Origin of Dark Matter:
Theoretical review and complementarity of searches

Julien Lavalle
LUPM – CNRS-IN2P3 – U. Montpellier
(on behalf of a bunch of people from several IN2P3/INP/INSU labs)

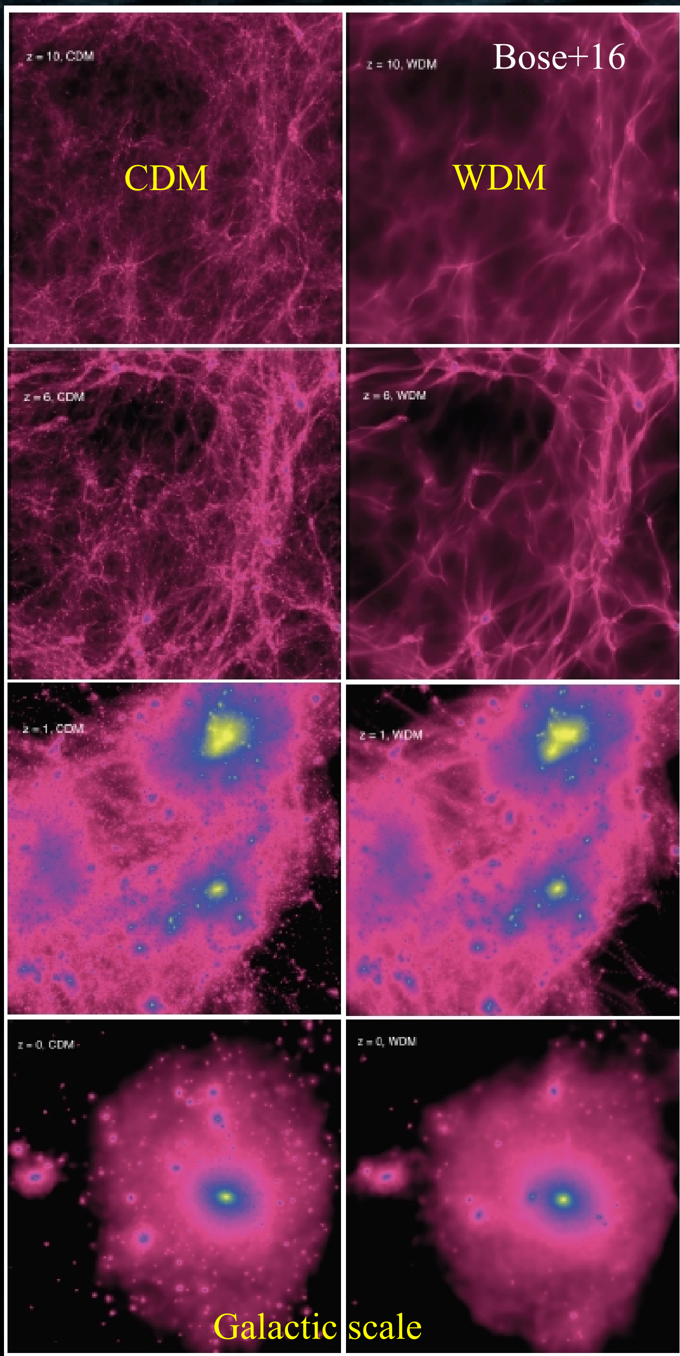
Prospectives IN2P3 2020 – GT04 Neutrinos et Matière Noire

Bordeaux, 28 October 2019

Much less theoretical contribs submitted than actual effort!

Contribs from:
IPNL
and
LAM+LAPTh+LPSC+LUPM+Obs.Stras. (IN2P3/INP/INSU)

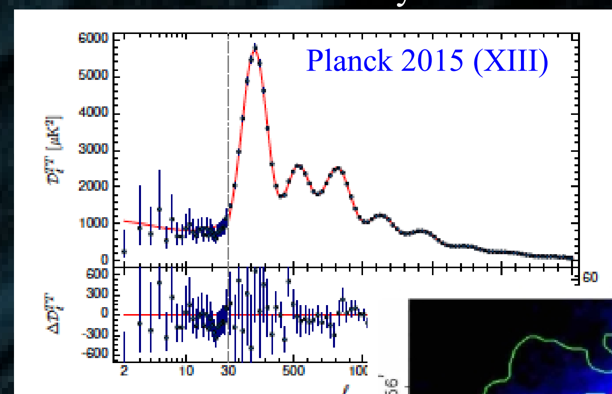
The cold Dark Matter (CDM) paradigm

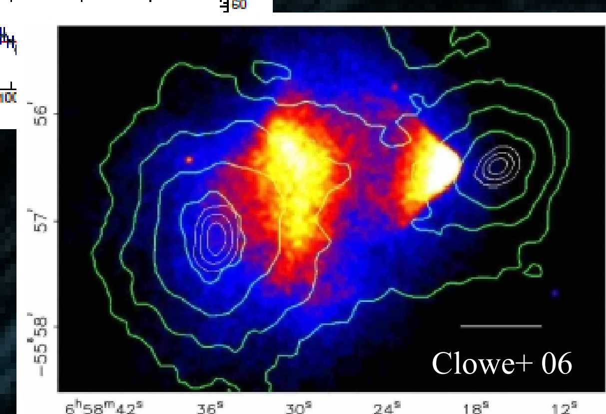


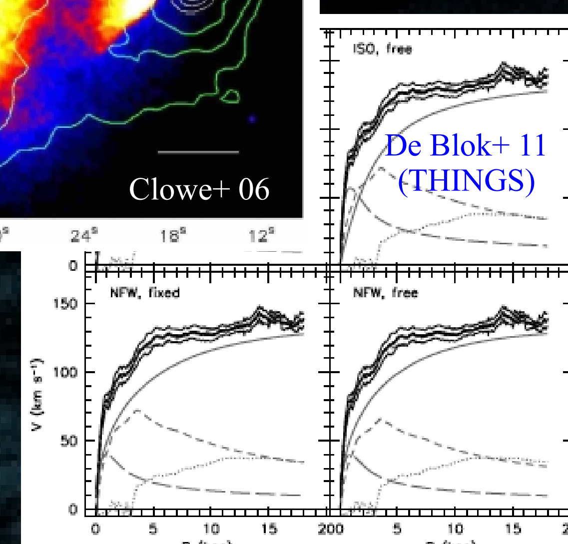
So far, only gravitational evidence for DM
(cosmological structures+CMB)

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)







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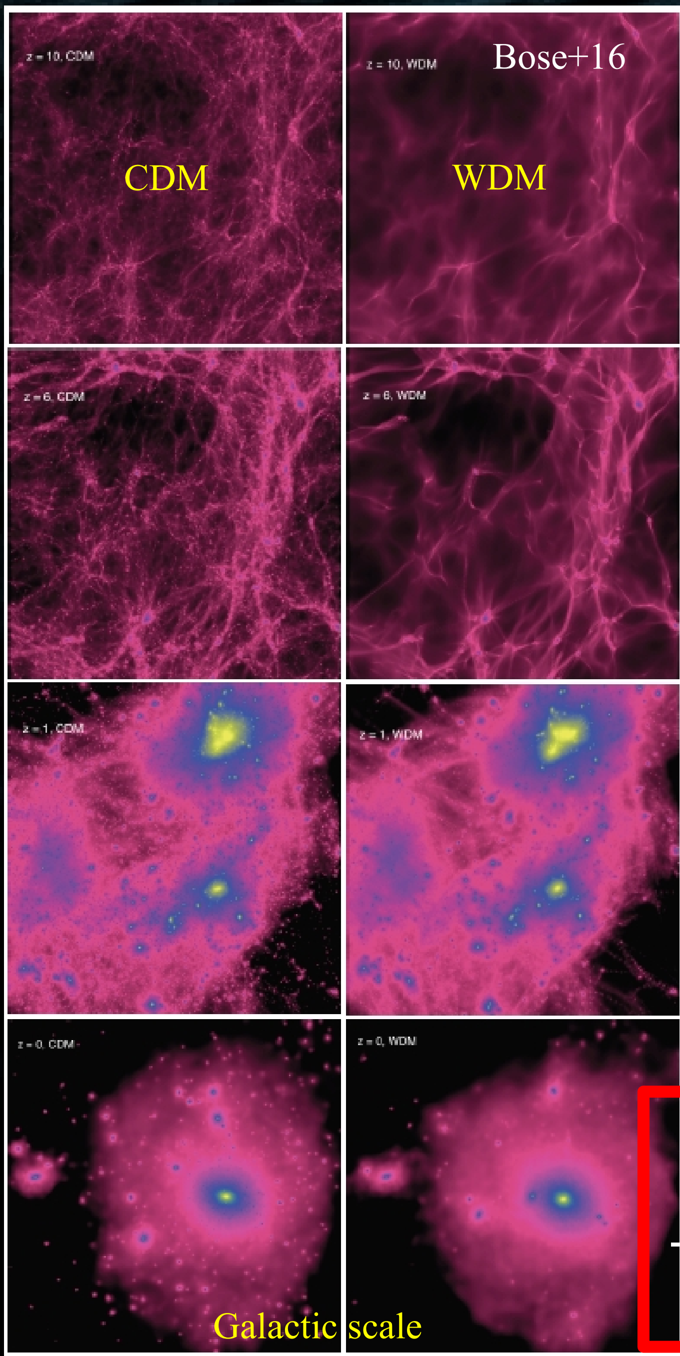

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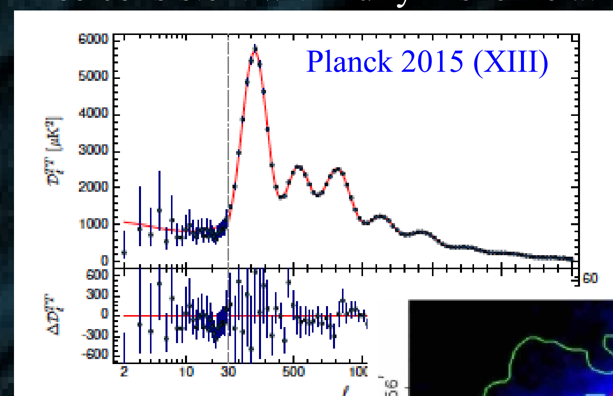
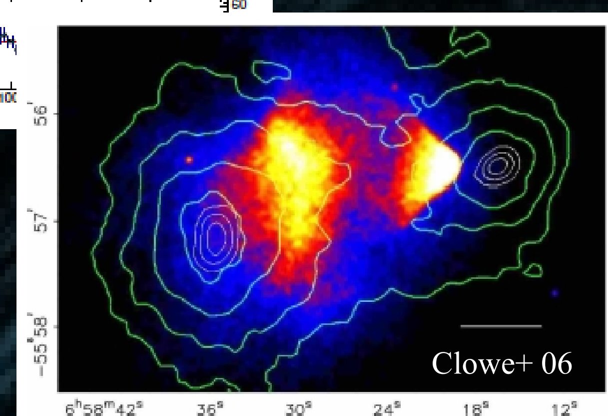
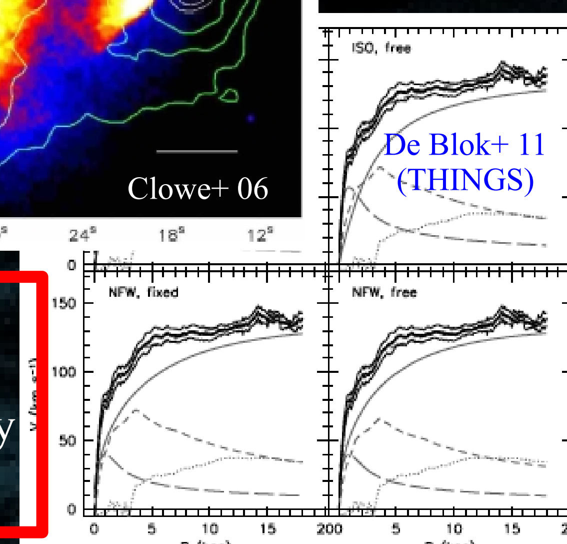




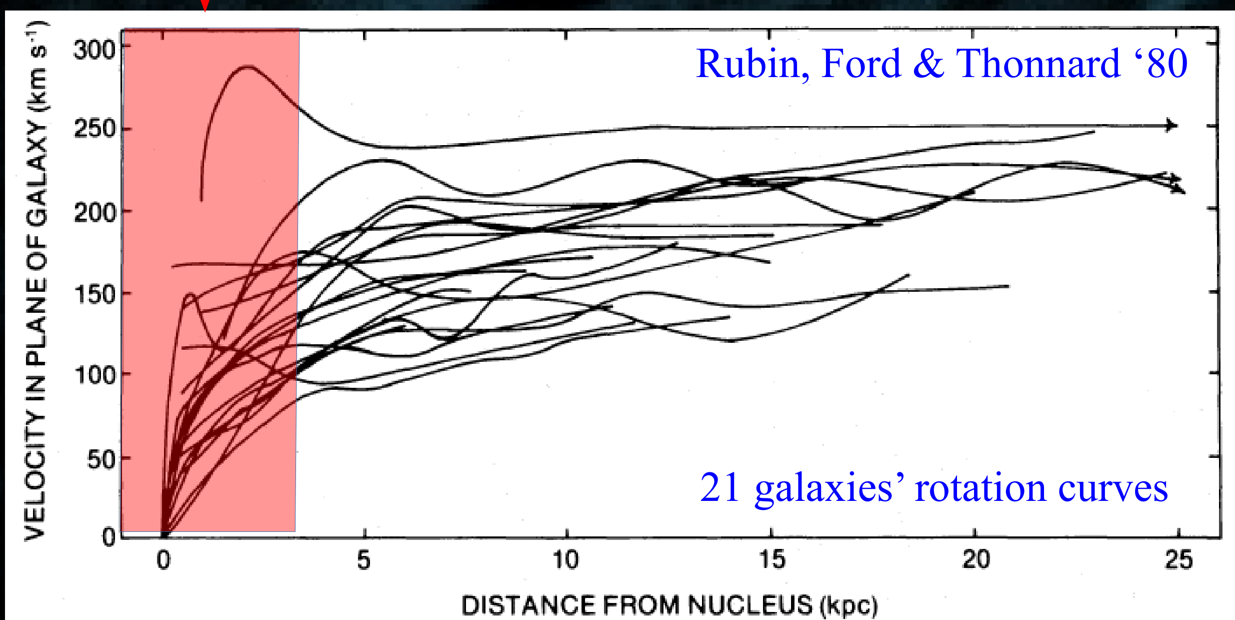


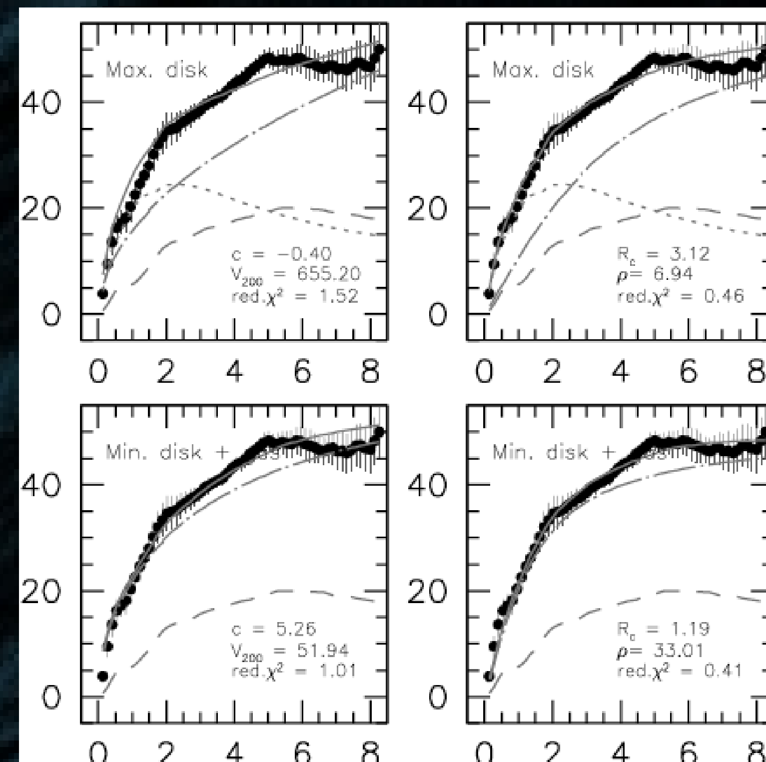
Not a 2-sigma tension
Assumptions:
- General relativity applied to cosmology
- Standard particle + nuclear physics

Dark Matter on galactic scales

Bulk of luminous matter

Oh+11





Ostriker+'74 => spherical dark matter halos!

* Keplerian decrease of rotation velocity not observed
* Stars and gas not bounded to the object unless invisible mass there
=> Spherical dark matter halo could explain this + natural stabilizer

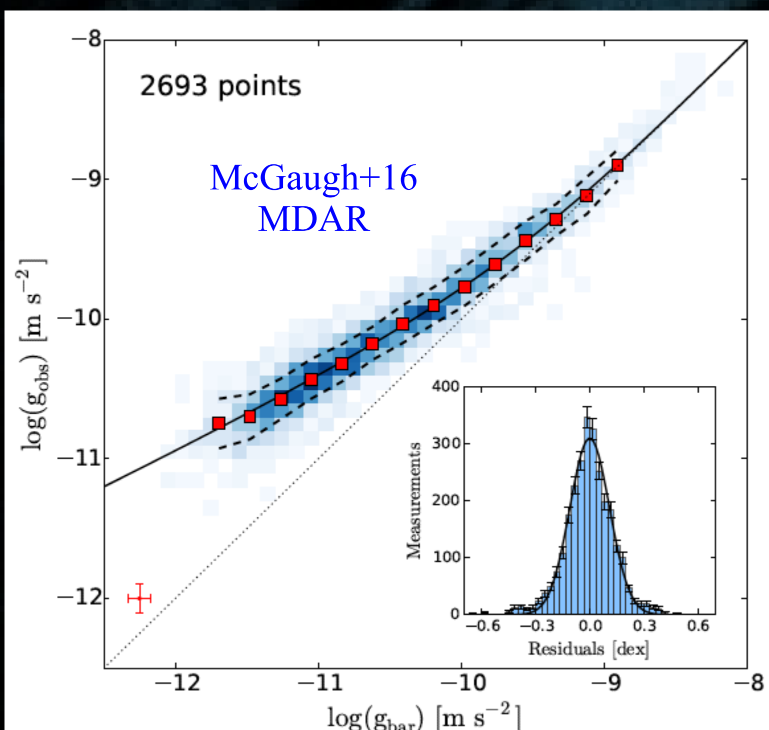
CDM issues on small (subgalactic) scales

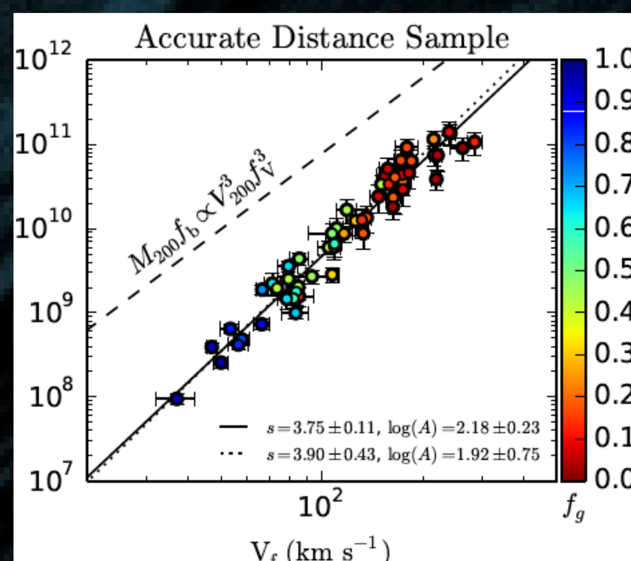
Small-Scale Challenges to the ΛCDM Paradigm

arXiv:1707.04256

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

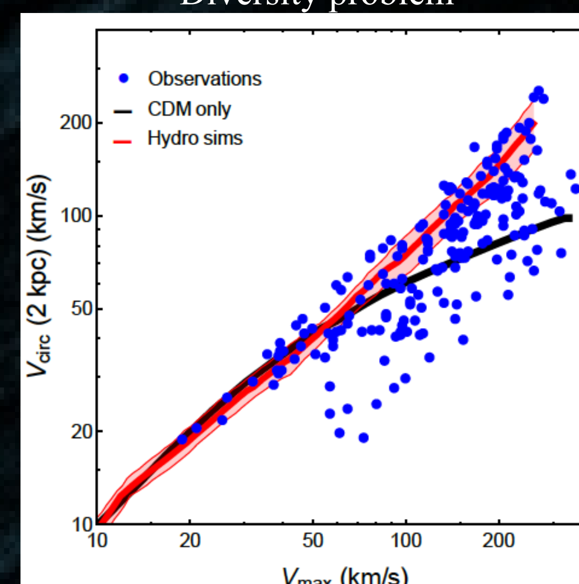
[1]Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA; email: bullock@uci.edu
[2]Department of Astronomy, The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, TX 78712, USA; email: mbk@astro.as.utexas.edu





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?

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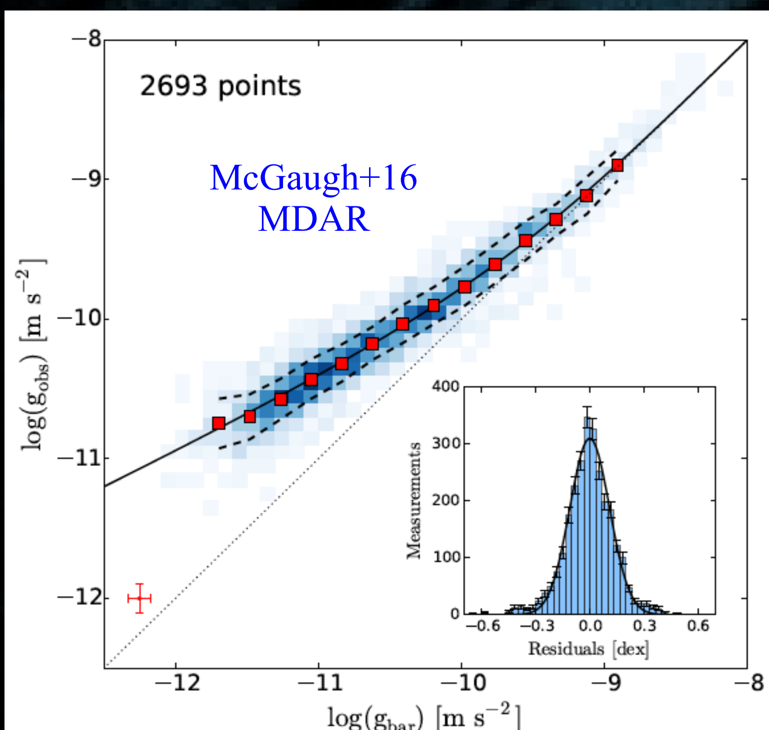
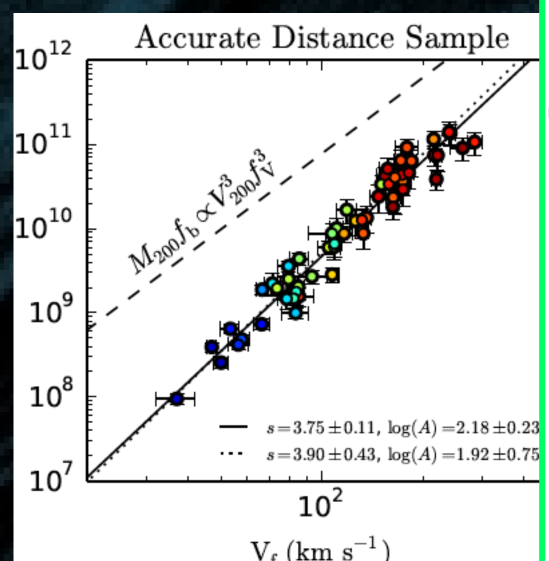
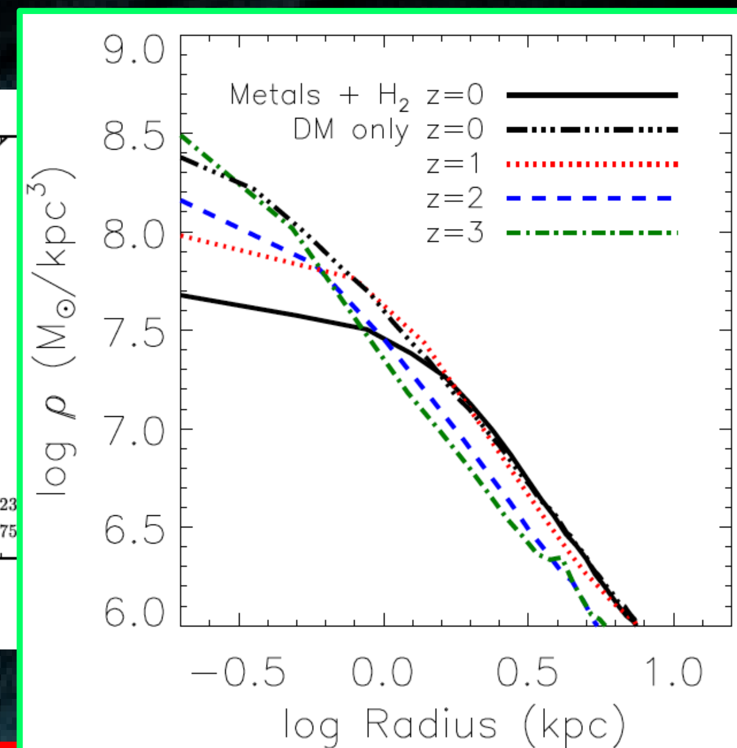




Lelli+15, BTFR

Governato+12
Cusps→cores



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Generic constraints on DM particles

→ **Assume 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!**

Fermions: **the Tremaine-Gunn limit ('78) => use dwarf galaxies as test systems**

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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

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

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

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

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

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

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Lower mass bounds only!
(except for unitarity constraints – thermal case)
↔ m < 100 TeV
(see Griest & Kamionkowski '90)

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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
but SI cross sections bounded
→ Possibility of entire dark sector(s)

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

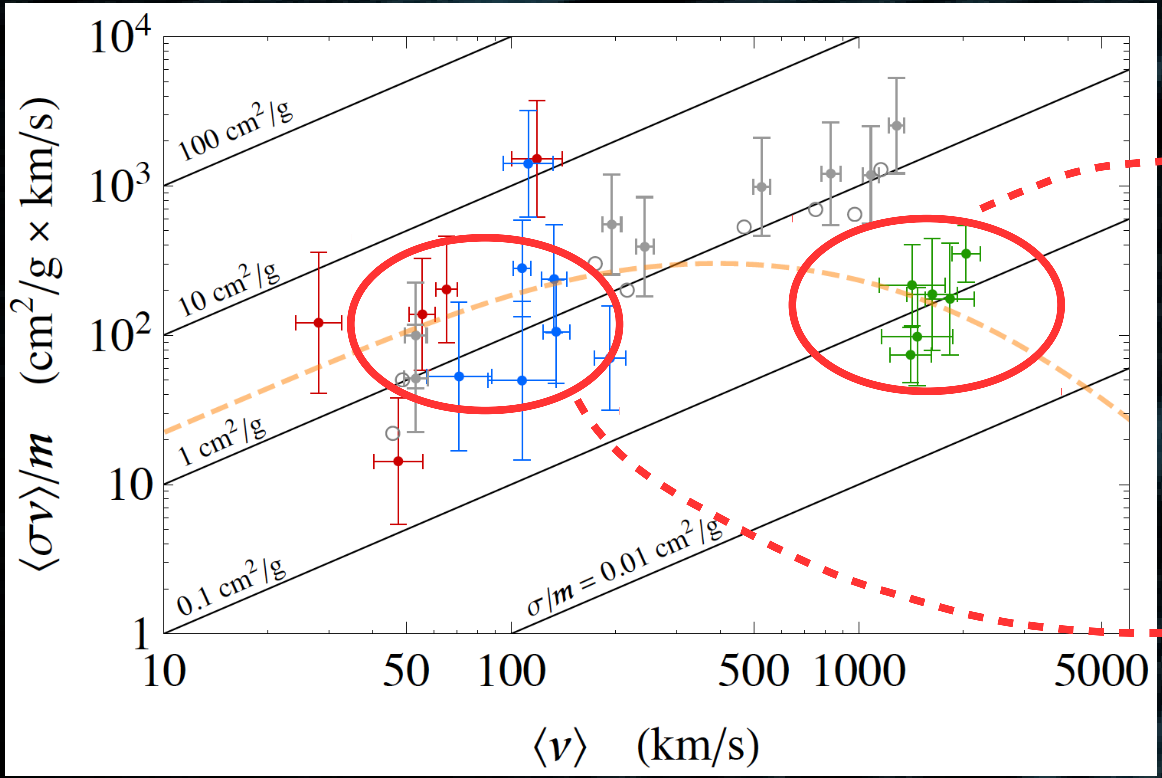
Original proposal by Carlson+'92

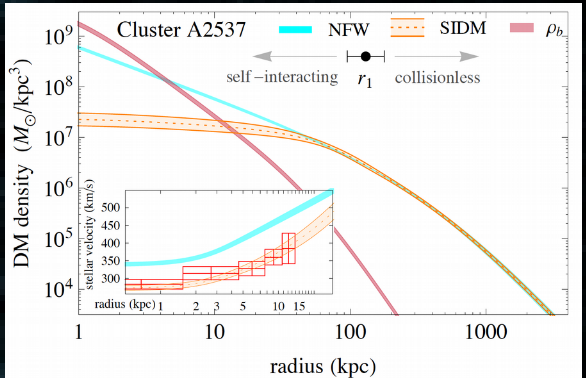
To solve core-cusps (e.g. Spergel+'00, Calabrese+'16)

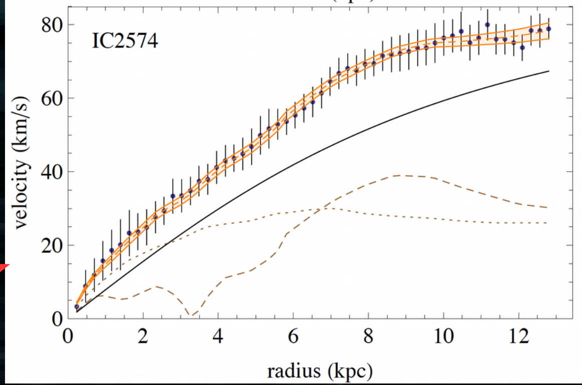
Dynamics of clusters (Kaplinghat+'15)

(Self-interacting dark matter – SIDM)

Kaplinghat+'15
See also review in Tulin & Yu '17







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

Model building

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)

*** Motivation from Cosmology**
- scalar field cosmology (for the sake of itself)
- non-minimal inflation (primordial black holes)

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

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

Model building

Two main approaches

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

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

δm_H^2 **Challenged by LHC** $- y_t^2 \big]$

(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

STANDARD
NEW
STANDARD

DM: neutralino, sneutrino, gravitino, etc.

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

*** Bottom-up**
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+++ Production mechanism/s
+++ DM phenomenology with a minimal set of parameters => predictive
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Status of current searches

*** WIMPs (thermal DM)**
+ “Portal models”

- Many ongoing experiments (multiwavelength, multimessenger + laboratory)

- Sensitivity in the right ballpark for mass range 10-100 GeV => many constraints

- Still to probe: m<10 GeV, m>100 GeV

- Gamma-rays, cosmic rays, CMB, 21 cm, collider+lab searches, impact on stellar evolution, gravitational searches.

*** Axions**

- Several ongoing experiments (probe conversion of axions to photons, absorption of photons)

- QCD axion: mass range (10μeV) not reached yet.

- Axion-like particles (ALP, e.g. ULA): ongoing studies, astrophysical probes.

*** Sterile neutrinos**

- Excitement after the 3.5 keV line (evidence disputed)

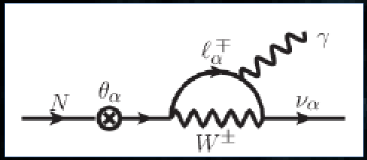
- Tiny room left in parameter space from structure formation (Ly-alpha) and X-ray constraints.

Sterile neutrino (W/C)DM

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

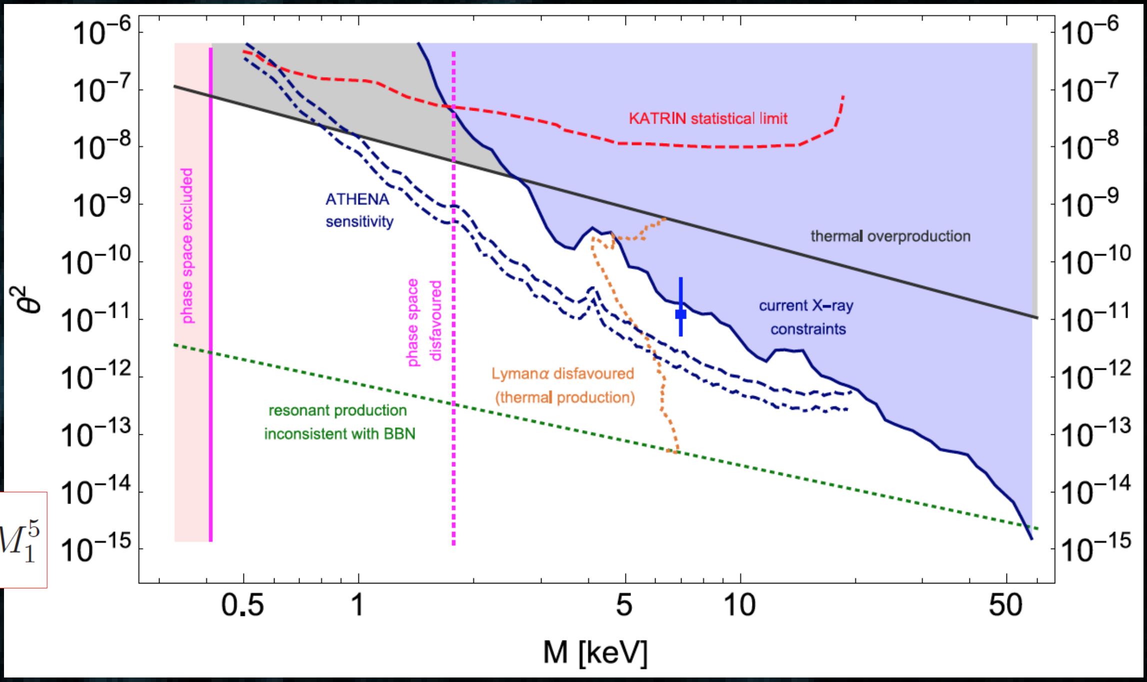
→ Neutrino masses (see-saw)
→ Leptogenesis
→ DM candidates (more or less warm)
→ keV mass range (!= thermal mass)

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



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

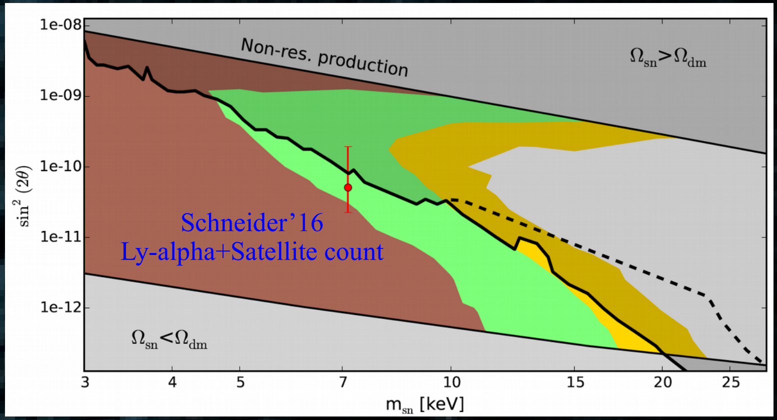
Boyarsky+ '19
(very conservative X-ray limits)



Aspects relevant to cosmology:
* suppress power on small scales
→ viable? (e.g. Schneider '16)
* current limits on thermal masses > 1-10 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)
→ Hitomi excludes excess in Perseus cluster (1607.07420 see also 1608.01684)

Constraints: Resonant-production mechanism almost excluded ------------------ →



Sterile neutrino (W/C)DM: a strong case + technical case

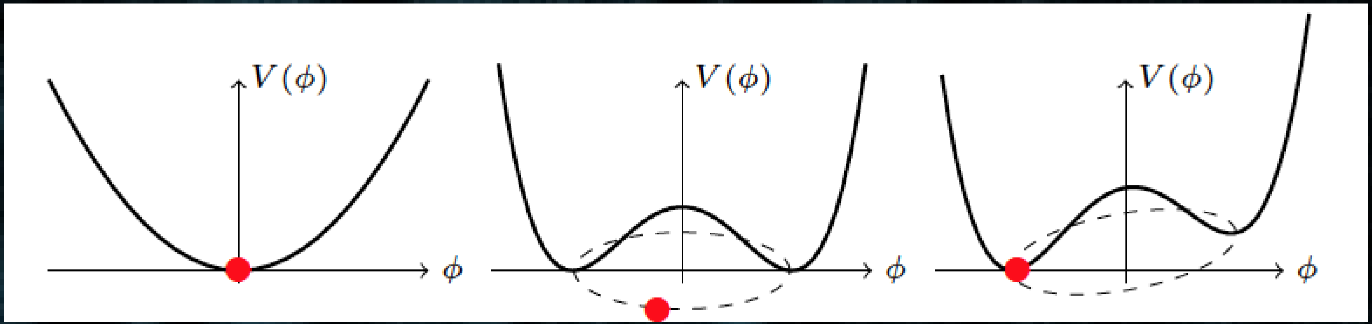
A theoretically appealing scenario
- Neutrino masses + leptogenesis (independent from DM)
- Parameter space rather well defined in minimal scenarios => predictive: ~ 5-50 keV
- Warmish/Coldish DM candidate: suppression of power spectrum on small scales (no subhalos expected)
- Next generation X-ray telescopes (e.g. Athena will tell) + small-scale probes (e.g. Ly-alpha, 21 cm)

Technicalities
- Fine-tuned (e.g. resonant production)
- Sterile neutrino DM not involved in leptogenesis (can be model dependent)
- Very technical (relic density calculation difficult)
- Non-minimal scenarios (e.g.embedded in GUTs, SUSY, etc.) cumbersome
- Complementarity between searches is model dependent (e.g. double-beta decay)

Sterile neutrinos in France (theory)

(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

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

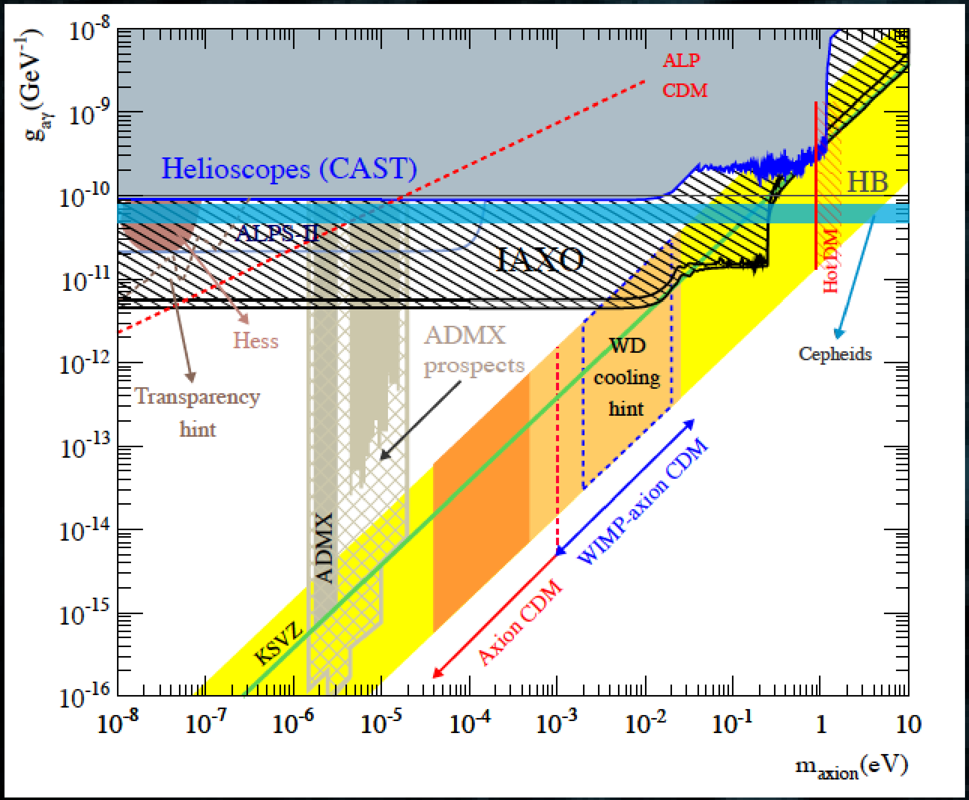
NB: QCD axion needs physics beyond standard model
Production mechanism (relevant to DM axions):
* Misalignment mechanism (generic)
* Decay of topological defects (if PQ broken after inflation)
⟶ compact axion asteroids! (f~0.5) – Tkachev'86
* m << eV => large occupation # => classical field
* QCD axions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

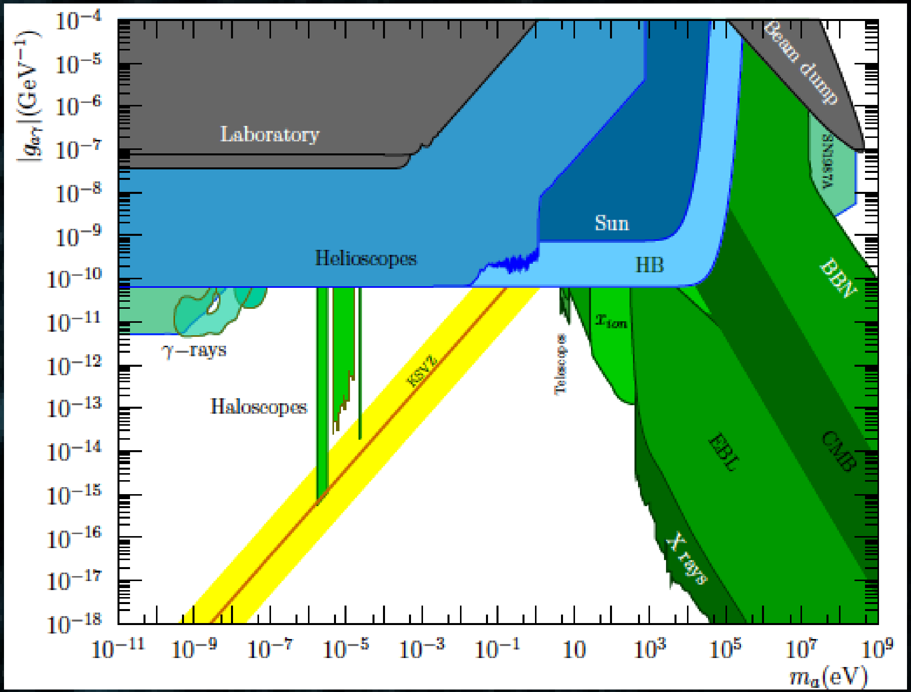
$$\Omega_a h^2 \sim 2\times 10^4 \left(\frac{f_a}{10^{16}\ \mathrm{GeV}}\right)^{7/6} \langle\theta_{a,i}^2\rangle$$

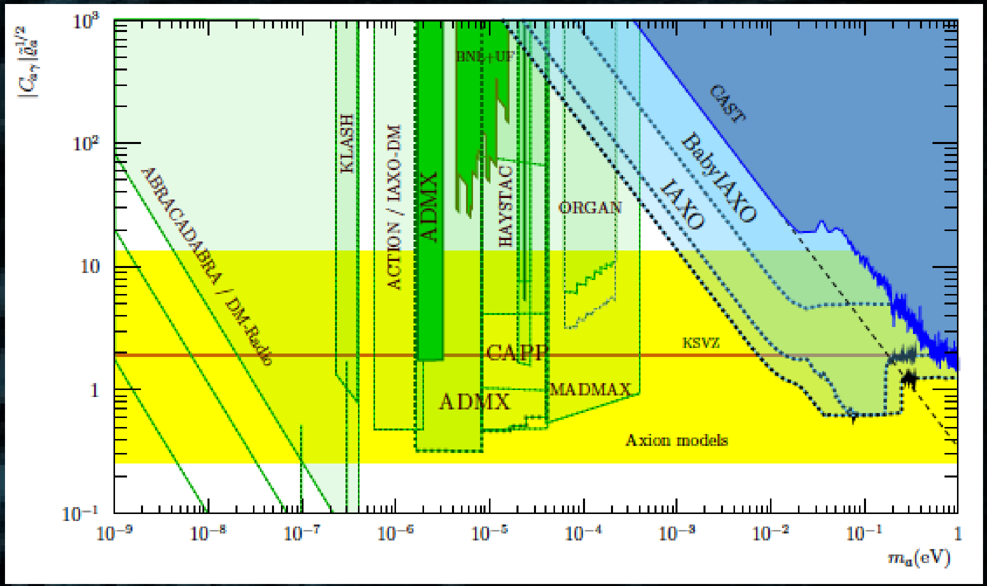
$$m_a^2 = \frac{m_\pi^2 f_\pi^2}{(f_a/N_{\mathrm{DW}})^2}\frac{m_u m_d}{(m_u+m_d)^2}$$

Axion cosmology
(review)
Marsh'15

Constraints on QCD axions







See reviews in
Marsh'15 + Irastorza & Redondo '19

=> QCD axions viable candidates
(very cold DM)

QCD axions: strong theoretical case + rich pheno

An appealing scenario:

- Motivations independent from cosmology: the strong CP problem

  [non-QCD axions motivated by string theory – less compelling for the moment]
- Pending theoretical uncertainties, well defined and small parameter space
- Light + electromagnetic interactions: can be probed from experiments "on the table" + many astrophysical phenomena (e.g. stellar physics)
- Clustering properties (post-inflation scenarios)? A possible issue for haloscopes

Challenges:

- Very hard to detect in labs (amplification + magnetic fields)

  [But historically very active collaborations between theorists and experimentalists]

Further motivations for light bosons or ALPs?

- Small-scale issues in CDM [ULAs … but start to be in trouble]
- Early dark energy [Hubble tension]
- …
- A playground for theorists! e.g. self-gravitating boson stars, early universe, phase transitions, etc.

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

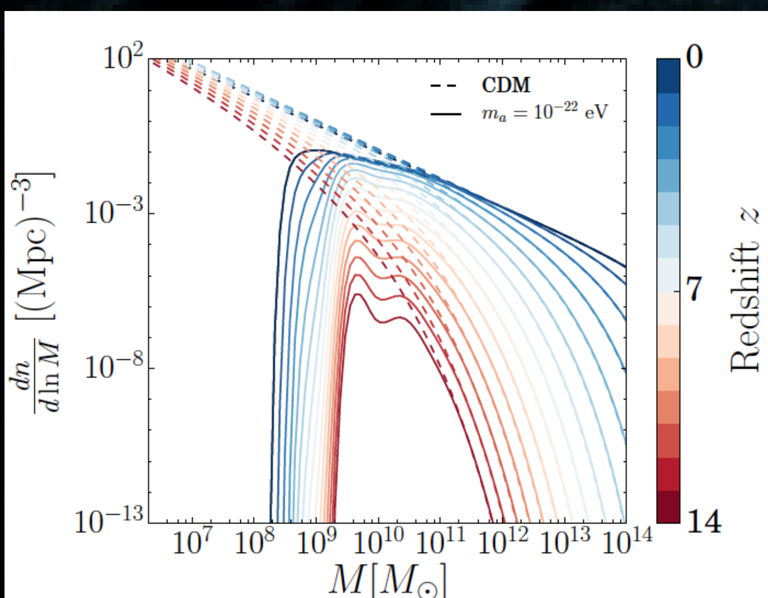
Hu+00, Peebles'00, Marsh+15, Hui+16, Schive+14, Du+18, etc.

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

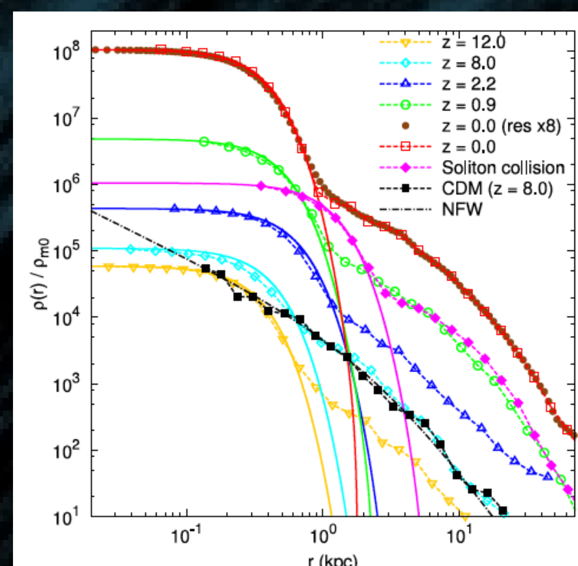
Main properties:
*** Suppression of small-scale perturbations**
*** incoherent interference pattern and granularity on scales ~ 1-100 kpc**
*** formation of solitonic cores at halo centers**
*** core/cusp solved in galaxies if m~10^{-22} eV**

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

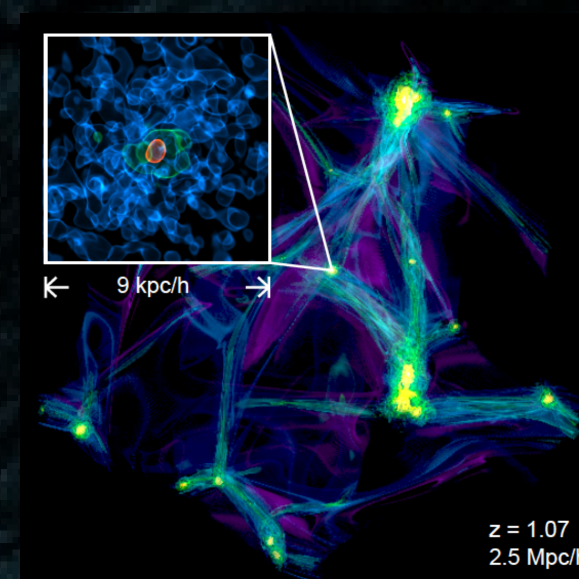
$$\nabla^2\Phi = 4\pi G m_a|\psi|^2$$



Bozek+15
Halo mass function

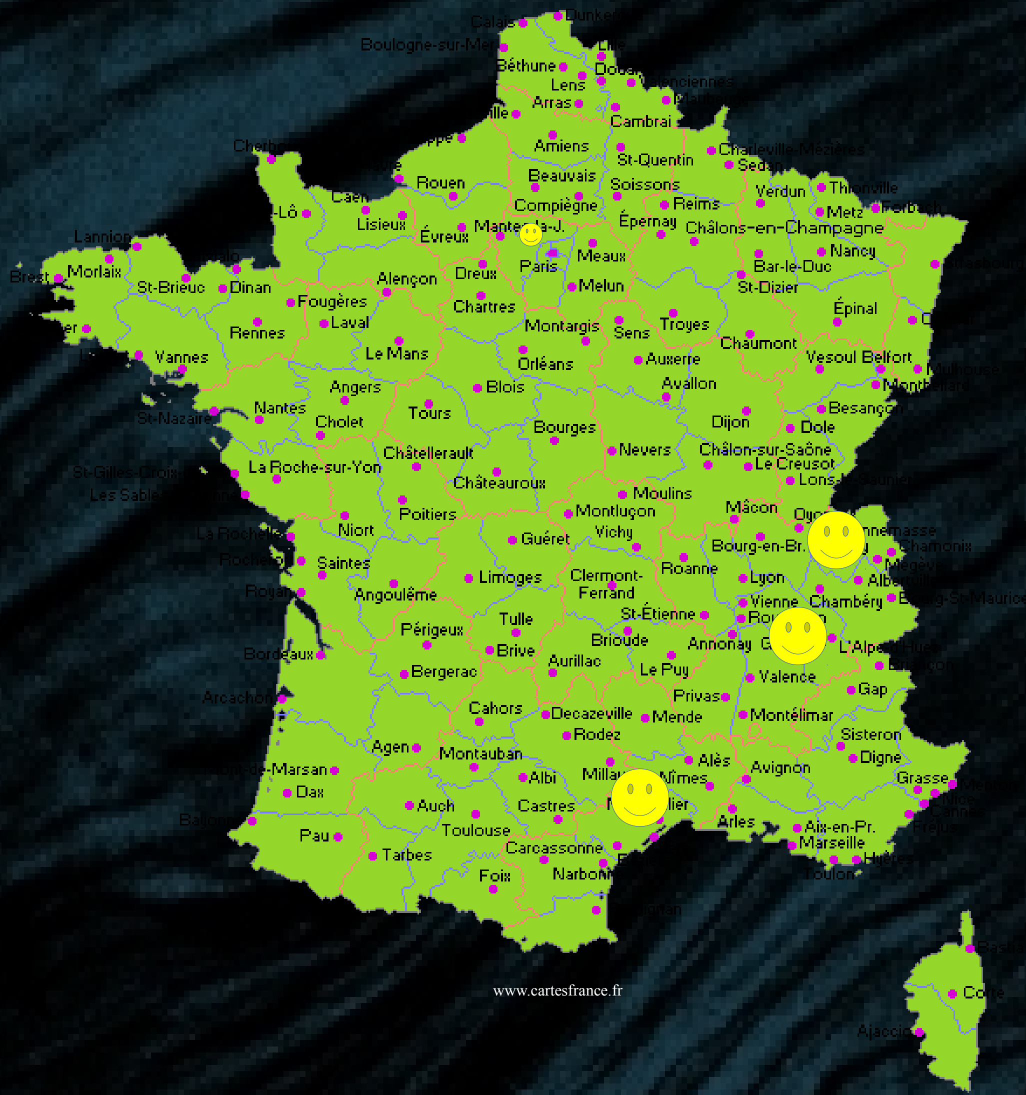


Schive+14
Solitonic cores in
Fuzzy DM simulations



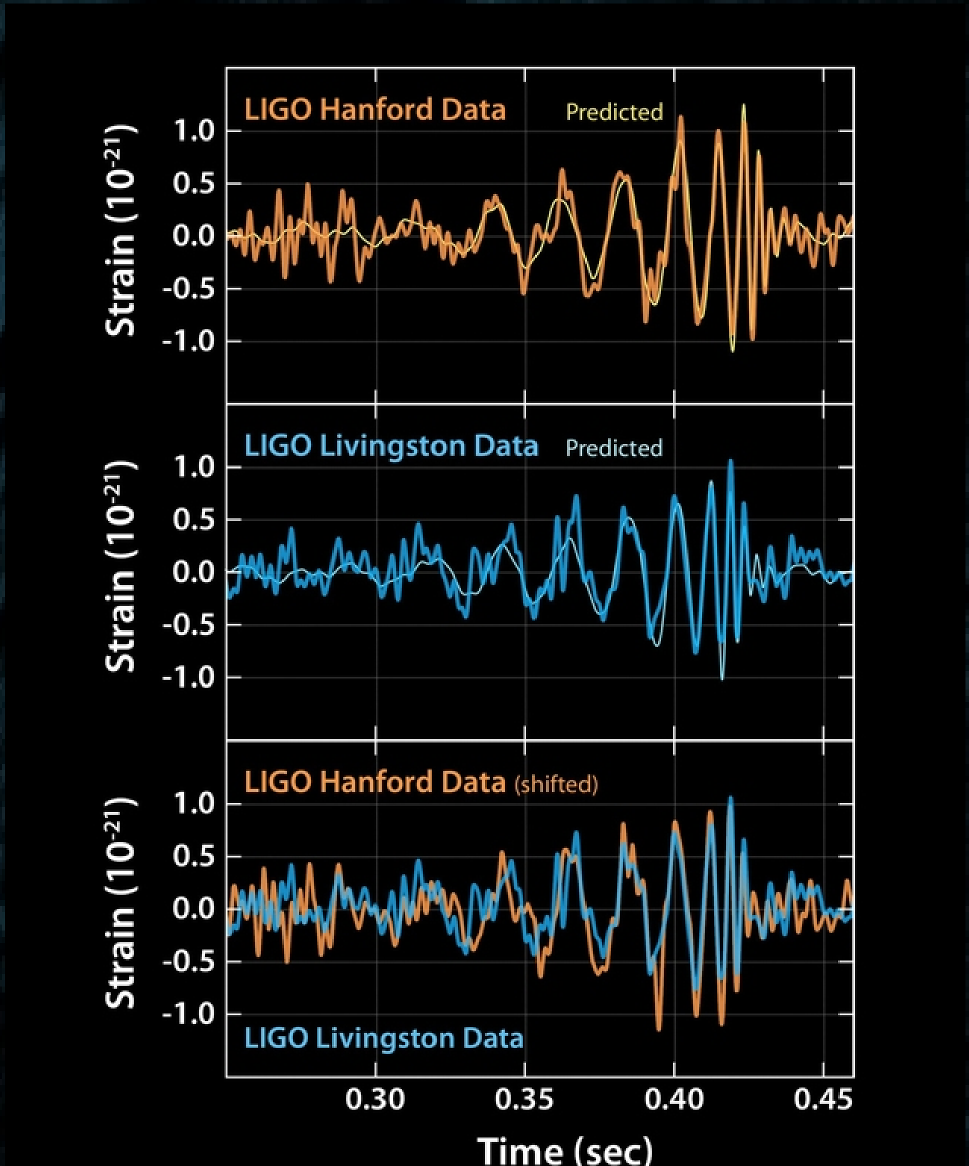
Veltmaat+18
Evolution of solitonic cores

DM axions in France (theory)



Black holes as DM?

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]

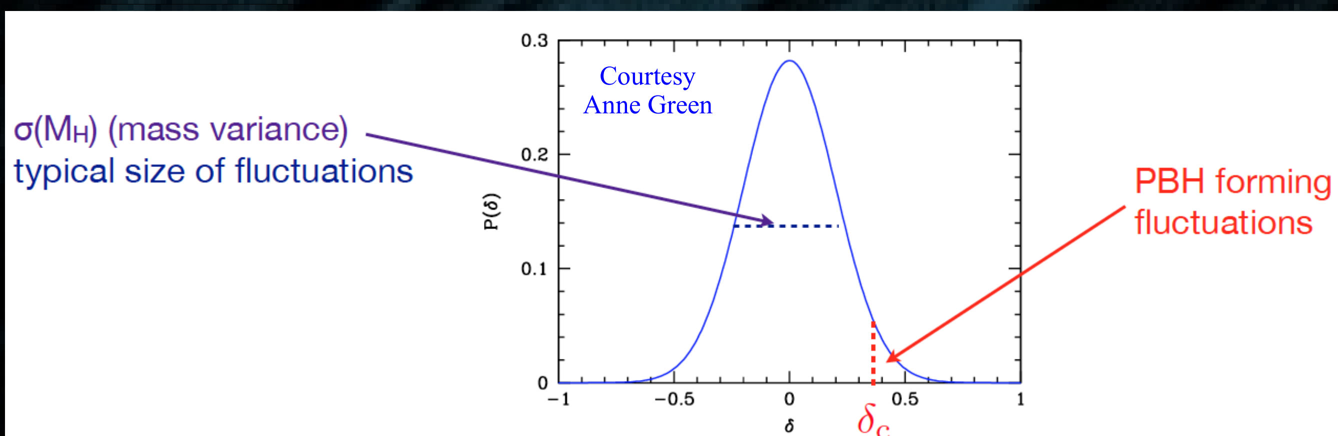
[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

arXiv:1603.00464 (PRL)

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 M_{sun})
* A potentially macroscopic CDM candidate

Review in Carr+16



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

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

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

Gaussian spectrum →

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

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

CMB scale →

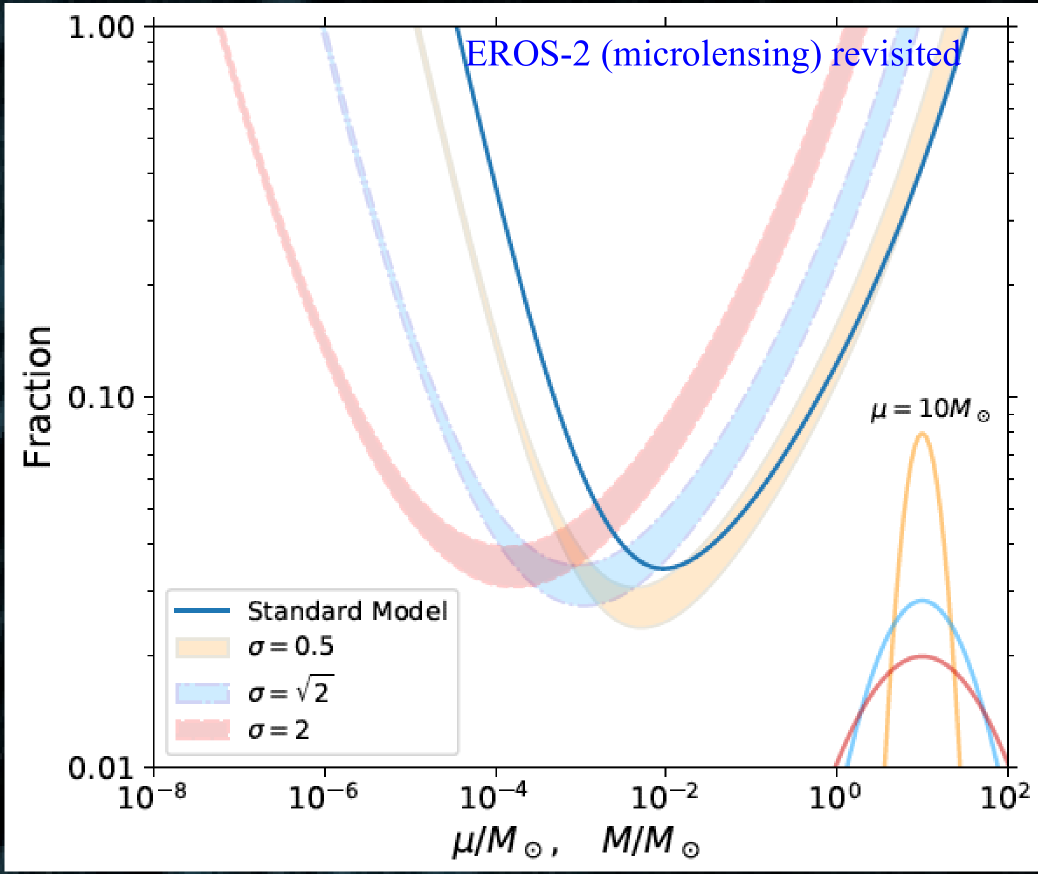
$$\sim 10^5 \exp\left[-(10^5)^2\right]$$

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

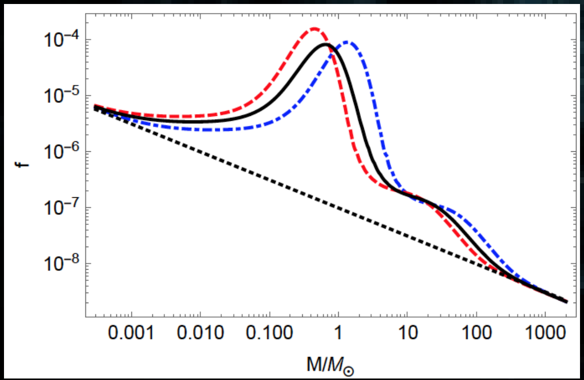
Primordial black holes

* 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 might be ~100% of DM
→ if 1-100 Msun, might solve core/cusp
→ GW with < 1 Msun a specific signature

Calcino+18



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

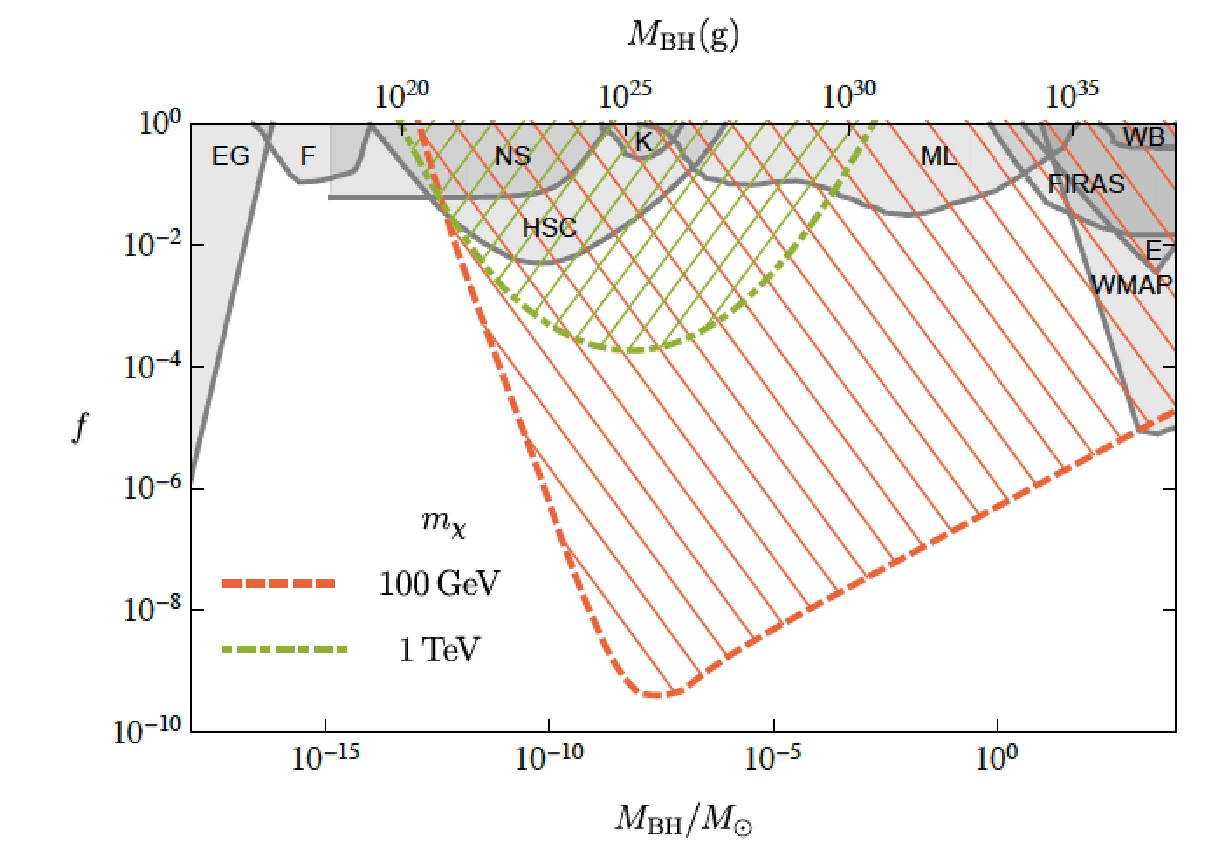


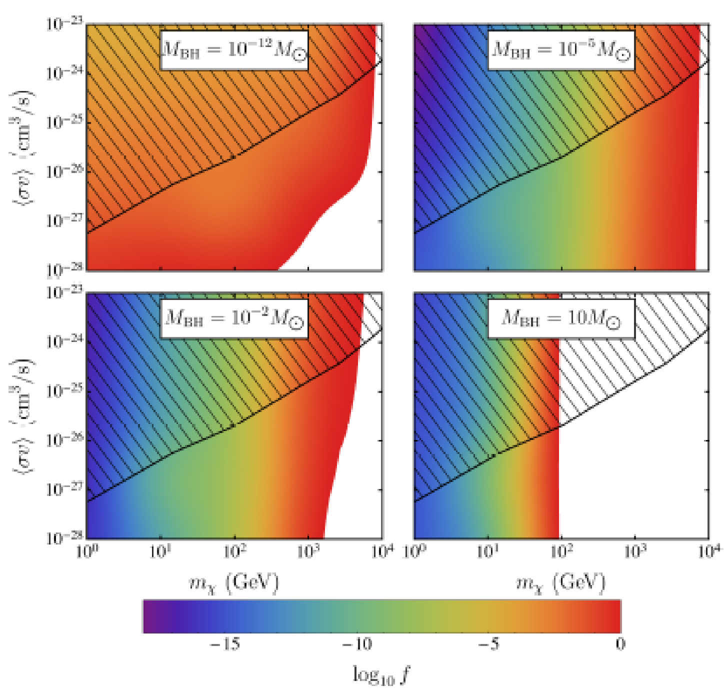
Byrnes+18 – impact of QCD PT
Extended mass function (logN)
(also Choptuik; Niemeyer & Jedamzik; Musco+)

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

Primordial black holes + WIMPs?

Boucenna+'18
(see also Eroshenko'16)





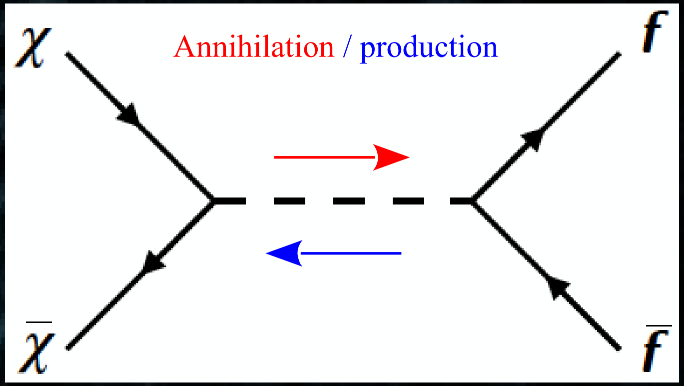
Primordial black holes in France (theory)

www.cartesfrance.fr

WIMPs + portal models + dark sectors

Simple production mechanism from thermal plasma:
→ chemical equilibrium reached or not (freeze out/in)
→ interaction strength constrained by relic abundance + power spectrum
→ can be made more complex with dark sectors
→ symmetric or asymmetric DM can be realized

** Non-thermal production also possible



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

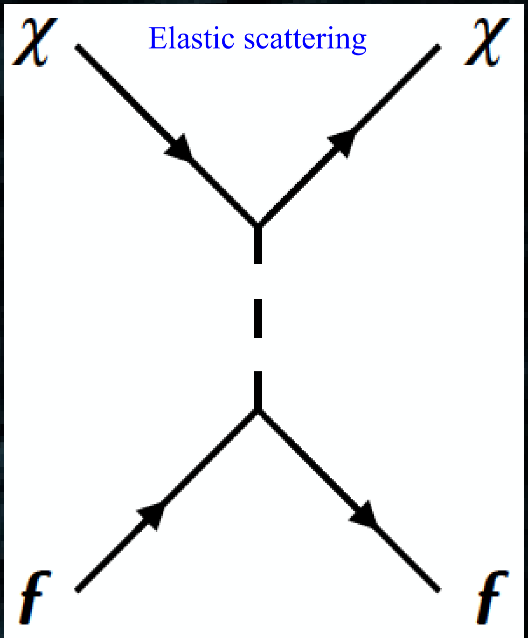
Searches based on the existence of DM/SM interactions (except for gravitational searches)

→ Colliders: rather model dependent (DM + mediator masses do matter)

→ Indirect: DM annihilation or decay
[Not sensitive to stable asymmetric DM]

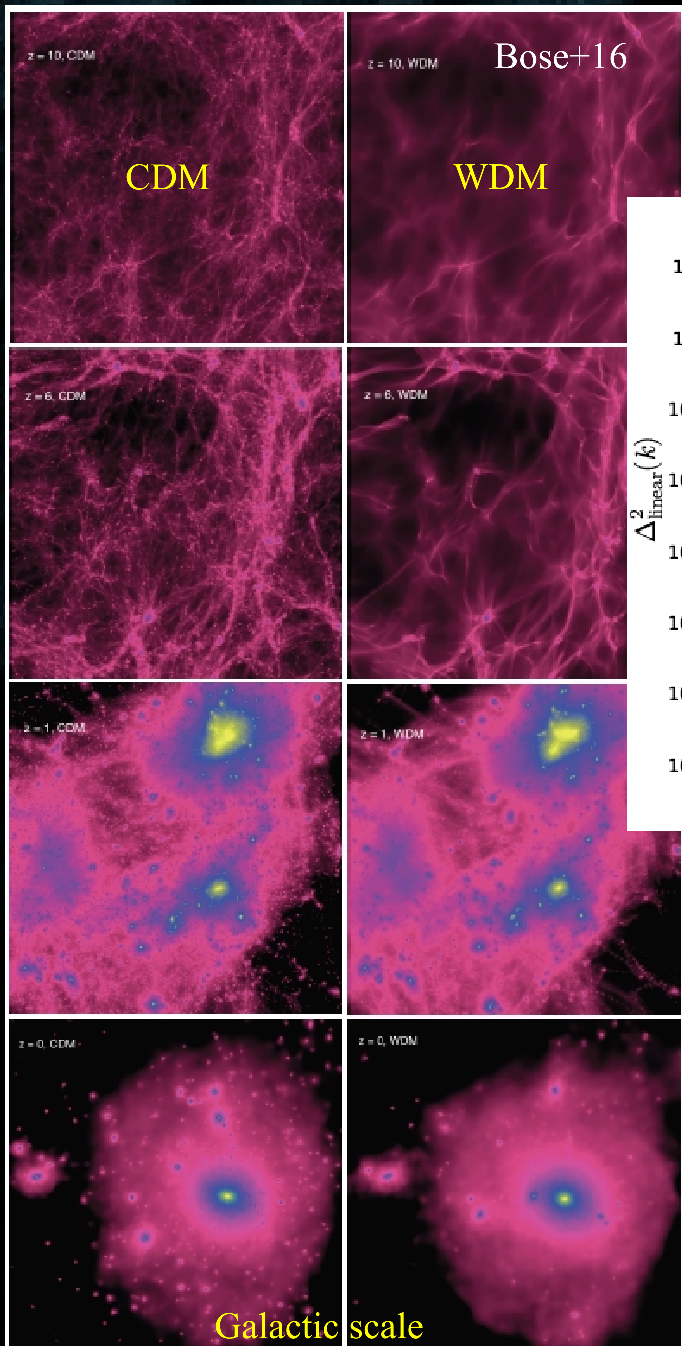
→ Extra-Indirect: e.g. stellar physics

→ Direct: elastic/inelastic collisions in laboratory

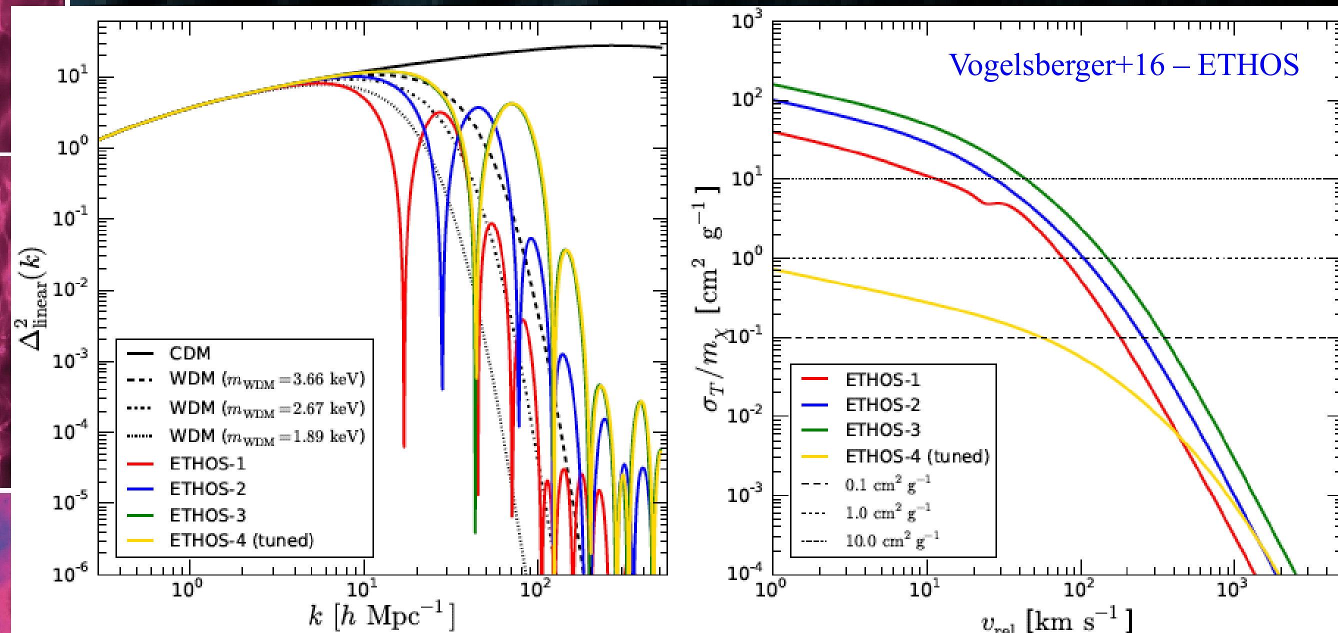


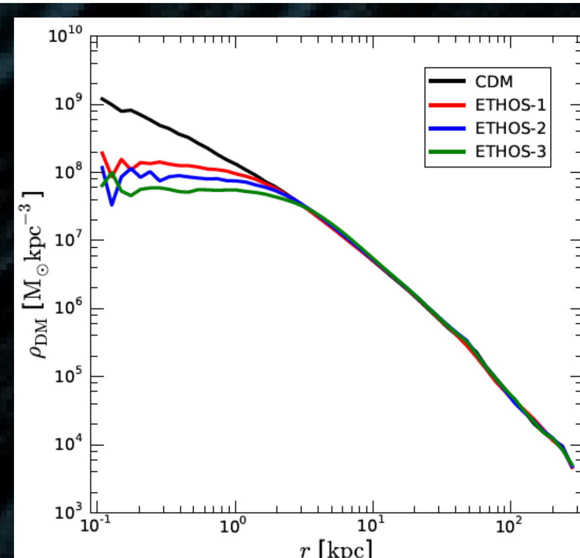
$$\Gamma_{\rm scatt.} = n_{\rm f} \langle \sigma_{\rm scatt} v \rangle$$

Kinetic decoupling, free streaming scale, and small-scale structures



$$\lambda_{\rm fs} = a_{\rm eq}\int_{t_{\rm kd}}^{t_{\rm eq}} dt\,\frac{v(t)}{a(t)} \approx v_{\rm kd}(a_{\rm kd}/a_{\rm eq})/H_{\rm eq}$$

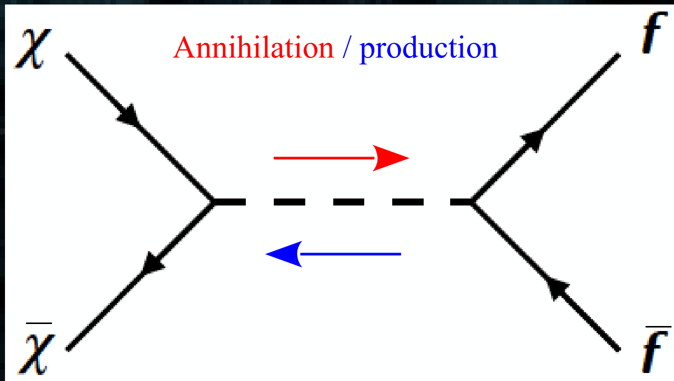


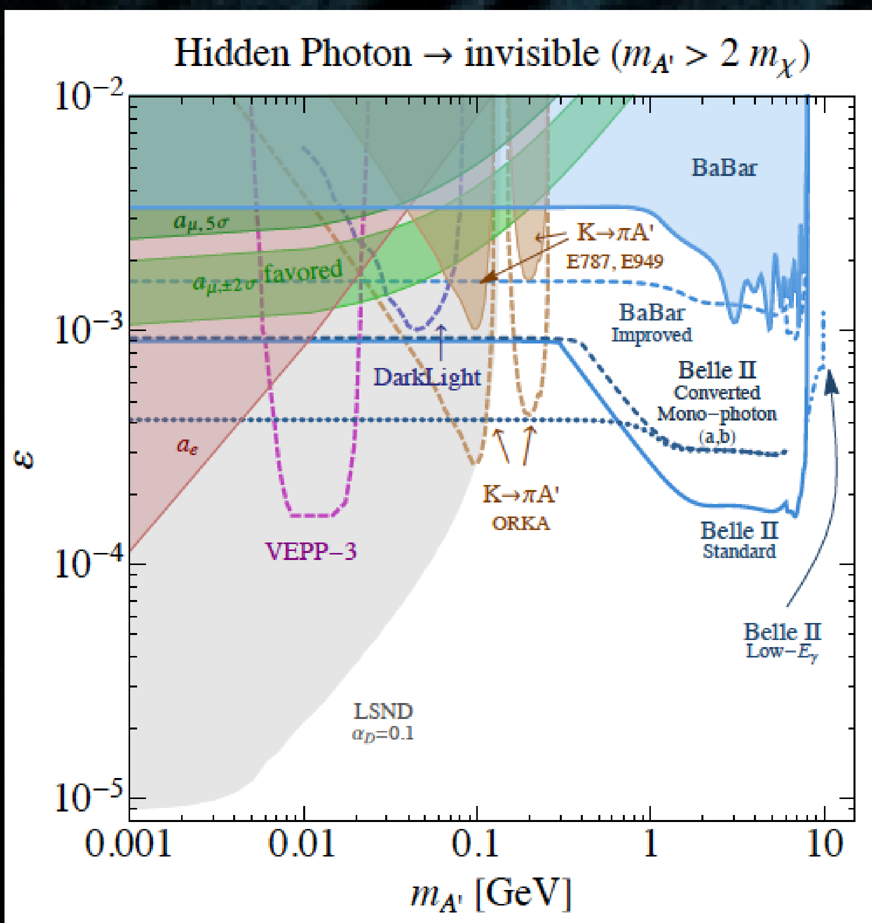


CDM candidates: minimal scale of structures depend on interactions. For TeV particle, can be ~10^{-10}M

SIDM: self-interactions set cores in massive objects (not in light objects).

Collider searches





New Physics around TeV?
- No sign at LHC so far
- Status of hierarchy problem?

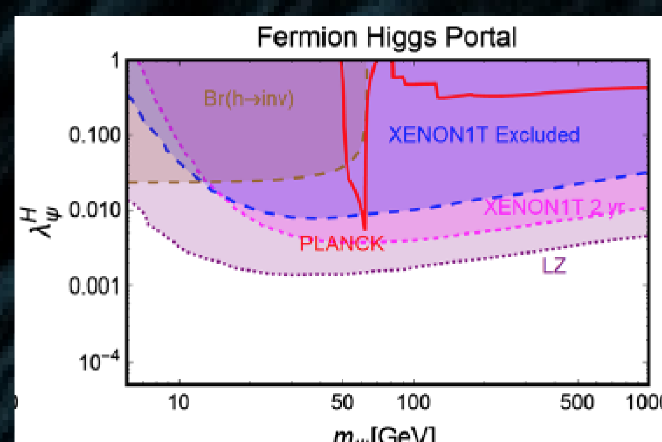
Motivations?
- Simple mechanism production in early universe
- Can be probed in current/future experiments

Effective/minimal approaches
- e.g. Minimal DM (Cirelli et al)
- Simplified models (portal models)

DM searches:
- mono-X
- Z/H width

DM / mediators can be …
- Heavy (> TeV)
- Light (< 10 GeV)

… difficult to look for at colliders
→ extend searches to sub-GeV
(e+e-, beam dump

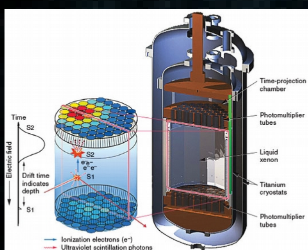


Reviews in e.g.:
Arcadi+'18
Penning'18

Astro/particle complementarity

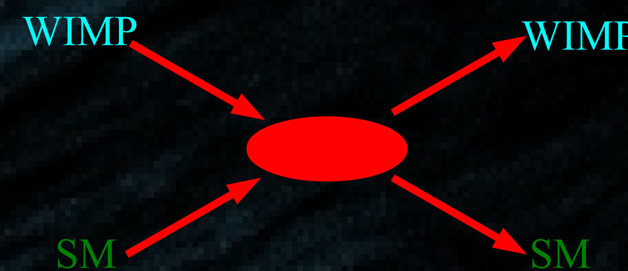
Direct detection rate – WIMP-matter scattering

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



Scattering

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



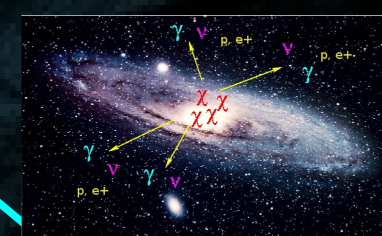
$$\Gamma_{\mathrm{scat}} = \langle \sigma_{\mathrm{scat}}\, v\rangle\, n_{\mathrm{plasma}}$$

Annihilation vs. scattering

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

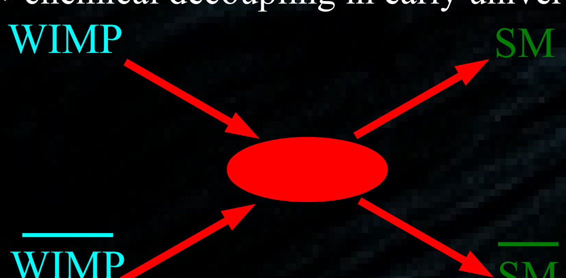
Dark matter profile + phase space (+ cosmic-ray transport)

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



Annihilation

(→ chemical decoupling in early universe)



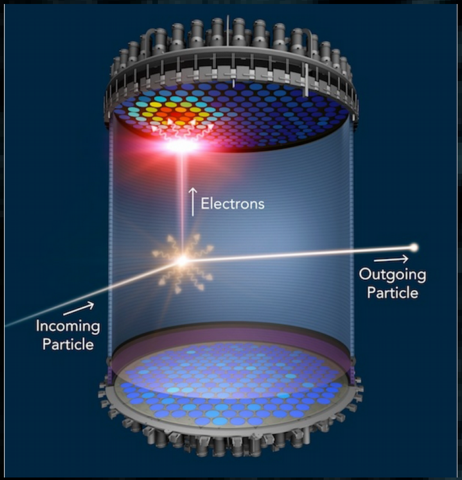
$$\Gamma_{\mathrm{ann}} = \langle \sigma_{\mathrm{ann}}\, v\rangle\, n_\chi$$

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

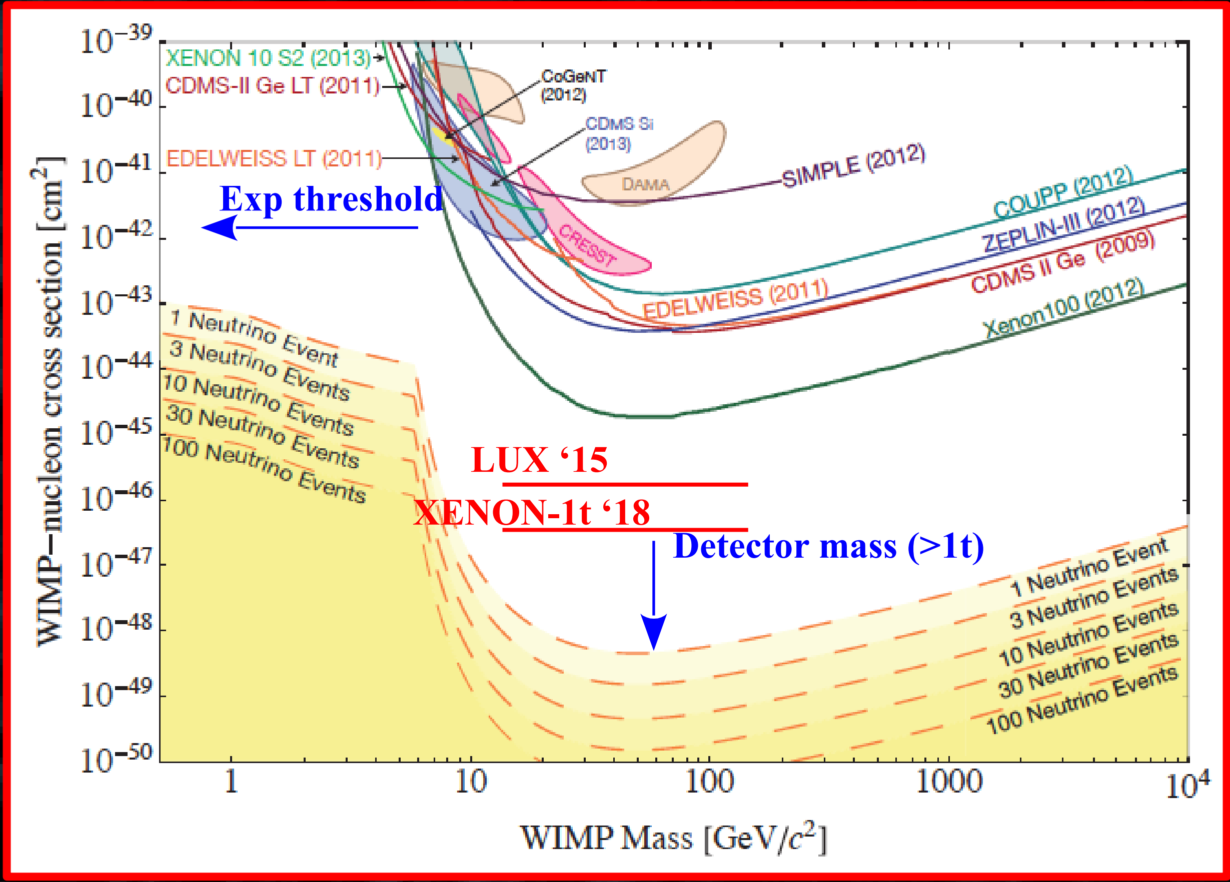
$$\frac{d\phi_\gamma^{\mathrm{ann.}}}{dE} = \frac{\delta\,\langle\sigma v\rangle}{4\,\pi}\,\frac{dN_\gamma}{dE}\int_{\mathrm{res.}} d\Omega \int_{\mathrm{l.o.s}} dl\,\left[\frac{\rho(r)}{m_\chi}\right]^2$$

Direct WIMP searches

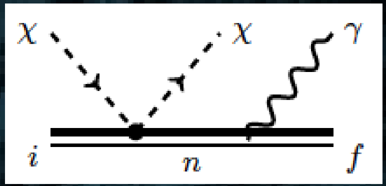
XENON-1t results:
=> the sub-zepto-barn era!



Billard+ 13

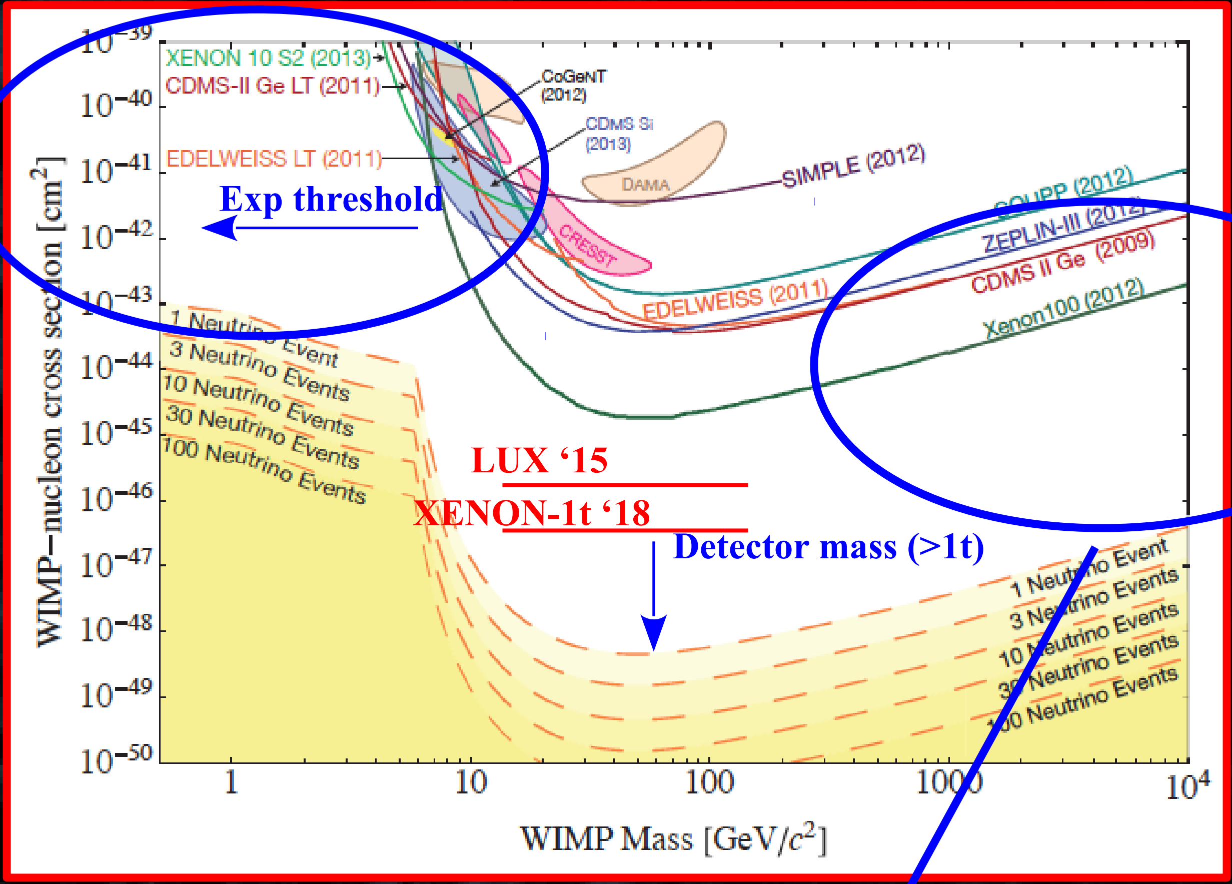


Also sensitive at lower energy:
* electronic recoils (e.g. Essig+12)
* Bremsstralhung (e.g. Pradler & Kouvaris 17)



Direct WIMP searches

Billard+ 13



Motivations for Sub-GEV?
- Light mediators and dark sectors can help achieve SIDM scenarios

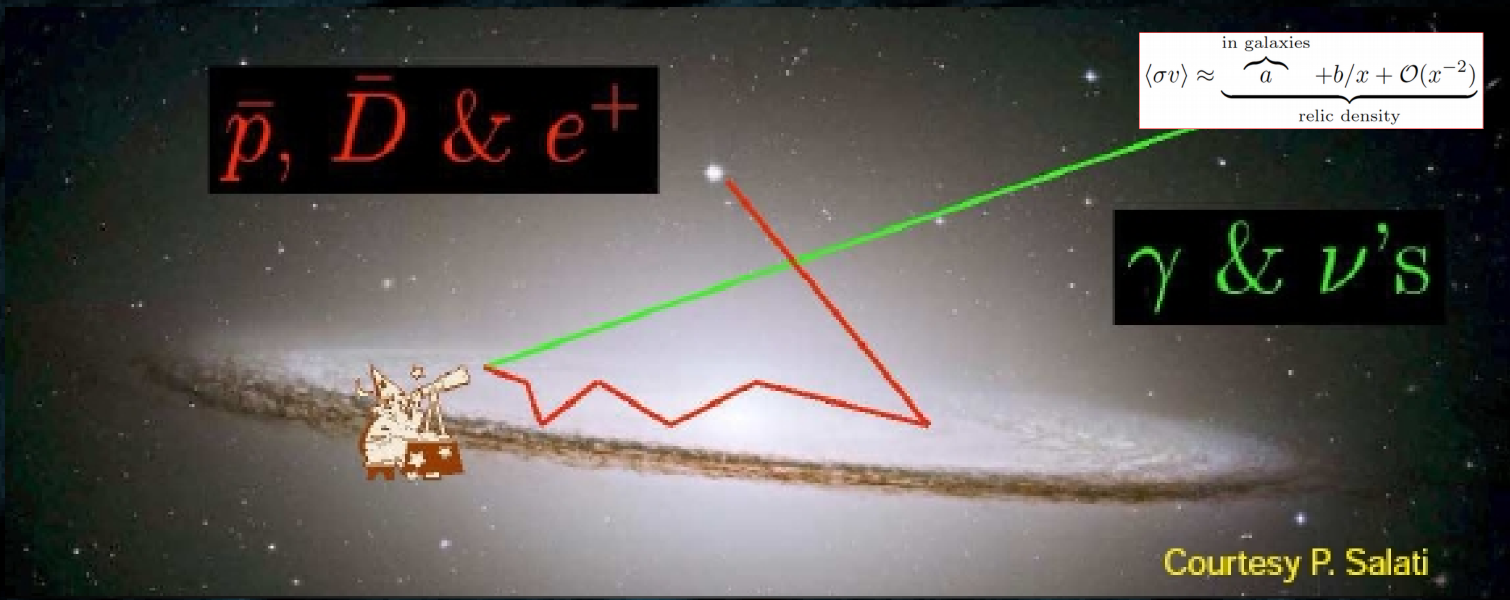
Difficulties:
- Scattering off electrons and phonons + other effects (e.g. Midgal) cumbersome

→ Complementary with collider searches + astro/cosmo

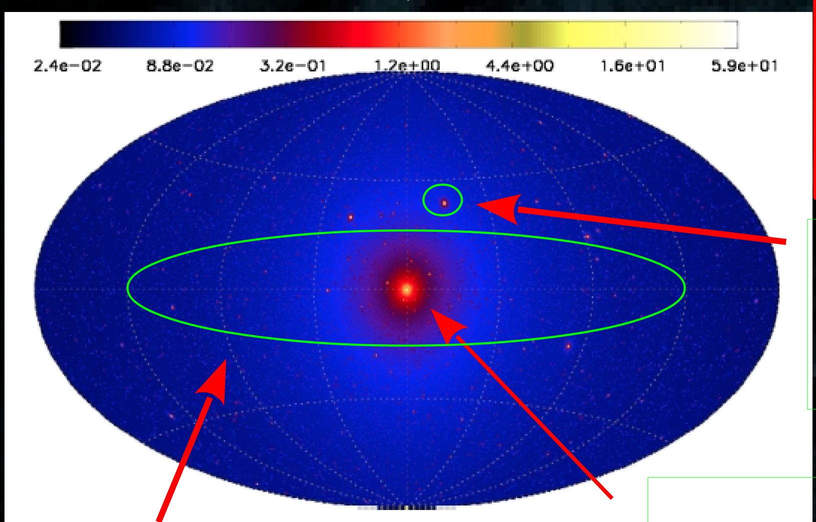
Motivations for multi-TeV
- Electroweak multiplets still possible (e.g. MDM)

Difficulties:
- Some non-perturbative effects, e.g. Sommerfeld enhancement, bound states (Petraki+)

Up to the skies!



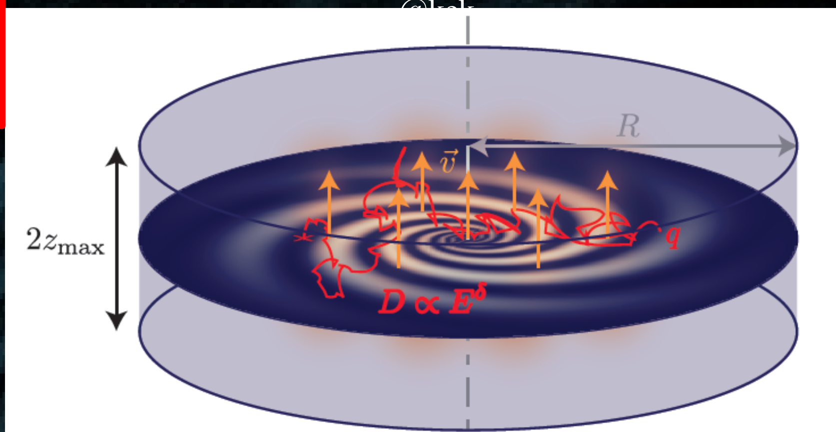
Pieri, JL+ '11



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

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

Cosmic-ray transport



Mertsch PhD thesis '10

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

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

Indirect DM searches: the realm of "fake news"?

* Diffuse gamma-ray "excess" (EGRET ~ 00's)

* 511 keV line at Galactic center (Integral 05's)

* Cosmic-ray positron "excess" (PAMELA+AMS 10's)

* Gamma-ray "excess" at Galactic center (Fermi 10's)

* 3.5 keV line (Chandra + XMM 10's)

* Cosmic-ray antiproton "excess"

* etc.

Indirect DM searches: the realm of "fake news"?

* Diffuse gamma-ray "excess" (EGRET ~ 00's)
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* 3.5 keV line (Chandra + XMM 10's)
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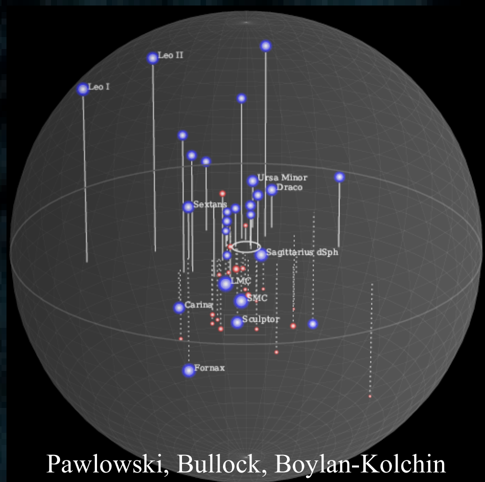
* etc.

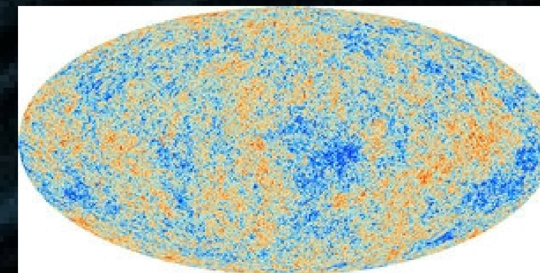
* Mostly astrophysical phenomena
(much more difficult to predict)

=> Need very clean signatures!
+ controlling backgrounds
very important!

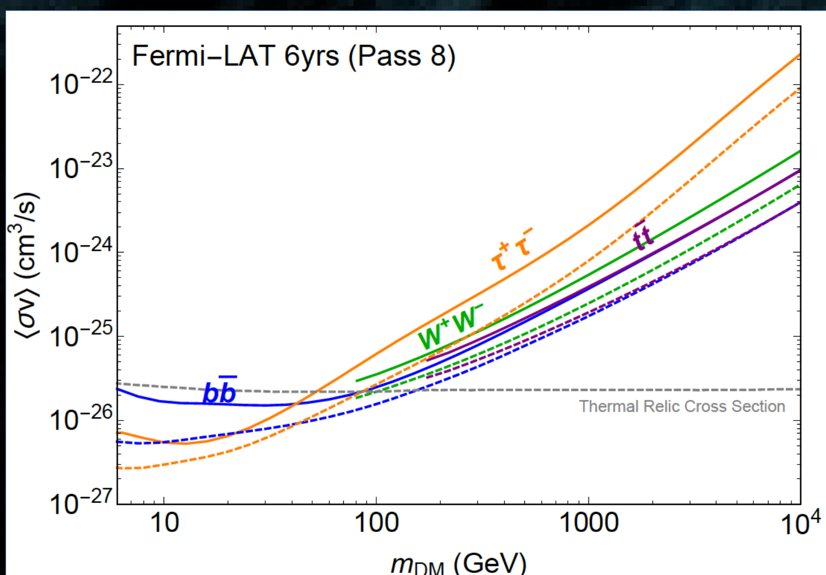
Some constraints (annihilating DM)



Pawlowski, Bullock, Boylan-Kolchin

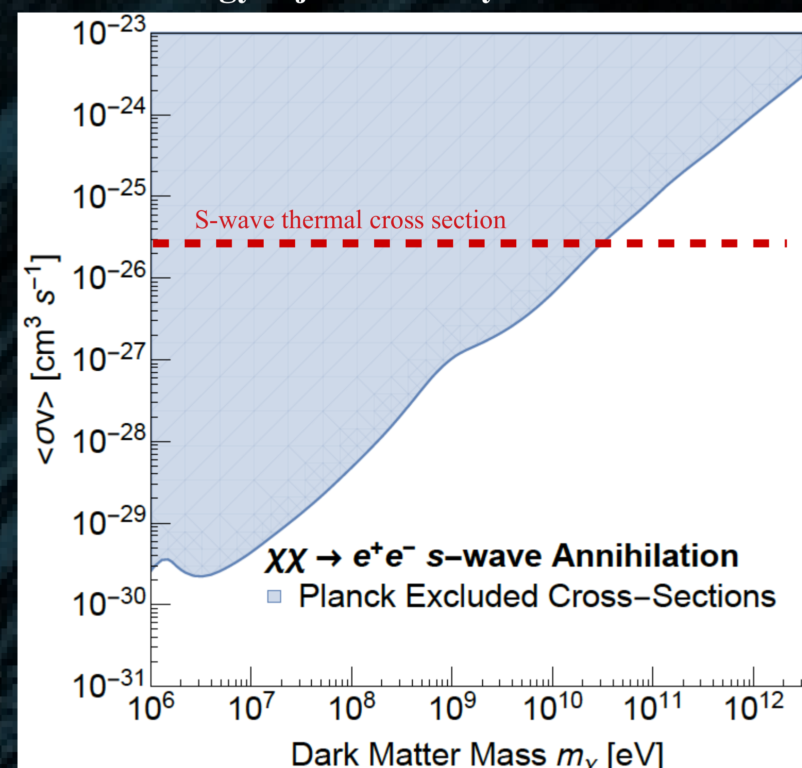

Planck @ ESA

Hayashi+ '16
Gamma-rays from Dwarf Satellite Galaxies (Fermi data)

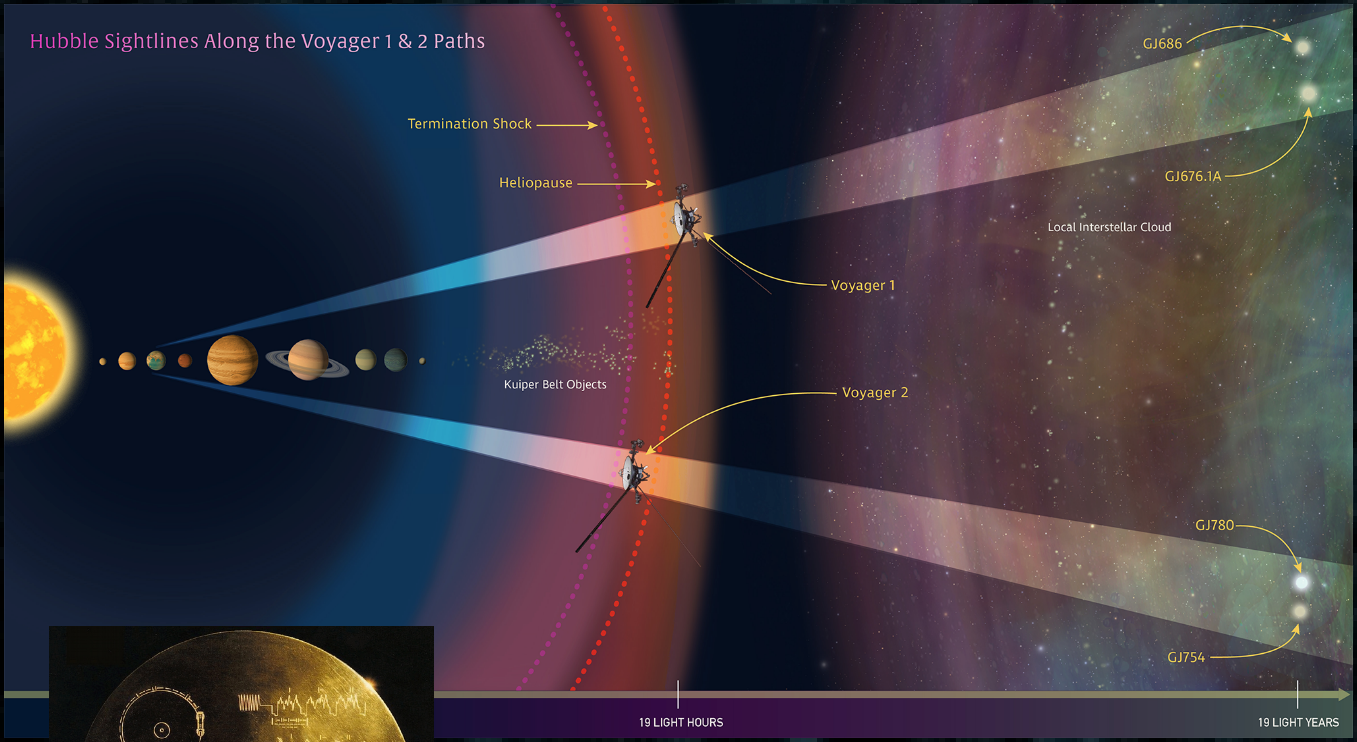


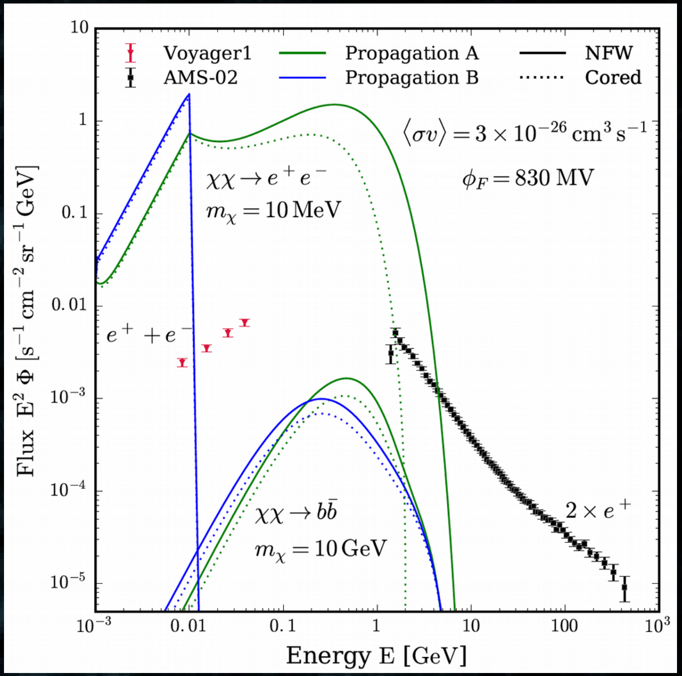
Beware:
Constraints on s-wave annihilation only (model-dependent)

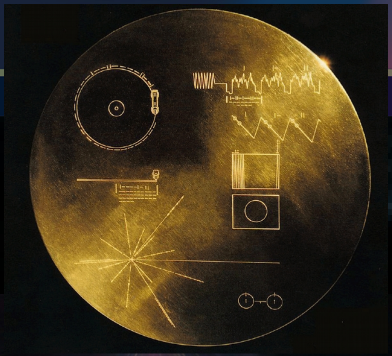
Slatyer '16, Liu+'17
CMB (Planck data '15)
→ energy injection delays recombination



Down to MeV DM with cosmic rays + p-wave







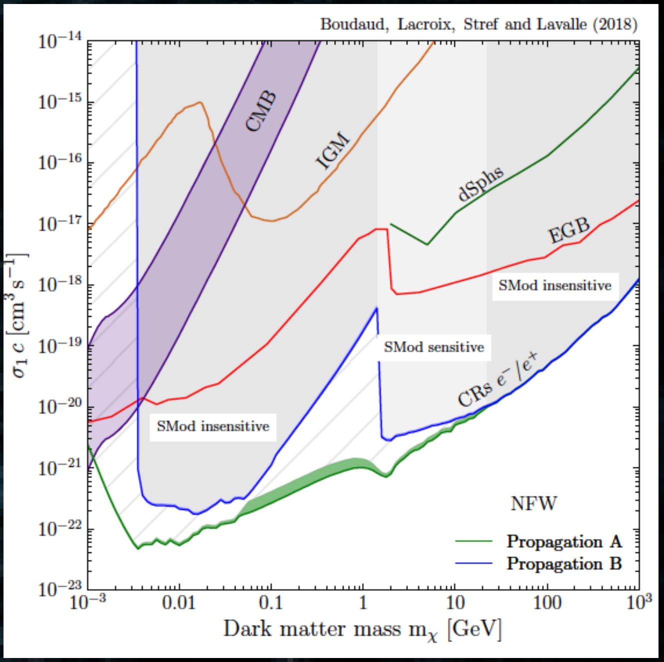
Voyager 1 has passed the heliopause in 2012!

=> 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.

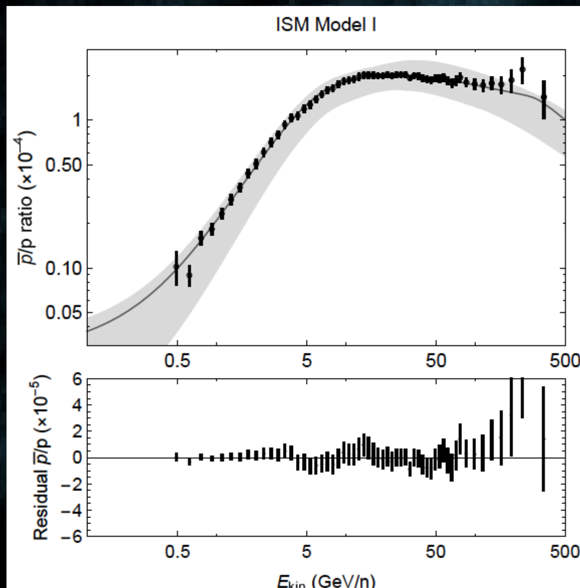
Boudaud+17-18.

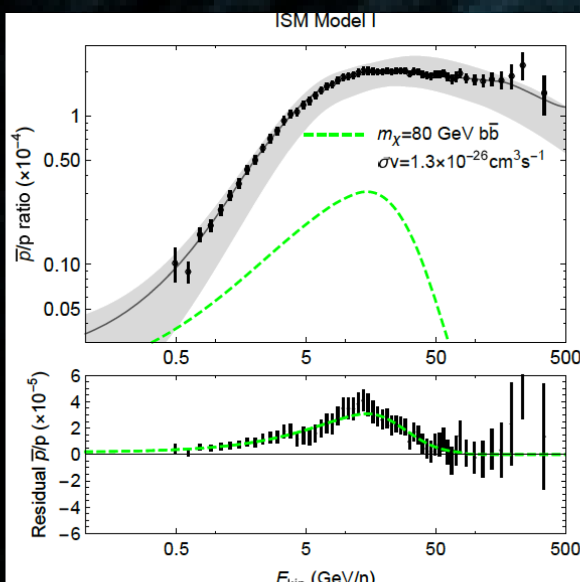


A Robust Excess in the Cosmic-Ray Antiproton Spectrum: Implications for Annihilating Dark Matter

Ilias Cholis,[1,*] Tim Linden,[2,†] and Dan Hooper[3,4,‡]

(arXiv:1903.02549)





* A strong claim based on a simple Delta chi2 argument
→ Chi2/dof good for background
→ Very large Delta chi2 when DM annihilation is added

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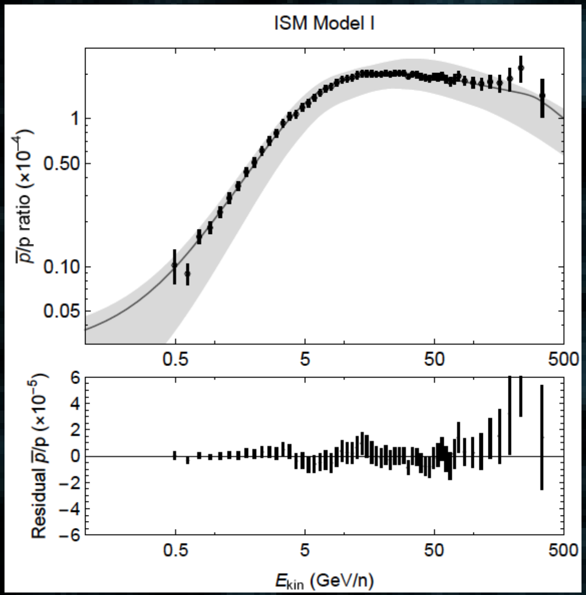
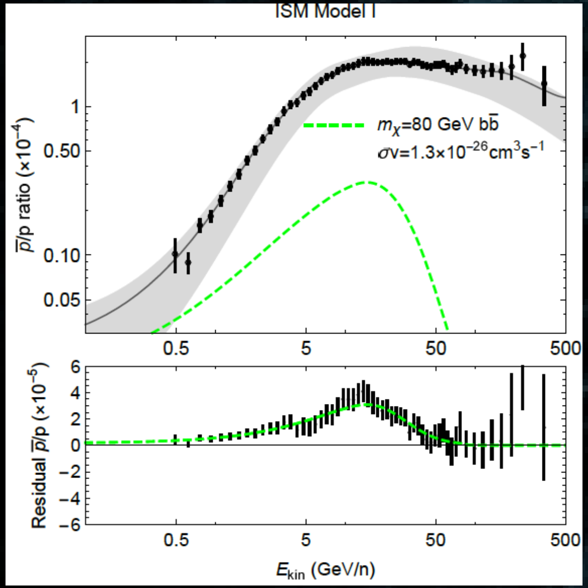
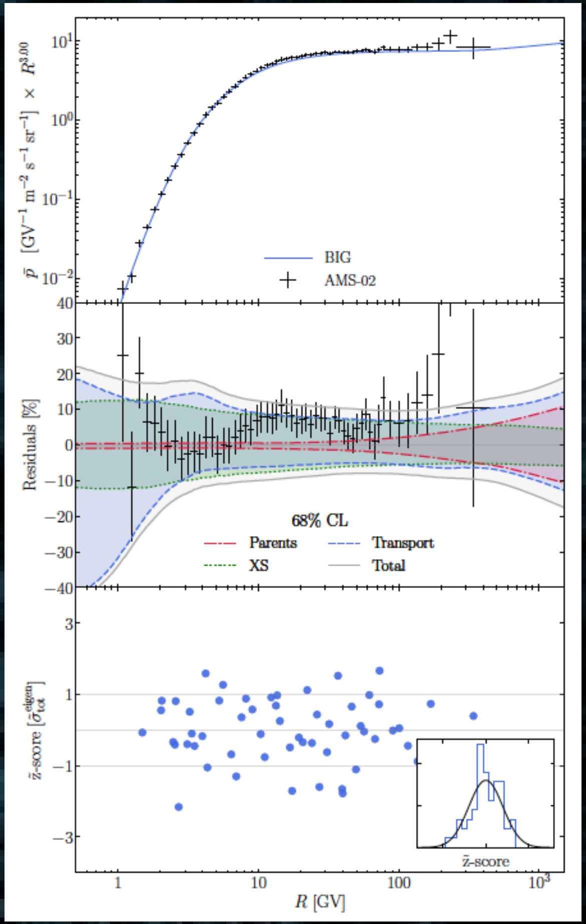




Antiprotons from AMS-02 are consistent with a secondary astrophysical origin

Mathieu Boudaud,[1,*] Yoann Génolini,[2,†]
Laurent Derome,[3] Julien Lavalle,[4] David Maurin,[3] Pierre Salati,[5] and Pasquale D. Serpico[5]

(To appear soon)



Perspectives in indirect searches

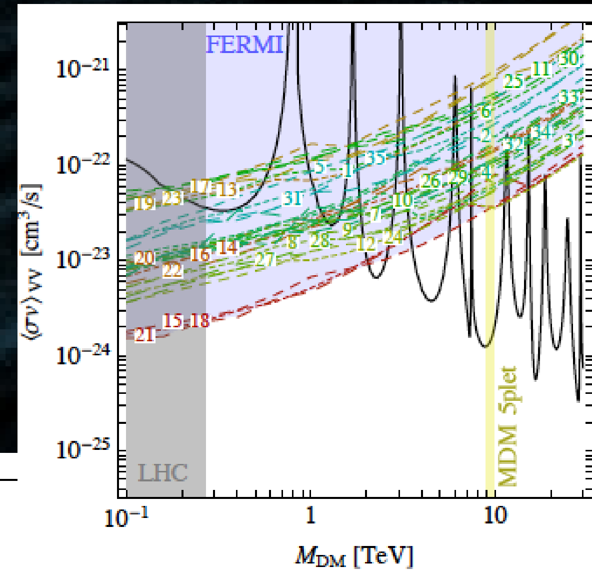
Improve:
- dark matter distribution in the MW: halo shape + subhalos
- modeling of astrophysical background
- define clean ROI

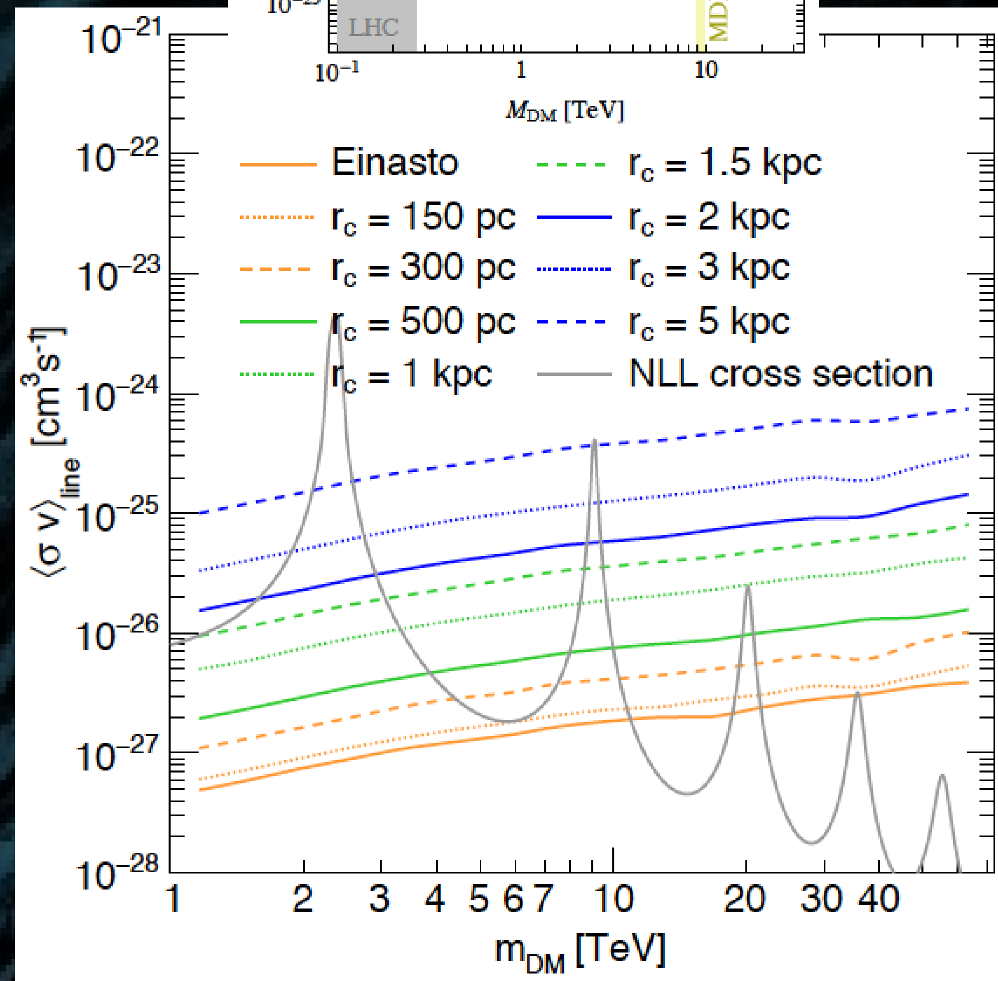
Neutrinos:
- DM capture by Sun
- Nice complementarity with SD-DD
- Super-heavy DM

Gamma-rays:
- The origin of the GC emission
- Fermi still very useful (GeV)
- Go TeV! CTA
- Go to MeV– complementary with CMB

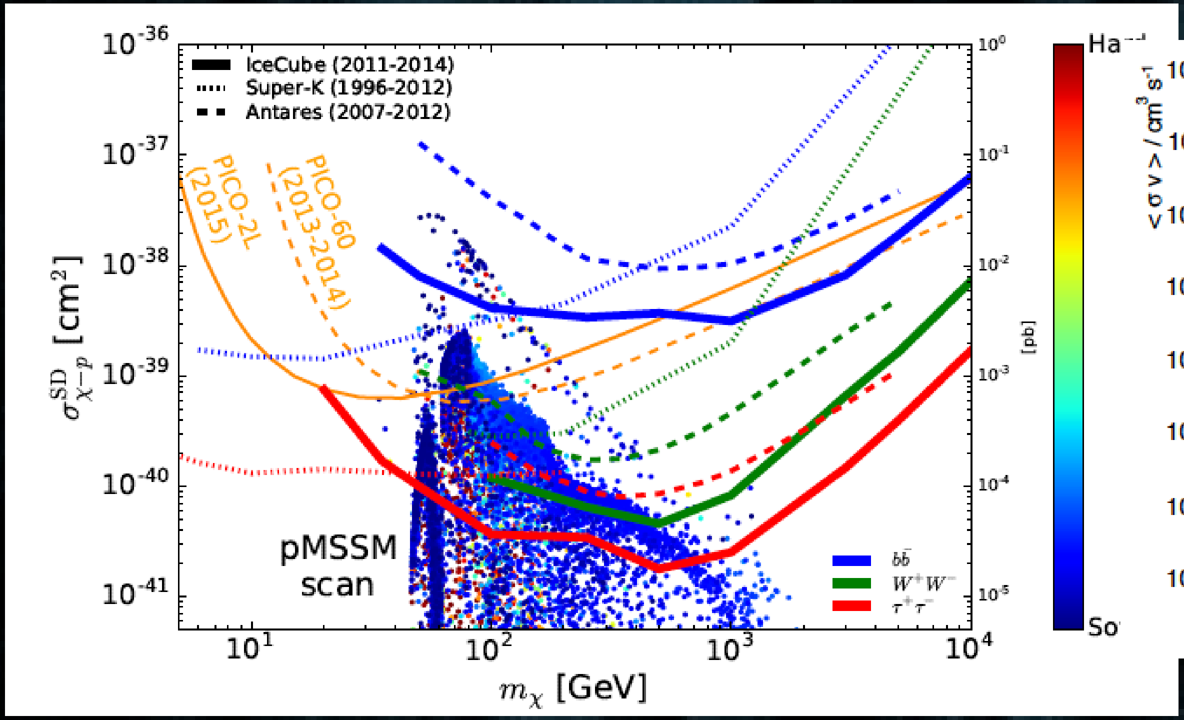
Antimatter:
- Antiprotons currently discussed
- GAPS will probe anti-d
- Strong progress in theory of CR propagation expected [AMS02 has been game changing]

[Plots from Cirelli+’15 (Fermi on MDM) and Rinchiuso+’19 (CTA on Wino DM)].

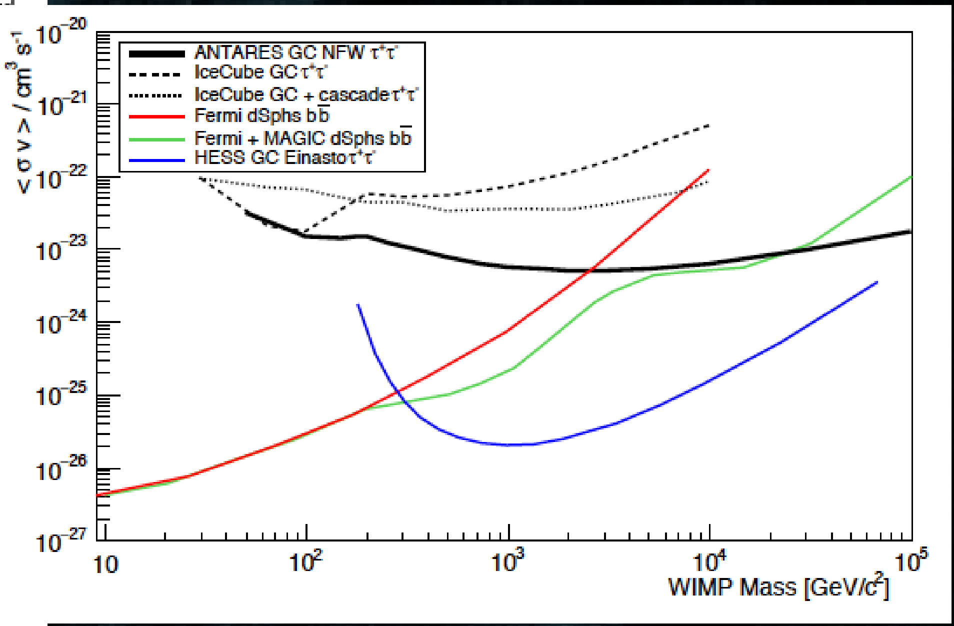




Neutrino telescopes



Aarsten+'17
(Icecube)



Albert+'17
(Antares)

WIMP-like DM in France (theory)

www.cartesfrance.fr

Gravitational searches for dark matter

Rationale:

- Distribution of DM in galaxies
  - → core/cusp + diversity problem
  - → density profiles in target systems (e.g. Milky Way + satellites)
- Probe of DM halo "granularity"
  - → Subhalos (a prediction of CDM – even with self-interactions)
  - → Compact objects (PBHs are back + ultra-compact subhalos)
- Reduce astrophysical uncertainties for predictions + identify best targets

Techniques:

- Precise astrometry + kinematical studies
- Gravitational lensing (compact objects + subhalos)
- Gravitational waves (only for PBHs)

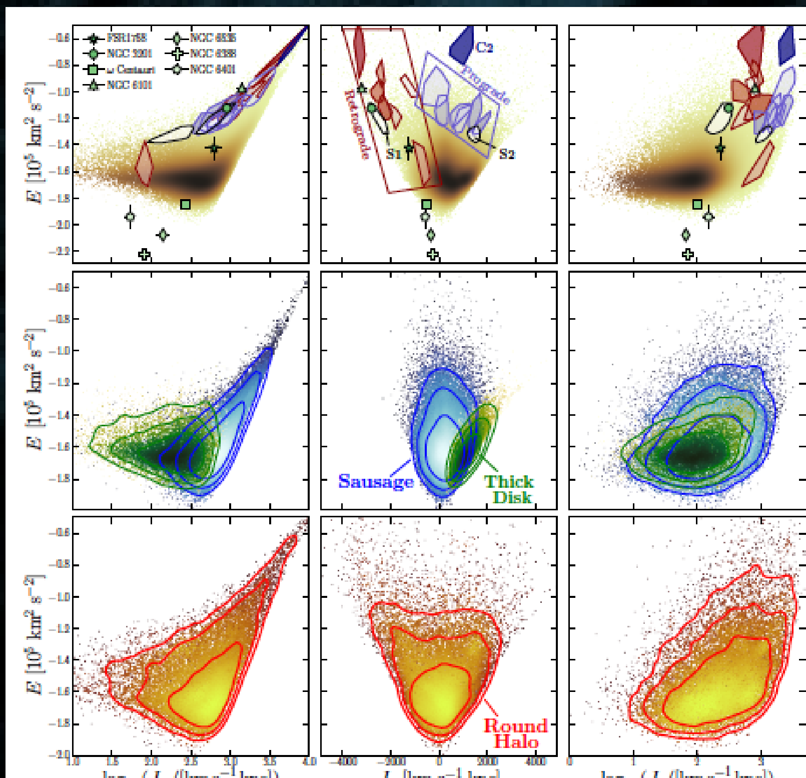
\+ indirect: e.g. Ly-alpha, etc.

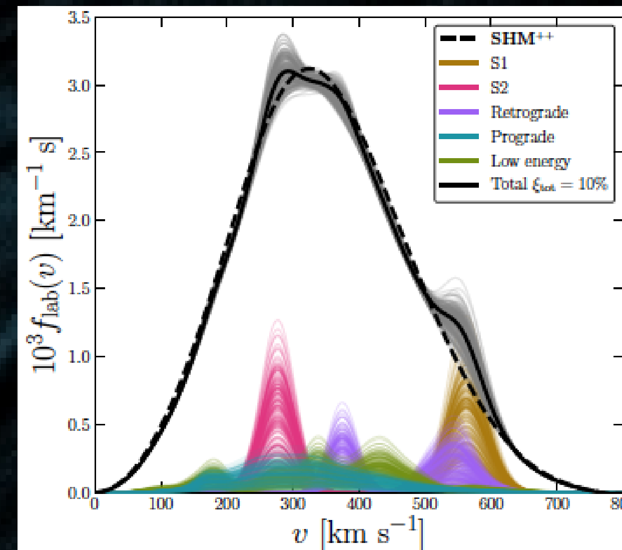
@ IN2P3: LSST, 21 cm, VIRGO++, LISA

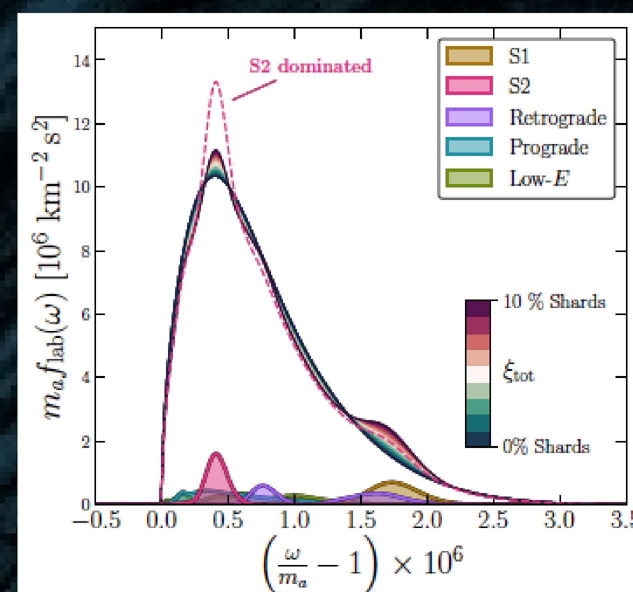
Gravitational searches for dark matter

Example: Astrometry with Gaia

(bottom-up: modeling a posteriori to make sense of data)







O'Hare+19: the dark shards

⟶ Stellar structures in phase space

⟶ If coming from merged subhalos => DM counterparts

⟶ Leads to structure in f(v)

⟶ Relevant to direct DM searches (WIMPs and axions)

Put all constraints together?

Numerical tools exist for some scenarios (e.g. WIMPs):
- Micromegas, SuperIso, PPPC4DM, etc. (lots of international efforts, e.g. Gambit, etc.)
- They try to integrate as many constraints as possible: production mechanism, colliders/direct/indirect
- Caveats: astro/cosmo uncertainties hard to fully integrate (see bayesian tools like Gambit)

Dedicated tools for specific searches:
- Annihilation spectra (e.g. PPPC spectra) still affected by uncertainties: sub-GeV / multi-TeV
- Etc.

Further developments expected, but … multiplication of scenarios makes it difficult to cover everything

Take home message

Astro/cosmo 1:

- DM case very strong
- Based on GR applied to cosmology + standard particle/nuclear physics + Gaussian assumption for primordial perturbations
- Even if DM is modified GR, it must effectively look/behave like CDM on observed scales

Astro/Cosmo 2:

- Potentially some issues on small scales: SIDM/ULA or baryonic physics?

Astro/Cosmo 3:

- Still many uncertainties

→ Primordial spectrum on small scales + Pre-BBN history not constrained

→ Distribution of DM in halos: detailed shapes and subhalos

→ Impact on model parameter space + input for astro searches

Model building:

- Only a few scenarios with independent motivations
- WIMP no longer the reference case: enlarge th/exp perspectives
- Maybe DM is not 100% made of particles

Search strategies:

Complementarity!!!!!

Some theoretical guidelines

*** Some challenges:**

- Still some technical challenges for different candidates (e.g. …)
- Mixed scenarios (what if DM is not made of a single species?)
- Assess theoretical uncertainties (astro/cosmo/particles)

*** Reinforce collaborations between**

- Experts in model building + technicalities
- Experts in early universe physics (production + early universe pheno: BBN, CMB, etc.)
- Experts in structure formation
- Experts in phenomenology: searches at colliders, direct/indirect searches, gravitational searches, stellar physics, etc.

*** Maintain strong links with experiments**

- Is GdR SUSY → Terascale the appropriate format? (more collider oriented)
- DM is a wide and active scientific topic: time for a dedicated "GdR" in France?

→ if so, must also involve INSU and INP

→ Virtues: increase global understanding of progress in different fields

DM = an **interdisciplinary field** => important to find a place where to discuss everything together

Backup