Self-Interacting Right-Handed Neutrinos as Warm Dark Matter & Small-Scale Cosmology

KING'S College LONDON

Nick E. Mavromatos

King's College London

Summer School & Workshop on the Standard Model & Beyond

August 31 – Sept. 12 2016

EISA

European Institute for Sciences and Their Applications

E I S A


Corfu Summer Institute

16th Hellenic School and Workshops on Elementary Particle Physics and Gravity

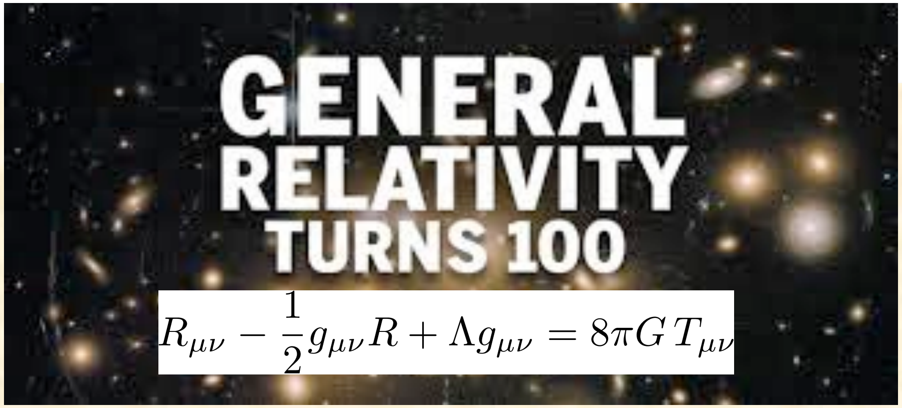
Corfu, Greece 2016

INTERNATIONAL
YEAR OF LIGHT
2015

INTERNATIONAL
YEAR OF LIGHT
2015

COSMIC
LIGHT
IAU

in 2015:



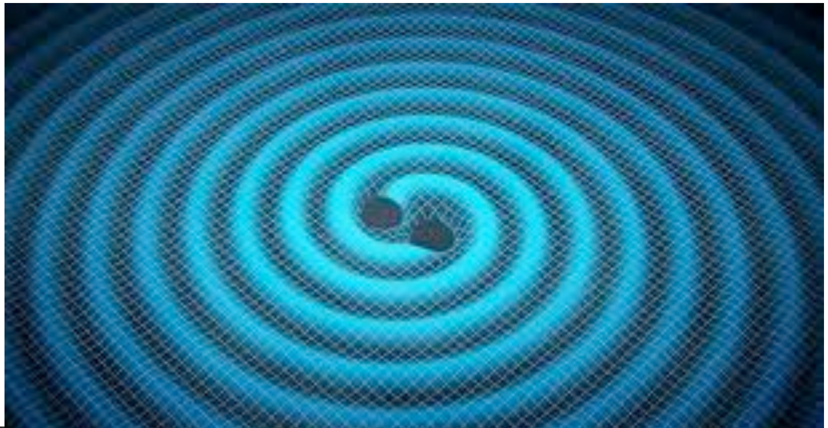
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

100 anniversary of the (classical) theory of General relativity

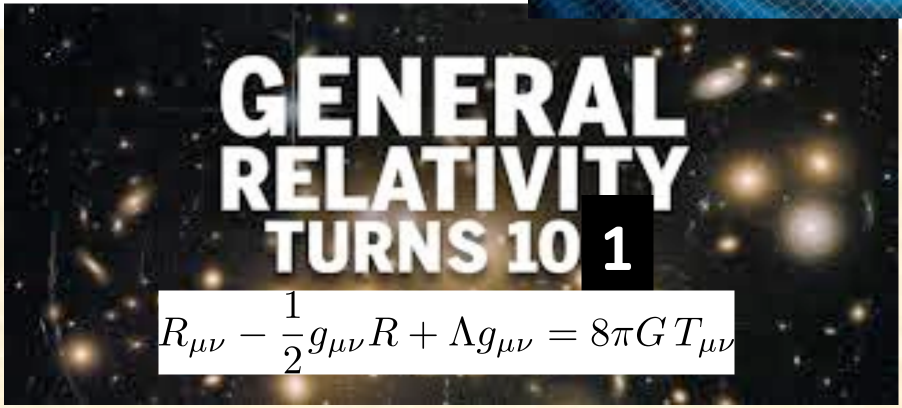
Year of Light

Use Cosmic light to probe / falsify:

Cosmology models : (current) energy budget of Cosmos
Inflation
Evolution of Universe



in 2016:



$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = 8\pi G\,T_{\mu\nu}$$

DETECTION OF Gravitational Waves (GR IMPORTANT PREDICTION) ARE ANNOUNCED BY VIRGO-LIGO Colls (signals GW150914 & GW151226, interpreted as Black-Hole mergers!)

Cosmology models : (current) energy budget of Cosmos
Inflation
Evolution of Universe

Fundamental Questions (still unanswered) in Cosmology
101 years after Einstein

- How did the Universe begin? is there something before Big Bang?
- Is there inflation (as it seems) and if yes what is its microscopic mechanism?
- Exit from Inflation into Radiation phase , reheating of the Universe?
- Why is the cosmological constant so small today, despite the fact that there is > 70% dark energy ?
- Why Dark Matter? what is it, if there?

WHAT IS THE DARK SECTOR OF THE (OBSERVED) UNIVERSE MADE OF?

Fundamental Questions (still unanswered) in Cosmology
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WHAT IS THE DARK SECTOR OF
THE (OBSERVED) UNIVERSE MADE OF?

OUTLINE

- **PART I:** **Overview of current astrophysical/cosmological Data**

  (Supernovae, Baryon Acoustic Oscillations, CMB-Planck 2015)

  Cosmological constant – Cold Dark Matter Model (ΛCDM)

  fits them very well at Large scales

- **PART II**: WHAT ABOUT SMALLER SCALES (eg GALACTIC SCALES, DWARF GALAXIES) – **DISCREPANCY between ΛCDM-based simulations and observations** – **“small scale Cosmology crisis” - 3 basic problems**

  (i) Core-cusp problem

  (ii) The missing satellites problem

  (iii) Too-Big-to-fail problem

- **Self-Interacting Dark matter (SIDM)** as a solution (on top of astrophysical ones) ?

- **PART III:** Right-Handed (keV) neutrinos as a concrete SIDM model & consequences for galactic structure

Arguelles, NEM, Rueda, Ruffini
JCAP 1604 (2016) no.04, 038

PART I

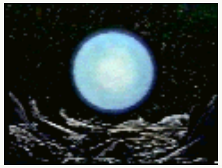
Astro/Cosmological Phenomenology

THE DARK SECTOR OF THE UNIVERSE

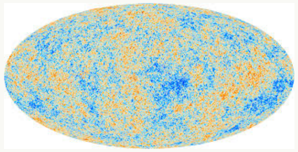
Current (100 yrs after Einstein GR) Energy Budget of the Cosmos

Observations from:

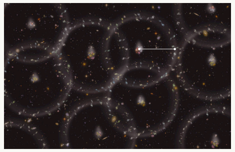
Supernovae Ia



CMB

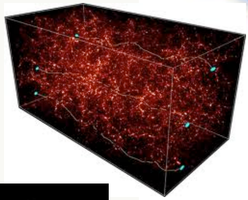


Baryon Acoustic Oscillations

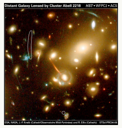


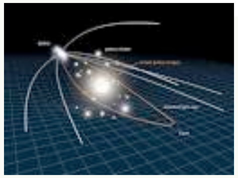
Galaxy Surveys

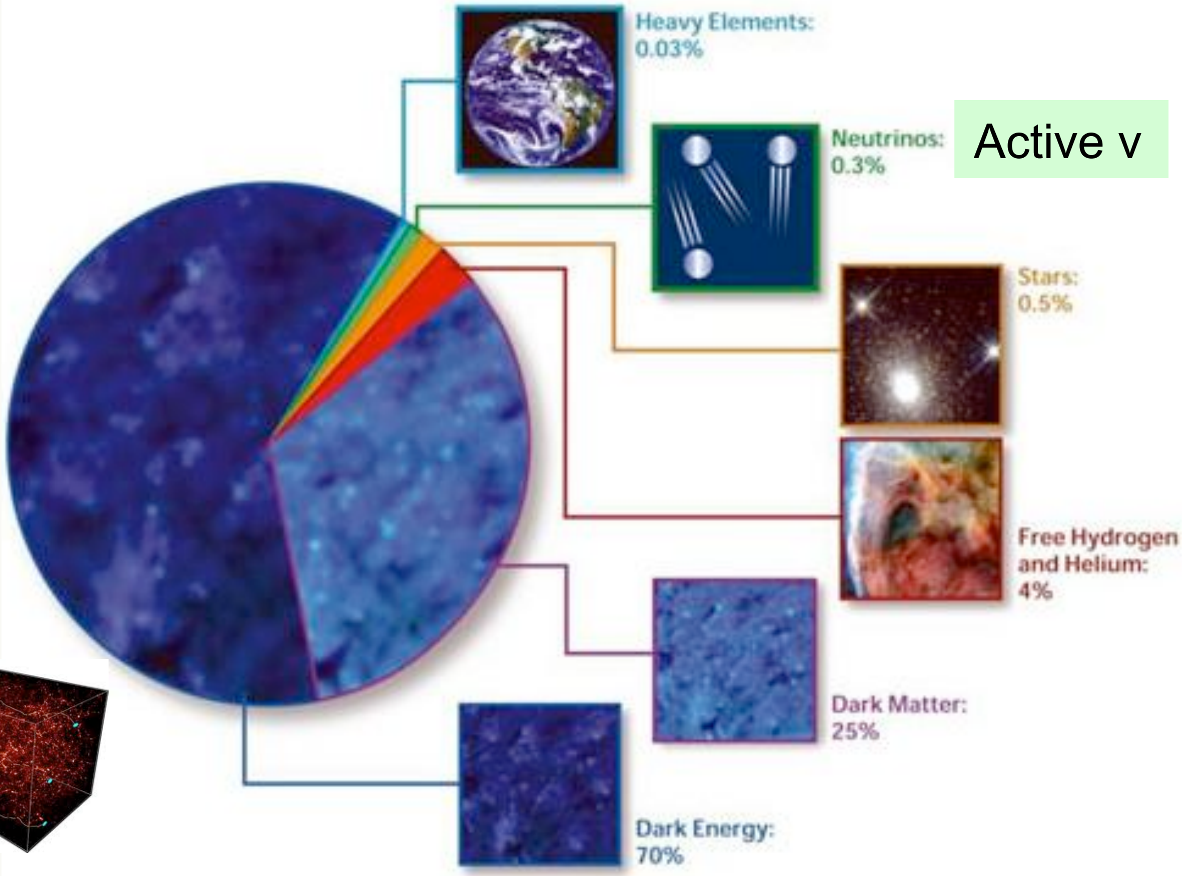
Structure Formation data



Strong & Weak lensing

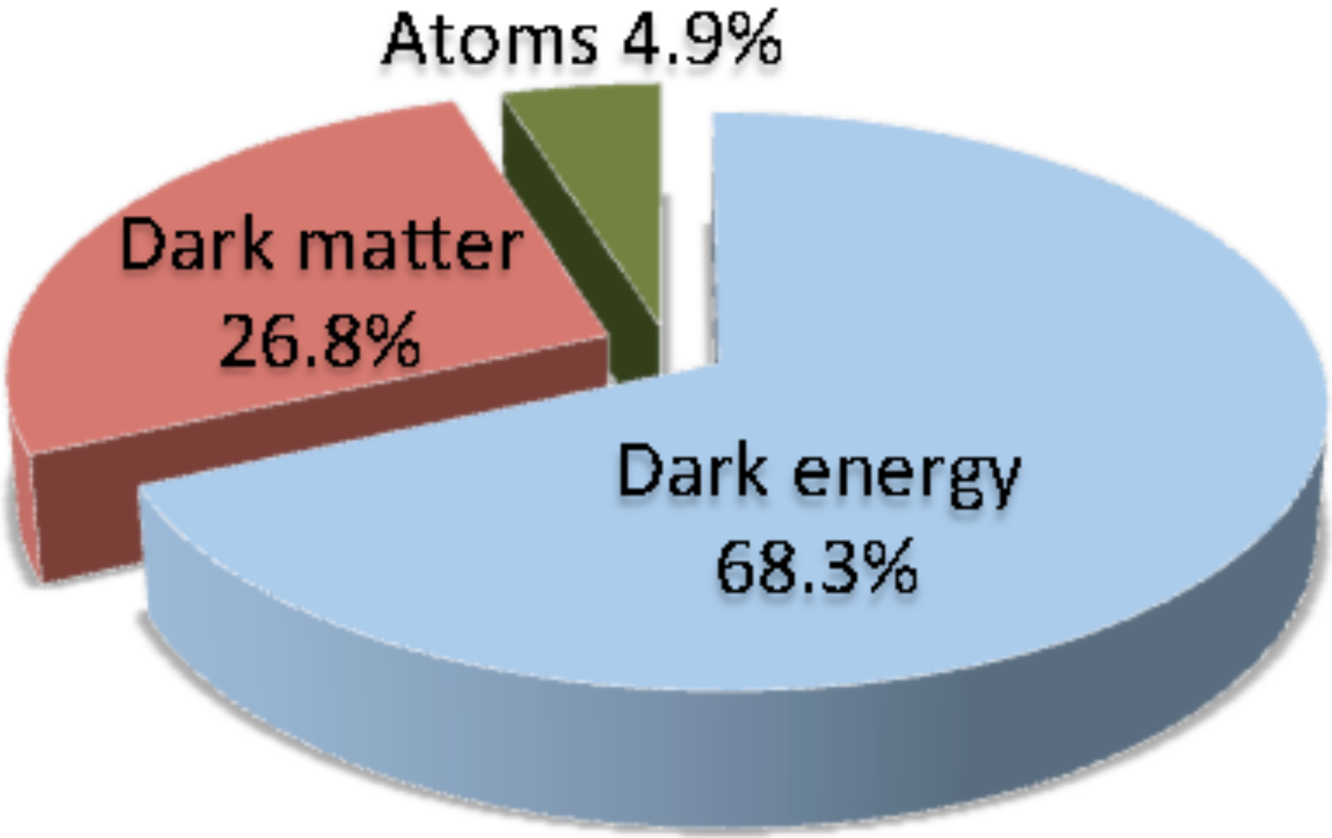






Active ν

Energy Budget of the Cosmos after Planck 2015



http://www.cosmos.esa.int/web/planck/publications#Planck2015

Dark Matter

DARK MATTER (DM):

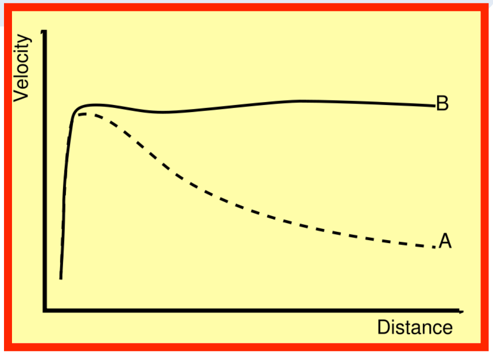
CURRENT EVIDENCE

Arguments in Favour

Rotational Curves of galaxies,

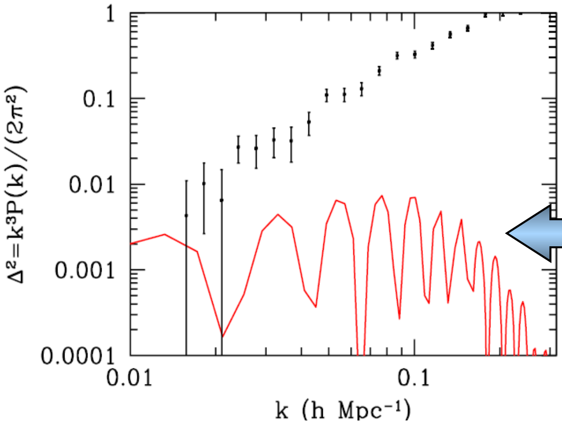
gravitational lensing

growth of structure



TYPES OF DM: hot, warm, cold

ASTROPHYSICAL CONSTRAINTS (MODEL INDEPENDENT)



Baryon-only Models, without Dark Matter

INDIRECT SEARCHES:

collider (LHC & beyond) searches

photons, neutrinos,

matter-antimatter asymmetries

(electron-positron, proton-antiproton)

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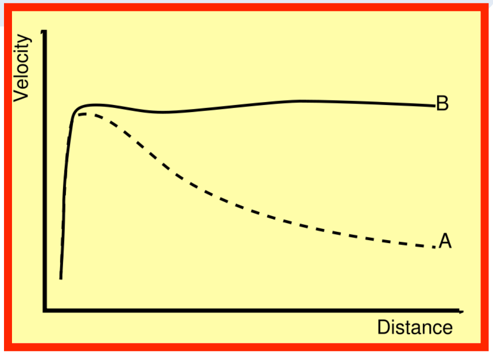

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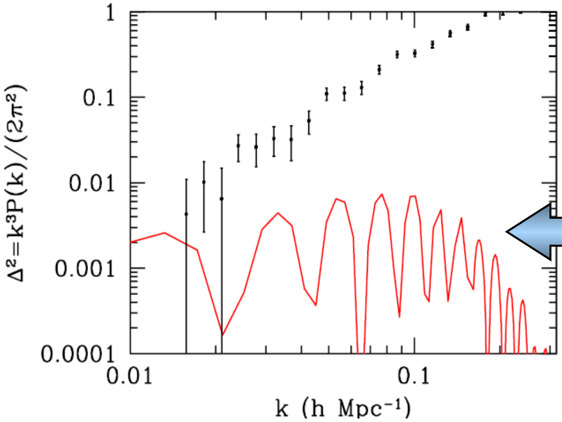

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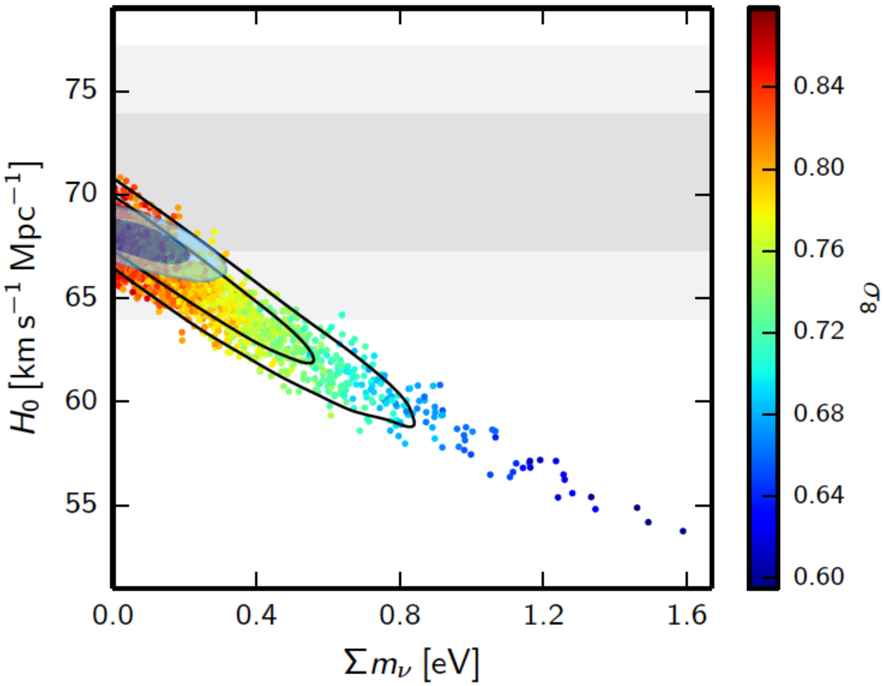
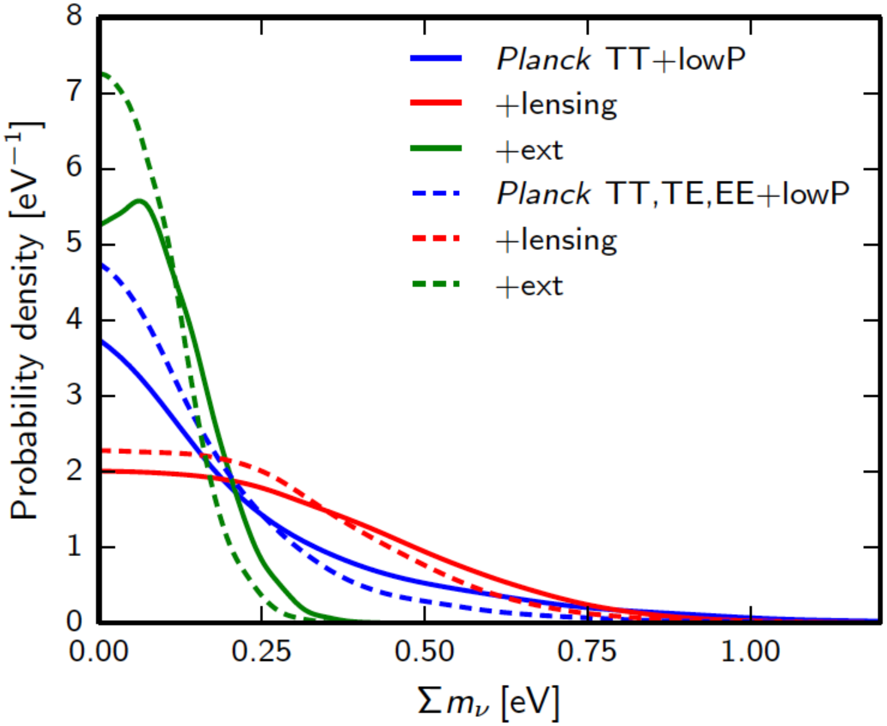
WMAP-Planck Results Exclude Hot Dark matter at Large Scales

Planck Coll 2015

Light (active) neutrino species





$$H_0 = 67.7 \pm 0.6$$

$$\left.\begin{array}{l} \sum m_\nu < 0.23\ \text{eV} \\ \Omega_\nu h^2 < 0.0025 \end{array}\right\} \quad 95\%,\ \textit{Planck}\ \text{TT+lowP+lensing+ext.}$$

$$\Omega_\nu h^2 = \frac{\sum_{i=1}^{3} m_i}{94.0\,\text{eV}} \leq 0.0025$$

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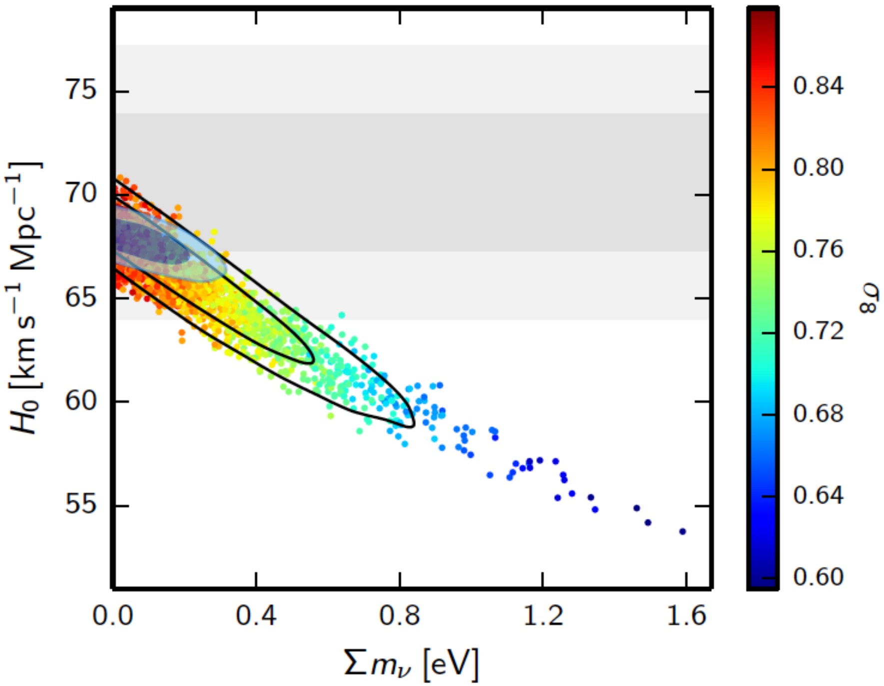

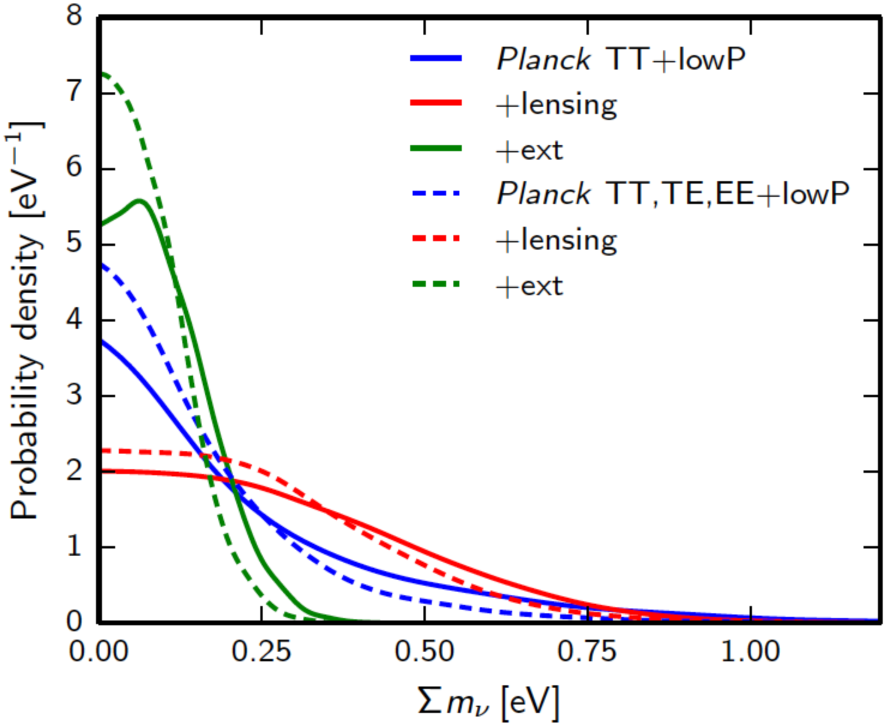

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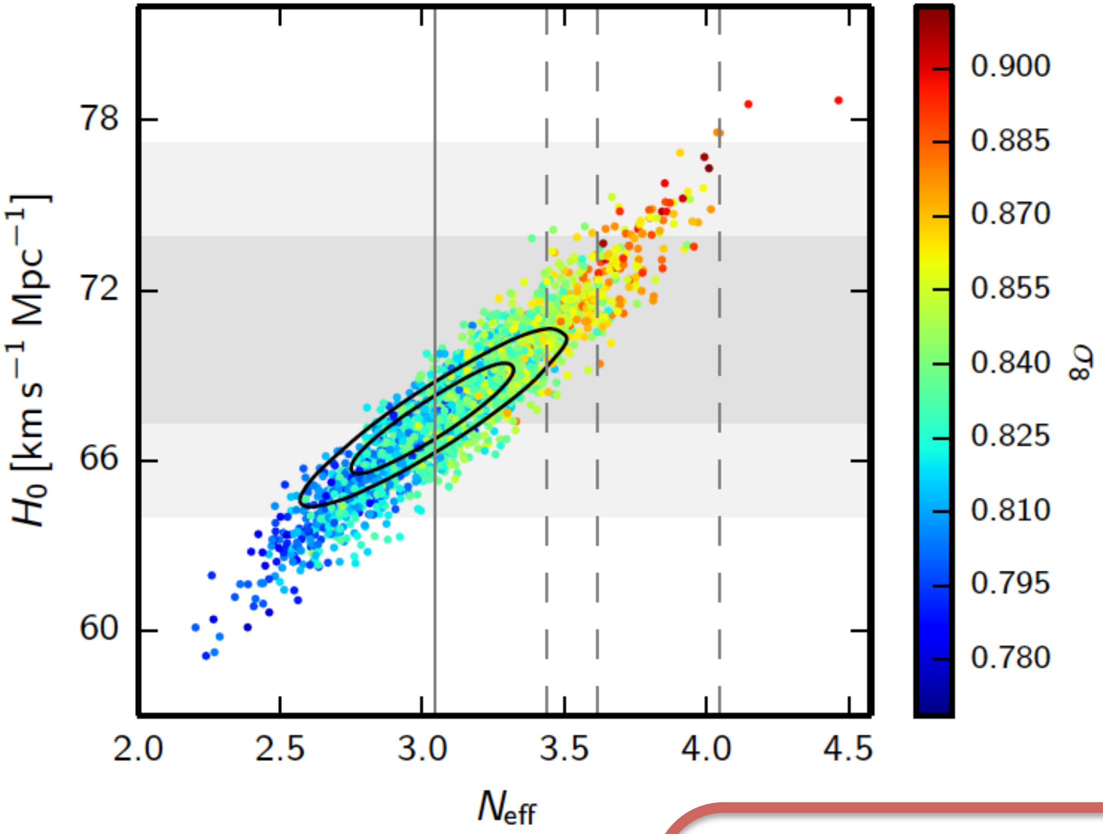
excludes Hot DM !

Planck constraints on relativistic neutrino species in Universe

Planck Coll 2015



significant dark radiation still allowed at 68% CL

$N_{\rm eff} = 3.13 \pm 0.32$ *Planck* TT+lowP ;

$N_{\rm eff} = 3.15 \pm 0.23$ *Planck* TT+lowP+BAO ;

$N_{\rm eff} = 2.99 \pm 0.20$ *Planck* TT, TE, EE+lowP ;

$N_{\rm eff} = 3.04 \pm 0.18$ *Planck* TT, TE, EE+lowP+BAO .

Dark Matter

DARK MATTER (DM):

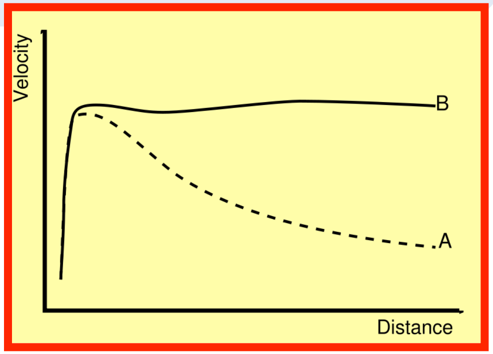
CURRENT EVIDENCE

Arguments in Favour

Rotational Curves of galaxies,

gravitational lensing

growth of structure



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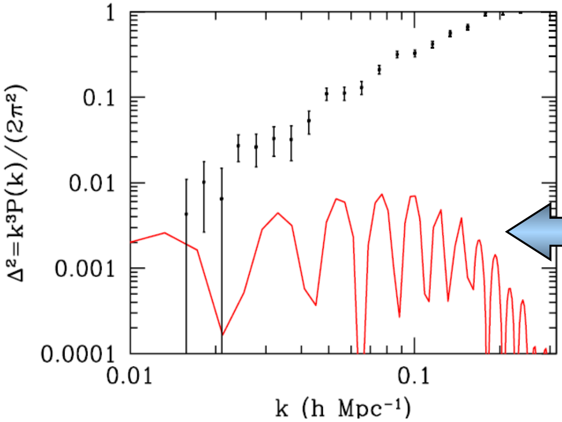

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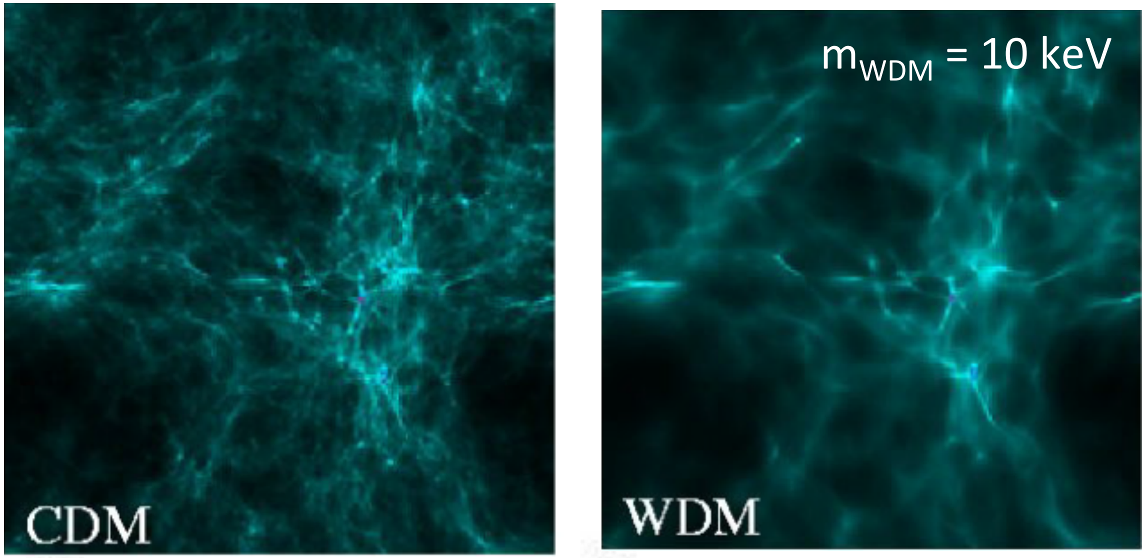
WMAP-Planck Results Exclude Warm Dark matter at Large Scales

WMAP,
Planck Coll 2015

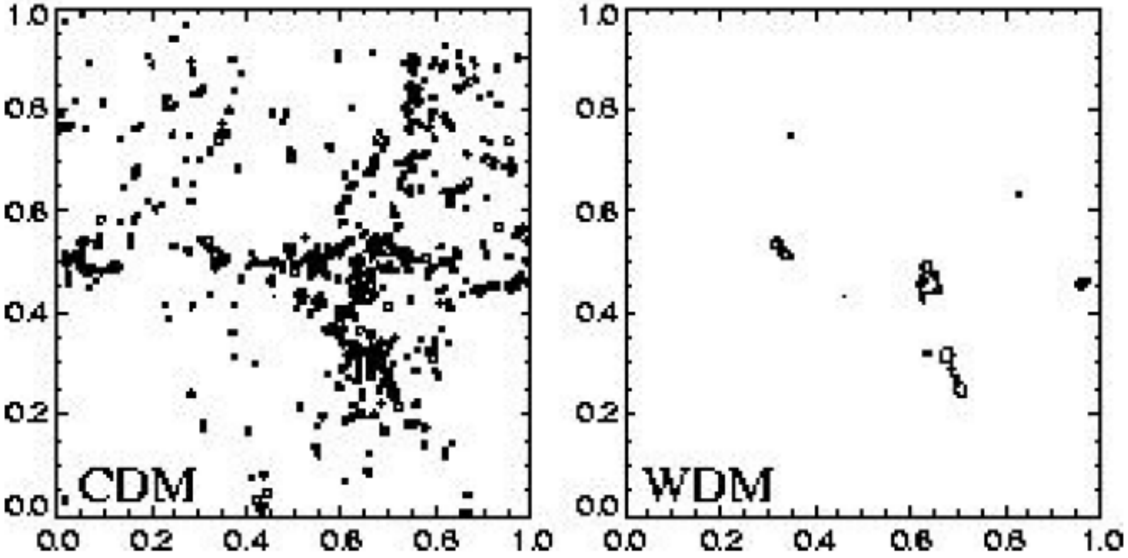
Yoshida *et al.*
astro-ph/0303622

Re-ionization of the Universe at redshift z=20

numerical N-body **simulations** based on **warm** and **cold ΛCDM** models



projected gas distributions



Distribution of dark haloes with mass M > $10^5 M_\odot$

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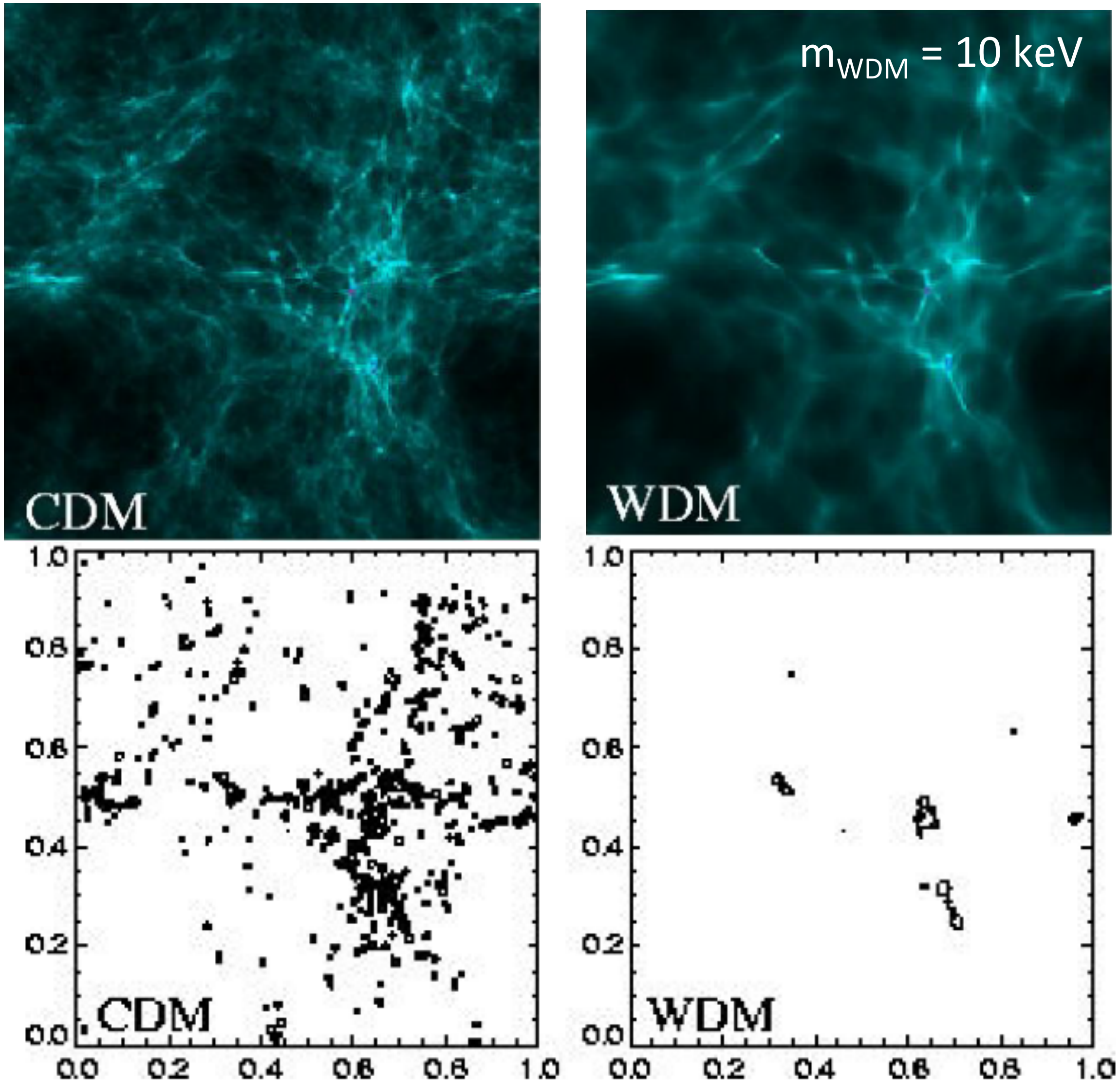

projected gas distributions

Distribution of dark haloes with mass M > $10^5 M_\odot$

excludes Warm DM
$m_{WDM} \leq 10$ keV !

Dark Matter

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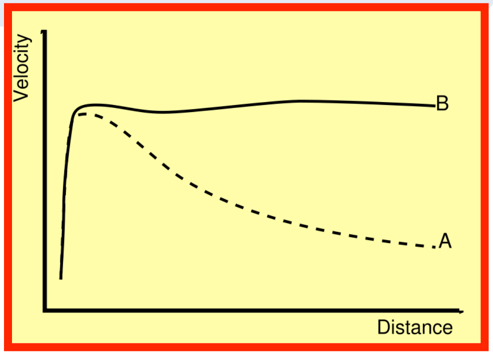
CURRENT EVIDENCE

Arguments in Favour

Rotational Curves of galaxies,
gravitational lensing
growth of structure



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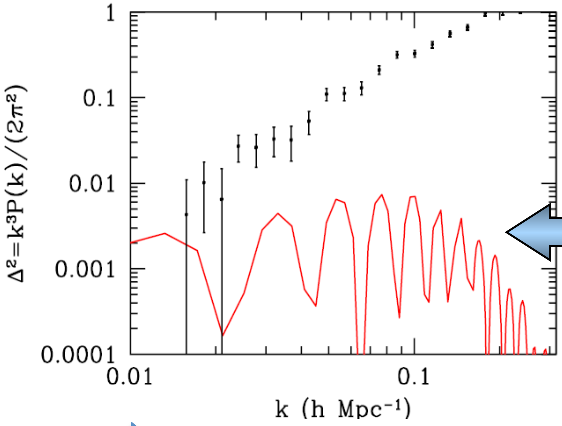

Baryon-only Models, without Dark Matter

INDIRECT SEARCHES:

collider (LHC & beyond) searches

photons, neutrinos,

matter-antimatter asymmetries

(electron-positron, proton-antiproton)

Compatible with all current data !
$m \geq 100$ keV
100 keV $\leq m_{WDM} = m_{CDM}$

Dark Matter

DARK MATTER (DM):

CURRENT EVIDENCE

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TYPES OF DM: hot, warm, cold

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THEORETICAL SCENARIOS

SUPERSYMMETRY ***neutralino***

SUPERGRAVITY ***gravitino (if sufficiently light)***

AXIONS ***(standard QCD or stringy)***

STERILE NEUTRINOS

…

Dark Matter

e.g. typical **thermal WIMPs**
CMB-observations-compatible
DM relic abundance

$$\Omega_\chi \simeq \frac{0.1\,\mathrm{pb}\cdot \mathrm{c}}{\langle\sigma(\chi\,\chi \to \mathrm{SM}\,v\rangle} \simeq 0.22$$

occurs cross sections of
weak-interactions type

$$\sigma(\chi\,\chi \to \mathrm{SM}\,v\rangle) \simeq 3\cdot 10^{-26}\mathrm{cm}^3\,\mathrm{s}^{-1}$$

``WIMP miracle''

$$m_\chi \sim O(100\ \mathrm{GeV} - \mathrm{TeV})$$

THEORETICAL SCENARIOS

SUPERSYMMETRY ***neutralino***

SUPERGRAVITY ***gravitino (*****if sufficiently light*****)***

AXIONS ***(standard QCD or stringy)***

STERILE NEUTRINOS

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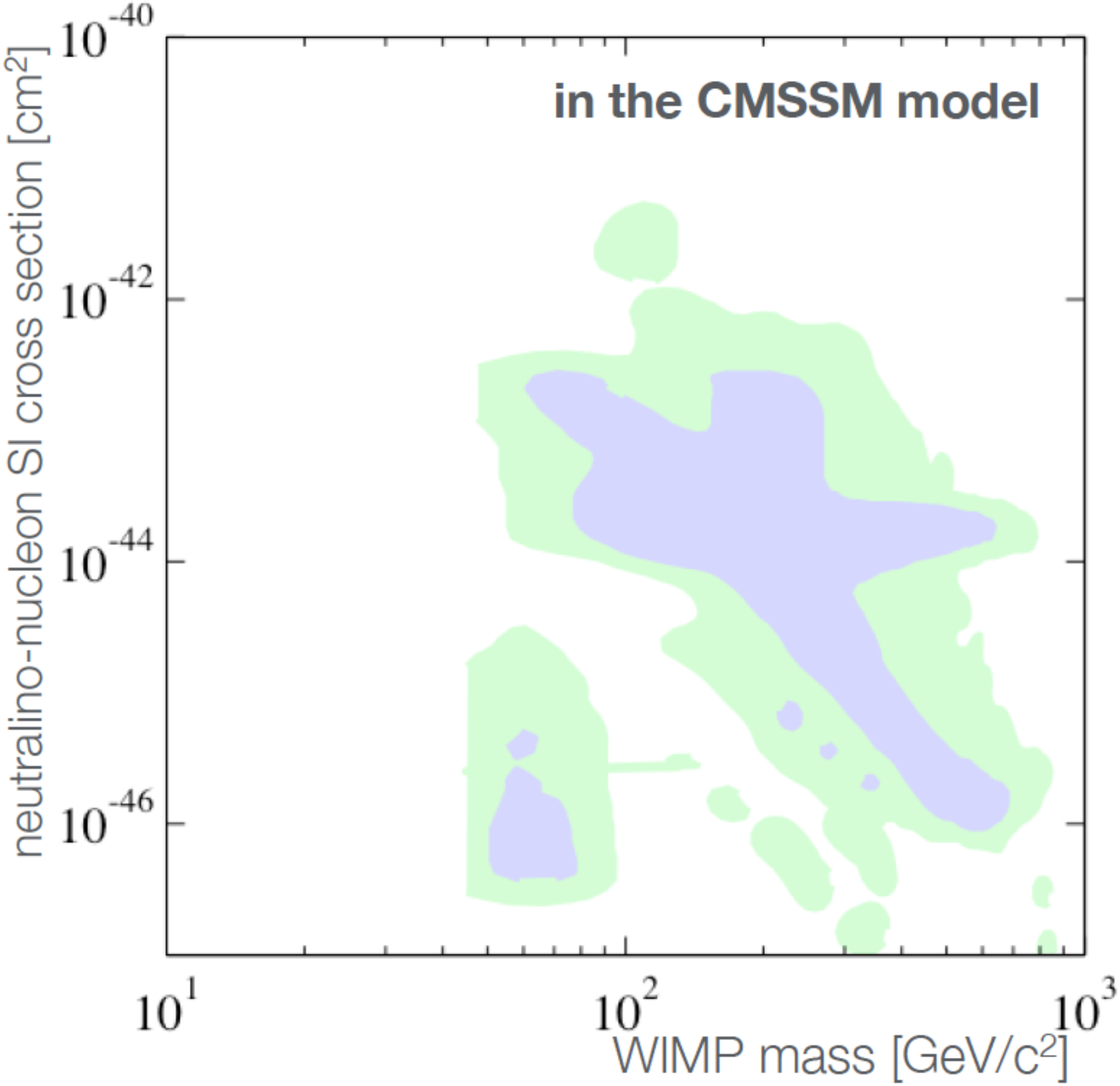
Theoretical Model dependence

in deriving bounds in experimental searches

- Predictions from supersymmetry [10^{-8} pb = 10^{-44} cm^2]:

$\sigma/m \approx 10^{-22}$ barn/GeV



CMSSM2008

(Roszkowski, Ruiz, Trotta)

Dark Matter

e.g. typical thermal WIMPs
CMB-observations-compatible
DM relic abundance

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occurs cross sections
weak-interaction

$\sigma(\chi\chi \to \mathrm{SM}$

``WIMP miracle''

$$m_\chi \sim O(100\ \mathrm{GeV} - \mathrm{TeV})$$

But….None of these particles has been observed as yet…..

THEORETICAL SCEN

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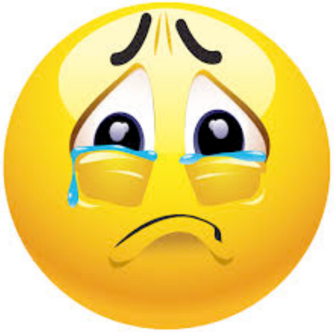
XIONS *(standard QCD o*



STERILE NEUTRINOS

…

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Dark Matter

DARK MATTER (DM):

CURRENT EVIDENCE

Arguments in Favour

TYPES OF DM: hot, warm

ASTROPHYSICA
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photons, neu s,

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TY ***gravitino (if sufficiently light)***

IONS *(standard QCD or stringy)*

STERILE NEUTRINOS

…

Theoretical Model dependence

in deriving bounds in experimental searches

Moreover…..

DM may consist of more than one dominant species !

Dark Matter

DARK MATTER (DM):

CURRENT EVIDENCE

Arguments in Favour

TYPES OF DM: hot, warm, cold

ASTROPHYSICAL CONSTRAINTS (MODEL INDEPENDENT)

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THEORETICAL SCENARIOS

SUPERSYMMETRY ***neutralino***

SUPERGRAVITY ***gravitino (*** *if sufficiently light* ***)***

AXIONS ***(standard QCD or stringy)***

STERILE NEUTRINOS This talk

…

Theoretical Model dependence

in deriving bounds in experimental searches

PART II

Small-scale Cosmology
"crisis"

Collisionless ΛCDM - based N-body simulations

$\neq$

galactic scale observations

The 3-Problems of Galactic-Scale-Cosmology (GSC)

(i) The Core-Cusp problem (or cuspy-halo problem):

Discrepancy between the **observed dark matter density profiles** of low-mass galaxies (e.g. **dwarf spheroidals DSph of Milky way, extragalactic Dwarves, low surface brightness galaxies**) and the corresponding **density profiles** predicted by **cosmological N-body simulations** based on **collisionless** ΛCDM.

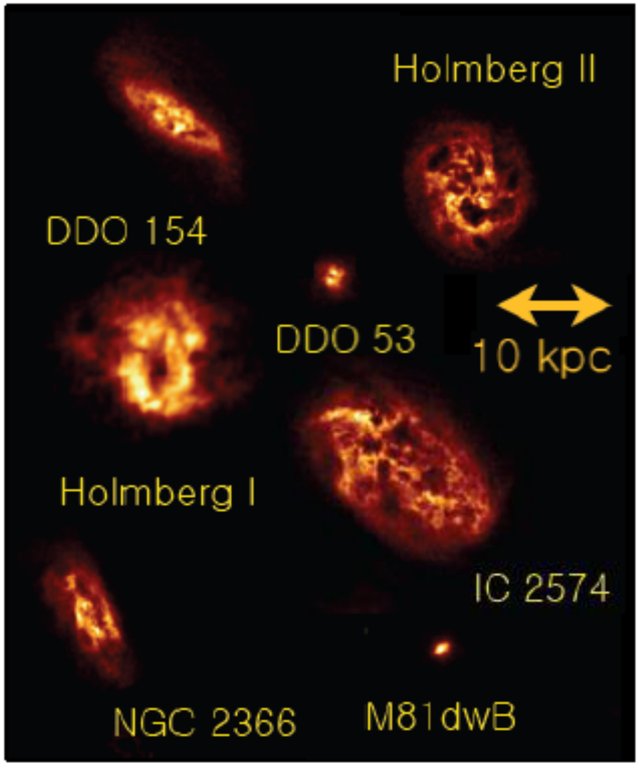
Nearly all **simulations** form dark matter halos which have ***cuspy dark matter*** distributions, with the density increasing steeply at small radii;
on the contrary, ***the rotation curves*** of most of the observed ***dwarf galaxies*** indicate flat central density profiles ("***cores***”).

B. Moore (1994)
J.G. de Blok [arXiv:0910.3538]
Se-Heon Oh *et al.* ,
Astrophys. J. 149 (6), 96 (2015).

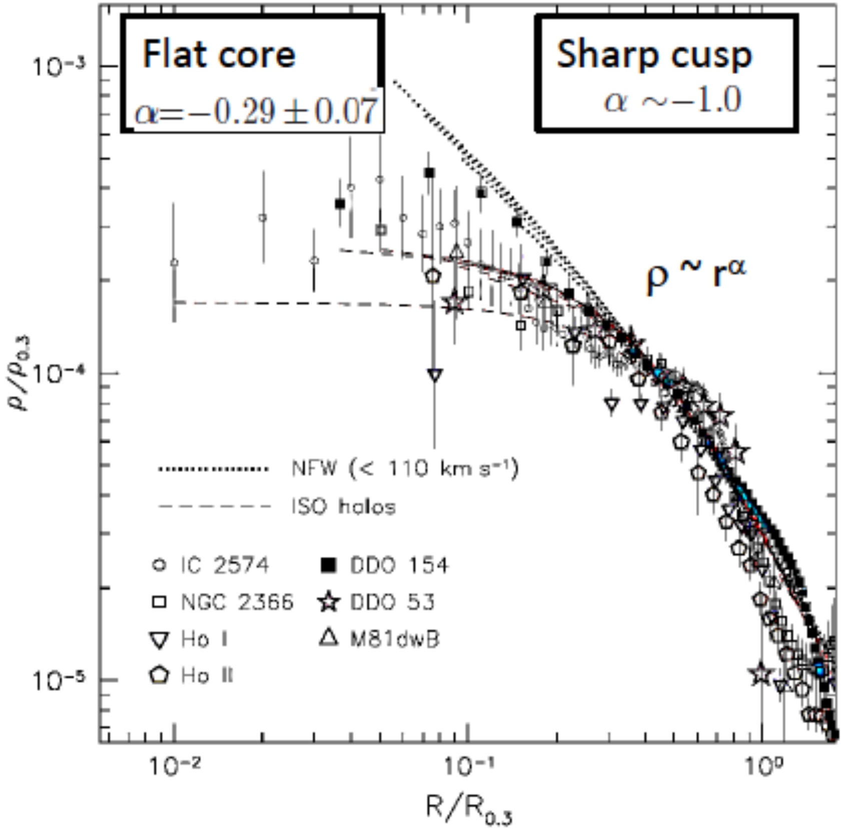
(i) The Core-Cusp Problem

1. Cores in dwarfs outside MW halo

Moore (1994), Flores & Primack (1994), …



THINGS (dwarf galaxy survey) - Oh et al. (2011)



Sean Tulin (Michigan)

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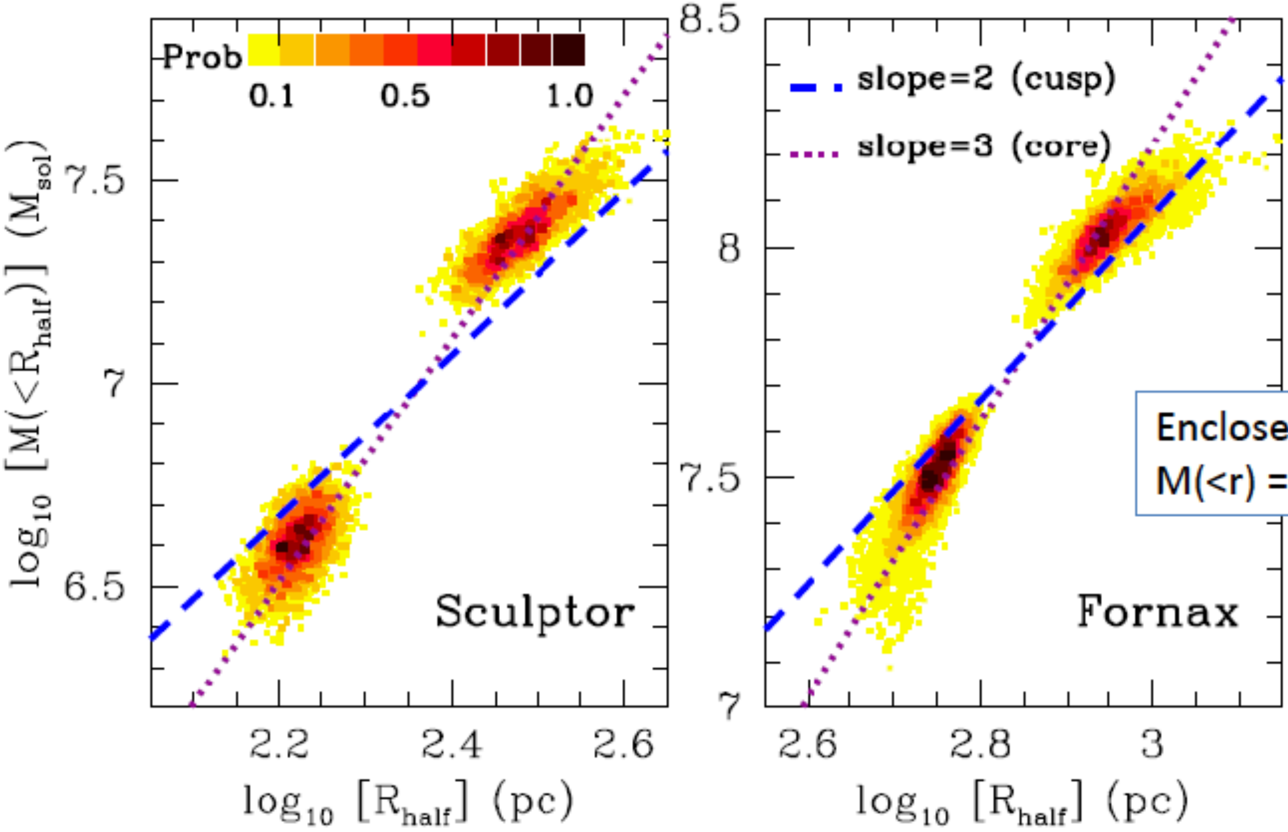


Enclosed mass
$M(<r) = \int d^3r\, \rho$

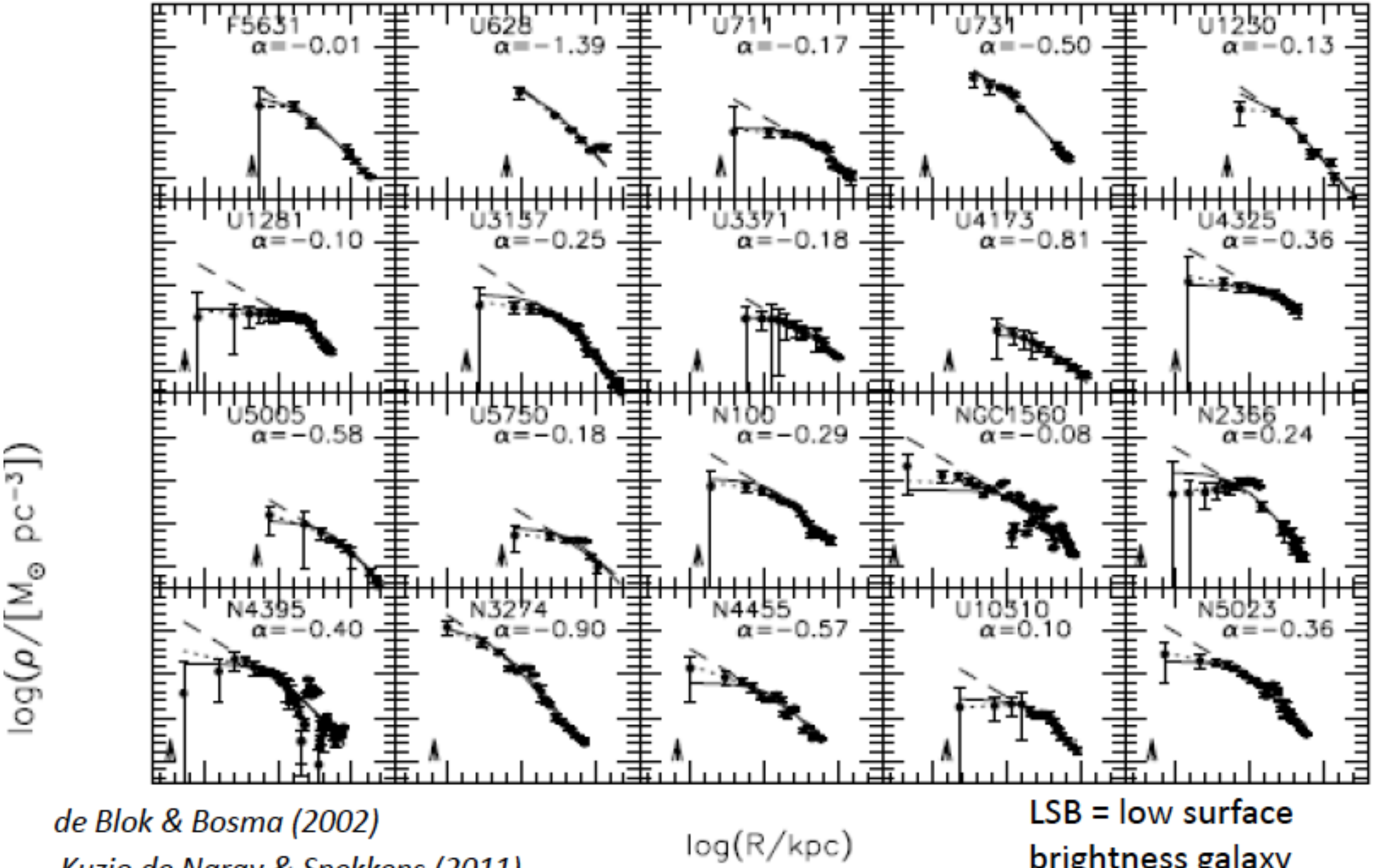
Stellar subpopulations (metal-rich & metal-poor) as "test masses" in gravitational potential

Walker & Penarrubia (2011)

Sean Tulin (Michigan)

(i) The Core-Cusp Problem

1. Cores in LSBs



de Blok & Bosma (2002)

Kuzio de Naray & Spekkens (2011)

LSB = low surface brightness galaxy

Sean Tulin (Michigan)

The 3-Problems of Galactic-Scale-Cosmology (GSC)

(ii) The missing satellite problem (or, dwarf galaxy problem)

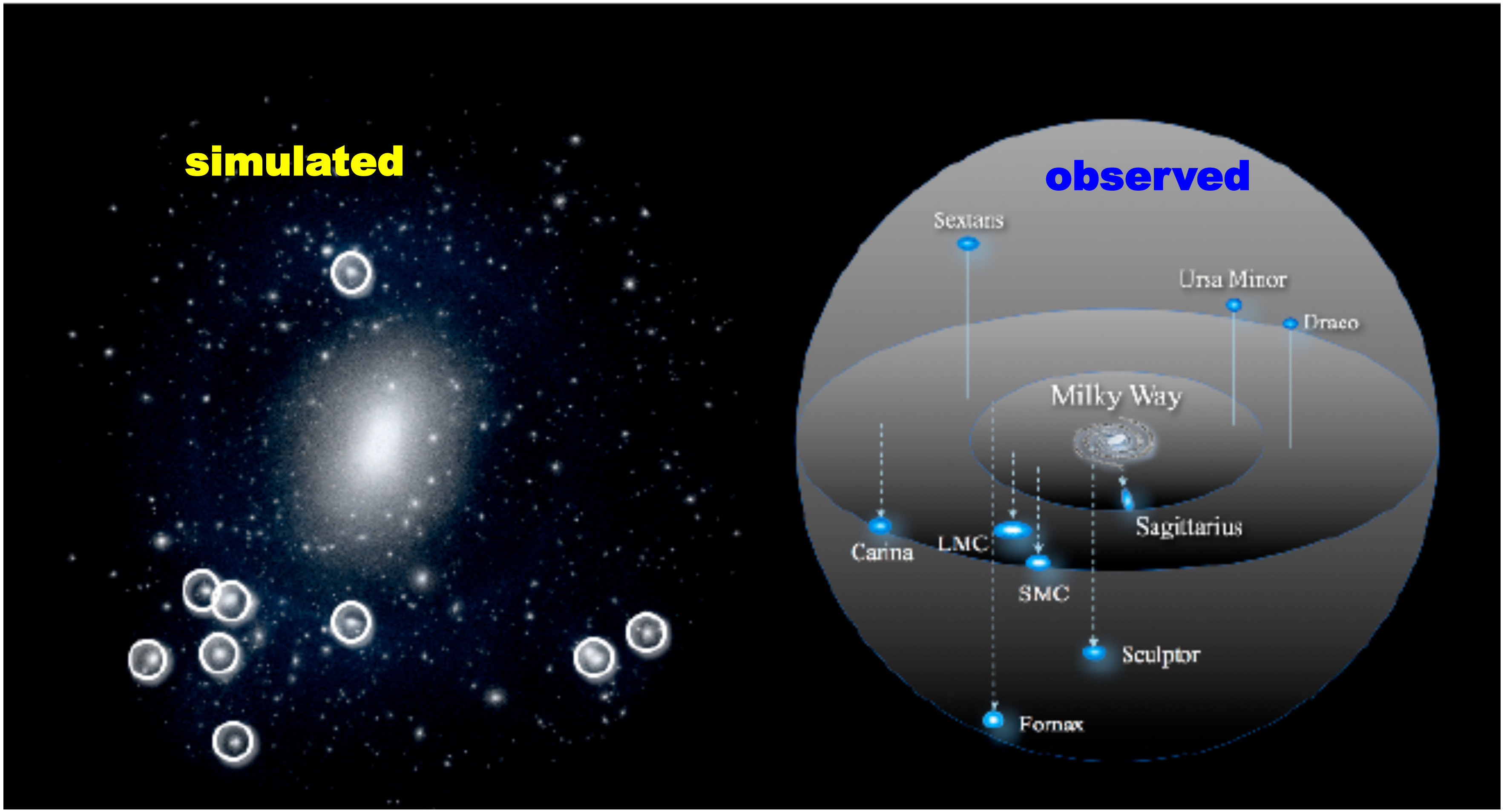
Discrepancy between numerical cosmological **simulations**
that predict the evolution of the distribution of matter in the universe - pointing towards a **hierarchical clustering** of DM in the sense **of ever increasing for smaller and-smaller-sized halos** - **and observations**.

Although there seem to be **enough observed normal-sized galaxies** to account for such a distribution, **the number of dwarf galaxies** is orders of magnitude **lower than** that expected from the **simulations**.

E.g. there were observed to be around 38 dwarf galaxies in the Local Group,
and only around 11 orbiting the Milky Way,
yet one **dark matter simulation** predicted around **500 Milky Way dwarf satellites**

B. Moore *et al.*, Astrophys. J. 524 , L19 (1999)
A. Klypin, *et al.*,Astrophys. J. 522, 82 (1999)
E. Polisensky and M. Ricotti, PR D83, 043506 (2011)

(ii) The missing satellite (dwarves) problem

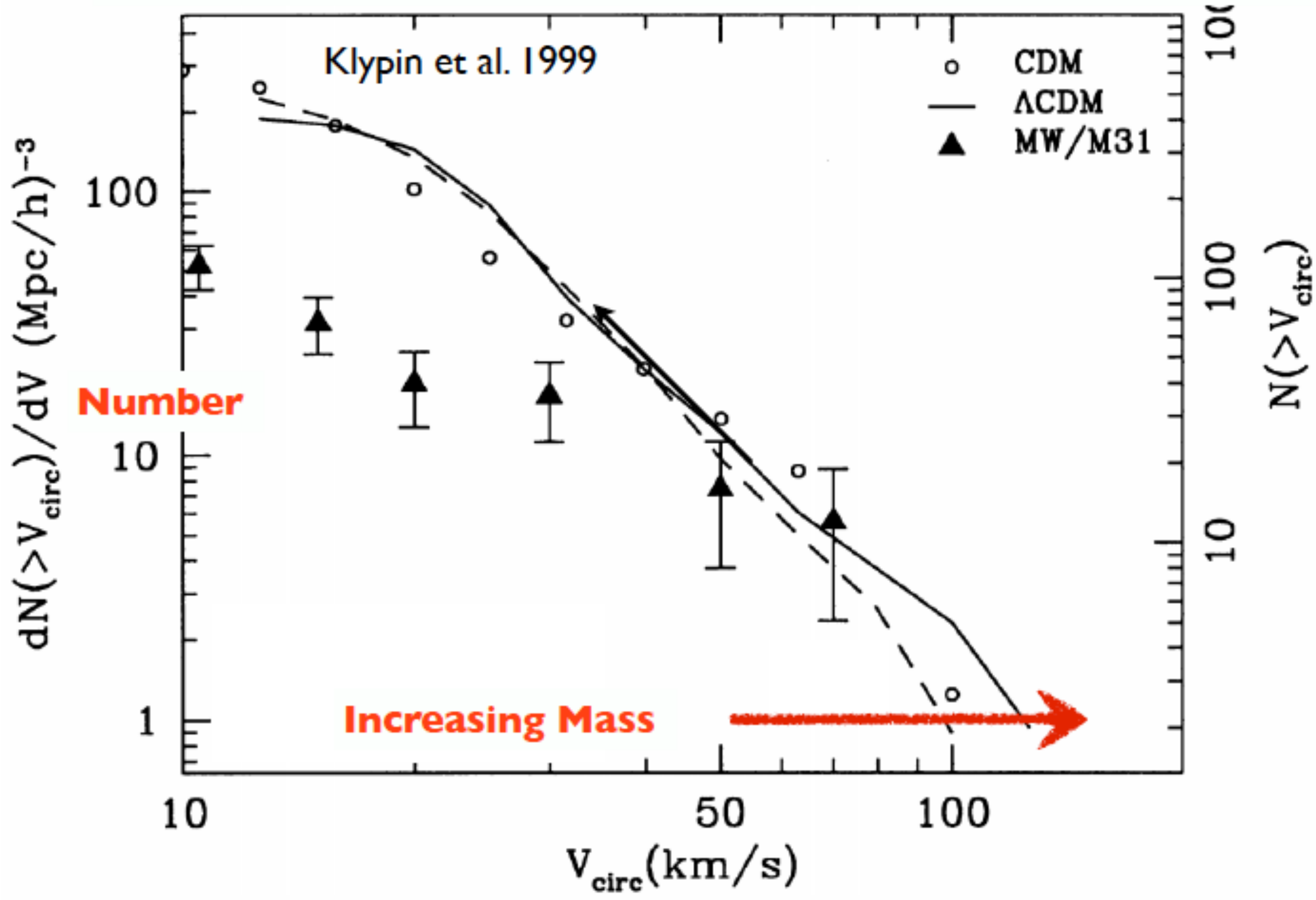


Weinberg et al. 2013, arXiv:1306.0913

(ii) The missing satellite (dwarves) problem

Missing Satellite Problem (MSP)

A quantitative comparison of # satellites at r < 400 kpc.



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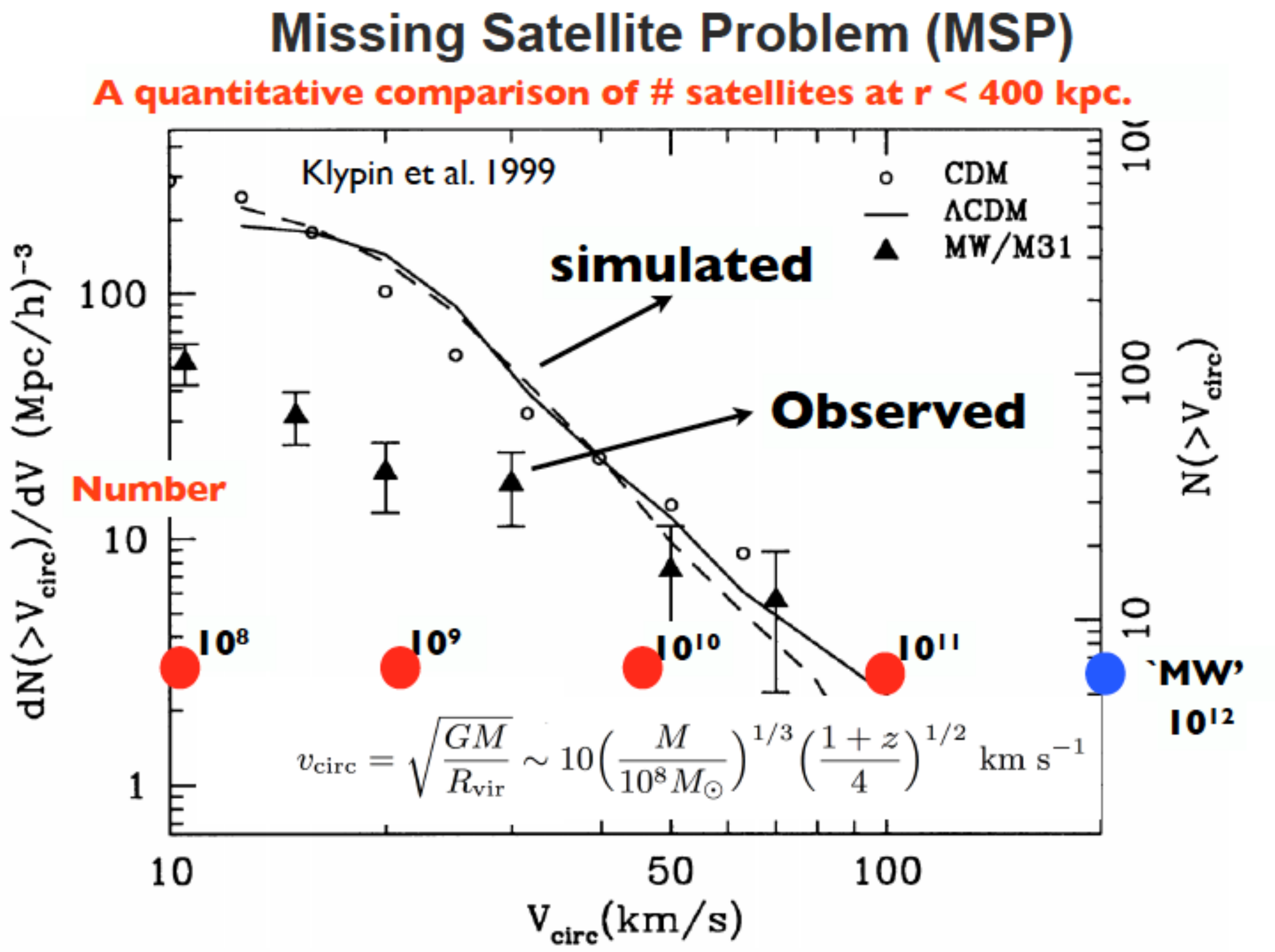

$$v_{\rm circ} = \sqrt{\frac{GM}{R_{\rm vir}}} \sim 10\left(\frac{M}{10^8 M_\odot}\right)^{1/3}\left(\frac{1+z}{4}\right)^{1/2} \text{km s}^{-1}$$

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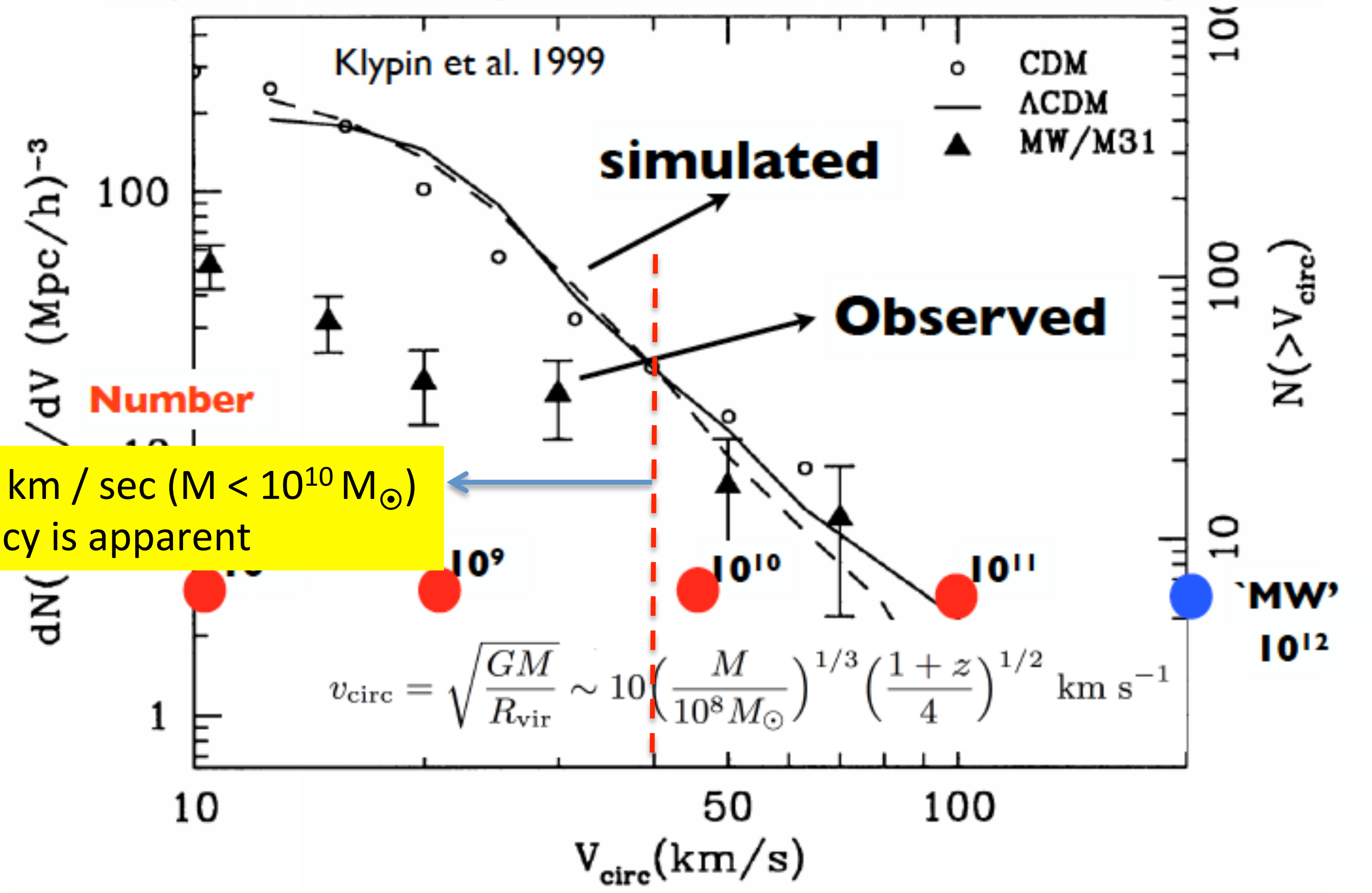
Missing Satellite Problem (MSP)

A quantitative comparison of # satellites at r < 400 kpc.



$$v_{\rm circ} = \sqrt{\frac{GM}{R_{\rm vir}}} \sim 10\left(\frac{M}{10^8 M_\odot}\right)^{1/3}\left(\frac{1+z}{4}\right)^{1/2}\ \mathrm{km\ s^{-1}}$$

for v < 40 km / sec ($M < 10^{10}\ M_\odot$) discrepancy is apparent

The 3-Problems of Galactic-Scale-Cosmology (GSC)

(iii) The too-Big-to-Fail Problem

Discrepancy between the most **massive subhaloes of the Milky Way**, as predicted by numerical cosmological **simulations in collisionless ΛCDM**, and the **dynamics** of **its brightest dwarf spheroidals.**

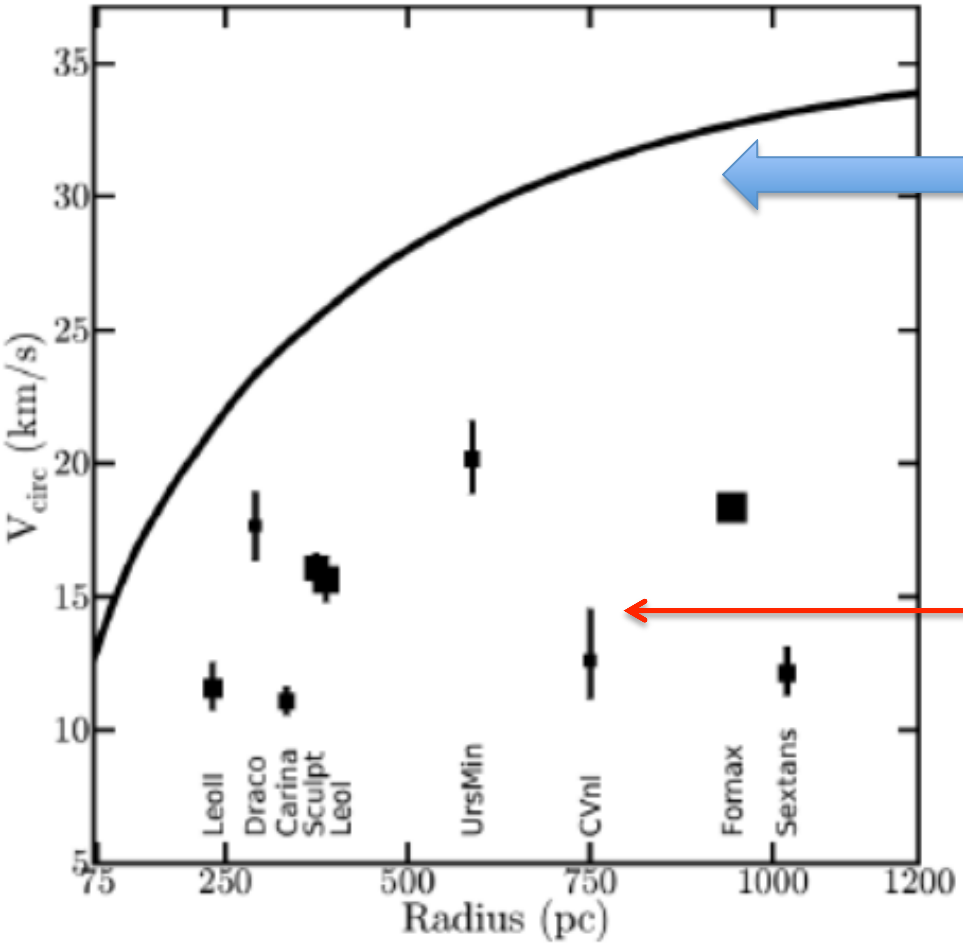
ΛCDM simulations predict that the most massive subhaloes of the Milky Way are too dense to host any of its brightest satellites, with luminosity higher than 10^5 the luminosity of the Sun.

(Models that are based on simulations predict much larger rotational velocities than the observed ones

Rotational velocities → measure of enclosed mass → ΛCDM predicted satellites are too massive (too big).)

M. Boylan-Kolchin, J.S. Bullock & M. Kaplinghat, MNRAS 415, L11 (2011); *ibid.* 422, 1203 (2012)

(iii) The too-big-to-fail Problem



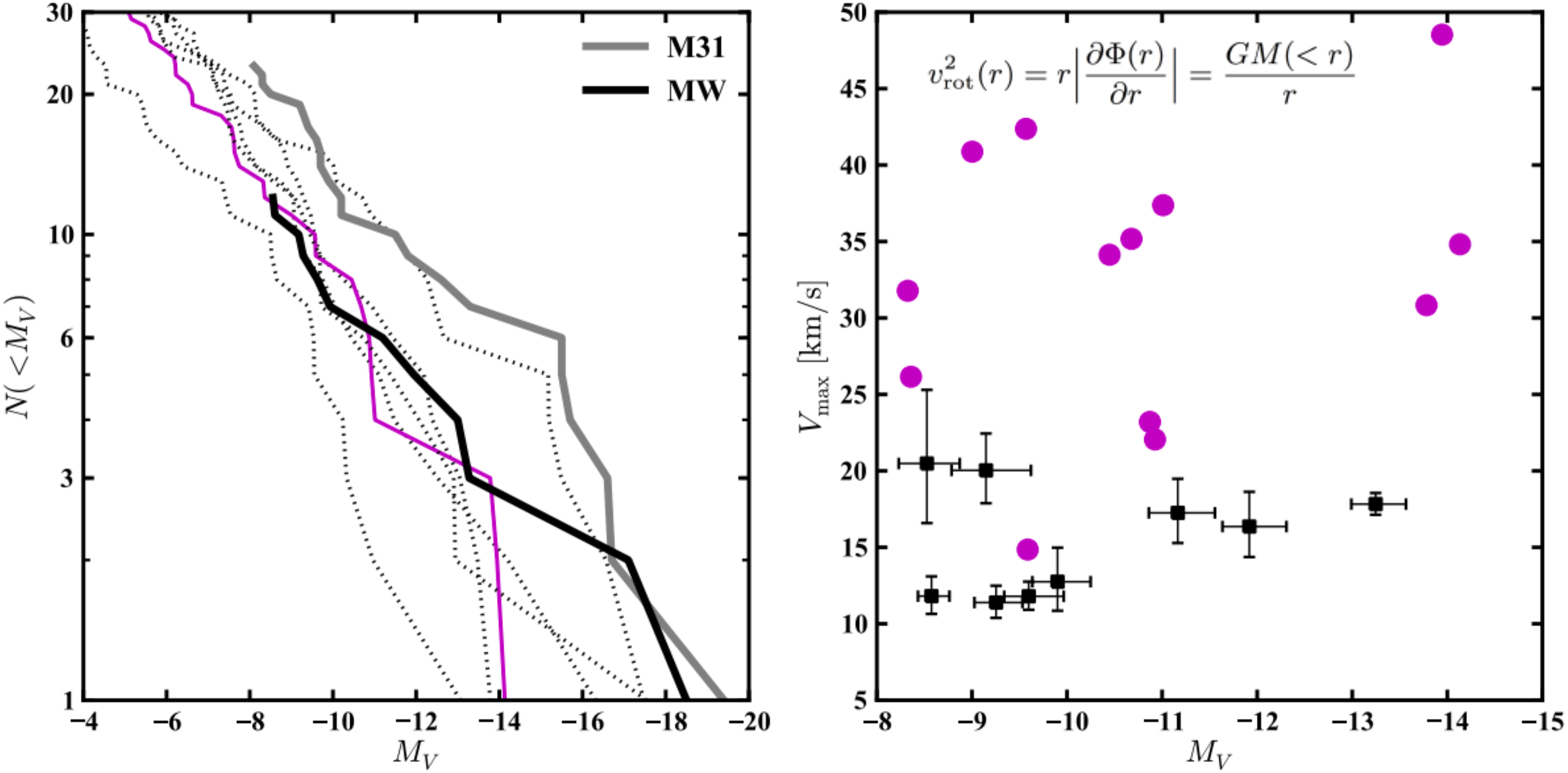
Continuous curve: rotation curve of typical largest sub-halo of the Milky Way as **simulated by collisionless ΛCDM**

Data points pertain to **observed** circular **velocities** of the largest subhaloes of the Milky Way at their half-light radii

$$v_{\rm rot}^2(r) = r\left|\frac{\partial\Phi(r)}{\partial r}\right| = \frac{GM(<r)}{r}$$

M. Boylan-Kolchin, J.S. Bullock & M. Kaplinghat, MNRAS 415, L11 (2011); *ibid.* 422, 1203 (2012)

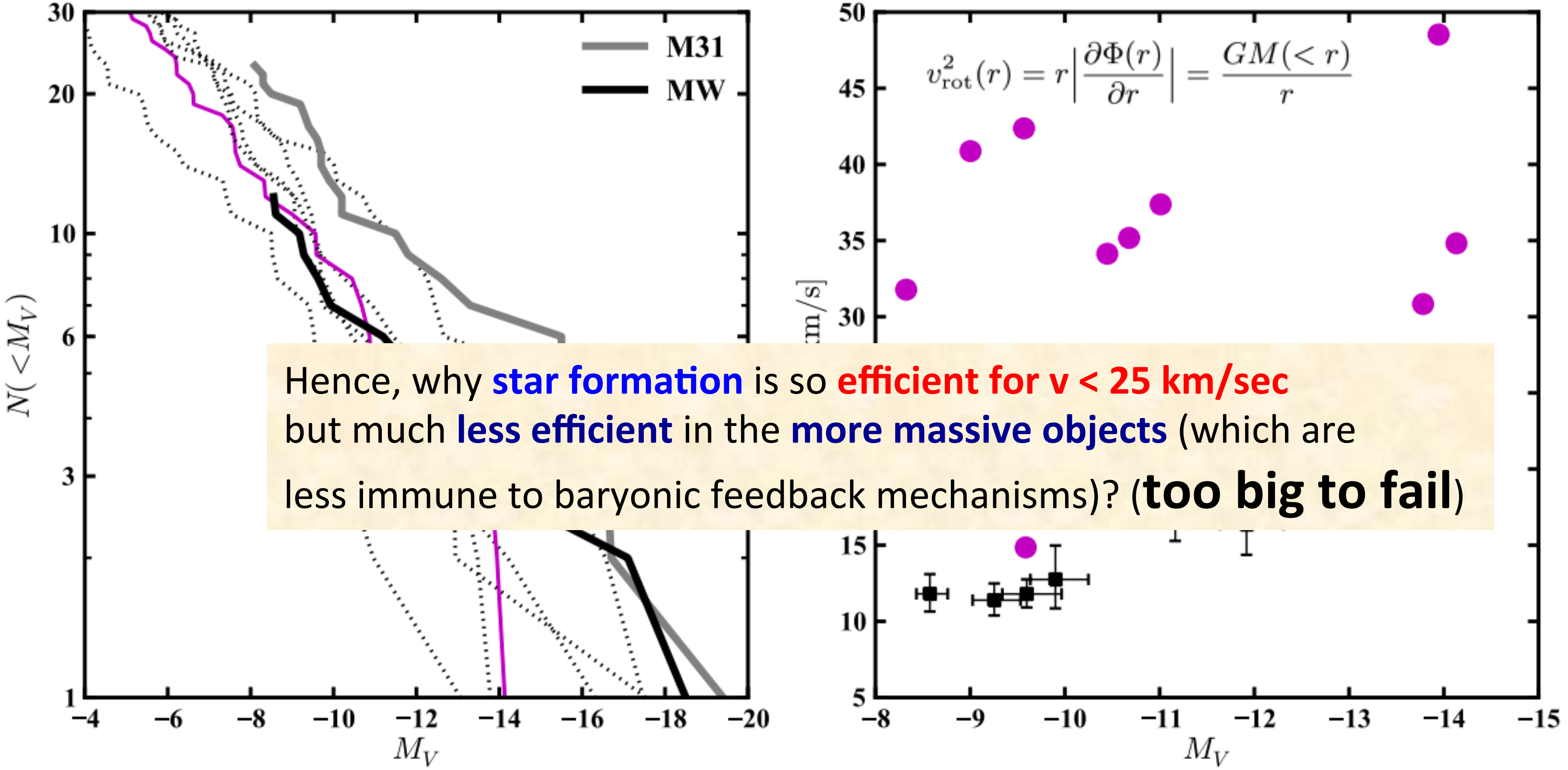
(iii) The too-big-to-fail Problem



NB: Models that reproduce observed satellite luminosity function – and thus solve the missing satellite problem, predict significantly larger rotational velocities for satellites than the observed ones (**v_{obs} < 25 km/sec**)

M. Boylan-Kolchin, J.S. Bullock & M. Kaplinghat, MNRAS 415, L11 (2011); *ibid.* 422, 1203 (2012)

(iii) The too-big-to-fail Problem



Hence, why **star formation** is so **efficient for v < 25 km/sec** but much **less efficient** in the **more massive objects** (which are less immune to baryonic feedback mechanisms)? (**too big to fail**)

NB: Models that reproduce observed satellite luminosity function – and thus solve the missing satellite problem, predict significantly larger rotational velocities for satellites than the observed ones (**v_{obs} < 25 km/sec**)

M. Boylan-Kolchin, J.S. Bullock & M. Kaplinghat, MNRAS 415, L11 (2011); *ibid.* 422, 1203 (2012)

Towards a Solution of the 3-Problems of Galactic-Scale-Cosmology (GSC)

Towards a Solution of the 3-Problems of Galactic-Scale-Cosmology (GSC)

Microscopic Physics explanations needed...

All of the above problems seem that **cannot be entirely solved**
by **conventional Astrophysics** explanations (**faint dwarfs, baryonic feedback, tidal stripping apart of dwarfs by (or merging into) larger galaxies....**)
- **discrepancies still remain, moreover: case by case studies**

The root of the 3 problems lies on the fact that the **CDM particles**
entering the Λ**CDM-based simulations** have
too short free streaming length
during the epochs of galaxy formation, and therefore
they form too clumped
and **too many structures compared** to those **observed.**

Towards a Solution of the 3-Problems of Galactic-Scale-Cosmology (GSC)

Microscopic Physics explanations

All of the above problems seem that **cannot be entirely solved** by **conventional Astrophysics** explanations
– **discrepancies still remain**

CHANGE THE ΛCDM →

Towards a Solution of the 3-Problems of Galactic-Scale-Cosmology (GSC)

Microscopic Physics explanations

All of the above problems seem that **cannot be entirely solved** by **conventional Astrophysics** explanations
– **discrepancies still remain**

CHANGE THE ΛCDM →

(i) modify gravity models (no DM except neutrinos)
→ lensing problematic (bullet cluster or other merging galaxies, offer observational support for DM)

Milgrom, Bekenstein (TeVeS)

Towards a Solution of the 3-Problems of Galactic-Scale-Cosmology (GSC)

Microscopic Physics explanations

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for our talk

Towards a Solution of the 3-Problems of Galactic-Scale-Cosmology (GSC)

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All of the above problems seem that **cannot be entirely solved** by **conventional Astrophysics** explanations
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CHANGE THE ΛCDM →

(i) modify ~~gravity models (no DM except neutrinos)~~
→ lensing ~~problematic (bullet cluster~~ or
other merging ~~galaxies, offer observational~~ support for DM)

for our talk

(ii) CHANGE the DM properties → include self interactions
or assume more than one dominant species
… with non-trivial role in
galactic structure

Self-Interacting Dark Matter (SIDM) & small-scale Cosmology

Early pioneering works in implementing SIDM in N-body simulations

D. N. Spergel and P. J. Steinhardt, PRL 84 , 3760 (2000)

Figure of merit: (total) cross section per unit DM particle mass

σ/m

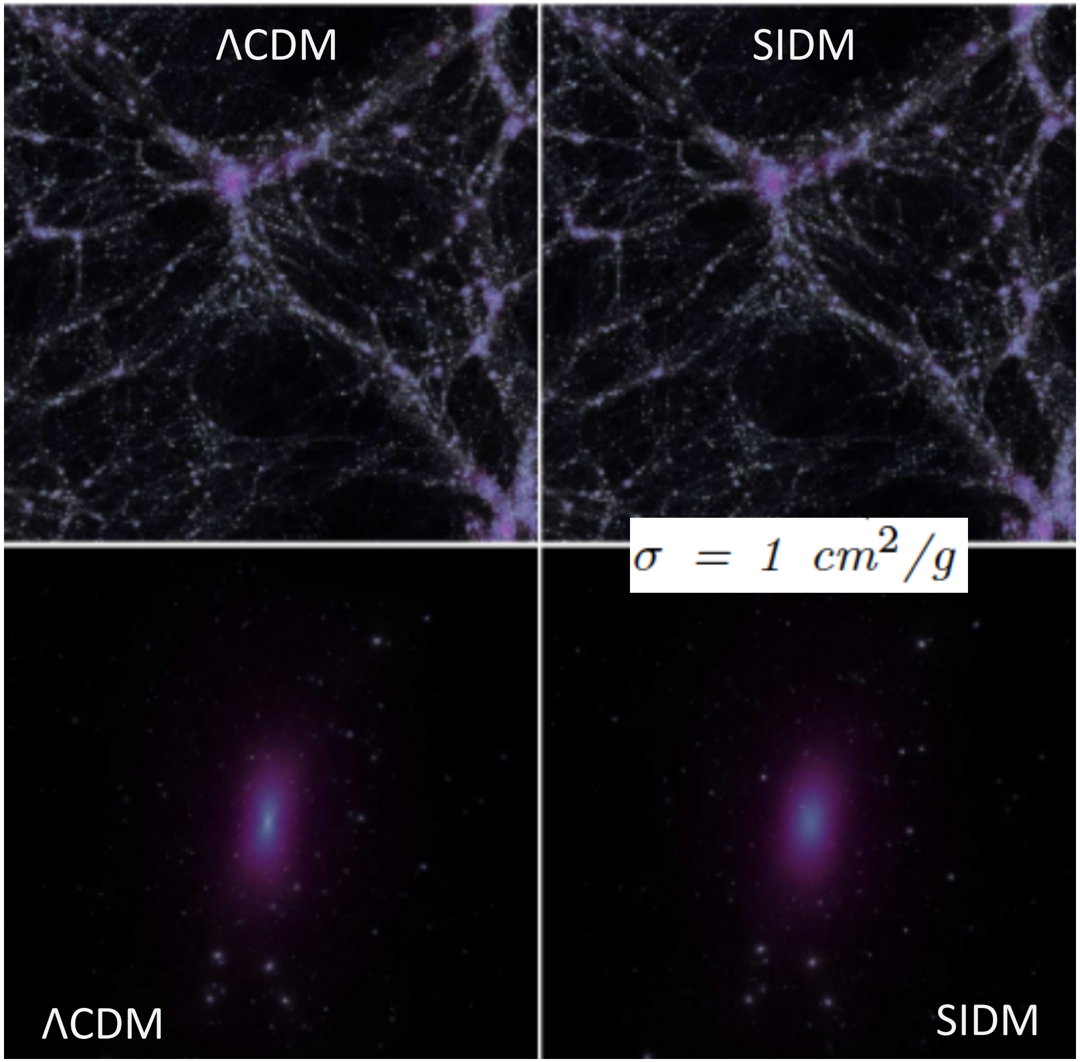
Early days: 10 GeV $c^{-2} \geq m \geq 1$ MeV c^{-2}

in DM haloes with densities $10^{-2} M_{\odot}/\mathrm{pc}^3$

$$\sigma/m \sim 0.1 - 100 \ \mathrm{cm}^2/\mathrm{g}$$

would imply observational effects in the inner haloes

Self-Interacting Dark Matter (SIDM) & small-scale Cosmology



Large Scale Structure: roughly the same

Individual galaxies: more cored & spherical in SIDM models

M Rocha *et al.* MNRAS 430, 81 (2013)

Self-Interacting Dark Matter (SIDM) & small-scale Cosmology

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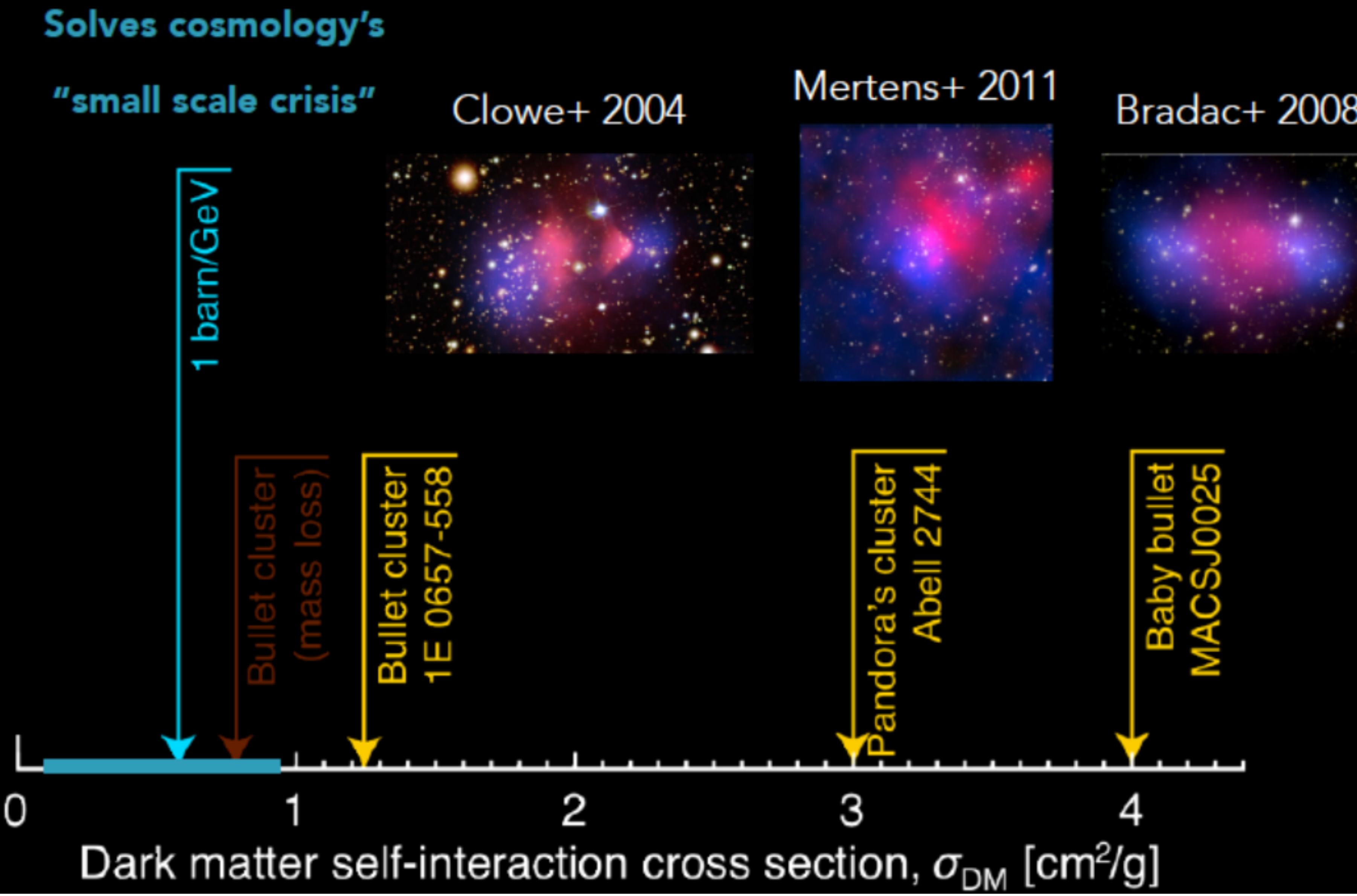
$$\sigma/m \sim \boxed{0.1} - 100\ \text{cm}^2/\text{g}$$

=1 barn/GeV

consistent with all current constraints of GSC

would imply observational effects in the inner haloes

CONSTRAINTS ARE LIMITED



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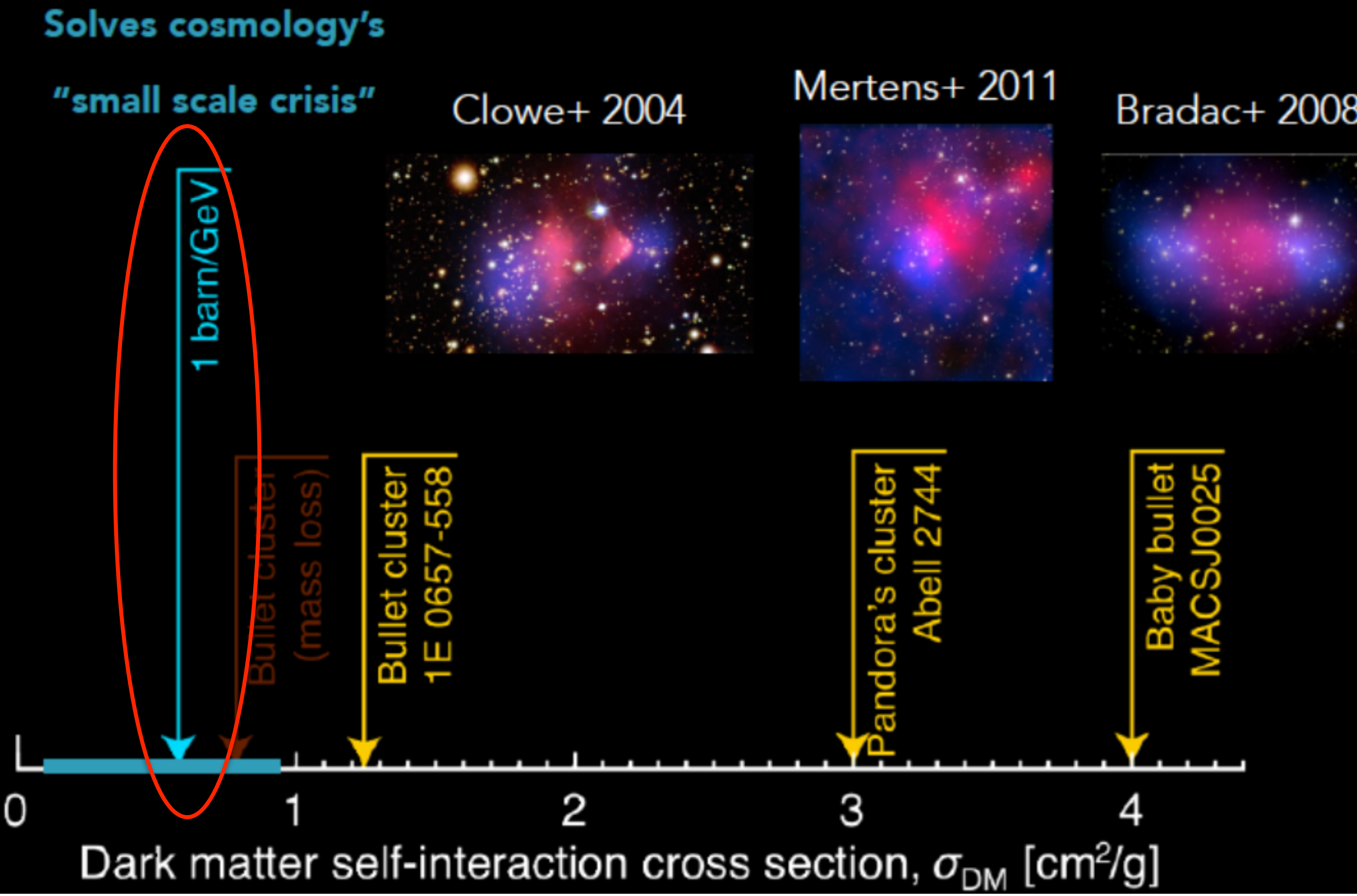
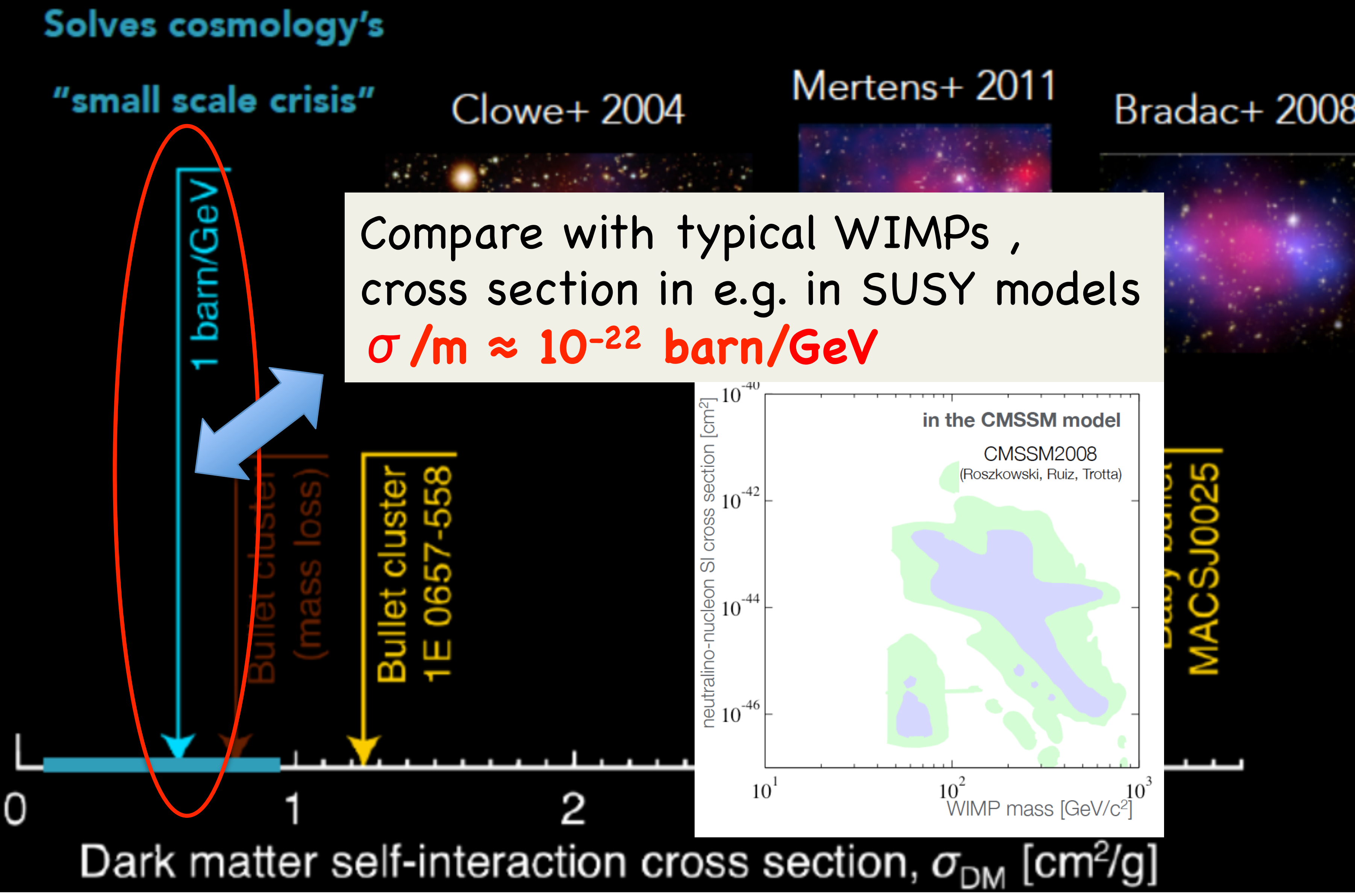


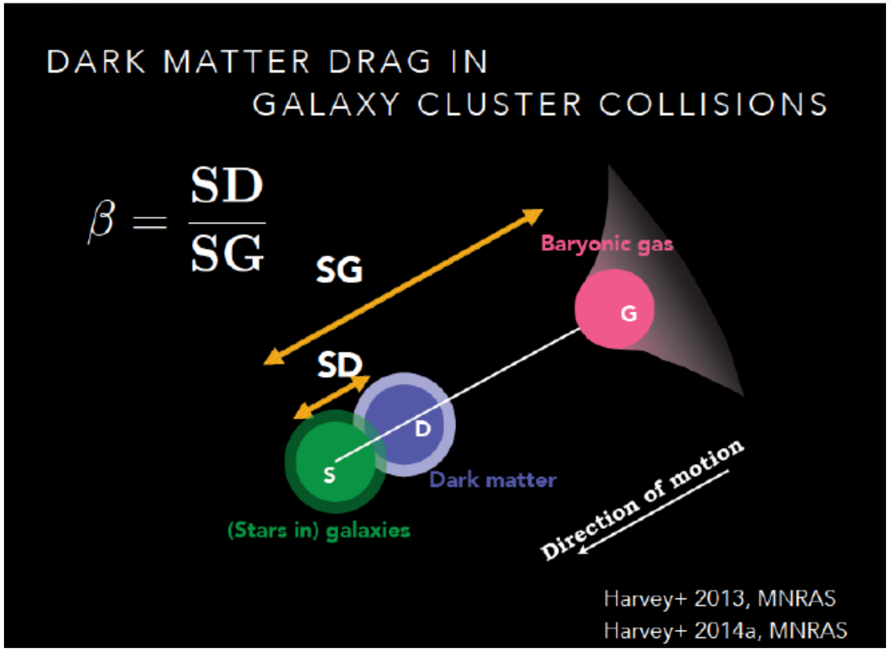
CONSTRAINTS ARE LIMITED



Compare with typical WIMPs ,
cross section in e.g. in SUSY models
$\sigma/m \approx 10^{-22}$ barn/GeV

Recent Developments – New Observables due to DM drag in **collding galaxy clusters**

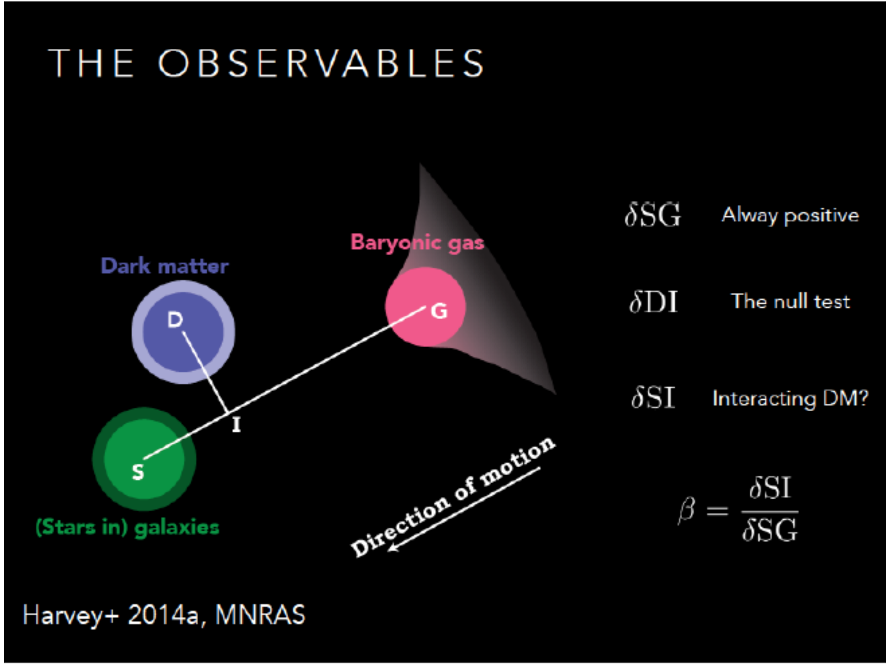
Harvey,Massey,Kitching,Taylor,Titley
arXiv:1503.07675, *Science*



DARK MATTER DRAG IN GALAXY CLUSTER COLLISIONS

$$\beta = \frac{\mathrm{SD}}{\mathrm{SG}}$$

Harvey+ 2013, MNRAS
Harvey+ 2014a, MNRAS

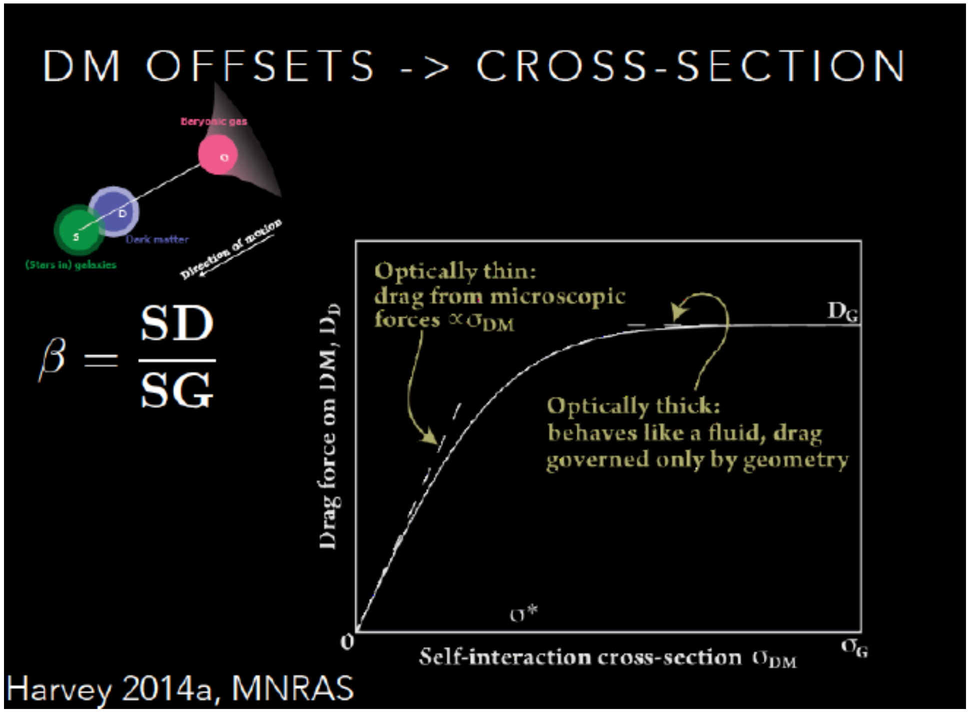


THE OBSERVABLES

$\delta\mathrm{SG}$	Alway positive
$\delta\mathrm{DI}$	The null test
$\delta\mathrm{SI}$	Interacting DM?

$$\beta = \frac{\delta\mathrm{SI}}{\delta\mathrm{SG}}$$

Harvey+ 2014a, MNRAS



DM OFFSETS -> CROSS-SECTION

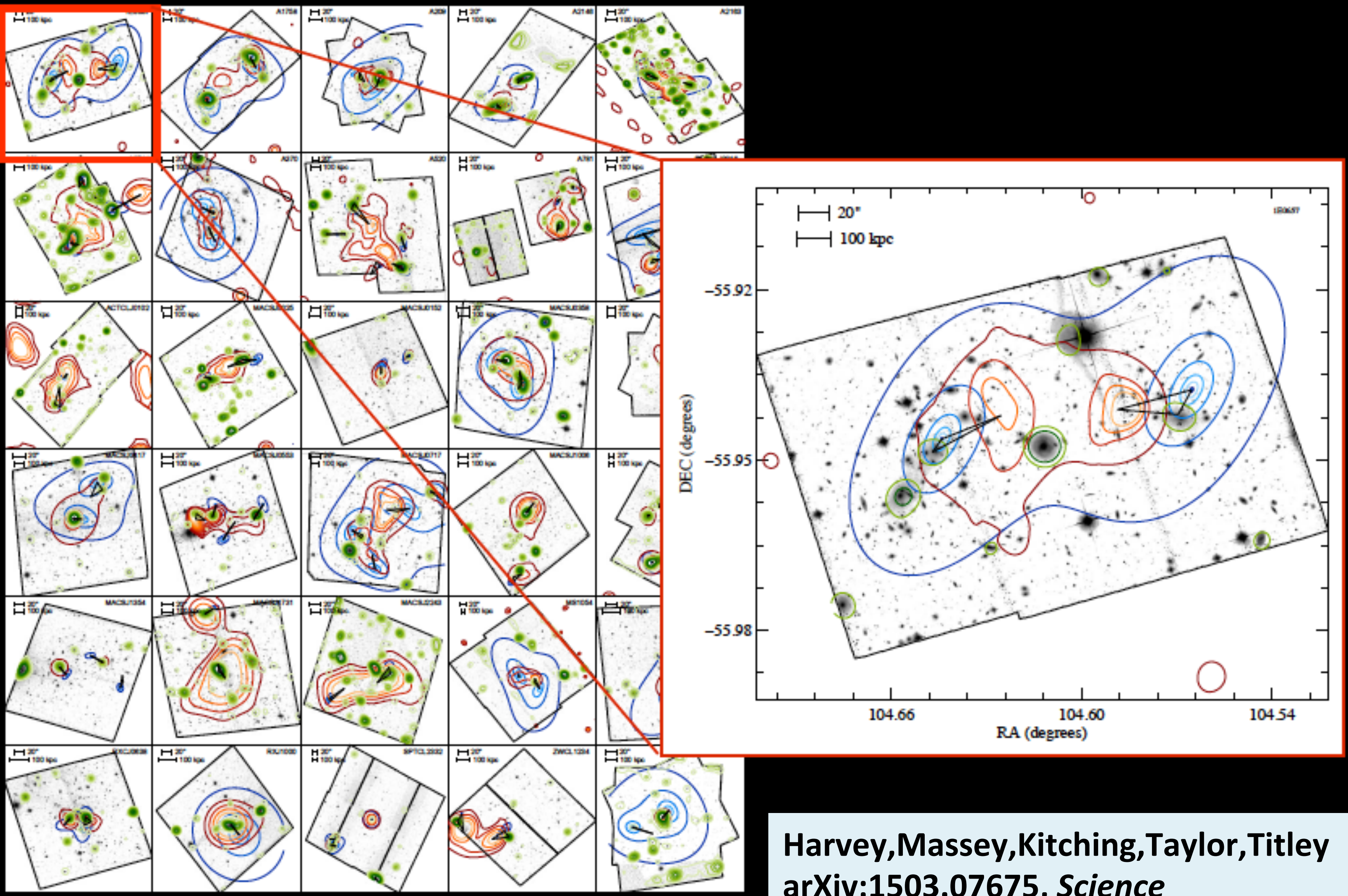
$$\beta = \frac{\mathrm{SD}}{\mathrm{SG}}$$

Optically thin: drag from microscopic forces $\propto \sigma_{DM}$

Optically thick: behaves like a fluid, drag governed only by geometry

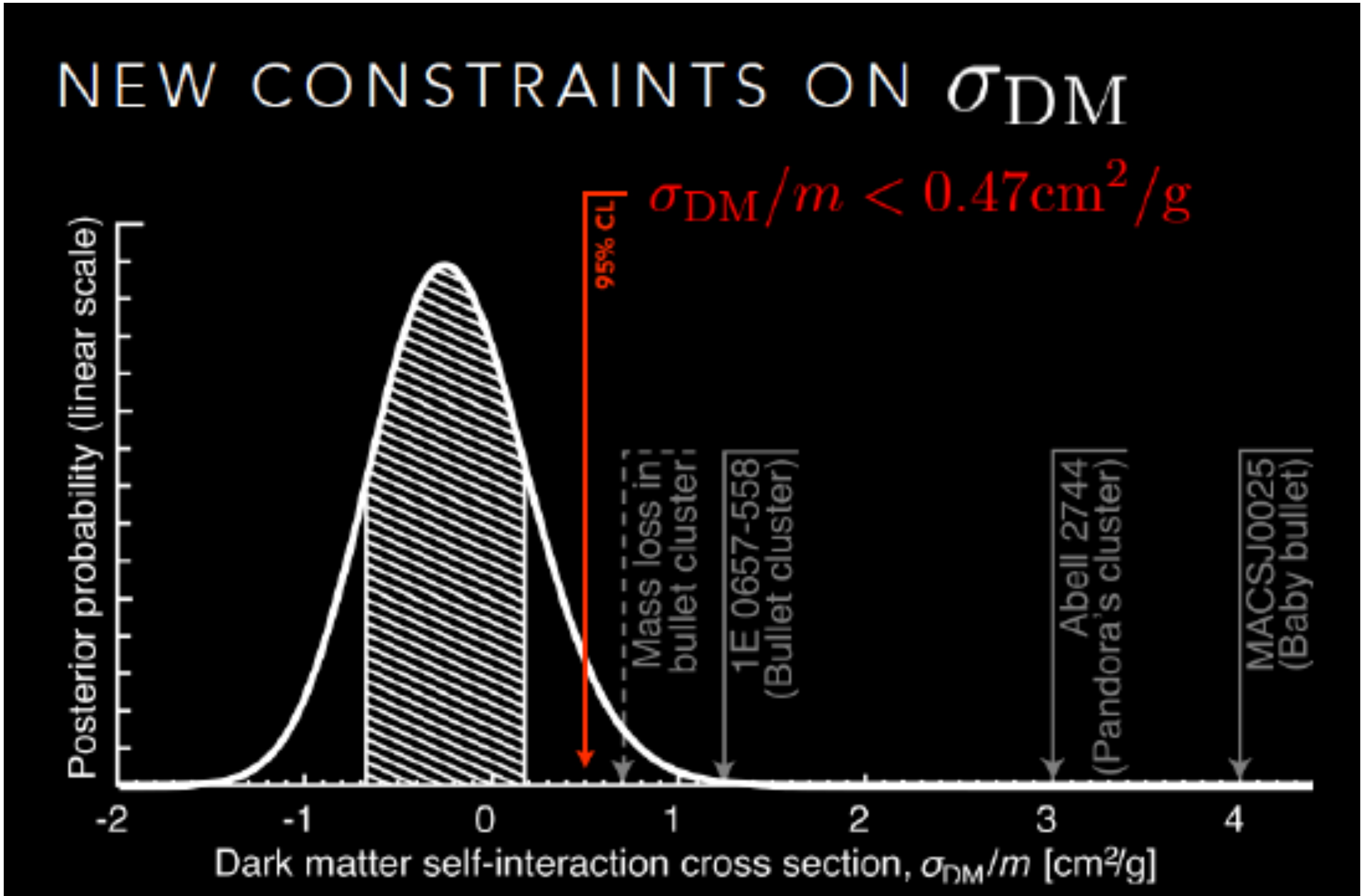
Harvey 2014a, MNRAS

30 MERGING GALAXY CLUSTERS



Harvey,Massey,Kitching,Taylor,Titley arXiv:1503.07675, *Science*

Self-Interacting Dark Matter (SIDM) & small-scale Cosmology



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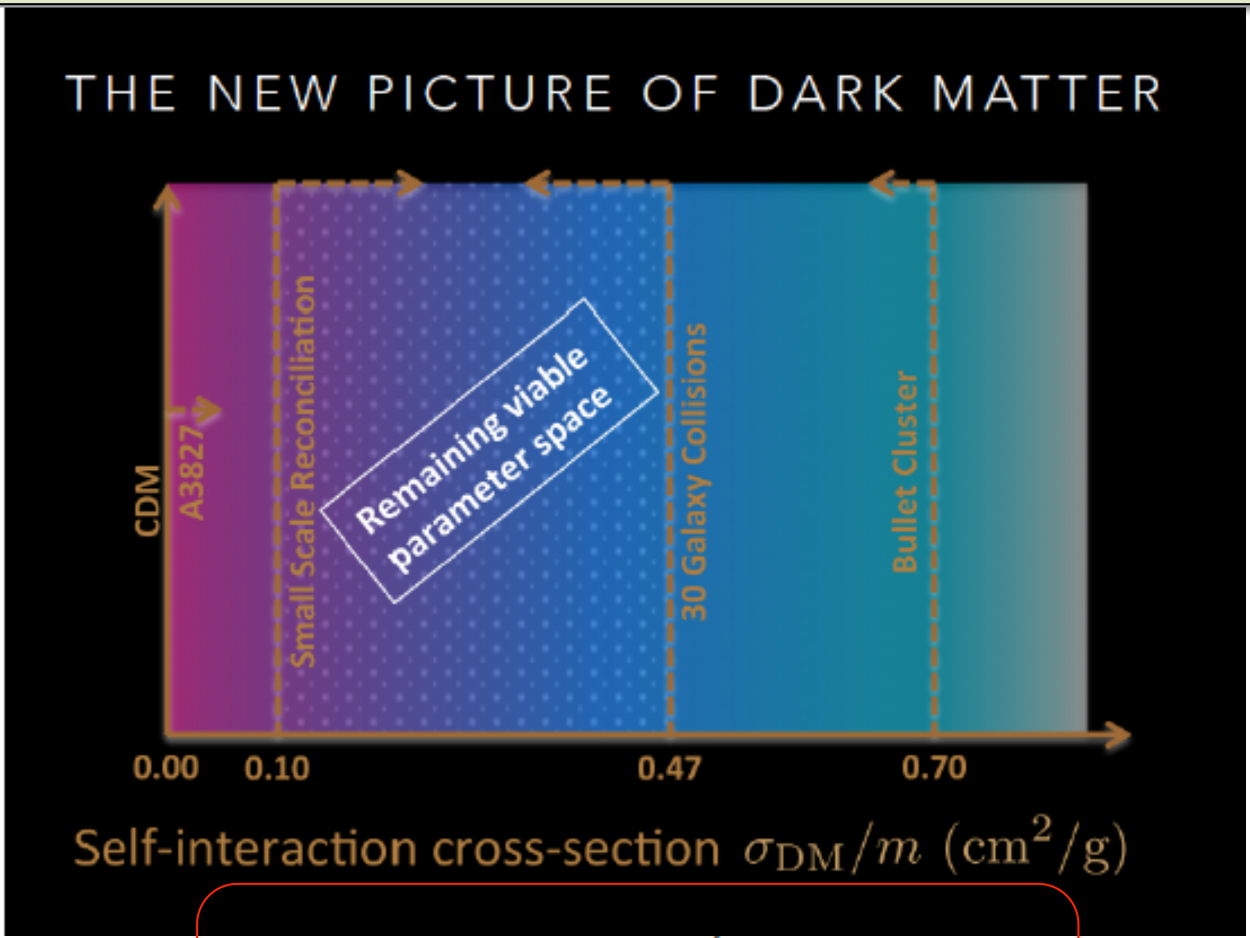
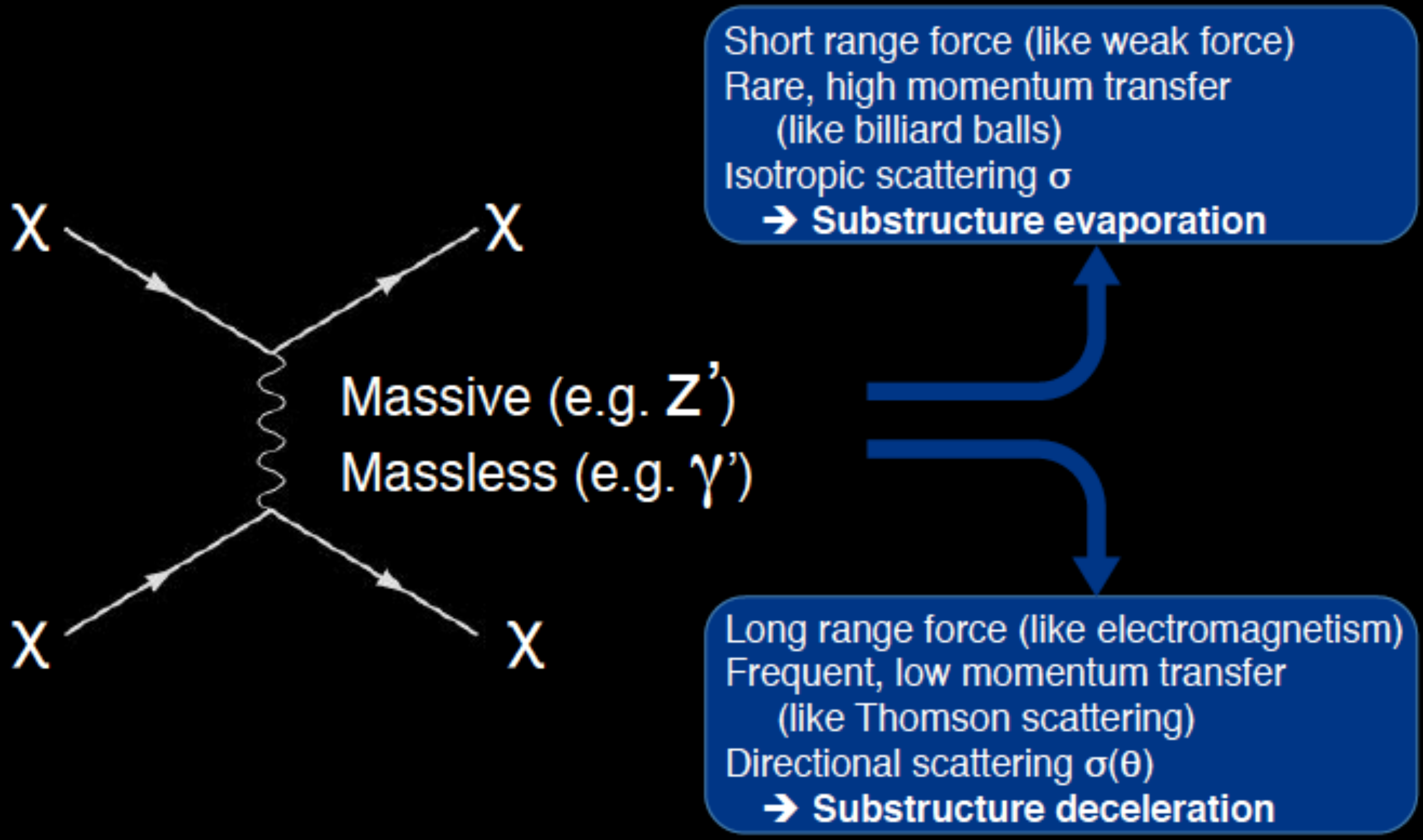
Self-Interacting Dark Matter (SIDM) & small-scale Cosmology



$$0.1 \leq \frac{\sigma_{\rm SIDM}/m}{{\rm cm}^2\, g^{-1}} \leq 0.47$$

OBSERVABLE MANIFESTATION OF SELF-INTERACTIONS IN COLLIDING CLUSTERS



Massive (e.g. Z')

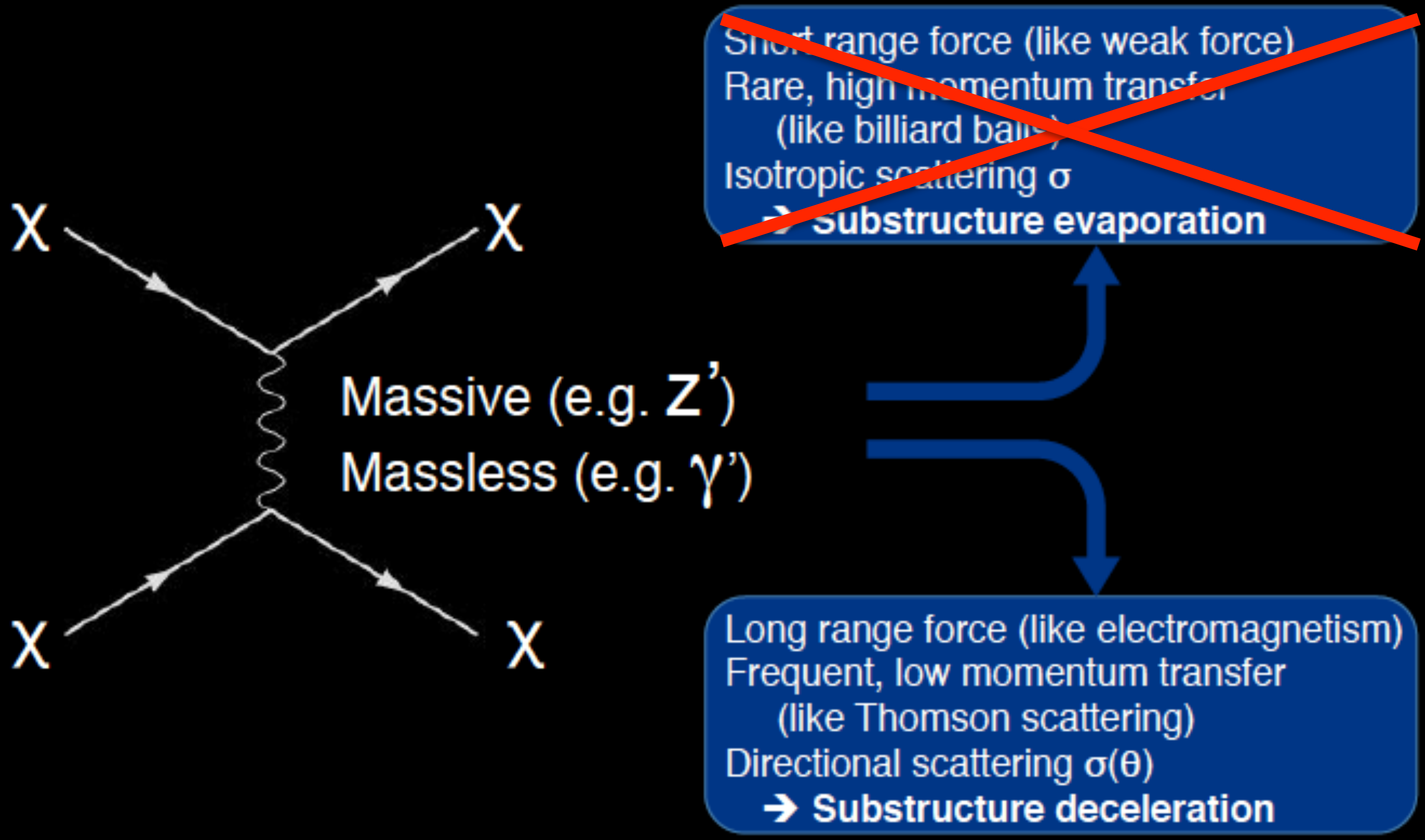
Massless (e.g. γ')

Short range force (like weak force)
Rare, high momentum transfer
(like billiard balls)
Isotropic scattering σ
→ **Substructure evaporation**

Long range force (like electromagnetism)
Frequent, low momentum transfer
(like Thomson scattering)
Directional scattering σ(θ)
→ **Substructure deceleration**

Kahlhoefer et al. 2014, MNRAS 437, 5865
Boehm et al. 2010, PRL 105, 1301

OBSERVABLE MANIFESTATION OF SELF-INTERACTIONS IN COLLIDING CLUSTERS



Massive (e.g. Z')
Massless (e.g. γ')

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Long range force (like electromagnetism)
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Kahlhoefer et al. 2014, MNRAS 437, 5865
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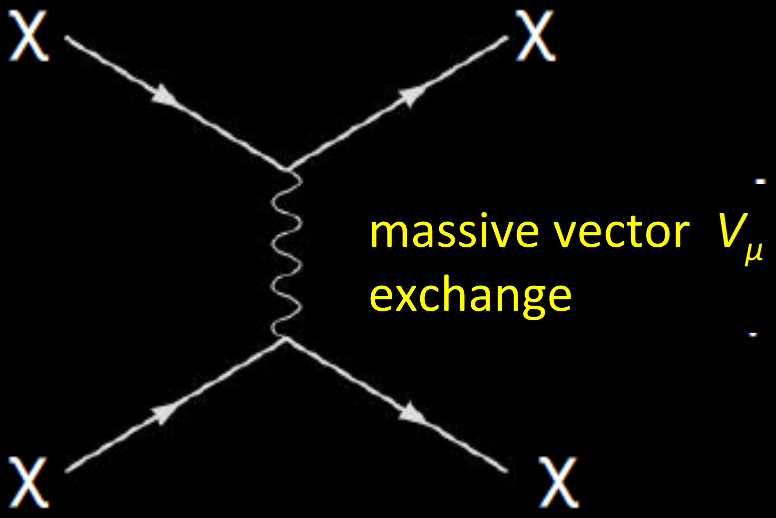
OBSERVABLE MANIFESTATION OF SELF-INTERACTIONS IN COLLIDING CLUSTERS

χ = Right-handed neutrino



In **Right-handed neutrino** WDM:
(i) mass of O(50) keV, interactions
(ii) stronger than the weak force, $10^8\,G_F$
(iii) massive ~ 10^4 keV exchange vector
is **OK** for **core-galaxy structure**

Arguelles, NEM, Ruffini, Rueda, JCAP (2016)

PART III

Self-Interacting Right-Handed Neutrino Warm Dark matter
&
galactic core-halo structures

Earlier Studies:
massive (non-interacting) fermions in galaxies
@ a quantum level

Collisionless Relaxation mechanics in galaxies (**King Model**)

$$\frac{\partial f}{\partial t} + \mathbf{v}\frac{\partial f}{\partial \mathbf{r}} - \nabla\Phi(\mathbf{r},t)\frac{\partial f}{\partial \mathbf{v}} = 0 \qquad \triangle\Phi = 4\pi G\int f d^3\mathbf{v}$$

$$f \to \bar{f}$$

average

Violent relaxation (**Lynden Bell (1967)**)

$$\frac{dE}{dt} = \frac{\partial\Phi}{\partial t}|_{r(t)}$$

total **energy not conserved**

$$S = \int \rho(\mathbf{r},\mathbf{v},\eta)\ln\rho(\mathbf{r},\mathbf{v},\eta)d\eta d^3\mathbf{r}d^3\mathbf{v} \qquad \bar{f}(\mathbf{r},\mathbf{v}) = \int \rho(\mathbf{r},\mathbf{v},\eta)\eta d\eta$$

entropy maximization at fixed total mass &energy

$$\delta S = 0 \Rightarrow \bar{f} = \frac{1}{e^{\beta[\epsilon(p)-\alpha]}+1}$$

Earlier Studies:
massive (non-interacting) fermions in galaxies
@ a quantum level

Ruffini & Stella, A & A (1983)

Collisionless Relaxation mechanics in galaxies

$$\frac{\partial f}{\partial t} + \mathbf{v}\frac{\partial f}{\partial \mathbf{r}} - \nabla\Phi(\mathbf{r},t)\frac{\partial f}{\partial \mathbf{v}} = 0 \qquad \triangle\Phi = 4\pi G\int f d^3\mathbf{v}$$

$$f \rightarrow \bar{f}$$

average

$$\boxed{\begin{aligned} f(v) &= \frac{1-\exp\left[-j^2(v_e^2 - v^2)\right]}{\exp\left[j^2(v^2-\bar{\mu})\right]+1}, & v \le v_e \\ &= 0, & v > v_e, \end{aligned}}$$

rotational velocities

$j^2 = m/(2kT)$, $\bar{\mu} = 2\mu/m$ and $\theta = j^2\bar{\mu}$.

$\theta \rightarrow -\infty \Rightarrow$ dilute limit (King distribution at classical level)

Earlier Studies:
massive (non-interacting) fermions in galaxies @ a quantum level

Gao, Merafina, Ruffini, A & A (1990)

Collisionless Relaxation mechanics in galaxies

$$\frac{\partial f}{\partial t} + \mathbf{v}\frac{\partial f}{\partial \mathbf{r}} - \nabla\Phi(\mathbf{r},t)\frac{\partial f}{\partial \mathbf{v}} = 0 \qquad \triangle\Phi = 4\pi G \int f d^3\mathbf{v}$$

$$f(p) = \frac{1}{e^{\frac{\epsilon(p)-\mu}{kT}} + 1}, \qquad \epsilon(p) = \sqrt{c^2p^2 + m^2c^4} - mc^2$$

Fermi distribution

Pauli exclusion principle

Equation of State

$$\begin{aligned} \rho &= m\frac{2}{h^3}\int f(p)\left[1+\frac{\epsilon(p)}{mc^2}\right] d^3p, \\ P &= \frac{1}{3}\frac{2}{h^3}\int f(p)\left[1+\frac{\epsilon(p)}{mc^2}\right]^{-1}\left[1+\frac{\epsilon(p)}{2mc^2}\right]\epsilon\, d^3p, \end{aligned}$$

in curved metric

$$ds^2 = e^{\nu}c^2dt^2 - e^{\lambda}dr^2 - r^2d\theta^2 - r^2\sin^2\theta d\phi^2$$

Earlier Studies:
massive (non-interacting) fermions in galaxies
@ a quantum level

Gao, Merafina, Ruffini, A & A (1990)

Einstein equations

$$e^{-\lambda} = 1 - \frac{2GM}{c^2 r}.$$

$$\begin{aligned} \frac{dM}{dr} &= 4\pi r^2 \rho, \\ \frac{dP}{dr} &= -\frac{1}{2}\frac{d\nu}{dr}(c^2\rho + P), \quad \frac{d\nu}{dr} = \frac{2G}{c^2}\frac{M + 4\pi r^3 P/c^2}{r^2[1 - 2GM/(c^2 r)]} \end{aligned}$$

First law of **thermodynamics** (**Klein conditions**)

$$\begin{aligned} e^{\nu/2} T &= \text{constant}, \\ e^{\nu/2}(\mu + mc^2) &= \text{constant}. \end{aligned}$$

Earlier Studies:
massive (non-interacting) fermions in galaxies
@ a quantum level

Gao, Merafina, Ruffini, A & A (1990)
Ruffini, Arguelles, Rueda, MNRAS (2015)

Dimensionless form of equations

$(\hat{r} = r/\chi,\ \chi \propto m^{-2})$

m=fermion mass
(``**ino**'')

$$\frac{d\hat{M}}{d\hat{r}} = 4\pi\hat{r}^2\hat{\rho},$$

$$\frac{d\theta}{d\hat{r}} = -\frac{1-\beta_0(\theta-\theta_0)}{\beta_0}\frac{\hat{M}+4\pi\hat{P}\hat{r}^3}{\hat{r}^2(1-2\hat{M}/\hat{r})},$$

$$\beta(r) = \beta_0 e^{-\frac{\nu(r)+\nu_0}{2}}$$

$$\frac{d\nu}{d\hat{r}} = \frac{\hat{M}+4\pi\hat{P}\hat{r}^3}{\hat{r}^2(1-2\hat{M}/\hat{r})},$$

Free parameters: $\beta_0 = kT_0/mc^2$, $\theta_0 = \mu_0/kT_0$ and m

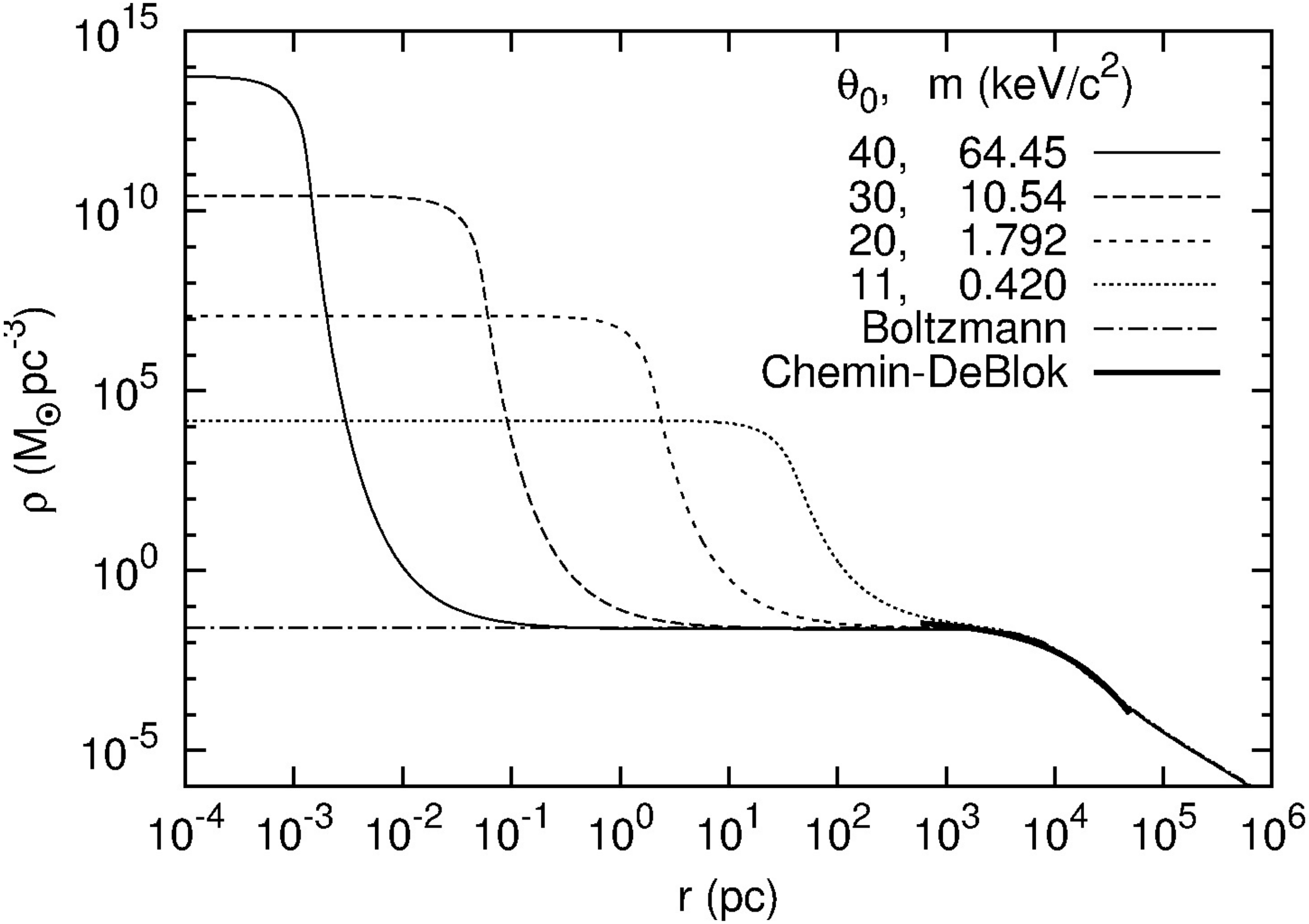
Initial conditions $M(0)=0;\quad \nu_0=0;\quad \theta(0)=\theta_0>0;\quad \beta(0)=\beta_0;$

Dark matter halo observables
of spiral galaxies (**boundary conditions**)

$r_h = 25\,\mathrm{Kpc};\ \mathrm{v_h} = 168\,\mathrm{km/s};$
$\mathrm{M_h} = 1.6\times10^{11}\mathrm{M_\odot}$

Earlier Studies:
massive (non-interacting) fermions in galaxies @ a quantum level

Ruffini, Arguelles, Rueda, MNRAS (2015)

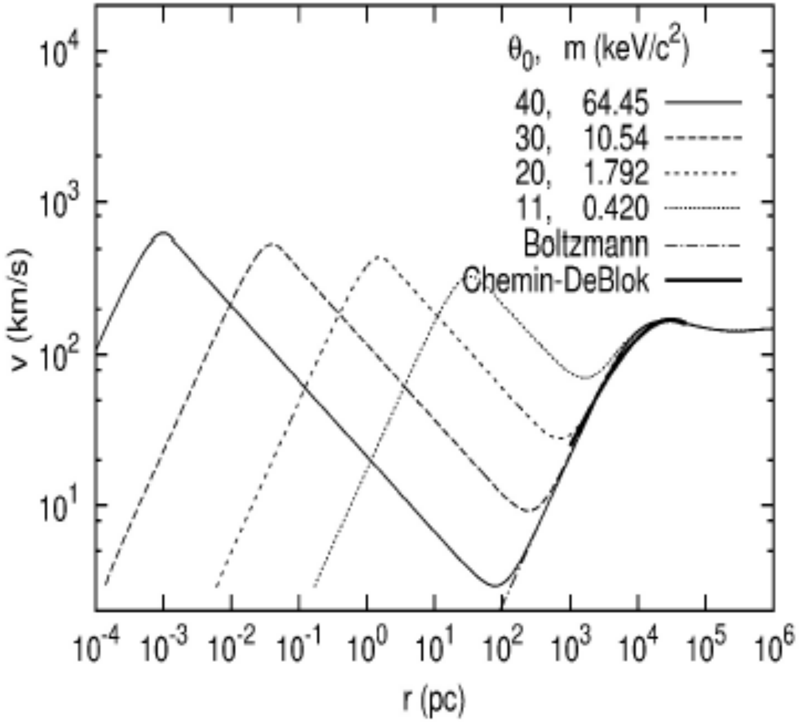


Density profiles of galaxies

Earlier Studies:
massive (non-interacting) fermions in galaxies
@ a quantum level

Ruffini, Arguelles, Rueda, MNRAS (2015)

- ROTATION CURVES AND THE CORE CHARACTERISTICS
- m is strongly dependent ONLY on the core characteristics!
- For $m \sim 10\text{keV}/c^2 \rightarrow M_c \sim 10^6 M_\odot$ (SgrA* candidate)

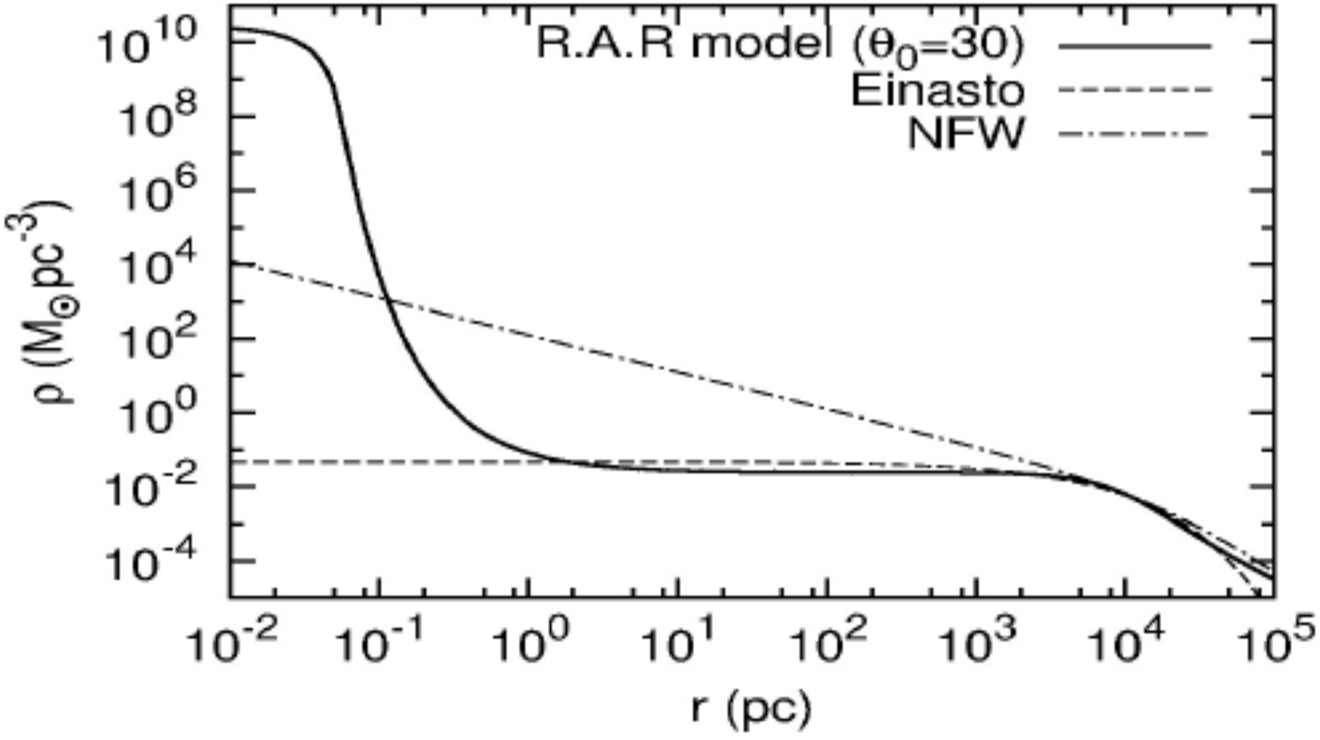


θ_0	$m(keV/c^2)$	$r_c(pc)$	$M_c(M_\odot)$
11	0.420	3.3×10^1	8.5×10^8
25	4.323	2.5×10^{-1}	1.4×10^7
30	10.540	4.0×10^{-2}	2.7×10^6
40	64.450	1.0×10^{-3}	8.9×10^4
58.4	2.0×10^3	9.3×10^{-7}	1.2×10^2
98.5	3.2×10^6	3.2×10^{-13}	7.2×10^{-5}

Earlier Studies:
massive (non-interacting) fermions in galaxies @ a quantum level

m =O(10) keV

Ruffini, Arguelles, Rueda, MNRAS (2015)



In halo region RAR model behaves similar to Einasto or NFW profiles
The core region needs revisiting → **self interacting fermionic dark matter**

A concrete model for SIDM –
Right-handed keV Neutrinos with vector interactions

Arguelles, NEM, Rueda, Ruffini, JCAP 1604, 038 (2016)

- Assume **minimal extension of the Standard Model (non-supersymmetric) with right-handed neutrinos (RHN) self interacting via massive vector exchange interactions** in the dark sector

- Use models of particle physics, e.g. ν**MSM** (**Shaposhnikov *et al***.) with three RHN, but augment them with these self-interactions
- among the lightest of the RHN (**quasi stable → DM**)

- Consistency of the **halo-core profile** of dwarf galaxies in Milky Way or large Elliptical → **mass** of lightest RHN in **O(10) keV (WDM)** ← **Cosmological constraints** of νMSM

Two different approaches yield similar range for WDM mass!

SM Extension with N extra right-handed neutrinos

$$L = L_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\, \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2}\, \bar{N}_I^c N_I + \text{h.c.}$$

Paschos, Hill, Luty , Minkowski, Yanagida, Mohapatra, Senjanovic, de Gouvea..., Liao, Nelson, Buchmuller, Anisimov, di Bari... Akhmedov, Rubakov, Smirnov, Davidson, Giudice, Notari, Raidal, Riotto, Strumia, Pilaftsis, Underwood, Shaposhnikov ... Hernandez, Giunti...

SM Extension with N extra right-handed neutrinos

$$L = L_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\, \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2}\, \bar{N}_I^c N_I + \mathrm{h.c.}$$

Right-handed Massive **Majorana** neutrinos

Leptons

$$L_\alpha = \begin{pmatrix} \nu_\alpha \\ \alpha^- \end{pmatrix}, \quad \alpha = e, \mu, \tau$$

SM Extension with N extra right-handed neutrinos

$$L = L_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\, \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2}\, \bar{N}_I^c N_I + \mathrm{h.c.}$$

Higgs scalar SU(2)
Dual: $\tilde{\phi}_i = \epsilon_{ij}\phi_j^*.$

SM Extension with N extra right-handed neutrinos

νMSM

$$L = L_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I}\, \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2}\, \bar{N}_I^c N_I + \text{h.c.}$$

For Constraints (compiled ν oscillation data) on (light) sterile neutrinos cf.:
Giunti, Hernandez , …
N=1 *excluded by data*

Yukawa couplings
Matrix *(I=* 1, …N=2 or 3)

Model with 2 or 3 singlet fermions works well in reproducing Baryon Asymmetry and is consistent with Experimental Data on neutrino oscillations

Model with N=3 also works fine, and in fact it allows ***one*** of the Majorana fermions to almost ***decouple*** from the rest of the SM fields, thus providing candidates for ***light*** (keV region of mass) sterile neutrino ***Dark Matter.***

SM Extension with N extra right-handed neutrinos

νMSM

Boyarski, Ruchayskiy, Shaposhnikov

$$L = L_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\,\bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2}\,\bar{N}_I^c N_I + \text{h.c.}$$

Yukawa couplings
Matrix (*I= 1, …*N=3)

SM Extension with N extra right-handed neutrinos

νMSM

Boyarski, Ruchayskiy, Shaposhnikov

$$\boxed{L = L_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I}\, \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2}\, \bar{N}_I^c N_I + \text{h.c.}}$$

$$\Downarrow$$

Yukawa couplings
Matrix (*I=1,2,*3)

$$F = \widetilde{K}_L\, f_d\, \widetilde{K}_R{}^\dagger$$

$$f_d = \text{diag}(f_1, f_2, f_3)\,, \quad \widetilde{K}_L = K_L P_\alpha\,, \quad \widetilde{K}_R{}^\dagger = K_R{}^\dagger P_\beta$$

$$P_\alpha = \text{diag}(e^{i\alpha_1}, e^{i\alpha_2}, 1)\,, \quad P_\beta = \text{diag}(e^{i\beta_1}, e^{i\beta_2}, 1)$$

Majorana phases

Mixing

$$K_L = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{L23} & s_{L23} \\ 0 & -s_{L23} & c_{L23} \end{pmatrix} \begin{pmatrix} c_{L13} & 0 & s_{L13} e^{-i\delta_L} \\ 0 & 1 & 0 \\ -s_{L13} e^{i\delta_L} & 0 & c_{L13} \end{pmatrix} \begin{pmatrix} c_{L12} & s_{L12} & 0 \\ -s_{L12} & c_{L12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{Lij} = \cos(\theta_{Lij})$ and $s_{Lij} = \sin(\theta_{Lij})$.

SM Extension with N extra right-handed neutrinos

νMSM

$$L = L_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\, \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2}\, \bar{N}_I^c N_I + \text{h.c.}$$

Majorana masses to (2 or 3) active neutrinos via ***seesaw***

Yukawa couplings Matrix (N=2 or 3)

$$F = \tilde{K}_L\, f_d\, \tilde{K}_R{}^\dagger$$

NB: Upon Symmetry Breaking
<Φ> = v ≠ 0 → Dirac mass term

$$L = L_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\, \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2}\, \bar{N}_I^c N_I + \text{h.c.}$$

Light Neutrino Masses through see saw

Minkowski,
Yanagida,
Mohapatra, Senjanovic

$$m_\nu = -M^D \frac{1}{M_I} [M^D]^T .$$

$$M_D = F_{\alpha I} v$$

$$v = \langle \phi \rangle \sim 175 \text{ GeV}$$

$$M_D \ll M_I$$

mass of lightest of *N_I*
by agreement
with Cosmological data

$$L = L_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I}\, \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2}\, \bar{N}_I^c N_I + \text{h.c.}$$

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$$M_D \ll M_I$$

$N \rightarrow H\,\nu$

$$L = L_{SM} + \bar{N}_I i\partial_\mu\gamma^\mu N_I - F_{\alpha I}\,\bar{L}_\alpha N_I\tilde{\phi} - \frac{M_I}{2}\,\bar{N}_I^c N_I + \mathrm{h.c.}$$

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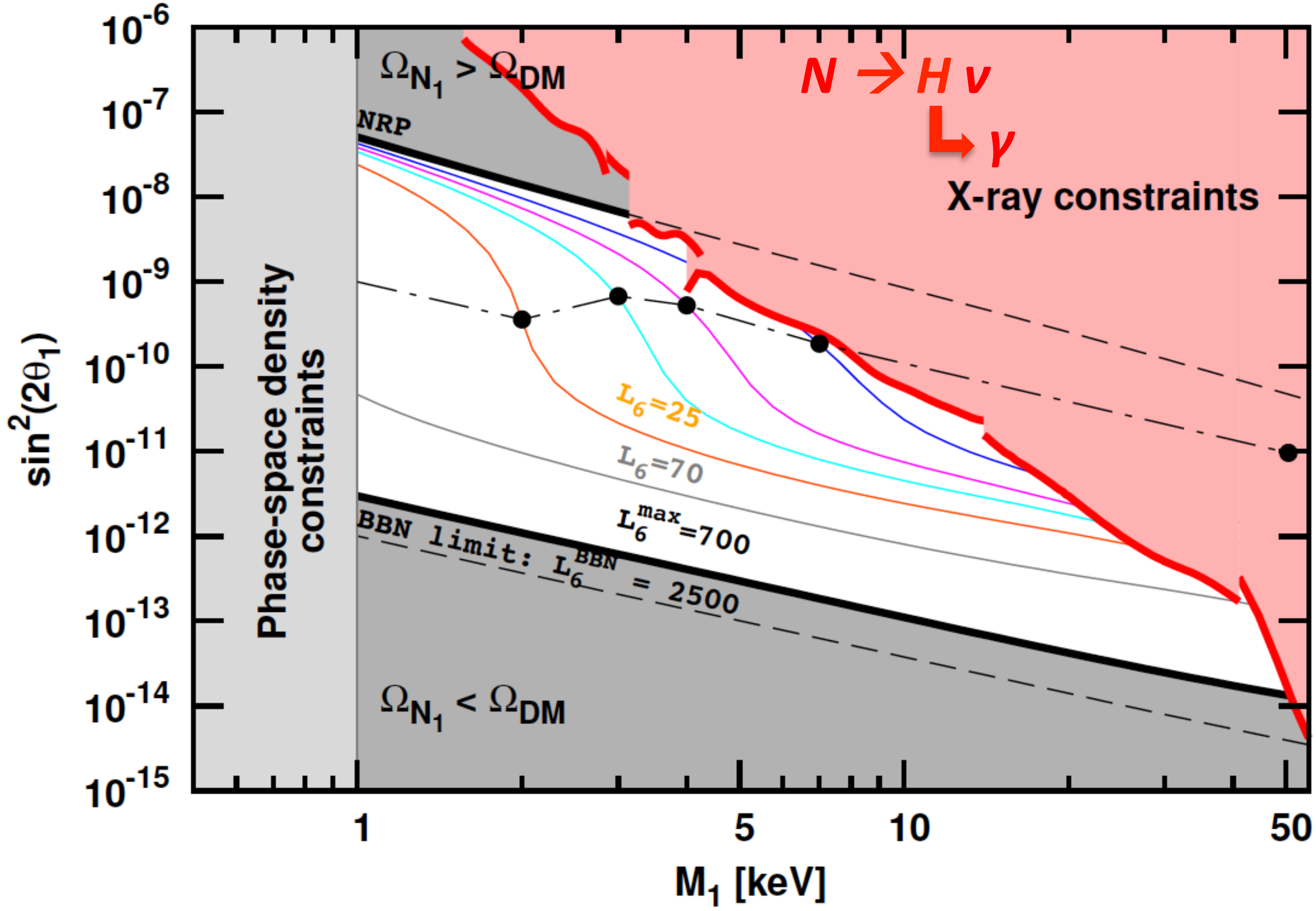
$$F_{\alpha 1} \approx 10^{-10} \rightarrow m_\nu^2 \approx 10^{-3}\,\mathrm{eV}^2$$

νMSM

Boyarski, Ruchayskiy, Shaposhnikov…

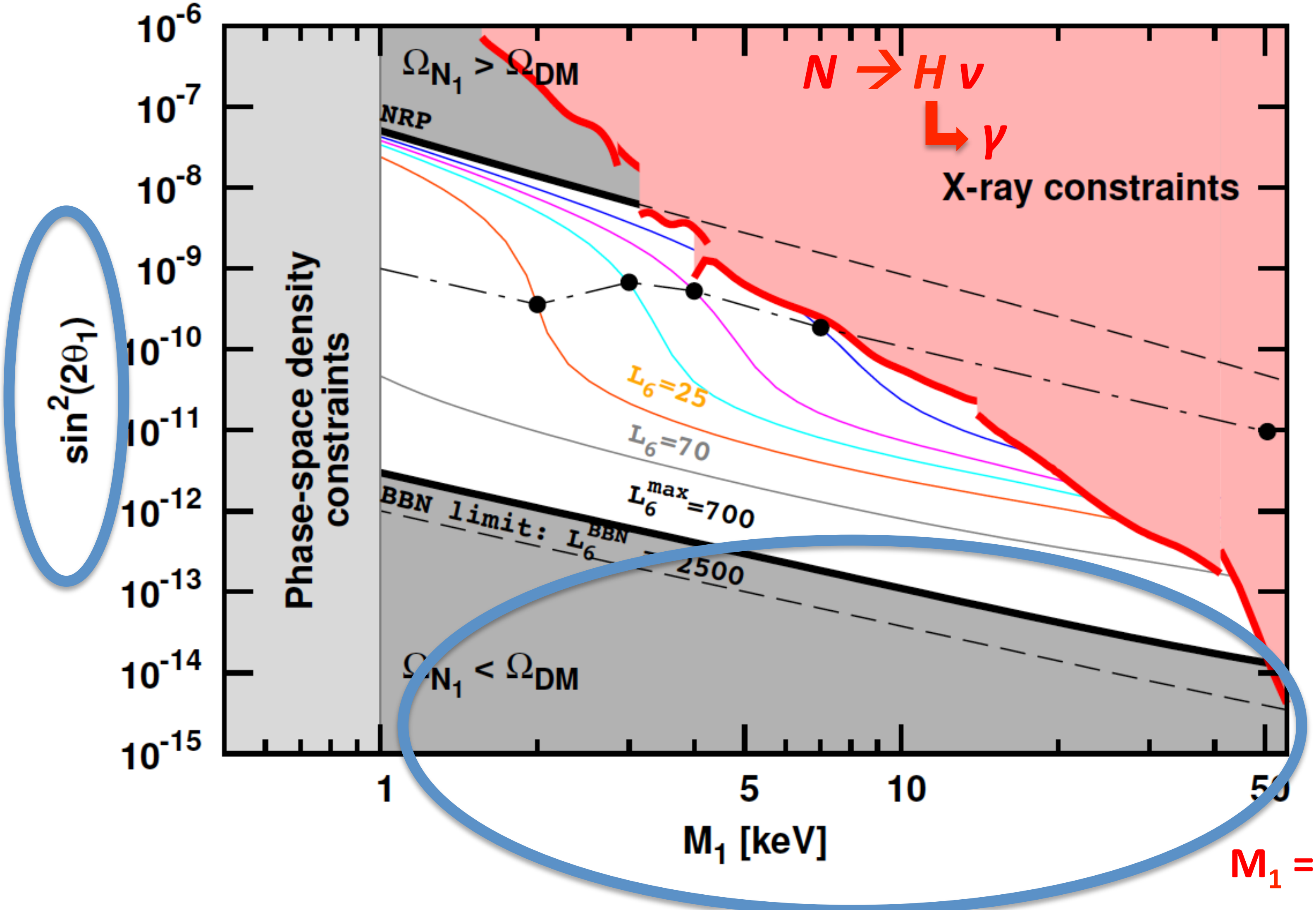
MODEL CONSISTENT WITH BBN, STRUCTURE FORMATION DATA IN THE UNIVERSE & ALL OTHER ASTROPHYSICAL CONSTRAINTS



νMSM

Boyarski, Ruchayskiy, Shaposhnikov…

MODEL CONSISTENT WITH BBN, STRUCTURE FORMATION DATA IN THE UNIVERSE & ALL OTHER ASTROPHYSICAL CONSTRAINTS

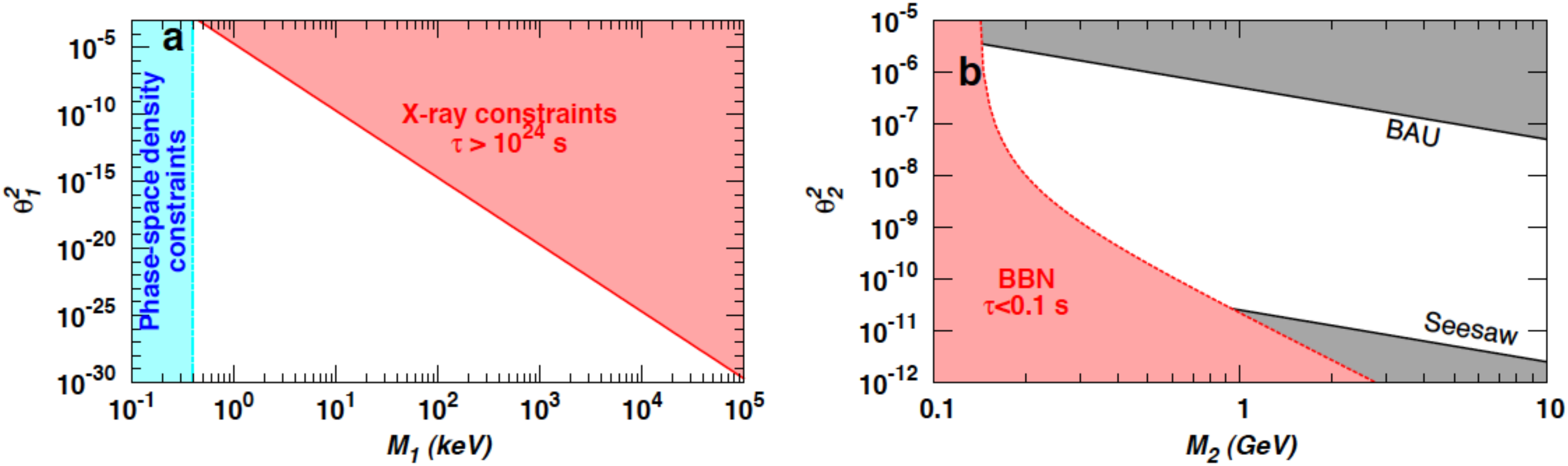


$M_1 = O(10)$ keV

More than one sterile neutrino needed to reproduce Observed oscillations

νMSM

Boyarski, Ruchayskiy, Shaposhnikov…



Constraints on two heavy degenerate singlet neutrinos

N_1 DM production estimation in Early Universe must take into account its interactions with $N_{2,3}$ heavy neutrinos

This talk: restrict mass of N_1 by agreement with observed galactic core-halo structure in SIDM versions of the model

$$\boxed{L = L_{SM} + \bar{N}_I i\partial_\mu\gamma^\mu N_I - F_{\alpha I}\,\bar{L}_\alpha N_I\tilde{\phi} - \frac{M_I}{2}\,\bar{N}_I^c N_I + \text{h.c.}}$$

Minkowski,
Yanagida,
Mohapatra, Senjanovic

Light Neutrino Masses through see saw

$$\boxed{m_\nu = -M^D\frac{1}{M_I}[M^D]^T\,.}$$

$$M_D = F_{\alpha I}v$$

$$v = \langle\phi\rangle \sim 175\ \text{GeV}$$

$$M_D \ll M_I$$

$F_{\alpha 1} \approx 10^{-10} \rightarrow m_\nu^2 \approx 10^{-3}\,\text{eV}^2$


kingvector.blogspot.com

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$$L = L_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \, \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2} \bar{N}_I^c N_I + \text{h.c.}$$

Minkowski,
Yanagida,
Mohapatra, Senjanovic

Light Neutrino Masses through see saw

$$m_\nu = -M^D \frac{1}{M_I} [M^D]^T .$$

$$M_D = F_{\alpha I} v$$

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$$M_D \ll M_I$$

~~$F_{\alpha 1} \approx 10^{-10}$~~ → $m_\nu^2 \approx 10^{-3}\,\mathrm{eV}^2$

Ignore in front of strong self-interactions for our purposes

Right-handed keV Neutrinos with vector self-interactions & galactic structure

Arguelles, NEM, Rueda, Ruffini, JCAP 1604, 038 (2016)

Place the vMSM in **curved space time**

$$g_{\mu\nu} = \mathrm{diag}(e^{\nu}, -e^{\lambda}, -r^2, -r^2 \sin^2 \varphi)$$

$v=v(r)$ $\lambda = \lambda(r)$

$$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_{N_{R1}} + \mathcal{L}_{V} + \mathcal{L}_{I}$$

$$\mathcal{L}_{GR} = -\frac{R}{16\pi G}, \; \mathcal{L}_{N_{R1}} = i\,\overline{N}_{R1}\gamma^{\mu}\nabla_{\mu} N_{R1} - \frac{1}{2} m \overline{N^{c}}_{R1} N_{R1},$$

$$\mathcal{L}_{V} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_{\mu} V^{\mu}, \; \mathcal{L}_{I} = -g_V V_{\mu} J_V^{\mu} = -g_V V_{\mu} \overline{N}_{R1} \gamma^{\mu} N_{R1}$$

$$\nabla_{\mu} = \partial_{\mu} - \frac{i}{8}\, \omega_{\mu}^{ab} [\gamma_a, \gamma_b]$$

Classical fields (eqs of motion) satisfy detailed **thermodynamic equilibrium conditions** in a galaxy at a temperature T < O(keV)

Right-handed keV Neutrinos with vector self-interactions & galactic structure

Arguelles, NEM, Rueda, Ruffini, JCAP 1604, 038 (2016)

Place the νMSM in **curved space time** $g_{\mu\nu} = \mathrm{diag}(e^{\nu}, -e^{\lambda}, -r^2, -r^2 \sin^2 \varphi)$

$\nu = \nu(r)$ $\lambda = \lambda(r)$

$$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_{N_{R\,1}} + \mathcal{L}_V + \boxed{\mathcal{L}_I}$$

$$\mathcal{L}_{GR} = -\frac{R}{16\pi G}, \; \mathcal{L}_{N_{R\,1}} = i\,\overline{N}_{R\,1}\gamma^{\mu}\nabla_{\mu}N_{R\,1} - \frac{1}{2}m\,\overline{N^c}_{R\,1}N_{R\,1},$$

$$\mathcal{L}_V = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_{\mu}V^{\mu}, \; \boxed{\mathcal{L}_I = -g_V V_{\mu}J_V^{\mu} = -g_V V_{\mu}\overline{N}_{R\,1}\gamma^{\mu}N_{R\,1}}$$

$$\nabla_{\mu} \doteq \partial_{\mu} - \frac{i}{8}\,\omega_{\mu}^{ab}[\gamma_a, \gamma_b]$$

Classical fields (eqs of motion) satisfy detailed **thermodynamic equilibrium conditions** in a galaxy at a temperature T < O(keV)

NB: Alternatively one may have four-fermion (attractive) current-current interactions

$$\boxed{\mathcal{L}_I \ni g_{\rm v} J^{\mu}_{V} J_{V\,\mu}}$$

$$J^{\mu}_{V} = \overline{N}_{R\,I}\gamma^{\mu} N_{R\,I}$$

Corresponds to a limiting case where vector boson mass *m_V >> momentum scale*

Similar effects on galactic structure for sufficiently strioing interaction couplings g_v

Right-handed keV Neutrinos with vector self-interactions & galactic structure

Measure of Strength of self Interactions

$$\boxed{C_V \equiv g_V^2/m_V^2}$$

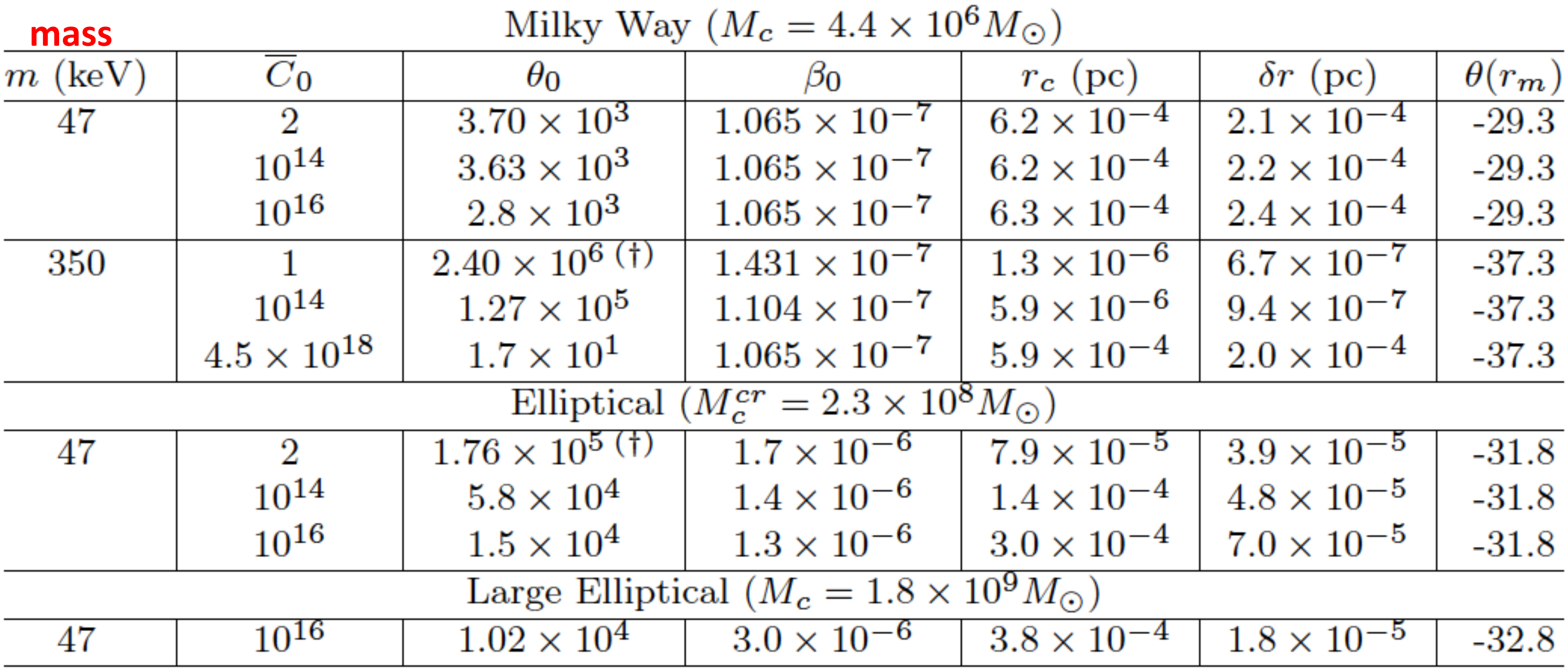
$$C_V(r) = \begin{cases} C_0 & \text{at} \quad r < r_m \quad \text{when} \quad \lambda_B/l > 1 \\ 0 & \text{at} \quad r \geqslant r_m \quad \text{when} \quad \lambda_B/l < 1 \end{cases}$$

inter-particle mean distance l
at temperature T

de-Broglie wavelength $\lambda_B = \frac{h}{\sqrt{2\pi m k_B T}}$

Right-handed keV Neutrinos with vector self-interactions & galactic structure

sterile ν mass



Milky Way ($M_c = 4.4 \times 10^6 M_\odot$)						
m (keV)	$\overline{C}_0$	θ_0	β_0	r_c (pc)	δr (pc)	$\theta(r_m)$
47	2	3.70×10^3	1.065×10^{-7}	6.2×10^{-4}	2.1×10^{-4}	-29.3
	10^{14}	3.63×10^3	1.065×10^{-7}	6.2×10^{-4}	2.2×10^{-4}	-29.3
	10^{16}	2.8×10^3	1.065×10^{-7}	6.3×10^{-4}	2.4×10^{-4}	-29.3
350	1	2.40×10^6 (†)	1.431×10^{-7}	1.3×10^{-6}	6.7×10^{-7}	-37.3
	10^{14}	1.27×10^5	1.104×10^{-7}	5.9×10^{-6}	9.4×10^{-7}	-37.3
	4.5×10^{18}	1.7×10^1	1.065×10^{-7}	5.9×10^{-4}	2.0×10^{-4}	-37.3
Elliptical ($M_c^{cr} = 2.3 \times 10^8 M_\odot$)						
47	2	1.76×10^5 (†)	1.7×10^{-6}	7.9×10^{-5}	3.9×10^{-5}	-31.8
	10^{14}	5.8×10^4	1.4×10^{-6}	1.4×10^{-4}	4.8×10^{-5}	-31.8
	10^{16}	1.5×10^4	1.3×10^{-6}	3.0×10^{-4}	7.0×10^{-5}	-31.8
Large Elliptical ($M_c = 1.8 \times 10^9 M_\odot$)						
47	10^{16}	1.02×10^4	3.0×10^{-6}	3.8×10^{-4}	1.8×10^{-5}	-32.8

$$\beta \equiv k_B T/m = \beta_0 \, e^{(\nu_0 - \nu(r))/2}$$

$$\theta \equiv \mu/(k_B T)$$

at the core (β_0, θ_0)

No solution for

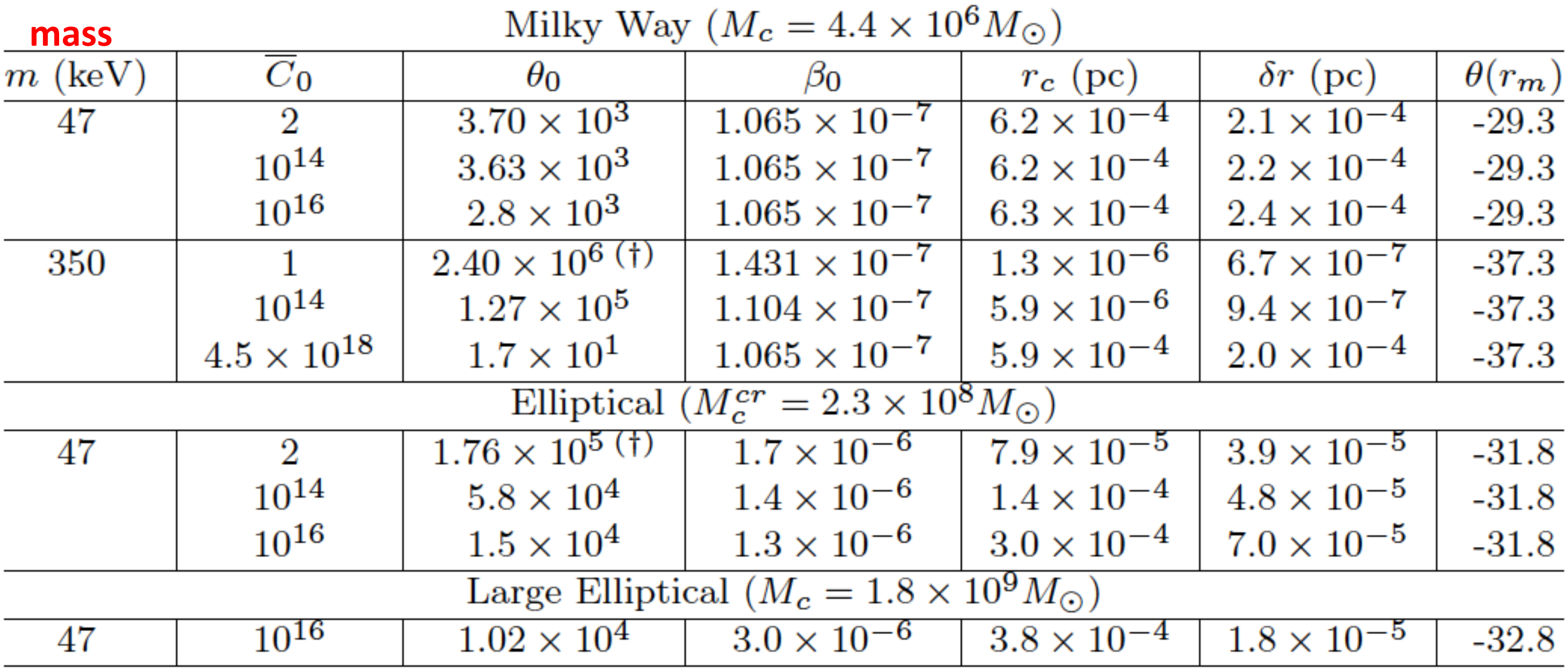
$m \; < 47 \text{ keV}/c^2$

$m \; > \; 350 \text{ keV}/c^2$

gravitational collapse

Right-handed keV Neutrinos with vector self-interactions & galactic structure

sterile ν mass



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$$\beta \equiv k_B\, T/m = \beta_0\, e^{(\nu_0 - \nu(r))/2}$$

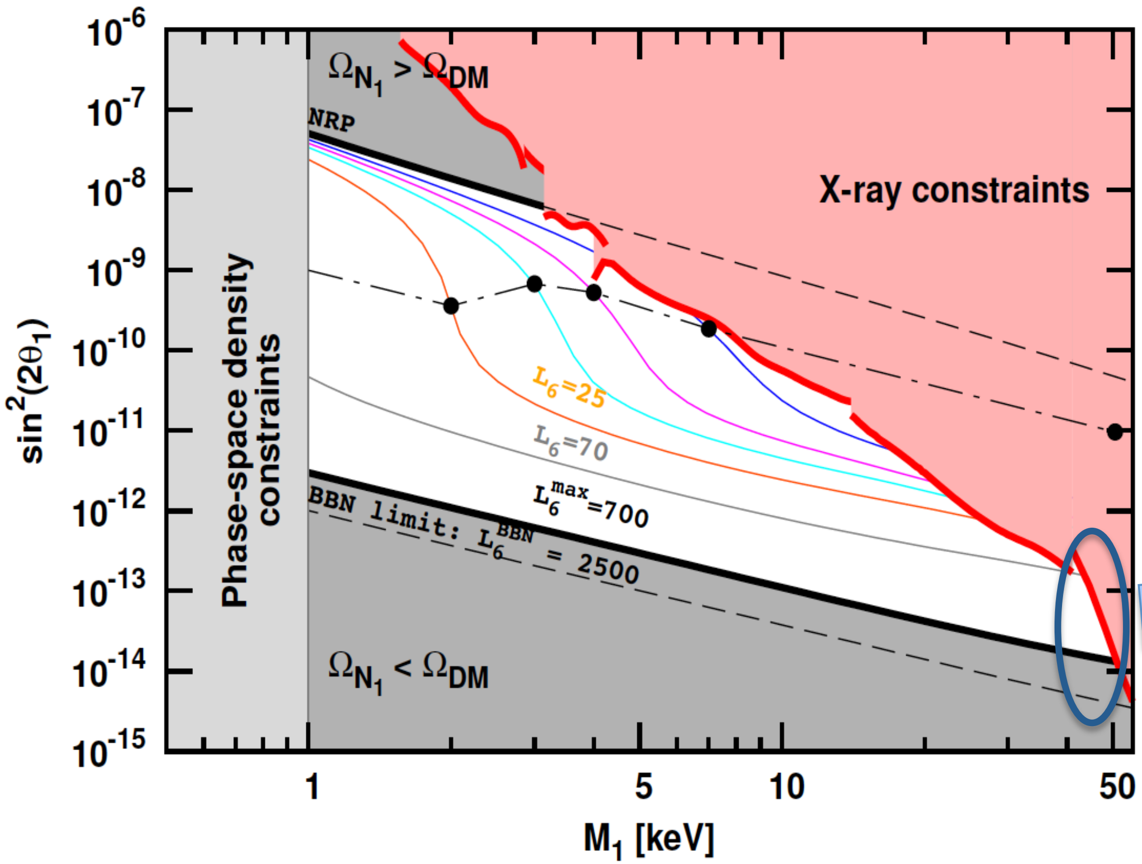
$$\theta \equiv \mu/(k_B T)$$

at the core (β_0, θ_0)

Allowed WDM mass range

47 keV $c^{-2} \leq$ m $\leq$ 350 keV c^{-2}

Right-handed keV Neutrinos with vector self-interactions & galactic structure



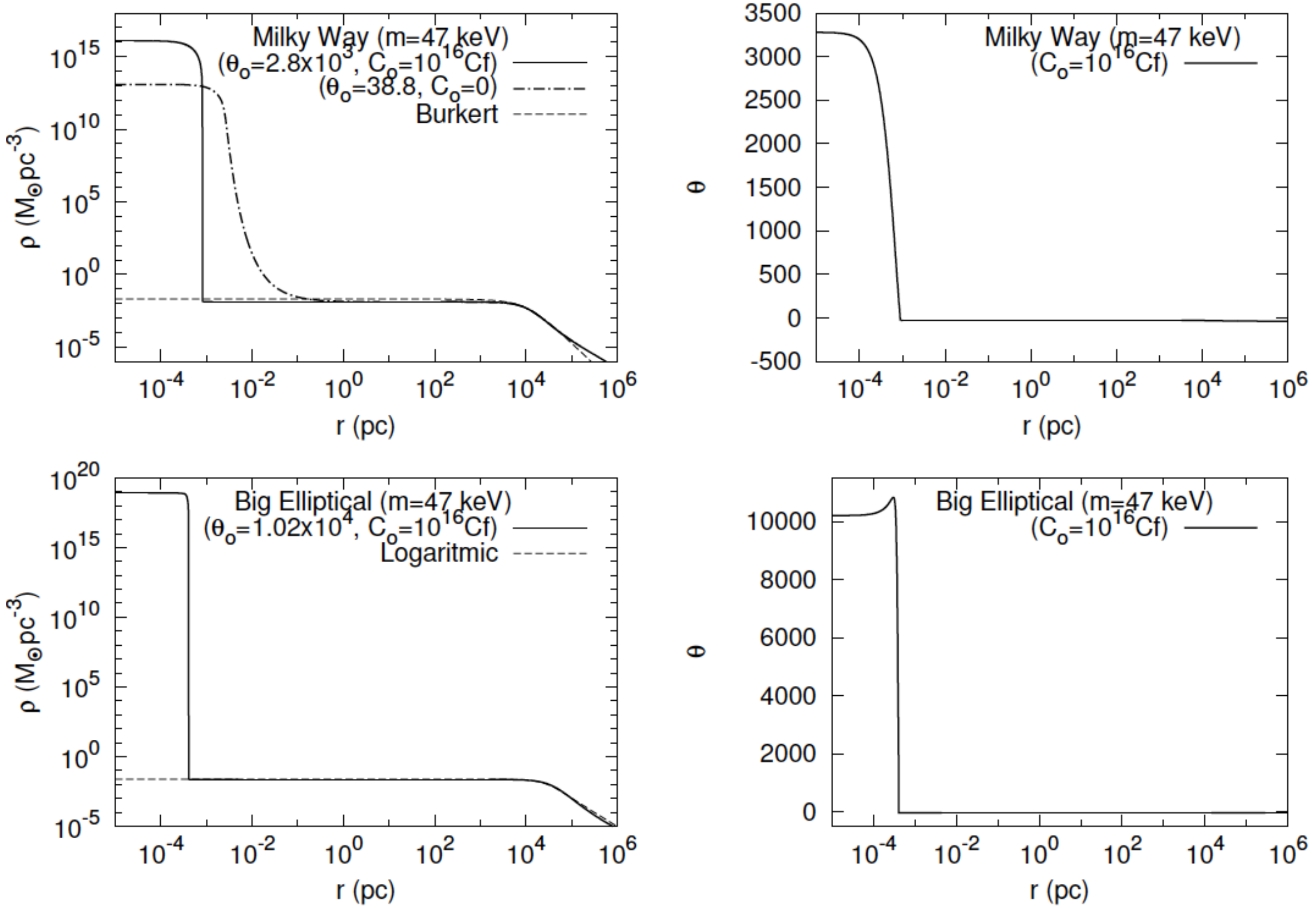
If **mixing** with observable sector is **non zero** (νMSM)

→ **narrow window of allowed WDM mass!**

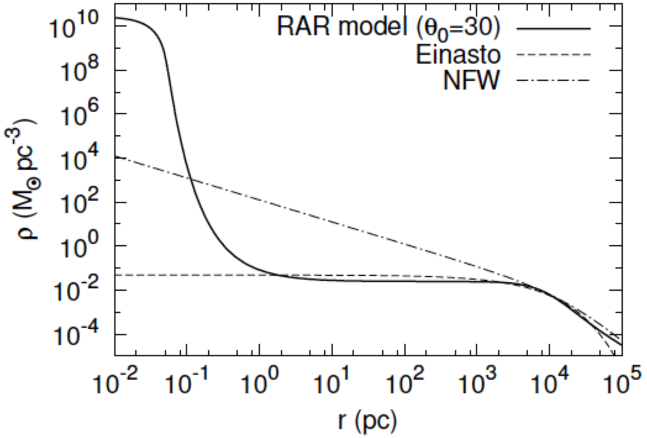
$$m < 47\ \mathrm{keV}/c^2$$

$$m > 350\ \mathrm{keV}/c^2$$

Arguelles, NEM, Rueda, Ruffini, JCAP 1604, 038 (2016)



Interactions make inner Core more compact and increase central degeneracy compared to non-interacting case



Non interacting right-handed neutrino case with m = O(10) keV

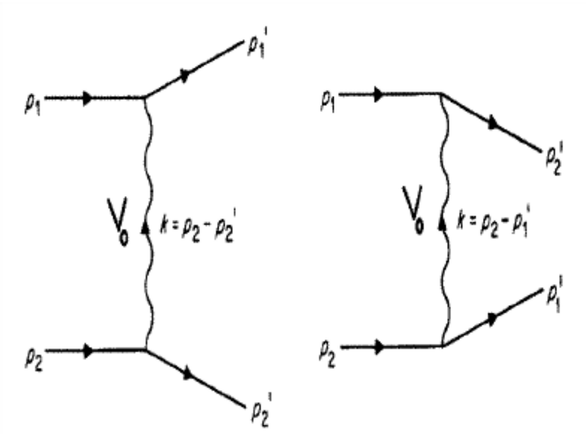
Ruffini, Arguelles, Rueda, MNRAS (2015)

Arguelles, NEM,
Rueda, Ruffini,
JCAP 1604, 038 (2016)

Provide natural resolution of Core-Cusp Problem because the density profiles based on **fermionic (as RH neutrinos) phase-space distributions** develop always an **extended plateau on halo scales**, resembling Burkert or cored Einasto profiles

Moreover, as the right-handed neutrino DM mass is `**colder' by a few keV** (m ≈ 47 keV $c^{-2}$ ) compared to most of the WDM models available in the literature, our model does **not suffer** from standard **WDM problems**, associated with the `too warm' nature of the particles involved

N-N Cross sections under massive vector exchange (perturbation theory $g_V < 1$ OK)



$$m \in (47, 350)\ \text{keV}$$

$$\sigma^{tot}_{core} \approx \frac{(g_V/m_V)^4}{4^3\pi} 29m^2 \qquad (p^2/m^2 \ll 1)$$

Hidden sector vector interactions -> Much stringer than weak interactions in visible sector

$$\overline{C}_V = \left(\frac{g_V}{m_V}\right)^2 G_F^{-1} \Rightarrow \overline{C}_V \in (2.6 \times 10^8, 7 \times 10^8)$$

to resolve issues of small-scale cosmology crisis

Arguelles, NEM, Rueda, Ruffini, JCAP 1604, 038 (2016)

$$m_V \lesssim 3 \times 10^4\ \text{keV}$$

Conclusions-Outlook

- At galactic scales **ΛCDM model suffers** from discrepancies with observations regarding the **core-cusp, missing satellite,** and **too big to fail** problems of ***small-scale Cosmology ``crisis"*** ...

- To remedie this, **self interactions among DM** have been introduced with relatively strong cross sections per unit dark matter mass σ/m :

$$0.1 \leq \frac{\sigma_{\rm SIDM}/m}{{\rm cm}^2\, g^{-1}} \leq 0.47$$

- We have considered the role of **the lightest of the right-handed neutrinos in νMSM** extensions of the standard model, and **added appropriately strong vector interactions** in the dark sector among the neutrinos → **increase inner degeneracy and inner core** region in dwarf satellites of the Milky Way or Large elliptical galaxies
  For interaction strengths **10^8 G_F**, **WDM mass = 47-50 keV**, & **vector mass < 10^4 keV**, we can **resolve the three small-scale Cosmology problems**.

- **The RH neutrino WDM**, which solves core-halo structure in galaxies, may **co-exist** with other **CDM DM species** → **search** for it in **particle physics** and neutrino **oscillation** experiments (eg SHiP) ...

THANK YOU !

SPARES

Towards a Solution of the 3-Problems of Galactic-Scale-Cosmology (GSC)

Astrophysical explanations

The missing satellite problem:

(i) Smaller halos do exist but only a few of them end up becoming visible
(have not been able to attract enough baryonic matter to create a visible dwarf)
(**cf Keck observations (2007) of eight newly discovered ultrafaint Milky Way dwarf satellites** showed that six were almost exclusively composed of DM, around 99.9% (with a mass-to-light ratio of about 1000)) –
Such ultra-faint dwarfs substantially alleviate the discrepancy, but there are still discrepancies by a factor of about four too few dwarves over a signicant range of masses.

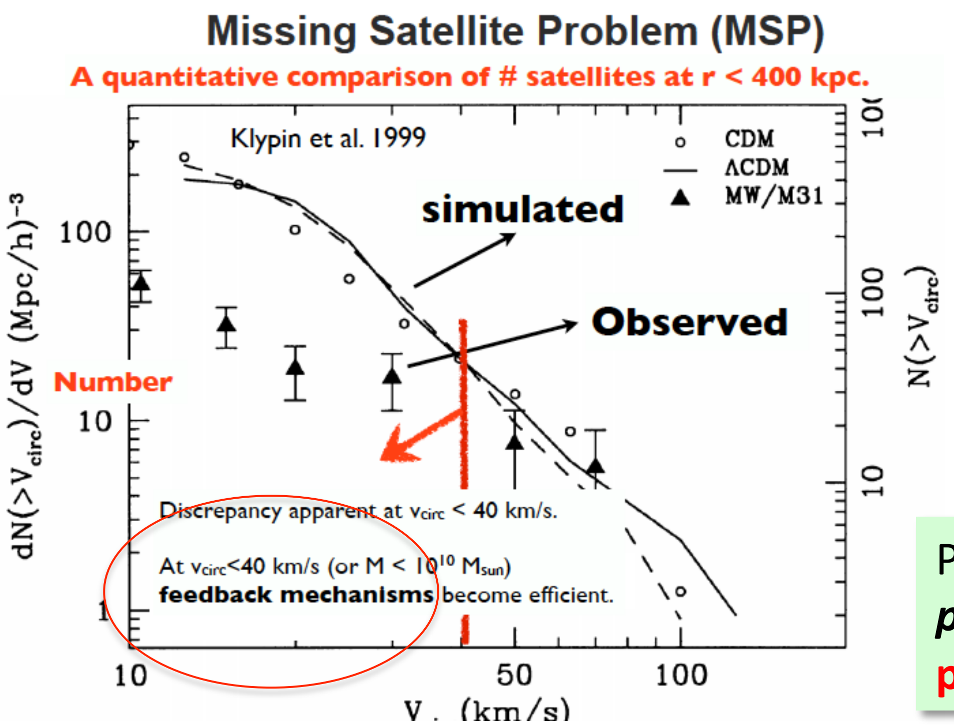
(ii) **Galaxy formation** in low-mass dark matter halos is **strongly suppressed after re-ionization** → simulated circular velocity function of CDM subhalos in approximate agreement with the observed circular velocity function of Milky Way satellite galaxies.

(iii) Dwarves tend to **be merged into or tidally stripped apart by larger galaxies** due to complex interactions. This tidal stripping has been part of the problem in identifying dwarf galaxies in first place, which is difficult due to their low surface brightness and high diffusion so that they **are virtually unnoticeable**.

Towards a Solution of the 3-Problems of Galactic-Scale-Cosmology (GSC)

Astrophysical explanations

(iv) (Baryonic) Feedback plays an important role: complex processes by means of which star formation and matter accretion onto black holes deposit energy in the surrounding environments of galaxies



Missing Satellite Problem (MSP)

A quantitative comparison of # satellites at r < 400 kpc.

Discrepancy apparent at $v_{circ} < 40$ km/s.

At v_{circ}<40 km/s (or $M < 10^{10}\ M_{sun}$) **feedback mechanisms** become efficient.

Various types of feedback:

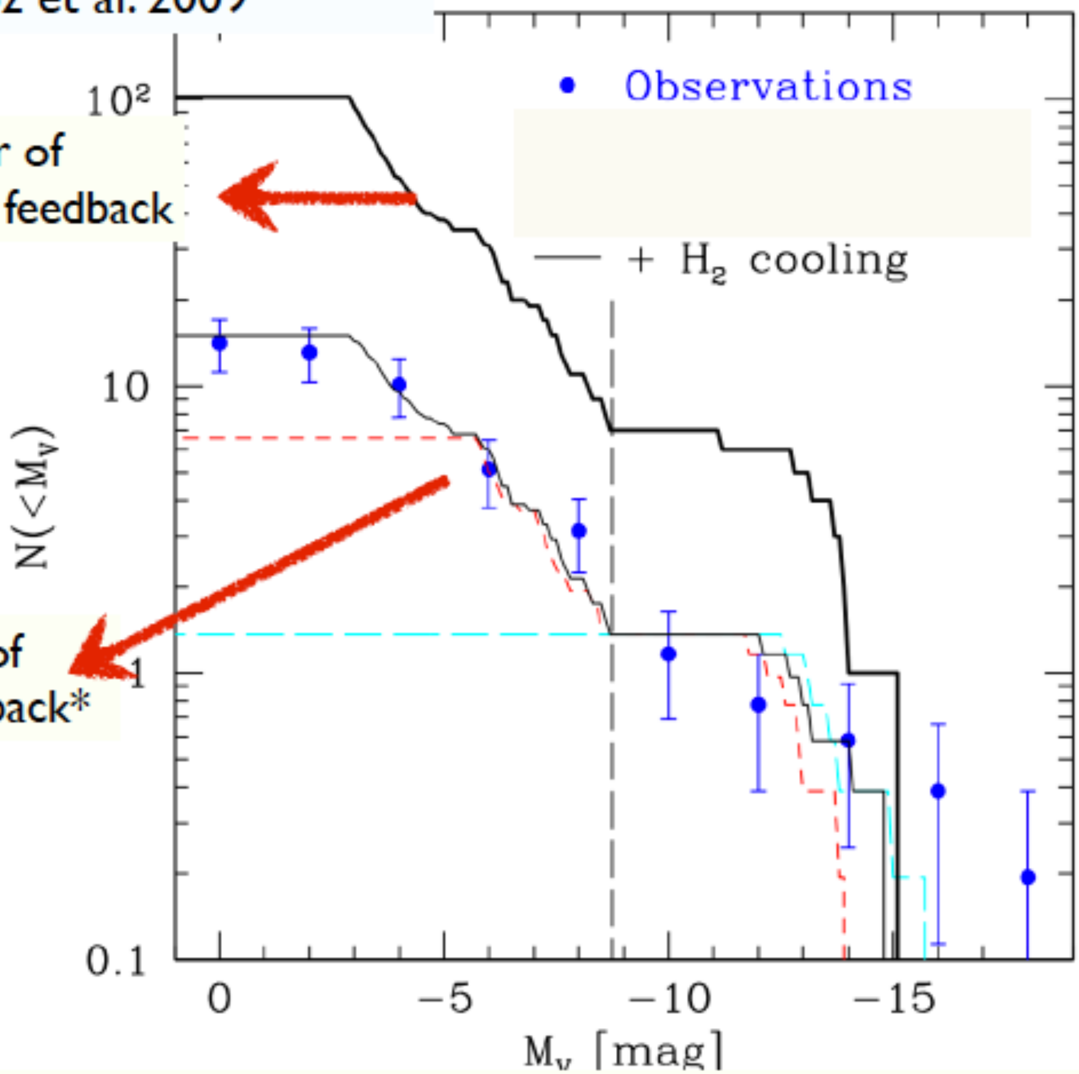
Radiative: photoionization,
radiation pressure
(***stellar***, or from accretion
disk of a supermassive BH
(***AGN***))

Mechanical: supernovae explosions,
cosmic ray exerted pressure

Possible to explain ***Missing satellite problem*** with **Baryonic (not well understood) physics feedback**

Missing Satellite Problem in Models that Include Feedback

Munoz et al. 2009



Predicted number of satellites with no feedback

Predicted number of satellites with feedback*

* **Note:** feedback tuned to reproduce observations.

Towards a Solution of the 3-Problems of Galactic-Scale-Cosmology (GSC)

Astrophysical explanations

Baryonic Feedback can also offer **resolution**
to the **Core-Cusp Problem**,

as it can “**flatten out**" the **core of a galaxy's dark matter profile**, since feedback-driven gas outflows produce a **time-varying gravitational potential** that transfers energy to the orbits of the collisionless dark matter particles

J.Navarro *et al*. MNRAS 283 L72 (1996)

Towards a Solution of the 3-Problems of Galactic-Scale-Cosmology (GSC)

Astrophysical explanations

Undertstanding the **shape and depth of gravitational potential** in dwarf galaxies may be essential, as the latter determines the rotational velocities

$$v_{\rm rot}^2(r) = r\left|\frac{\partial\Phi(r)}{\partial r}\right| = \frac{GM(<r)}{r}$$

and hence may have important bearings in resolving the **too-big-to-fail** and the **the core-cusp** problems of small-scale cosmology

e.g. Richardson & Fairbairn (2015) claim that **Dwarf Spheroidals in Milky Way** are **not cored**, if one uses new methods for estimating their gravitational potential, using ***higher-order analogues of Virial Theorem***

→ ***unconventional view point for resolving Core-Cusp problem,***
....analysis based based only on Sculptor galaxy study case
but an interesting suggestion nevertheless