Title: ETHOS: a framework for structure formation with non-gravitational dark matter interactions

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Abstract: <p>The standard structure formation model is based on the Cold Dark Matter (CDM) hypothesis where non-gravitational dark matter interactions are irrelevant for the formation and evolution of galaxies. Surprisingly, current observations allow for significant departures from the CDM hypothesis,</p>

<p>which could potentially leave signatures of the dark matter particle nature in the properties of galaxies. In this talk, I will describe a framework we have proposed that generalizes the theory of structure formation (in both the linear and non-linear regimes) to include new dark matter physics in order to explore galaxy formation and evolution in the broadest sense.</p>

ETHOS: a framework for structure formation with non-gravitational dark matter interactions

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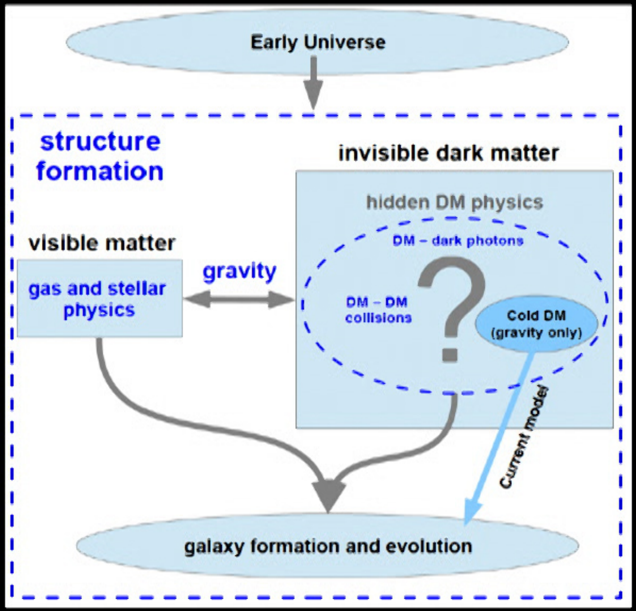
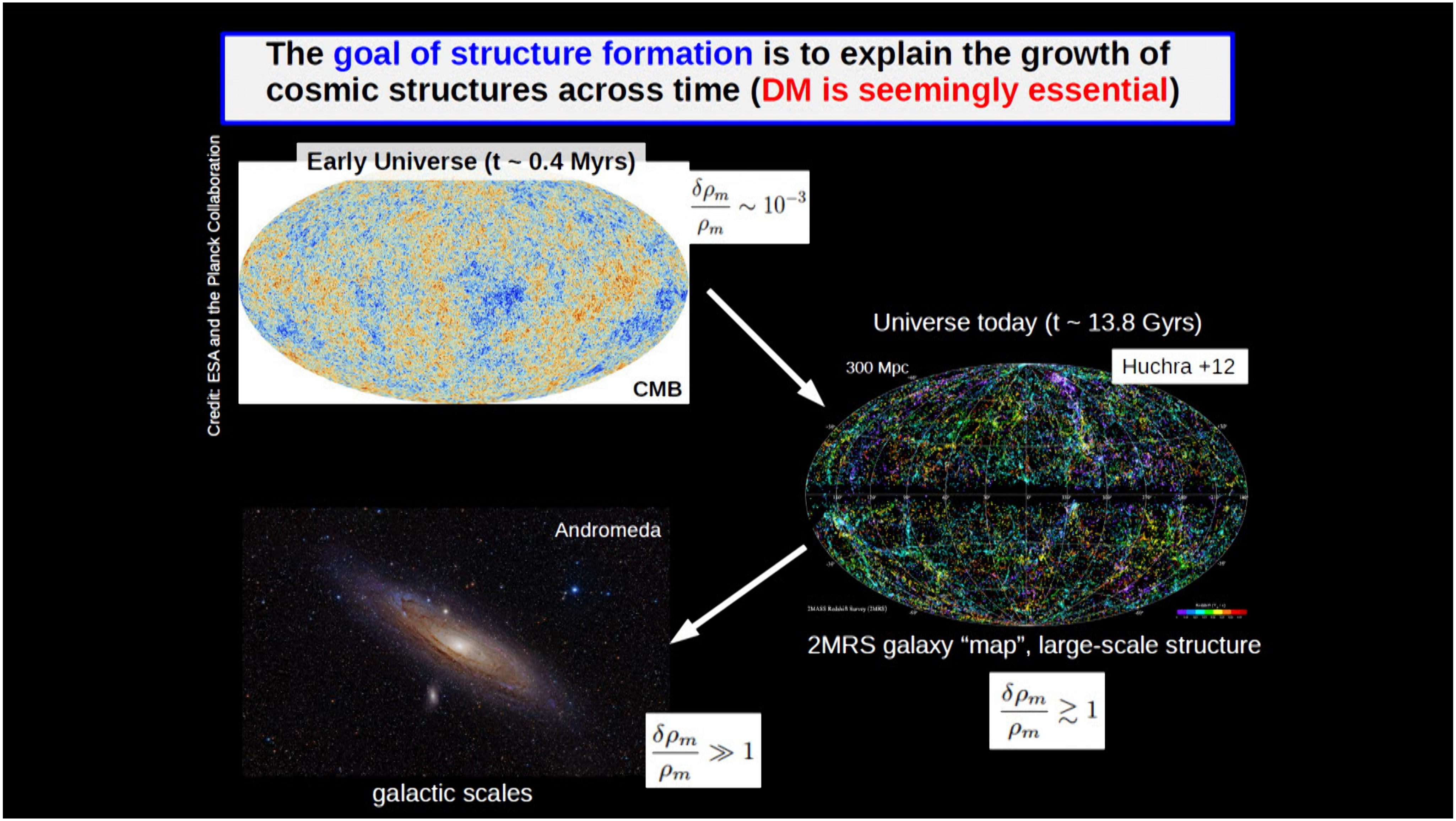
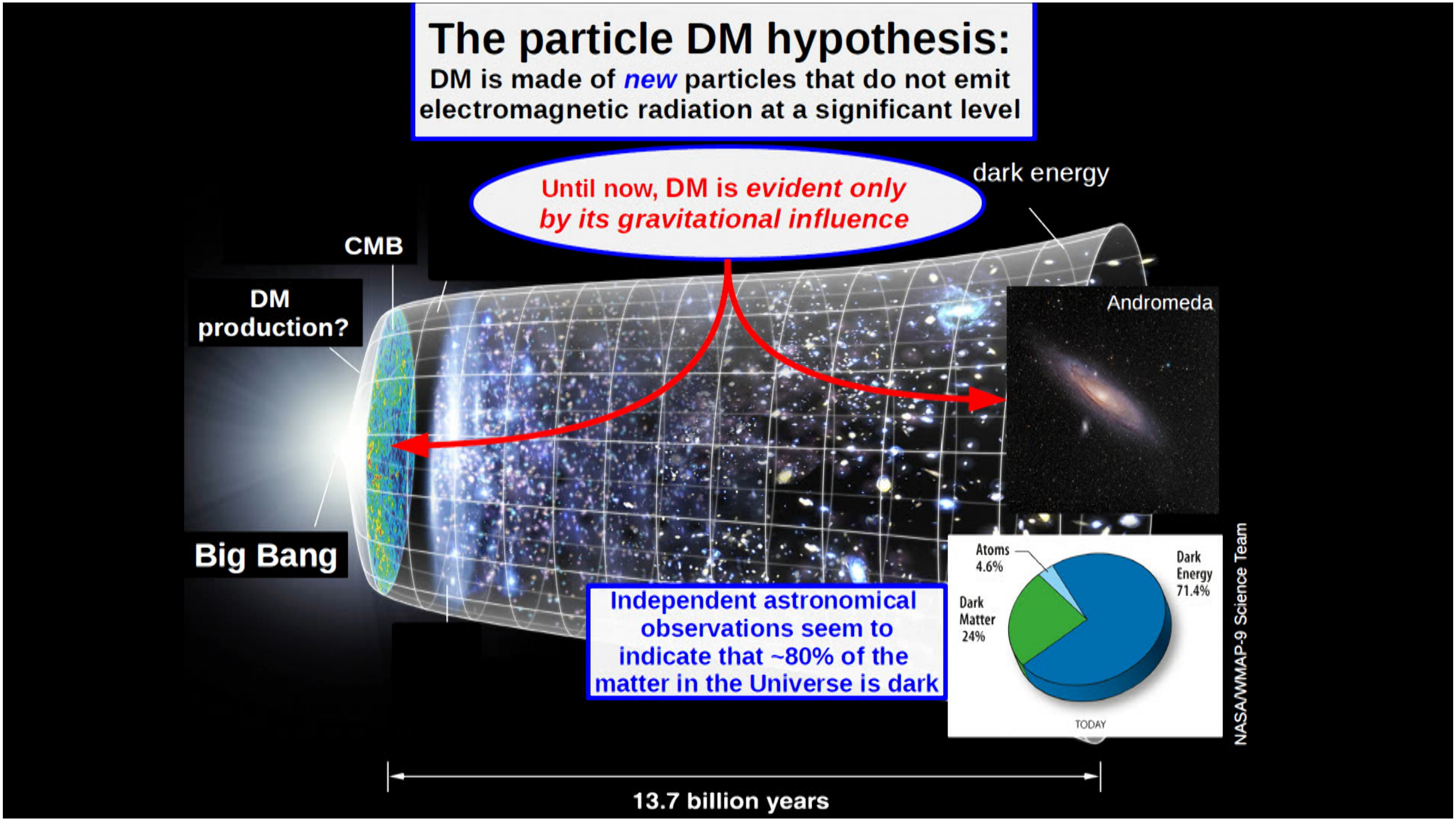
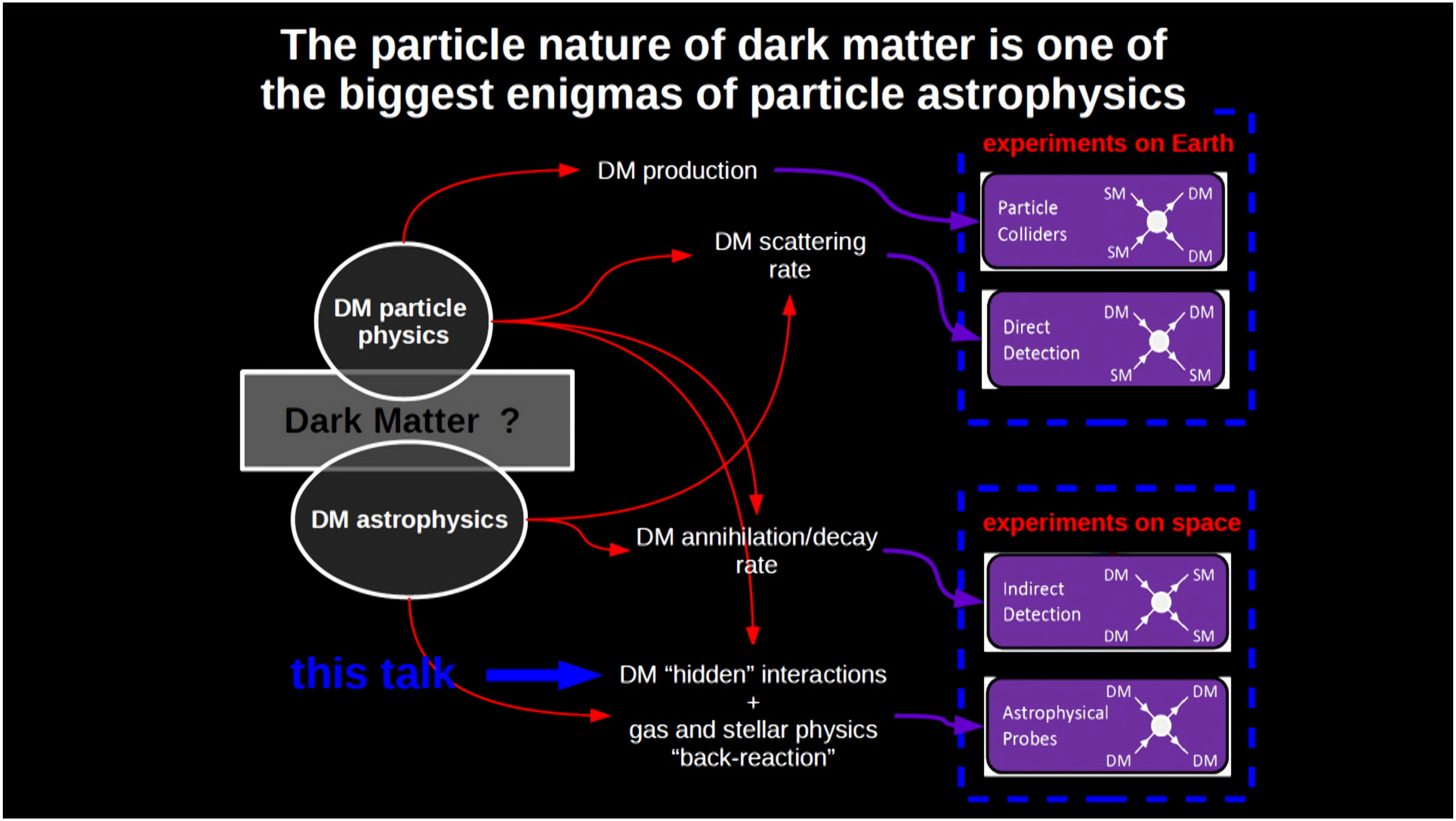


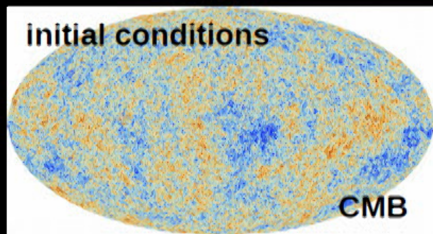
Cosmology & Gravitation Seminar, Perimeter Institute, January 2018


The goal of structure formation is to explain the growth of cosmic structures across time (DM is seemingly essential)
Credit: ESA and the Planck Collaboration
Early Universe (t ~ 0.4 Myrs)
$\frac{\delta\rho_m}{\rho_m} \sim 10^{-3}$
CMB
Universe today (t ~ 13.8 Gyrs)
300 Mpc
Huchra +12
2MRS galaxy "map", large-scale structure
$\frac{\delta\rho_m}{\rho_m} \gtrsim 1$
Andromeda
$\frac{\delta\rho_m}{\rho_m} \gg 1$
galactic scales


The particle DM hypothesis:
DM is made of *new* particles that do not emit electromagnetic radiation at a significant level
Until now, DM is *evident only by its gravitational influence*
dark energy
CMB
DM production?
Big Bang
Andromeda
Independent astronomical observations seem to indicate that ~80% of the matter in the Universe is dark
Atoms 4.6%
Dark Matter 24%
Dark Energy 71.4%
TODAY
NASA/WMAP-9 Science Team
13.7 billion years


The particle nature of dark matter is one of the biggest enigmas of particle astrophysics
experiments on Earth
DM production
DM scattering rate
DM particle physics
Dark Matter ?
DM astrophysics
Particle Colliders
SM
DM
SM
DM
Direct Detection
DM
DM
SM
SM
experiments on space
DM annihilation/decay rate
Indirect Detection
DM
SM
DM
SM
this talk
DM “hidden” interactions
+
gas and stellar physics “back-reaction”
Astrophysical Probes
DM
DM
DM
DM

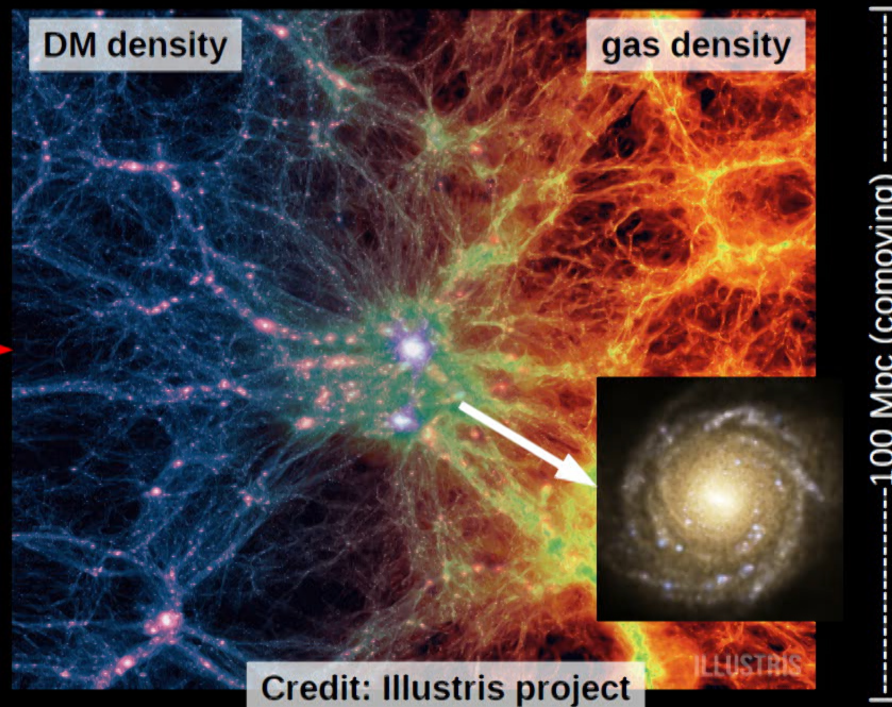
The Cold Dark Matter (CDM) hypothesis is the cornerstone of the current structure formation theory



CDM assumes that the only DM interaction that matters is gravity!!

cosmological simulations

DM gravity only
+
"baryonic" physics
(radiative cooling,
gas hydrodynamics,
star formation,
supernova and AGN
feedback,...)



2000 CPU years!!

Opening remarks

Structure formation theory has become powerful enough to predict the phase-space distribution of dark matter across time down to galactic scales.

- The Cold Dark Matter (CDM) hypothesis has been the standard for nearly three decades and implies that DM gravity is the only relevant interaction (for galactic scales and above). It implies that structure formation within CDM has no free DM parameters. However:

CDM/WDM/SIDM are incomplete DM theories

They are "effective" structure formation theories that need completion from a particle physics model (all beyond SM: "exotic")

despite the spectacular progress in developing a galaxy formation/evolution theory, it remains incomplete since we still don't know:

what is the nature of dark matter?

What is the mass(es) of the DM particle(s) and through which forces does it interact?

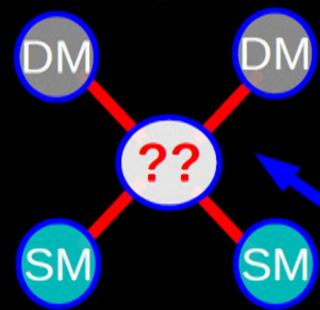
this talk → **In the physics of galaxies, is gravity the only dark matter interaction that matters?**

Although there is no indisputable evidence that the CDM hypothesis is wrong, there are reasonable physical motivations to consider alternatives

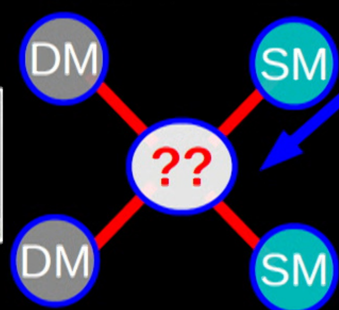
Possible but irrelevant interactions for structure formation

Does DM interacts with visible particles?

Scattering with nuclei



DM self-annihilation



Interactions with visible particles are too weak to impact galaxy formation/evolution

Cross section σ/m_χ [cm^2/gr]	Characteristic velocity $\tilde{v}$ [km/s]
SI $\chi-$nucleon $\lesssim 10^{-23}$	~ 200
$m_\chi \in (0.1-5)$ TeV	(local halo)
LUX	
$\chi\chi \to b\bar{b}$ $\lesssim 10^{-10}$	~ 10
$m_\chi \in (0.1-1)$ TeV	(dSphs)
Fermi-LAT	

circa 2015-16

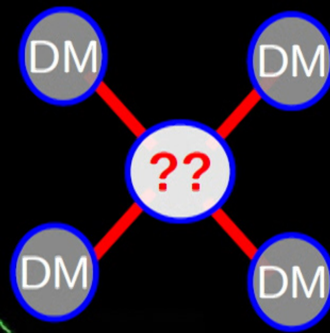
1 cm^2/g ~ 2 barns/GeV

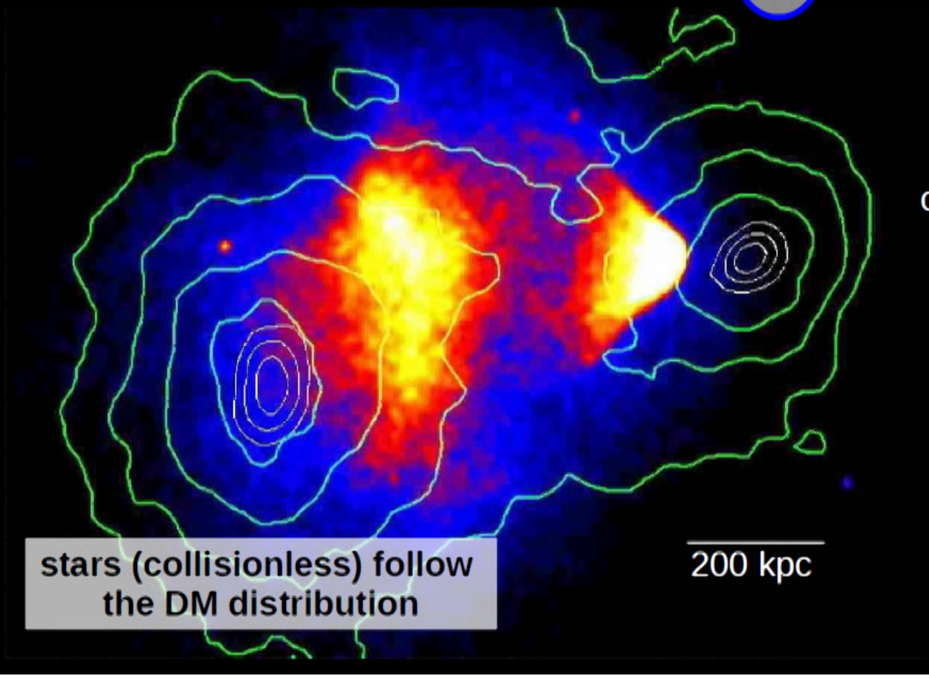
dark matter is quite "dark" (invisible)

nucleon-nucleon elastic scattering: ~10 cm^2/gr

What types of DM interactions could impact structure formation?

Can DM particles collide with themselves?





Bullet Cluster (Clowe +06)

constraint on DM self-collisions

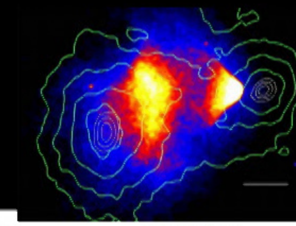
$$\sigma / m \lesssim 2\, cm^2 / gr$$

Robertson+2016

nucleon-nucleon elastic scattering: ~10 cm^2/gr

Could DM particles collide with themselves?

constraints allow collisional DM that is astrophysically significant in the center of galaxies

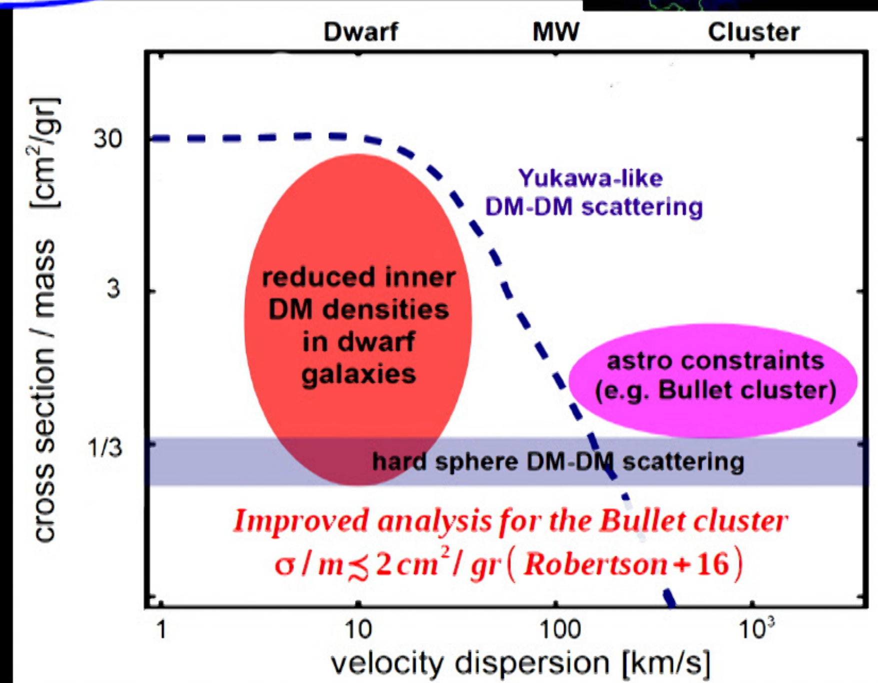


average scattering rate per particle:

$$\frac{\overline{R}_{sc}}{\Delta t} = \left(\frac{\sigma_{\rm sc}}{m_\chi}\right) \overline{\rho}_{\rm dm}\ \overline{v}_{\rm typ}$$

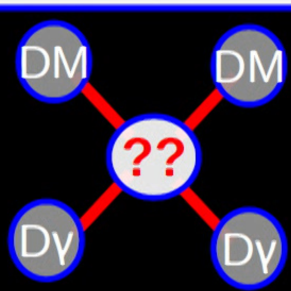
~ 1 scatter / particle / Hubble time

Neither a fluid nor a collisionless system:
~ rarefied gas
(Knudsen number = λ_{mean}/L >~ 1)



DM interactions that impact structure formation?

Can DM particles interact with other "dark" particles?

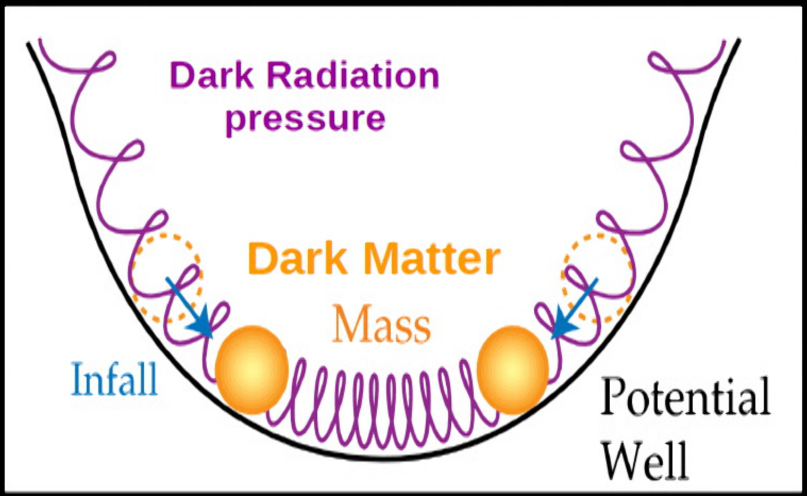


"dark photons"

Allowed interactions between DM and relativistic particles (e.g. "dark radiation") in the early Universe introduce pressure effects that impact the growth of DM structures (phenomena analogous to that of the photon-baryon plasma)

e.g. Boehm+02, Buckley+14

Dark Acoustic Oscillations



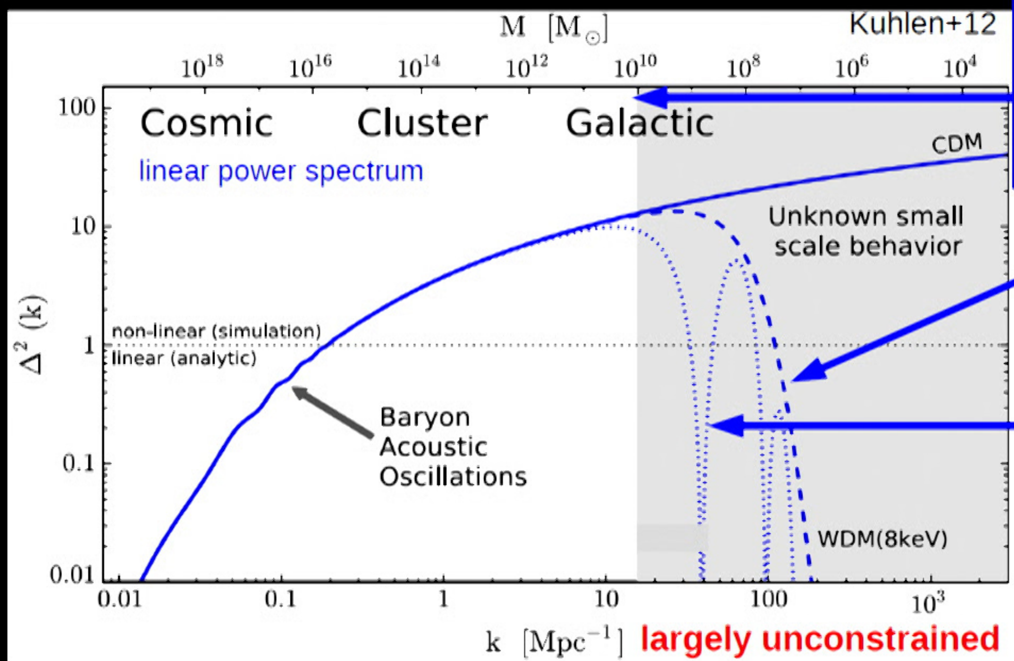
Credit: Wayne Hu (U. Of Chicago)

DM interactions that impact structure formation?

can new DM physics induce a galactic-scale primordial power spectrum cut-off?

Observations have yet to measure the clustering of dark matter at the scale of the smallest galaxies

Dwarf galaxies



DM is relativistic at earlier times 'thermal' cut-off (WDM free-streaming)

DM interacts with relativistic particles at earlier times: DM-DR DAOs and Silk (collisional) damping

An opportunity

- Galaxies remain the best “dark matter detectors” we have
- Looking in detail at the properties of the galaxy population across time might give us a hint about the particle nature of dark matter
- Given the current situation (obs. constraints, complexity of baryonic physics), it is timely to consider additional free DM parameters, which might play a key role in the physics of galaxies. The window is relatively narrow and within reach of upcoming observations:

SIDM transfer cross section

$$0.1\,cm^2/gr \lesssim \sigma/m \lesssim 2\,cm^2/gr$$

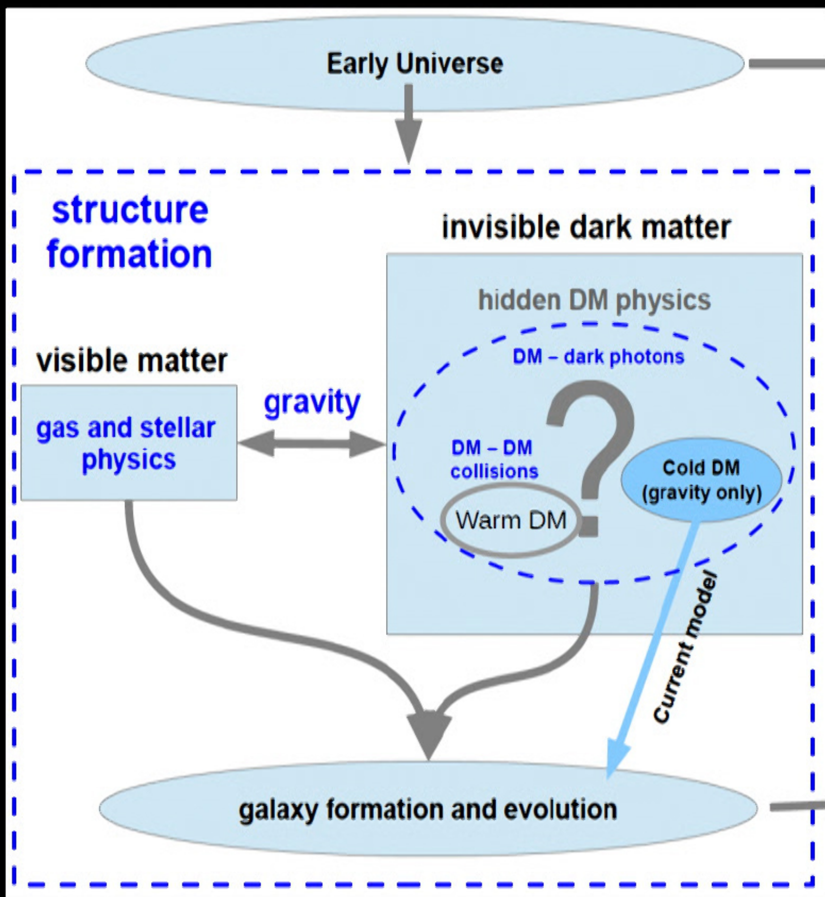
- below this value, the behaviour is the same as CDM
- above this value constraints are strong (at cluster scales)

‘cutoff’ halo mass at z=0

$$10^{9.5}\,M_{Sun} \lesssim M_{cut} \lesssim 10^{10.5}\,M_{Sun}$$

- below this value galaxy formation Is highly supressed (reionisation)
- above this value DM clustering must be as in CDM

Towards an Effective THeory Of Structure formation (ETHOS)



DM production mechanism (verify consistency with global DM abundance)

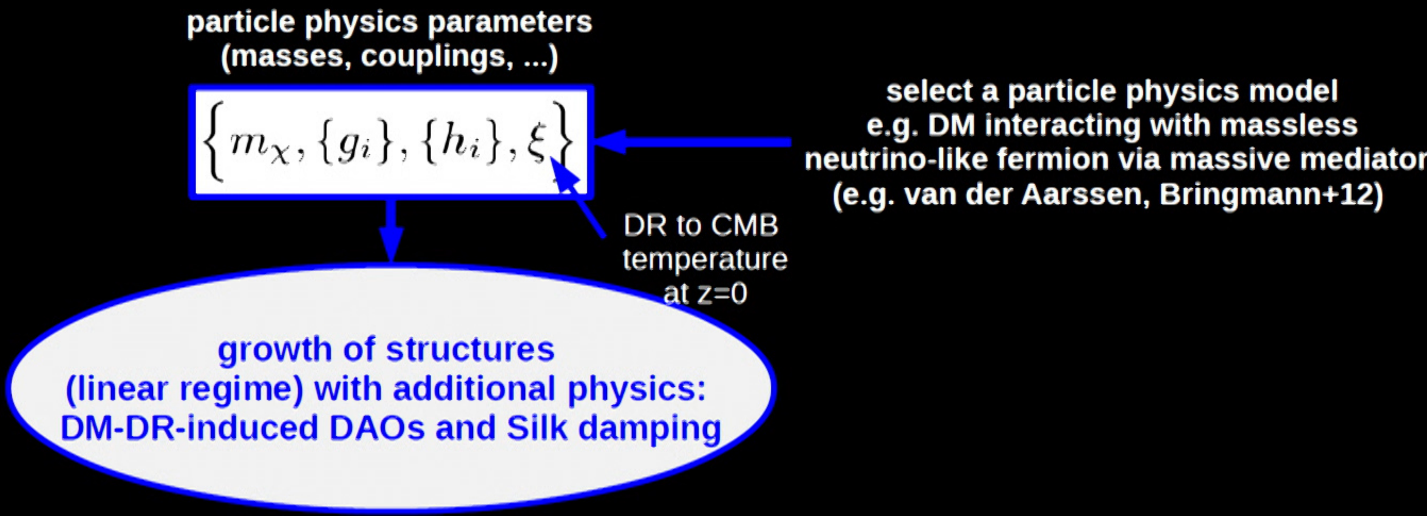
Generalize the theory of structure formation (CDM) to include **a broader range of allowed DM phenomenology** coupled with our knowledge of galaxy formation/evolution

Signatures of non-gravitational DM interactions (dynamical, visible byproducts)

Ingredients

- DM-DR impact the linear regime
- DM-DM interactions impact the non-linear regime
- "effective" parameters for structure formation

ETHOS: classify DM models according to their effective parameters for structure formation



ETHOS: the linear regime

coupled collisional Boltzmann eqs.

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

in the linear regime: $\delta_\chi(x,t) \ll 1$

↓

cosmological perturbation theory

eqs. for DM perturbations in Fourier space

$$\dot{\delta}_\chi + \theta_\chi - 3\dot{\phi} = 0,$$

$$\dot{\theta}_\chi - c_\chi^2 k^2 \delta_\chi + \mathcal{H}\theta_\chi - k^2\psi = \dot{\kappa}_\chi[\theta_\chi - \theta_{\rm DR}]$$

related to DR opacity to DM scattering
(collisional term of the Boltzmann eq.)

$$C_{\chi\tilde{\gamma}\leftrightarrow\chi\tilde{\gamma}}[f_\chi, f_{\rm DR}]$$

ETHOS: the linear regime

coupled collisional Boltzmann eqs.

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

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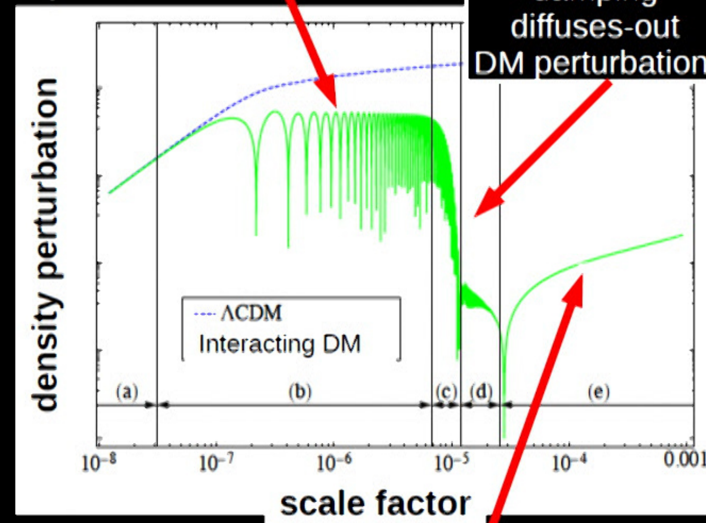
related to DR opacity to DM scattering (collisional term of the Boltzmann eq.)

$$C_{\chi\tilde{\gamma}\leftrightarrow\chi\tilde{\gamma}}[f_\chi, f_{\rm DR}]$$

DR pressure counteracts gravity creating "dark acoustic oscillations"

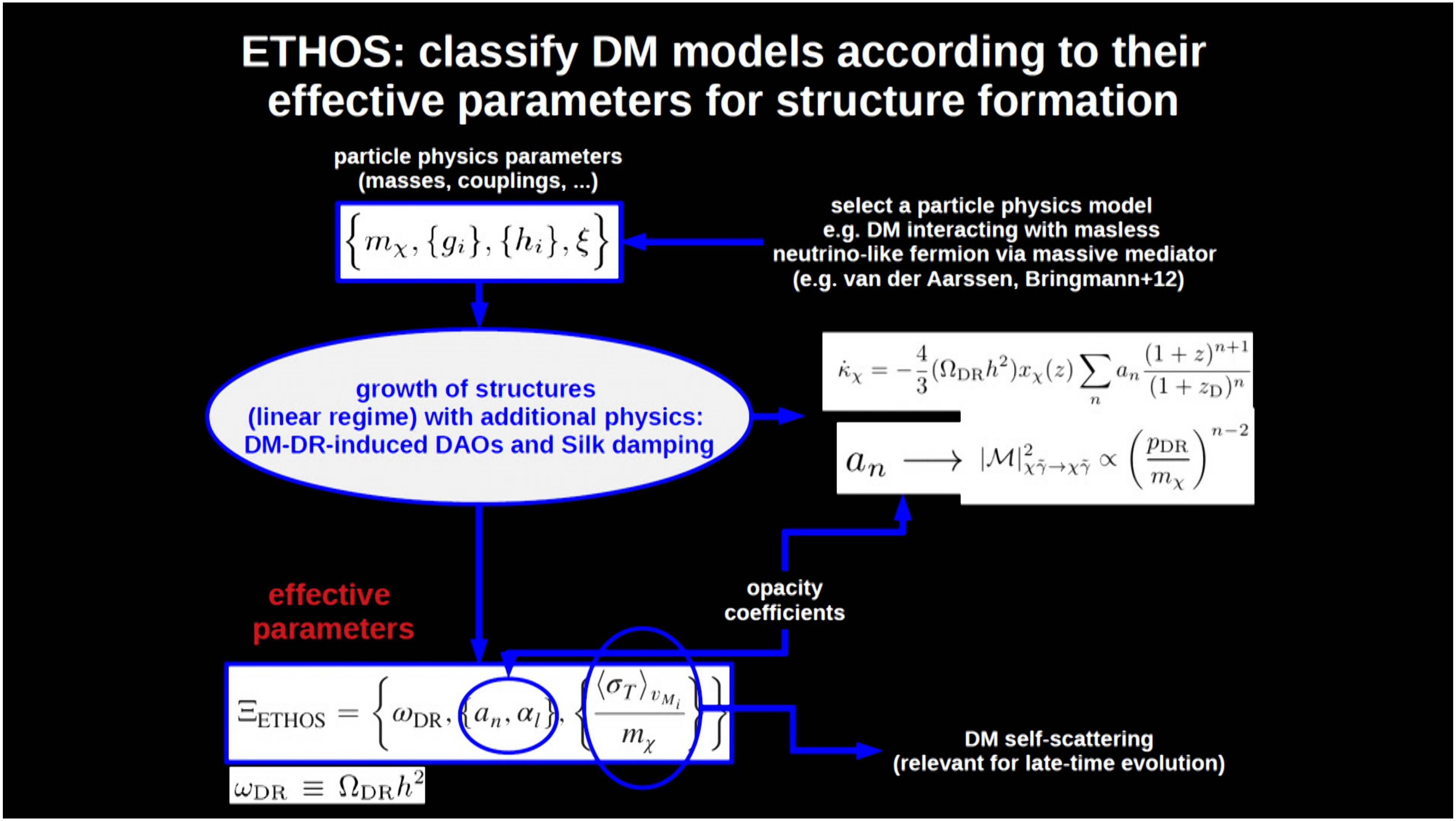
Cyr-Racine+13



collisional (Silk) damping diffuses-out DM perturbations

once kinetic decoupling (DM-DR) occurs DM behaviour is like CDM

analogous to the photon-electron-baryon plasma case


ETHOS: classify DM models according to their effective parameters for structure formation
particle physics parameters (masses, couplings, ...)
$\left\{m_\chi, \{g_i\}, \{h_i\}, \xi\right\}$
select a particle physics model
e.g. DM interacting with masless
neutrino-like fermion via massive mediator
(e.g. van der Aarssen, Bringmann+12)
growth of structures
(linear regime) with additional physics:
DM-DR-induced DAOs and Silk damping
$\dot{\kappa}_\chi = -\frac{4}{3}(\Omega_{\rm DR}h^2)x_\chi(z)\sum_n a_n \frac{(1+z)^{n+1}}{(1+z_{\rm D})^n}$
$a_n \longrightarrow |\mathcal{M}|^2_{\chi\tilde{\gamma}\to\chi\tilde{\gamma}} \propto \left(\frac{p_{\rm DR}}{m_\chi}\right)^{n-2}$
opacity
coefficients
effective
parameters
$\Xi_{\rm ETHOS} = \left\{\omega_{\rm DR}, \{a_n, \alpha_l\}, \left\{\frac{\langle\sigma_T\rangle_{v_{M_i}}}{m_\chi}\right\}\right\}$
$\omega_{\rm DR} \equiv \Omega_{\rm DR}h^2$
DM self-scattering
(relevant for late-time evolution)

ETHOS: classify DM models according to their effective parameters for structure formation

particle physics parameters
(masses, couplings, ...)

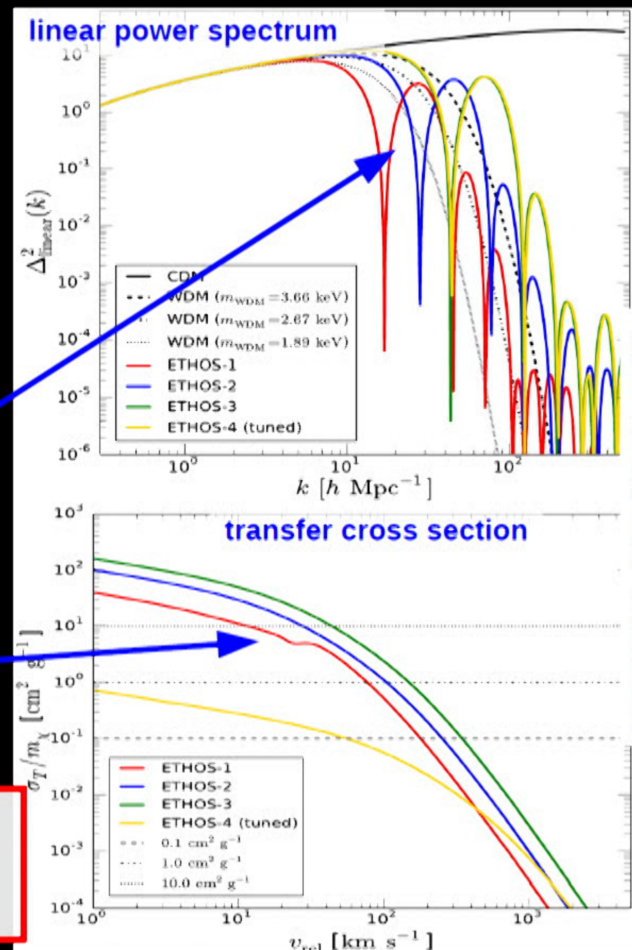
$$\left\{m_\chi, \{g_i\}, \{h_i\}, \xi\right\}$$

growth of structures
(linear regime) with additional physics:
DM-DR-induced DAOs and Silk damping

effective parameters

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

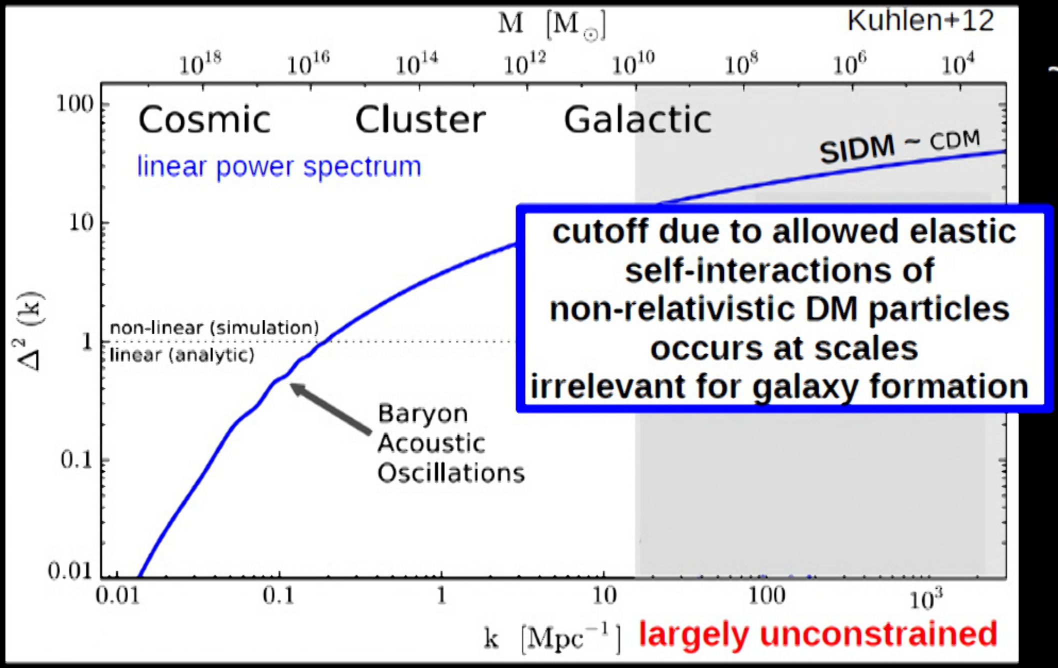
All DM particle physics models that map into the same ETHOS parameters can be studied (constrained) at the same time



ETHOS I: Cyr-Racine+16

ETHOS: the linear regime

Impact of DM self-interactions in the linear regime?



~ 1 scatter / particle / t_{age}

(scatt. rate ~ exp. rate)

self-decoupling temp. and Jeans mass

e.g. $M_J \sim 10^{-11} M_{Sun}$

$\sigma / m \sim 0.1\, cm^2 / gr$

$m \sim 100\, GeV$

ETHOS: the non-linear regime

If $\delta(x,t) \ll 1$ *perturbation theory*

If $\delta(x,t) \gtrsim 1$

- DM-DR interactions no longer relevant (kinetic decoupling)
- DM-DM interactions increasingly relevant
- perturbation theory breaks down!!

Far from the fluid and collisionless regimes (Knudsen number ~ 1) → **full Collisional Boltzmann equation**

$$|\vec{v}_{\rm rel}| = |\vec{v}_1 - \vec{v}| = |\vec{v'}_1 - \vec{v'}|$$

$$\frac{Df(\mathbf{x},\mathbf{v},t)}{Dt} = \Gamma[f,\sigma]$$

$$= \int d^3\mathbf{v}_1 \int d\Omega \frac{d\sigma}{d\Omega} |\mathbf{v}-\mathbf{v}_1| \left[f(\mathbf{x},\mathbf{v}',t) f(\mathbf{x},\mathbf{v}'_1,t) - f(\mathbf{x},\mathbf{v},t) f(\mathbf{x},\mathbf{v}_1,t) \right]$$

Rate of scattered particles into phase-space patch

Differential cross section

Rate of scattered particles out of phase-space patch

Discretization → N-body simulation

ETHOS: the non-linear regime

The coarse-grained distribution is given by a discrete representation of N particles:

macro-to-micro-particle mass ratio

each particle is smoothed in space to give a smooth local density

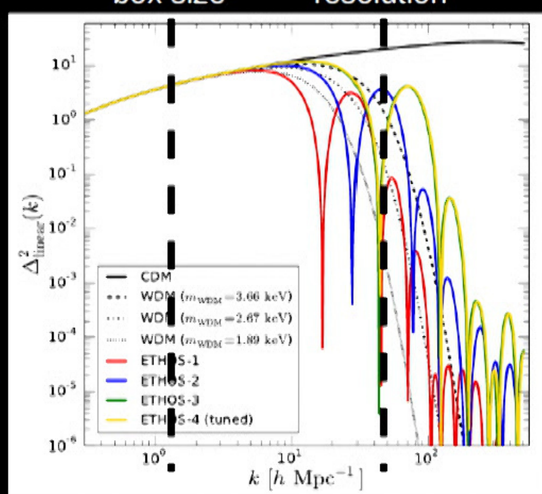
each macro-particle travels at one speed

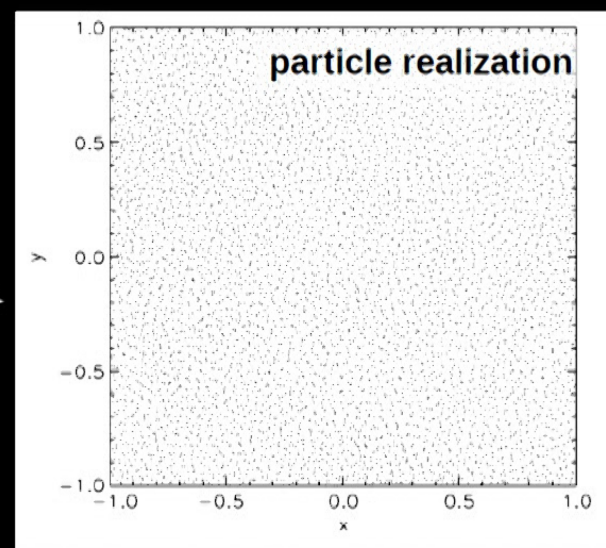
$$\hat{f}(\mathbf{x},\mathbf{v},t) = \sum_i (M_i/m) W(|\mathbf{x}-\mathbf{x}_i|; h_i)\delta^3(\mathbf{v}-\mathbf{v}_i)$$

Algorithm: Gravity + Probabilistic method for elastic scattering

input power spectrum

box size resolution





Dolag+2008

DM self-collisions in N-body simulations (probabilistic approach)

The coarse-grained distribution is given by a discrete representation of N particles:

$$\hat{f}(\mathbf{x},\mathbf{v},t) = \sum_i (M_i/m) W(|\mathbf{x}-\mathbf{x}_i|; h_i)\delta^3(\mathbf{v}-\mathbf{v}_i)$$

Algorithm: Gravity + Probabilistic method for elastic scattering

Consider a neighbourhood around each particle:

in pairs:

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

total for a particle:

$$P_i = \sum_j P_{ij}/2$$

discrete version of the collisional operator

A collision happens if: $x \leqslant P_i$, where x is a random number between 0 and 1

sort neighbours by distance and pick the one with: $x \leqslant \sum_i^l P_{ij}$

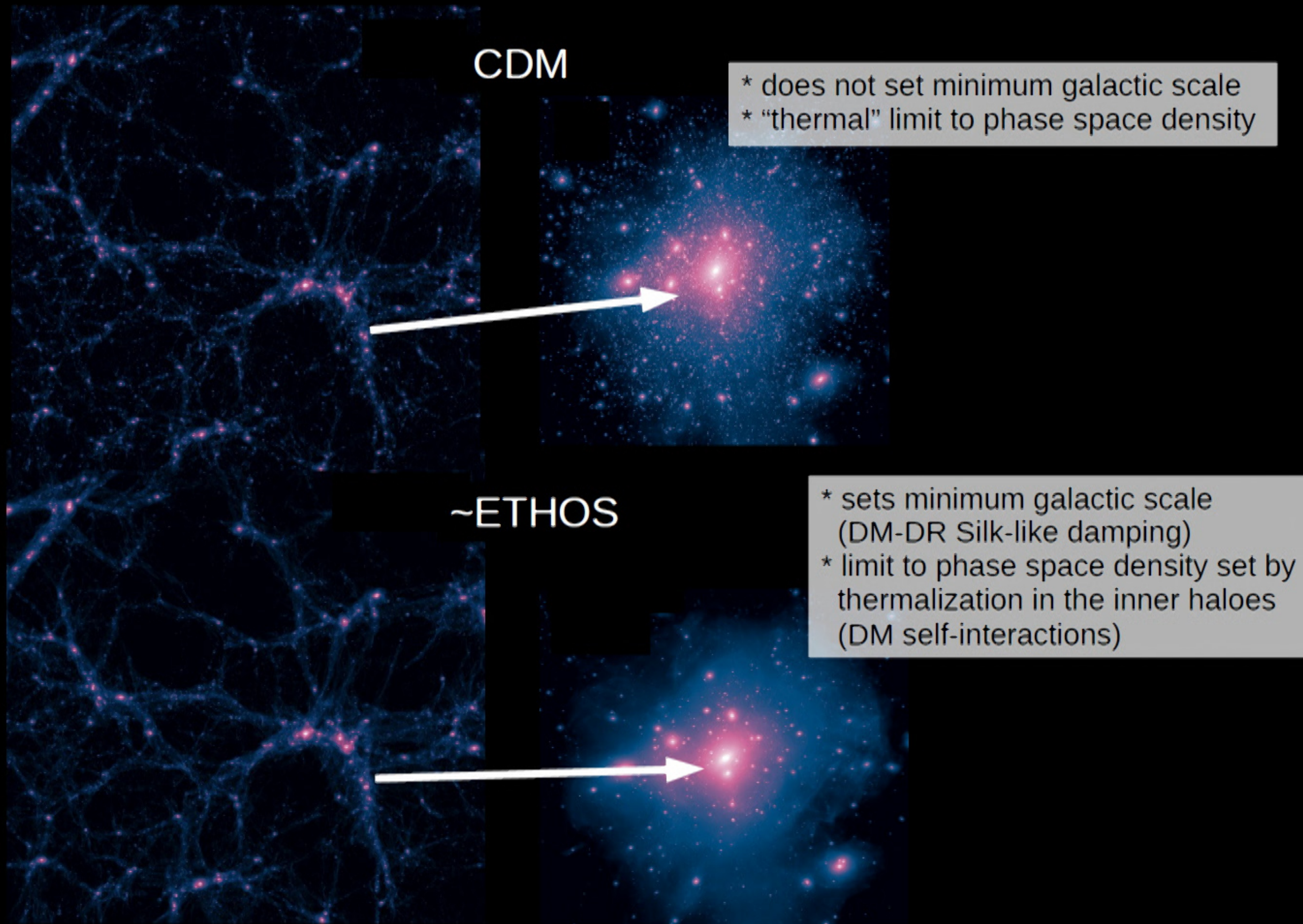
Elastic collision:

$$\vec{v}_i = \vec{v}_{cm} + (\vec{v}_{ij}/2)\,\hat{e}$$
$$\vec{v}_j = \vec{v}_{cm} - (\vec{v}_{ij}/2)\,\hat{e}$$

randomly scattered

Kochanek & White 2000, Yoshida+2000,...Vogelsberger, Zavala, Loeb 2012, Rocha+2013

ETHOS: difference with the standard CDM model



ETHOS: the abundance of DM haloes

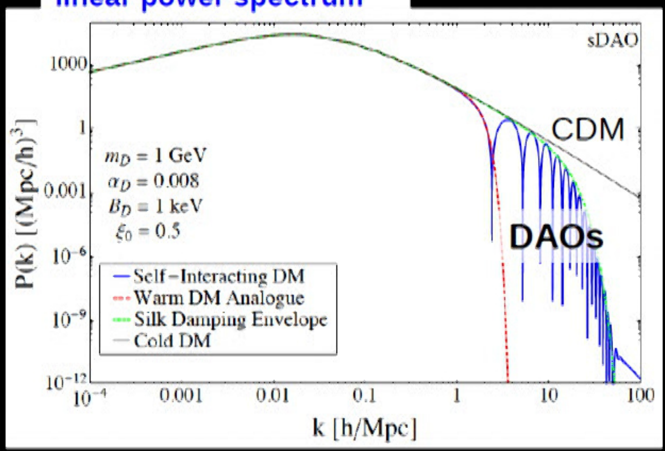
If gravity is the only relevant DM interaction, the abundance of low-mass haloes is ever increasing (down to the free-streaming scale)

With substantial DM-DR interactions in the early Universe, the abundance can be suppressed at galactic scales

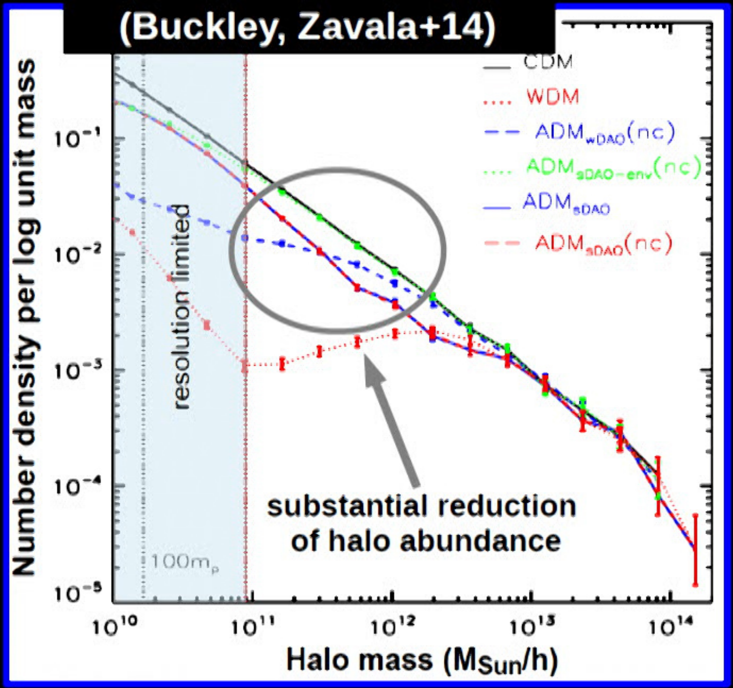
similar to WDM but with DAOs

see also Boehm+14

linear power spectrum



Abundance of DM haloes (Buckley, Zavala+14)

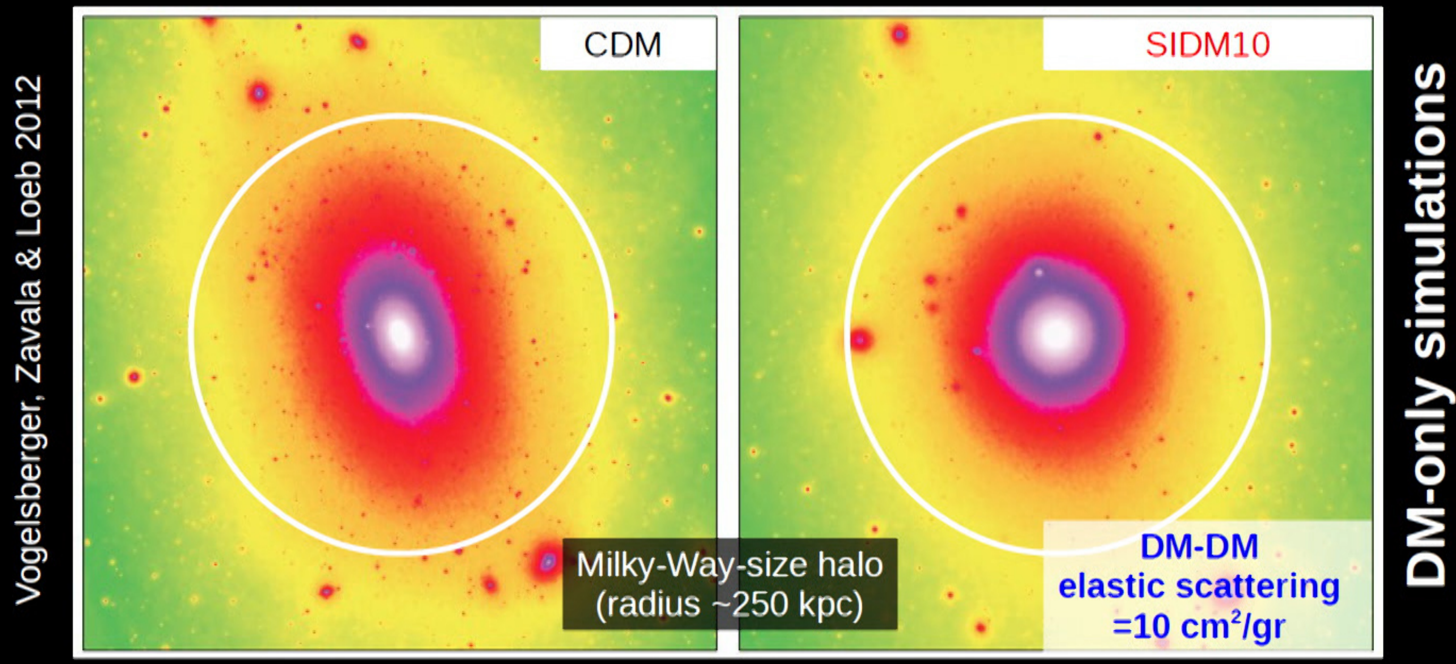


interactions between DM and dark radiation

ETHOS: the structure of SIDM haloes

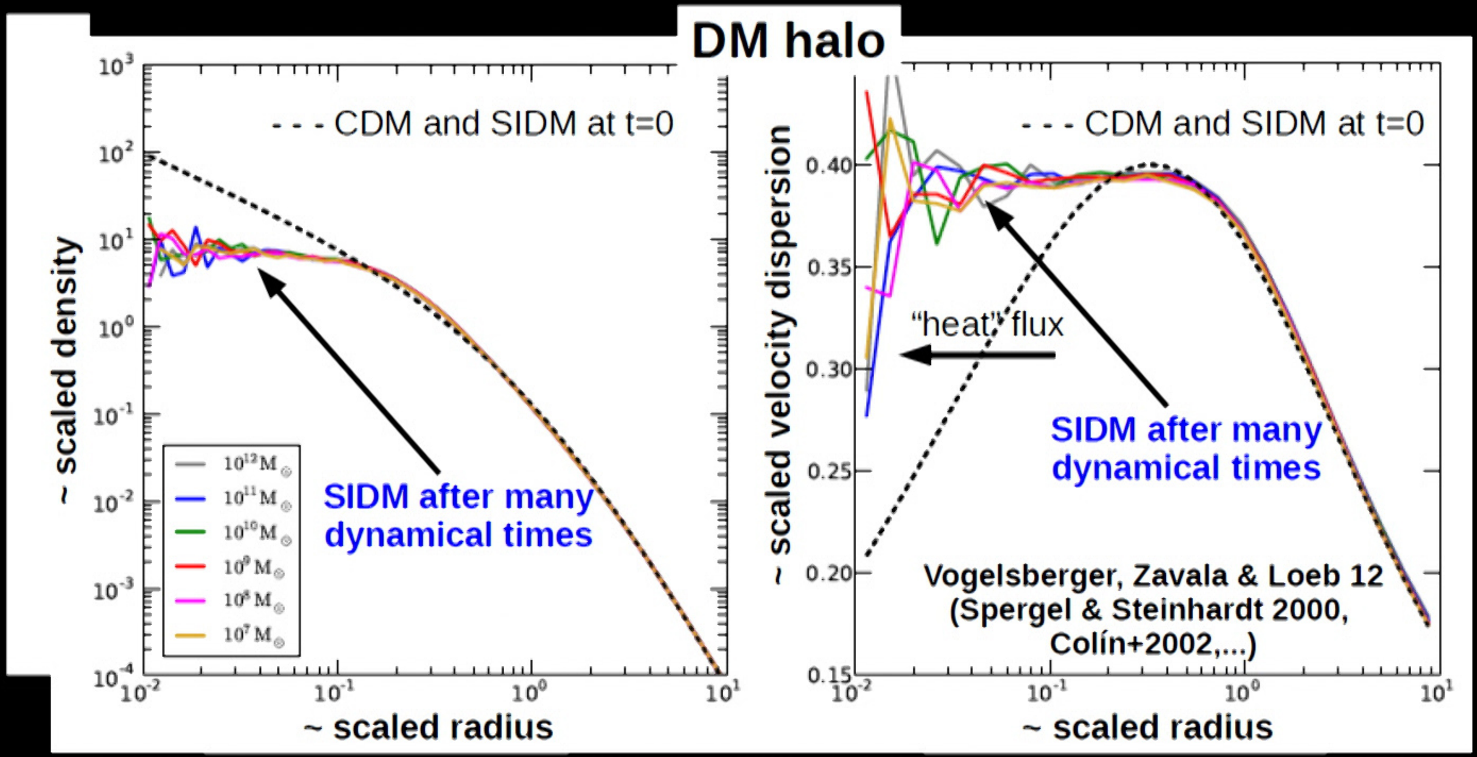
If gravity is the only relevant DM interaction, the central density of haloes is ever increasing

With strong self-interactions $(\sigma/m \gtrsim 0.5\,cm^2/gr)$
DM haloes develop nearly spherical"isothermal" cores



(Carlson+92, Spergel & Steinhardt 00, Yoshida+00, Davé+01, Colín+02, Rocha+13, Peter+13....)

ETHOS: isothermal core formation with SIDM



The fate of all SIDM haloes (gravothermal fluid approximation)

spherically symmetric ideal gas in hydrostatic equilibrium
Lynden-Bell & Eggleton 1980

$$\frac{\partial(\rho\nu^2)}{\partial r} = -\frac{GM\rho}{r^2}$$ isotropic Jeans equation

heat flux $$\frac{L}{4\pi r^2} = -\kappa\frac{\partial T}{\partial r}$$ (κ: conductivity)

$$\frac{\partial L}{\partial r} = -4\pi\rho r^2\nu^2\left(\frac{\partial}{\partial t}\right)_M \ln\frac{\nu^3}{\rho},$$ 1^{st} law (mass shell)

$$\kappa\sim(3k/2m)\rho\lambda^2/\tau$$

$$\tau\equiv relaxation\quad time$$

since Kn~1 conductivity is found as an empirical interpolation between fluid and collisionless regimes

$$\lambda\rightarrow l_{mean}=1/(\rho\sigma)\qquad Kn\ll 1$$

$$\lambda\rightarrow\lambda_J^2=\nu^2/(4\pi G\rho)\qquad Kn\gg 1\ \ (LBE)$$

requires calibration from N-body sims

e.g. Balberg, Shapiro & Inagaki 2002, Koda & Shapiro 2011, Pollack, Spergel & Steinhardt 2015

The fate of all SIDM haloes (gravothermal fluid approximation)

spherically symmetric ideal gas in hydrostatic equilibrium

Lynden-Bell & Eggleton 1980

$$\frac{\partial\left(\rho\nu^2\right)}{\partial r} = -\frac{GM\rho}{r^2}$$

heat flux $$\frac{L}{4\pi r^2} = -\kappa\frac{\partial T}{\partial r}$$

conductivity (κ)

$$\frac{\partial L}{\partial r} = -4\pi\rho r^2\nu^2\left(\frac{\partial}{\partial t}\right)_M \ln\frac{\nu^3}{\rho},$$

mass shell

1st law

$$\kappa \sim (3k/2m)\rho\lambda^2/\tau$$

$$\tau \equiv \textit{relaxation time}$$

since Kn~1 conductivity is found as an empirical interpolation between fluid and collisionless regimes

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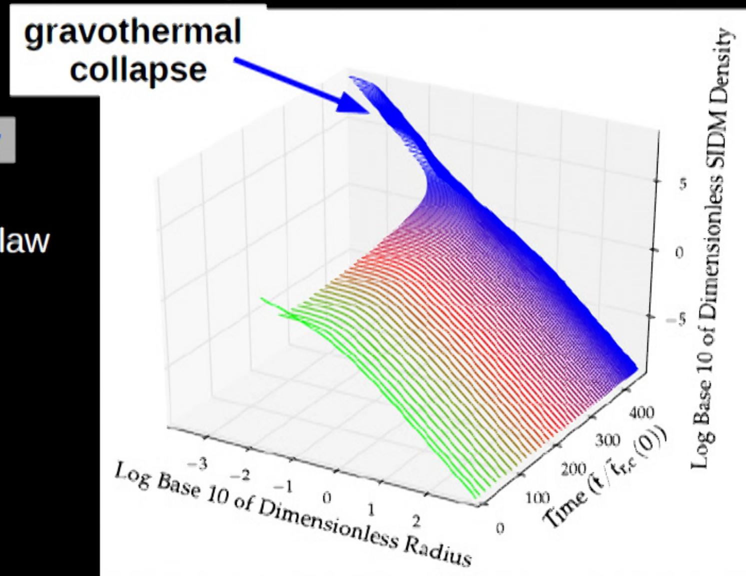
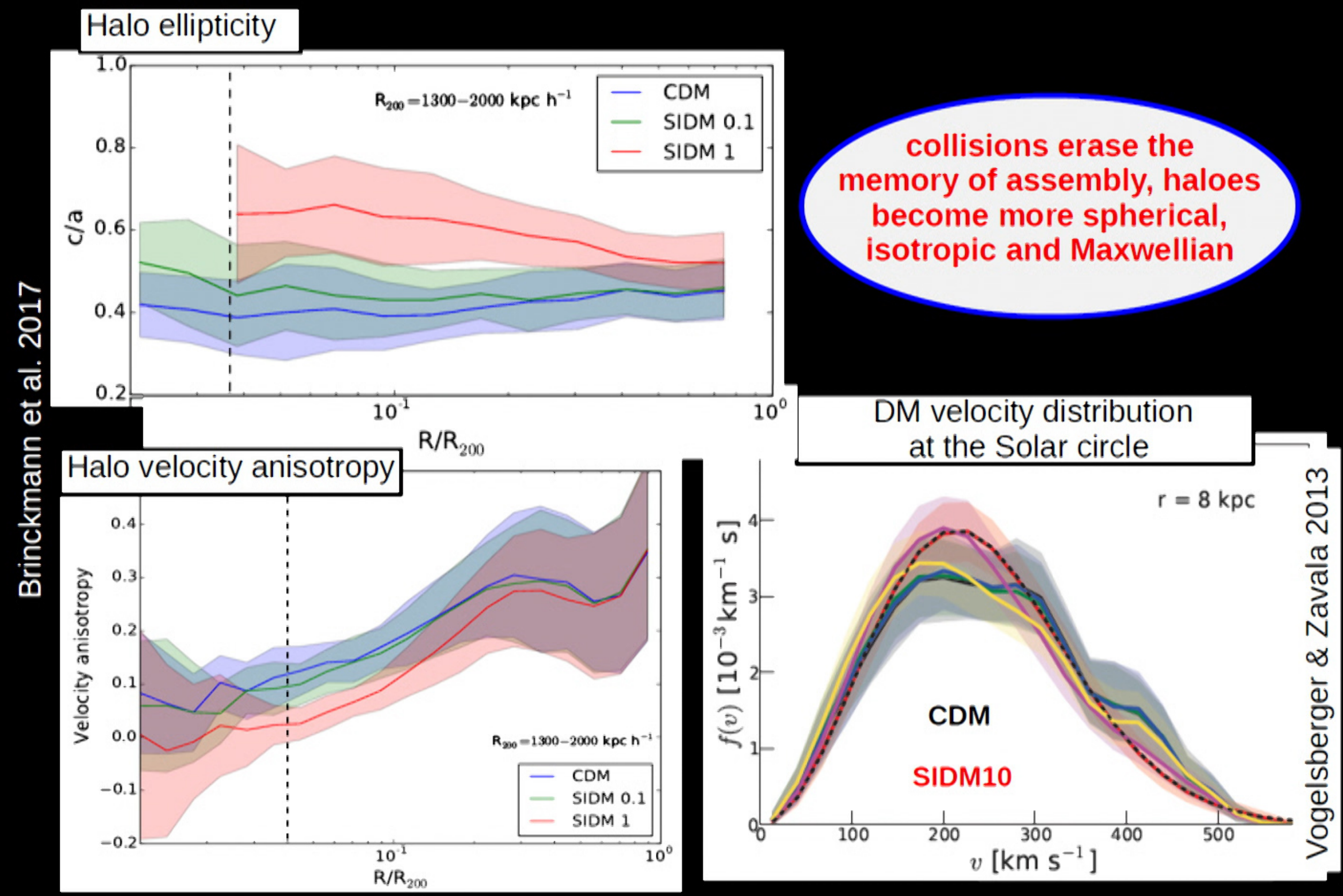


e.g. Balberg, Shapiro & Inagaki 2002, Koda & Shapiro 2011, Pollack, Spergel & Steinhardt 2015

ETHOS: the structure of SIDM haloes



Concluding remarks

- The window for the DM particle nature to be relevant for structure formation is narrow and within reach of upcoming observations:

SIDM transfer cross section

$$0.1\, cm^2/gr \lesssim \sigma/m \lesssim 2\, cm^2/gr$$

'cutoff' halo mass at z=0

$$10^{9.5}\, M_{Sun} \lesssim M_{cut} \lesssim 10^{10.5}\, M_{Sun}$$

- ETHOS: 'effective' framework for structure formation to cover this window AND establish a classification of particle physics models according to the characteristics of the cosmic structures they predict

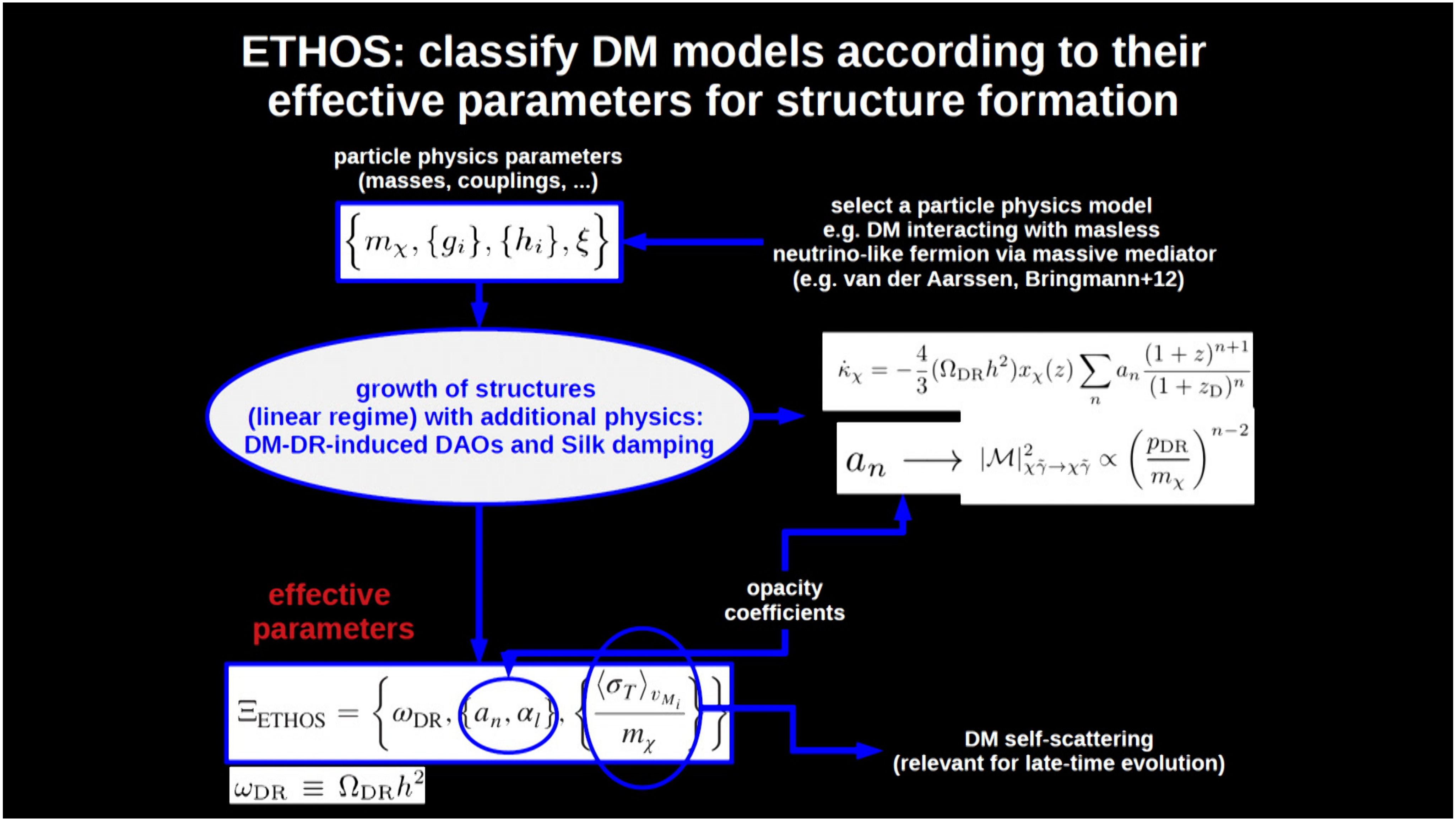
- DM-DR Silk-like damping could set the minimum scale for galaxy formation

- DM self-collisions could have an impact in the non-linear evolution of haloes:

  - Spherical, Maxwellian and isotropic DM cores of size $\sim r_{max}$ are the quasi-equilibrium stage of SIDM haloes if the central scattering rate per particle is $\sim 1/t_H$

  - Runaway collapse of the SIDM cores is the ultimate evolutionary stage

- Development of ETHOS with "baryonic physics" is underway (talk at UW tomorrow)


ETHOS: classify DM models according to their effective parameters for structure formation
particle physics parameters
(masses, couplings, ...)
$\left\{m_\chi, \{g_i\}, \{h_i\}, \xi\right\}$
select a particle physics model
e.g. DM interacting with masless
neutrino-like fermion via massive mediator
(e.g. van der Aarssen, Bringmann+12)
growth of structures
(linear regime) with additional physics:
DM-DR-induced DAOs and Silk damping
$\dot{\kappa}_\chi = -\frac{4}{3}(\Omega_{\rm DR}h^2)x_\chi(z)\sum_n a_n \frac{(1+z)^{n+1}}{(1+z_{\rm D})^n}$
$a_n \longrightarrow |\mathcal{M}|^2_{\chi\tilde{\gamma}\to\chi\tilde{\gamma}} \propto \left(\frac{p_{\rm DR}}{m_\chi}\right)^{n-2}$
opacity
coefficients
effective
parameters
$\Xi_{\rm ETHOS} = \left\{\omega_{\rm DR}, \{a_n, \alpha_l\}, \left\{\frac{\langle\sigma_T\rangle_{v_{M_i}}}{m_\chi}\right\}\right\}$
$\omega_{\rm DR} \equiv \Omega_{\rm DR}h^2$
DM self-scattering
(relevant for late-time evolution)

ETHOS: classify DM models according to their effective parameters for structure formation

particle physics parameters
(masses, couplings, ...)

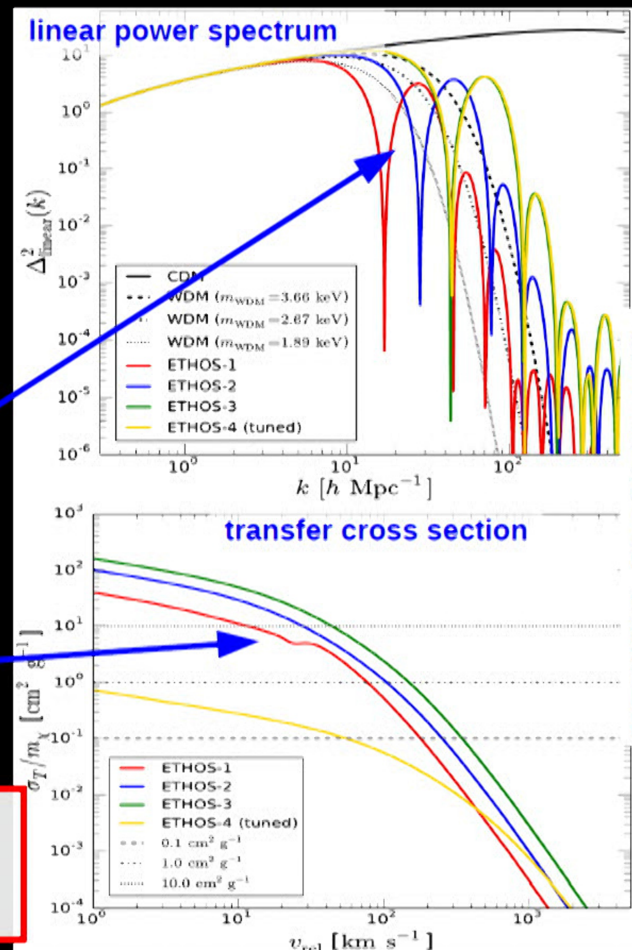
$$\left\{ m_\chi, \{g_i\}, \{h_i\}, \xi \right\}$$

growth of structures
(linear regime) with additional physics:
DM-DR-induced DAOs and Silk damping

effective parameters

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

All DM particle physics models that map into the same ETHOS parameters can be studied (constrained) at the same time



ETHOS I: Cyr-Racine+16