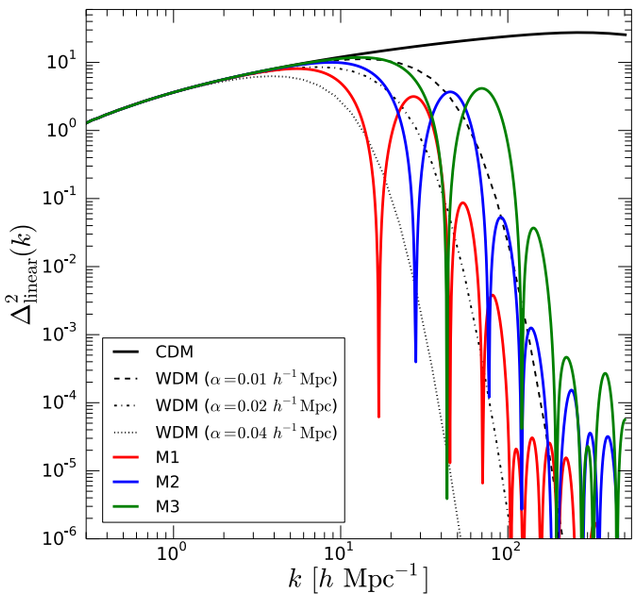
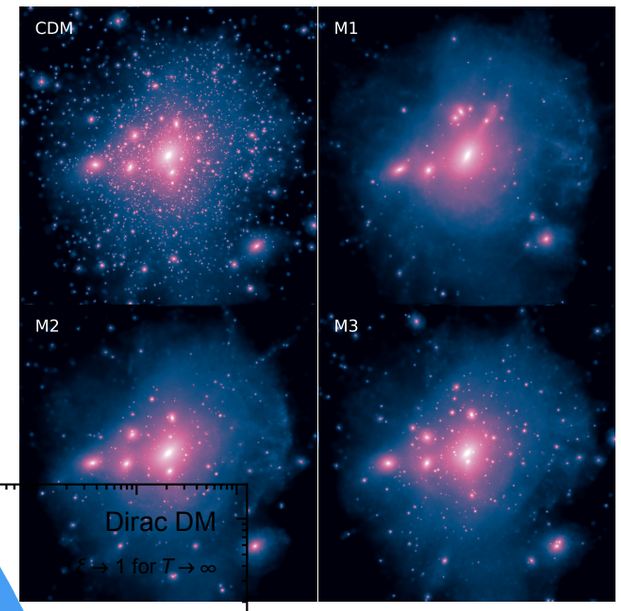
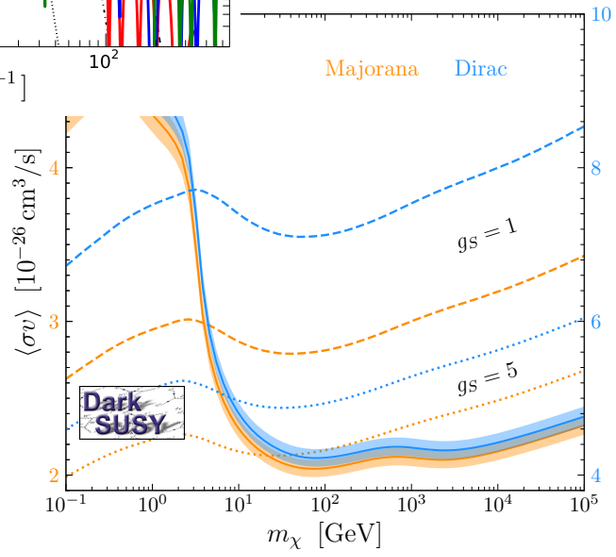
Cosmological tests of hidden sector models

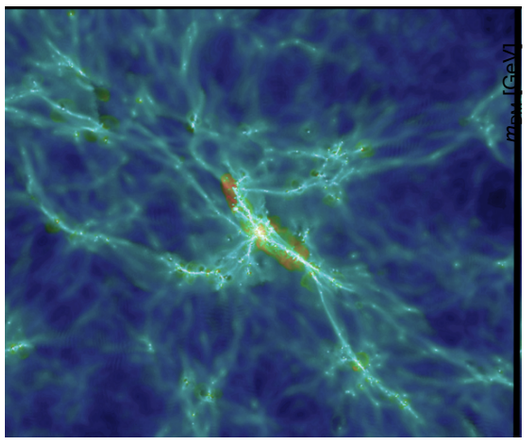


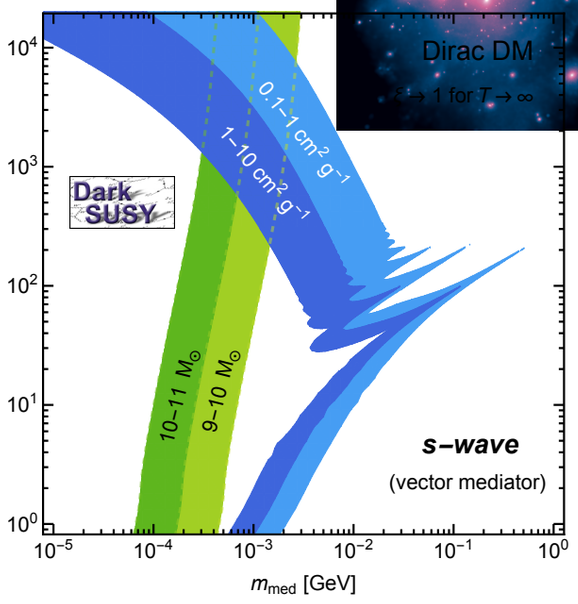
Torsten Bringmann

UiO : University of Oslo

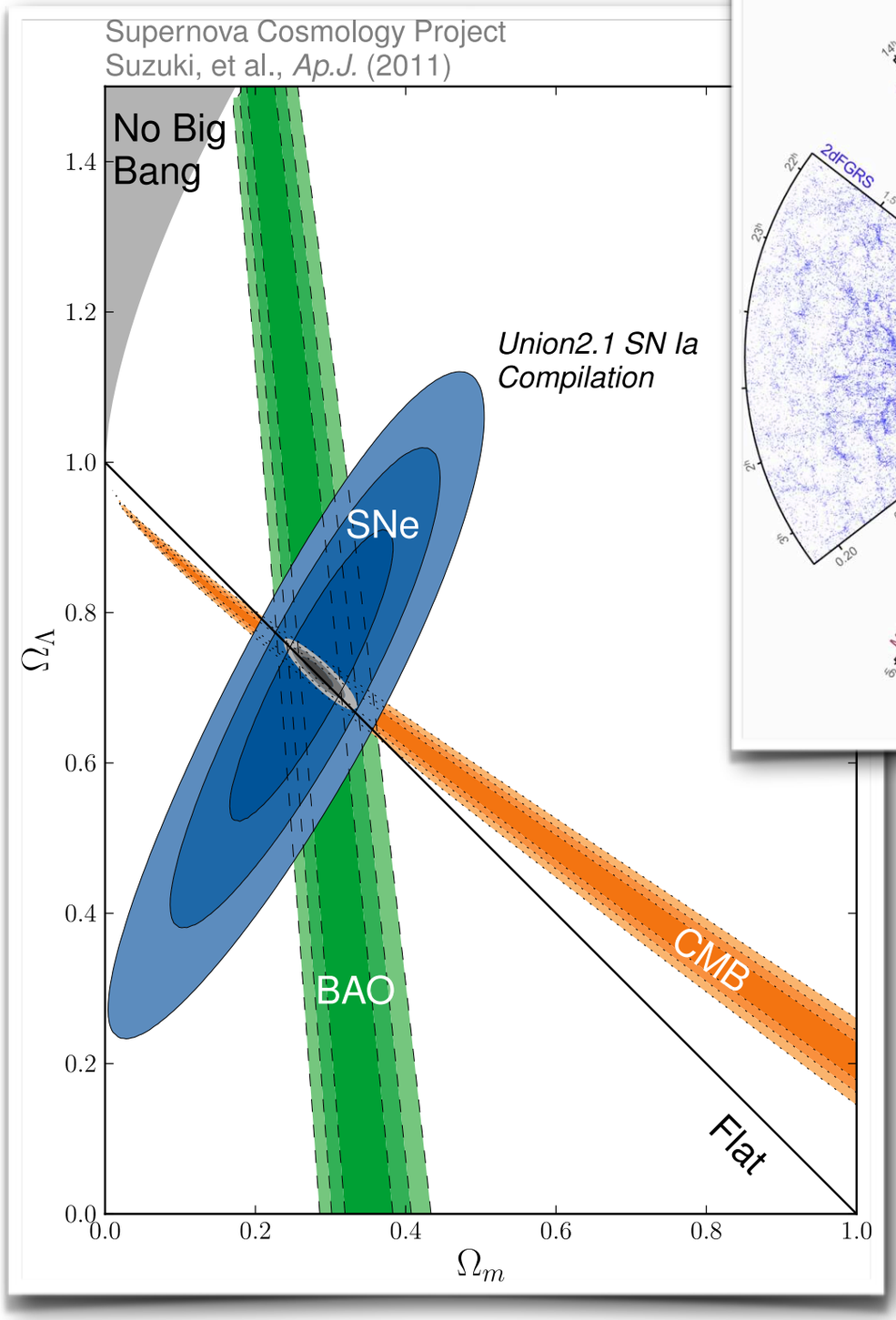


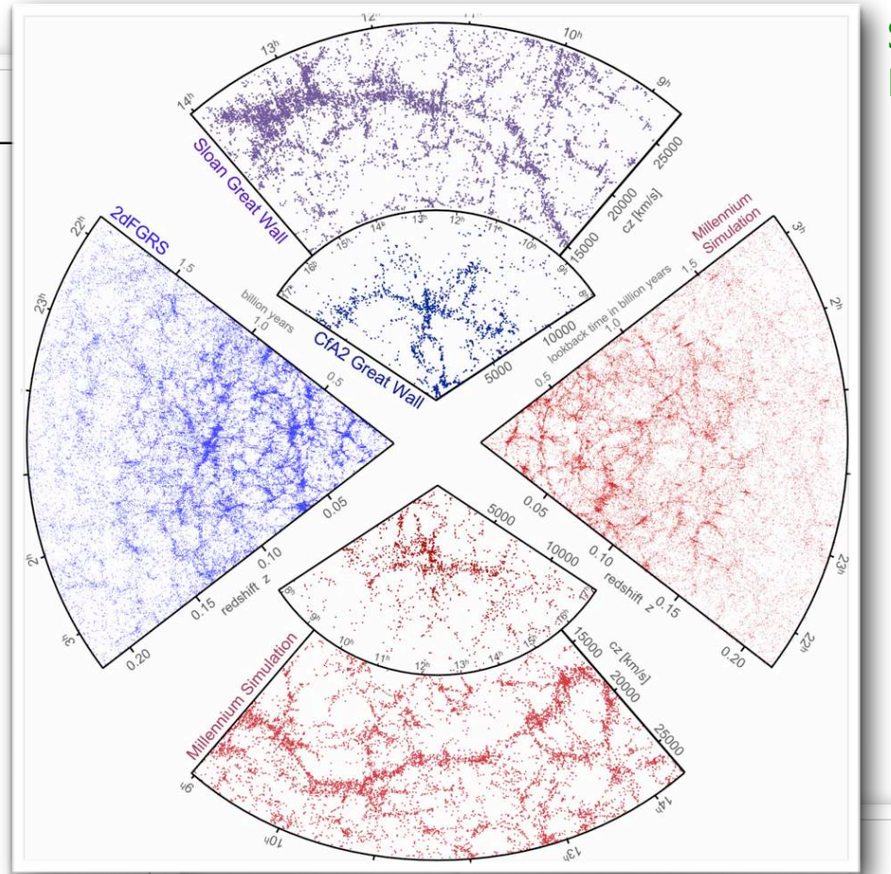






ΛCDM cosmology

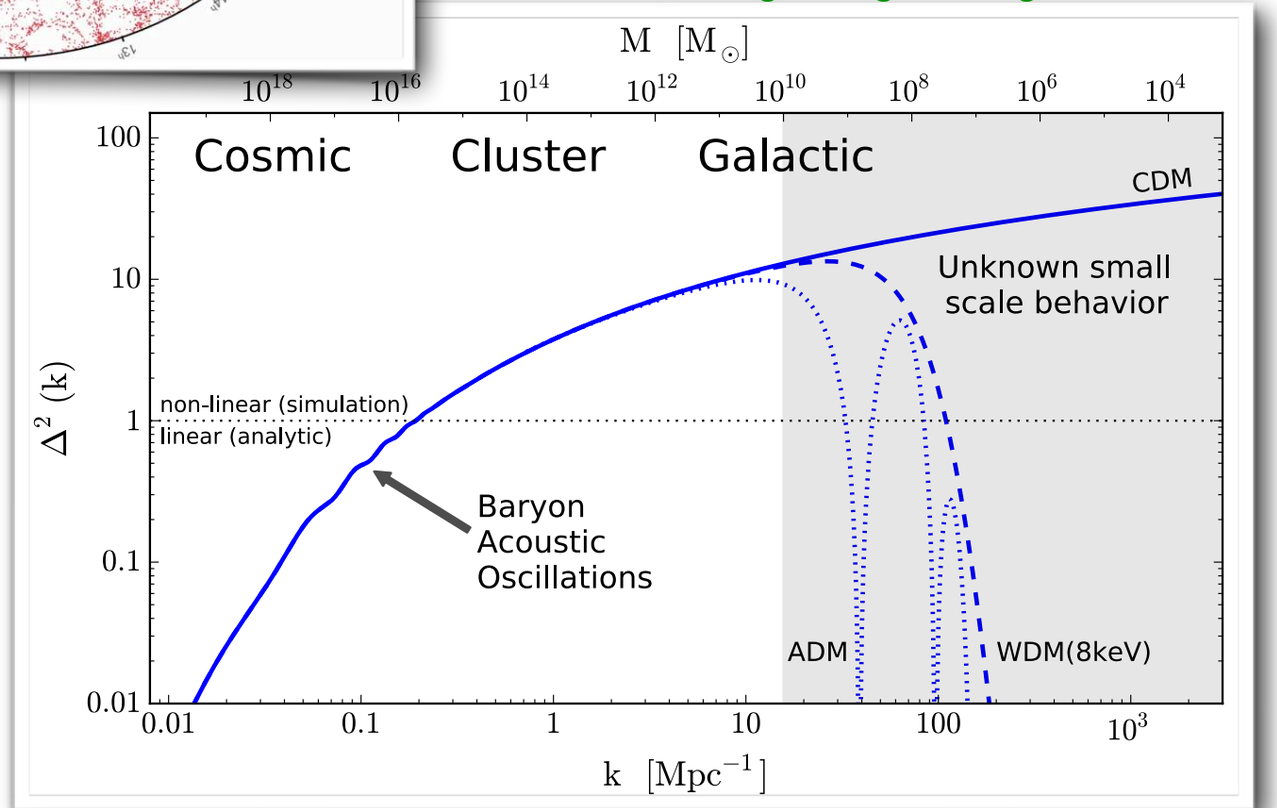




Springel, Frenk & White, Nature '06

A great success on large scales...

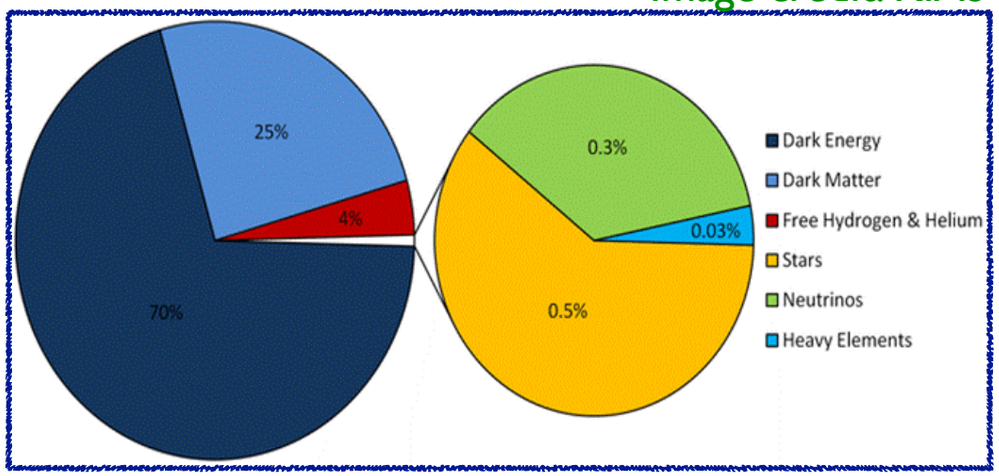
Kuhlen, Vogelsberger & Angulo, PDU '12



ΛCDM cosmology

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

Image credit: KIAS



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

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
  - DM self-interactions
  - DM — dark radiation interactions

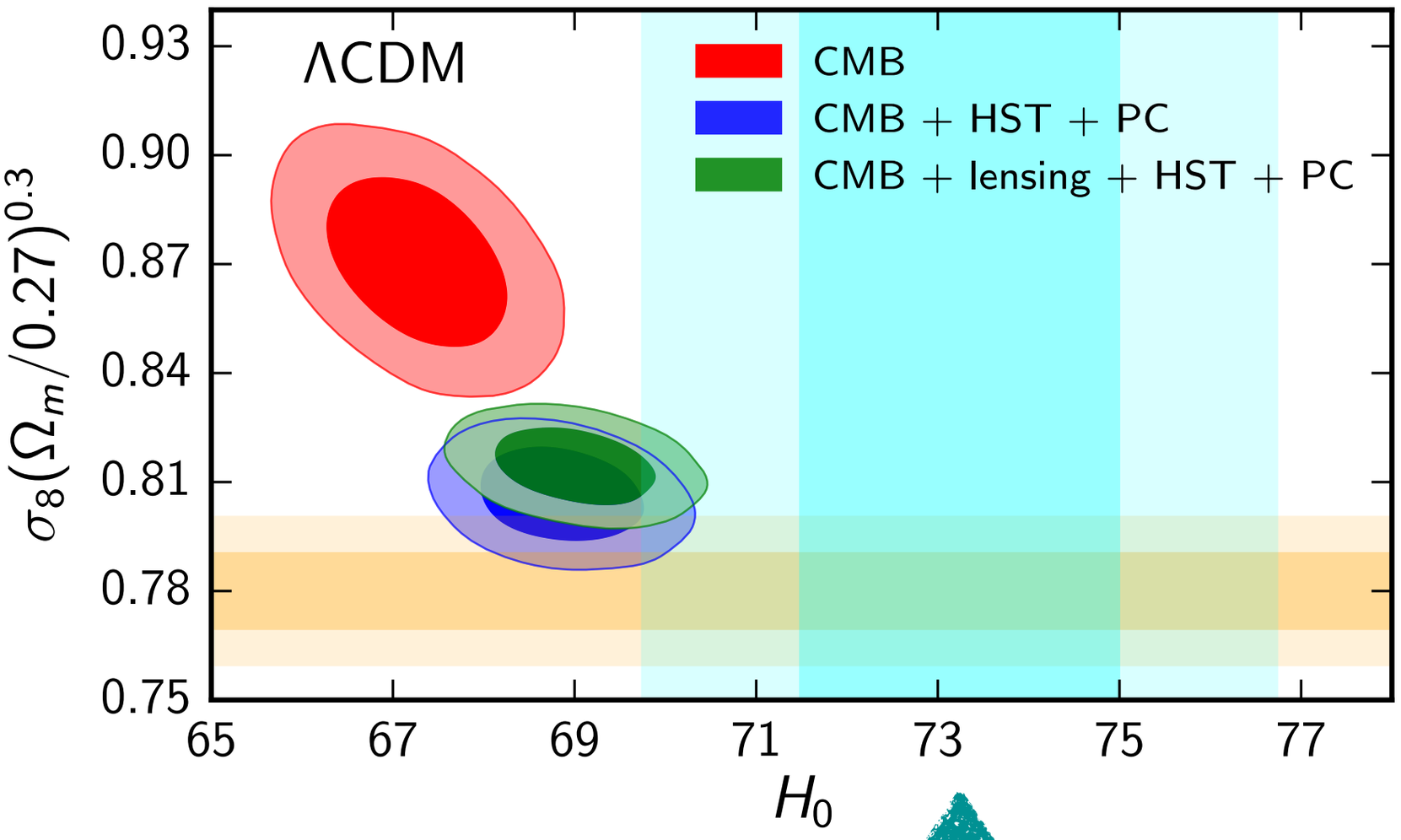
⇐ ***this talk…***

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)

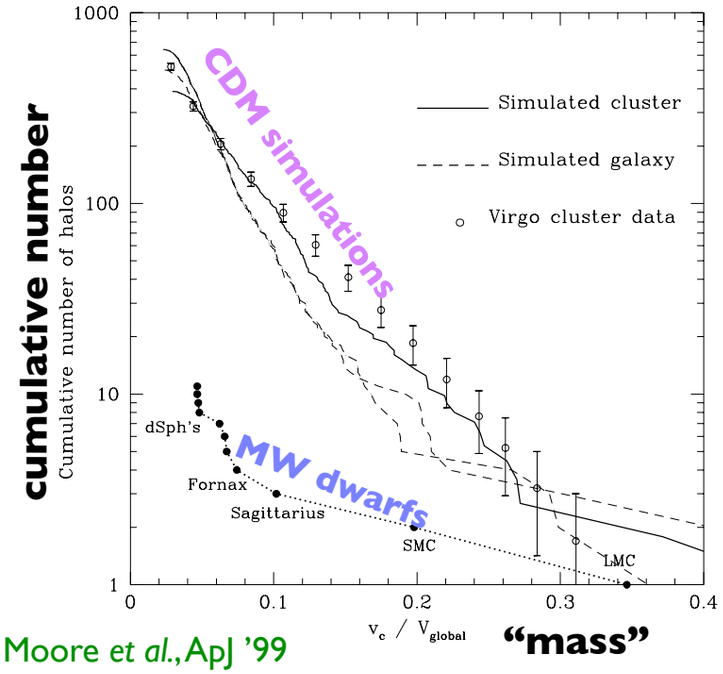
normalisation of power spectrum (from Planck clusters)

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 ?

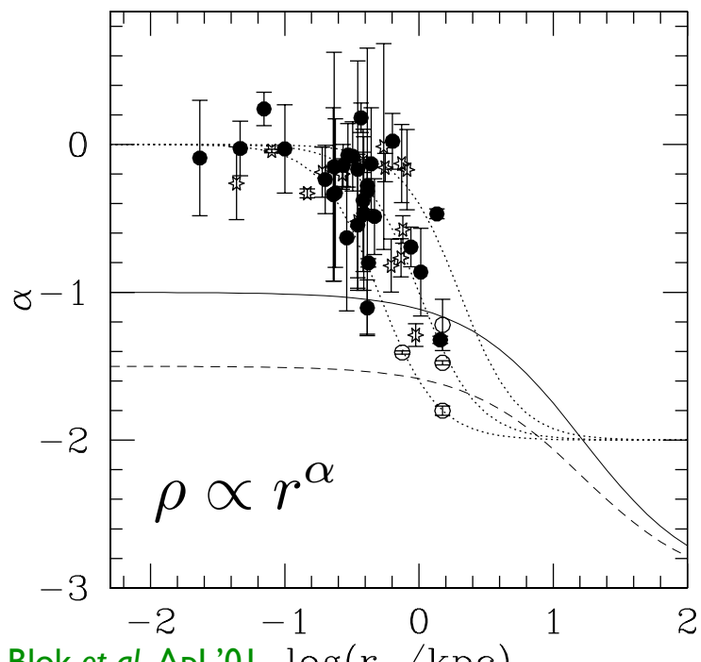
1. Missing satellites?



Moore *et al.*, ApJ '99

More satellites in simulations of MW-like galaxies than observed

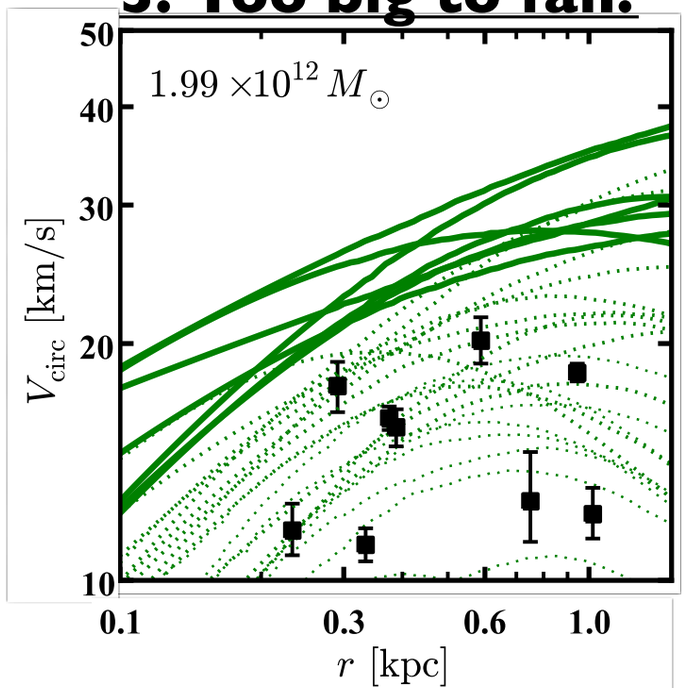
2. Cusps or cores?



Blok *et al.*, ApJ '01

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

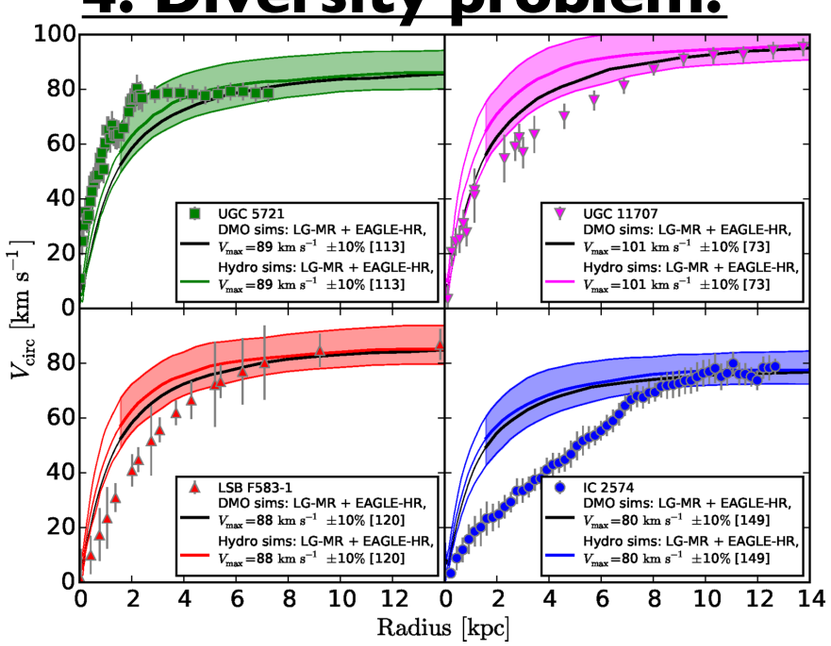
3. Too big to fail?



Boylan-Kolchin, Bullock & Kaplinghat, '11

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

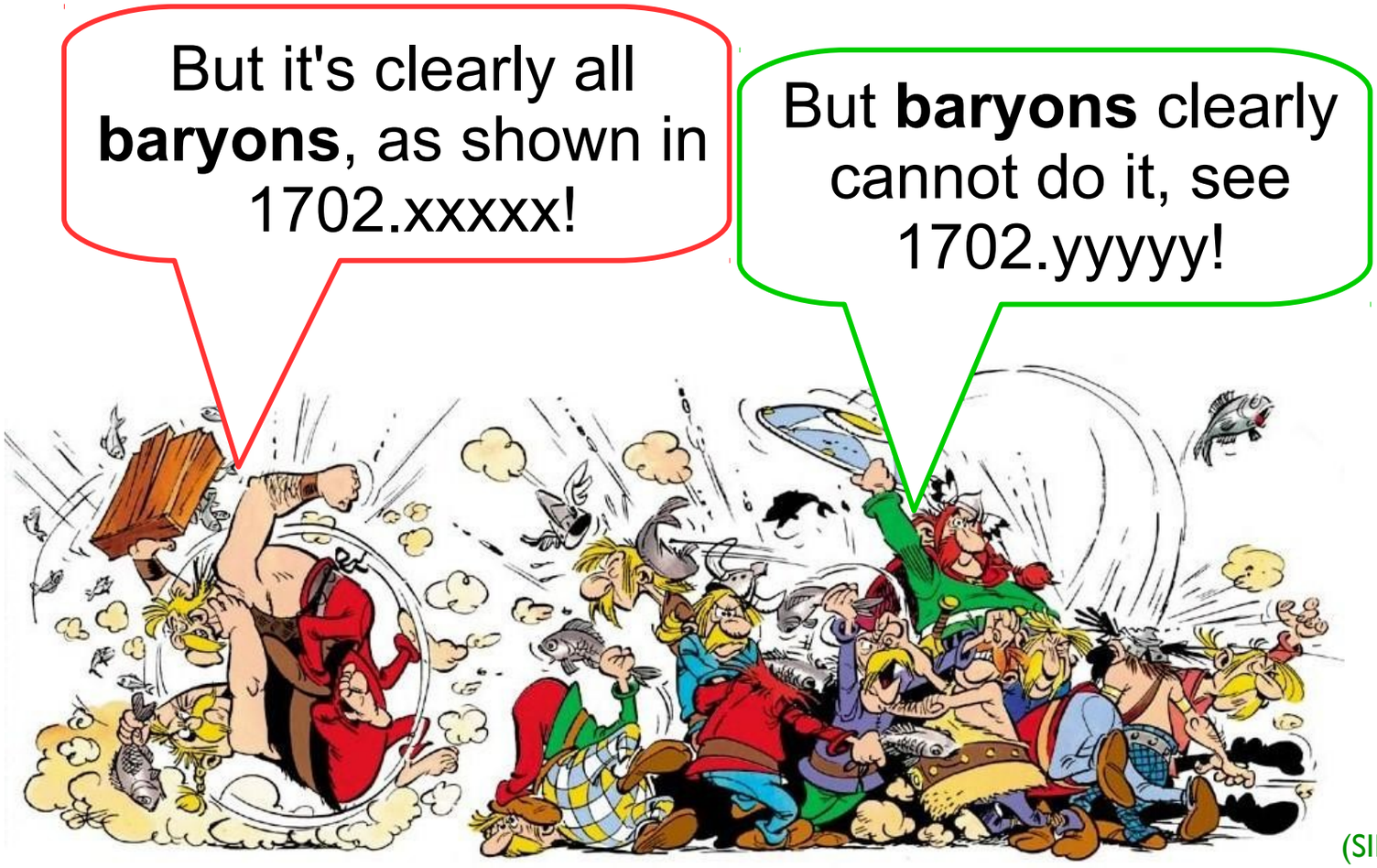
4. Diversity problem?



Oman+, MNRAS '15

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

Current status (still)



Courtesy: Kai Schmidt-Hoberg
(SIDM workshop, Copenhagen '17)

➡ *Maybe more healthy not to take sides… ;)*

BUT: *In **either** case, these examples serve as possible proof-of-principle(s) that relevant observables connected to non-gravitational, 'dark' interactions can been identified…*

Generic dark sector models

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

Standard Model

- SM particles

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

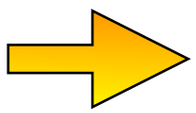
e.g. $U(1)_X \times ...$

Dark Sector

- Dark matter
- Dark radiation

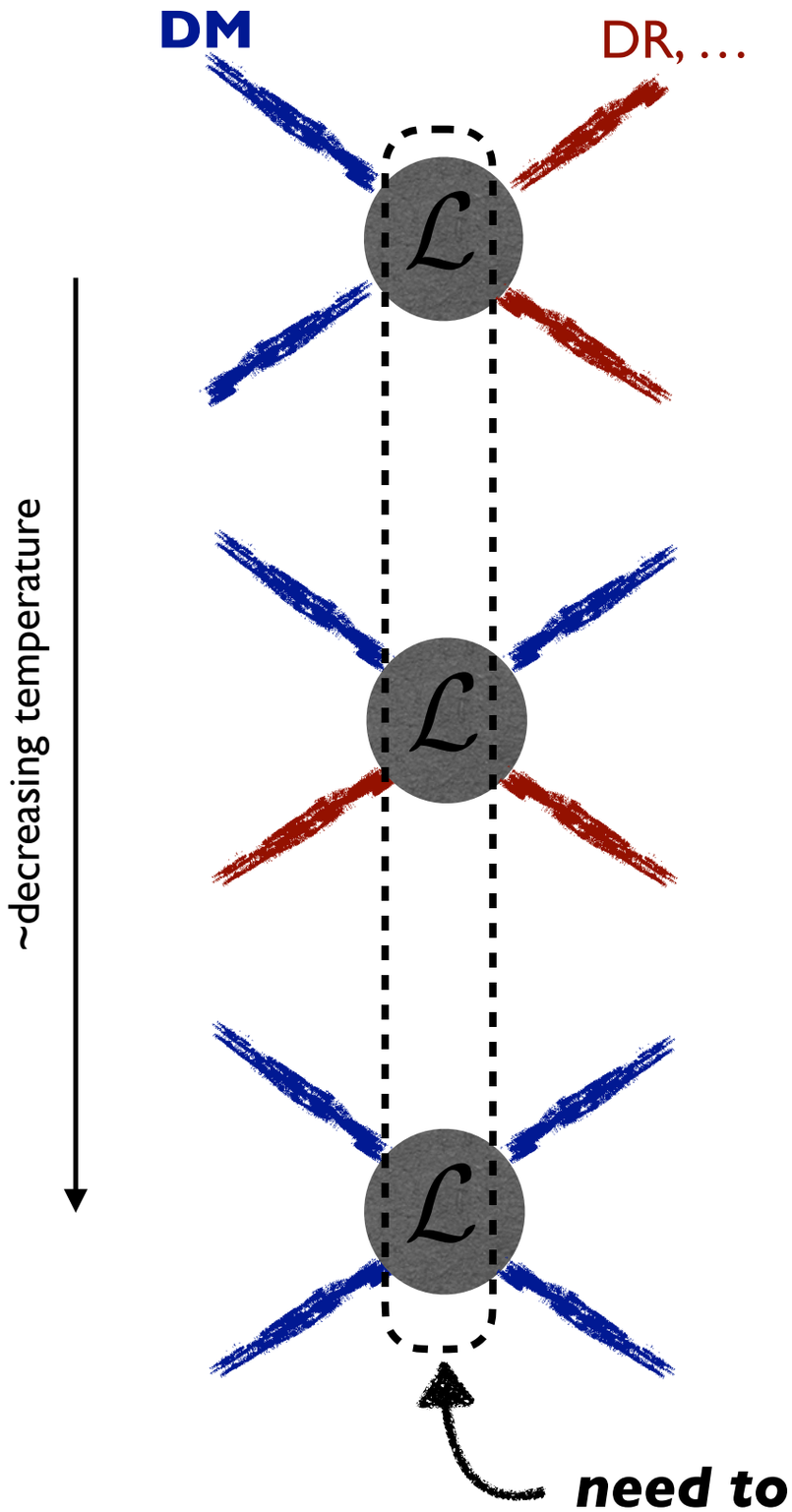
('sterile neutrinos', 'dark photons', ...)

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



Very predictive scenarios

Observing the 'unobservable' ?



relic density

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

imprints on inner
(sub-)halo structure

need to treat consistently!

DarkSUSY



;)



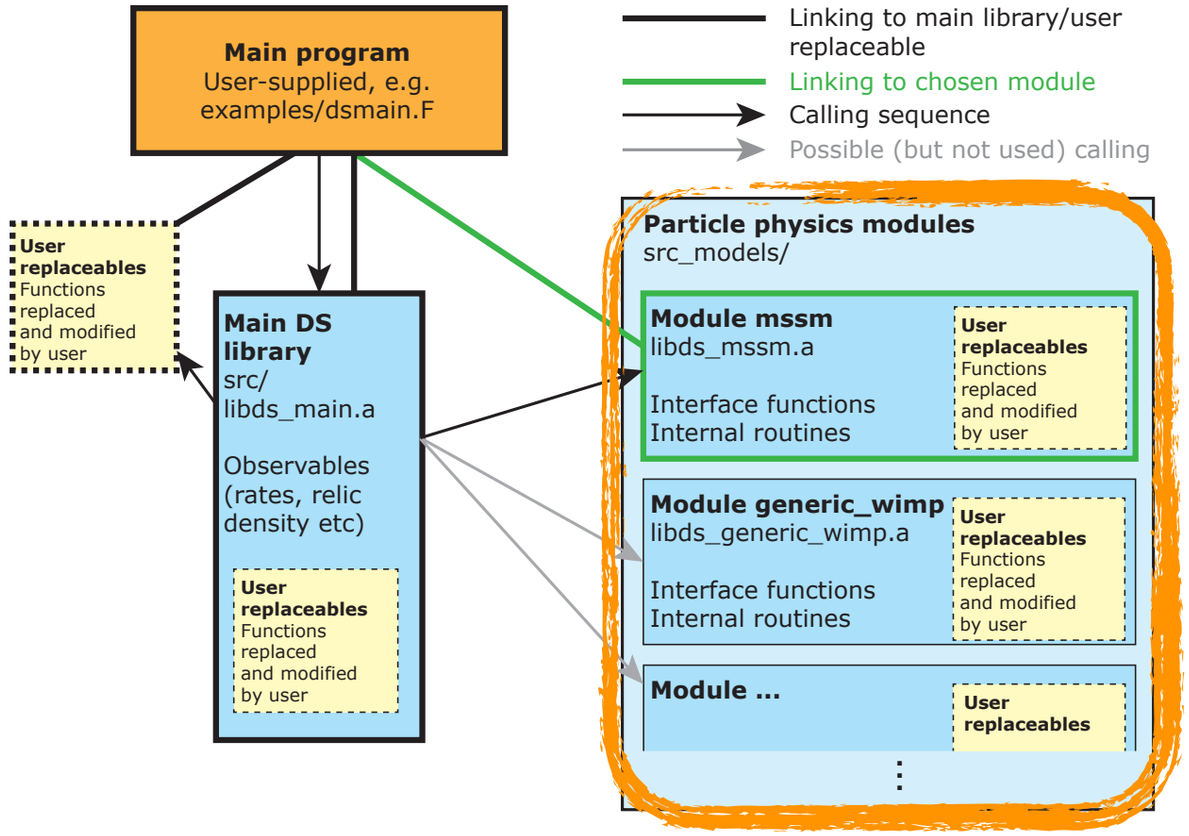
TB, Edsjö, Gondolo, Ullio & Bergström, JCAP '18

http://darksusy.hepforge.org

Since version 6: no longer restricted to supersymmetric DM !

➡ **strong focus on general *dark sector* observables**

- Numerical package to calculate 'all' DM related quantities:
  - *relic density + kinetic decoupling* **(also for $T_{\rm dark} \neq T_{\rm photon}$)**
  - *generic SUSY models + laboratory constraints implemented*
  - *cosmic ray propagation*
  - particle yields for generic DM annihilation or decay
  - *indirect detection rates: gammas, positrons, antiprotons, neutrinos*
  - *direct detection rates*
  - …

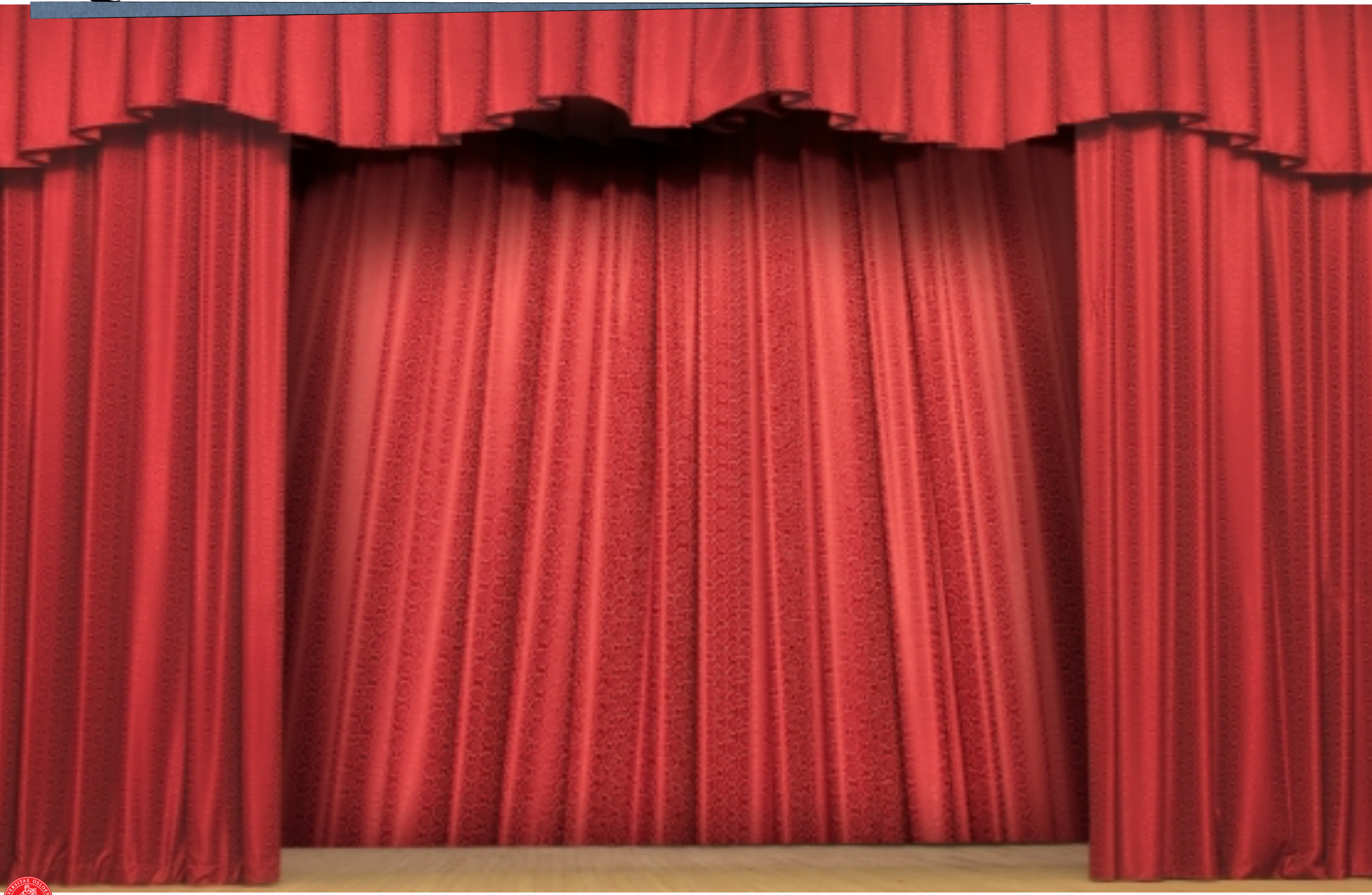


since 6.1: DM self-interactions, $\Delta N_{\rm eff}$

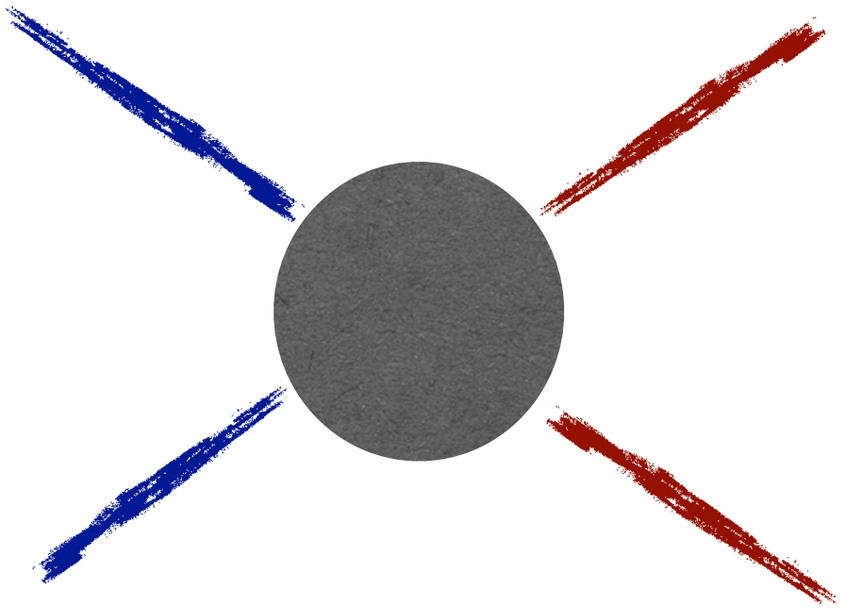
since 6.2: 'reverse' direct detection

TB & Pospelov, PRL '18

Questions so far?



Part II.a



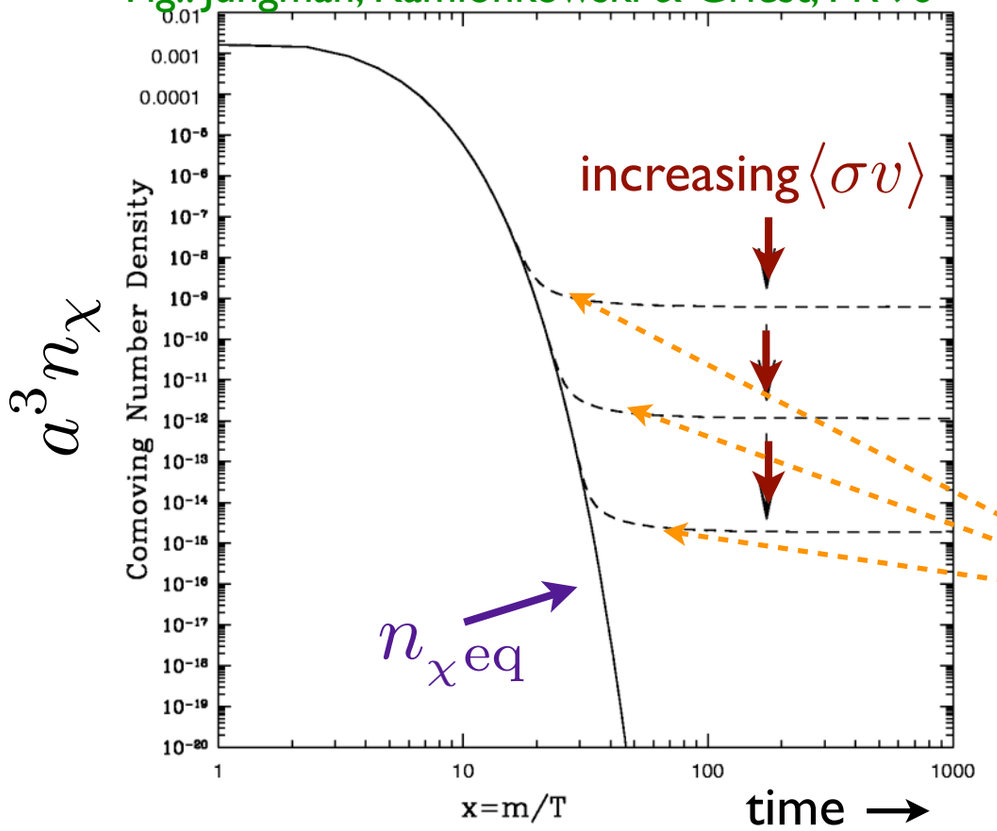
Relic density in secluded dark sectors

TB, Depta, Hufnagel & Schmidt-Hoberg, 2007.03696

The standard treatment™ (Gelmini & Gondolo, NPB '91)

- Abundance of species χ initially in equilibrium with SM:

Fig.: Jungman, Kamionkowski & Griest, PR'96



$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\chi\,\mathrm{eq}}^2\right)$$

$\langle\sigma v\rangle$: $\chi\chi \to \mathrm{SM\ SM}$ (thermal average)

"Freeze-out" when annihilation rate falls behind expansion rate

Relic density (today): $\Omega_\chi h^2 \sim \dfrac{3\cdot 10^{-27}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle} \sim \mathcal{O}(0.1)$

for weak-scale interactions!

= WIMP 'miracle'

- WIMP DM is seriously pressured, but not (yet) 'dead' !

Arcadi+, EPJC '18
Athron+, EPJC '19
(+ many more)

(Often forgotten) assumptions

- Boltzmann equation at phase-space level:

[$\int d^3p$ gives Eq for number density n_χ]

$$E(\partial_t - H\mathbf{p}\cdot\nabla_\mathbf{p})f_\chi = C[f_\chi]$$

Expansion
(in FRW spacetime)

Interactions with SM:



I) DM becomes non-relativistic while still in (full) EQ:

$$f_\chi^{\rm eq} = e^{-E/T} \ll 1$$

II) DM remains in kinetic EQ during freeze-out

$$f_\chi = e^{-(E-\mu_\chi)/T} = e^{\mu_\chi/T} f_\chi^{\rm eq} \qquad \mu_\chi/m_\chi \ll 1$$

III) SM particles never build up significant chemical potentials

$$f_{\rm SM} = e^{-E_{\rm SM}/T}$$

(energy conservation: $E_{\rm SM} = E_\chi$)

Generic dark sector models

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

Standard Model

- SM particles

.....

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

Dark Sector

- Dark matter
- Dark radiation

('sterile neutrinos', 'dark photons', ...)

$$\xi(T) \equiv \frac{T_\chi(T)}{T} = \frac{\left[g_*^{\rm SM}(T)/g_*^{\rm SM}(T_{\rm dec})\right]^{\frac{1}{3}}}{\left[g_*^{\rm DS}(T)/g_*^{\rm DS}(T_{\rm dec})\right]^{\frac{1}{3}}}$$

- Let's study a simple set-up for concreteness:
  - *only fermionic DM (χ) and a scalar (S) in dark sector (with $m_S < m_\chi$)*
  - *decoupling at high temperatures: $T_{\rm dec} \gg m_t, m_\chi$*
  - *(directly) afterwards EQ in DS through $\bar{\chi}\chi \leftrightarrow SS$*



Case I: massless DS 'heat bath'

- Vanishing chemical potential for S
  - e.g. *because of* $\bar{\chi}\chi \to \bar{\chi}\chi S$

$$\xi(T) \equiv \frac{T_\chi(T)}{T} = \frac{\left[g_*^{\rm SM}(T)/g_*^{\rm SM}(T_{\rm dec})\right]^{\frac{1}{3}}}{\left[g_*^{\rm DS}(T)/g_*^{\rm DS}(T_{\rm dec})\right]^{\frac{1}{3}}}$$

➡ identical assumptions to standard case possible, after replacing $T \to T_\chi$

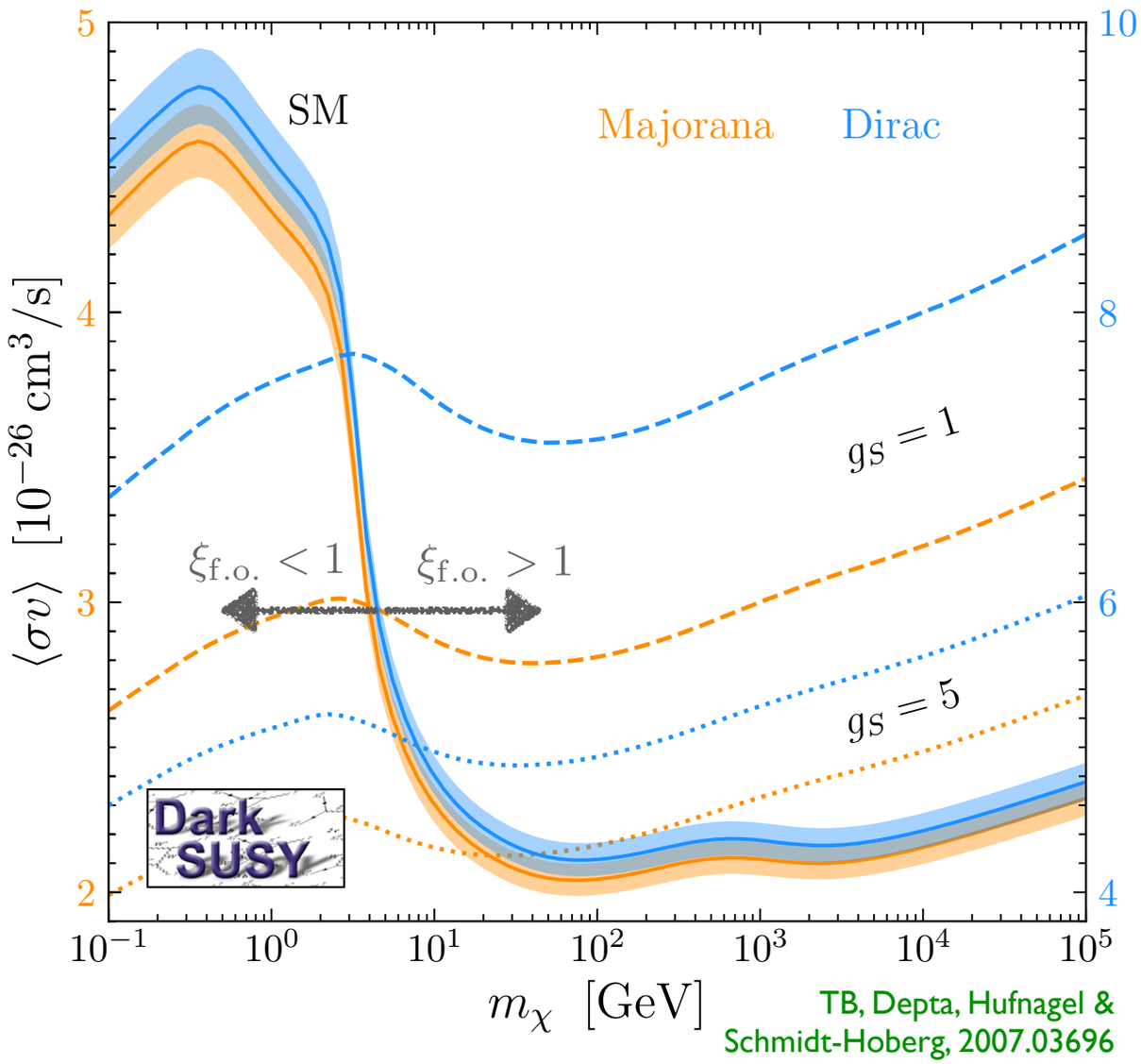
➡ Can use *same* Boltzmann equation for n_χ, after changing

$$\langle\sigma v\rangle = \int_1^\infty d\tilde{s}\, \sigma_{\bar{\chi}\chi\to\bar{f}f} v_{\rm lab} \frac{2m_\chi\sqrt{\tilde{s}-1}(2\tilde{s}-1)K_1\left(\frac{2\sqrt{\tilde{s}}m_\chi}{T}\right)}{T K_2{}^2(m_\chi/T)}$$

$$n_{\chi,\rm eq} = g_\chi m_\chi^2 T K_2(m_\chi/T)/(2\pi^2)$$

$$H^2 = \frac{8\pi G}{3}\rho \equiv \frac{8\pi^3 G}{90} g_{\rm eff} T^4$$

$$= g_{\rm eff}^{\rm SM} + g_{\rm eff}^{\rm DS}$$

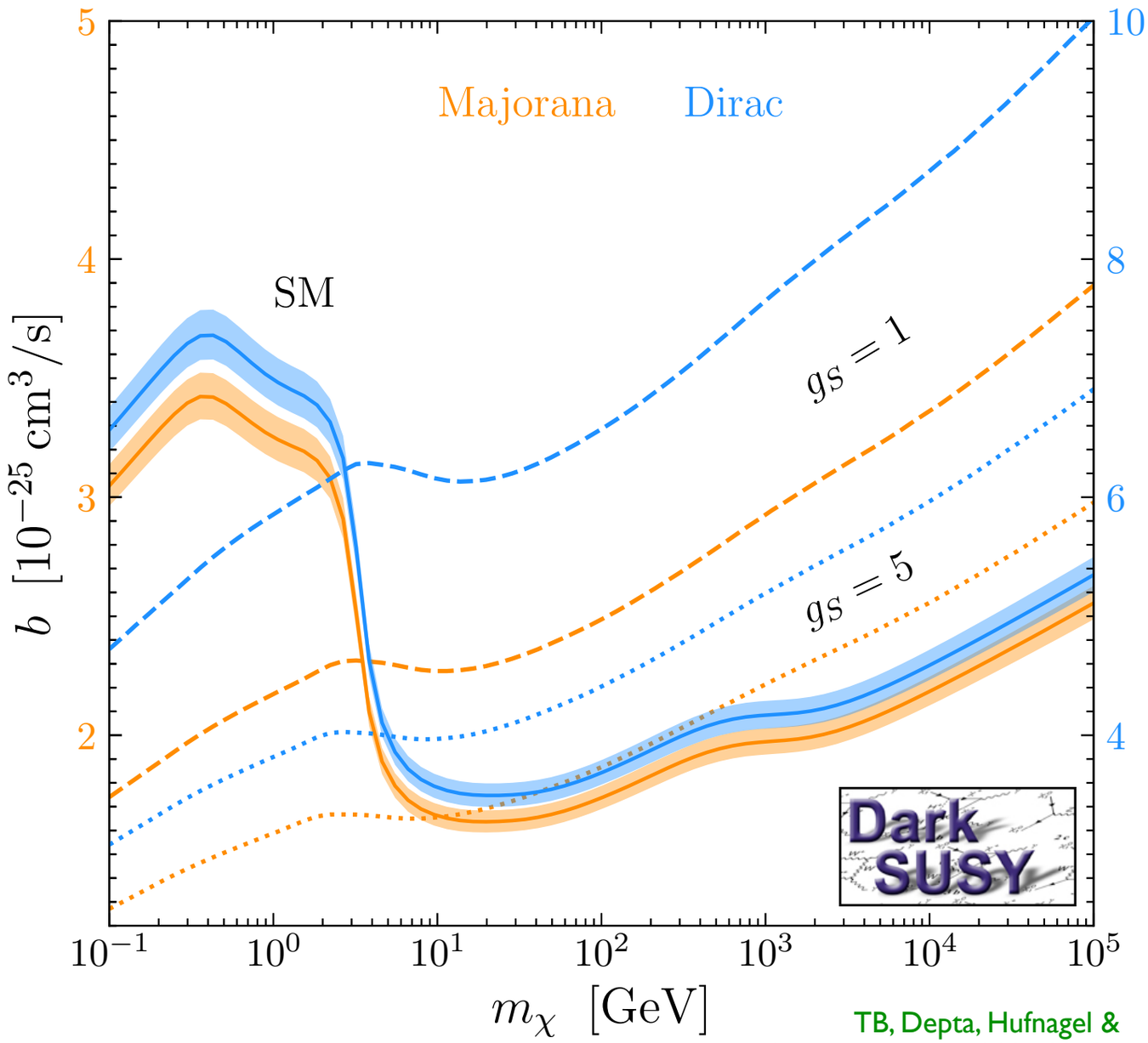


TB, Depta, Hufnagel & Schmidt-Hoberg, 2007.03696

p-wave annihilation

[In case you ever wondered how the 'Steigman plot' looks like for non-constant cross sections…]

$$\sigma v_{\rm lab} = b\, v_{\rm lab}^2$$



TB, Depta, Hufnagel & Schmidt-Hoberg, 2007.03696

Case II: massive annihilation products

- In general, nothing prevents S to build up chemical potentials
  - *unless adding new physics, e.g. massless states N with* $\Gamma_{\bar{N}N\leftrightarrow SS} \gg \Gamma_{\bar{\chi}\chi\leftrightarrow SS}$

➡ Underlying assumptions for standard Boltzmann equation not satisfied anymore, even when assuming kinetic EQ:

$$f_S \neq e^{-E_S/T_\chi}$$

$$f_\chi^{\rm eq} \neq e^{-E/T_\chi} \not\ll 1$$

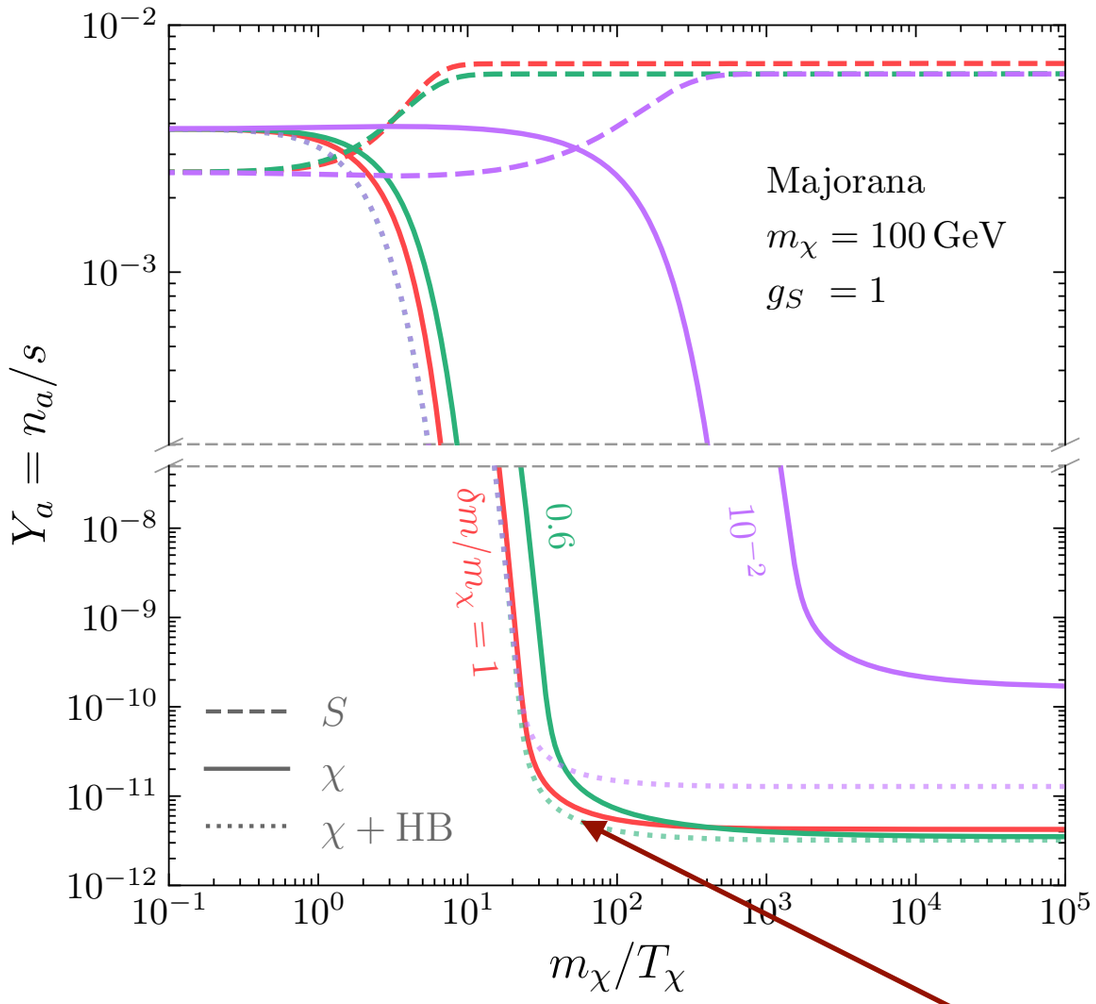
$$f_\chi \neq e^{-(E-\mu_\chi)/T_\chi} \neq e^{\mu_\chi/T_\chi} f_\chi^{\rm eq}$$

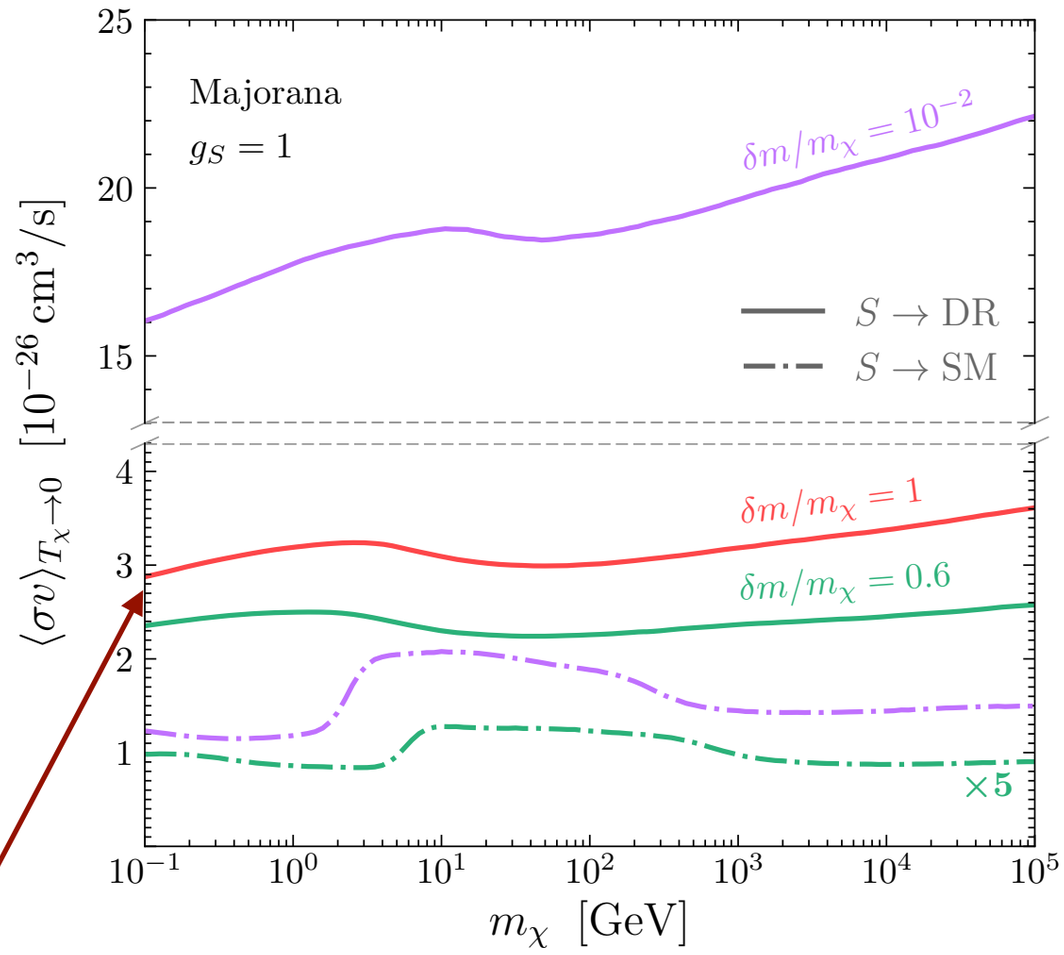
- In kinetic EQ, particles will still follow BE / FD distributions

➡ Need to independently solve for T_χ, μ_χ and μ_S, with full spin-statistics!

  - *number conservation* $\dot{n}_i + 3Hn_i = \mathfrak{C}/N_\chi, \quad \dot{n}_S + 3Hn_S = -\mathfrak{C}$
  - *energy conservation* $\nabla_\mu T^{0\mu}_{\rm DS} = 0$
  - *transform all time derivatives as* $\dot{Q} = \frac{\partial Q}{\partial T_\chi}\dot{T}_\chi + \frac{\partial Q}{\partial \mu_\chi}\dot{\mu}_\chi + \frac{\partial Q}{\partial \mu_S}\dot{\mu}_S$

Case II: results

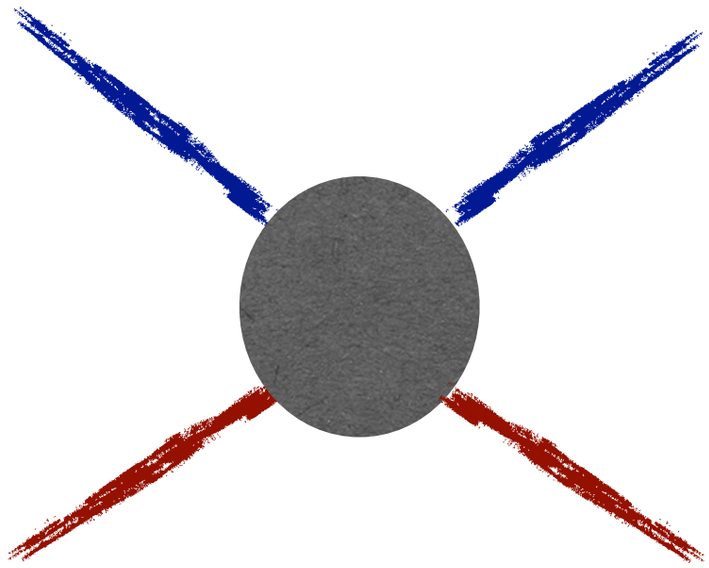




$m_S = 0$ (case I)

TB, Depta, Hufnagel & Schmidt-Hoberg, 2007.03696

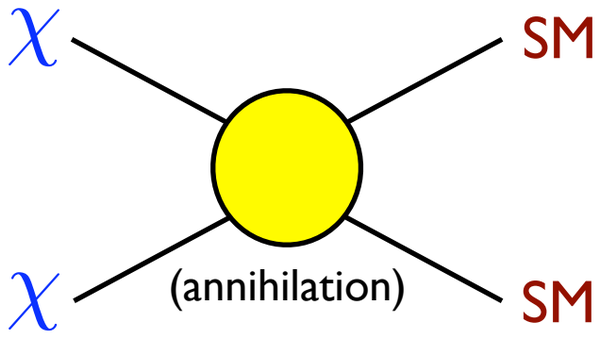
Part II.b

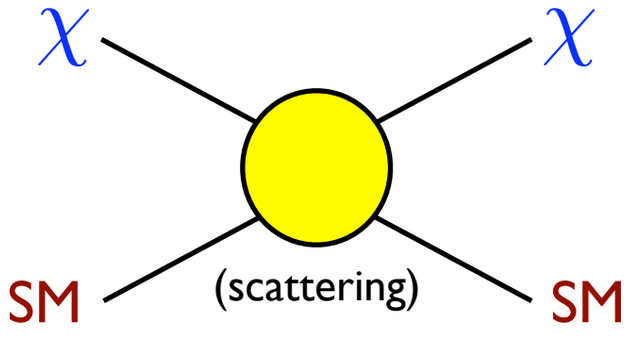


Dark matter — dark radiation interactions

Freeze-out ≠ decoupling !

- Expect WIMPs (and similar DM particles) to stay much longer in kinetic than in chemical equilibrium:





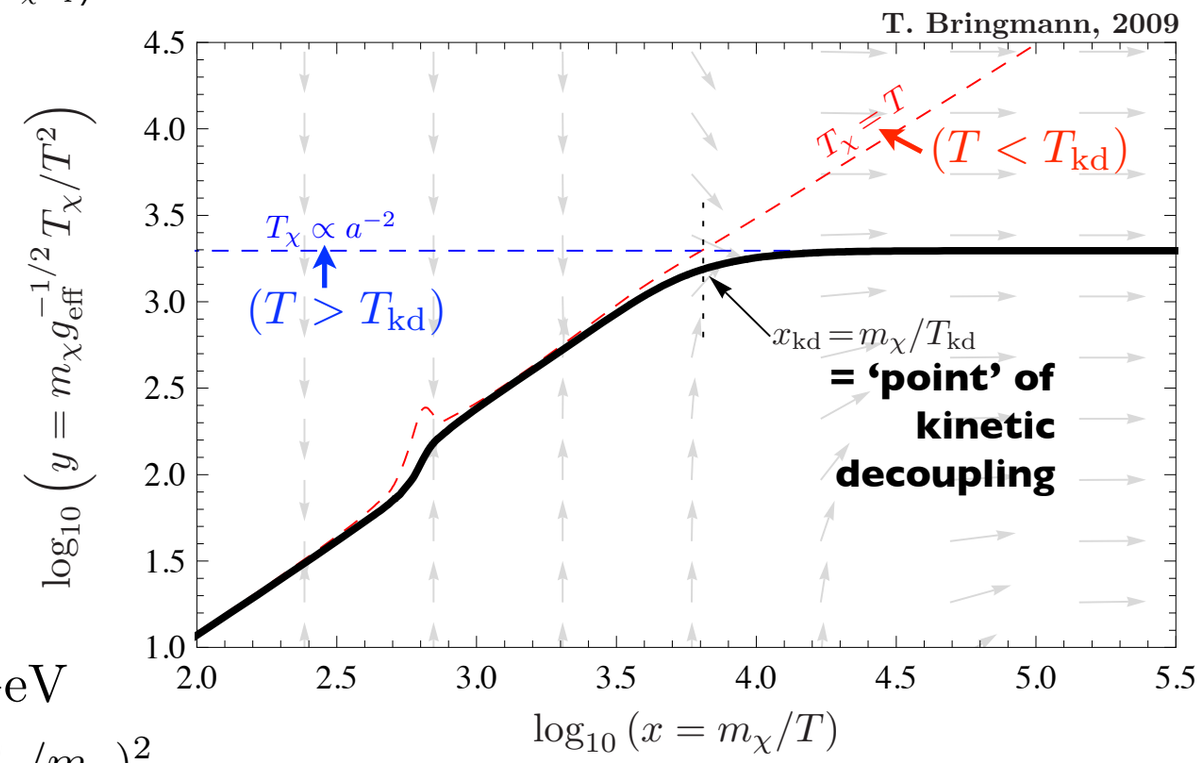
- Boltzmann equation in FRW spacetime: $E(\partial_t - H\mathbf{p}\cdot\nabla_\mathbf{p})f_\chi = C[f_\chi]$
  - $\int d^3p$ recovers familiar $\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\chi\,\mathrm{eq}}^2\right)$
  - Now consider 2nd moment, introducing

$$T_\chi n_\chi \equiv \int \frac{d^3p}{(2\pi)^3}\frac{\mathbf{p}^2}{3m_\chi} f(\mathbf{p})$$

Bertschinger, PRD '06
TB & Hofmann, JCAP '07
TB, NJP '09

➡ solve resulting ODE for T_χ

[See also Binder, TB, Gustafsson & Hryczuk, PRD '18 for detailed treatment]



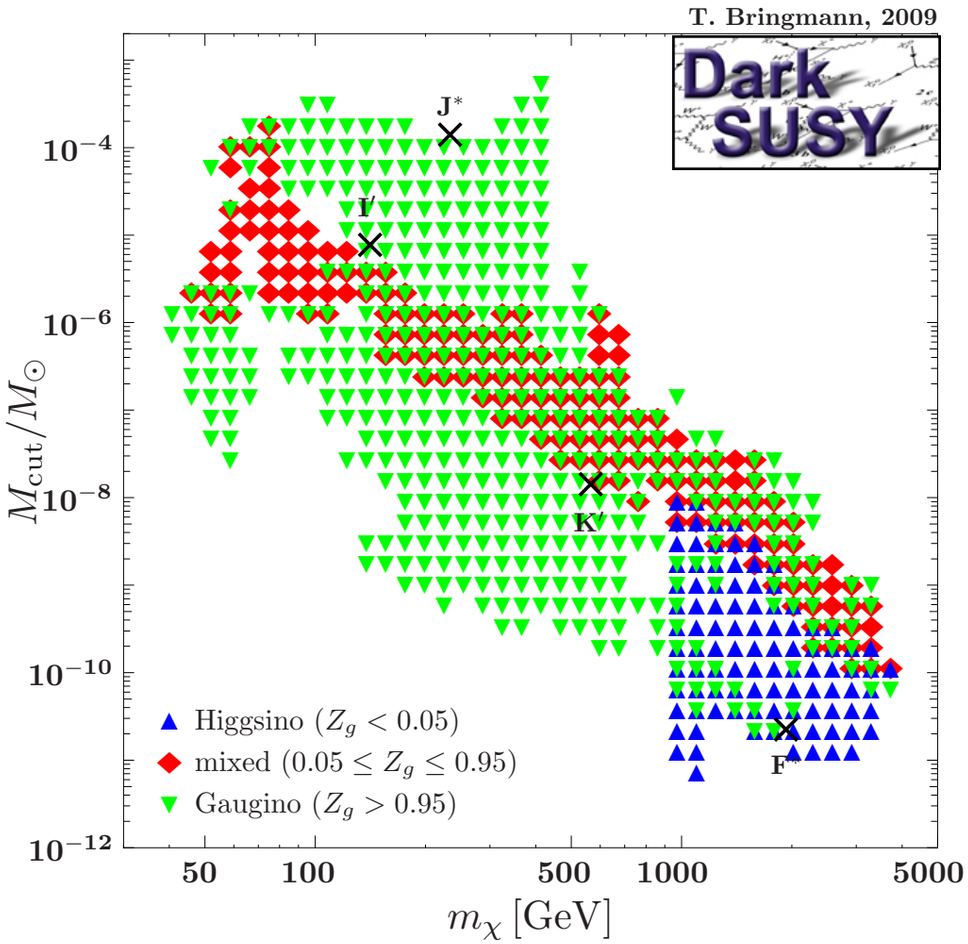
Example:
$m_\chi = 100\,\mathrm{GeV}$
$|\mathcal{M}|^2 \sim g_Y^4 (E_\chi/m_\chi)^2$

The smallest protohalos

- In kinetic equilibrium, density contrasts in DM component immediately erased

- Around and after decoupling, two effects suppress the growth of overdensities:
  - free-streaming e.g. Green, Hofmann & Schwarz, JCAP '05
  - baryonic ('dark') acoustic oscillations

    Loeb & Zaldarriaga, PRD '05;Bertschinger, PRD '06



- Resulting small-scale cutoff in power spectrum corresponds to mass of smallest gravitationally bound structures
  - Not 'earth-mass' but strongly model-dependent!

- Much later kinetic decoupling (i.e. larger cutoffs) possible for scattering with dark radiation, e.g. with light mediators
  - way to address the missing satellite 'problem' with cold DM!

TB, Ihle, Kersten & Walia, PRD '16
[full simplified model classification]

Linear perturbations

Details: Cyr-Racine+, PRD '16

- Fundamentally, have to solve coupled Boltzmann equations:

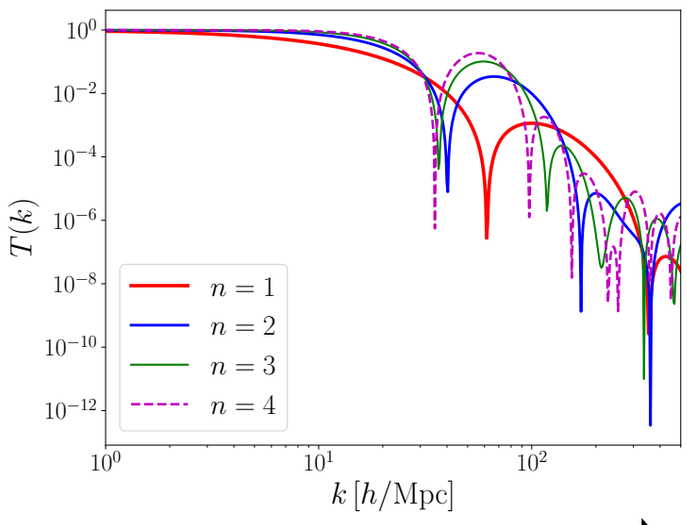
$$\frac{df_\chi}{d\lambda} = C_{\chi\tilde{\gamma}\leftrightarrow\chi\tilde{\gamma}}[f_\chi, f_{\rm DR}], \qquad \frac{df_{\rm DR}}{d\lambda} = C_{\chi\tilde{\gamma}\leftrightarrow\chi\tilde{\gamma}}[f_{\rm DR}, f_\chi] + C_{\tilde{\gamma}\tilde{\gamma}\leftrightarrow\tilde{\gamma}\tilde{\gamma}}[f_{\rm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

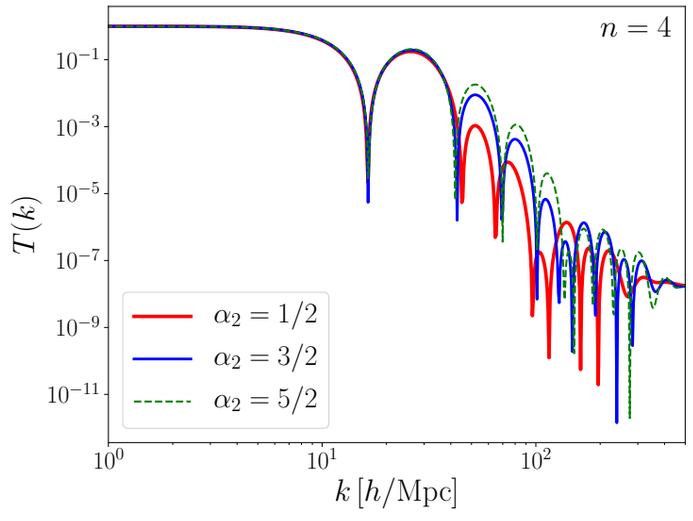
  - rewrite as differential equations for DM density, velocity and 'temperature':

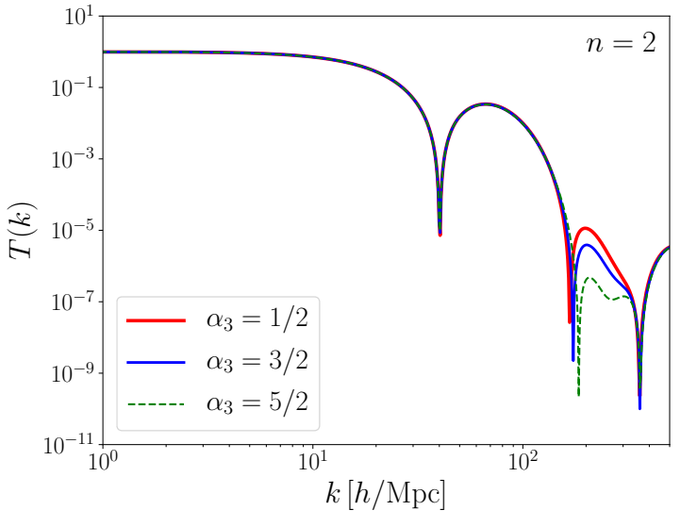
$$n_\chi \equiv \eta_\chi \int \frac{d^3p}{(2\pi)^3} f_\chi(\mathbf{p}) \qquad \vec{v}_\chi \equiv \frac{\eta_\chi}{n_\chi} \int \frac{d^3p}{(2\pi)^3} f_\chi(\mathbf{p}) \frac{p\,\hat{\mathbf{p}}}{E} \qquad T_\chi \equiv \frac{\eta_\chi}{3n_\chi^{(0)}} \int \frac{d^3p}{(2\pi)^3} \frac{\mathbf{p}^2}{m_\chi}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

  - keep terms up to first order in perturbations

- Dedicated Boltzmann solver: https://bitbucket.org/franyancr/ethos_camb
  - modified version of CAMB Lewis & Bridle, PRD '02
  - detailed examples for calculating pheno parameters from given model $\left(|\mathcal{M}|^2\right)$ (also TB+, PRD '16)

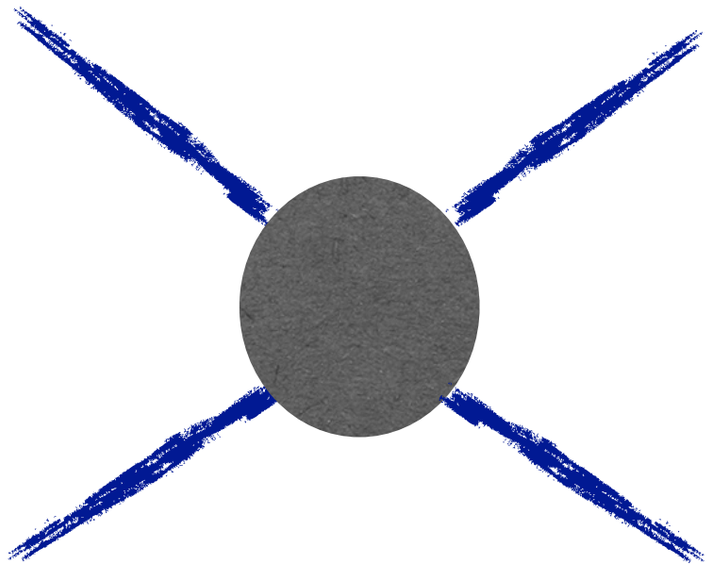






'Dark acoustic oscillations'

Part II.c



Dark matter self-interactions

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 @ time of proposal:

Update today
(after detailed simulations)

- ΛCDM unchanged above Mpc scales
  [less than one collision per Hubble time]

  ✓

- DM (sub)halos will develop cores
  [scattering increases entropy of DM phase spase distribution]

  ✓ for cusp/core, need $\sigma/m_\chi \sim 1\mathrm{cm}^2/\mathrm{g}$

- more spherical (sub)halos
  [same as above]

  ✓ indeed gives rise to relevant constraints

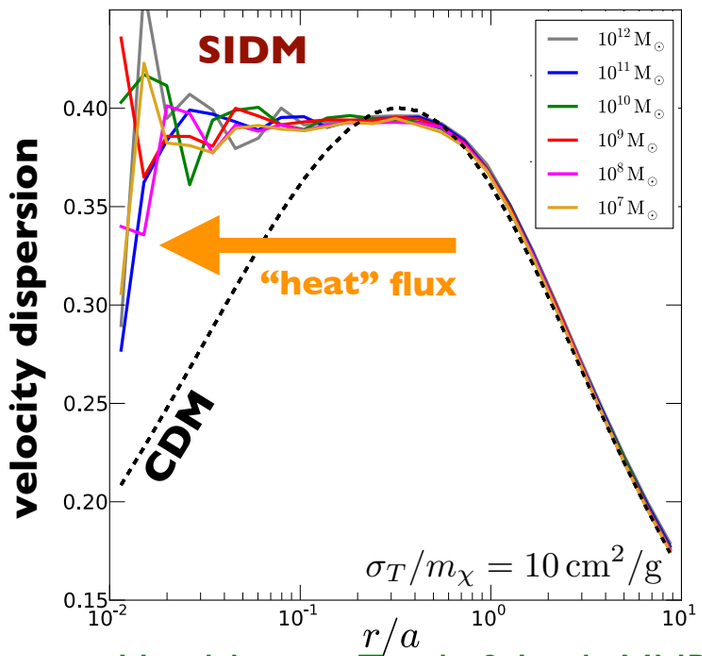
- Less dense subhalos will `evaporate'
  [scattering destroys substructure]

  ✗ only for $\sigma/m_\chi \gg 1\mathrm{cm}^2/\mathrm{g}$

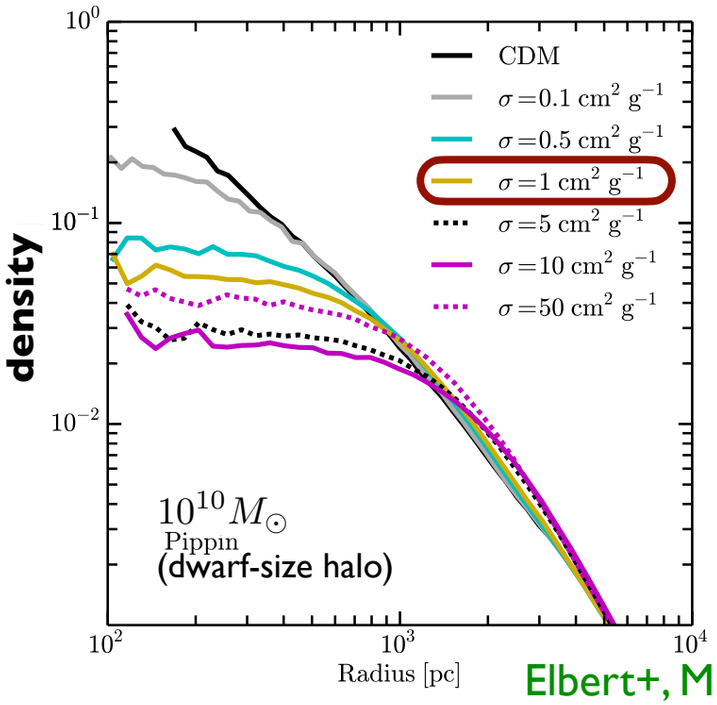
SIDM simulations

- DM-DM scatterings
  - 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

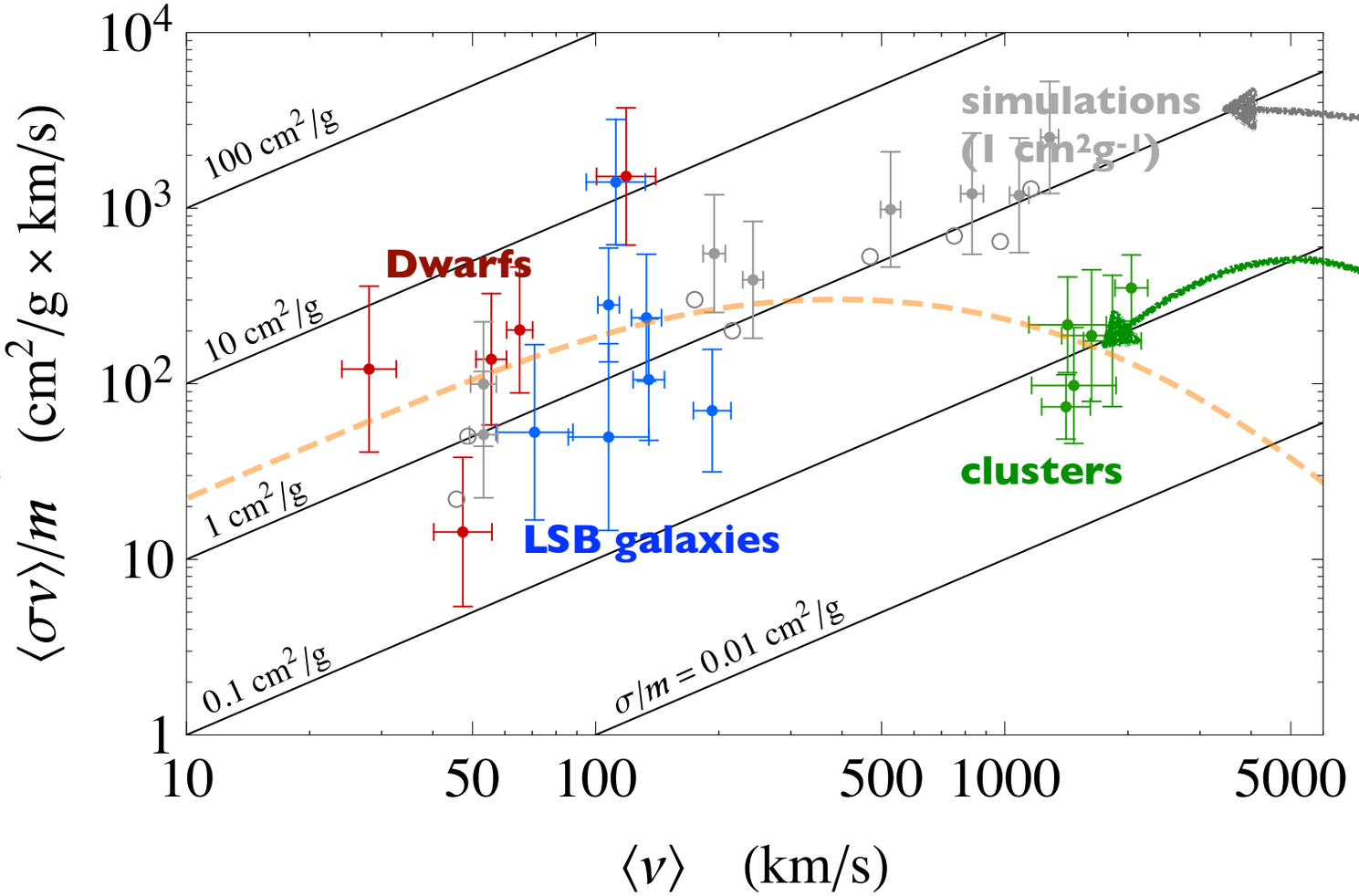
- Simple analytic models to predict core radius from σ_{SIDM}
  - reproduce DM-only simulation results for $\rho_\chi(r)$ remarkably well

    Kaplinghat, Tulin & Yu, PRL '15
  - but underlying (microphysics) assumptions not really satisfied

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

    Sokolenko+, JCAP '18

SIDM simulations



verify model + estimate systematics

max. cluster core size: ~10 kpc
(1 cm²/g would instead imply 100!)

apply model to kinematic data

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

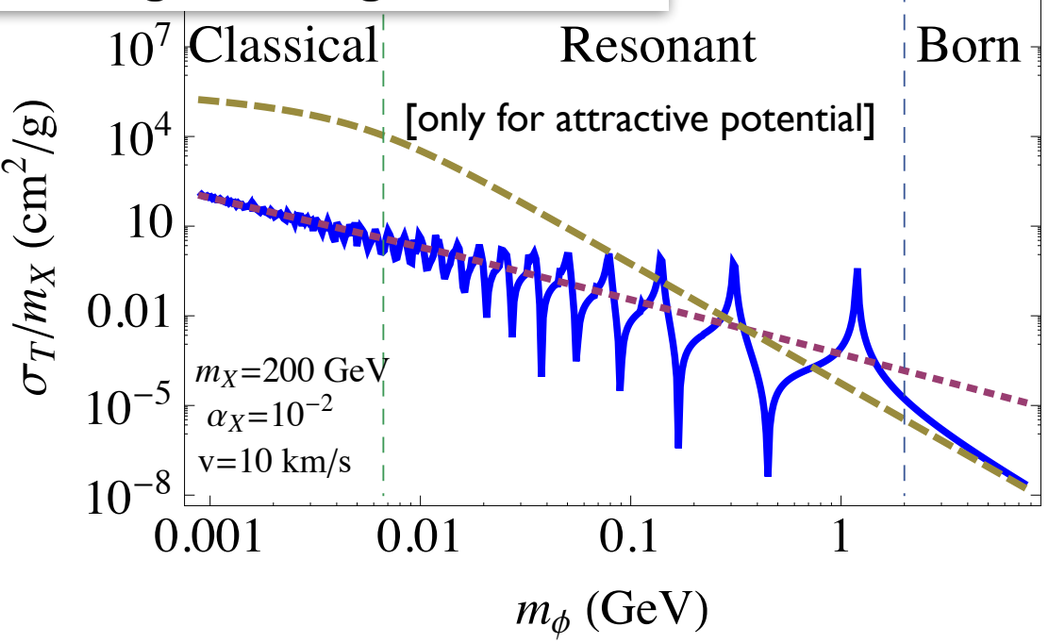
➡ *Use caution when applied to systems including baryons!* ⚠ — Sokolenko+, JCAP '18

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

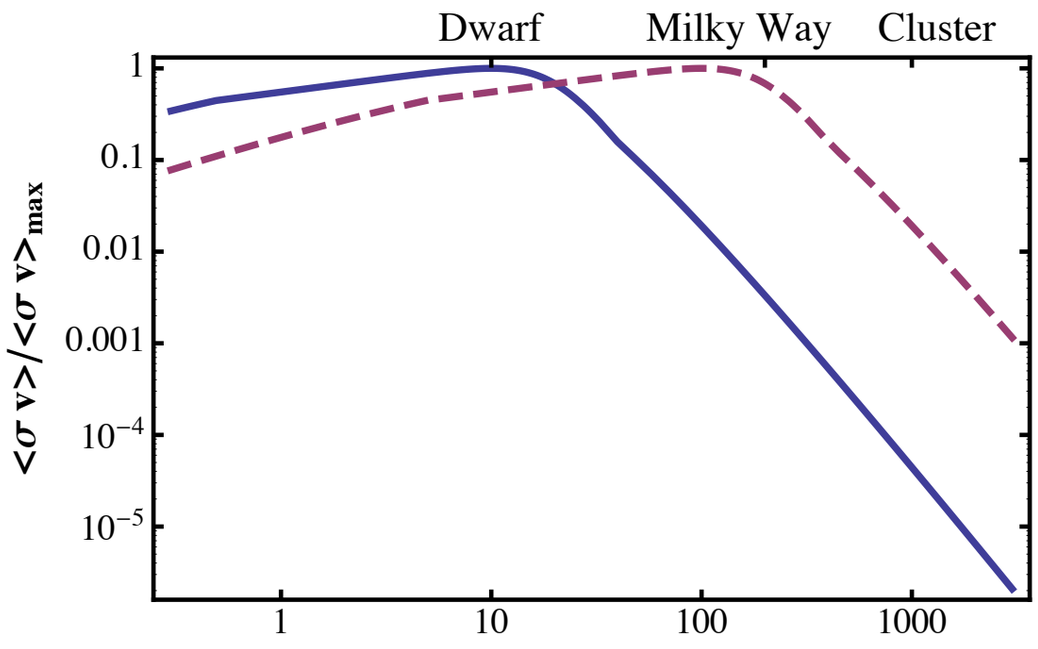


$$\sigma_T \equiv \int d\Omega (1-\cos\theta)\frac{d\sigma}{d\Omega}$$

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

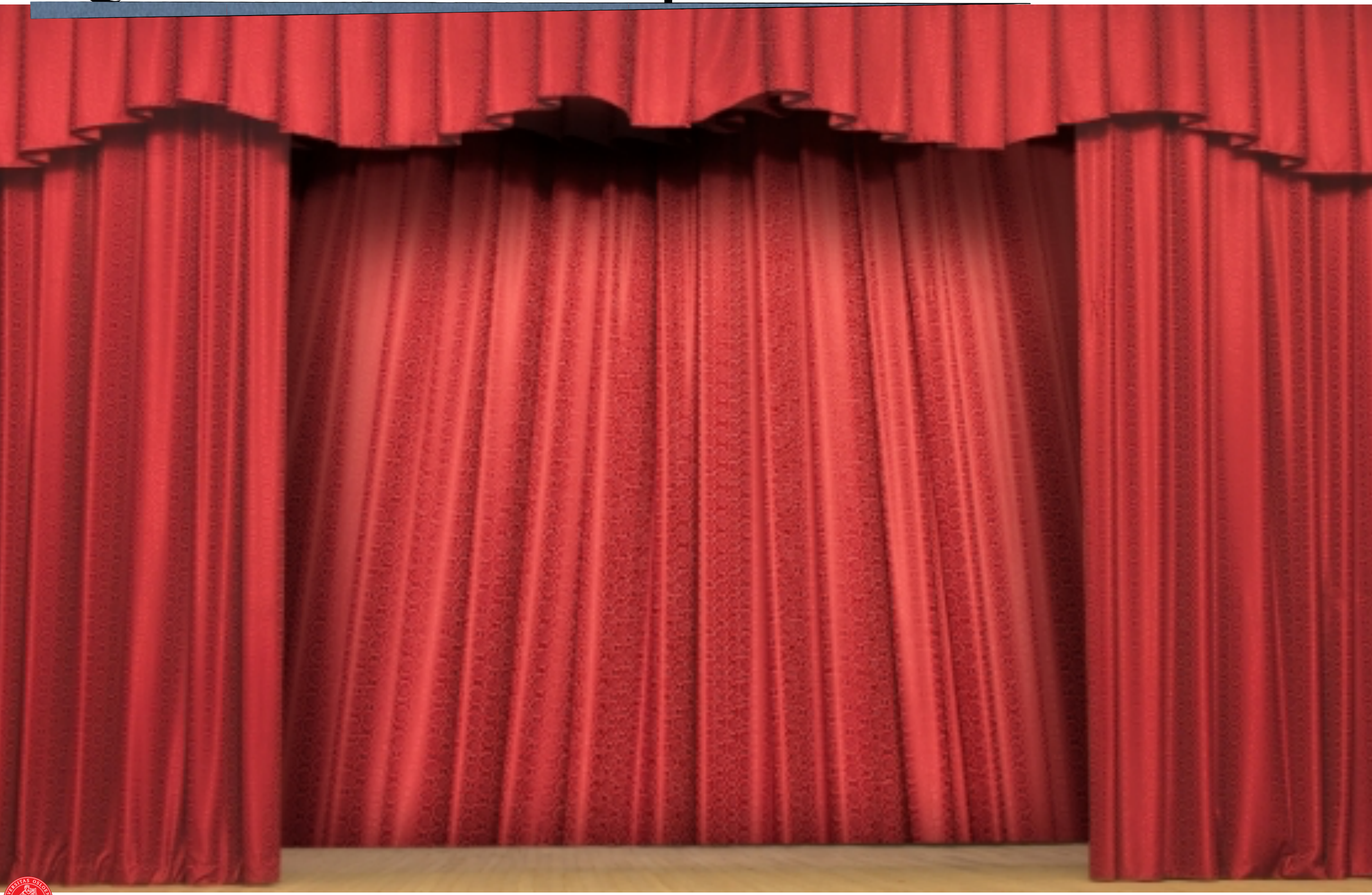
- Phenomenologically important: characteristic velocity dependence

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

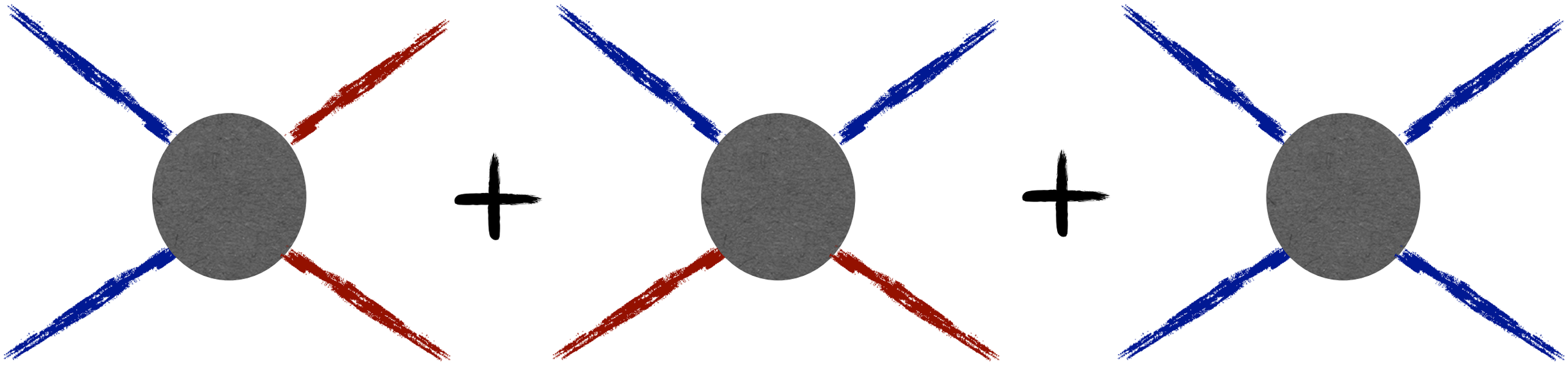


Loeb & Weiner, PRL '11

Questions about part II ?

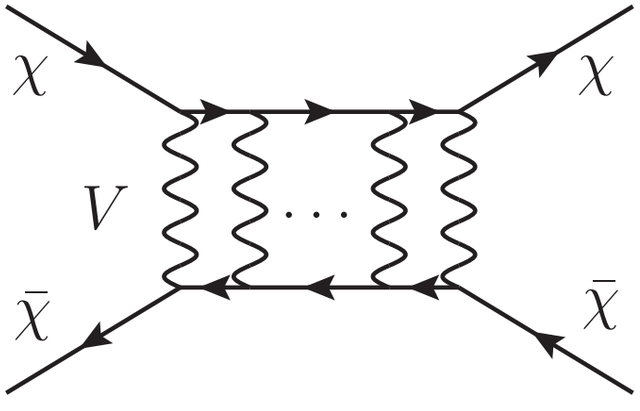


Part III



Towards a consistent framework

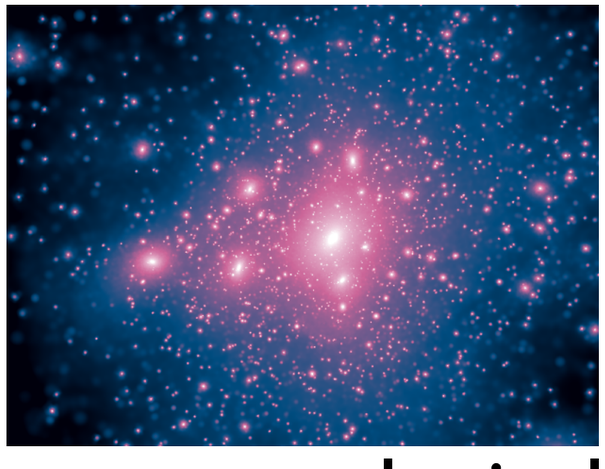
An Effective Theory Of Structure Formation



particle model

input:
masses, spins, coupling constants

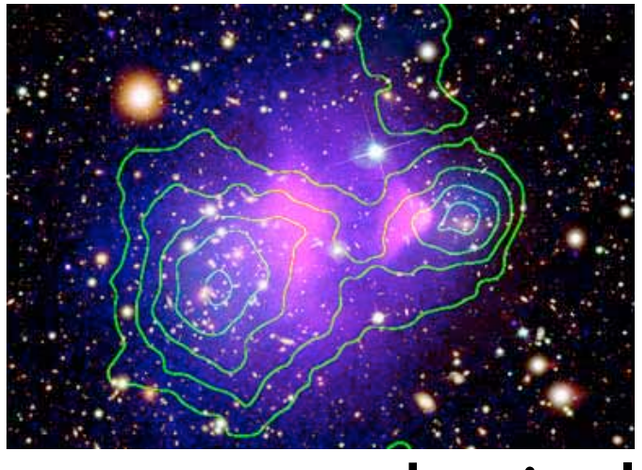
task 1



cosmological simulations

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

task 2



astrophysical observables

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 (⇝ no need to re-compute each model!)

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

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
  - isotropic scattering of macroscopic 'particles' with mass m_i

Vogelsberger, Zavala & Loeb, MNRAS '12

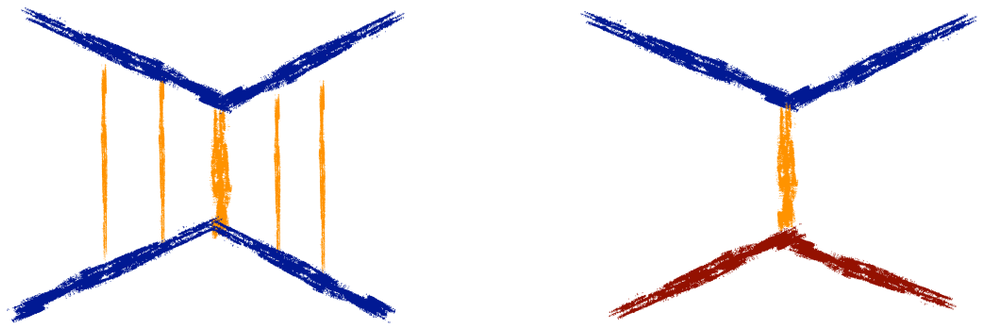
$$P_{ij} = \frac{m_i}{m_\chi} W(r_{ij}, h_i)\, \sigma_{\rm T}(v_{ij}) v_{ij}\, \Delta t_i$$

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



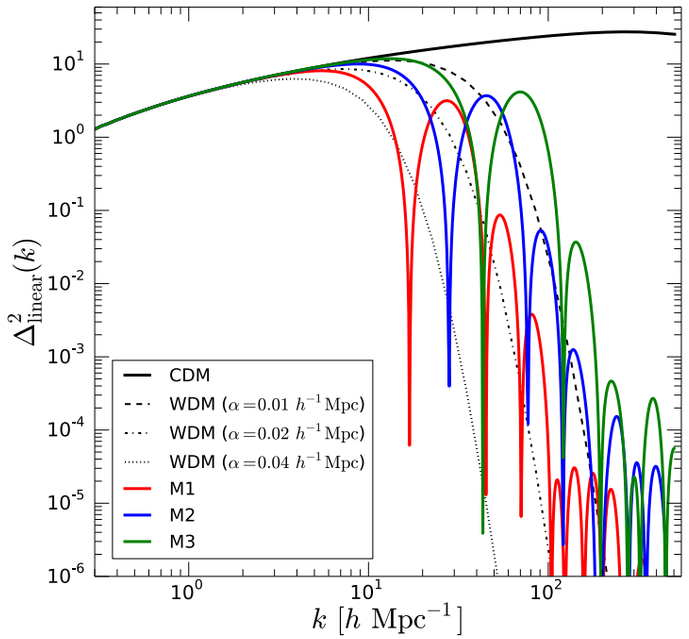
$$\{m_\chi, m_\phi, g_\chi, g_\nu, \eta_\chi, \eta_\nu, \xi\}$$

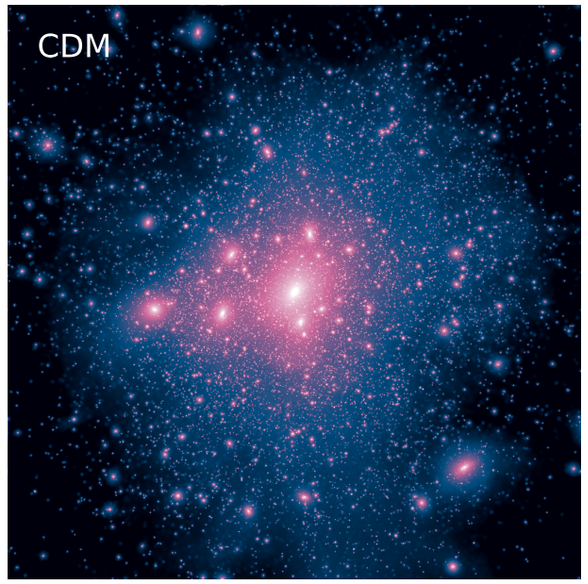
task 1

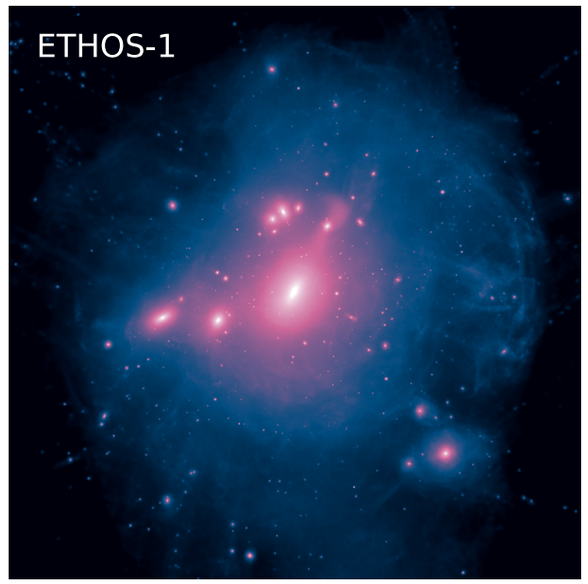
$$\left\{\omega_{\rm DR}, a_4, \alpha_{l\geq 2} = \frac{3}{2}, \frac{\langle\sigma_T\rangle_{30}}{m_\chi}, \frac{\langle\sigma_T\rangle_{220}}{m_\chi}, \frac{\langle\sigma_T\rangle_{1000}}{m_\chi}\right\}$$

Late kinetic decoupling

- Select four benchmarks: Vogelsberger+, MNRAS'16







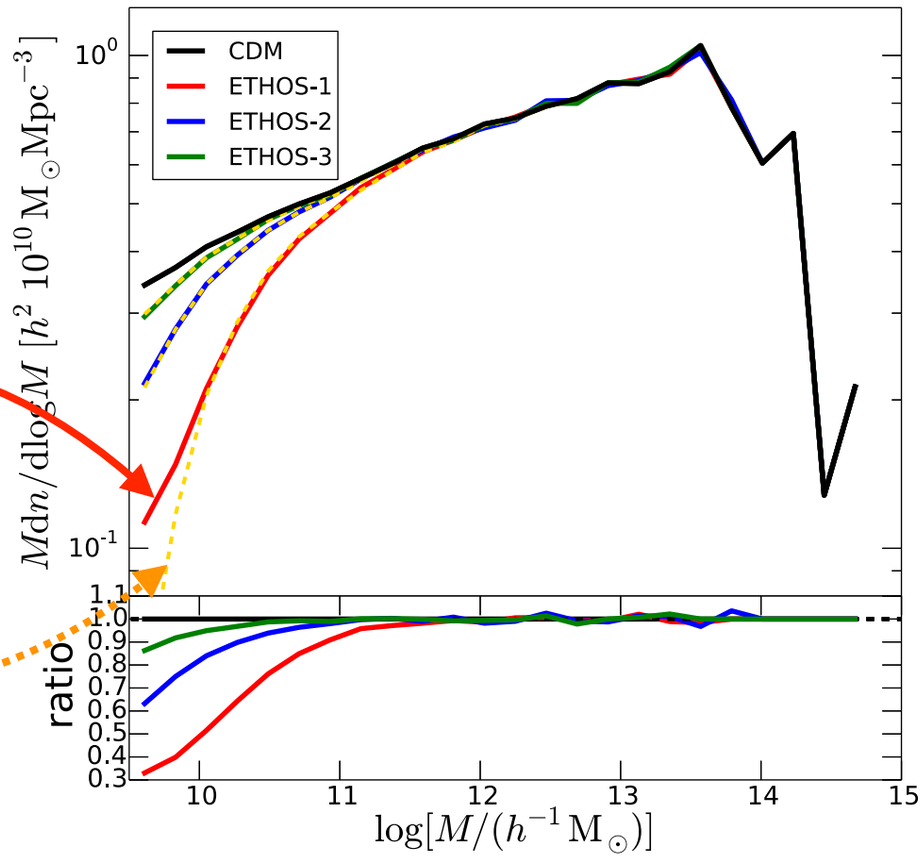
- Almost identical suppression of halo mass function as for WDM cosmology:

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

[solid lines: CDM with late kinetic decoupling**]**

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

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

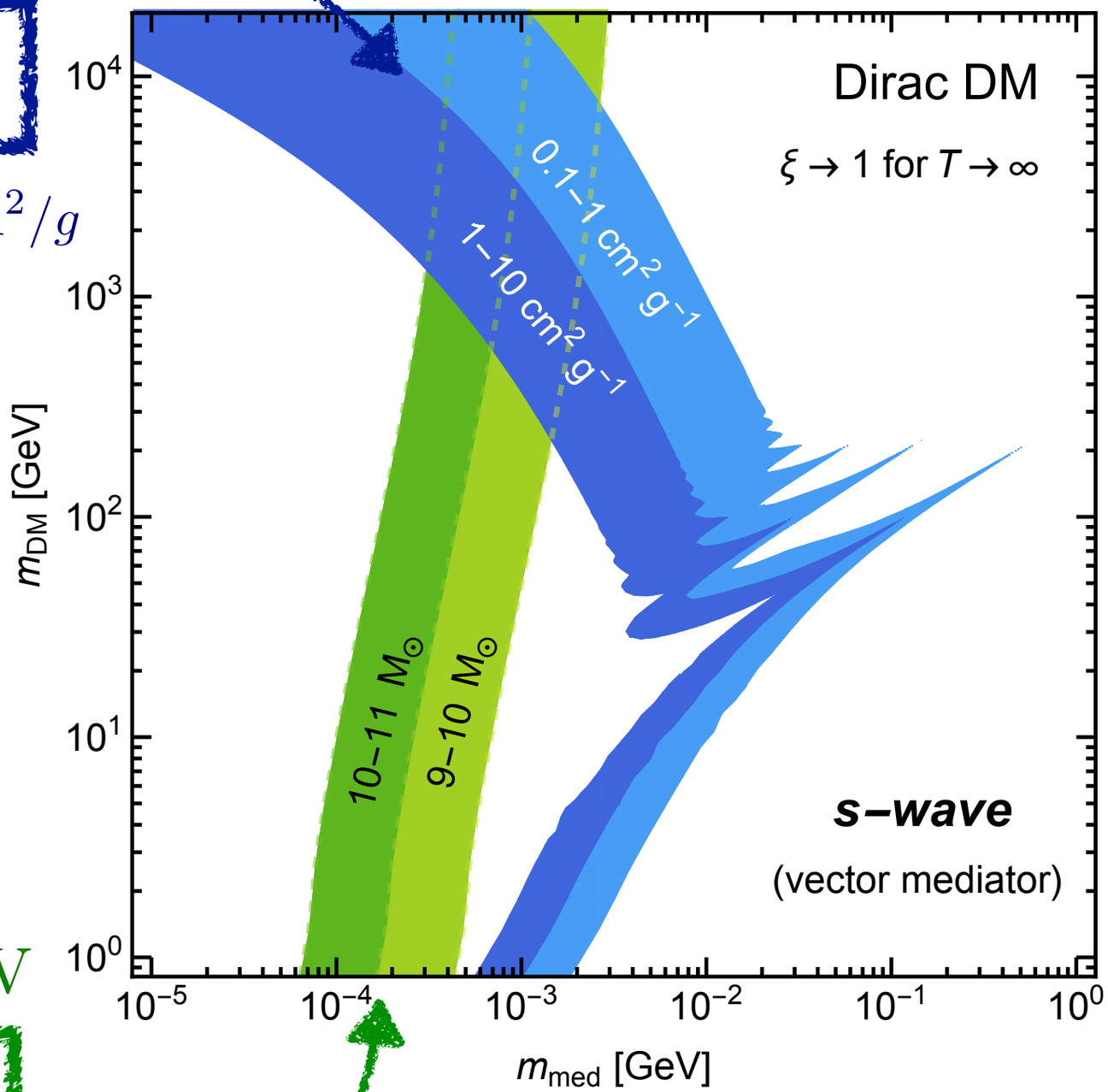


Full parameter scan

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 ?

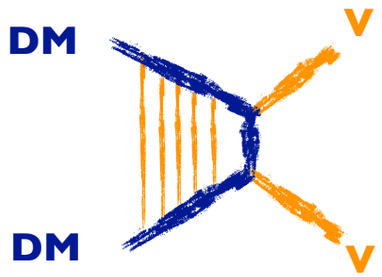




- NEW since v6.1:
  - SIDM
  - Sommerfeld
  - handle varying

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

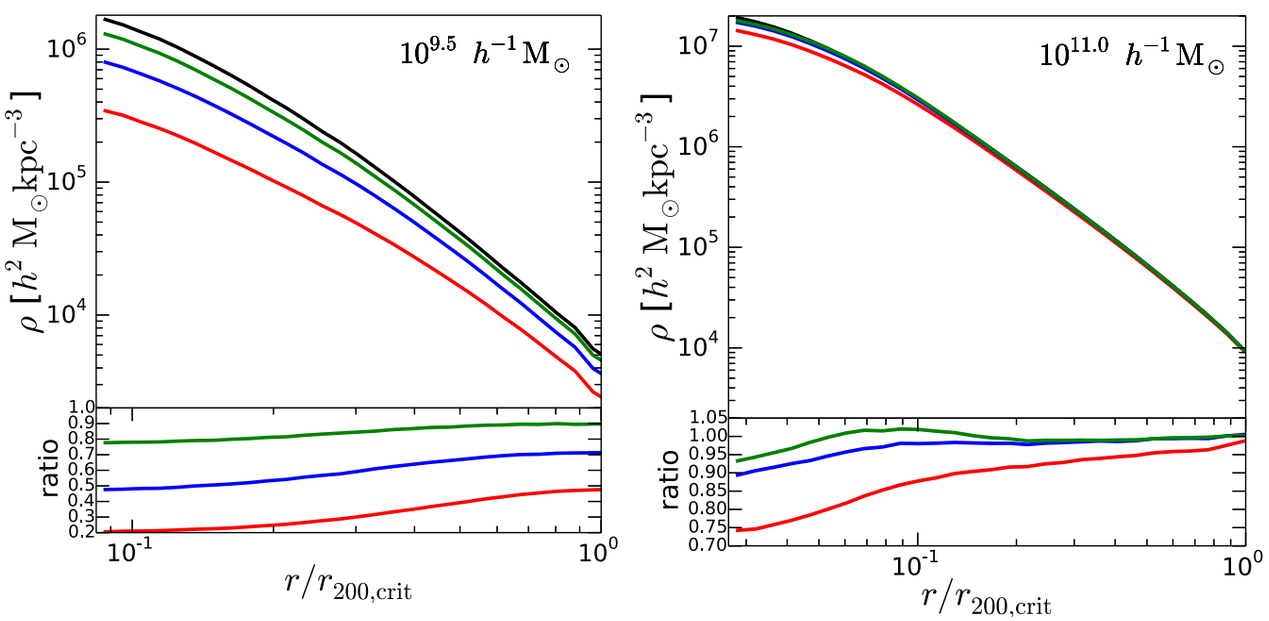
coupling fixed by thermal relic density



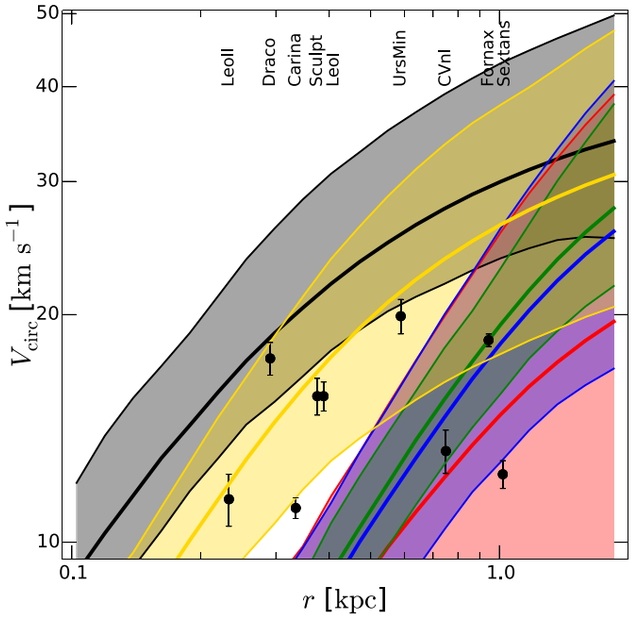
Inner halo structure

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' !*

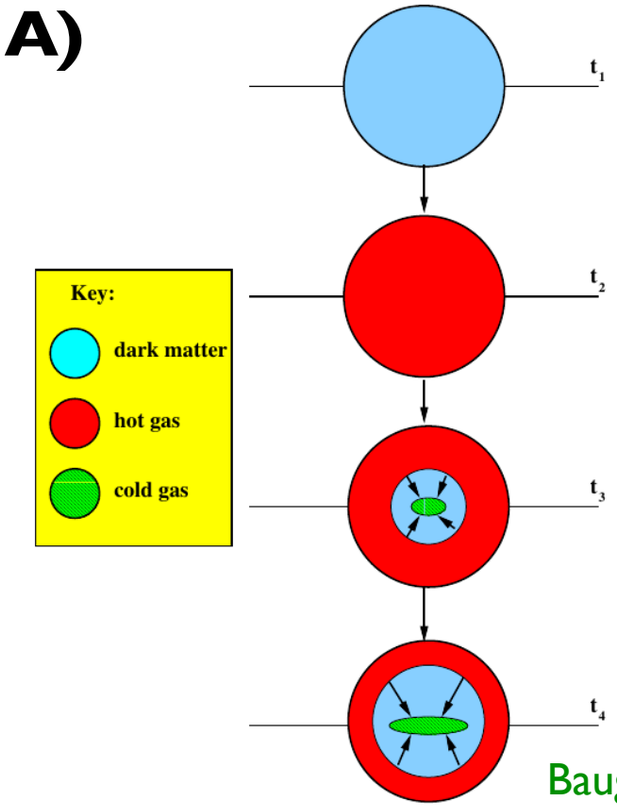
- Also, this is still without baryonic physics…

  [though dSphs highly DM dominated]

Adding Baryons

- Simplest picture: two competing effects

A)

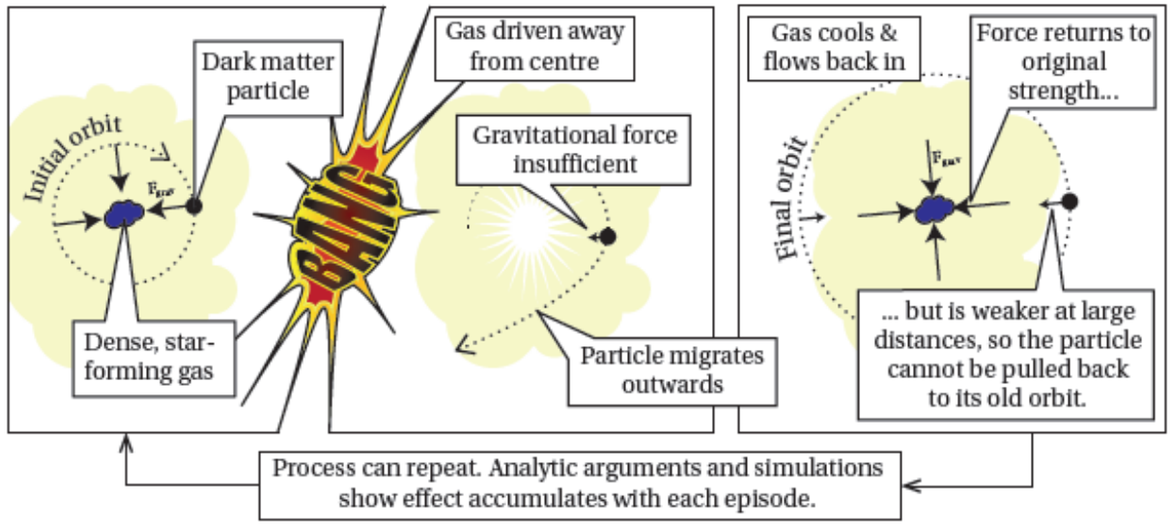


Baugh, RPP '06

Adiabatic contraction due to disk assembly

↑ *increase of inner DM density*

B)



Pontzen & Governato, Nature '14

gas and DM heating due to supernova feedback

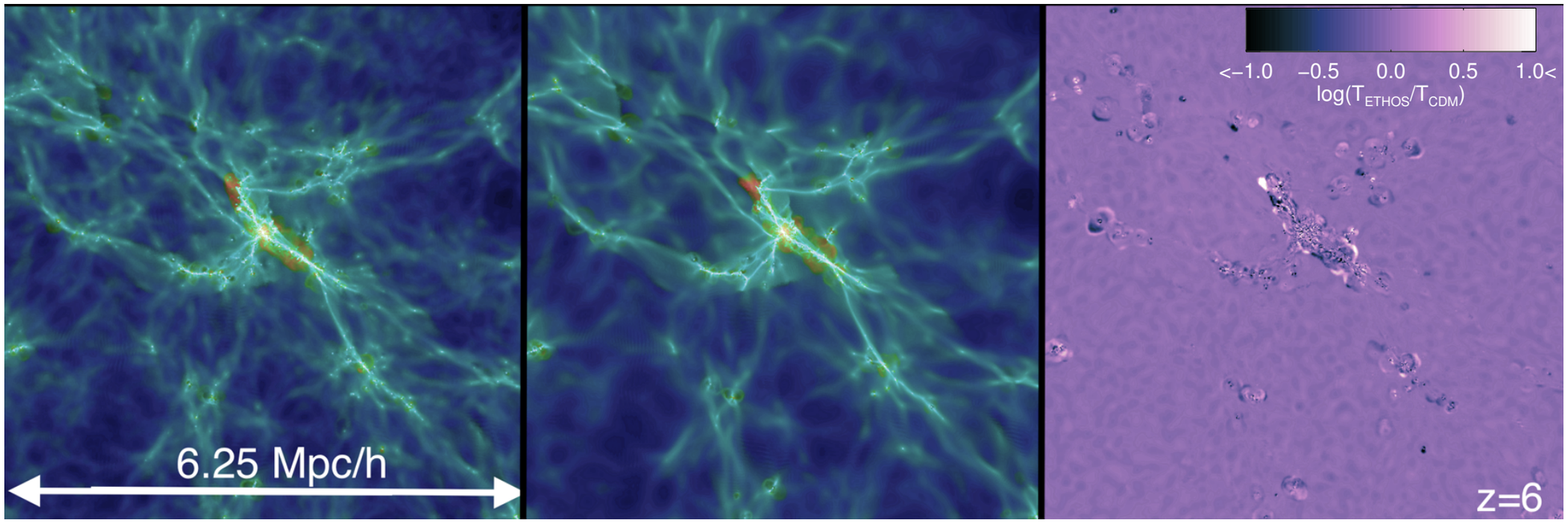
↓ *decrease of inner DM density*

- 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

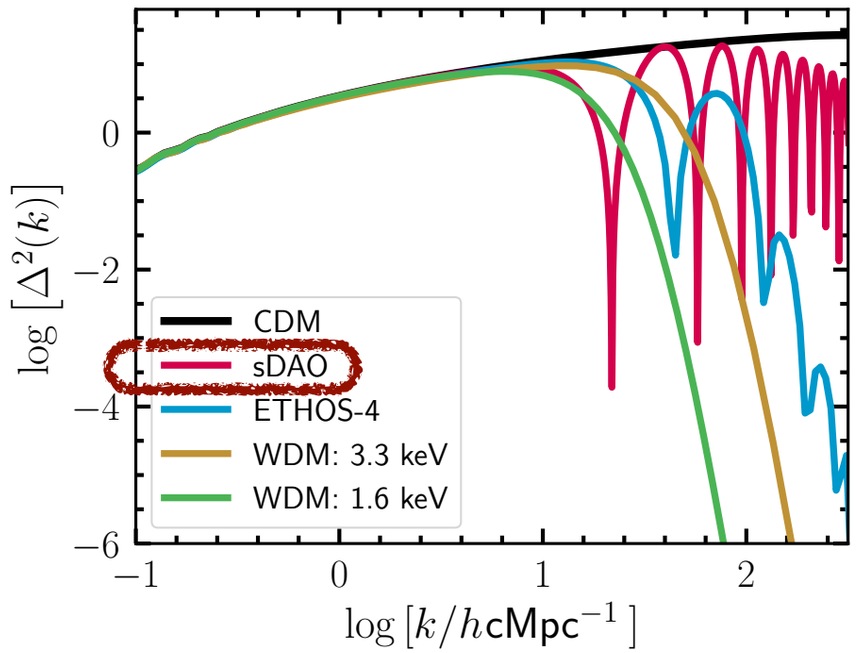
Imprint on Lyman alpha spectra ?

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

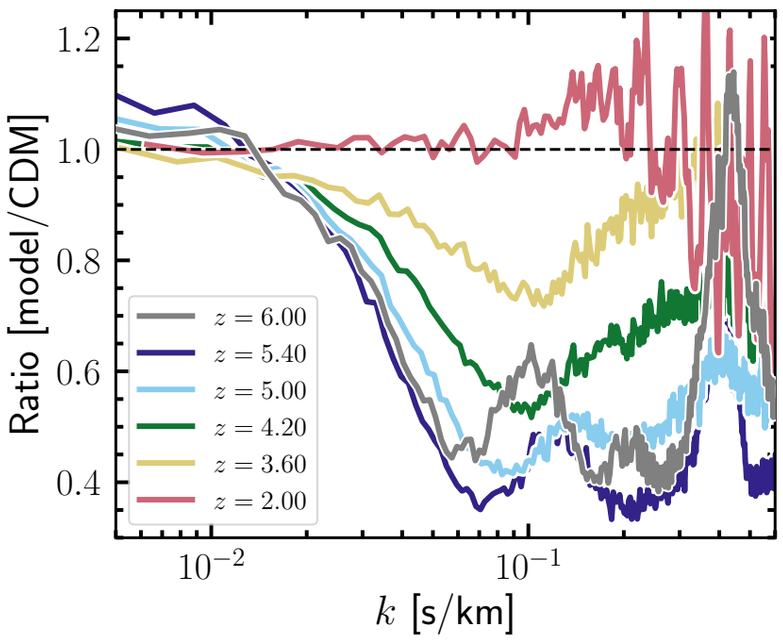
    Kaplan+, JCAP '10
    Cyr-Racine & Sigurdson, PRD '13
  - galaxy formation model as in IllustrisTNG

    Marinacci+, MNRAS '18; …

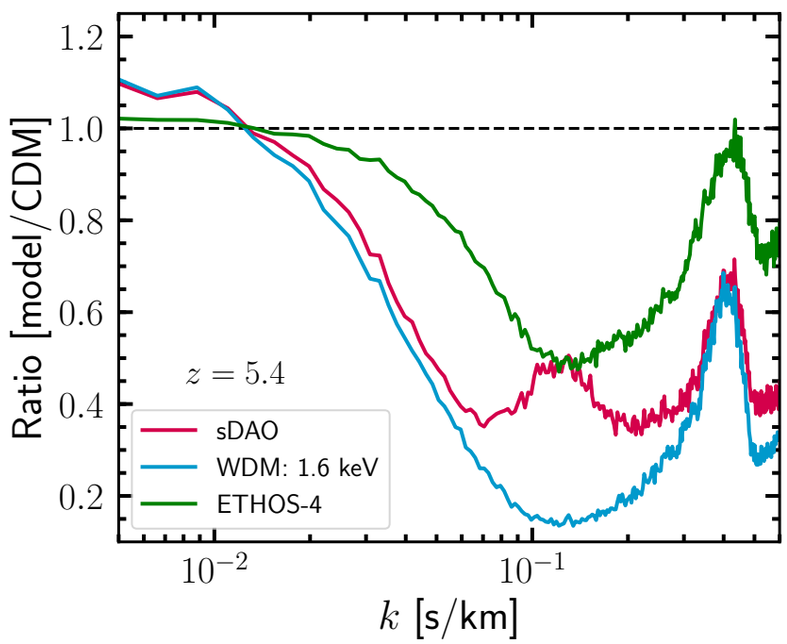
Bose+, MNRAS '19



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



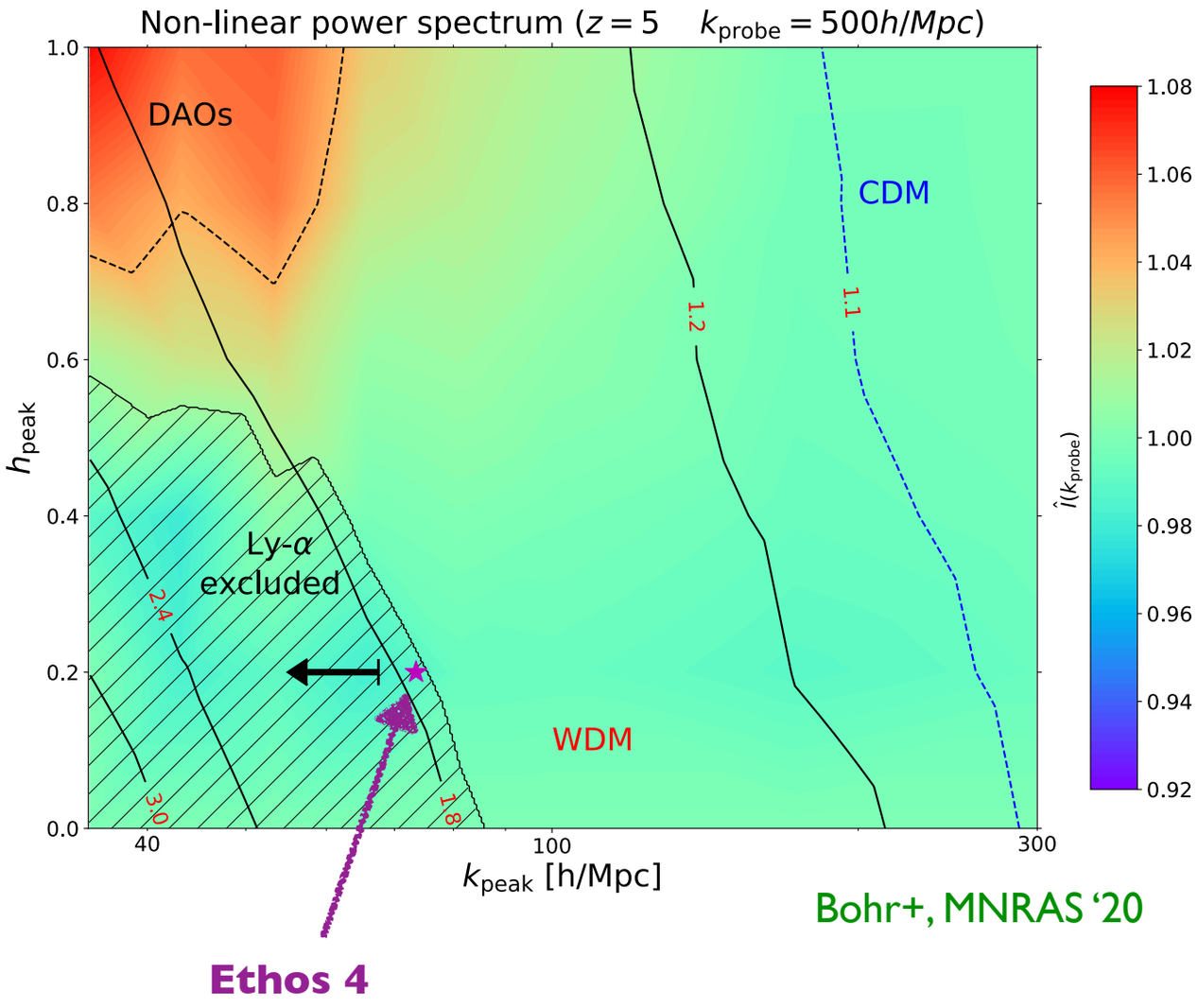
NB: bump at ~0.4 s/km set by numerical resolution!

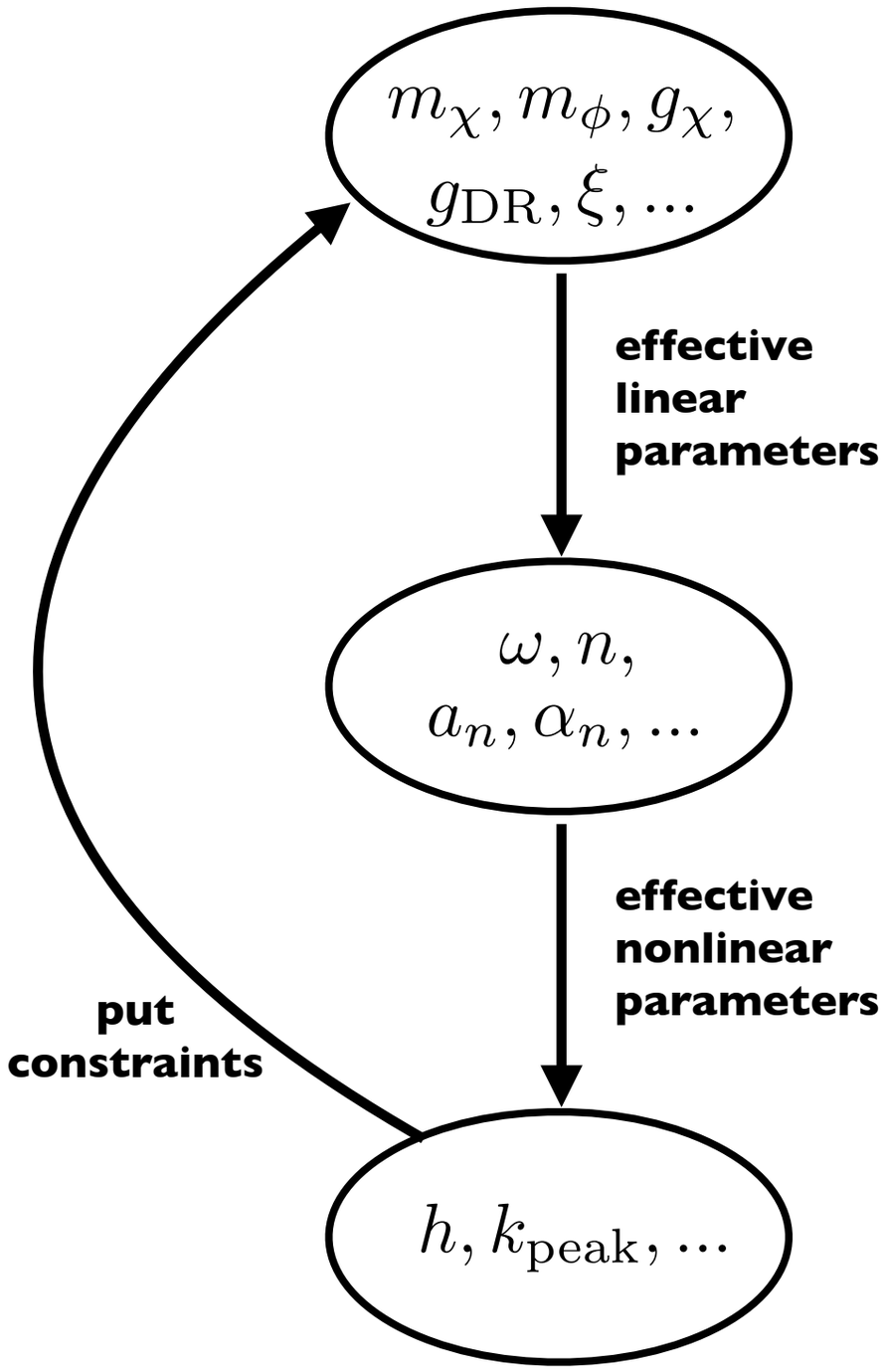


➡ *In principle, this allows to disentangle WDM from sDAO!*

Outlook ?

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



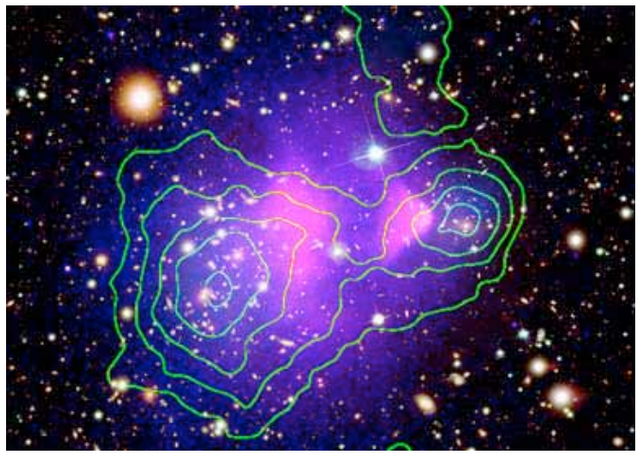


Conclusions

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

- DarkSUSY SECTOR is your friend:
  - relic density with self-consistent $T_{\rm dark}(T)$
  - kinetic decoupling
  - $\Delta N_{\rm eff}$
  - DM self-interactions with light mediators
  - ... incl. 'standard' DM observables

- Goal of ETHOS: provide a consistent framework to test new physics with structure formation

$\mathcal{L}_{\rm BSM}$ → **task 1** → ✓ →  → **task 2** → [✓] → 

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

first (promising) steps: *stay tuned !*

Thanks for your attention!

