Astrophysical constraints on DM

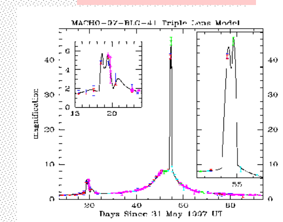
Gravity

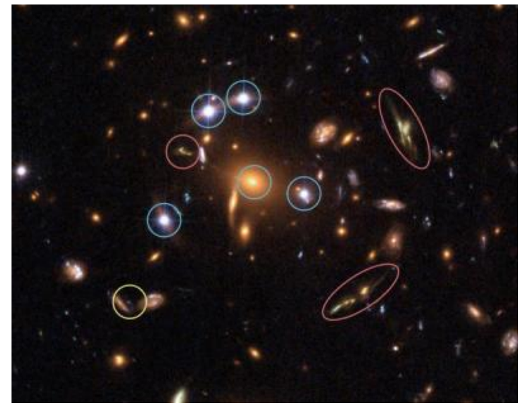
Poussières

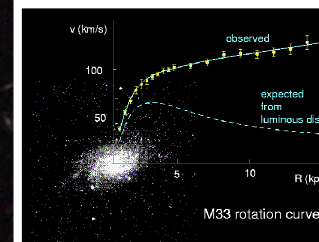
Cold molecular

MACHOs

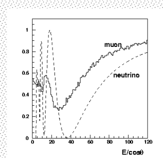
Black Holes







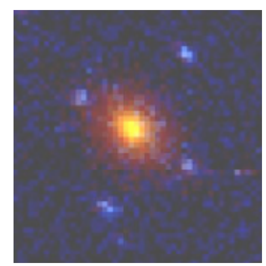
SIMPs



Neutrino

axions

WIMPs
10-1000GeV



Charling Tao
tao@cppm.in2p3.fr

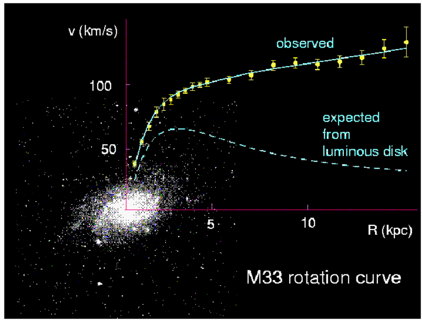
October 11, 2019 @ CPPM

Today's talk

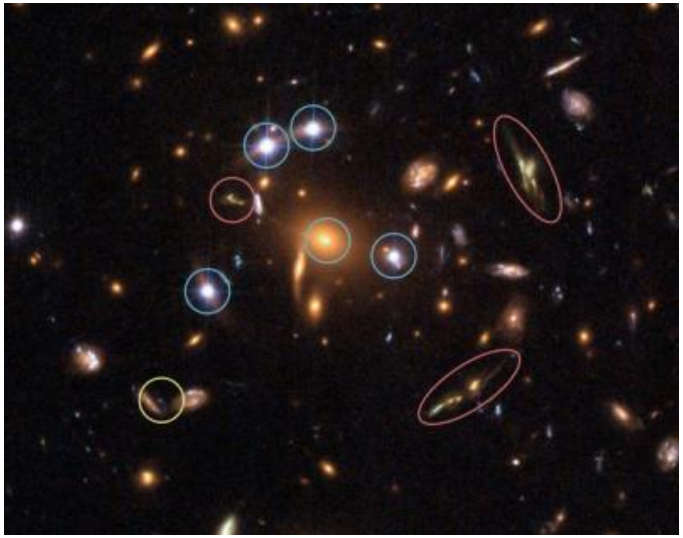
- Evidence for DM is astrophysical
- LSS simulations: → DM is not hot
- What do we know about DM? Not much
- Some Observations and Comments

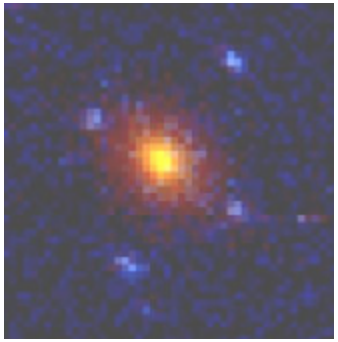
Wealth of Evidence for DM

- Galaxy rotation curves (V. Rubin)



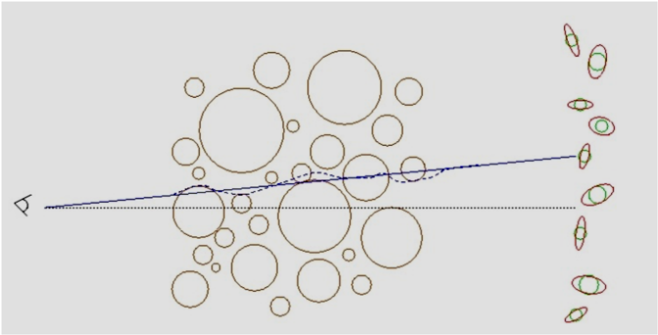
- Dynamics of galaxy clusters (Zwicky)
- Gravitational lensing mass reconstruction

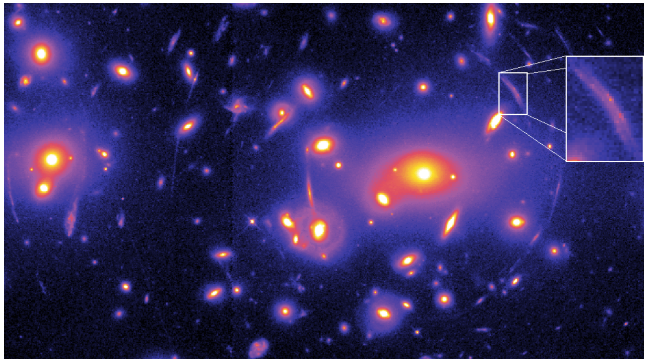




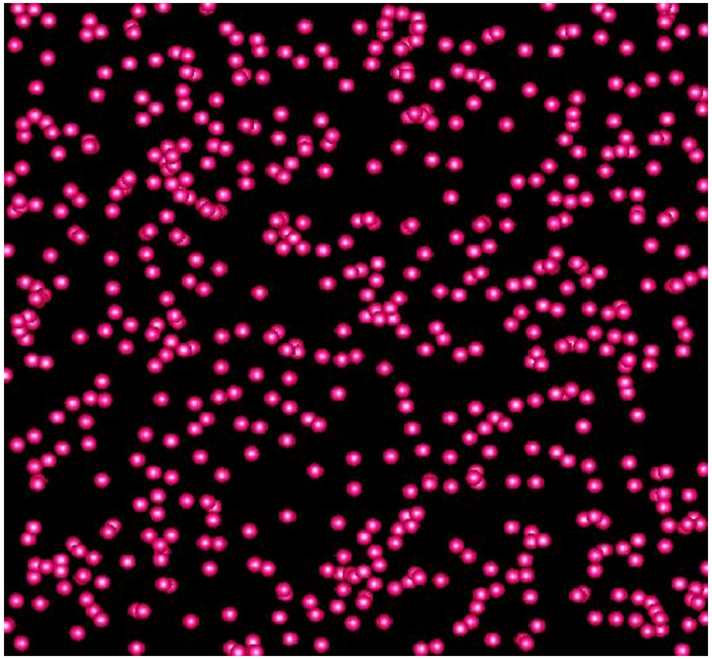
- Bullet cluster (Clowe+,2006)

Weak Lensing

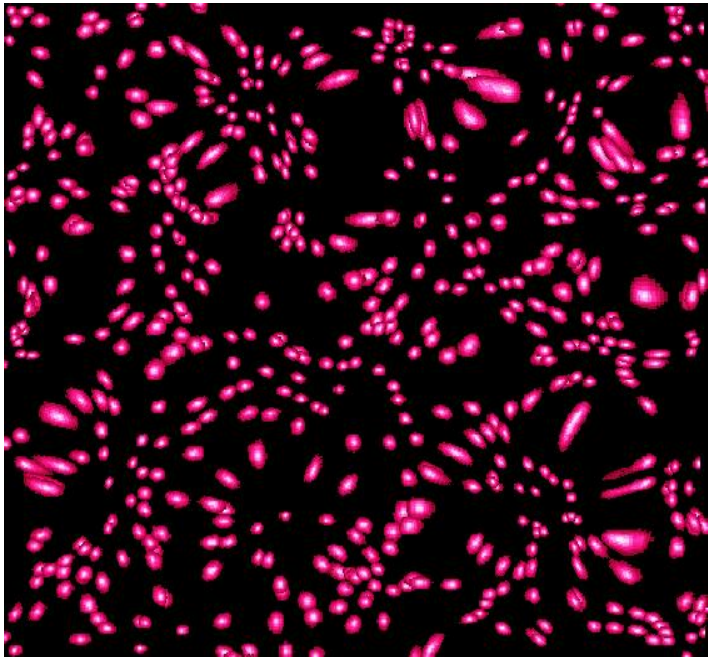




Distorsion of galaxy shapes by foreground matter



without lensing



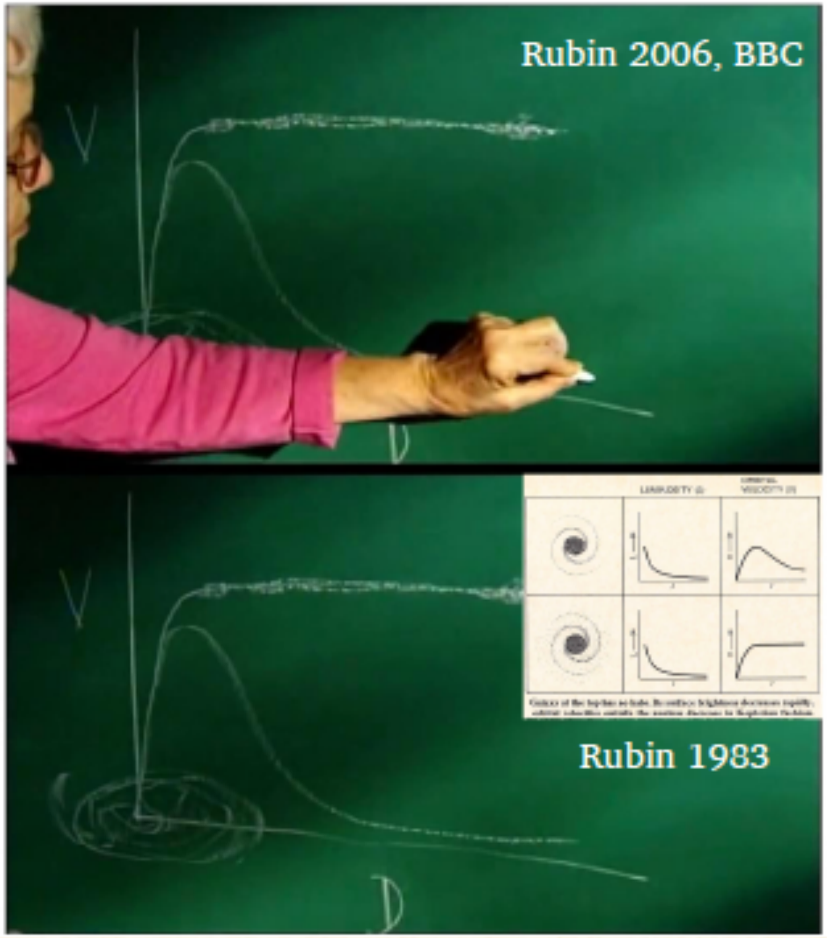
Lensing effect

Wealth of evidence for DM

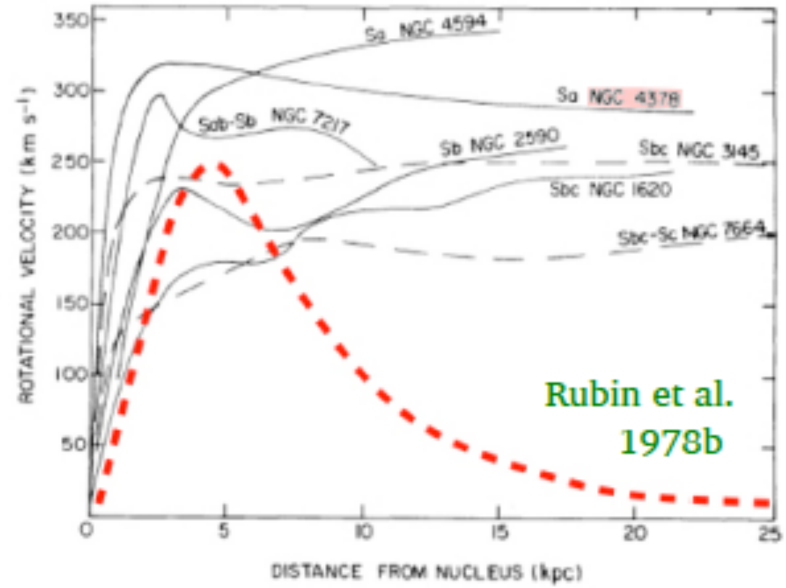
is astrophysical!

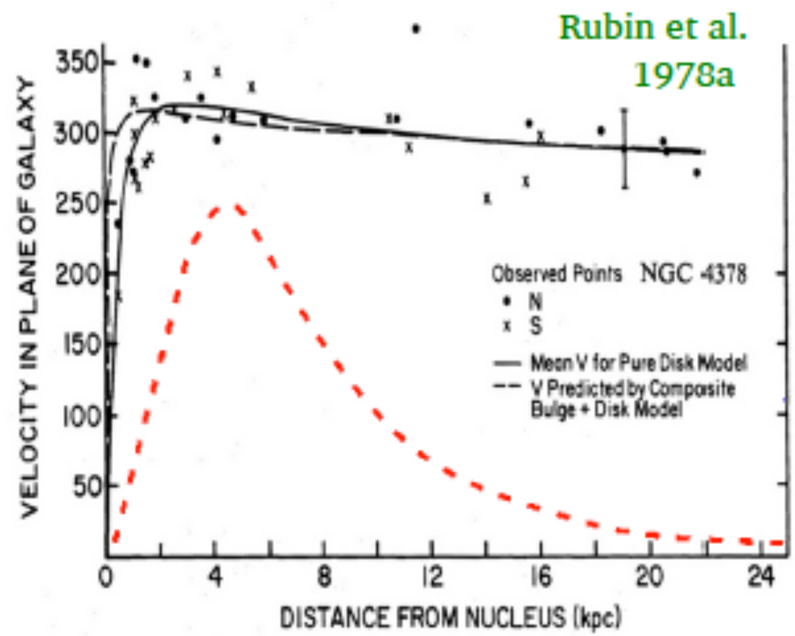
More complex than presented usually!

Rotation curves : what is often said [incorrectly] to be expected



Galaxy at the top has no halo. Its surface brightness decreases rapidly, orbital velocities outside the nucleus decrease in Keplerian fashion.



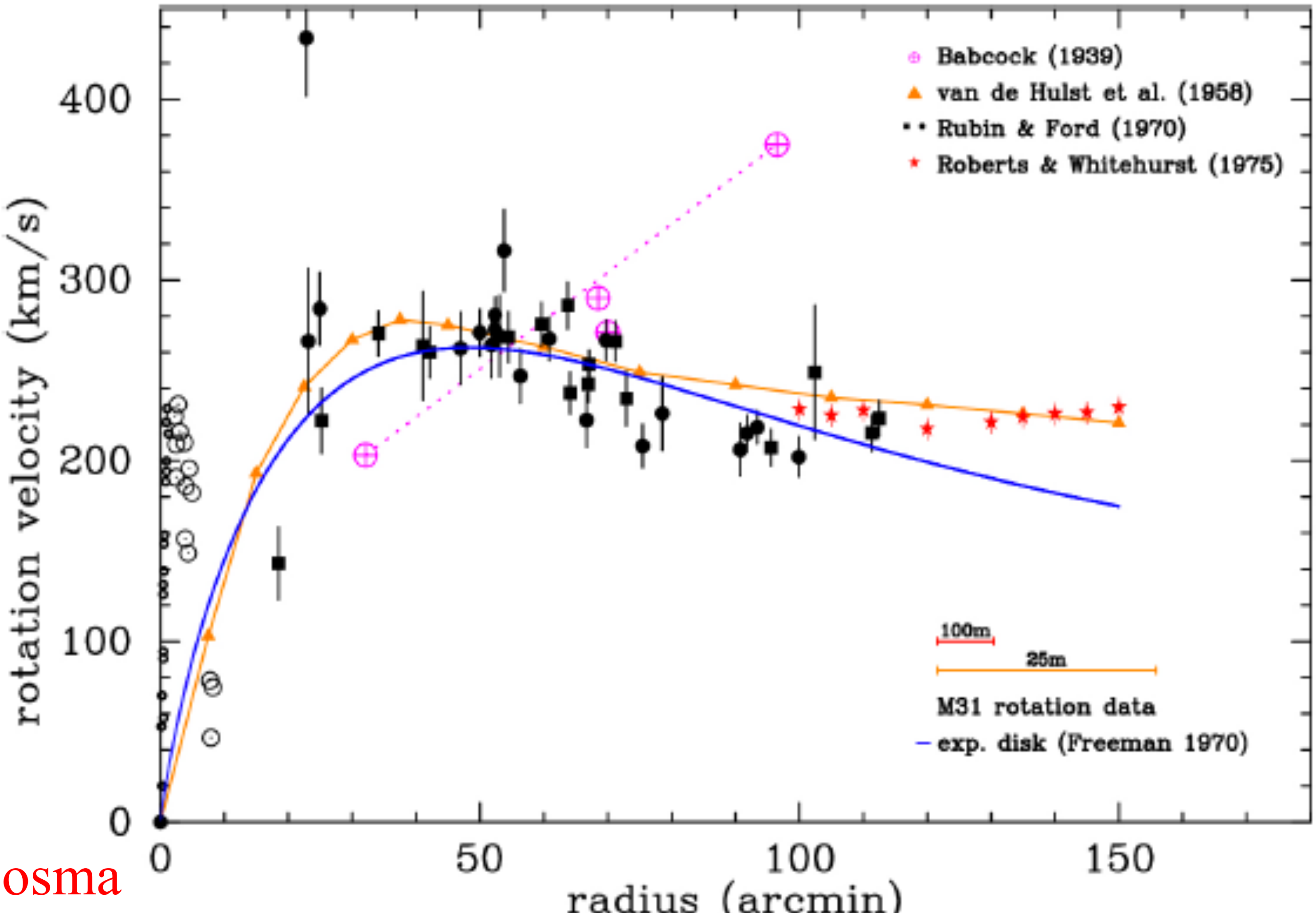


Keplerian behaviour just outside the nucleus can NOT be expected

A. Bosma (LAM)

Freeman 1970, appendix For NGC 300 and M33, the 21-cm data give turnover points near the photometric outer edges of these systems. These data have relatively low spatial resolution; if they are correct, then there must be in these galaxies additional matter which is undetected, either optically or at 21 cm. Its mass must be at least as large as the mass of the detected galaxy, and its distribution must be quite different.

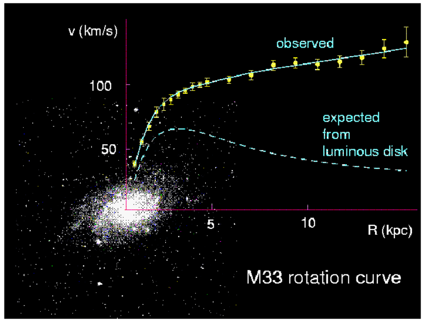
M31 – Need for dark matter based on radio data

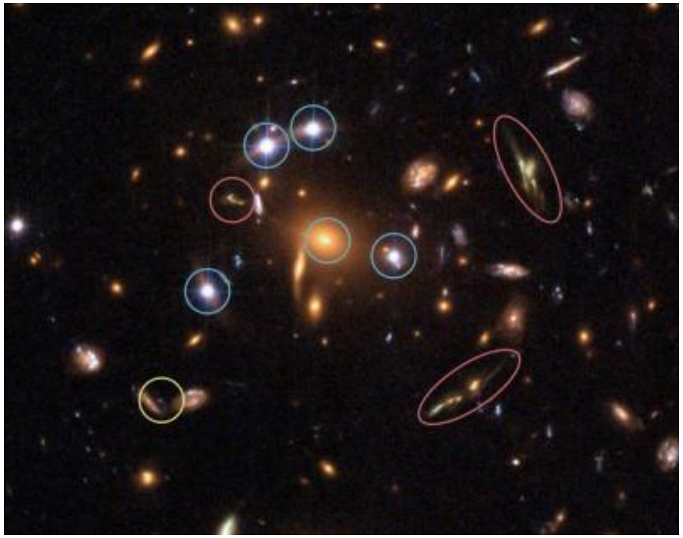


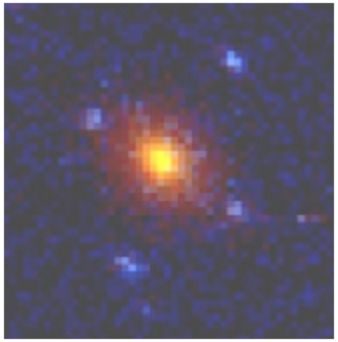
A. Bosma

Wealth of Evidence for DM

- Galaxy rotation curves (V. Rubin) Bosma (HI)
- Dynamics of galaxy clusters (Zwicky)
- Gravitational lensing mass reconstruction







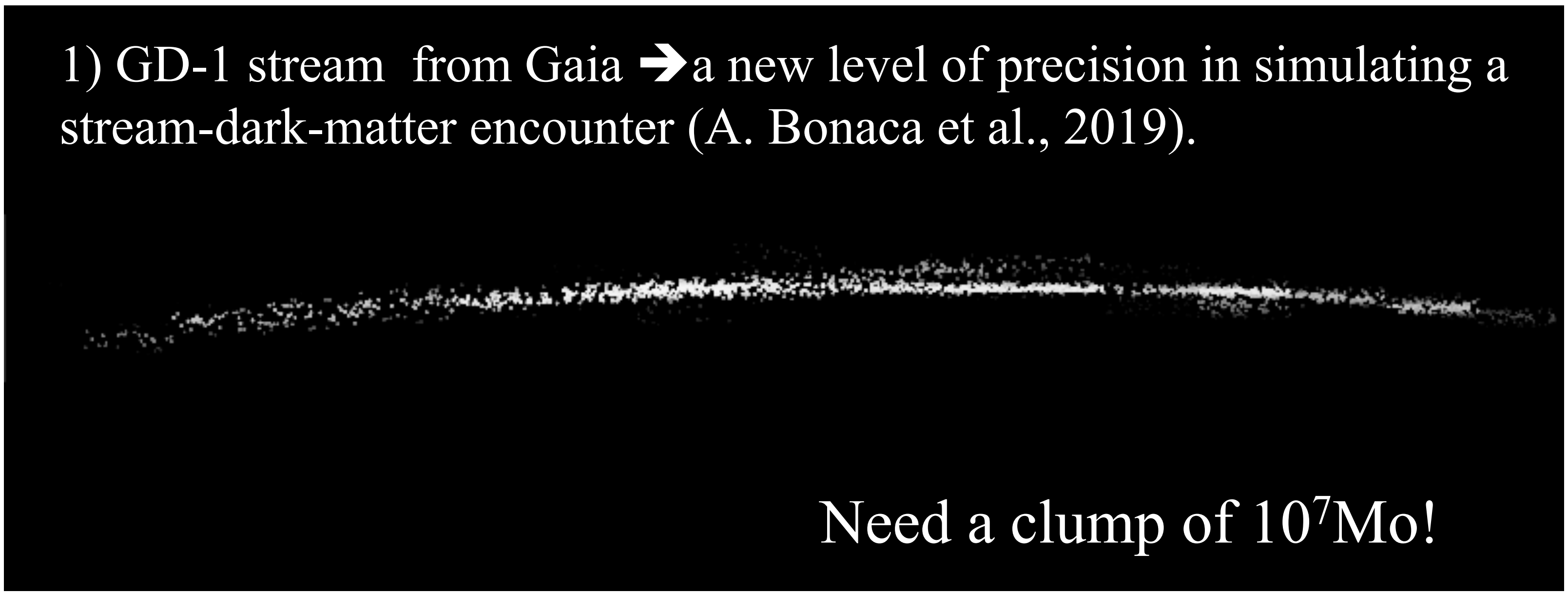
- Bullet cluster (Clowe+,2006)

Dynamics of clusters and galaxies:
Deducted from assumptions of
« equilibrium »

BUT…

In our Galaxy: Analysis of Gaia results

second release april 2018: high-precision positions, velocities, and distances for 1.3 billion stars



2) Lisanti et al 2019: 2 non disk populations of stars :

i) Old, isotropic velocity distributions

ii) Young, large radial velocities from merger 7 billion years ago!

Each should have its own DM population!!!

Galactic scale N-body simulations with Baryons

Ling+ 2009 Dark Matter Direct Detection Signals inferred from a Cosmological N-body Simulation with Baryons

➔ 2 DM populations :
halo DM +disk DM
➔ only measurements can tell

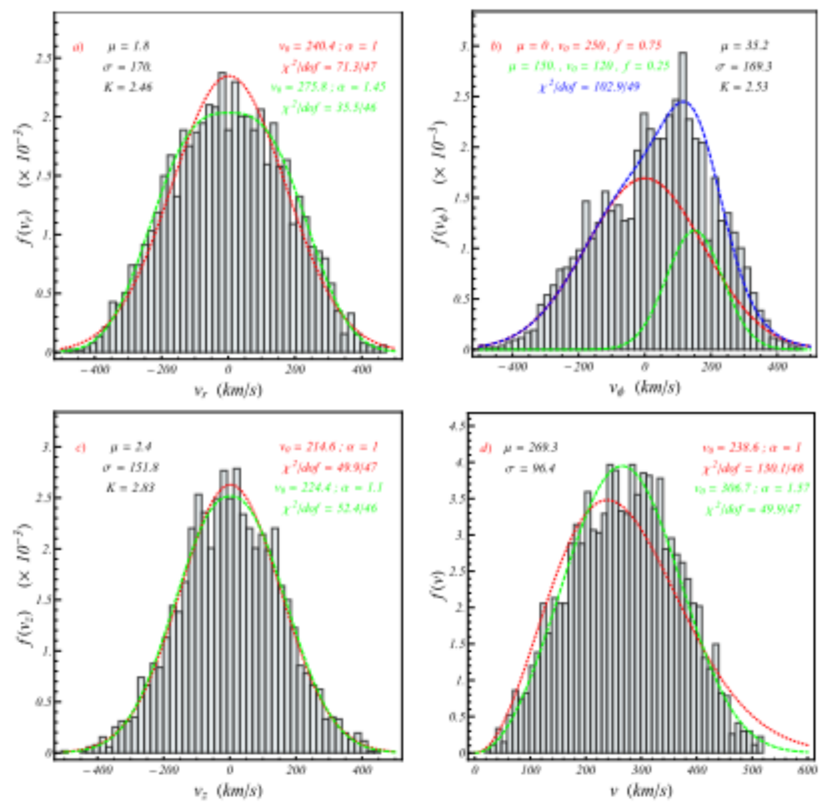


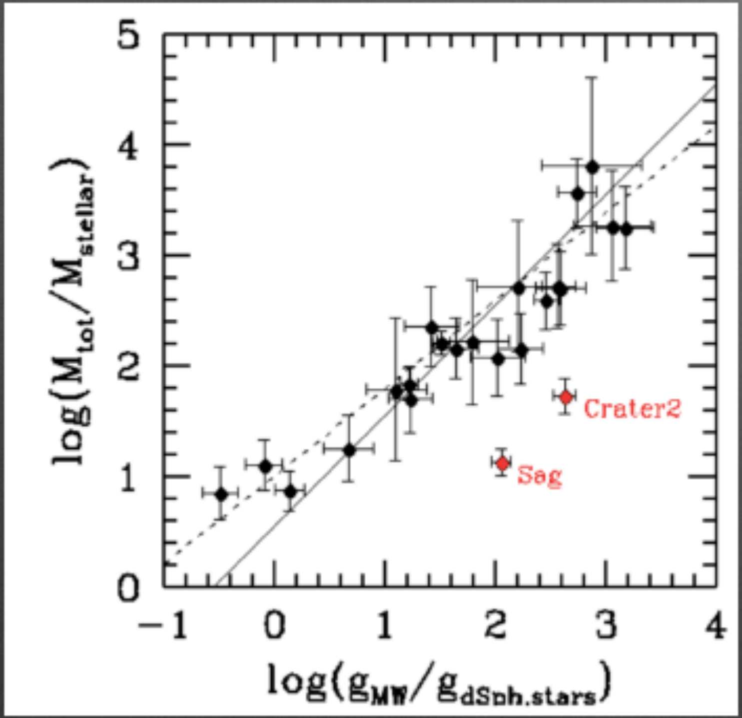
Figure 5: *Velocity distributions of dark matter particles ($N_{ring} = 2,662$) in a ring $7 < R < 9$ kpc, $|z| < 1$ kpc around the galactic plane.*
a) Radial velocity v_r, with Gaussian (red) and generalized Gaussian (green) fits (cfr. Eq. (2.1)).
b) Tangential velocity v_ϕ, with a double Gaussian fit. f indicates the fraction of each component.
c) Velocity across the galactic plane v_z, with Gaussian (red) and generalized Gaussian (green) fits (cfr. Eq. (2.1)).
d) Velocity module, with Maxwellian (red) and a generalized Maxwellian (green) fit (cfr. Eq. (2.2)).
μ, σ (both in km/s) and K stand for the mean, the standard deviation and the Kurtosis parameter of the distribution. The goodness of fit is indicated by the value of the χ^2 vs. the number of degrees of freedom (dof).

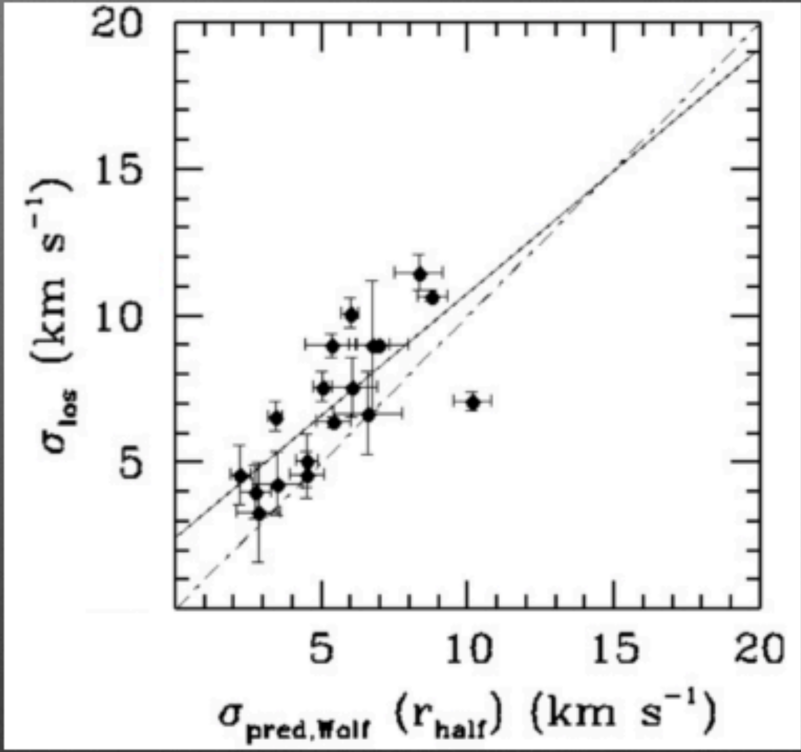
No need for DM
in Dwarf galaxies ?

Yang Yanbin Yunnan Sino French meeting Nov 2018

Galactic forces rule dynamics Milky Way dwarf galaxies

Hammer et al. 2018, ApJ





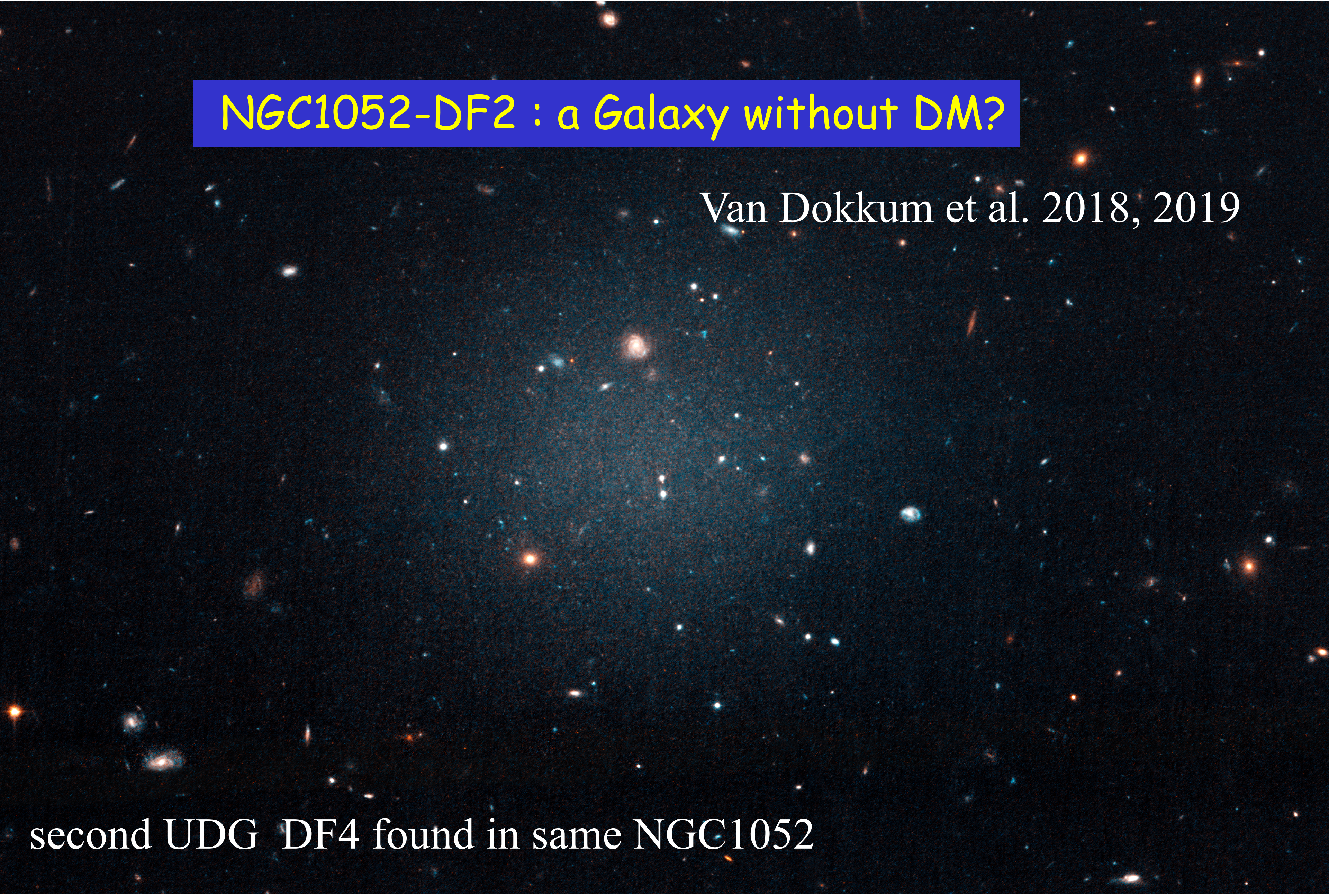
$$\sigma^2_{los,MW} = \sqrt{2}\, g_{MW}\, r_{half}$$

MW tidal shock predicts

This correlation falsifies the hypothesis of neglecting the MW impact!

NGC1052-DF2 : a Galaxy without DM?

Van Dokkum et al. 2018, 2019



second UDG DF4 found in same NGC1052

➔ Evidence for DM? (against modified gravity)

ΛCDM : Dominant theory of Structure formation and evolution

- Primordial Universe: Vacuum ? Inflation?

- Tiny perturbations seed the later formation of structures
- Nearly scale-invariant Gaussian random field *Bardeen, Bond, Kaiser, Szalay 1986*
- Structures form by gravitational instability
- Biased galaxy formation from DM haloes
- **Matter** dense regions **contract** under gravity while

Many questions:

Origins of DM? What DM?

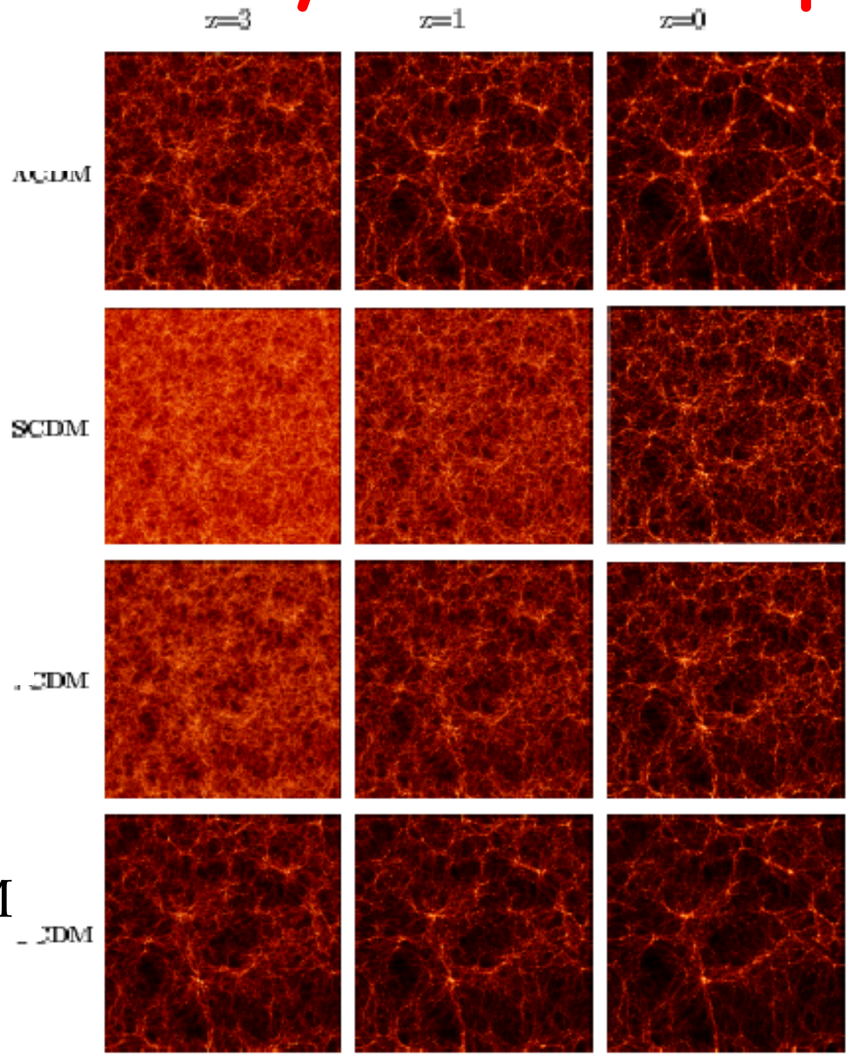
Comparisons of LSS observations with pre-2000 N-body Simulations prefer **CDM**

ΛCDM

SCDM

τCDM

OCDM



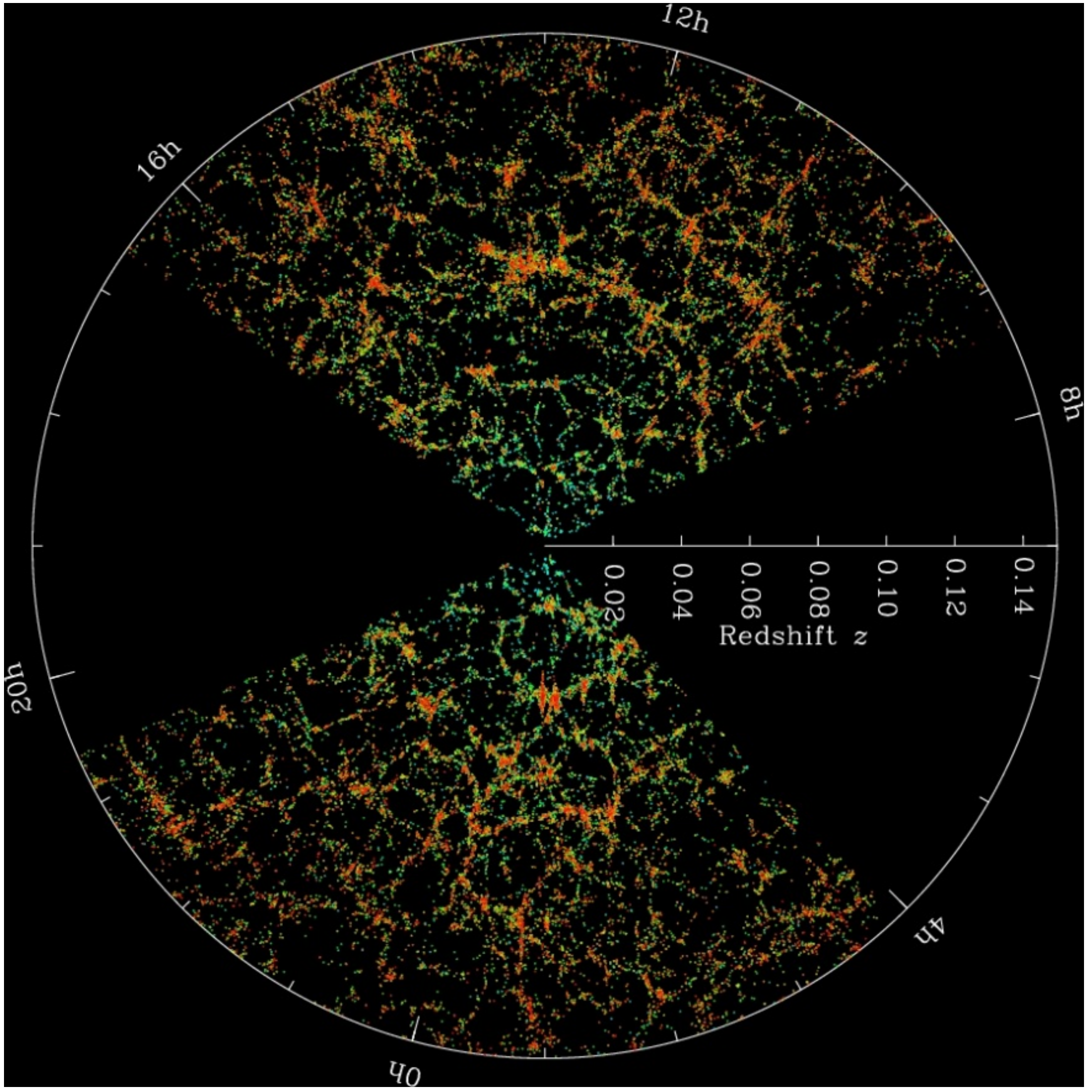
OMEGA = 0.3
LAMBDA = 0.7
H0 = 70 km/(Mpc sec)
Sigma8 = 0.9

OMEGA = 0.3
LAMBDA = 0
H0 = 70 km/(Mpc sec)
Sigma8 = 0.85

Collaboration VIRGO 1996
http://www.mpa-garching.mpg.de/~virgo/virgo/

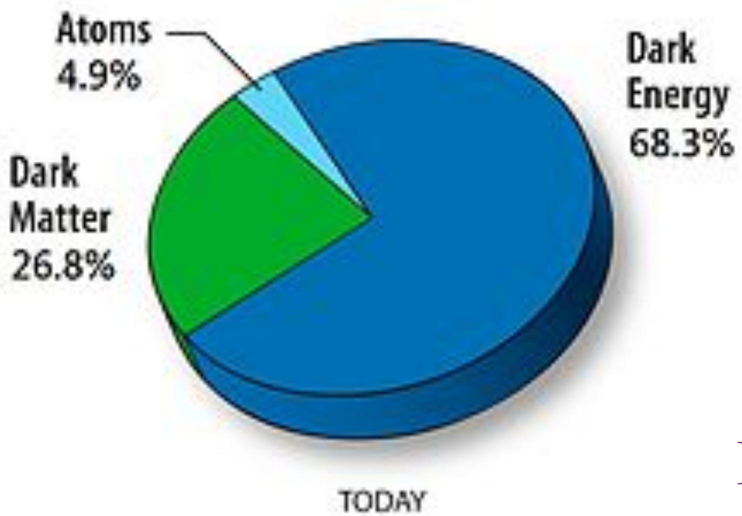
Cosmic Web: Knots, Filaments, Sheets and Voids

From large scale structure surveys, eg, data in redshift



Voids = low density regions in space

The Universe energy density content after Planck

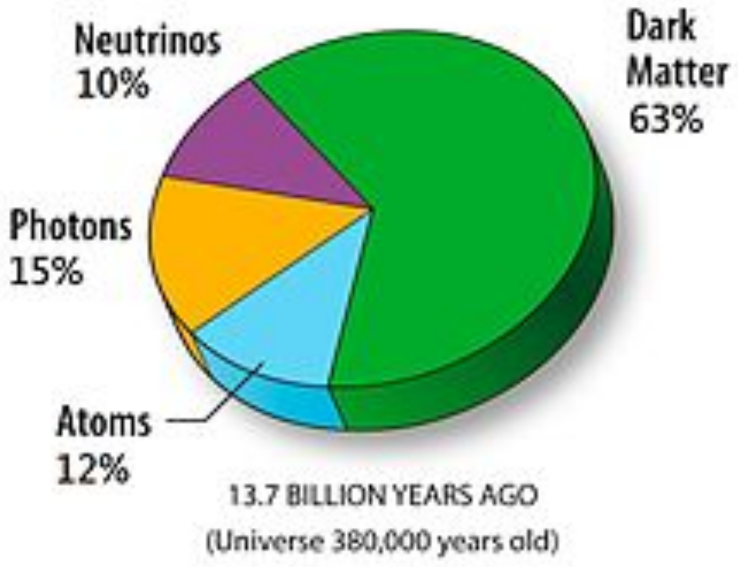


% precision

Cf Planck march 2018 papers

For Λ or DE, cf another seminar!

Wikipedia



Matter today ~ 32% energy density of the Universe

85% of the matter is dark matter

Do we trust ΛCDM?

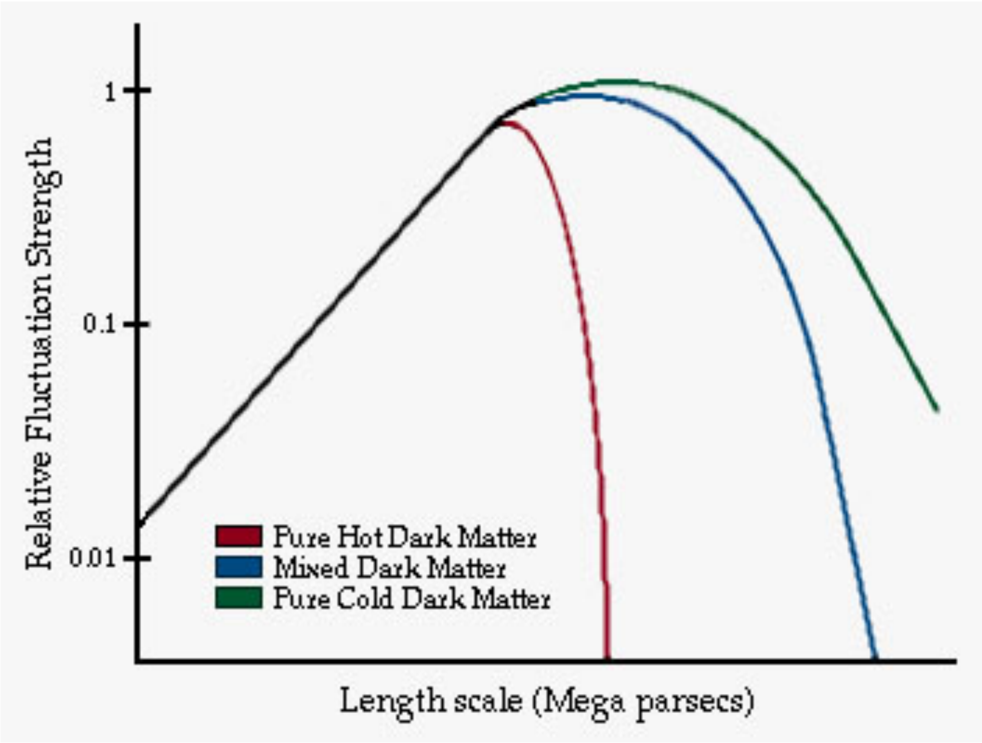
- Fits well the observations, except for…

- Some issues in N-body simulations (resolved by introducing baryons?)
- H0 tension : could be rS in the early Universe
- Large mass galaxies

<2000: Nature of DM
Hot or Cold?

CDM is non-relativistic at decoupling, forms structures in a hierarchical, bottom-up scenario.

HDM is tightly bound by observations and LSS formation

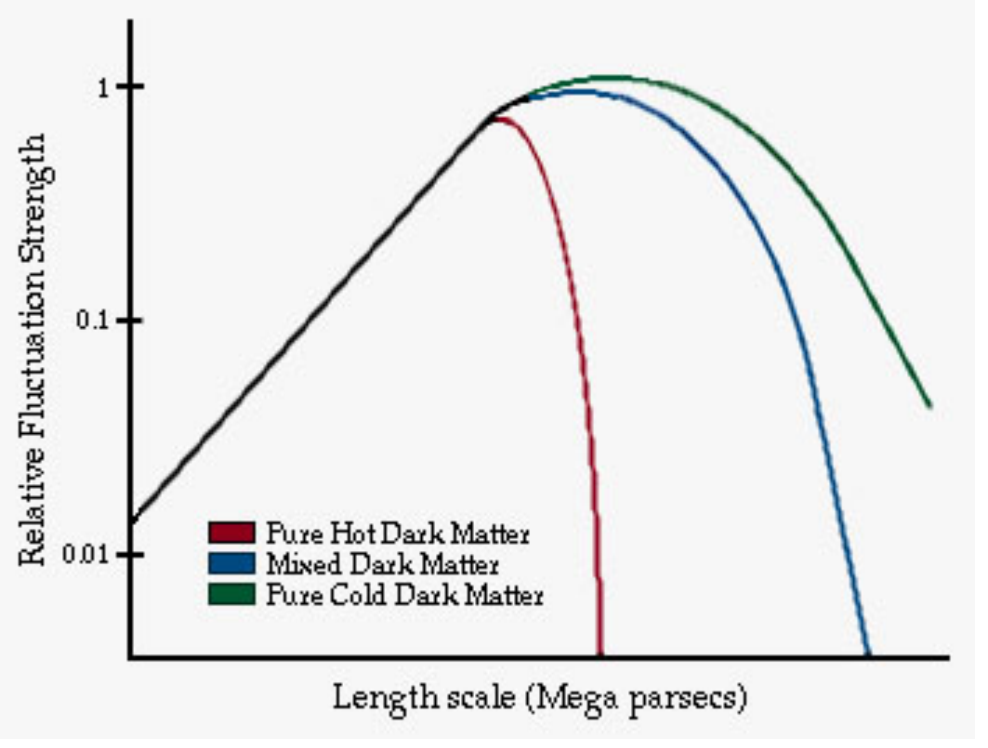


Nature of DM
Hot or Cold, or Warm?

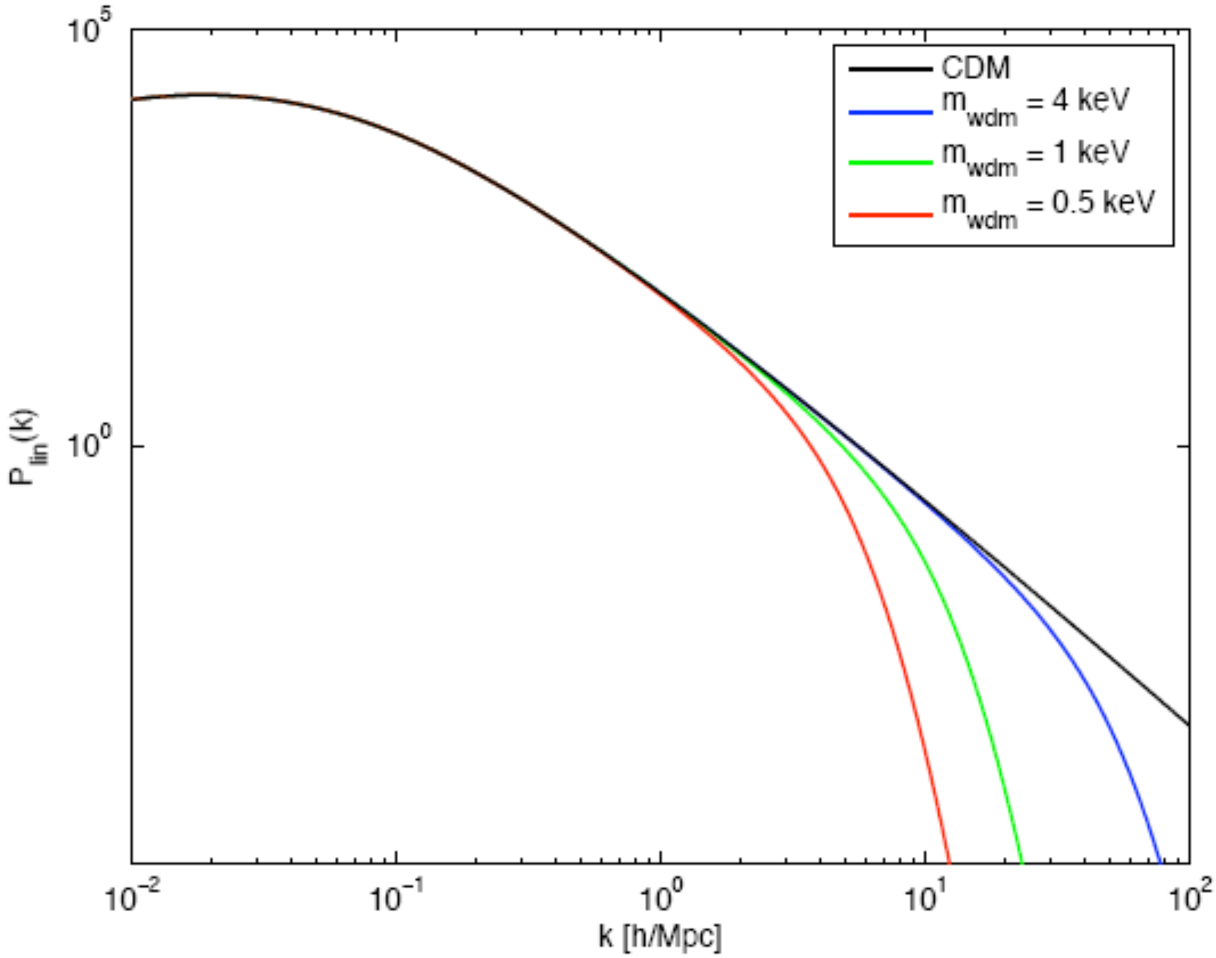
CDM is non-relativistic at decoupling, forms structures in a hierarchical, bottom-up scenario.

HDM is tightly bound by observations and LSS formation

WDM
10 h/Mpc, keV



keV WDM effect around k=10 h/Mpc



Baryon effects different from low mass standard model neutrino effects

Semboloni et al. 2011

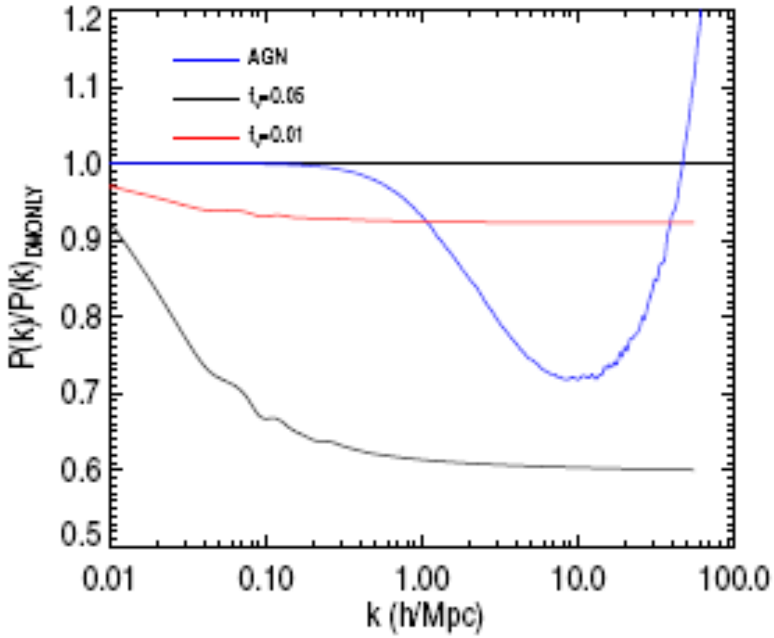


Figure 14. Ratio of the AGN/DMONLY power spectra (blue line), and dark matter power spectra with $f_\nu \equiv \Omega_\nu/\Omega_m = 0.01$ and 0.05, which correspond to neutrino masses of $\sum m_\nu \sim 6.0$ and $\sum m_\nu \sim 1.2$ eV, respectively. The effect of massive neutrinos on the power spectrum is quite different from that of baryon physics, even if neutrinos are light.

Galaxies…

Clusters of stars, but how are stars forming?
Today: Hierachical merging model with ΛCDM is leading

Oldest most distant observed galaxy: **GN-Z11** observed by CANDELS (HST) at $z = 11.09$ in Ursa Major, at proper distance: 32E9 ly (9.8 E9 parsecs)

The impossible Early Galaxy Problem

The Impossibly Early Galaxy Problem

arXiv:1506.01377 Charles L. Steinhardt, Peter Capak, Dan Masters, Josh S. Speagle

The current hierarchical merging paradigm and ΛCDM predict that the **$z\sim4-8$ universe** should be a time in which the most massive galaxies are transitioning from their initial halo assembly to the later baryonic evolution seen in star-forming galaxies and quasars.

However, **no evidence of this transition** has been found in many high redshift galaxy surveys including CFHTLS, CANDELS and SPLASH the first studies to probe the high-mass end at these redshifts.

Indeed, if halo mass to stellar mass ratios estimated at lower-redshift continue to **$z\sim6-8$** CANDELS and SPLASH report **several orders of magnitude more $M\sim1012-13M_\odot$ halos** than are possible to have formed by those redshifts, implying these massive galaxies formed impossibly early.

We consider various systematics in the stellar synthesis models used to estimate physical parameters and possible galaxy formation scenarios in an effort to reconcile observation with theory. Although known uncertainties can greatly reduce the disparity between recent observations and cold dark matter merger simulations, even taking the most conservative view of the observations, **there remains considerable tension with current theory.**

A dominant population of optically invisible massive galaxies in the early Universe

August 2019, Wang, Schreiber, Elbaz et al… arxiv: 1908.02372

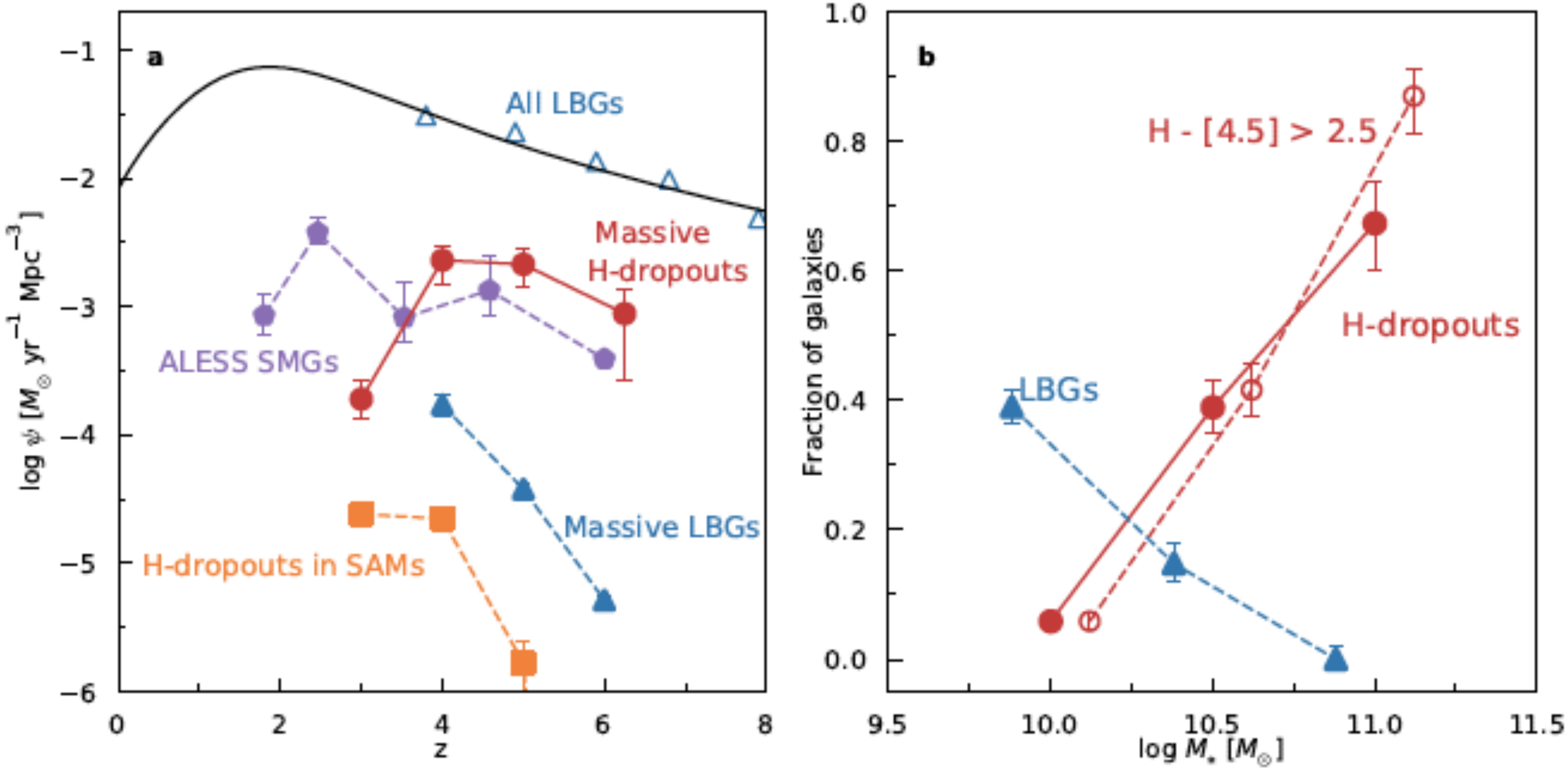
https://www.nature.com/articles/s41586-019-1452-4

Here we report submillimetre (wavelength 870 micrometres) detections of 39 massive star-forming galaxies at $z > 3$, which are unseen in the spectral region from the deepest ultraviolet to the near-infrared.

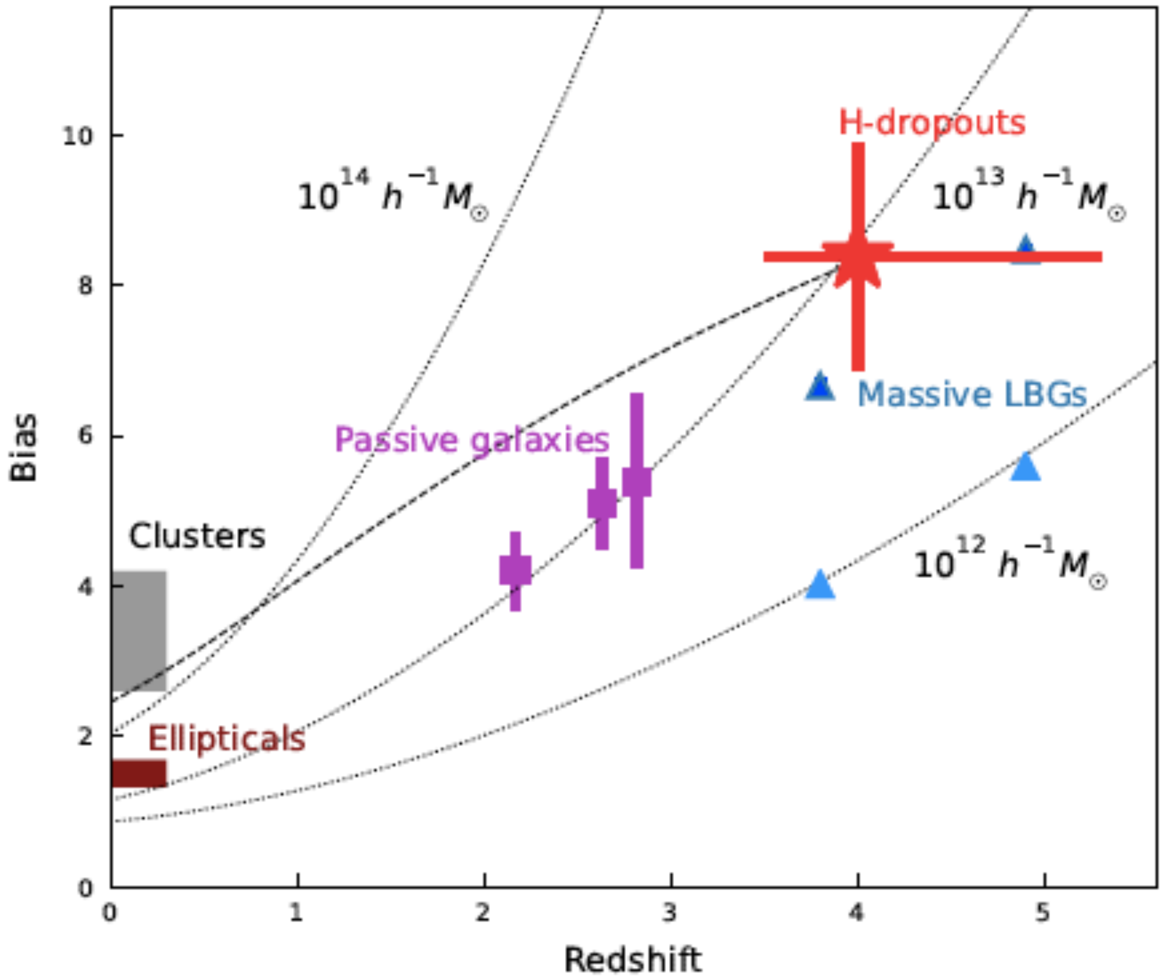
With a space density of about 2 E^{-5} and SFR of 200 Mo/y these galaxies represent the bulk population of massive galaxies that has been missed from previous surveys.

Total SFR density ten times larger than that of equivalently massive ultraviolet-bright galaxies at $z > 3$. Residing in the most massive dark matter haloes at their redshifts, they are probably the progenitors of the largest present-day galaxies in massive groups and clusters.

Such a high abundance of massive and dusty galaxies in the early Universe challenges our understanding of massive-galaxy formation.



a
All LBGs
Massive
H-dropouts
ALESS SMGs
Massive LBGs
H-dropouts in SAMs
log ψ [M⊙ yr−1 Mpc−3]
z
b
H - [4.5] > 2.5
H-dropouts
LBGs
Fraction of galaxies
log M* [M⊙]



H-dropouts
$10^{14}\ h^{-1} M_\odot$
$10^{13}\ h^{-1} M_\odot$
Massive LBGs
Passive galaxies
Clusters
$10^{12}\ h^{-1} M_\odot$
Ellipticals
Bias
Redshift
0
2
4
6
8
10
0
1
2
3
4
5

What do we know about the nature of DM?

Particle : stable?
mass?
interaction cross-sections?
charge?
spin ?

Constraints from non-observation in direct/indirect/LHC searches
AND
Observations in Astrophysics / Cosmology

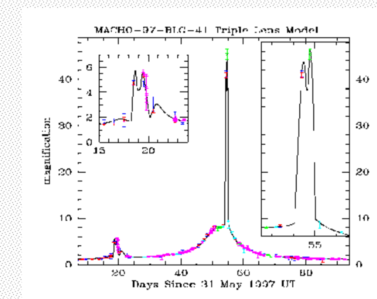
Very different DM candidates

Modified Gravity

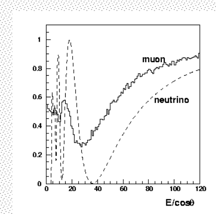
Cold Molecular Hydrogen

MACHOs

Black holes



SIMPs

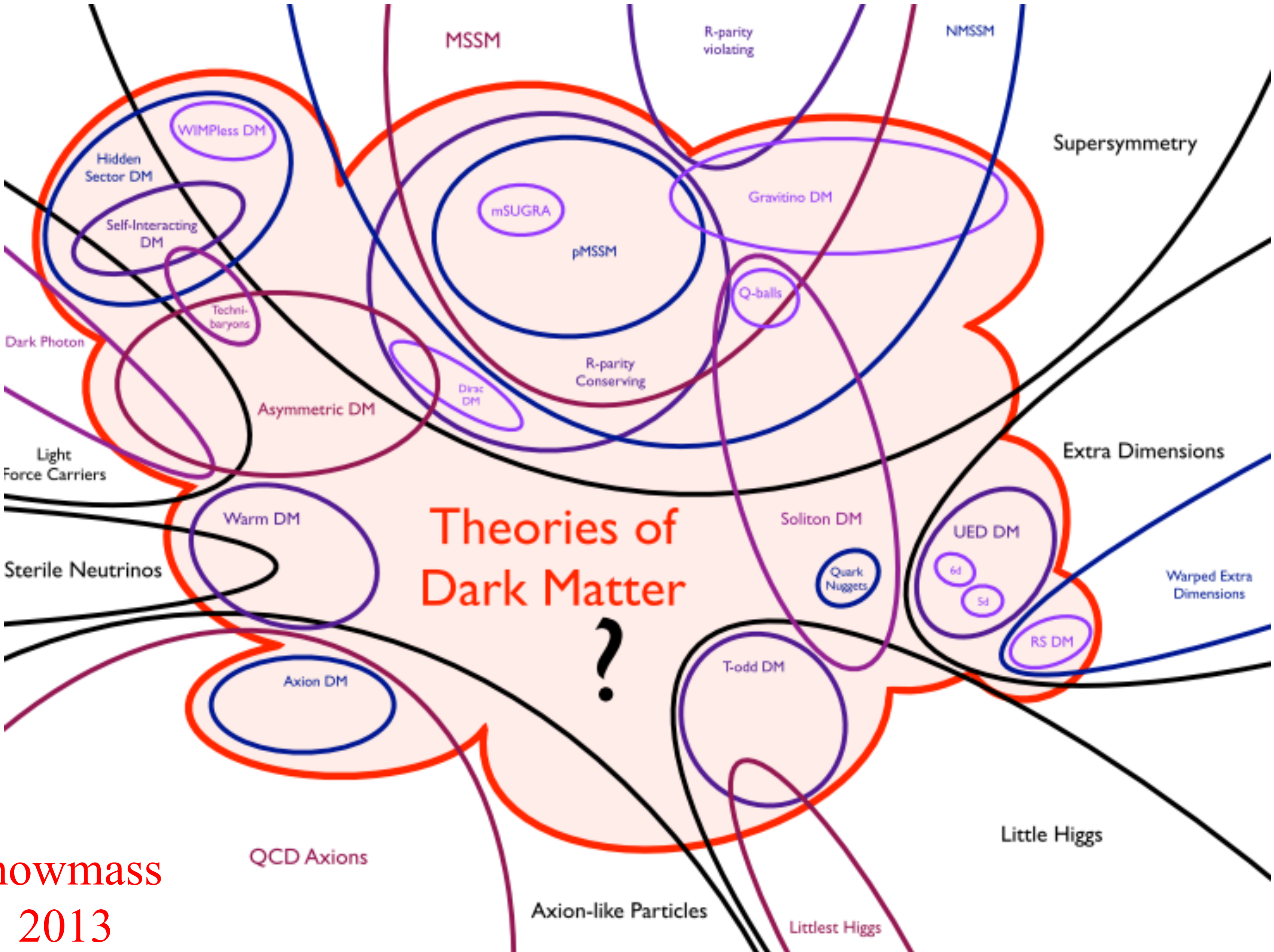


1Neutrino

2. WIMPs
Weakly interacting massive particles
10-1000GeV

3. Light axions

Exotica



Snowmass 2013

Fashionable DM particle candidates : ultralight DM, eg, fuzzy DM

Old idea

Wayne Hu, R. Barkana, and A. Gruzinov. Fuzzy Cold Dark Matter: The Wave Properties of Ultralight Particles.
Physical Review Letters, 85:1158{1161, August 2000.

Revival 2015-2016

Hlozek, D. Grin, D. J. E. Marsh, and P. G. Ferreira. A search for ultralight axions using precision cosmological data. Phys. Rev. D , 91(10):103512, May 2015.
- L. Hui, J. P. Ostriker, S. Tremaine, and E. Witten. On the hypothesis that cosmological dark matter is composed of ultra-light bosons. ArXiv e-prints, October 2016

➔ If the dark matter is composed of FDM, most observations favor a particle mass> 10^-22 eV and the most signicant observational consequences occur if the mass is in the range (1-10) 10^-22 eV.

A case for FDM: Hui et al. 2016

- Small haloes do not form in FDM
- FDM halos central core
- FDM delays galaxy formation but its galaxy-formation history

Still consistent with current observations

If FDM, most observations favor a particle mass in the range

(1-10) 10^{-22} eV

- There is tension with observations of the Lyman α forest

- More sophisticated models of reionization may resolve this tension.

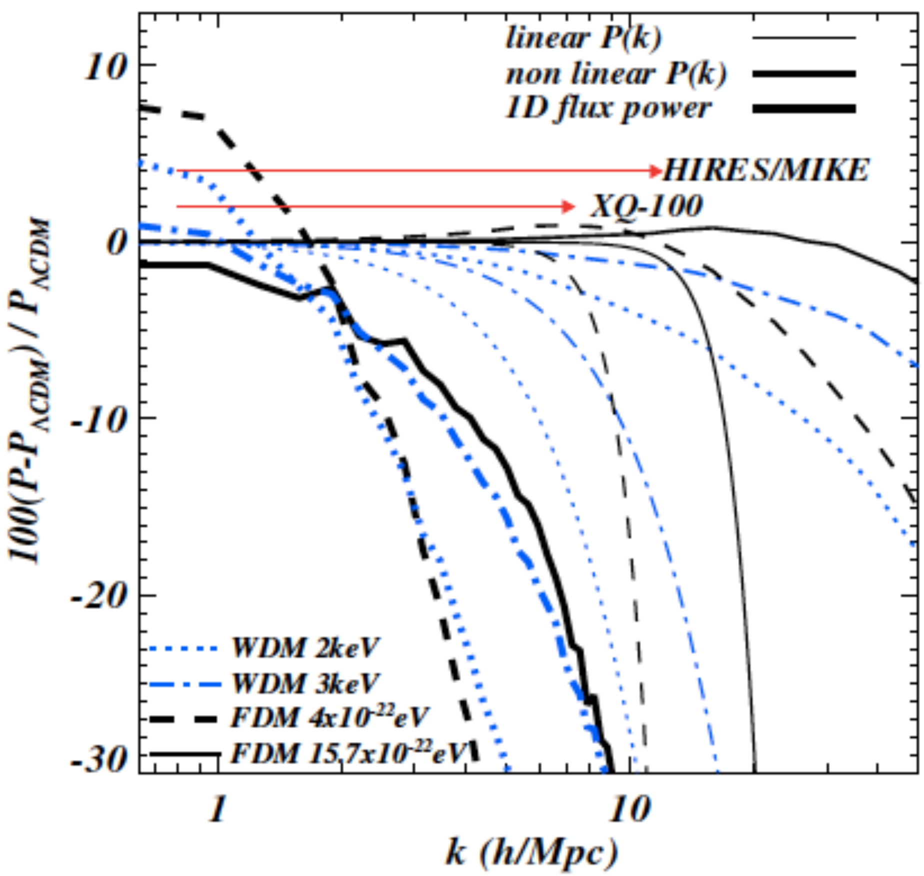
First constraints on fuzzy dark matter from Lyman-forest data and hydrodynamical simulations

Irsic, Viel, Haehnelt, Bolton , and Becker. 1703.04683

XQ-100 and HIRES/MIKE quasar spect

lower combined limits 20 to 37.5 10^{-22} eV (2σ C.L.).

Light boson masses in the range
(1- 10) 10^{-22} eV
are ruled out at high significance
by our analysis, casting strong doubts
that FDM helps solve the "small scale
crisis" of the cold dark matter models.



Reionization could save FDM?

FIG. 1: Power spectrum relative to ΛCDM at $z = 5.4$ (in per cent). Linear matter, non-linear matter and flux power spectra are represented by the thin, thick and very thick curves, respectively. Black (blue) curves are for FDM (WDM) models with $m_{FDM} = 5.7, 15.7 \times 10^{-22}$ eV ($m_{WDM} = 2$, 3 keV).

Why WIMPs?

"WIMP" = "Weakly Interacting" Massive Particles

Arguments in the 1980's:

- Need for Cold Dark Matter from Large Scale Structures
- Very good Particle physics candidate: SUSY LSP
- Weak neutrino size cross sections expected which our detectors Ge, NaI were sensitive to…

(String) **Requiem for WIMPS** ?

Acharya, SE, Gane, Nelson, Perry, 1604.05320, 1707.04530

Typical properties of known solutions of string/*M*-theory,
➔ LSP not stable.

Most important argument: SUSY not seen yet!

Particle physics preferred DM: SUSY Neutralinos ?

- A natural particle physics solution
- Stable linear combination gauginos and higgsinos (LSP)
- SUSY > 7 parameters MSSM ➔ no predictive power
- Experimental Constraints LEP, pp, b-->sγ, + LHC ...

Look everywhere possible !

Direct and Indirect

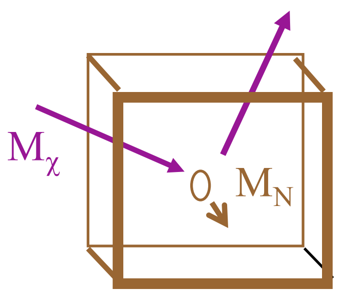
Detections


I'M LOOKING FOR MY Dark Matter!
DID YOU DROP IT HERE?
NO, I DROPPED IT TWO BLOCKS DOWN THE STREET!
THEN WHY ARE YOU LOOKING FOR IT HERE?
BECAUSE THE LIGHT IS BETTER HERE!
?

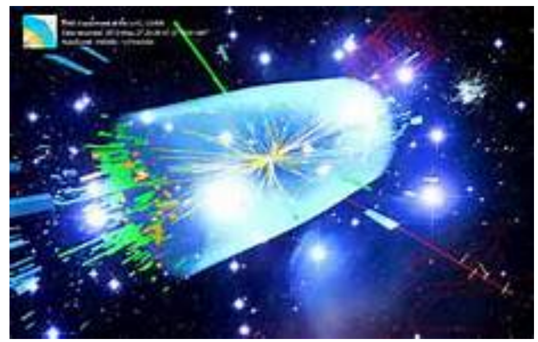
Fisher (1942)

WIMP searches

Direct detection

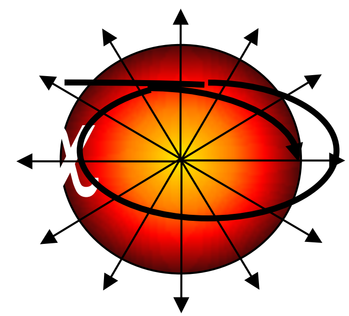


Ge, Si, NaI, LXe, …



Accelerator particle production,
eg, LHC

Indirect detection



ν, γ, p, e^+

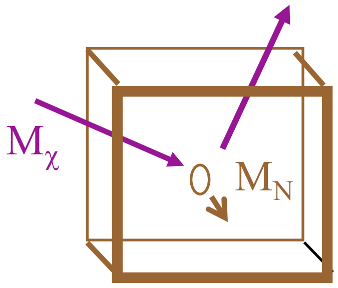
+ Galactic, cluster, Universe scales…

WIMP searches: Direct detection

Principle : (Goodman and Witten,1985, Drukier and Stodolsky 1984)

Elastic scattering of galactic DM off detector nuclei

Nuclear recoils of a few keV



Ge, Si, NaI, LXe, …

Direct DM detection: Interaction rates

Cf presentation of Julien Lavalle

Depend on several parameters

- Astrophysical hypothesis: model of DM in Galaxy (SMMG)

  ρ_{DM}, $f(v)$

- Nuclear form factors F^2 important for heavy nuclei
- Detector response Quenching factors, resolutions, thresholds,....
- Particle physics Nature of WIMP and cross-sections

σ_χ

Coherent	Axial
Spin Independent (SI)	**Spin Dependent (SD)**
eg, Dirac ν	eg, Majorana ν

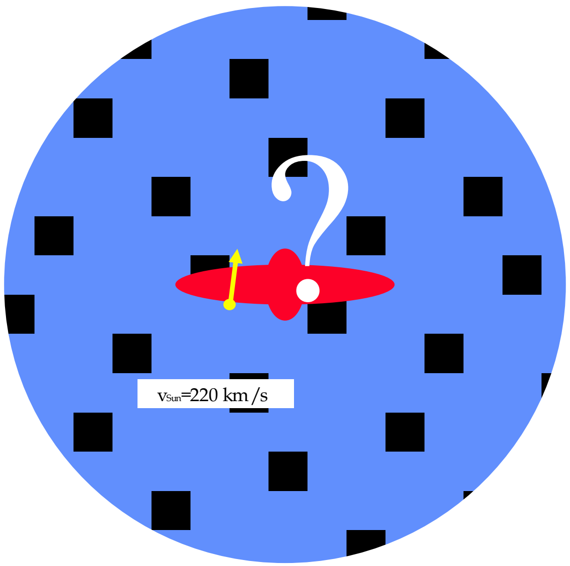
Neutralinos are a linear combination of higgsinos and gauginos

with cross-sections $< 0.1\ \sigma_\nu$

Usual assumptions of DM distribution in our Galaxy

Usual assumptions:

ρ_{DM}= 0.3 GeV/cm^3, β=10^{-3},
Maxwellian distribution of velocities, v_{rms}=270 km/s



« Simplified Model »of Matter in our Galaxy: SMMG

Used for most comparisons…

But is it the reality? Clumps? Corotation?

Some numbers ... Local density

Milky Way or Andromeda: total visible mass of about 6×10^{10} M_{sun}.

- rotation velocity ~220 km/sec
- radius about ~ 30 kpc

Newton:

$$v_{rot} = \sqrt{\frac{GM}{R}} \Rightarrow M = \frac{v_{rot}^2 R}{G}$$

$\Rightarrow$ total mass: 3.3×10^{11} M_o

$\Rightarrow \Rightarrow$ **~5 times more dark mass than visible**

Local density: (0.3- 0.4 GeV/cm^3) ?

0.0159 +0.0047 –0.0057 M⊙/pc^3, LAMOST (China). 0.7GeV/cm^3

1 M⊙ = 2. E30 kg, 1pc=3.0857E16 m, 1M⊙/pc^3= 6.8 E-8 kg/cm3

1kg = 5.625 * 10^{26} GeV/c^2

Work of Tao Yi PhD student in Tsinghua U.

Two Component DM Model

L. Necib et al., arXiv: 1807.02519

Recent observations from *Gaia*

$$f(\mathbf{v}) = \xi_{\rm h} f_{\rm h}(\mathbf{v}) + \xi_{\rm s} f_{\rm s}(\mathbf{v})$$

$$f_{\rm h}(\mathbf{v}) \propto \mathcal{N}(\boldsymbol{\mu}_{\rm h}, \boldsymbol{\Sigma}_{\rm h})$$

$$f_{\rm s}(\mathbf{v}) \propto \frac{1}{2}\left[\mathcal{N}(-\boldsymbol{\mu}_{\rm s}, \boldsymbol{\Sigma}_{\rm s}) + \mathcal{N}(\boldsymbol{\mu}_{\rm s}, \boldsymbol{\Sigma}_{\rm s})\right]$$

	μ_r	μ_θ	μ_ϕ	σ_r	σ_θ	σ_ϕ
Halo (best-fit)	$8.5^{+0.29}_{-0.29}$	$6.49^{+0.26}_{-0.26}$	$13.38^{+0.43}_{-0.43}$	$140.3^{+4.2}_{-4.9}$	$114.2^{+3.3}_{-1.8}$	$125.9^{+4.1}_{-3.4}$
Substructure	$\pm177.7^{+1.8}_{-2.1}$	$-3.1^{+0.9}_{-0.9}$	$35.5^{+1.8}_{-1.8}$	$108.2^{+1.2}_{-1.3}$	$57.7^{+0.7}_{-0.8}$	$61.2^{+1.5}_{-1.5}$

B. Coşkunoğlu et al., arXiv: 1011.1188

$+\ 235$

Unit: km/s

For comparison: parameters of SHM (0, 0, 220, 156, 156, 156)

Expected Signal of WIMP DD by Monte Carlo Simulati

3D Distribution Model (**v** space):

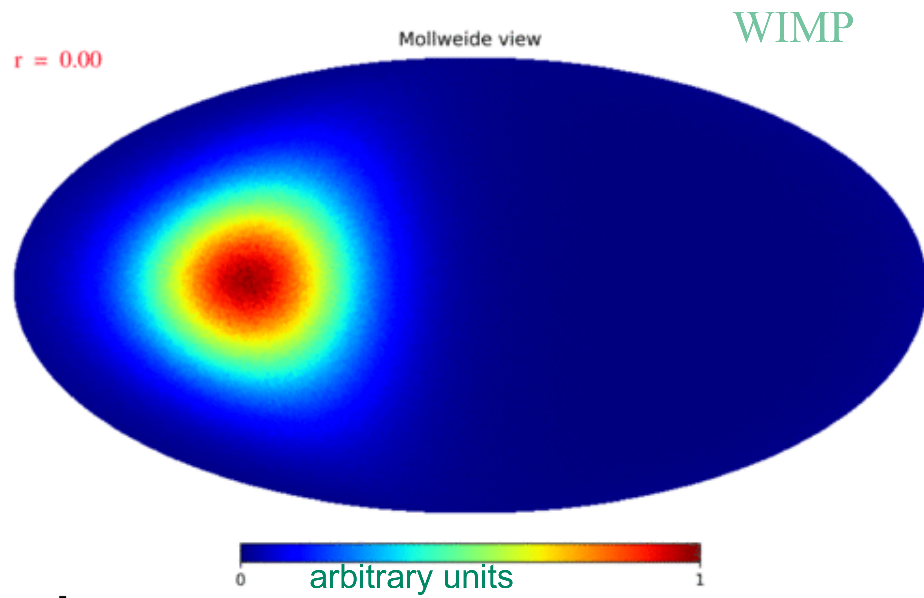
Halo + Substructure

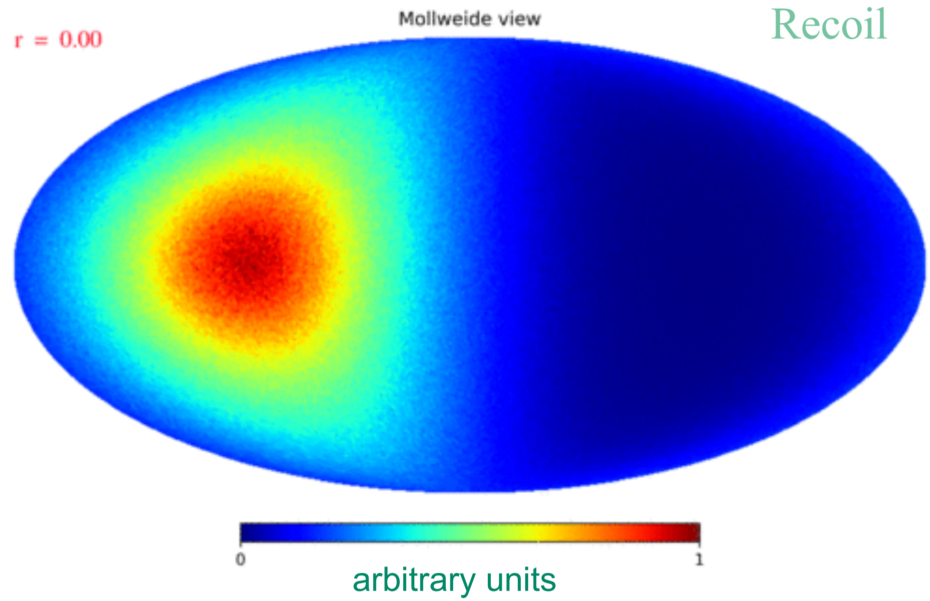
$$f(\mathbf{v}) = \xi_{\rm h} f_{\rm h}(\mathbf{v}) + \xi_{\rm s} f_{\rm s}(\mathbf{v})$$

Fraction parameter: $$r = \frac{\xi_{\rm s}}{\xi_{\rm h} + \xi_{\rm s}} \in [0, 1]$$

Top: WIMP distribution

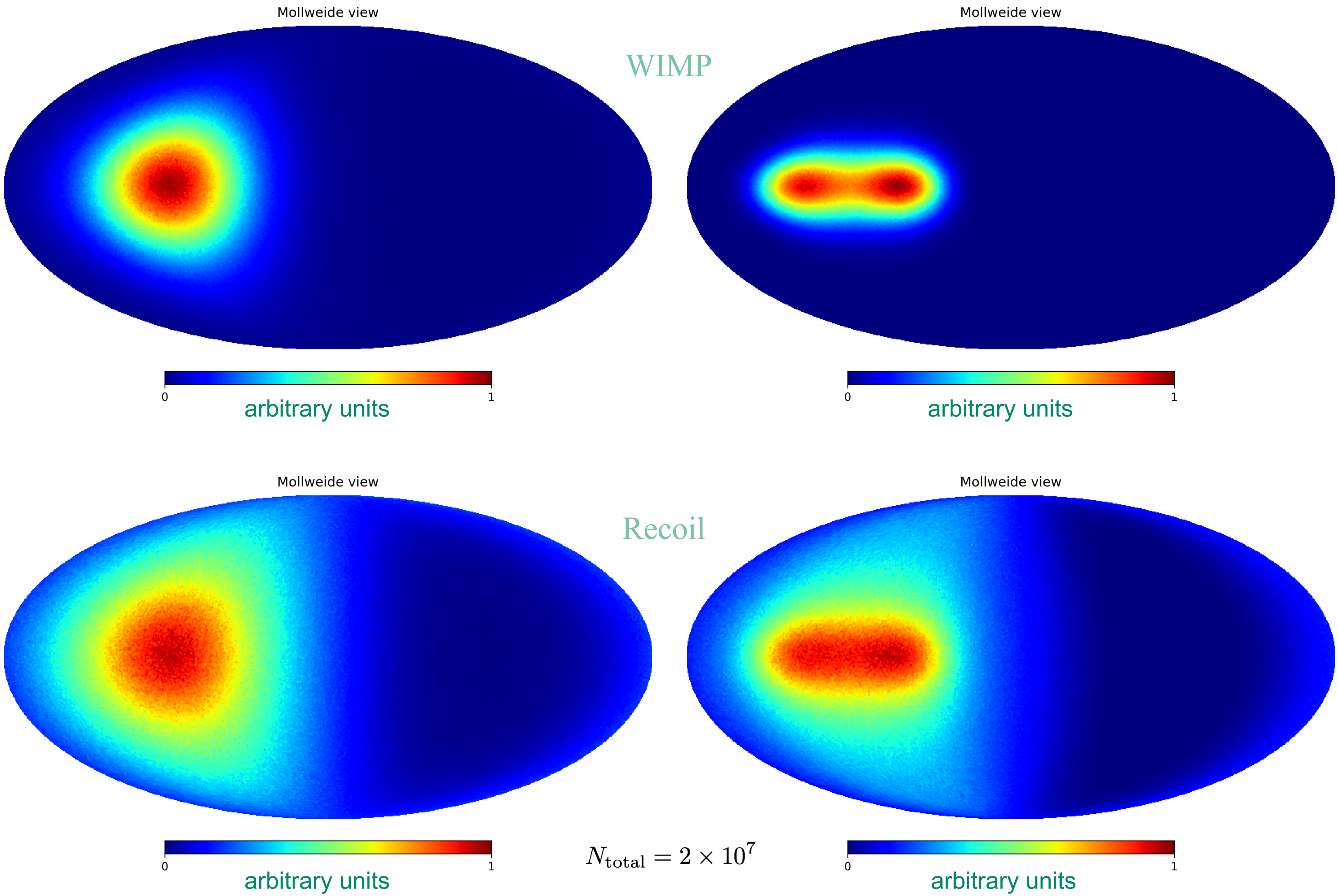
Bottom: Induced nuclear recoil distribution





$N_{\rm total} = 2 \times 10^7$

Halo only (r=0) **Substructure only (r=1)**



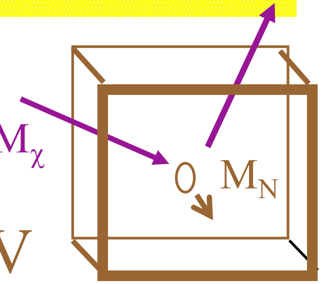
Why a Directional Dark Matter detector?

WIMP searches: Direct detection

- Principle :

Drukier and Stodolsky 1984

Elastic scattering of galactic DM off detector nuclei



Nuclear recoils of a few keV

Ge, Si, NaI, LXe, …

- Exponential recoil energy distribution

$$\frac{dR}{dE_R} = \frac{R_o}{E_o r} e^{-E_R/E_o r}$$

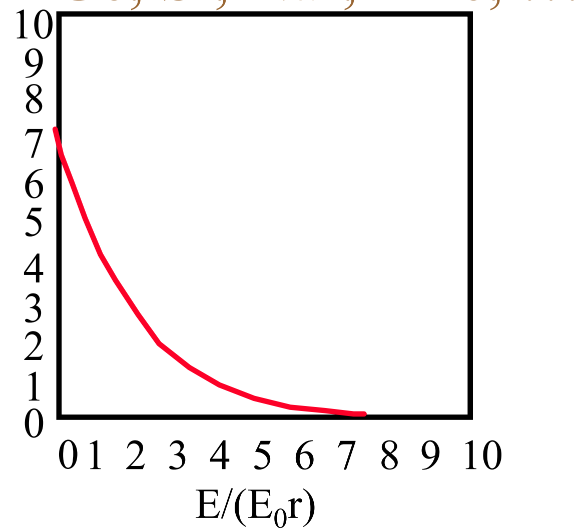
event rate per unit mass (dR/dE_R)

total event rate (point like nucleus) (R_o)

recoil energy (E_R)

incident energy (E_o)

kinematic factor $r = 4M_\chi M_N/(M_\chi + M_N)^2$



- Rates: Weak interactions or smaller

- Need of signatures for identifying galactic origin
  - Annual modulation with MASSIVE detectors
  - Directionality : low pressure TPC?
  - Dependence on nucleus

Why a Directional Dark Matter detector?

Need **signatures:**

1) *A* signal in different detectors with different nuclei
2) Show the *Galactic* origin

All experiments

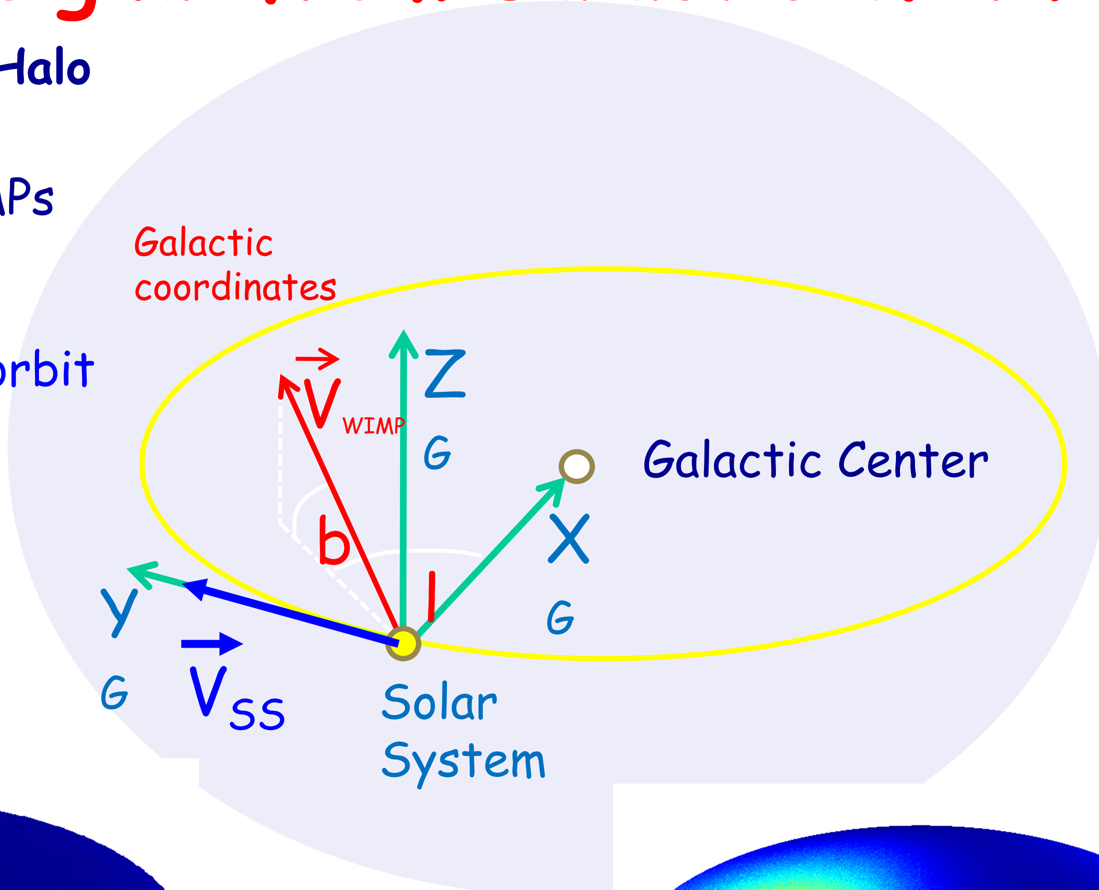
not in competition

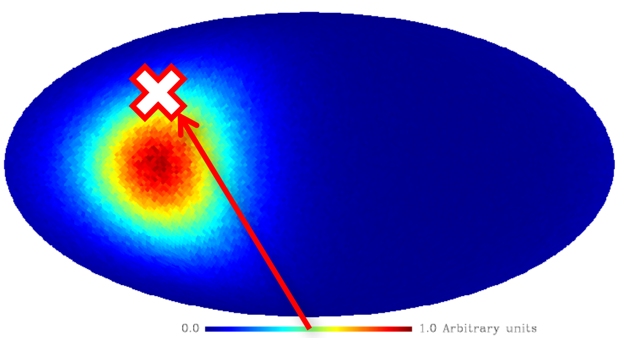
but **complementary!**

Expected signal from Galactic WIMPs

Dark matter Halo
=
gaz of WIMPs

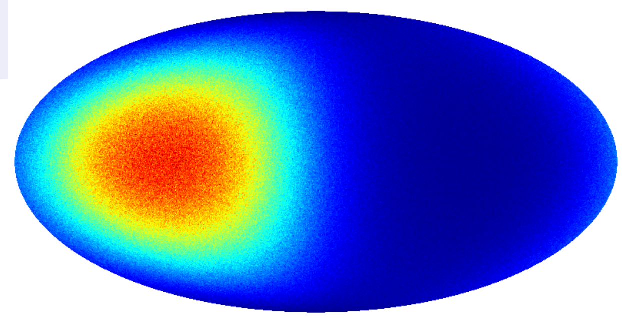
Solar System's orbit





Cygnus Constellation (l = 90°,b = 0°)

After collision



WIMP signal
ected

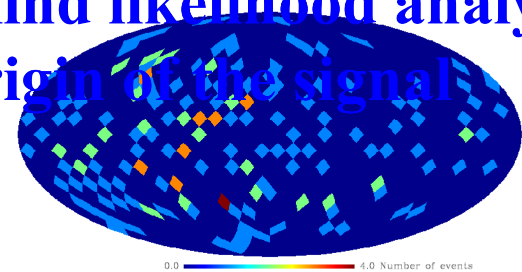
J. Billard *et al.*, PLB 2010
J. Billard *et al.*, arXiv:1110.6079

Phenomenology: Discovery

J. Billard *et al.*, PLB 2010
J. Billard *et al.*, arXiv:1110.6079

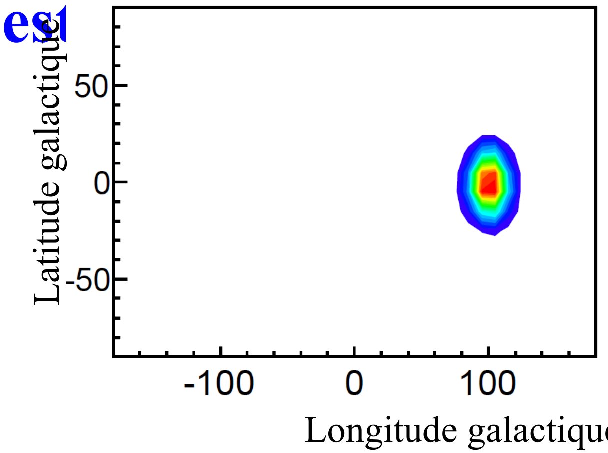
Proof of discovery: **Signal pointing toward the Cygnus constellation**

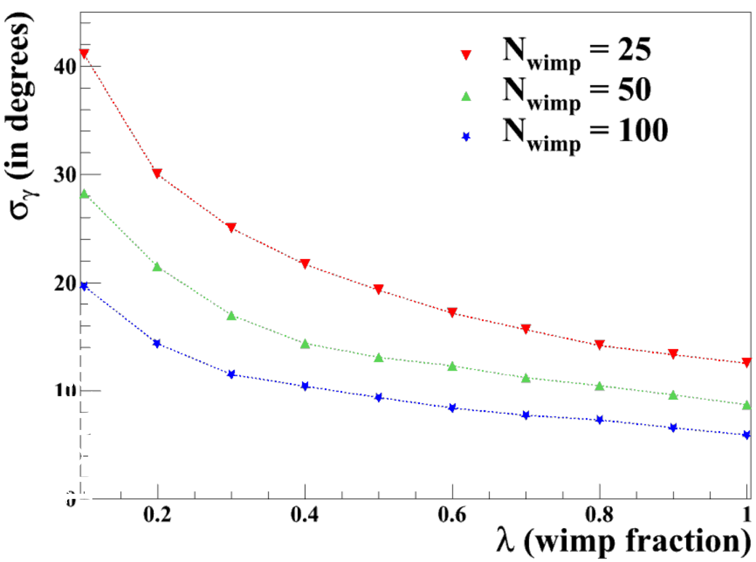
Blind likelihood analysis in order to est[...] origin of the signal



100 WIMP + 100 BKG

$$\mathscr{L}(\ell, b, m_\chi, \lambda)$$





Strong correlation possible with the direction of the Cygnus Constellation **even with a large background contamination**

Angular resolution < 20deg: R&D studies for requirements

- Measurable track length
- Measurable directionality
- Head-tail separation
- Ion/electron separation
- Quenching factor
- Reconstruction of initial recoil angle
- ,...

↓

The MIMAC project

What is DM?

not understood yet!.

the next Graal of physics!

DM: most fundamental problem in Physics today?

- Do gravitational waves exist? After A-LIGO
  Gravitational astronomy!
- Dark Energy: maybe cosmological constant
- **Dark Matter:**
  is there DM? and what is its Nature?

Future DM Astronomy?

Dark Matter:
What do we really know?

DM: - particles that does not emit observable radiation
- interacts gravitationally…
- non baryonic

DM: we know it exists!
But not much more… Need more data!!!

Or do we even really know it exists?

Alternatives to DM?

Not so many models any more, but still…

some are still doubting:

eg http://www.astro.uni-bonn.de/~pavel/kroupa_SciLogs.html

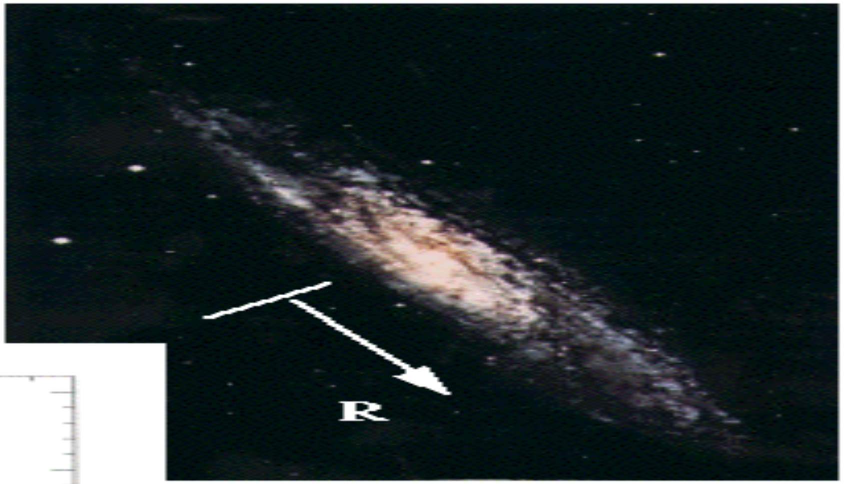
Famaey & Mc Gaugh

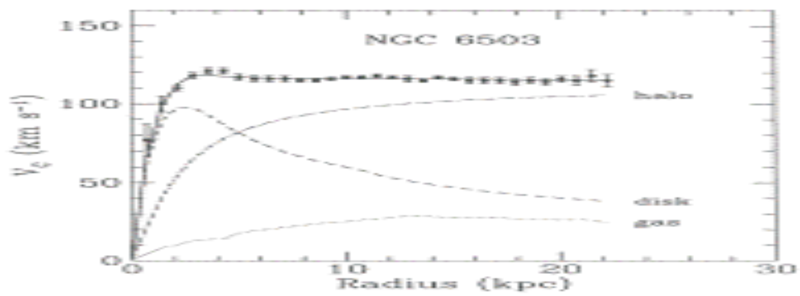
- **MOND-** Milgrom /TEVES-Beckenstein needs neutrinos to explain Bullet Cluster…
- **MOG** : Moffat and collaborators

  Scalar-Tensor-Vector Model of gravity : "few parameters can explain away DE and DM".
- **GR with torsion**

MOND

A model without dark matter





Milgrom MOdified Newtonian Dynamics (MOND)

for flat Galaxy rotation curves

modification of Newton's law at very weak accelerations,

$$\mu(a/a_0) = M\,G / r^2 = a_N \quad \text{where} \quad \mu(x)=1\ ,\ x \gg 1$$
$$= x,\ \ x \ll 1$$

$$a_0 \sim 1.2\ \text{A/s}^2$$

MOND = phenomenological model

- Violates equivalence principle
- Violates conservation of momentum
- Violates Lorentz invariance
- Violates Cosmological Principle
- ….

Excludes it ?

or

More interesting?

Bekenstein astro-ph/0403604, a coherent scalar-tensor theory?

TEVES a tensor-vector theory

Effective theory?

- Fits all rotation curves with 1 parameter variable: galaxy M/L
- Predicts Tully Fisher Mass-rotation (R. Sanders)

  M prop v^4
- Fits CMB without CDM S. Mc Gaugh

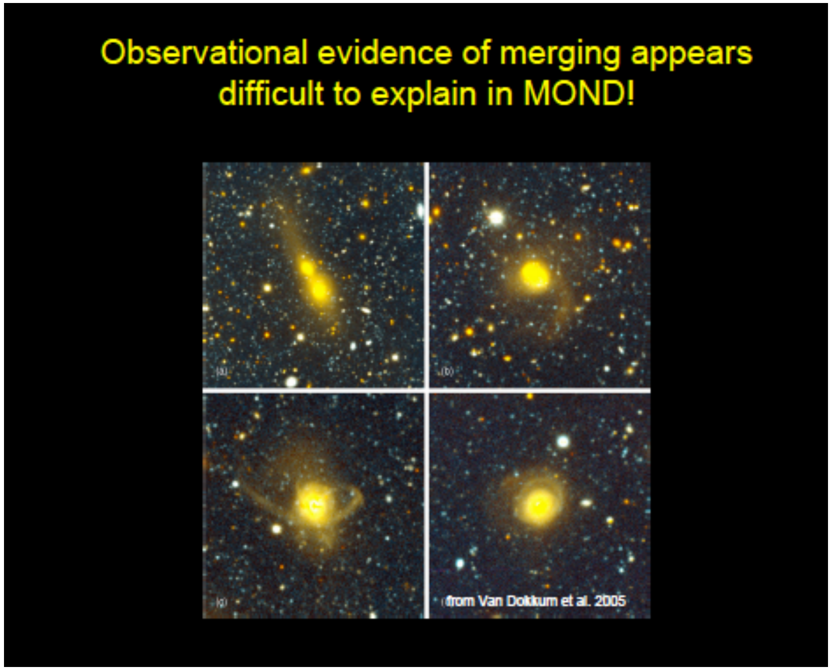
N-body simulations with no DM?

- Modified gravity f(R) simulations often have DM

- MOND/TeVes (Zhao Hongsheng, N-Mody,…)

  Status?

- Torsion model, etc…?



Universe with Torsion

- Extension to GR:

  in simplest CARTAN model :

  (eg, Schucker and Tilquin, 2012)

  Lambda/DE still needed but... DM reduced (to zero?)

- Difficulties with many extensions

eg Gauss theorem not valid, pathologies...

Summary: What do we know about DM?

- Astrophysical observations

  ➔ existence of non baryonic Dark Matter

- N-Body simulations and Observations of LSS

  ➔ existence of not-hot DM?

. Many problems with CDM simulations can be solved with

O(1keV) WDM or Baryon physics ?

- More work on baryonic N-body simulations needed!

Need to find **DM**

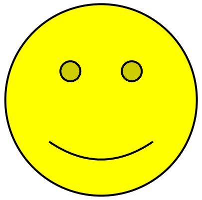
in

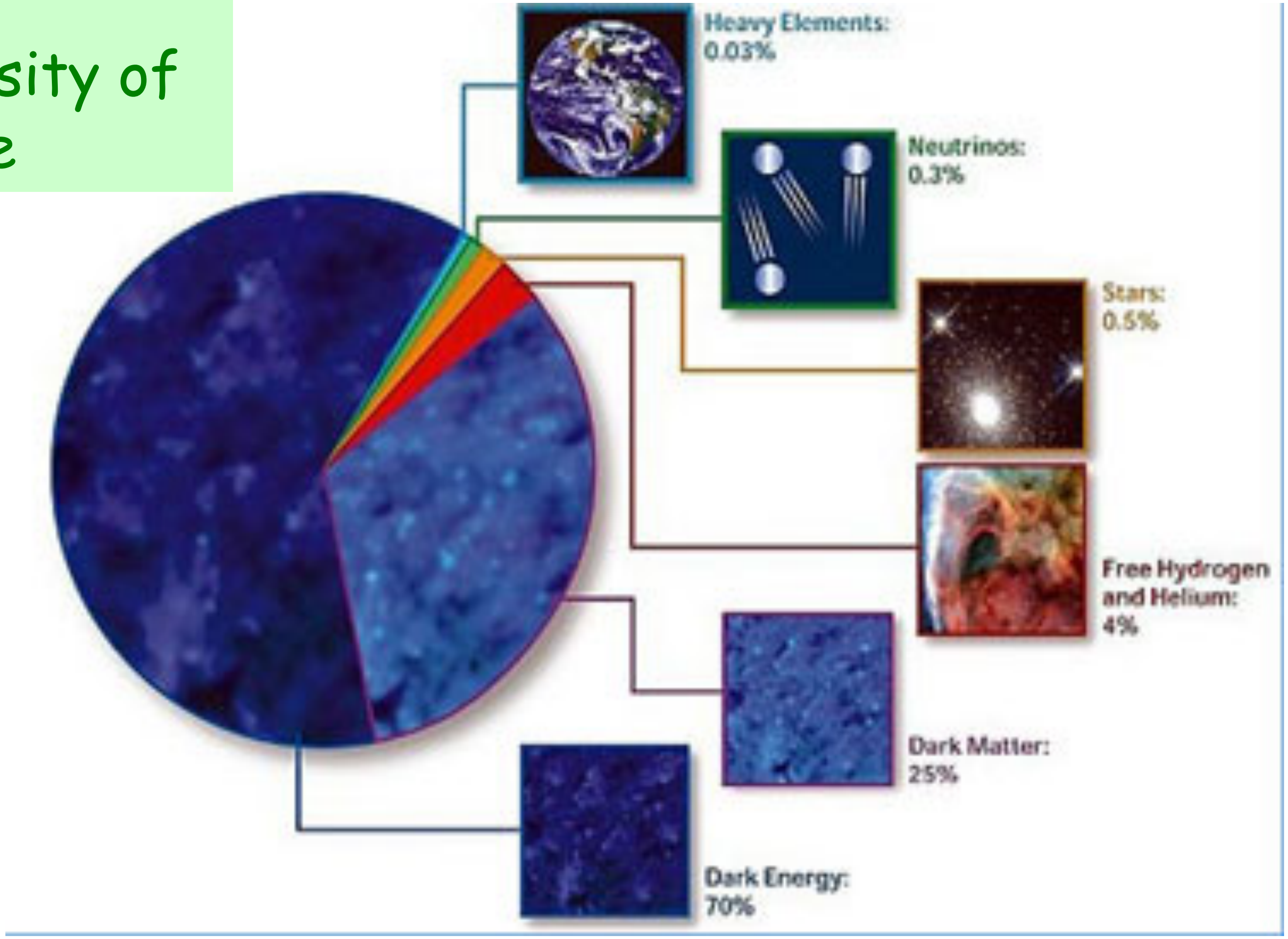
accelerators and DD/ID experiments!

A mysterious Dark Universe !

What we know is only
4-5 %
of the energy density of
the Universe

We now measure
with **precision**
the extent of
our ignorance !





Graph source: Wikipedia

Thank you

谢谢