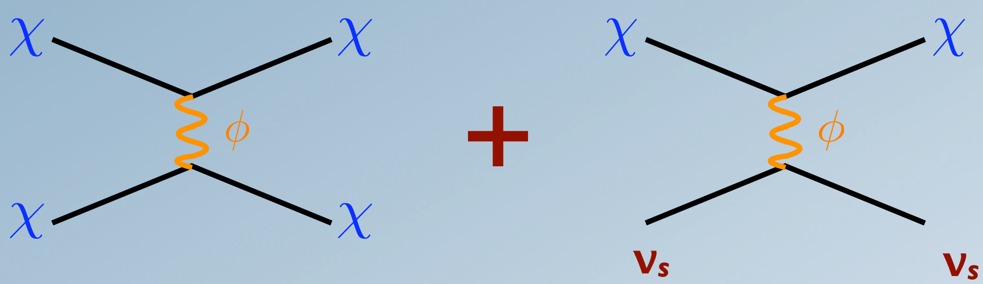
Barolo Astroparticle Meeting
03.-06.09.2017

Impact of particle DM models in dSph formation

Torsten Bringmann

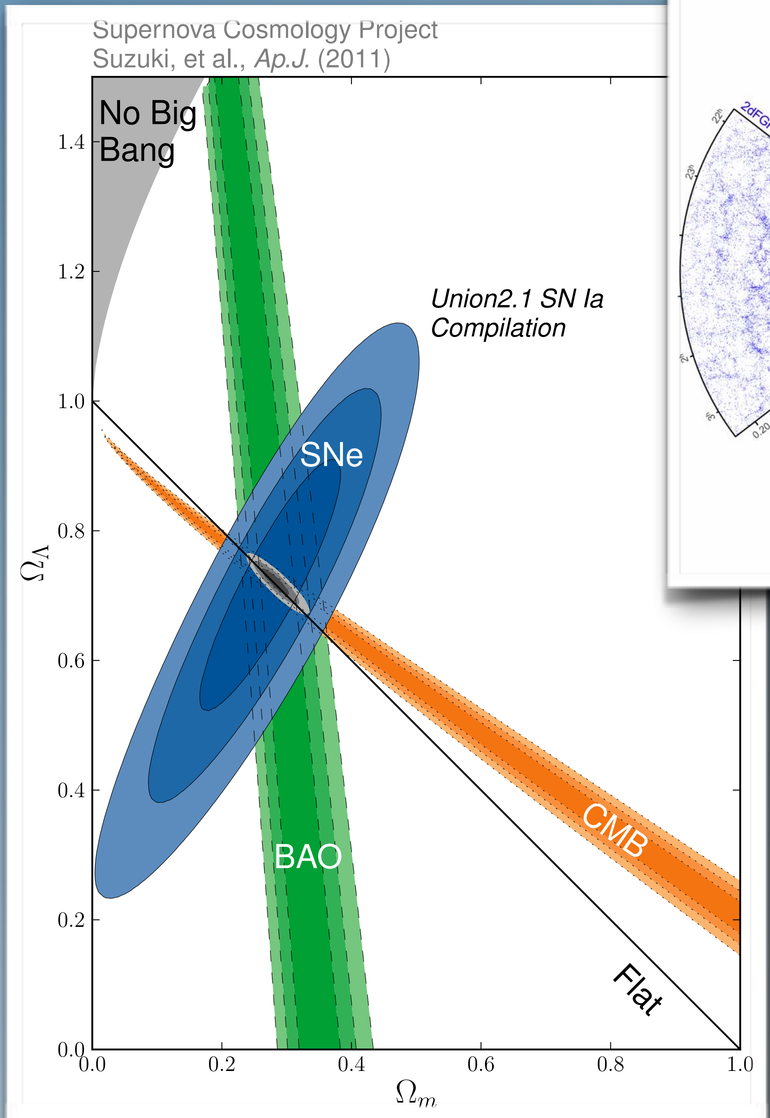


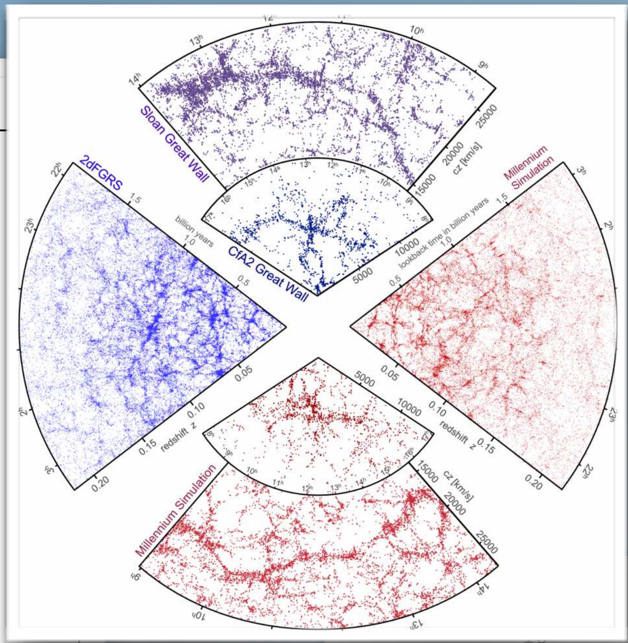
Based on work with

Laura van den Aarssen, Francis-Yan Cyr-Racine, Jasper Hasenkamp, Håvard Ihle, Felix Kahlhoefer, Jörn Kersten, Christoph Pfrommer, Kai Schmidt-Hoberg, Kris Sigurdsson, Mark Vogelsberger, Parampreet Walia, Jesús Zavala, …

UiO : University of Oslo

ΛCDM cosmology

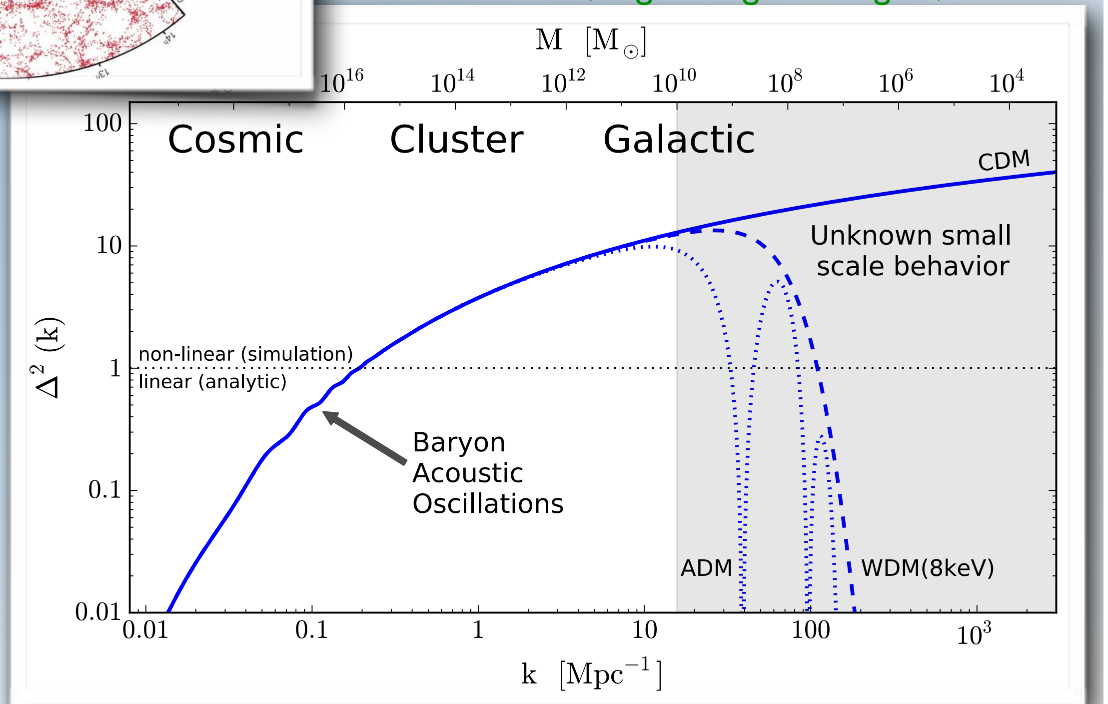




Springel, Frenk & White, Nature '06

A great success on large scales...

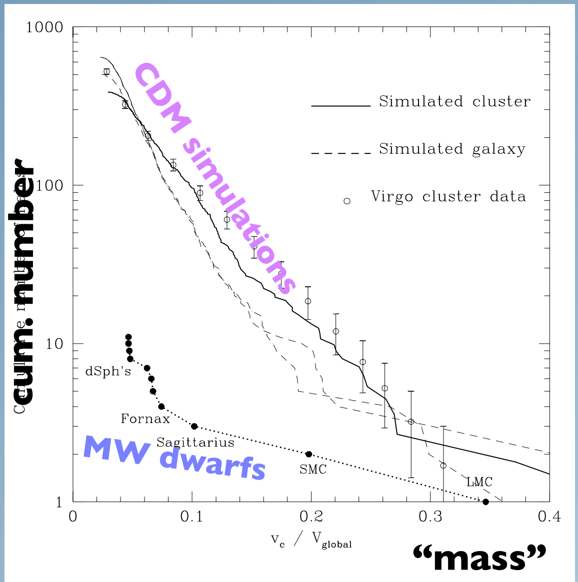
Kuhlen, Vogelsberger & Angulo, PDU '12



Small-scale problems

...but less impressive on *small* *scales !?*

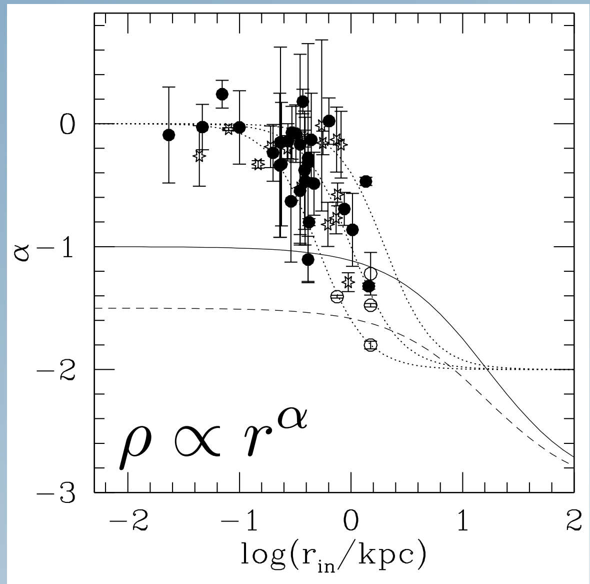
1. Missing satellites?



Moore *et al.*, ApJ '99

Many *more* *satellites* *in simulations* of MW-like galaxies than observed

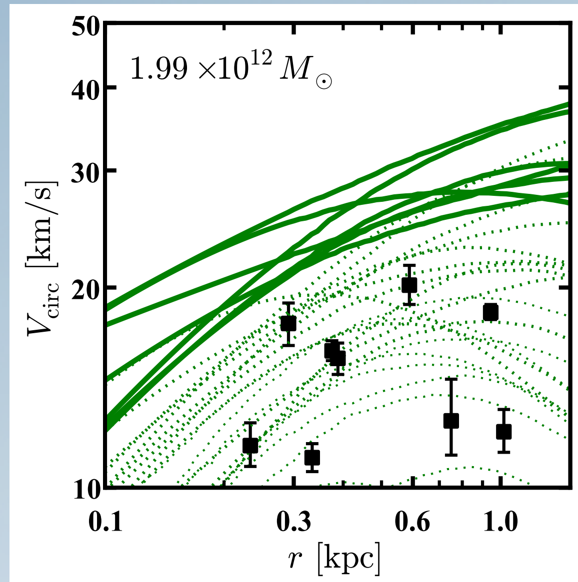
2. Cusps or cores?



Blok *et al.*, ApJ '01

Cuspy inner density profiles predicted by simulations not found in (all) observations

3. Too big to fail?

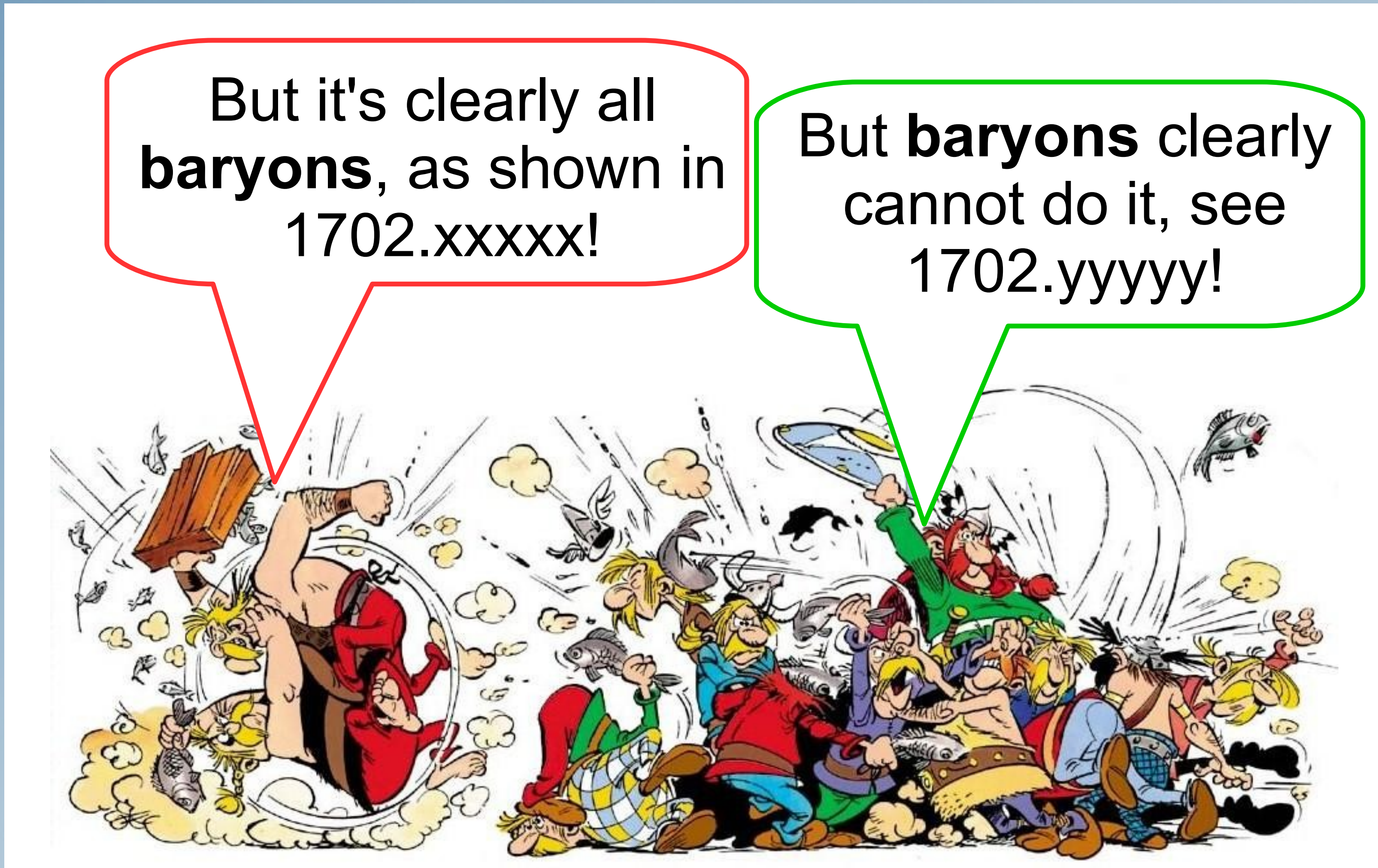


Boylan-Kolchin, Bullock & Kaplinghat, '11

Most massive subhalos in simulations are too dense to form observed brightest dwarf galaxies

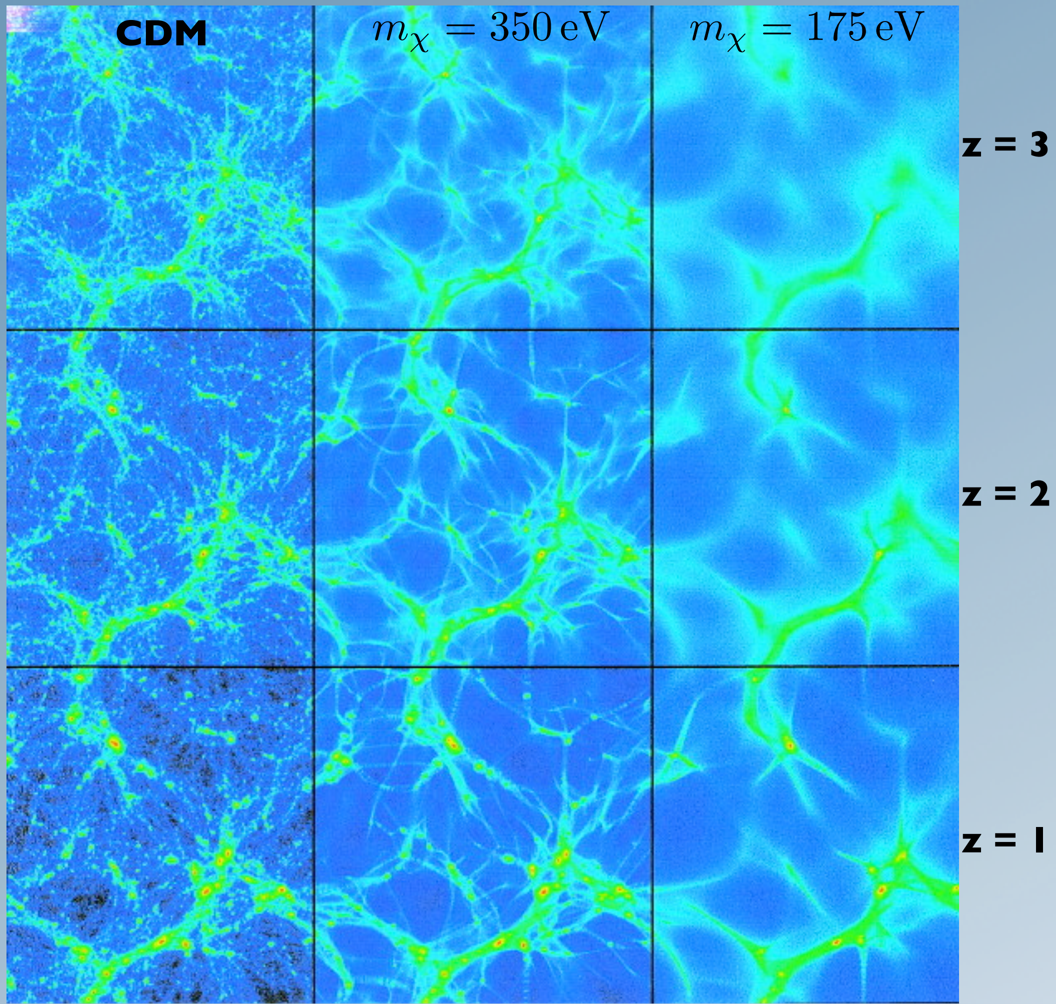
Small-scale problems

current status:



Courtesy: Kai Schmidt-Hoberg

Warm Dark Matter



Bode & Ostriker, ApJ 556, 93 (2001)

Free streaming of warm DM washes out density contrasts on small scales

Strongest constraints from Lyman-alpha observations

➔ Missing satellites could be explained this way ✓

WDM also produces cores in dwarfs ✗

➔ but only if so warm that free-streaming length larger than dwarf size!

"catch 22"

Macció, MNRAS '12

Models on the market

	Missing satellites	Cusp vs. core	Too big to fail
Baryons	✓	✓	✓
SIDM	✗	✓	✓
SIDM + DR	✓	✓	✓
WDM	✓	✗	✓
DDM	✓	✗	✓
LFDM	✓	✗	✓
BSI	✓	✓	✗

this talk (SIDM + DR)

(warm DM) (WDM)

(decaying DM) (DDM)

(Late Forming DM) (LFDM)

(Inflation w/ broken scale-invariance) (BSI)

•••
[list continues]

Summary slide by M. Archidiacono,
SIDM workshop Copenhagen 08/2017

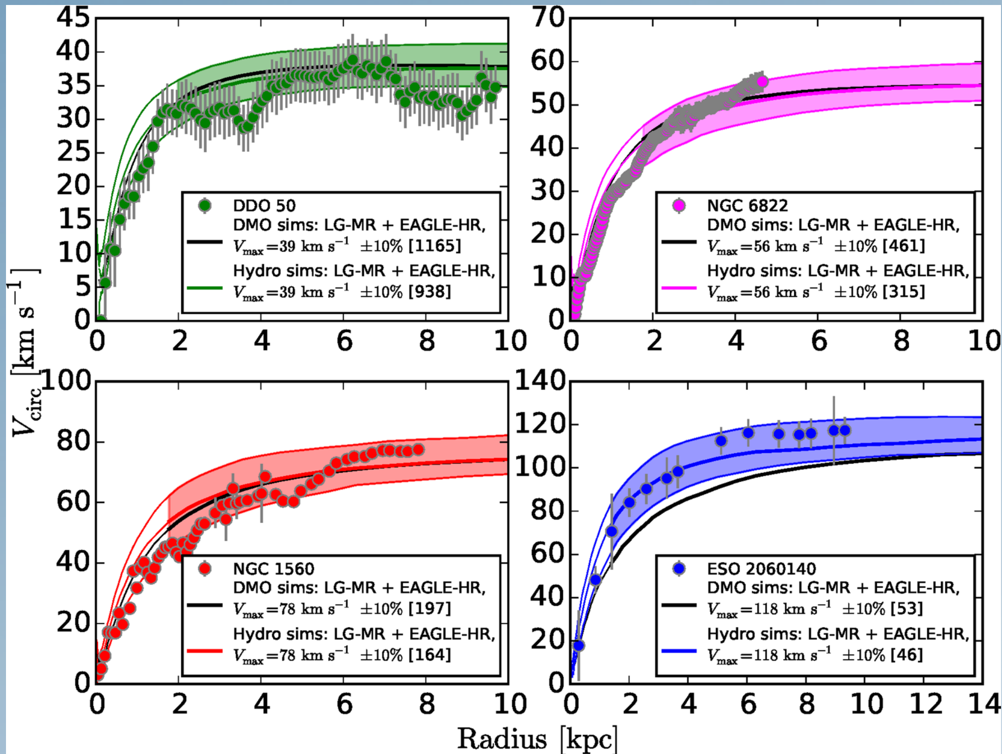
4. The diversity problem

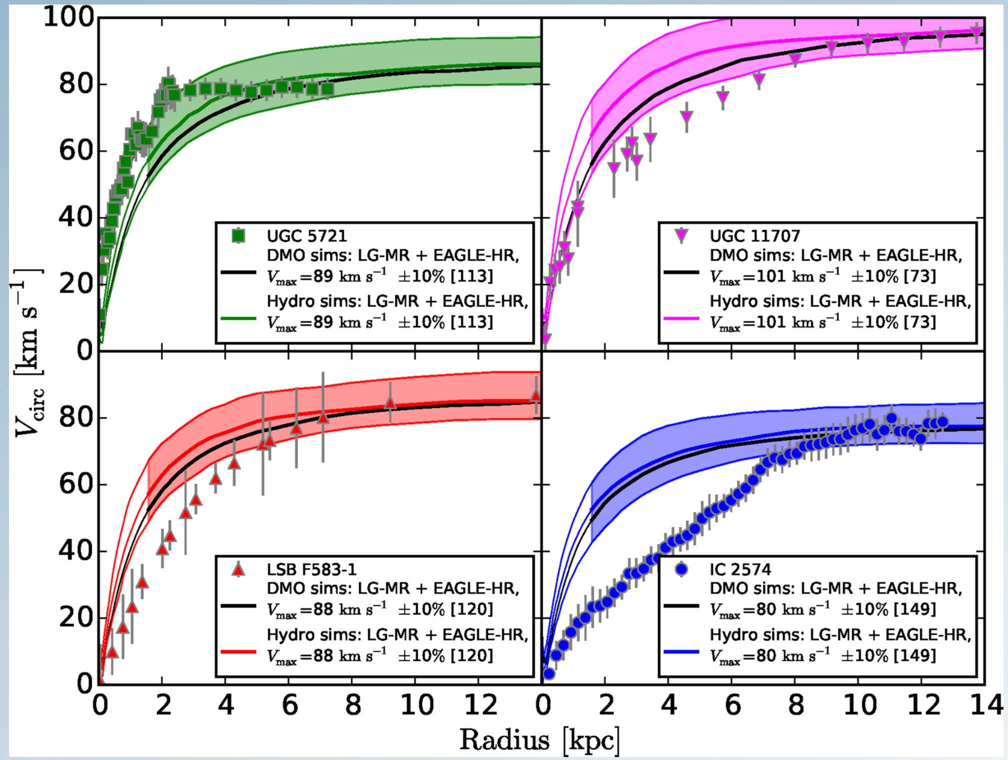
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **452,** 3650–3665 (2015)

The unexpected diversity of dwarf galaxy* rotation curves

Kyle A. Oman,[1★] Julio F. Navarro,[1†] Azadeh Fattahi,[1] Carlos S. Frenk,[2] Till Sawala,[2] Simon D. M. White,[3] Richard Bower,[2] Robert A. Crain,[4] Michelle Furlong,[2] Matthieu Schaller,[2] Joop Schaye[5] and Tom Theuns[2]

***) not dSph!**





Adding baryons significantly improves agreement with *some* observations
(*also* by increasing the scatter…)

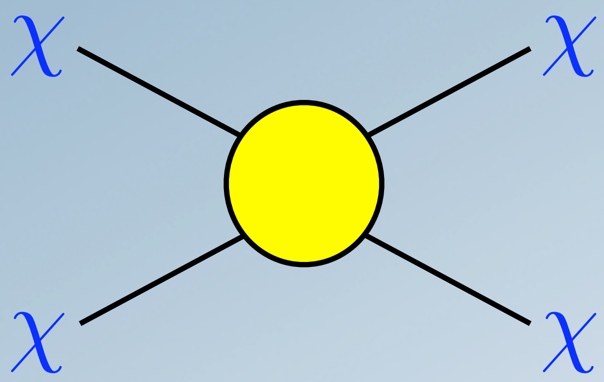
But cannot explain the diversity of observed rotation curves!

Models on the market

	Missing satellites	Cusp vs. core	Too big to fail	Diversity
Baryons	✓	✓	✓	✗ (so far)
SIDM	✗	✓	✓	✓
SIDM + DR (this talk)	✓	✓	✓	✓
WDM	✓	✗	✓	✗
DDM	✓	✗	✓	✗
LFDM	✓	✗	✓	✗ (?)
BSI	✓	✓	✗	✗ (?)

Summary slide by M. Archidiacono,
SIDM workshop Copenhagen 08/2017

Self-interacting Dark Matter



The SIDM proposal

Spergel & Steinhardt, PRL '99

Allow for DM-DM interaction strength

$$\sigma/m_\chi \sim (0.5 - 500)\,\mathrm{cm}^2/\mathrm{g}$$

➡ Expectation:

Update after detailed simulations:

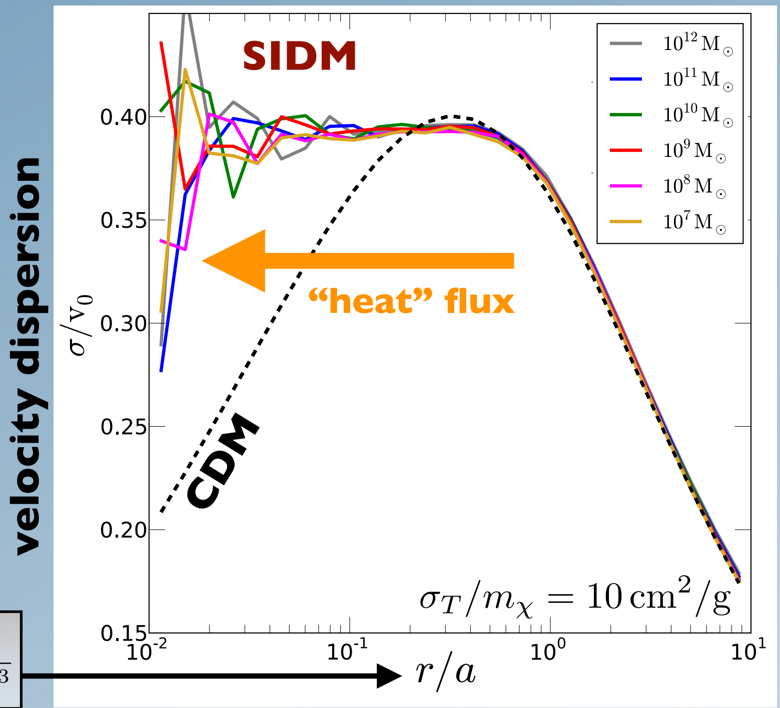
- ΛCDM unchanged above Mpc scales ✓
  [less than one collision per Hubble time]
- DM (sub)halos will develop cores ✓ for cusp/core, need $\sigma/m_\chi \sim 1\mathrm{cm}^2/\mathrm{g}$
  [scattering increases entropy of DM phase spase distribution]
- more spherical (sub)halos ✓ indeed gives rise to relevant constraints
  [same as above]
- Less dense subhalos will \`evaporate' ✗ only for $\sigma/m_\chi \gg 1\mathrm{cm}^2/\mathrm{g}$
  [scattering destroys substructure]

SIDM simulations

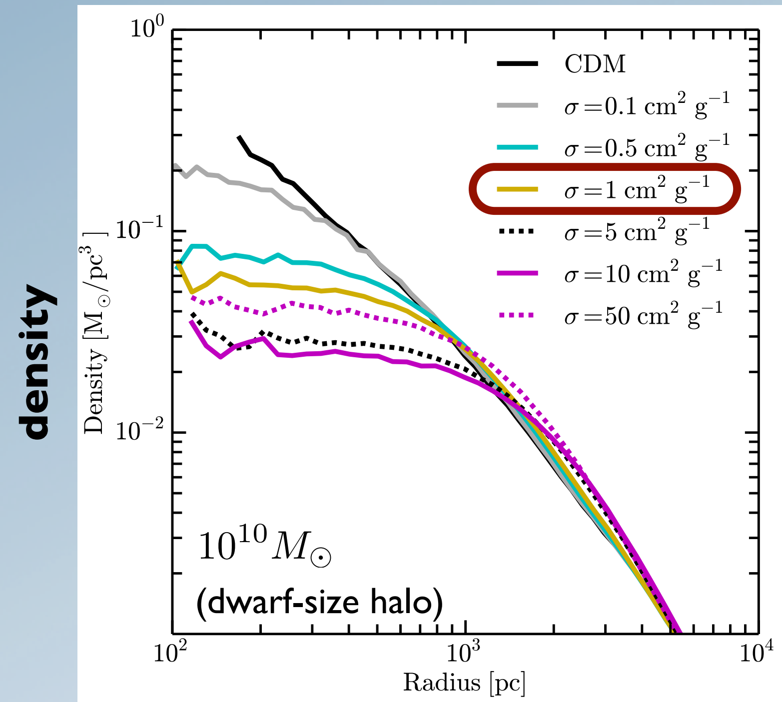
- Self-interactions isotropise DM in inner halo
  - ⇨ formation of core once $\mathcal{O}(1)$ scatters per dynamical time

Hernquist profile

$$\rho(r) = \frac{Ma}{2\pi r}\frac{1}{(r+a)^3}$$



Vogelsberger, Zavala & Loeb, MNRAS '12



roughly needed for **cusp/core**

Elbert+, MNRAS '15

- Same effect also mitigates too-big-to-fail problem!

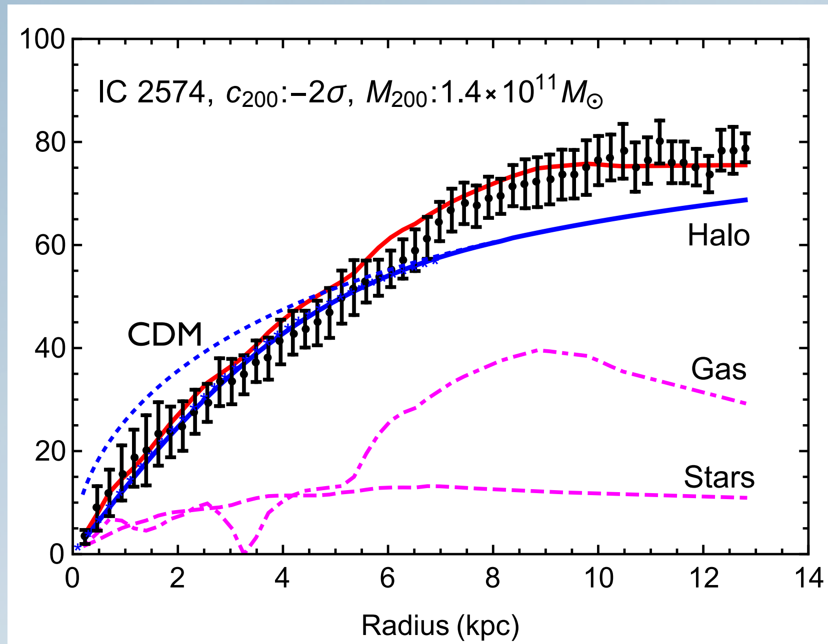
SIDM + baryons

- How to include baryons in the model?
  - SIDM distribution should still be thermal (inside some r_1), independent of assembly history!

  ➡ simply replace $\rho_{\rm iso}(r) \propto e^{\Phi_{\rm DM}/\sigma_0^2}$ with $\rho_{\rm iso}(r) \propto e^{(\Phi_{\rm DM}+\Phi_{\rm b})/\sigma_0^2}$

Kamada, Kaplinghat, Pace & Yu, 1611.02716

- In this way, the diversity problem might be addressed by correlating DM and baryon distributions!



- First SIDM simulations with baryons ongoing…

Velocity dependence

- Many constraints at all scales
  - e.g. from merging clusters →
  - extensive & updated review: Tulin & Yu, 1705.02358

Cluster	σ/m	Method used	Ref.
Bullet Cluster (1E 0657-558)	$< 3\ \mathrm{cm}^2/\mathrm{g}$	Scattering depth ($\Sigma_{\mathrm{dm}} \approx 0.3\ \mathrm{cm}^2/\mathrm{g}$)	[264]
	$< 0.7\ \mathrm{cm}^2/\mathrm{g}$	Mass loss $< 23\%$	[68]
	$< 1.2\ \mathrm{cm}^2/\mathrm{g}$	DM-galaxy offset 25 ± 29 kpc	[68]
Abell 520	$3.8 \pm 1.1\ \mathrm{cm}^2/\mathrm{g}$	Scattering depth ($\Sigma_{\mathrm{dm}} \approx 0.07\ \mathrm{cm}^2/\mathrm{g}$)	[292]
	$0.94 \pm 0.06\ \mathrm{cm}^2/\mathrm{g}$	Scattering depth ($\Sigma_{\mathrm{dm}} \approx 0.14\ \mathrm{cm}^2/\mathrm{g}$)	[92]
Abell 2744	$< 1.28\ \mathrm{cm}^2/\mathrm{g}$	Offset	[306]
	$< 3\ \mathrm{cm}^2/\mathrm{g}$	Scattering depth ($\Sigma_{\mathrm{dm}} \approx 0.3\ \mathrm{cm}^2/\mathrm{g}$)	[295]
Musket Ball Cluster (DLSCL J0916.2+2951)	$< 7\ \mathrm{cm}^2/\mathrm{g}$	Scattering depth ($\Sigma_{\mathrm{dm}} \approx 0.15\ \mathrm{cm}^2/\mathrm{g}$)	[282]
Baby Bullet (MACS J0025.4-1222)	$< 4\ \mathrm{cm}^2/\mathrm{g}$	Scattering depth ($\Sigma_{\mathrm{dm}} \approx 0.25\ \mathrm{cm}^2/\mathrm{g}$)	[284]
Abell 3827	~~$1.5\ \mathrm{cm}^2/\mathrm{g}$~~	Offset gone… (R. Massey)	[91]

- Rough agreement:

"cluster constraints are severe — but constant scattering cross section may still work"

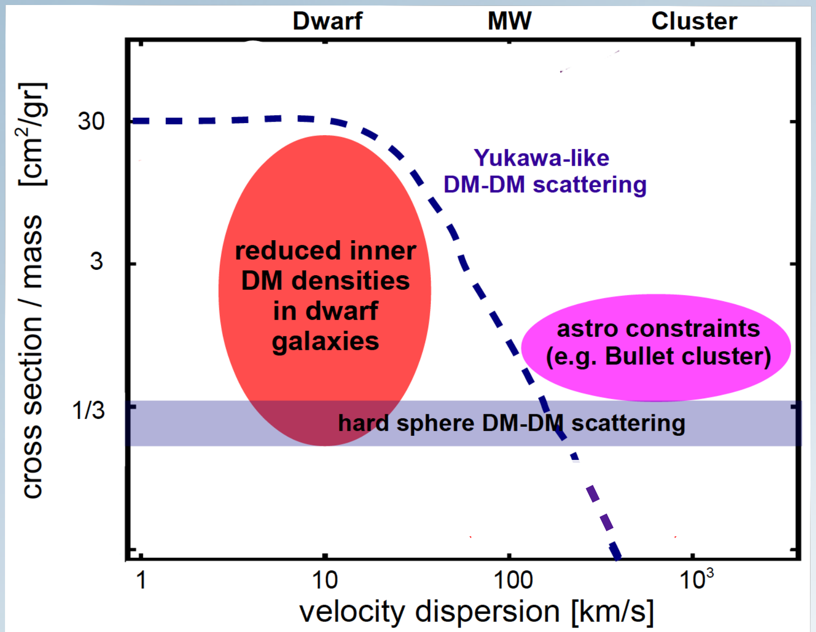
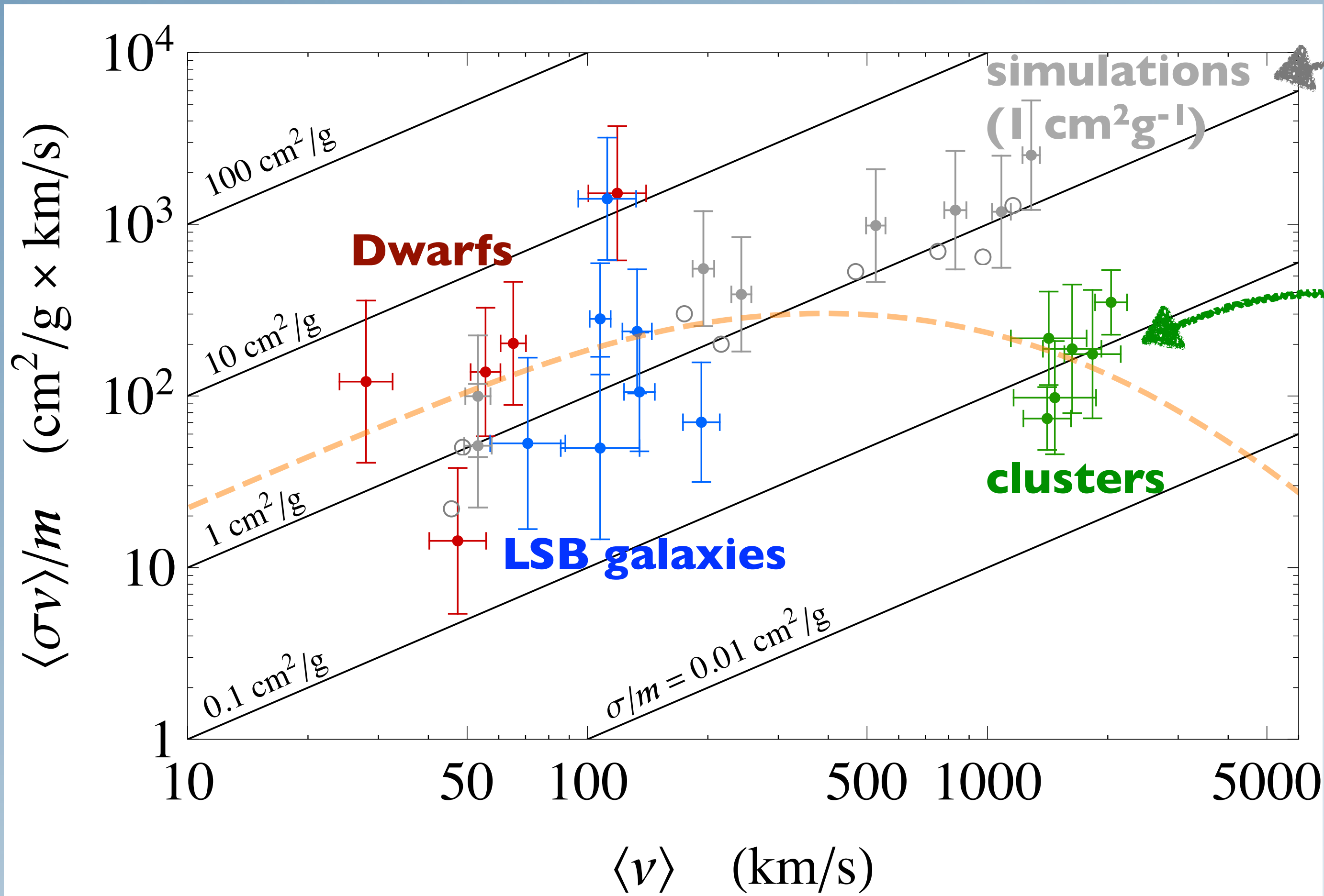


Fig: Jesús Zavala, SIDM workshop Copenhagen 08/17

Velocity dependence (2)

- Most stringent constraints from cluster core size
  - ⚠ fit same analytical (SIDM only) model to existing data

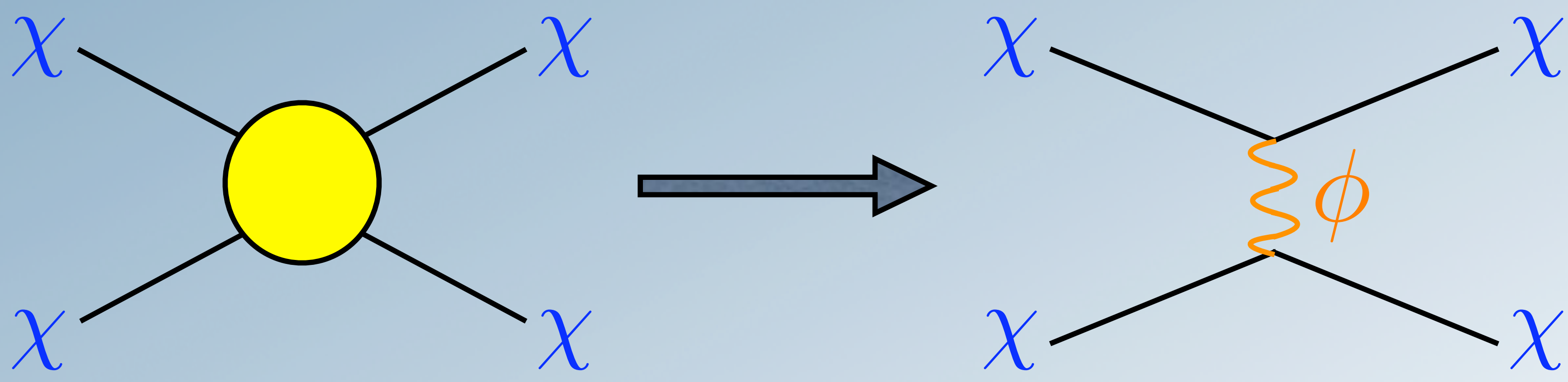


Kaplinghat, Tulin & Yu, PRL '15

verify model + estimate systematics

max. cluster core size: ~10 kpc
(1 cm^2/g would instead imply 100!)

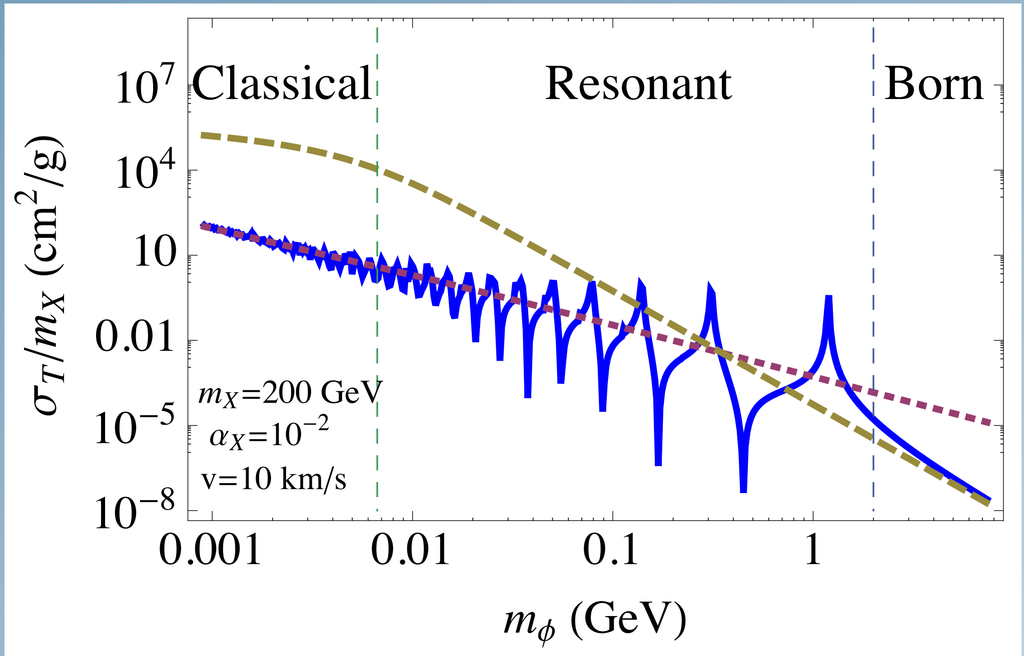
Equipping WIMPs with long-range forces



Self-interacting dark matter

- Scattering of non-relativistic particles in a Yukawa potential:

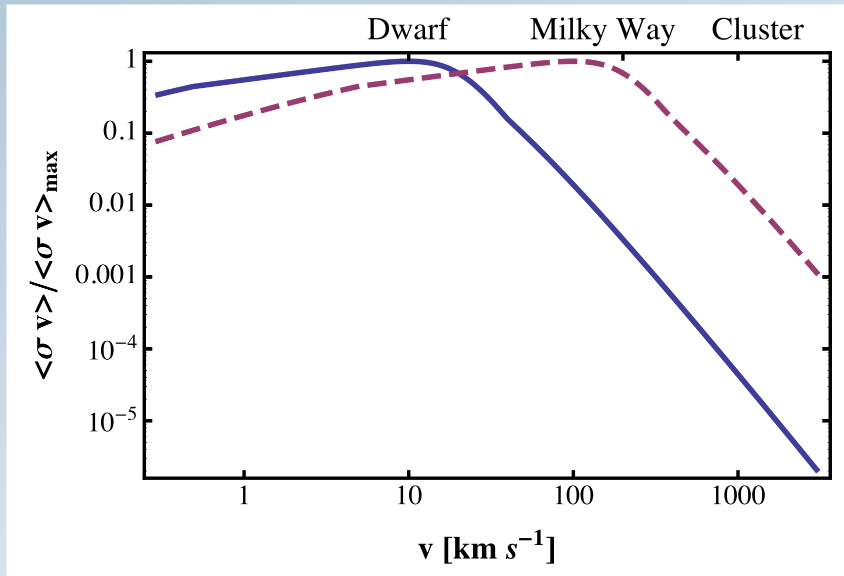
$$\left(-\frac{\nabla^2}{m_\chi}+V\right)\psi(r)=m_\chi v^2\,\psi(r)$$



$$\sigma_T \equiv \int d\Omega(1-\cos\theta)\frac{d\sigma}{d\Omega}$$

see e.g. Tulin, Yu & Zurek, PRD '13

[resonances only for attractive potential]



+ *characteristic velocity dependence !*

Loeb & Weiner, PRL '11

Parameter region of interest

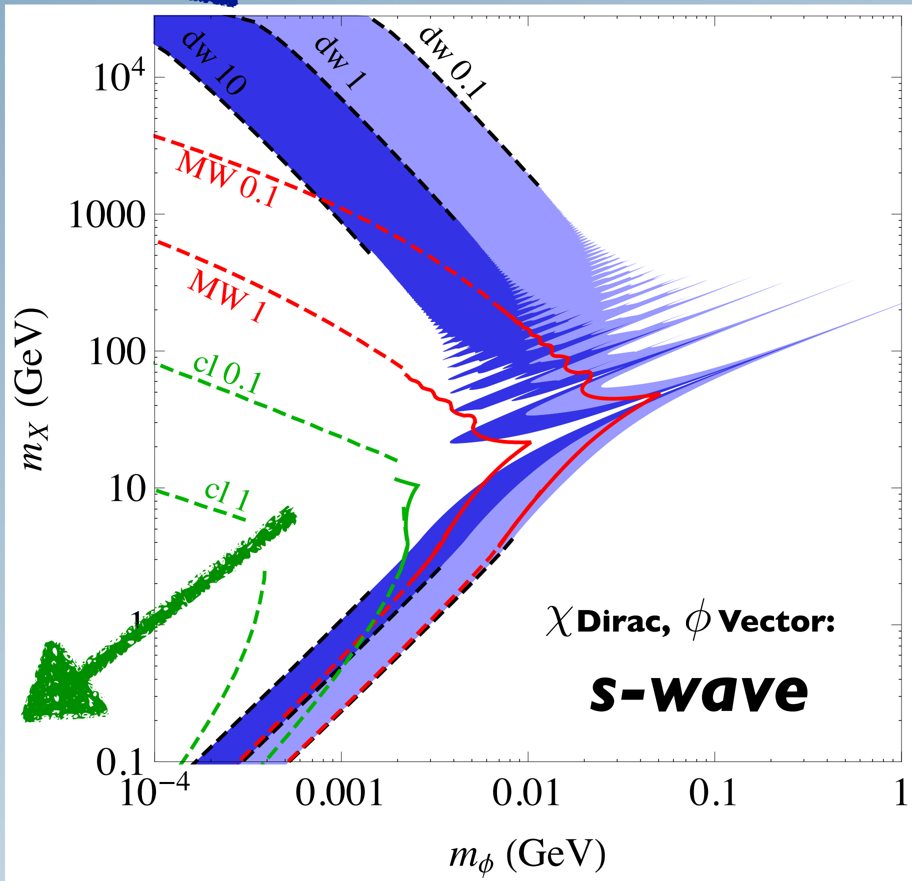
- Additional advantage: Thermal production via $\chi\chi \leftrightarrow \phi\phi$

$\rightsquigarrow$ fix $\alpha = \alpha(m_\chi, m_\phi)$

affect core/ cusp + TBTF

$\langle\sigma_T\rangle/m_\chi \sim 1\,\mathrm{cm}^2/g$

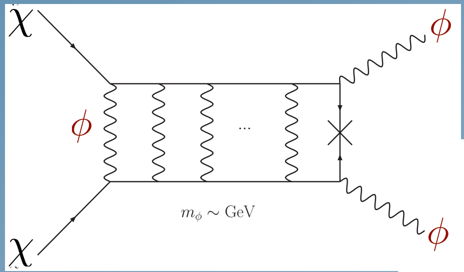
excluded by Bullet cluster & co

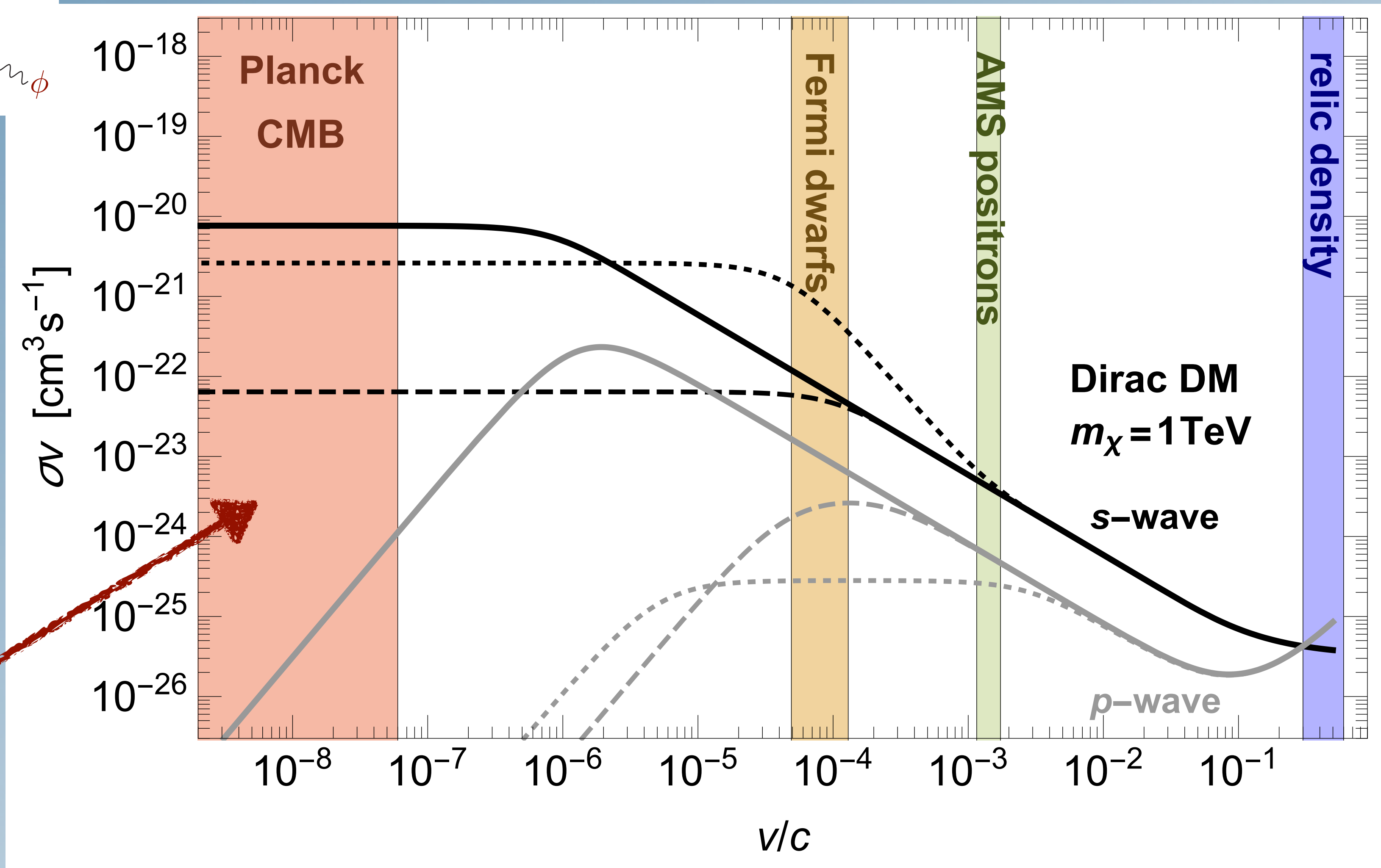


Tulin, Yu & Zurek, PRD '13

Sommerfeld effect for SIDM

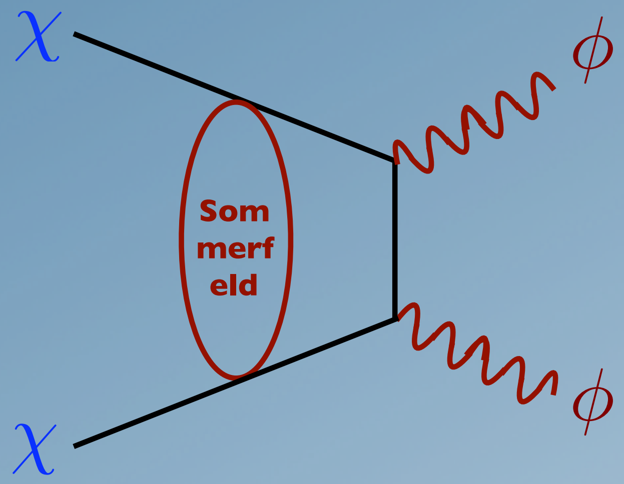
TB, Kahlhoefer, Schmidt-Hoberg & Walia, 1612.00845

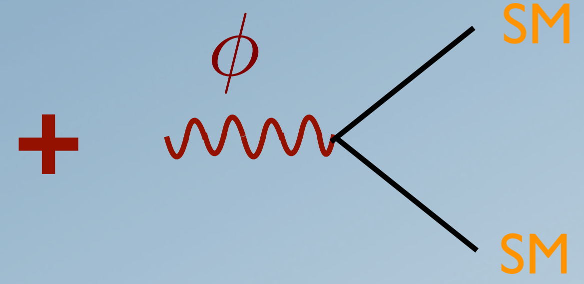




During CMB, DM moves at (most at) pedestrian speed!

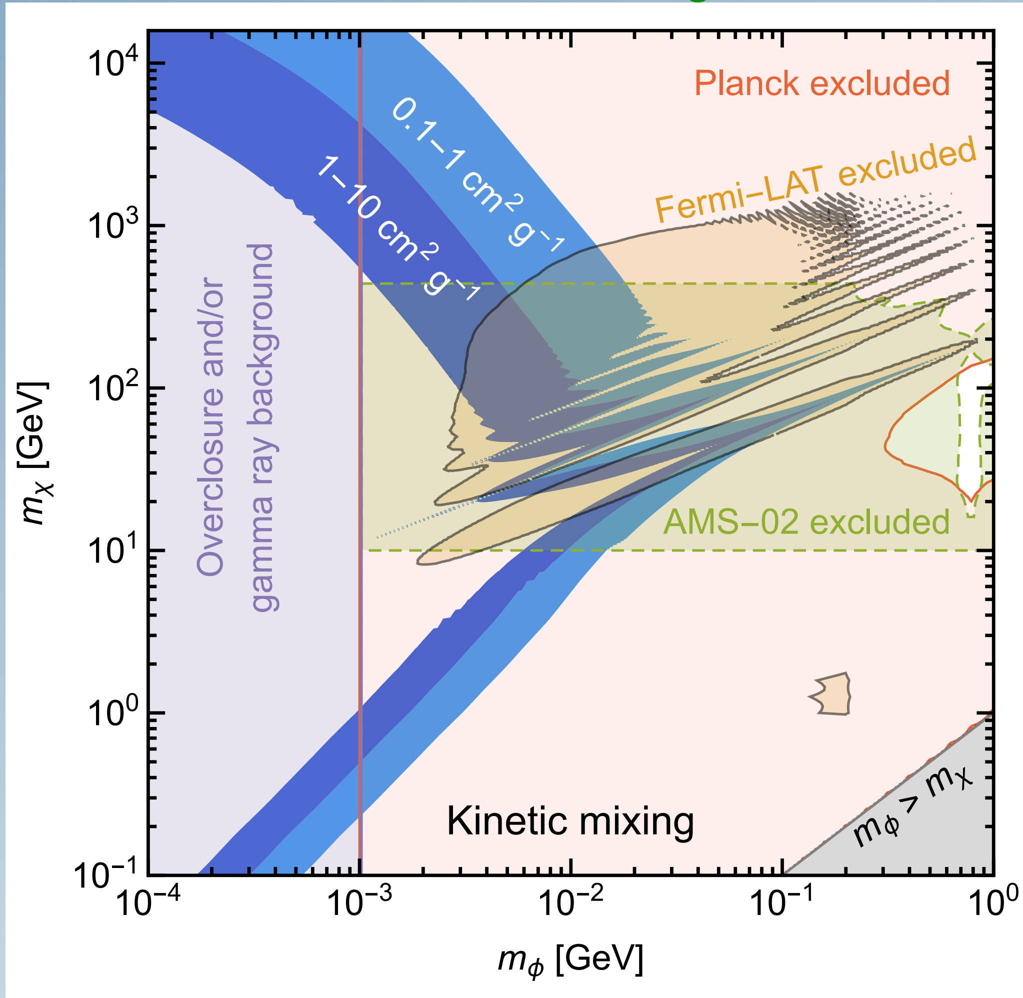
Constraints





- ϕ must decay to be cosmologically viable
- helps to thermalise dark sector in the first place (?)
- …

TB, Kahlhoefer, Schmidt-Hoberg & Walia, PRL '17



All relevant parameter space excluded !

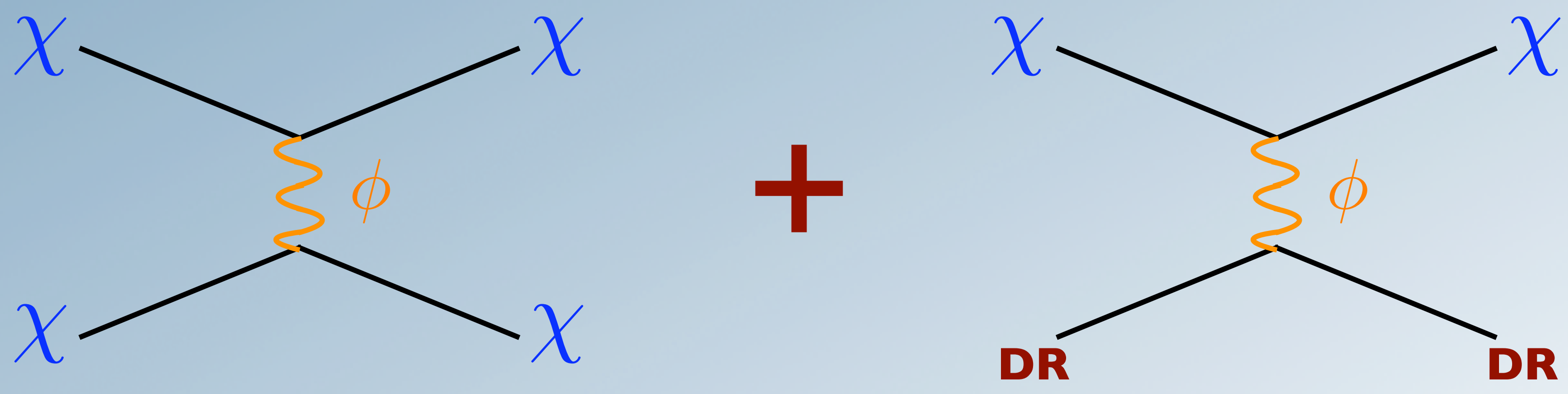
Ways out?

- ϕ not in thermal equilibrium during DM freeze-out
  - ✗ thermal contact at earlier time $\rightsquigarrow T_{\rm dark}/T_{\rm visible}$ cannot be too small!
    - ➡ conclusions ~unchanged! TB+, PRL '17
  - ✓ no thermal production at all $\rightsquigarrow$ predictivity ?

- *p*-wave rather than *s*-wave annihilation
  - ✗ only possible for *scalar* mediators! $\rightsquigarrow$ ruled out by direct detection!
    E.g. Kaplinghat, Tulin & Yu, PRD '14; Bernal+, JCAP '16
  - ✓ exception: tuned(?) mixing between scalar and pseudoscalar
    Kahlhoefer, Schmidt-Hoberg & Wild, 1704.02149

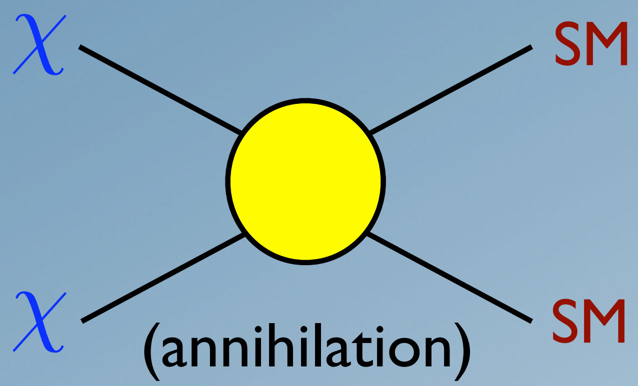
- Invisible decays!
  - ✓ Cheating? Proposed in this context *before* those constraints were known…
    van den Aarssen, TB & Pfrommer, PRL '12

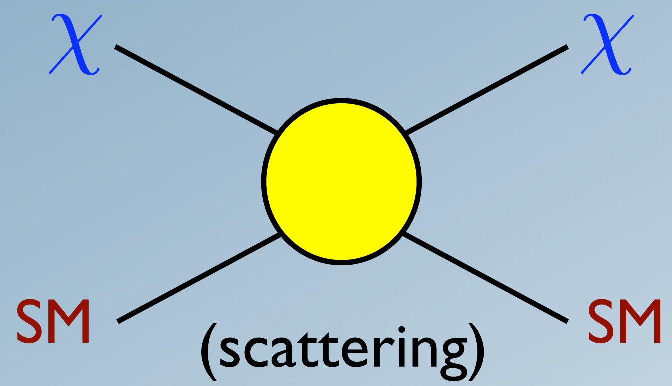
Light mediators coupling to DM and 'dark' radiation



Freeze-out ≠ decoupling !

- WIMP interactions with heat bath of SM particles:





- Boltzmann suppression of n_χ
  - scattering processes much more frequent
  - continue even after chemical decoupling ("freeze-out") at $T_{\rm cd} \sim m_\chi/25$

- Kinetic decoupling much later:

$$\tau_{\rm r}(T_{\rm kd}) \equiv N_{\rm coll}/\Gamma_{\rm el} \sim H^{-1}(T_{\rm kd})$$

← Random walk in momentum space $\rightsquigarrow N_{\rm coll} \sim m_\chi/T$

Schmid, Schwarz, & Widerin, PRD '99; Boehm, Fayet & Schaeffer, PLB '01; Green, Hofmann & Schwarz, JCAP '05, ...

The smallest protohalos

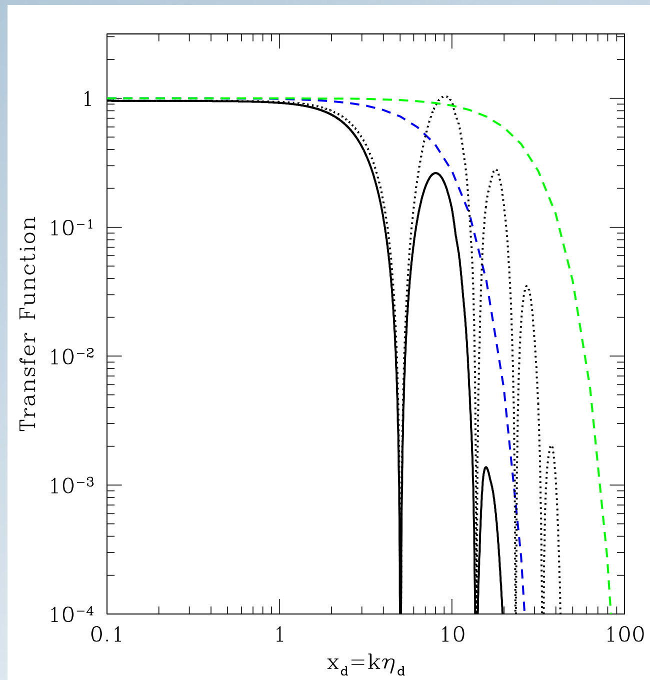
- Free streaming of WIMPs after $t_{\rm kd}$ washes out density contrasts on small scales
  e.g. Green, Hofmann & Schwarz, JCAP '05

$$M_{\rm fs} = 2.9\times10^{-6}\left(\frac{1+\ln\left(\frac{g_{\rm eff}^{\frac{1}{4}}T_{\rm kd}}{30\,\rm MeV}\right)/18.6}{\left(\frac{m_\chi}{100\,\rm GeV}\right)^{\frac{1}{2}}g_{\rm eff}^{\frac{1}{4}}\left(\frac{T_{\rm kd}}{30\,\rm MeV}\right)^{\frac{1}{2}}}\right)^3 M_\odot$$

- Similar effect from baryonic /'dark acoustic' oscillations Loeb & Zaldarriaga, PRD '05 Bertschinger, PRD '06

$$M_{\rm ao} = 3.4\times10^{-6}\left(\frac{T_{\rm kd}\,g_{\rm eff}^{\frac{1}{4}}}{50\,\rm MeV}\right)^{-3} M_\odot$$

- Cutoff in power spectrum corresponds to smallest gravitationally bound objects in the universe



Loeb & Zaldarriaga, PRD '05

The smallest protohalos

- Free streaming of WIMPs after $t_{\rm kd}$ washes out density contrasts on small scales
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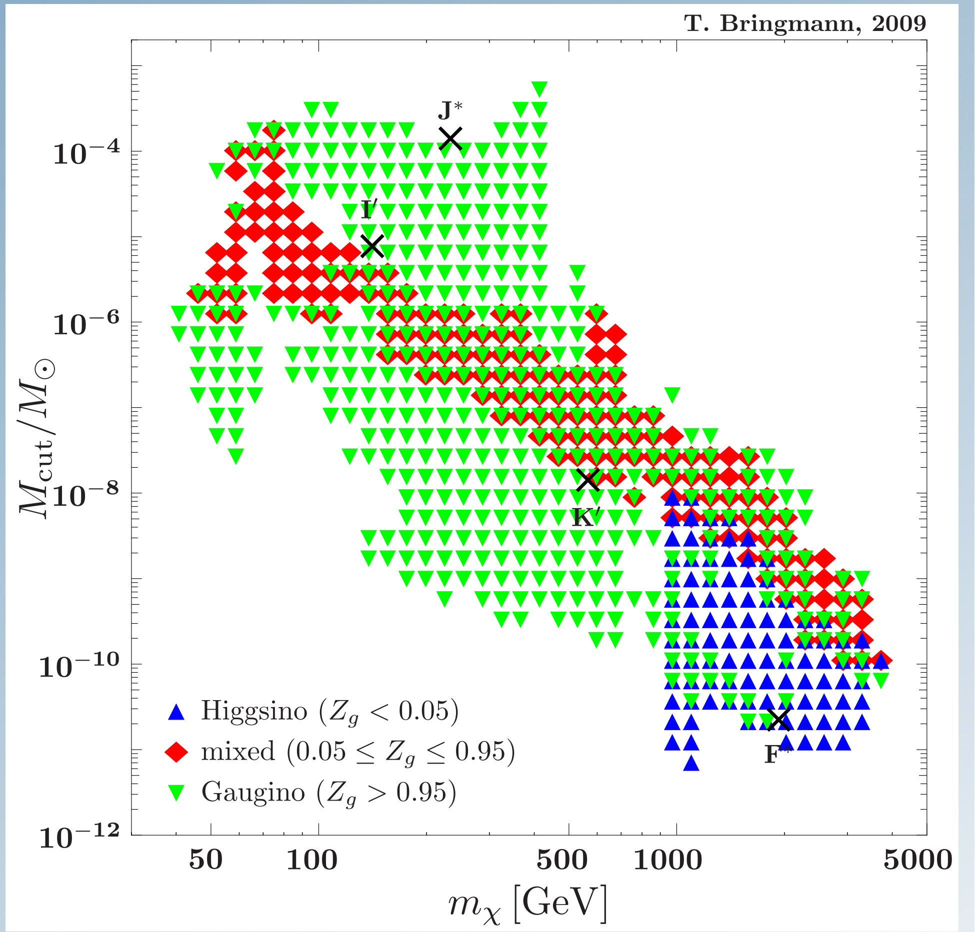


⇨ *Strong dependence on particle physics properties!*

in particular: no "typical" value of $M_{\rm cut} \sim 10^{-6} M_\odot$

(see also Profumo, Sigurdson & Kamionkowski, PRL '06)

Very late kinetic decoupling ?

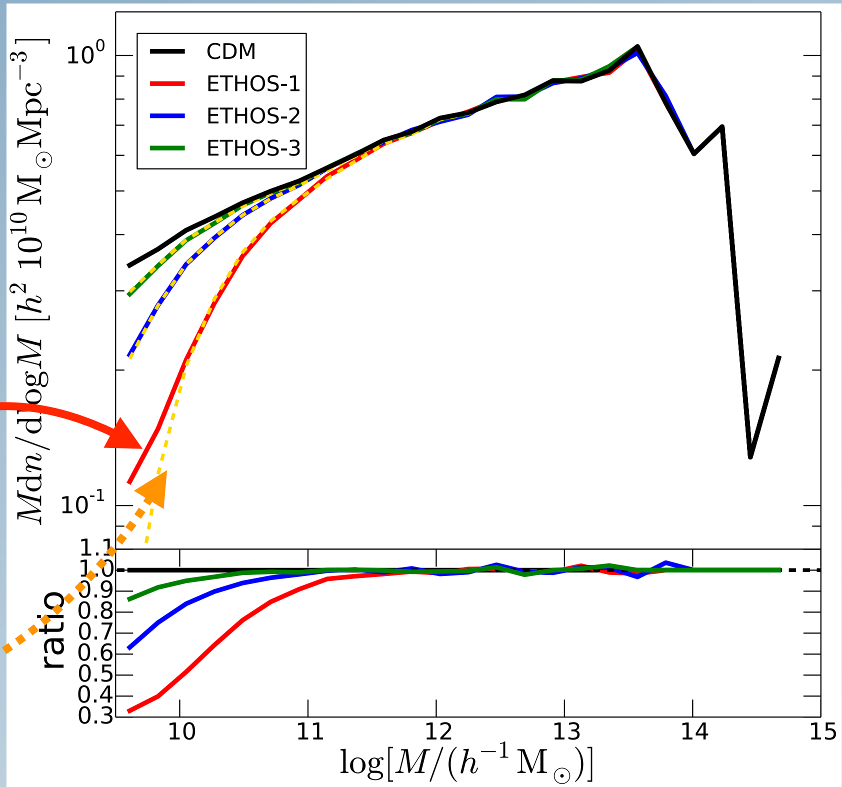
- *N*-body simulations confirm very similar suppression of halo mass function as for WDM cosmology:

$$M_{\rm cut,kd} = 5\cdot 10^{10}\left(\frac{T_{\rm kd}}{100\,{\rm eV}}\right)^{-3} h^{-1}\,M_\odot$$

[**solid lines**; NB: up to factor ~2 same as analytic estimate!]

$$M_{\rm cut,WDM} = 10^{11}\left(\frac{m_{\rm WDM}}{\rm keV}\right)^{-4} h^{-1}\,M_\odot$$

[**dashed lines**; would-be result from WDM free-streaming]



Vogelsberger+, MNRAS '16

➩ *The `missing satellite problem' may be equally well addressed by **cold** dark matter!*

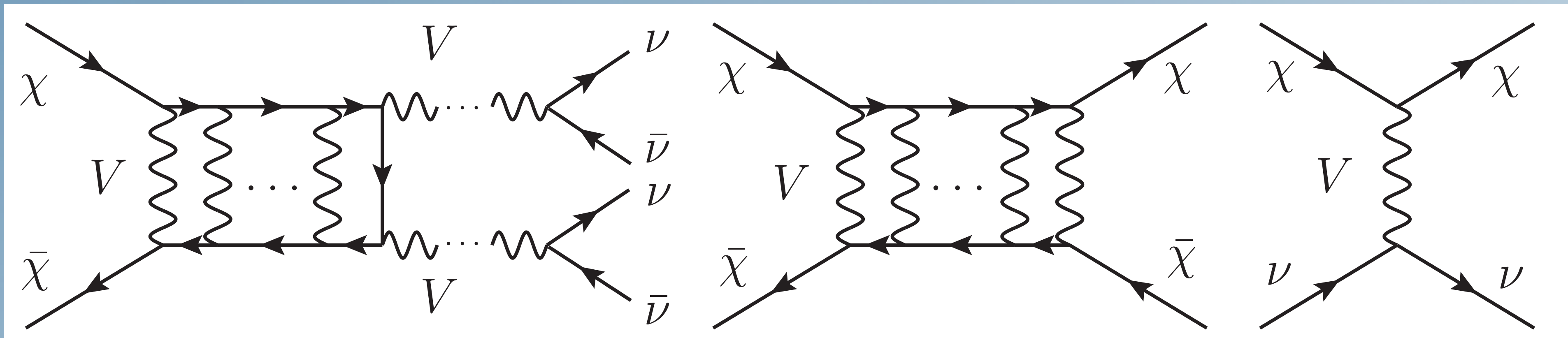
[alt.: $T_{\rm kd}$ can be constrained by Ly-α just as well as $m_{\rm WDM}$]

A simple framework

van den Aarssen, TB & Pfrommer, PRL '12

- Assume light vector mediator coupling to dark matter and (sterile) neutrinos:

$$\mathcal{L}_{\rm int} \supset -g_\chi \bar{\chi} \not{V} \chi - g_\nu \bar{\nu} \not{V} \nu$$



relic density
(+indirect detection signal!?)

changes inner density and velocity profiles of dwarf galaxies
(Yukawa potential)

Large $M_{\rm cut}$
(late kinetic decoupling)

- NB: only requiring late KD already leads to such a setup with DR + MeV mediators!
(generic solution from full simplified model classification)

TB, Ihle, Kersten & Walia, PRD '16

Concrete model building example

Tying DM to *sterile* neutrinos

A dark sector with a $U(1)_X$

TB, Hasenkamp & Kersten, JCAP '14

Standard Model ······ **"Higgs portal"** ······ **Dark Sector**

$\mathcal{L}_{\rm Higgs} \supset \kappa|\phi|^2|\Theta|^2$

$SU(3)_c \times SU(2)_L \times U(1)_Y$ — $U(1)_X$

- Particles contained in Dark Sector:
  - ~TeV CDM particle χ
  - Majorana sterile neutrinos N_1 (~eV), N_2 (~MeV)
  - ~MeV $U(1)_X$ gauge boson

  } **charges** $(1, X_{\nu_R}, -X_{\nu_R})$

  - Dark Higgs Θ for SSB of $U(1)_X$
  - Scalar ξ for active-sterile neutrino mixing ($\rightsquigarrow M_{LR} \sim v_\phi v_\xi/\Lambda$)

Thermalisation & Decoupling of DS

- Full thermalisation of *U(1)*$_X$ sector at $T > m_\chi$
  $\rightsquigarrow$ Higgs portal coupling $\kappa \gtrsim 10^{-6}$
- Decoupling of *whole U(1)*$_X$ sector
  when Higgs portal no longer effective
  - ➡ entropy conserved separately in SM and dark sector
    (note strong *U(1)*$_X$ coupling!)
  - ➡ when particles become non-relativistic,
    temperature increases as $(g_{*,\nu/N_1}^{\text{before}}/g_{*,\nu/N_1}^{\text{after}})^{\frac{1}{3}}$
- Additional effective d.o.f.:

$$\Delta N_{\text{eff}}(T) = \frac{T_{N_1}^4}{T_\nu^4} = \left(\frac{g_{*,\nu}}{g_{*,N_1}}\right)^{\frac{4}{3}}\Bigg|_T \left(\frac{g_{*,N_1}}{g_{*,\nu}}\right)^{\frac{4}{3}}\Bigg|_{T_x^{\text{dpl}}}$$

max. contribution at BBN:

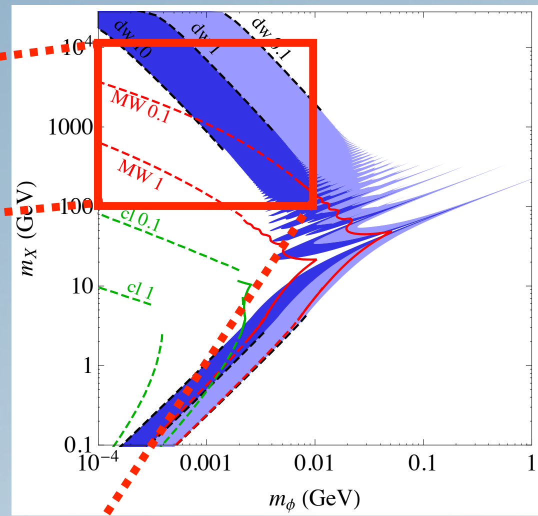
$$\Delta N_{\text{eff}}\big|_{\text{bbn}}^{\text{max}} \simeq \left[58.4/g_{*,\nu}(T_x^{\text{dpl}})\right]^{\frac{4}{3}}$$

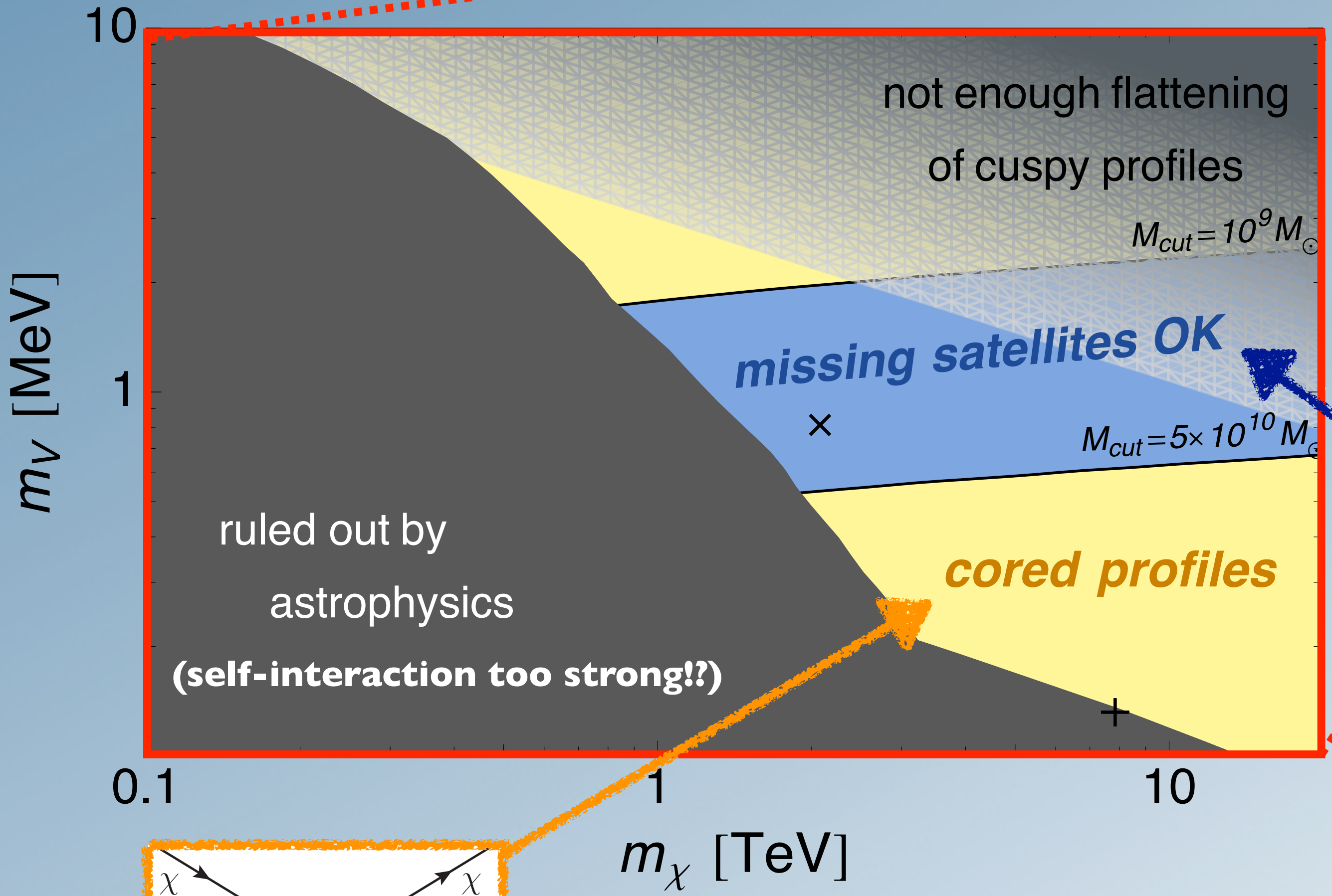
(when only N_1 is relativistic!)

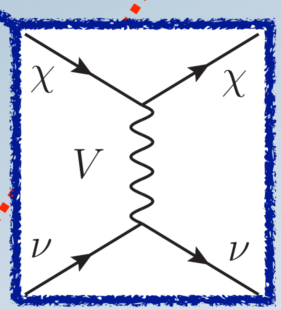
$\rightsquigarrow$ *well within BBN bounds for* $T_x^{\text{dpl}} \gtrsim 1\,\text{GeV}!$

The CDM component

- Relic density: fix $\alpha = \alpha(m_\chi, m_\phi)$



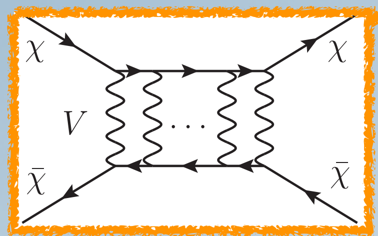




- Kinetic decoupling

$$m_V \propto X_{\nu_R}^{1/2} (T_{N_1}/T)_{\rm kd}^{3/2}$$

[Here, $X_{\nu_R} = 0.2$
and $(T_{N_1}/T)_{\rm kd}^4 = 0.46$]



- Self-scattering

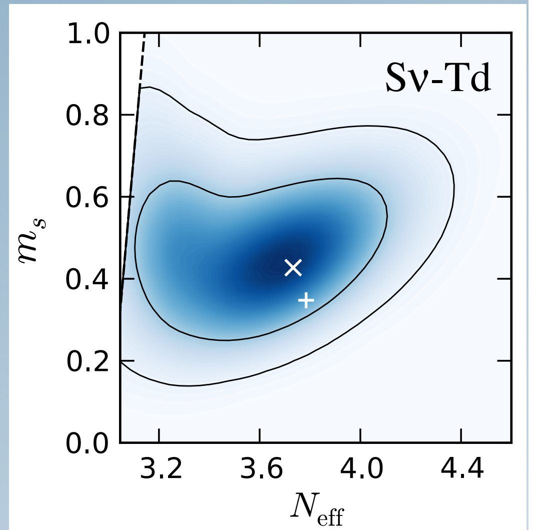
Hot Dark Matter

PRL **112,** 051302 (2014) PHYSICAL REVIEW LETTERS week ending 7 FEBRUARY 2014

Neutrinos Help Reconcile Planck Measurements with the Local Universe

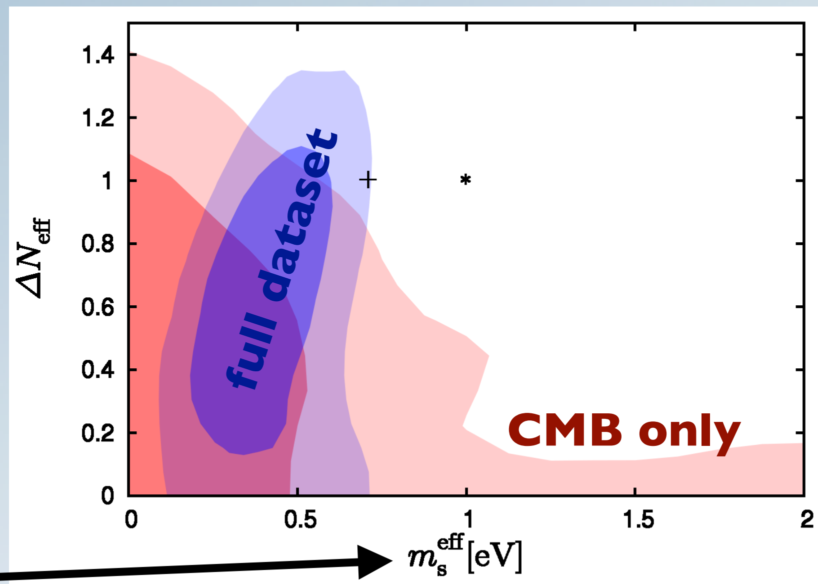
Mark Wyman,* Douglas H. Rudd, R. Ali Vanderveld, and Wayne Hu
Kavli Institute for Cosmological Physics, Department of Astronomy & Astrophysics, Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA
(Received 5 August 2013; published 6 February 2014)

~same:
Hamann & Hasenkamp, JCAP '13
Battye & Moss, PRL '14
Gariazzo, Giunti & Laveder, JHEP '13



- Tension between cosmological data at high ($z \gtrsim 1000$) and low redshifts ($z \lesssim 10$)
  - normalisation σ_8 of matter density perturbations higher in Planck data than in local galaxy cluster data
  - Expansion rate H_0 higher in local redshift-distance measurements than in measurements of acoustic scale (CMB, BAO)

Ade+ [Planck coll.], A&A '14



HDM: $m_{\rm s}^{\rm eff} = (T_{\rm s}/T_\nu)^3 m_{\rm s}$

Hamann & Hasenkamp, JCAP '13

The HDM component

- No additional N_I production:

$$\Delta N_{\rm eff}|_{\rm cmb} = \Delta N_{\rm eff}|_{\rm bbn}^{\rm max} \simeq \left[58.4/g_{*,\nu}(T_x^{\rm dpl})\right]^{\frac{4}{3}}$$

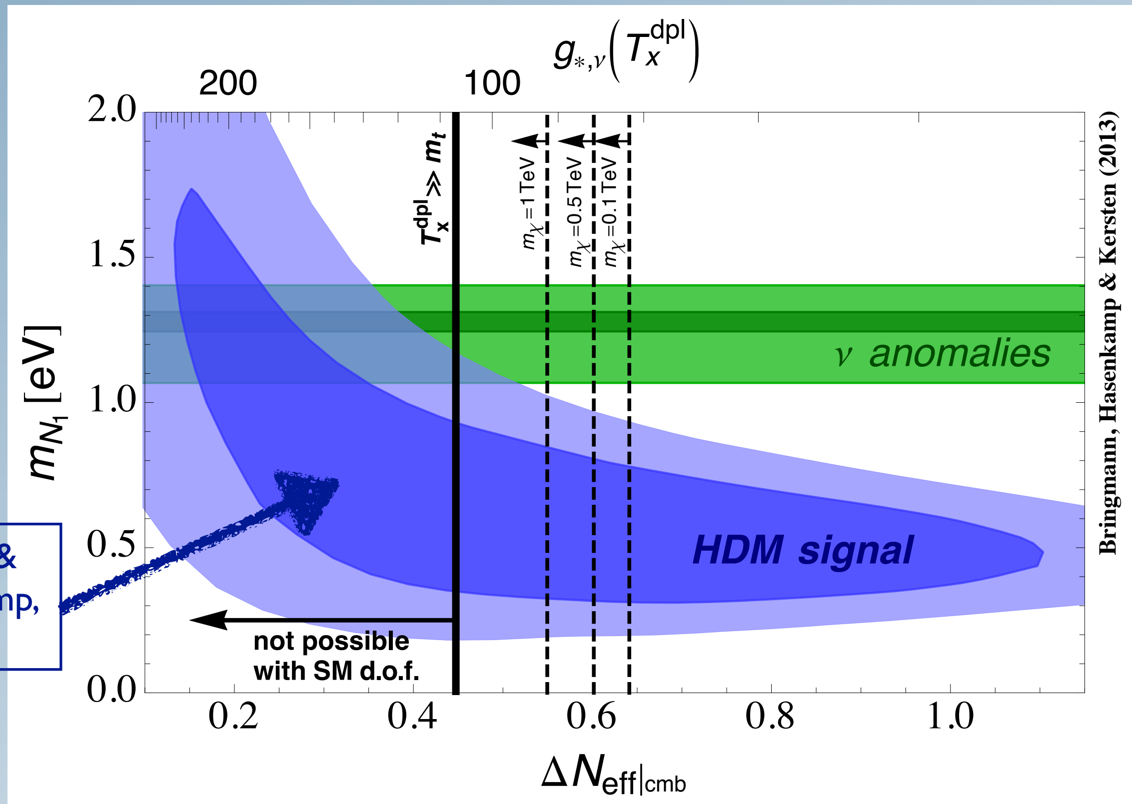
= function of Higgs portal coupling…

$$m_{\rm hdm}^{\rm eff} \equiv \left[T_{N_1}/T_\nu^{\Lambda{\rm CDM}}\right]^3 m_{N_1} = (\Delta N_{\rm eff}|_{\rm cmb})^{\frac{3}{4}} m_{N_1}$$

In this model
sterile neutrinos
naturally account
for the desired
HDM component

Giunti+, PRD '13

Hamann & Hasenkamp, JCAP'13



- Update: ν_s *do* seem to re-thermalize
  ⇝ **blue region moves down by factor ~2**

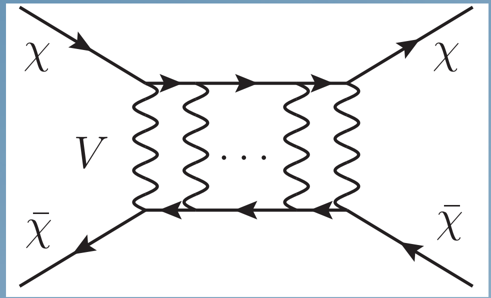
Saviano, Pisanti, Mangano & Mirizzi, PRD '14
Mirizzi, Mangano, Pisanti, Saviano, PRD '15
Chu, Dasgupta & Kopp, JCAP '15
…

ETHOS

Towards an Effective Theory Of Structure formation

with Francis-Yan Cyr-Racine, Christoph Pfrommer, Kris Sigurdsson, Mark Vogelsberger, Jesús Zavala

From theory to observations



step 1

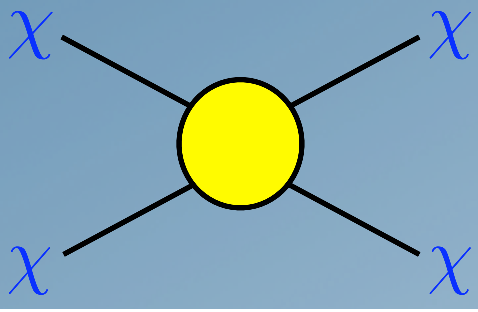
step 2

particle model	cosmological simulations	astrophysical observables
<u>input</u>: masses, spins, coupling constants	**<u>input</u>:** consistent initial conditions, non-gravitational forces between "particles"	**input (<u>for interpretation of data</u>):** output from simulations

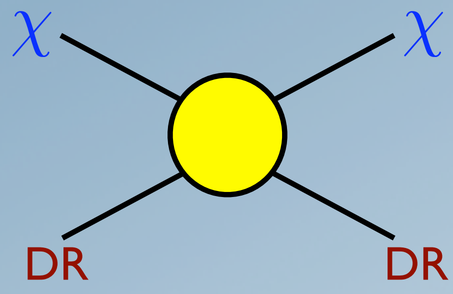
- The first step can be demanding,
the second in addition computationally very expensive
- But expect large degeneracies, so very inefficient…
- **Idea of ETHOS**: introduce effective parameters and provide maps for each of those steps ($\rightsquigarrow$ no need to re-compute each model!)

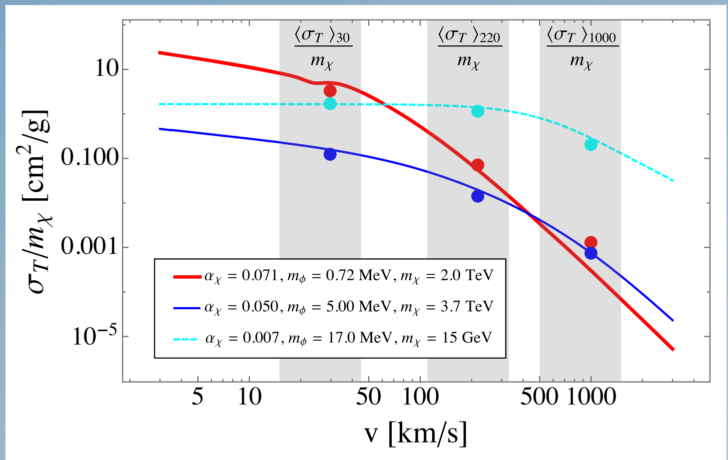
Cyr-Racine+, PRD'16, Vogelsberger+, *MNRAS'16*

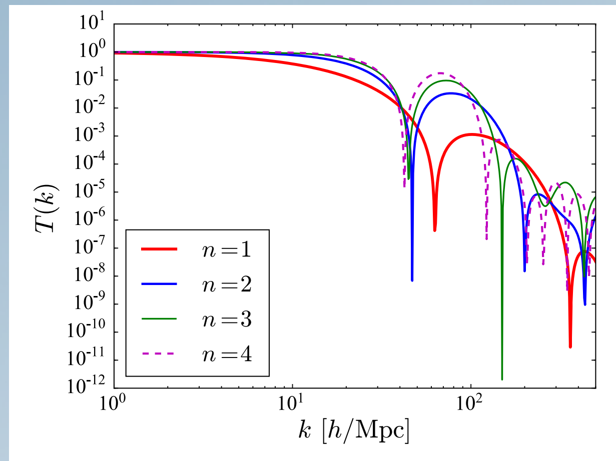
First ETHOS application



+







step 1 Identification of effective variables

Cyr-Racine+, PRD'16

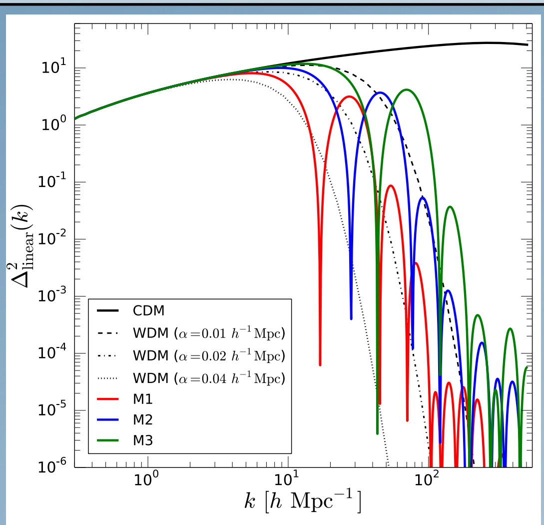
$$\Xi_{\rm ETHOS} = \left\{ \omega_{\rm DR}, \{a_n, \alpha_l\}, \left\{ \frac{\langle \sigma_T \rangle_{v_{M_i}}}{m_\chi} \right\} \right\}$$

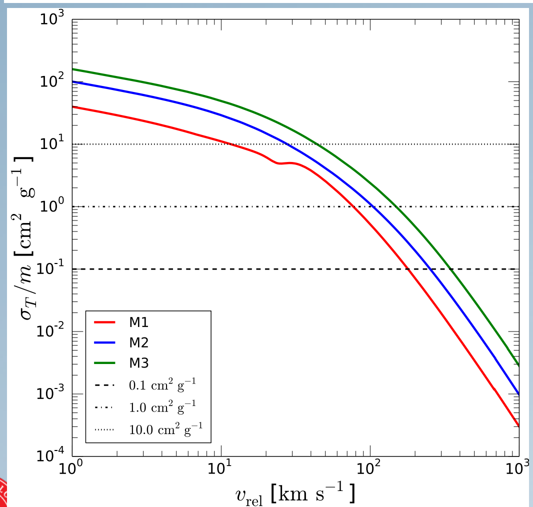
- Various concrete model examples for how to compute parameters
- Public Boltzmann code to get $P(k)$ from these parameters

First ETHOS application (2)

select four benchmark models as in sterile neutrino case:

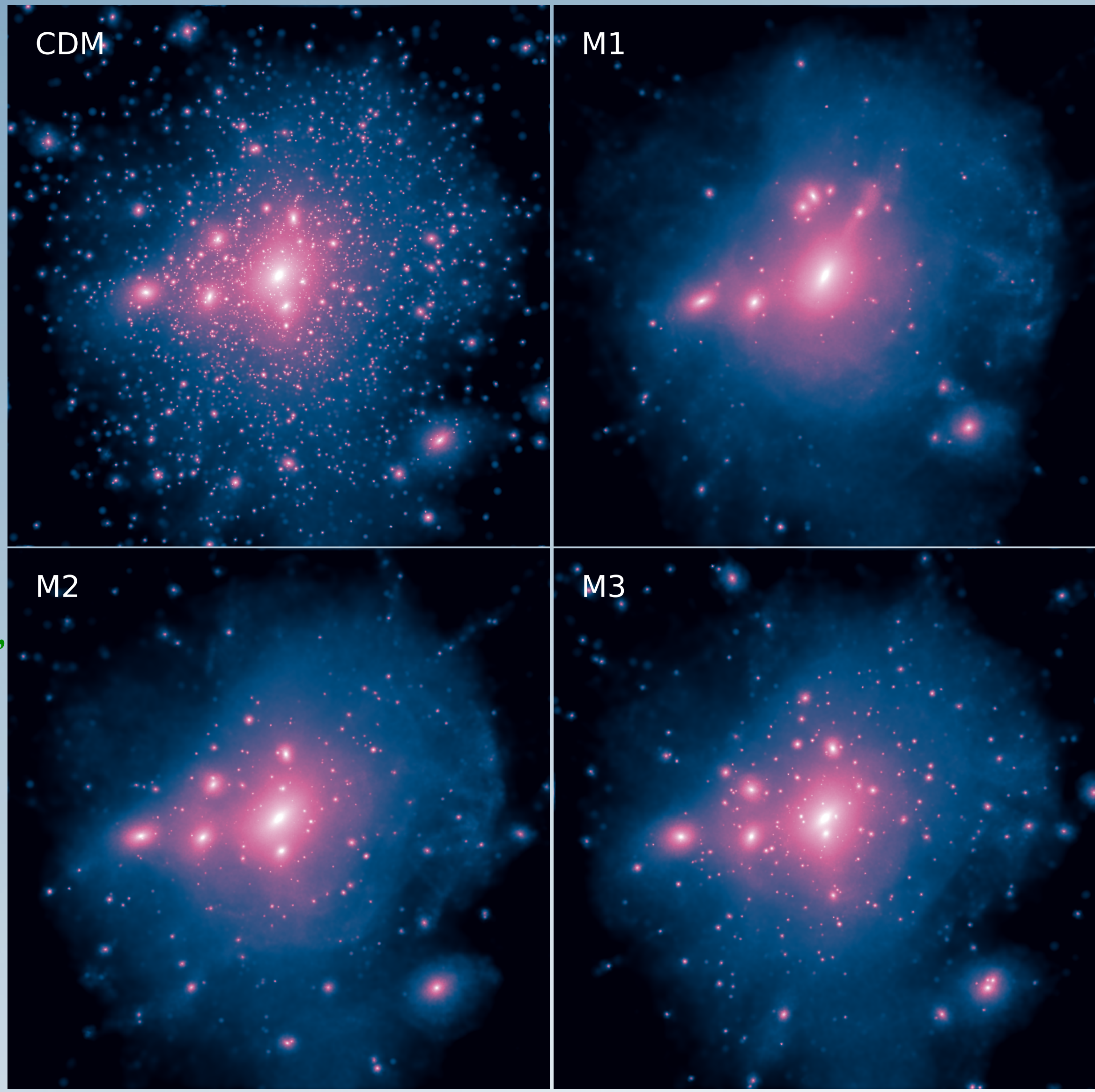
$$\{m_\chi, m_\phi, g_\chi, g_\nu, \eta_\chi, \eta_\nu, \xi\}$$
$$\longrightarrow \left\{\omega_{\rm DR}, a_4, \alpha_{l\geq 2} = \frac{3}{2}, \frac{\langle\sigma_T\rangle_{30}}{m_\chi}, \frac{\langle\sigma_T\rangle_{220}}{m_\chi}, \frac{\langle\sigma_T\rangle_{1000}}{m_\chi}\right\}$$



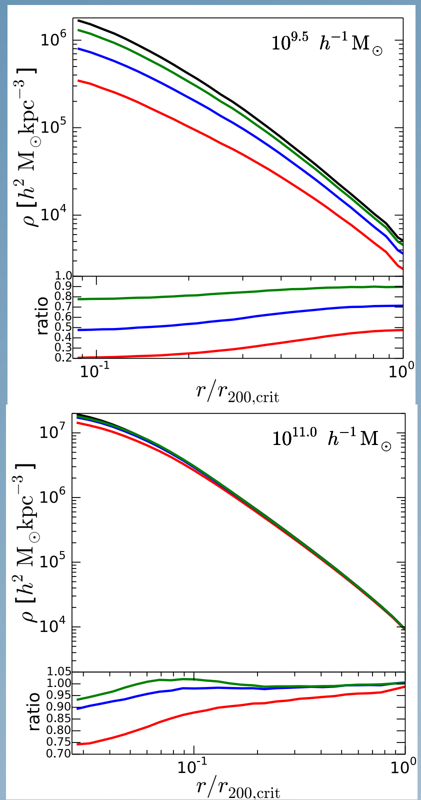


step 2

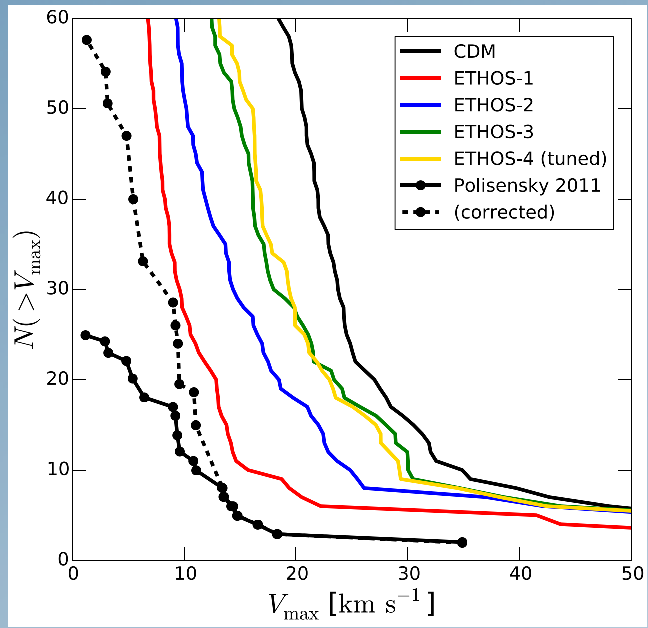
Vogelsberger+, *MNRAS'16*



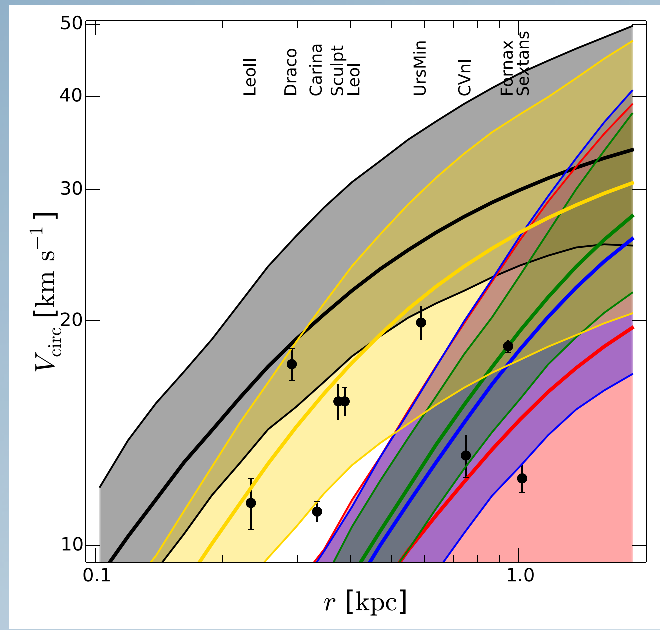
Simulation results



central halo densities reduced (cusp-core)



subhalo abundance strongly affected ('missing' satellites)



most massive subhalos less dense (TBTF)

- ΛCDM problems can indeed be alleviated
  - for the first time demonstrated in a fully consistent framework
  - non-linear interference between modified power spectrum and self-interaction
  - ⊖ some fine-tuning needed ⊕ constraining power

Vogelsberger+, *MNRAS'16*

Conclusions

	Cost *(new theory d.o.f.)*	**Benefit** *(issues addressed)*
	Vanilla CDM particle χ	ΛCDM (above ~Mpc scales) ✓
+	SIDM w/ $\sigma_T \sim 1\,\mathrm{cm}^2/\mathrm{g}$	cusp-core ✓ too-big-to-fail ✓ diversity ✓
+	light mediator ϕ	velocity dependence (cluster constraints + core "measurements") ✓ relic density ✓ (predictivity!)
+	DR/HDM coupled to ϕ (e.g. sterile neutrino)	evade CMB bounds ✓ missing satellites ✓ σ_8/H_0 discrepancy ✓

shortcut !? TB, Ihle, Kersten, Walia, PRD '16