Setting FIRE on Self-Interacting Dark Matter

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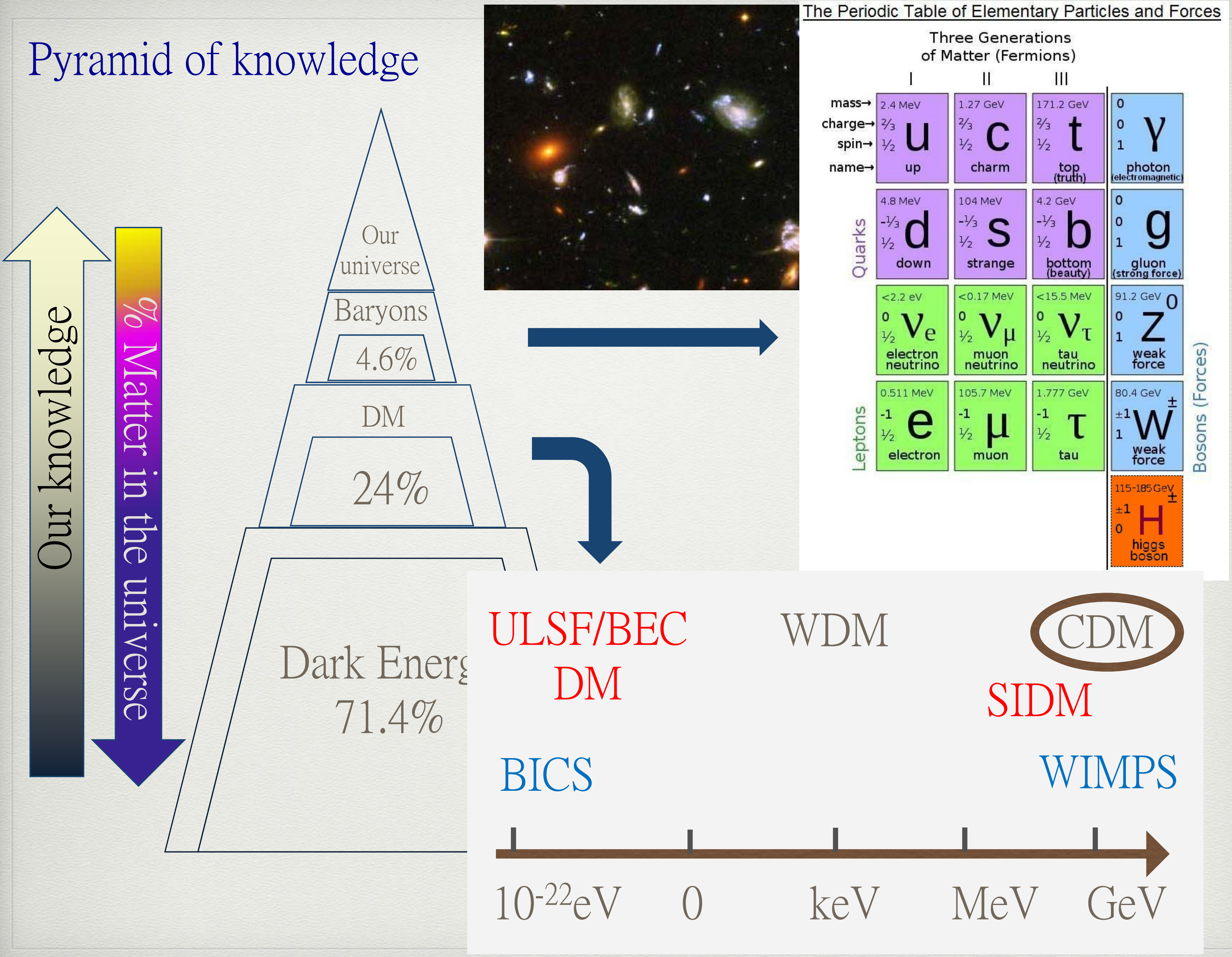
Mike Boylan-Kolchin, Alex Fitts(UT Austin)
Philip Hopkins & the FIRE team

Also See Poster P4-40
Observational consequences of
Scalar Field/Wave Dark Matter

2017 APRIM
IAU Meeting
3-7 July 2017
Taipei,Taiwan

Pyramid of knowledge



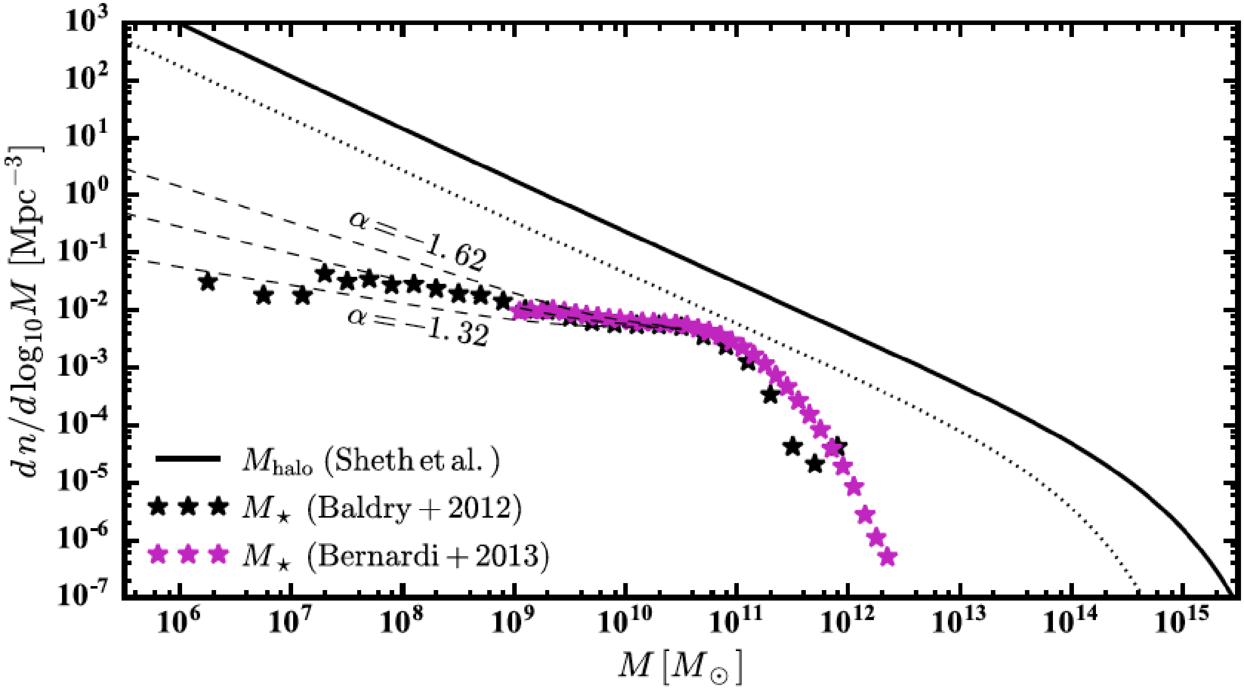
The Periodic Table of Elementary Particles and Forces

Three Generations of Matter (Fermions)

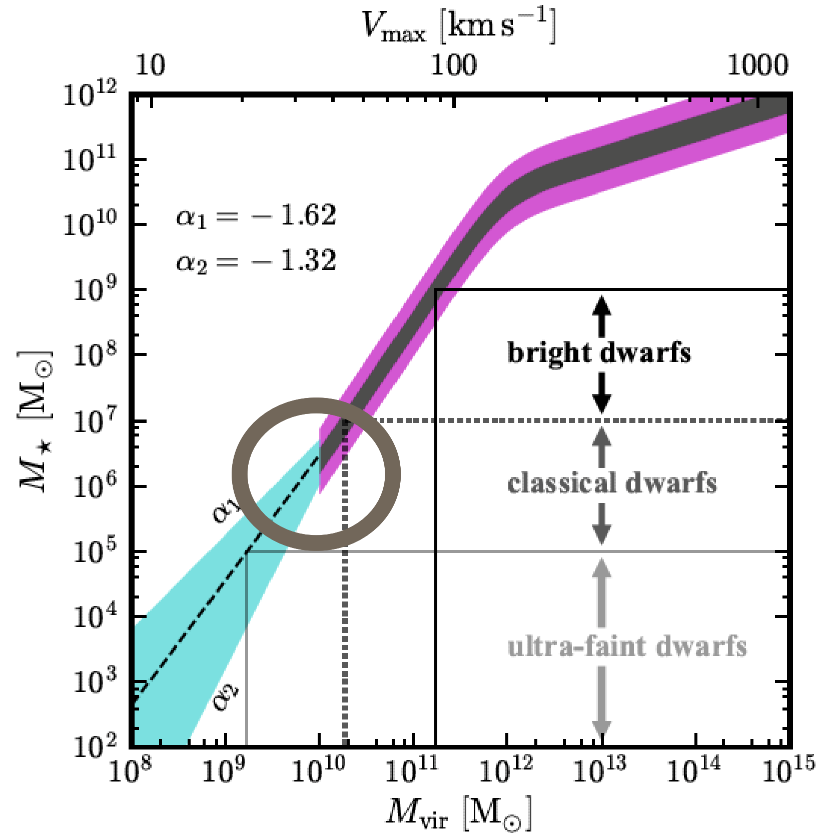
		I	II	III	Bosons (Forces)
	mass→ charge→ spin→ name→	2.4 MeV ⅔ ½ u up	1.27 GeV ⅔ ½ c charm	171.2 GeV ⅔ ½ t top (truth)	0 0 1 γ photon (electromagnetic)
Quarks		4.8 MeV -⅓ ½ d down	104 MeV -⅓ ½ s strange	4.2 GeV -⅓ ½ b bottom (beauty)	0 0 1 g gluon (strong force)
Leptons		<2.2 eV 0 ½ ν_e electron neutrino	<0.17 MeV 0 ½ ν_μ muon neutrino	<15.5 MeV 0 ½ ν_τ tau neutrino	91.2 GeV 0 1 Z^0 weak force
		0.511 MeV -1 ½ e electron	105.7 MeV -1 ½ μ muon	1.777 GeV -1 ½ τ tau	80.4 GeV ±1 1 $W^\pm$ weak force
					115-185 GeV ±1 0 $H^\pm$ higgs boson

LCDM

Mass functions compared:
observed stars vs. **predicted dark matter**



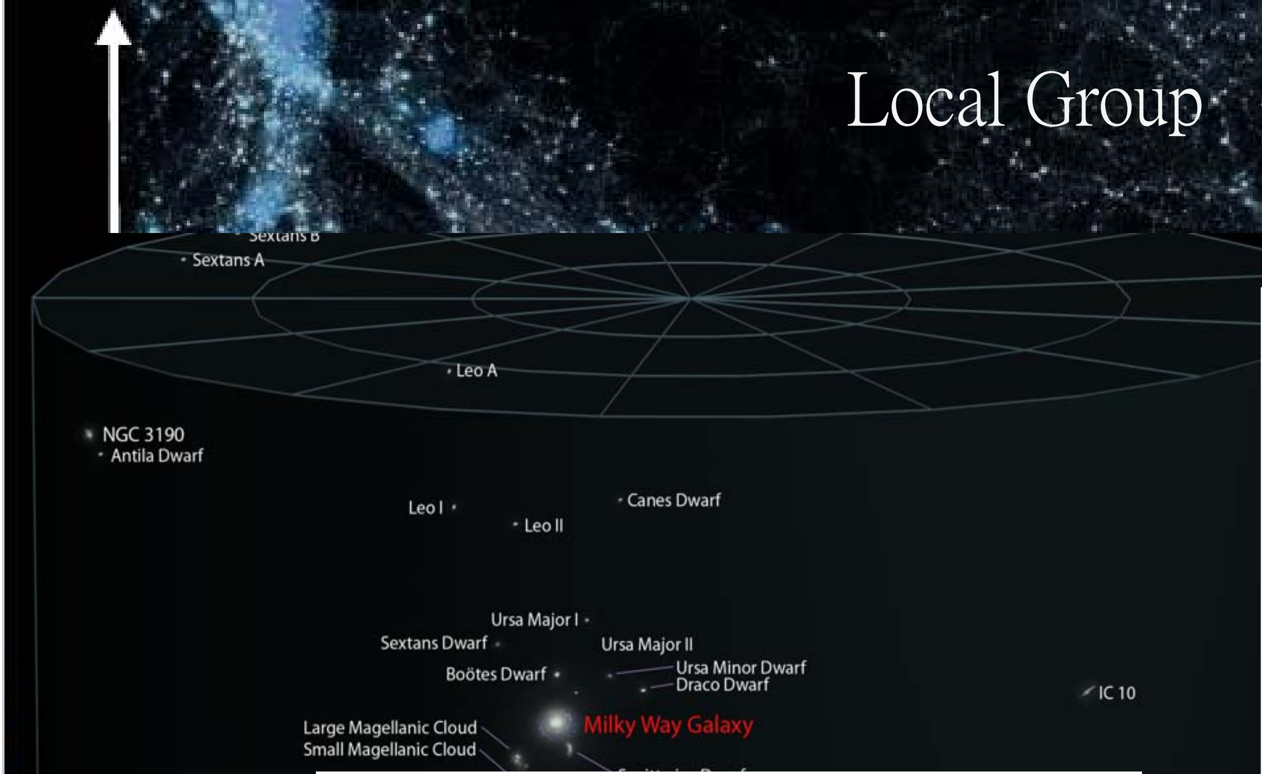
M_* vs. $M_{\rm halo}$
that works



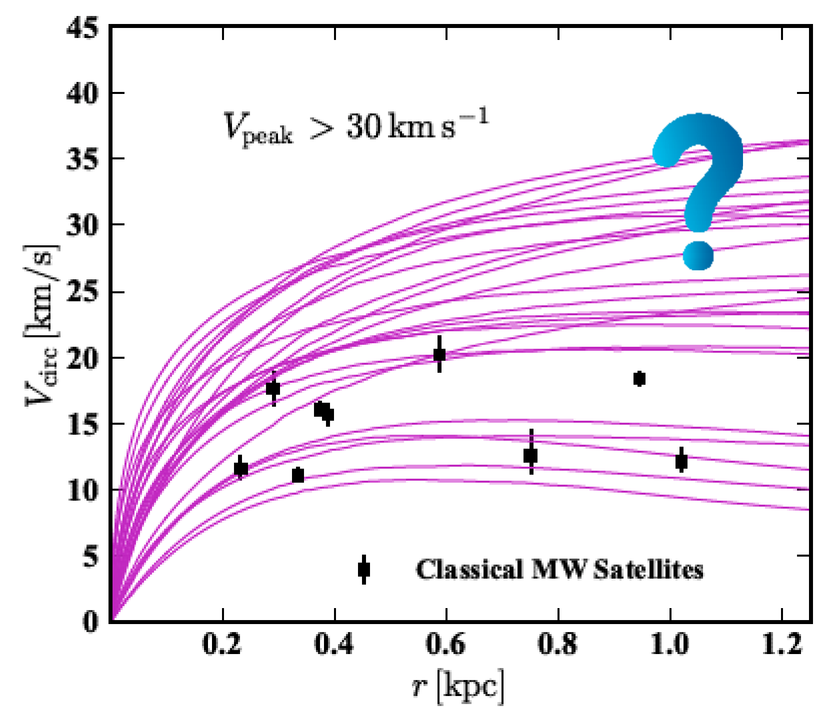
Miguel Rocha

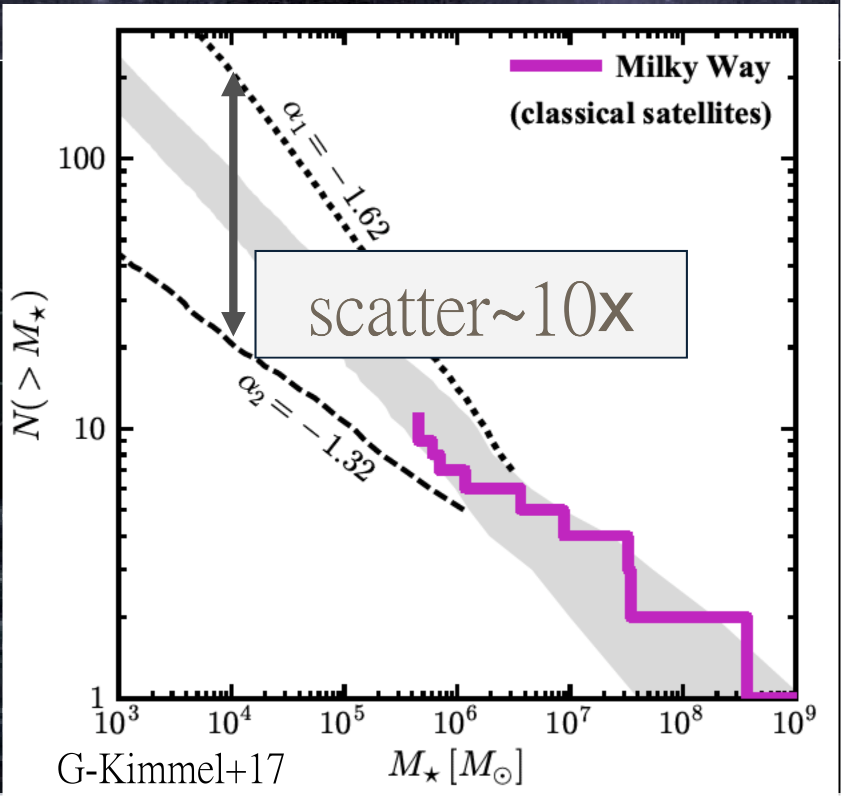
LCDM

Too Big to Fail



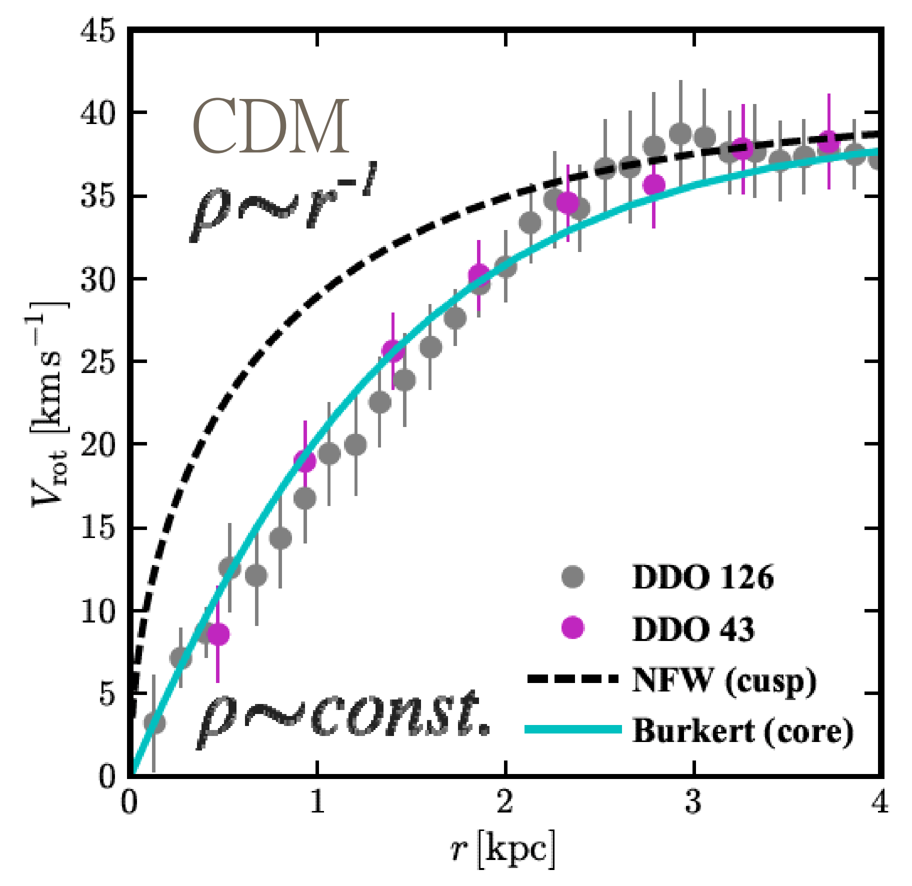
Garrison-Kimmel+14

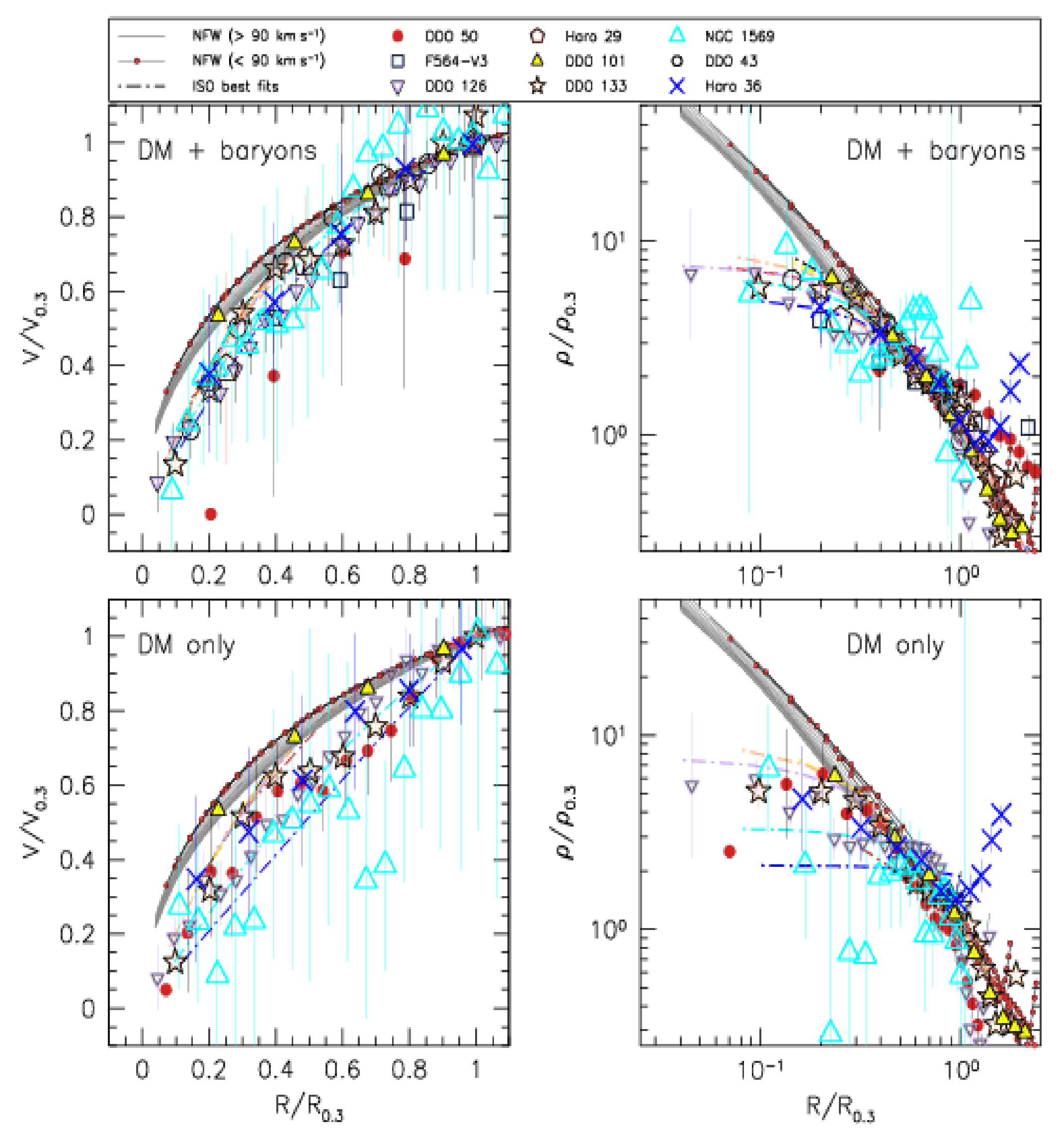




G-Kimmel+17

CUSP-CORE PROBLEM





Bullock and Boylan-Kolchin+17
Oman+15,17 (gal. diversity)

Oh et al. 2015

FIRE-2: Feedback in Realistic Environments

(Hopkins+2014; Chan et al. 2015; Oñorbe et al. 2015).

Hopkins+17(FIRE-2)

Star formation + Radiation pressure

Stellar winds

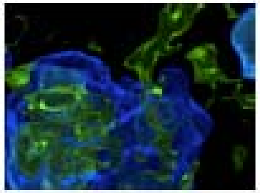
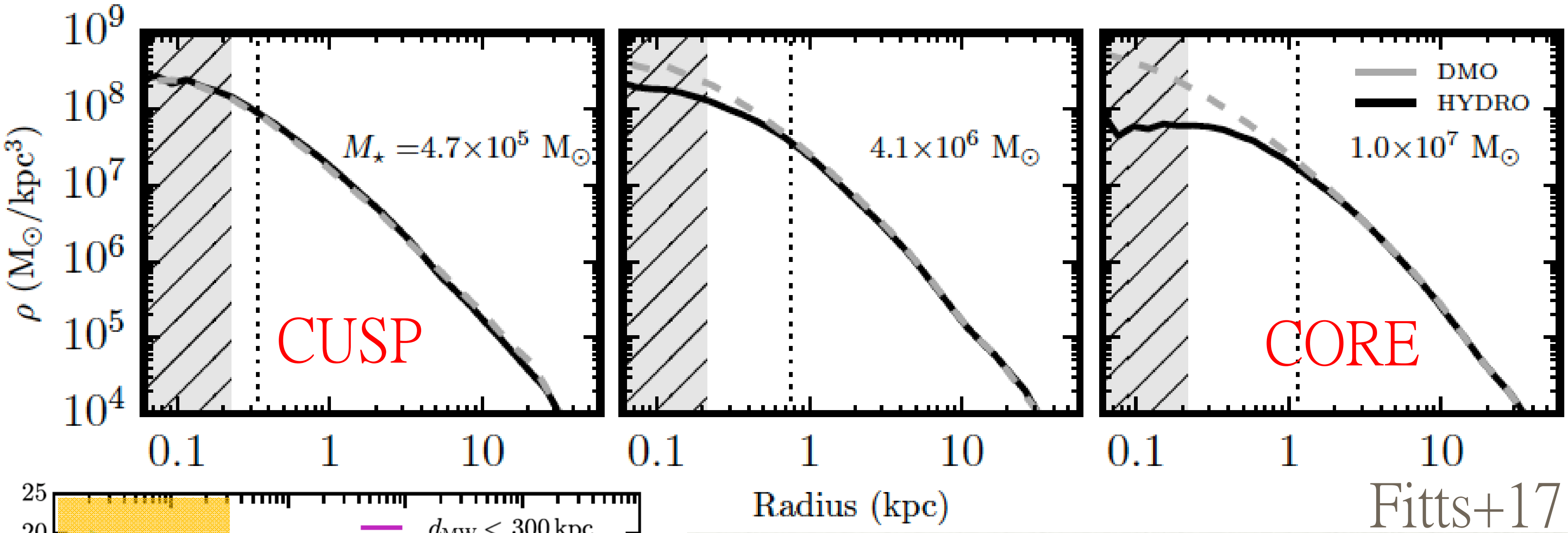


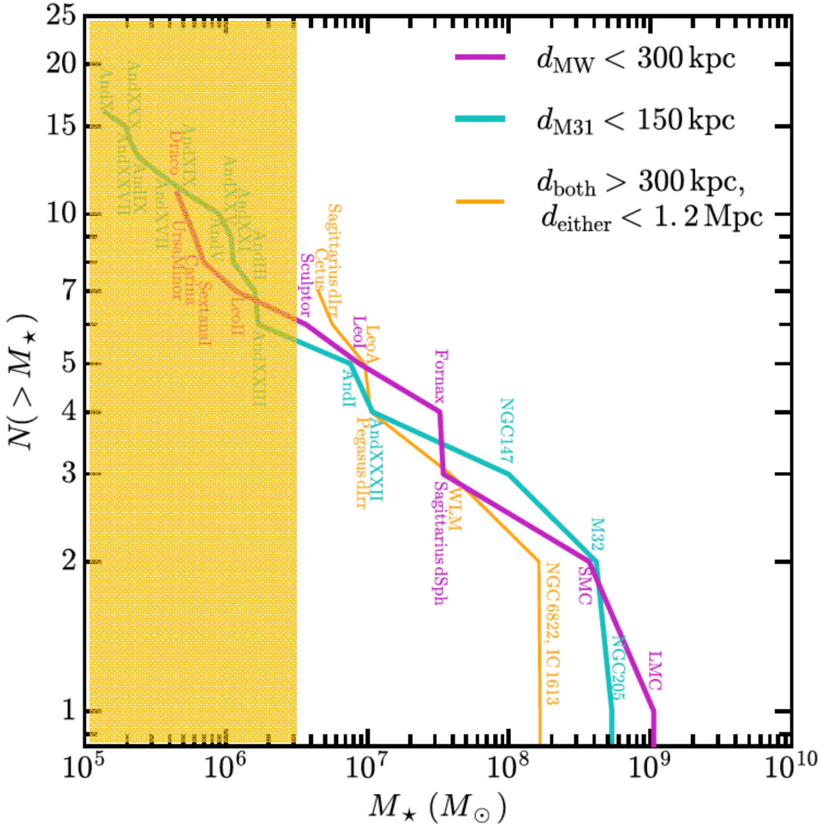
Photo-Ionization

Supernovae: Impart energy & momentum directly into local particles, never turn off cooling.

M_*~10^5 M$_\odot$ ~10^6 M$_\odot$ ~10^7 M$_\odot$



Fitts+17

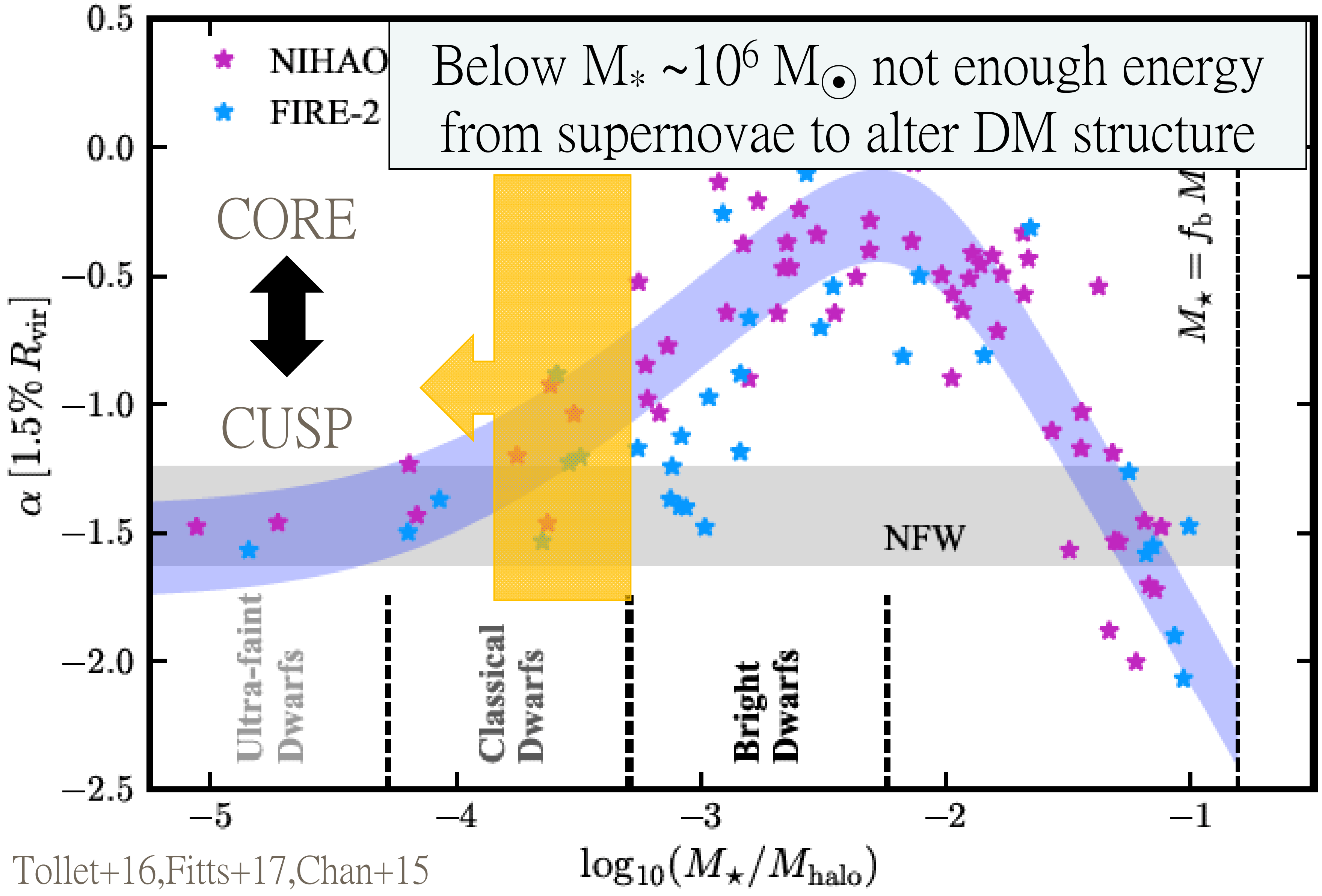


HYDRO simulations (FIRE+CDM)!

ϵ_{gas}~ 1.4 pc, ϵ_{dm}~25 pc
m_{gas}~ 500 M , m_{dm}~ 2500 M

Central density strongly dependent on M_* !

Need >3.e6M_{sun} stars to affect DM density profile



Below M_* ~10^6 $M_\odot$ not enough energy from supernovae to alter DM structure

Tollet+16,Fitts+17,Chan+15

What about Self-Interacting DM?

SIDM models with self-scattering cross sections as large as ~Barn/GeV (~nuclear scale) are not ruled out.

(Peter+12; Rocha+12; Elbert+15;Vogelsberger+14,Lin&Loeb16).

$$\Gamma = \rho_{\mathrm{dm}} \left(\frac{\sigma}{m}\right) v_{\mathrm{rms}}$$

If rate > 0.1/Gyr

Interesting effects at galaxy scales

$\sigma \sim 1\,\mathrm{cm}^2\,(m_X/\mathrm{g}) \sim 2\times10^{-24}\,\mathrm{cm}^2\,(m_X/\mathrm{GeV})$

For a WIMP: $\sigma \sim 10^{-38}\,\mathrm{cm}^2\,(m_X/100\,\mathrm{GeV})$

Differ by $\sim 10^{14}$

Spergel & Steinhardt (2000)

SIDM DM-only

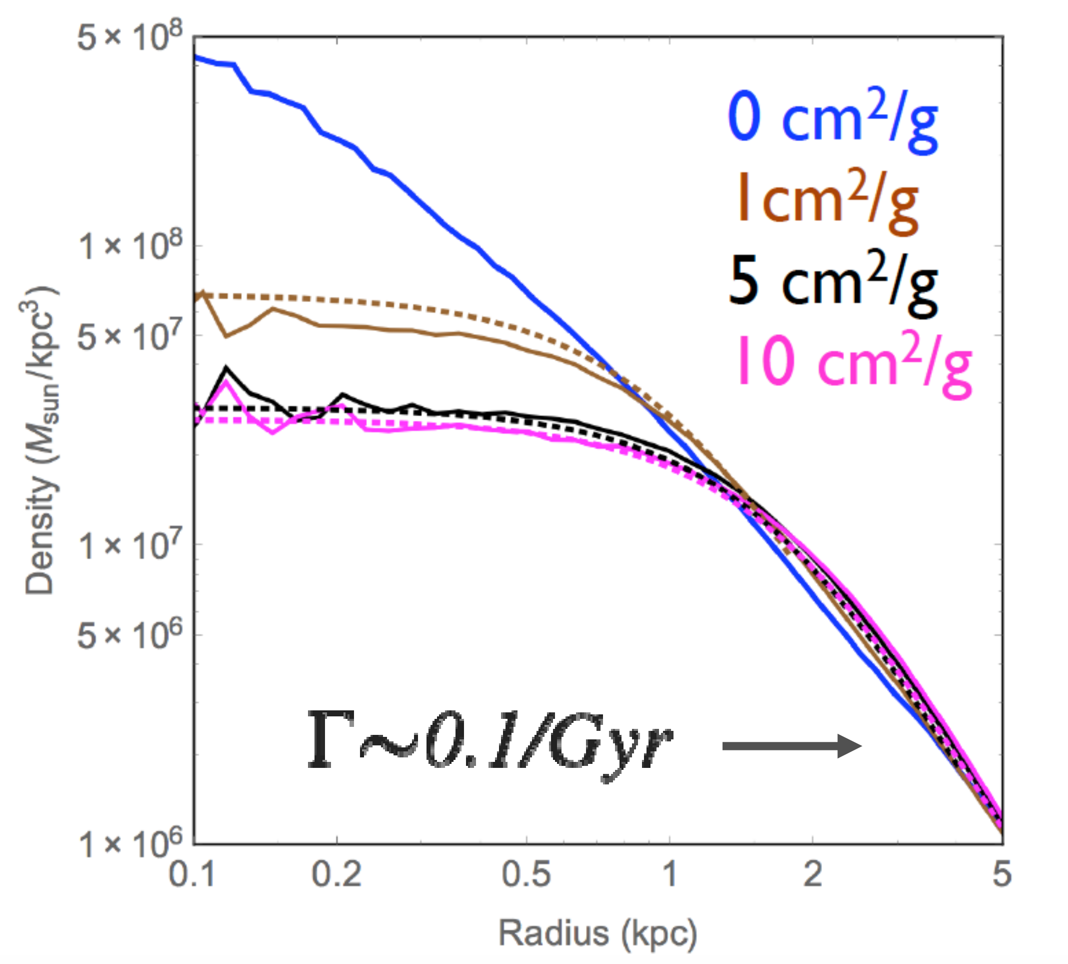
Only difference observed
is core density:

CDM: high density ~1/r
SIDM: low-density ~const.

$$\frac{\sigma}{m} \sim 1 cm^2/g$$

Dwarfs with core sizes ~500 pc

Observed sizes (r_{eff})
of dwarf galaxies



Elbert+15,16, Kaplinghat+15

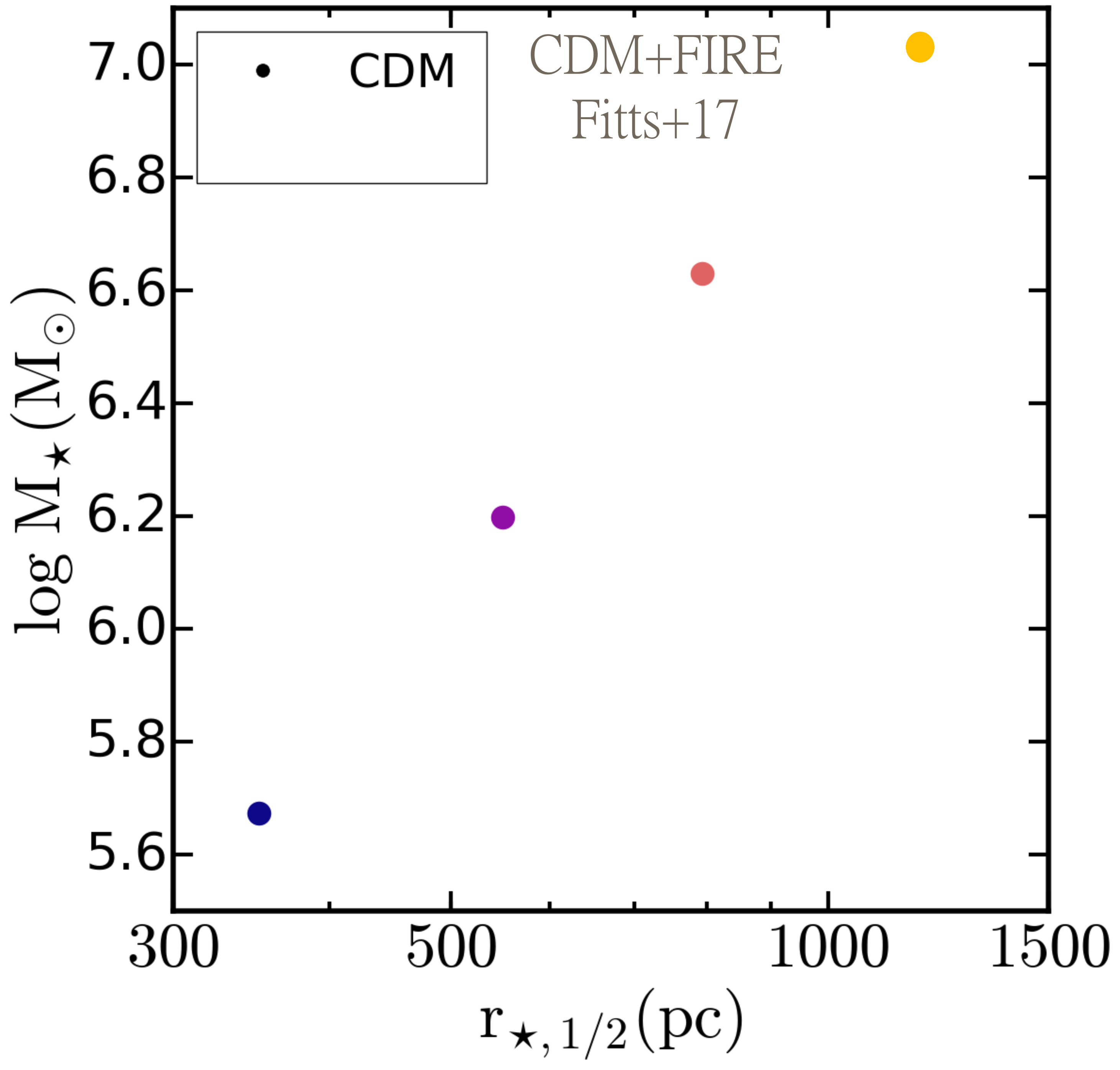
Dwarf galaxies agree with SIDM!

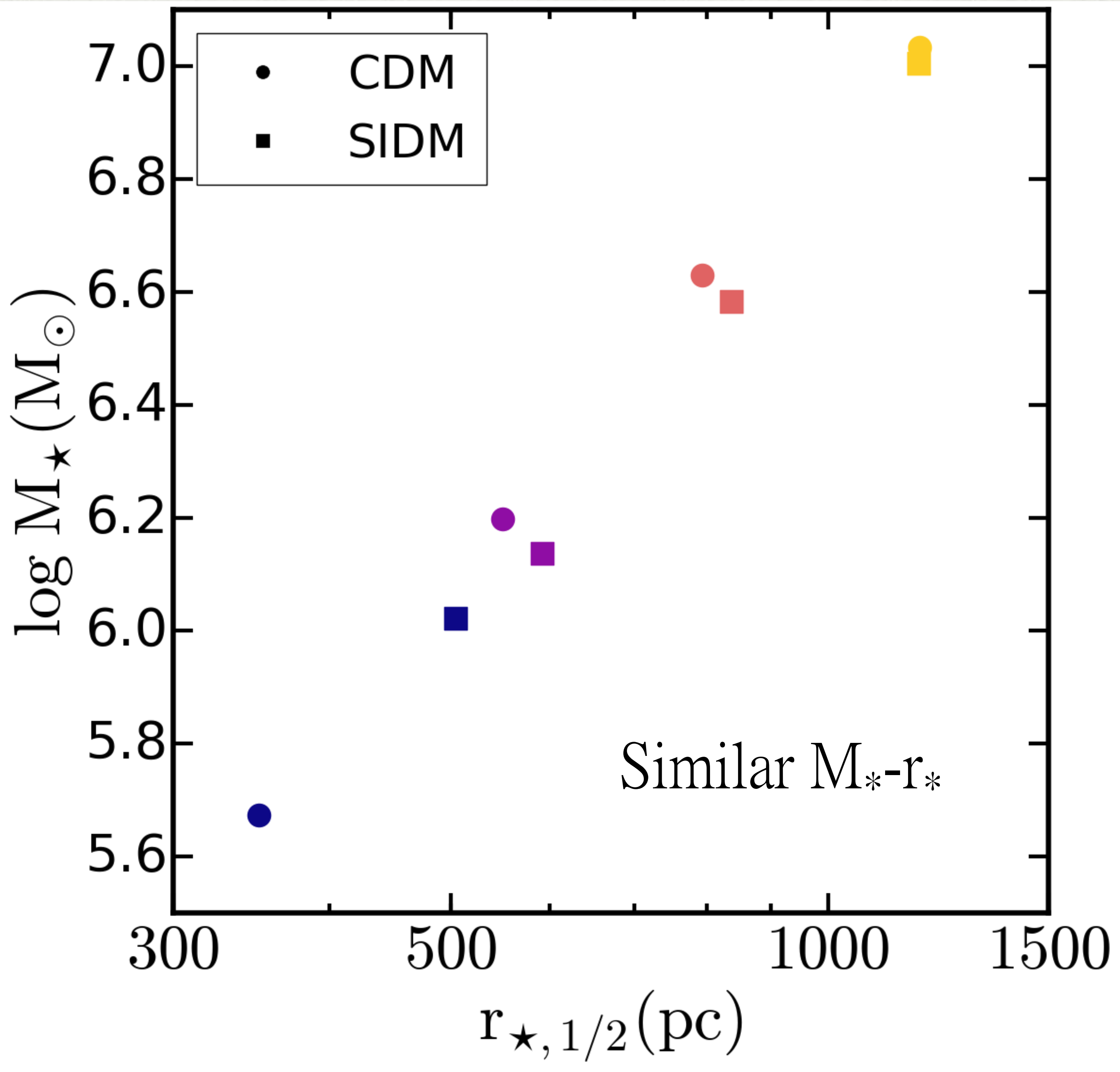
Is the agreement lost with stellar feedback?

SIDM on FIRE

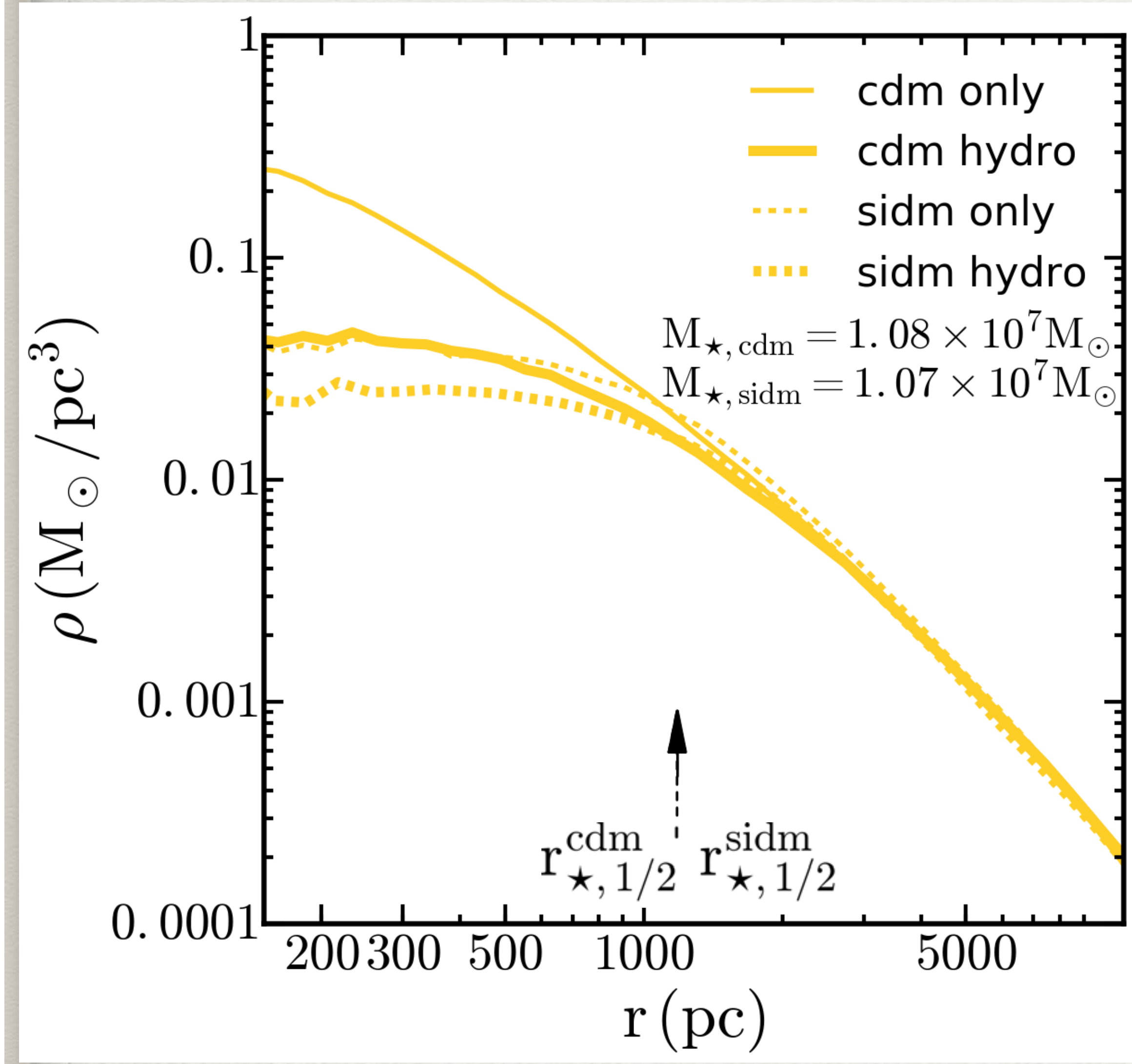
Robles +17

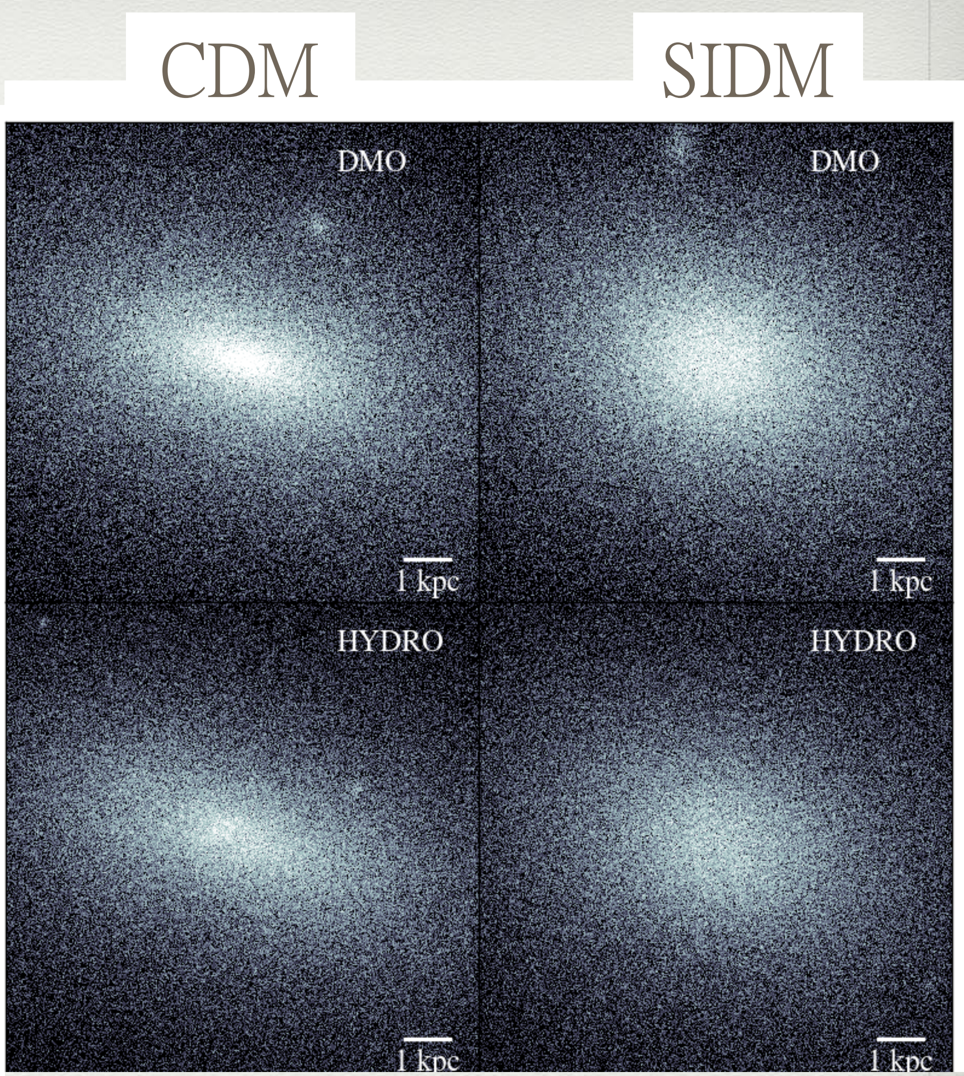
Arxiv: 1706.07514


CDM
CDM+FIRE
Fitts+17
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
$\log M_\star (M_\odot)$
300
500
1000
1500
$r_{\star,1/2}(\mathrm{pc})$


CDM
SIDM
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
$\log M_\star (M_\odot)$
300
500
1000
1500
$r_{\star,1/2}(\mathrm{pc})$

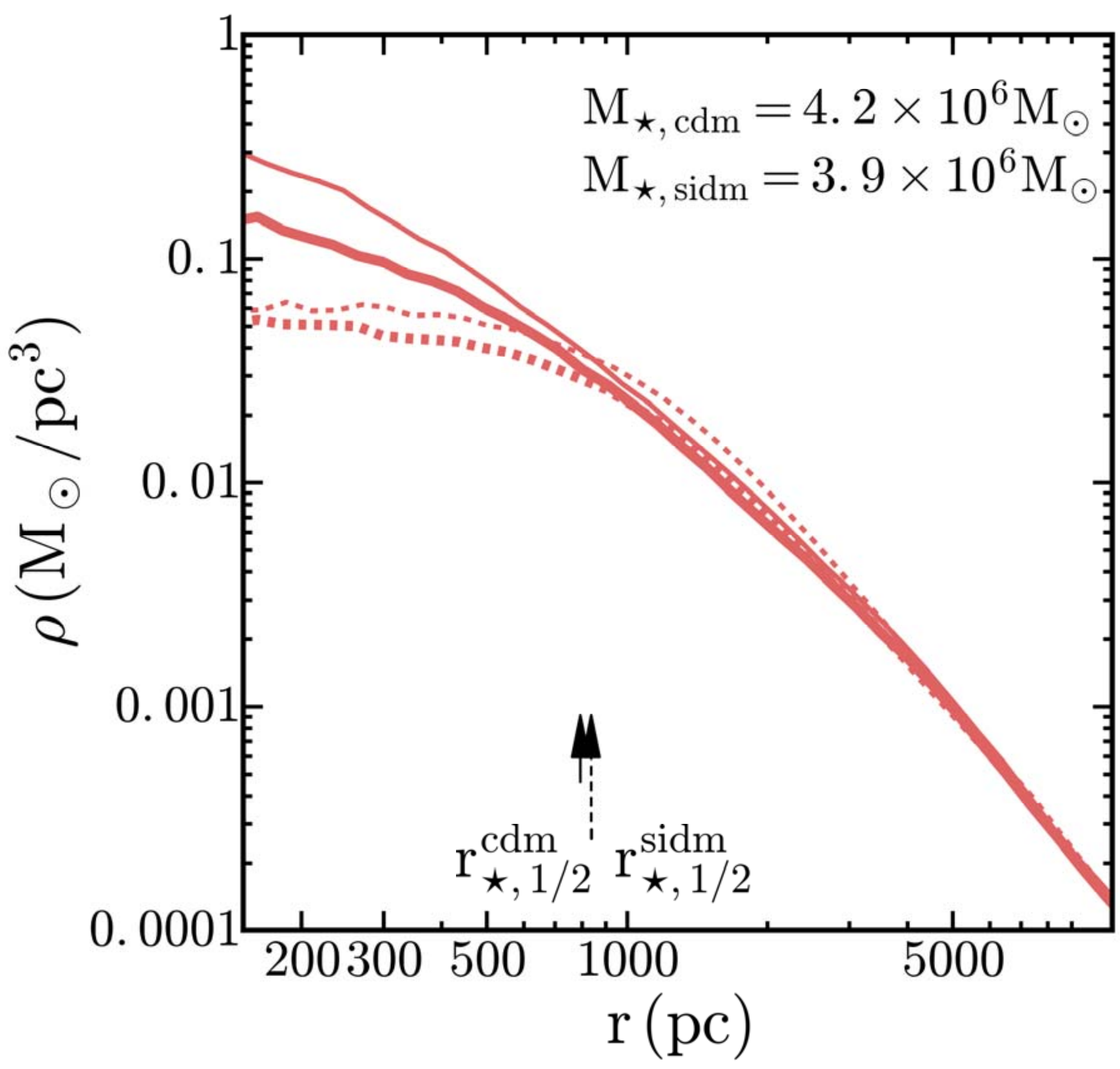
Similar M_*-r_*



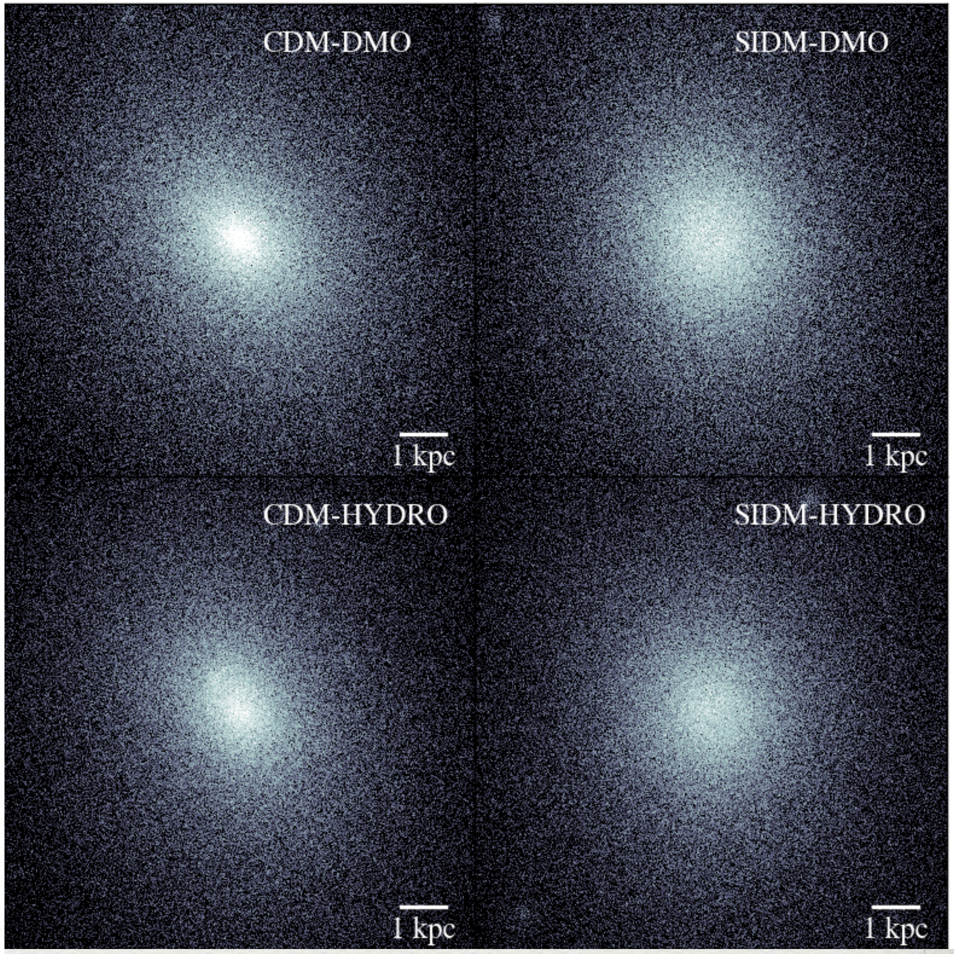


SIDM:
“rounder”
halos

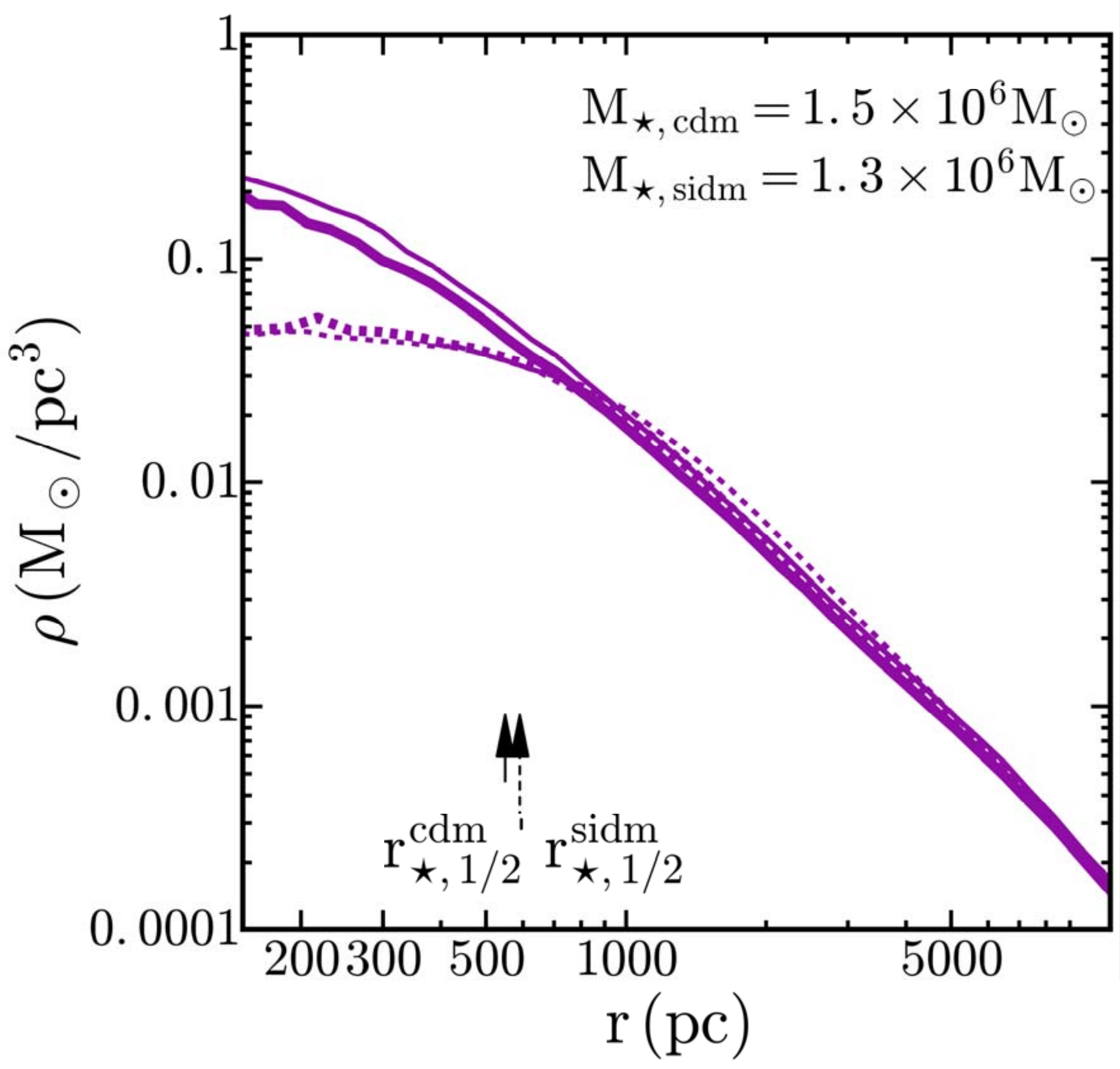
Robles+17a

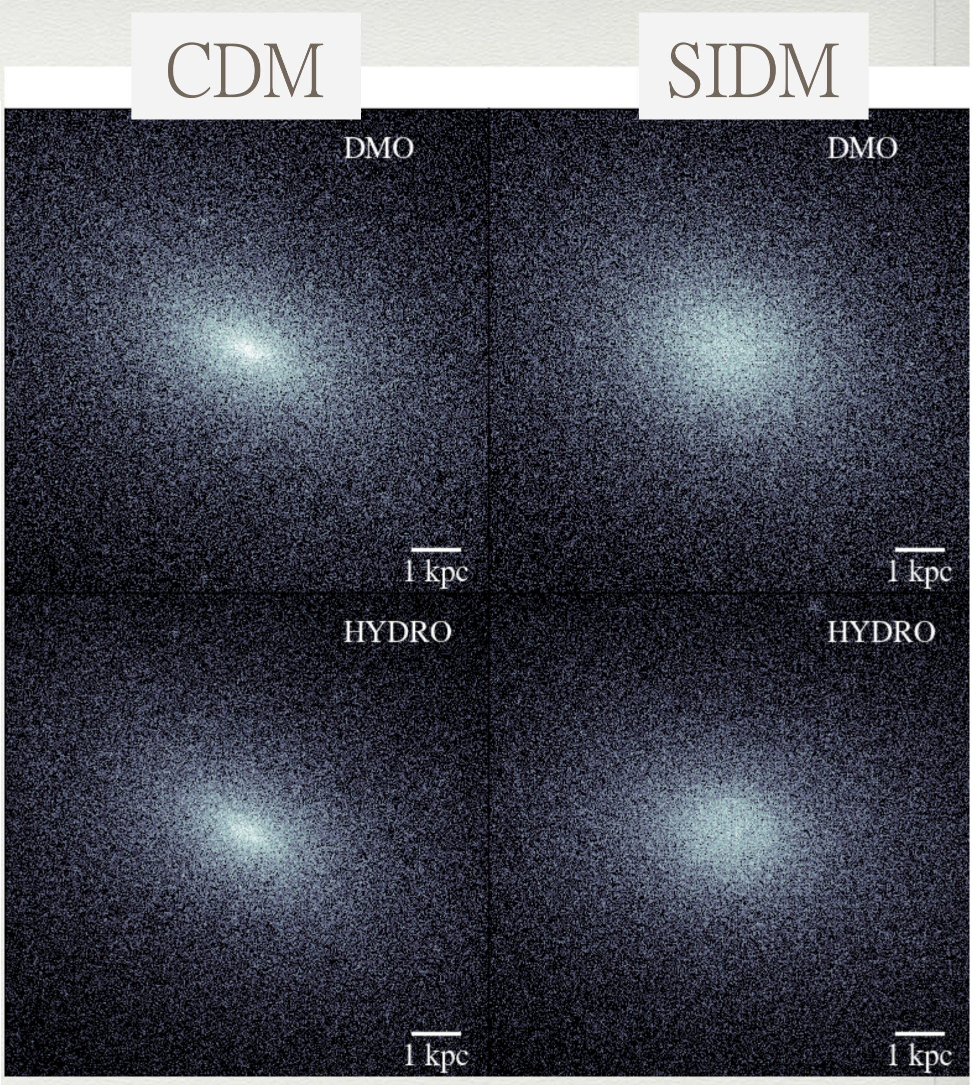


CDM SIDM

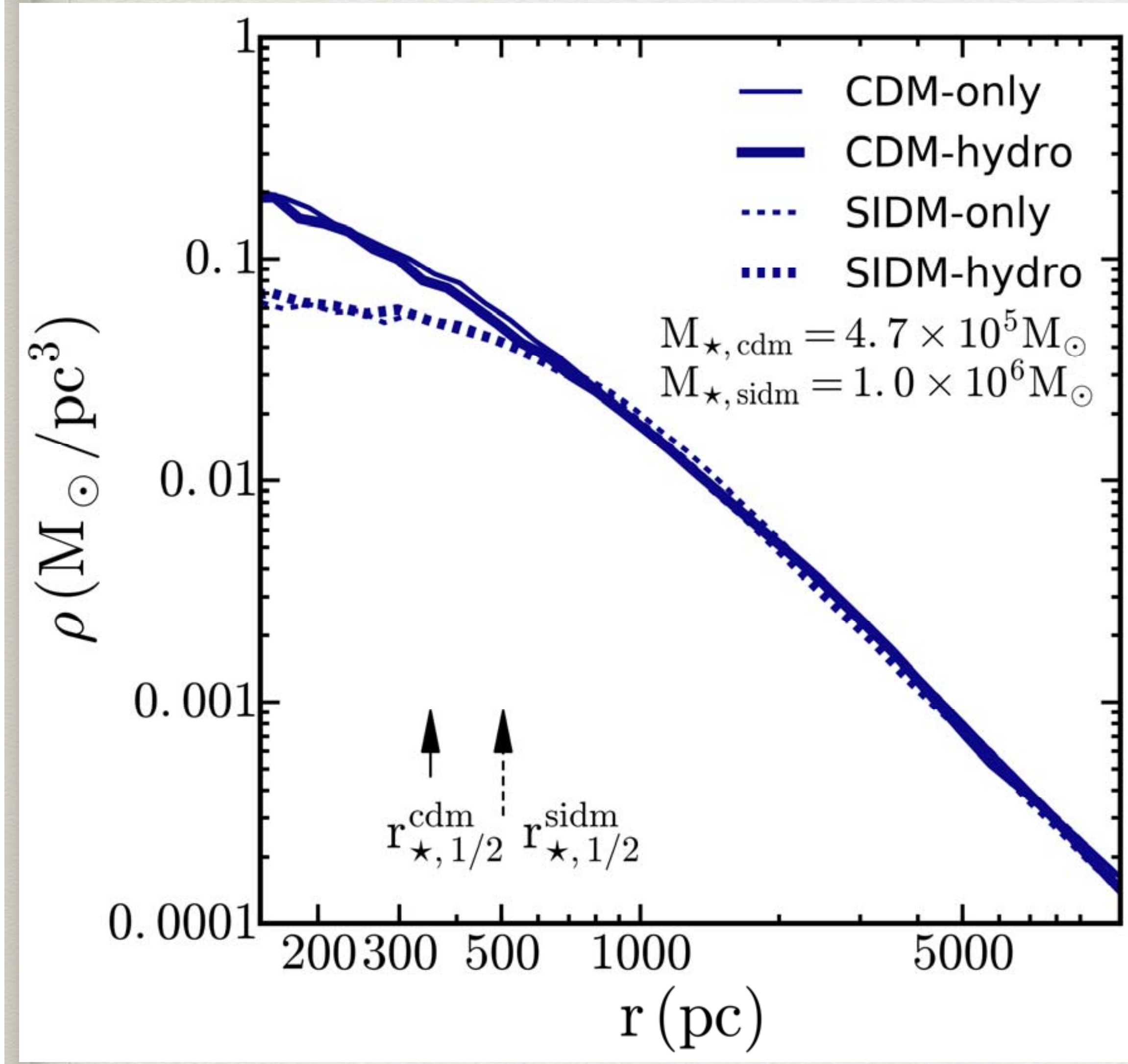


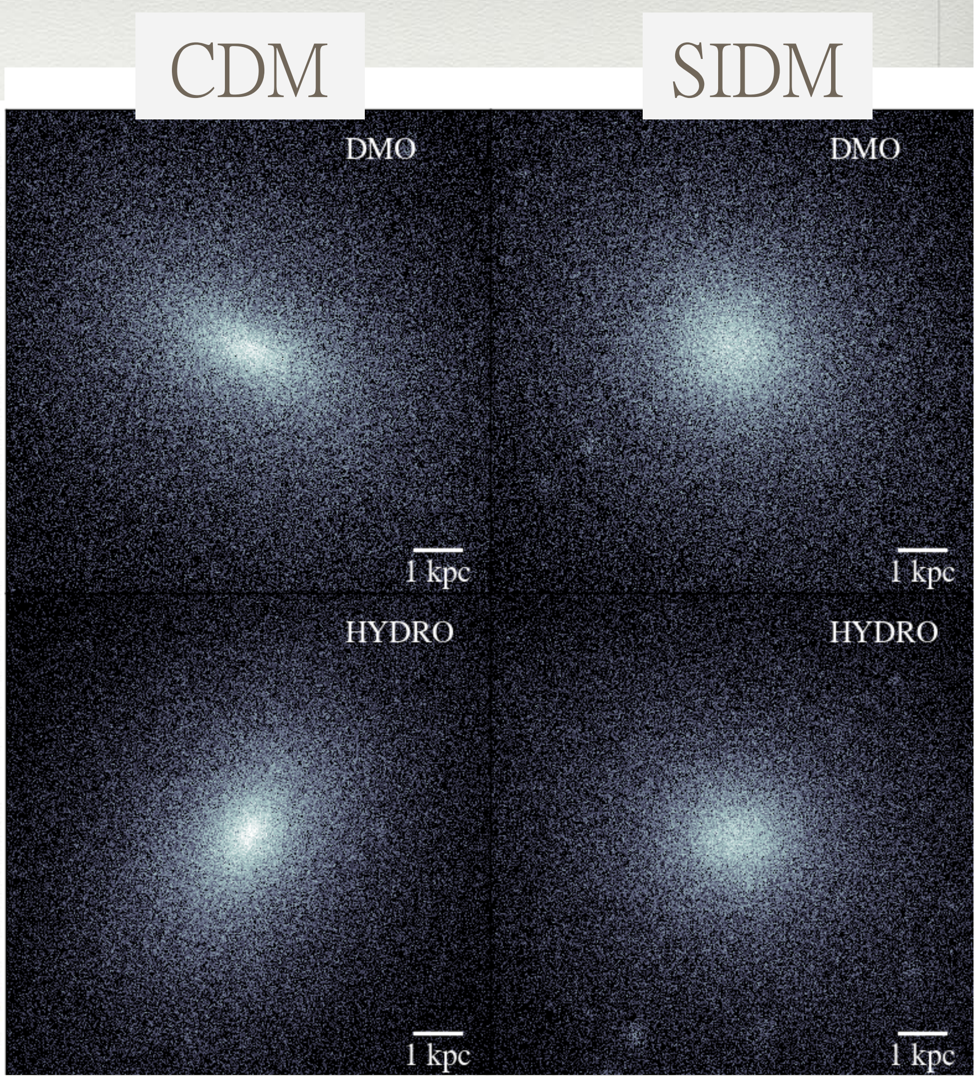
Robles+17a


$M_{\star,\,cdm} = 1.5 \times 10^6 M_\odot$
$M_{\star,\,sidm} = 1.3 \times 10^6 M_\odot$
$\rho\,(M_\odot/pc^3)$
1
0.1
0.01
0.001
0.0001
$r^{cdm}_{\star,\,1/2}$
$r^{sidm}_{\star,\,1/2}$
200
300
500
1000
5000
r (pc)


CDM
SIDM
DMO
DMO
HYDRO
HYDRO
1 kpc
1 kpc
1 kpc
1 kpc

Robles+17a

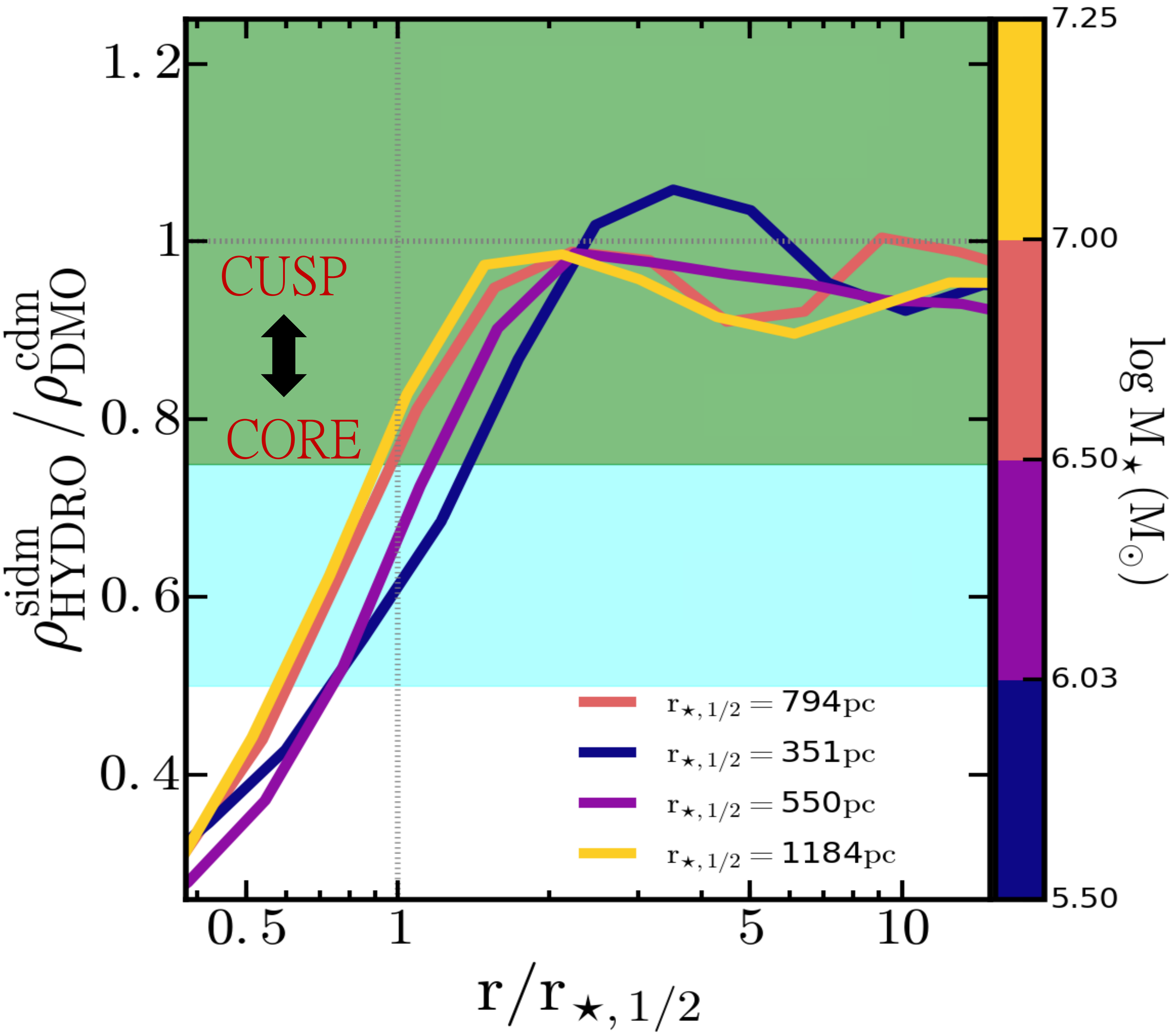




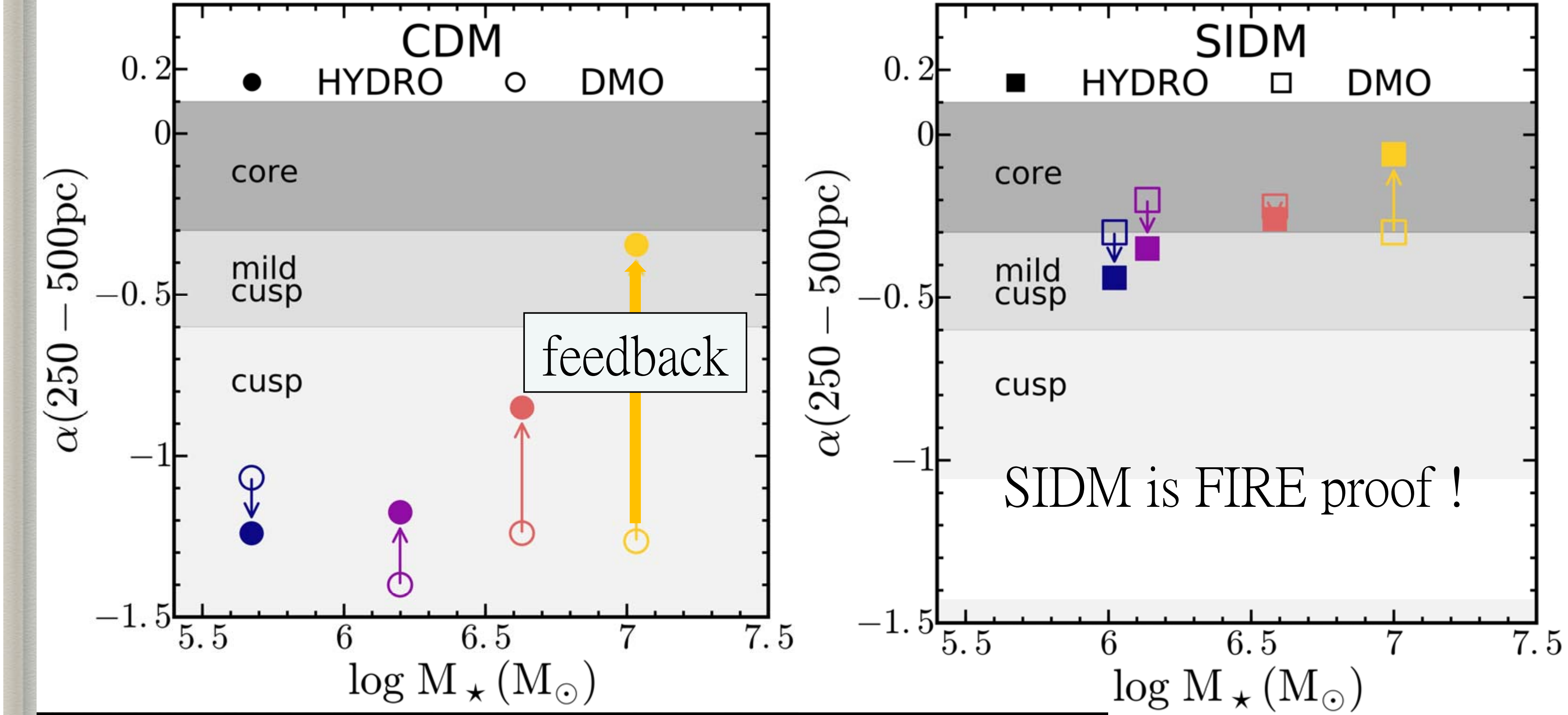
Baryonic feedback has much less impact in SIDM hydro simulations!

Robles+17a

SIDM vs CDM: densities differ at $r \leq 2r_{1/2}$



SIDM vs CDM: Inner Slopes

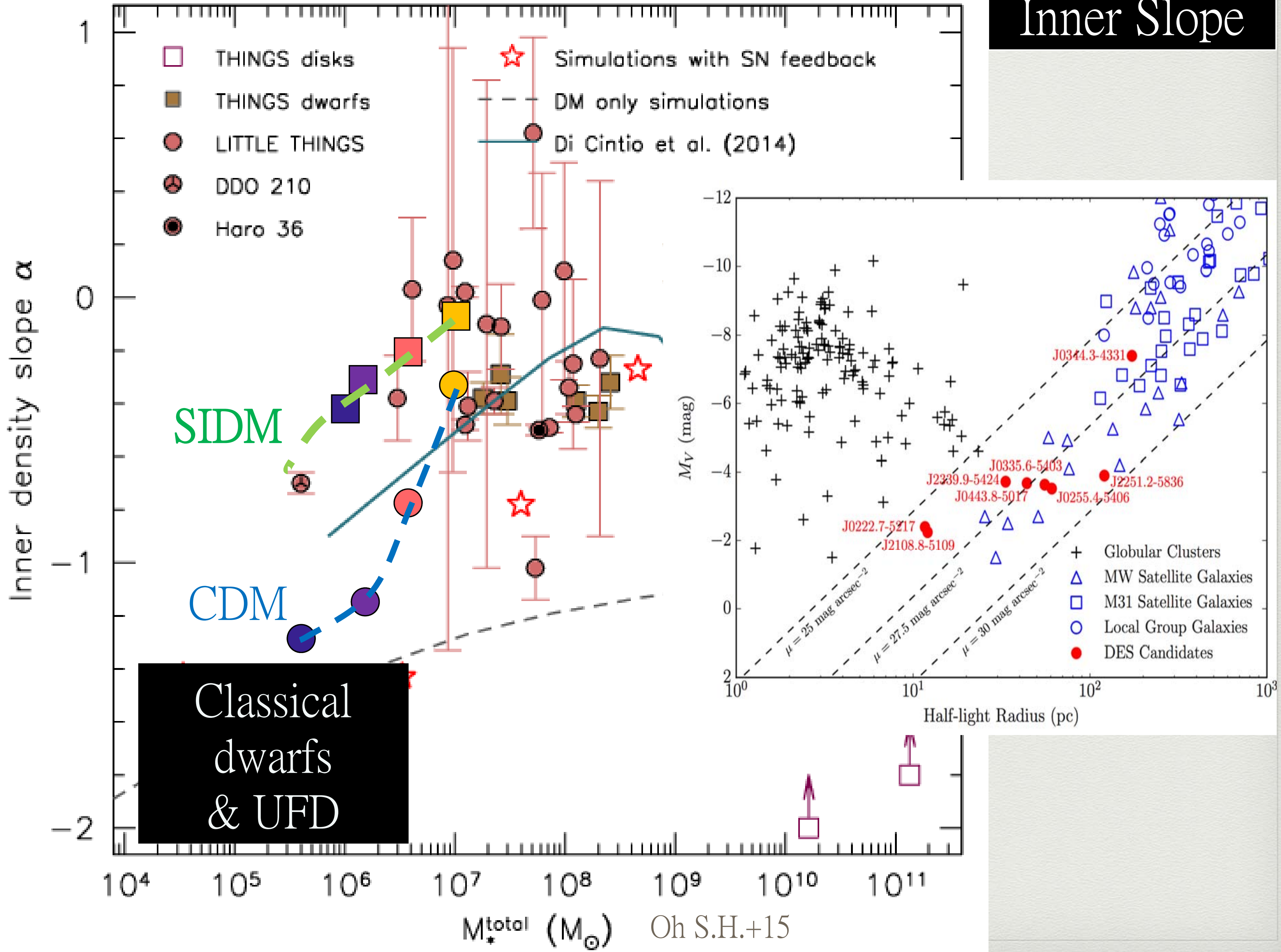


SIDM is FIRE proof !

Dwarf galaxies in SIDM are much less sensitive to feedback

Robles+17a

Inner Slope



Classical dwarfs & UFD

Oh S.H.+15

CONCLUSIONS

Response to baryons	CDM	SIDM
Galaxy Inner density (slope)	FIRE predicts cusps for $r<r_{1/2}$ if $M_*<3.10^6 M_\odot$	Galaxies have cores ~500 pc for $\sigma/m \sim 1$ cm^2/g w/wo FIRE
Satellite abundance	Astrophysics may solve it but requires specific M_*-M_{halo} relationship	Same halo abundance as CDM needs $\sigma/m>1 cm^2/g$ Clusters $<0.2 cm^2/g$
TBTF	Persists, observed small galaxy densities are too low compared to AM relation	Solved for $\sigma/m \sim 0.5$-$5 cm^2/g$ SIDM resilient to feedback
Profile features	$r<<1$ $\rho\sim 1/r$ (cold) $r>>1$ $\rho\sim r^{-3}$ smooth	$r<<1$ $\rho\sim r^0$ (hot) $r>>1$ $\rho\sim r^{-2}$ smooth

See Poster P4-40 for Scalar Field/Wave DM

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Observational consequences of Ultra Light Scalar Field/Wave Dark Matter

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In collaboration with P. Mocz, M. Vogelsberger, J. Zavala, M. Boylan-Kolchin and Lars Hernquist (arxiv:1705.05845)

ABSTRACT

One alternative dark matter model to Cold Dark Matter (CDM) is an ultra light boson of mass $m \sim 10^{-22} eV/c^2$ that forms a Bose Einstein condensate (BEC) behaving as CDM in large scales but capable to alleviate the galaxy-scale issues, called BEC/Wave DM.

We simulate Wave DM halo formation through mergers of 100 different configurations evolved under the Schrodinger-Poisson (SP) equations[1,2].

All our haloes show a central soliton or *core* supported against gravitational collapse by the Heisenberg uncertainty principle an outer NFW-like profile. Our halos display turbulent behavior driven by the continuous reconnection of vortex lines due to continuous wave interference. The dominant turbulent mode is about the soliton diameter, implying the soliton-sized granules carry most of the turbulent energy in BECDM haloes.

We also find a fundamental relation of the core mass with the dimensionless invariant $\Xi=|E|M^3/(2" Gm/h)^2$ of $M_c/M \approx 2.5\Xi^{1/3}$, in contrast to previous works[3].

Theory

The equations of motion that describe the WaveDM are[1]:

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + mV\psi \qquad (1)$$

$$\nabla^2 V = 4\pi G(\rho - \overline{\rho}) \qquad (2)$$

$\psi = \sqrt{\rho}e^{iS/\hbar}$, $\mathbf{u} = \nabla S/m$, (Madelung transformation)

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{u}) = 0$$

$$\frac{\partial\mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = -\frac{1}{m}\nabla(Q+V)$$

$$Q = -\frac{\hbar^2}{2m}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}.$$

$$E = \int\left[\frac{\hbar^2}{2m^2}|\nabla\psi|^2 + \frac{1}{2}V|\psi|^2\right]d^3 = \int\frac{\hbar^2}{2m^2}(\nabla\sqrt{\rho})^2 d^3x + \int\frac{\rho}{2}v^2 d^3x + \int\frac{\rho}{2}V\, d^3x$$

Quantum Kinetic Potential

Scaling symmetry of SP equations(%dimensionless parameter):

$$\{M,E,L\} \rightarrow \left\{\lambda\hat{M}, \lambda^3\hat{E}, \lambda\hat{L}\right\}$$

$$\{t,x,V,\psi,\rho\} \rightarrow \left\{\lambda^{-2}\hat{t}, \lambda^{-1}\hat{x}, \lambda^2\hat{V}, \lambda^2\hat{\psi}, \lambda^4\hat{\rho}\right\}$$

Results

Halo turbulence driven by vortex lines due to quantum interference. Turbulent spectrum characterized by 1-D radial superfluid velocity spectrum $E_{v2}(k)$:

$$E_{v^2}(k) = \frac{1}{L^3}\int\frac{1}{2}|\mathbf{v}|^2\,d\mathbf{x} = \int E_{v^2}(k)\,dk.$$

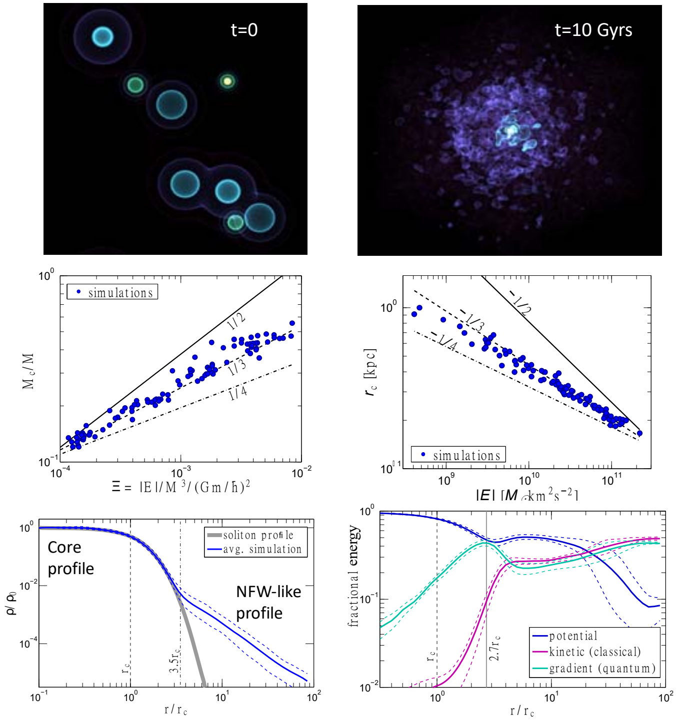


Fig.2 Top: Visualization of one of our realizations of 8 WaveDM halos merging into one halo with a central solitonic core displaying turbulence outside of the soliton ($r_{soliton} \approx 3.5r_c$).The box size is 1Mpc.
Middle: (Left)Core-mass to total mass vs Ξ relation, core mass depends on total energy E. (Right) Core radius vs Energy relation.
Bottom: Normalized density profiles and fractional energy of vs distance normalized to the core radius of each simulated halo.

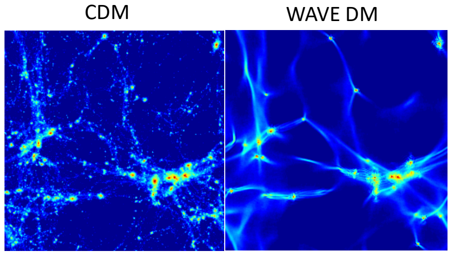
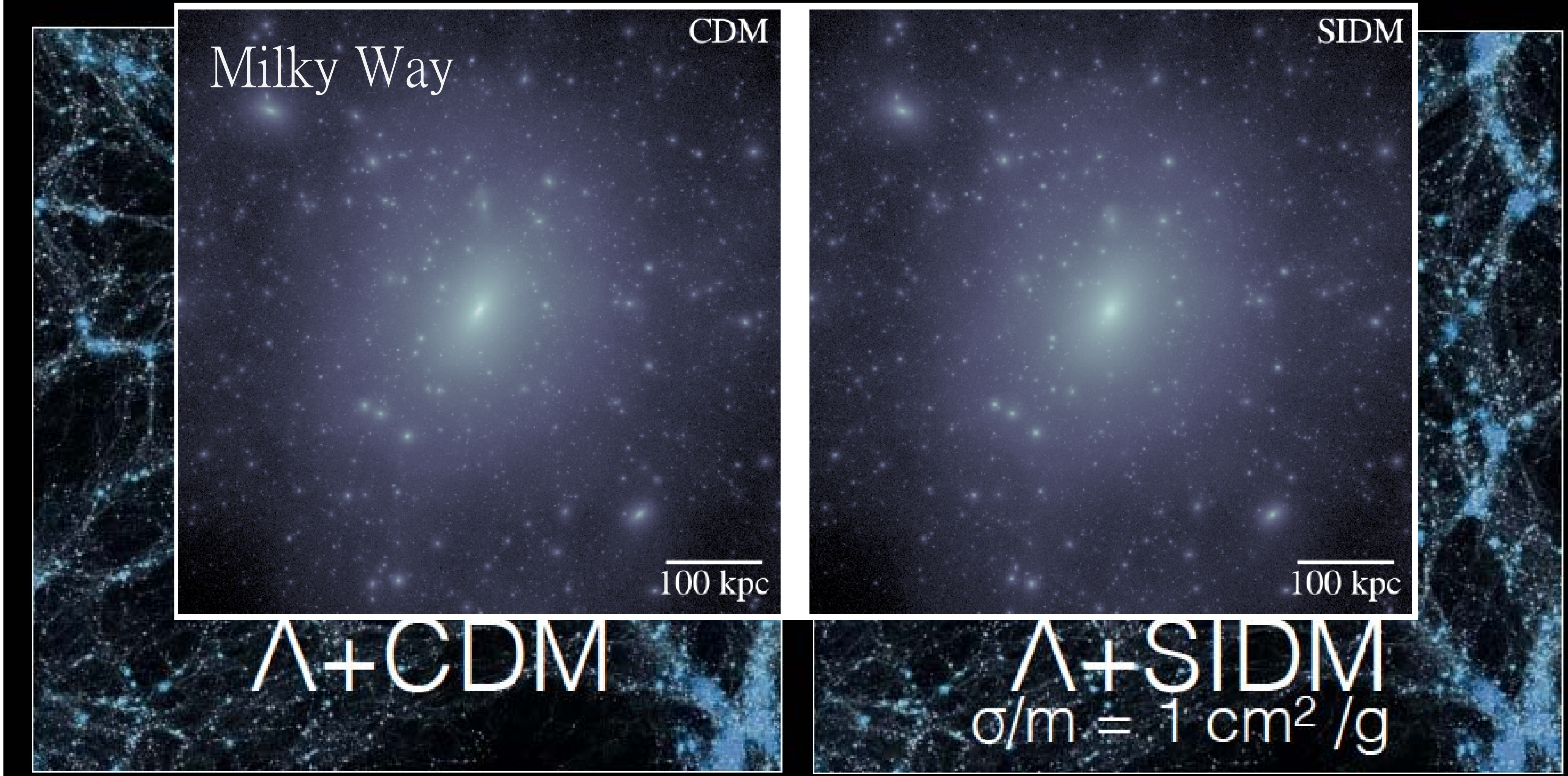


Fig. 3 Comparison of cosmological simulations with periodic boundary conditions in CDM and Wave DM cosmologies in a 1Mpc/h comoving box at z=0.
BEC/Wave DM shows less substructure in filaments and less clumpy halos than CDM.

Thank you

SIDM vs. CDM

- same large scale structure
- same DM halo mass functions

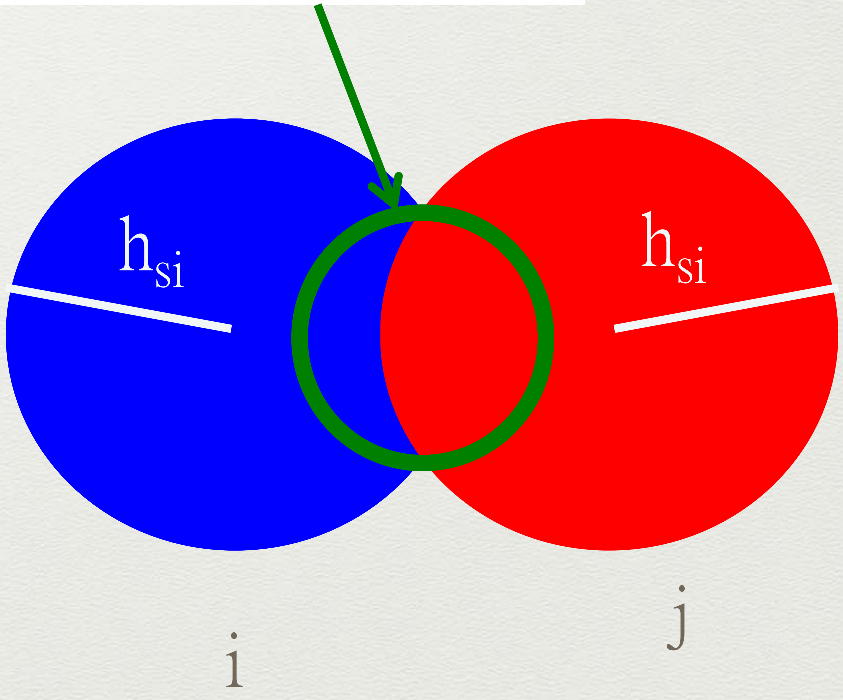


Self-interactions in the code computed as in Rocha+13

Pair-wise probability

$$\Gamma(i|j) = (\sigma/m) m_{\mathrm{p}} |\mathbf{v}_i - \mathbf{v}_j| g_{ji}$$

$$g_{ji} = \int_0^{h_{\mathrm{si}}} d^3\mathbf{x}' W(|\mathbf{x}'|, h_{\mathrm{si}}) W(|\delta\mathbf{x}_{ji} + \mathbf{x}'|, h_{\mathrm{si}})$$



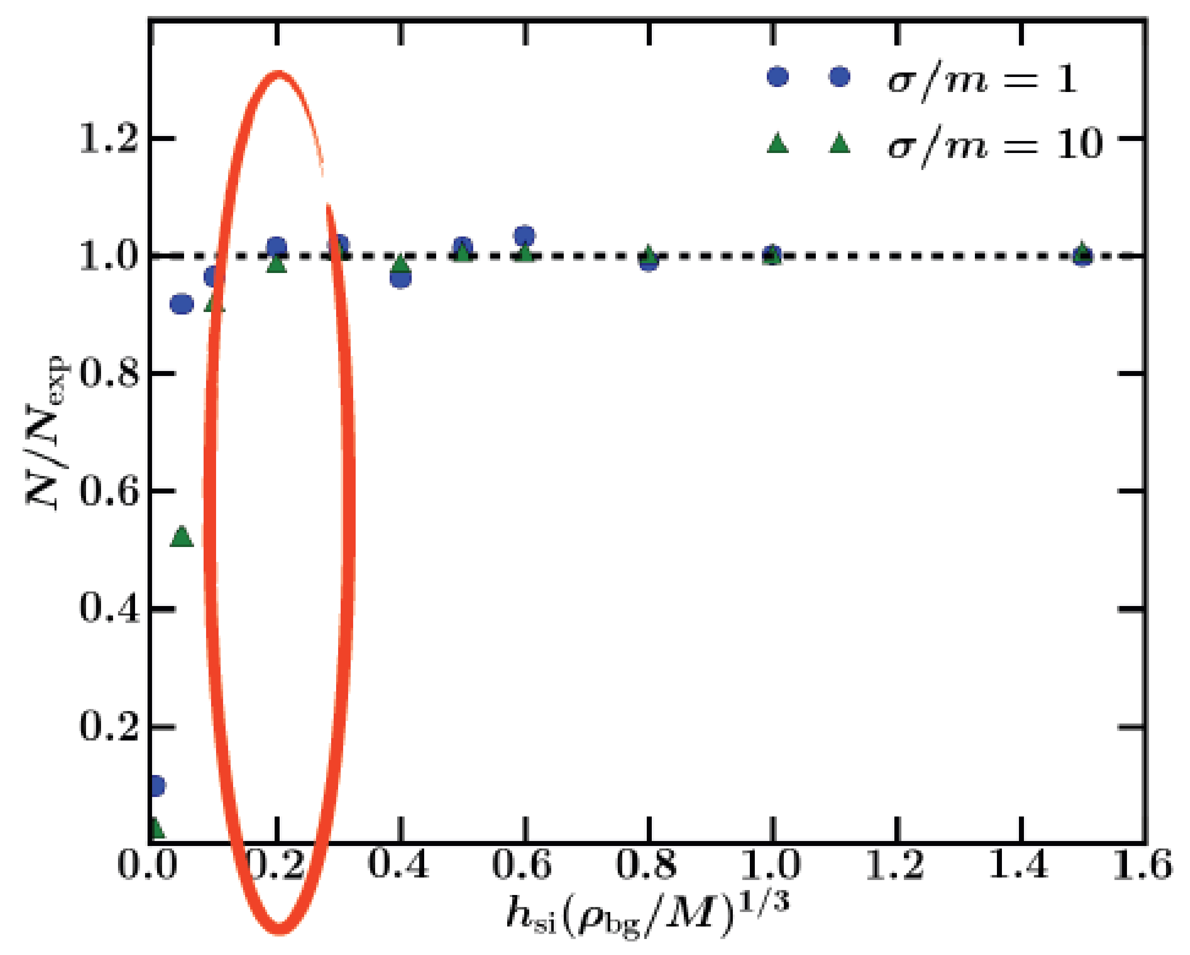
Probability of scattering

$$P(i|j) = \Gamma(i|j)\,\delta t$$

Interaction rate converges to the expected value for:

h_{si} >0.2*(the interparticle separation)

Wind tunnel test



Interaction rate converges to the expected value
When:

h_{si} >(0.2)(the interparticle separation)

Rocha et al. 2013
Peter et al. 2013