Dark Matter candidates
And
How to probe them on the Galactic (Milky Way) scale

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LUPM – CNRS – U. Montpellier

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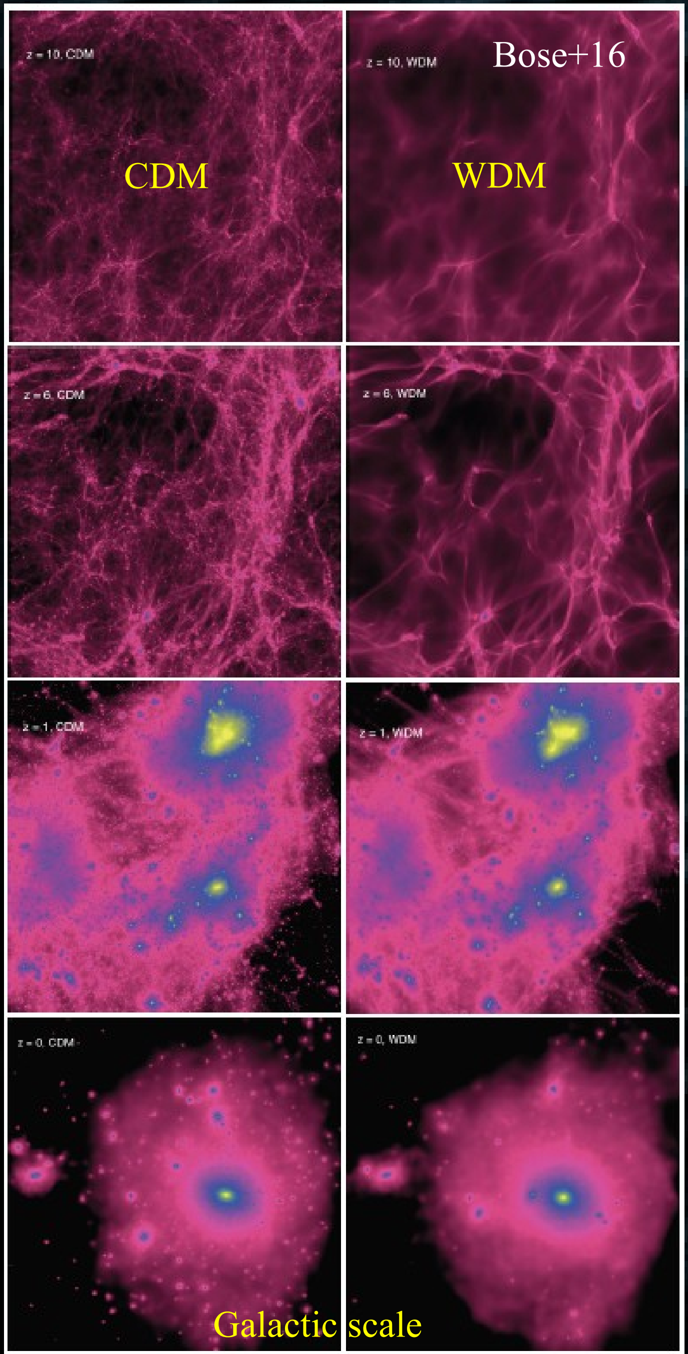
The GaDaMa Project

The cold Dark Matter (CDM) paradigm



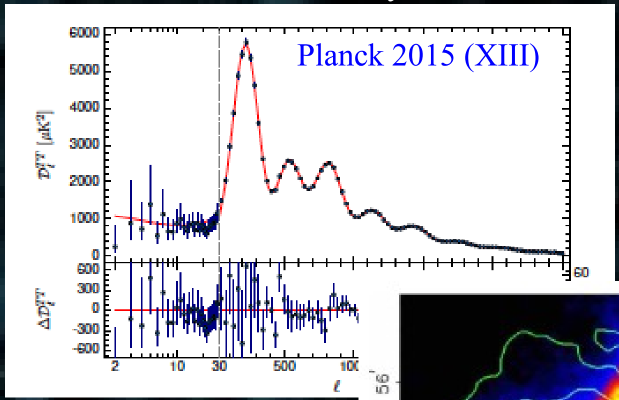
<u>So far, only gravitational evidence for DM</u>
(cosmological structures+CMB)

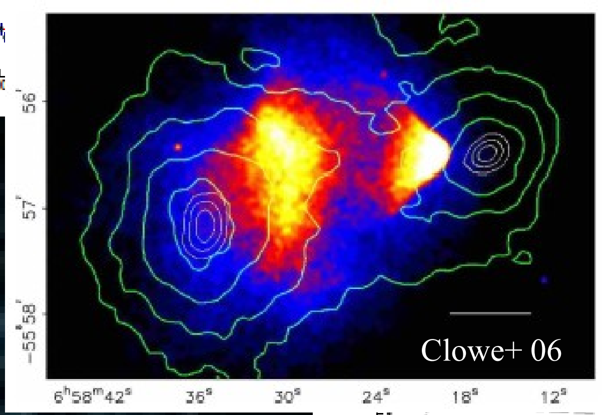
<u>CDM successes:</u>

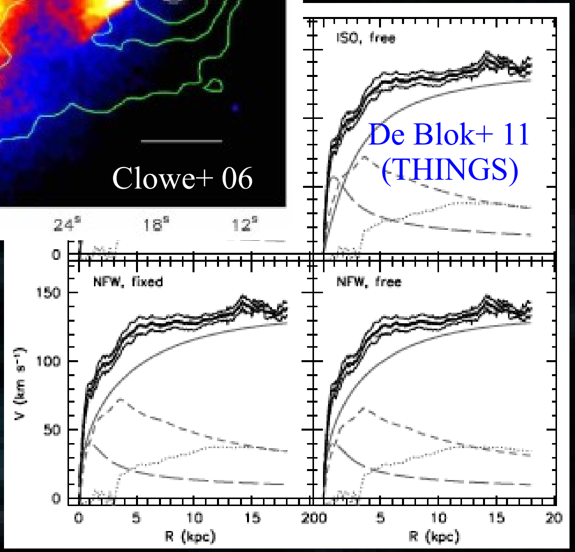
- CMB peaks
- Successful structure formation (from CMB perturbations)

=> CDM seeds galaxies, galaxies embedded in DM halos

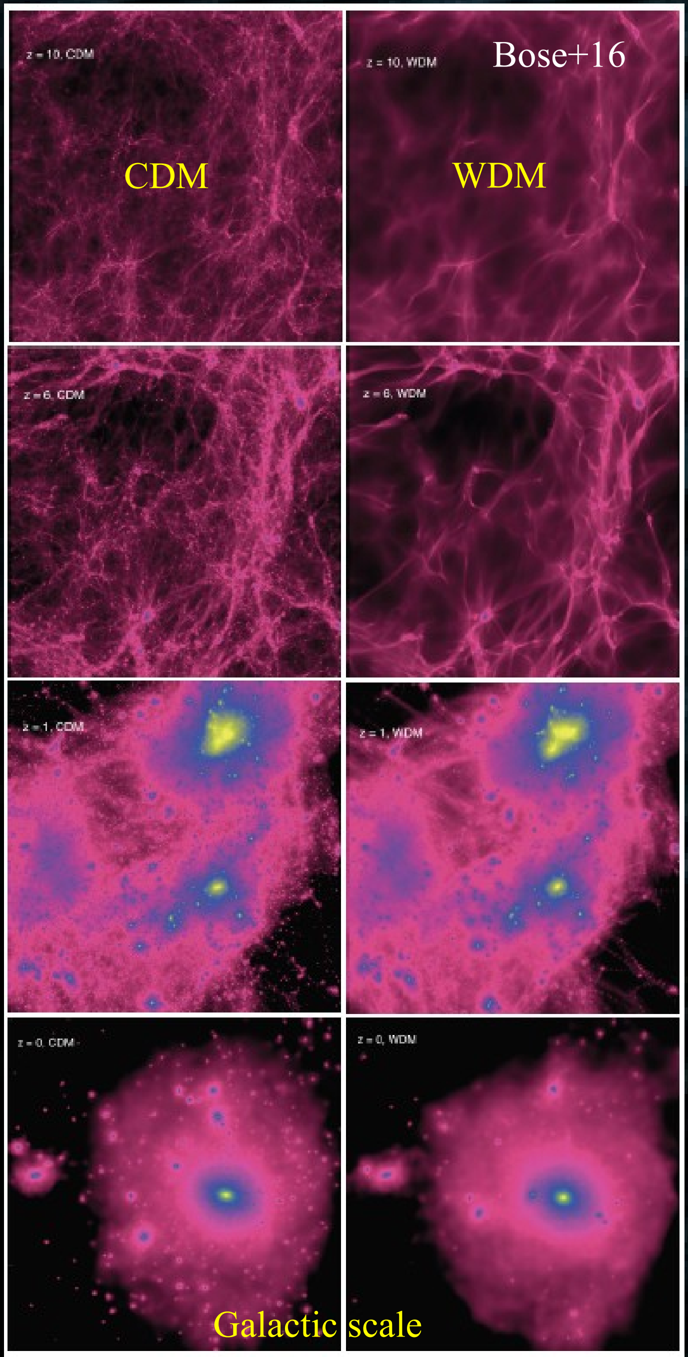
- Lensing in clusters + rotation curves of galaxies
- Also consistent with Tully-Fisher relation (baryonic physics)







The cold Dark Matter (CDM) paradigm



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ISSUES:

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

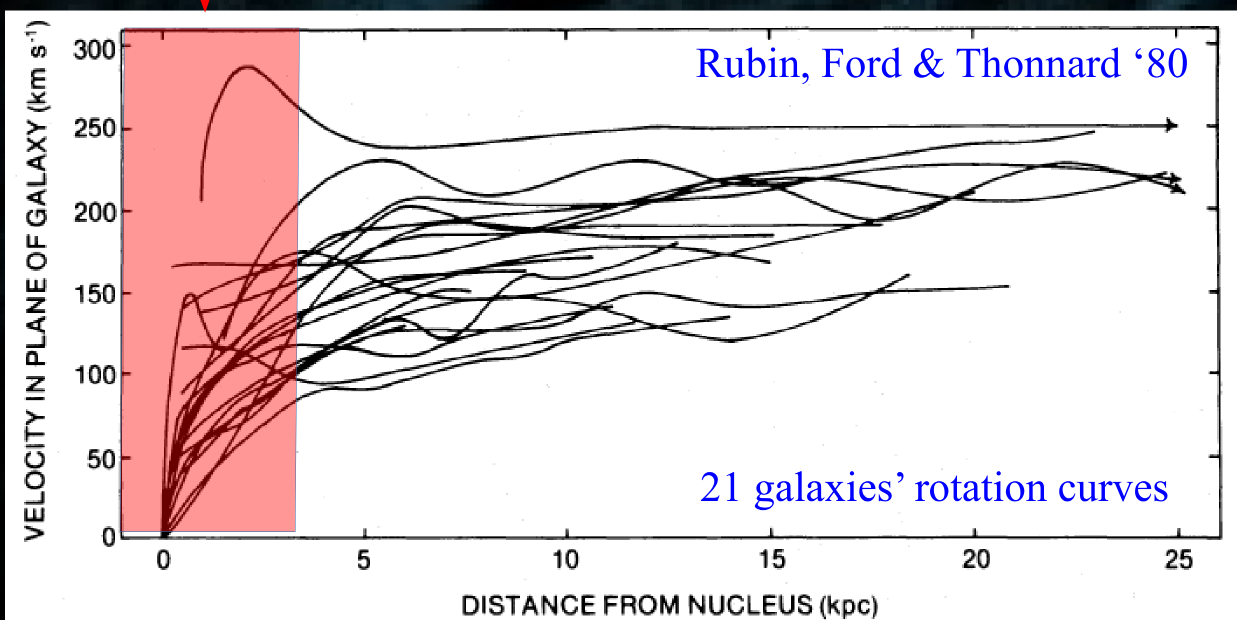
* How cold must it be?

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

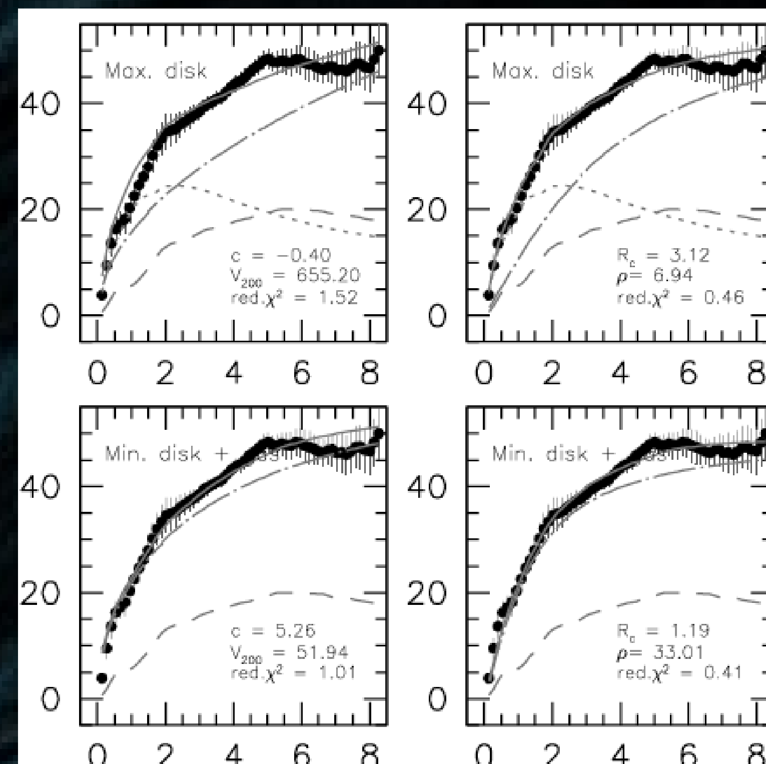
* Some observational issues (challenges?) on small scales

Dark Matter on galactic scales

Bulk of luminous matter



Oh+11



* 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

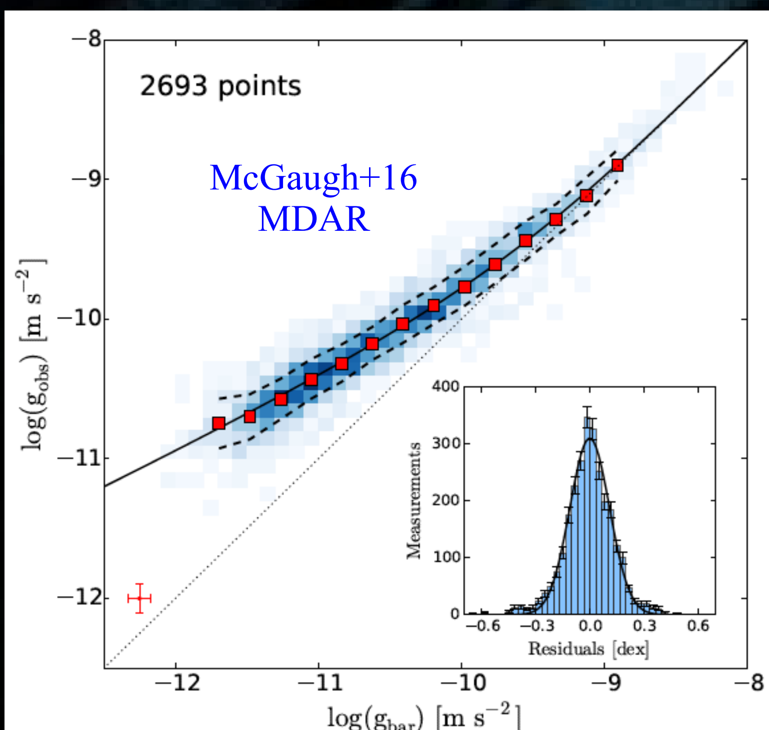
CDM issues on small (subgalactic) scales

Small-Scale Challenges to the ΛCDM Paradigm

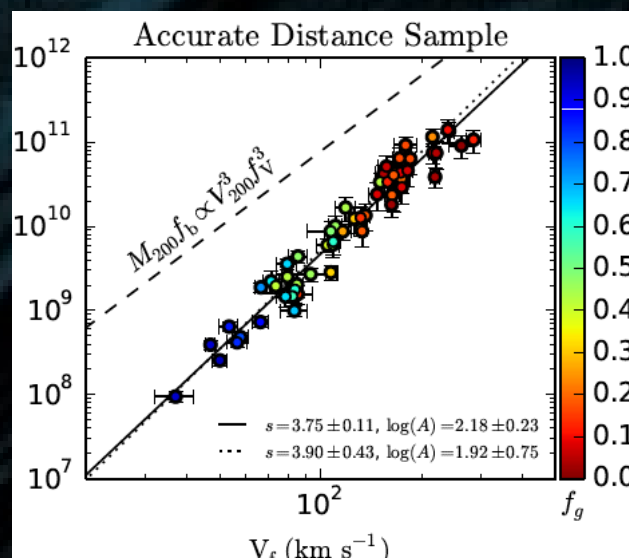
arXiv:1707.04256

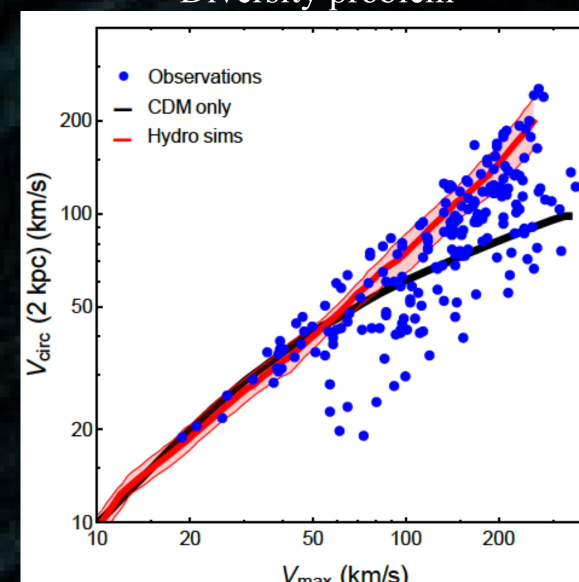
James S. Bullock[1] and Michael Boylan-Kolchin[2]

[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



Tulin+18 after Oman+15
Diversity problem





Lelli+15, BTFR

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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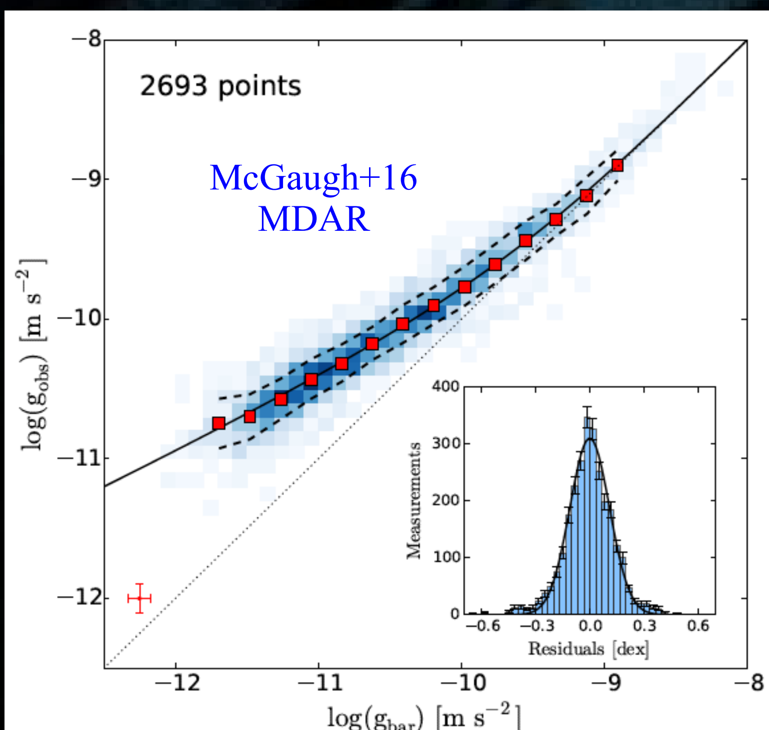
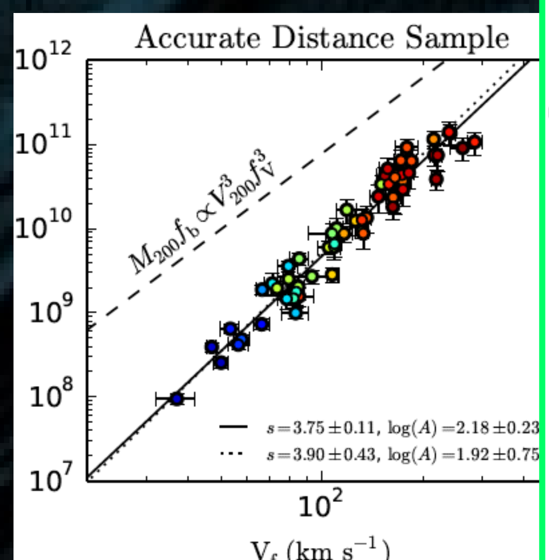
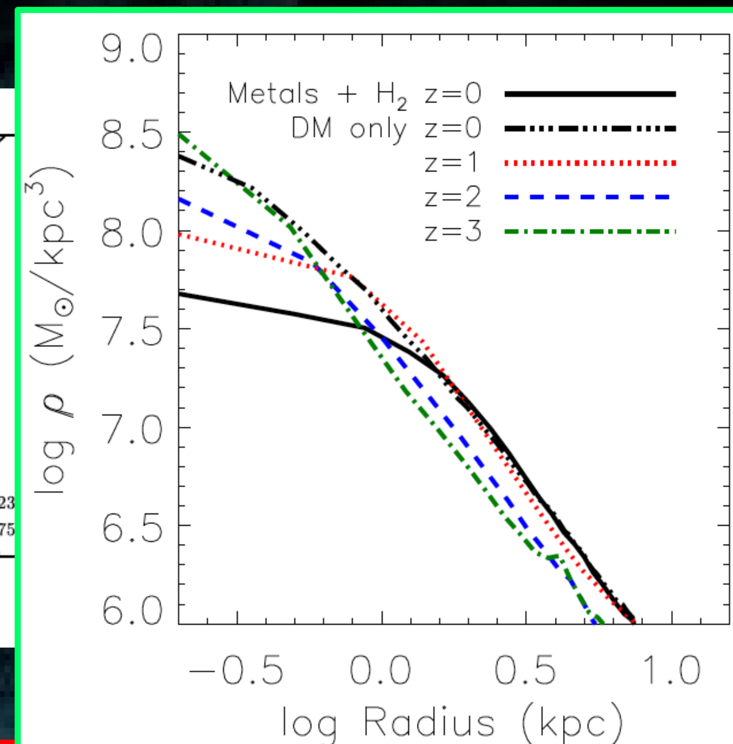




Lelli+15, BTFR

Governato+12
Cusps→cores



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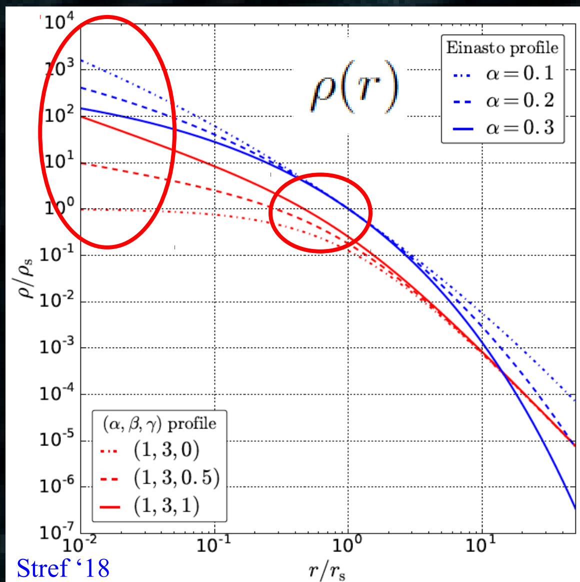
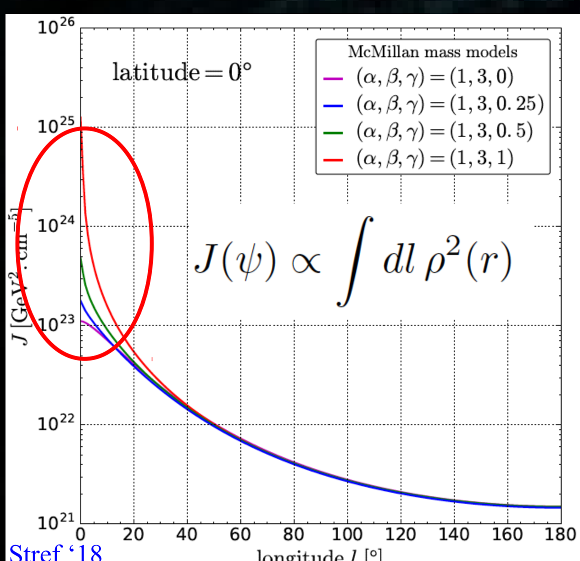
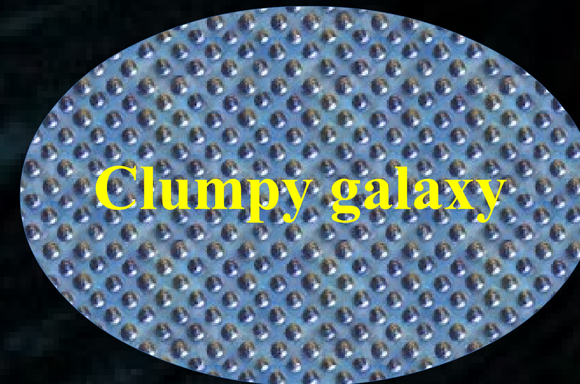
Dark matter distribution properties (and why it matters)



Mass density profile/s

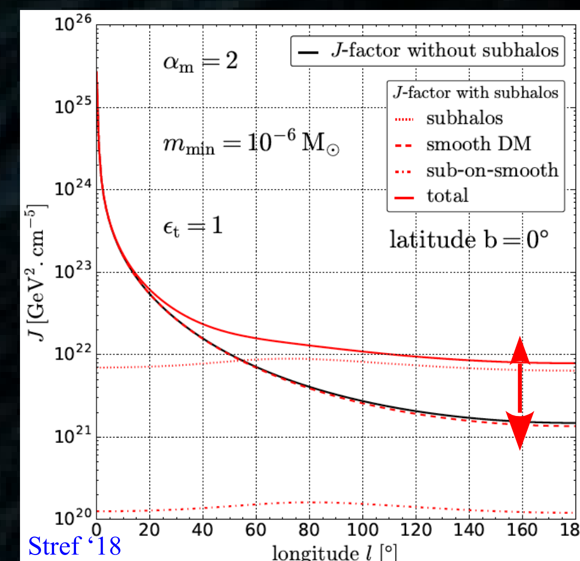
(but mind potentially strong difference between peculiar objects and average expectations)





Granularity of halos (aka subhalos)

Related to clustering properties of dark matter
→ Impact on a bulk of predictions



++ Phase-space distribution of dark matter

Many observables related to dark matter searches may depend on velocity (e.g. cross sections, microlensing events, etc.)

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

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

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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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→ Updated by Boyarsky+09: **m> 0.5 keV**

Bosons: **de Broglie wavelength > size of system =>** **m > 10^{-22} eV**
→ see review in e.g. Marsh '15 (axion-like particles)

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

Generic constraints on DM 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
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)

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"

→

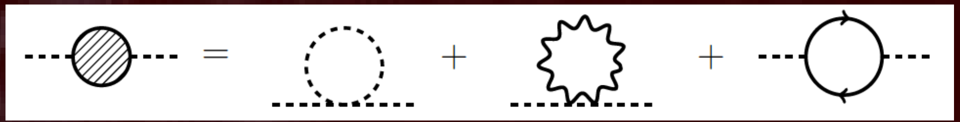
*** Consistent QFT**
+++ Production mechanism/s
+++ DM phenomenology with a minimal set of parameters => predictive
- - - built on purpose (ad hoc)

Model building

Two main approaches

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

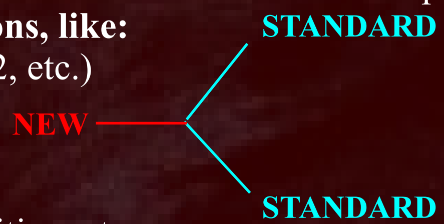
The **hierarchy pb** (Higgs stability),
aka the theoretical particle physics crisis



(e.g. Csaki & Tanedo '16)

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

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



DM: neutralino, sneutrino, gravitino, etc.

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

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

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Status of current searches

*** WIMPs (thermal DM)**

- 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)

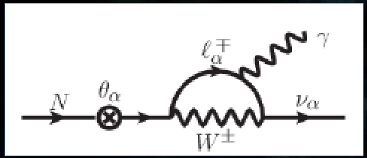
- Tiny room left in parameter space from structure formation (Ly-alpha) and X-ray constraints.

Sterile neutrino (W/C)DM

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

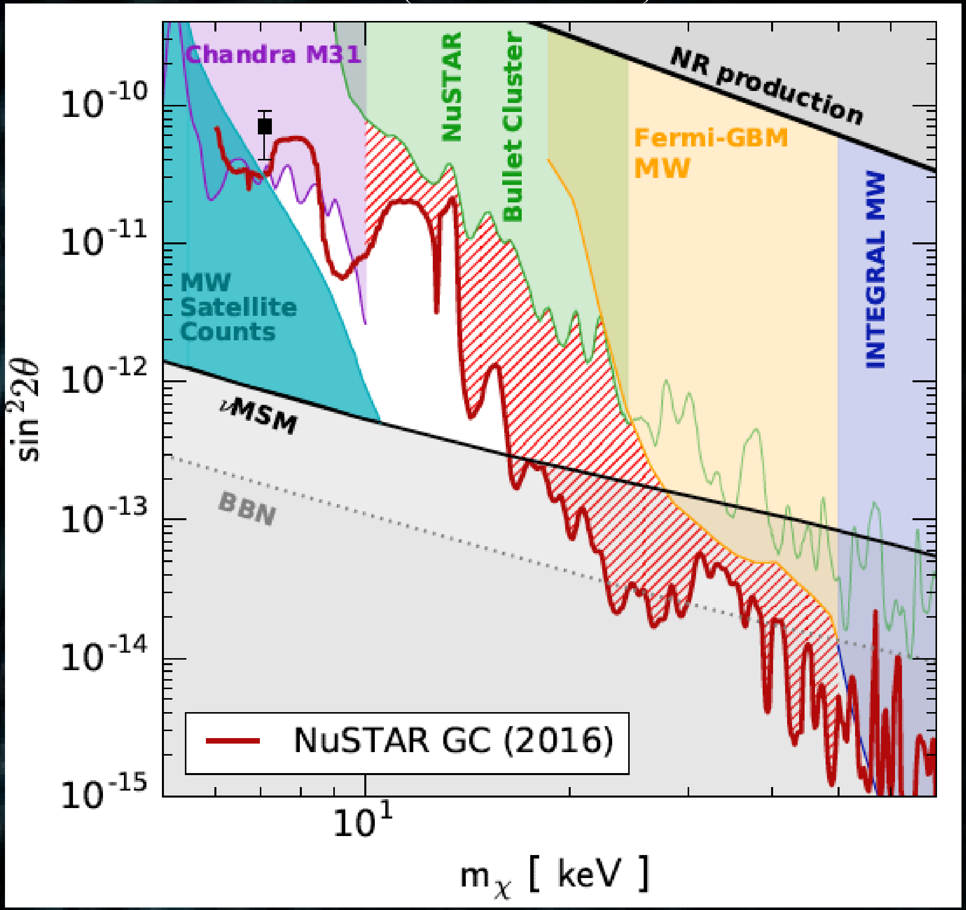
→ Neutrino masses (see-saw)
→ Leptogenesis
→ DM candidates (more or less warm)
→ keV mass range (!= thermal mass)

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



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

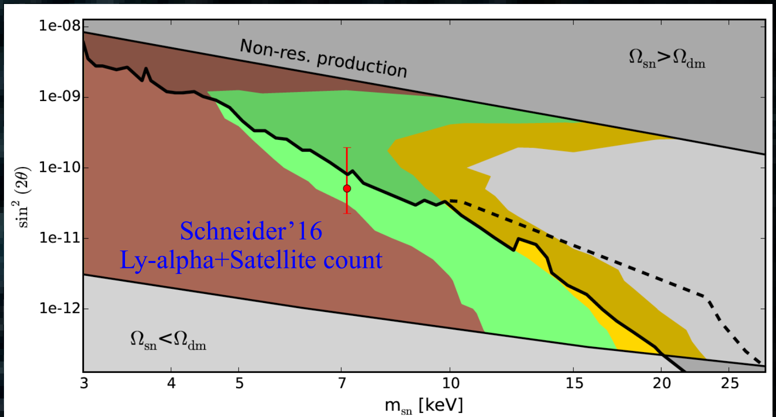
Perez+ '16
(also Neronov+'16)



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

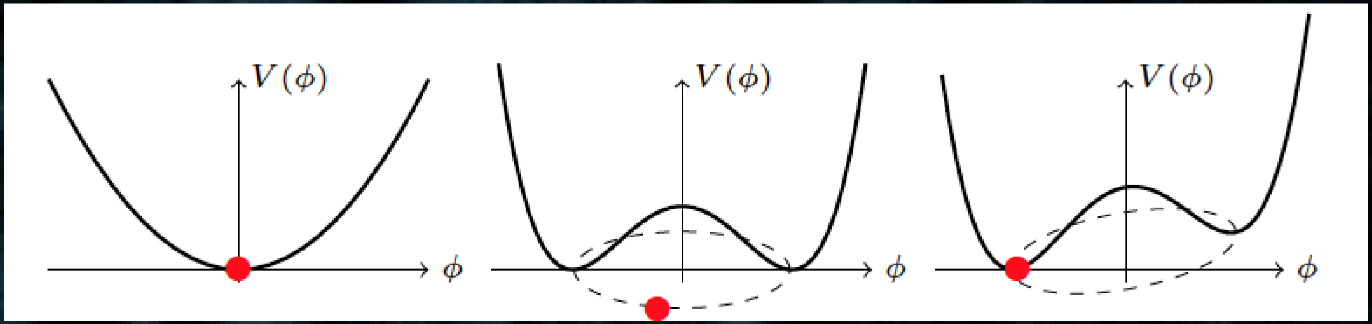
Detection (main):
* neutrino experiments (double ß decay)
* decays to **X-ray line: hints @ 3.5 keV** (Bulbul+14, Boyarsky+14)
→ 7 keV consistent with thermal mass of 2 keV(e.g. Abazajian 14)
→ hot debate, could be systematics (cf. Jeltema & Profumo)
→ Hitomi excludes excess in Perseus cluster (1607.07420 see also 1608.01684)

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



(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

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

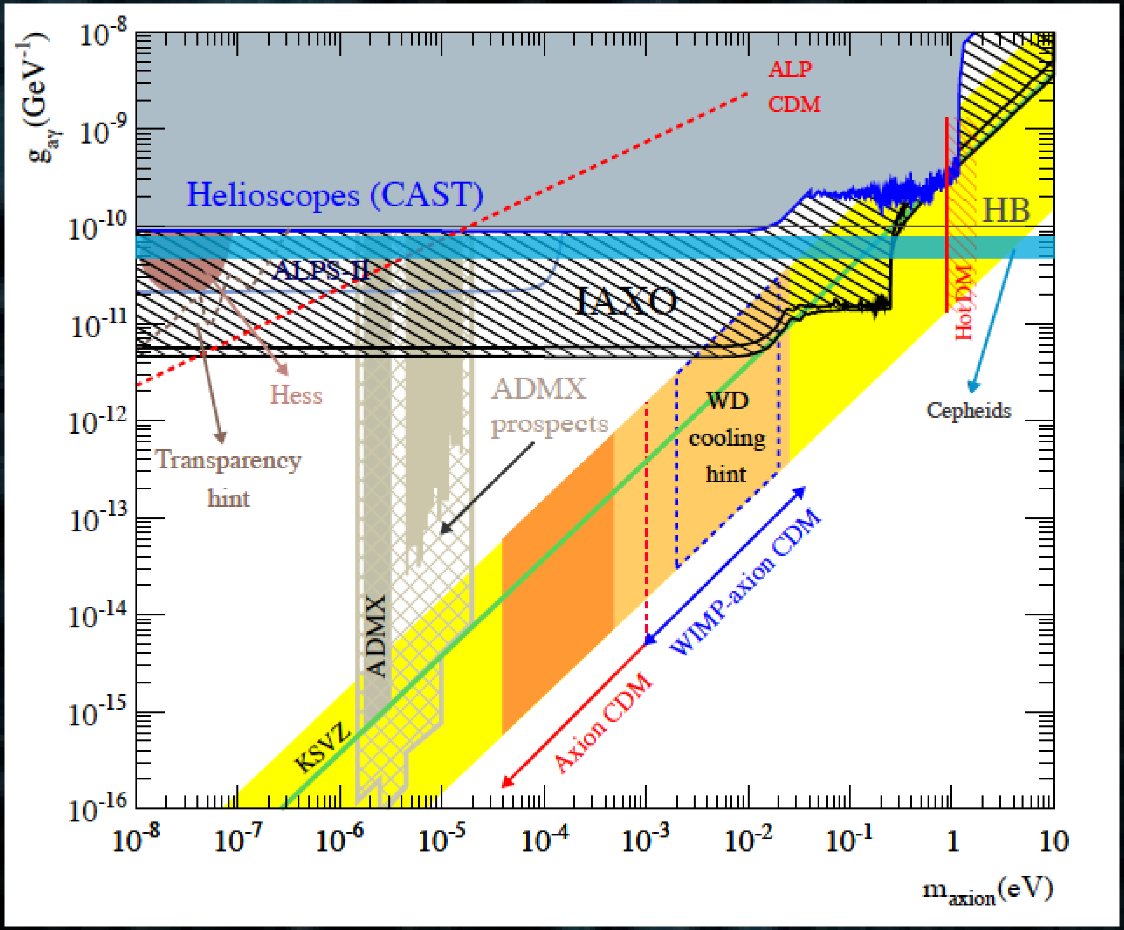
NB: QCD axion needs physics beyond standard model
Production mechanism (relevant to DM axions):
* Misalignment mechanism (generic)
* Decay of topological defects (if PQ broken after inflation)
⟶ compact axion asteroids! (f~0.5) – Tkachev'86
* m << eV => large occupation # => classical field
* QCD axions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



Compiled by Marsh’15

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

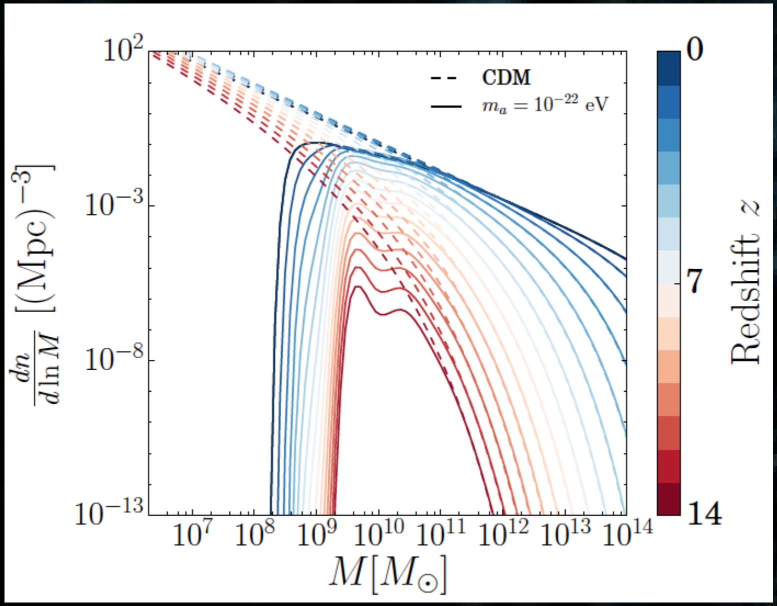
Hu+00, Peebles'00, Marsh+15, Hui+16, Schive+14, Du+18, etc.

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

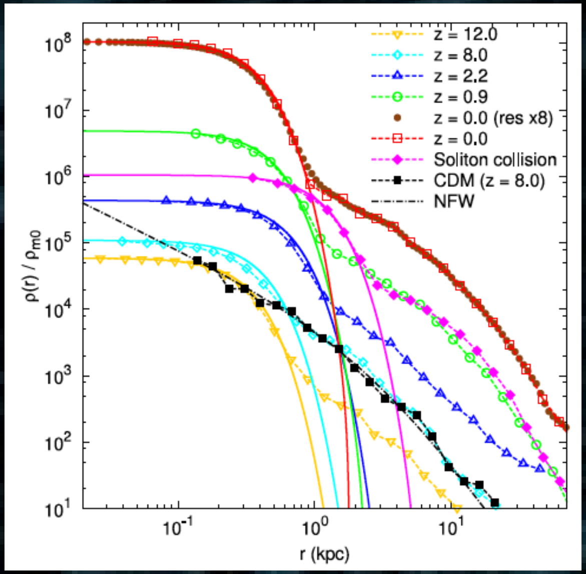
Main properties:
*** Suppression of small-scale perturbations**
*** incoherent interference pattern and granularity on scales ~ 1-100 kpc**
*** formation of solitonic cores at halo centers**
*** core/cusp solved in galaxies if m~10^{-22} eV**

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

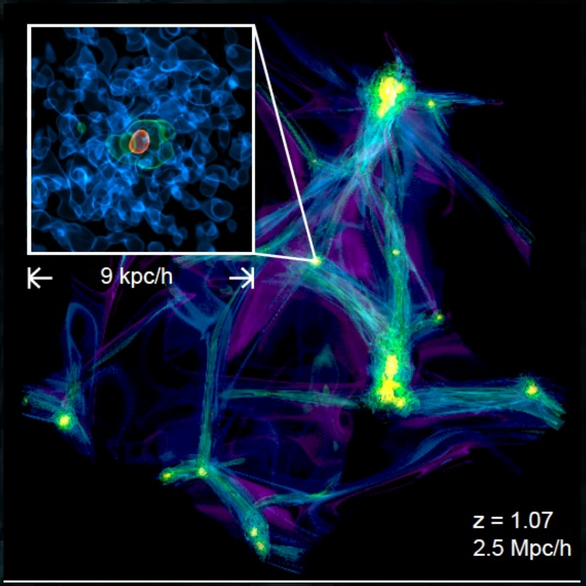
$$\nabla^2\Phi = 4\pi G m_a |\psi|^2$$



Bozek+15
Halo mass function



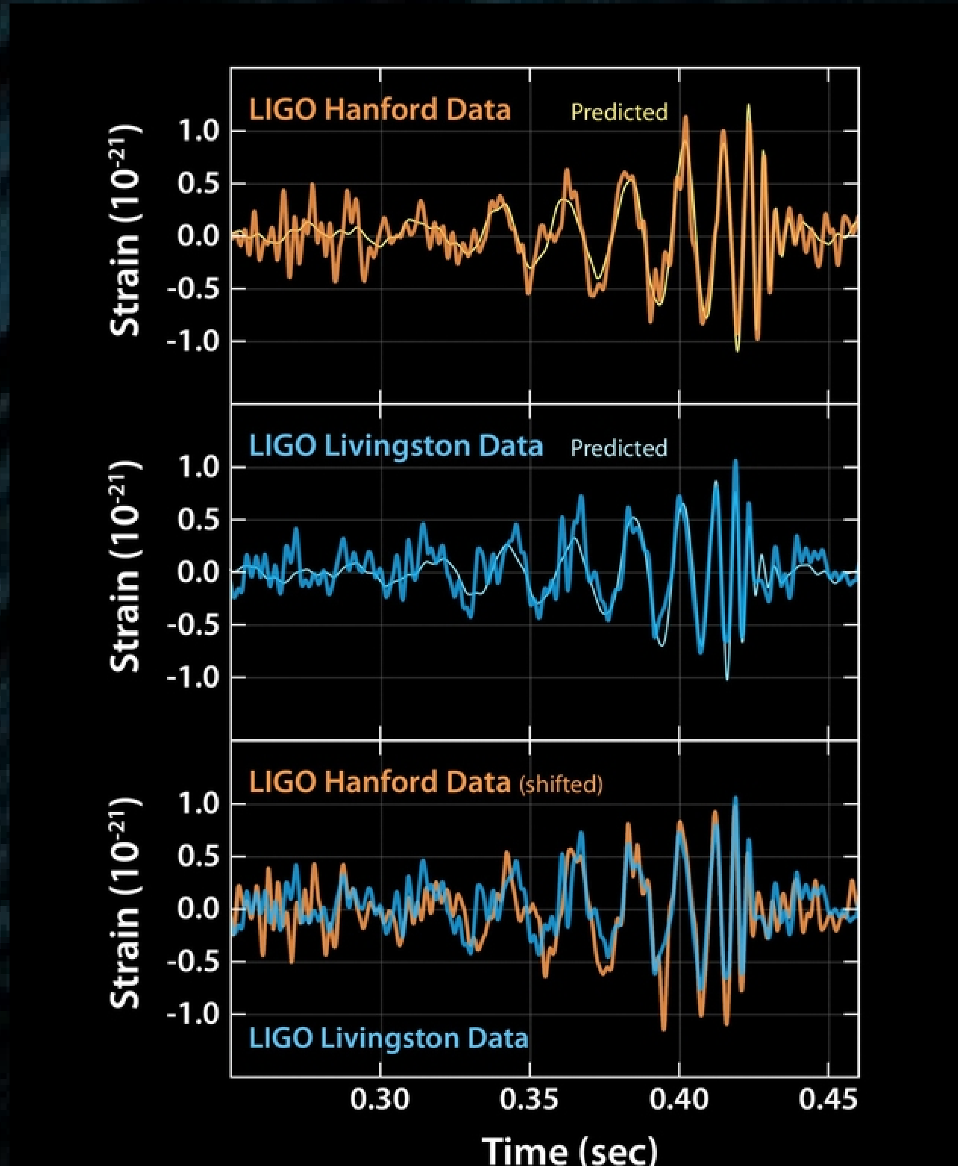
Schive+14
Solitonic cores in
Fuzzy DM simulations



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]

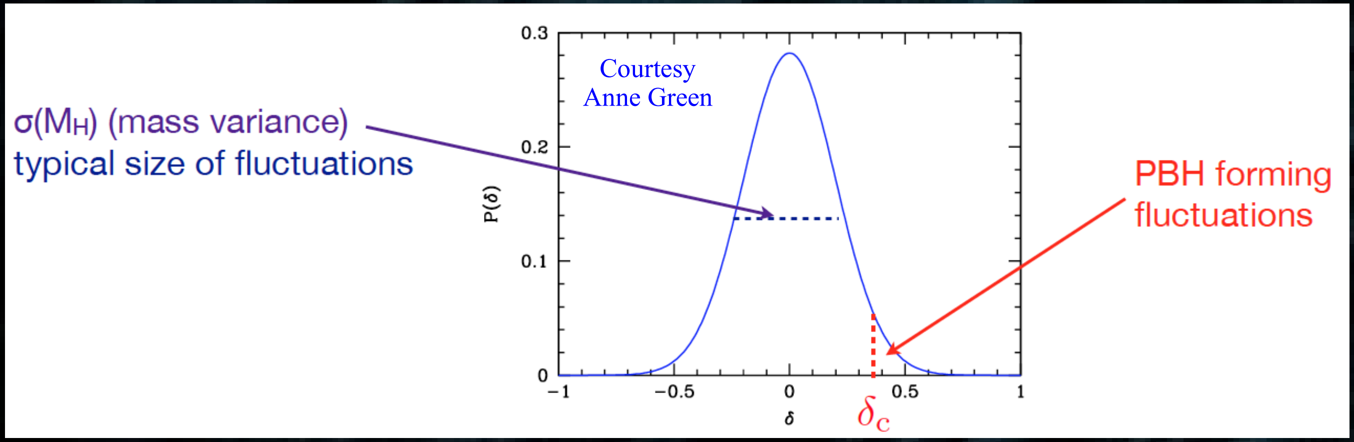
[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

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



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

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

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

Gaussian spectrum →

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

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

CMB scale →

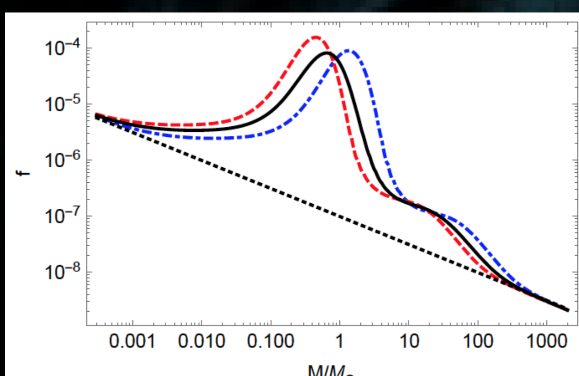
$$\sim 10^5 \exp\left[-(10^5)^2\right]$$

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

Primordial black holes

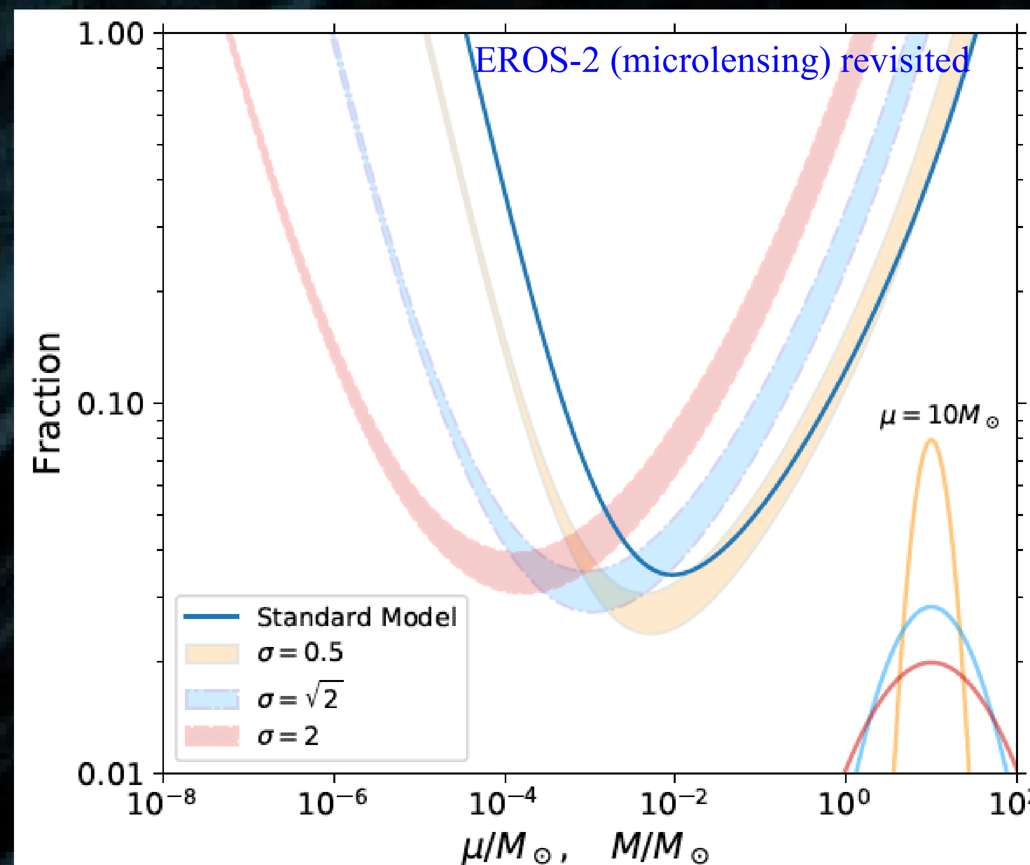
*** Most (past) constraints based on assuming peak mass function**
*** Huge effort to reconsider them (e.g. Green+, Kamionkowski+, Carr+, Garcia-Bellido+)**
*** Typically two windows: below and above microlensing constraints.**
*** If mass function extended enough, PBHs could be ~100% of DM**
→ if 1-100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

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



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

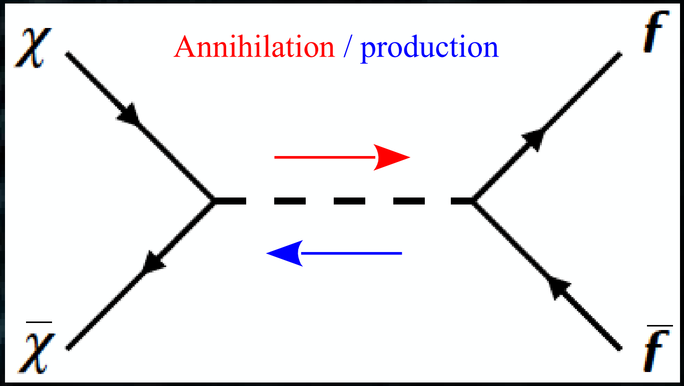
Calcino+18



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

Thermal production in the early Universe

Assume DM particle coupled to SM:
→ Production of DM from plasma if T>m
→ Chemical equilibrium if production rate > expansion rate
(then production = annihilation)
→ Annihilation if m>T (species is depleted)
→ Annihilation ceases when rate < expansion rate
=> Freeze out (or in) ↔ relic abundance

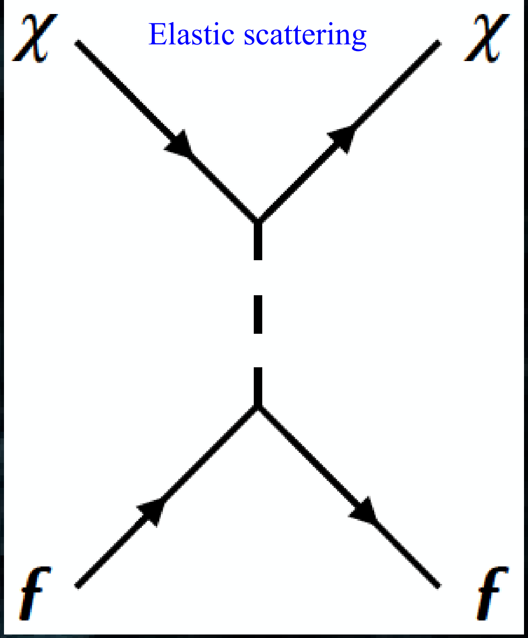


$$\Gamma_{\rm ann} = n_\chi \left\langle \sigma_{\rm ann} v \right\rangle$$

Thermal contact (DM temperature) ensured by both
* production/annihilation;
* elastic scattering.

After freeze out, DM still thermally coupled to plasma.

Thermal/kinetic decoupling
when scattering rate < expansion rate
=> Free streaming DM particles
=> Sets the minimal size of DM structures



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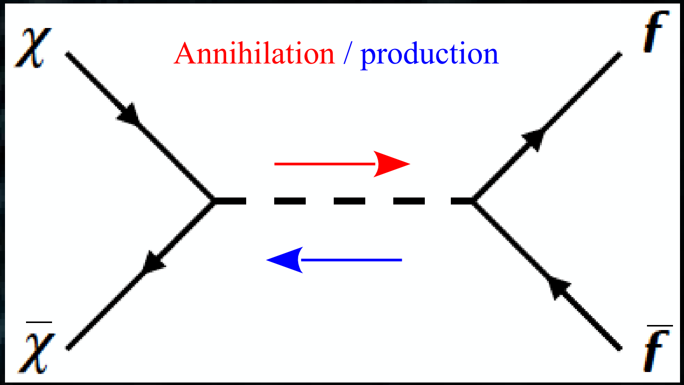

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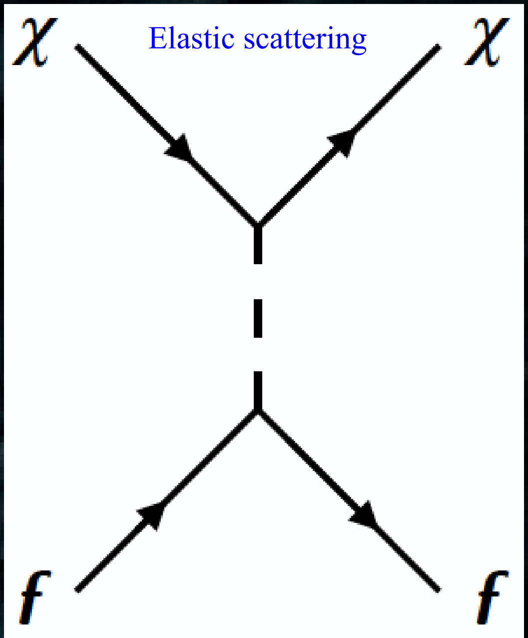


$$\Gamma_{\rm scatt.} = n_{\rm f} \left\langle \sigma_{\rm scatt} v \right\rangle$$

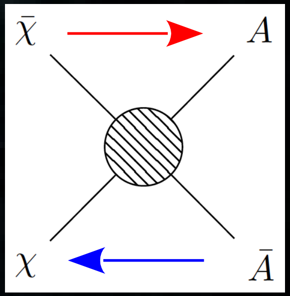
Solve moments of Liouville-Boltzmann equation for coupled species

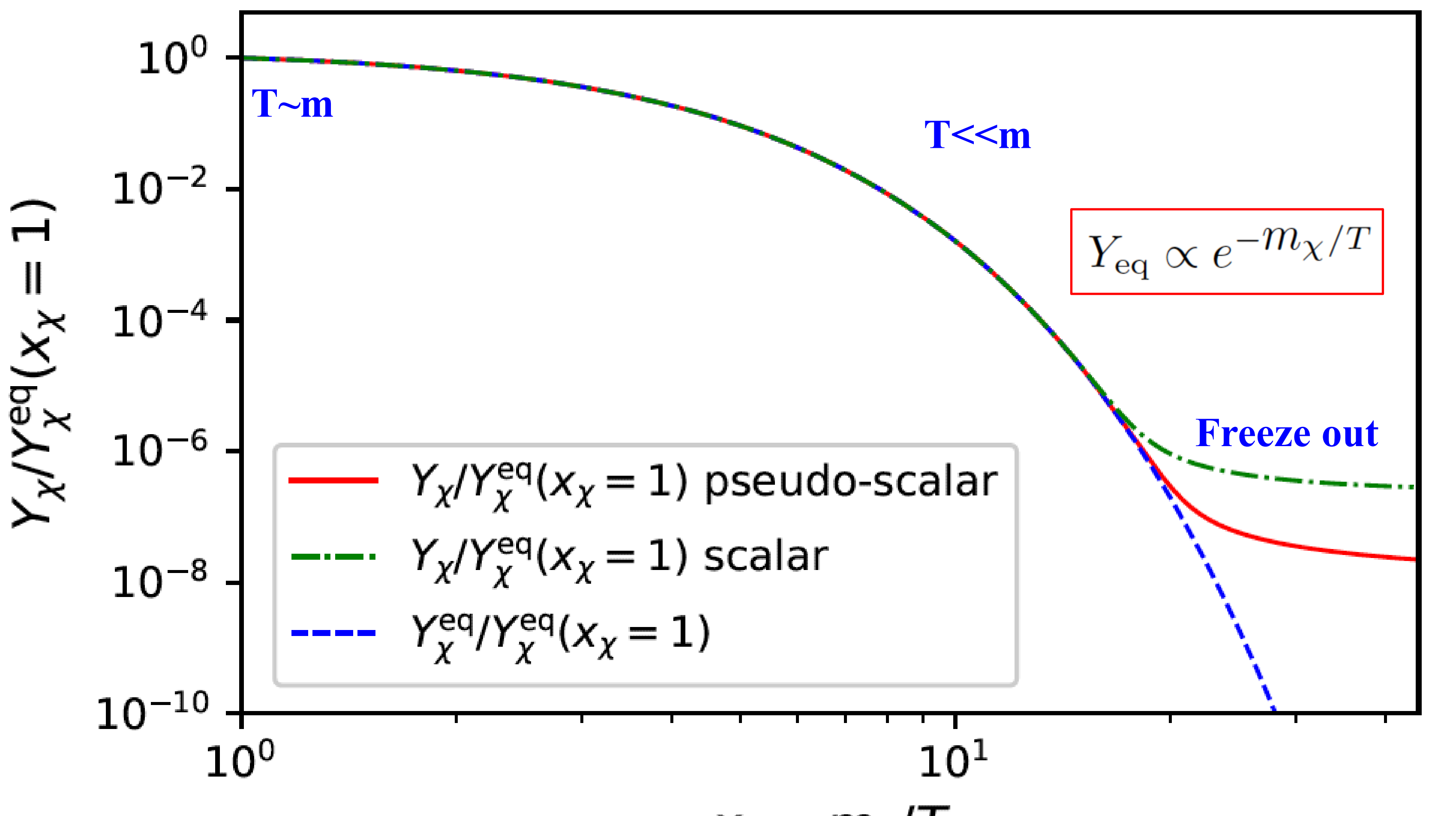
$$\frac{d\, f(x^\mu, p^\mu)}{d\lambda} = \widehat{C}[f]$$

Thermal production in the early Universe

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

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





Facchinetti 18 (PhD th)

Thermal production in the early Universe

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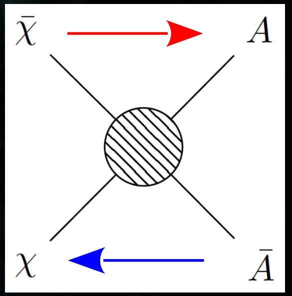
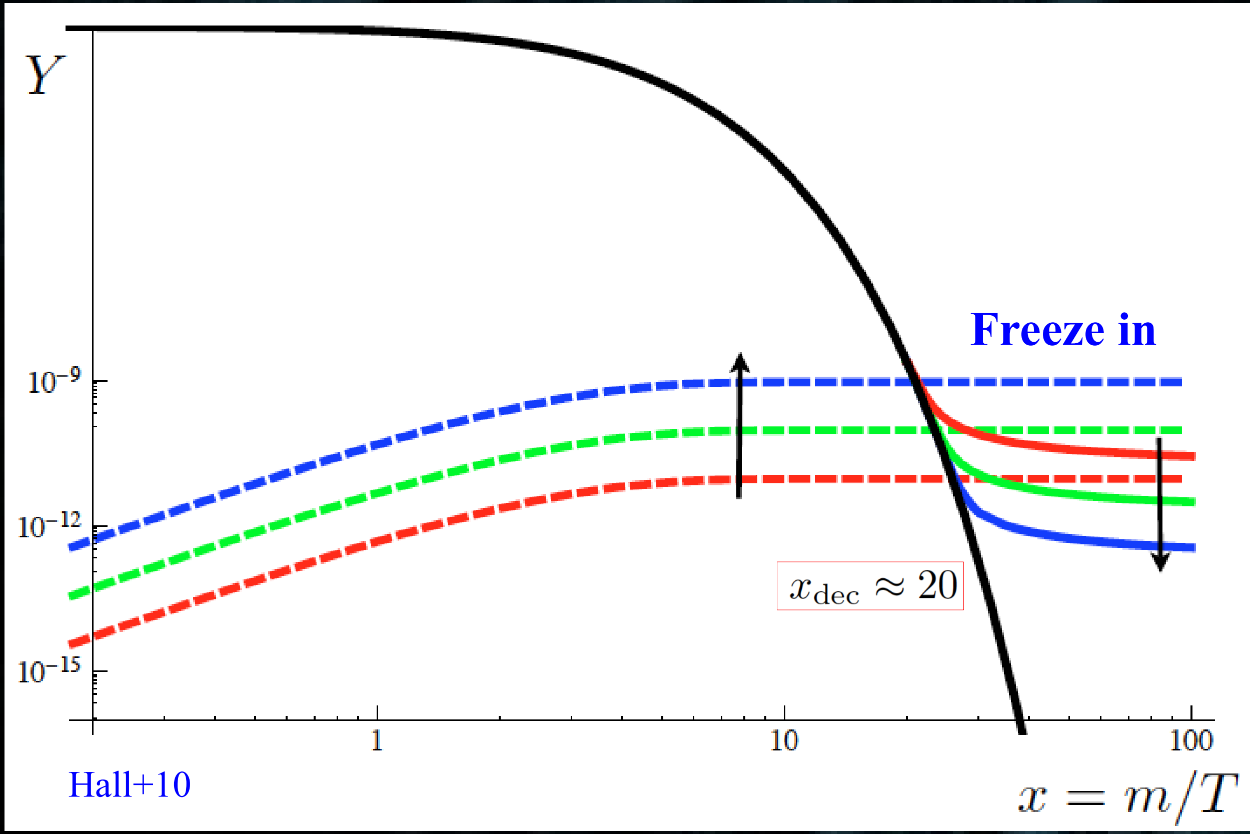




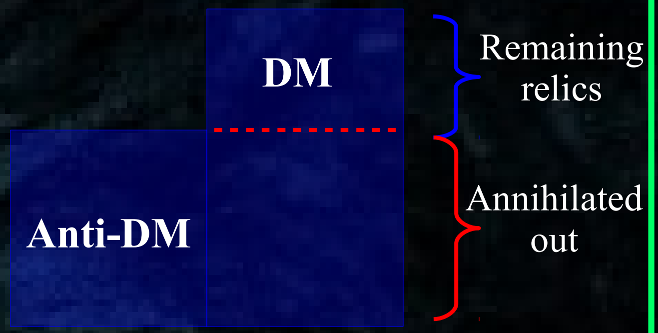
Freeze-in mechanism:
Dodelson & Widrow '94
McDonald '02
Hall+ 10

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

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

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

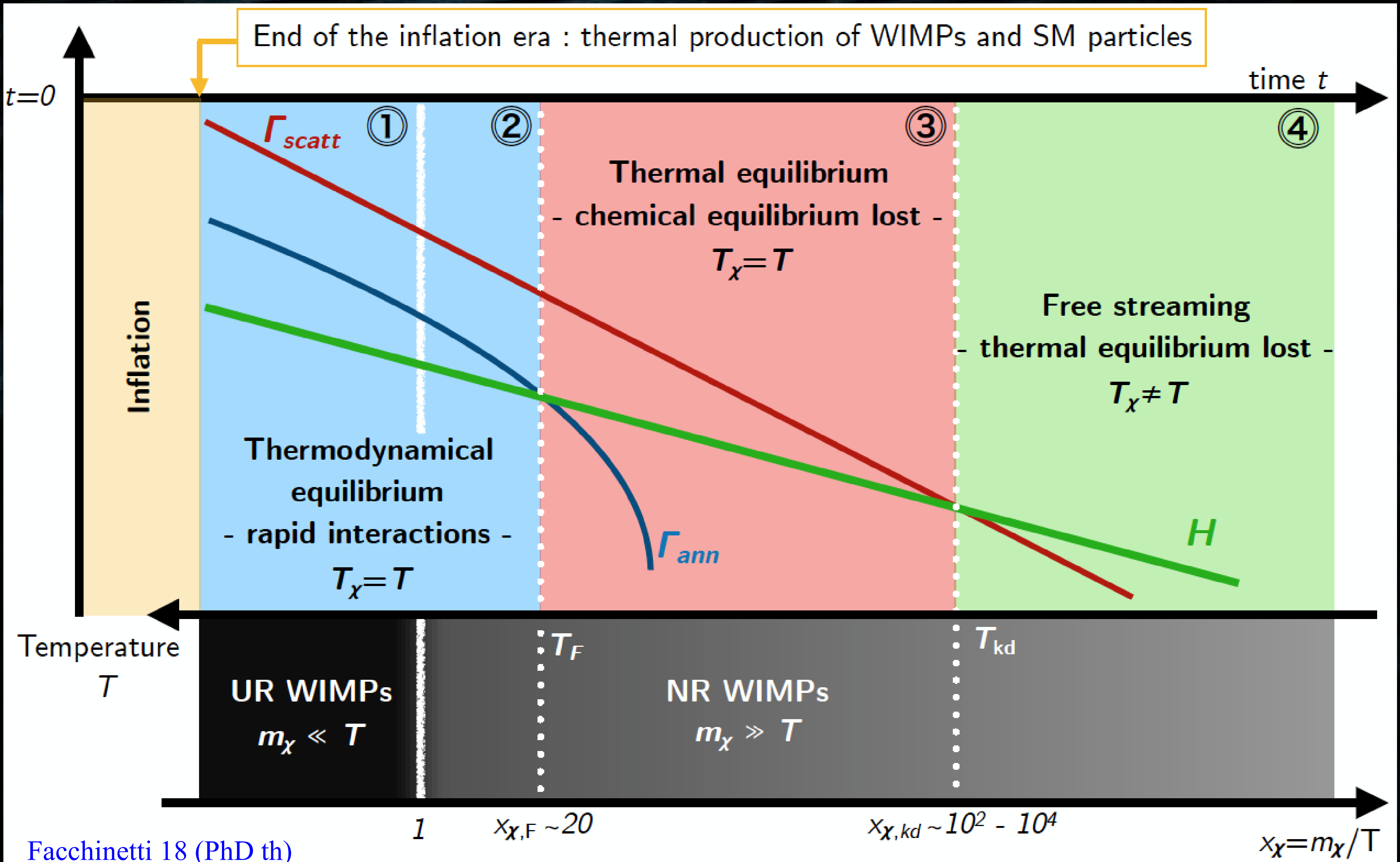
Asymmetric DM (Nussinov' 85)



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

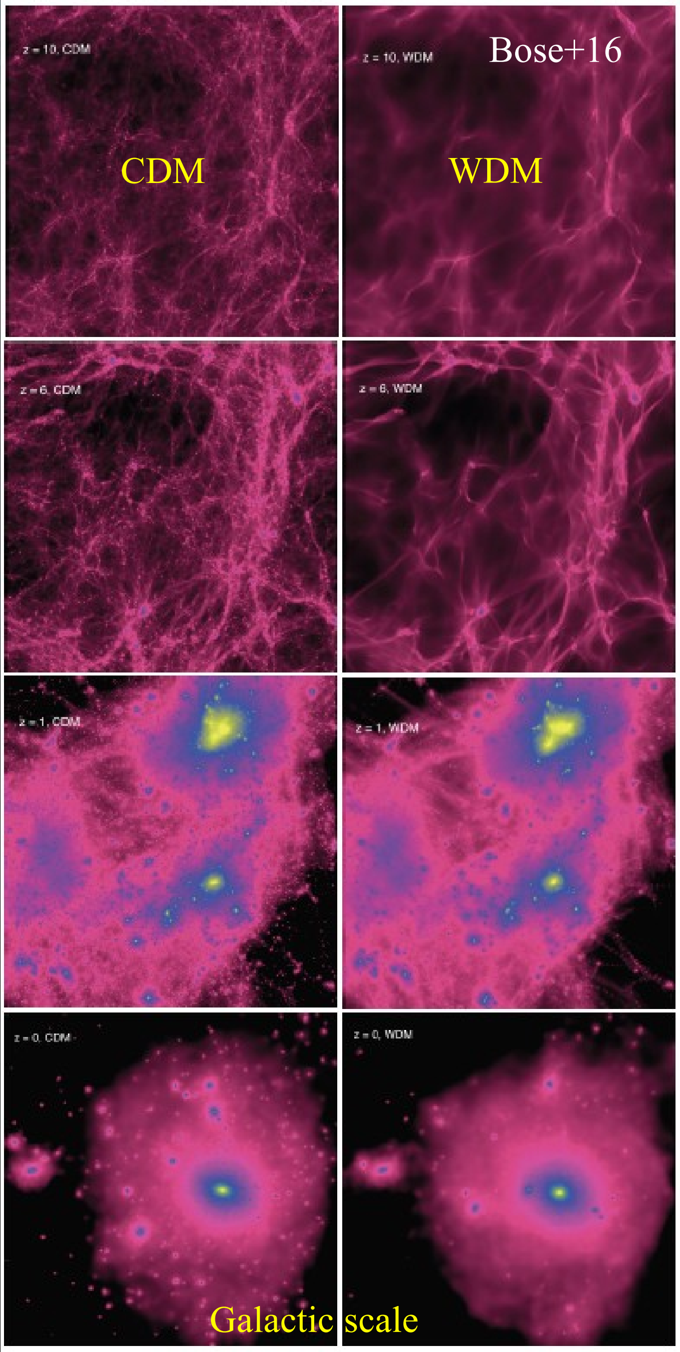
All this picture is also valid for self-interacting dark matter (SIDM)
→ generic properties: extended dark sector (interaction mediators)

Thermal production in the early Universe



Facchinetti 18 (PhD th)

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



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

* Density perturbations grow efficiently after matter-radiation equivalence

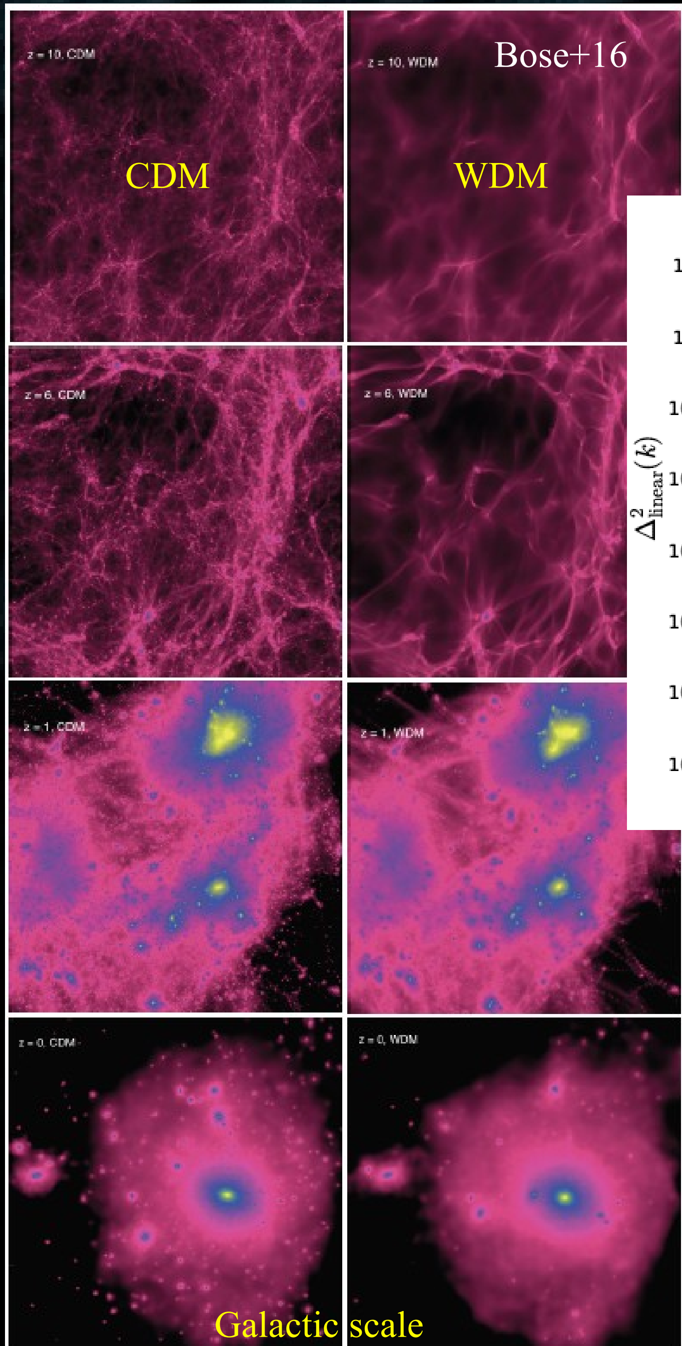
* Kinetic decoupling time sets free-streaming scale

* Other competing effects (collisional damping)

=> Minimal size of structures have impact on DM searches
=> Depends on DM interaction properties

[e.g. Hofmann+01, Berezinsky+03, Green+04-05, Bertschinger 06, Bringmann+07, Facchinetti+ in prep.]

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



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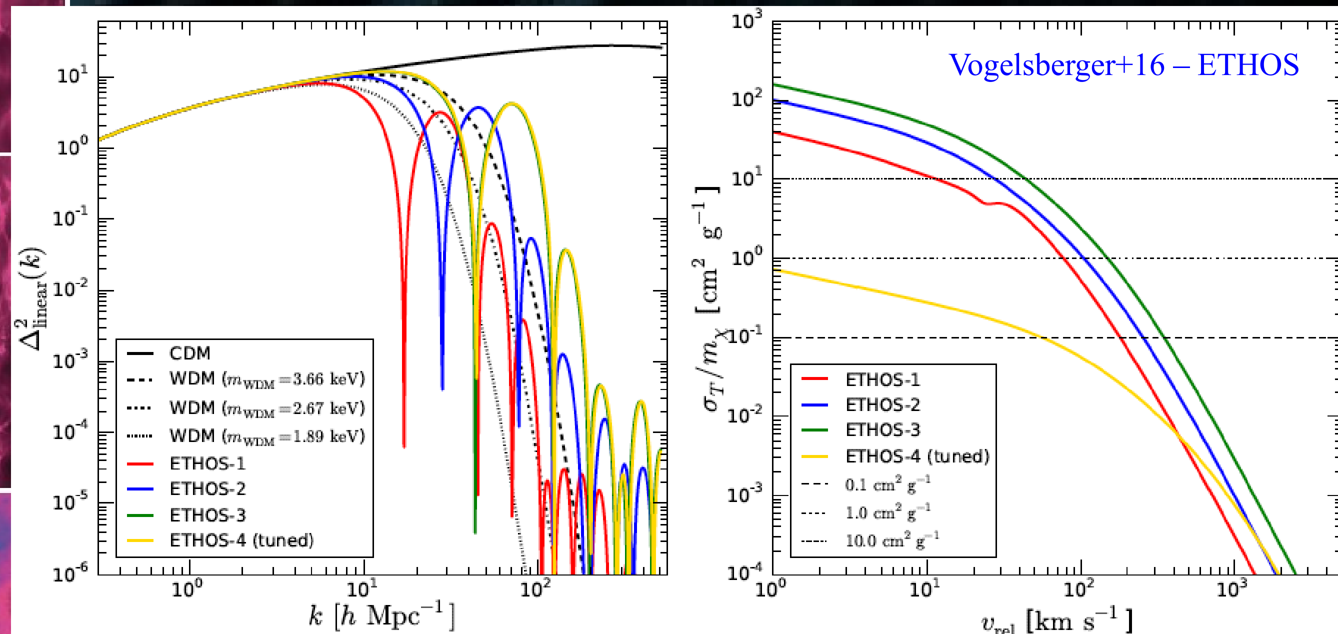
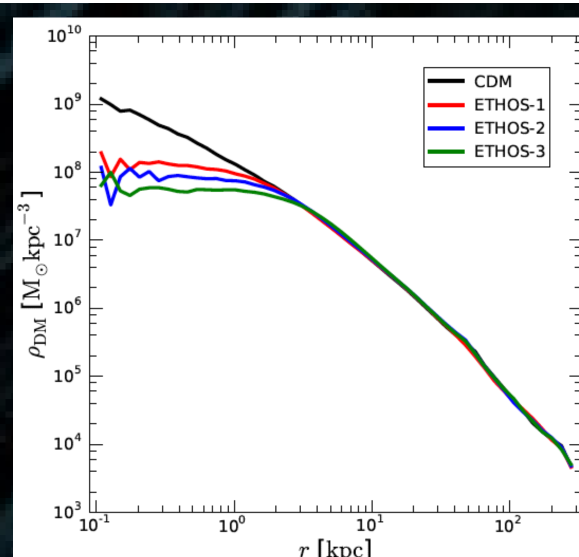
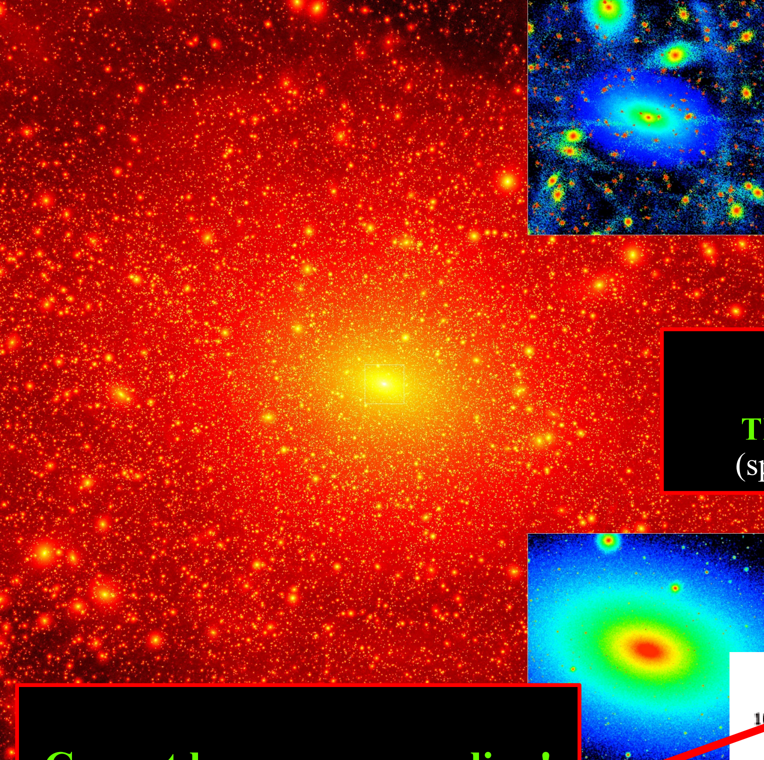




CDM candidates: minimal scale of structures depend on interactions. For TeV particle, can be ~10^{-10}M

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

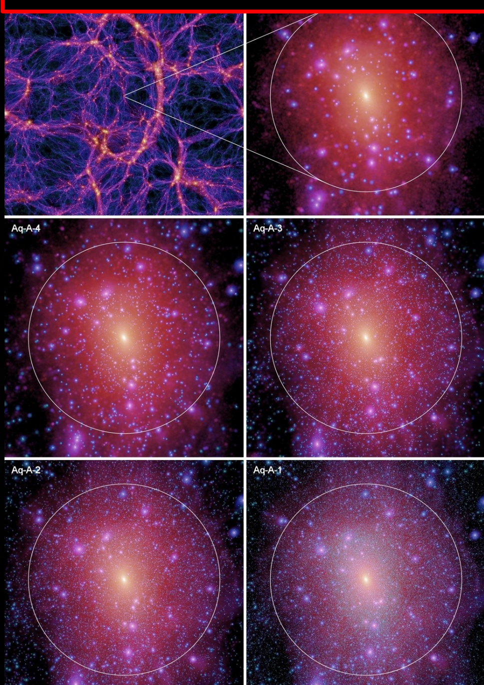
Dark matter in the Milky Way



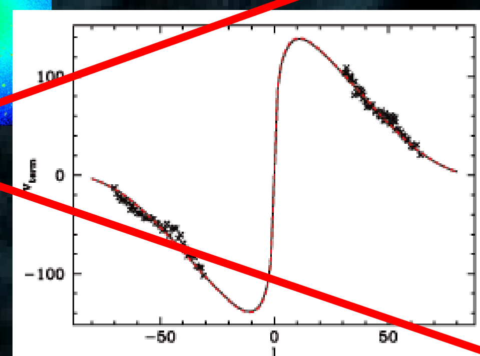
Making predictions for DM searches?

The Milky Way a strongly constrained system!
(specific history + properties + observational data)

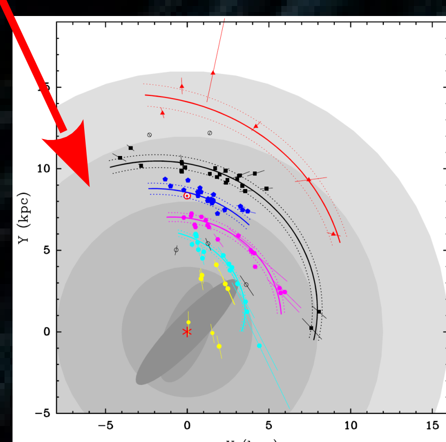
Cannot be a mere rescaling!



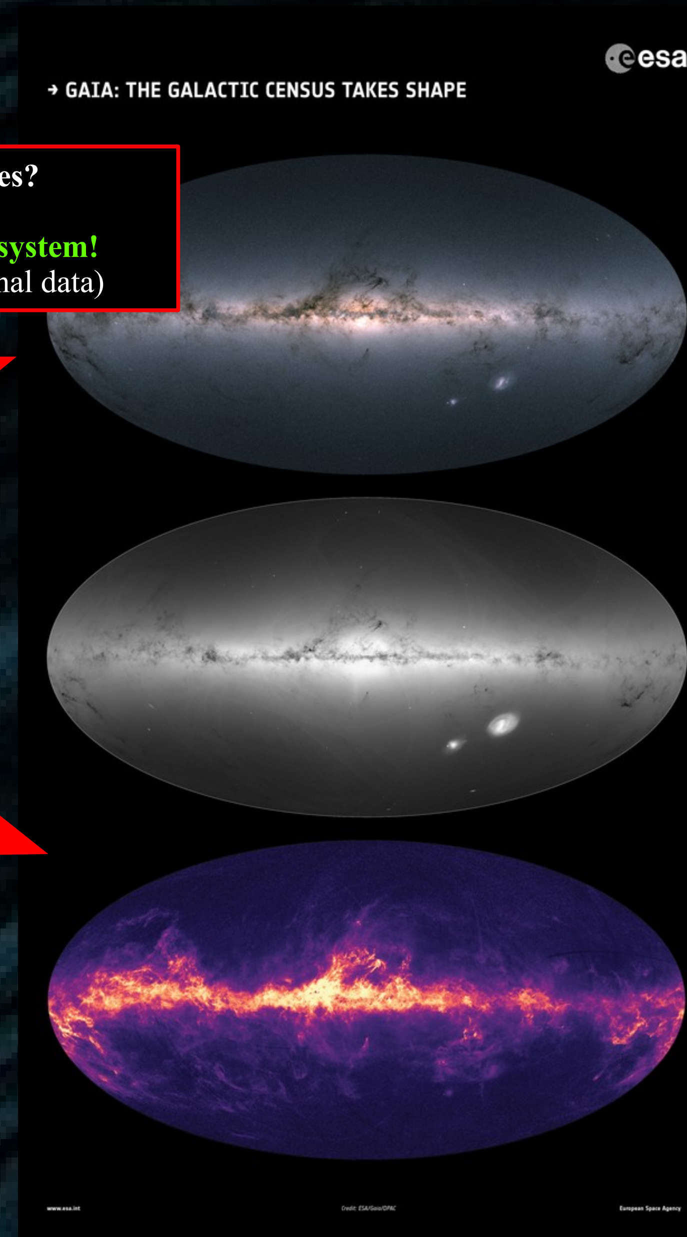
Aquarius, Springel+08
[see also Molitor+'15]



MW terminal velocities, McMillan '11

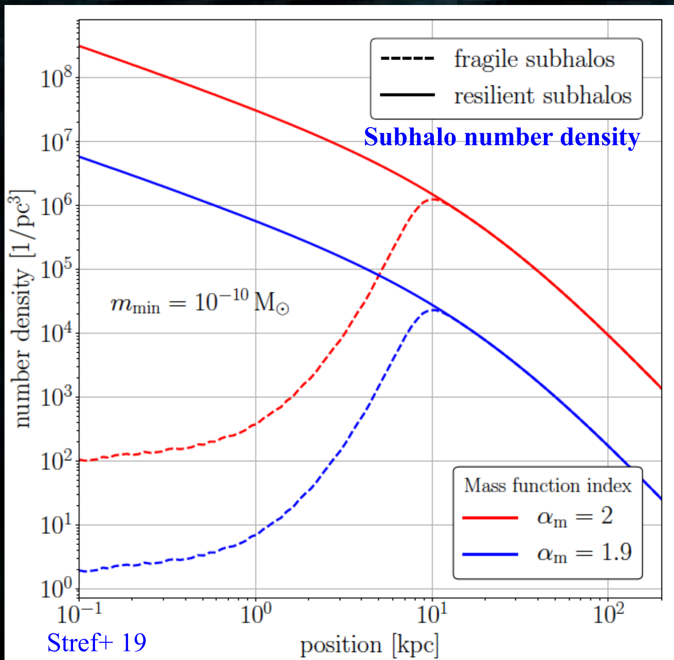


MW masers, Reid+14

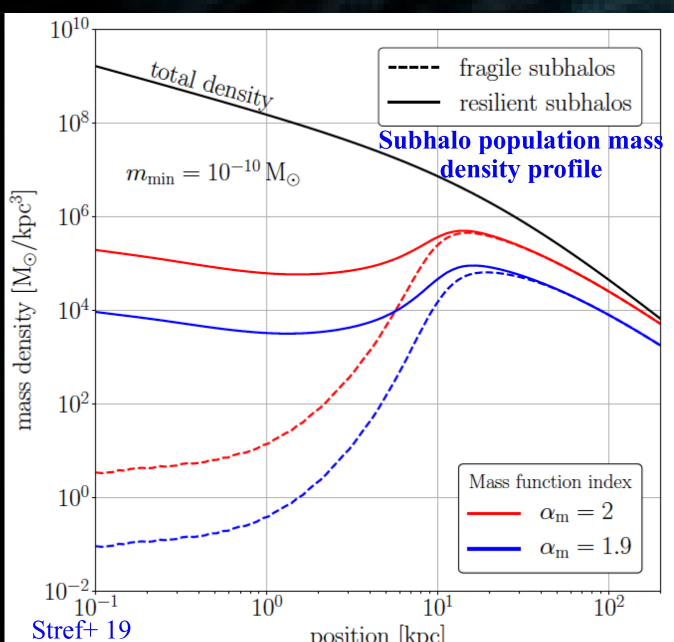


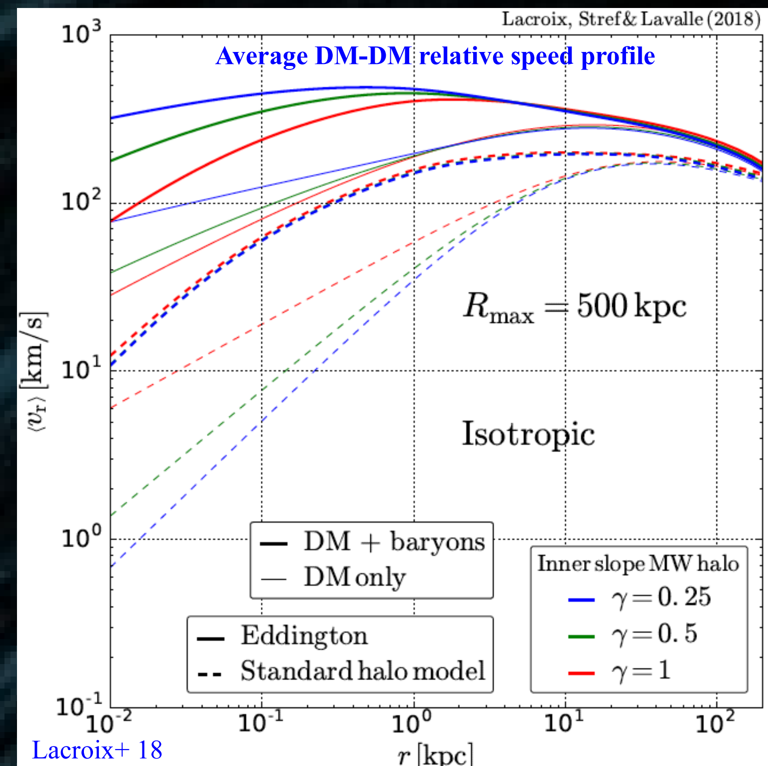
Gaia: Data Release 2 (DR2) @ESA

Constrained MW mass models matter in predicting/constraining …



The Galactic subhalo population down to the tiniest masses
→ Subhalo number density + mass density profiles





The velocity distribution of dark matter
→ moments of the relative speed from improved Eddington equation

Will improve with Gaia

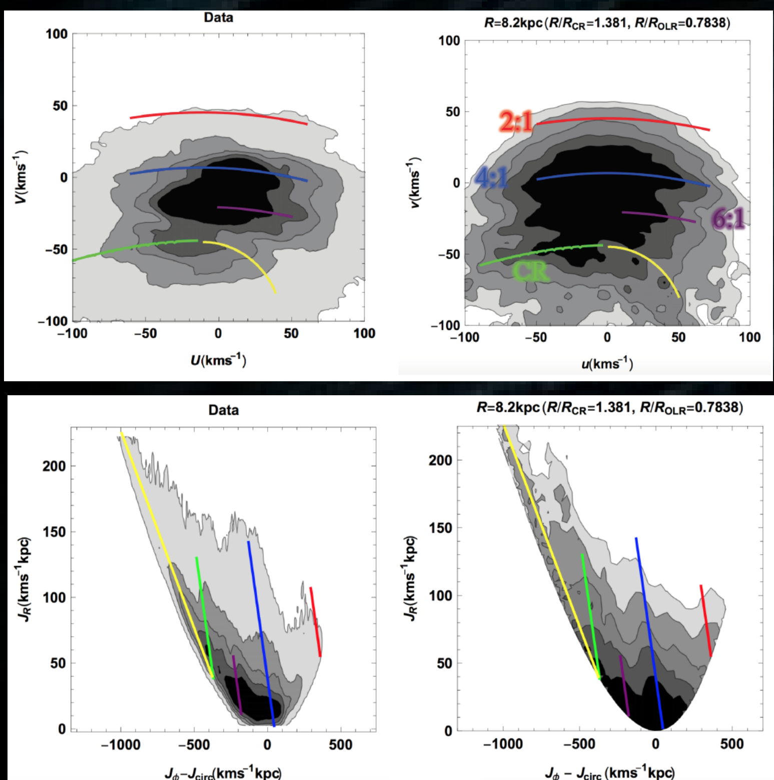
Local dynamics probed with Gaia

* Jeans theorem: Phase-space distribution of steady-state system naturally described by functions of closed integrals of motion

* Natural basis is: action (***J***) and angle (**θ**) conjugate variables; the Hamiltonian reads H(***J***) (Binney & Tremaine '08)

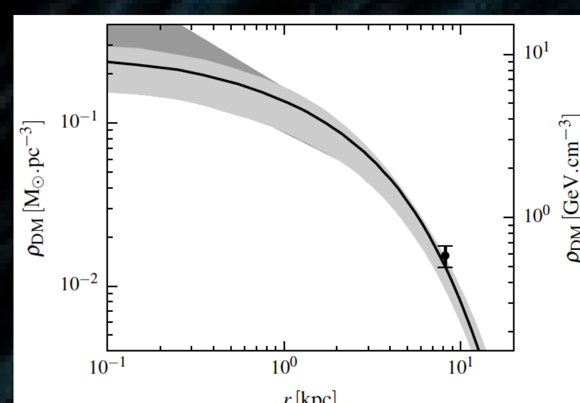
* At equilibrium, f_0(***J***) solution of collisionless Boltzmann equation

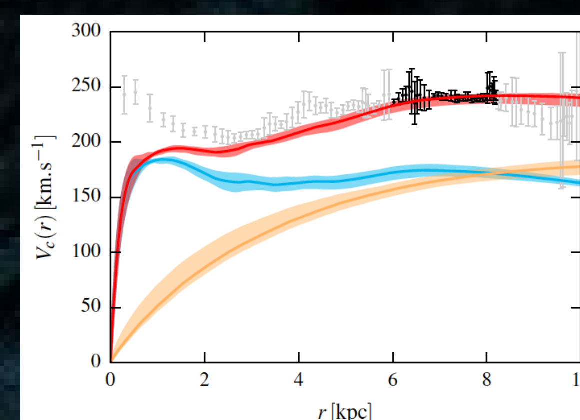
* Take perturbations of the bar and spiral arms into account: **resonances (trapped orbits)**!
=> new set of action-angle coordinates (Monari, Famaey, Fouvry, Binney '17)
=> applied to **Gaia DR2** (Monari, Famaey, Siebert, Wegg & Gerhard '19), using Galactic bar model of Portail+'17



Sample of $3x10^5$ stars within 200 pc + bar model only (no spiral arms)
=> find the predicted resonant orbits in the data!
=> somewhat a unique long-distance test of the Portail+ bar model

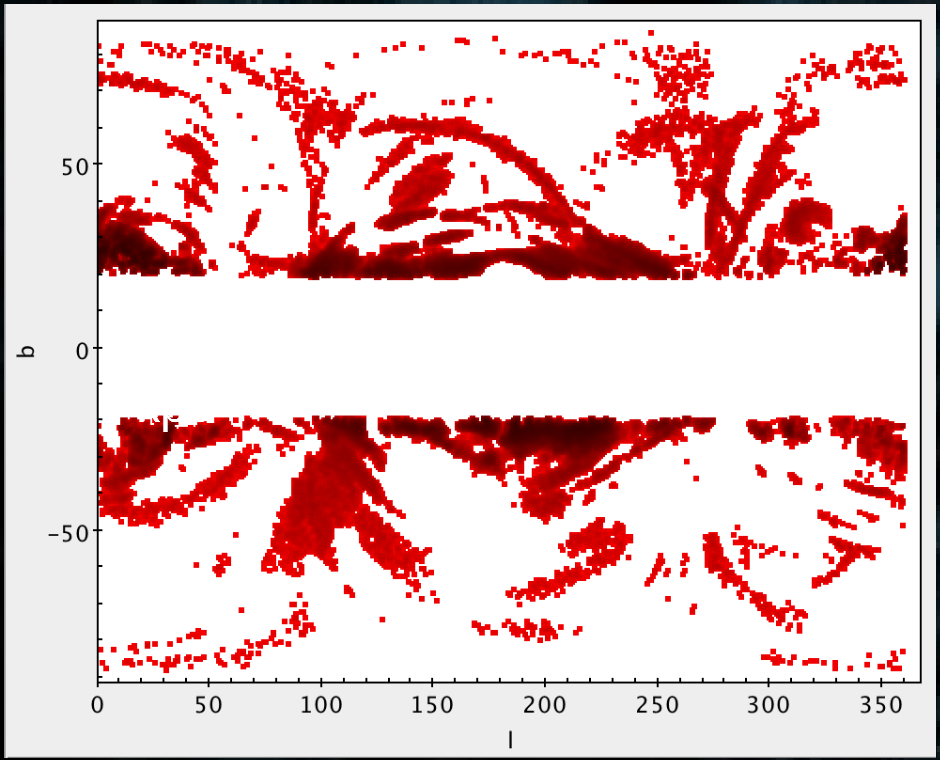
=> favors a DM core at the Galactic center (but doesn't match inner RC)





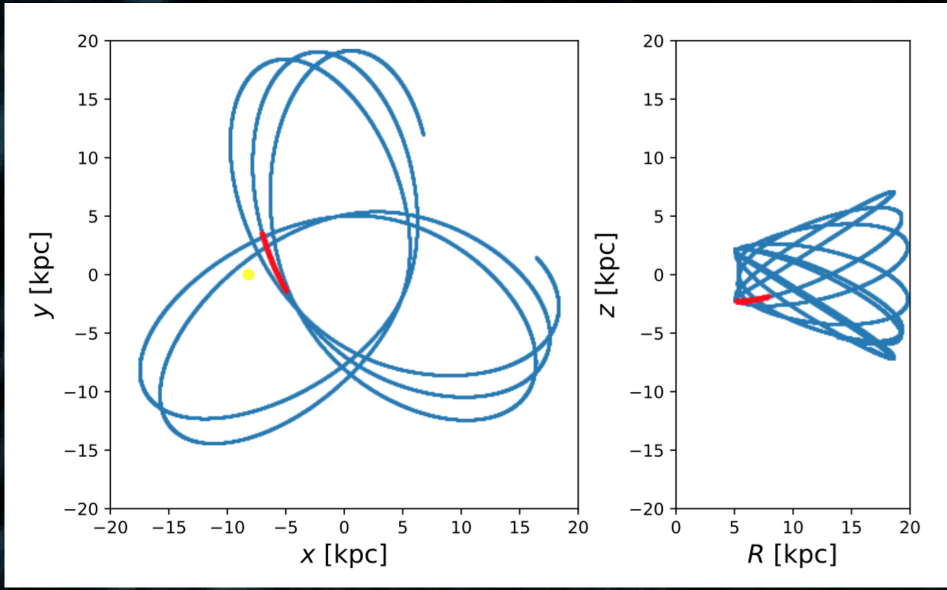
Global dynamics probed with Gaia

Streams (Ibata et al.):



>10 new confirmed streams in total

Integrate streams orbits by exploring all distances and radial velocities until stream candidate found (STREAMFINDER)



Phlegethon: a faint nearby(3.8 kpc) disk-like retrograde stream (~2580 M) Ibata et al (2018)

Stellar streams: a powerful probe of global dynamics + subhalos (e.g. heating and gaps)

Conclusions

* DM candidates
→ no longer particle-theory driven
→ focus on production mechanism and interaction properties vs. observational signatures
→ a rich phenomenology, but many potentially observable signatures
→ astrophysical (multiwavelength+multimessenger – photons, neutrinos + gravitational) + cosmological observations (CMB+21cm+Ly-alpha) very powerful probes

* The Milky Way (MW) itself provides many probes of fundamental dark matter properties

* MW is a single object:
→ detailed properties NOT predicted by cosmological simulations (specific baryonic distribution, merger history, etc.)
→ not overstate the theoretical consequences of (non)observations (e.g. core/cusp in the MW)

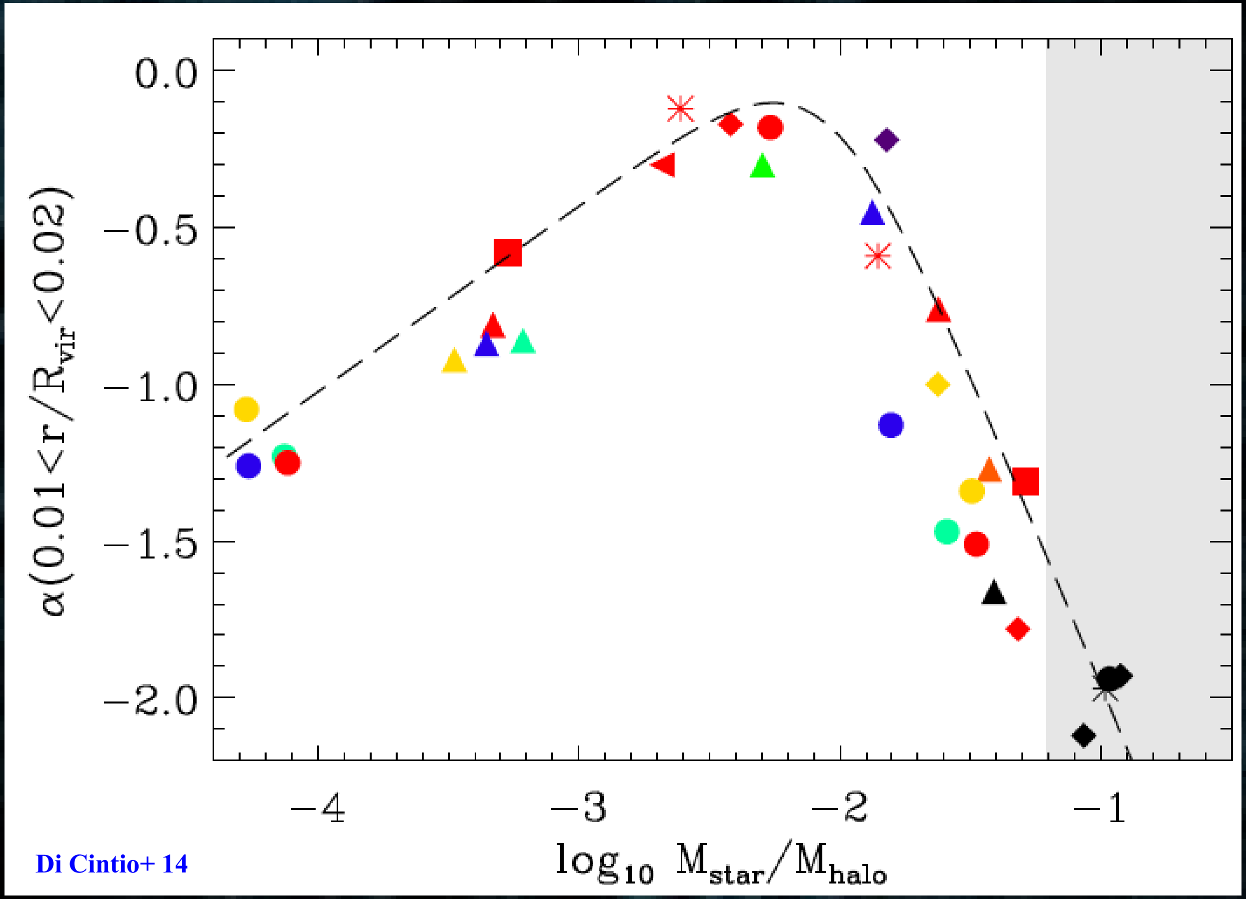
* Strong complementarity with other probes (other galaxies, other scales, other ages).

* Dark matter structuring properties on small scales very important (far below resolution of cosmological simulations → need to build and rely on analytical models) → strong impact on several observables + gravitational searches

* Gaia DR2: (already) impressive improvement on dynamical understanding of MW (incl. merger history).
→ global dynamics (DM halo + gravitational potential)
→ local dynamics (local DM density)
→ subhalos (gaps in stellar streams, etc.)

* A lot theoretical/modeling work needed to improve predictions

Backup

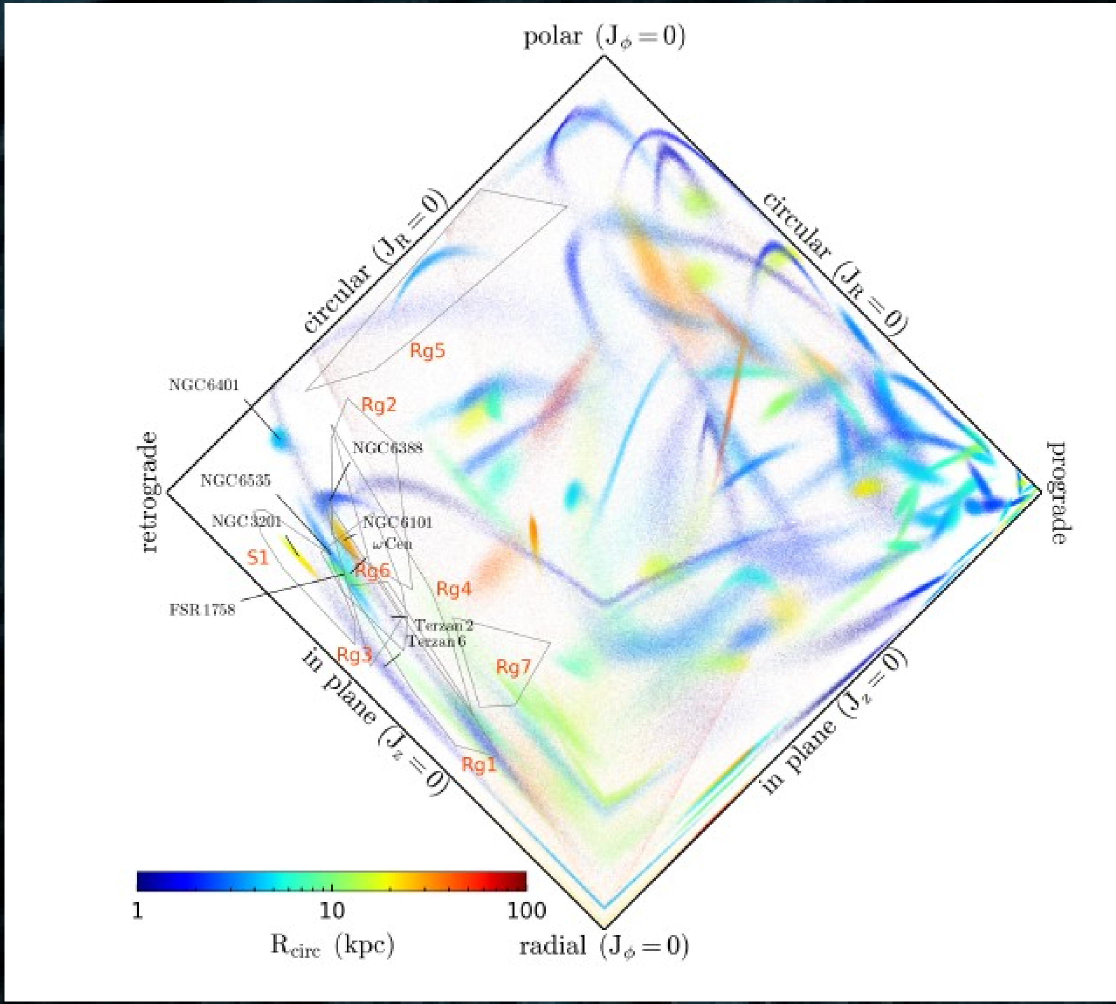


0.0
−0.5
−1.0
−1.5
−2.0
α(0.01<r/R_vir<0.02)
−4
−3
−2
−1
log10 M_star/M_halo
Di Cintio+ 14

Evidence for Two Early Accretion Events That Built the Milky Way Stellar Halo

G. C. Myeong[1], E. Vasiliev[1,2], G. Iorio[1], N. W. Evans[1], V. Belokurov[1]
[1] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
[2] Lebedev Physical Institute, Leninsky Prospekt 53, Moscow 119991, Russia

arXiv:1904.03185v1



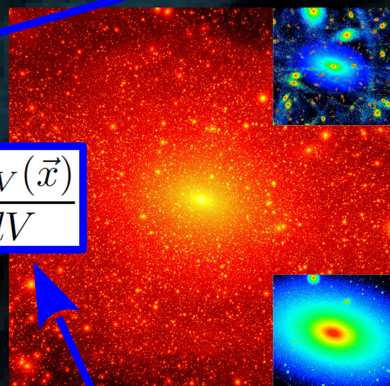
Defining the whole subhalo "phase space"

At MW formation, all (cosmological) properties factorize out

$$\frac{d^n N^0}{d\omega^n} = N_0 \frac{d\mathcal{P}^0_V(\vec{x})}{dV} \times \frac{d\mathcal{P}^0_m(m)}{dm} \times \frac{d\mathcal{P}^0_c(c,m)}{dc}$$

$$\frac{d\mathcal{P}^0_V(\vec{x})}{dV} = \frac{\rho_{\rm tot}(\vec{x})}{M_{\rm h}} = \frac{d\mathcal{P}_V(\vec{x})}{dV}$$

Hard sphere approx: subhalos track the evolving DM distribution, even after disruption.
=> redistribution of DM from subhalos to the smooth component.



1st step: compute tides induced by final MW halo
=> parameter space becomes intricate!

=> generic enough to be calibrated from simulations
=> subhalo mass fraction ~10% in range $(10^{-5},10^{-2})\ M_h$ (eg Diemand+08) fixes N_{tot}

$$\frac{d^n \bar{N}}{d\omega^n} = \frac{\bar{N}_{\rm tot}}{\bar{K}_w} \frac{d\bar{\mathcal{P}}_V(\vec{x})}{dV} \times \frac{d\bar{\mathcal{P}}_m(m,\vec{x})}{dm} \times \frac{d\bar{\mathcal{P}}_c(c,m,\vec{x})}{dc}$$

2nd step: compute tides induced by MW baryons
=> parameter space even more intricate

=> CANNOT be calibrated from simulations

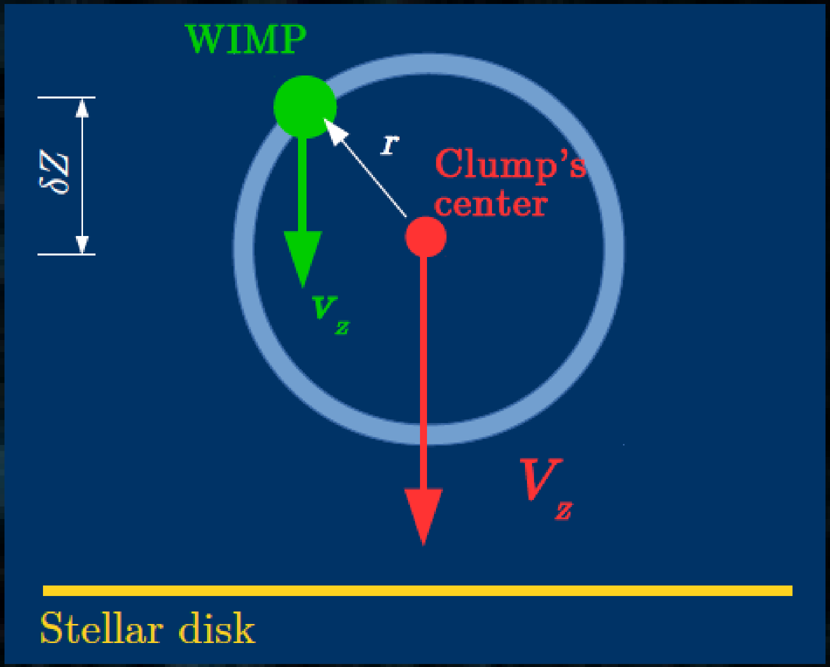
$$\frac{d^n N}{d\omega^n} = \frac{N_{\rm tot}}{K_w} \frac{d\mathcal{P}_V(\vec{x})}{dV} \times \frac{d\mathcal{P}_m(m,\vec{x})}{dm} \times \frac{d\mathcal{P}_c(c,m,\vec{x})}{dc}$$

Tides from stellar encounters and disk shocking

Encounters with stars:
(Ostriker+,Weinberg+, Gnedin+,80-00, Berezinsky+03)
*** impulse approximation during fly-by**
=> negligible wrt disk shocking

$$\Delta E = \frac{1}{2}\int \mathrm{d}^3\vec{r}\,\rho_{\rm int}(r)(\delta v_x - \delta\tilde{v}_x)^2$$

$$\Delta E = \frac{2\pi}{3}\left(\frac{2G_{\rm N}M_*}{v_{\rm rel}l^2}\right)^2\int_0^R \mathrm{d}r\,r^4\,\rho_{\rm int}(r)$$



Disk shocking:
*** impulse approximation during crossing**
*** adiabatic invariance correction**
=> the dominant effect

$$\frac{\mathrm{d}v_z}{\mathrm{d}t} = g_{\rm d}(R,z_{\rm p}) - g_{\rm d}(R,z_{\rm c}) \simeq \Delta z\,\frac{\partial g_{\rm d}}{\partial z}(z_{\rm c})\;,$$

$$\Delta v_z = \int \mathrm{d}t\,\Delta z(t)\,\frac{\partial g_{\rm d}}{\partial z}\left[z_{\rm c}(t)\right]$$

$$\epsilon_k(z) \equiv \frac{2\,g^2_{z,\rm disk}(z=0)\,z^2}{V_z^2}A(\eta)$$

Associated tidal radius

Differential definition (default)

$$r_{t,i} \text{ such that } \langle\epsilon_k\rangle(r_{t,i}) = -\tilde{\phi}(r_{t,i}, r_{t,i-1})$$

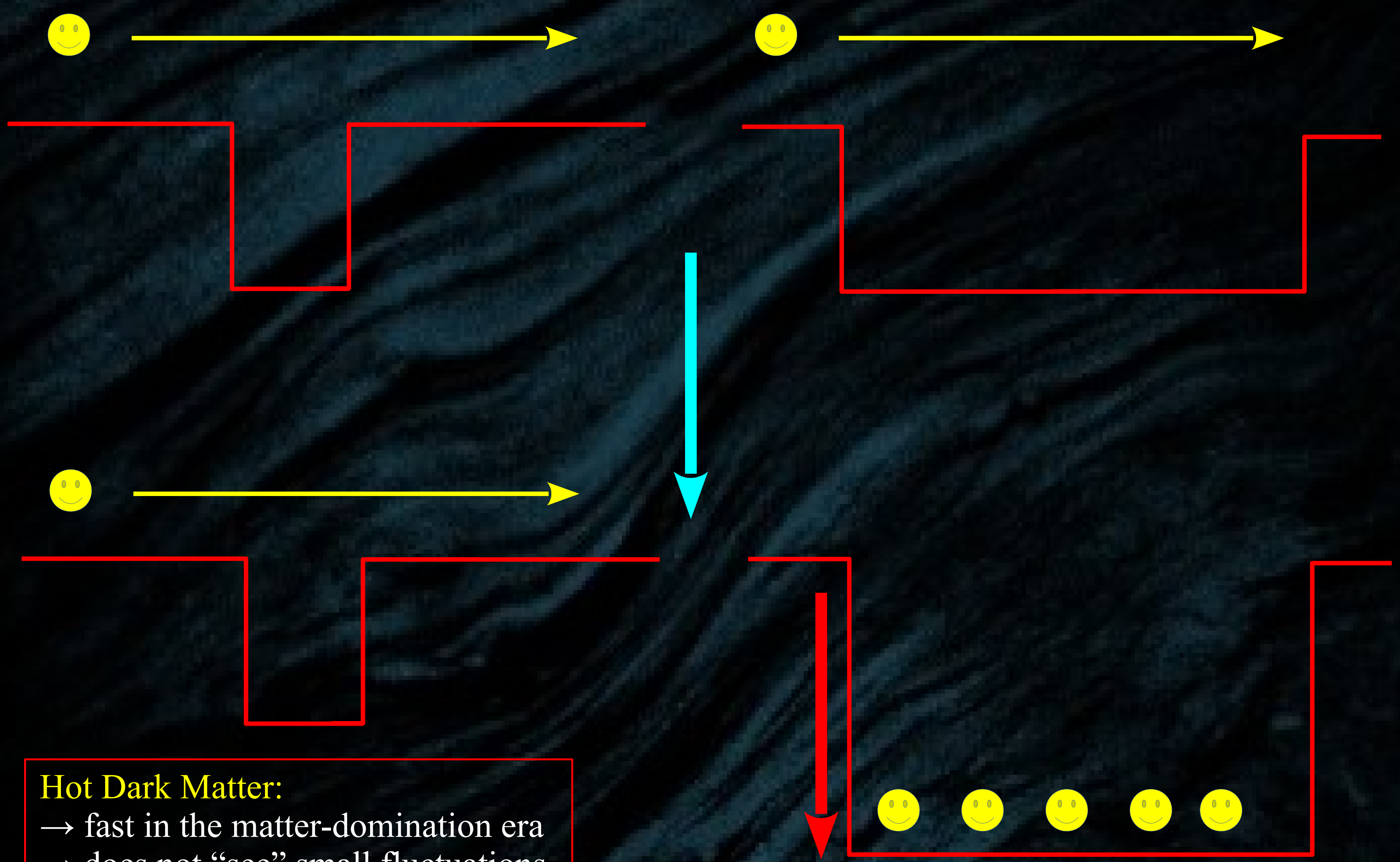
Integrated definition

$$r_t \text{ such that } N_{\rm cross}\,E_k(r_t,R) = E_b(r_t)$$

Fit from D'Onghia+10

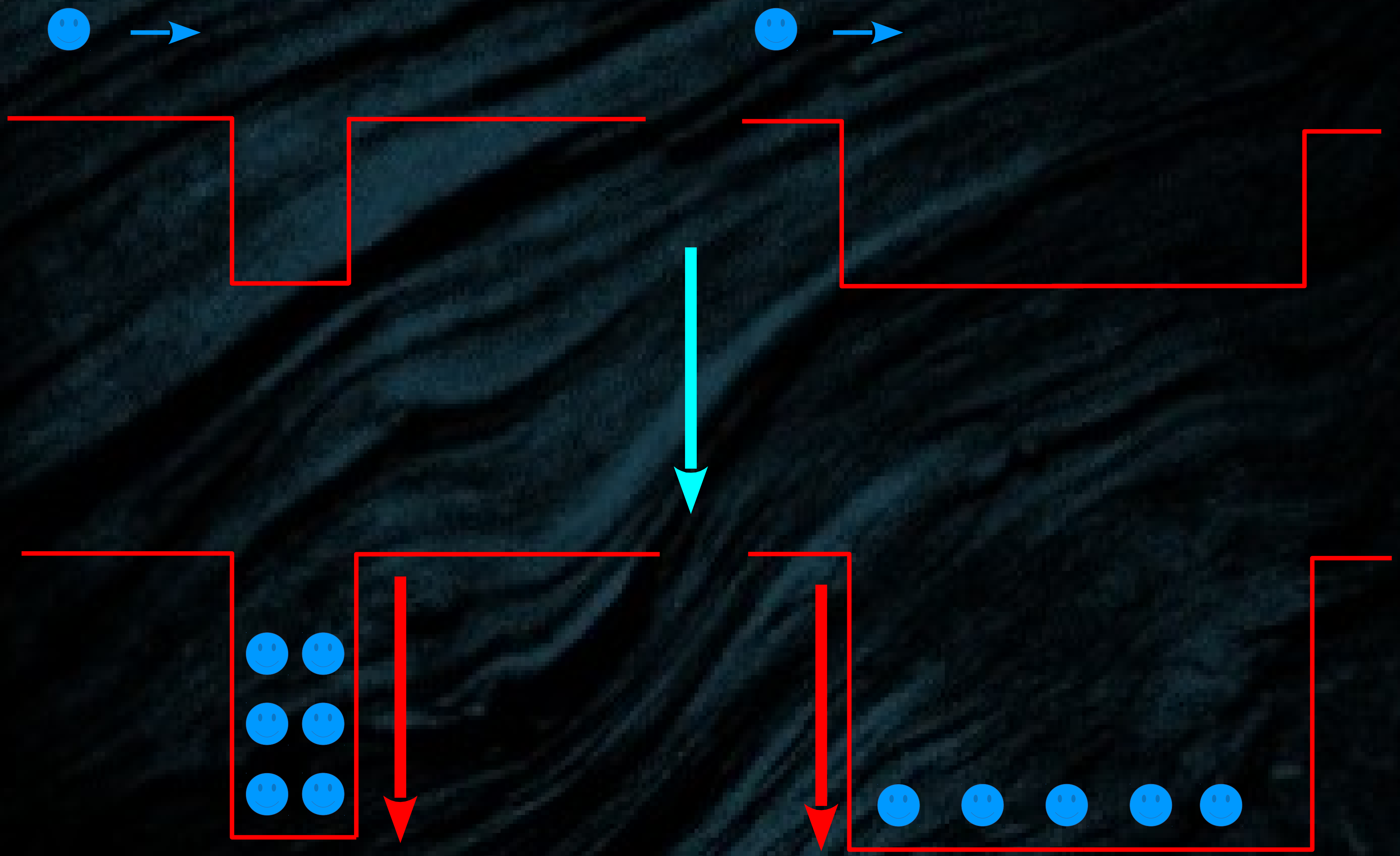
$$\frac{\tilde{E}_k(r_t,R)}{E_b(r_t)} = \frac{(1.84\,r_{1/2})^2\,g^2_{z,\rm disk}}{3\,\tilde{\sigma}_v^2\,V_z^2}$$

The coldness of Dark Matter



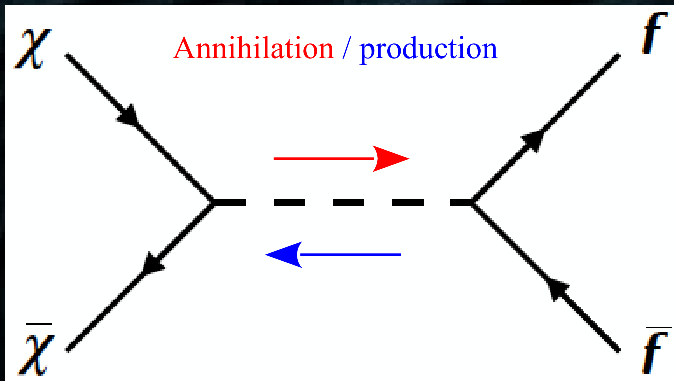
Hot Dark Matter:
→ fast in the matter-domination era
→ does not “see” small fluctuations
→ falls only in big ones
=> Big structures form first

The coldness of Dark Matter



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

Searches for thermal dark matter

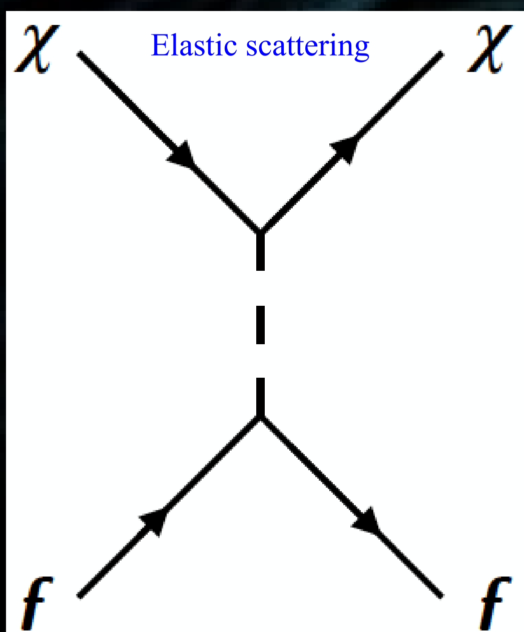


$$\Gamma_{\rm ann} = n_\chi \langle \sigma_{\rm ann} v \rangle$$

* Production at colliders (model dependent)
=> collider searches

* Annihilation/decay rate potentially large in dense DM regions: centers of halos + CMB
=> indirect searches

* Beware velocity dependence
(scalar exchange between fermions v-suppressed; pseudo-scalar exchange is not)



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

* elastic or inelastic scattering
→ nuclear recoils at underground experiments
=> direct searches

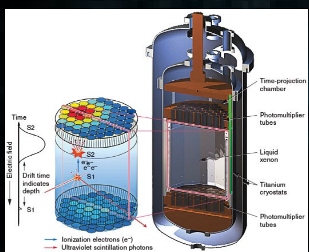
→ scattering with astrophysical objects
=> stellar physics
=> neutrinos from capture+annihilation in stars
=> indirect searches

* Beware velocity dependence
(pseudo-scalar exchange v-suppressed;
scalar exchange is not)

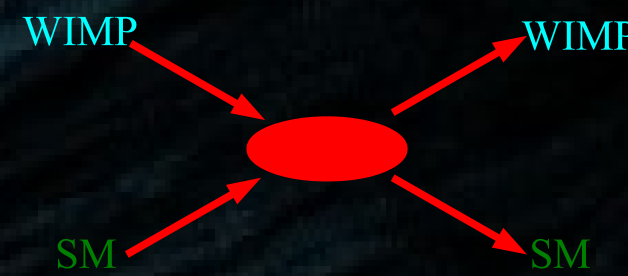
Astro/particle complementarity

Direct detection rate – WIMP-matter scattering

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



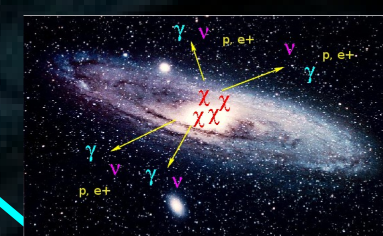
Scattering
(→ kinetic decoupling in early universe + subhalo mass cutoff)



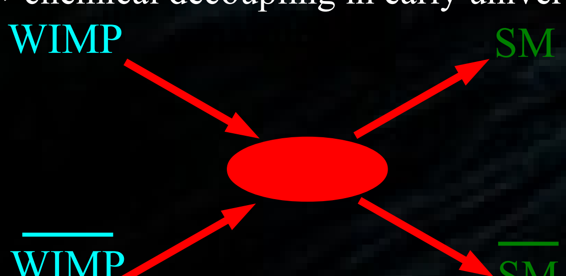
$$\Gamma_{\mathrm{scat}} = \langle \sigma_{\mathrm{scat}}\, v\rangle\, n_{\mathrm{plasma}}$$

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)



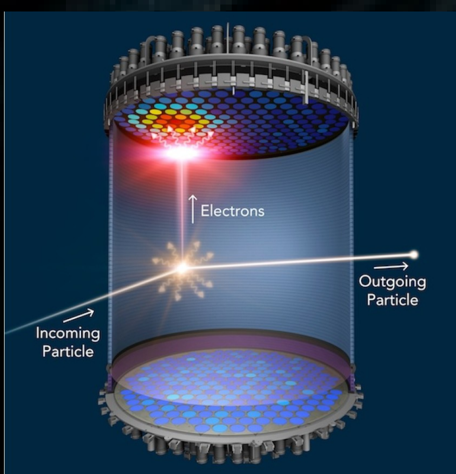
$$\Gamma_{\mathrm{ann}} = \langle \sigma_{\mathrm{ann}}\, v\rangle\, n_\chi$$

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

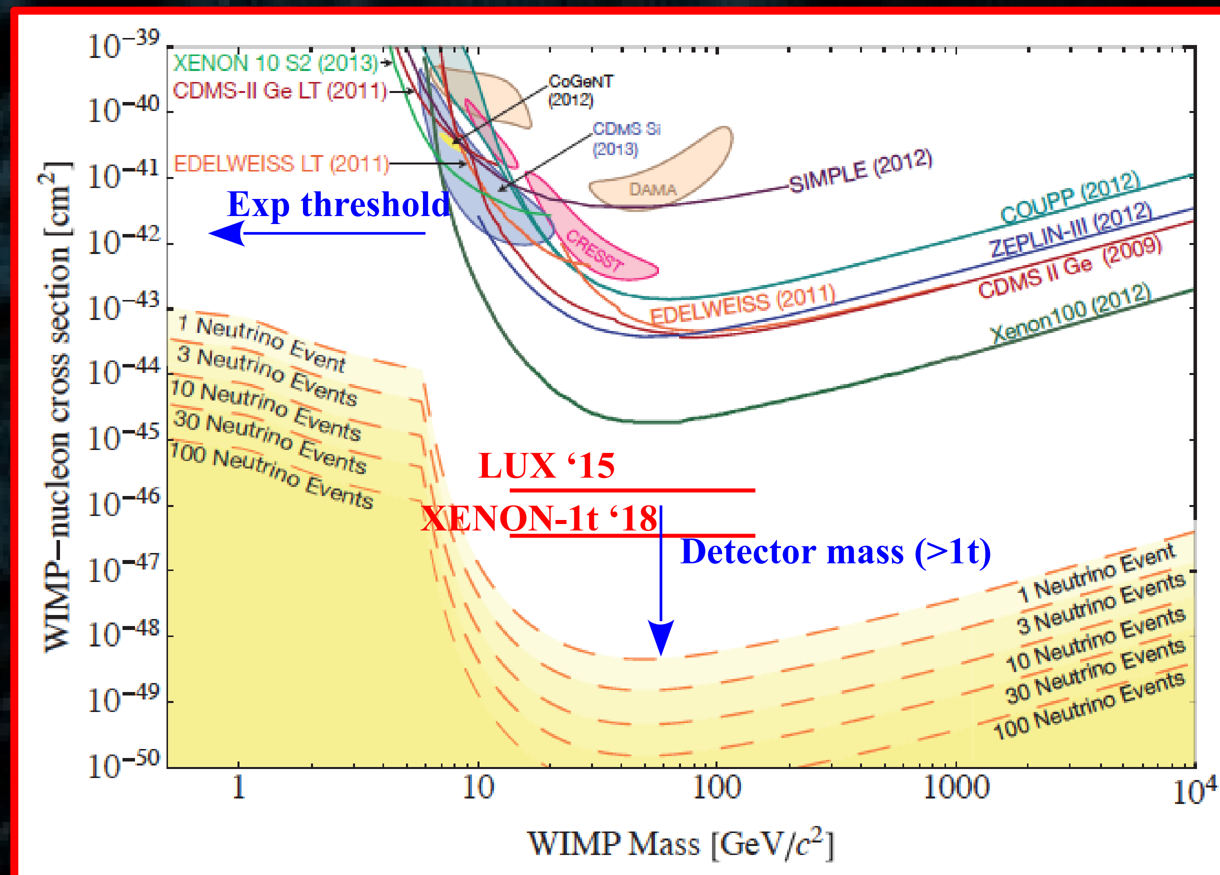
$$\frac{d\phi_\gamma^{\mathrm{ann.}}}{dE} = \frac{\delta\,\langle\sigma v\rangle}{4\,\pi}\,\frac{dN_\gamma}{dE}\int_{\mathrm{res.}} d\Omega\int_{\mathrm{l.o.s}} dl\left[\frac{\rho(r)}{m_\chi}\right]^2$$

Direct WIMP searches

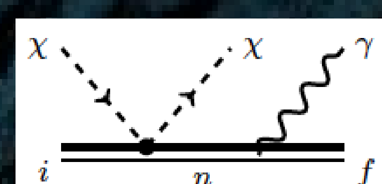
XENON-1t results:
=> the sub-zepto-barn era!



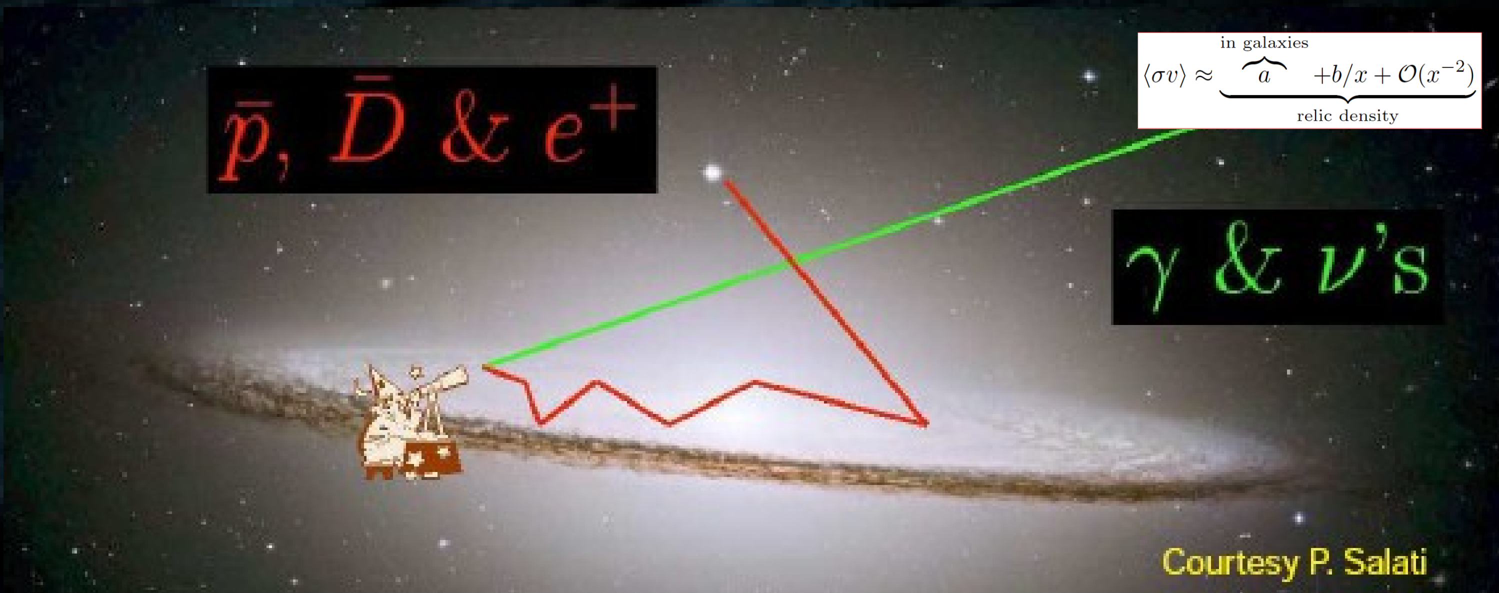
Billard+ 13



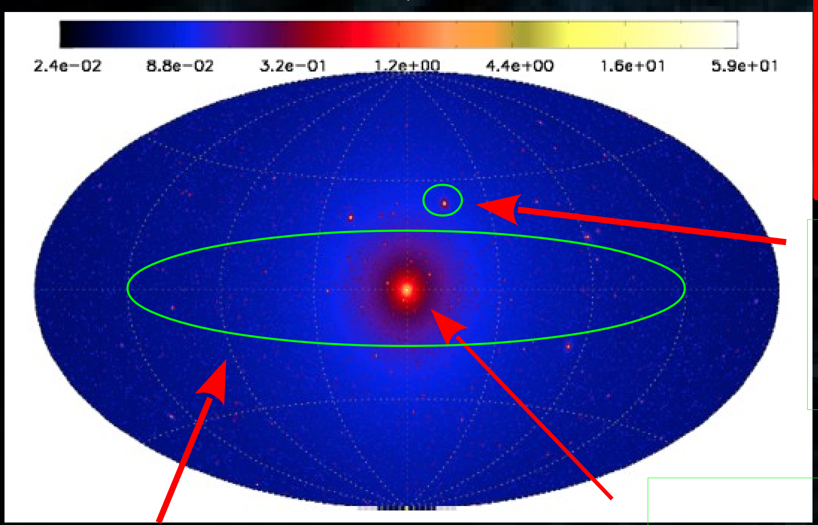
Also sensitive at lower energy:
* electronic recoils (e.g. Essig+12)
* Bremsstralhung (e.g. Pradler & Kouvaris 17)



Up to the skies!



Pieri, JL+ '11



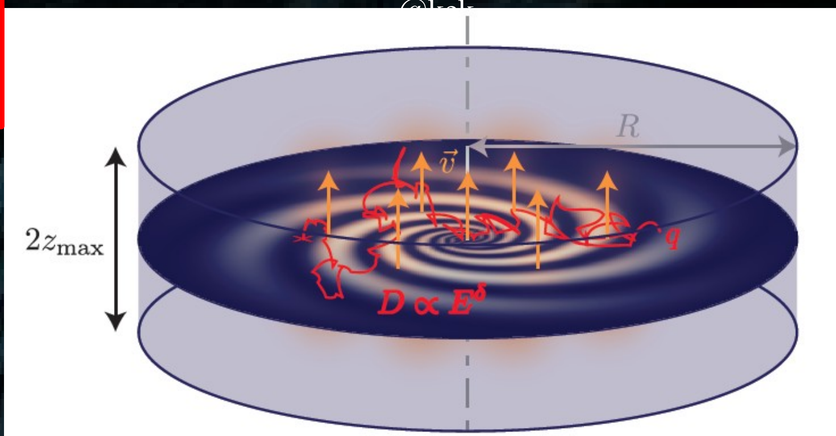
Requirements (and/or):
*** clean signal**
(spectral lines or features)
*** large signal/noise ratio**
=> Control astrophysical backgrounds

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

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

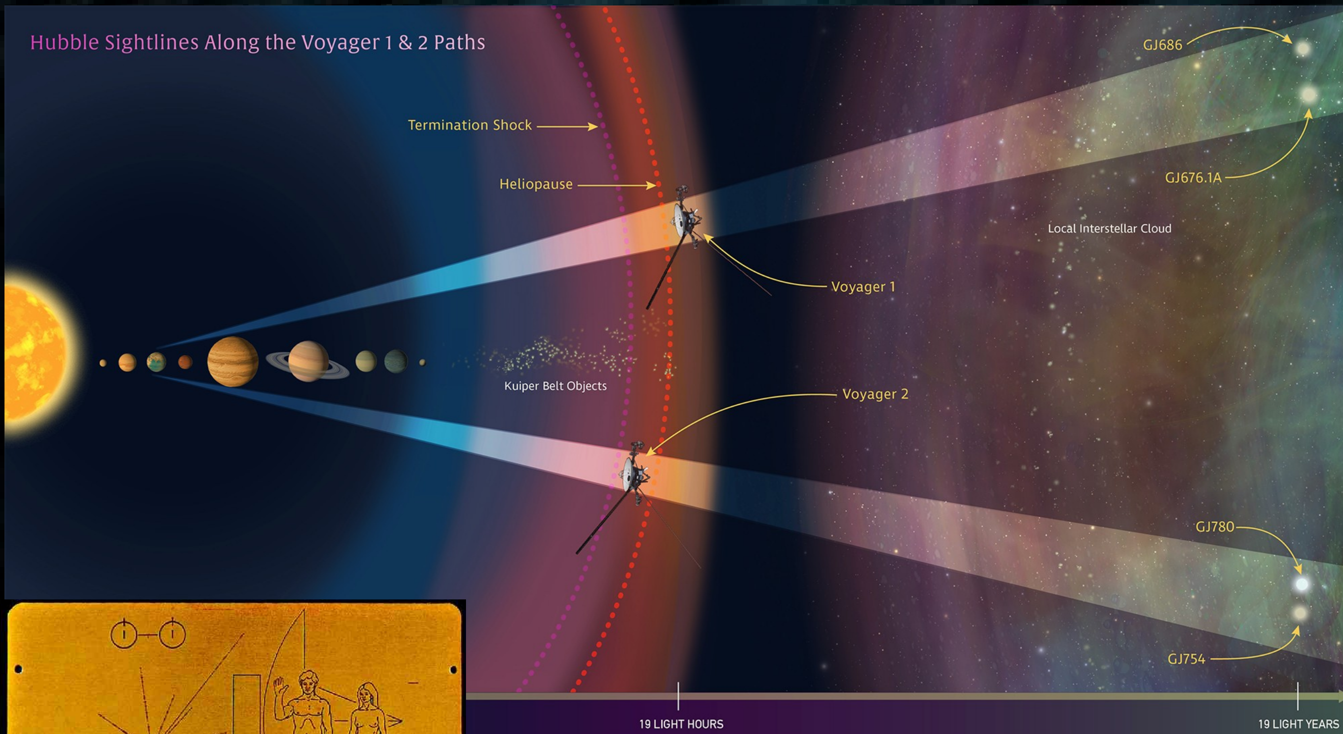
Diffuse gamma-ray emission
=> check spectral/spatial properties wrt background

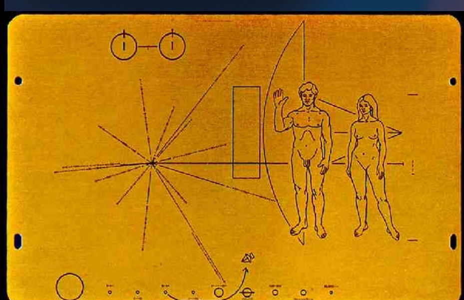
Cosmic-ray transport



Mertsch PhD thesis '10

Down to MeV DM with cosmic rays + p-wave

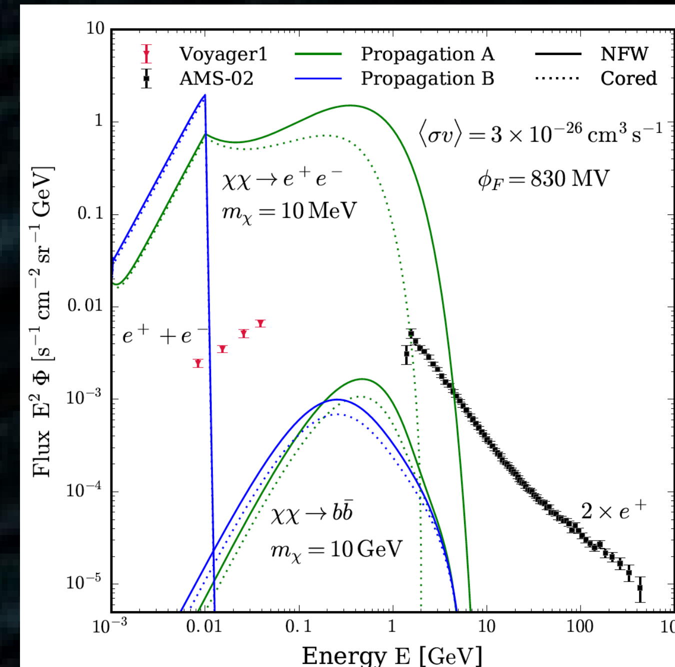


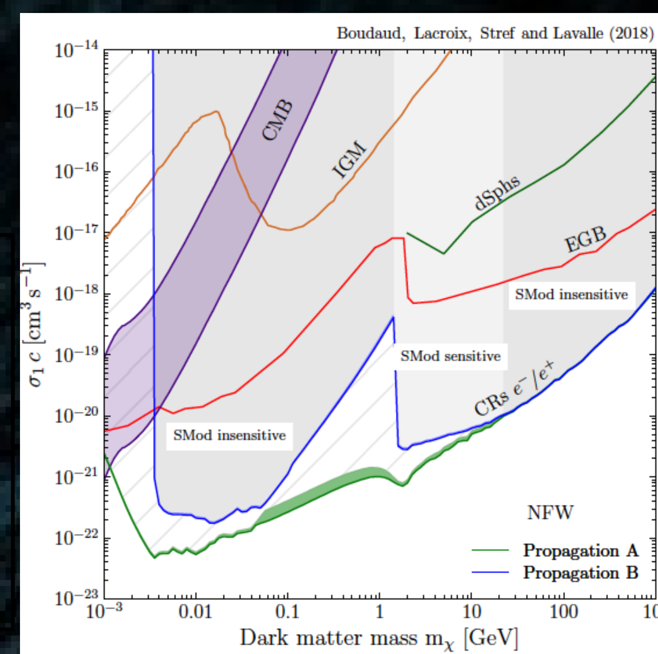


Voyager 1 has passed the heliopause in 2012!
=> cosmic rays no longer shielded by solar magnetic fields
=> use MeV e+e- data on tape + AMS-02 beyond

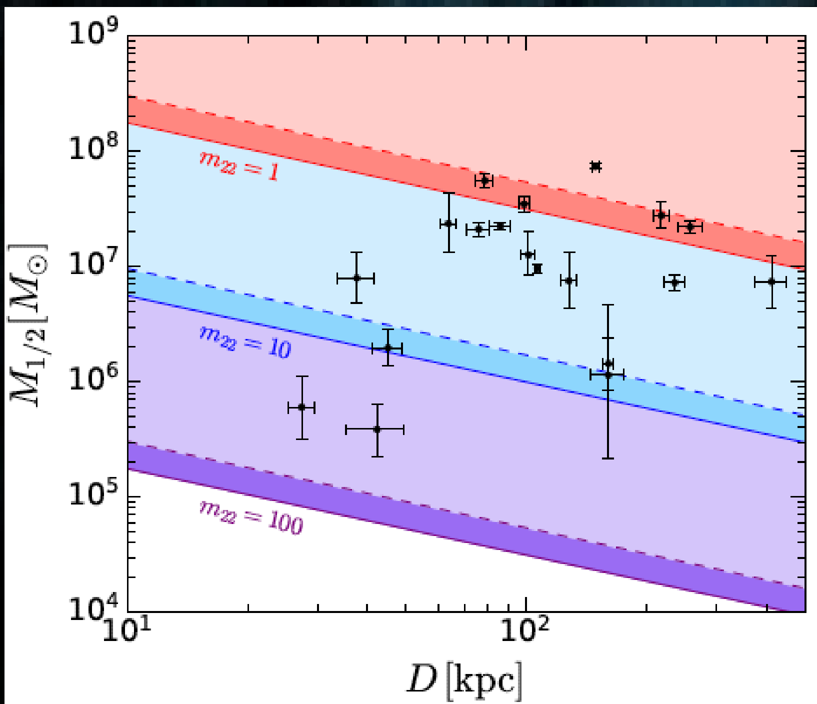
=> Constraints on annihilating MeV dark matter as stringent as those obtained with CMB.

Boudaud+17-18.

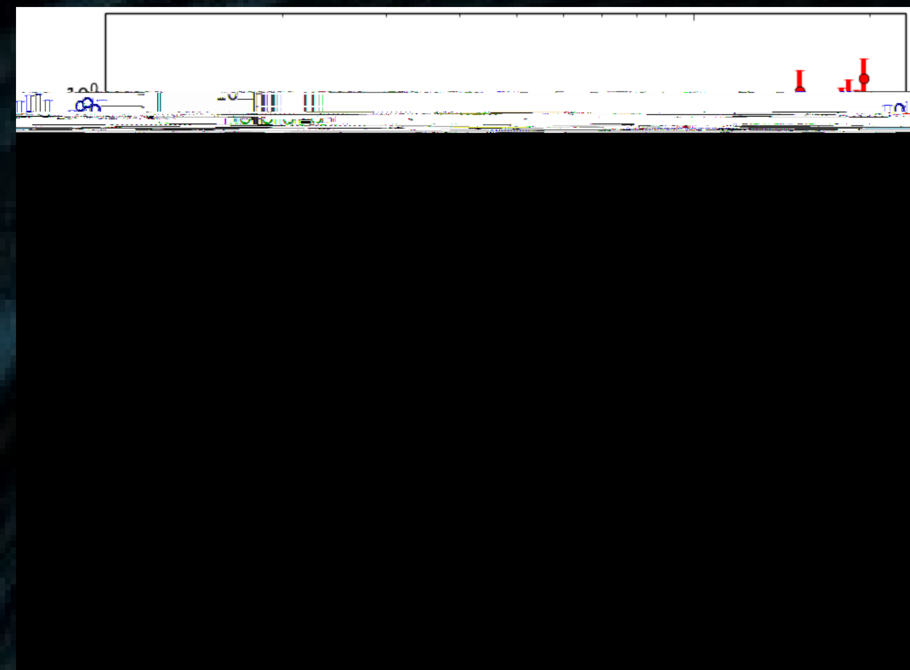




ULA probes



Du+18
Tidal disruption of subhalo solitonic cores

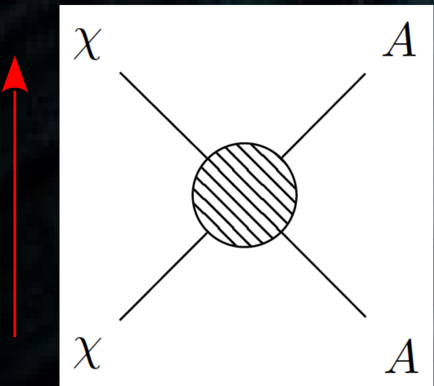


Armengaud+'17 (Ly-alpha from SDSS DR9)

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

e.g. Goodmann & Witten '84, Drukier+ '85

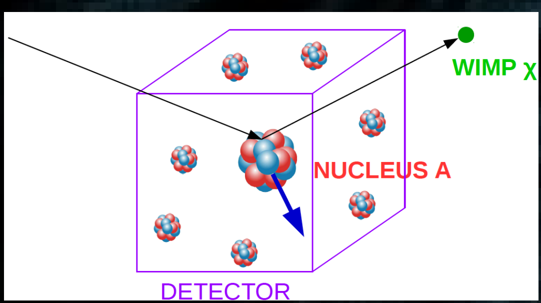
Only terms not velocity suppressed (v ~ 0.001 c in MW halo)



$$\mathcal{L}_{\rm int} \supset \begin{cases} \sum_{\rm quarks} \left\{ \underbrace{\alpha_{\rm v}\, \bar\chi\, \gamma_\mu\, \chi \bar q\, \gamma^\mu\, q}_{\text{Dirac WIMPs}} + \alpha_{\rm scal.}\, \bar\chi\, \chi \bar q\, q \right\} \\ \sum_{\rm quarks} \{\alpha_{\rm a}\, \bar\chi\, \gamma_\mu\, \gamma_5\, \chi\, \bar q\, \gamma^\mu\, \gamma_5\, q\} \end{cases}$$

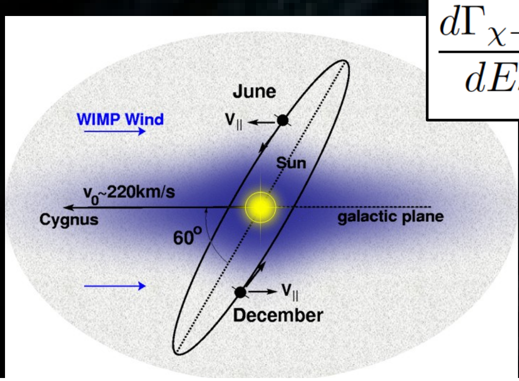
$$f_n \propto \langle n | \sum_{\rm quarks} \alpha_q \frac{m_q}{m_n} \bar q q | n \rangle$$

Quark mass content of nucleons:
Lattice QCD calculations
(ongoing)



$$\sigma_{\chi-{\rm N}} \propto \begin{cases} (Z\, f_p + (A-Z)\, f_n)^2 \approx A^2\, f_p^2 \quad \text{(spin-independent)} \\ (a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2 \quad \text{(spin-dependent)} \end{cases}$$

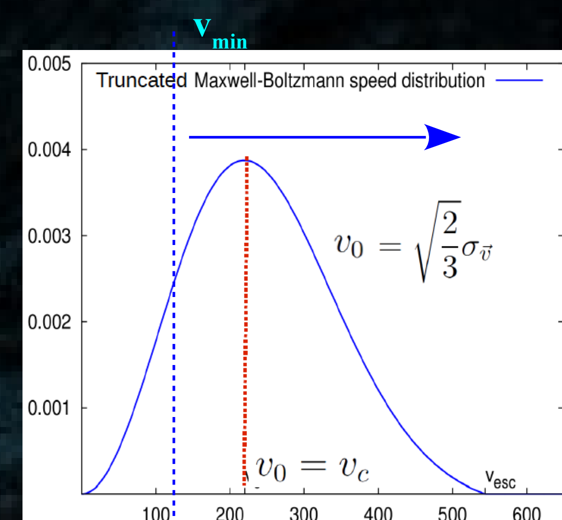
$$\frac{d\Gamma_{\chi-{\rm N}}}{dE_r}(E_r, t) = \frac{\sigma_{\chi-{\rm N}}\, F^2(E_r)}{2\, \mu_r^2} \frac{\rho_\odot}{m_\chi} \int_{v>v_{\rm min}} d^3\vec{v}\, \frac{f(\vec{v}, t)}{v}$$



$$\vec{v}_{\rm obs} = \vec{v}_{\rm halo} - \{\vec{v}_\oplus(t) \equiv \vec{v}_\odot + \vec{v}_{\oplus/\odot}(t)\}$$

Astro uncertainties:
*** local WIMP phase space**
*** local DM density**

$$v_{\rm min}(E_r) = \sqrt{\frac{m_N\, E_r}{2\, \mu}}$$



Initial statistical/cosmological properties

The initial mass function
(linear + ~non-linear)

From primordial spectrum to mass function (ext. Press-Schechter)

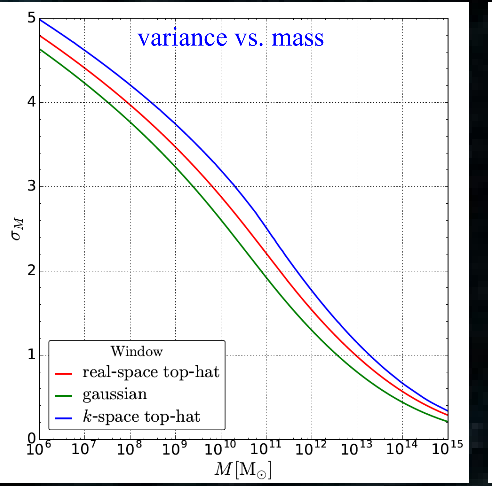
$$P(k,t) = D_+^2(t)\ \{P(k) \equiv A_0\, T^2(k)\, P_{\rm prim}(k)\}$$

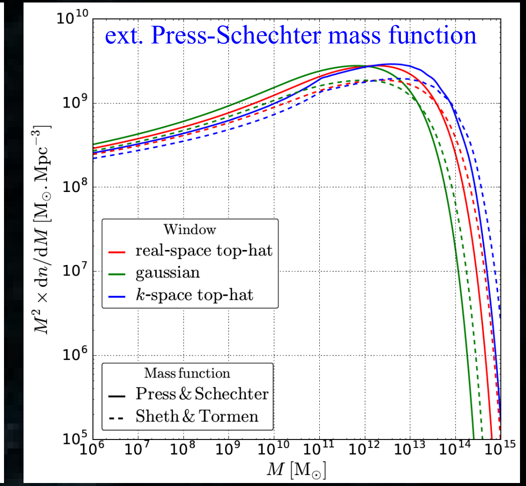
$$\sigma^2(R) \equiv \varepsilon_R(|\vec{r}| \to 0) = \int d\ln k\, \Delta^2(k)\, |\tilde{W}(k,R)|^2$$

$$\frac{dn}{dM} = \left\{V_M^{-1} \equiv \frac{\rho_M}{M}\right\} \left|\frac{dF(\delta > \delta_c)}{dM}\right| = \frac{\rho_M}{M^2} \left|\frac{d\ln\sigma}{d\ln M}\right| \nu\, f(\nu)$$

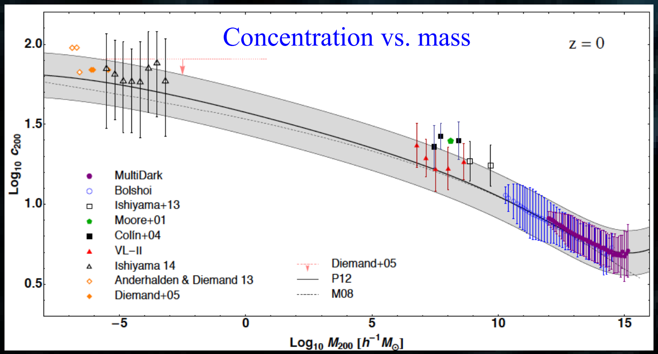
$$\frac{d\mathcal{P}(m_{200})}{dm_{200}} \tilde{\propto}\ m_{200}^{-\alpha_m} \left\{1 - e^{-\left[\frac{m_{200}}{m_{\rm cut}}\right]^n}\right\}$$

Typically a power law with a cutoff (minimal) mass.

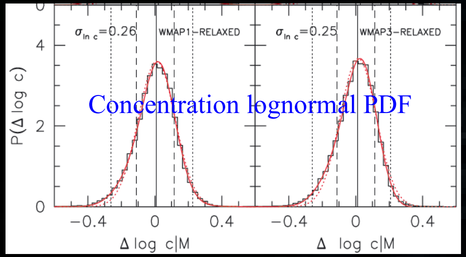




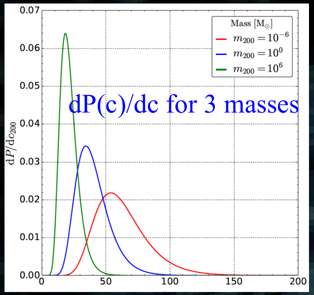
Stref, PhD th. '18



Sanchez-Conde+13



Maccio+08



Stref, PhD th. '18

Concentration function

Traces the density at collapse time.
Modeling based on 2-parameter fit
(Bullock+01, Maccio+08, Prada+12, Dutton+14, etc.)

$$m_{200}(z) = G_z\, m_*(z_c) \qquad \sigma(m_*(z_c)) = \sigma_c^0\, D_+(z)$$

$$\bar{c}_{200}(m_{200}, z) = K_{200} \left[\frac{\rho_c(z_c)}{\rho_c(z)}\right]^{1/3}$$

Fitting formula from Sanchez-Conde+13 + lognormal DF

$$\frac{d\mathcal{P}_c}{dc}(c,m) = \frac{1}{K_c} \frac{\exp\left\{-\frac{(c-\bar{c}(m))^2}{2\,\sigma_c^2}\right\}}{c\,\sqrt{2\,\pi\,\sigma_c^2}}$$