Q&A session, 6 May 2016
Dark Matter in the Milky Way
MITP, 2-13 May 2016

1. Which upcoming direct detection experiments are going to be most interesting to constrain dark matter? How do you select the ideal target nuclei for direct detection and how does this choice limit the type of dark matter particle you are able to detect?

   Speaker: Riccardo Catena

2. What is and how do you use abundance matching?

   Speaker: Chris Brook

3. What is the difference between a Dirac and a Majorana mass term, and how do they fit together with the Higgs mechanism (or not as may be the case for Majorana particles)?

   Speaker: Filippo Sala

4. What is the missing baryon problem?

   Speaker: Kyle Oman

5. Which is the ideal target/object for indirect searches?

   Speakers: Fabio Iocco & Mattia Fornasa

6. Too big to fail problem and its relation with missing satellite and core/cusp problems.

   Speaker: Jose Oñorbe

7. In cosmological simulations, the mass of an individual gas or dark matter “particle” is millions of solar masses. Why can we expect that the actual dark matter particles in the universe have the same phase space distribution as such massive “particles” in the simulations?

   Speaker: Matthieu Schaller

1) How do you select the ideal target nuclei for direct detection search and how does this choice limit the type of DM particle you are able to detect?

2) Which upcoming direct detection experiments are going to be most interesting to constrain DM?

1) Ideal nuclei / impact on testable DM properties

2) most interesting DD exp.

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{|\vec{v}| \leq v_{min}} d^3\vec{v}\, v\, f(\vec{v}+\vec{v}_\oplus) \frac{d\sigma}{dE_R}$$

(b)

(a)

$$v_{min} = \frac{\sqrt{2 M_T E_R}}{2\mu_T^2}$$

target nucleus

a) $$\frac{d\sigma}{dE_R} = \frac{\sigma}{E_{max}} \quad ; \quad f(\vec{v}+\vec{v}_\oplus) \propto \exp\left(-\frac{|\vec{v}+\vec{v}_\oplus|^2}{v_0^2}\right)$$

$$\frac{dR}{dE_R} \propto \exp\left(\frac{-E_R}{E_0 r}\right) \quad ; \quad E_0 = \frac{1}{2} M_\chi v_0^2$$

$$r = \frac{4 M_\chi M_T}{(M_\chi + M_T)^2}$$

$$\ln \frac{dR}{dE_R} = c_1 - \frac{E_R}{E_0 r}$$

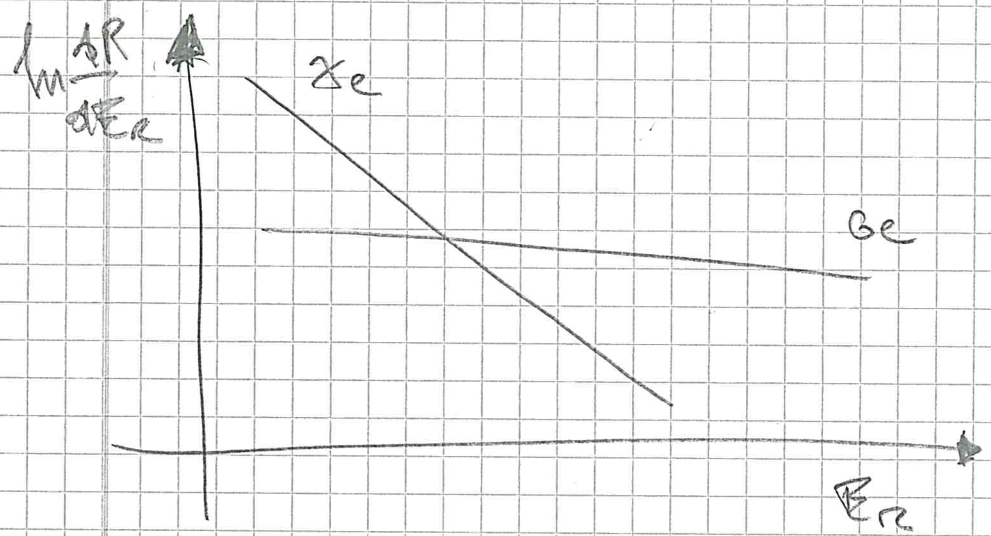
$$\alpha_i = \frac{1}{E_0 r_i}$$

$$\frac{\alpha_1}{\alpha_2} = \frac{r_2}{r_1} = \frac{(m_\chi + m_{T_1})^2}{(m_\chi + m_{T_2})^2} \cdot \frac{m_{T_2}}{m_{T_1}}$$

$$= \left(\frac{m_{T_1}}{m_{T_2}}\right)^2 \left(\frac{1 + \frac{m_\chi}{m_{T_1}}}{1 + \frac{m_\chi}{m_{T_2}}}\right)^2 \frac{m_{T_2}}{m_{T_1}}$$

$$\approx \frac{m_{T_1}}{m_{T_2}}$$

$$\boxed{\frac{\alpha_1}{\alpha_2} = \frac{m_{T_1}}{m_{T_2}}}$$



b)

$$\frac{d\sigma}{dE_R} \propto \sum_{\text{spins}} \left| \langle F | \sum_{i=1}^{A} \int d^3\vec{r}\, e^{-i\vec{q}\cdot\vec{r}}\, H_I(\vec{r})\, | I \rangle \right|^2$$

$\langle F|$, $|I\rangle$ → χ-nucleus states

$H_I(\vec{r})$ → Hamiltonian for dark matter nucleon interaction

→ $\vec{q}$, $\vec{v}^\perp$, $\vec{S}_\chi$, $\vec{S}_N$

(3)

1) $H_i(\vec{r}) = \sum_{\tau=0,1} c_1^\tau \mathbb{1}_{\chi N} t^\tau \delta^{(3)}(\vec{r}-\vec{r}_i)$ $\quad t^0 = \mathbb{1}$, $t^1 = \tau_3$

small q → $\langle F | \cdot | I \rangle \sim A$ ⇒ Use large mass number

2) $H_i(\vec{r}) = \sum_{\tau=0,1} c_4^\tau \vec{S}_\chi \cdot \vec{S}_N t^\tau \delta^{(3)}(\vec{r}-\vec{r}_i)$

small q → $\langle F | \cdot | I \rangle \sim \langle J, T | \vec{S}_N | J, T \rangle$

↳ nucleon spin content of the nucleus

⇒ Use nuclei with unpaired nucleons
→ ^{19}F, ^{23}Na unpaired proton
→ ^{73}Ge, ^{131}Xe unpaired neutron

3) $\langle F | \cdot | I \rangle \sim \langle J, T | \vec{L}_N | J, T \rangle$

⇒ Use nuclei with unpaired nucleons in nuclear shells with $l \neq 0$

↳ not the case for ^{19}F

4) $\langle F | \cdot | I \rangle \sim \langle J, T | \vec{L}_N \cdot \vec{S}_N | J, T \rangle$

⇒ Use nuclei with non fully occupied shells with $j = l \pm 1/2$

↳ heavy nuclei

Good detectors:

1) signal / background discrimination

2) low threshold

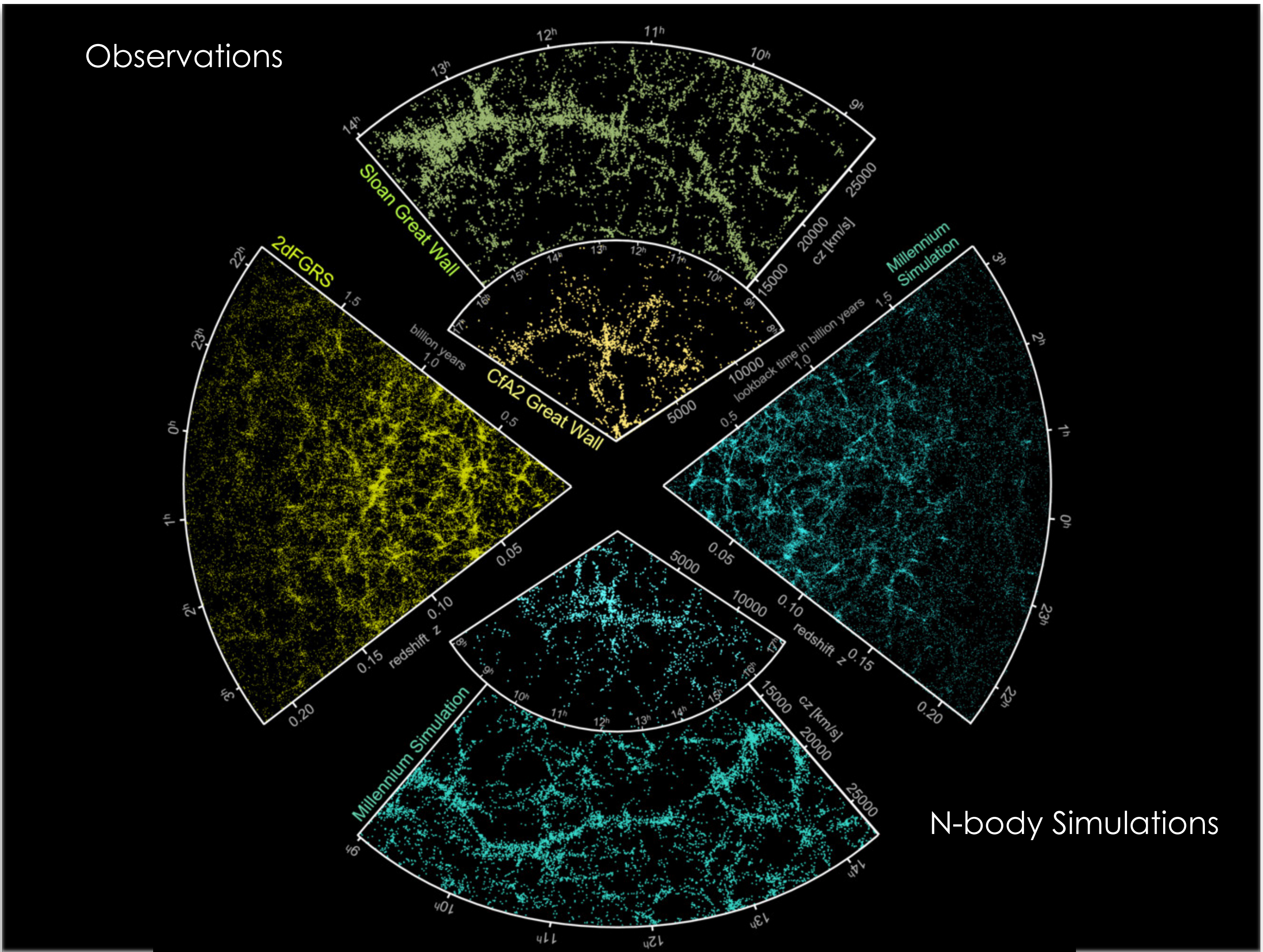
3) large N_T

Good nuclear properties + good detector

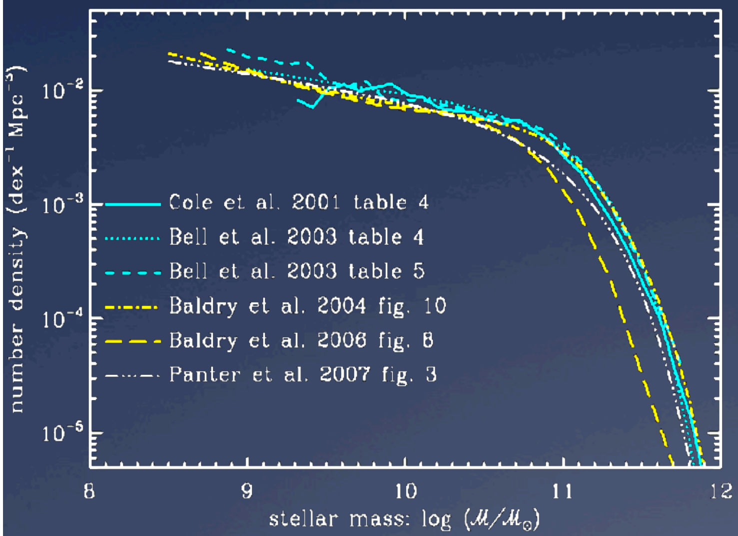
1) Xe $m_\chi \gtrsim 5$ GeV SI

2) Ge $1\,\text{GeV} \lesssim m_\chi \lesssim 5$ GeV SI

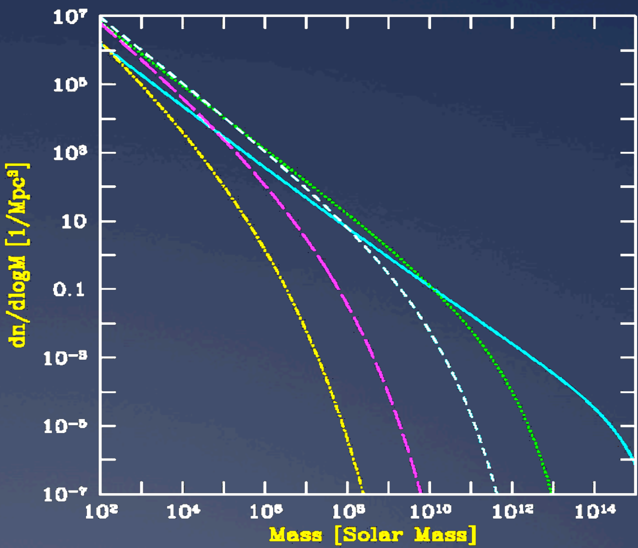
3) F $m_\chi \gtrsim 5$ GeV SD (p)


Observations
Sloan Great Wall
CfA2 Great Wall
2dFGRS
Millennium Simulation
Millennium Simulation
N-body Simulations
billion years
lookback time in billion years
redshift z
redshift z
cz [km/s]
cz [km/s]

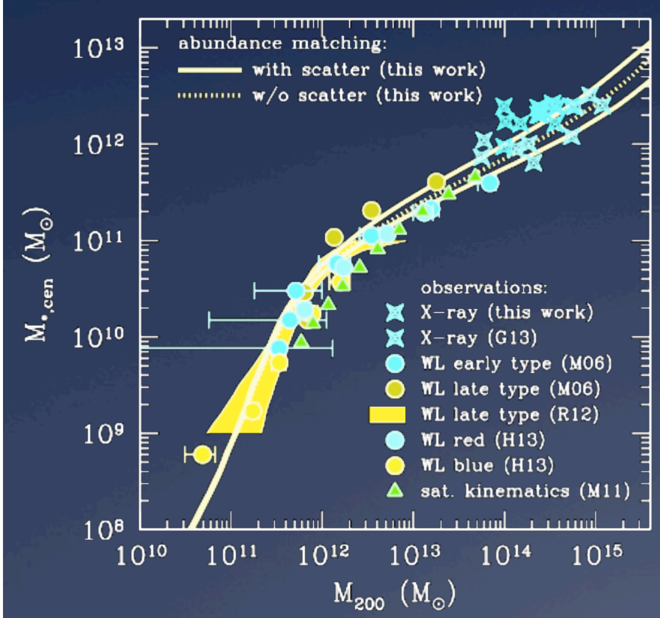
Stellar Mass Function
observed

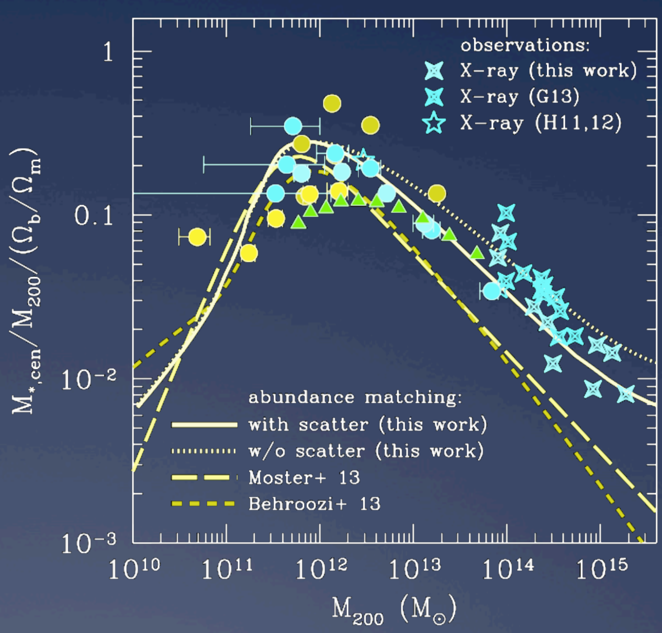


Halo Mass Function
from simulations

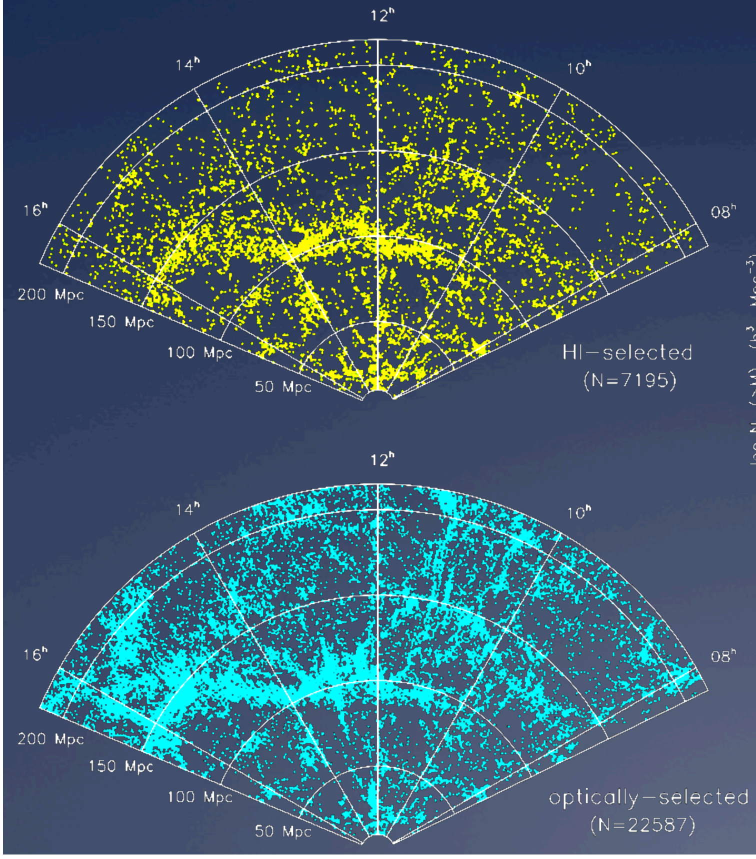


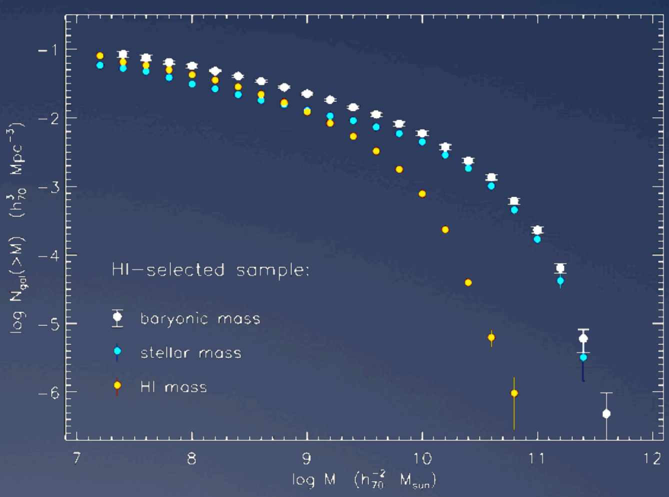
Abundance matching
Halo mass-stellar mass





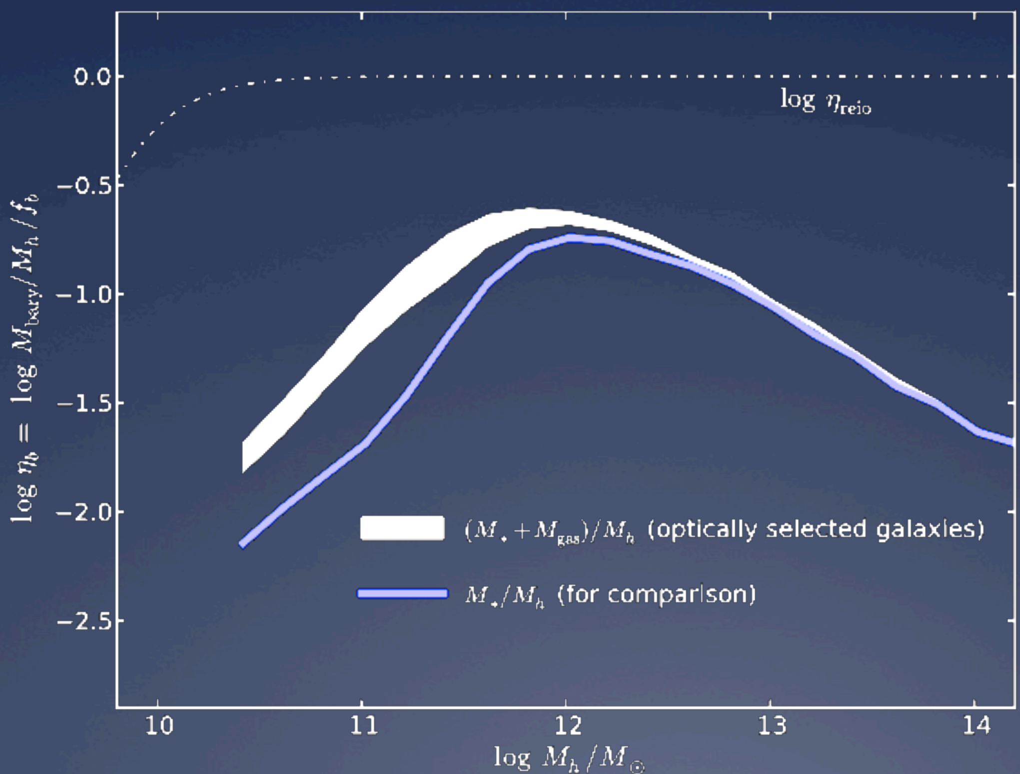
Abundance matching
Halo mass-baryon mass (stars+HI)





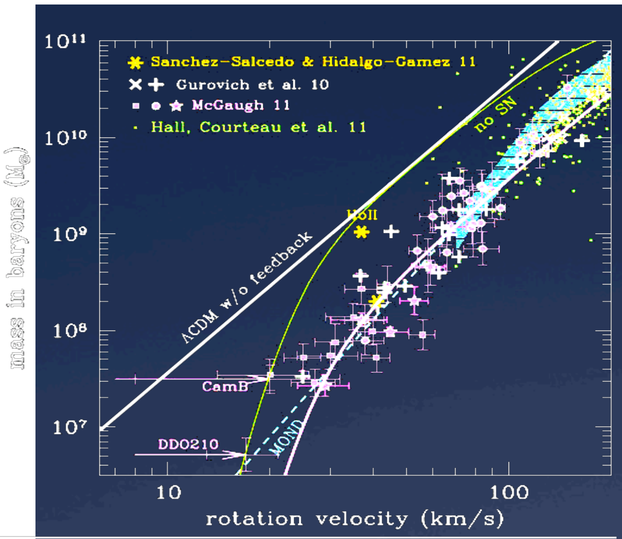
Papastergis et al. 2012

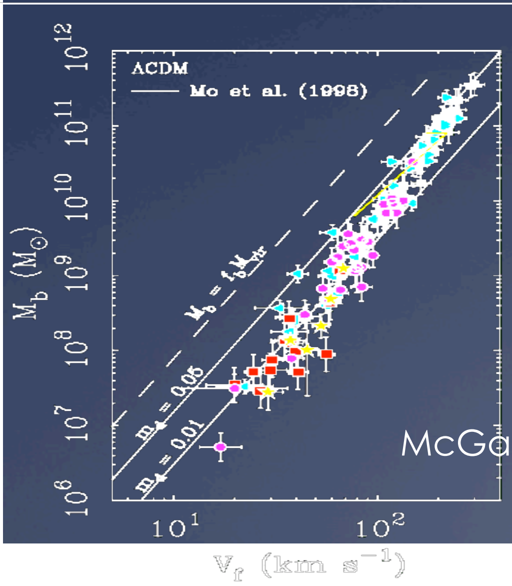
Abundance matching
Halo mass-baryon mass (stars+HI)



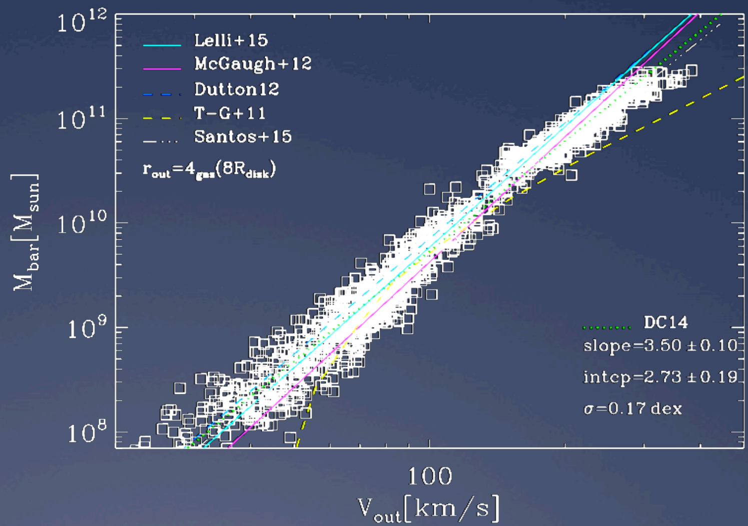
Papastergis et al. 2012

Baryonic Tully Fisher in LCDM

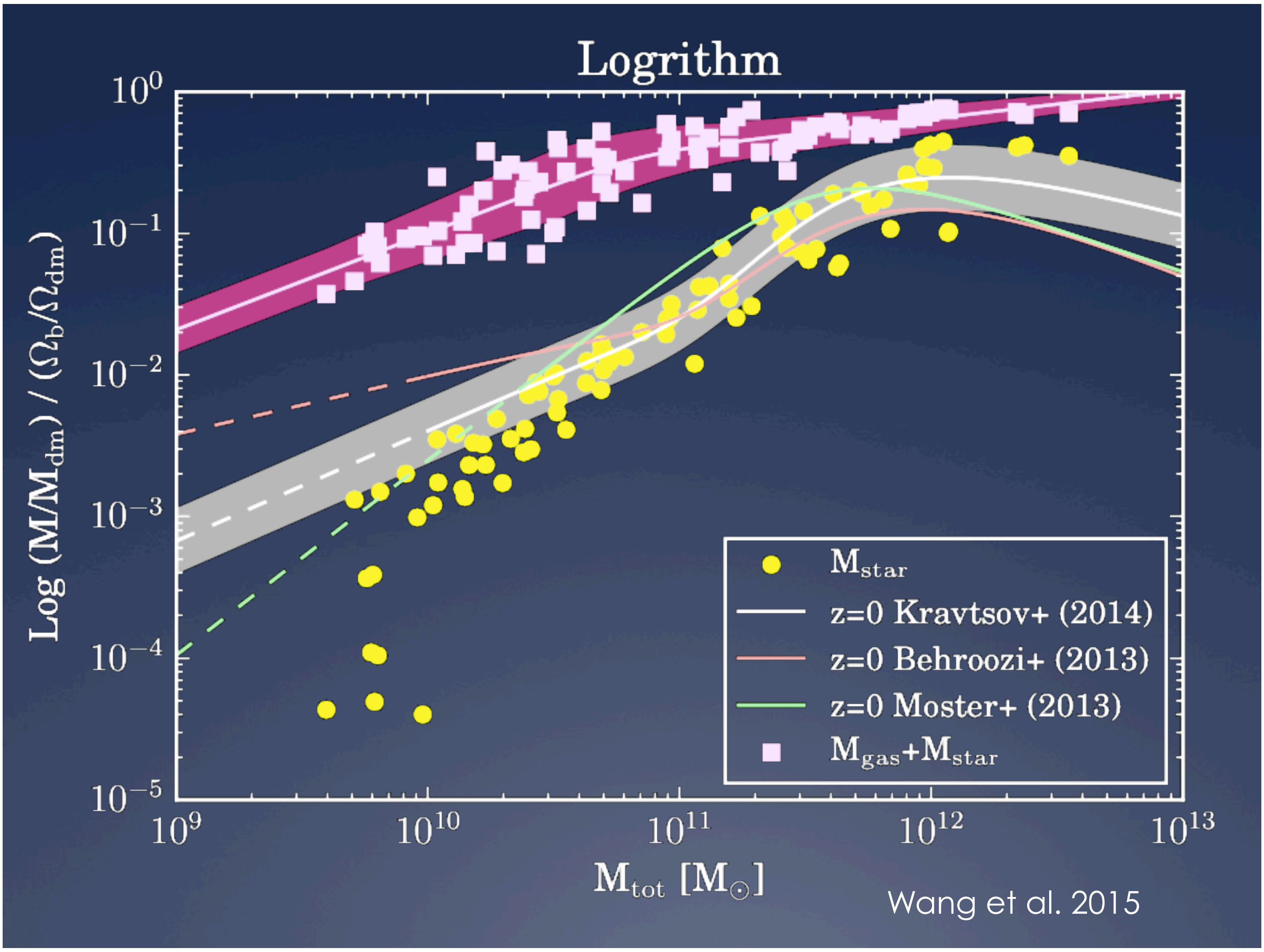




McGaugh et al. 2012



Di Cintio & Lelli 2016
See also Dutton 2012


Logrithm
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Log (M/M$_{dm}$) / (Ω_b/Ω_{dm})
10^9
10^{10}
10^{11}
10^{12}
10^{13}
M_{tot} [$M_\odot$]
M_{star}
z=0 Kravtsov+ (2014)
z=0 Behroozi+ (2013)
z=0 Moster+ (2013)
M_{gas}+M_{star}
Wang et al. 2015

FILIPPO SALA

(6 May 2016)

see e.g. S. Martin hep-ph/9709356v6, sect. 2

Type of fermions

	# of degrees of freedom	Particle = antiparticle?
Weyl	2	NO
Majorana	2	YES
Dirac	4	NO

(1 degree of freedom = 1 real scalar)

Weyl are fermions you use to build theories, like Standard Model in the sense that you assign quantum numbers to (left) Weyl fermions

Example $l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = 2_{-\frac{1}{2}}$, $e_R^+ = 1_1$

[left Weyl, e_R = right Weyl]

$SU(2)_L$ ↑ hypercharge ↑

Notation: Weyl fermion $= \xi, \chi^+$, each with 2 d.o.f.

$\Psi_M = \begin{pmatrix} \xi_\alpha \\ \xi^{+\dot\alpha} \end{pmatrix}$ $\quad \mathcal{L}_M = \frac{i}{2}\overline{\Psi}_M(\partial_\mu \gamma^\mu - M)\Psi_M = i\xi^+\bar\sigma^\mu\partial_\mu\xi - \frac{1}{2}M(\xi\xi + \xi^+\xi^+)$

Majorana mass

$\Psi_D = \begin{pmatrix} \xi_\alpha \\ \chi^{+\dot\alpha} \end{pmatrix}$ $\quad \mathcal{L}_D = i\overline{\Psi}_D(\partial_\mu\gamma^\mu - M)\Psi_D$

$= i\xi^+\bar\sigma^\mu\partial_\mu\xi + i\chi^+\bar\sigma^\mu\partial_\mu\chi - M(\xi\chi + \xi^+\chi^+)$

Dirac Mass

$P_L\Psi_D = \begin{pmatrix} \xi_\alpha \\ 0 \end{pmatrix}$

$P_R\Psi_D = \begin{pmatrix} 0 \\ \chi^{+\dot\alpha} \end{pmatrix}$

(α vs $\dot\alpha$ just as bookkeeping of L vs R; $\xi\xi$ understands $\xi_\alpha\xi^\alpha = \xi_\alpha\varepsilon^{\alpha\beta}\xi_\beta$)

EXAMPLE: electron mass

$e = \begin{pmatrix} e_L \\ e_R^* \end{pmatrix}$ $\quad \mathcal{L} \supset y_e\, l_L\, e_R^+\, H^+ + h.c. \rightsquigarrow y_e(e_L\, e_R^+ + \ldots)v = m_e\bar{e}e$

contract SU(2) indices; Higgs boson; $e_L \sim \xi$, $e_R^+ \sim \chi$; $m_e\bar{e}e$ = Dirac electron mass

NB $e_R \sim \chi^+$

What is the "missing baryons problem"?

- We know the cosmic baryon abundance Ω_b from CMB measurements, and how it scales with the expansion of the universe, so we know $\rho_b(t)$.

- At $z \sim 2$ the baryon density can be measured/estimated using the absorption spectrum of quasars, the "Lyα forest", and seems consistent with the CMB value.

- At $z \sim 0$ the baryon density is very difficult to measure as most baryons are thought to be in either the circumgalactic media (CGM) of galaxies or the warm-hot intergalactic medium (WHIM) at $T \sim 10^5 - 10^7$ K. This implies highly ionized species with spectral features in the far UV or soft X-ray. Observations must therefore be done in space, but telescopes are small, have poor spectral resolution (features are sharp → difficult to get good S/N) and features are faint/weak, which together implies impractical exposure times to achieve a detection.

- We have a good idea of where the baryons are at $z=0$, but they are as yet (partially) unobserved, and therefore "missing".

Mainz Institute for Theoretical Physics
Tobias Jacco

Best target objects for indirect DM detection

... Well it depends!

Principle of indirect DM searches is

$$d\phi^{OBSERVED} = d\phi^{ASTRO} + d\phi^{DM}$$

channel (γ, νs, $p\bar{p}$, $l\bar{l}$, ...)

$d\phi^{DM}$ → our target!

$$\phi_{DM} \propto \left(\frac{\sigma v}{m^2}\right) \int_{los} \rho^2_{DM}(r)\, dV$$

$\left(\frac{\sigma v}{m^2}\right)$ → our goal

$\int_{los} \rho^2_{DM}(r)\, dV$ → depends on Astro where obs.

⇓

$$\sigma\phi^{OBS} - \sigma\phi^{ASTRO} \le \phi^{DM}$$

σ → uncert.

⇓

Choice of Channel + Locus ...
(Astro where observed)

Mainz Institute for Theoretical Physics

Fabio Iocco

ch ϕ^{ASTRO}_{Locus} vs ch ϕ^{DM}_{Locus}

Know your "background" (or astrophysically interesting signal)

Which channel? (less "polluted")

$$\frac{\langle \sigma v \rangle}{m^2} \int_{los} \rho^2_{DM}(r)\, dV$$

Maximise ρ_{DM} but Minimise uncertainties (NFW, Einasto, core, AC?) etc etc

Choice of locus + channel

feedback

Uncertainty on ρ_{DM} can be crucial, too

Mainz Institute for Theoretical Physics — Fabio Iocco

My take on Pros and cons (focusing on γs)

↳ more later on why?

-) Galaxy Clusters

relatively few objects, for axay (foreground contamination?)

Potential high ϕ^{ASTRO} contamination

(Cosm. Rays Propagation inside Cluster)

Never seen a γ from there (yet!)

but if ....

Not my favorite candidate.

-) Dwarf Galaxies

ϕ^{ASTRO}

No γ rays expected!! (small ϕ^{ASTRO} yuhuh!!)

Many objects!

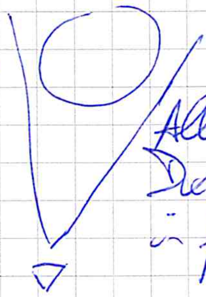
Love them!!

ϕ^{DM}

$J \propto \int_{l.o.s} \rho^2_{DM} \, dV$

↓

little dependence on ρ_{DM} +



All Dwarf in field

+ see caveats!! Ullio & Valli 2016

My personal take...

④

Mainz Institute for Theoretical Physics

Fabio Iocco

Galactic Center

ϕ^{ASTRO} very high...

but VERY WELL characterised...

"Excess" seems real

(over known astro)

Know your astro!!

ϕ^{DM}

$\int \rho_{DM}^2 \, dV$

↓

Very high but VERY (very very) uncertain

Very promising, use with caution!

CMB

ϕ^{ASTRO}

Limited floor in Standard ΛCDM

⇓

CMB "Perfectly" known

$\phi^{DM} \propto \frac{\langle \sigma v \rangle}{m^2} \left(\rho_c (1+z)^3 \right)^2$

↓ Perfectly known expectation

↓ cosmological smooth component

... so?

"Calorimetric" signature

Spectrum in CMB unique but... even cautious

FANTASTIC for RULE-OUTS; CAVEATS for DISCOVERY

(5)

Mattia Fornasa

Mainz Institute for Theoretical Physics

-) Diffuse Gamma-Ray Background: i.e. the cumulative emission produced by all sources (both astrophysical and DM) that are not bright enough to be detected individually

Φ_{astro}

it allows to constrain the low-luminosity tail of the gamma-ray luminosity function of astrophysical sources (blazars, misaligned AGNs, star-forming galaxies)

BUT

the signal is the sum of the components of all sources so there are a lot of degeneracies

Φ_{DM}

it contains all the emission associated to DM annihilations or decays

BUT

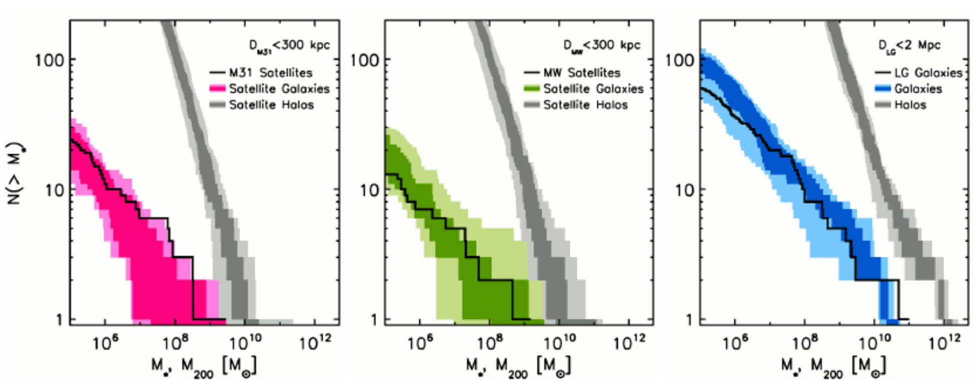
still DM may be a subdominant component

BUT

you can study the DGRB with multiple complementary techniques and hopefully reconstruct its composition.

Could you explain the too big to fail problem and its relation with missing satellite and core/cusp?

Missing Satellite problem: CDM predicts thousands of subhalos around the MW, why we see way less galaxies around us? (Moore+1999, Klypin+1999)



Sawala+2016

Solutions:

- ➢ Star formation efficiency: subhalos are there but forming a galaxy depends on several baryonic processes: cooling mass, reionization, stellar feedback.
- ➢ Reduce the number of subhalos: Dark matter physics (WDM)

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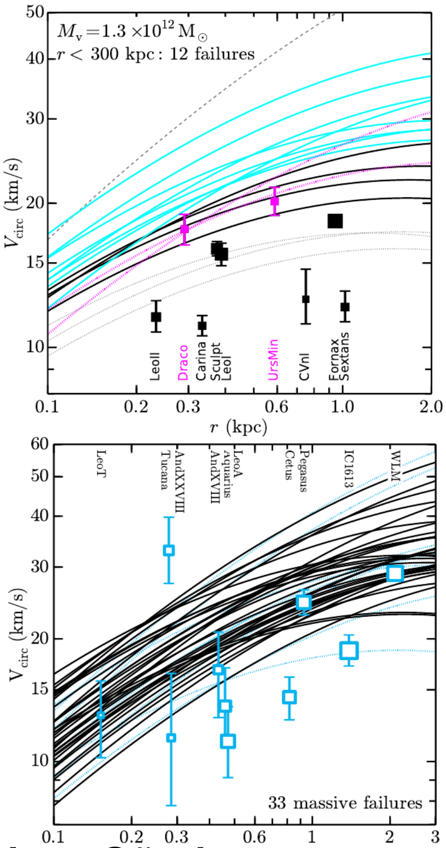
Could you explain the too big to fail problem and its relation with missing satellite and core/cusp?



Garrison-Kimmel+2014

Too big to fail: observations of enclosed mass in nearby dwarfs indicate lower values than what LCDM (N-body simulations) predict (Boylan-Kolchin+2012)

First order solution: Most massive subhalos are dark. But they are *too big to fail* forming stars!

Real solutions:

- Reduce the number of massive halos in the MW: reduce the MW halo mass.
- Reduced the inner density of subhalos:
  - Baryon physics: dm cores (core/cusp)
  - Dark matter physics: SIDM
- Errors in these observations?

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In cosmological simulations, the mass of an individual gas or dark matter 'particle' is millions of solar masses. Why can we expect that the actual dark matter particles in the universe have the same phase space distribution as such massive 'particles' in the simulations?

For a "standard" dark matter (DM) particle candidate with the mass of the order GeV and a very small cross-section, one can describe the evolution of structures in the Universe using a collisionless self-gravitating fluid. This fluid can be fully-characterized by its phase-space density distribution $f(\vec{x}, \vec{v}, t)$ defined such that $f(\vec{x}, \vec{v}, t)d^3xd^3v$ represents the mass at position $\vec{x}$ moving at velocity $\vec{v}$ at time t. This is a statistical description of all the dark matter particles in the system. The total mass in the system is:

$$M_{tot} = \int_{-\infty}^{\infty} f(\vec{x}, \vec{v}, t)d^3vd^3x \quad (1)$$

The DM density at any point in space is recovered by integrating over velocities:

$$\rho(\vec{x}, t) = \int_{-\infty}^{\infty} f(\vec{x}, \vec{v}, t)d^3v \quad (2)$$

The distribution f function obeys the Liouville theorem and if the only force acting on the particle is the gravitational potential $\Phi(x)$, we can write a closed system of equations for the formation of structures (ignoring here the cosmological expansion factors):

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \frac{\partial f}{\partial \vec{x}} - \vec{\nabla}\Phi \cdot \frac{\partial f}{\partial \vec{v}} = 0, \quad (3)$$

$$\nabla^2\Phi = 4\pi G\rho(\vec{x}, t) = 4\pi G \int_{-\infty}^{\infty} f(\vec{x}, \vec{v}, t)d^3v \quad (4)$$

This integro-differential system of equations in 7 dimensions (3 space, 3 velocity and 1 time) is know as the Vlasov-Poisson system of equations and is almost impossible to solve analytically in the general case.
One could try to solve this system directly by using simple discretisation methods. However, as the problem is 6-dimensional and that in general f will have a very complex shape, it is almost impossible to do. Instead, one can approach the problem using a Monte-Carlo approximation. To this end, one constructs f as a sum of N dirac distributions in phase-space:

$$f(\vec{x}, \vec{v}) \approx \frac{1}{N} \sum_{i=0}^{N} m_i \delta(\vec{x} - \vec{x}_i)\delta(\vec{v} - \vec{v}_i), \quad (5)$$

with $m_i = M_tot/N$. In the limit $N \to \infty$ this approximation will converge towards the original distribution function $f(\vec{x}, \vec{v}, t)$. Note that m_i is unrelated to the DM particle mass. Each term in the sum in equation 5 can be represented as a "meta-particle" in the simulation codes that, i.e. a small body with a fixed mass, a position and a velocity.

Inserting this version of f in the Vlasov-Poisson system leads to a much simpler set of equations to solve for the individual meta-particles.

References

[1] Walter Dehnen and Justin I Read, *N -body simulations of gravitational dynamics*, European Physics Journal Plus **126** (2011), 55.