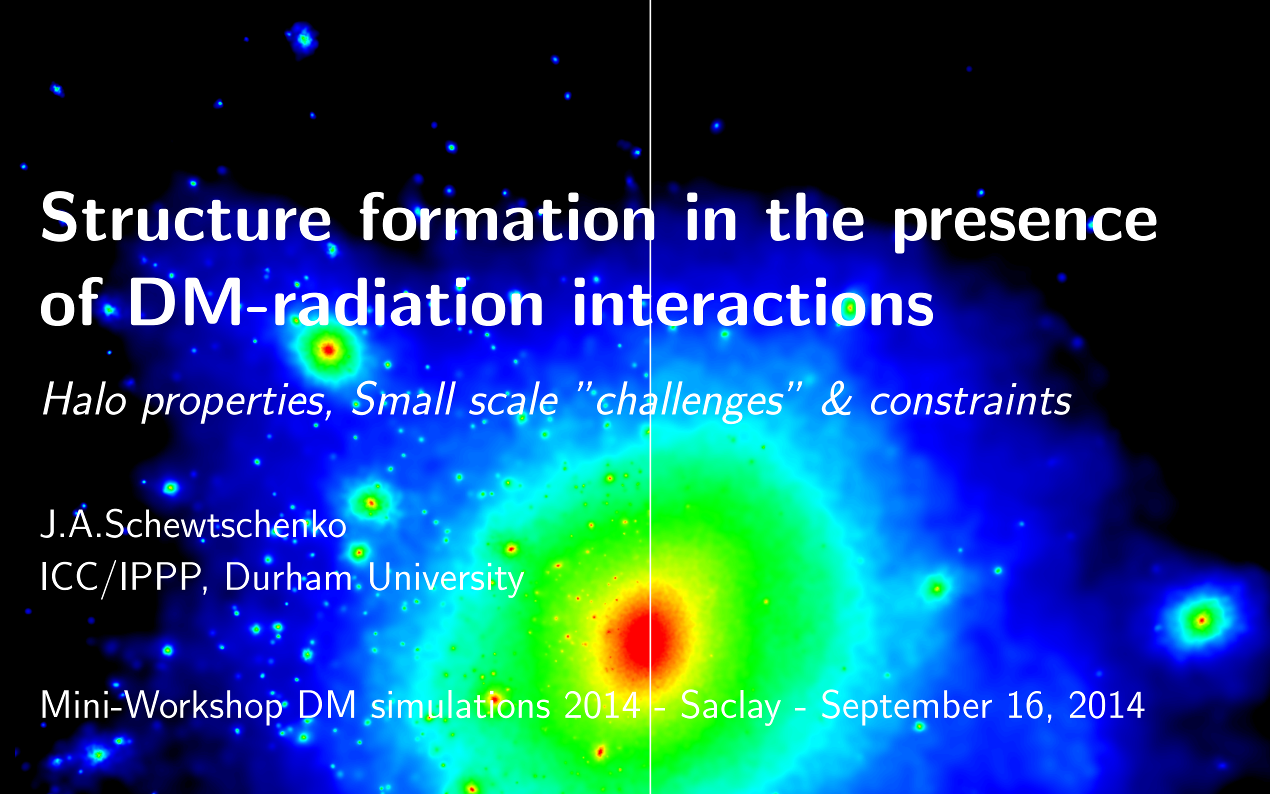


Structure formation in the presence of DM-radiation interactions

Halo properties, Small scale "challenges" & constraints

J.A.Schewtschenko
ICC/IPPP, Durham University

Mini-Workshop DM simulations 2014 - Saclay - September 16, 2014

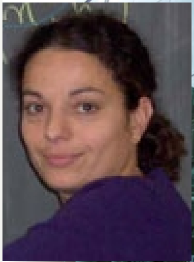
Collaborators

Odgen Center Dream Team

Silvia Pascoli (IPPP)

Carlton Baugh (ICC)

Institute for Computational Cosmology



Celine Boehm (IPPP)

Institute for Particle Physics Phenomenology

Ryan Wilkinson (IPPP)

Till Sawala, Adrian Jenkins
John Helly (ICC)

Table of Contents

Theoretical Background

Global properties

Small-scale "challenges" & constraints

Conclusion

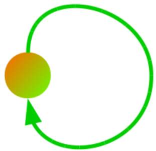
Theoretical Background
Standard Model of Cosmology

Dark Matter

- "**Cold**" with **NO** (effective) interactions (besides gravity)

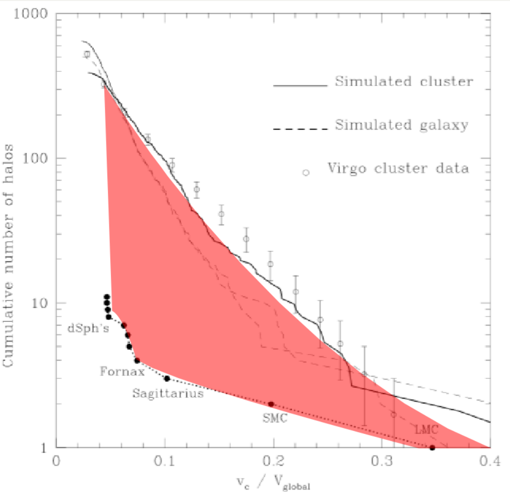
SM (Atoms, γ, ν)

- Self-interactions (hydrodynamics)
- Interactions with γ (cooling,feedback)



Theoretical Background

Motivation #1: Small scale "challenges" of CDM

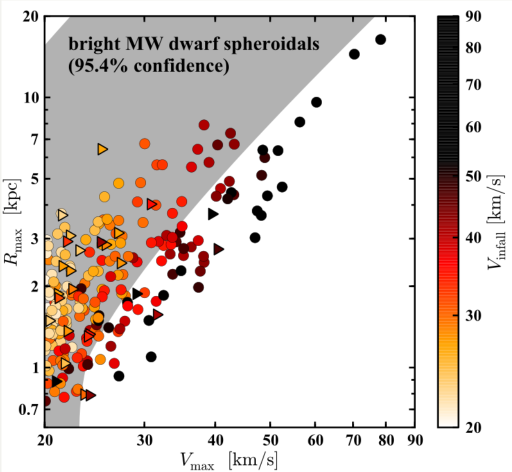


[Moore et al., 1999]

- The amount of predicted small sub-structures exceeds number of observed MW satellites ("Missing satellite problem")

Theoretical Background

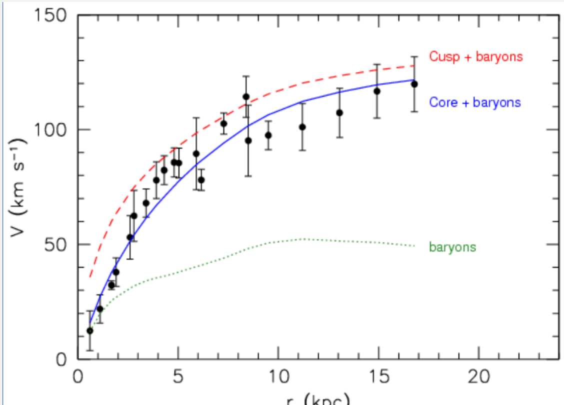
Motivation #1: Small scale "challenges" of CDM



[Boylan-Kolchin 2011]

- The amount of predicted small sub-structures exceeds number of observed MW satellites ("Missing satellite problem")
- The majority of the most massive subhaloes of the Milky Way are too dense to host any of its bright satellites ("Too big to fail")

Motivation #1: Small scale "challenges" of CDM



[SDSS /Weinberg 2013]

- The amount of predicted small sub-structures exceeds number of observed MW satellites ("Missing satellite problem")
- The majority of the most massive subhaloes of the Milky Way are too dense to host any of its bright satellites ("Too big to fail")
- Observed inner density profiles of (sub)structures not cuspy as predicted by CDM N-body simulations

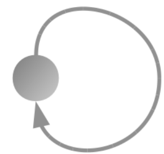
Dark Matter

- “~~Cold~~” Warm with **NO** (effective) interactions (besides gravity)
- free streaming (→ Andrea's talk)

m_{WDM}/T

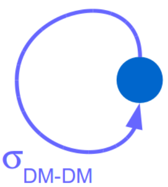
SM (Atoms, γ, ν)

- Self-interactions (hydrodynamics)
- Interactions with γ (cooling,feedback)



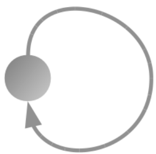
Dark Matter

- "**Cold**" with ~~NO~~ self- (effective) interactions (besides gravity)
- free streaming (→ Andrea's talk)
- **SIDM** (→ Jesús' talk)



SM (Atoms, γ, ν)

- Self-interactions (hydrodynamics)
- Interactions with γ (cooling,feedback)

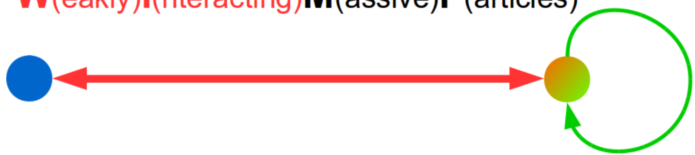


Theoretical Background
Standard Model of Cosmology (revisited)

Dark Matter ⟷ **SM (Atoms, γ, ν)**

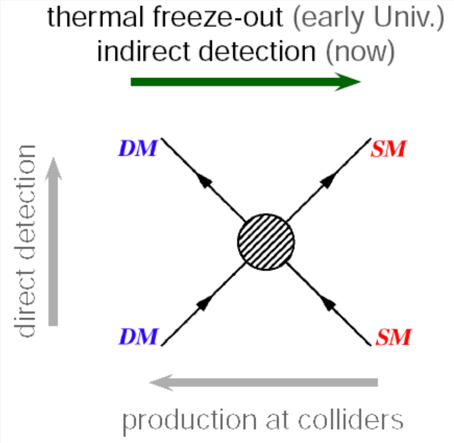
- “**Cold**” with ~~NO~~ SM- (effective) interactions (besides gravity)
- free streaming (→ Andrea's talk)
- **SIDM** (→ Jesús' talk)
- Self-interactions (hydrodynamics)
- Interactions with γ (cooling,feedback)

W(eakly)**I**(nteracting)**M**(assive)**P**(articles)



Theoretical Background

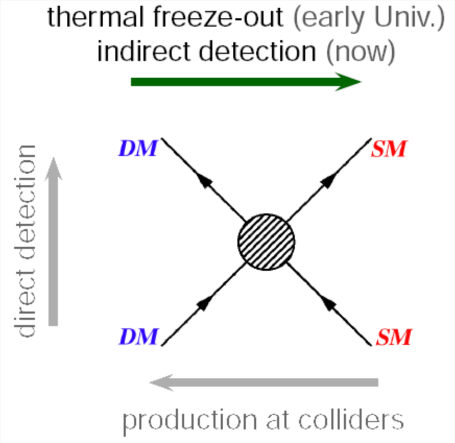
Motivation #2: Does DM interact with SM sector?



- Here we focus on the phenomenology → **data**-driven, model-independent, effective theory

Theoretical Background

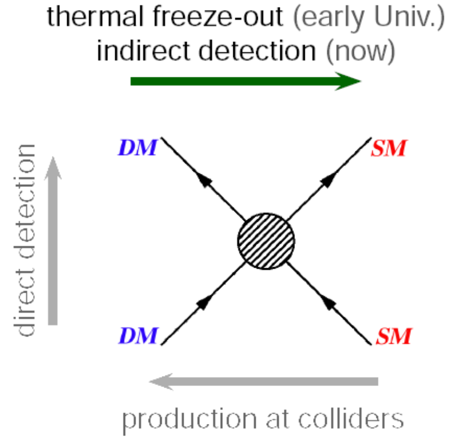
Motivation #2: Does DM interact with SM sector?



- Here we focus on the phenomenology → **data**-driven, model-independent, effective theory
- Constraints on annihilation of (thermal) relic DM from observed abundance (Planck) (→ WIMP)

Theoretical Background

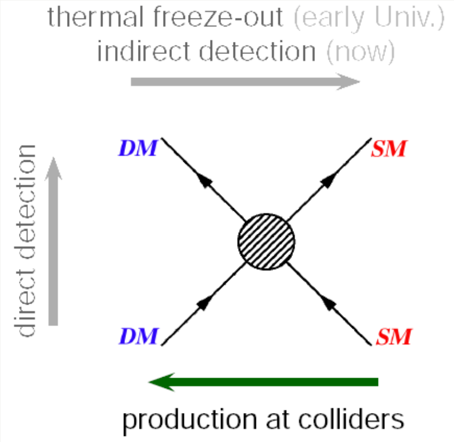
Motivation #2: Does DM interact with SM sector?



- Here we focus on the phenomenology → **data**-driven, model-independent, effective theory
- Constraints on annihilation of (thermal) relic DM from observed abundance (Planck) (→ WIMP)
- Possible "signal" from Fermi-LAT at 130 GeV [Cohen+,2012][Weninger+,2014] / 3.5 keV [Bulbul+,2014][Boyarski+,2014] from (stacked) X-ray spectra, but indirect cross-section results depend on uncertain parameters (asym. in dark sector, DM morphology, etc.)

Theoretical Background

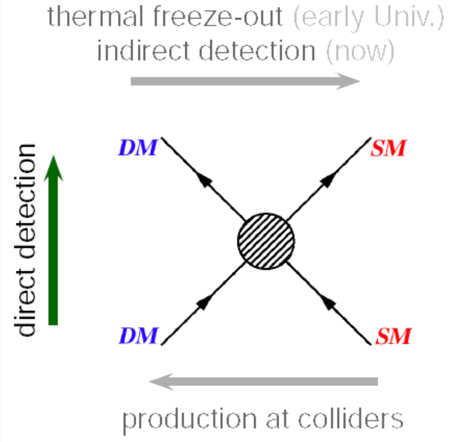
Motivation #2: Does DM interact with SM sector?



- Here we focus on the phenomenology → **data**-driven, model-independent, effective theory
- Constraints on annihilation of (thermal) relic DM from observed abundance (Planck) (→ WIMP)
- Possible "signal" from Fermi-LAT at 130 GeV [Cohen+,2012][Weninger+,2014] / 3.5 keV [Bulbul+,2014][Boyarski+,2014] from (stacked) X-ray spectra, but indirect cross-section results depend on uncertain parameters (asym. in dark sector, DM morphology, etc.)
- Search for missing (transverse) energy / monojets at LHC

Theoretical Background

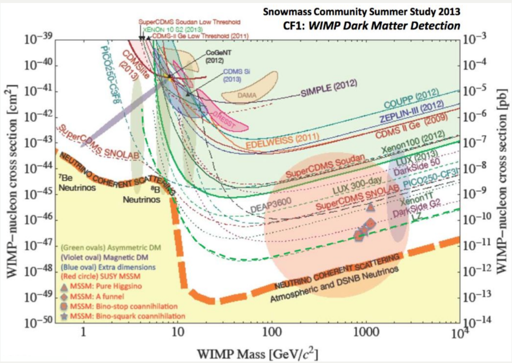
Motivation #2: Does DM interact with SM sector?



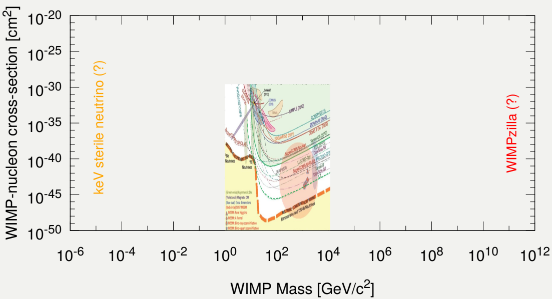
- Here we focus on the phenomenology → **data**-driven, model-independent, effective theory
- Constraints on annihilation of (thermal) relic DM from observed abundance (Planck) (→ WIMP)
- Possible "signal" from Fermi-LAT at 130 GeV [Cohen+,2012][Weninger+,2014] / 3.5 keV [Bulbul+,2014][Boyarski+,2014] from (stacked) X-ray spectra, but indirect cross-section results depend on uncertain parameters (asym. in dark sector, DM morphology, etc.)
- Search for missing (transverse) energy / monojets at LHC
- Scattering of DM on SM particles

Theoretical Background

Motivation #2: Does DM interact with SM sector?



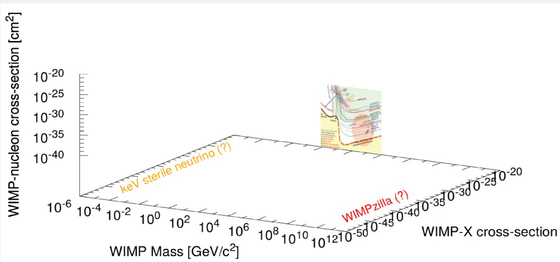
Theoretical Background
Motivation #2: Does DM interact with SM sector?



- Direct detection experiments only sensitive in part of (WIMP) mass range

Theoretical Background

Motivation #2: Does DM interact with SM sector?



- Direct detection experiments only sensitive in part of (WIMP) mass range
- Alternative constraints from (linear) cosmology [Dvorkin+,2013]:
  e.g. $\sim 10^{-33}\mathrm{cm}^2(m/\mathrm{GeV})$ (electr. dipol) $\sim 4 \cdot 10^{-30}\mathrm{cm}^2(m/\mathrm{GeV})$ (heavy boson exchange)
- (Possible) constraints on non-quark scattering:
  - from annihilation/production cross-section [Kopp,2011]
  - "Absorbtion" features in quasar spectra in case of resonant scattering ("Dark shadows")[Profumo+,2007]

- Example: (elastic) DM-photon scattering
- Euler Equations (modified):

$$\dot{\theta}_b = k\Phi - H\theta_b + c_2^2 k^2 \delta_b - R^{-1}\dot{\kappa}(\theta_b - \theta_\gamma)$$

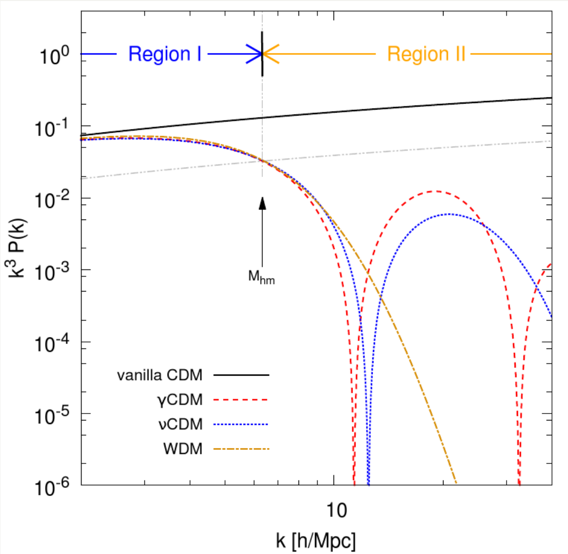
$$\dot{\theta}_\gamma = k^2\Phi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) - \frac{1}{6}k\pi_\gamma - \dot{\kappa}(\theta_\gamma - \theta_b) - \dot{\mu}(\theta_\gamma - \theta_{DM})$$

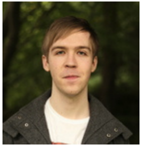
$$\dot{\theta}_{DM} = k^2\Phi - H\theta_{DM} - S^{-1}\dot{\mu}(\theta_{DM} - \theta_\gamma)$$

[Boehm, 2002c]

Theoretical Background

Interactions with relic radiation: Linear Theory

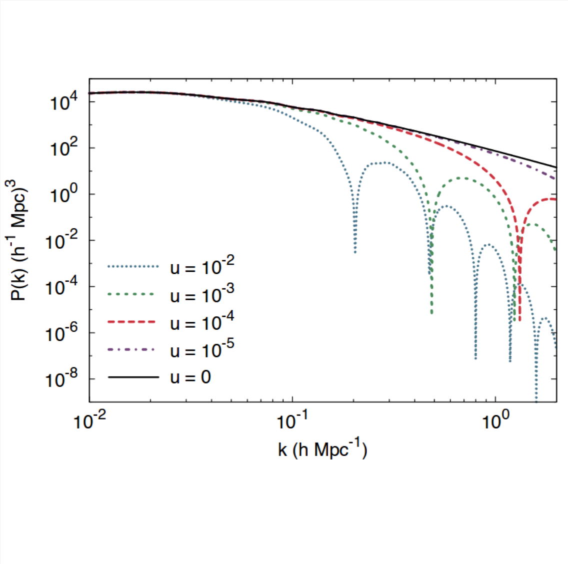




- Solving linearized Boltzm.Eq. → Implementation of interacting DM in CLASS solver [Lesgourgues+,2011][Wilkinson+,arXiv:1309.7588]
- Oscillations in transfer function for γCDM as well as (strongly damped) for νCDM
- Characteristic scale *half-mode mass* $M_{\rm hm}$ defined as suppression of power by factor of 4 → significant reduction of primordial fluctuations

Theoretical Background

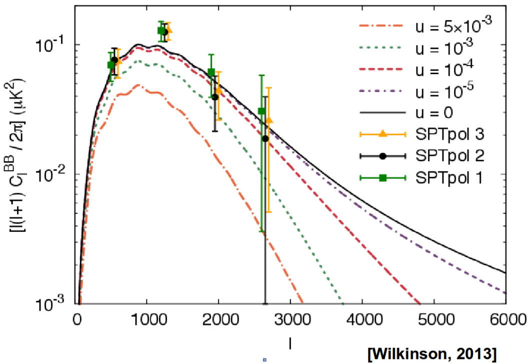
Interactions with relic radiation: Linear Theory



- Solving linearized Boltzm.Eq. → Implementation of interacting DM in CLASS solver [Lesgourgues+,2011][Wilkinson+,arXiv:1309.7588]
- Oscillations in transfer function for γCDM as well as (strongly damped) for νCDM
- Characteristic scale *half-mode mass* $M_{\rm hm}$ defined as suppression of power by factor of 4 → significant reduction of primordial fluctuations

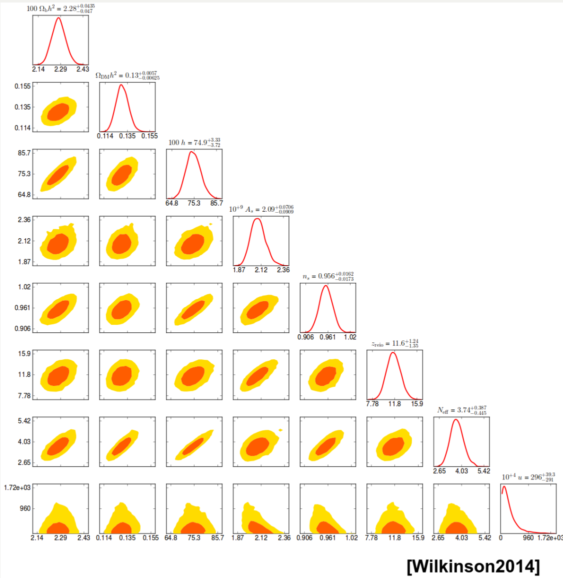
Theoretical Background

Interactions with relic radiation: CMB constraints



- Comparison of predicted lin. evolution in early Universe with most recent CMB data.

Theoretical Background
Interactions with relic radiation: CMB constraints



- Comparison of predicted lin. evolution in early Universe with most recent CMB data.
- Constraining models with MCMC runs:

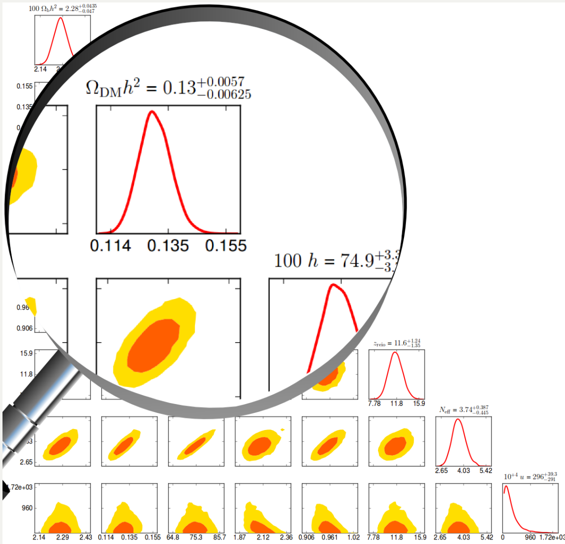
$$\sigma_{\mathrm{dm}-\gamma} \leq 8 \times 10^{-31} (m_{\mathrm{DM}}/GeV)\mathrm{cm}^2$$
$$\sigma_{\mathrm{dm}-\nu} \leq 2 \times 10^{-28} (m_{\mathrm{DM}}/\mathrm{GeV})\mathrm{cm}^2$$

at 68% CL for constant cross-section

[Wilkinson+,2014a][Wilkinson+,2014b]

Theoretical Background

Interactions with relic radiation: CMB constraints



[Wilkinson2014]

- Comparison of predicted lin. evolution in early Universe with most recent CMB data.
- Constraining models with MCMC runs:

$$\sigma_{\mathrm{dm}-\gamma} \leq 8 \times 10^{-31} (m_{\mathrm{DM}}/GeV)\mathrm{cm}^2$$
$$\sigma_{\mathrm{dm}-\nu} \leq 2 \times 10^{-28} (m_{\mathrm{DM}}/\mathrm{GeV})\mathrm{cm}^2$$

at 68% CL for constant cross-section

[Wilkinson+,2014a][Wilkinson+,2014b]

- Introducing DM interactions can ease tension for H_0 & Ω_m (?)

free-streaming:

$$l_{fs} \sim \int_{t_{dec}(dm)}^{t_0} \frac{v}{a} dt$$

collisional:

self-interaction   scattering with other species

$$l_{cd}^2 \sim \int^{t_{dec}(dm)} \frac{\rho_{dm} v_{dm}^2}{\rho \Gamma_{dm} a^2} dt + \sum_{i \supset e, \gamma, \ldots} \int^{t_{dec}(dm-i)} \frac{\rho_i v_i^2}{\rho \Gamma_i a^2} dt$$

$$+ \int^{min(t_{dec}(dm-\nu), t_{dec}(\nu))} \frac{\rho_\nu c_i^2}{\rho \Gamma_\nu a^2} dt$$

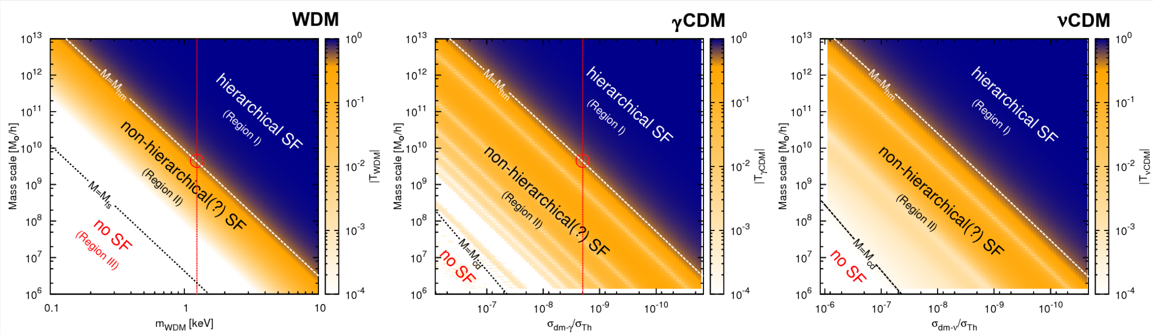
Interaction with ν

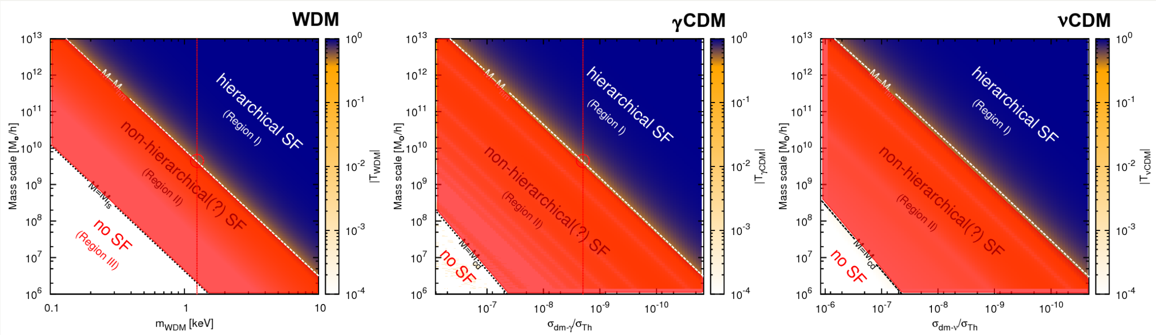
mixed:

$$l_{md}^2 \sim \int_{t_{dec}(\nu)}^{t_{dec}(dm-\nu)} \frac{\rho_{dm} c^2}{\rho H a^2} dt \sim \left(\frac{c\,t}{a}\right)^2 \Big|_{t_{dec}(dm-\nu)}$$

Theoretical Background

Interactions with relic radiation: Damping scales

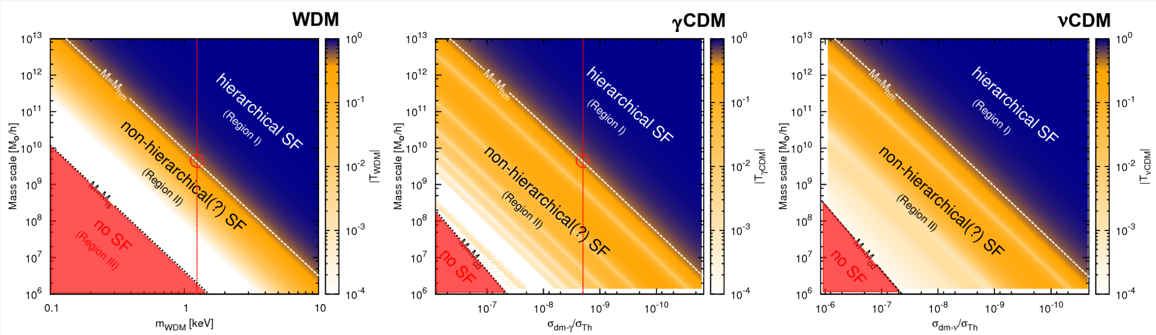




- Region II defined by half-mode mass → significant suppression of progenitors for hierarchical structure formation (SF).

Theoretical Background

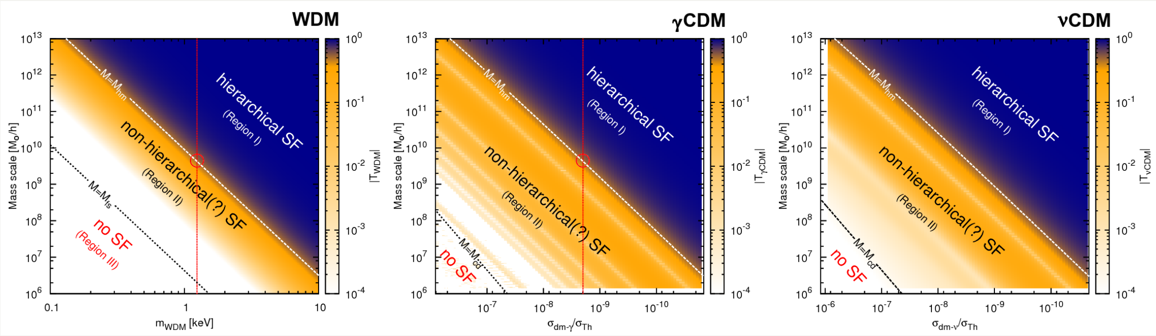
Interactions with relic radiation: Damping scales



- Region II defined by half-mode mass → significant suppression of progenitors for hierarchical structure formation (SF).
- Region III defined by free-streaming/collisional damping scale → (almost) no (hierarchical) structure formation, fragmentation possible.

Theoretical Background

Interactions with relic radiation: Damping scales



- Region II defined by half-mode mass → significant suppression of progenitors for hierarchical structure formation (SF).
- Region III defined by free-streaming/collisional damping scale → (almost) no (hierarchical) structure formation, fragmentation possible.
- For interacting DM, Region II reaches down to smaller mass scales.

Table of Contents

Theoretical Background

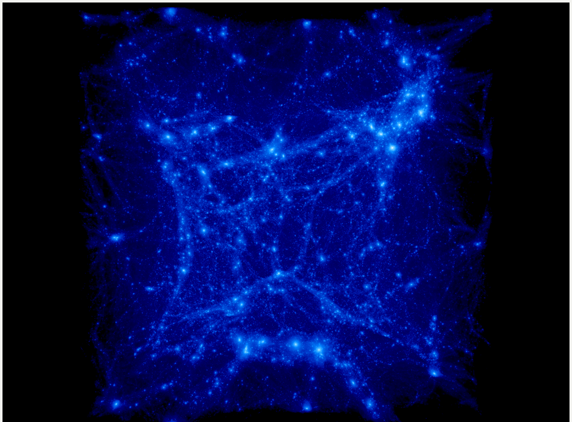
Global properties

Small-scale "challenges" & constraints

Conclusion

Global properties

Simulations: Cosmological Box

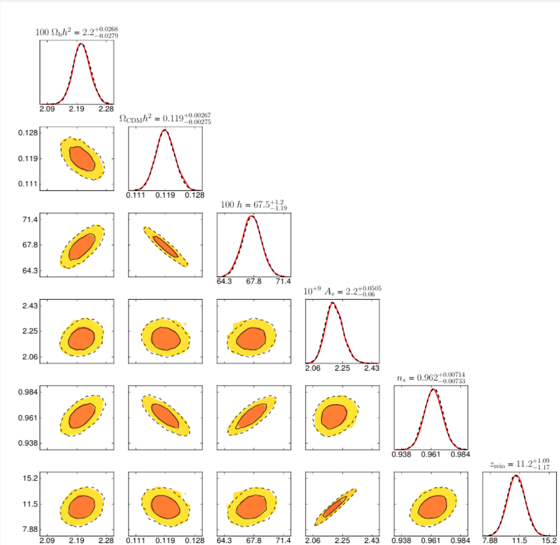


- N-Body simulation using GADGET-3.
- Planck1 cosmology.
- various γCDM cross-section & matching νCDM/WDM models
- ICs (z=49) with modified `2LPTic`.
- Full cosmological box
  - 30 Mpc box at $2 \cdot 10^6$ $M_\odot$ mass resolution.
  - $\gtrsim 10^2$ MW-like galaxies (CDM).
  - 100 Mpc box at $9 \cdot 10^6$ $M_\odot$ mass resolution.
  - 300 Mpc box at $2 \cdot 10^7$ $M_\odot$ mass resolution.
- On first glance, it is obvious that CMB upper limits produce unrealistic results $\rightarrow$ more realistic cross-section are a few

- Is it okay to use Planck1 best-fit parameters for ICs with interacting DM?

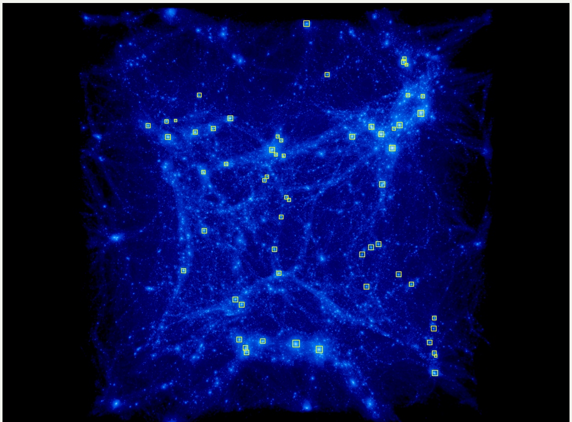
Global properties

Simulations: Initial conditions / Cosmological parameters



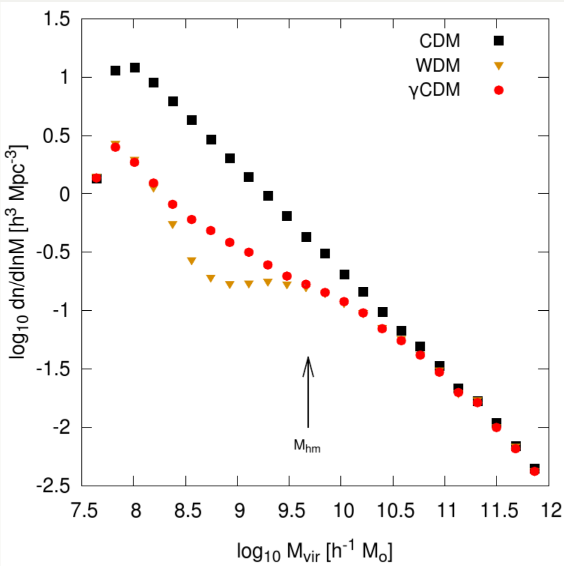
- Is it okay to use Planck1 best-fit parameters for ICs with interacting DM?
- For realistic cross-sections, no significant deviation from CDM anymore $\rightarrow$ choice consistent ☺/☹

Global properties
Simulations: Identifying haloes



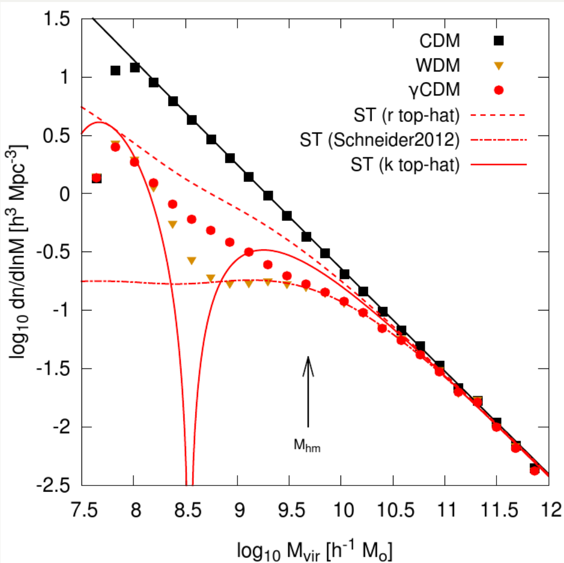
- Halo finders: FoF/`subfind` and `AHF`
  - halo defined as virialized region (overdensity according to spherical top-hat collapse)
  - ensemble properties: median, its error (95% CI) and the variance in the sample spread.
  - relaxation criteria [Maccio+,2007][Neto+2007]

Global properties
Halo mass function



- Abundance of small halos suppressed (as expected) for both γCDM and WDM.
- Spurious halos contaminate HMF on scale below $9 \cdot 10^9 h^{-1} M_\odot$.

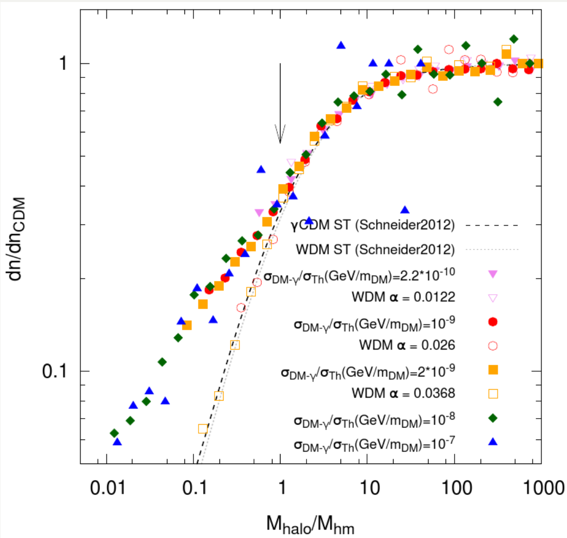
Halo mass function



- Abundance of small halos suppressed (as expected) for both γCDM and WDM.
- Spurious halos contaminate HMF on scale below $9 \cdot 10^9 h^{-1} M_\odot$.
- (Semi-)Analytical predictions
  - Sheth-Tormen (ST) formalism with conf. space top-hat matches CDM HMF
  - ST formalism with conf. space top-hat & mod. Schneider fudge factor matches WDM HMF /tiny [Schneider+,2012]
  - ST formalism with k-space top-hat gets turn-over correct for WDM HMF, but predicted "gap" not seen in γCDM HMF
- Analytical collapse models fail to predict HMF for γCDM $\rightarrow$ Non-hierarchical growth? Fragmentation?

Global properties

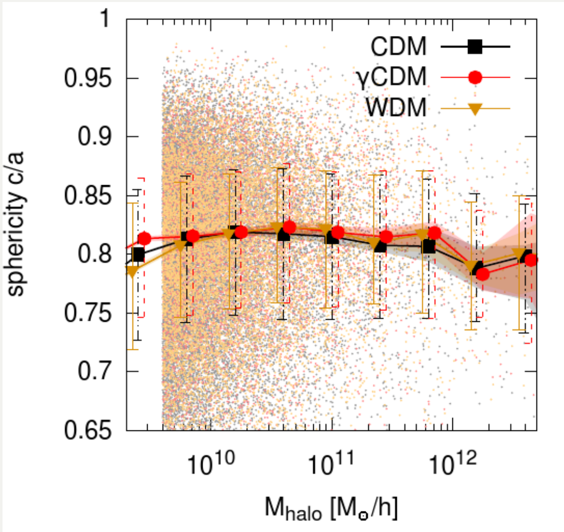
Halo mass function



- HMF is universal if normalized by M_{hm}.
- Excess in structures in γCDM compared to WDM below M_{hm}

Global properties

Halo properties: Shape



- We measured the sphericity, triaxiality & elongation for CDM, γCDM
- No significant deviations from CDM detected.

Global properties

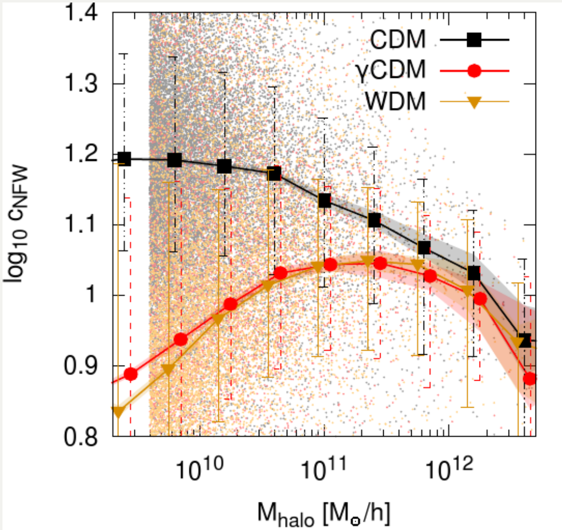
Halo properties: Halo density profile

- DM density profiles can be fit to NFW profile:

$$\rho^{\mathrm{NFW}}(r) = \frac{\rho_c(M)}{cr/r_{\mathrm{vir}}\left(1 + cr/r_{\mathrm{vir}}\right)^2}$$

- Universal density profile completely parametrized by concentration parameter c

Global properties
Halo properties: Halo density profile



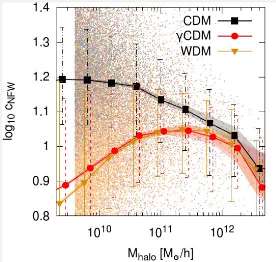
- DM density profiles can be fit to NFW profile:

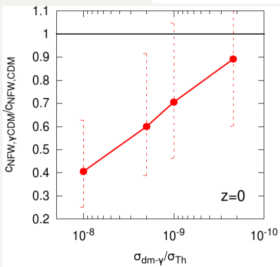
$$\rho^{\mathrm{NFW}}(r) = \frac{\rho_c(M)}{cr/r_{\mathrm{vir}}\left(1 + cr/r_{\mathrm{vir}}\right)^2}$$

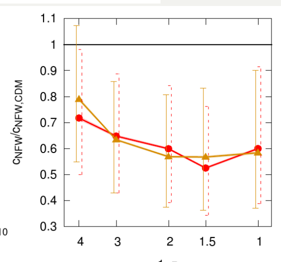
- Universal density profile completely parametrized by concentration parameter c
- γCDM and WDM indistinguishable: lower concentration for lower-mass halos

Global properties

Halo properties: Halo density profile





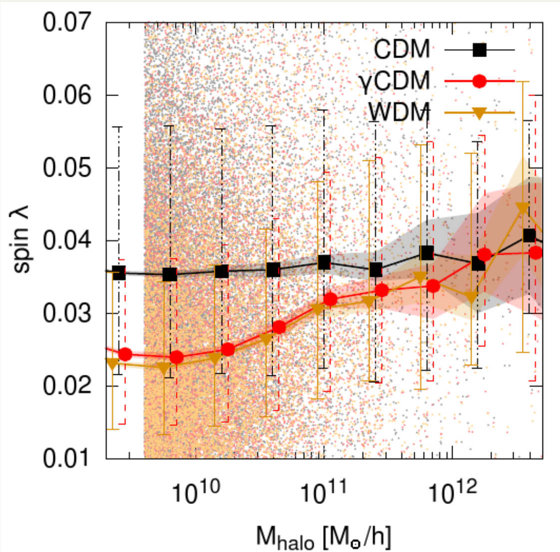


- DM density profiles can be fit to NFW profile:

$$\rho^{\rm NFW}(r) = \frac{\rho_c(M)}{cr/r_{\rm vir}\,(1+cr/r_{\rm vir})^2}$$

- Universal density profile completely parametrized by concentration parameter c
- γCDM and WDM indistinguishable: lower concentration for lower-mass halos
- lower concentration results from delayed halo formation (as for WDM)

Global properties
Halo properties: Halo spin



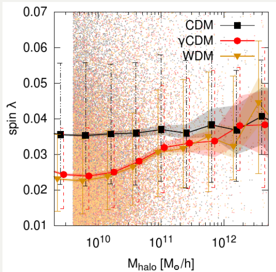
- Peebles definition:

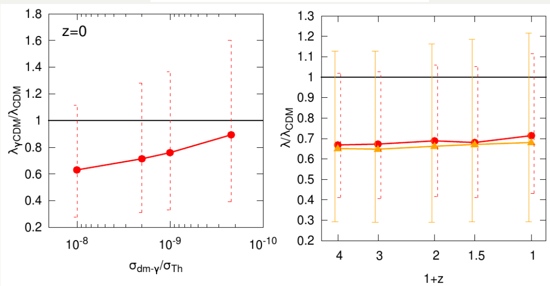
$$\lambda = \frac{J|E|^{1/2}}{GM_{\mathrm{vir}}^{5/2}} \qquad (1)$$

- γCDM and WDM indistinguishable: lower spin for lower-mass halos

Global properties

Halo properties: Halo spin





- Peebles definition:

$$\lambda = \frac{J|E|^{1/2}}{GM_{\rm vir}^{5/2}} \quad (1)$$

- γCDM and WDM indistinguishable: lower spin for lower-mass halos
- Can be evidence for delayed halo formation (TTT)
- Alternative explanation by vorticity of late-time environment / merger history (?)

Global properties

Non-linear matter powerspectrum

Table of Contents

Theoretical Background

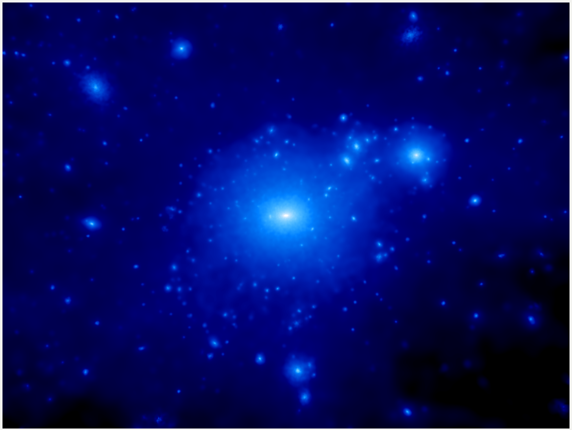
Global properties

Small-scale "challenges" & constraints

Conclusion

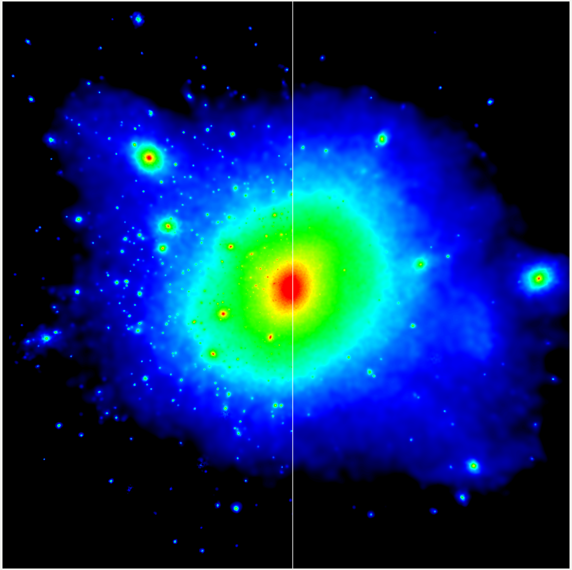
Small-scale "challenges" & constraints

Simulation Suite: MW-like Halos



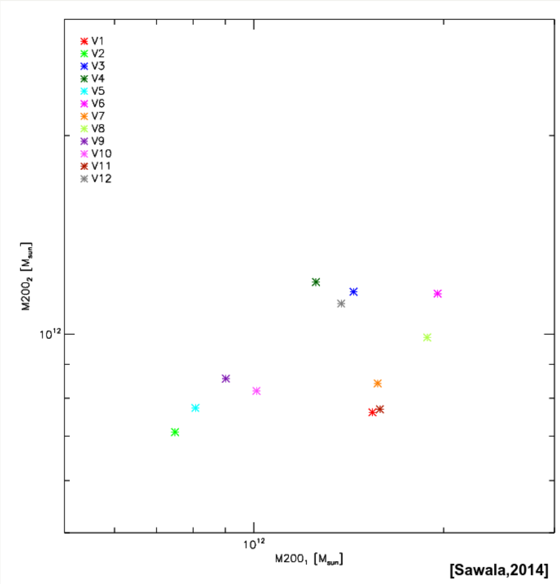
- Milky Way-like galaxies in cosmological box sims:
  - virial mass: $0.8 - 2.7 \times 10^{12} M_{\odot}$
    [Piffl, 2013][Boylan-Kolchan,2013]
  - sufficiently isolated (no larger object within 2 Mpc)
  - $\gtrsim 10^2$ MW-like galaxies in 30 Mpc/h box (CDM)

Simulation Suite: Zooms



- N-Body simulation using `GADGET-3`.
- WMAP7 cosmology.
- ICs (z=127) with `ic-gen` [Jenkins2014]
- zoom simulations based on DOVE simulation
  - 12 LG candidates [Sawala2014]
  - Up to 10^4 $M_\odot$ mass resolution (HR).

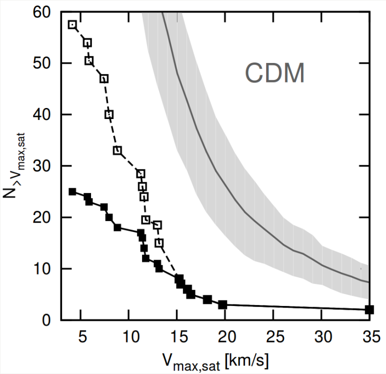
Small-scale "challenges" & constraints
Simulation Suite: Zooms



- N-Body simulation using `GADGET-3`.
- WMAP7 cosmology.
- ICs (z=127) with `ic-gen` [Jenkins2014]
- zoom simulations based on DOVE simulation
  - 12 LG candidates [Sawala2014]
  - Up to 10^4 $M_\odot$ mass resolution (HR).

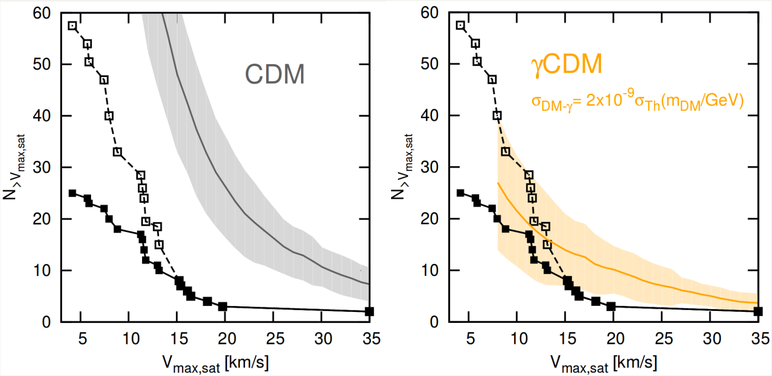
Small-scale "challenges" & constraints
Missing satellite problem

Small-scale "challenges" & constraints
Missing satellite problem



Small-scale "challenges" & constraints

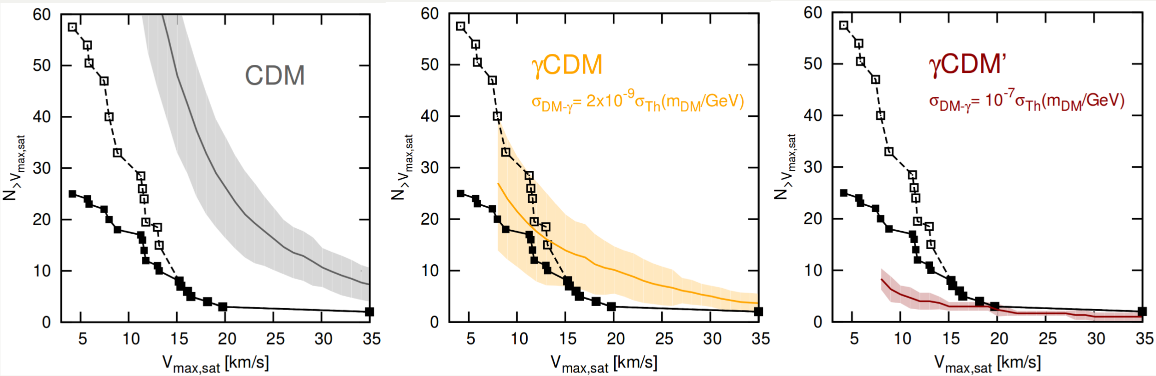
Missing satellite problem



- Interacting CDM reduces subhaloes → MSP solved
- cross-section at CMB limit indeed ruled out as too many MW substructures are erased

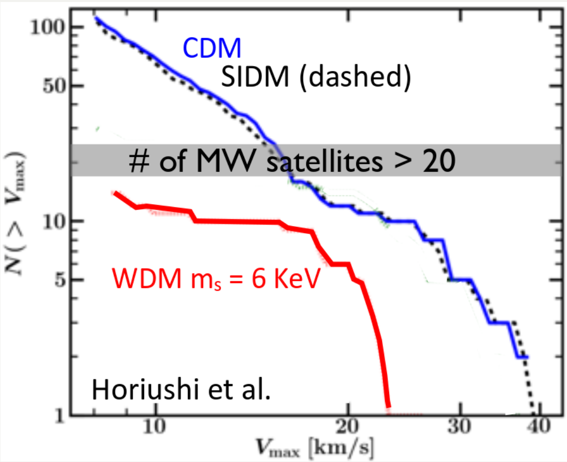
Small-scale "challenges" & constraints

Missing satellite problem



- Interacting CDM reduces subhaloes → MSP solved
- cross-section at CMB limit indeed ruled out as too many MW substructures are erased

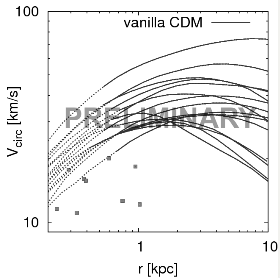
Small-scale "challenges" & constraints
Too big to fail



- small parameter window at best to solve problem with WDM ("Catch-22" between MSP and TBTF)

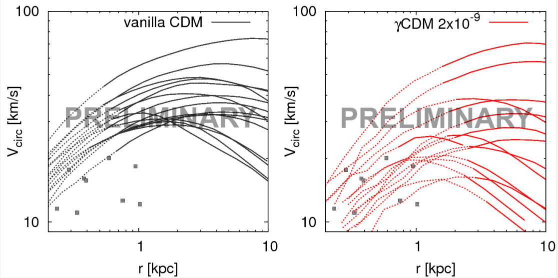
Small-scale "challenges" & constraints

Too big to fail



- small parameter window at best to solve problem with WDM ("Catch-22" between MSP and TBTF)

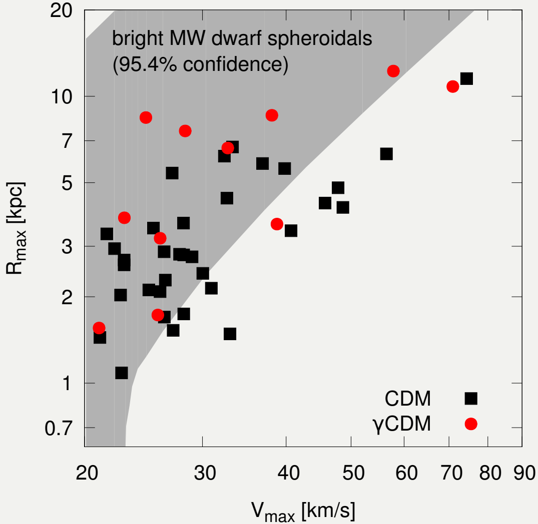
Small-scale "challenges" & constraints
Too big to fail



- small parameter window at best to solve problem with WDM ("Catch-22" between MSP and TBTF)
- Interacting DM reduces satellite counts & changes velocity profile correctly, but avoid over-suppression of small satellites to solve TBTF

Small-scale "challenges" & constraints

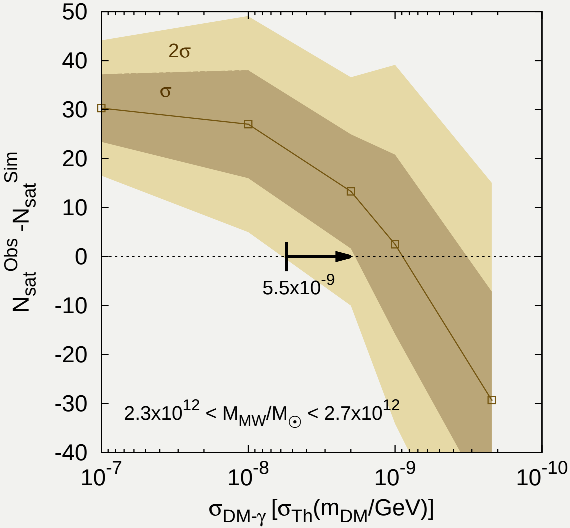
Too big to fail



- small parameter window at best to solve problem with WDM ("Catch-22" between MSP and TBTF)
- Interacting DM reduces satellite counts & changes velocity profile correctly, but avoid over-suppression of small satellites to solve TBTF

Small-scale "challenges" & constraints

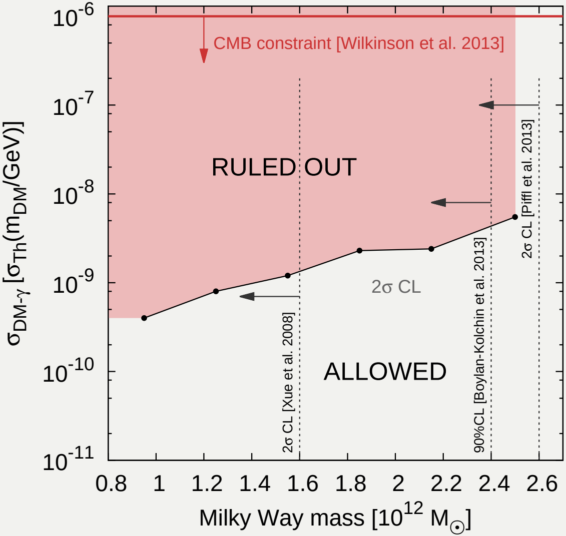
Structure constraints



- Most conservative bounds: γCDM has to produce at least enough DM halos to host visible satellite galaxies (+sky coverage correction)

Small-scale "challenges" & constraints

Structure constraints



- Most conservative bounds: γCDM has to produce at least enough DM halos to host visible satellite galaxies (+sky coverage correction)
- Constraints depend on Milky Way mass
- For high-mass end:

$$\sigma_{\mathrm{dm}-\gamma} \quad \leq \quad 3 \times 10^{-33} (m_{\mathrm{DM}}/GeV)\mathrm{cm}^2$$

at 95 % CL.

Table of Contents

Theoretical Background

Global properties

Small-scale "challenges" & constraints

Conclusion

Conclusion

- IDM, in particular γ(C)DM, provides a natural mass/velocity-independent suppression of small scale structures (MSP,TBTF may indicate its WIMP nature)
- We performed first N-Body simulations for γ/νCDM (with correct input spectrum)
- γ/ν(C)DM can solve/ease the problems of vanilla CDM on small scales (at least on par with WDM!)
- Structure surveys allow to constrain cross-section independently and much tighter than CMB and provide lowest conservative bound so far for elastic DM-photon interaction.
- Our constraints are "in the right ballpark" for observed abundance of thermal relic if $m_{\rm dm}$ *MeV* (or below).

Future work

- Model-building: Check all possible constraints against a specific, preferable model
- Merger "graphs" to study origin of HMF (where do halos in gap originate from?)
- Prediction of Luminosity function at high redshift using SAMs
- Halo bias $\rightarrow$ do we see deviation from WDM? (as in HMF)
- Halo model/Halofit $\rightarrow$ how precise are (semi-)analytical predictions
- Hydrodynamic simulations with baryons $\rightarrow$ how does the presence of baryons/feedback affect our constraints?