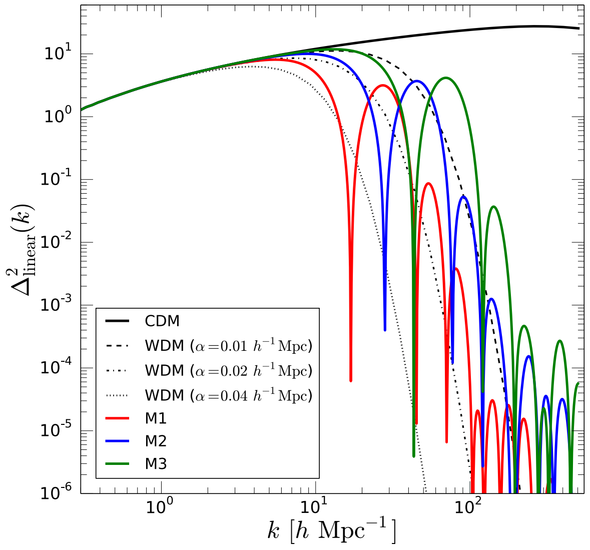
TeVPA 2019, Sydney

An Effective Theory Of Structure Formation

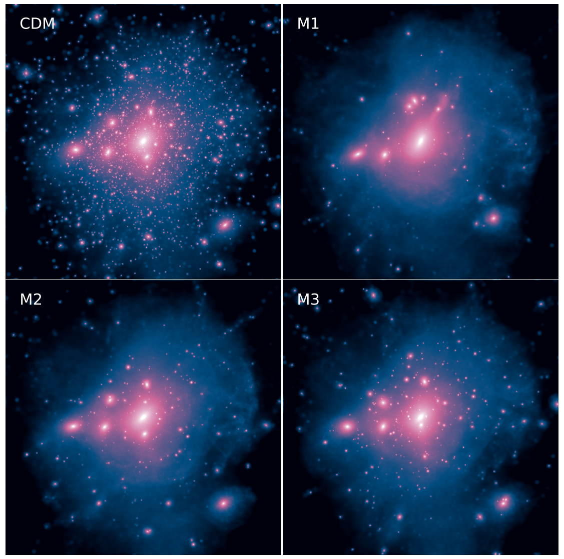
or

Structure formation with non-gravitational dark matter interactions



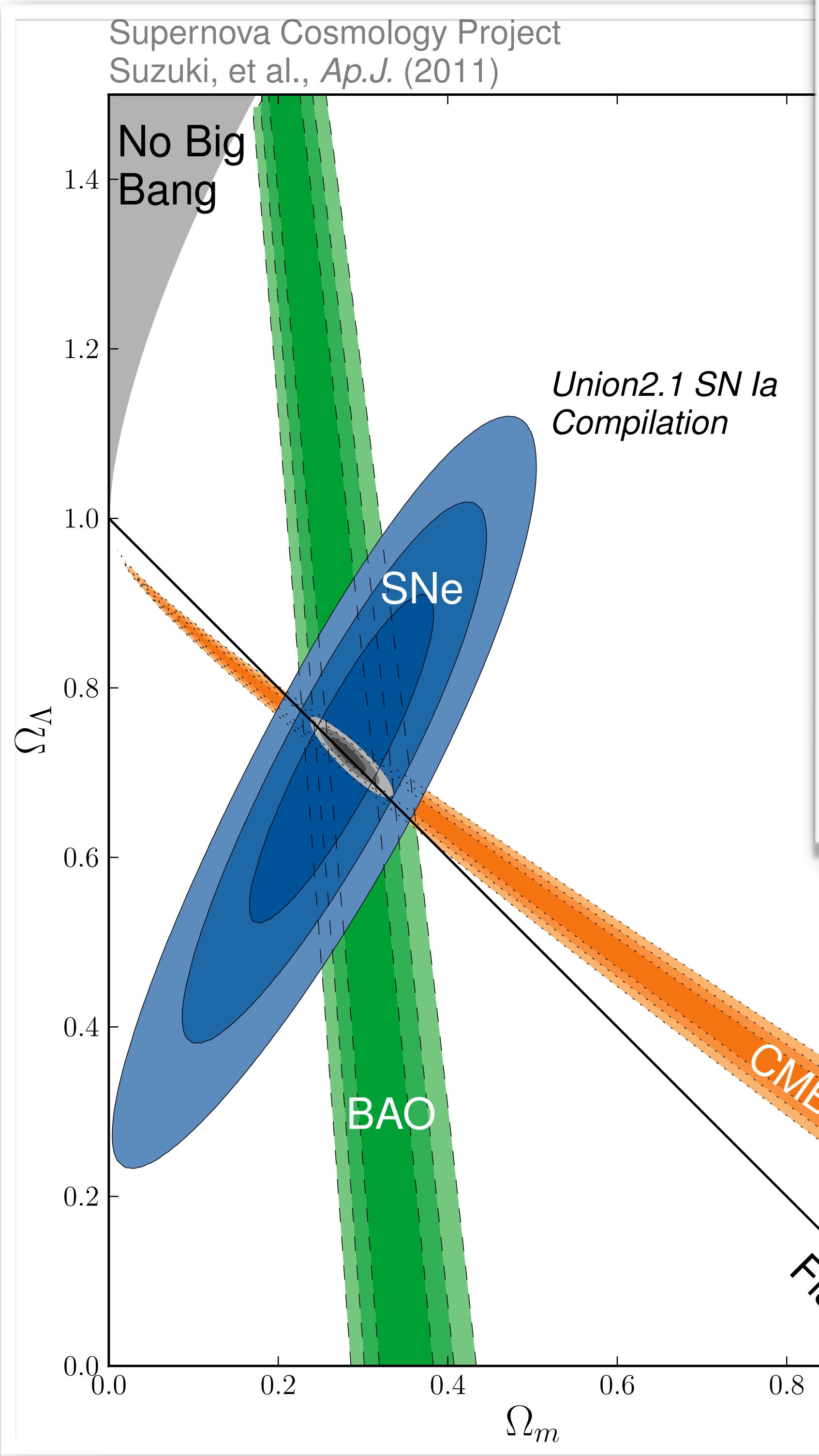
Torsten Bringmann

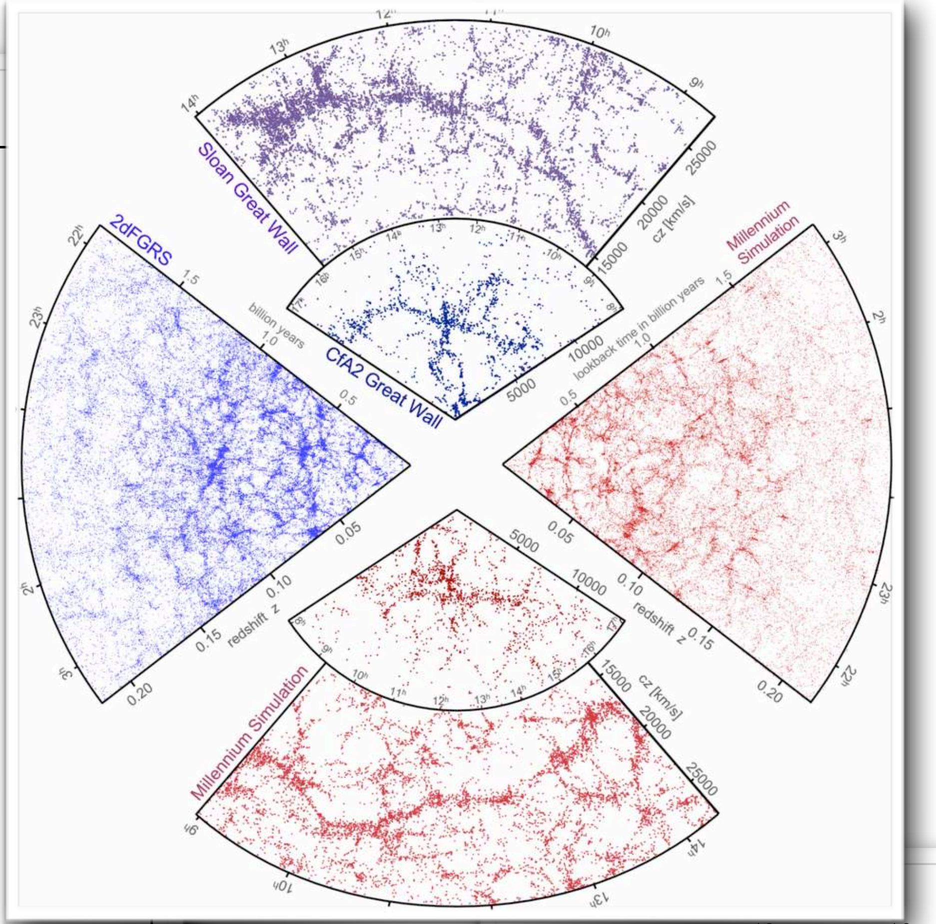
With Francis-Yan Cyr-Racine, Christoph Pfrommer,
Mark Vogelsberger, Jesús Zavala, …



	'ETHOS 1': theory set-up	Cyr-Racine+ [1512.05344]
	'ETHOS 2': first N-body simulations	Vogelsberger+ [1512.05349]
hydrodynamical simulations	*'ETHOS 3': Galaxy abundance & re-ionization*	Lovell+ [1711.10497]
	'ETHOS 4': Ly-α signatures	Bose+ [1811.10630]
	'ETHOS 5': First star formation	Lovell+ [1812.04627]

ΛCDM cosmology

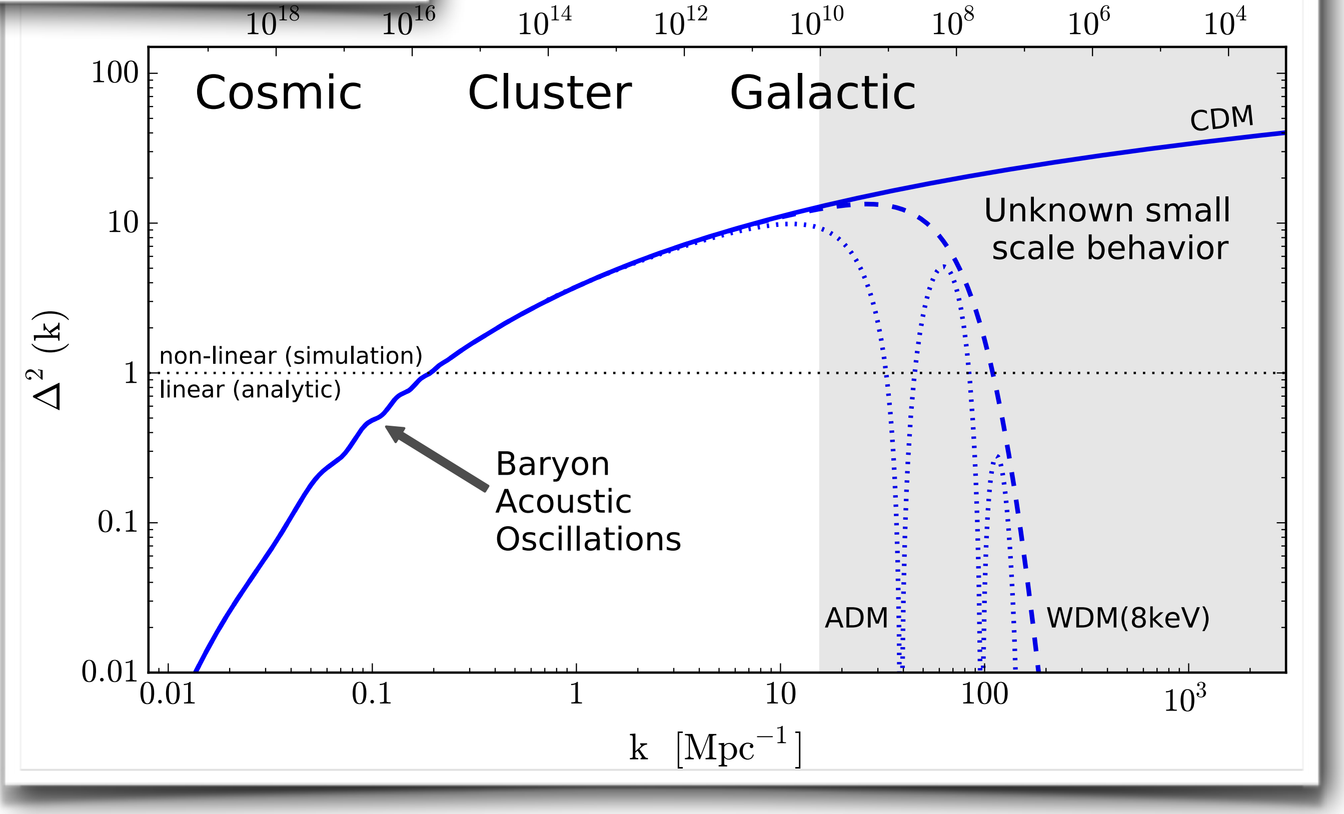

Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)



Springel, Frenk & White, Nature '06

A great success on large scales…

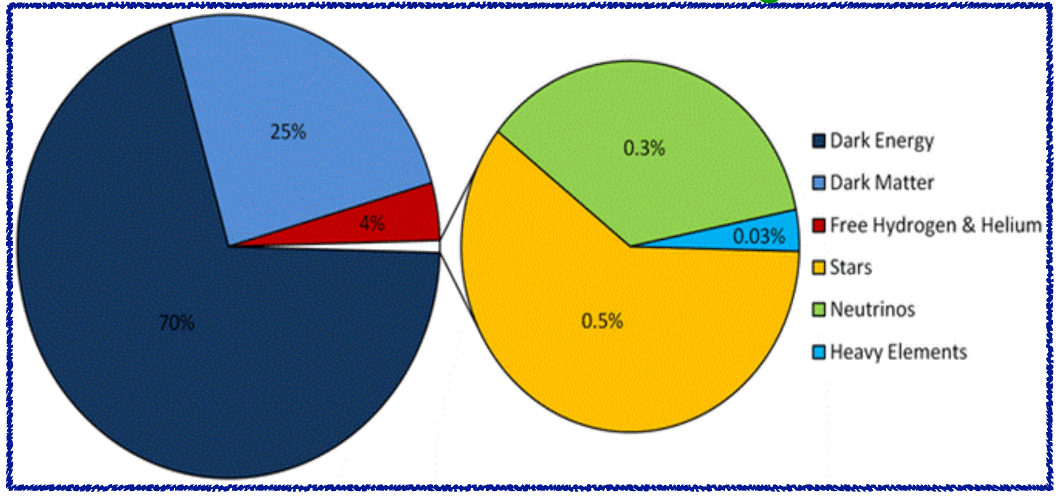
Kuhlen, Vogelsberger & Angulo, PDU '12



ΛCDM cosmology

- Dark matter (DM) is a crucial ingredient
  - constant co-moving energy density
  - only gravitational interactions
  - cold + dissipation-less

Image credit: KIAS



⇒ $$\boxed{\Omega_{\rm CDM}h^2 = 0.1188 \pm 0.0010}$$

Ade+ [Planck Coll.], A&A '16

Percent-level measurements of a single parameter!

- DM conversion into (in)visible energy?
  - E.g. decays, late-time annihilation, coalescing PBHs, …

⇒ $\Omega_{\rm CDM}$ decrease of up to 10% possible during matter domination!

(model-independent; much more allowed during RD) TB, Kahlhoefer, Schmidt-Hoberg & Walia, PRD '18

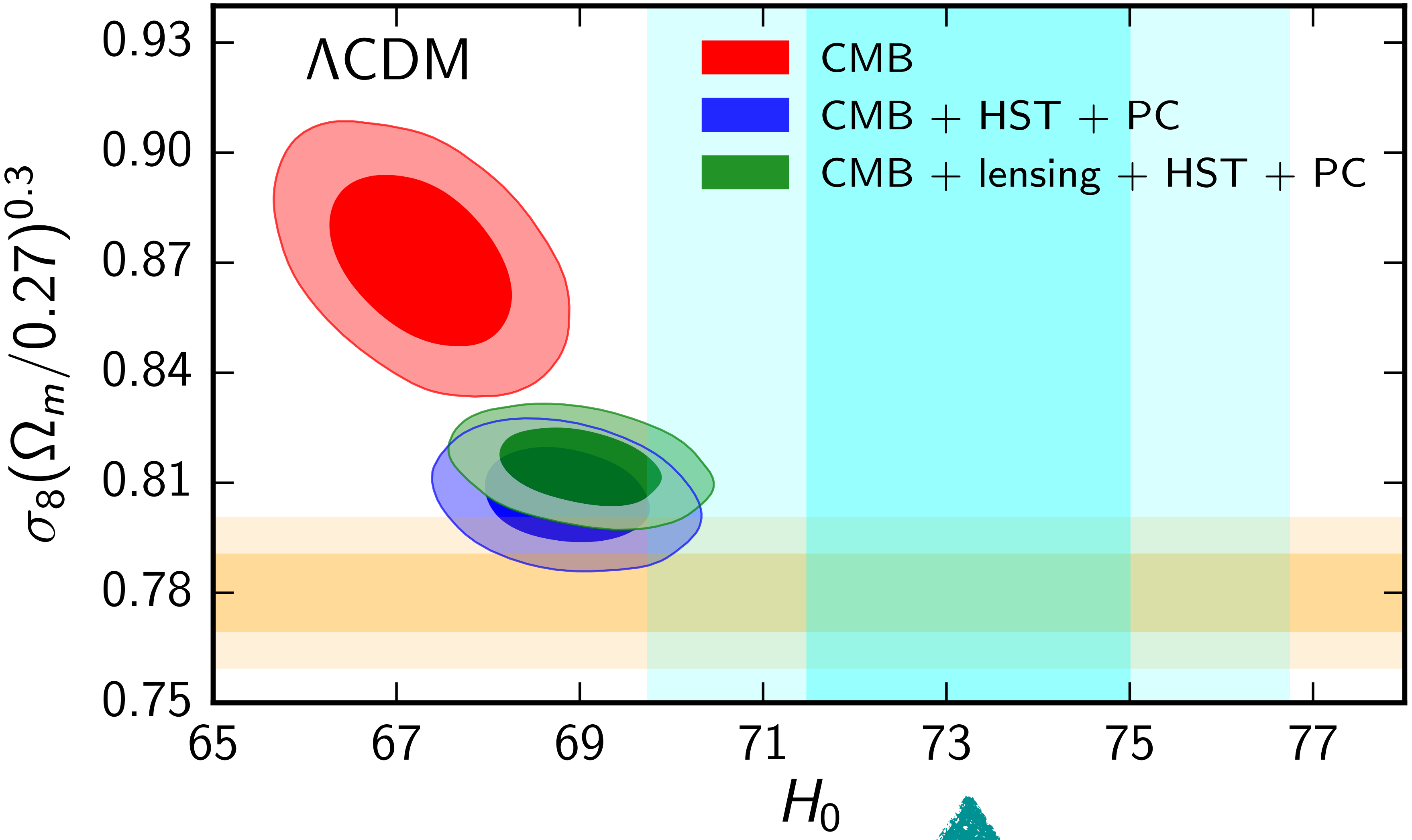
- Non-gravitational interactions?
  - DM — SM: strong constraints from standard DM searches — ***cf.* yesterday's talks**
  - DM self-interactions
  - DM — dark radiation interactions

***many* possible models** ⇝ **ETHOS**

ΛCDM = the perfect success story?

Every party has a pooper…

- Measurements at high and low redshifts do not seem to *quite* agree Ade+ [Planck coll.], A&A '14



(Fig from 1803.03644)

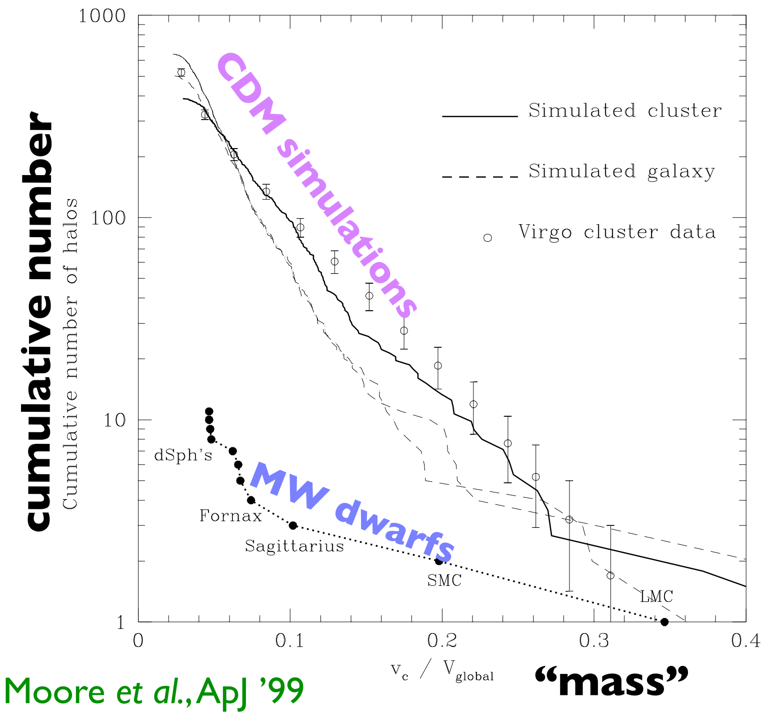
normalisation of power spectrum (from Planck clusters)

Direct measurements of Hubble constant (HST)

Health warning:
DES *is* consistent with CMB … !
Macaulay+, MNRAS '19
see also Rameez & Sarkar, 1911.06456

Small-scale problems ?

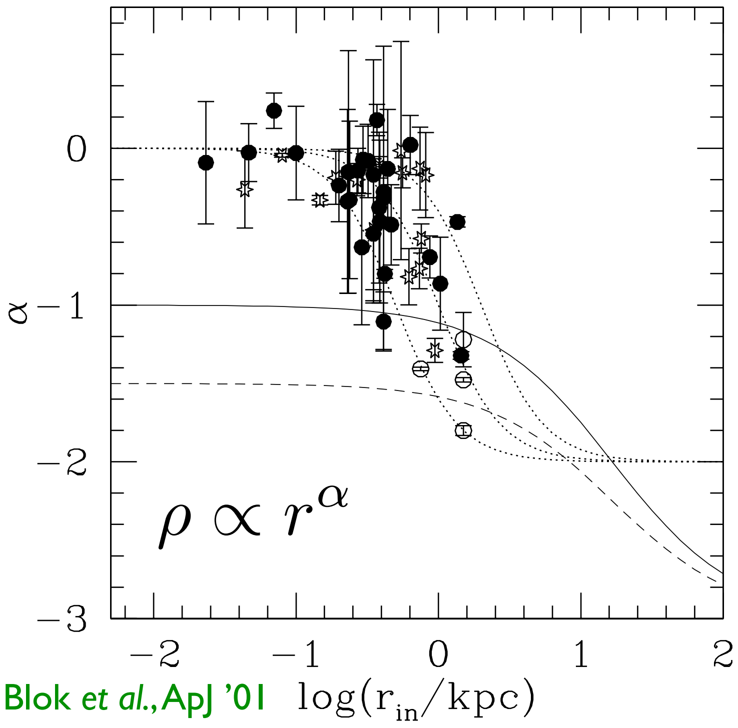
1. Missing satellites?



Moore *et al.*, ApJ ’99

More satellites in simulations of MW-like galaxies than observed

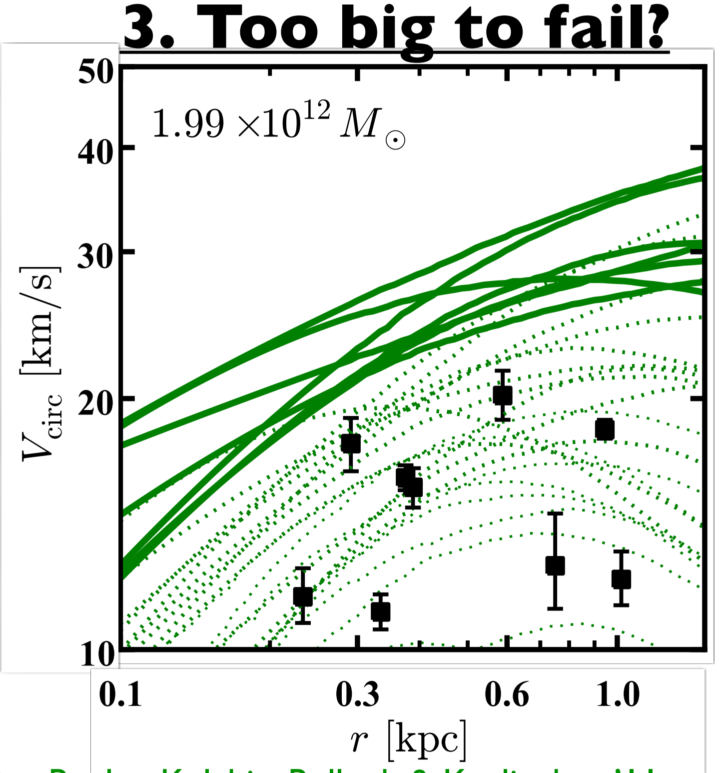
2. Cusps or cores?



Blok *et al.*, ApJ ’01

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

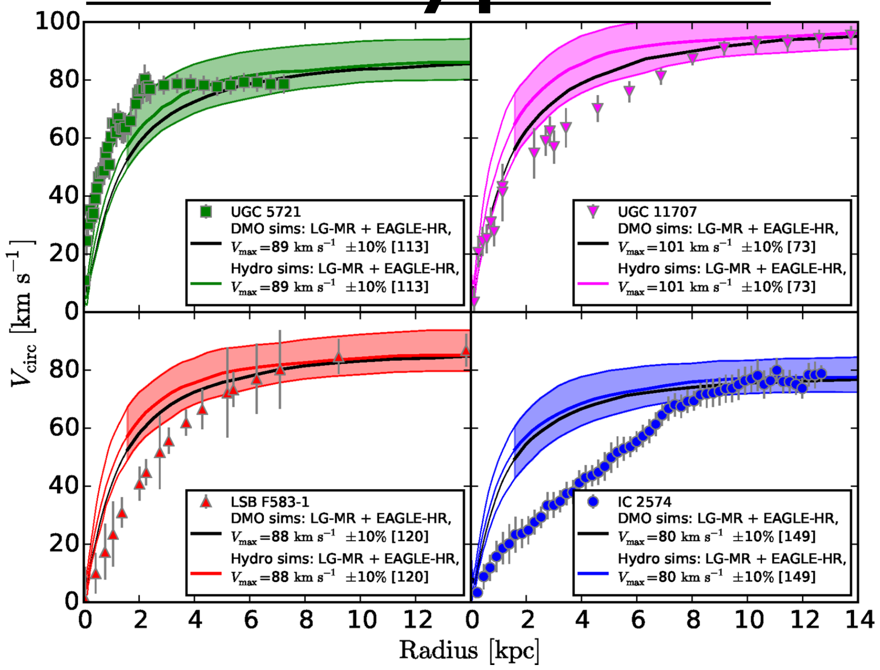
3. Too big to fail?



Boylan-Kolchin, Bullock & Kaplinghat, ’11

Most massive simulated sub-halos too dense to form observed brightest dwarf galaxies

4. Diversity problem?



Oman+, MNRAS ‘15

Real rotation curves vary more than in simulations with(!) baryons

Disclaimer

ETHOS does not primarily attempt to address these issues!

(Nor claims that this would be necessary)

But being able to do so serves as possible proof-of-principle that relevant observables connected to non-gravitational, 'dark' interactions can been identified…

Generic dark sector models

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

e.g. $U(1)_X \times ...$

Standard Model

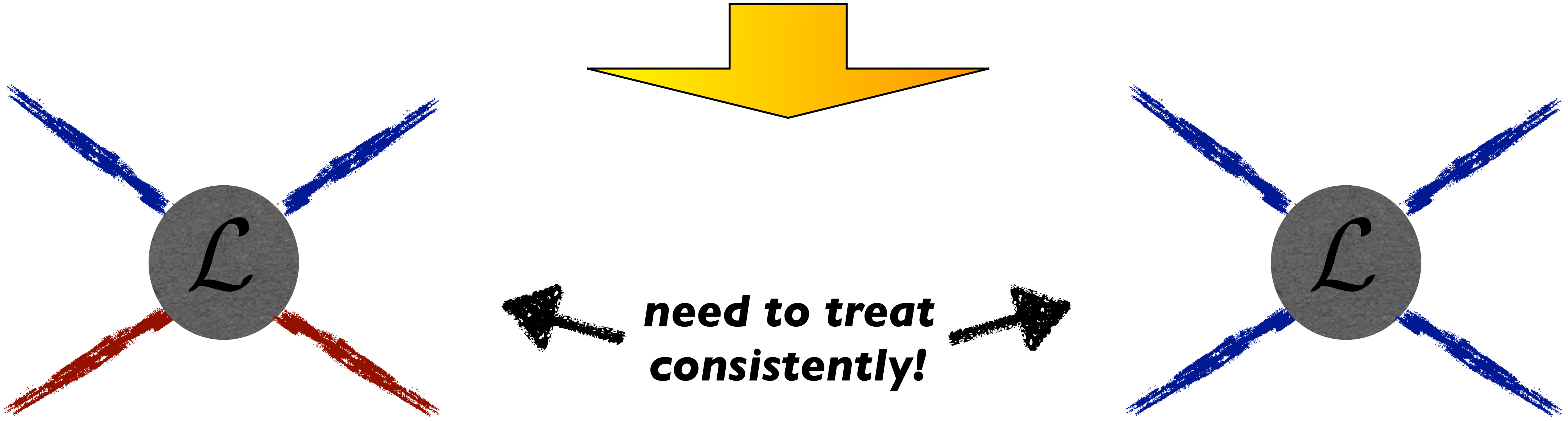
e.g. $\mathcal{L}_{\rm Higgs} \supset \kappa|\phi|^2|\Theta|^2$

Dark Sector

- SM particles

- Dark matter
- Dark radiation
  ('sterile neutrinos', 'dark photons', ...)

- A 'portal' typically still ensures thermalisation at high temperatures
  - Separate entropy conservation after decoupling $\rightsquigarrow T_{\rm photon} \neq T_{\rm dark}$

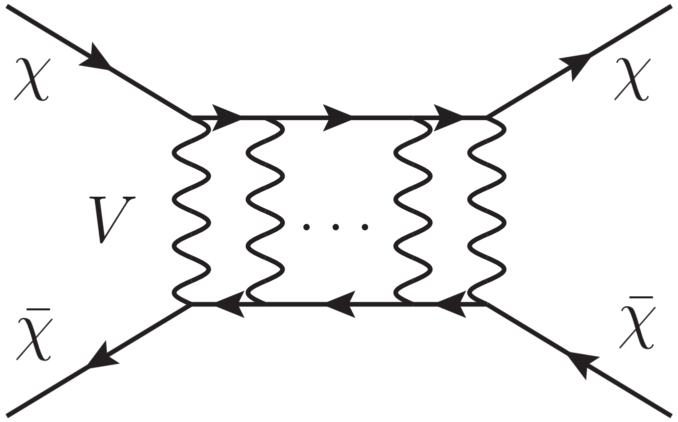


need to treat consistently!

- imprints on linear $\mathcal{P}(k)$

- imprints on inner (sub-)halo structure

From theory to observations

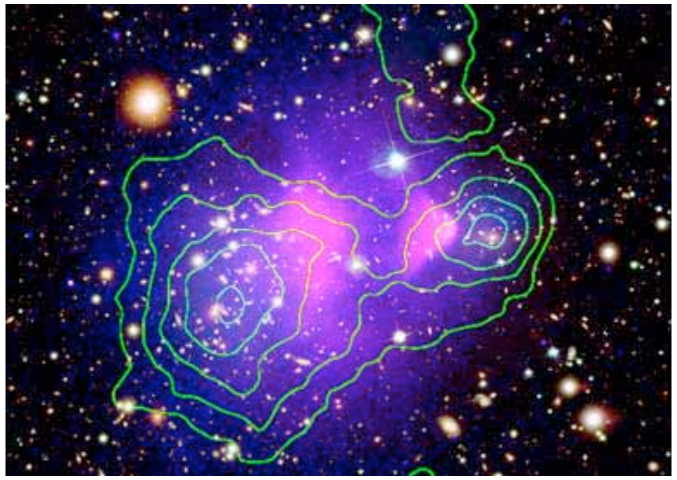


particle model

task 1

cosmological simulations

task 2



astrophysical observables

input:
masses, spins, coupling constants

input:
consistent initial conditions, non-gravitational forces between "particles"

input
(for interpretation of data):
output from simulations

- The first task can be demanding,
  the second in addition computationally very expensive
- But expect large degeneracies, so very inefficient…
- **Idea of ETHOS**: identify 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

Details: Cyr-Racine+, PRD '16

Linear perturbations - setup

- Fundamentally, have to solve coupled Boltzmann equations:

$$\frac{df_\chi}{d\lambda} = C_{\chi\tilde{\gamma}\leftrightarrow\chi\tilde{\gamma}}[f_\chi, f_{\rm DR}], \qquad \frac{df_{\rm DR}}{d\lambda} = C_{\chi\tilde{\gamma}\leftrightarrow\chi\tilde{\gamma}}[f_{\rm DR}, f_\chi] + C_{\tilde{\gamma}\tilde{\gamma}\leftrightarrow\tilde{\gamma}\tilde{\gamma}}[f_{\rm DR}]$$

  - rewrite as differential equations for DM density, velocity and 'temperature':

$$\boxed{n_\chi} \equiv \eta_\chi \int \frac{d^3p}{(2\pi)^3} f_\chi(\mathbf{p}) \quad \boxed{\vec{v}_\chi} \equiv \frac{\eta_\chi}{n_\chi} \int \frac{d^3p}{(2\pi)^3} f_\chi(\mathbf{p}) \frac{p\,\hat{\mathbf{p}}}{E} \quad \boxed{T_\chi} \equiv \frac{\eta_\chi}{3n_\chi^{(0)}} \int \frac{d^3p}{(2\pi)^3} \frac{\mathbf{p}^2}{m_\chi} f_\chi^{(0)}(p)$$

  - keep terms up to first order in perturbations

- Take advantage of various simplifications
  - Neglect (subdominant) DR-DR iterations
  - Assume DR close to EQ: $f_{\rm DR}(\mathbf{x}, \mathbf{q}, \tau) = f_{\rm DR}^{(0)}(q, \tau)[1 + \Theta_{\rm DR}(\mathbf{x}, \mathbf{q}, \tau)]$
  - Momentum transfer in DM-DR scatterings must be small!

$\boxed{\mu \equiv \hat{q}\cdot\hat{k}}$

- Derive hierarchy of Boltzmann moments
  - Expand in Legendre polynomials: $\Theta_{\rm DR}(k, \hat{q}, q, \tau) = \sum_{l=0}^{\infty}(-i)^l(2l+1)F_l(k, q, \tau)P_l(\mu)$

$$\left(\frac{1}{\eta_\chi \eta_{\rm DR}} \sum_{\rm states} |\mathcal{M}|^2\right)\Bigg|_{\substack{t=2p_1^2(\tilde{\mu}-1)\\ s=m_\chi^2+2p_1 m_\chi}} = \sum_{n=0}^{\infty}(2n+1)A_n(p_1)P_n(\tilde{\mu})$$

  - Integrate BEs on both sides with $\frac{1}{2(-i)^l}\int_{-1}^{1} d\mu P_l(\mu)$

Linear perturbations - summary

- Summary (1st order equations):

DM:

$$\boxed{\begin{gathered}\dot{\delta}_\chi + \theta_\chi - 3\dot{\phi} = 0,\\ \dot{\theta}_\chi - c_\chi^2 k^2 \delta_\chi + \mathcal{H}\theta_\chi - k^2\psi = \dot{\kappa}_\chi \left[\theta_\chi - \theta_{\rm DR}\right]\end{gathered}}$$

$\delta \equiv (\rho - \bar{\rho})/\bar{\rho}$

$\theta_j \equiv i\,\mathbf{k}\cdot\mathbf{v}_j$

ϕ, ψ : metric perturb.
in conformal
Newtonian gauge

Only way that (non-gravitational) DM physics enters !

'ETHOS'

DR:

$$\boxed{\dot{\Pi}_{{\rm DR},l} + \frac{k}{2l+1}\left((l+1)\Pi_{{\rm DR},l+1} - l\Pi_{{\rm DR},l-1}\right) = (\alpha_l \underbrace{\dot{\kappa}_{\rm DR-DM}}_{\sim\,\kappa_\chi} + \beta_l \underbrace{\dot{\kappa}_{\rm DR-DR}}_{\sim\,0})\, \Pi_{{\rm DR},l}}$$

$$\Pi_{{\rm DR},l}(k,\tau) = \frac{\int dq\, q^3 f^{(0)}_{\rm DR}(q,\tau) F_l(k,q,\tau)}{\int dq\, q^3 f^{(0)}_{\rm DR}(q,\tau)}$$

$\delta \sim \Pi_0 \quad \theta \sim \Pi_1$

- Step-by-step procedure:
  - calculate κ, α_l from $A_l(p) = \frac{1}{2}\int_{-1}^{1} d\tilde{\mu}\, P_l(\tilde{\mu}) \left(\frac{1}{\eta_\chi \eta_{\rm DR}} \sum_{\rm states} |\mathcal{M}|^2\right)\Bigg|_{\substack{t=2p^2(\tilde{\mu}-1)\\ s=m_\chi^2+2pm_\chi}}$

    Details: Cyr-Racine+, PRD '16
  - calculate $c_\chi^2 = \frac{T_\chi}{m_\chi}\left(1 - \frac{\dot{T}_\chi}{3\mathcal{H}T_\chi}\right)$ from $\frac{dT_\chi}{d\tau} = -2\mathcal{H}T_\chi + \Gamma_{\rm heat}(T_{\rm DR})\,(T_{\rm DR} - T_\chi)$

    aka '**momentum exchange rate**' γ

    Details: TB, NJP '09,
    TB+, PRD '16

Linear perturbations - results

- ETHOS comes with a dedicated Boltzmann solver:

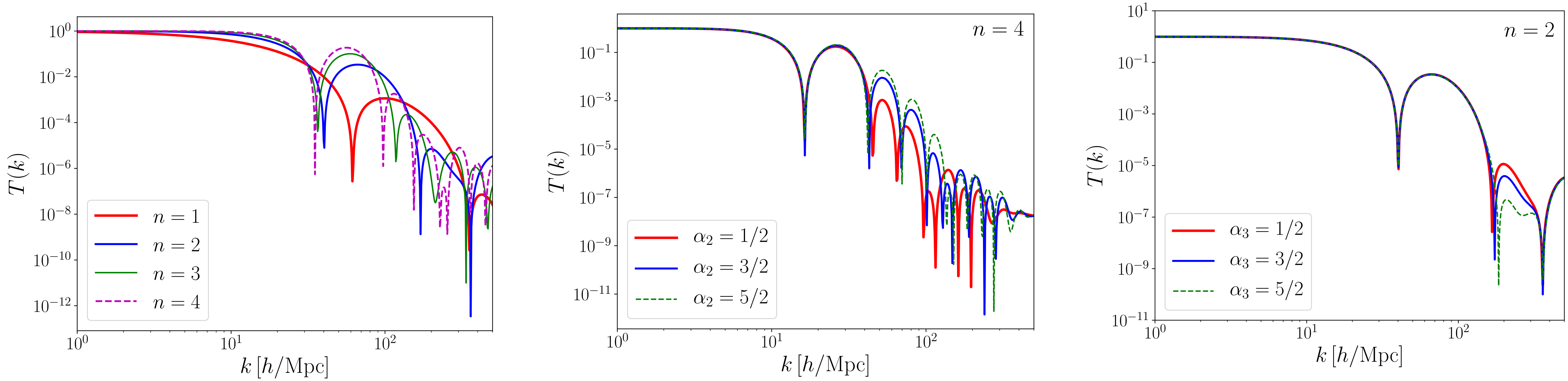
  https://bitbucket.org/franyancr/ethos_camb

  - modified version of CAMB Lewis & Bridle, PRD '02
  - Actual implementation based on phenomenological power-law ansatzes:

    $$\kappa \sim \sum_n a_n \left(\frac{1+z}{1+z_\mathrm{D}}\right)^n \qquad \Gamma_\mathrm{heat} \sim \sum_n d_n \frac{(1+z)^{n+1}}{(1+z_\mathrm{D})^n} \qquad \text{etc}$$

  - detailed examples for calculating a_n, d_n from given model $\left(|\mathcal{M}|^2\right)$ Cyr-Racine+, PRD '16
    TB+, PRD '16

- Example spectra:



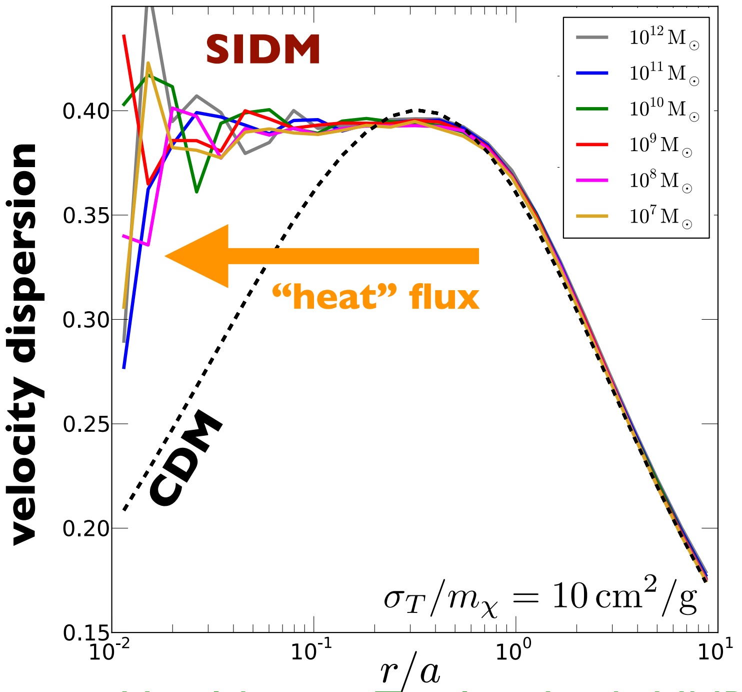
➡ 'Dark acoustic oscillations'

(Physics very similar to CMB photons scattering on electrons around decoupling!)

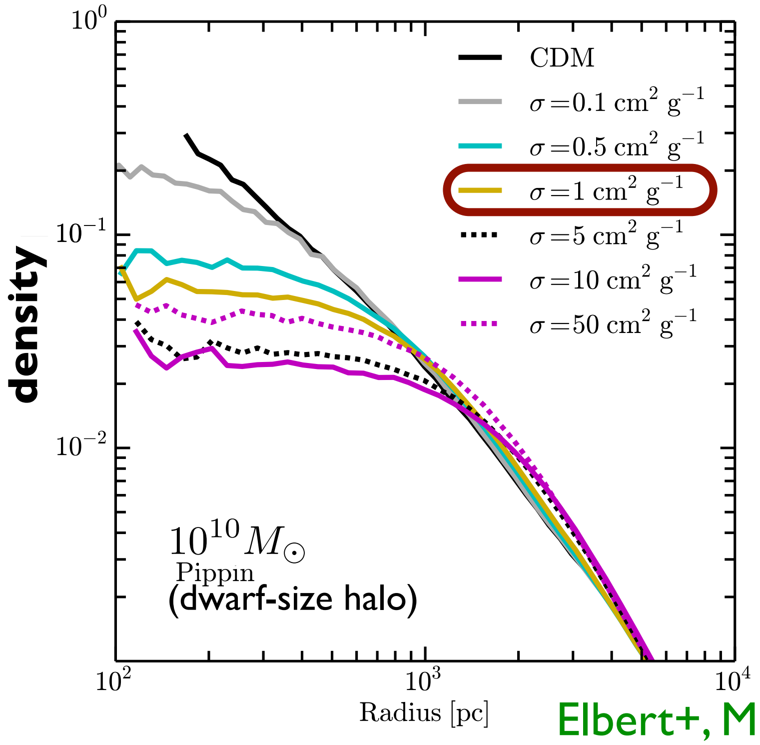
Self-interacting DM (SIDM)

- DM-DM scatterings Spergel & Steinhardt, PRL '99
  - do not affect linear perturbations (number densities!)
  - but isotropise DM distribution in inner parts of halo:

⇨ core formation once $\mathcal{O}(1)$ scatters per dynamical time



Vogelsberger, Zavala & Loeb, MNRAS '12



roughly needed for **cusp/core**

Elbert+, MNRAS '15

- Simple analytic models to predict core radius from σ_{SIDM}
  - reproduce CDM simulation results for $\rho_\chi(r)$ remarkably well Kaplinghat, Tulin & Yu, PRL '15
  - but underlying (microphysics) assumptions not really satisfied Sokolenko+, JCAP '18

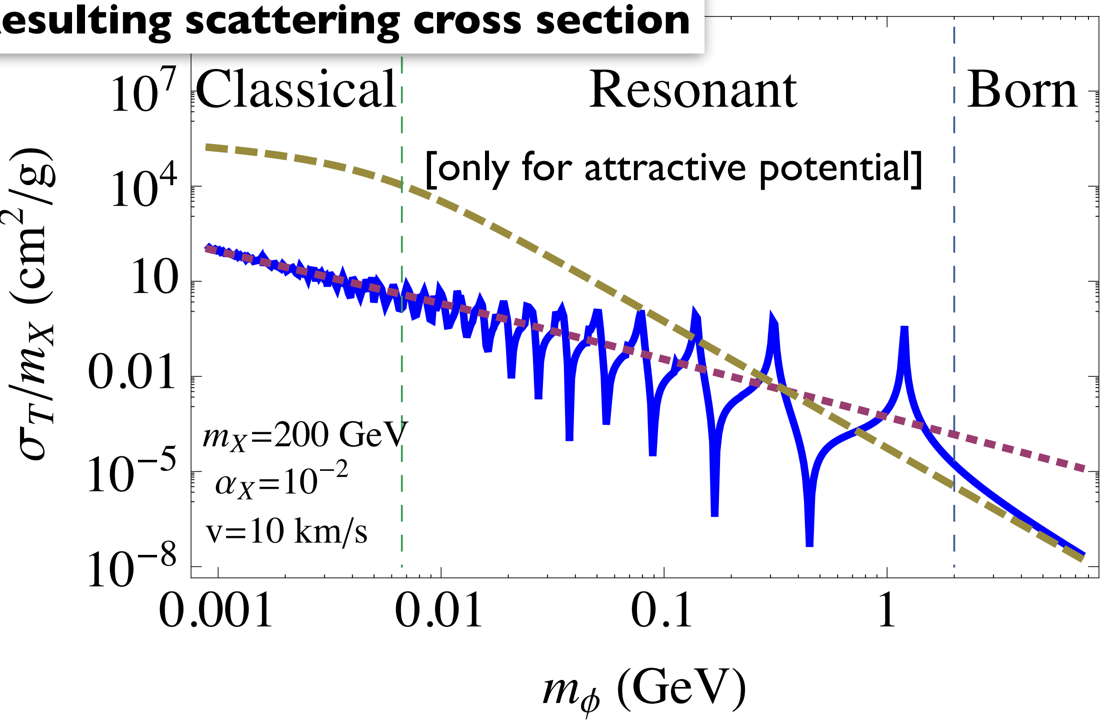
⇨ *Use caution when applied to systems including baryons!* ⚠

Velocity dependence

- Massive mediators induce a Yukawa potential between DM particles.

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

Resulting scattering cross section



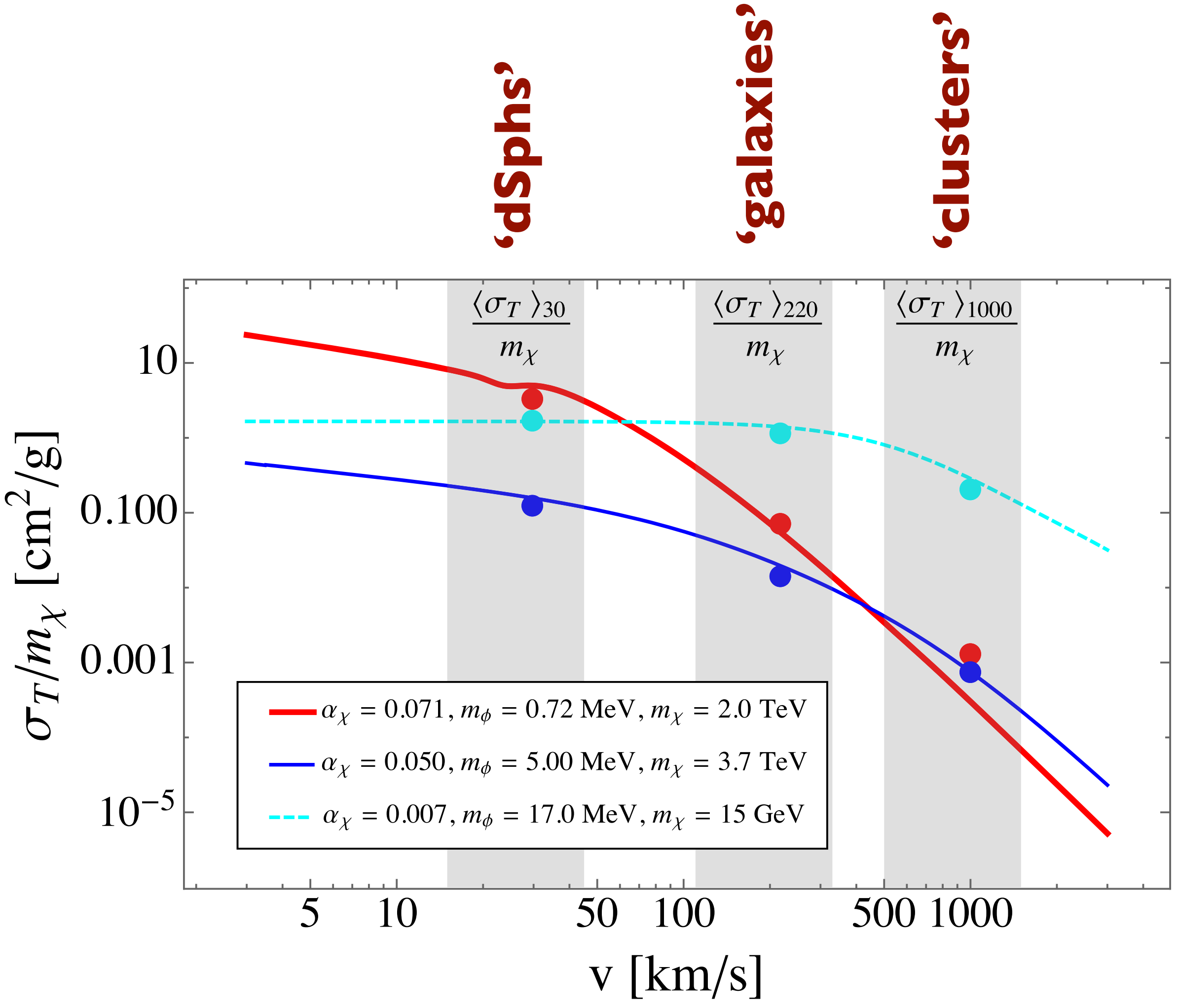
$$\boxed{\sigma_T \equiv \int d\Omega(1-\cos\theta)\frac{d\sigma}{d\Omega}}$$

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

- Phenomenologically important: characteristic velocity dependence

[*not only for Yukawa potentials!* Chu, Garcia-Cely & Murayama, PRL '19]

- ETHOS implementation:
  - sufficient to take average values for 3 characteristic velocities



Implementation

- Translate power spectrum to initial particle distribution
  - use MUSIC code Hahn & Abel, MNRAS '11 [see also Dolag+, '08]
- Probabilistic method to account for elastic scattering

Vogelsberger, Zavala & Loeb, MNRAS '12

  - isotropic scattering of macroscopic 'particles' with mass m_i

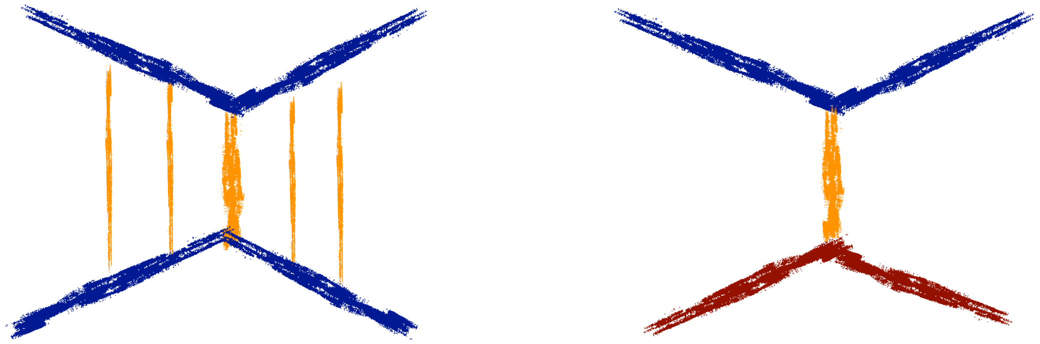
$$P_{ij} = \frac{m_i}{m_\chi} W(r_{ij}, h_i)\, \sigma_{\rm T}(v_{ij}) v_{ij}\, \Delta t_i$$

smoothing function to weight nearest neighbour highest

- Cosmological simulation with $m_i \sim 10^8 M_\odot$ $(\epsilon \sim 3\,{\rm kpc})$, zoom-in of MW-like halos down to $m_i \sim 3 \times 10^4 M_\odot$ $(\epsilon \sim 70\,{\rm pc})$

- First ETHOS example:
  - TeV-scale DM particle
  - MeV-scale vector mediator
  - massless (sterile) neutrino-like fermion

van den Aarssen, TB & Pfrommer, PRL '12
TB, Hasenkamp & Kersten, JCAP '14



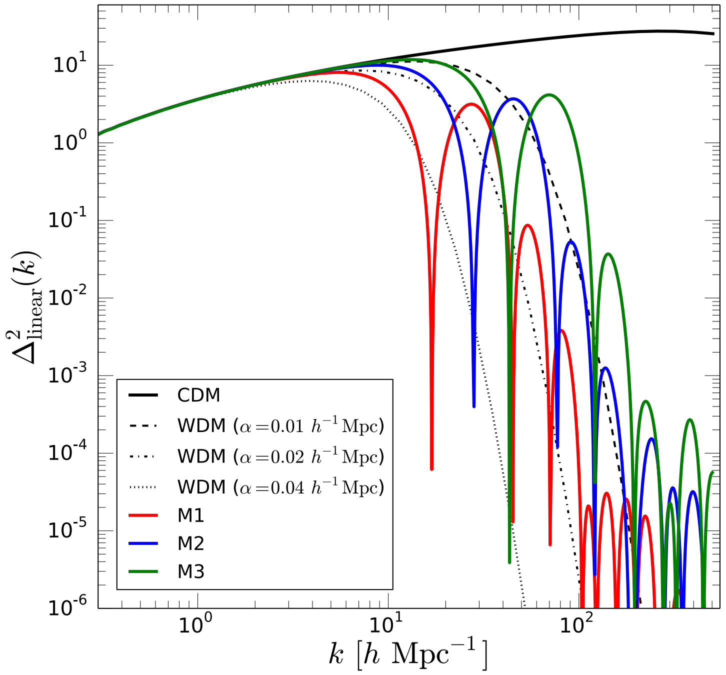
$$\{m_\chi, m_\phi, g_\chi, g_\nu, \eta_\chi, \eta_\nu, \xi\}$$

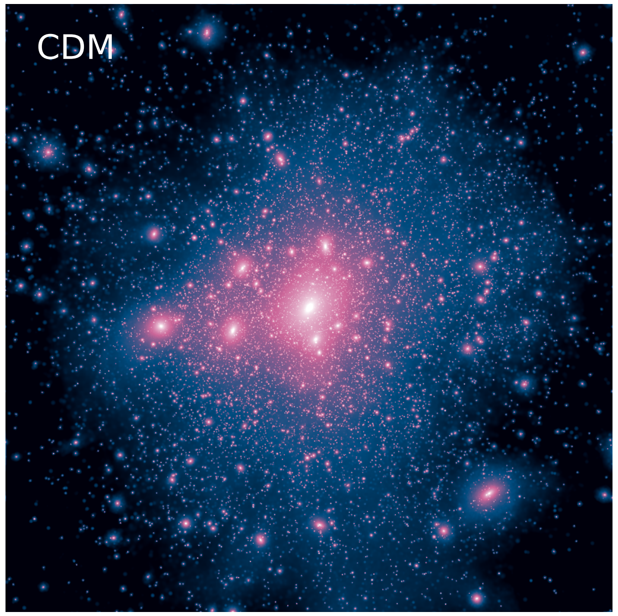
task I

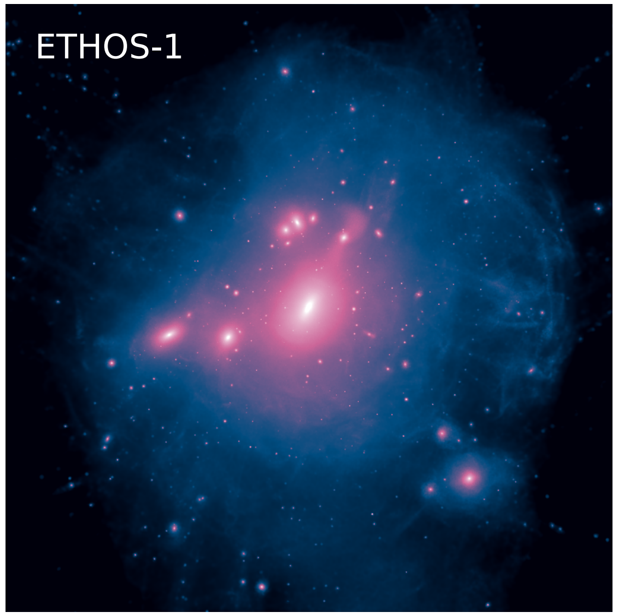
$$\left\{\omega_{\rm DR}, a_4, \alpha_{l\geq 2} = \frac{3}{2}, \frac{\langle\sigma_T\rangle_{30}}{m_\chi}, \frac{\langle\sigma_T\rangle_{220}}{m_\chi}, \frac{\langle\sigma_T\rangle_{1000}}{m_\chi}\right\}$$

Late kinetic decoupling

- Select four benchmarks: Vogelsberger+, MNRAS'16







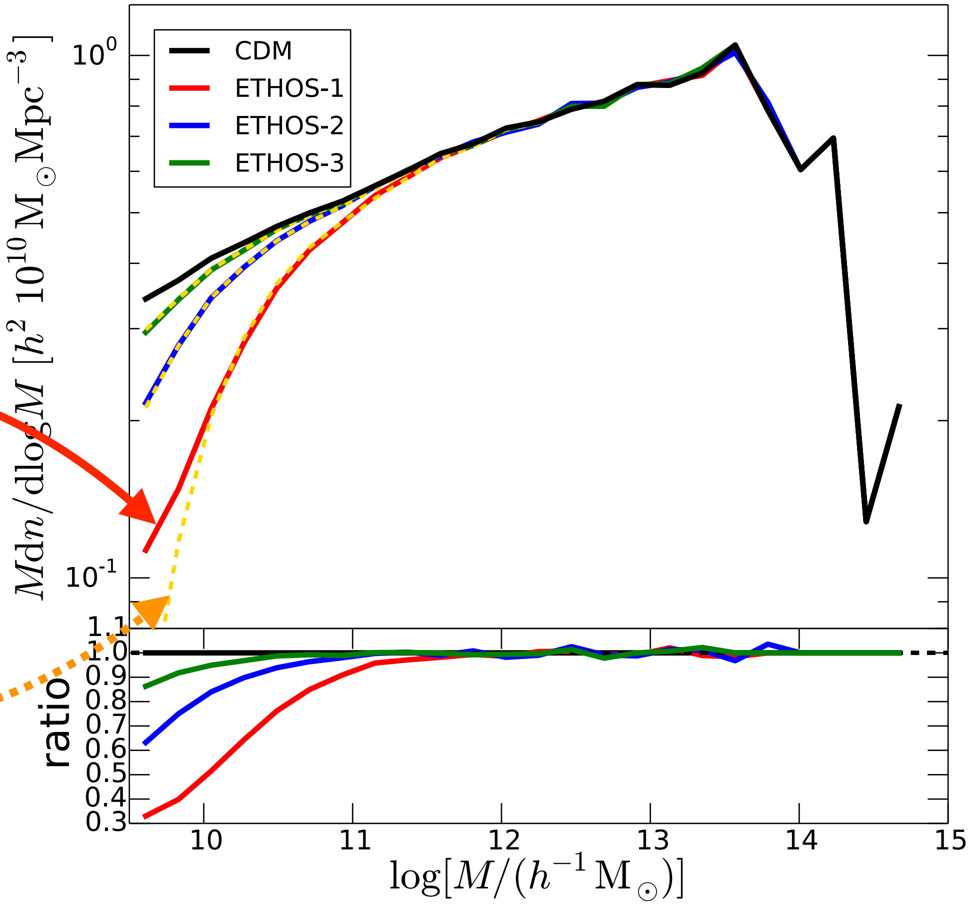
- Almost identical suppression of halo mass function as for WDM cosmology:

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

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

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

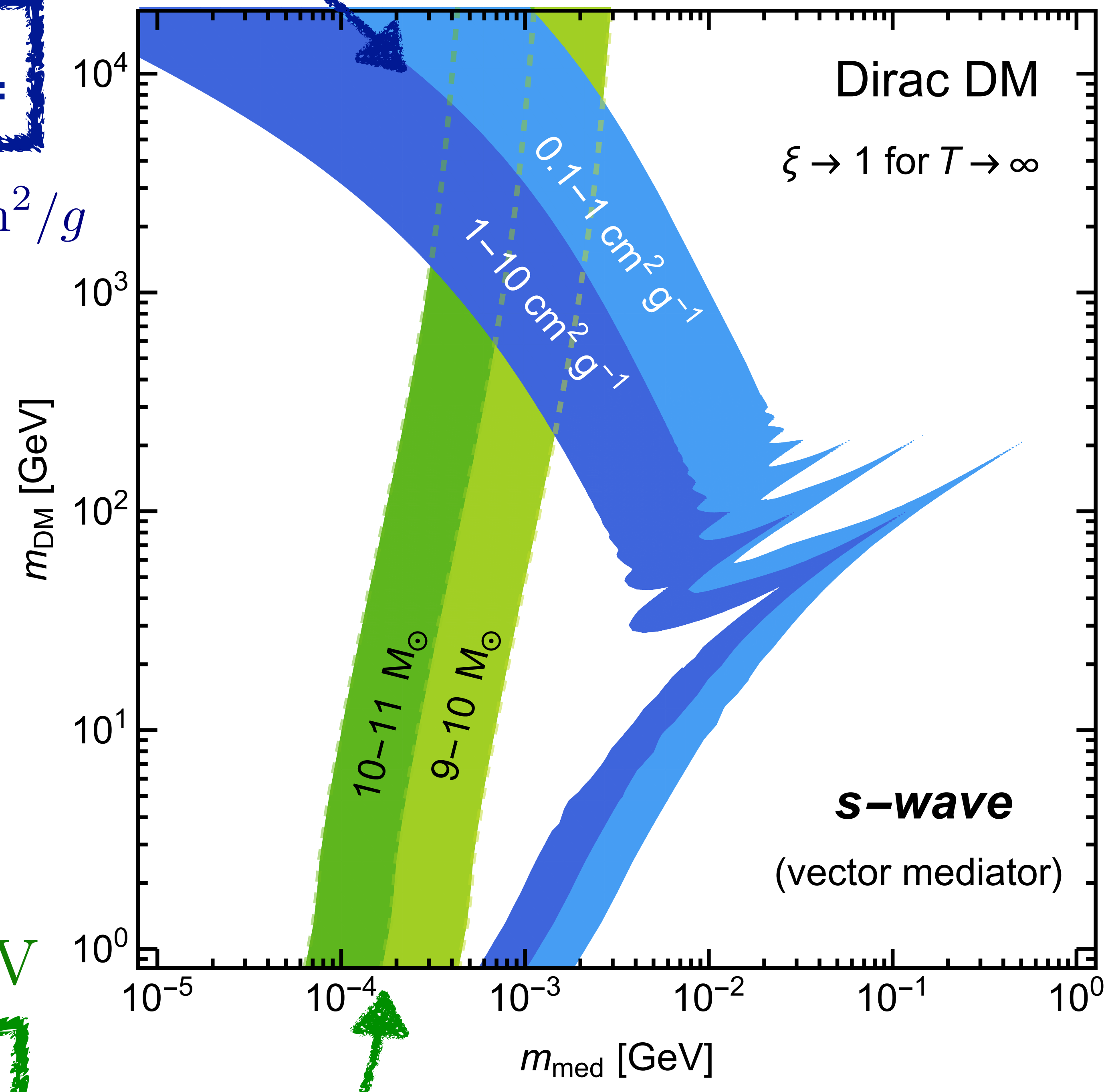
[dashed lines; would-be result from WDM free-streaming**]**



Full parameter scan

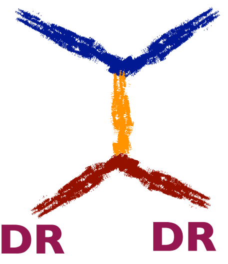
affect core/ cusp + TBTF

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



$T_{\rm kd} \sim 0.1\,\mathrm{keV}$

address missing satellites ?

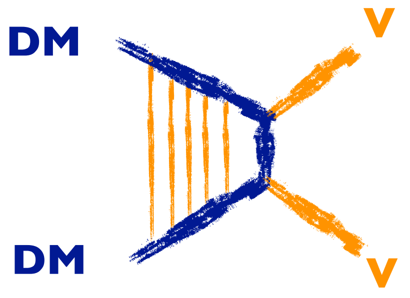


TB, Edsjö, Gondolo, Ullio & Bergström, JCAP '18

- NEW since v6.1:
  - SIDM
  - Sommerfeld
  - handle varying

$\xi \equiv T_{\rm dark}/T_{\rm photon}$

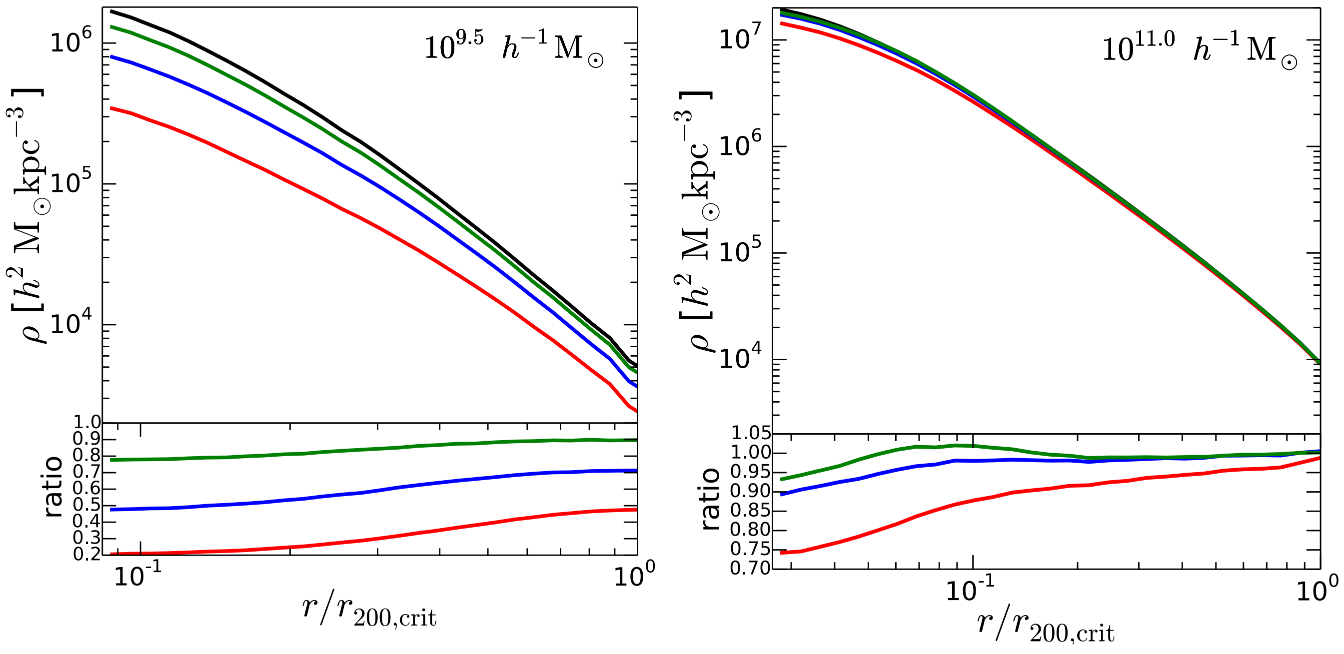
→ **coupling fixed by thermal relic density**



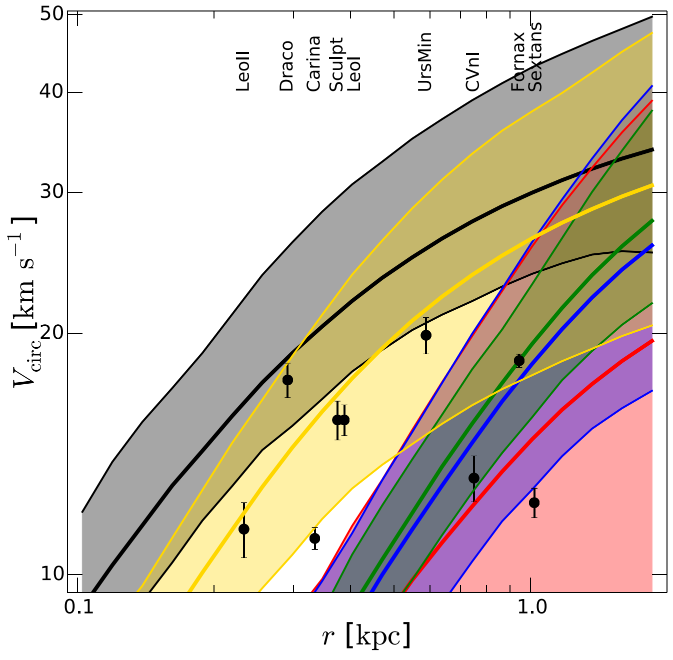
Inner halo structure

Vogelsberger+, MNRAS'16

- Closer look: can indeed address CDM abundance and structural 'problems' simultaneously, in a consistent particle framework:



central (sub)halo densities reduced
(→ core/cusp)



most massive subhalos less dense
(→ too-big-to-fail)

- NB: Non-trivial interplay between modified power spectrum and self-interactions

  ➡ *Details more complicated than the usual 'need ~1 cm²/g' !*

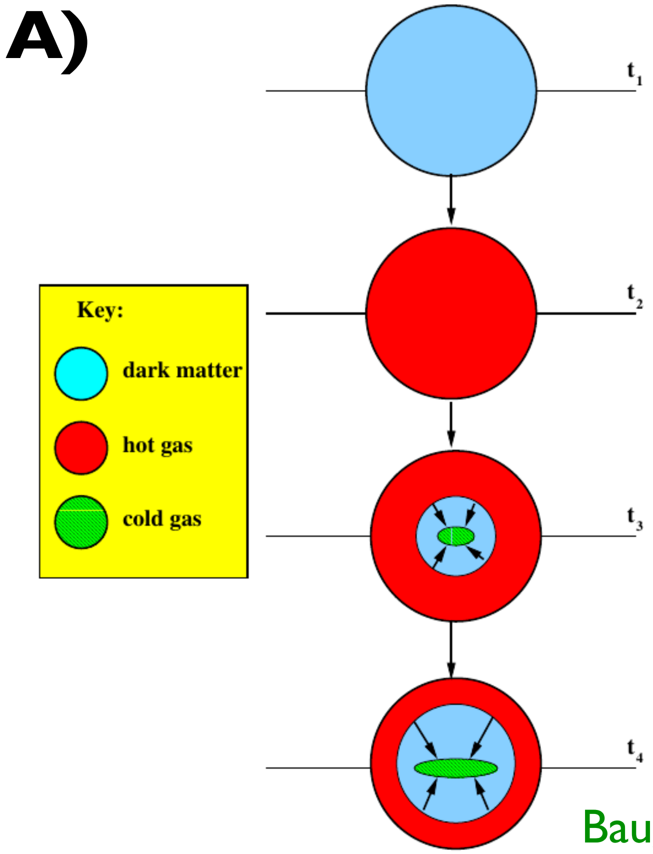
- Also, this is still without baryonic physics…

  [though dSphs highly DM dominated]

Adding Baryons

- Simplest picture: two competing effects

A)

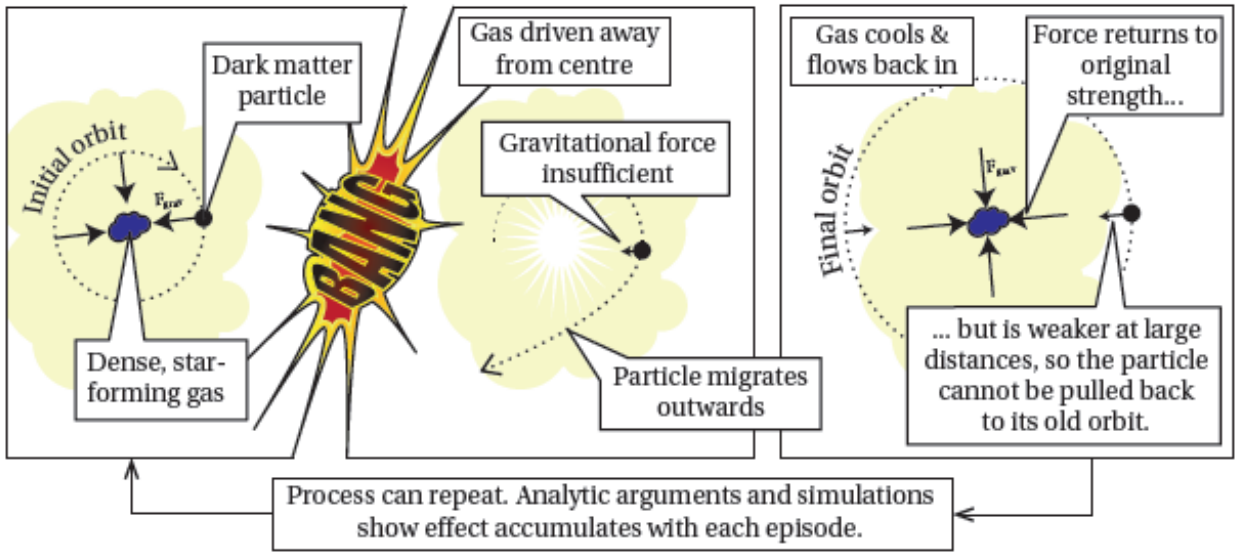


Baugh, RPP '06

Adiabatic contraction due to disk assembly

⇧ *increase*
of inner DM density

B)



Dark matter particle

Gas driven away from centre

Gravitational force insufficient

Dense, star-forming gas

Particle migrates outwards

Gas cools & flows back in

Force returns to original strength...

... but is weaker at large distances, so the particle cannot be pulled back to its old orbit.

Process can repeat. Analytic arguments and simulations show effect accumulates with each episode.

Pontzen & Governato, Nature '14

gas and DM heating due to supernova feedback

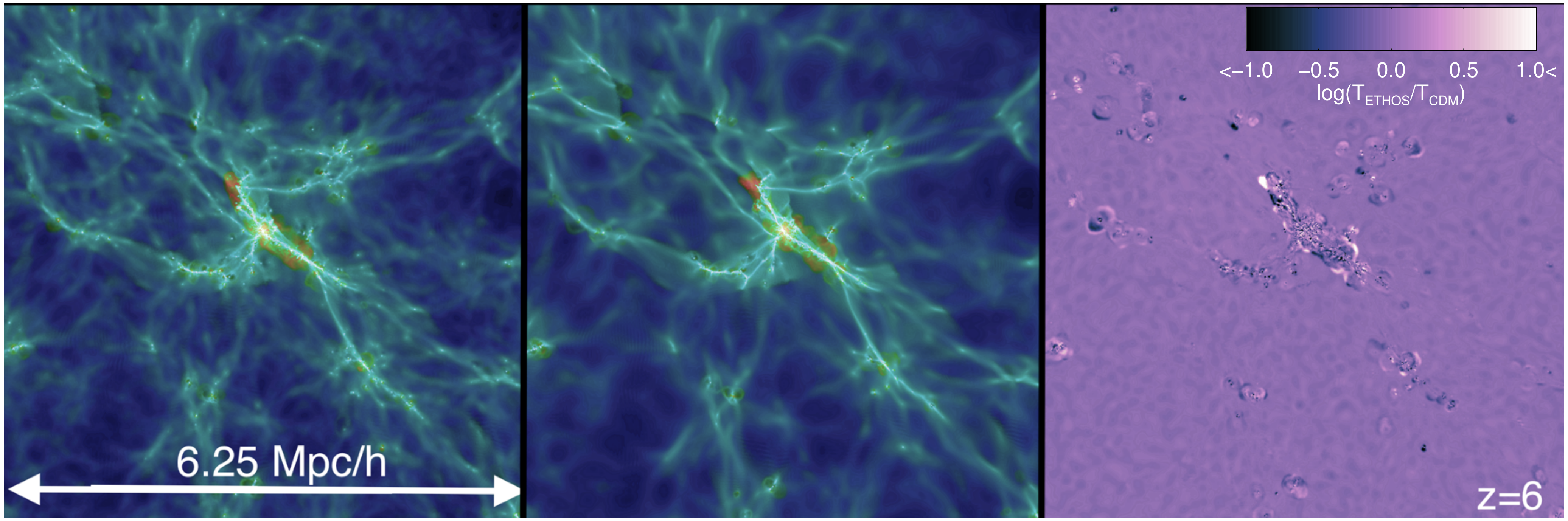
⇩ *decrease*
of inner DM density

- SIDM + A) may lead to core collapse Elbert+, ApJ '18

  ⇝ *A way to address the diversity problem?* Creasey+, MNRAS '17
  Kamada+, PRL '17
  ...

Re-ionization history

- Lack of small halos should delay onset of structure formation



IGM gas temperature

Lovell+, MNRAS '18

- Hydrodynamical simulations: Indeed — but effect on reionisation history is surprisingly small **[similar to WDM!]**
  - Suppression of high-z, low-mass galaxies: maybe visible with JWST
  - Brighter starbursts in these galaxies compensate effect on optical depth

- Follow-up: halo collapse comparison on individual basis
  - Virial masses of ETHOS halos are suppressed, but not stellar mass
  - Promising way to test/constrain ETHOS: large populations of very old stars $(z > 17)$

Lovell, Vogelsberger & Zavala, MNRAS '19

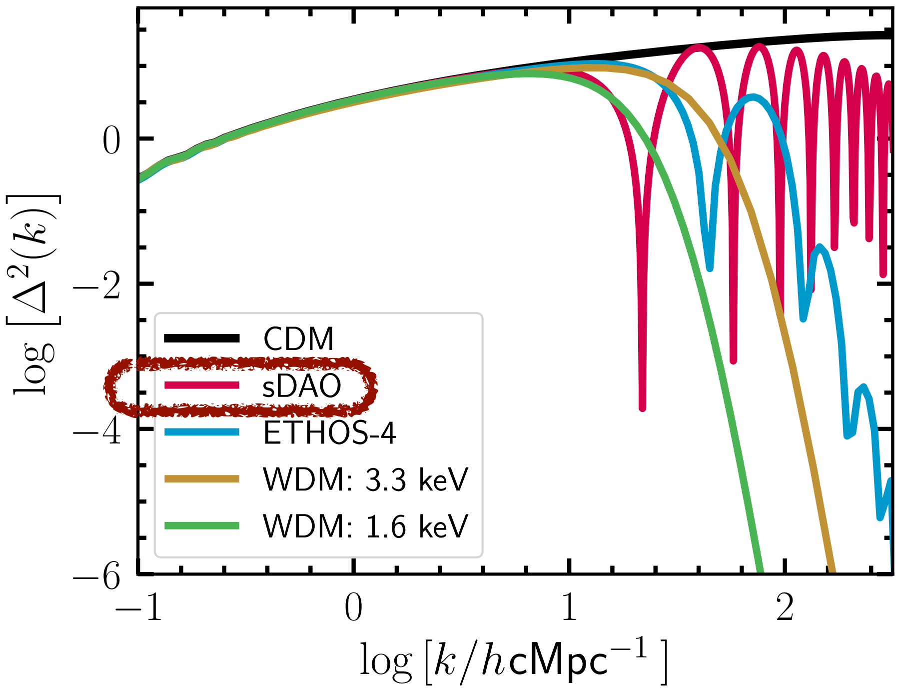
Imprint on Lyman alpha spectra ?

- Need strong features in linear $\Delta^2(k)$ to survive in non-linear regime
  - use atomic DM benchmark (sDAO)

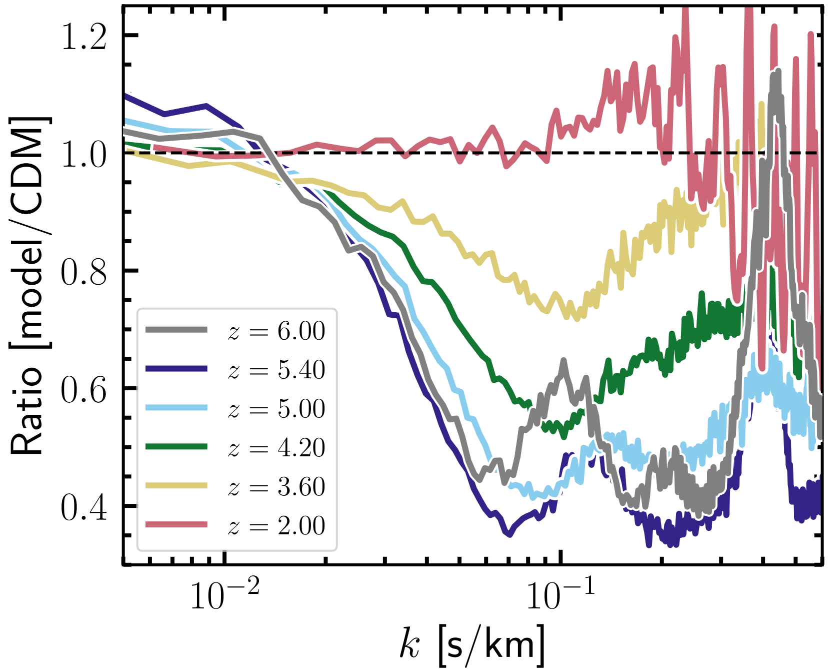
    Kaplan+, JCAP '10
    Cyr-Racine & Sigurdson, PRD '13
  - galaxy formation model as in IllustrisTNG

    Marinacci+, MNRAS '18; …

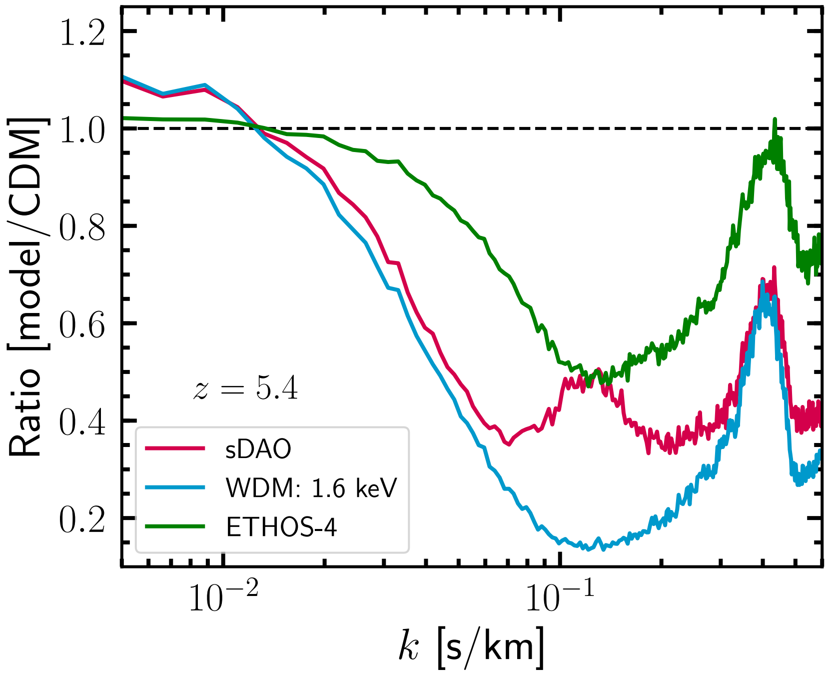
Bose+, MNRAS '19



- DAO bump visible in 1D Ly-α flux spectra only for $z \gtrsim 5$



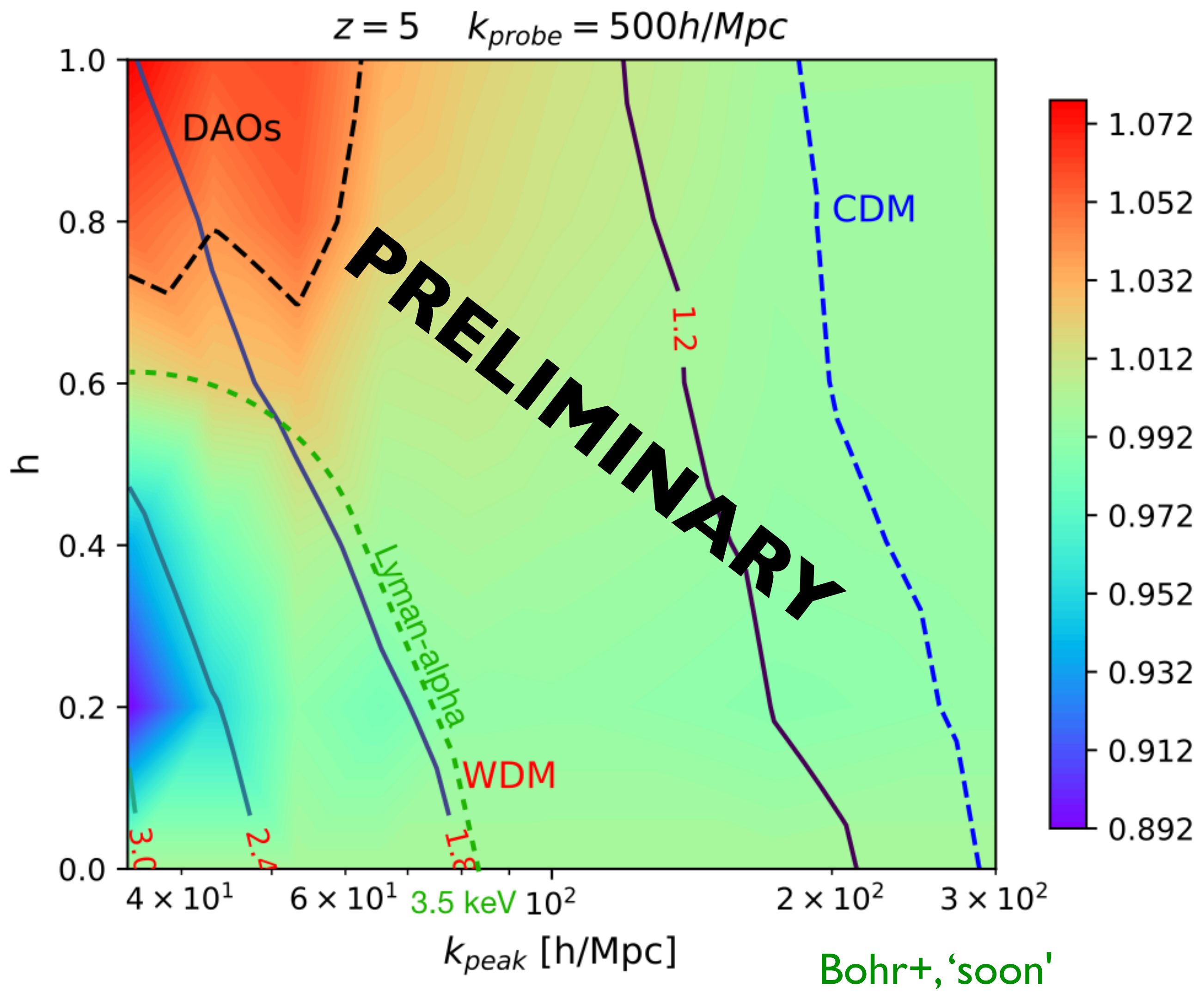
NB: bump at ~0.4 s/km set by numerical resolution!



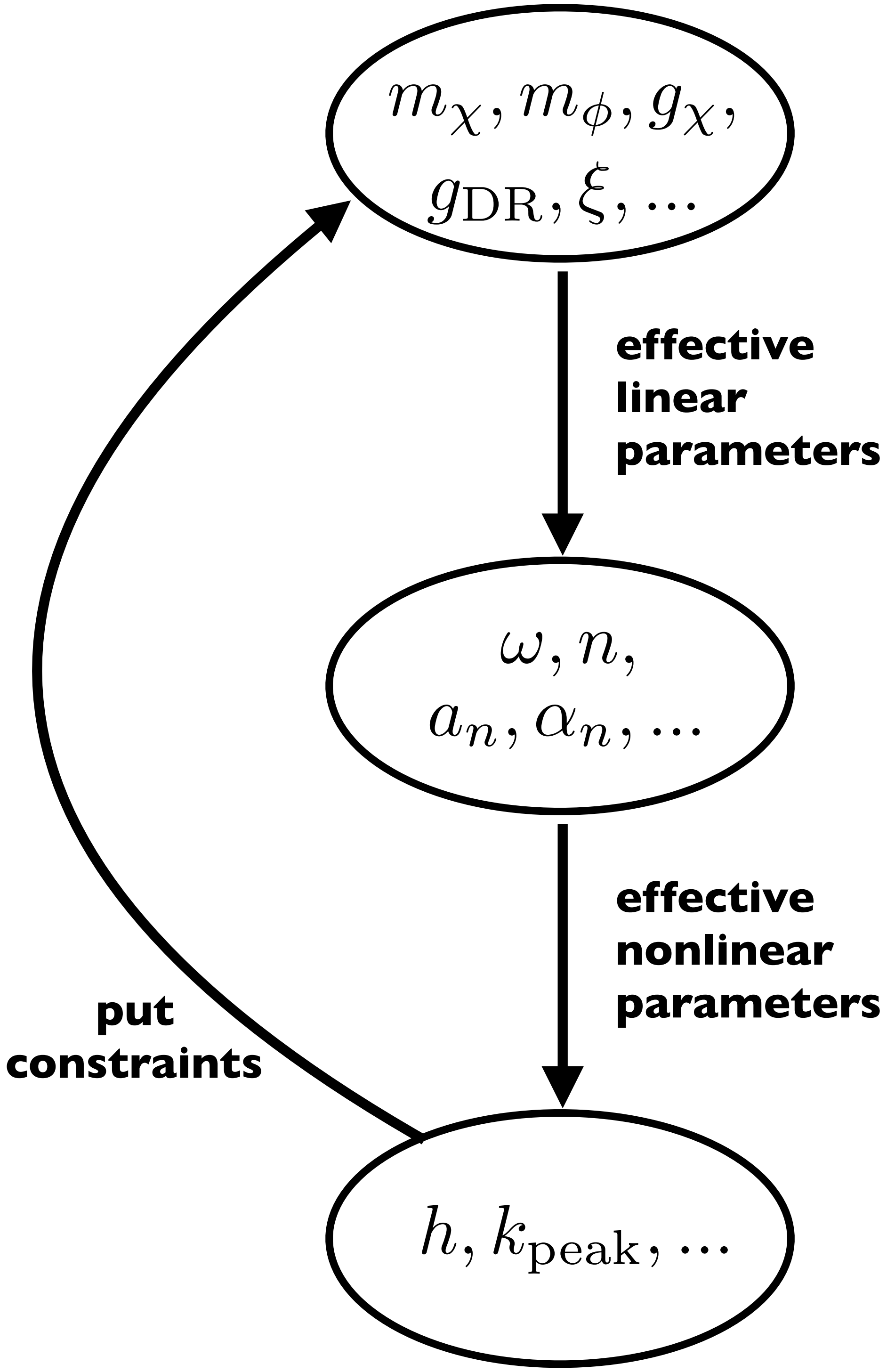
⇨ *In principle, this allows to disentangle WDM from sDAO!*

Outlook ?

- Goal: a fast and automated map instead of running expensive simulations!



Bohr+, 'soon'



$m_\chi, m_\phi, g_\chi, g_{\rm DR}, \xi, \ldots$

effective linear parameters

$\omega, n, a_n, \alpha_n, \ldots$

effective nonlinear parameters

$h, k_{\rm peak}, \ldots$

put constraints

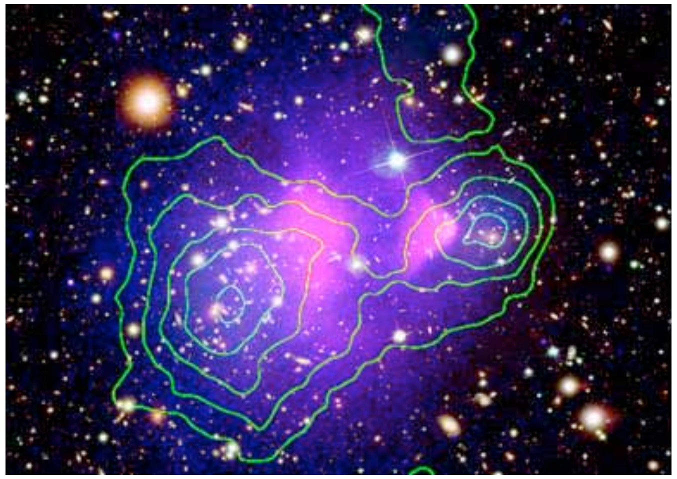
Conclusions

- Cosmological observations are a fascinating, and unique, tool to test 'invisible' dark sector interactions

- Goal of ETHOS: provide a consistent framework for this

$\mathcal{L}_{\rm BSM}$ **task 1**

task 2



✓

[for generic models with DM-DM & DM-DR interactions]

[✓]

first (promising) steps: ***stay tuned !***

Thanks for your attention!