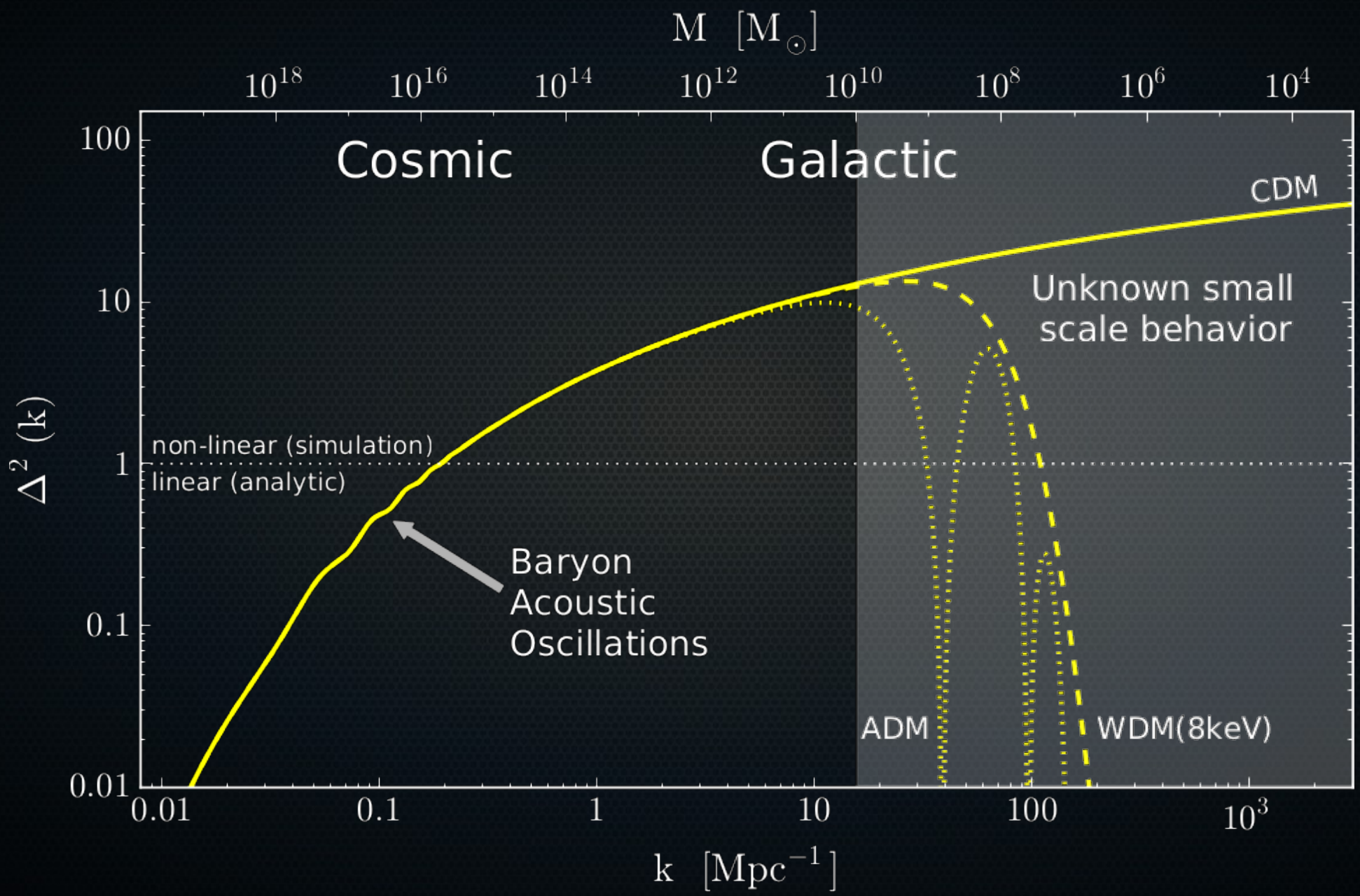
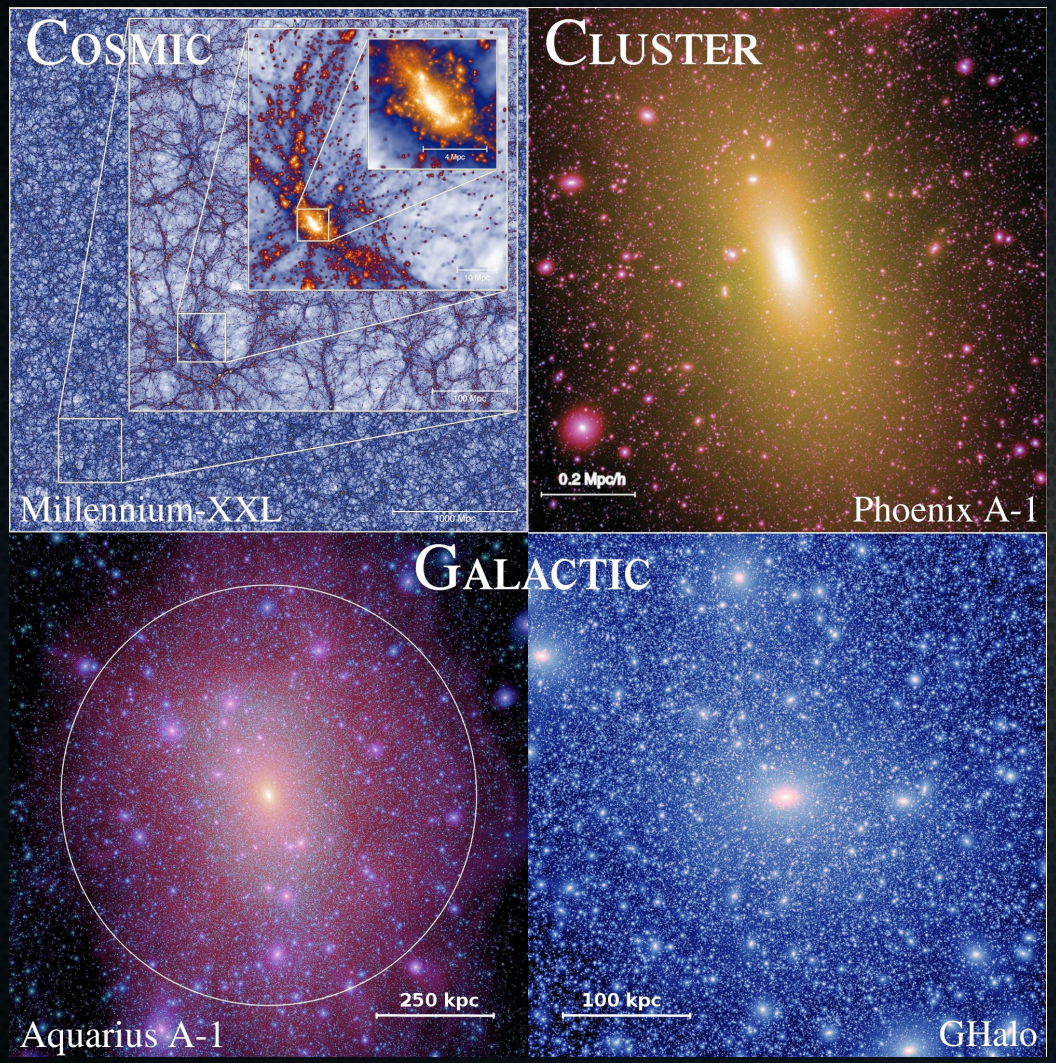
# N-body Simulations and Dark Matter: Status and Future

Michael Kuhlen, Berkeley

# The Domain of Dark Matter Simulations



# Current State Of The Art




Kuhlen, Vogelsberger & Angulo 2012 (arXiv:1209.5745)

DM-only simulations

**Cosmic**

| Name | Code | $L_{box}$ [$h^{-1}$Mpc] | $N_p$ [$10^9$] | $m_p$ [$h^{-1}$ $M_\odot$] | $\epsilon_{soft}$ [$h^{-1}$kpc] | $N_{halo}^{>100p}$ [$10^6$] |
|---|---|---|---|---|---|---|
| DEUS FUR | Ramses-Deus | 21000 | 550 | $1.2 \times 10^{12}$ | $40.0^\dagger$ | 145 |
| Horizon Run 3 | Gotpm | 10815 | 370 | $2.5 \times 10^{11}$ | 150.0 | ~ 190 |
| Millennium-XXL | Gadget-3 | 3000 | 300 | $6.2 \times 10^9$ | 10.0 | 170 |
| Horizon-4Π | Ramses | 2000 | 69 | $7.8 \times 10^9$ | $7.6^\dagger$ | ~ 40 |
| Millennium-II | Gadget-3 | 100 | 10 | $6.9 \times 10^6$ | 1.0 | 2.3 |
| MultiDark Run1 | Art | 1000 | 8.6 | $8.7 \times 10^9$ | $7.6^\dagger$ | 3.3 |
| Bolshoi | Art | 250 | 8.6 | $1.4 \times 10^8$ | $1.0^\dagger$ | 2.4 |

$^\dagger$For AMR simulations (Ramses, Art) $\epsilon_{soft}$ refers to the highest resolution cell width.

**Cluster**

| Name | Code | $L_{hires}$ [$h^{-1}$Mpc] | $N_{p,hires}$ [$10^9$] | $m_{p,hires}$ [$h^{-1}$ $M_\odot$] | $\epsilon_{soft}$ [$h^{-1}$kpc] | $N_{sub}^{>100p}$ [$10^3$] |
|---|---|---|---|---|---|---|
| Phoenix A-1 | Gadget-3 | 41.2 | 4.1 | $6.4 \times 10^5$ | 0.15 | 60 |

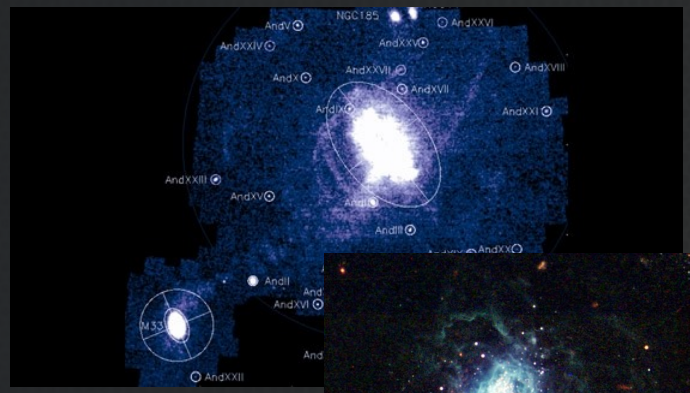
**Galactic**

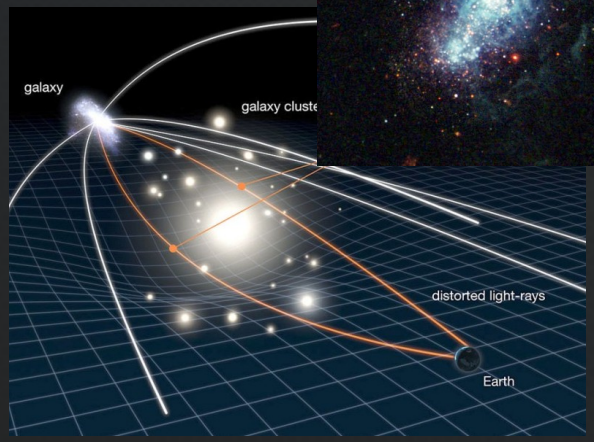
| Name | Code | $L_{hires}$ [Mpc] | $N_{p,hires}$ [$10^9$] | $m_{p,hires}$ [$M_\odot$] | $\epsilon_{soft}$ [pc] | $N_{sub}^{>100p}$ [$10^3$] |
|---|---|---|---|---|---|---|
| Aquarius A-1 | Gadget-3 | 5.9 | $4.3 \times 10^9$ | $1.7 \times 10^3$ | 20.5 | 82 |
| GHalo | Pkdgrav2 | 3.89 | $2.1 \times 10^9$ | $1.0 \times 10^3$ | 61.0 | 43 |
| Via Lactea II | Pkdgrav2 | 4.86 | $1.0 \times 10^9$ | $4.1 \times 10^3$ | 40.0 | 13 |

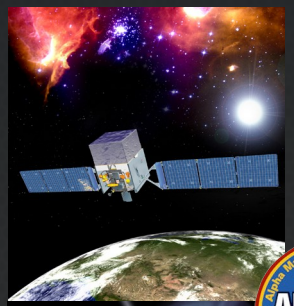
# Dark Matter Detection Applications

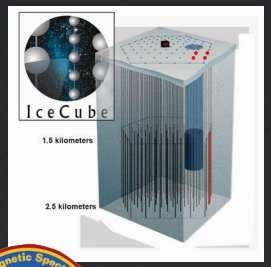
## Astro-physical Probes

- Dwarf galaxy census
- Stellar kinematics
- Stellar streams
- Gravitational lensing



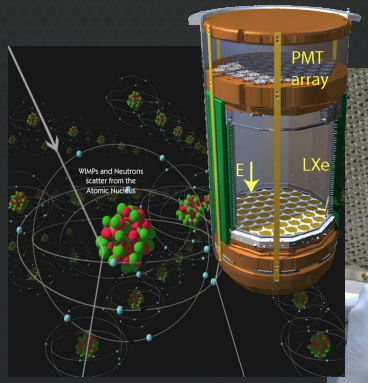


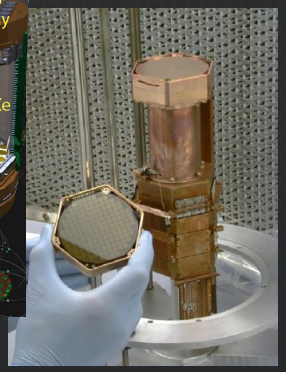





## Indirect Detection (Annihilation)

- Extra-galactic DGRB
- Galactic DGRB
- Clusters
- Galactic Center
- Milky Way Dwarfs
- Dark Subhalos
- e+/e- from local annihilation
- Neutrinos from Earth & Sun
- “Boost factor”



## Direct Detection (Nuclear Recoils)

- standard case: “vanilla” WIMPs
- low mass DM, inelastic DM, etc.
- directionally sensitive experiments

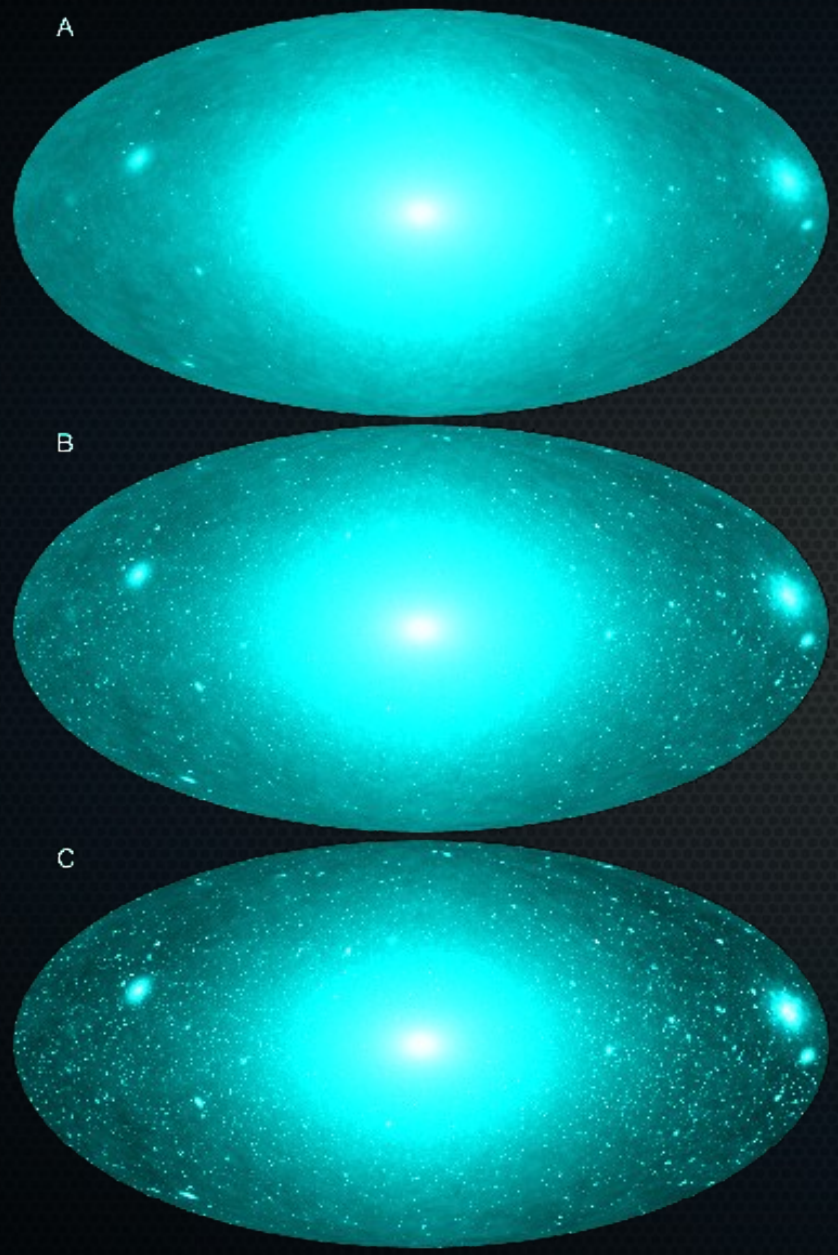
# N-body Simulations and DM Detection

From Kuhlen, Vogelsberger & Angulo 2012 (arXiv:1209.5745)

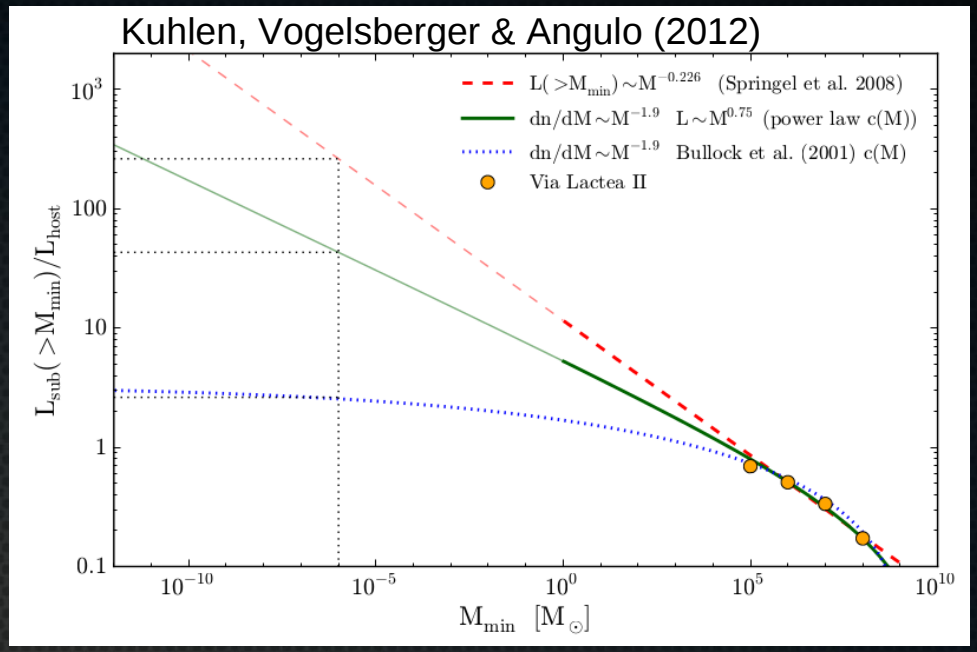
| | | LSS | | Halos | | | | Substructure | | | | | | Local | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | voids, walls, filaments | halo mass functions | concentration-mass relation | halo shapes | density profiles | pseudo-phase-space density | mass (or $V_{max}$) functions | density profiles | central density | spatial distribution | streams | folds & caustics | local density | tidal streams | dark disk |
| Astrophysical | Dwarf galaxy abundance | | | | ■ | ■ | | ■ | ■ | ■ | ■ | | | | ■ | ■ |
| | Dwarf galaxy kinematics | | | | | | | ■ | ■ | ■ | | | | | | |
| | Stellar streams | | | | ■ | ■ | | ■ | | | ■ | ■ | | | | |
| | Gravitational lensing | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | | ■ | | | | | |
| Indirect Detection | Extra-galactic DGRB | ■ | ■ | ■ | | ■ | | ■ | ■ | | | | | | | |
| | Galactic DGRB | | | | ■ | ■ | | ■ | ■ | | ■ | | | | | |
| | Clusters | | | ■ | ■ | ■ | | ■ | ■ | | | | | | | |
| | Galactic Center | | | | | ■ | | | | | | | | | | |
| | Milky Way Dwarfs | | | ■ | | ■ | | | ■ | ■ | | | | | | |
| | Dark Subhalos | | | ■ | | ■ | | ■ | ■ | ■ | ■ | | | | | |
| | Local anti-matter | | | | | | | | | | | | | ■ | | |
| | Neutrinos from Earth & Sun | | | | | | | | | | | | | ■ | ■ | ■ |
| | Substructure boost | | | | | | | ■ | ■ | | ■ | | ■ | | | |
| | Sommerfeld boost | | | | | | ■ | | | | | ■ | ■ | | ■ | ■ |
| Direct | "Vanilla" ~ 100 GeV DM | | | | | | | | | | | | | ■ | | |
| | light / inelastic DM | | | | | | | | | | | | | ■ | ■ | ■ |
| | axions | | | | | | | | | | | | ■ | ■ | ■ | ■ |
| | directionally sensitive experiments | | | | | | | | | | | | | ■ | ■ | ■ |

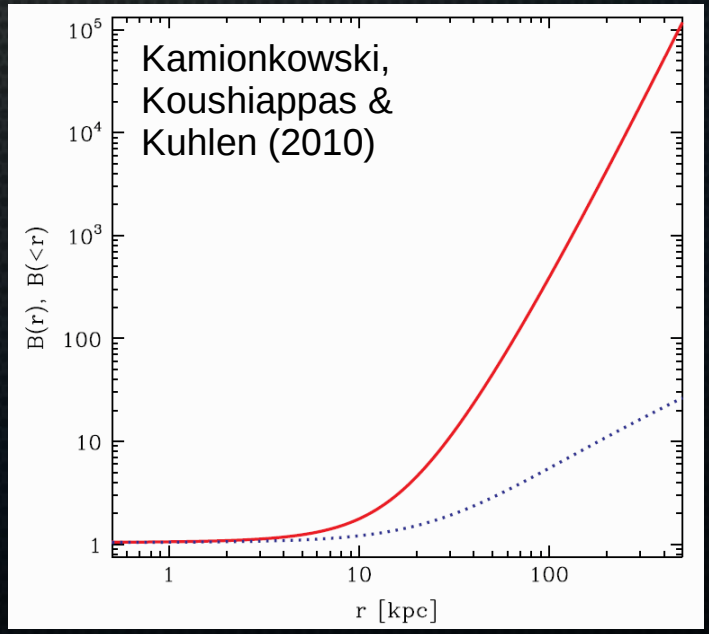
# N-body Simulations and Indirect Detection

Calcáneo-Roldán & Moore (2000), Kuhlen et al. (2008, 2009), Pieri et al. (2008, 2011), Springel et al. (2008), etc.




Kuhlen et al. (2009)

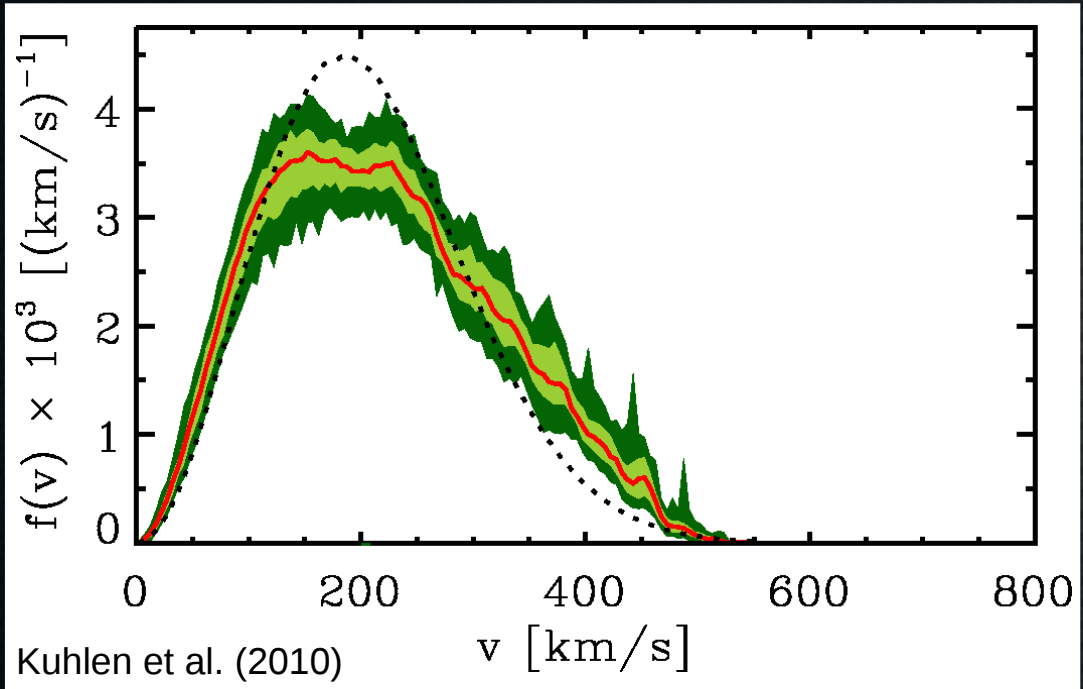


# N-body Simulations and Direct Detection

Hansen et al. (2005), Kuhlen et al. (2010, 2012), Vogelsberger et al. (2008, 2009), etc.

Non-Maxwellian f(v)
Velocity Substructure




Kuhlen et al. (2010)

Debris Flows

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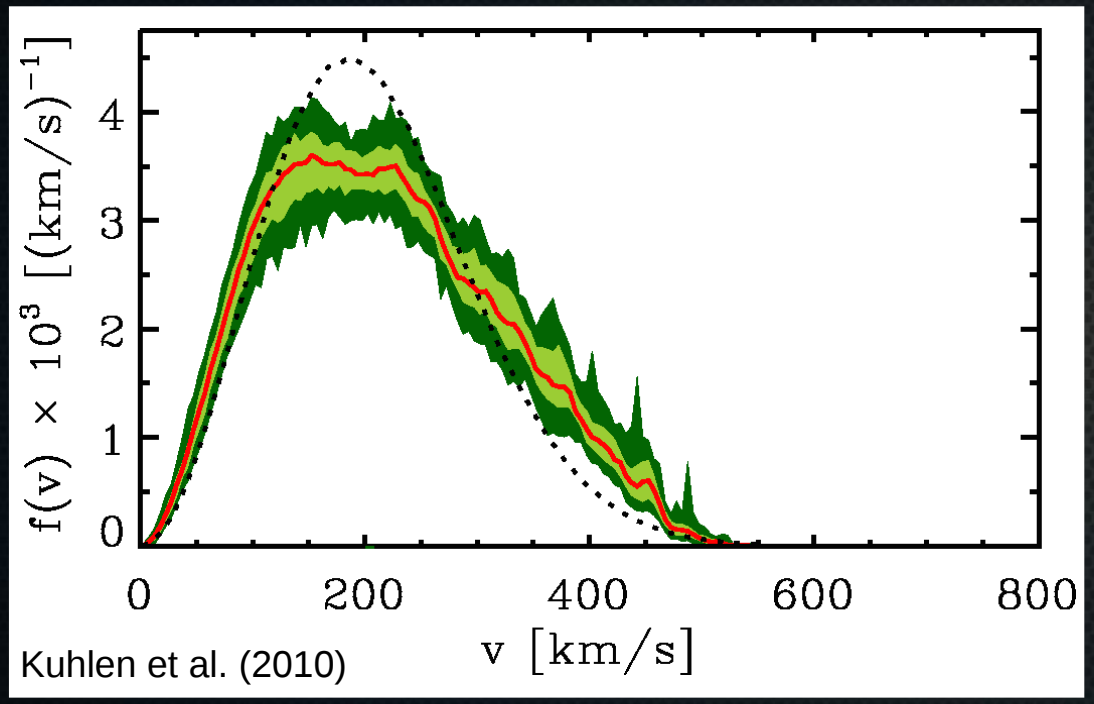


Kuhlen et al. (2010)

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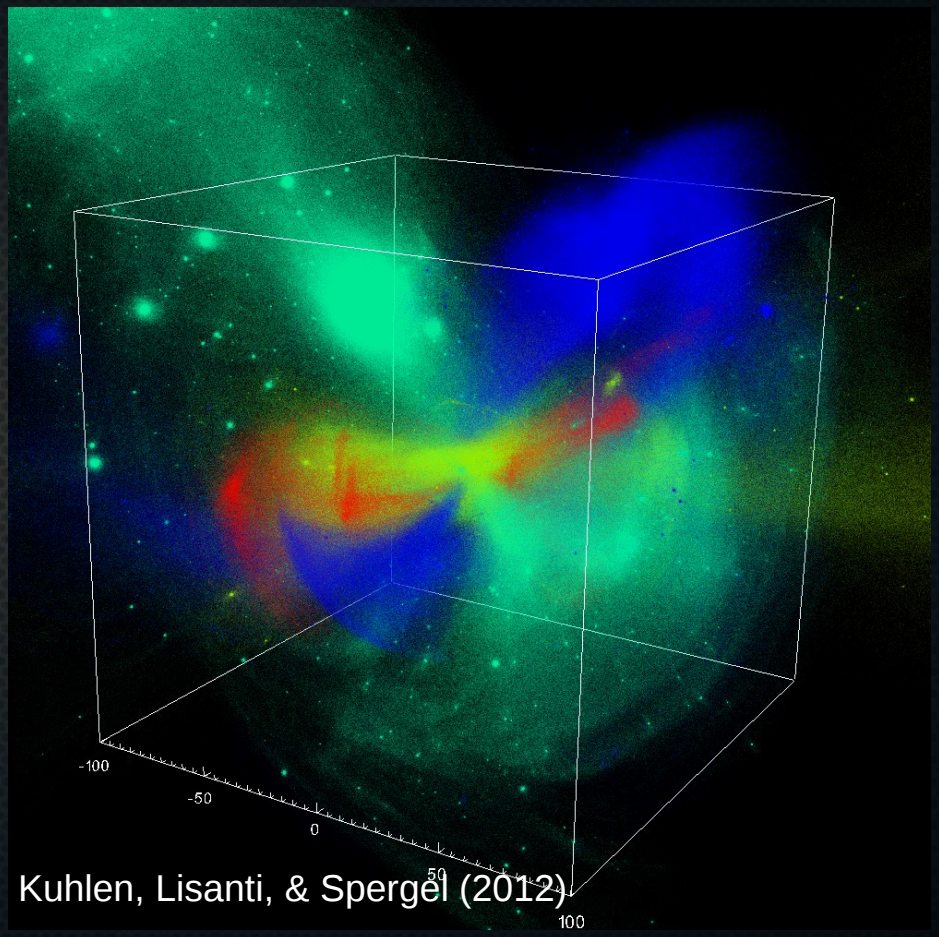
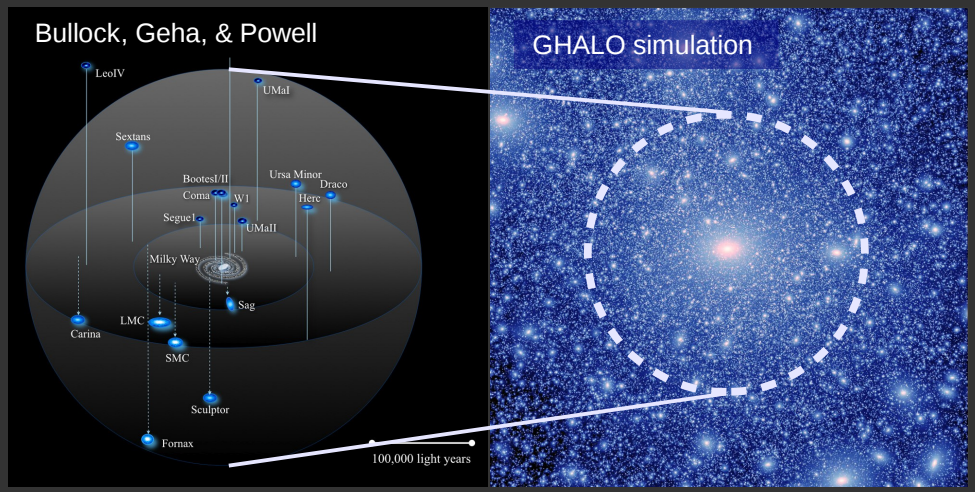


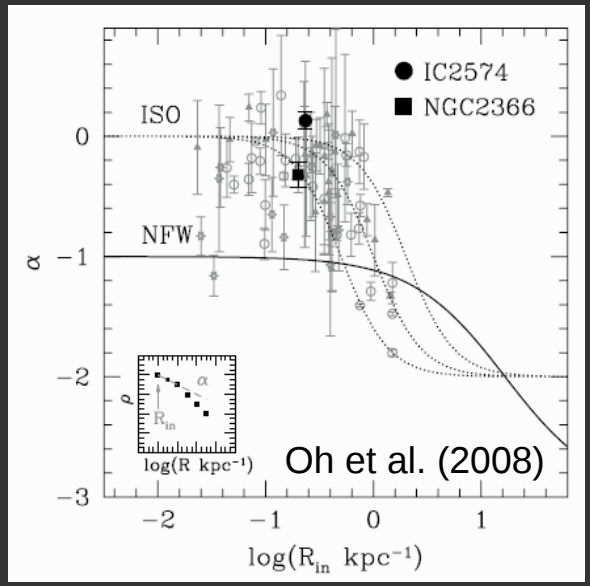

Kuhlen, Lisanti, & Spergel (2012)

# Small Scale Challenges for CDM

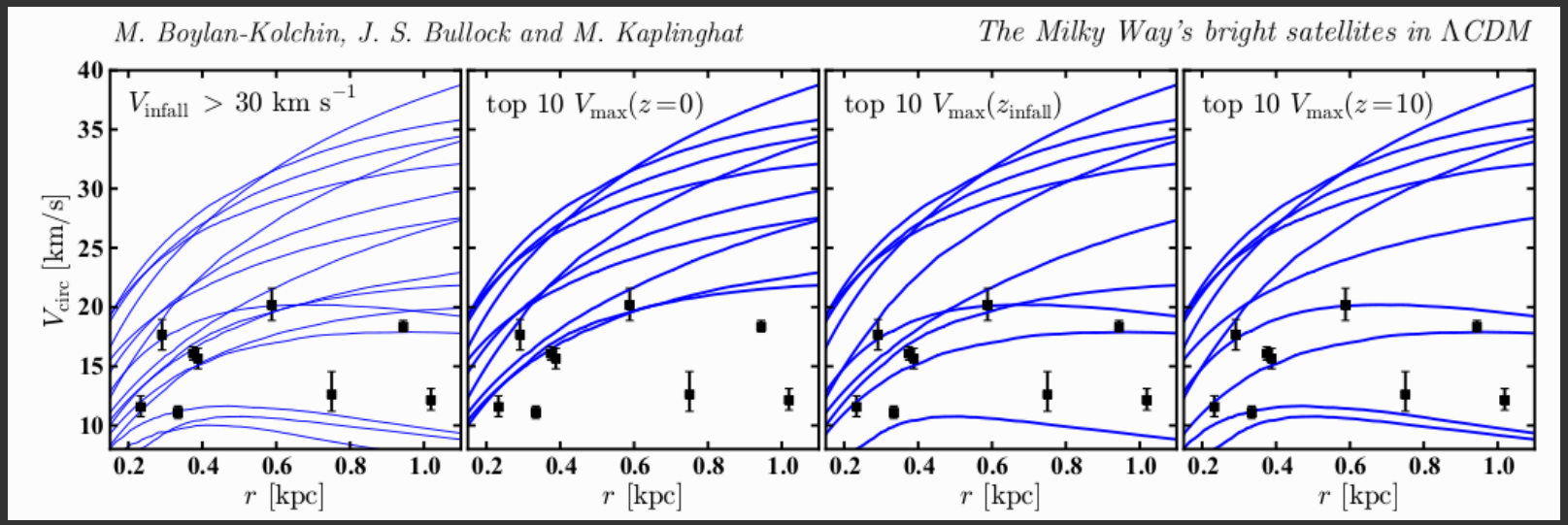
## Missing Satellites Problem




## Cusp/Core Problem




## Too Big To Fail Problem



# The Future: Beyond Cold & Collisionless DM-only Simulations

Cold and Collisionless DM-only Simulations
[Millennium II, Via Lactea II, Aquarius, etc.]

Alternative Dark Matter Physics

Warm Dark Matter
Self-Interacting Dark Matter
???

Include Baryonic Physics

Gas Cooling
Star Formation
Feedback

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# Beyond DM-only: including baryonic physics

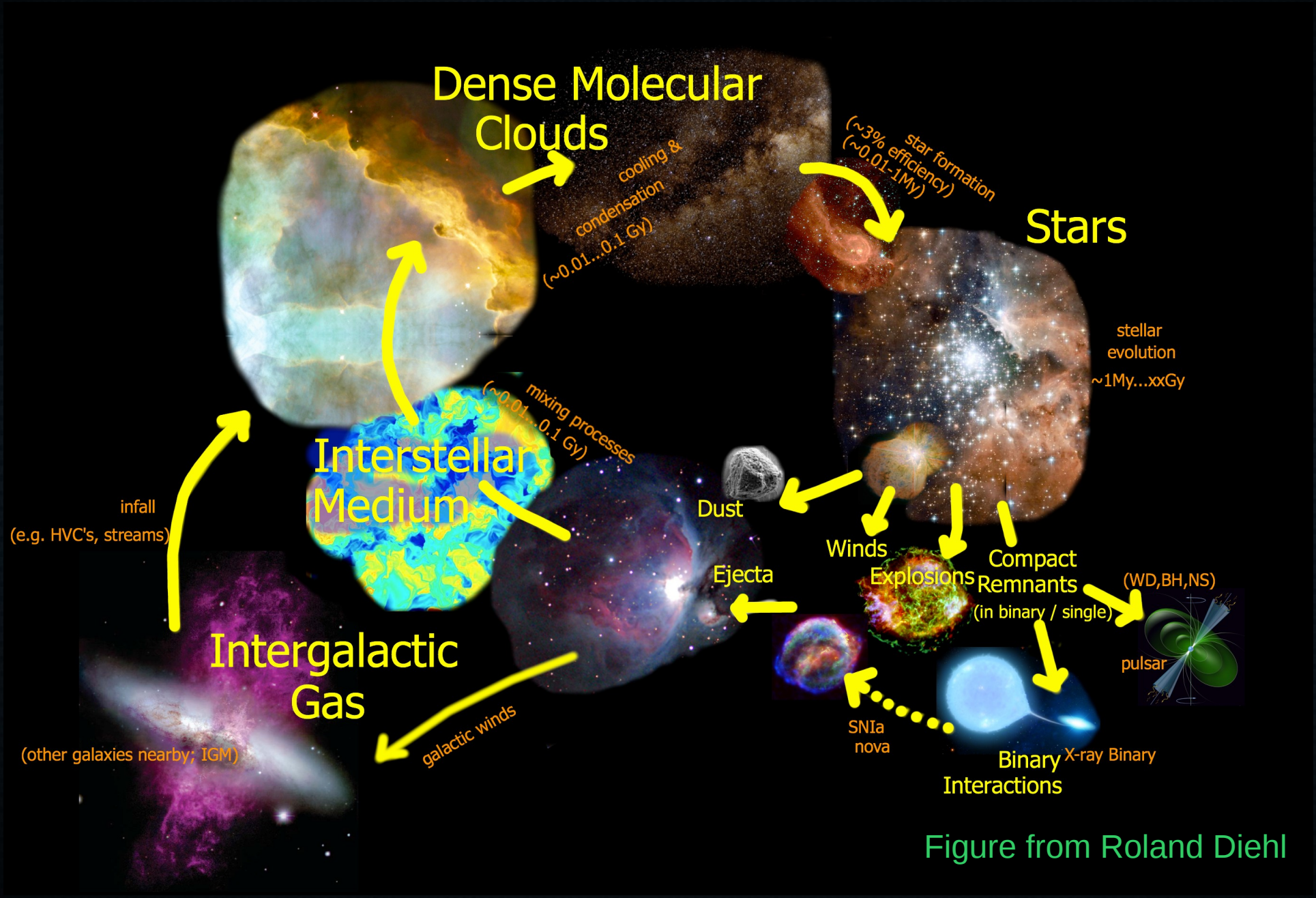
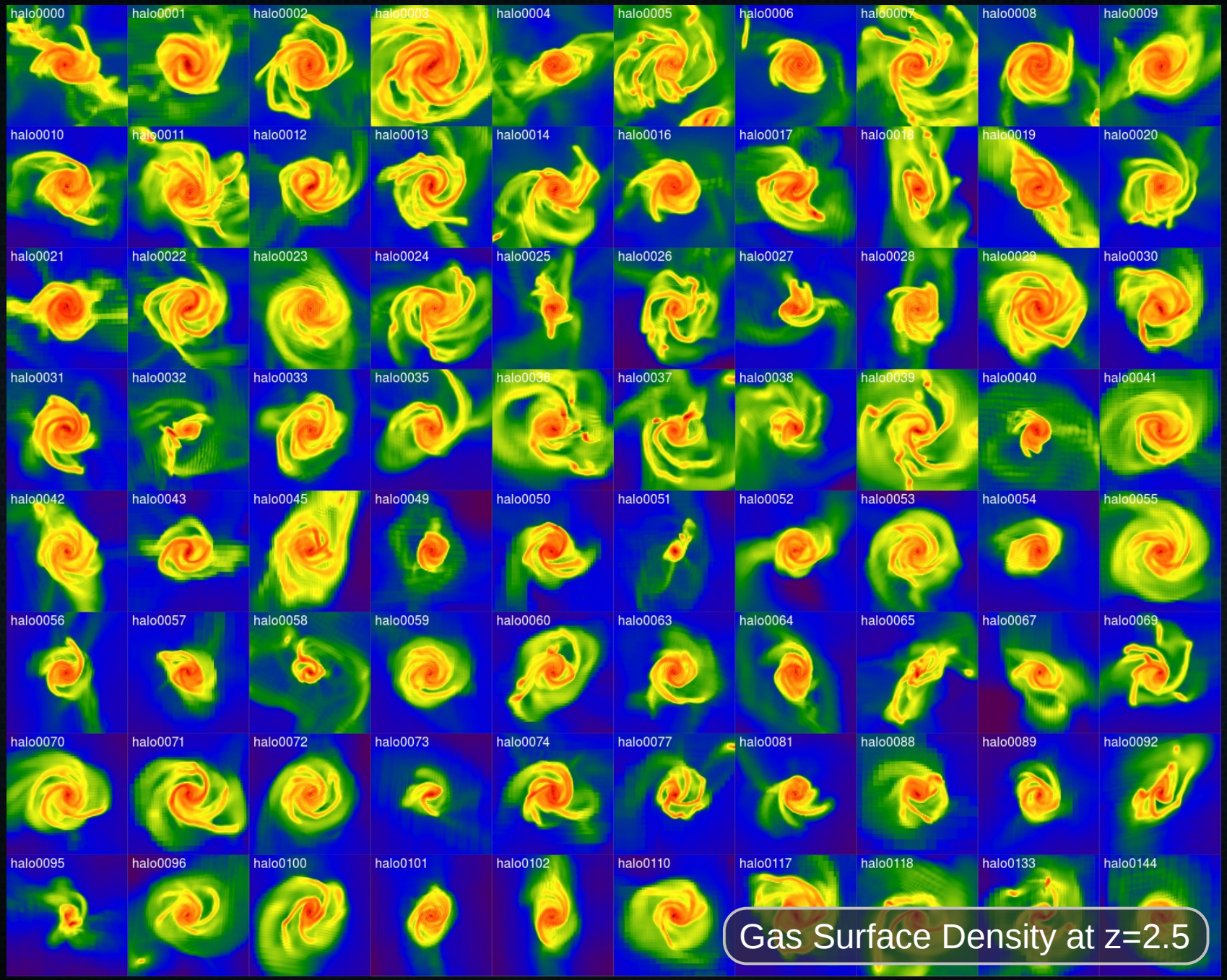



Figure from Roland Diehl

# Disk galaxies in cosmological full-box AMR simulations with Enzo




M. Kuhlen (in prep.)

# Disk galaxies in cosmological full-box AMR simulations with Enzo

Star Formation Rate Surface Density at z=2.5

M. Kuhlen (in prep.)

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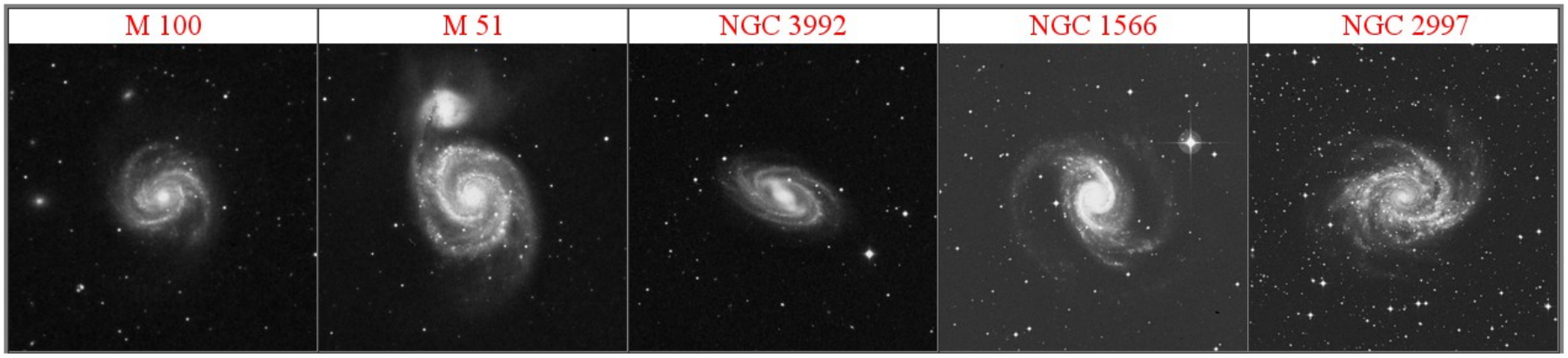
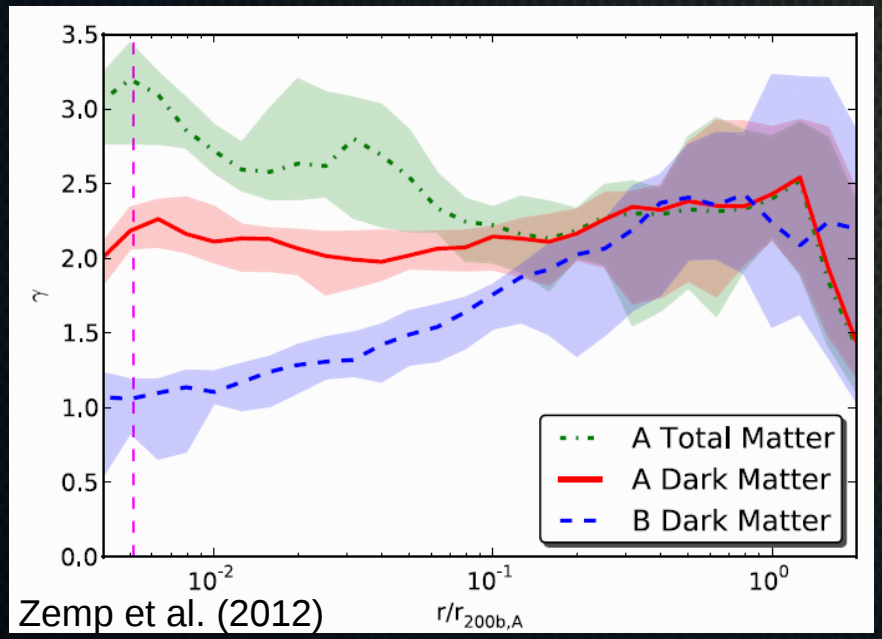


# Beyond DM-only: including baryonic physics

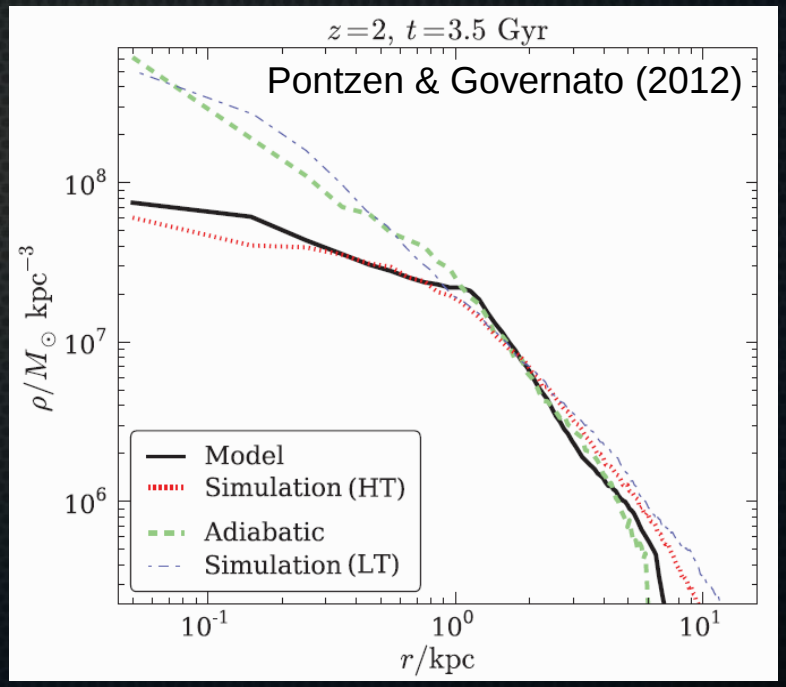
Often not even the sign of the effect is known...

Adiabatic contraction steepens the DM profile and **increases central DM densities**.

Impulsive supernova (or AGN) feedback **removes DM from the center** and flattens the DM cusp.




Zemp et al. (2012)

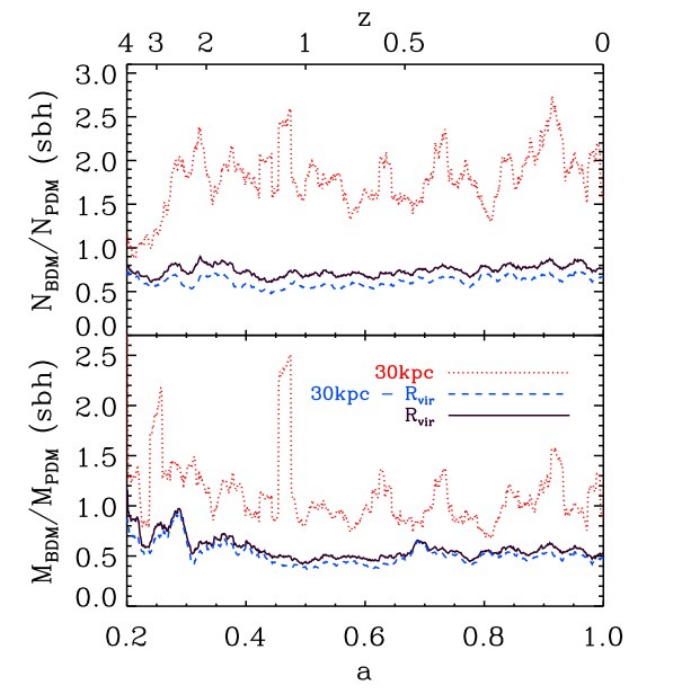


# Beyond DM-only: including baryonic physics

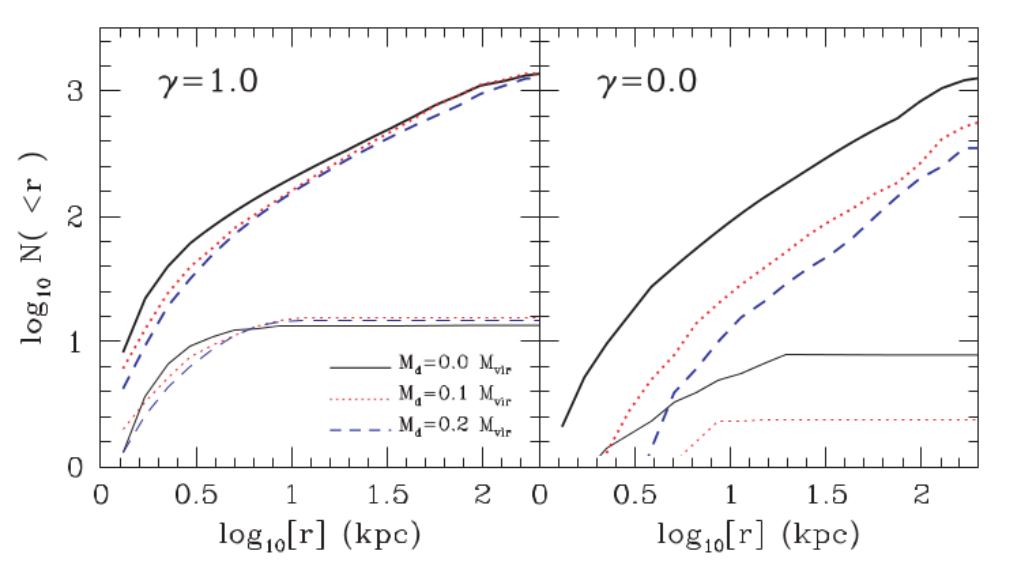
Often not even the sign of the effect is known...

Baryonic condensation in the centers of satellite halos makes them more resilient to tidal disruption and **increases abundance of inner subhalos**.

The deeper host halo potential, satellite cusp removal, and disk passages enhance tidal stripping and **reduce the number of surviving subhalos**.




Romano-Diaz et al. (2010)




Peñarrubia et al. (2010)

# The Eris Simulation

**For more details see Guedes et al. 2011**

Cosmological SPH Zoom-in Simulation

7 million DM particles ($10^5$ $M_\odot$)

3 million gas particles ($2\times10^4$ $M_\odot$)

8.6 million star particles ($4\text{-}6\times10^3$ $M_\odot$)

- radiative cooling
  (Compton, atomic, low-T metallicity-dependent)
- heating from cosmic UV
  (~ Haardt & Madau 1996)
- Supernova feedback ($\varepsilon_{SN}$=0.8)
  (Stinson et al. 2006)
- Star formation
  - threshold: $n_{SF}$ = 5 atoms/cm$^3$
  - efficiency: $\varepsilon_{SF}$ = 0.1
  - IMF: Kroupa et al. 1993
  - No AGN feedback

**Results in a realistic looking Milky-Way-like spiral disk galaxy at z=0.**

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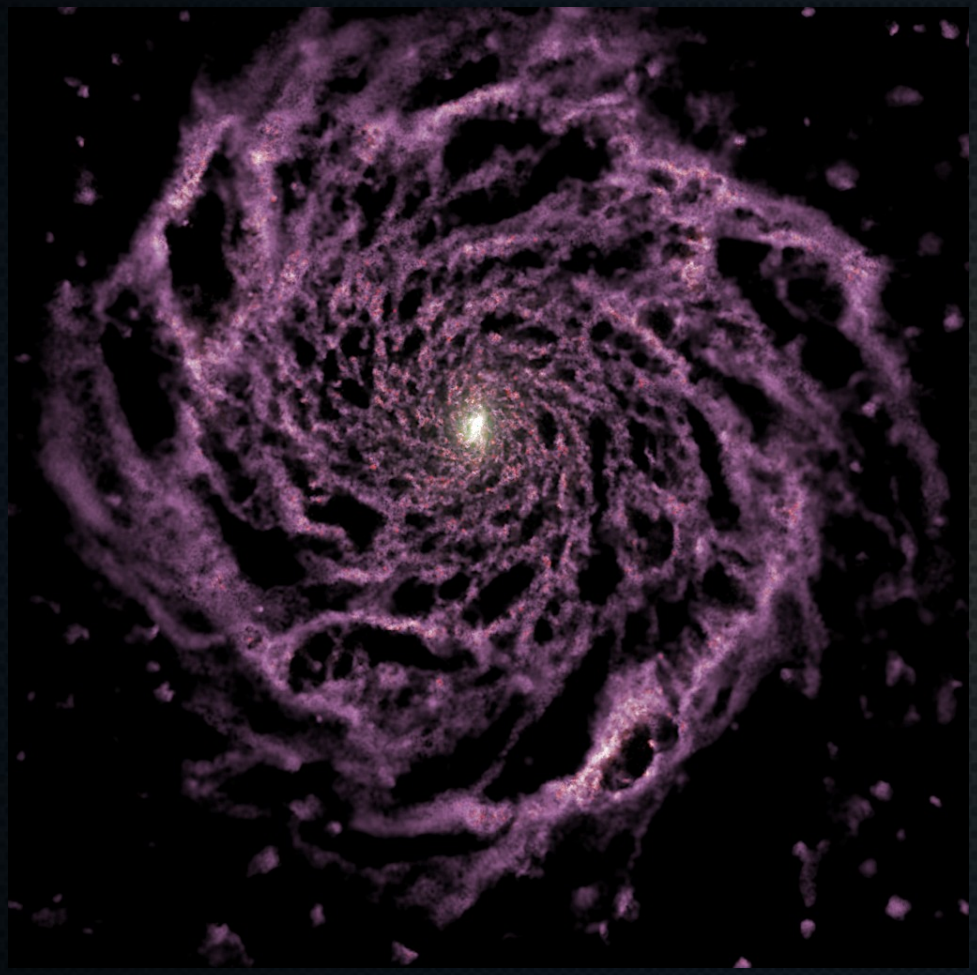

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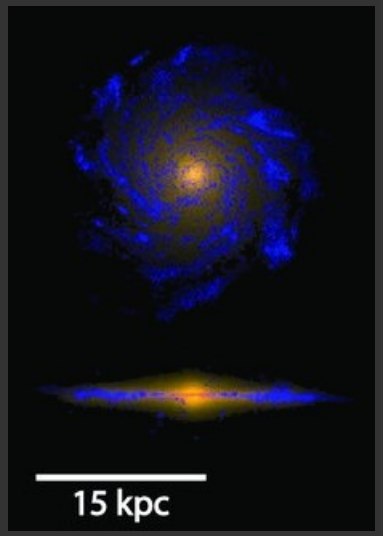
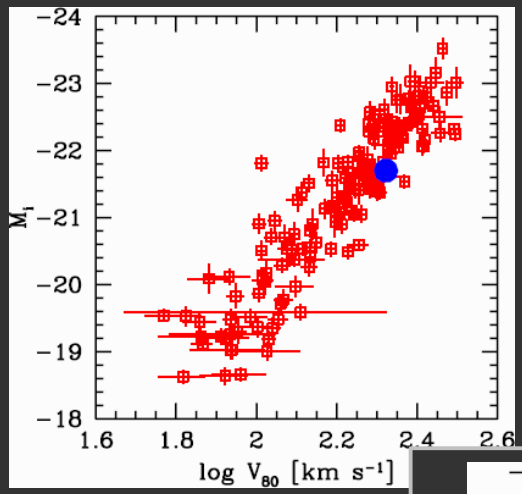
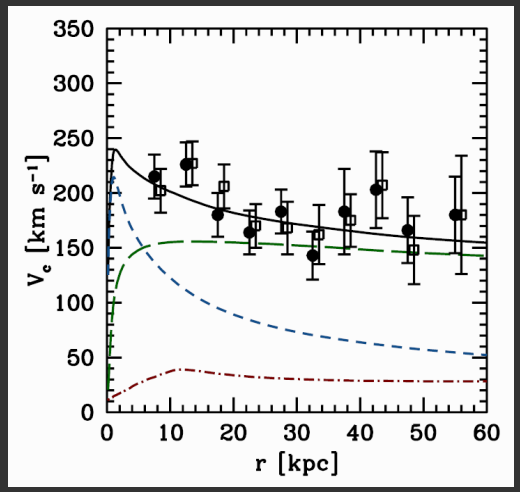
# The Eris Simulation

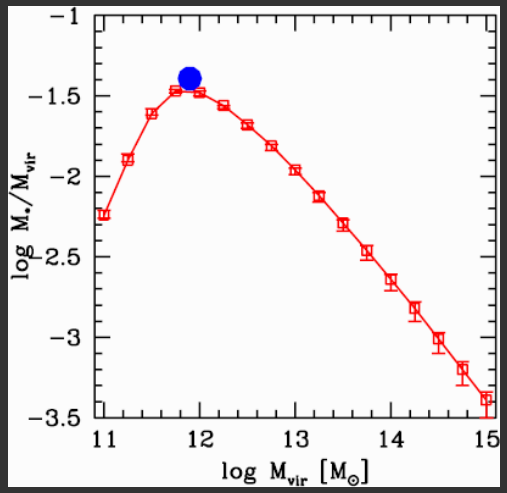
I-band (Sunrise) Bulge/Disk = 0.35, consistent with Sb, Sbc galaxies (Graham & Worley 2008).




Lies on Tully-Fisher relation from Pizagno et al. 2007.



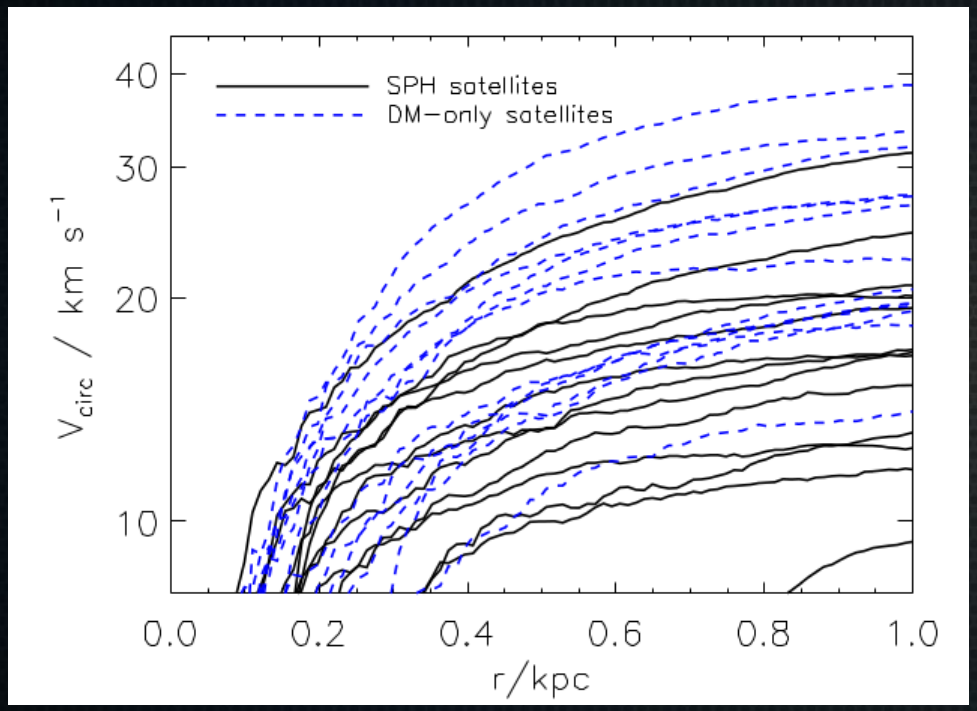

Lies on Behroozi et al. (2010) z=0 stellar-mass-halo-mass relation.

Slowly falling rotation curve, which matches Xue et al. (2008) SDSS measurement using BHB stars out to 60 kpc.

# Baryonic Solutions

## Results from hydro simulation...

[similar to Eris: GASOLINE SPH code, slightly poorer resolution, same feedback prescription, $H_2$-regulated SF; see Zolotov et al. 2012 & Brooks & Zolotov 2012 for details.]




Zolotov et al. (2012)

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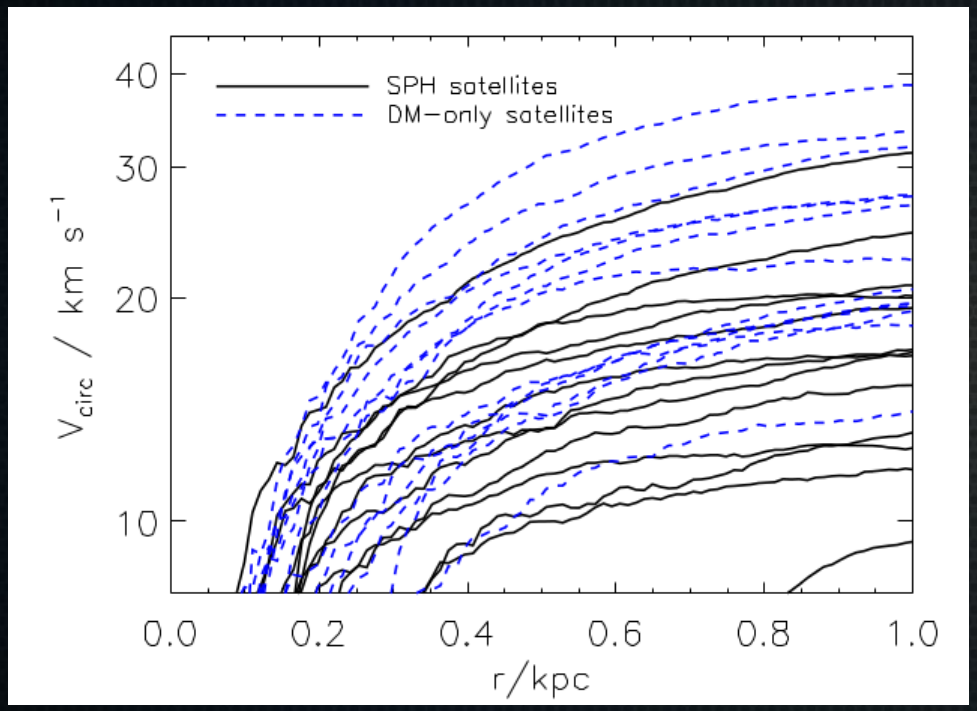
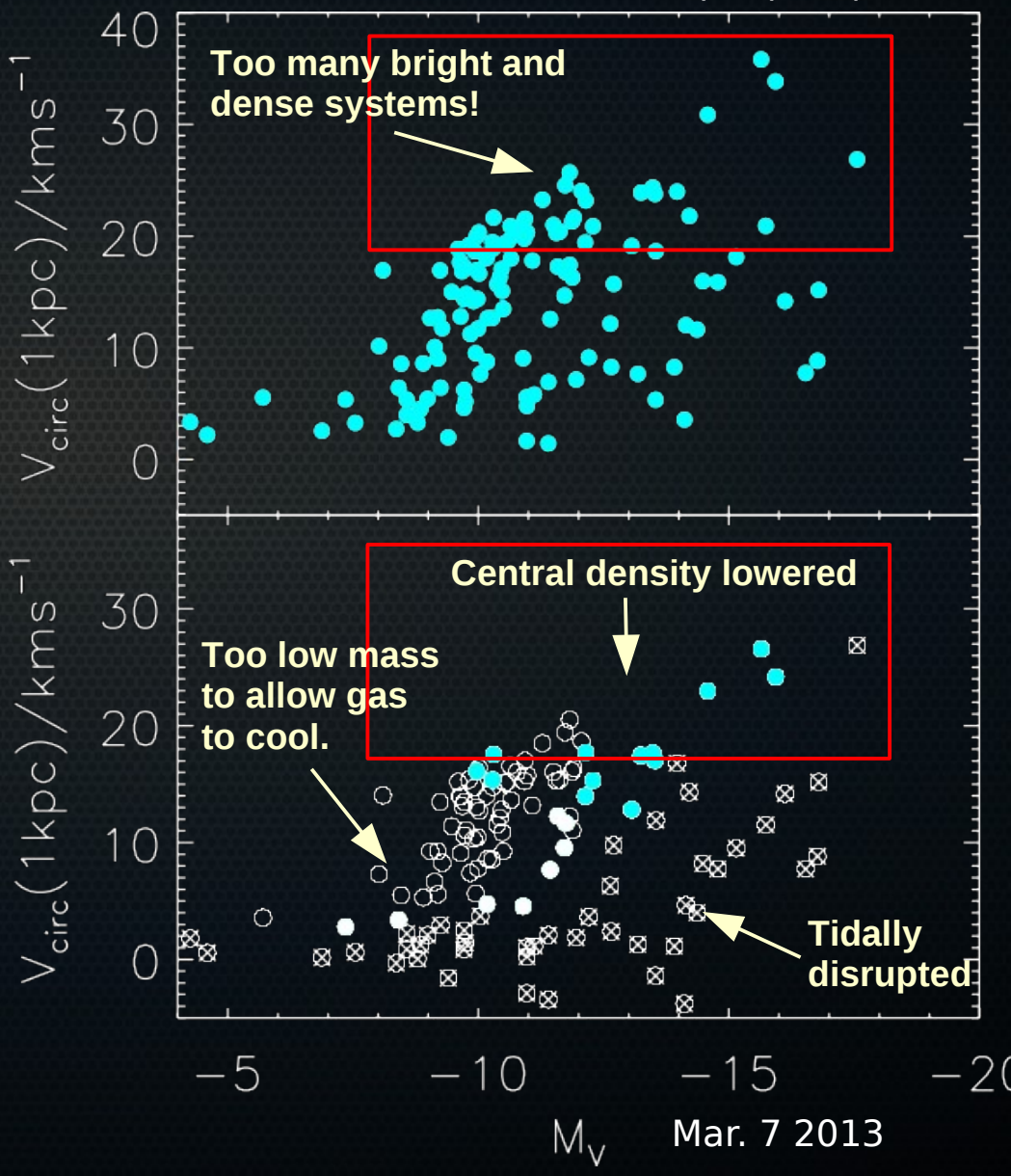



Zolotov et al. (2012)

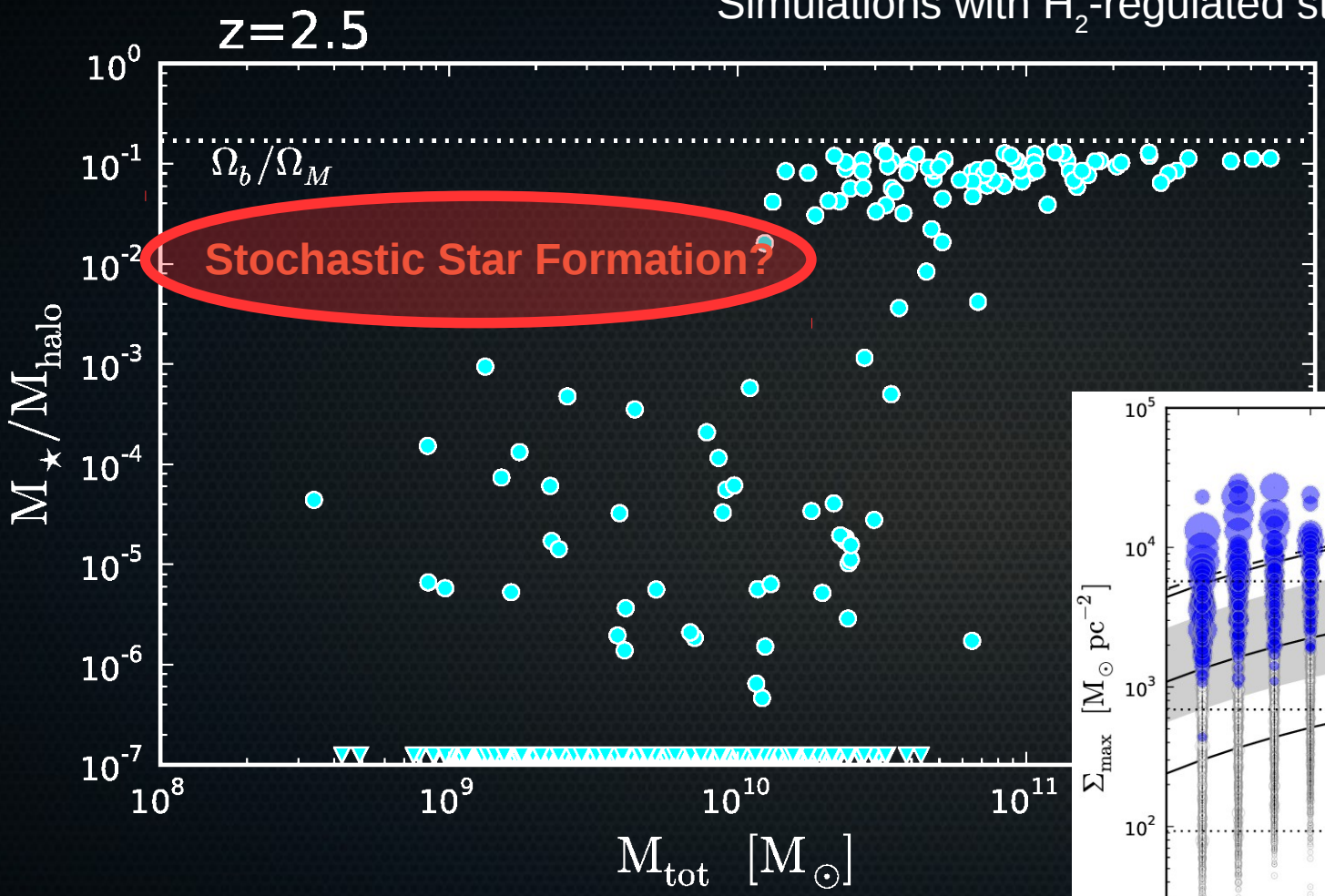
## ... applied to Via Lactea II.

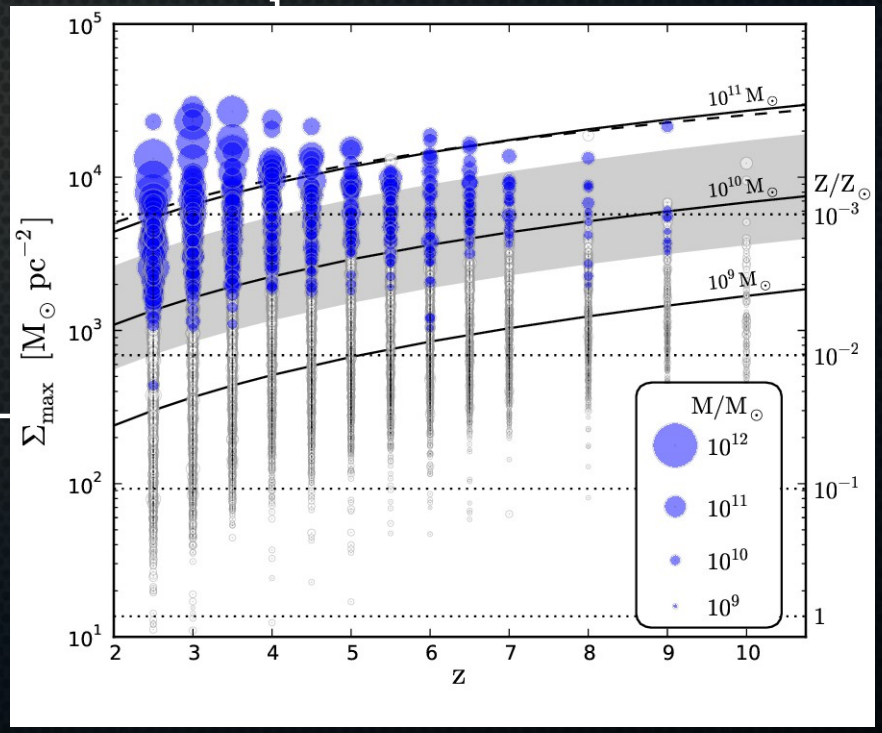
Brooks, Kuhlen, Zolotov, & Hooper (2012)



# Baryonic Solutions

Simulations with $H_2$-regulated star formation

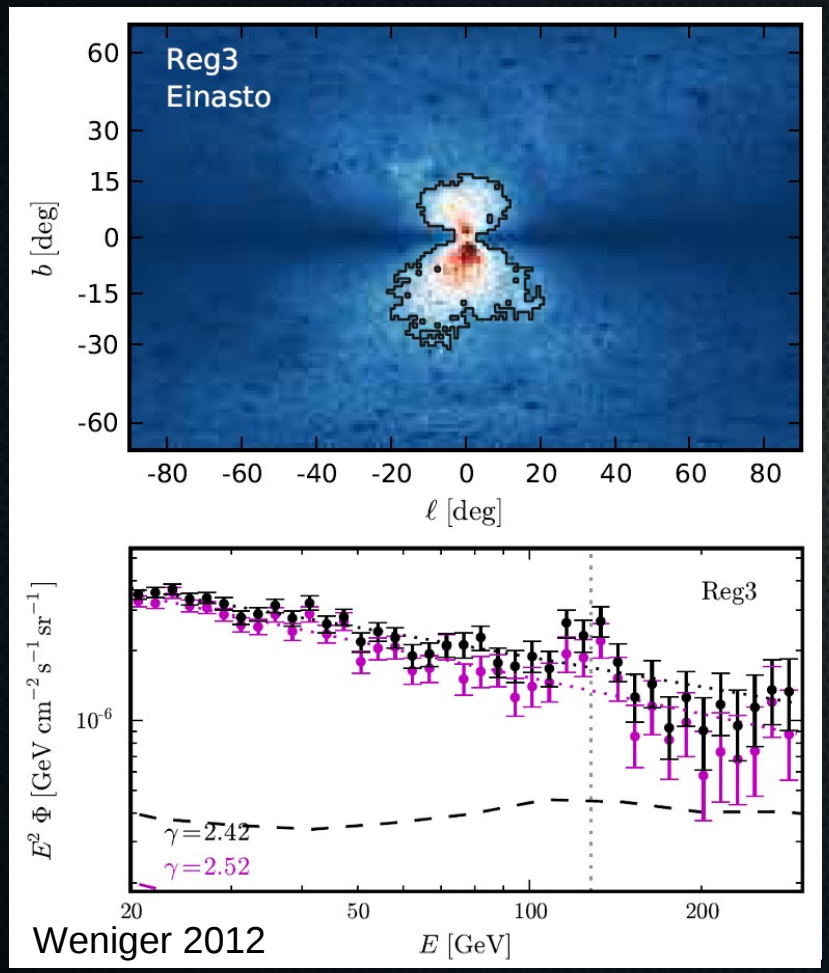



Kuhlen et al. (in preparation)

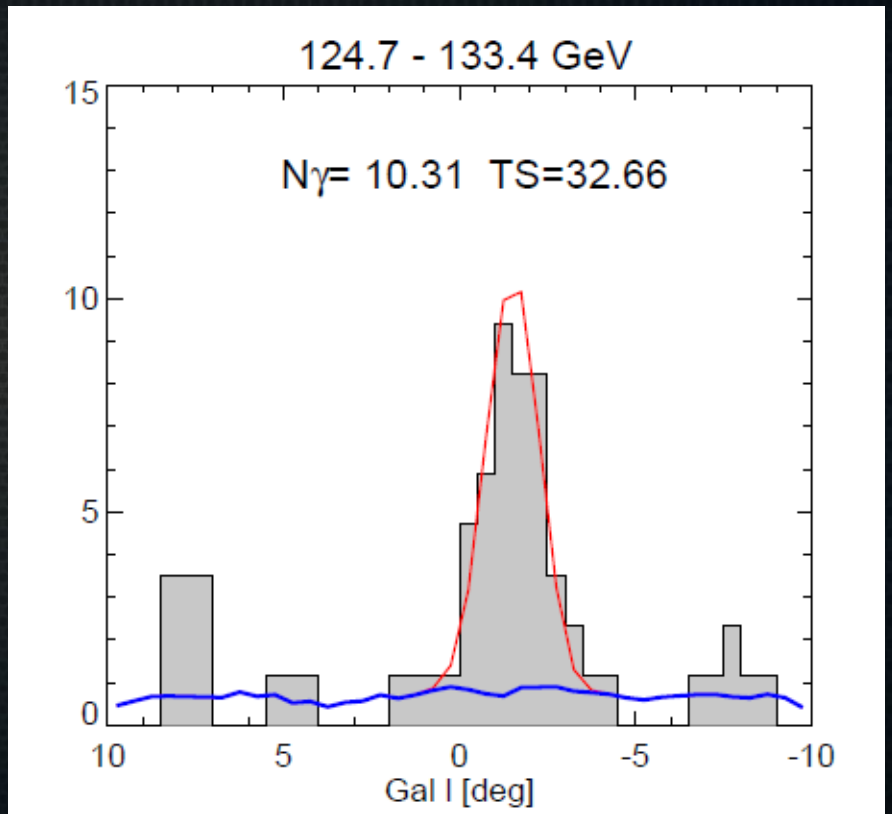
# Baryonic Effects on DM at the Galactic Center

## 130 GeV Line from the Galactic Center




Weniger 2012

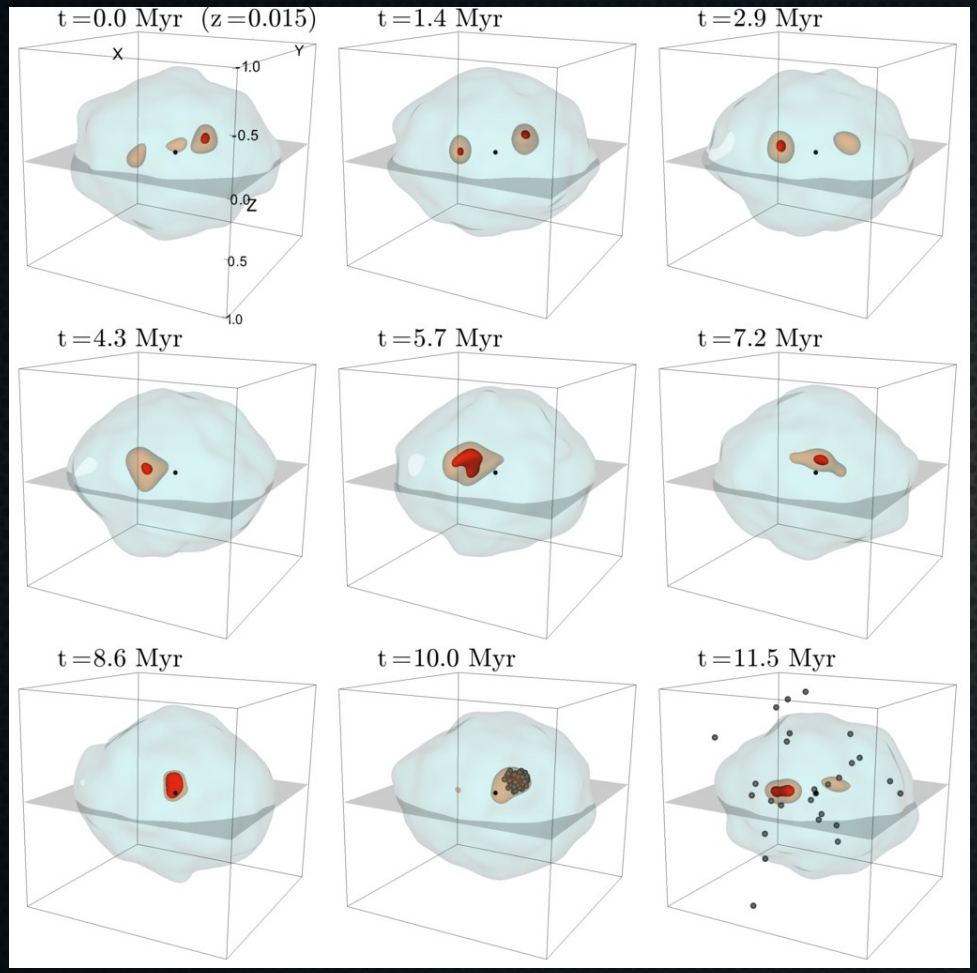
Offset from center?
Strike against DM annihilation?

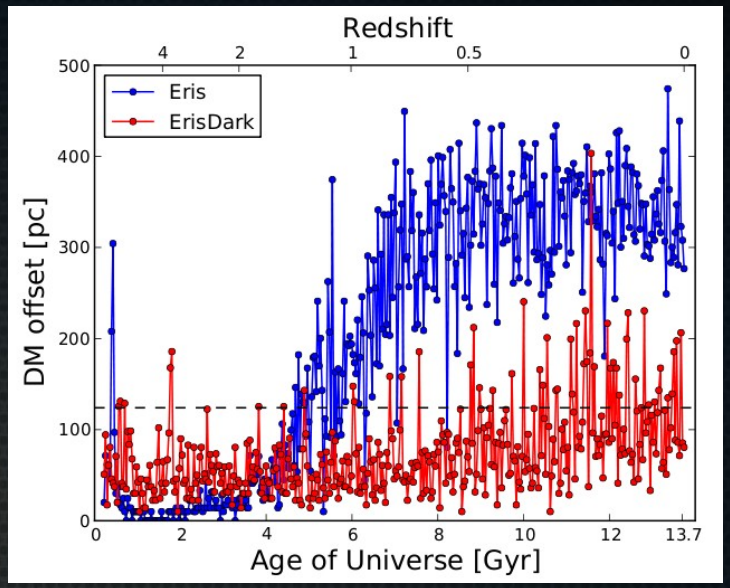


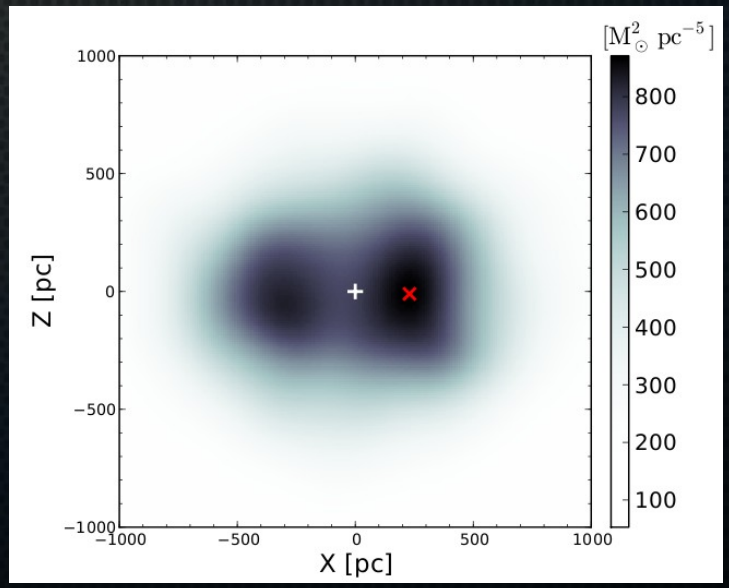

Su & Finkbeiner 2012

Bringmann et al. 2012, Weniger 2012, Su & Finkbeiner 2012, Tempel et al. 2012, etc.

# An Off-Center DM Density Peak




Kuhlen et al. 2013, ApJ, 765, 10

# Conclusions

- Ultra-high resolution DM simulations of Galactic structure predict enormous amounts of substructure, both in configuration space (subhalos) and in velocity space (streams, debris flow).
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  (i) explore departures from cold & collisionless DM, and
  (ii) improve the treatment of baryonic physics and our understanding of its effects on the underlying DM distribution.

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- The future of this field:
  (i) explore departures from cold & collisionless DM, and
  (ii) improve the treatment of baryonic physics and our understanding of its effects on the underlying DM distribution.
- Regarding baryonic physics simulations, currently everyting is very much in flux. Often even the sign of the effect (e.g. adiabatic contraction vs. cusp-to-core transformation) is unknown.
- Nevertheless, important progress is being made (e.g. Eris simulation), and for the first time it has become possible to simulate the formation of realistic disk galaxies like the Milky Way. This work has already yielded interesting and important modifications from the pure-DM simulation expectations.

# Extra Slides

# Beyond Cold & Collisionless DM-only Simulations

Cold and Collisionless DM-only Simulations
[Millennium II, Via Lactea II, Aquarius, etc.]

Alternative Dark Matter Physics

Warm Dark Matter
Self-Interacting Dark Matter
???

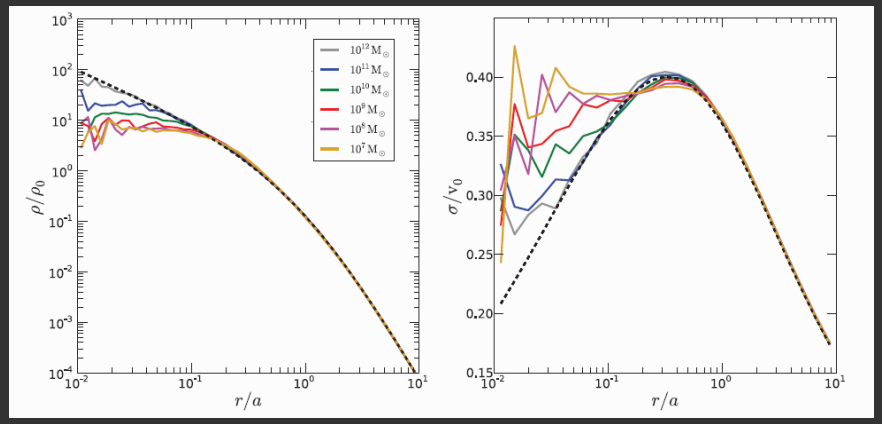
Include Baryonic Physics

Gas Cooling
Star Formation
Feedback

# Alternatives: Self-Interacting Dark Matter

Vogelsberger, Zavala, & Loeb (2012)
See also Rocha, Peter, et al. (2012)

## Halos develop a density core.

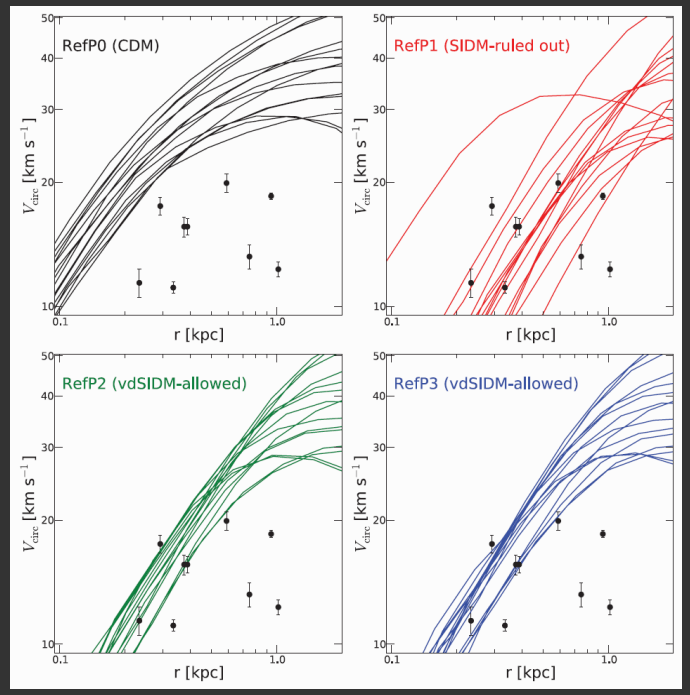



## Velocity-dependent scattering cross section:

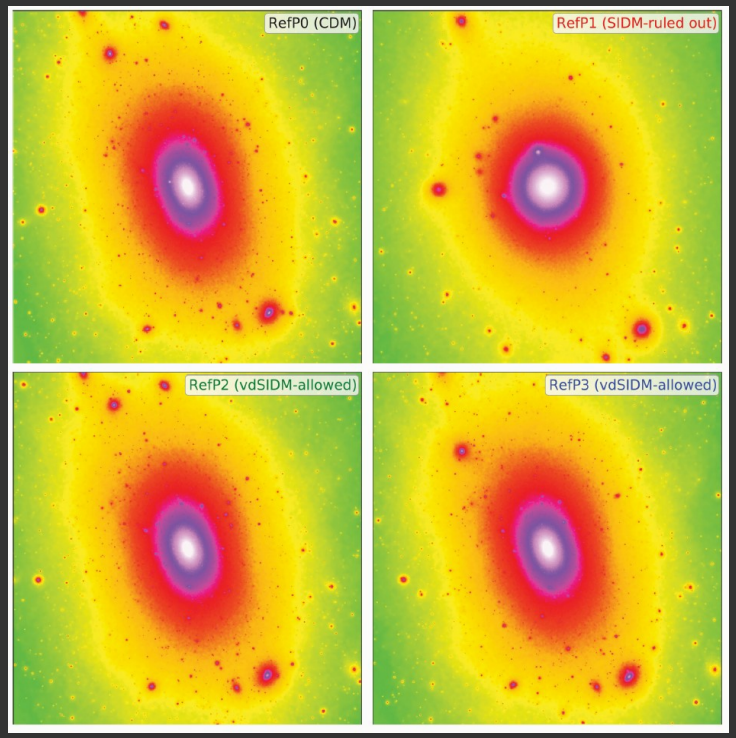
$$\frac{\sigma_T}{\sigma_T^{max}} \approx \begin{cases} \frac{4\pi}{22.7}\beta^2 \ln(1+\beta^{-1}), & \beta < 0.1, \\ \frac{8\pi}{22.7}\beta^2(1+1.5\beta^{1.65})^{-1}, & 0.1 < \beta < 10^3, \\ \frac{\pi}{22.7}\left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2, & \beta > 10^3, \end{cases}$$

Feng, Kaplinghat, & Yu (2010), Finkbeiner et al. (2011), Loeb & Weiner (2011)

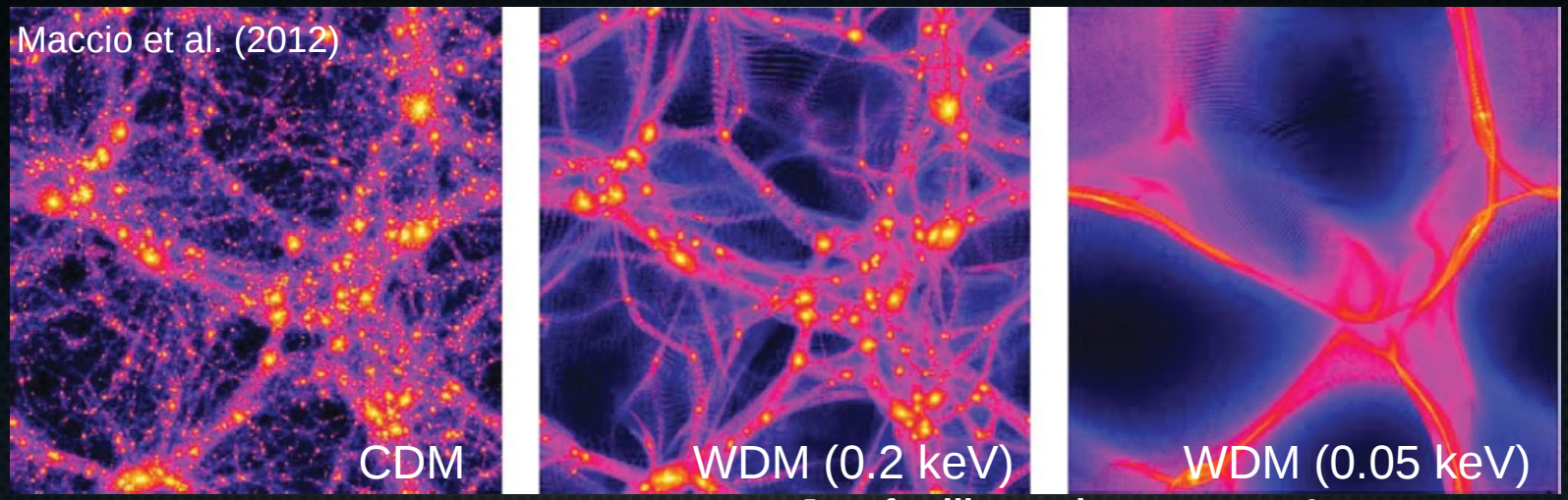
## Reduced central density.




## Makes halos rounder

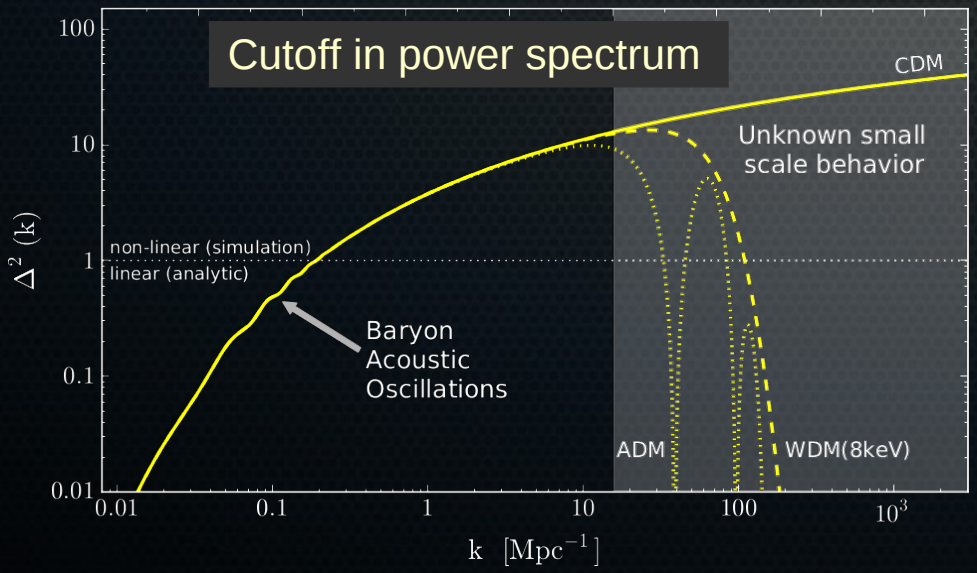


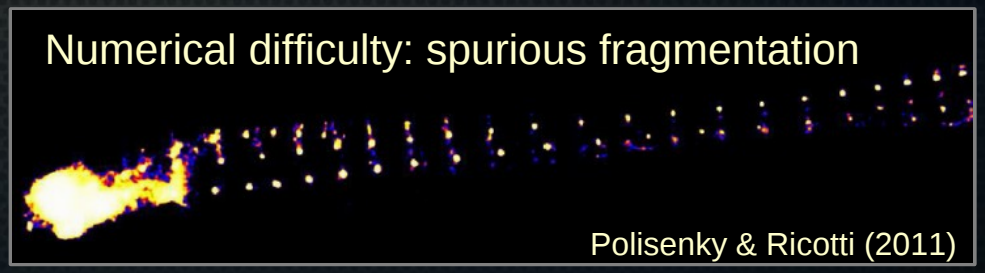
# Alternatives: Warm Dark Matter




**Just for illustration purposes!**

Observational Limits from Ly-$\alpha$ forest: $m_{WDM} > 2 - 4$ keV.
(Viel et al. 2006, 2008; Abazajian 2006; Seljak et al. 2006)




See also: Bode et al. (2001), Gao & Theuns (2007), Lovell et al. (2011), Maccio et al (2012)etc.

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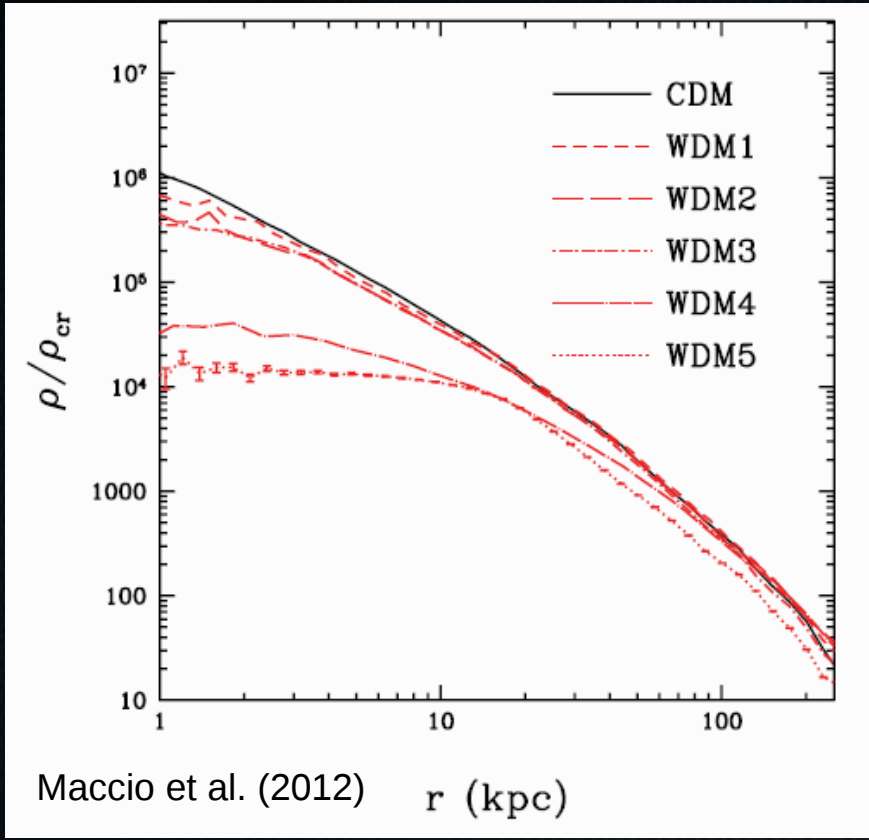
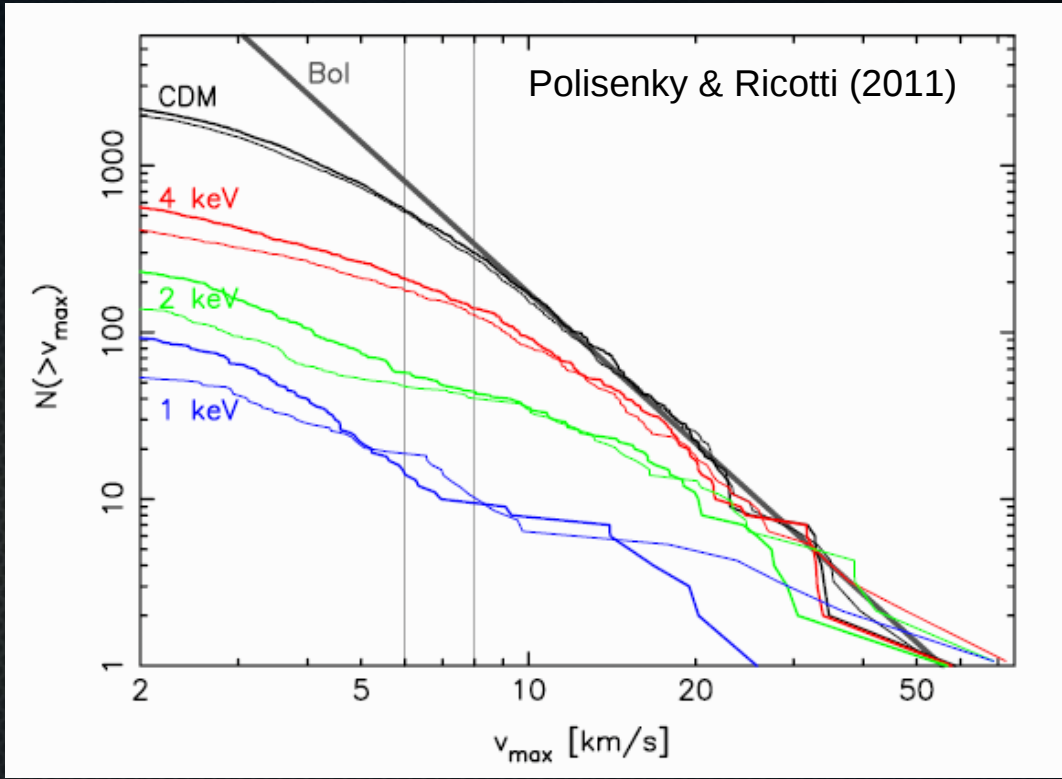



Maccio et al. (2012)




**Catch-22: either you get cores, but not enough subhalos, or you can match the ultra-faint dwarfs, but then you don't get big enough cores.**

Villaescusa-Navarro & Dalal (2011), Maccio et al. (2012)