News from (/in/about) the dark

Episode 3 : Gaia's lights and the good, the bad, and the ugly of dark matter scenarios

Montpellier – May 23-25 2018

LUPM
LABORATOIRE UNIVERS & PARTICULES MONTPELLIER

cnrs

UNIVERSITÉ MONTPELLIER

PNCG
Programme National de Cosmologie et Galaxies

PNHE
Programme national hautes énergies
cnrs cnes cea

WELCOME!

Julien Lavalle
CNRS
LUPM-Montpellier, Theory Group

News from/in/about the Dark (3)
Montpellier, May 23-25 2018

***SOC**: Benoit Famaey, JL.*
***LOC**: Thomas Lacroix, JL, Martin Stref*
Secretary (travel/stay): Lydie Le Clainche
Secretary (logistic): Amel Chennouf

Practical

- **Salle des Actes (build. 7): talks, breaks, discussions – Wed.-Thu.**
- **Friday morning in Room ???**
- **Rooms can be locked – but no insurance cover in case of robbery.**

- **WIFI: network is "UM-Net", then try login and pwd written on folder.**
- **…. or EDUROAM**

- **Lunches:**
  - **Cafeteria on the campus (follow those who know or check the map)**
  - **Lunch tickets include: starter + main course + dessert + drink + coffee**

- **Dinners:**
  - **Wednesday: free**
  - **Thursday: social dinner at Le Petit Jardin (20, rue Jean-Jacques Rousseau)**

- **Any question? Ask Martin, Thomas, or myself.**

- **Goodies: a pack available at the entrance.**

- **Advice: buy 10-travel tram tickets (more practical, less expensive).**

Formal acknowledgments

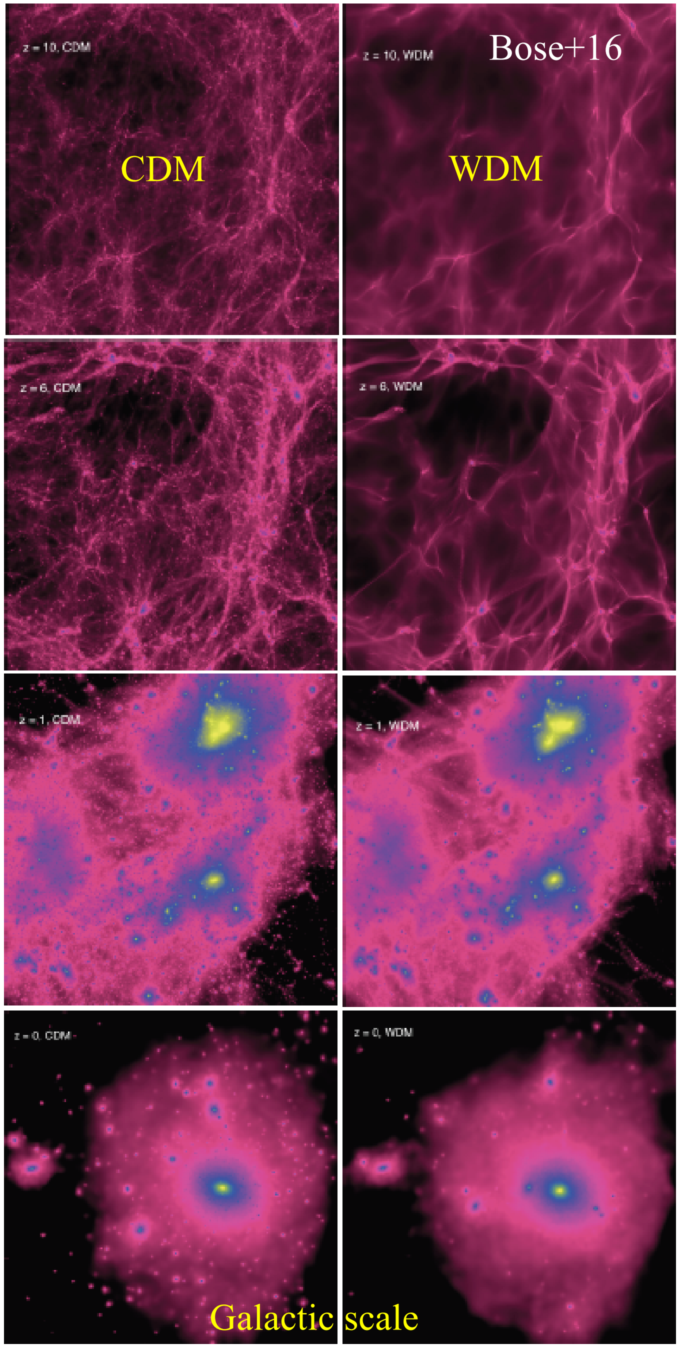
CNRS/IN2P3 funding for interdisciplinary theoretical networking project "Galactic Dark Matter" (P.I. JL/Montpellier + colleagues from IAP-Paris, LAM-Marseille, LAPTh-Annecy, Obs. Strasbourg, Oxford, Stockholm – can be extended) – 2017-2020.

Goal/s: address dark matter issue/searches on the Galactic scale by putting together astroparticle physicists + astrophysicists/cosmologists expert in galactic dynamics and structure formation.

Means: mini-worskhops (1 or 2/year) + collaborative visits. Small number of motivated people.

Constraints: for non-CNRS/IN2P3 members, only travels to steering lab; hence @Montpellier for this project.

Dark matter: successes and issues



So far, only gravitational evidence for DM
(cosmological structures+CMB)

CDM successes:

- CMB peaks
- Successful structure formation (from CMB perturbations)

=> CDM seeds galaxies, galaxies embedded in DM halos

- Lensing in clusters + rotation curves of galaxies
- Also consistent with Tully-Fisher relation (baryonic physics)

How cold?
Cold enough to form/bind Dwarf Galaxies:
Cold enough to be consistent with Lyman-alpha forest
=> Constraints on DM candidates depending on spin and production mechanism.

=> WDM and/or CDM allowed, but then WDM is almost CDM.

A SCENARIO NOT DEVOID OF ISSUES:
→ NOT DISCOVERED YET
→ ISSUES ON SMALL SCALES (eg Bullock & Boylan-Kolchin ‘17)**:**

1) The core-cusp / diversity pb
Some galaxies better fitted with DM cores than with predicted cusps (e.g. NFW profile) + apparent mass deficit in inner parts.

2) The “missing” satellite pb / too-big-to-fail pb
*** CDM predicts more satellite galaxies than observed.**
*** Big satellites should retain their baryons (too-big-to-fail)**
!!! Statistics has changed recently (SDSS, DES)
++ impact of cosmo params

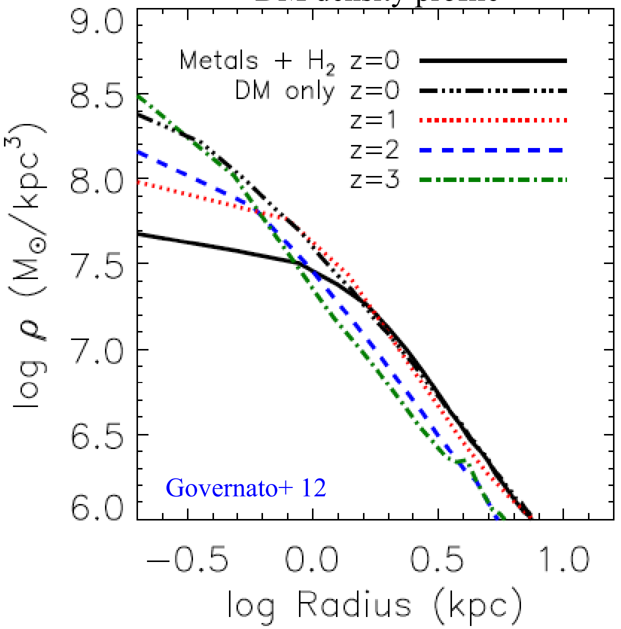
3) Others: MDAR (eg McGaugh+)**, satellite planes** (Pawlowski+, Ibata+)

CDM: solutions to small scale issues?

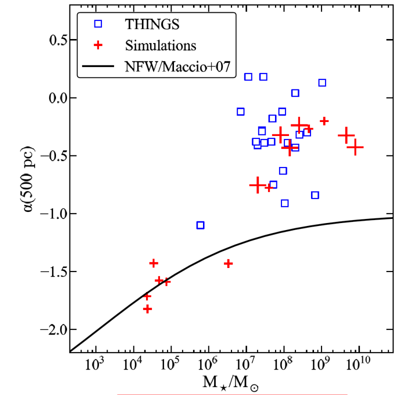
e.g. Governato+ 12:
CDM + more realistic physics for baryons => cusps are flattened
(From star formation: UV + winds + SN **feedback**)

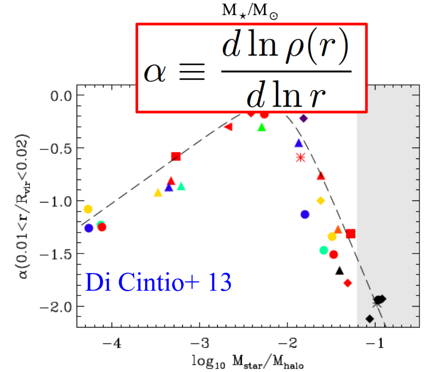
e.g. Maccio+ 12: WDM Catch 22 problem
To prevent cusps: m < 0.1 keV
=> cannot form dwarf galaxies
***** Forming DSphG => m > 1 keV**

DM density profile

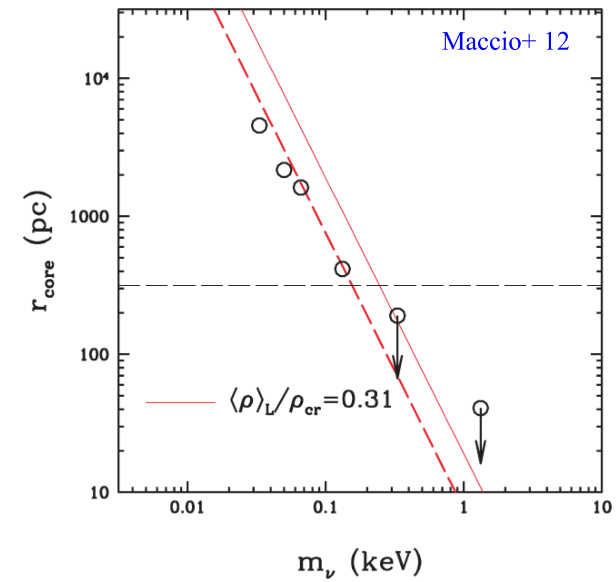


Inner slope vs. stellar/dm mass





Core DM radius vs. thermal mass



Solutions to core-cusp problem:
* **NB: WDM alone does not solve the issue**

* CDM/WDM: **baryonic effects (?)**
→ must be there, but to what extent?
* Other classes of DM:
→ **self-interacting DM (SIDM)**
→ **ultra-light bosonic dark matter (ULDM)**

Solutions to missing satellite problem:
(and **too-big-to-fail** pb)

* CDM: **baryonic effects (?)**
* **WDM**
* **SIDM**
* **ULDM**

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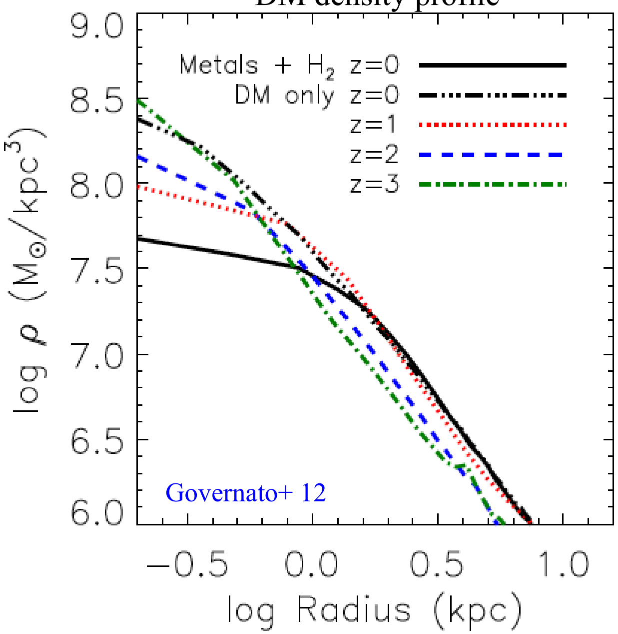

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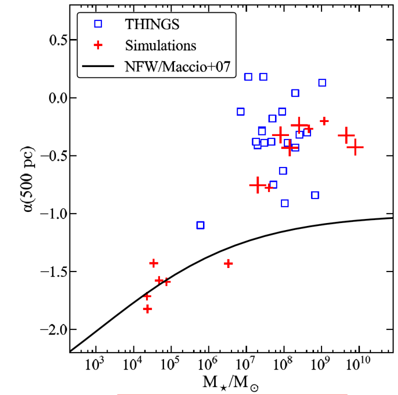
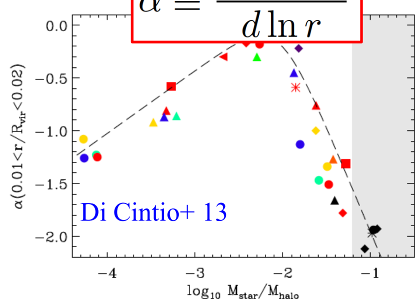
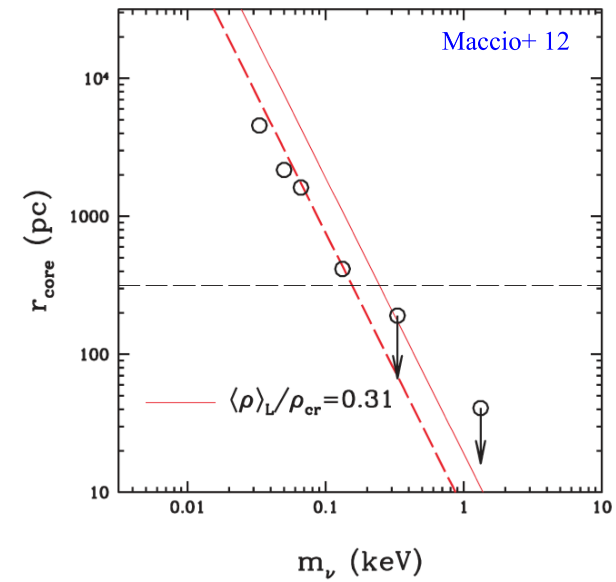


$$\alpha \equiv \frac{d \ln \rho(r)}{d \ln r}$$



Core DM radius vs. thermal mass



Actively debated!!!
Baryonic physics must play a role
on small scales anyway

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<u>Solutions to missing satellite problem:</u>
(and **too-big-to-fail** pb)

* CDM: **baryonic effects (?)**
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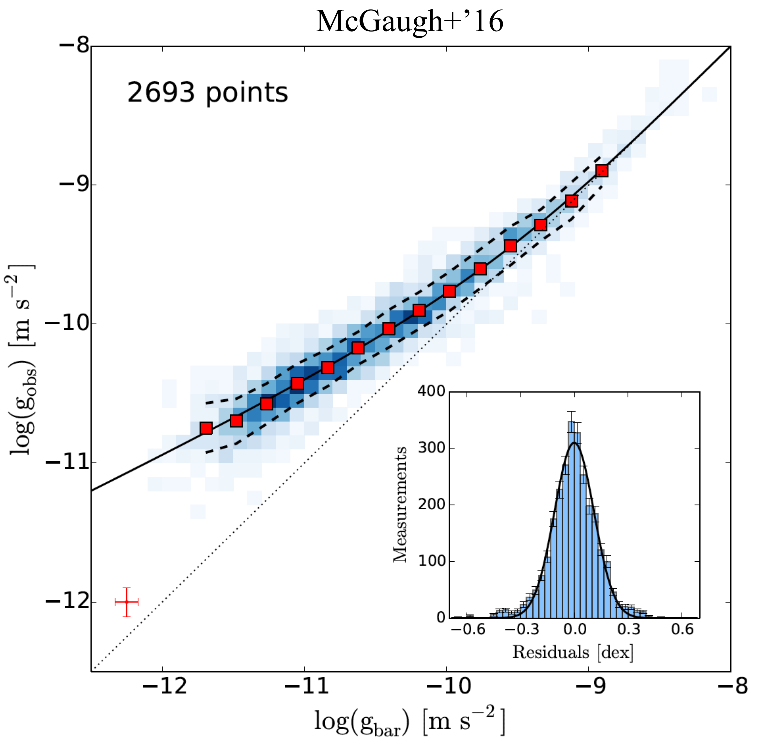
Selected intriguing observations

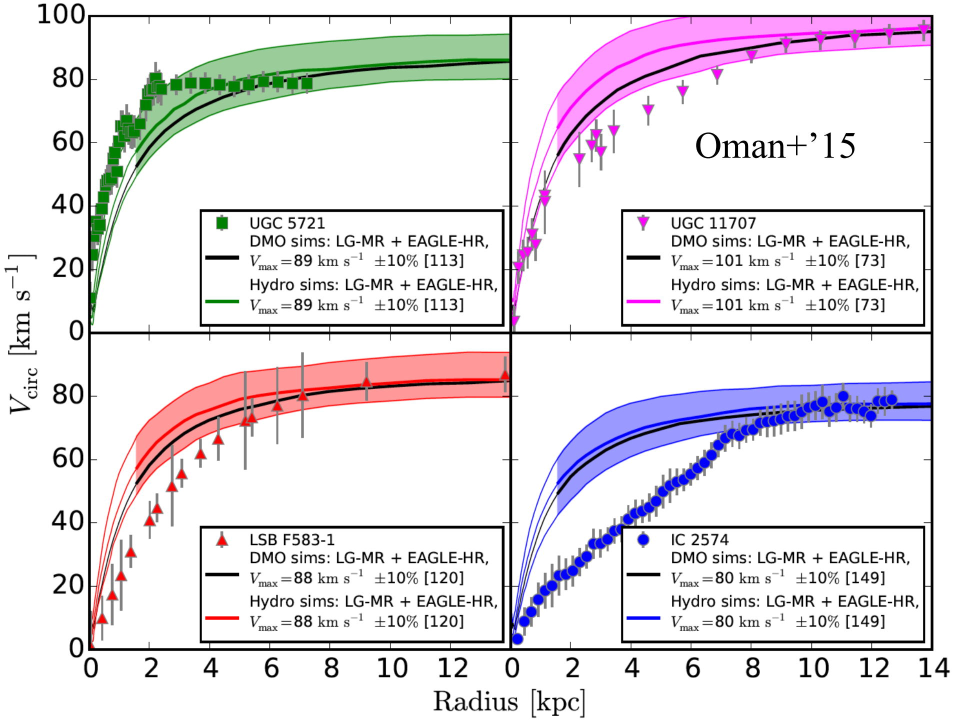
Mass discrepancy-acceleration relation



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

Guiding principle for model building? Talk by Benoit Famaey

"Diversity" problem: very different inner vcir curves for halos of similar masses (vmax). (another way to say core/cusp pb).



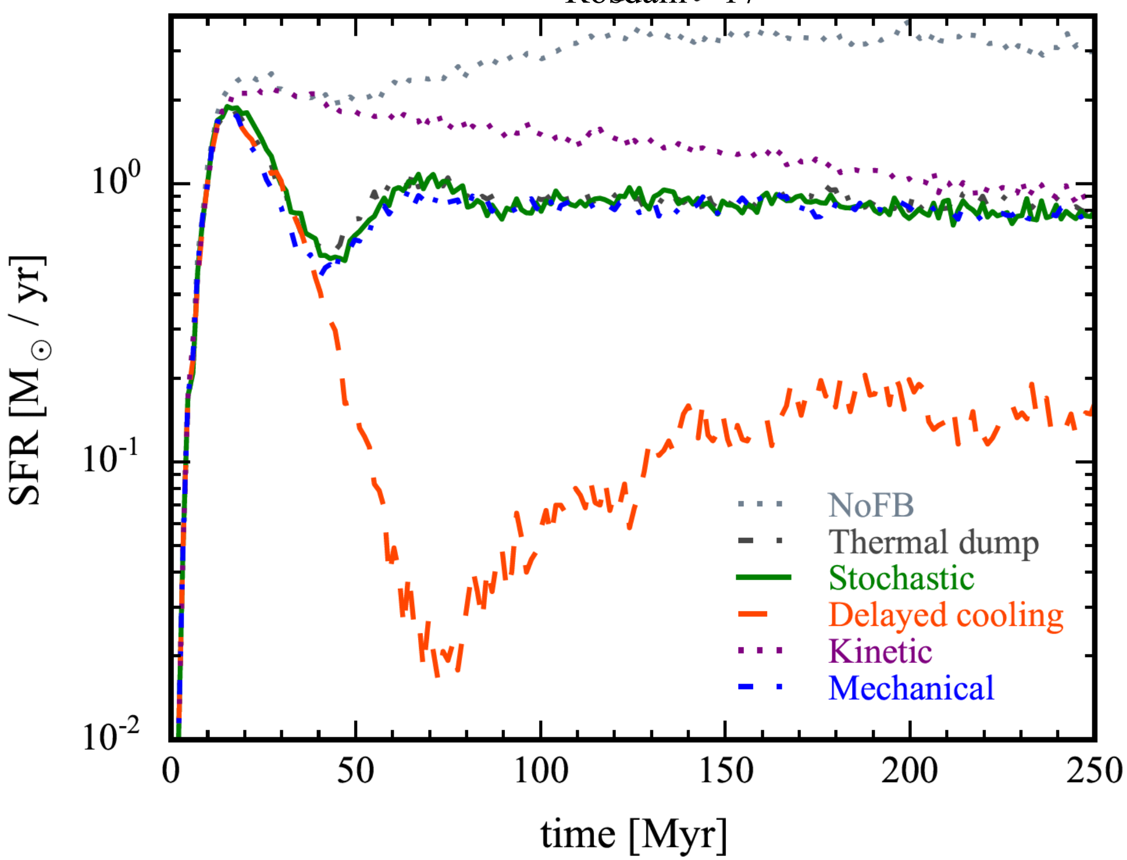
Core/cusp issue more severe in small galaxies, with vmax~80km/s (e.g. diversity of v-curves)
Remaining observational biases?
e.g. gas circular motion ~ biased inner measurement because of pressure support
(~ 5km/s in central kpc)

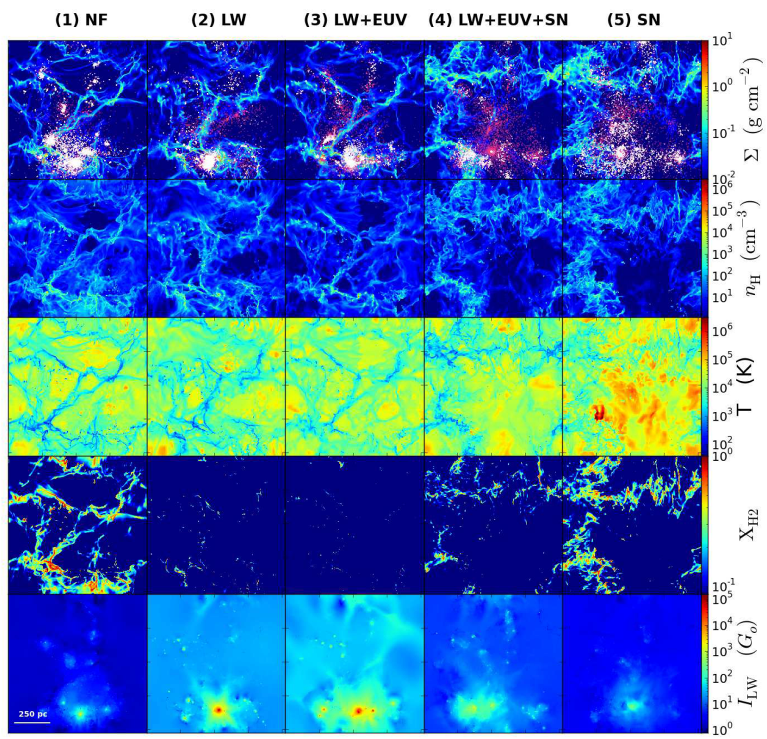
Core in the MW? Talk by James Binney

Can baryons rescue CDM?

Baryonic physics?
→ Still rather empirical / simplistic in simulations, but rapid progresses
→ Several ways to implement feedback
→ Not only supernova feedback, but also stellar feedback (e.g. H2 dissociation)
→ Complicated BUT BARYONS DO EXIST! May solve issues in the end.

Rosdahl+'17





Butler+'17

Talks by Oscar Agertz and Florent Renaud

Dark matter particles: model building

Main assumption: General relativity is correct on all relevant scales => DM = exotic matter/fluid
(new degrees of freedom beyond GR can be recast in terms of some field equations anyway)

Dark matter particles: model building

Two main approaches

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

→

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

+++ may solve several issues
- - - DM "solution" embedded in a very large parameter space (tricky phenomenology)

*** Bottom-up**
"DM is a requirement"

→

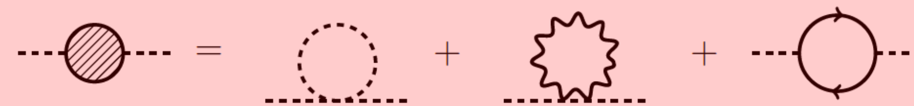
*** Consistent QFT**
+++ DM phenomenology with a minimal set of parameters => predictive
- - - built on purpose (ad hoc)

Dark matter particles: model building

Two main approaches

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

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

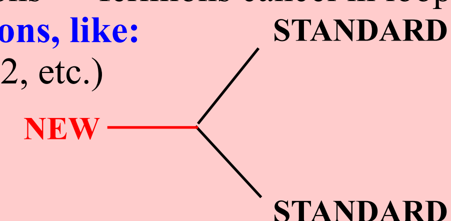


$$\delta m_H^2 = \frac{\Lambda^2}{32\pi^2}\left[6\lambda + \frac{1}{4}\left(9g^2 + 3g'^2\right) - y_t^2\right]$$

(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
+ (Sterile) right-handed neutrino DM
+ others (e.g. relaxions)

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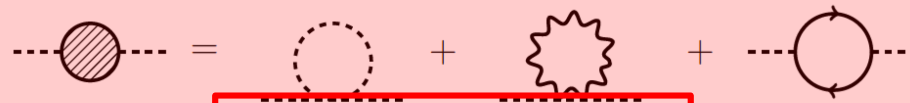

Challenged by LHC

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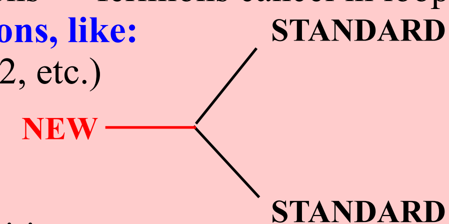

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=> CDM, WDM, SIDM, Wh(atever)DM

Dark matter particles: model building

Two main approaches

Talk by Florian Kuhnel

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

→

+++++
Primordial Black Holes
(as consequences of inflation)
++++++
(eg Carr+'16)

*** Bottom-up**
"DM is a requirement"

Owing to lack (or failure) of reliable theoretical guiding principles in particle model building, current tendency is: consistent QFT + observational constraints

Generic constraints on DM candidates

Generic constraints on DM candidates

→ 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)

=> For **DM produced non thermally** in the early universe: **particle statistics matters!**

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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!

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

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

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→ see review in e.g. Marsh '15 (axion-like particles)

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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)

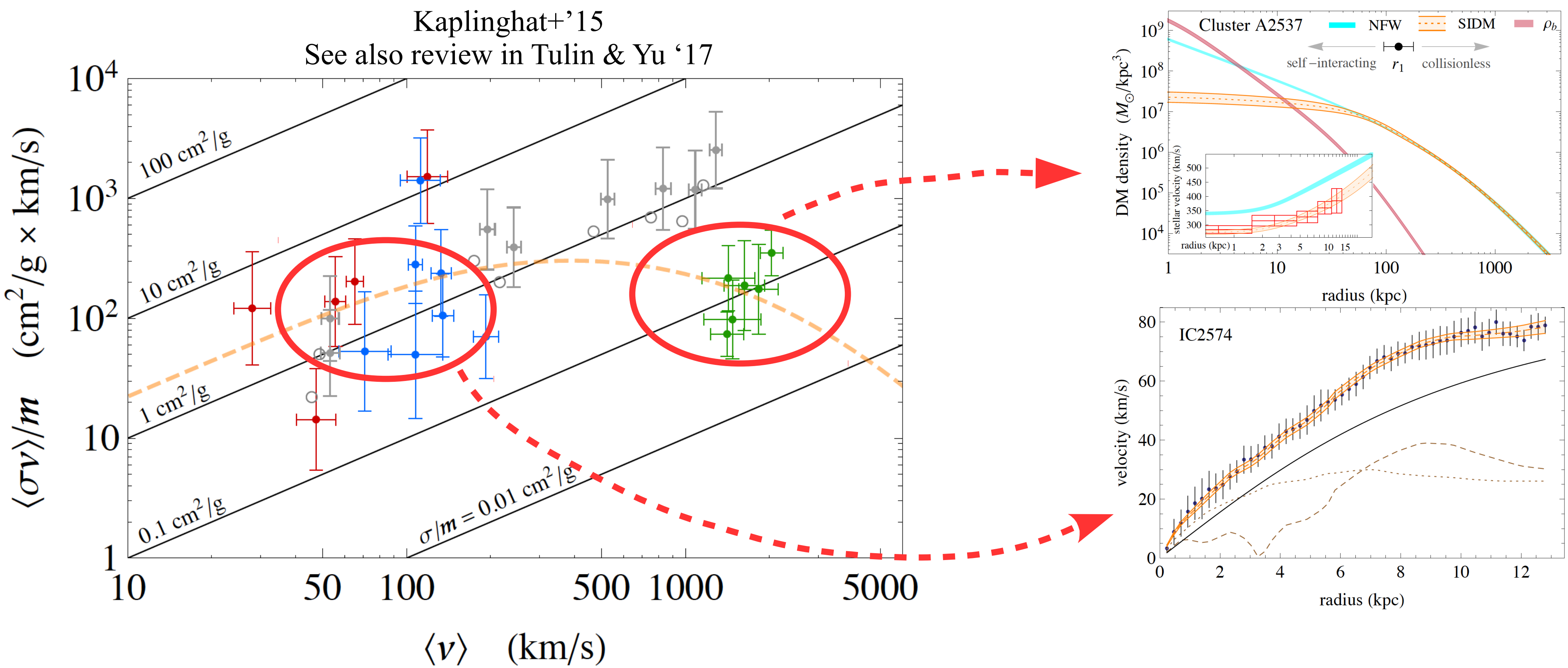
$$2\,\mathrm{cm}^2/\mathrm{g} \simeq 4\ \mathrm{b/GeV} \lesssim \frac{\sigma_{\rm self}}{m_\chi} \lesssim 0.4\ \mathrm{b/GeV}$$

Original proposal by Carlson+'92

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

Dynamics of clusters (Kaplinghat+'15)

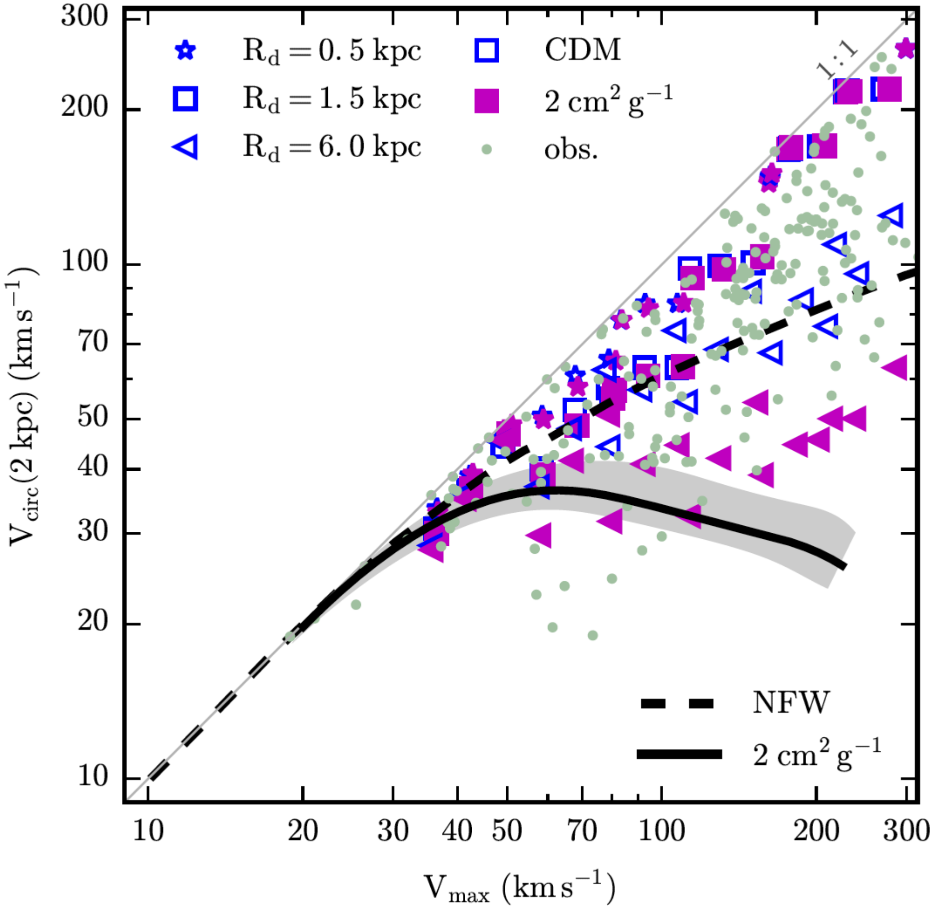
(SIDM)

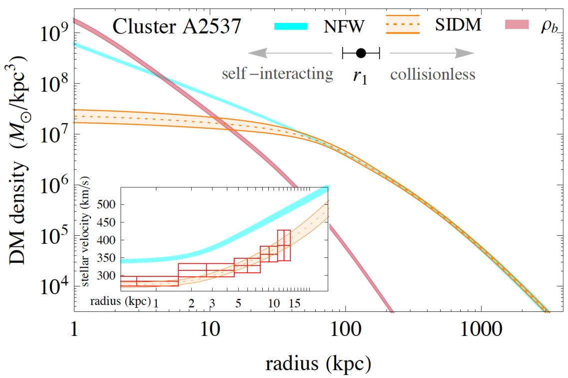


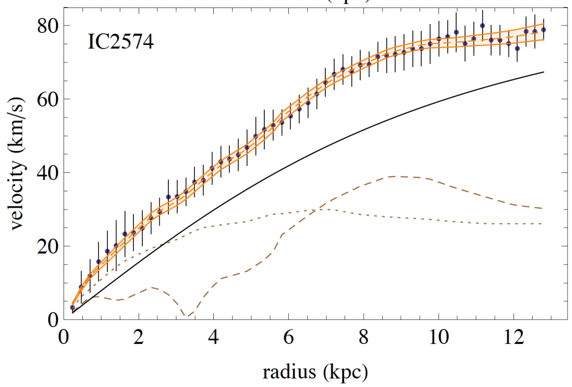
Combine constraints on small/large scales
=> velocity-dependent cross section
Can be achieved in diverse particle scenarios, even in the WIMP scenario (eg Kahlhoefer+) – review in Tulin & Yu '18

(SIDM)

Creasey+'17
→ diversity of v-curves reproduced







Talk by James Bullock (canceled)

Critical discussion:

Baryonic effects
vs.
specific properties of dark matter

Particle dark matter: structuring properties

* **Thermal dark matter particles**

** **WIMPs**: 10 GeV – 1 TeV currently probed. SubGeV and multiTeV in near future.
=> Cusps (pending baryonic effects)
=> Subhalos – cutoff mass depends on WIMP properties, typically ~$10^{-6}M_{sun}$ for GeV particles.
=> Galactic halos are cuspy and clumpy! (less and less as coldness decreases).

** **SIDM** (keV-TeV)
=> Evaporating subhalos
=> Cores at centers of galaxies (more or less concentrated, depending on baryons).

** **Sterile neutrinos** DM (~5-50 keV)
=> cutoff mass < dwarf galaxies
=> halos are smooth on mass/spatial scales < dwarf galaxies (~10^8Msun)
=> halos less concentrated than CDM

** **Dark sectors**
=> Get anything you want

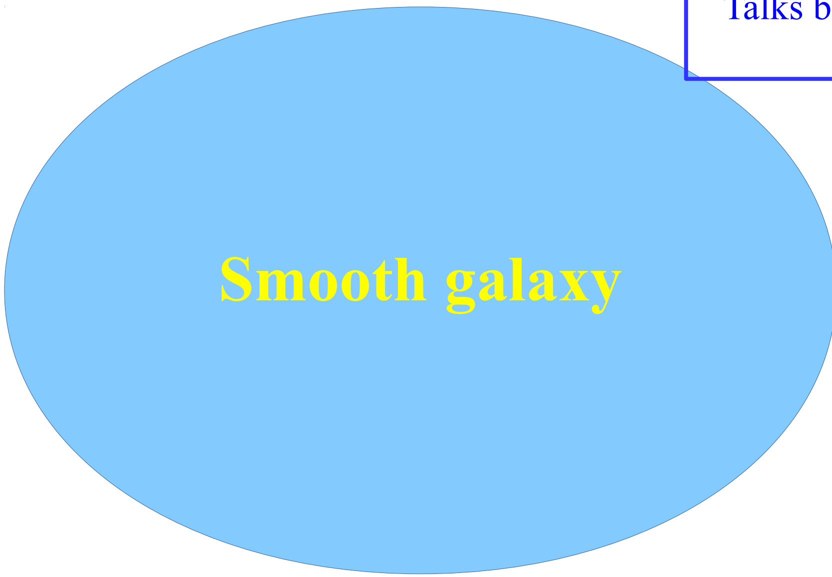
* **Non-thermal dark matter particles**

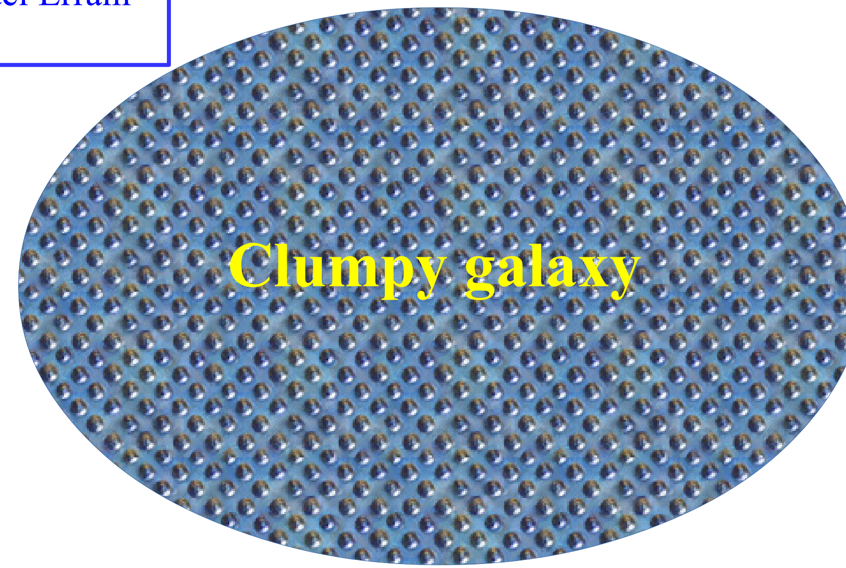
** **DM axion/s** (~ 100 μeV for the QCD axion DM)
=> depends on Peccei-Quinn symmetry broken before/after inflation
(i) before: abundance from misalignment mechanism
=> form "axion asteroids" of $10^{-12}M_{sun}$ (e.g. Kolb & Tkachev '93, Davidson & Schwetz '16).
=> cuspy halos with clumpy clumps! (depending on fraction of axion asteroids)
(ii) after: ~50% of axions come for string decays => asteroids + smooth DM.
=> cuspy halos with clumps

** **Ultra-light axion-like/bosonic DM** (down to ~10^{-22}eV)
=> extra-pressure + cores in halos => smooth cored halos with coherence features.

Graininess: Impact on DM searches

Talks by Go Ogiya, Raphael Errani and Martin Stref





Subhalos + PBHs: potential probes of the (primordial) power spectrum on unprecedented scales.

Gravitational signatures:
→ stellar streams, binaries, lensing, PBH merging rate.

Direct-like searches or effects: e.g. WIMP direct detection, axion haloscopes, capture by stars
→ total dynamically constrained density $\langle\rho\rangle = \rho_{smooth} + \langle\rho_{subhalos}\rangle$
=> ρ_{smooth} is smaller in principle (how much?), unless we are crossing subhalos
(remember that solar system constraints are $\langle\rho\rangle < \sim 10^{-20}$ g/cm^3 ($\sim 10^4$ GeV/cm^3) – e.g. Pitjev+'13

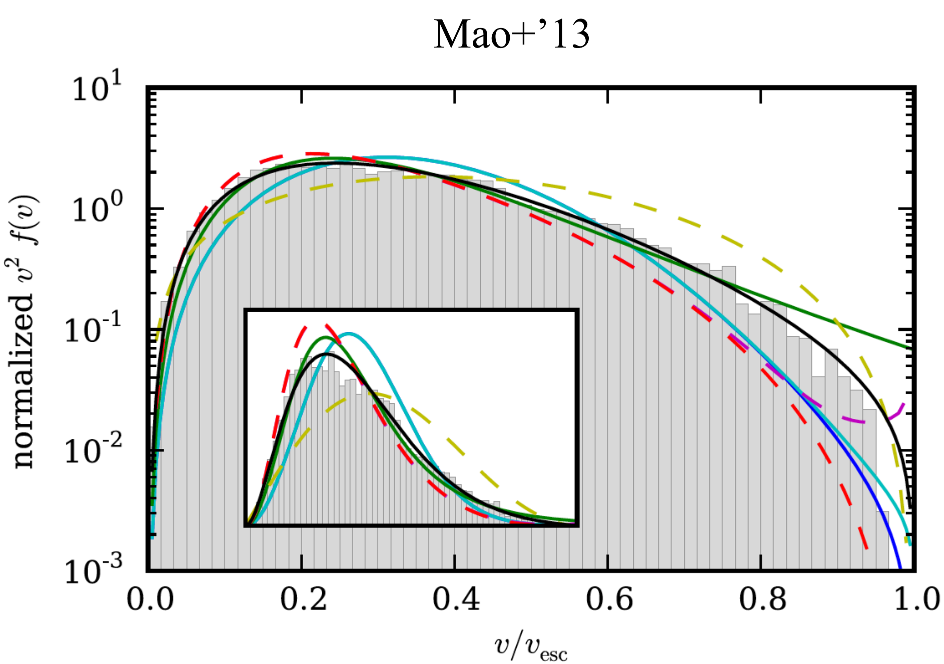
Indirect WIMP searches:
* WIMP annihilation signal prop to $\langle\rho^2\rangle$ => annihilation boost factor (depends on averaging volume)

$$\mathcal{B} = \frac{\langle\rho^2\rangle}{\langle\rho\rangle^2} \geq 1$$

(e.g. Silk & Stebbins '93)

DM phase-space distribution in the MW

Talks by James Binney, Giacomo Monari,
Thomas Lacroix, Arturo Nunez



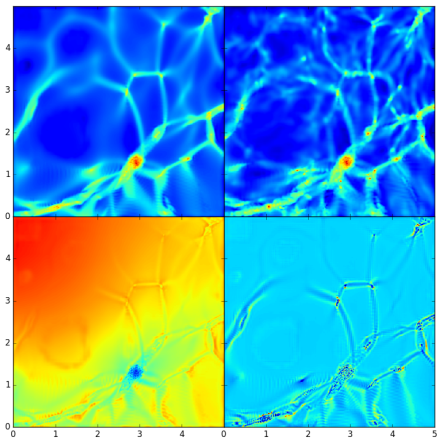
Relevant to:
*** Direct WIMP searches**
*** DM capture by stars**
*** v-dependent processes**
(e.g. p-wave annihilation, PBH microlensing)

Simulations:
*** f(v) not isothermal**
*** Provide insights on dynamical correlations between DM and baryons**

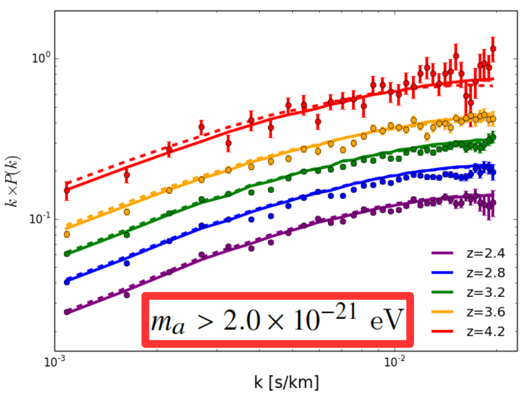
Simulations are not the Milky Way!
=> can be used to gain physical insight, not to predict detection rates in constrained systems.

=> Need other complementary theoretical tools: Self-consistent phase-space modeling

Important probes on small scales



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



Young universe:
reionization + first galaxies

A test of the power spectrum on small scales

→ Ly-alpha (Talk by Eric Armengaud)
→ 21 cm (Talk by Aurel Schneider)

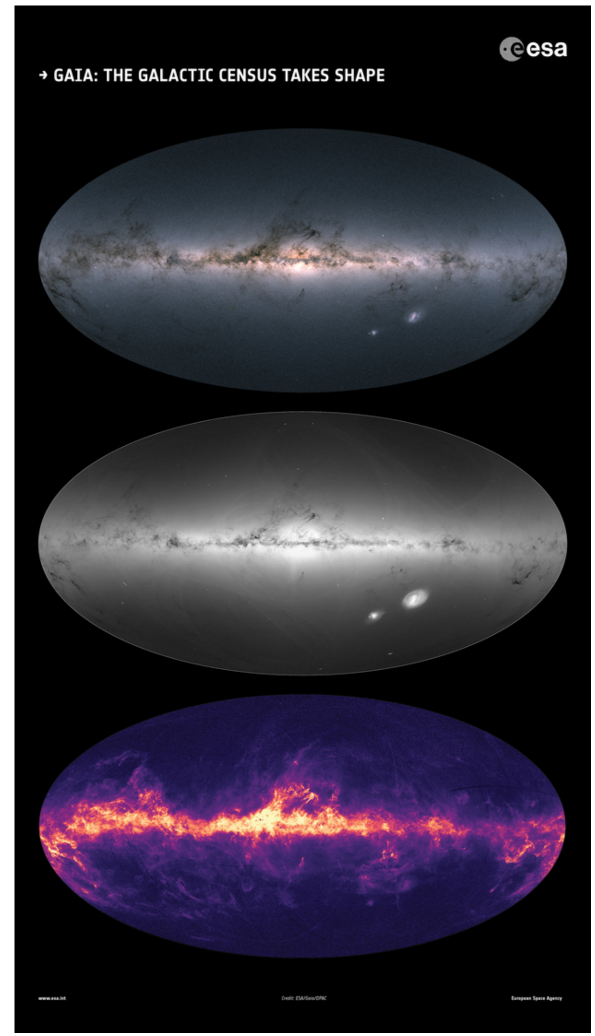
The very detailed dynamics of the Milky Way

GAIA!!!!

Data release n°2 end Apr. 2018

Review by David Katz

Interpretation:
James Binney, Giacomo Monary



See also:
Ly-alpha:
→ Irsic+'17 m22>20
Dwarf galaxies:
→ Calabrese+'16: m22<5
Abundance of HFF ultra-faint lensed galaxies:
→ Menci+'17: m22>8

Summary

Structure formation: small-scale issues

- **→ inspected through cosmological simulations**
- **→ impact of baryons / star formation**
- **→ alternative solutions to CDM (?)**
- **→ insight on DM features relevant to DM searches**

Galactic dynamics:

- **→ Make sense of observations**
- **→ Consistency of dynamical relations between baryons and DM**
- **→ Constraints of DM (phase-space) distribution**

Astro/particle physics:

→ combine particle physics properties with astro/cosmo constraints to define/assess potential of DM search strategies

=> Rationale to establish stronger links between communities

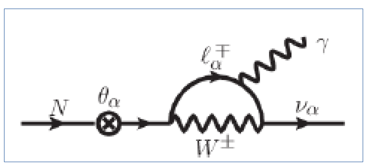
BACKUP

Sterile neutrino (W/C)DM

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

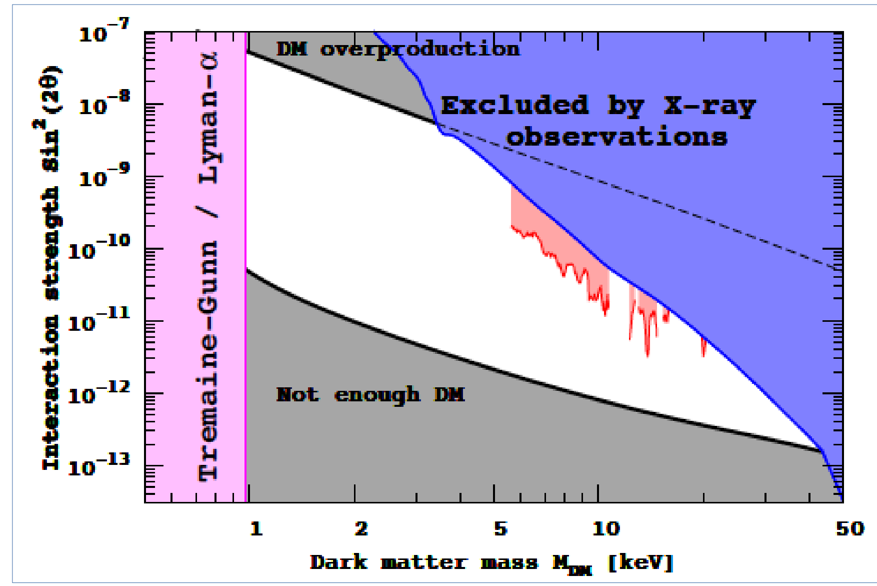
→ Neutrino masses (see-saw)
→ Leptogenesis
→ DM candidates (more or less warm)
→ keV mass range (!= thermal mass)

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

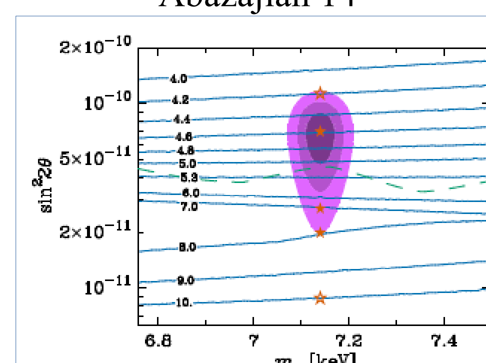


$$\Gamma_{N_1 \to \gamma\nu} = \frac{9\,\alpha\, G_F^2}{1024\pi^4} \sin^2(2\theta_1)\, M_1^5$$

Boyarsky+ '13



Abazajian 14



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)

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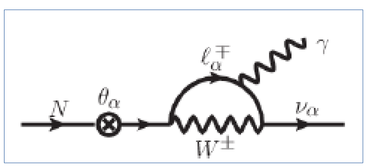

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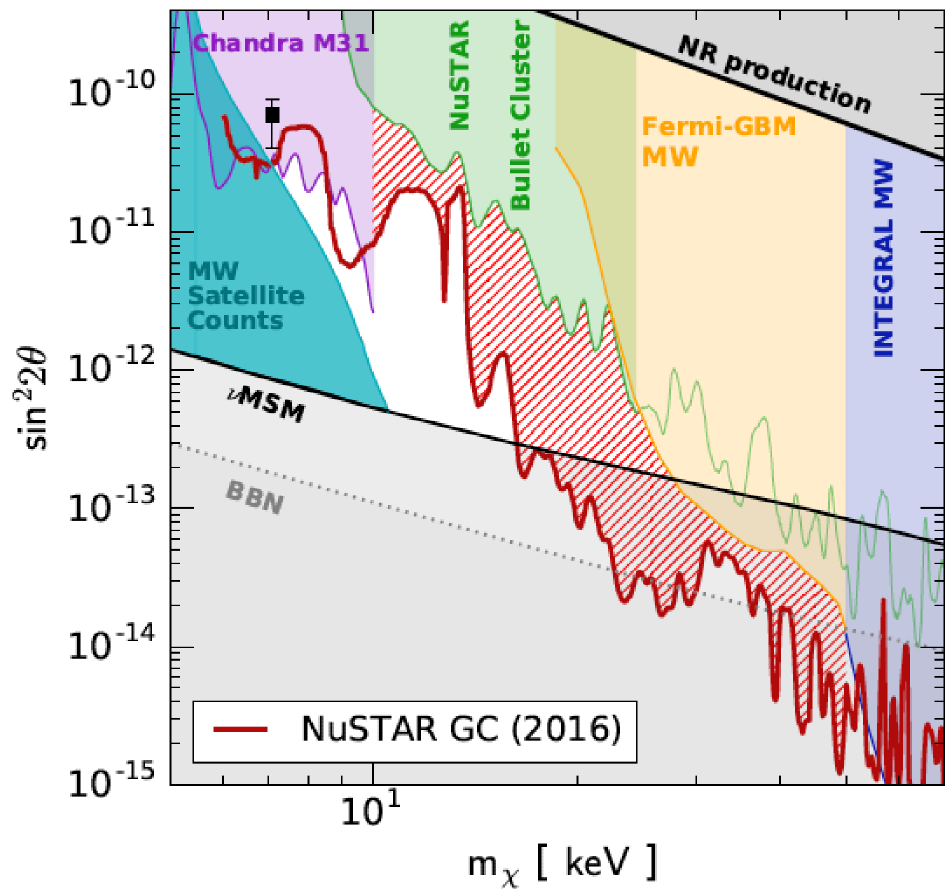
Perez+ '16
(also Neronov+'16)



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Talk on WDM by
Aurel Schneider

Axions

(+ axion-like particles + dark/hidden photons = WISPs)

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

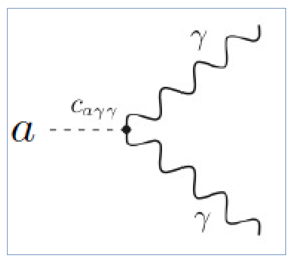
Talk by David Marsh

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

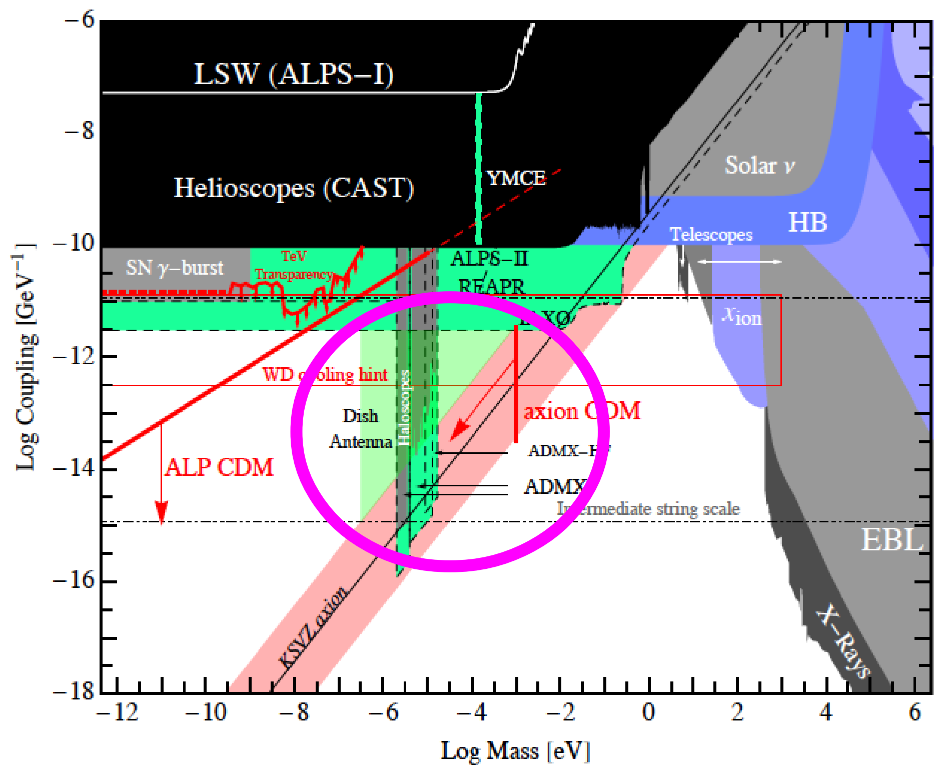
$$\mathcal{L} \supset \frac{\alpha_s}{8\,\pi} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

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

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



Essig+12



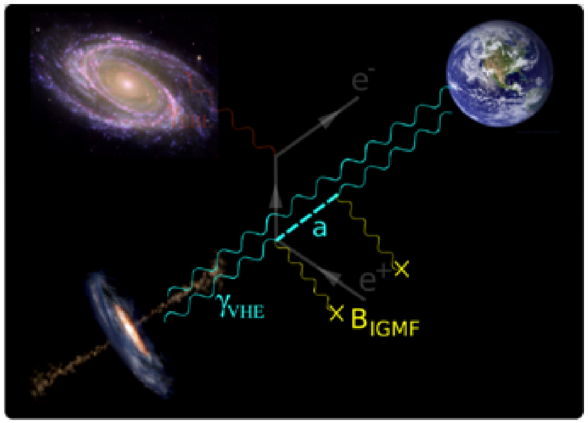
Aspects relevant to cosmology:
* non-thermal remnants => expected ultra-cold DM
→ minimal mass scale ~ 10^{-12} Msun subhalos
→ detailed structure formation under study

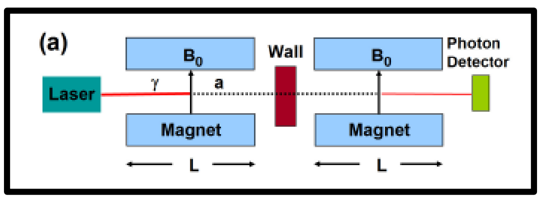
Detection (main):
* from interactions with photons: conversion
→ e.g. ADMX (ongoing): conversion of DM axions into photons

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

Axion searches

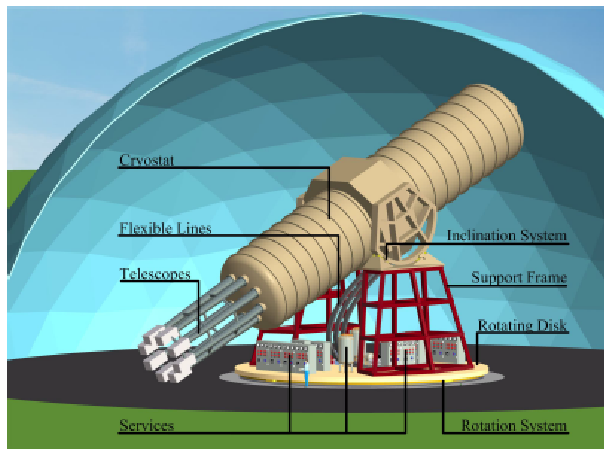
TeV blazar gamma-ray conversion to axions
e.g. HESS-CTA





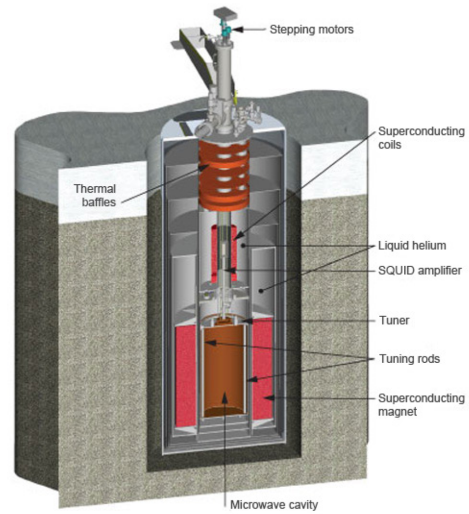
"Light shining through a wall"
(laser + B-field + wall)
e.g. ALPS@DESY

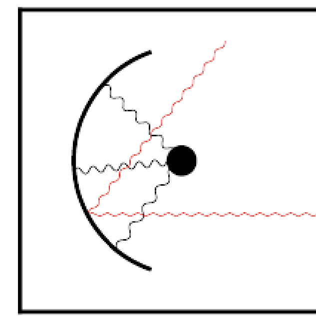
Not sensitive to DM



Helioscopes
CAST + IAXO @ CERN
B-field + micromegas

Sensitive to DM axions (irrespective of local DM density)

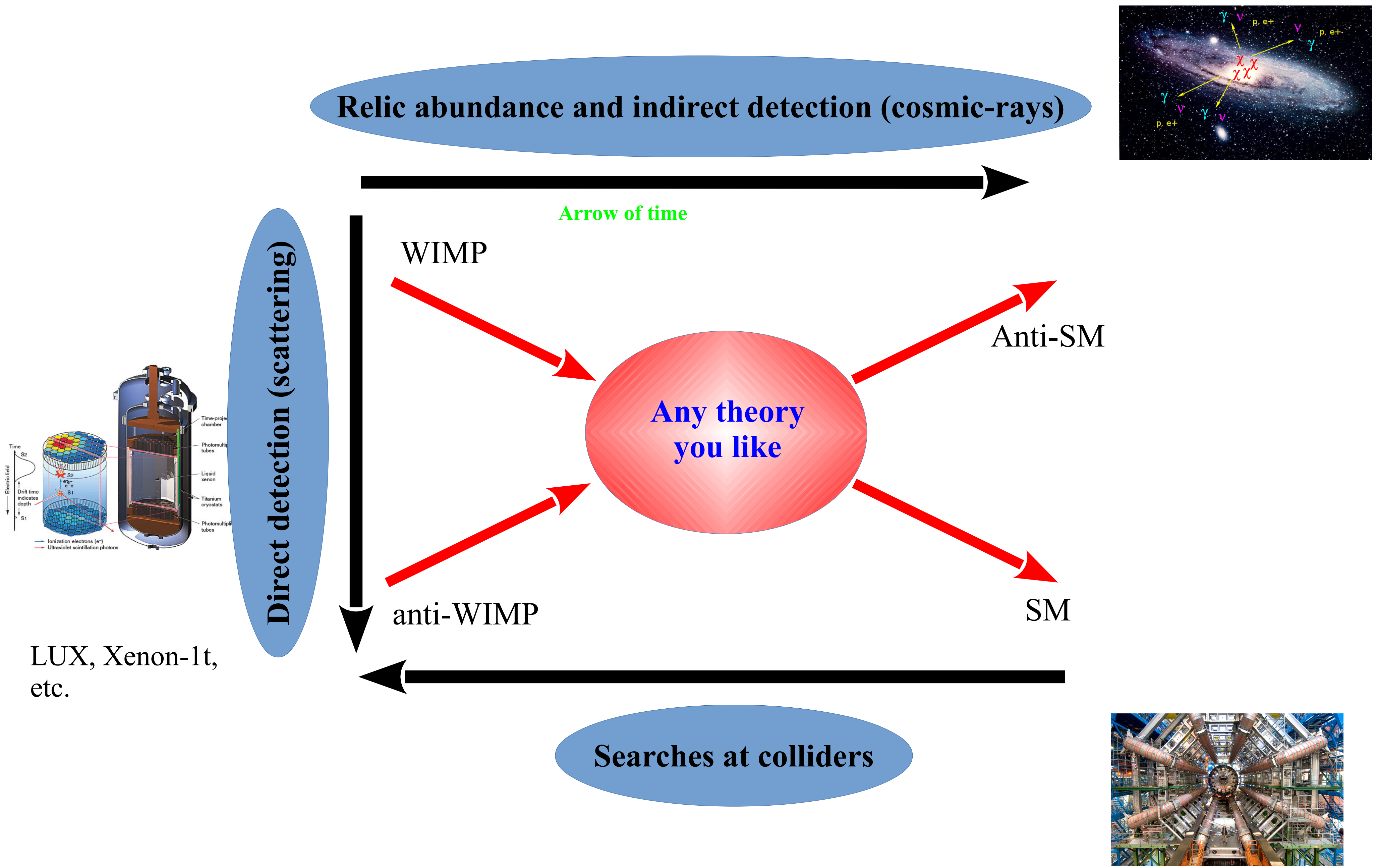




Haloscopes
Microwave cavities / dish antennae
B-field + detector (~GHz)

Needs that local DM density is made of axions

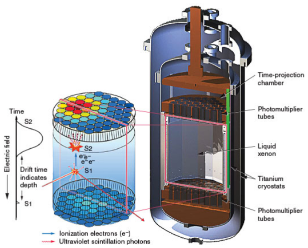
WIMP searches



Astro/particle complementarity

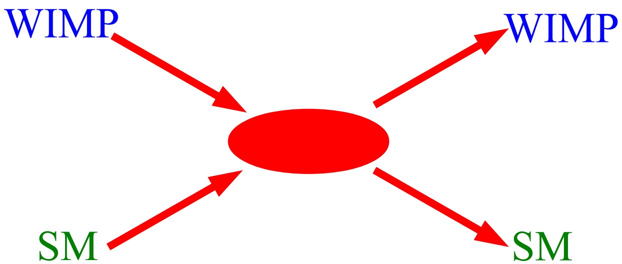
Direct detection rate – WIMP-matter scattering

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



Scattering

($\rightarrow$ kinetic decoupling in early universe)



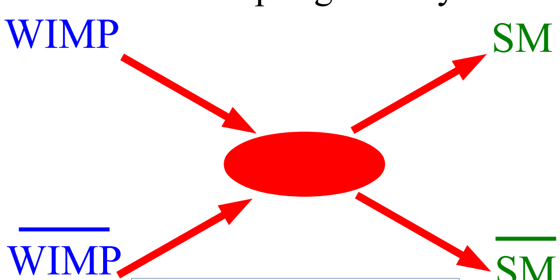
$$\Gamma_{\mathrm{scat}} = \langle \sigma_{\mathrm{scat}}\, v\rangle\, n_{\mathrm{plasma}}$$

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

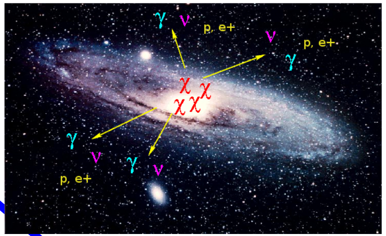
Dark matter profile + phase space
(+ cosmic-ray transport)
=> constrained by Milky Way-mass model
(full gravitational potential DM +
baryons)

Annihilation

($\rightarrow$ chemical decoupling in early universe)



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

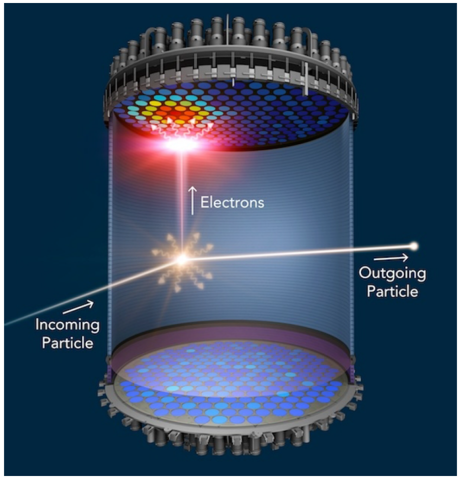


Indirect detection rate (e.g. gamma rays)
– WIMP annihilation

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

Direct DM searches: recent results

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



Aprile+'17