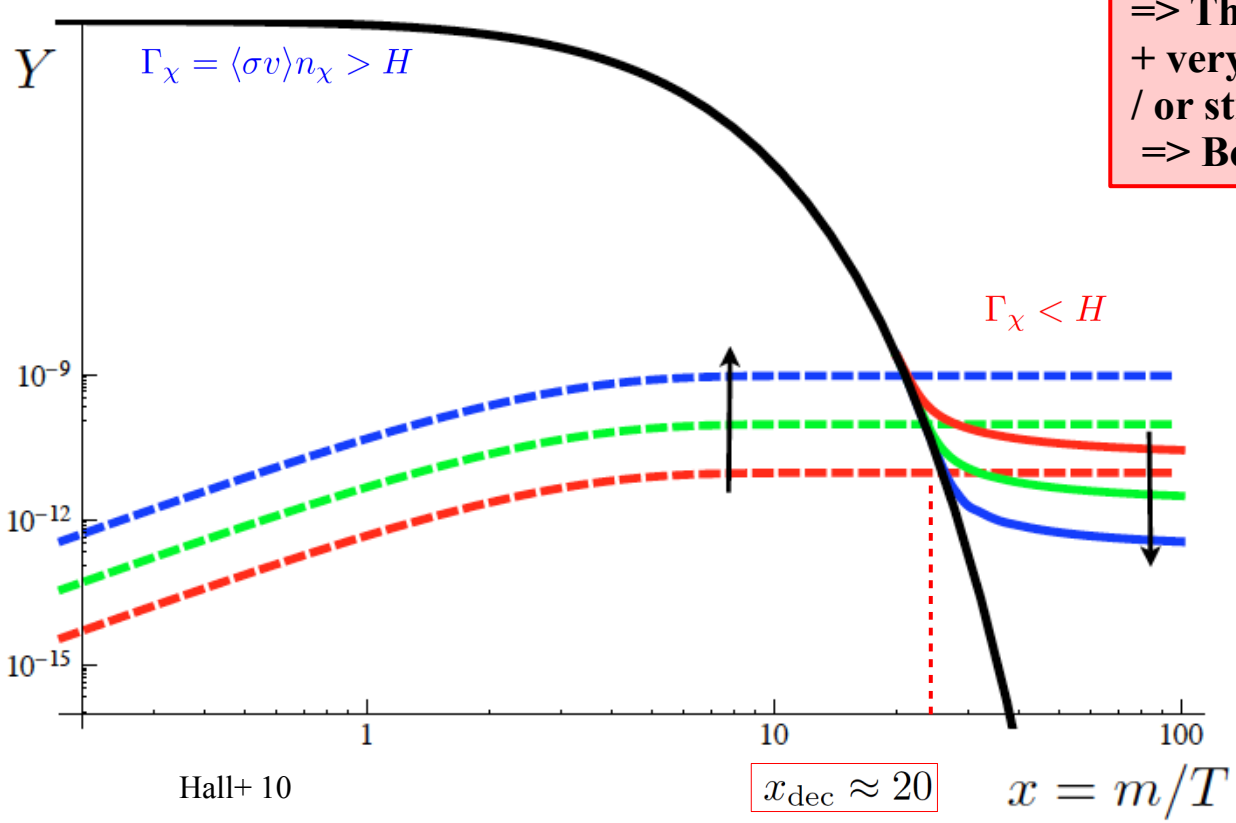


DM self-interactions DM annihilation

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

SIDM configs (how to get large *σ/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)

Could be very similar to WIMPs or FIMPs
=> Thermal production
+ very light mediator to get correct v-dependence
/ or strong cannibalizing 3→2
=> Both DM and mediator constrained



Hall+ 10

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

$$\Omega_{\mathrm{WIMP}} \tilde{\propto} \frac{1}{g_\star^{1/2}(x_{\mathrm{dec}})\,\langle\sigma v\rangle}$$

$$\Omega_{\mathrm{FIMP}} \tilde{\propto} g_\star^{1/2}(x_{\mathrm{dec}})\,\langle\sigma v\rangle$$

$$\langle\sigma_{\chi\bar{\chi}} v\rangle_{\mathrm{FIMP}} \ll \langle\sigma_{\chi\bar{\chi}} v\rangle_{\mathrm{WIMP}}$$

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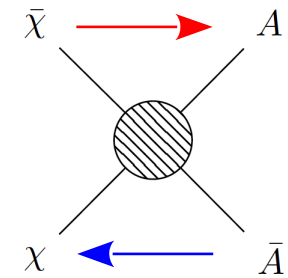

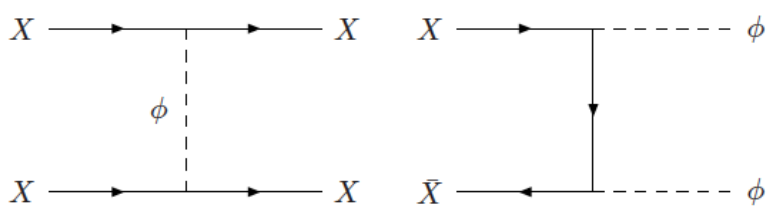

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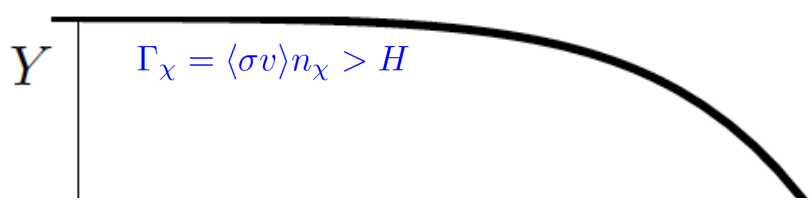

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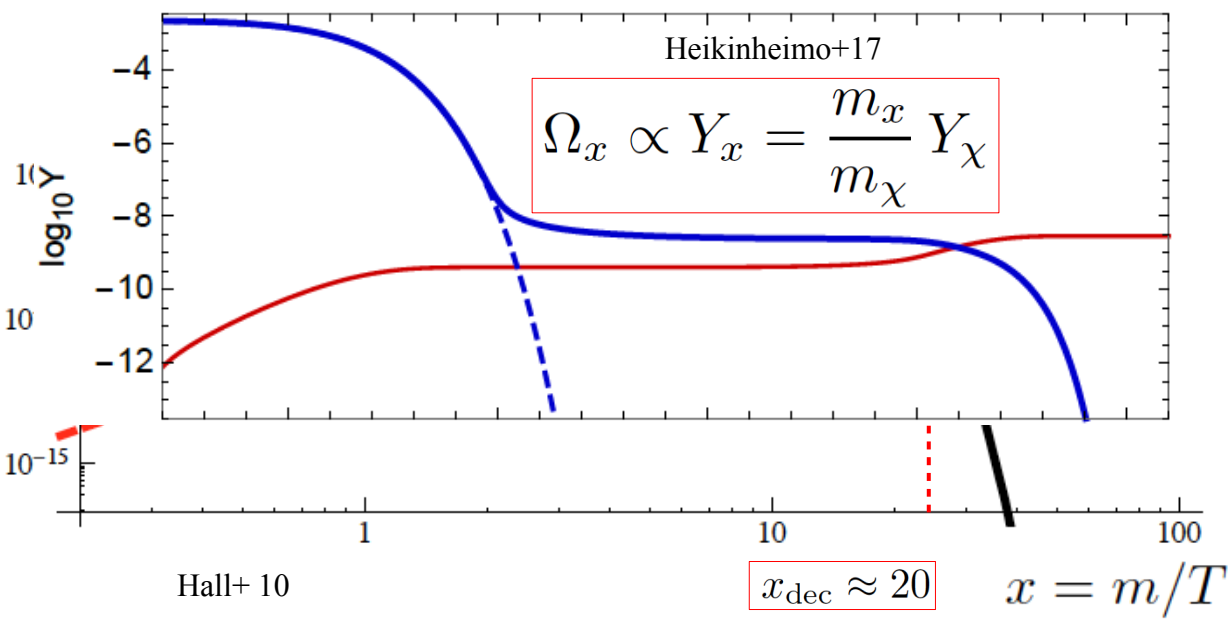

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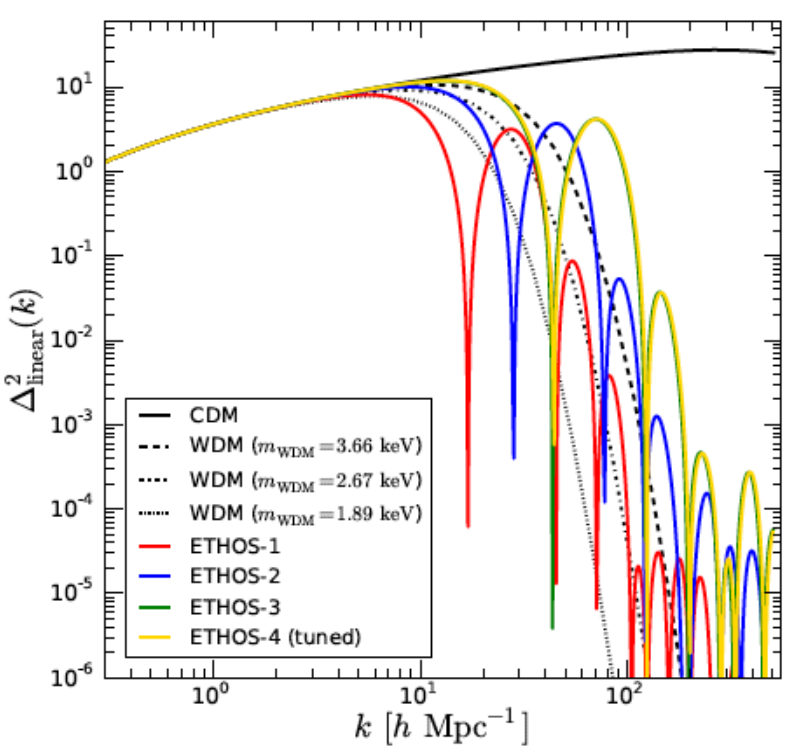
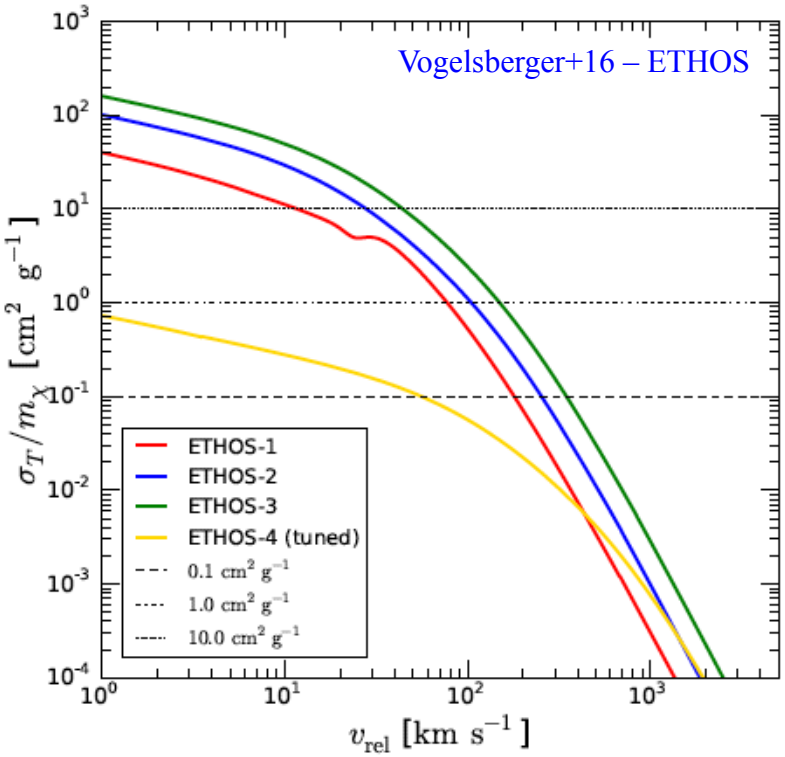
$$\langle\sigma_{\chi\bar{\chi}} v\rangle_{\mathrm{FIMP}} \ll \langle\sigma_{\chi\bar{\chi}} v\rangle_{\mathrm{WIMP}}$$

SIDM: potential signatures

Same as WIMPs! + Mediator searches



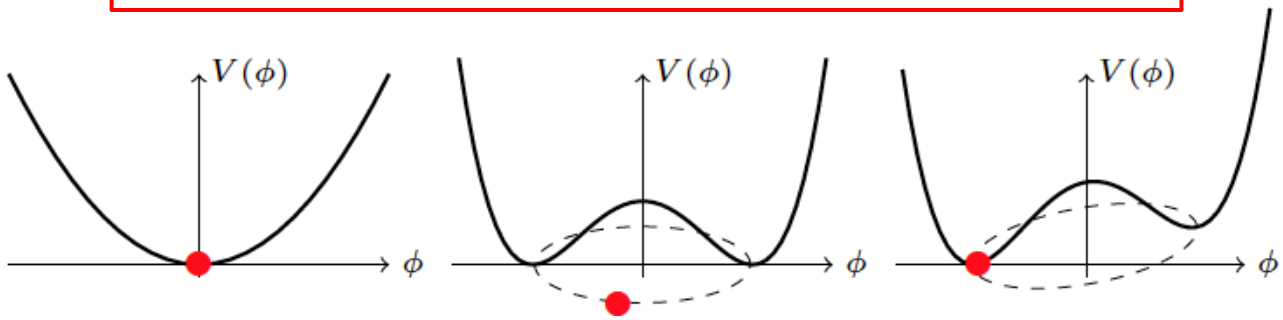


Particle searches (e.g. Tulin+18):
Indirect searches + direct searches + collider searches

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'



Peccei-Quinn (PQ) symmetry unbroken
Very high T

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

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

$$\mathcal{L}_{\theta\mathrm{QCD}} = \frac{\theta_{\mathrm{QCD}}}{32\pi^2}\mathrm{Tr}\ G_{\mu\nu}\tilde{G}^{\mu\nu}$$

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 << eV => large occupation # => classical field
* QCD axions = CDM => searches through EM couplings!

$$\Omega_a h^2 \sim 2\times 10^4 \left(\frac{f_a}{10^{16}\ \mathrm{GeV}}\right)^{7/6} \langle\theta_{a,i}^2\rangle$$

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

Axion cosmology
(review)
Marsh'15

Non-QCD ultra-light axions (ULA = fuzzy DM)

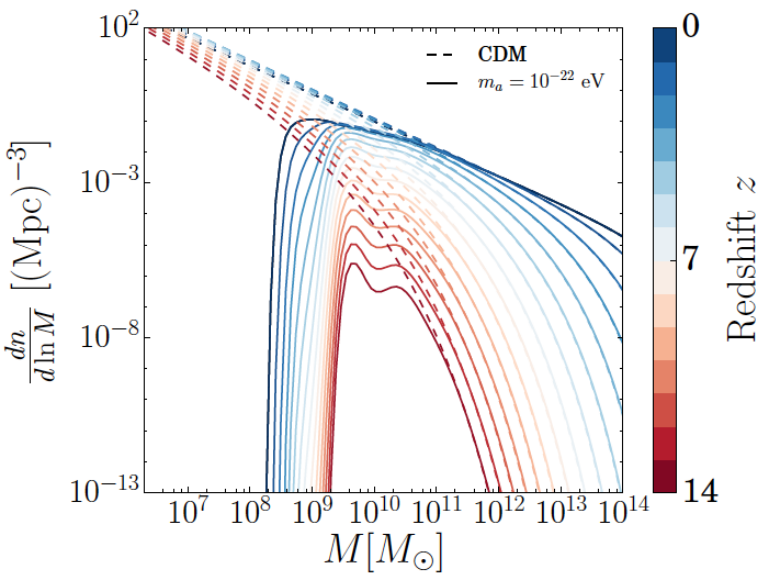
Hu+00, Peebles'00, Marsh+15, Hui+16, Schive+14, Du+18, etc.

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

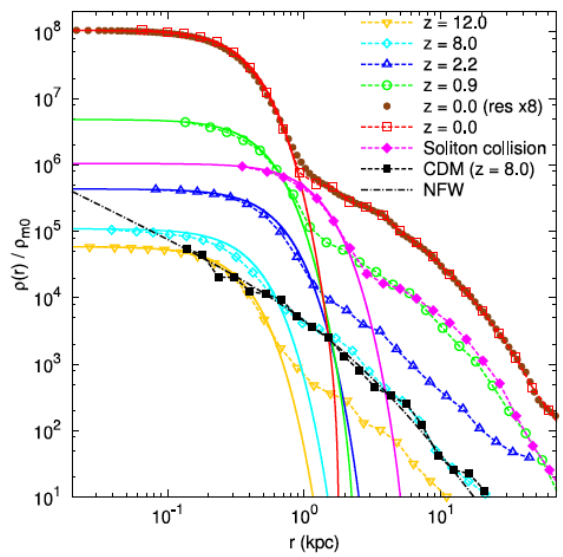
Main properties:
*** Suppression of small-scale perturbations**
*** incoherent interference pattern and granularity on scales ~ 1-100 kpc**
*** formation of solitonic cores at halo centers**
*** core/cusp solved in galaxies if m~10^{-22} eV**

$$i\hbar\left(\dot{\psi}+\tfrac{3}{2}H\psi\right)=\left(-\frac{\hbar^2}{2mR^2}\nabla^2+m\Phi\right)\psi$$

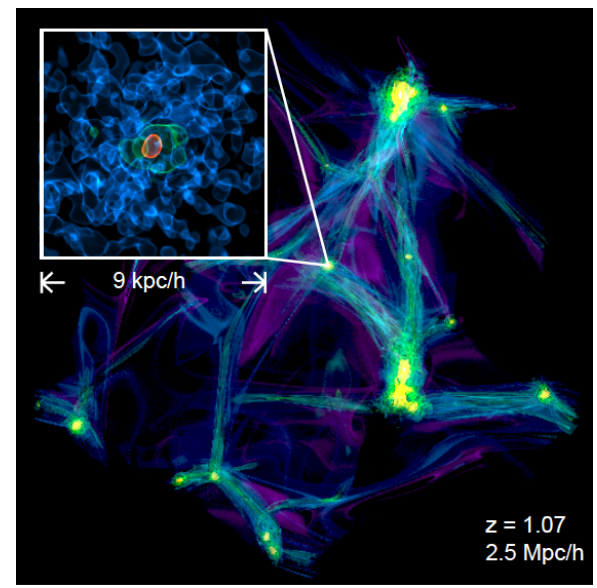
$$\nabla^2\Phi=4\pi G m_a|\psi|^2$$



Bozek+15
Halo mass function

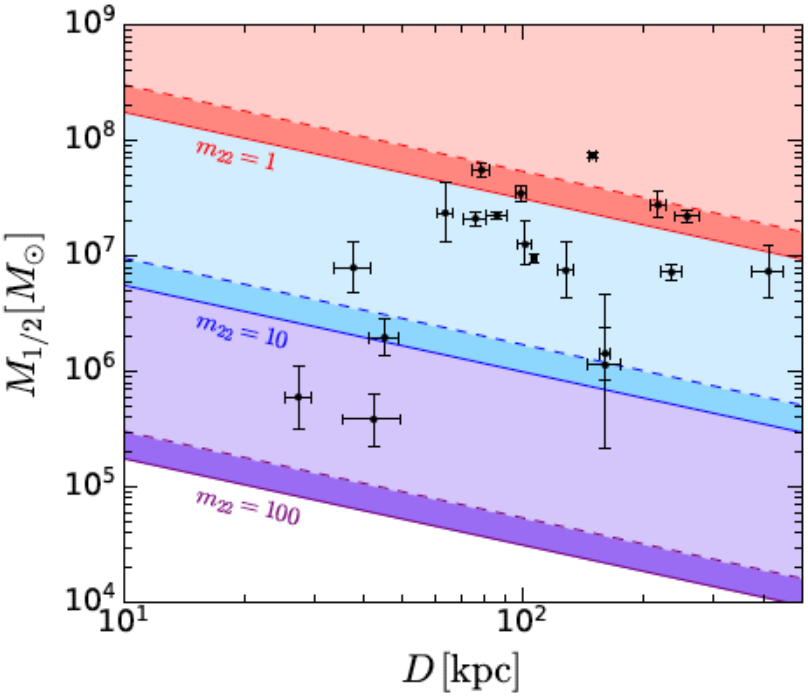


Schive+14
Solitonic cores in
Fuzzy DM simulations

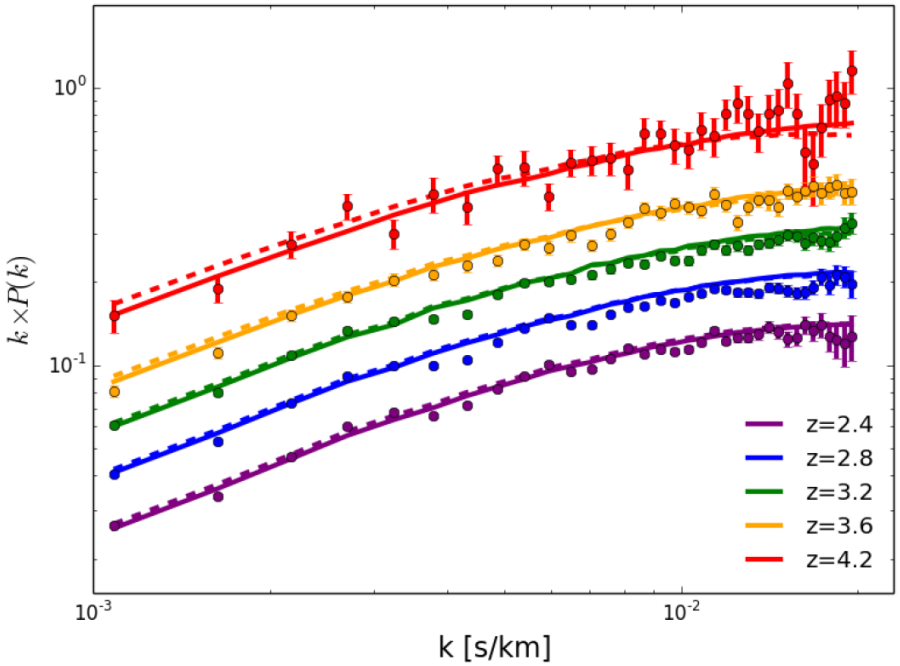


Veltmaat+18
Evolution of solitonic cores

ULA probes



Du+18
Tidal disruption of subhalo solitonic cores



Armengaud+'17 (Ly-alpha from SDSS DR9)

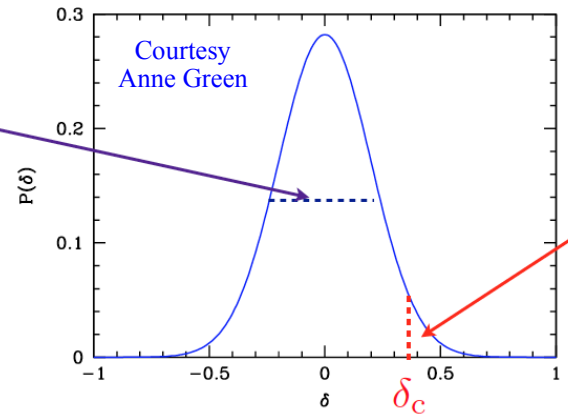
Other effects:
* Sizable oscillations of the core density (Veltmaat+18)
* $\rho_c = f(r_c)$ (Deng+18)
* Abundance of ultra-faint lenses HFF@z=6 (Menci+17)
* Probe incoherent zone (talk by N. Amorisco)
* Ly-alpha => A catch-22 scenario? (like Maccio+12 for WDM)
* 21cm? (See Schneider'18)

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_{pbh}* ~ mass within horizon**
* Fluctuation amplitude ~ 10^{-5} at CMB scales
* ~ 0.01 needed => **more power (e.g. non gaussianity) needed on very small scales**
* **Production enhanced at phase transitions** (e.g. QCD ↔ Mh~1 Msun)
* A potentially **macroscopic CDM candidate**

Review in Carr+16

σ(M_H) (mass variance)
typical size of fluctuations



PBH forming
fluctuations

$$\delta \geq \delta_c \sim w = \frac{p}{\rho} = \frac{1}{3}$$

$$M_H \sim 10^{15}\,\mathrm{g}\left(\frac{t}{10^{-23}\,\mathrm{s}}\right)$$

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

Gaussian spectrum →

$$\beta(M) = \mathrm{erfc}\left(\frac{\delta_c}{\sqrt{2}\sigma(M_H)}\right)$$

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

CMB scale →

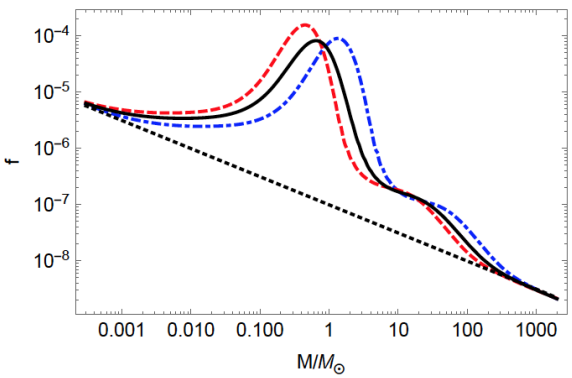
$$\sim 10^5 \exp\left[-(10^5)^2\right]$$

Mass fraction in PBHs strongly suppressed in standard inflation.
=> **Fine-tuned inflation models**

Primordial black holes

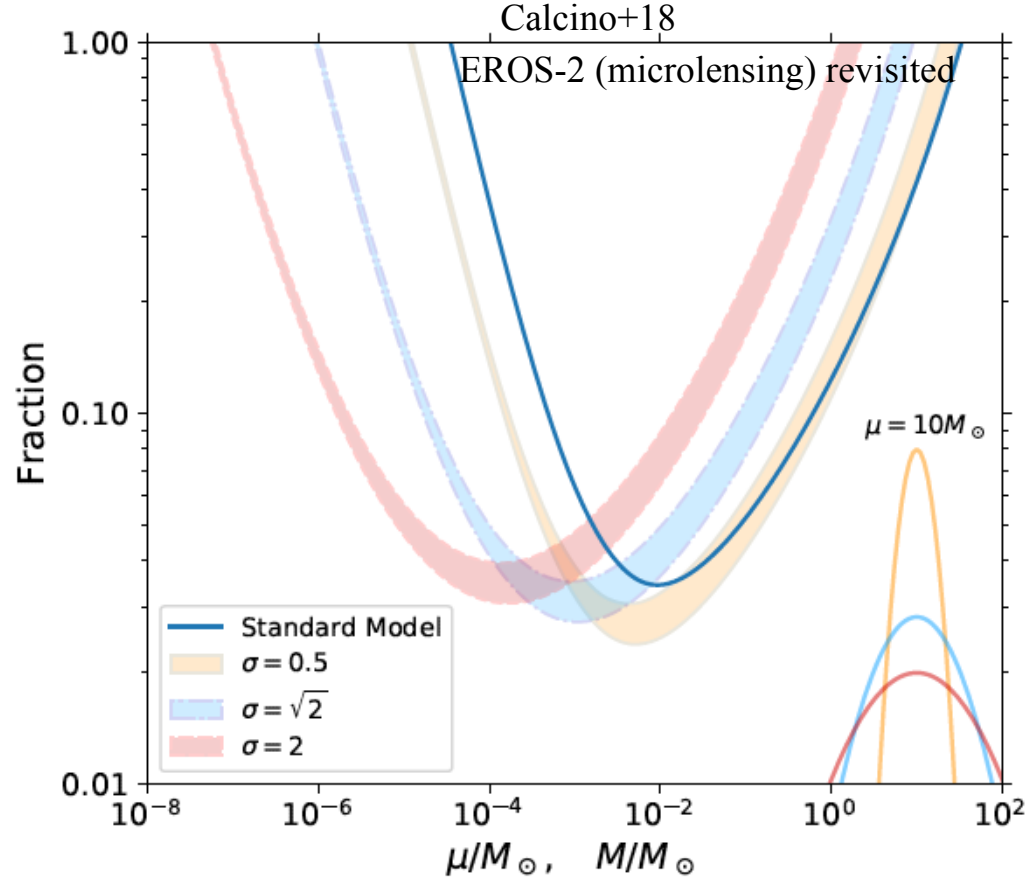
*** Most (past) constraints based on assuming peak mass function**
*** Huge effort to reconsider them (e.g. Green+, Kamionkowski+, Carr+, Garcia-Bellido+)**
*** Typically two windows: below and above microlensing constraints.**
*** If mass function extended enough, PBHs could be ~100% of DM**
→ if 1-100 Msun, might solve core/cusp
→ GW with < 1 Msun a specific signature

$$M = kM_{\rm H}(\delta - \delta_{\rm c})^{\gamma}$$



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

Calcino+18



Caveat:
potentially strong constraints from lensing of SNe Ia for $M_{pbh} > 1\ M_{sun}$
→ 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)

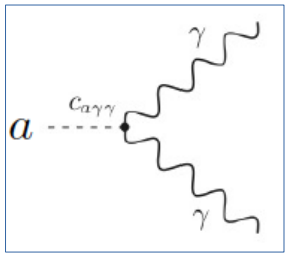
Peccei-Quinn, Wilczek, Weinberg, Kim, Shifman, Vainshtein, Zakharov, Dine, Fishler, Srednicki, Sikivie – 70'-80'

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

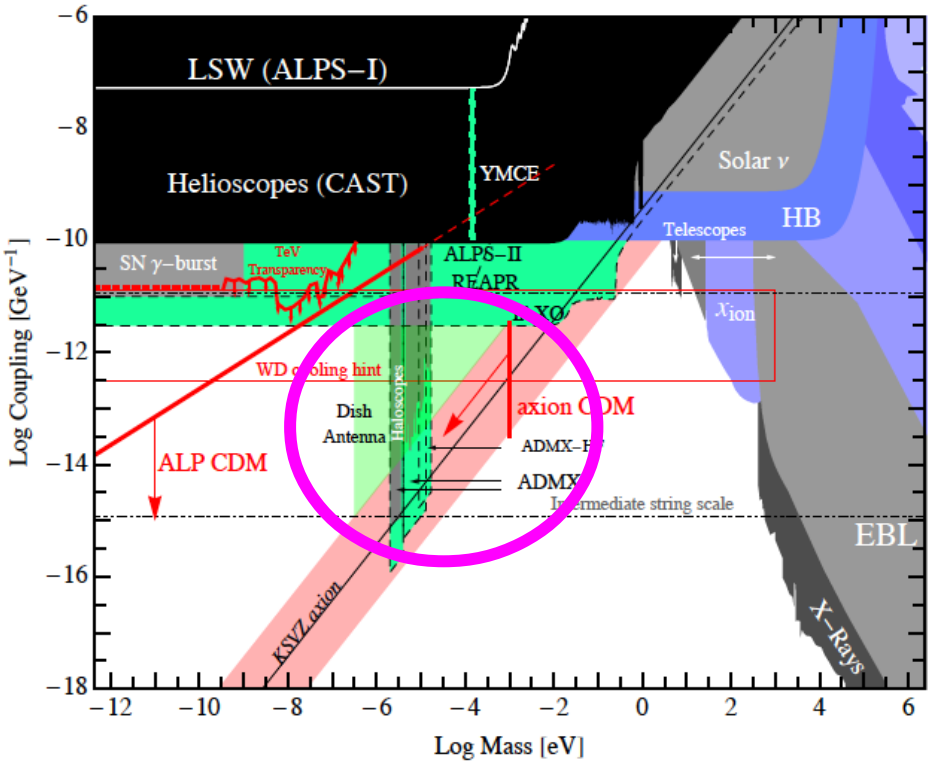
$$\mathcal{L} \supset \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

$$m_a \approx 0.6 \text{ meV} \times \left[\frac{10^{10}\text{ GeV}}{f_a}\right]$$

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4}\left\{g_{a\gamma} \equiv \frac{\alpha_s}{2\pi f_a} C_{a\gamma}\right\} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$



Essig+12

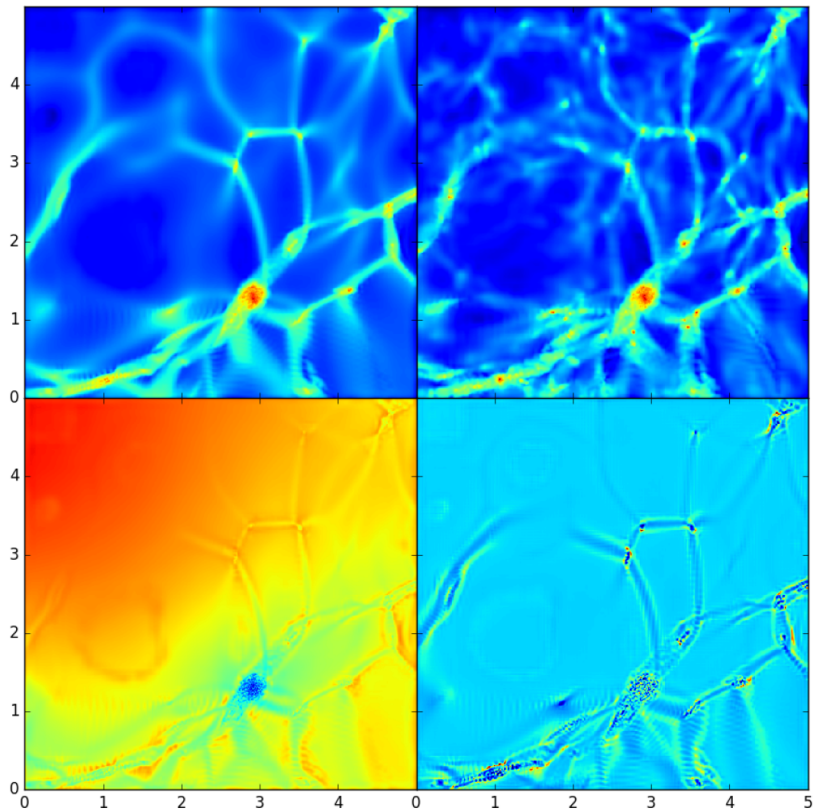


Aspects relevant to cosmology:
* non-thermal remnants => expected ultra-cold DM
→ minimal mass scale ~ 10^{-12} Msun subhalos
→ detailed structure formation under study

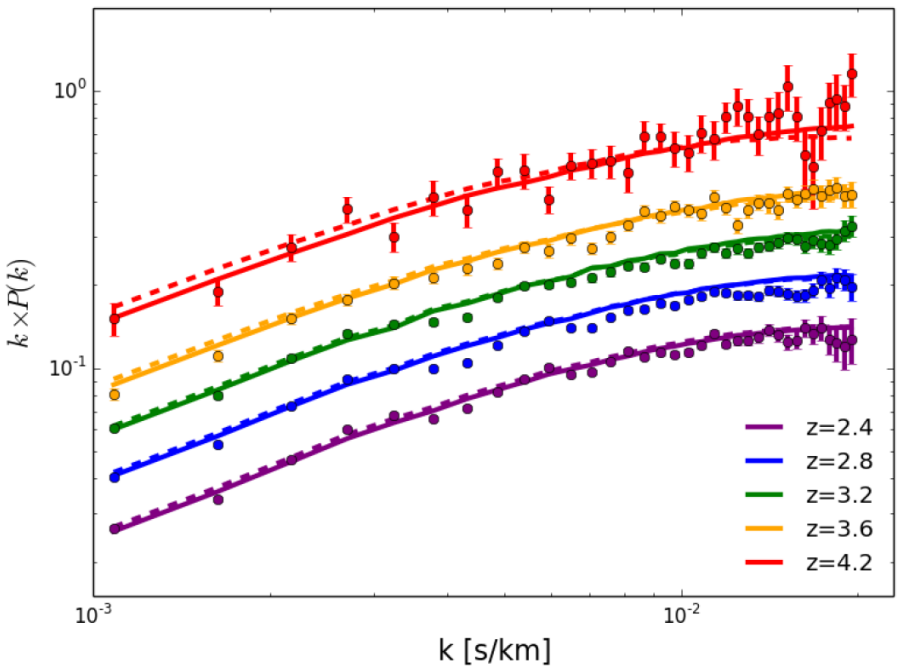
Detection (main):
* from interactions with photons: conversion
→ e.g. ADMX (ongoing): conversion of DM axions into photons

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



Armengaud+'17 (Ly-alpha from SDSS DR9)



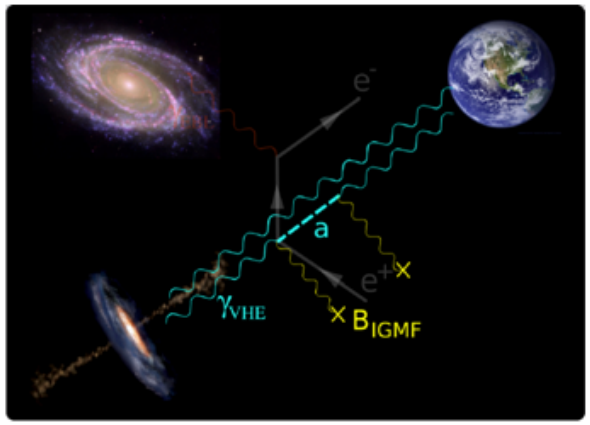
$$m_a > 2.0 \times 10^{-21}\ \mathrm{eV}$$

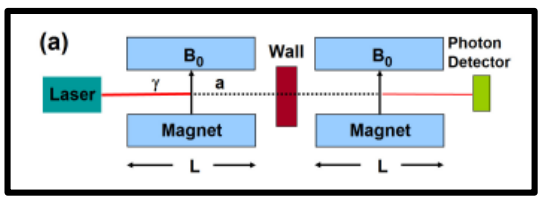
See also:
Irsic+'17 m22>20 (Ly-alpha)
Calabrese+'16: m22<5 (from dwarf spheroidals)
Menci+'17: m22>8 (from abundance of ultra-faint lensed galaxies @ z=6 in the HFF)

→ Scenario under strong pressure

Axion searches

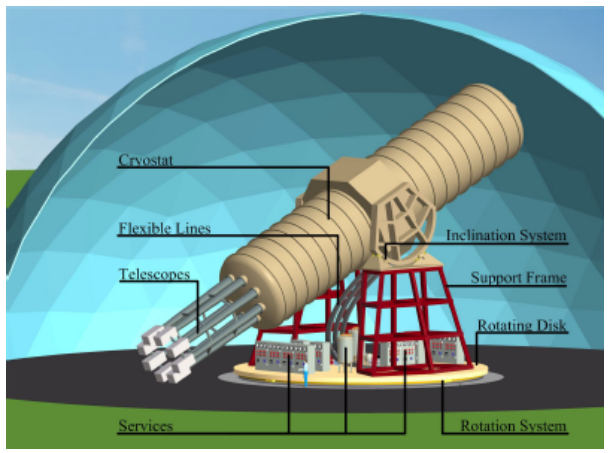
TeV blazar gamma-ray conversion to axions
e.g. HESS-CTA





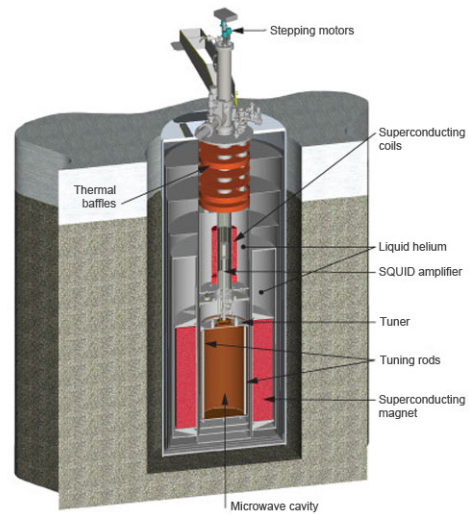
"Light shining through a wall"
(laser + B-field + wall)
e.g. ALPS@DESY

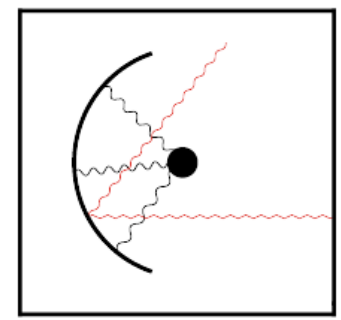
Not sensitive to DM



Helioscopes
CAST + IAXO @ CERN
B-field + micromegas

Sensitive to DM axions (irrespective of local DM density)

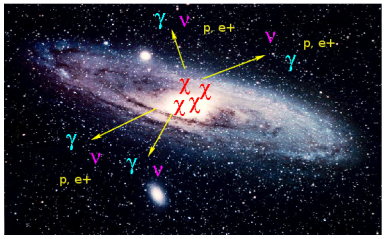




Haloscopes
Microwave cavities / dish antennae
B-field + detector (~GHz)

Needs that local DM density is made of axions

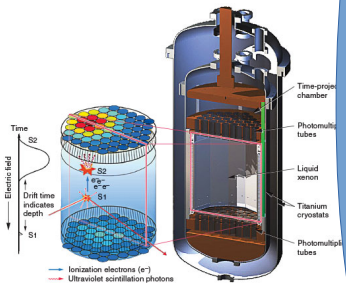
WIMP searches



Relic abundance and indirect detection (cosmic-rays)

Arrow of time

Direct detection (scattering)



LUX, Xenon-1t, etc.

WIMP

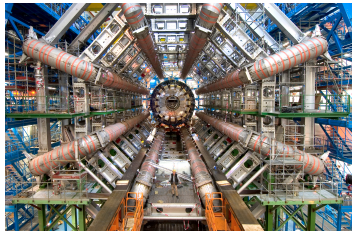
anti-WIMP

Any theory you like

Anti-SM

SM

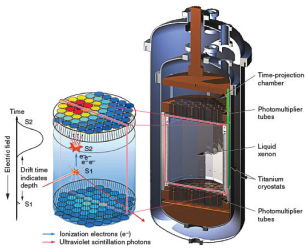
Searches at colliders



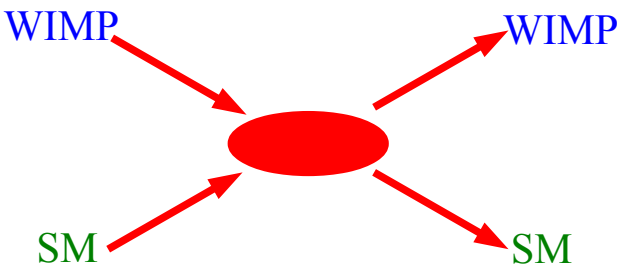
Astro/particle complementarity

Direct detection rate – WIMP-matter scattering

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



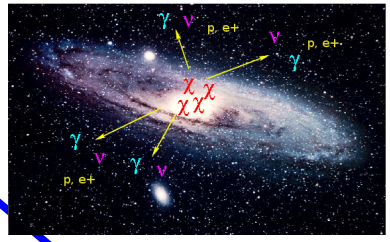
Scattering
(→ kinetic decoupling in early universe + subhalo mass cutoff)



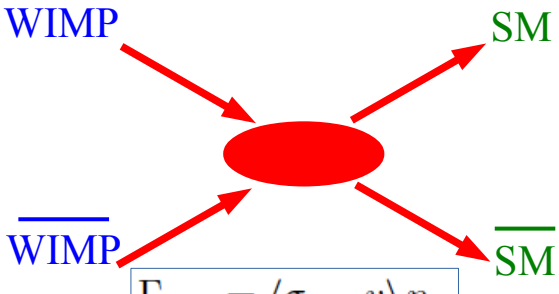
$$\Gamma_{\mathrm{scat}} = \langle \sigma_{\mathrm{scat}}\, v\rangle\, n_{\mathrm{plasma}}$$

Annihilation vs. scattering
=> constraints from cosmological abundance + minimal scale for DM structures (subhalos)

Dark matter profile + phase space (+ cosmic-ray transport)
=> constrained by Milky Way-mass model (full gravitational potential DM + baryons)



Annihilation
(→ chemical decoupling in early universe)



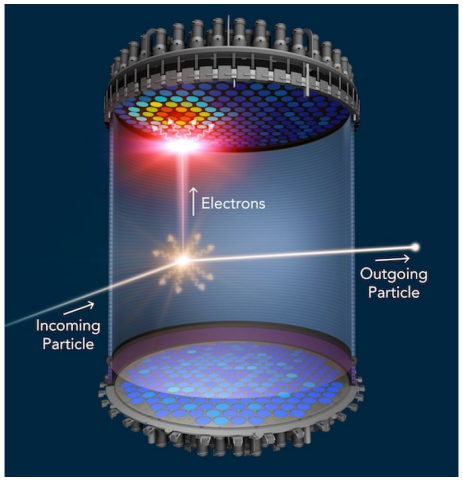
$$\Gamma_{\mathrm{ann}} = \langle \sigma_{\mathrm{ann}}\, v\rangle\, n_\chi$$

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

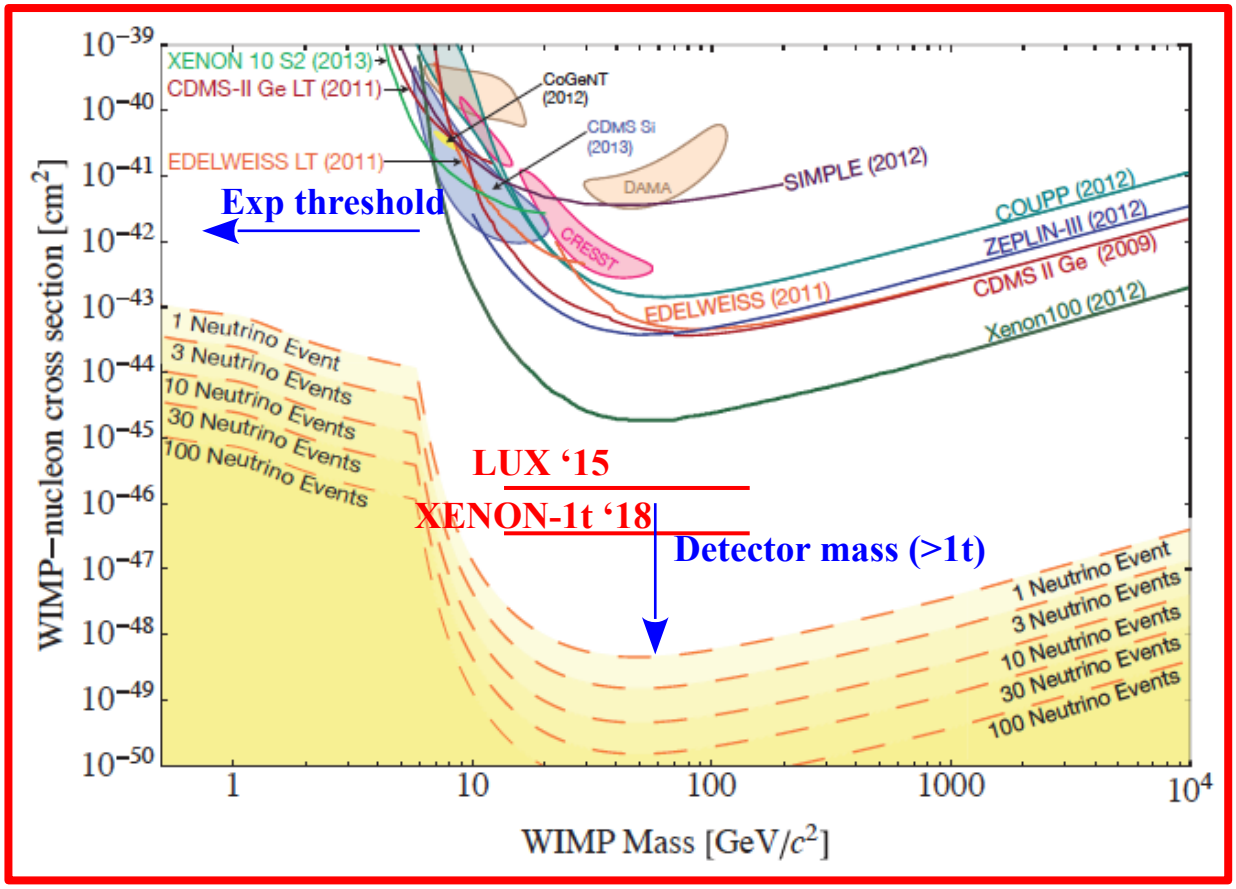
$$\frac{d\phi_\gamma^{\mathrm{ann.}}}{dE} = \frac{\delta\,\langle\sigma v\rangle}{4\,\pi}\,\frac{dN_\gamma}{dE}\int_{\mathrm{res.}} d\Omega \int_{\mathrm{l.o.s}} dl\,\left[\frac{\rho(r)}{m_\chi}\right]^2$$

Direct DM searches: recent results

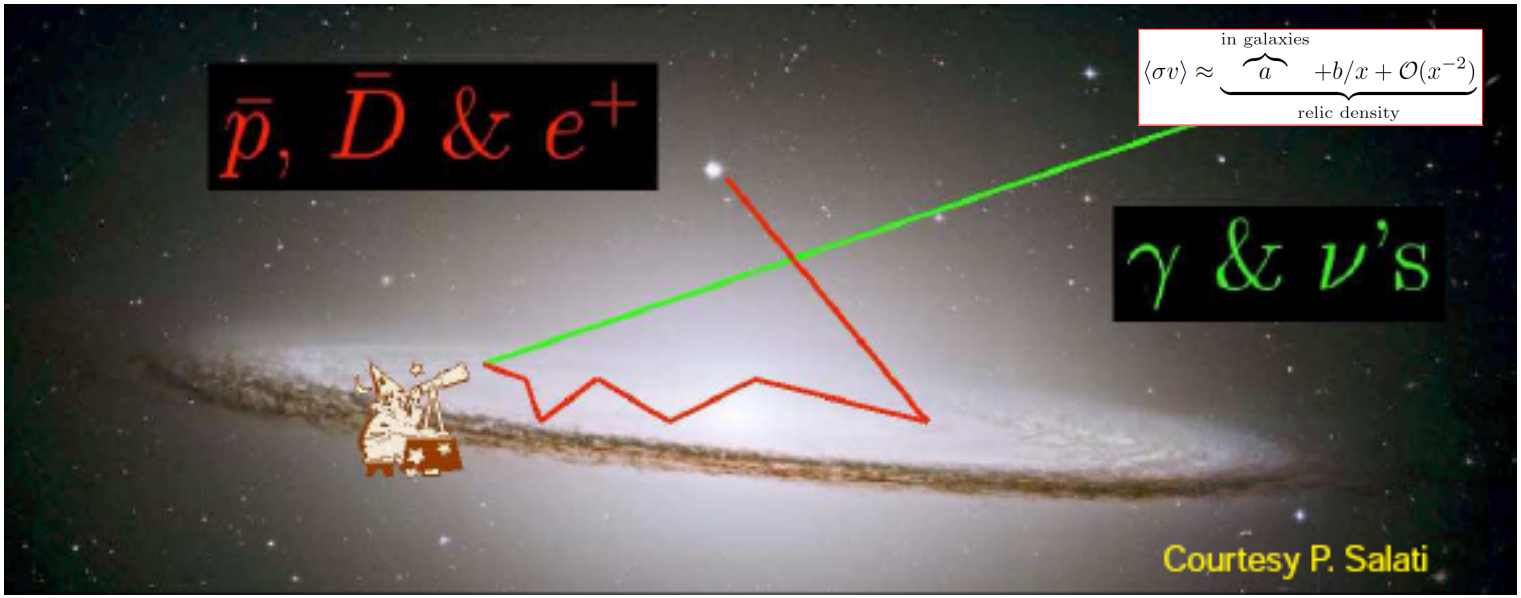
XENON-1t results:
=> the sub-zepto-barn era!



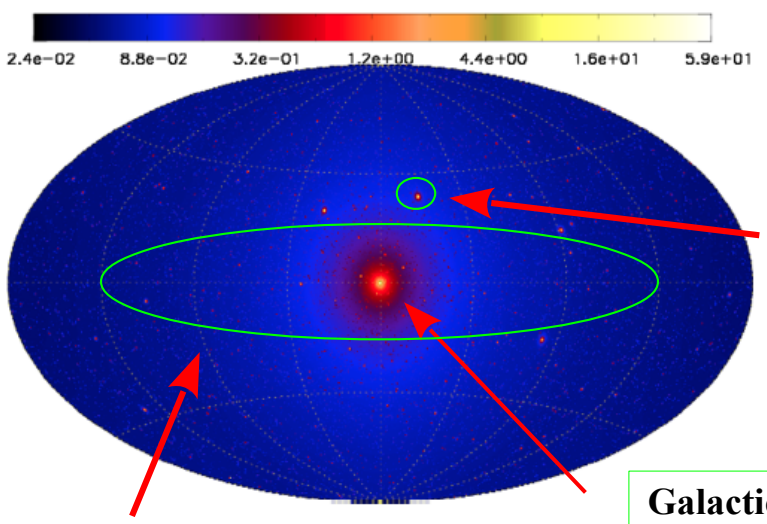
Billard+ 13



Up to the skies!



Pieri, JL+ '11



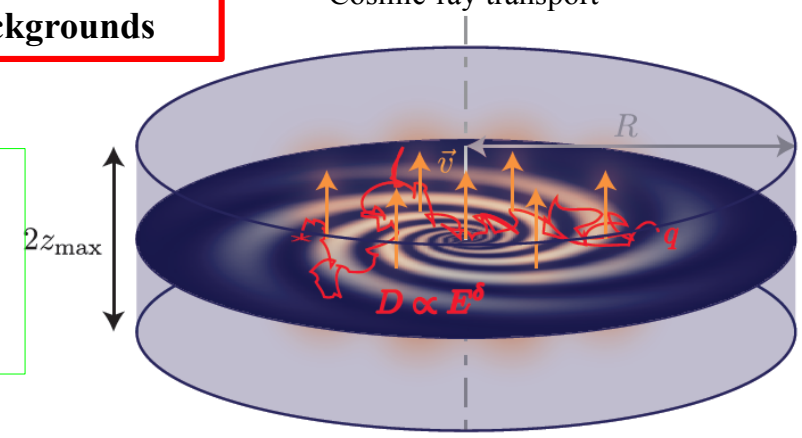
Requirements (and/or):
*** clean signal (spectral lines or features)**
*** large signal/noise ratio**
=> Control astrophysical backgrounds

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

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

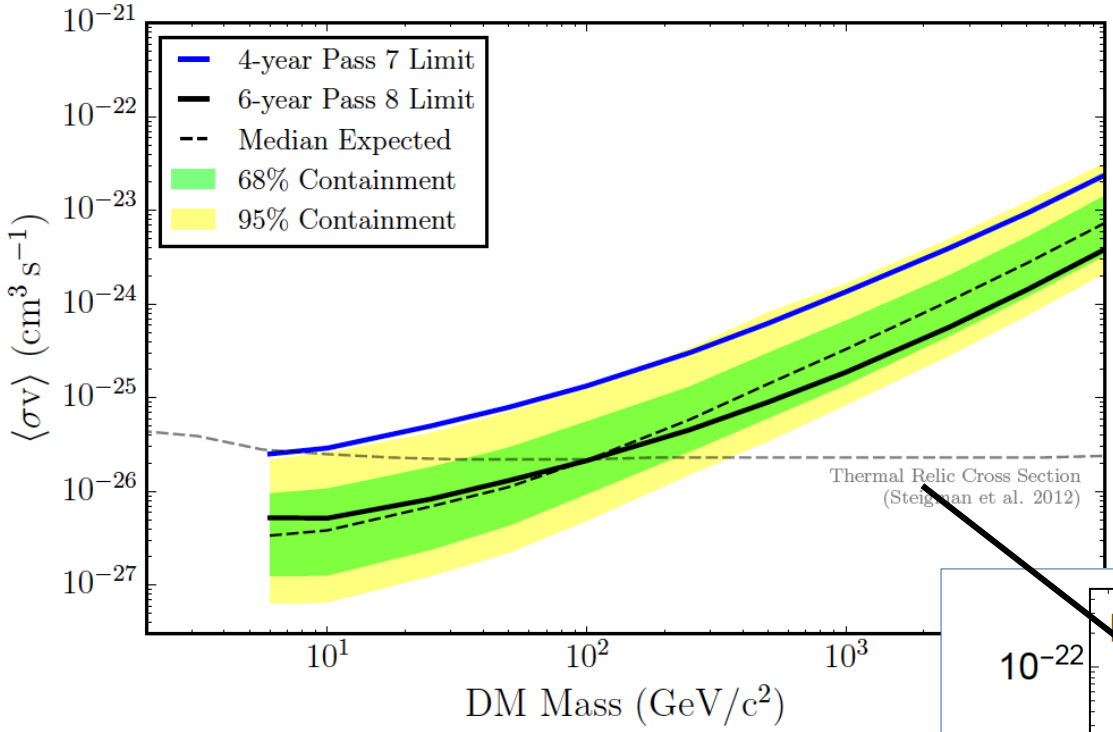
Diffuse gamma-ray emission
=> check spectral/spatial properties wrt background

Cosmic-ray transport



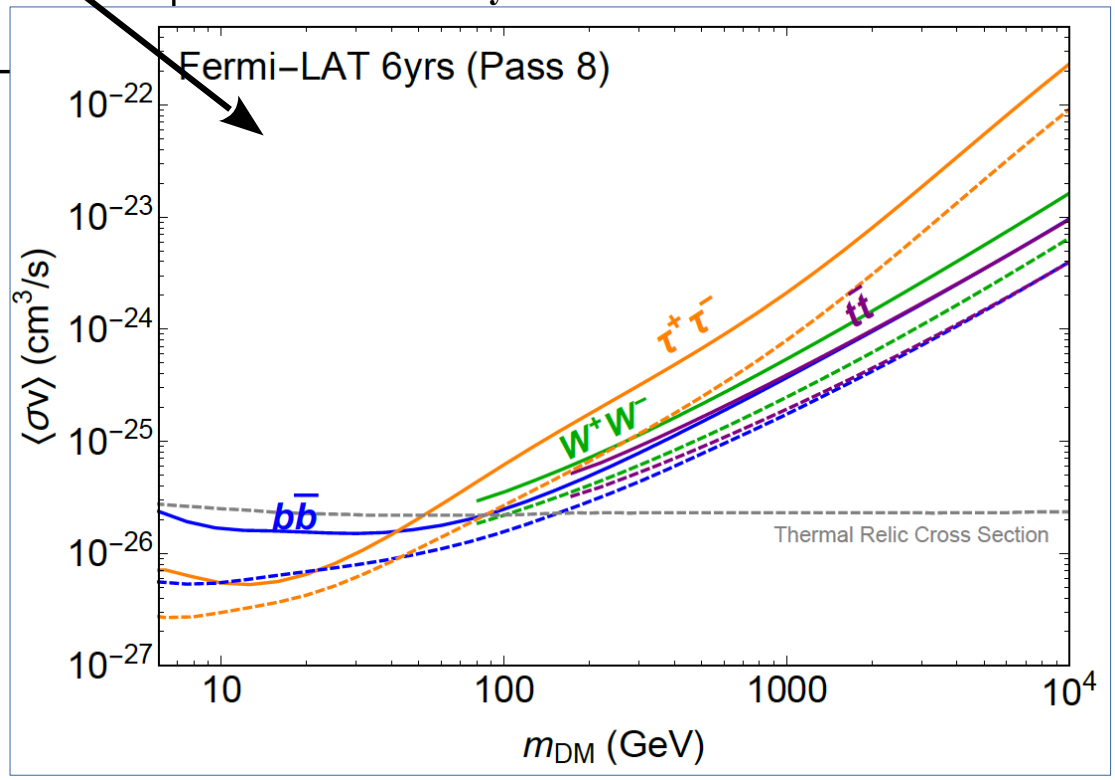
Mertsch PhD thesis '10

Satellite dwarf galaxies in gamma rays



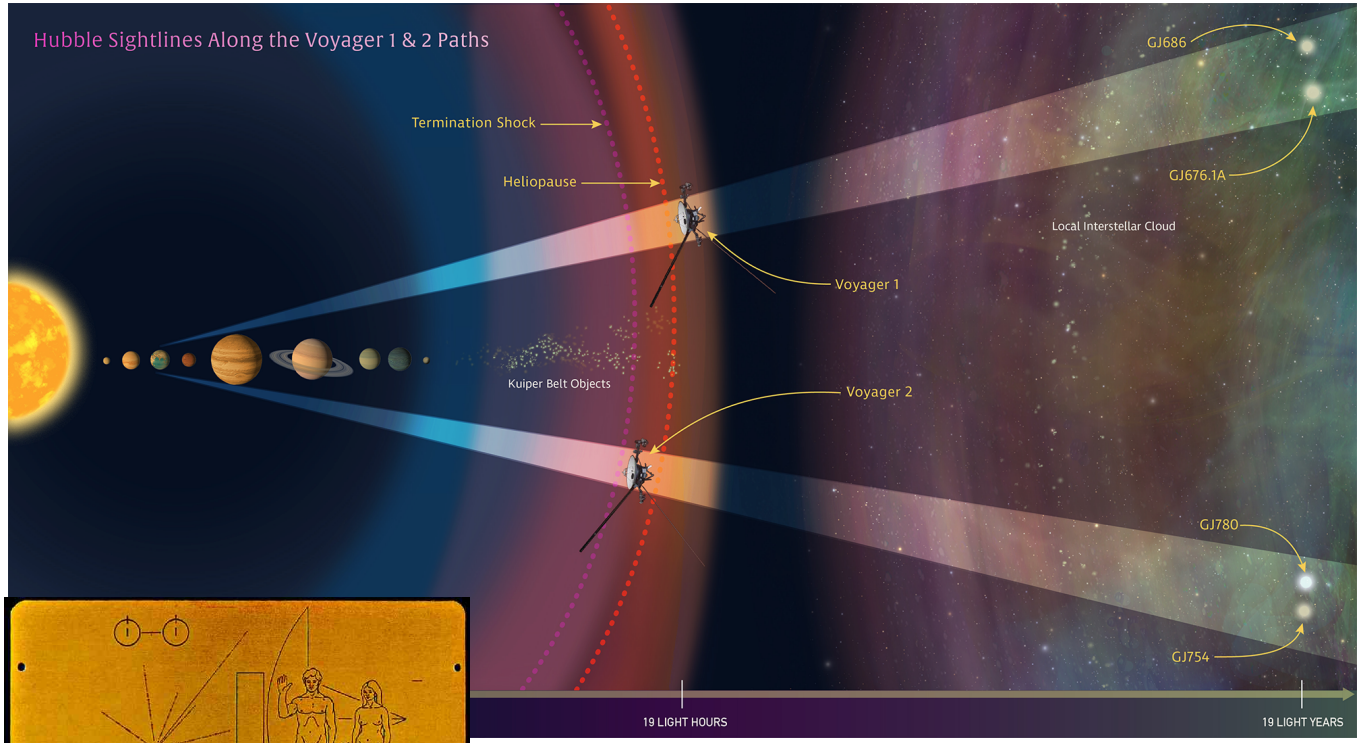
$$\frac{d\phi_\gamma^{\rm ann.}}{dE} = \frac{\delta\,\langle\sigma v\rangle}{4\,\pi}\,\frac{dN_\gamma}{dE}\int_{\rm res.} d\Omega \int_{\rm l.o.s} dl\,\left[\frac{\rho(r)}{m_\chi}\right]^2$$

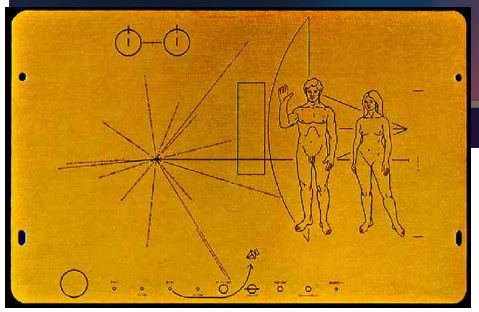
Hayashi+ '16

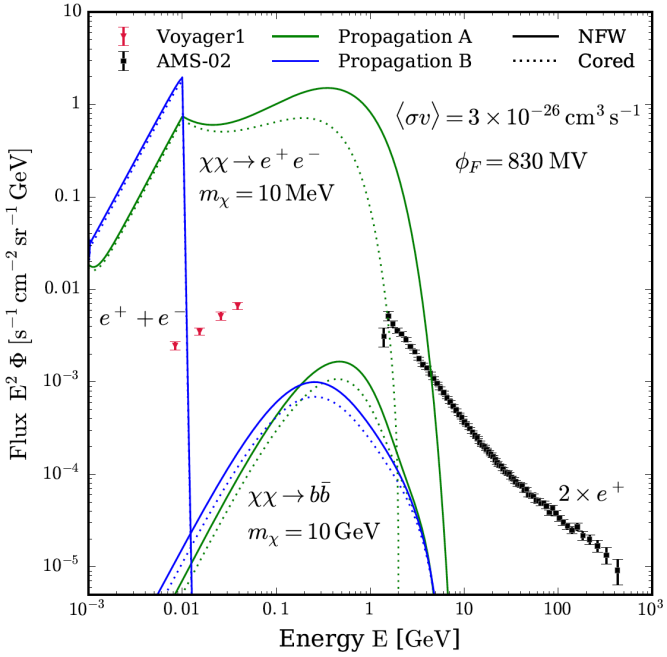


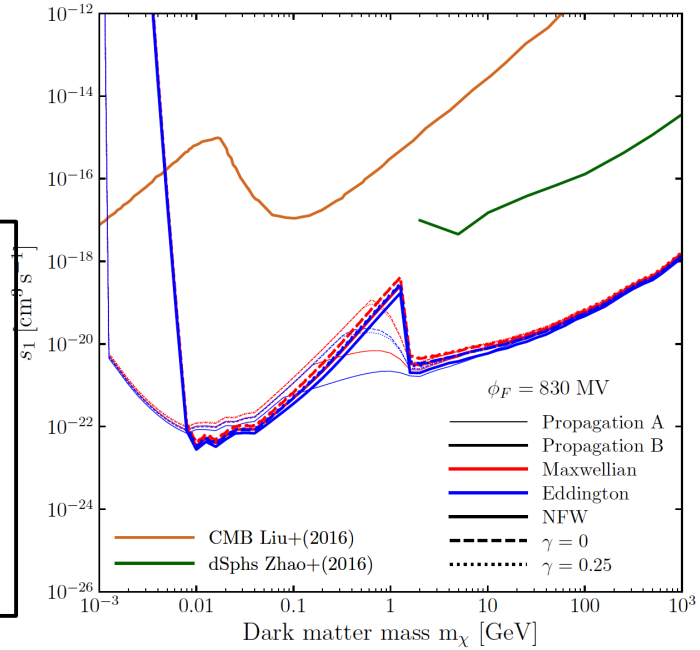
Bonnivard+15
→ Individual J-factors+errors:
* Careful Jeans analysis from velocity dispersion measures
* Systematics from mock data
=> Segue I overestimated
=> Fermi limit likely affected

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.

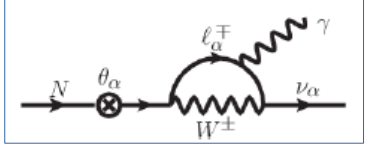
Boudaud, JL, Salati – to appear in PRL.

Sterile neutrino (W/C)DM

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

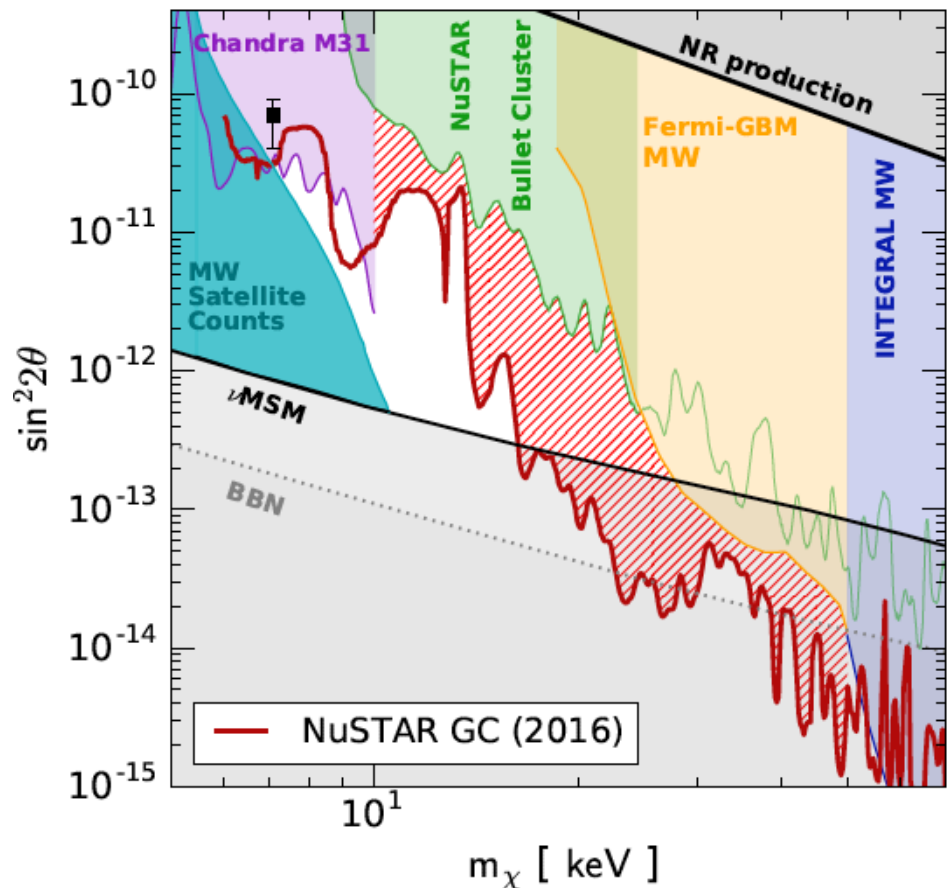
→ Neutrino masses (see-saw)
→ Leptogenesis
→ DM candidates (more or less warm)
→ keV mass range (!= thermal mass)

$$\mathcal{L} \supset \mu \left[\frac{\phi}{v}\right] \bar{\nu}_l \, \nu_r + M \, \nu_r \, \nu_r + \text{h.c.}$$



$$\Gamma_{N_1 \to \gamma\nu} = \frac{9\,\alpha\,G_F^2}{1024\pi^4} \sin^2(2\theta_1)\, M_1^5$$

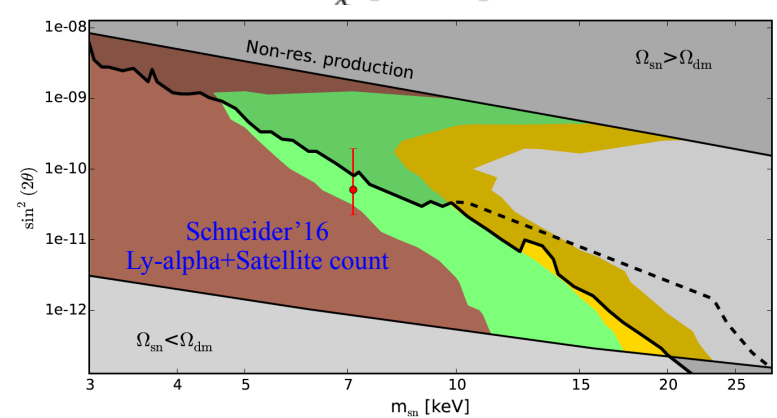
Perez+ '16
(also Neronov+'16)



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 ß decay)
* decays to **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[1,*] and Lavinia Heisenberg[2,3,†]

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Dipolar Dark Matter

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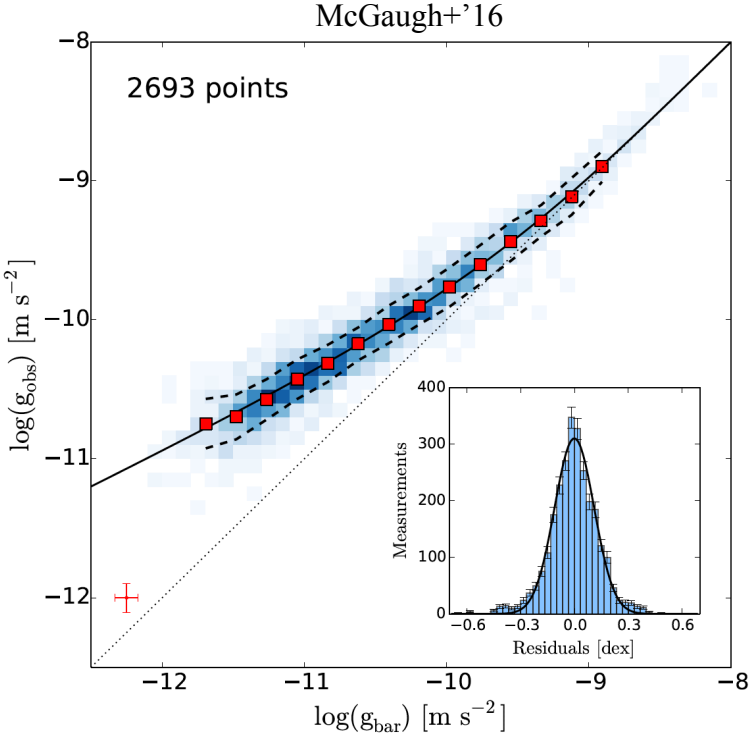
arXiv:1505.05146v1 [hep-th] 19 May 2015

2 metrics g and f + coupling btw then (geff)

$$\mathcal{L} = \sqrt{-g}\left(\frac{M_g^2}{2}R_g - \rho_{\rm bar} - \rho_g\right) + \sqrt{-f}\left(\frac{M_f^2}{2}R_f - \rho_f\right) + \sqrt{-g_{\rm eff}}\left[m^2 M_{\rm eff}^2 + A_\mu\left(j_g^\mu - j_f^\mu\right) + \lambda M_{\rm eff}^2 \mathcal{W}(\mathcal{X})\right]$$

baryons

McGaugh+'16



++ 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)