Dark Matter:

Review of (selected) scenarios and indirect searches

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Physics and Astrophysics of Cosmic Rays

Observatoire de Haute Provence, November 25-30 2019

Disclaimer

Indirect detection/searches:
observable effects induced by DM
outside from laboratory experiments

Here, focus on HE astrophysical signals
(not much on gravitational signatures)

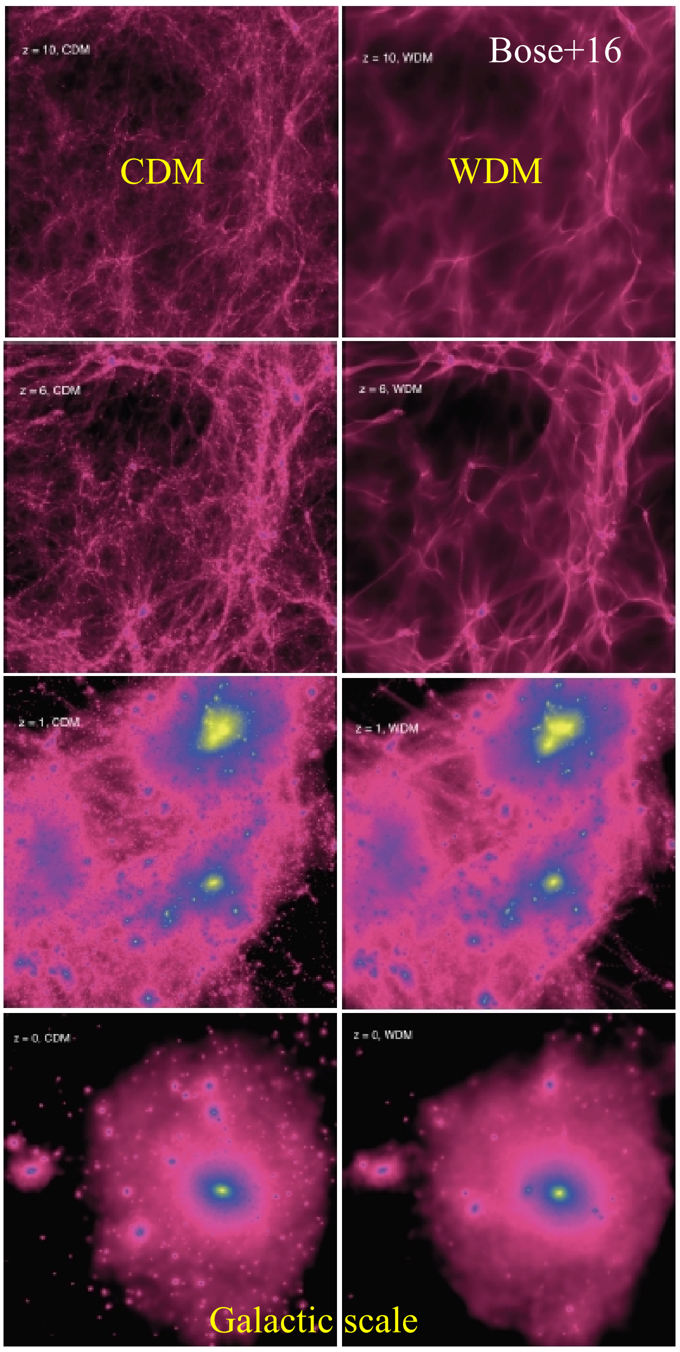
Tentative plan

* *Constrained properties of dark matter (DM) and issues*

* *Some theoretical scenarios and their indirect probes*
  - *Motivations and generic constraints*
  - *Thermal DM*
    * *WIMPs*
    * *Sterile neutrinos*
  - *Non-thermal DM*
    * *Axions*
    * *Primordial Black Holes (PBHs)*

* *Summary*

The cold Dark Matter (CDM) paradigm



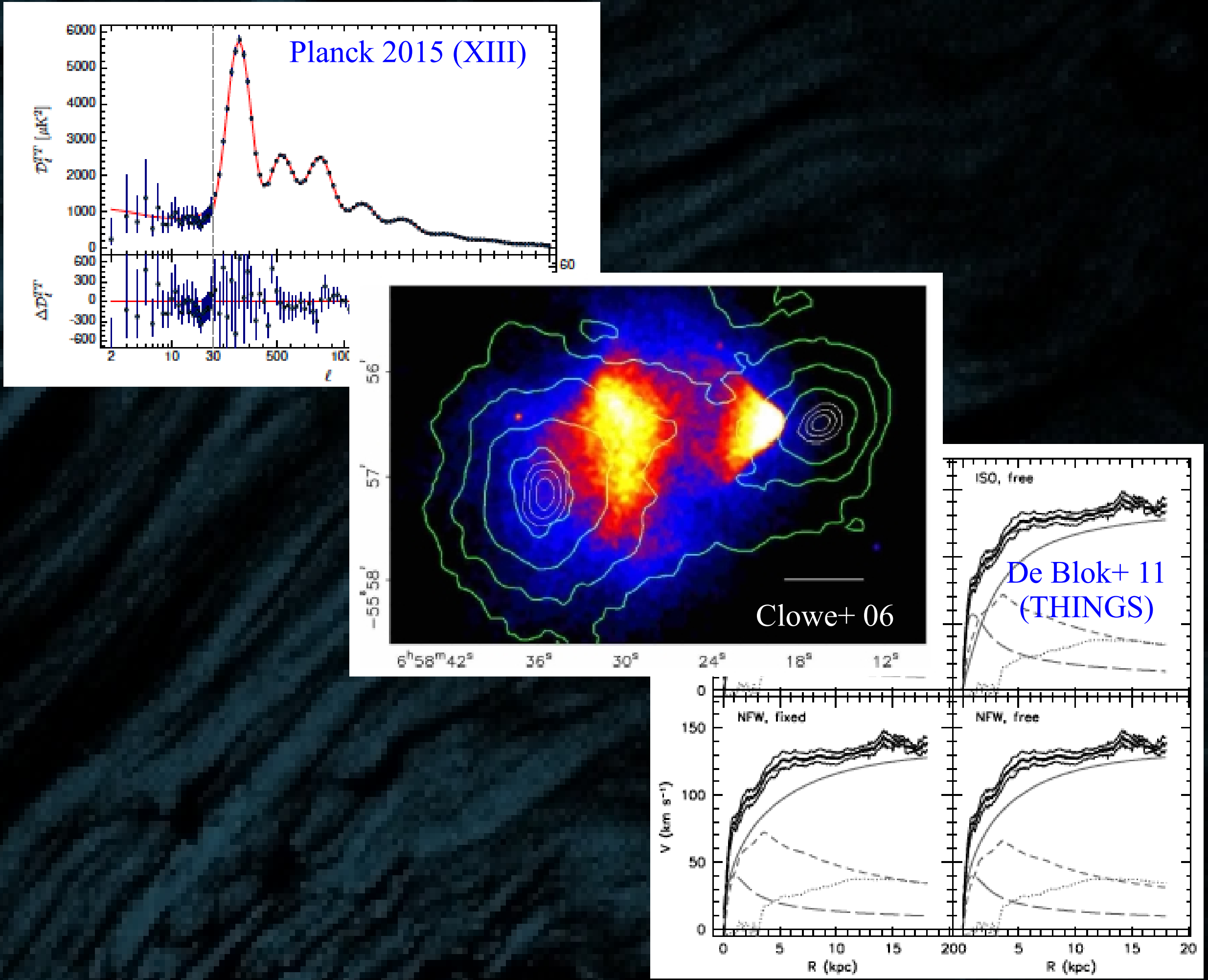
So far, only gravitational evidence for DM
(cosmological structures+CMB)

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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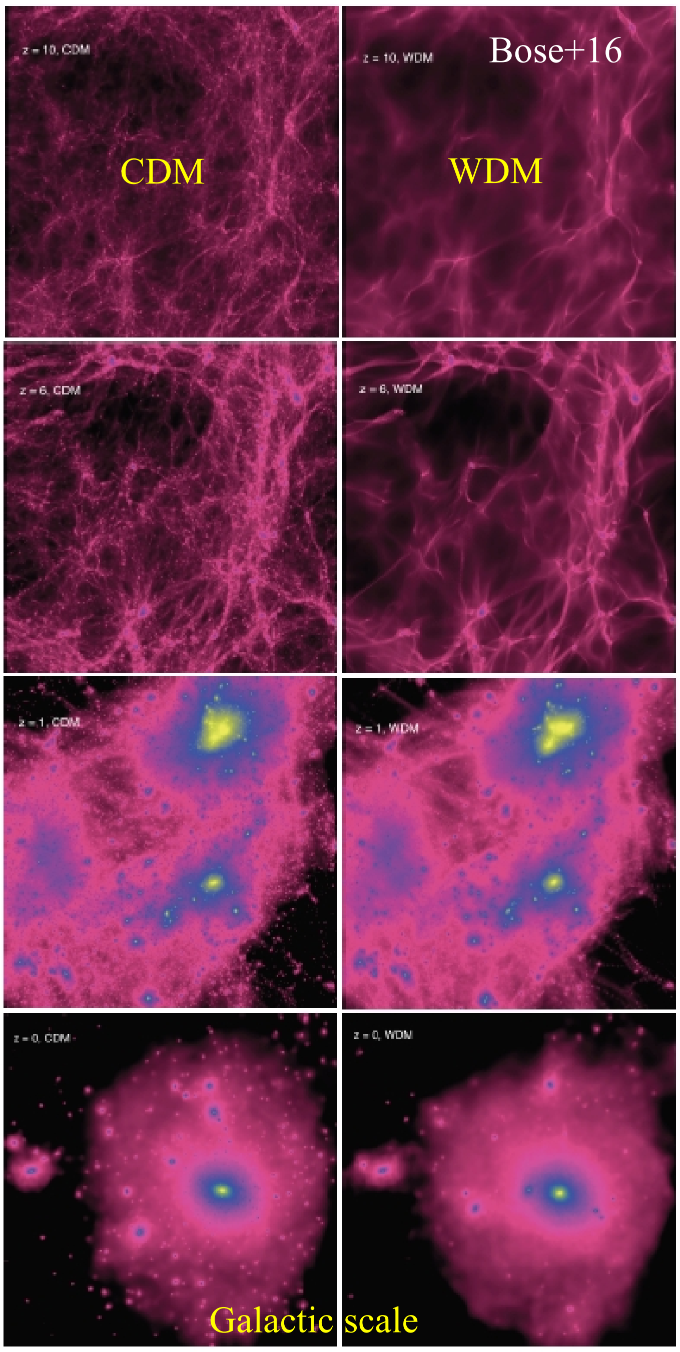

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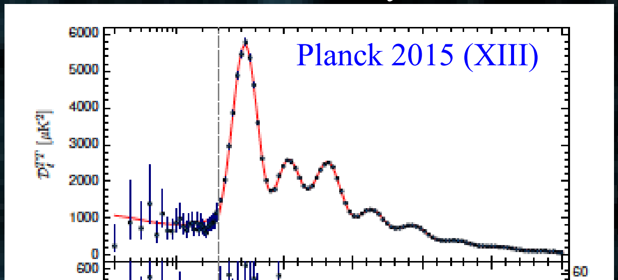
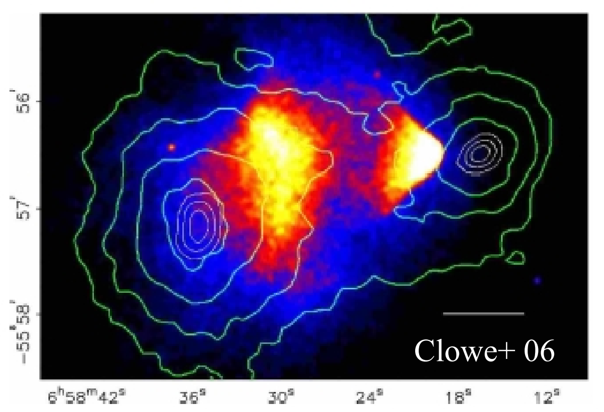
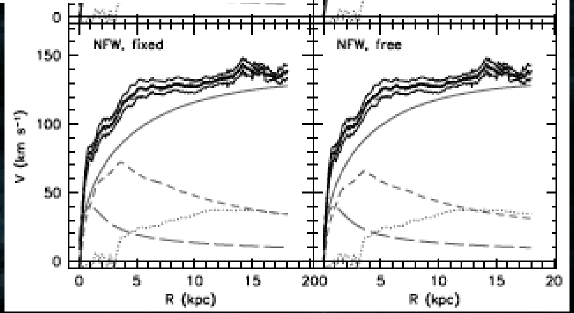


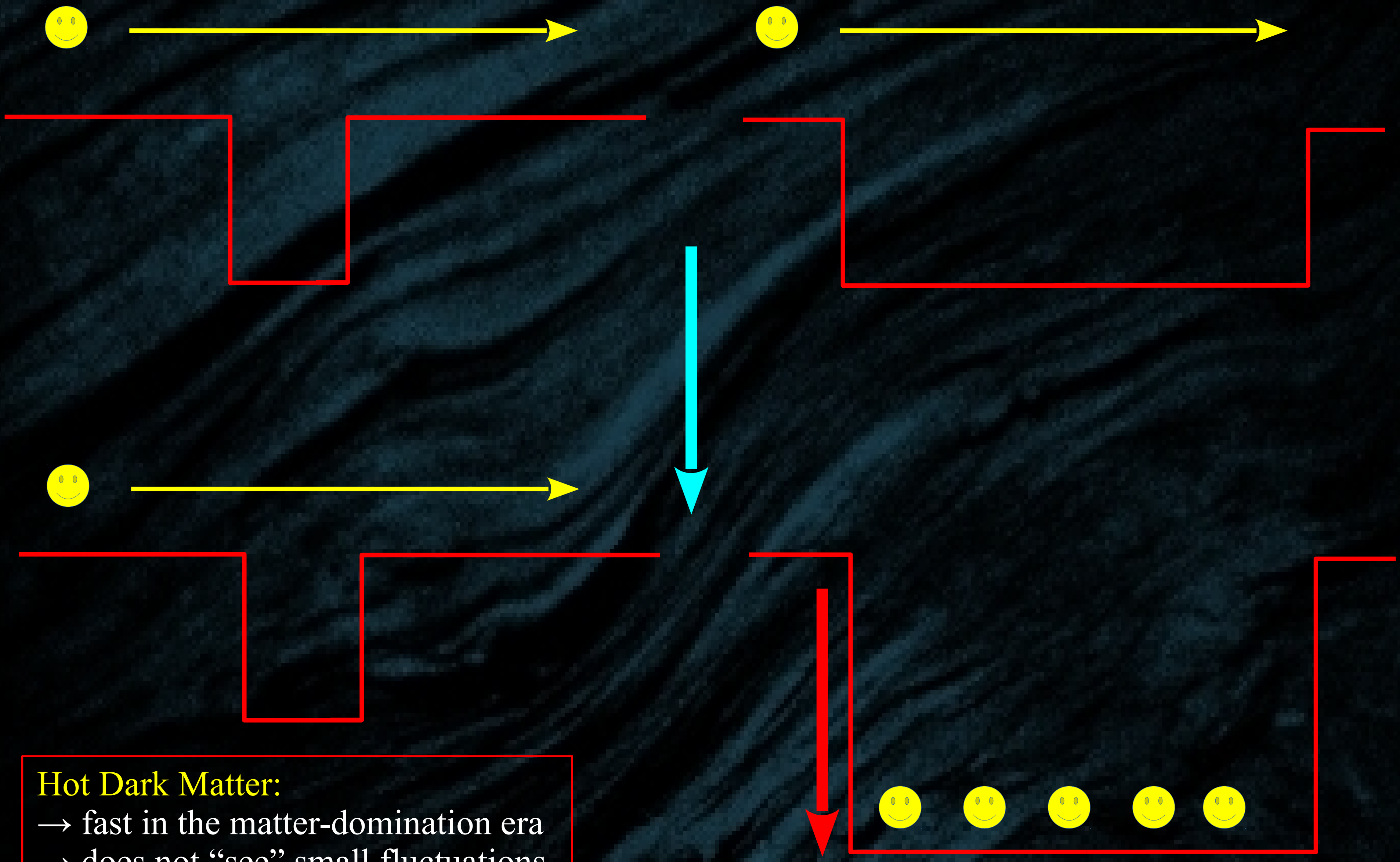




Not a mere 2-σ tension!

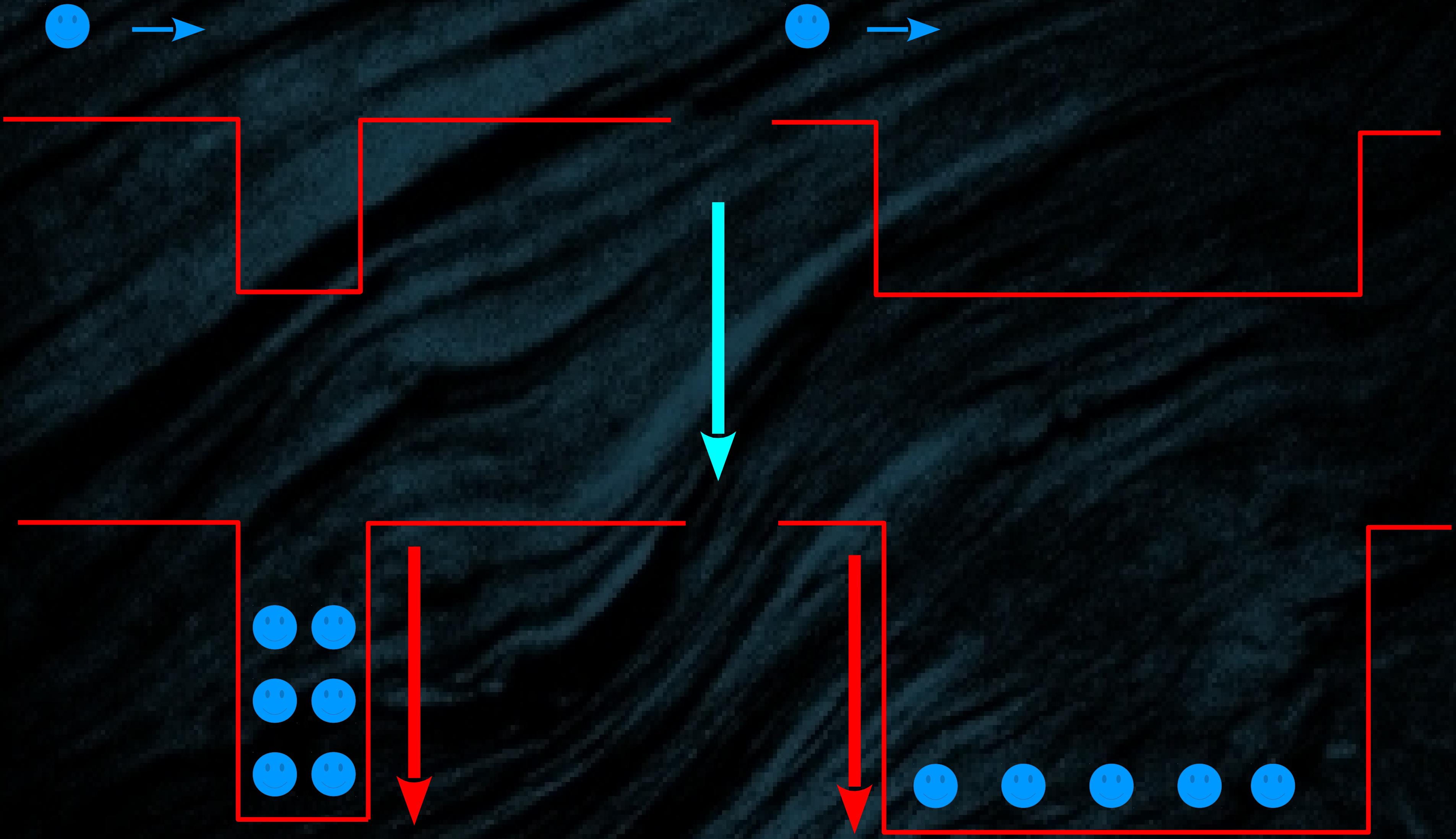
Assumptions:
- General relativity applied to cosmology
- Standard particle + nuclear physics

The coldness of (free streaming) DM



Hot Dark Matter:
→ fast in the matter-domination era
→ does not “see” small fluctuations
→ falls only in big ones
=> Big structures form first

The coldness of (free streaming) DM

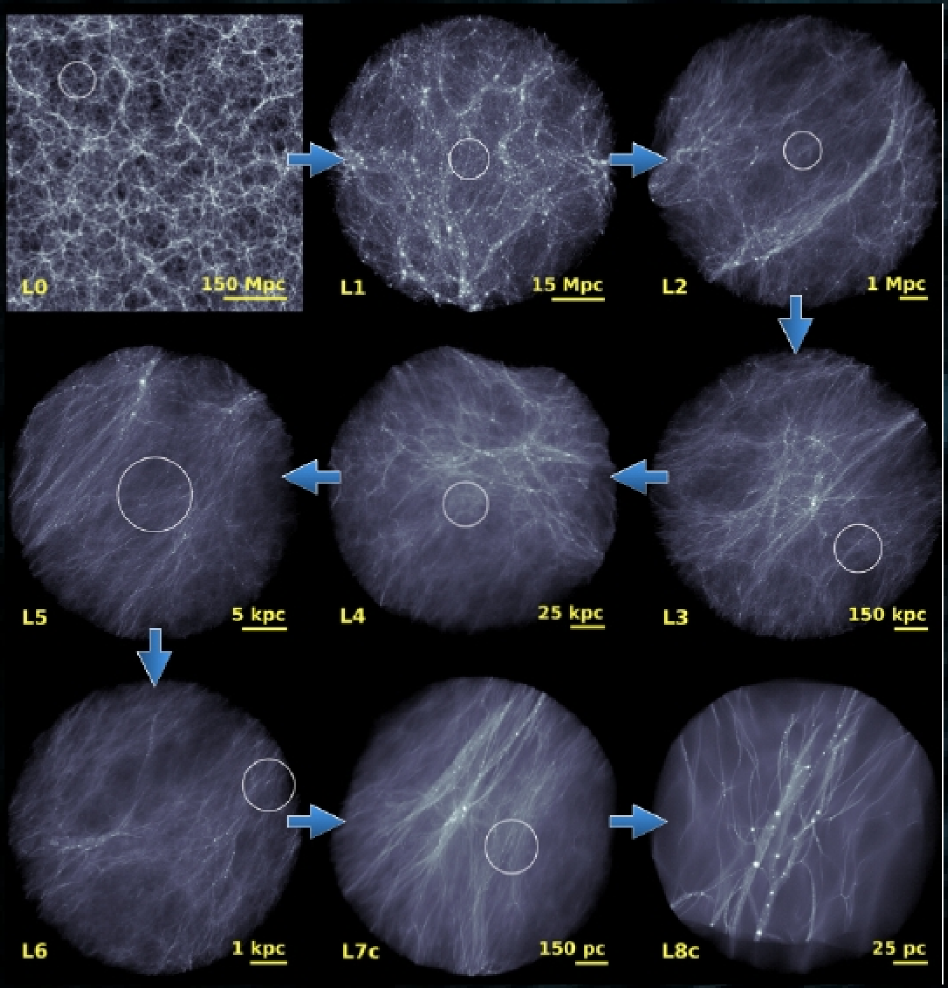


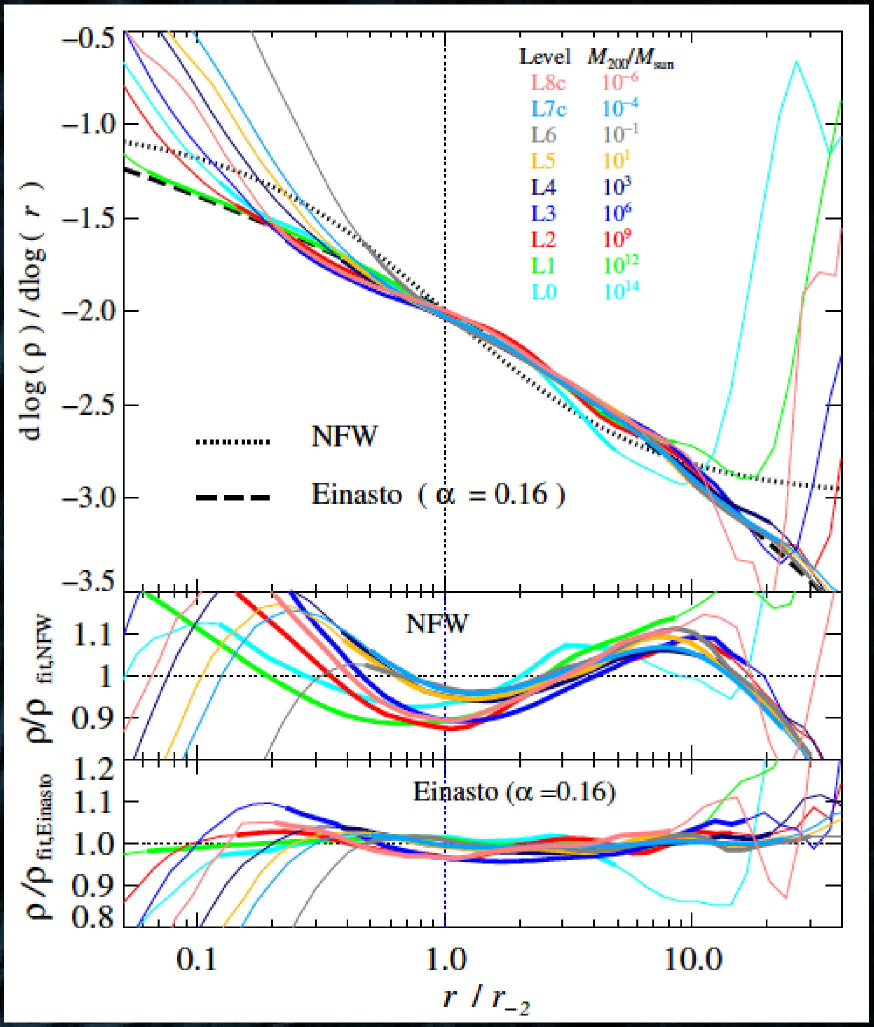
Cold Dark Matter:
→ slow during matter-domination era
→ falls in small fluctuations
=> small structures form first

Strong constraints coming from:
→ Abundance/properties of dwarf galaxies
→ CMB + Ly-alpha forest
→ CDM favored

Properties of CDM structures

Wang+’19





Scale-invariant density profile over >20 orders of magnitude in mass (DM-only, Wang+’19)

→ Cuspy profiles (NFW, Einasto)

→ Scale invariance of shape + inner density set by collapse time (lighter=more concentrated)

** Can be altered by baryonic physics on scales > 10^7 Msun (adiabatic contraction and/or feedback)

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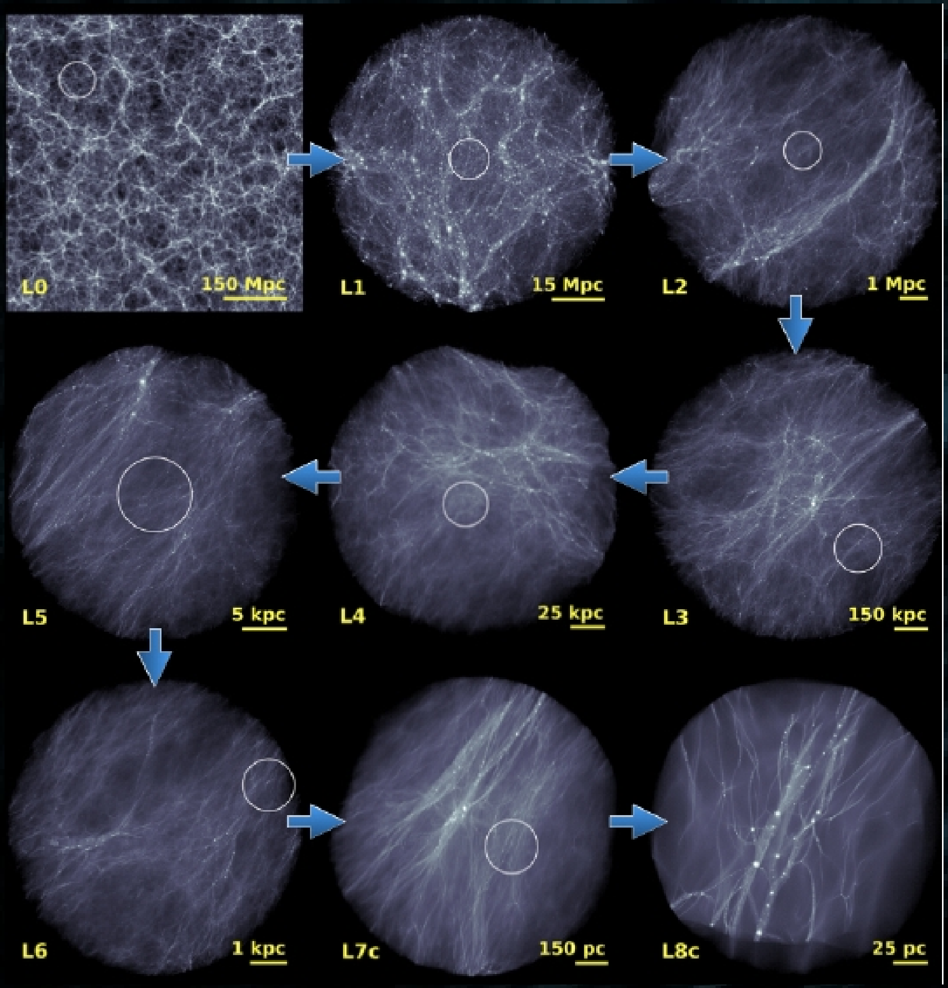
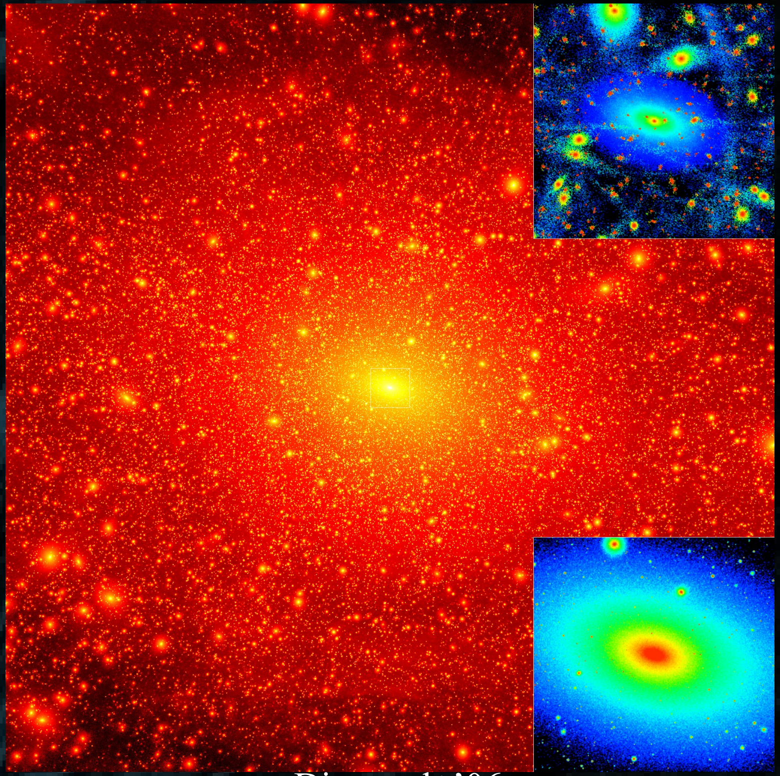


Galactic halos made of many subhalos
→ size/mass/number density depend on
  * DM candidate production + interaction properties
  * Primordial PP of density fluctuations
→ affect ID predictions for annihilating DM



Diemand+'06

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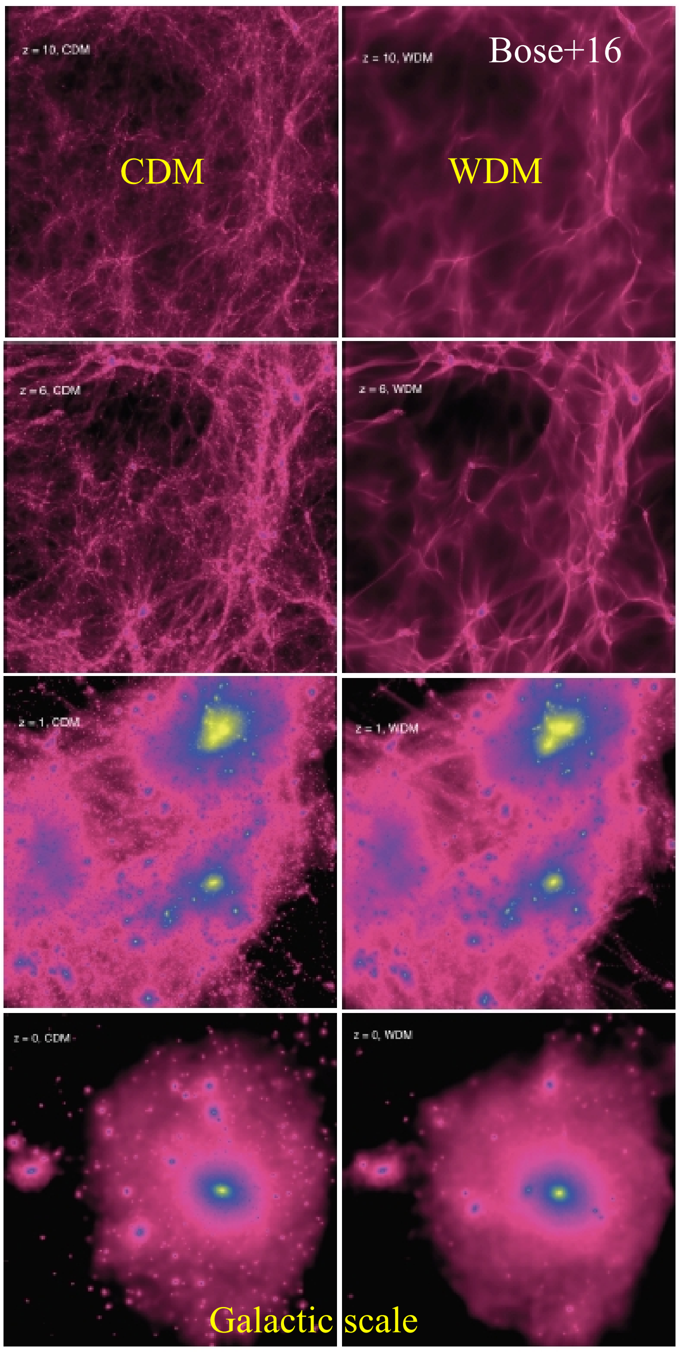

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ISSUES:

* No DM particles identified so far
(a generic statement for the dark universe: issue of the origin/s)

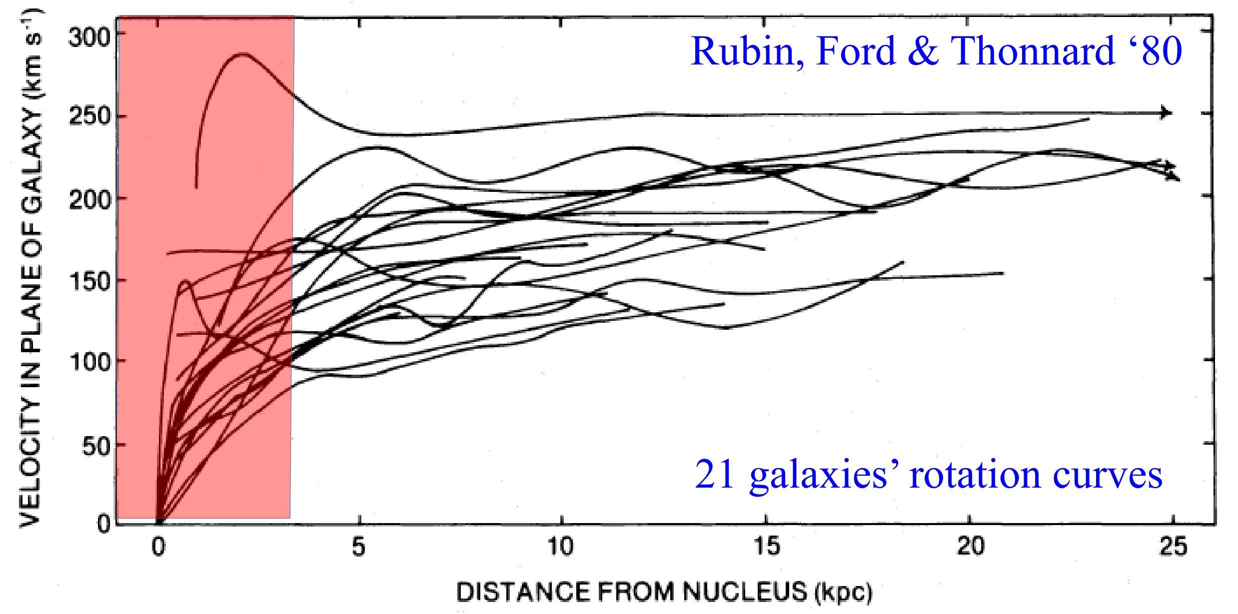
* How cold must it be?

* Some observational issues on cosmological scales? (e.g. Hubble tension)

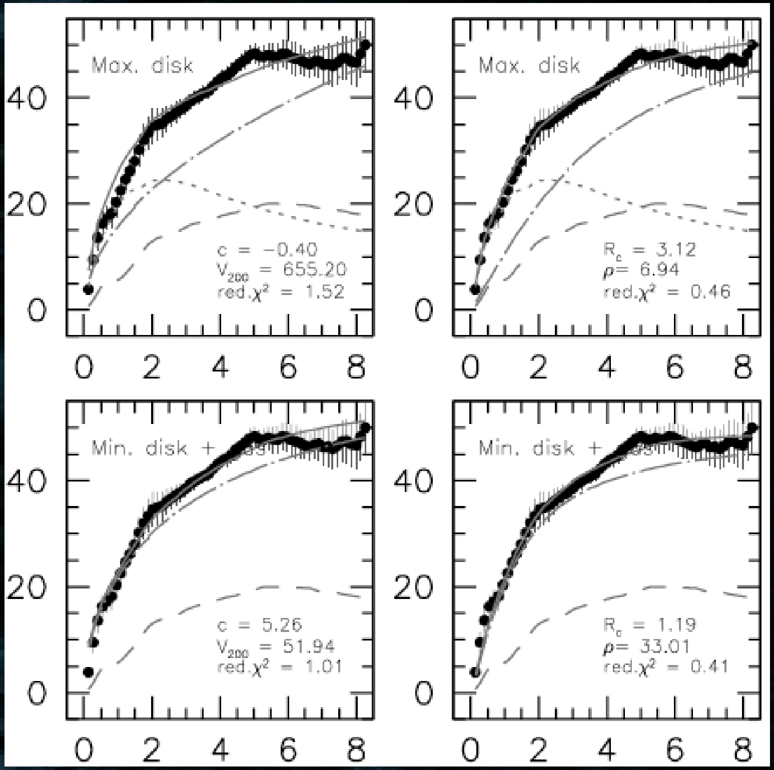
* Some observational issues (challenges?) on small scales

Dark Matter on galactic scales

Bulk of luminous matter



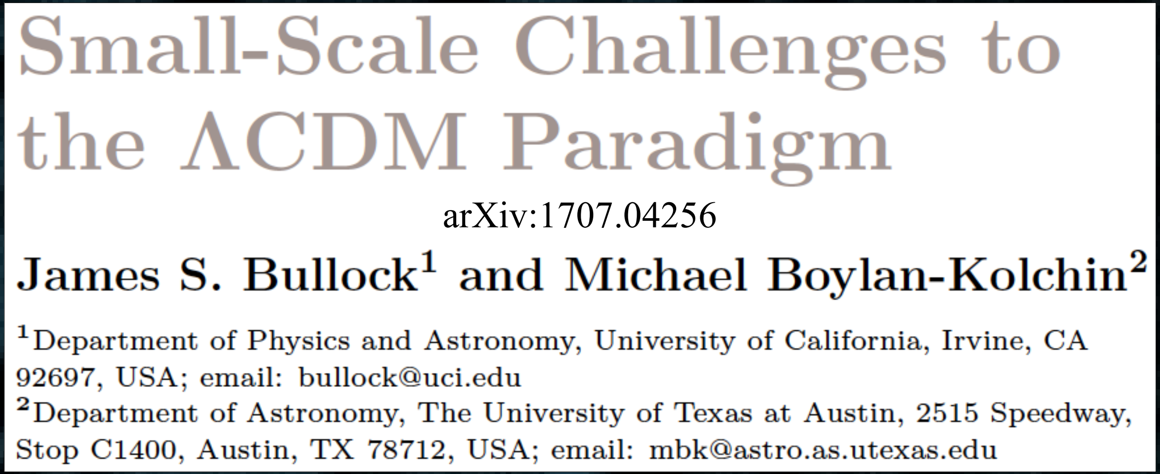
Oh+11



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]

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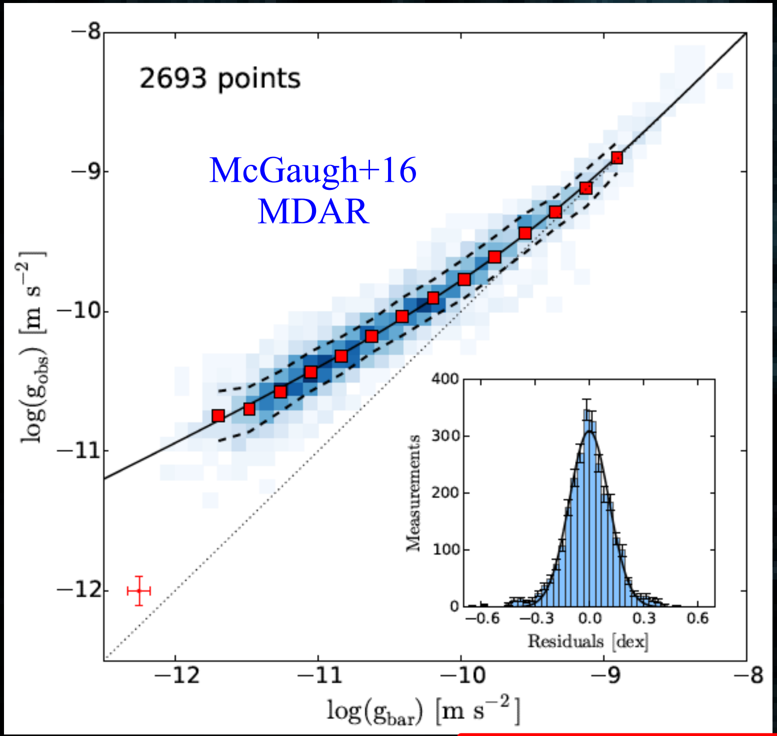
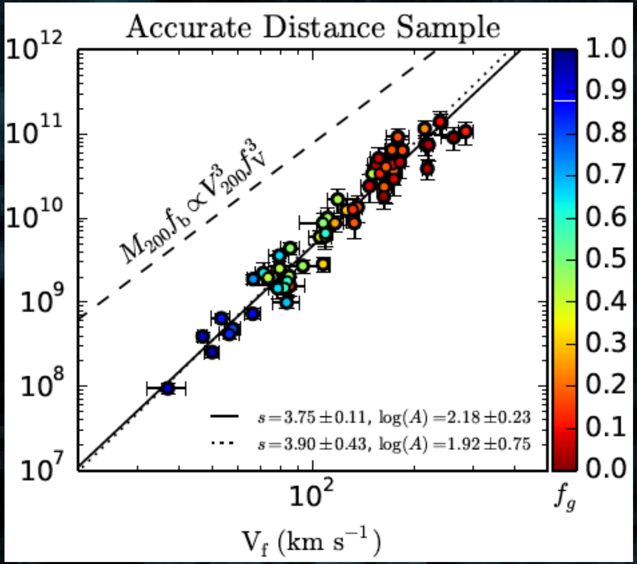
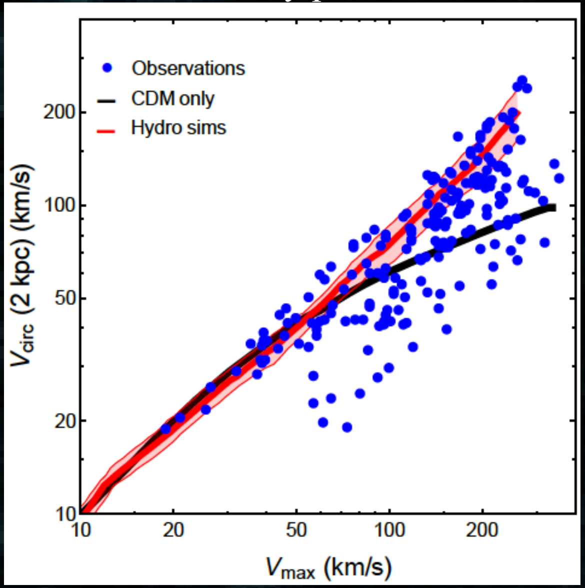


McGaugh+16
MDAR



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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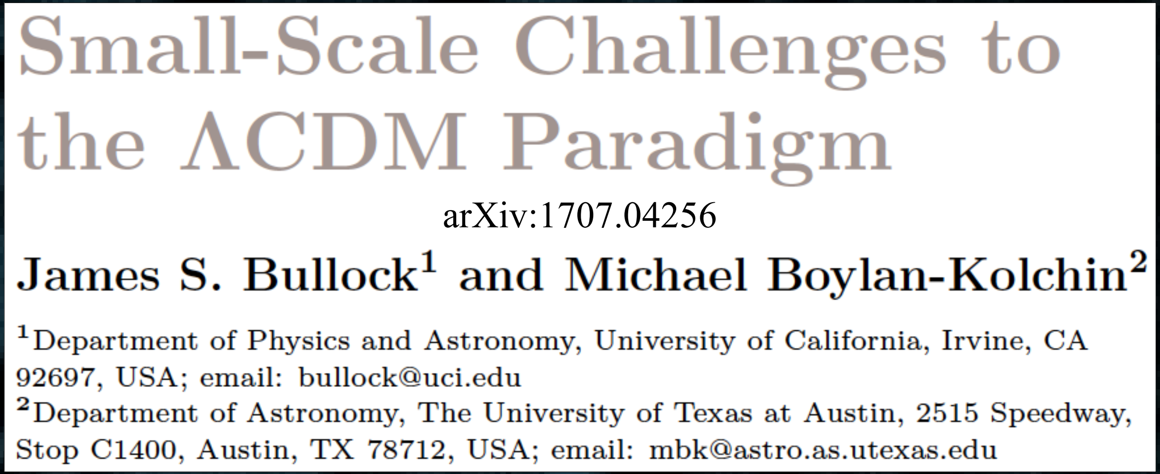

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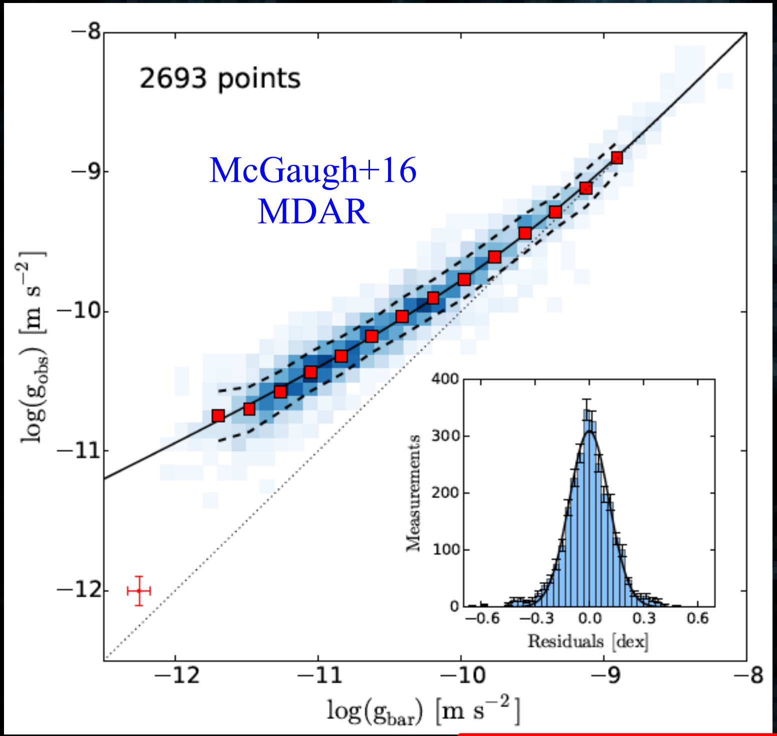

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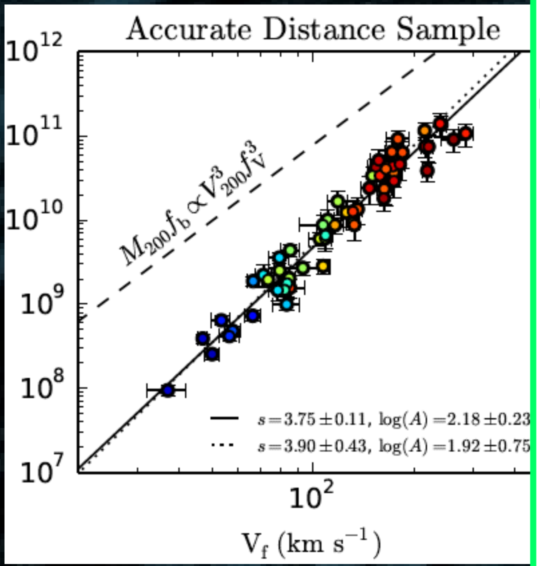
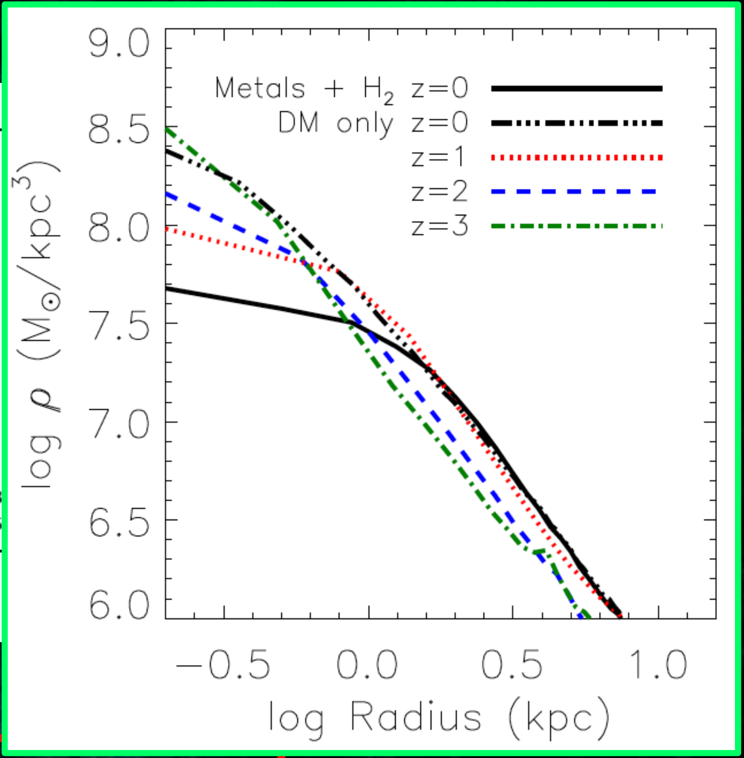


Lelli+15, BTFR

Governato+12
Cusps→cores



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?

Generic constraints on particle DM

→ 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: phase-space volume bounded from above!

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

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

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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Densest possible fermionic system: cannot exceed density of degenerate Fermi gas! (again Pauli excl. principle)

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

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

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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)

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

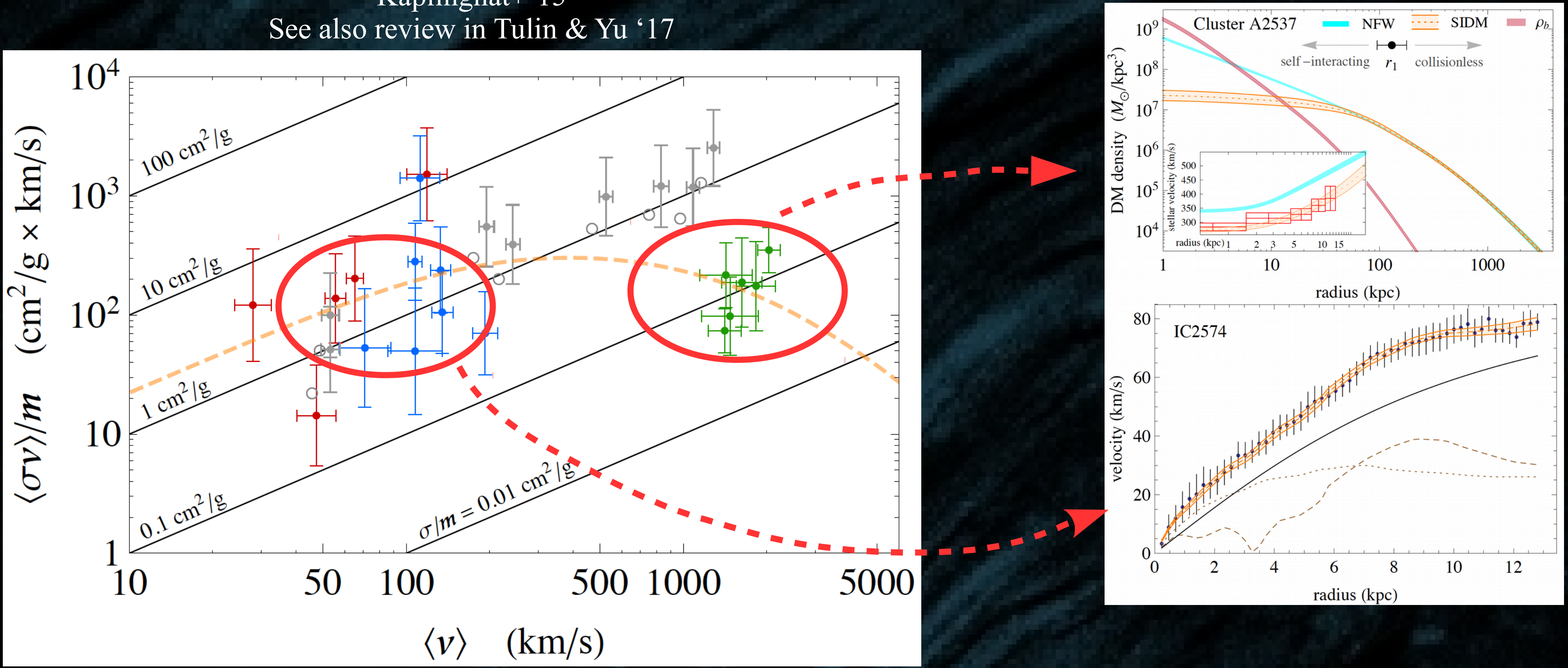
Original proposal by Carlson+'92

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"

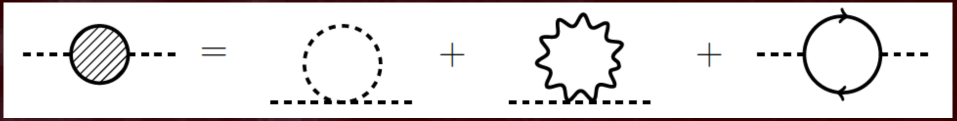
*** Consistent QFT**
+++ Production mechanism/s
+++ DM phenomenology with a minimal set of parameters => predictive
- - - built on purpose (ad hoc)

Model building

Two main approaches

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

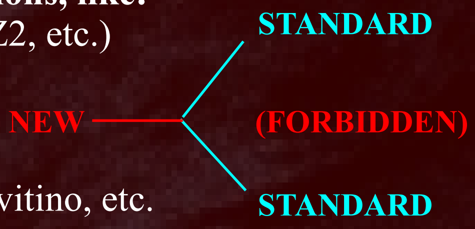
The **hierarchy pb** (Higgs stability),
aka the theoretical particle physics crisis



Challenged by LHC

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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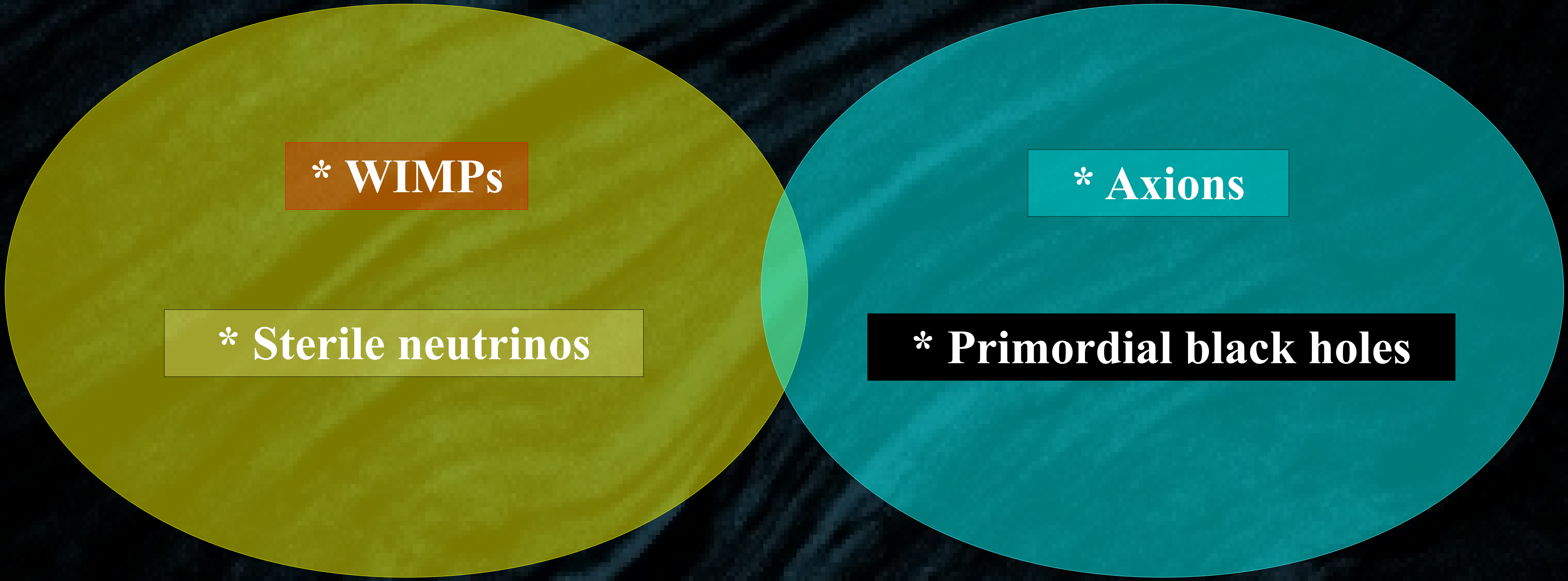
Popular scenarios



*** WIMPs**

*** Sterile neutrinos**

*** Axions**

*** Primordial black holes**

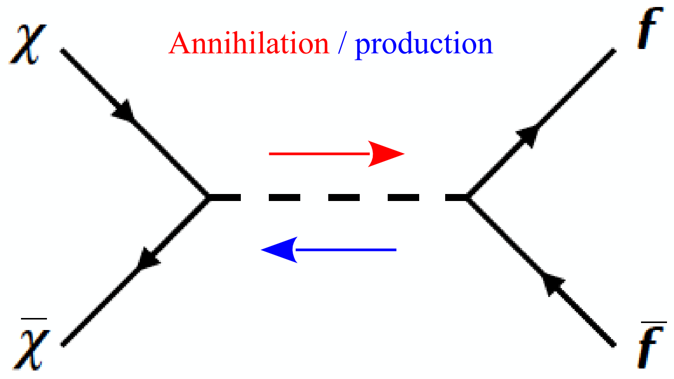
Thermal DM candidates:
* Couplings to SM necessary → signatures
* Produced from hot plasma in early universe (T>m)
* Can be probed by ID if self-annihilating or decaying
[e.g. stable asymmetric DM not probed by ID]

Non-thermal DM candidates:
* Tiny or no couplings to SM
* Produced from exotic decays or other mechanisms
* ID possible in some cases

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



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

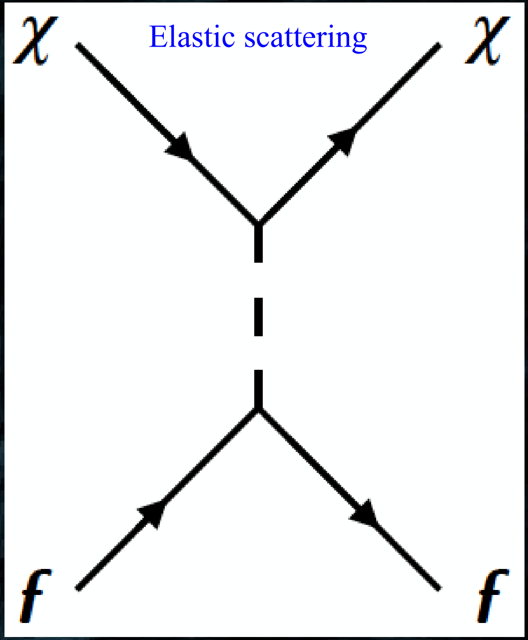
Searches based on the existence of DM/SM interactions (except for gravitational searches)

→ 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

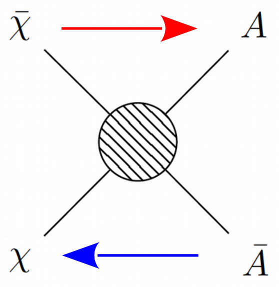
→ Direct: elastic/inelastic collisions in laboratory



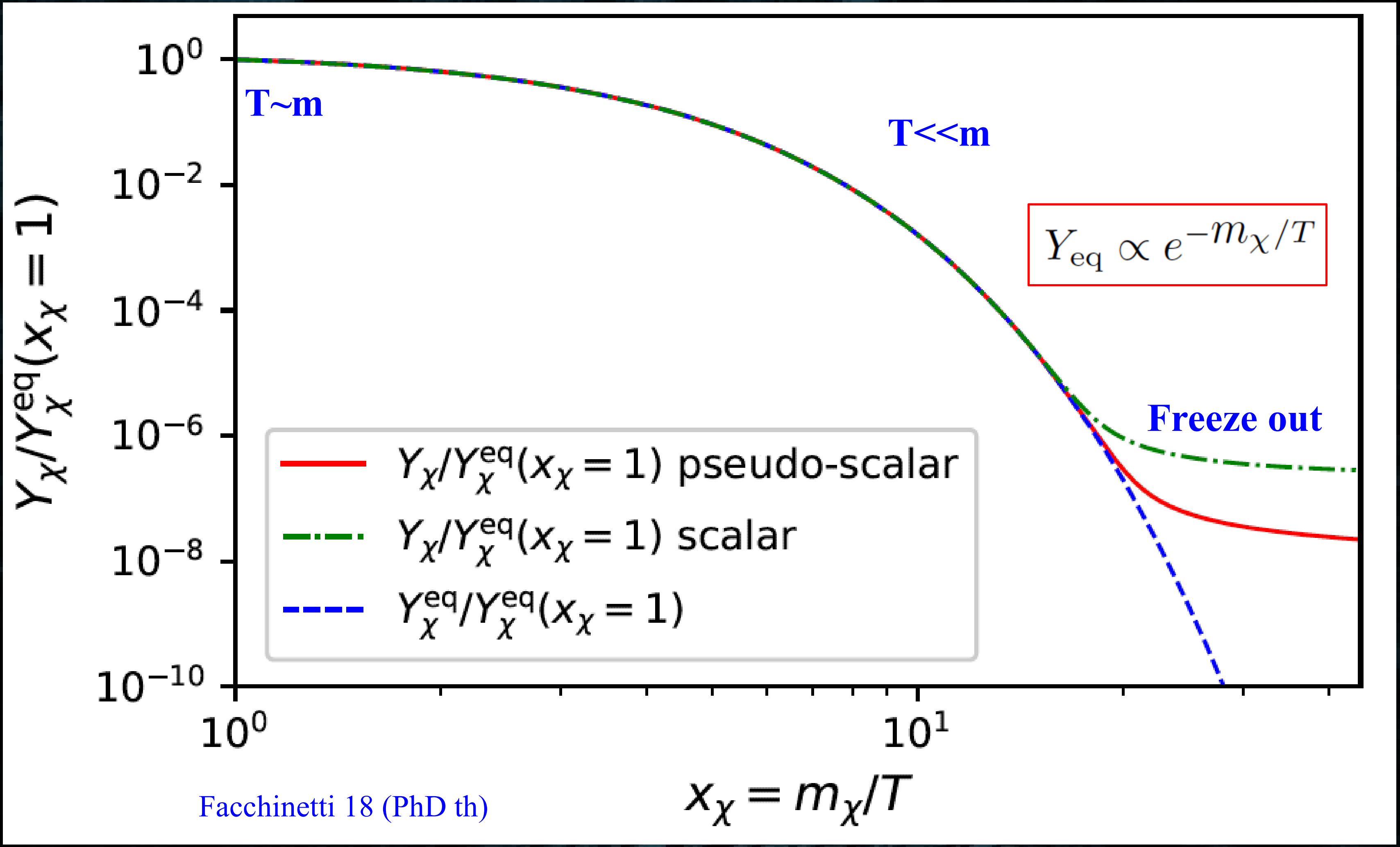
$$\Gamma_{\rm scatt.} = n_{\rm f} \left\langle \sigma_{\rm scatt} v \right\rangle$$

Thermal production in the early Universe

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



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



Facchinetti 18 (PhD th)

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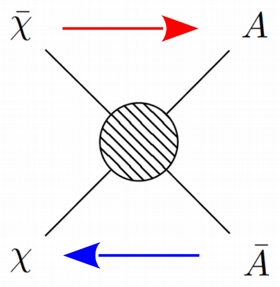
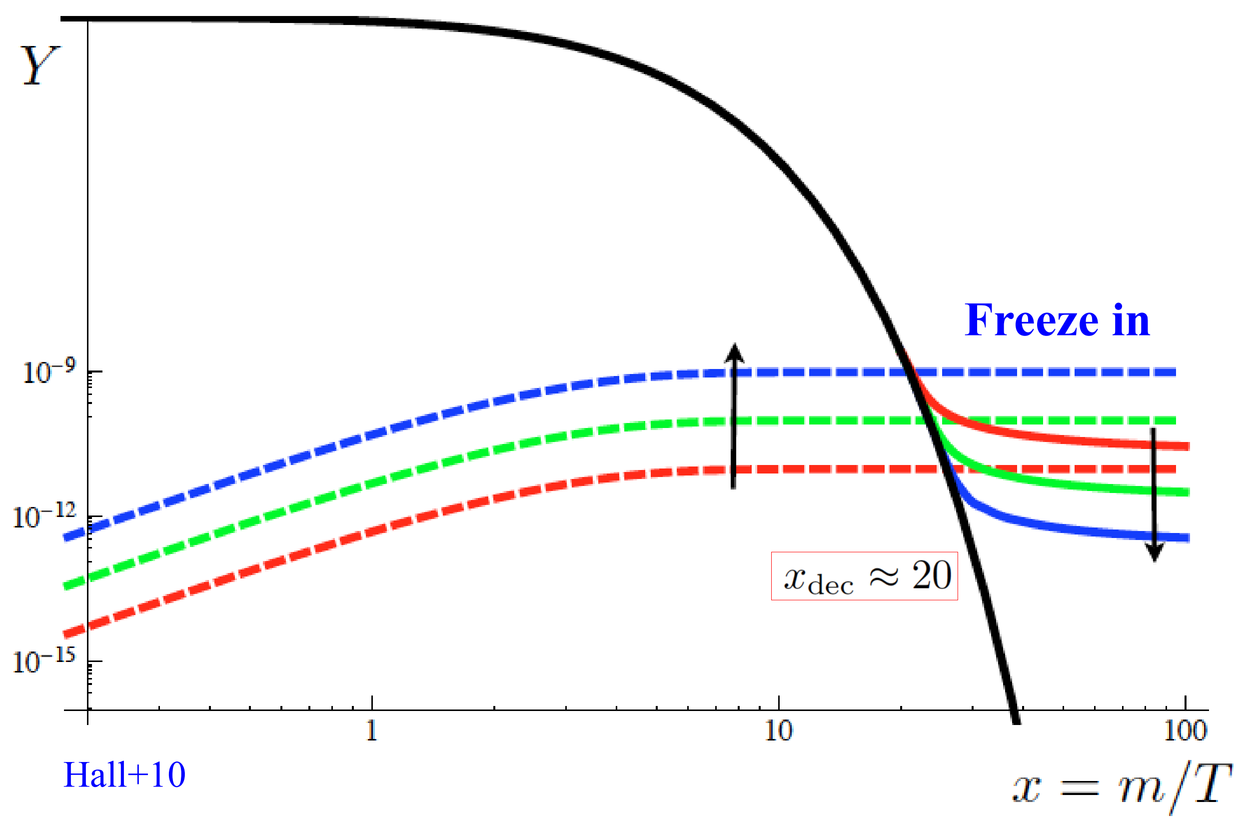




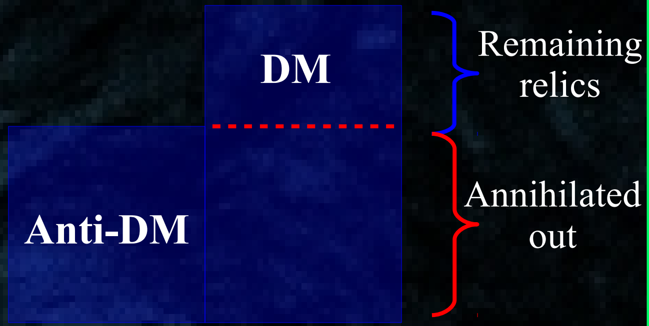
Freeze-in mechanism:
Dodelson & Widrow '94
McDonald '02
Hall+ 10

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

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

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

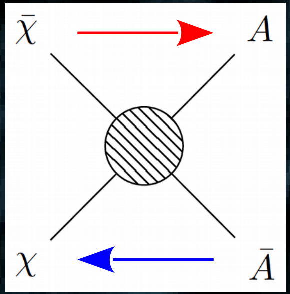
Asymmetric DM (Nussinov' 85)



$$\langle\sigma_{\chi\bar{\chi}} v\rangle_{\mathrm{ADM}} > \langle\sigma_{\chi\bar{\chi}} v\rangle_{\mathrm{WIMP}}$$

All this picture is also valid for self-interacting dark matter (SIDM)
→ generic properties: extended dark sector (interaction mediators)

Take home message...

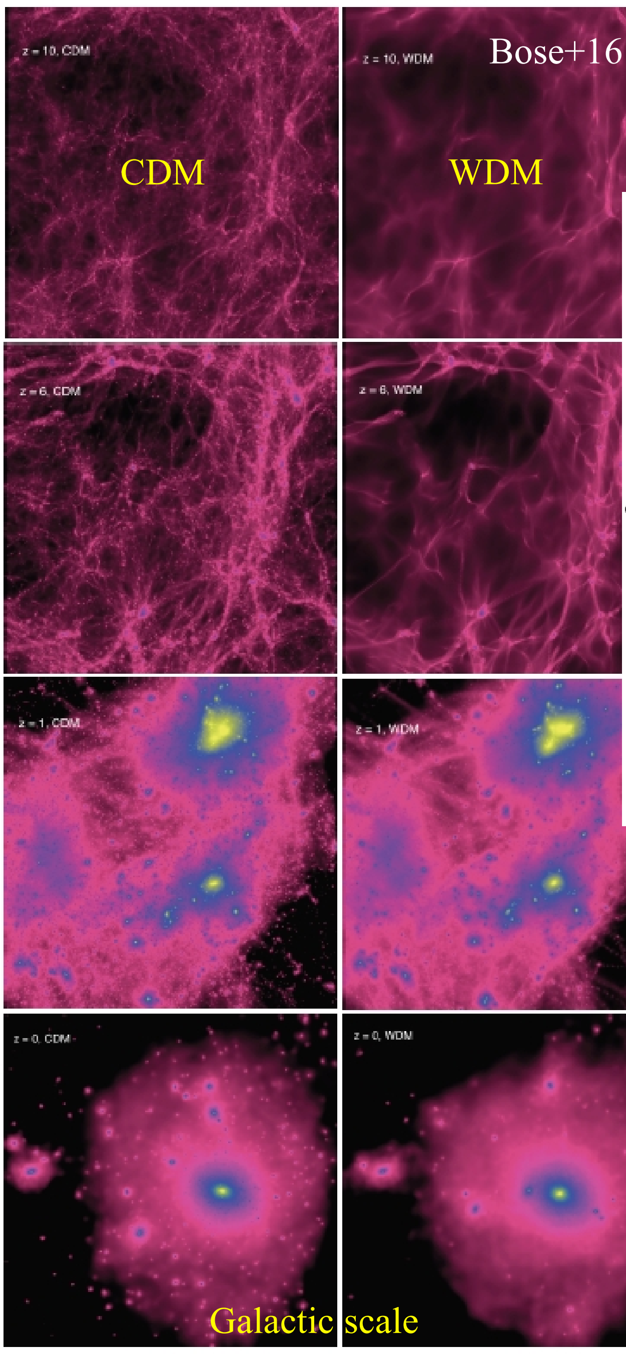


Constrained annihilation rate ∝ $\langle\sigma v\rangle \sim 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$ can be velocity dependent!
=> v suppressed in galaxies today wrt chemical decoupling time!

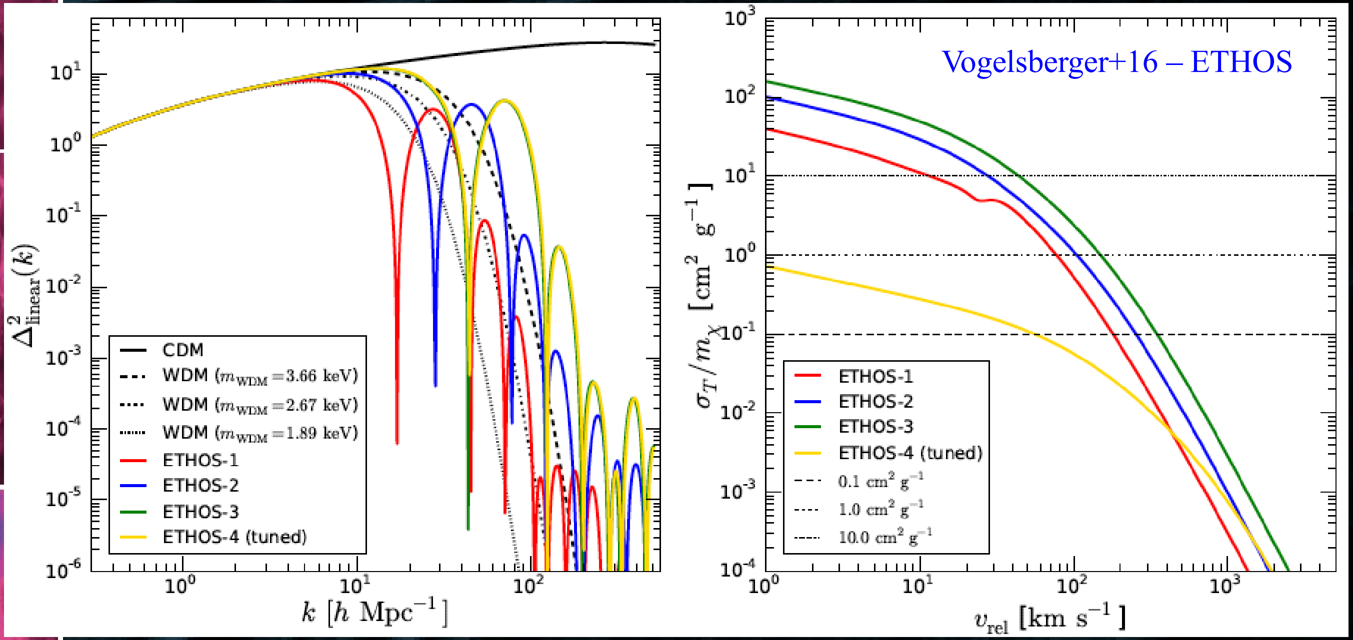
Unsuppressed $\langle\sigma v\rangle$ concerns only a subpart of the WIMP parameter space
→ called s-wave cross section ←

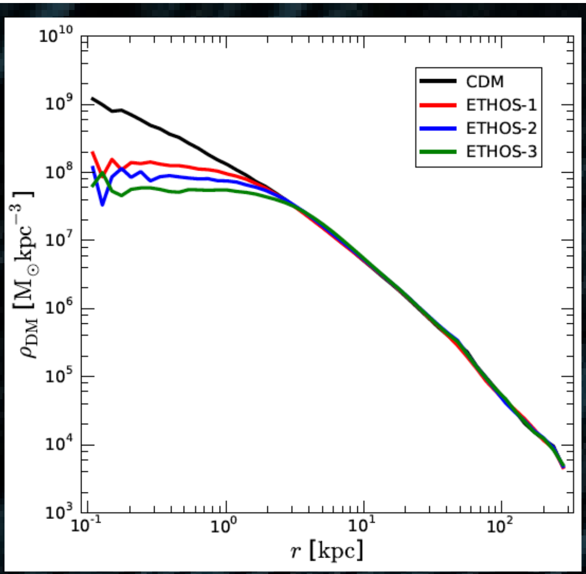
ID only cannot probe/exclude the full WIMP parameter space
=> complementarity important

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



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





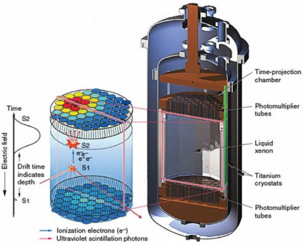
CDM candidates: minimal scale of structures depend on interactions. For TeV particle, can be ~10^{-10}M

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

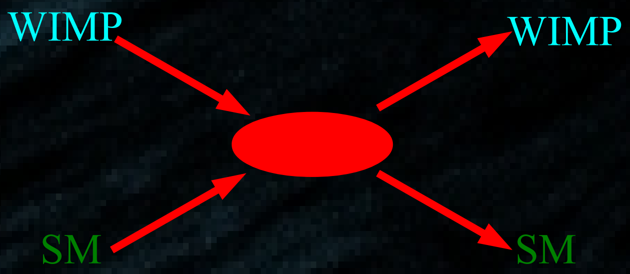
Astro/particle complementarity

Direct detection rate – WIMP-matter scattering

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



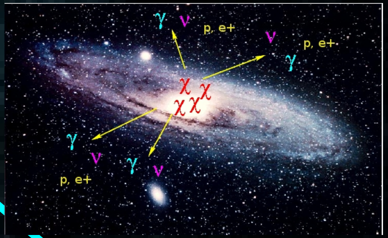
Scattering
(→ kinetic decoupling in early universe
+ subhalo mass cutoff)



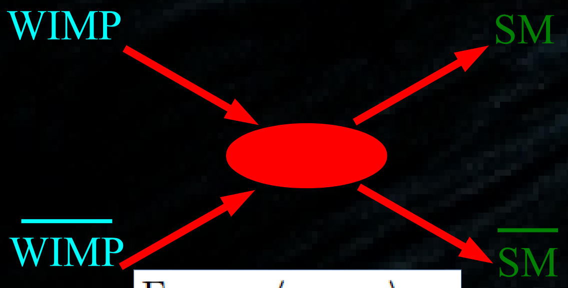
$$\Gamma_{\rm scat} = \langle\sigma_{\rm scat}\,v\rangle\,n_{\rm plasma}$$

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)

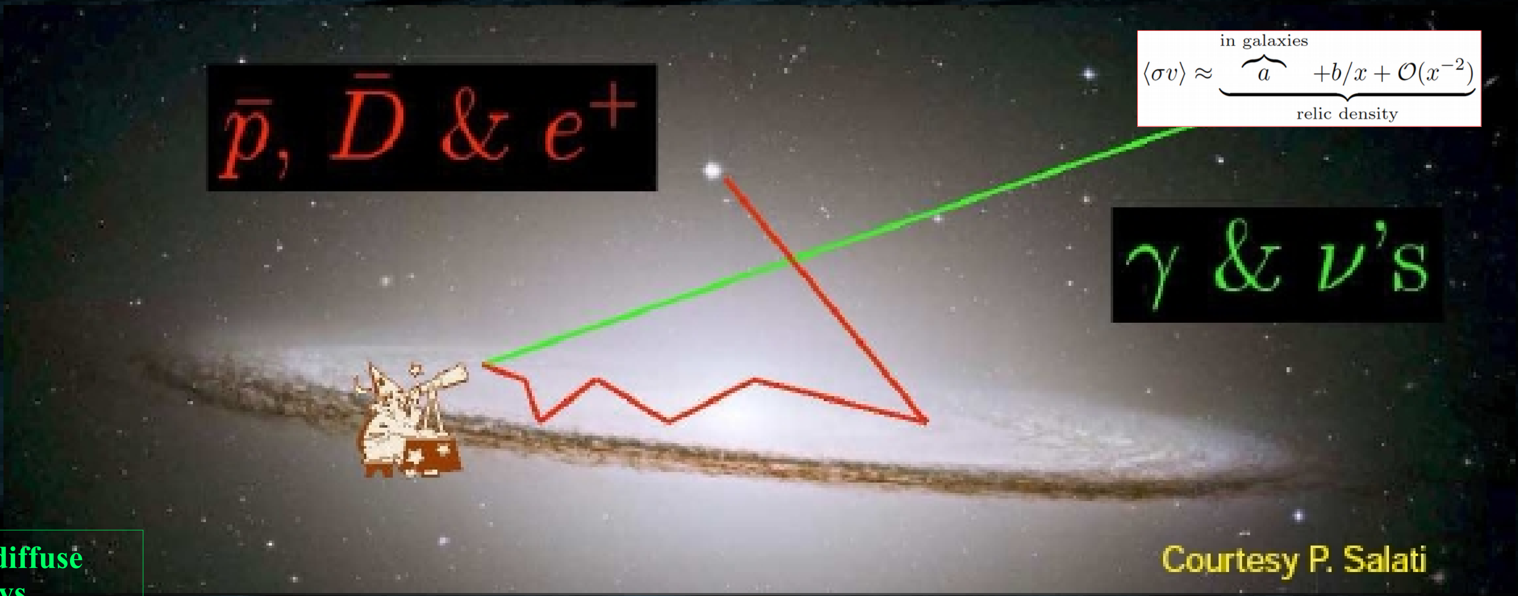


$$\Gamma_{\rm ann} = \langle\sigma_{\rm ann}\,v\rangle\,n_\chi$$

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

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

Up to the skies!

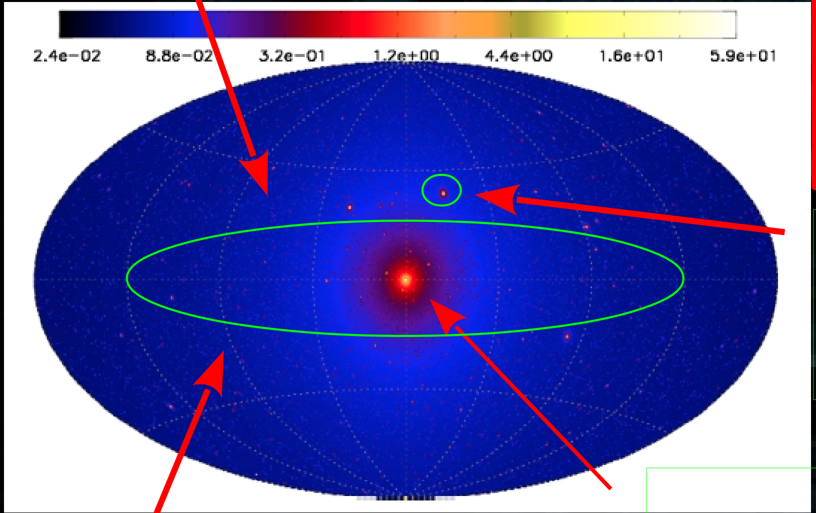


$$\langle\sigma v\rangle \approx \underbrace{\overbrace{a}^{\text{in galaxies}} + b/x + \mathcal{O}(x^{-2})}_{\text{relic density}}$$

Courtesy P. Salati

Extragalactic diffuse gamma-rays

Pieri, JL+ '11



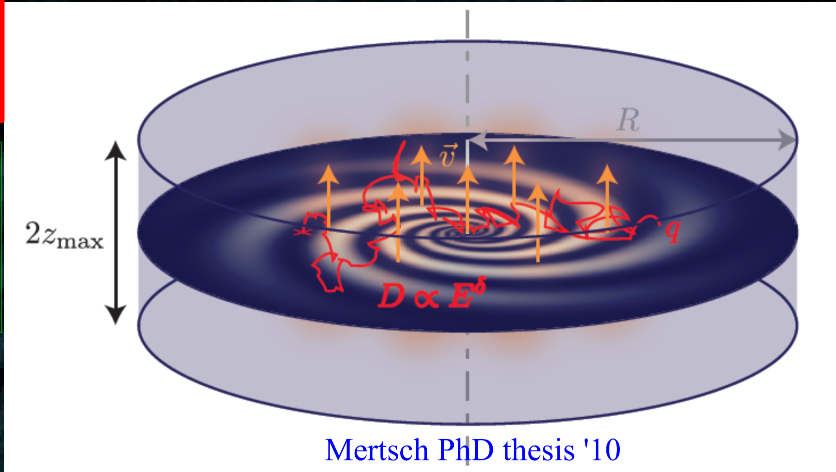
Diffuse gamma-ray emission
=> check spectral/spatial properties wrt background

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.

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

Cosmic-ray transport



Mertsch PhD thesis '10

Line-of-sight integrals...

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.

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

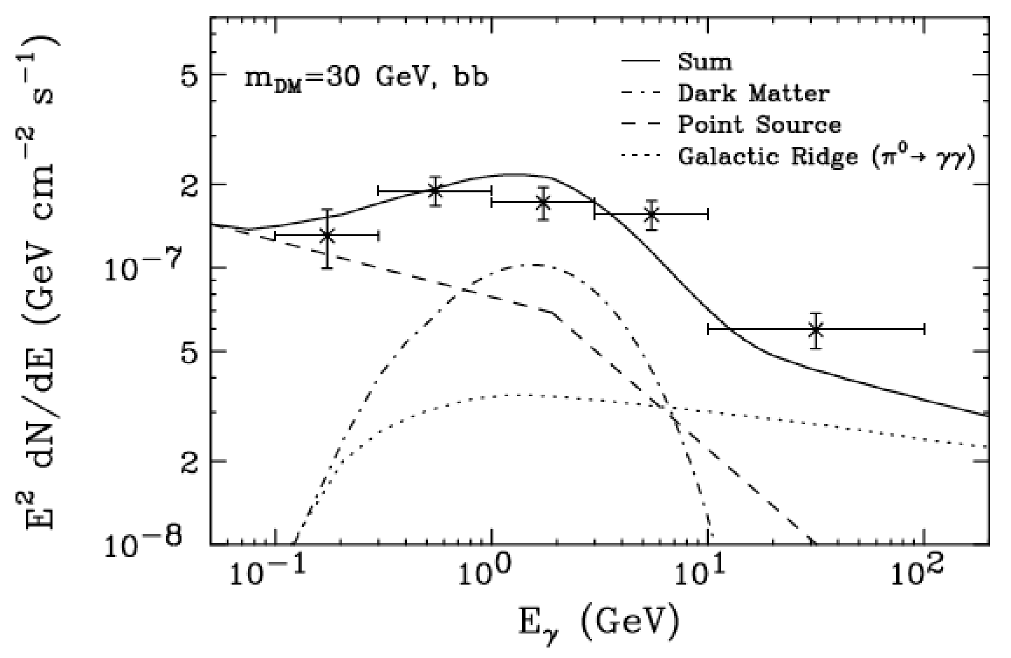
* Cosmic-ray antiproton "excess"

* etc.

* Mostly astrophysical phenomena
(much more difficult to predict)

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

Intense gamma-ray emission from the Galactic Center

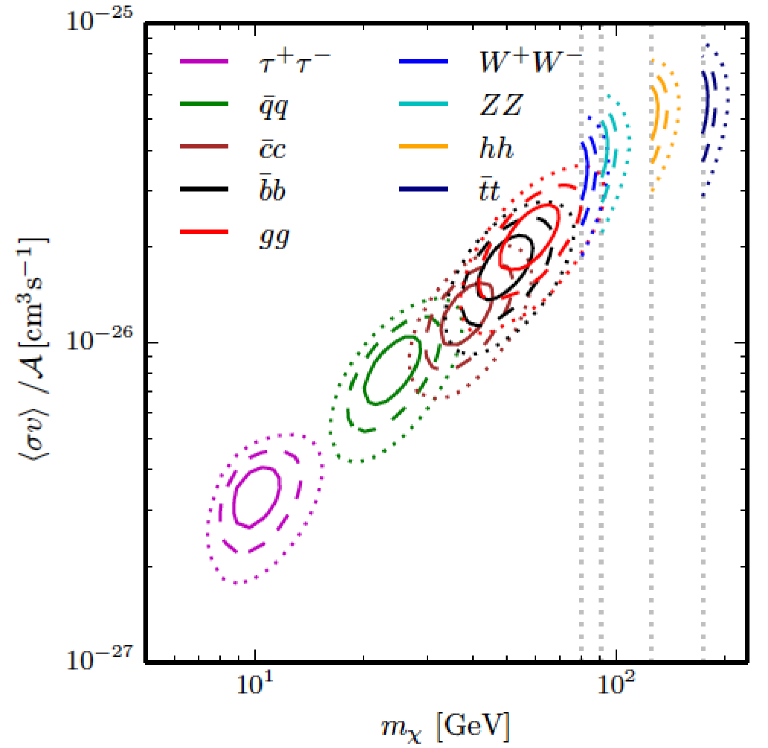


Hooper & Linden'11

→ Departure from "background model" interpreted as an "excess"

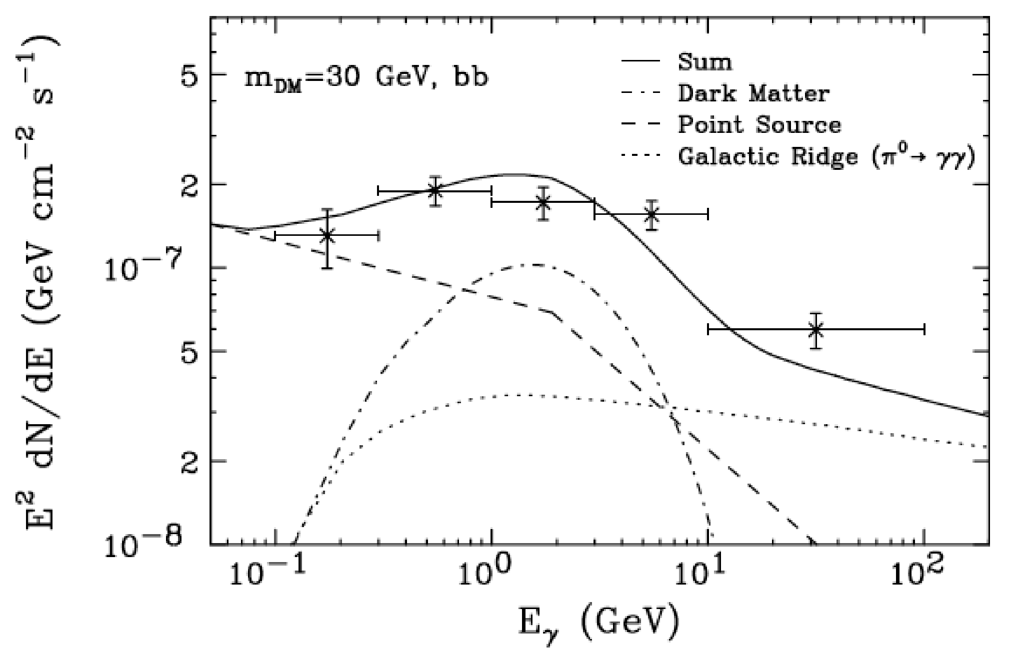
→ DM signal prediction easy!
[assumption of cuspy halo]

WHAT ABOUT THE BACKGROUND?
(excess → control of bckgd)



Calore+'15

Intense gamma-ray emission from the Galactic Center



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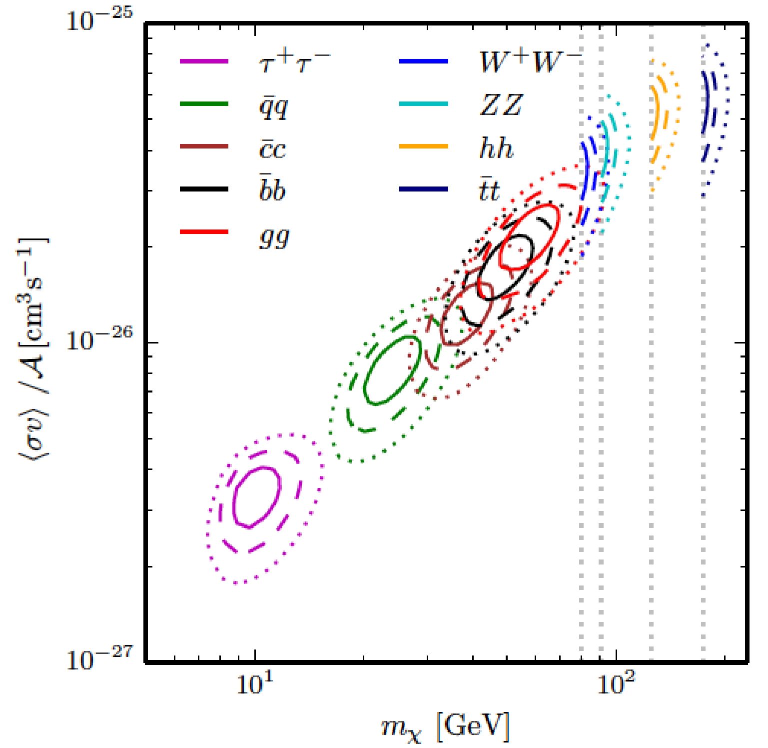


Calore+'15

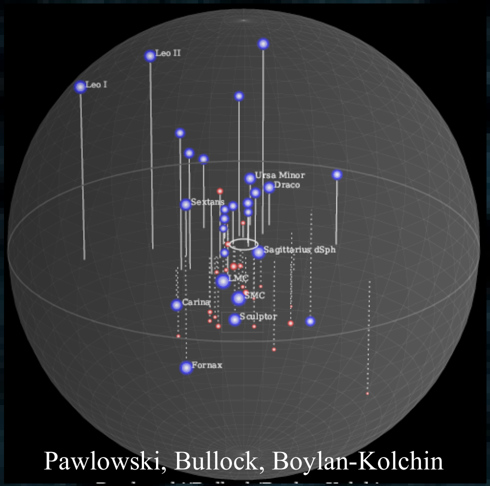
Galactic center a complicated region!

→ Distribution of (unresolved) sources?
→ ISM + magnetic field?
→ Cosmic-ray transport?

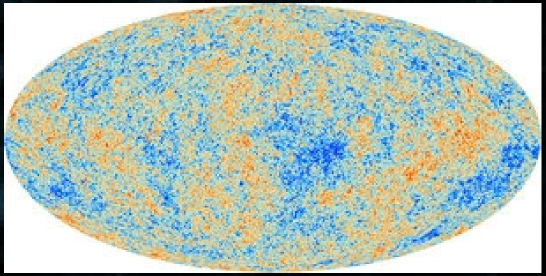
** milli-second pulsars? (e.g. Bartels+'16)
** several other possibilities

Definitely an interesting playground for astrophysics
Not yet compelling for DM

Some constraints (annihilating DM)

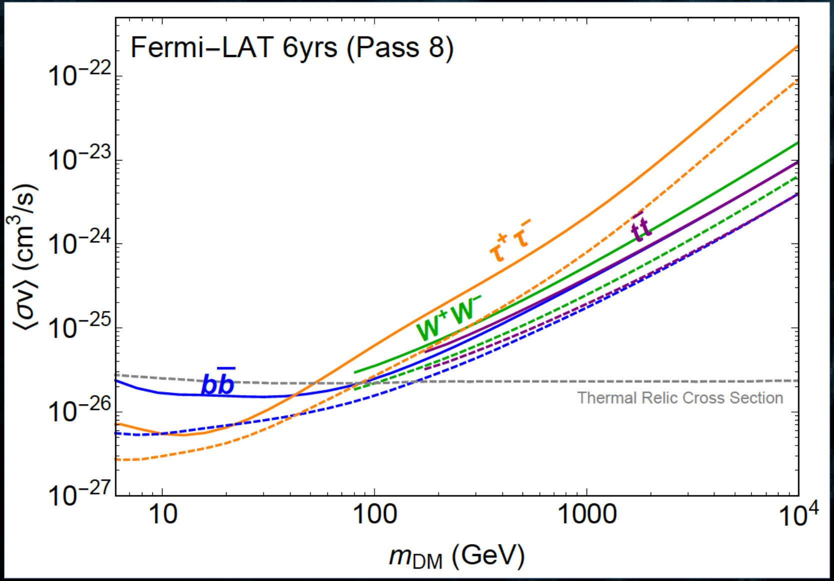


Pawlowski, Bullock, Boylan-Kolchin



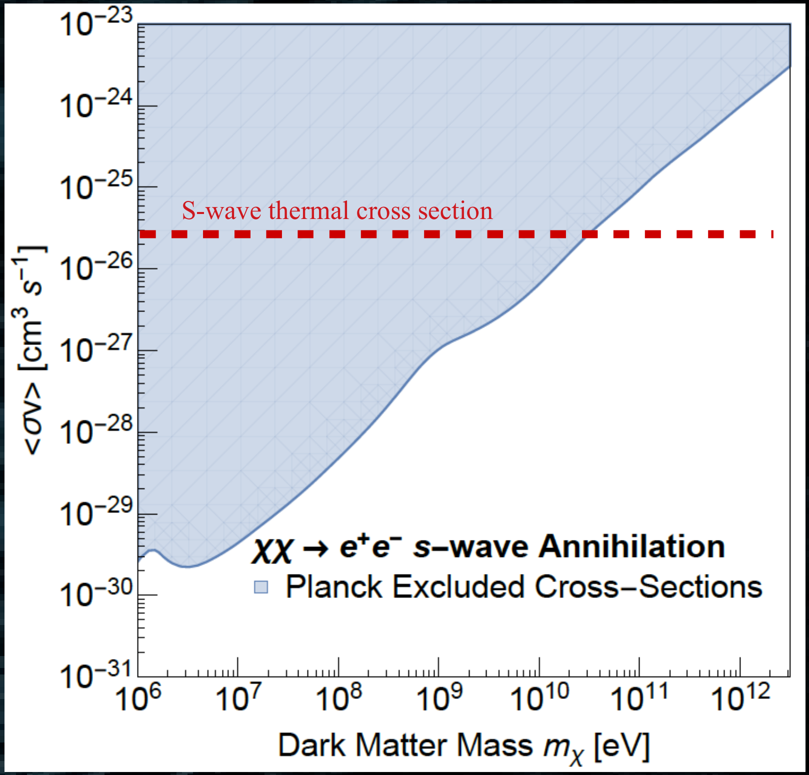
Planck @ ESA

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

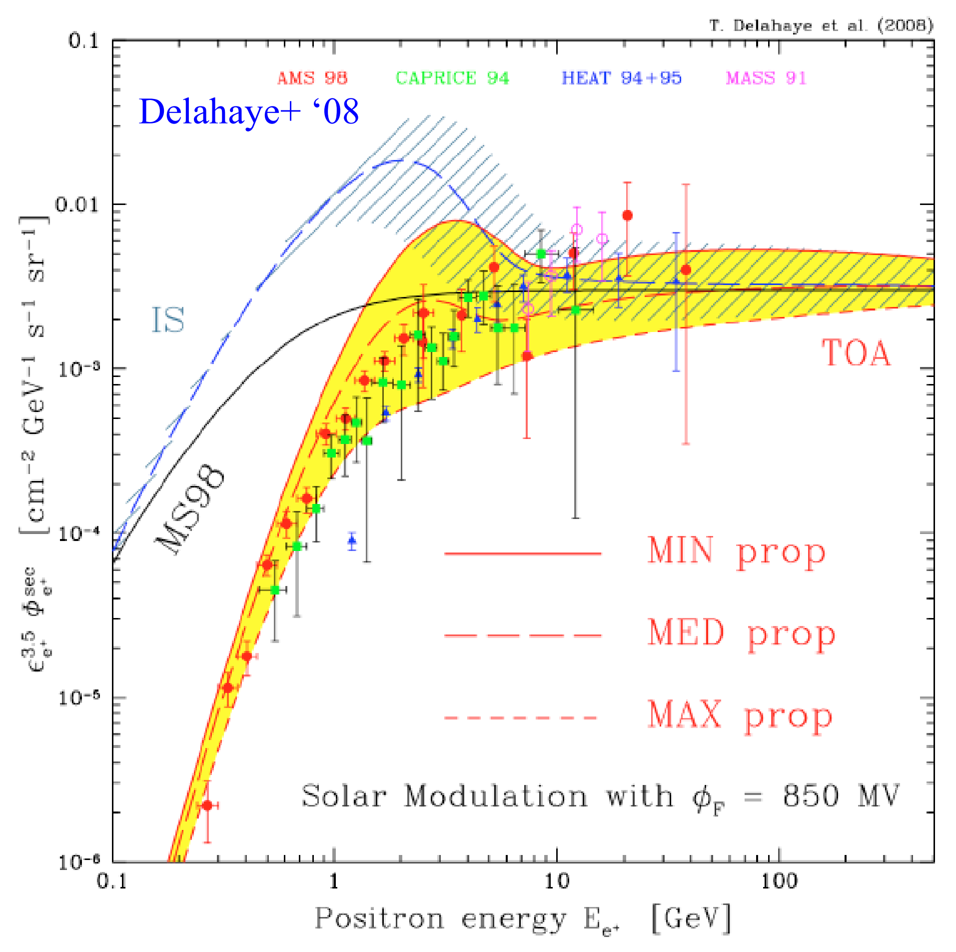


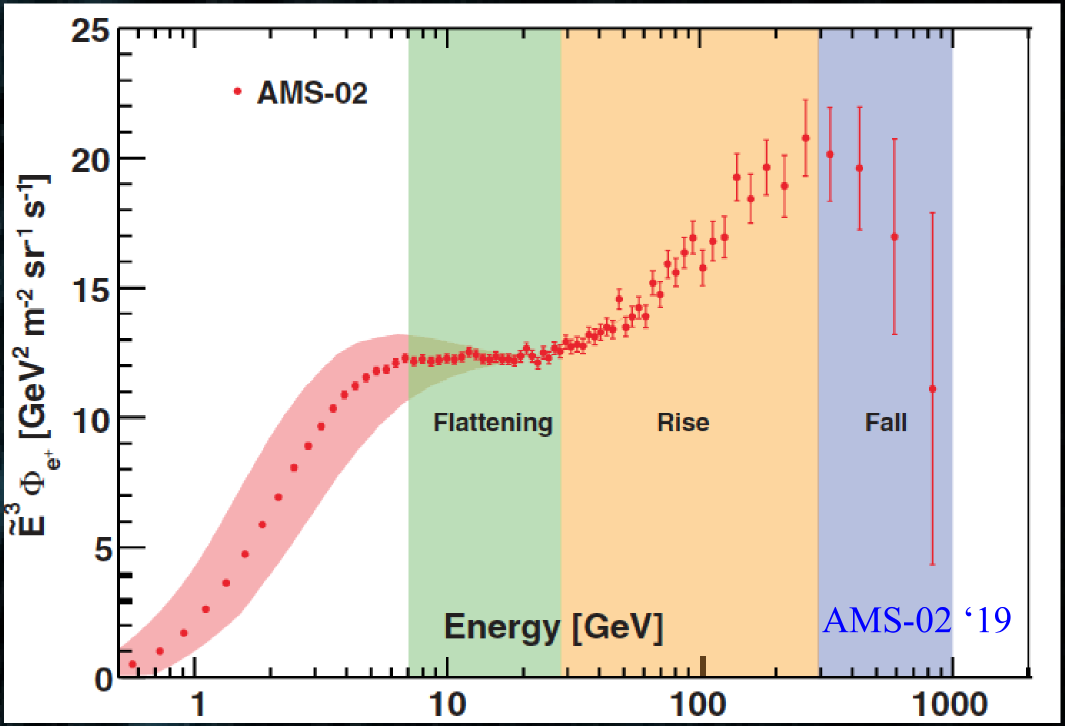
Constraints on s-wave annihilation only
+ systematics from DM profile modeling
[Bonnivard+'15]

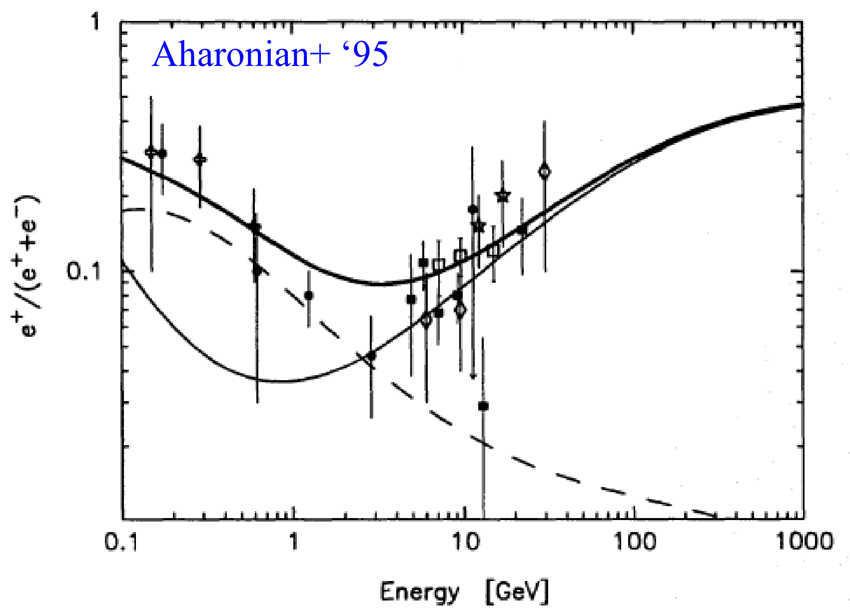
Slatyer '16, Liu+'17
CMB (Planck data '15)
→ energy injection delays recombination



Positrons: the quest for primaries

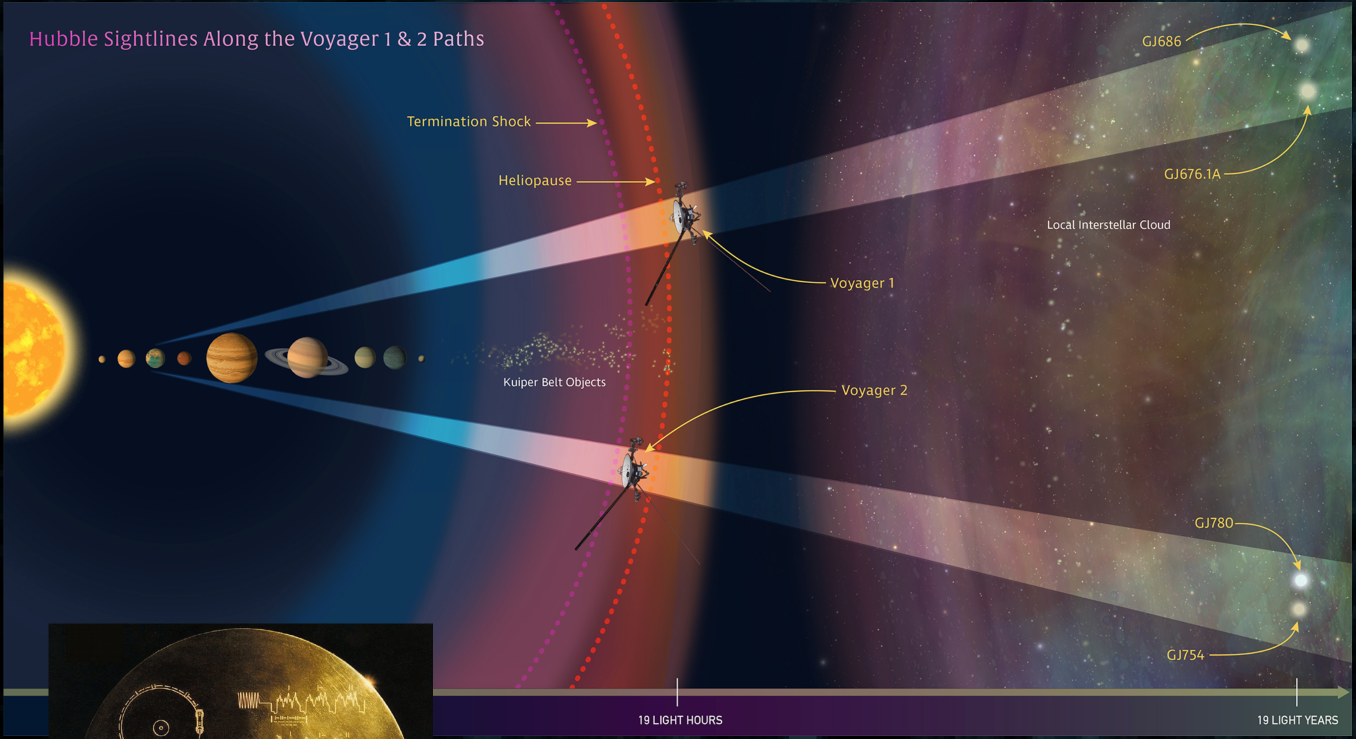






Secondaries under control (e.g. Boudaud+'15-19)
→ Need of primaries
→ Local PWNe good candidates (e.g. Shen '70, etc.)

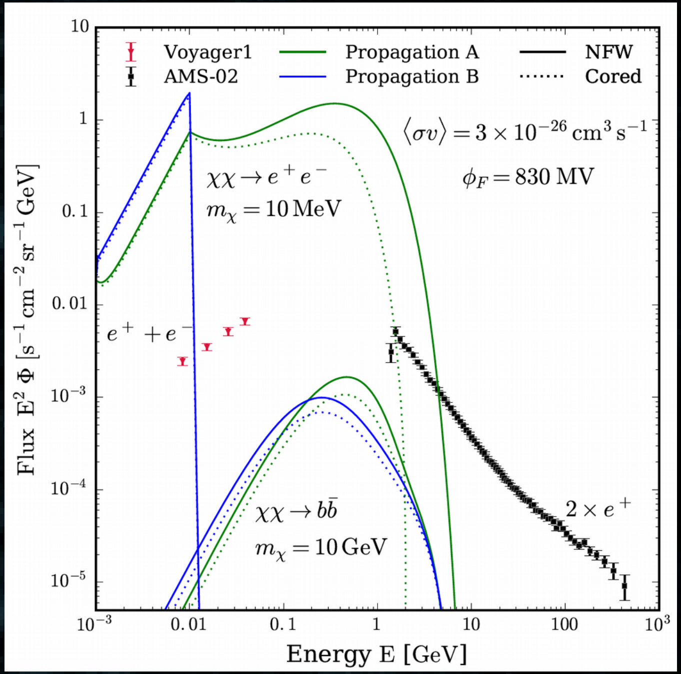
Down to MeV DM with cosmic rays + p-wave

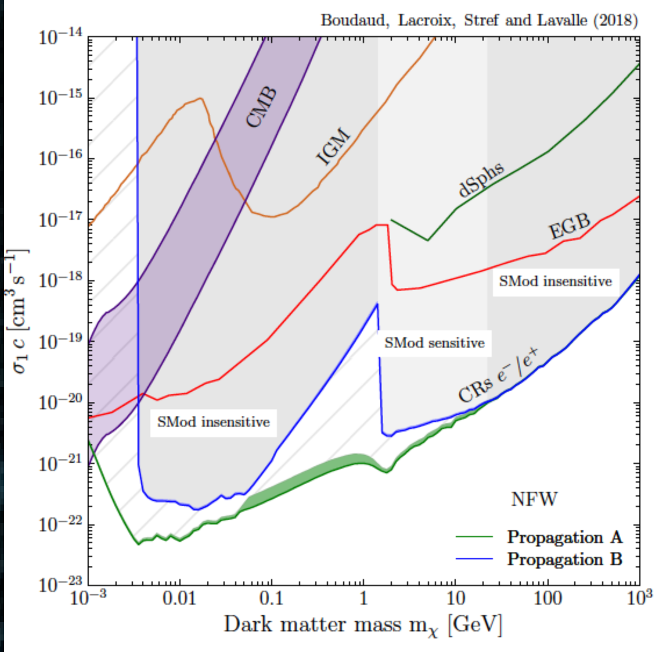


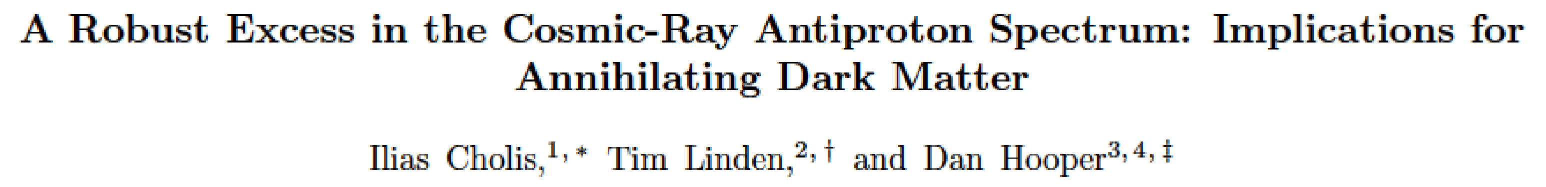
Voyager 1 has passed the heliopause in 2012!
=> cosmic rays no longer shielded by solar magnetic fields
=> use MeV e+e- data on tape + AMS-02 beyond

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

Boudaud+17-18.



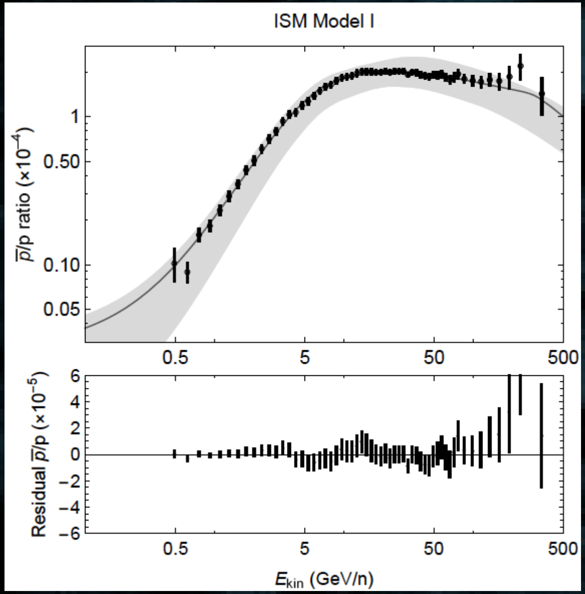


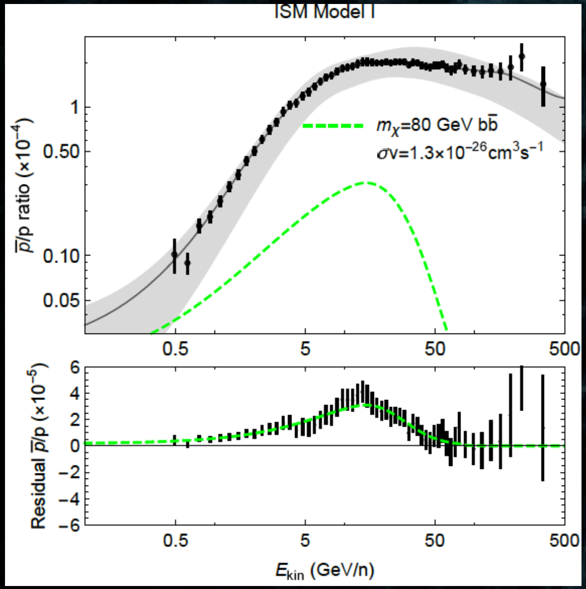


A Robust Excess in the Cosmic-Ray Antiproton Spectrum: Implications for Annihilating Dark Matter

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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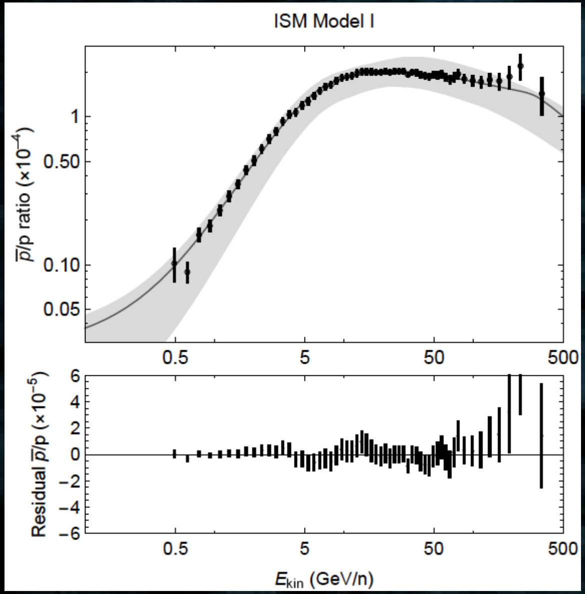
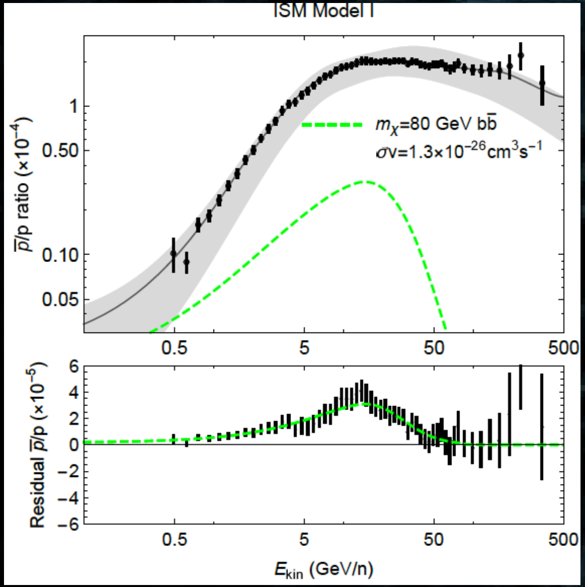
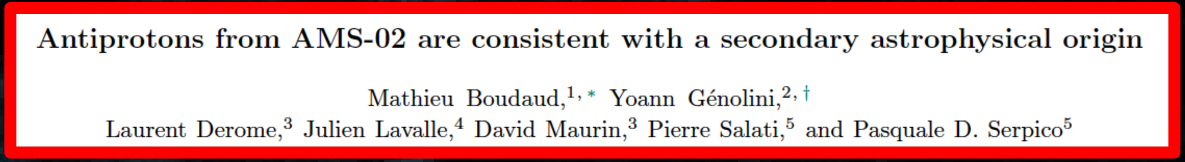


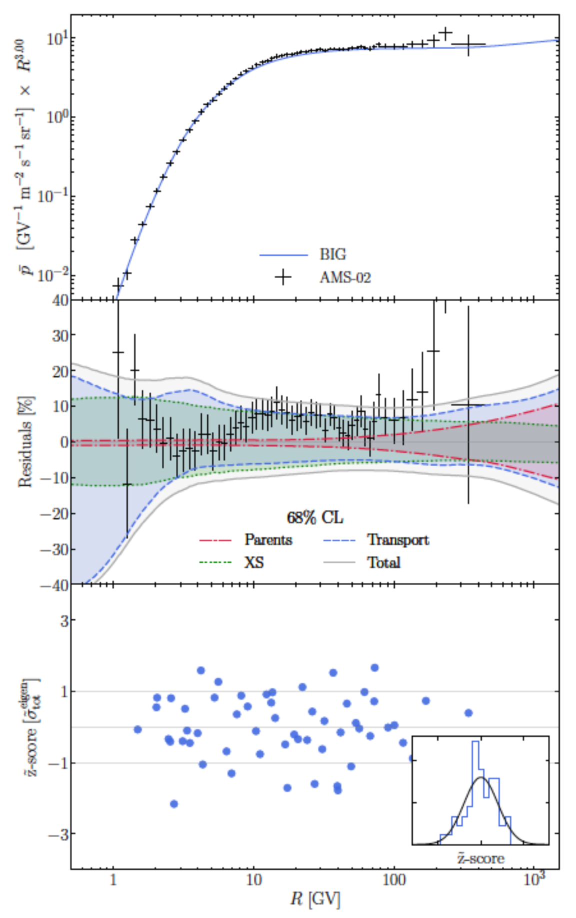


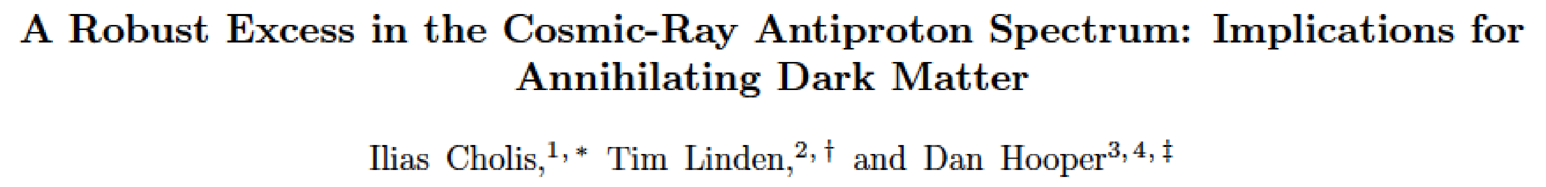


Antiprotons from AMS-02 are consistent with a secondary astrophysical origin

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

(arXiv:1906.07119)





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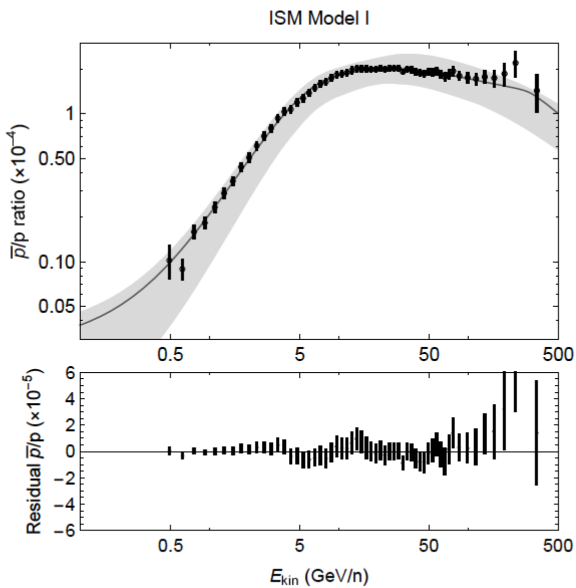
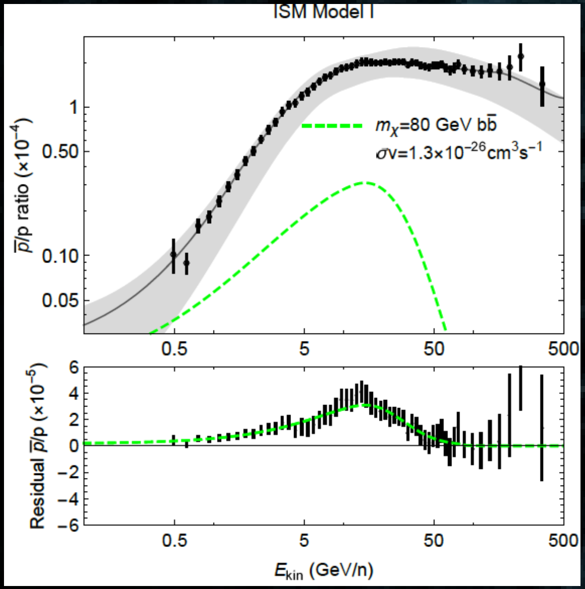
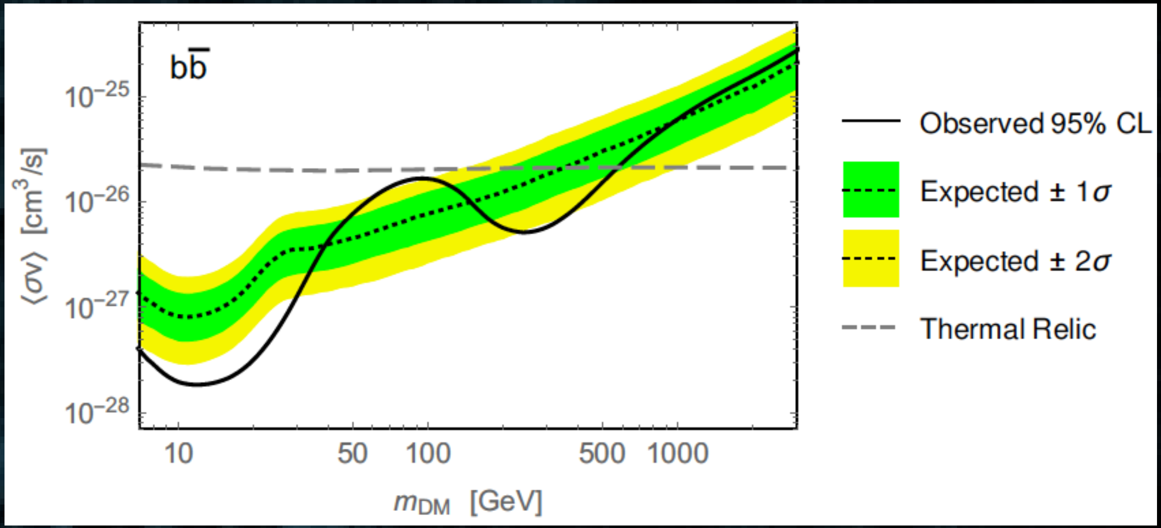






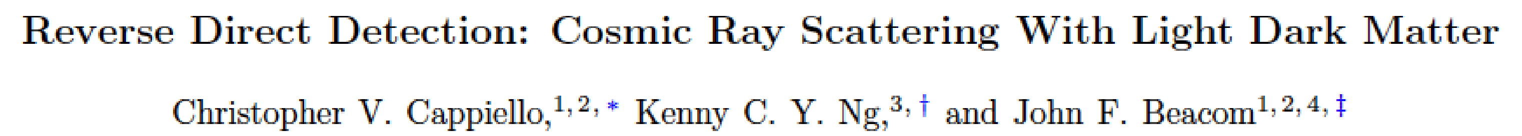
Reinert & Winkler '17

[ongoing USINE analysis by
Boudaud, Génolini+, soon]

For DM searches with antimatter CRs
the size of the magnetic halo L matters!

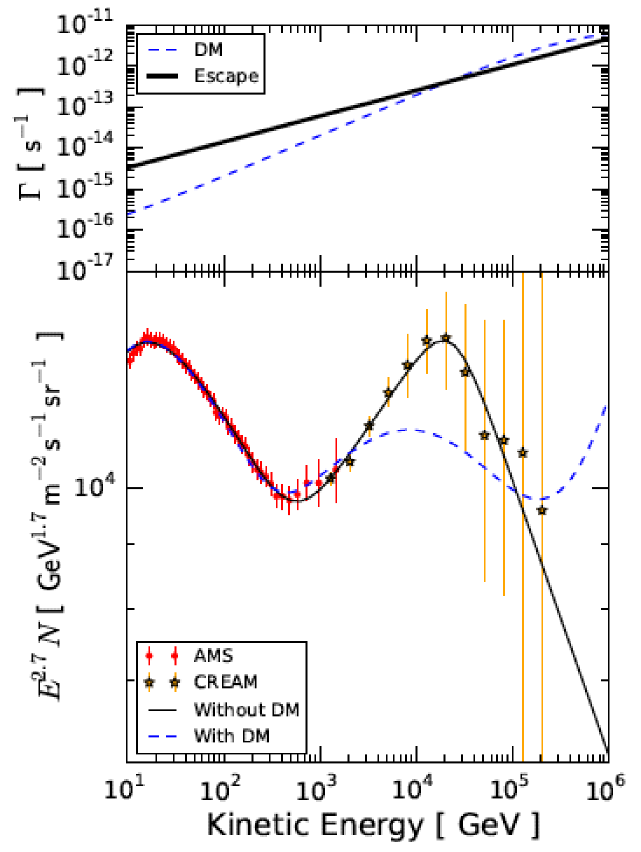
[Usually, DM subhalos neglected]

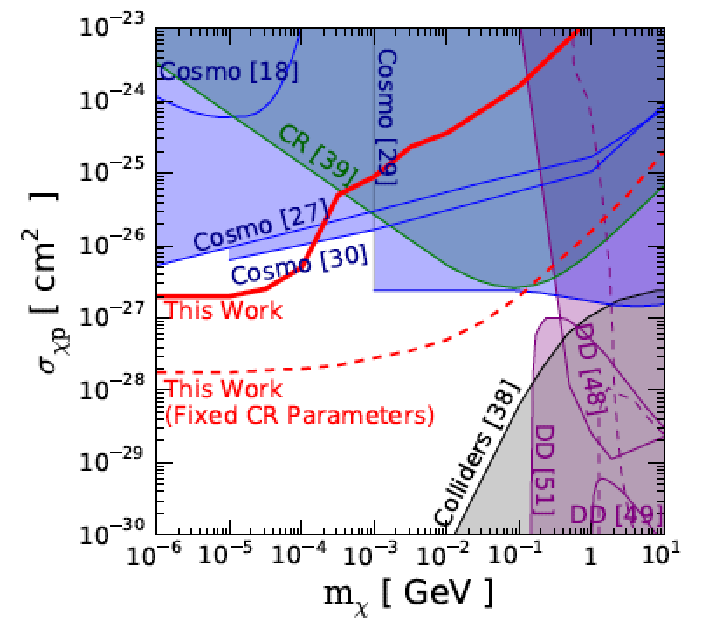
Other dark matter interactions with cosmic rays



Reverse Direct Detection: Cosmic Ray Scattering With Light Dark Matter

Christopher V. Cappiello,[1, 2, *] Kenny C. Y. Ng,[3, †] and John F. Beacom[1, 2, 4, ‡]

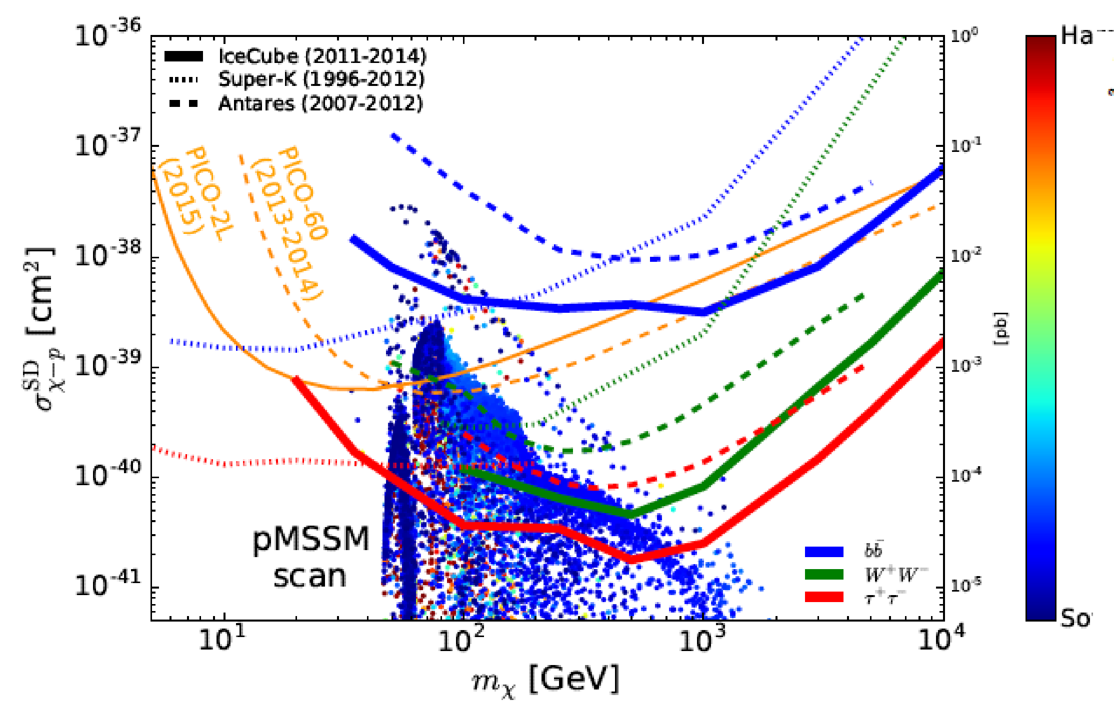


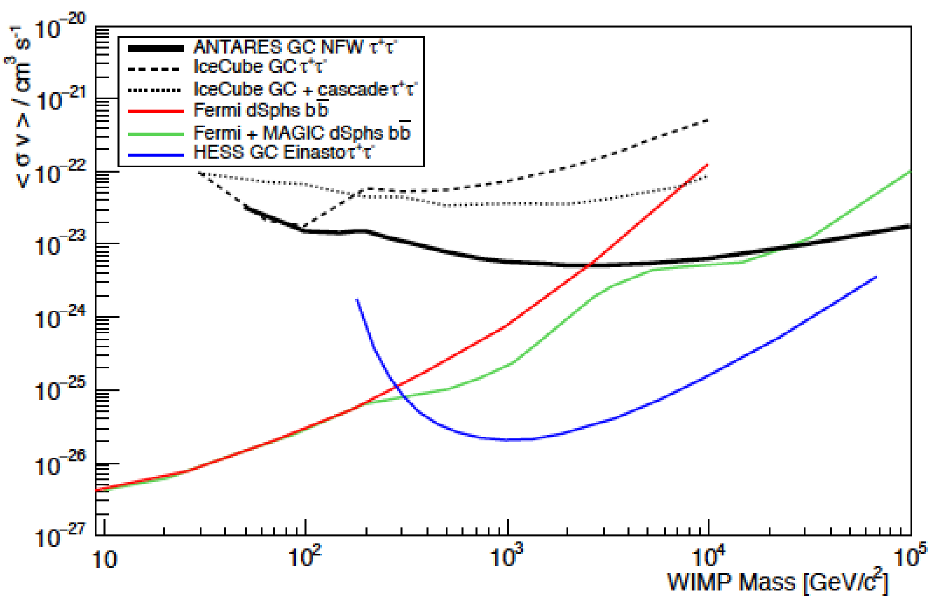


++ additional sensitivity of DD experiment to sub-GeV DM
(Bringmann & Pospelov ‘18)

→ See Eric’s lecture

Neutrino telescopes





Aarsten+’17
(Icecube)

Albert+’17
(Antares)

WIMP indirect searches: summary

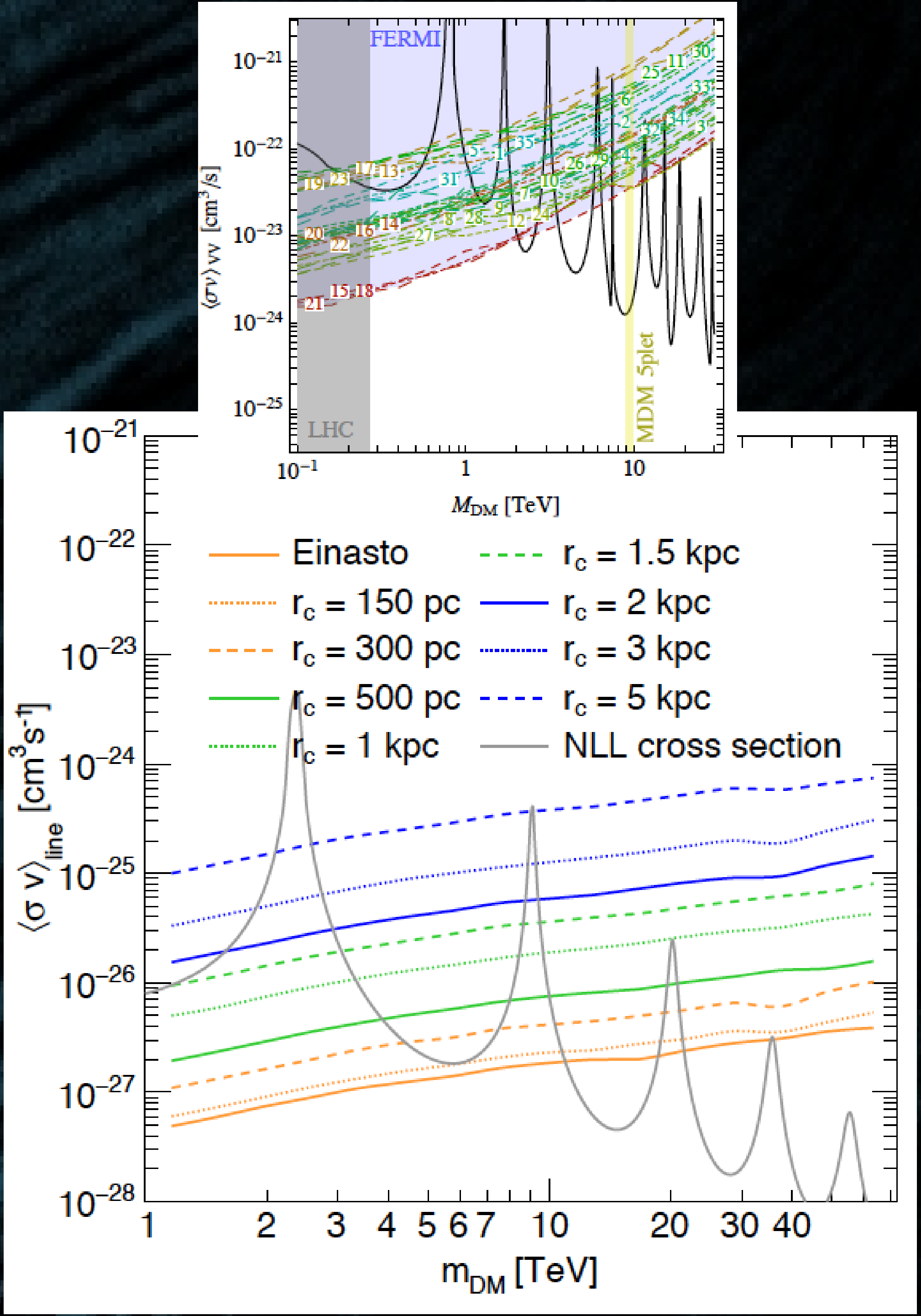
Improve:
- dark matter distribution in the MW: halo shape + subhalos
- modeling of astrophysical background
- define clean ROI

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)].

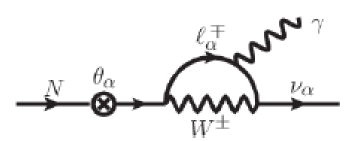


Sterile neutrino (W/C)DM

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)**

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



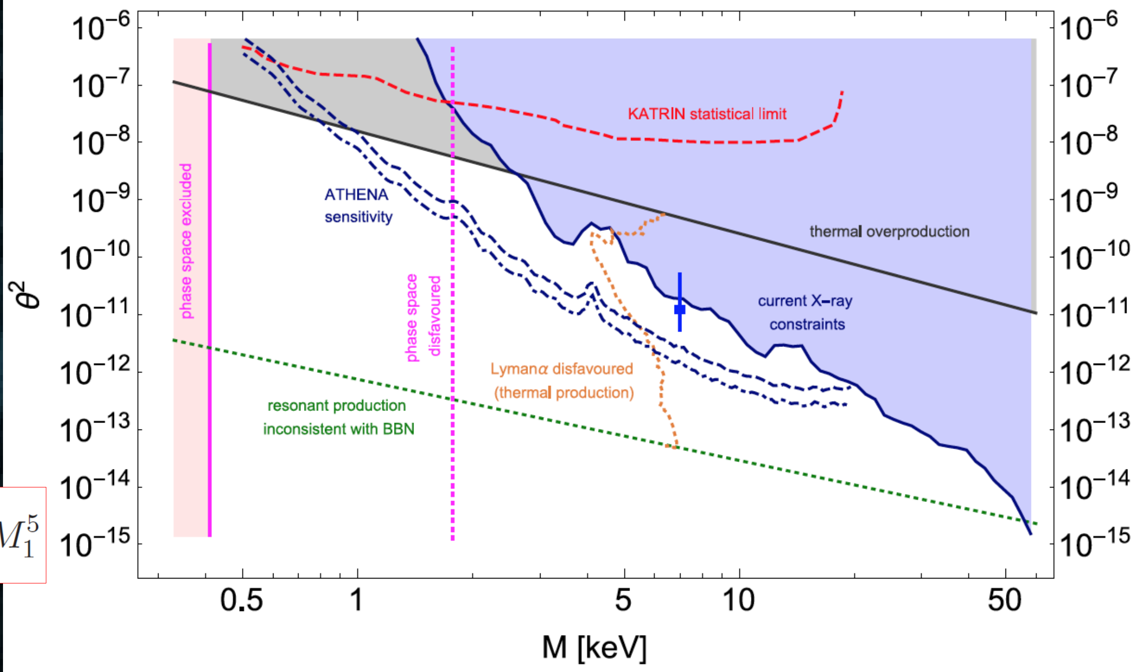
$$\Gamma_{N_1 \to \gamma\nu} = \frac{9\,\alpha\, G_F^2}{1024\pi^4} \sin^2(2\theta_1)\, M_1^5$$

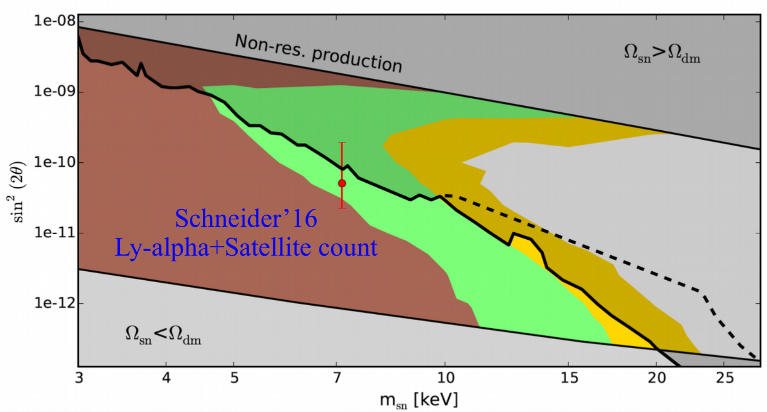
Aspects relevant to cosmology:
* suppress power on small scales
→ viable? (e.g. Schneider '16)
* current limits on thermal masses > 1-10 keV

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 ------------------- →

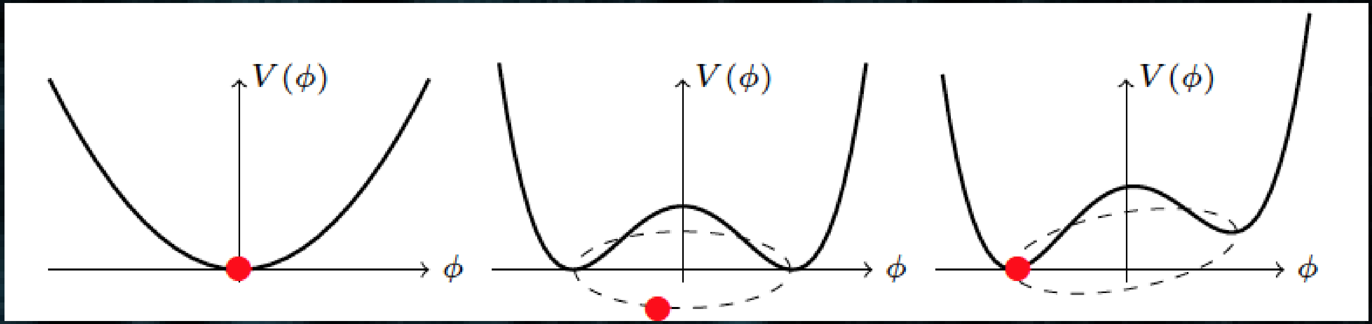
Boyarsky+ '19
(very conservative X-ray limits)





(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

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

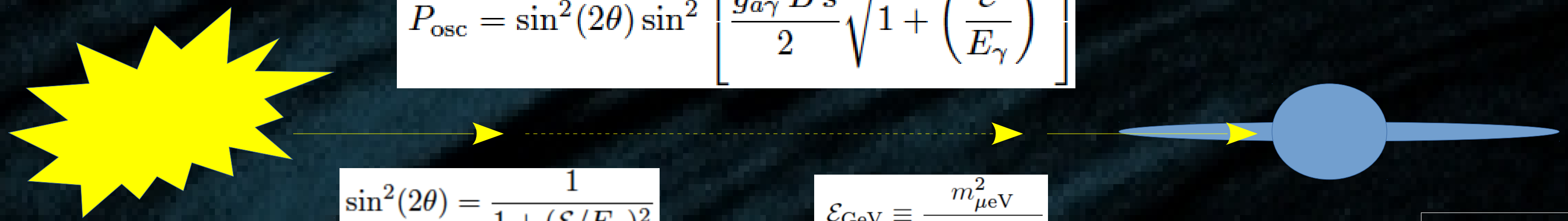
NB: QCD axion needs physics beyond standard model
Production mechanism (relevant to DM axions):
* Misalignment mechanism (generic)
* Decay of topological defects (if PQ broken after inflation)
⟶ compact axion asteroids! (f~0.5) – Tkachev'86
* m << eV => large occupation # => classical field
* QCD axions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

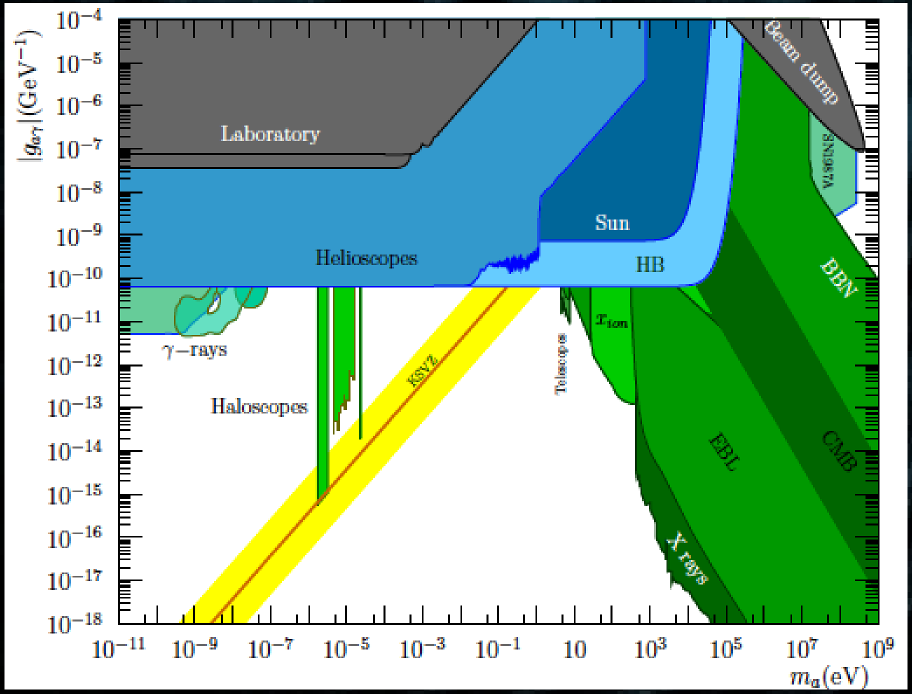


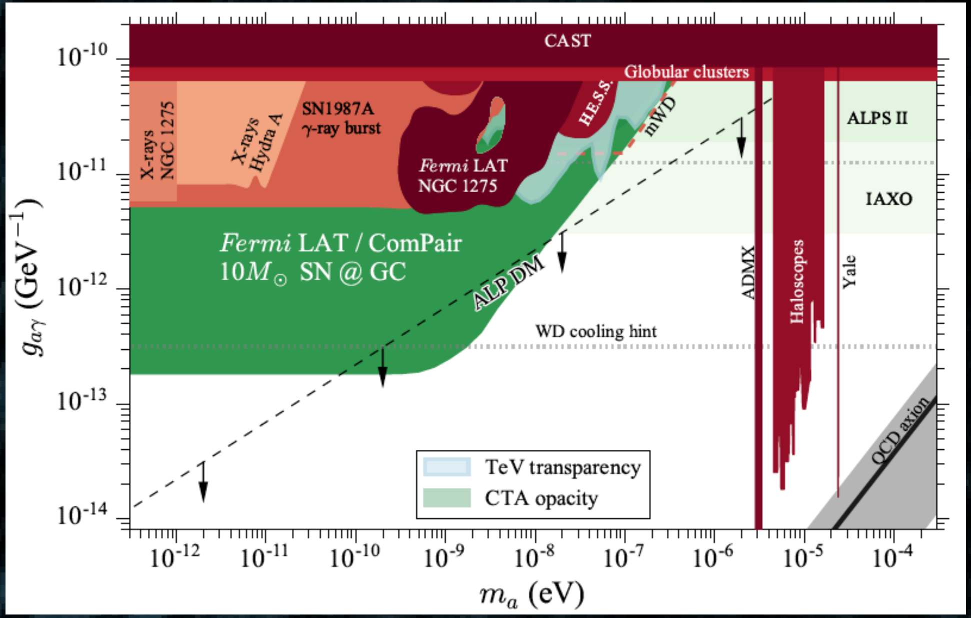
$$P_{\rm osc} = \sin^2(2\theta)\,\sin^2\left[\frac{g_{a\gamma}\,B\,s}{2}\sqrt{1+\left(\frac{\mathcal{E}}{E_\gamma}\right)^2}\right]$$

$$\sin^2(2\theta) = \frac{1}{1+(\mathcal{E}/E_\gamma)^2}$$

$$\mathcal{E}_{\rm GeV} \equiv \frac{m^2_{\mu\rm eV}}{0.4\,g_{11}\,B_{\rm G}}$$

e.g. Serpico+’08





See reviews in
Marsh’15 + Irastorza & Redondo ‘19

=> QCD axions viable candidates
(very cold DM)

HE astro blind to QCD axions
=> ALPs
GeV-TeV gamma-ray conversion to axions
(e.g. proc. Meyer’16)

[Large uncertainties from magnetic field modeling]

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

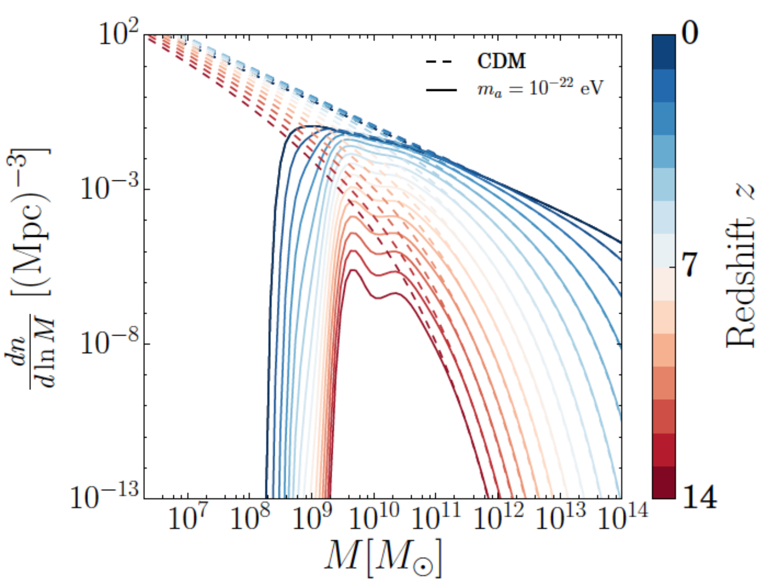
Hu+00, Peebles'00, Marsh+15, Hui+16, Schive+14, Du+18, etc.

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

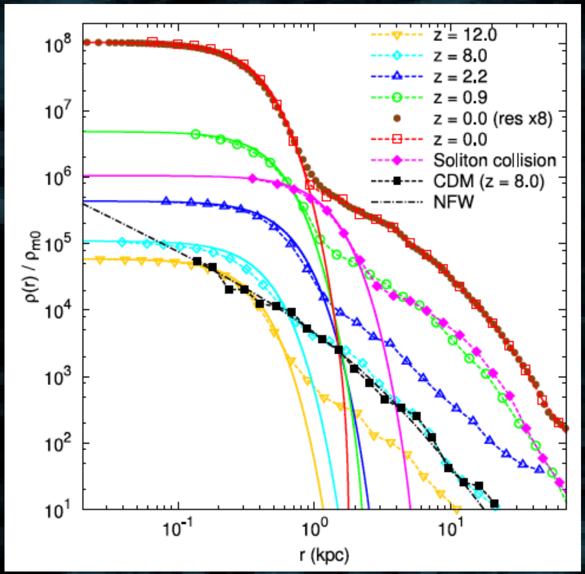
Main properties:
*** Suppression of small-scale perturbations**
*** incoherent interference pattern and granularity on scales ~ 1-100 kpc**
*** formation of solitonic cores at halo centers**
*** core/cusp solved in galaxies if m~10^{-22} eV**

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

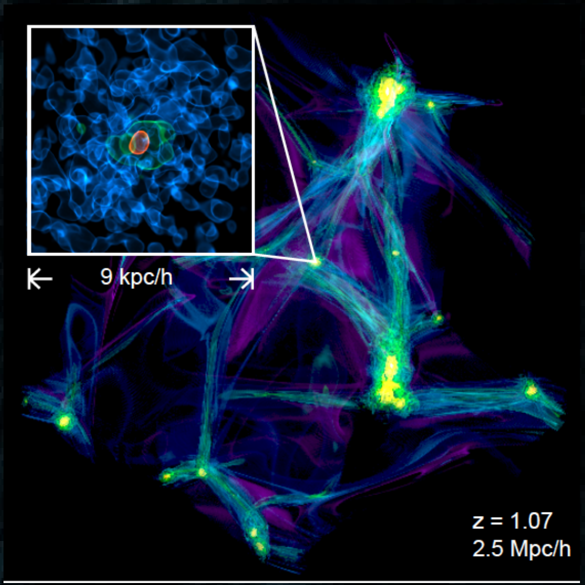
$$\nabla^2\Phi=4\pi G m_a|\psi|^2$$



Bozek+15
Halo mass function



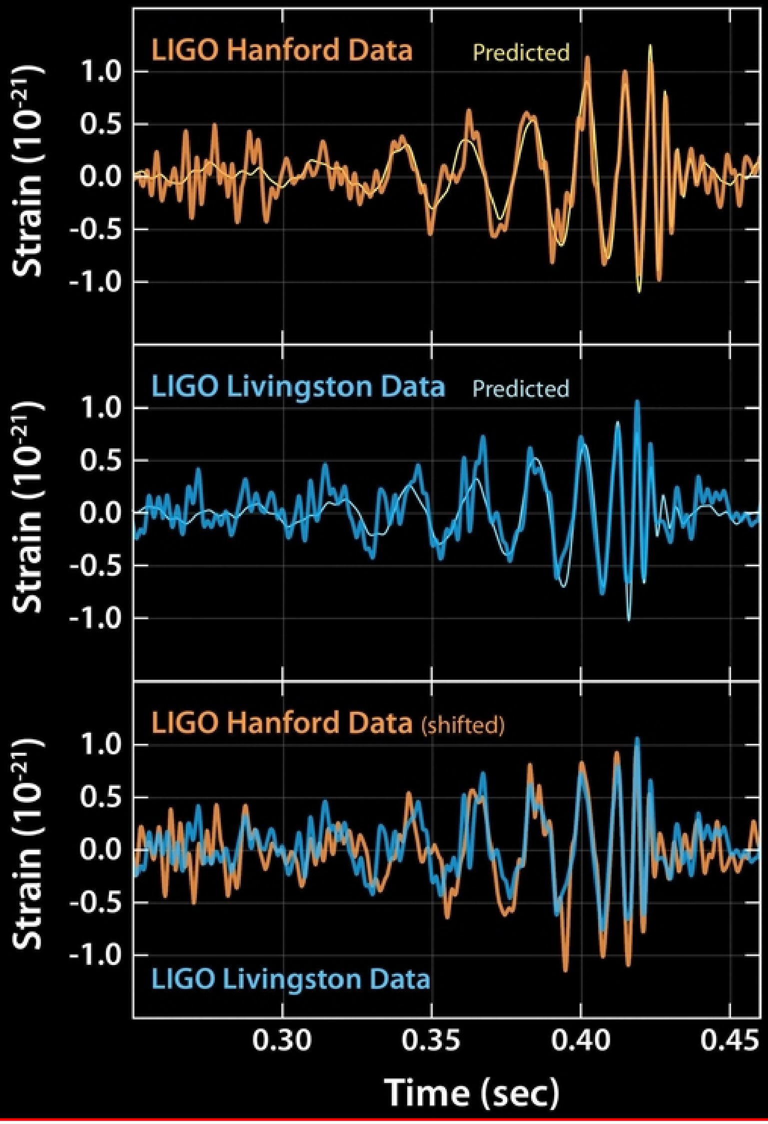
Schive+14
Solitonic cores in
Fuzzy DM simulations

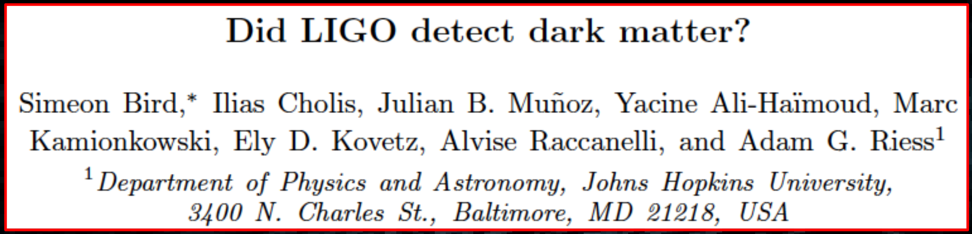


Veltmaat+18
Evolution of solitonic cores

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]

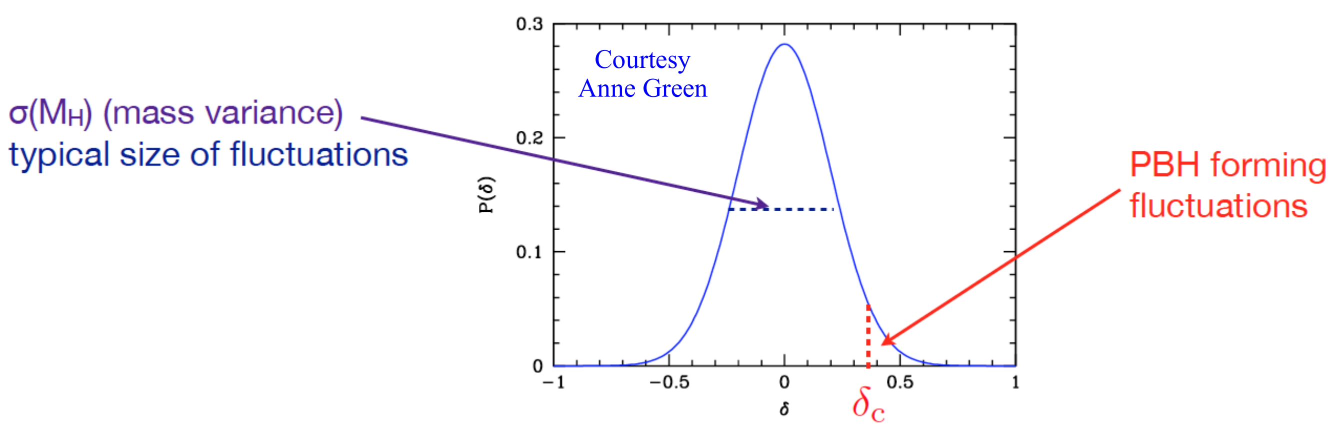
[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

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



Courtesy Anne Green

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

PBH forming fluctuations

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

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

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

Gaussian spectrum →

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

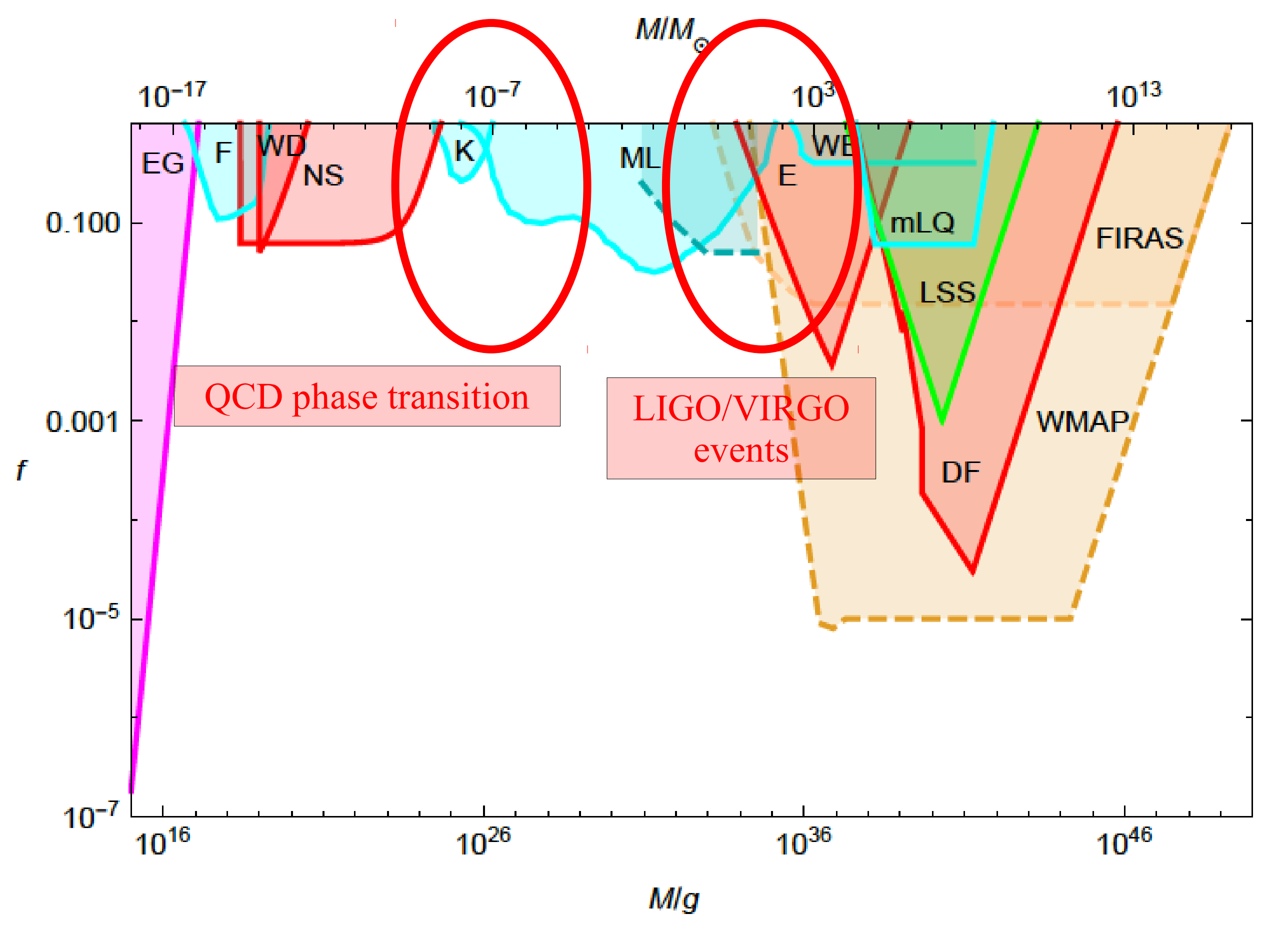
$$\sigma(M_H) \sim 10^{-5}$$

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



Carr+16

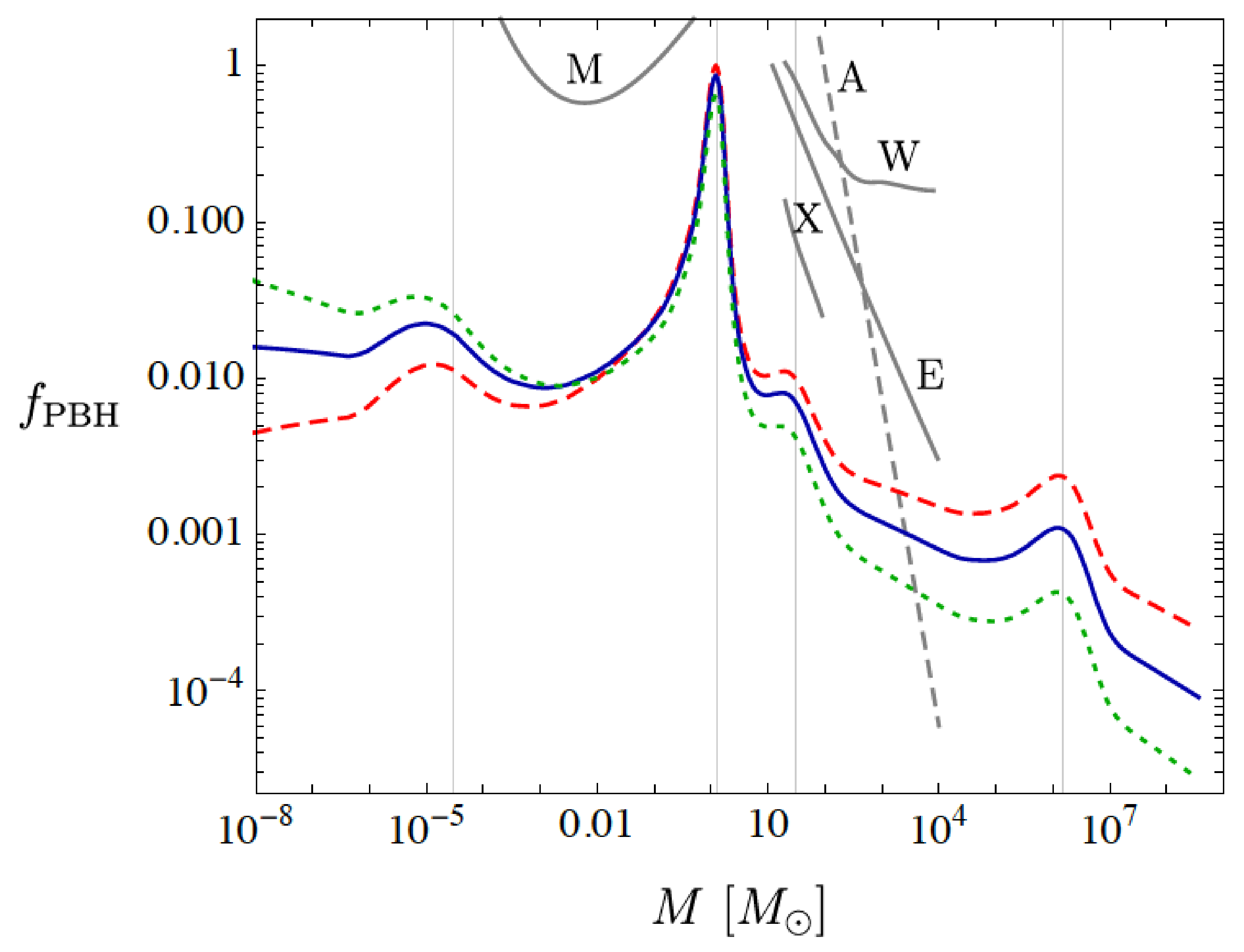
Take home:

→ most past constraints derived assuming delta mass function

→ several other unrealistic assumptions

=> Strong effort to revisit constraints

Primordial black holes



Carr, Clesse+'19

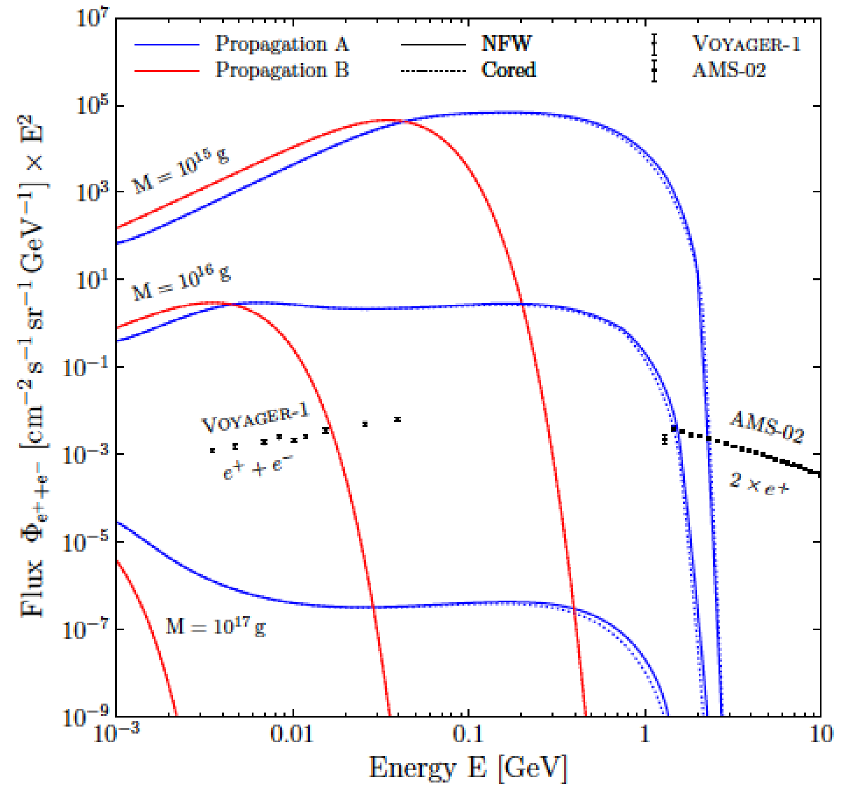
=> Extended mass function
(+most conservative bounds possible)

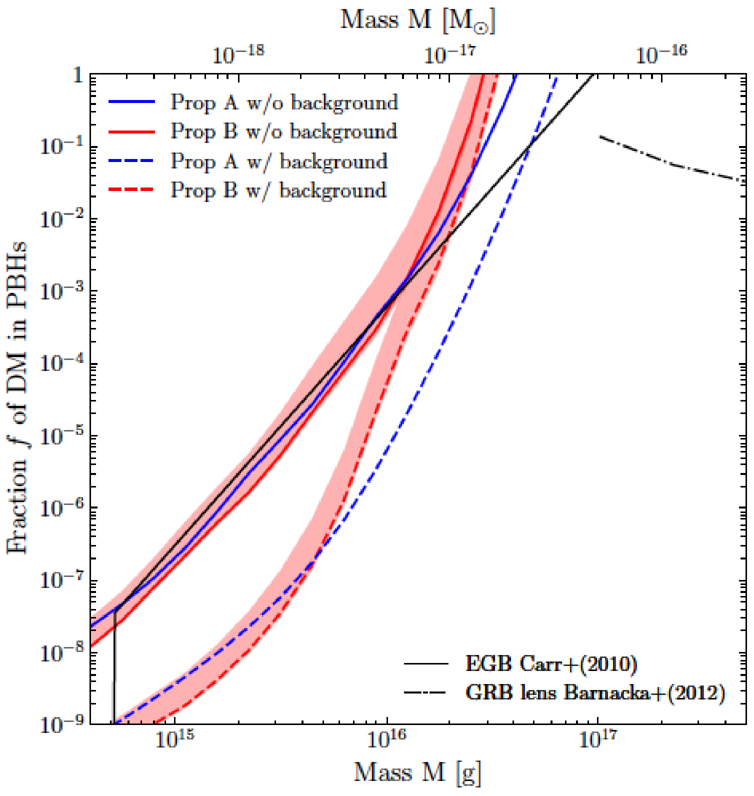
NB: inflation scenario not minimal!

Primordial black holes

Hawking radiation: BHs lose mass!

$$\frac{dM}{dt} = -5.34 \times 10^{25} f(M) \left(\frac{\text{g}}{M}\right)^2 \text{g/s}$$



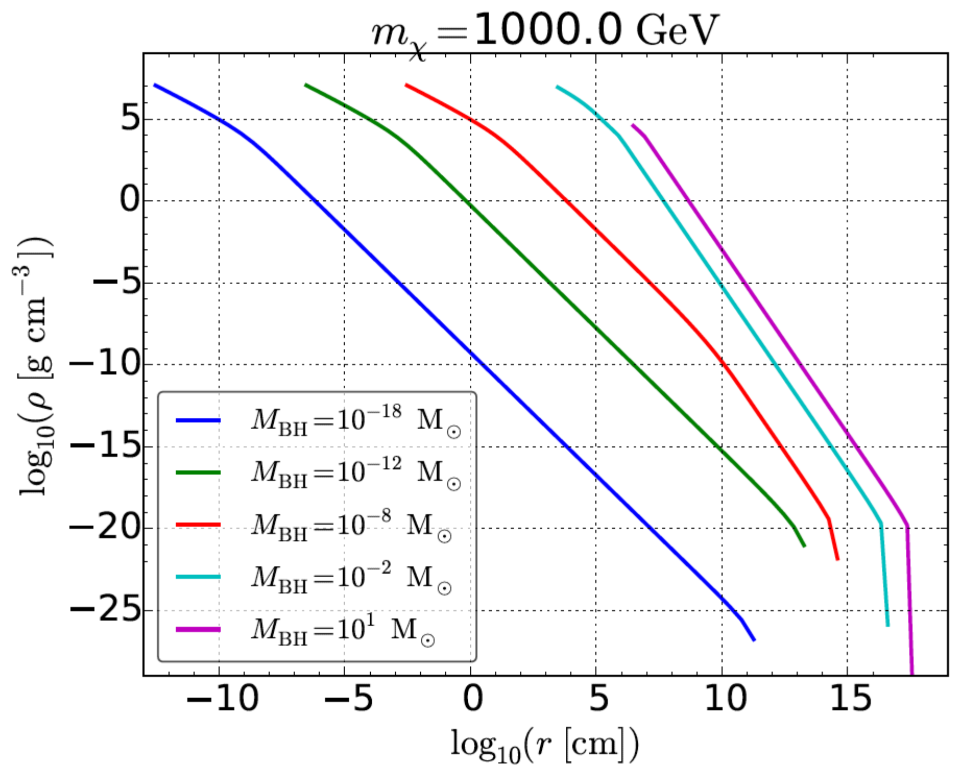


Boudaud+'18
→ MeV electron data of Voyager I
→ Complementary to diffuse EG gamma-rays

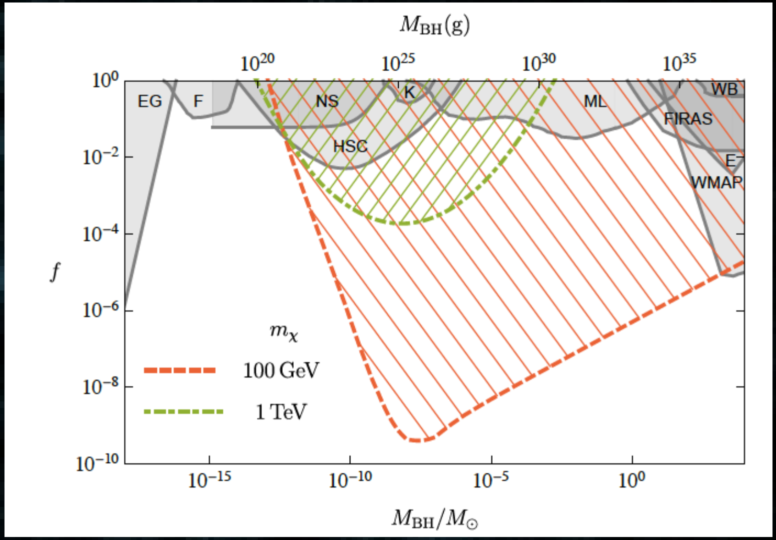
[though not preferred mass range for DM]

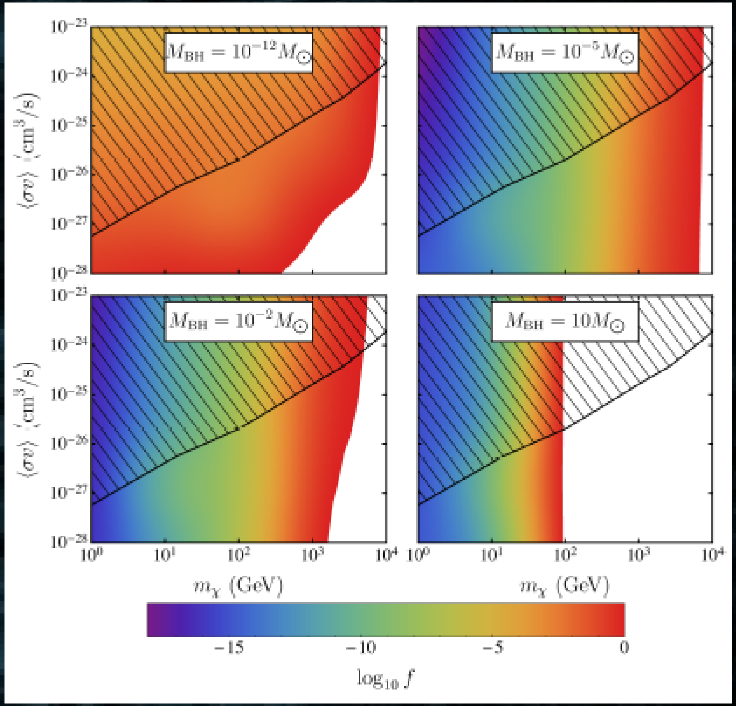
Primordial black holes + WIMPs?

WIMPs accumulate around PBHs in early universe
→ form density spikes
→ huge annihilation ate
→ even if PBH fraction << 1
(Eroshenko’16)



Boudaud, Lacroix, Stref+, in prep





Boucenna+’18
(see also Eroshenko’16)

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

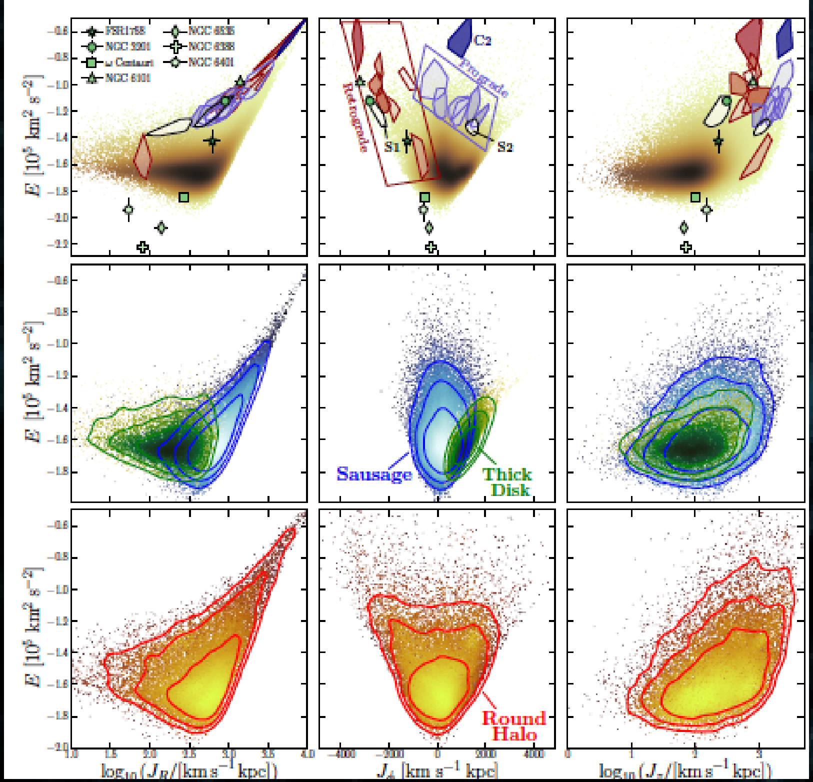
Techniques:
- Precise astrometry + kinematical studies
- Gravitational lensing (compact objects + subhalos)
- Gravitational waves (only for PBHs)

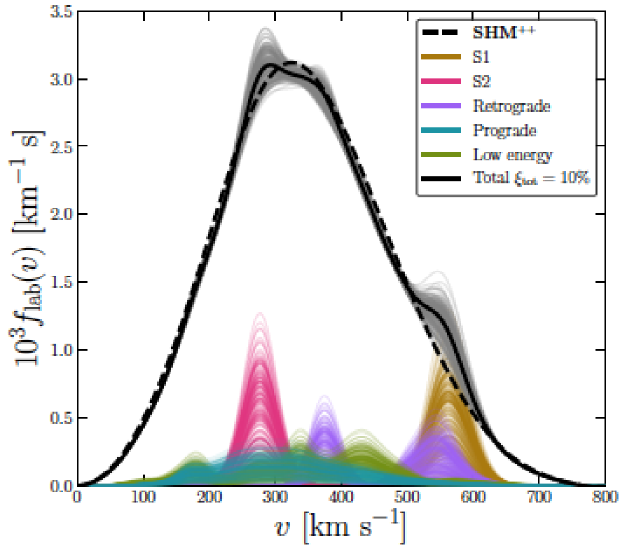
\+ indirect: e.g. Ly-alpha, etc.

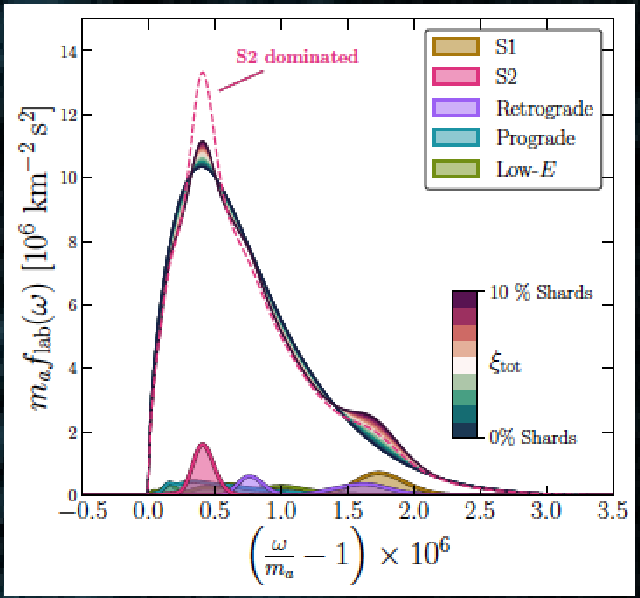
Gravitational searches for dark matter

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)

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:

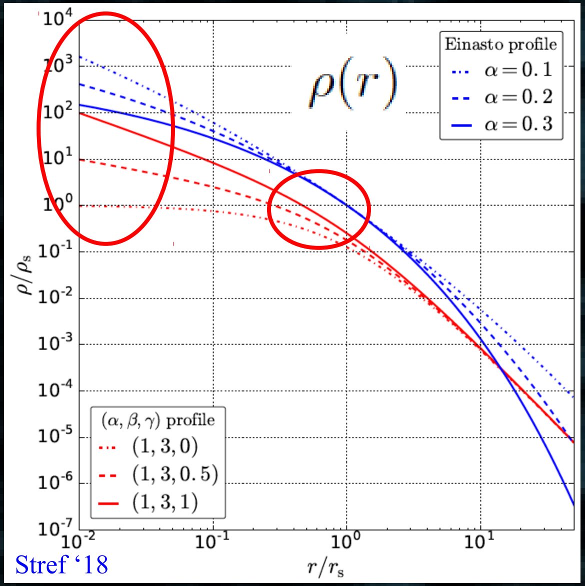
- Only a few scenarios with independent motivations: axions, rh neutrinos, PBHs
- WIMP no longer the reference case: enlarge th/exp perspectives
- Maybe DM is not 100% made of particles

Search strategies:

- HE astro can probe part of the parameter space => crucial to do it properly
- Complementarity!!!!!

Backup

Dark matter distribution properties (and why it matters)

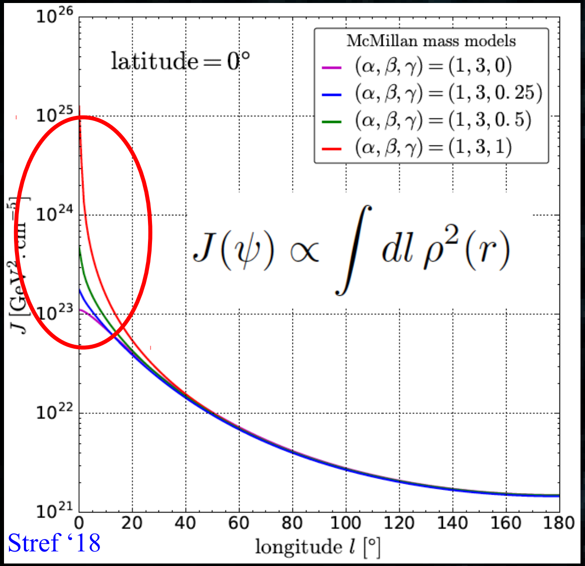


Stref '18

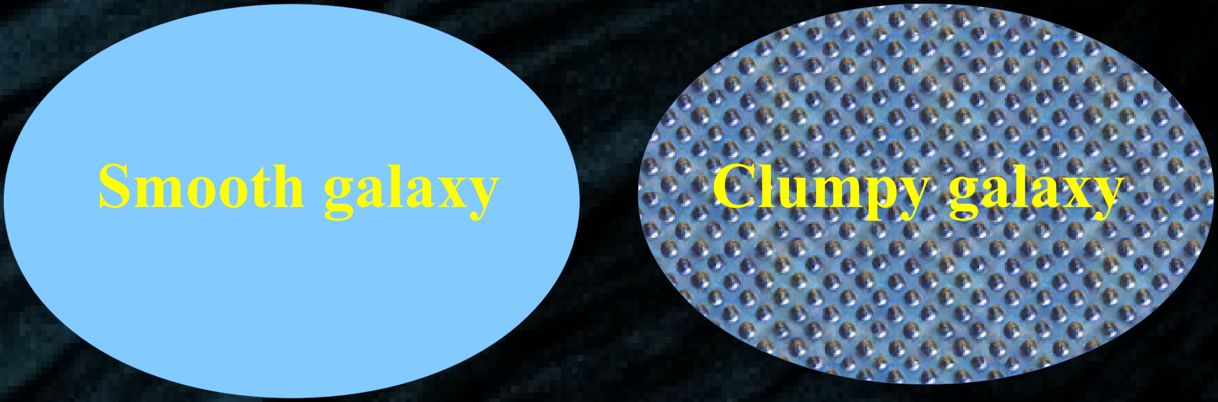
Mass density profile/s

(but mind potentially strong difference between peculiar objects and average expectations)

Squared density profile

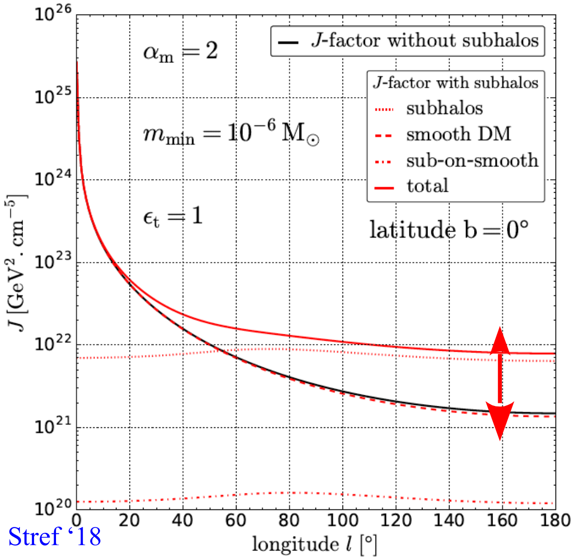


Stref '18



Granularity of halos
(aka subhalos)

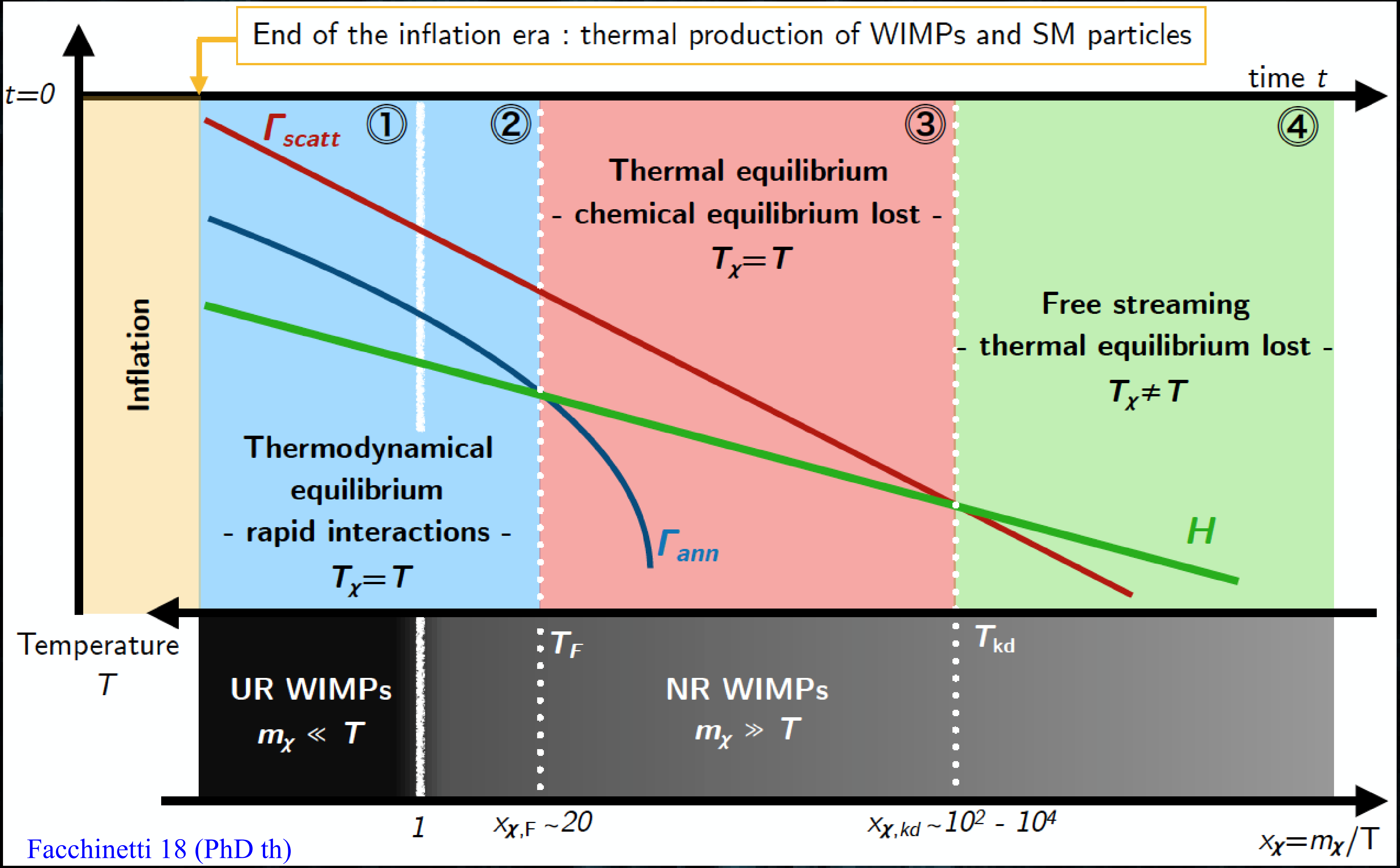
Related to clustering properties of dark matter
→ gravitational searches
→ affect other signatures



Stref '18

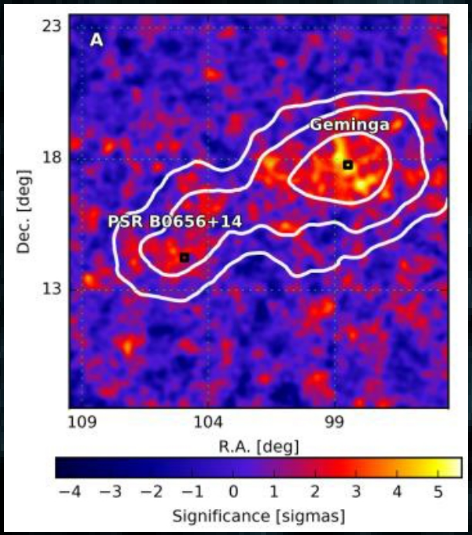
++ Phase-space distribution of dark matter
Many observables related to dark matter searches may depend on velocity (e.g. cross sections, microlensing events, etc.)

Thermal production in the early Universe

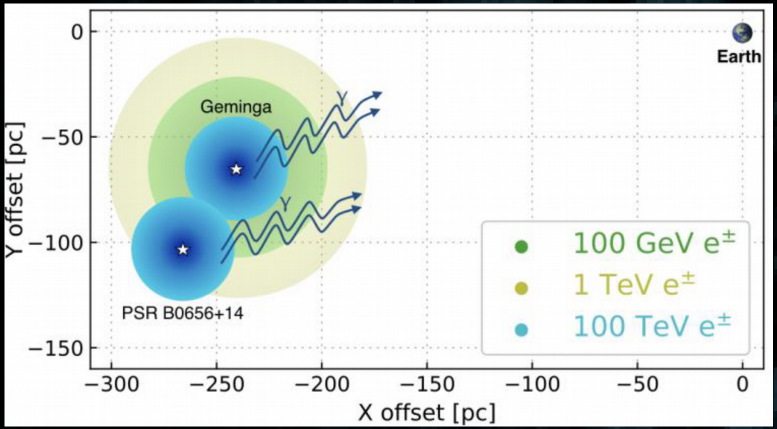


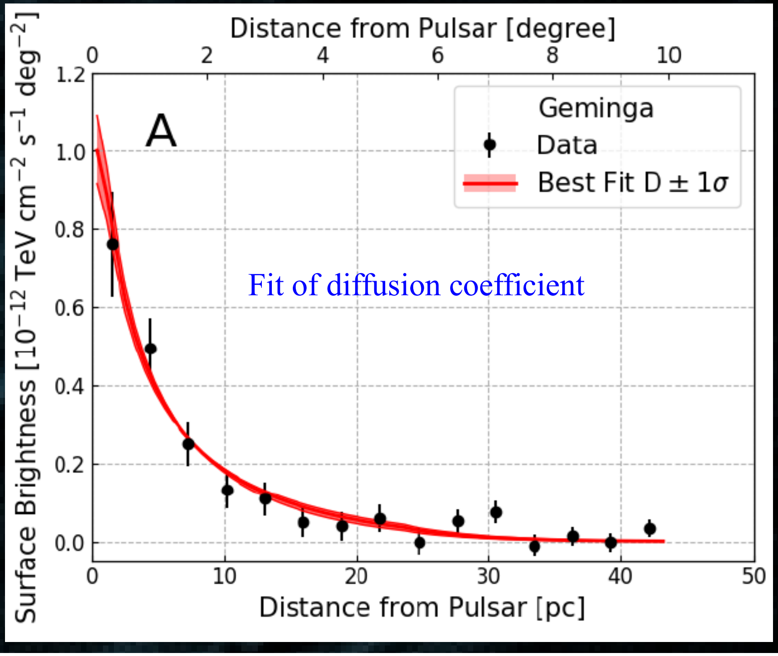
Facchinetti 18 (PhD th)

Positrons from pulsars: links to TeV gamma rays?



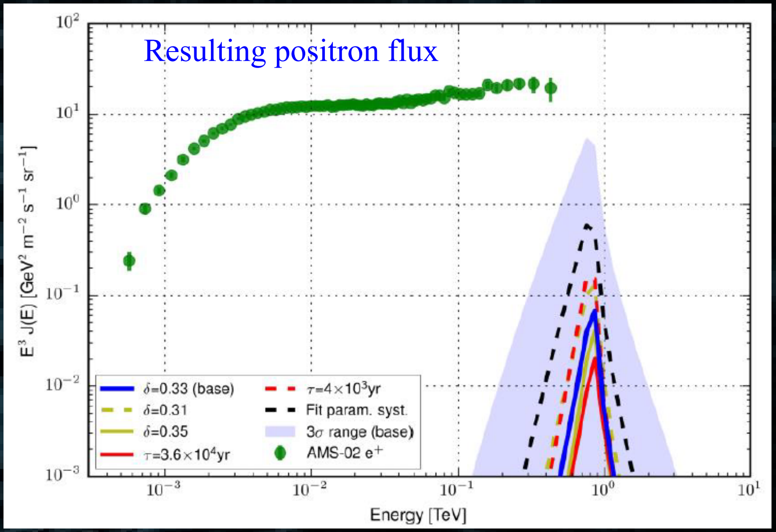
HAWC observation of Geminga + Monogem
TeV gamma rays
(Abeysekara+'17)



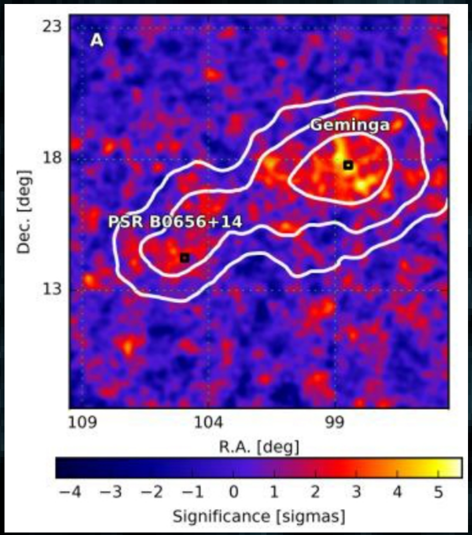


$$\mathcal{G}(\vec{x},E\leftarrow\vec{x}_s,E_s)\propto\exp\left\{-\frac{|\vec{x}_s-\vec{x}|^2}{4\,K_0\,\tau(E,E_s)}\right\}$$

Consequence on local positron flux



Positrons from pulsars: links to TeV gamma rays?



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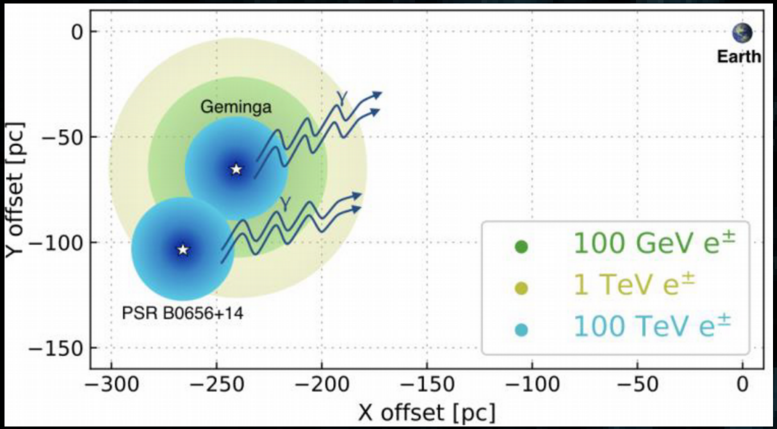
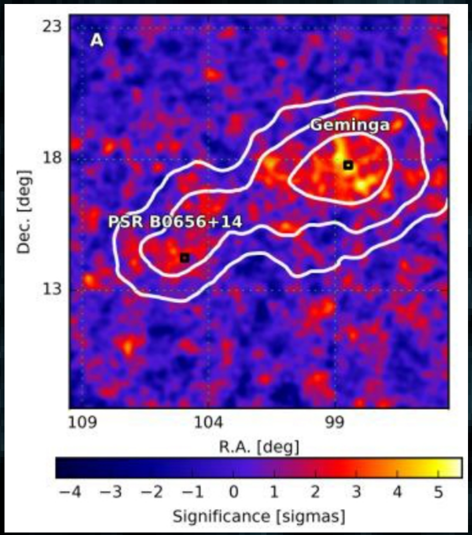


Problems are:

* Different diffusion coefficient close to / far from a source (should be smaller close to sources)

* Leptons responsible for TeV gamma rays close to the source are not those observed today on Earth!
→ The source has evolved
(different travel time for γs and CRs)

Positrons from pulsars: links to TeV gamma rays?



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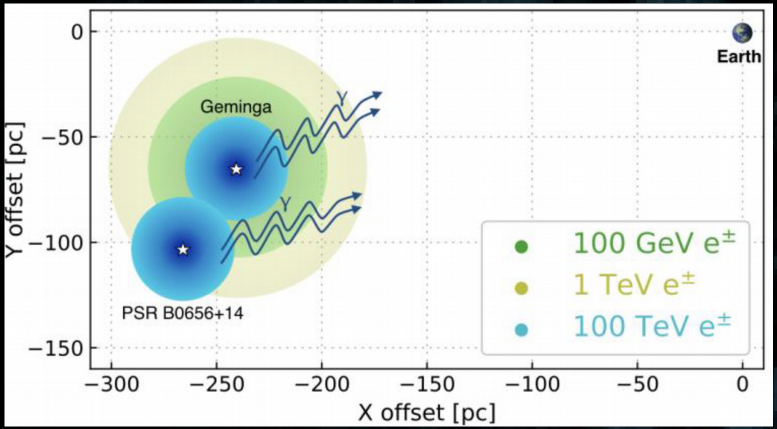
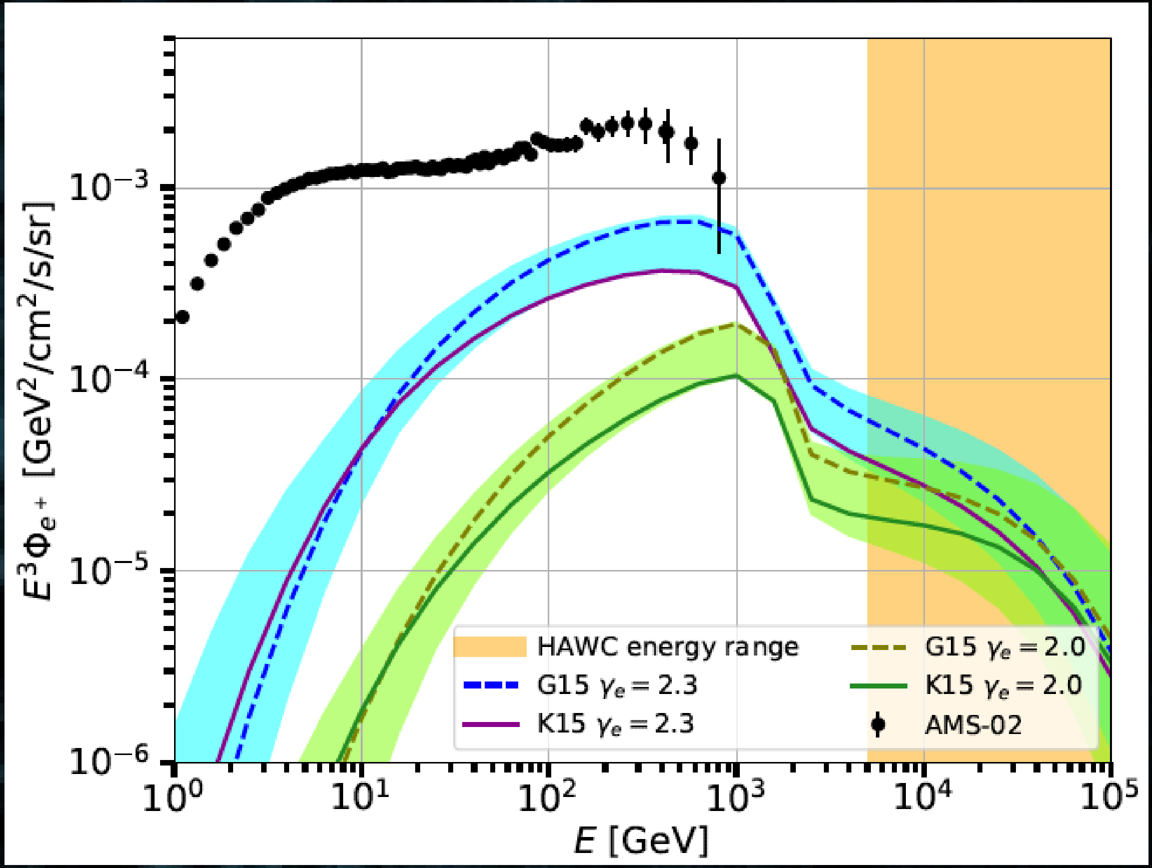
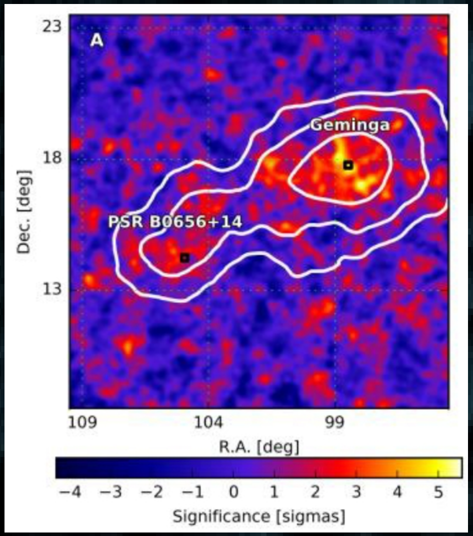




Di Mauro+'19

Positrons from pulsars: links to TeV gamma rays?



HAWC observation of Geminga + Monogem
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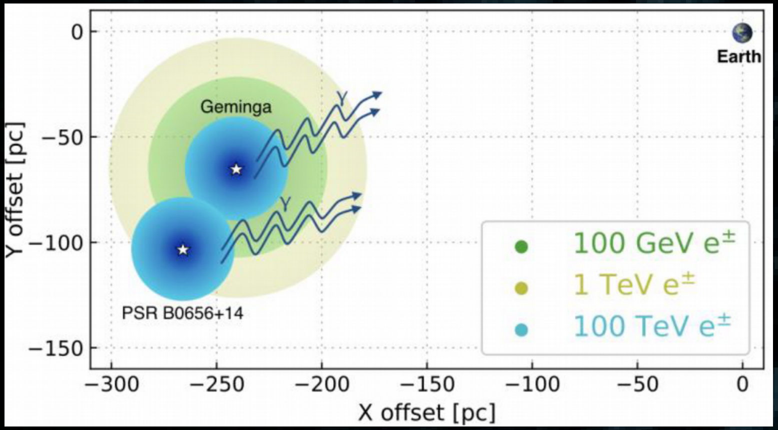


<u>To be continued…</u>

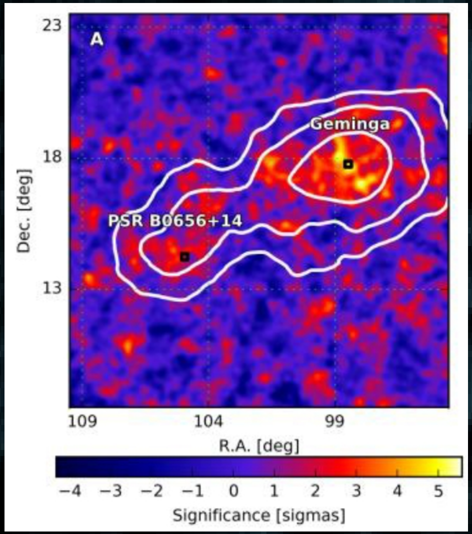
* Correct orders of magnitude reached with very simple models

* No compelling work yet using a dynamical model for the source evolution + transport of escaped particles to the Earth (acceleration+escape+EM constraints)

=> still to be done
(motivated PhD student or postdoc!)

[formally speaking, PWNe have not been fully proved yet to be responsible for all local VHE positrons, even if likely]

Positrons from pulsars: links to TeV gamma rays?



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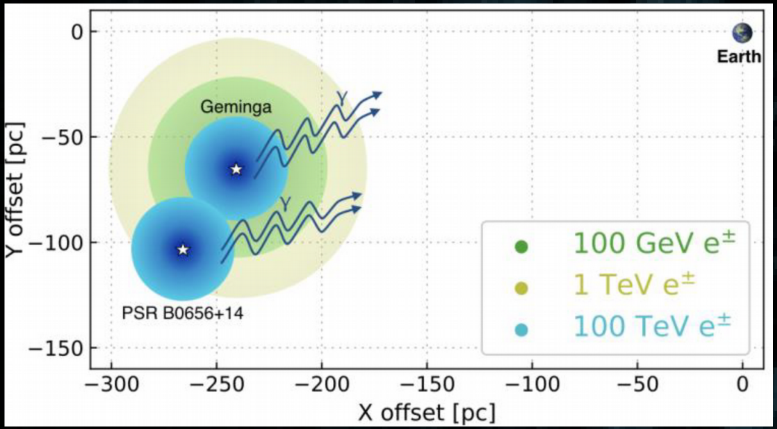

Broader consequences:

* Bubbles with low diffusion coefficients

=> "effective" diffusion coefficient should depend on source number density

=> effective spatial dependence of diffusion coefficient

[e.g. Hooper+'17, Profumo+'18, Johannesson+'19, etc.]