DM : an overview

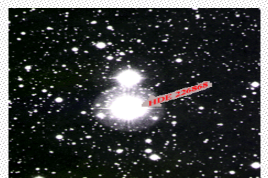
Gravity

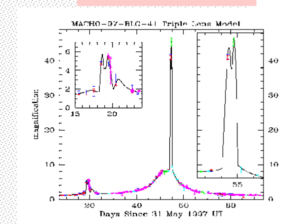
Poussières

Cold molecular

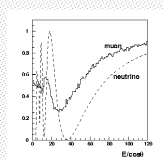
MACHOs

Black Holes





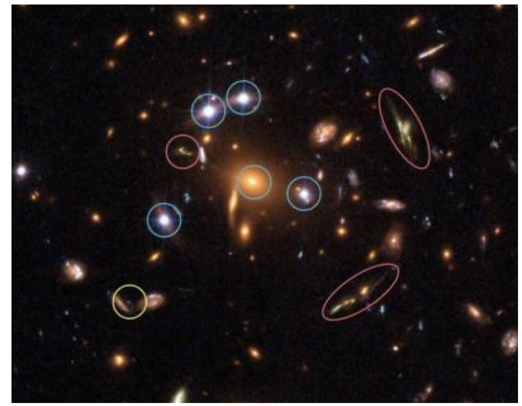
SIMPs

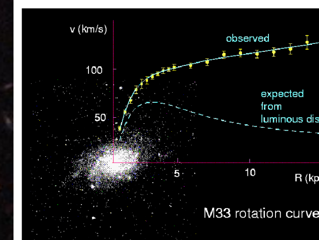


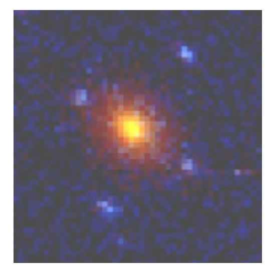
Neutrino

axions

WIMPs
10-1000GeV







Charling Tao
tao@cppm.in2p3.fr

May 17, 2019 @INFIERI 2019 - HUST

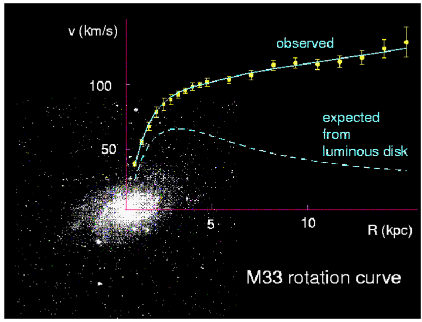
My presentation today

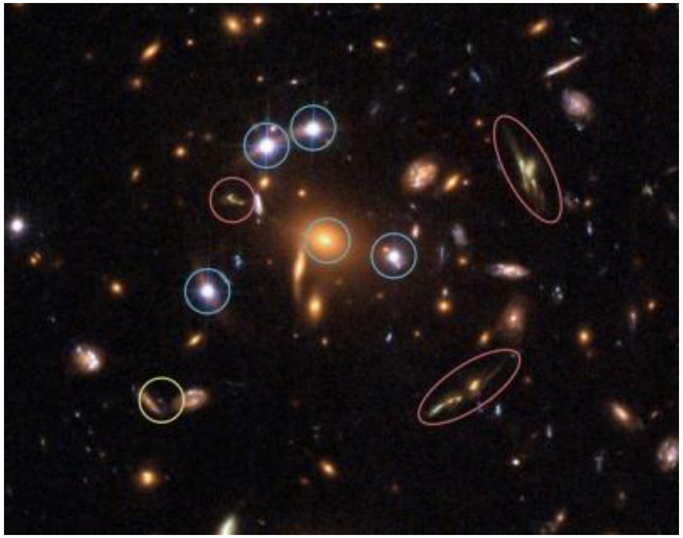
- Astrophysical evidence for DM:

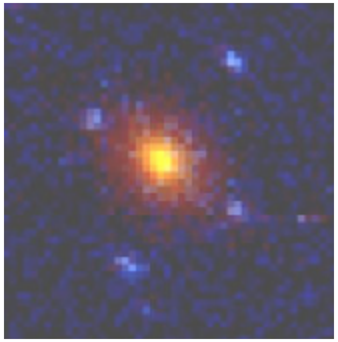
  comments on old and new data
- LSS simulations: → DM is not hot
- CDM candidates: comments on old and new
- Search for WIMPs : indirect and direct detection
- Directional DM detection
- Alternatives to DM

Wealth of Evidence for DM

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







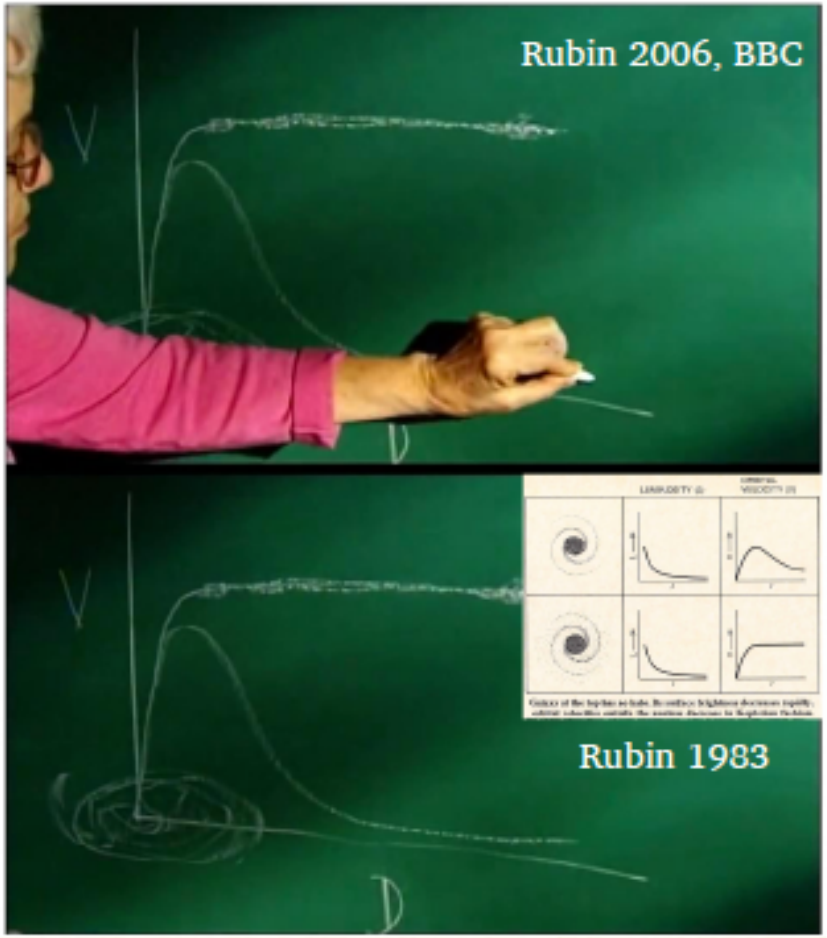
- Bullet cluster (Clowe+,2006)

Wealth of evidence for DM

is astrophysical!

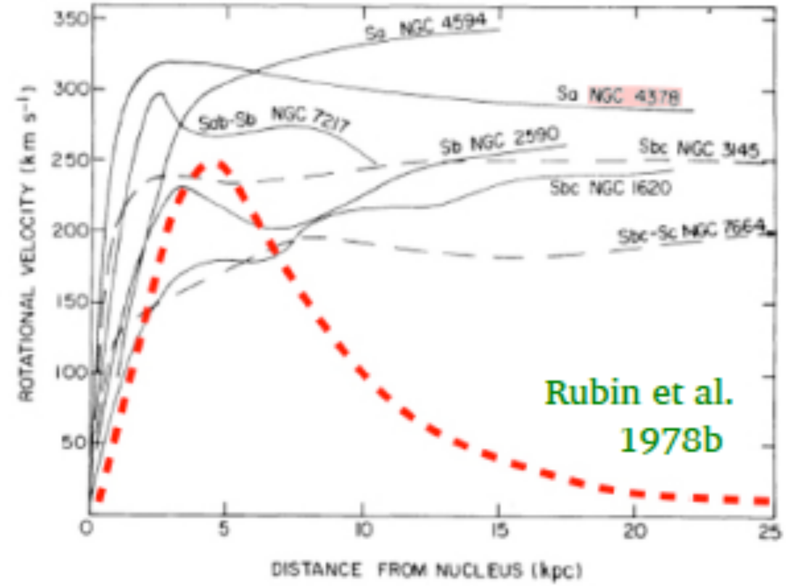
More complex than presented usually!

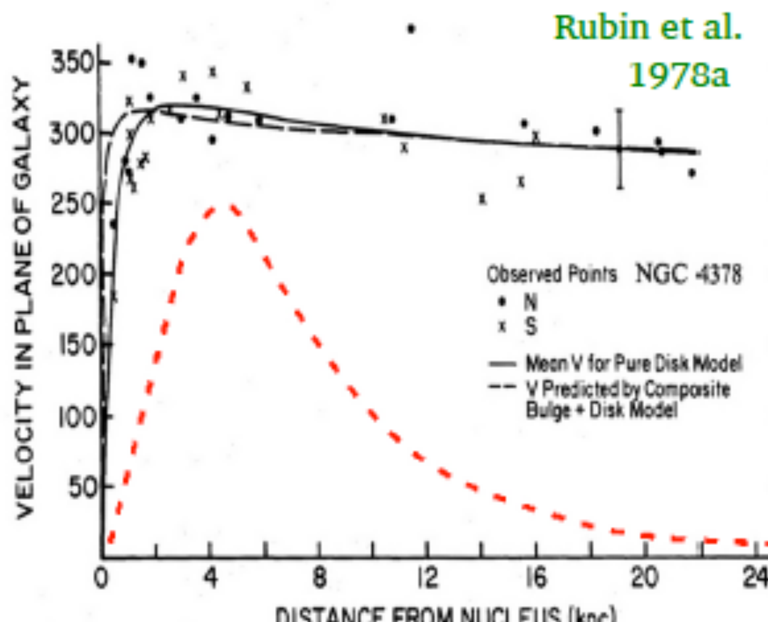
Rotation curves : what is often said [incorrectly] to be expected



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

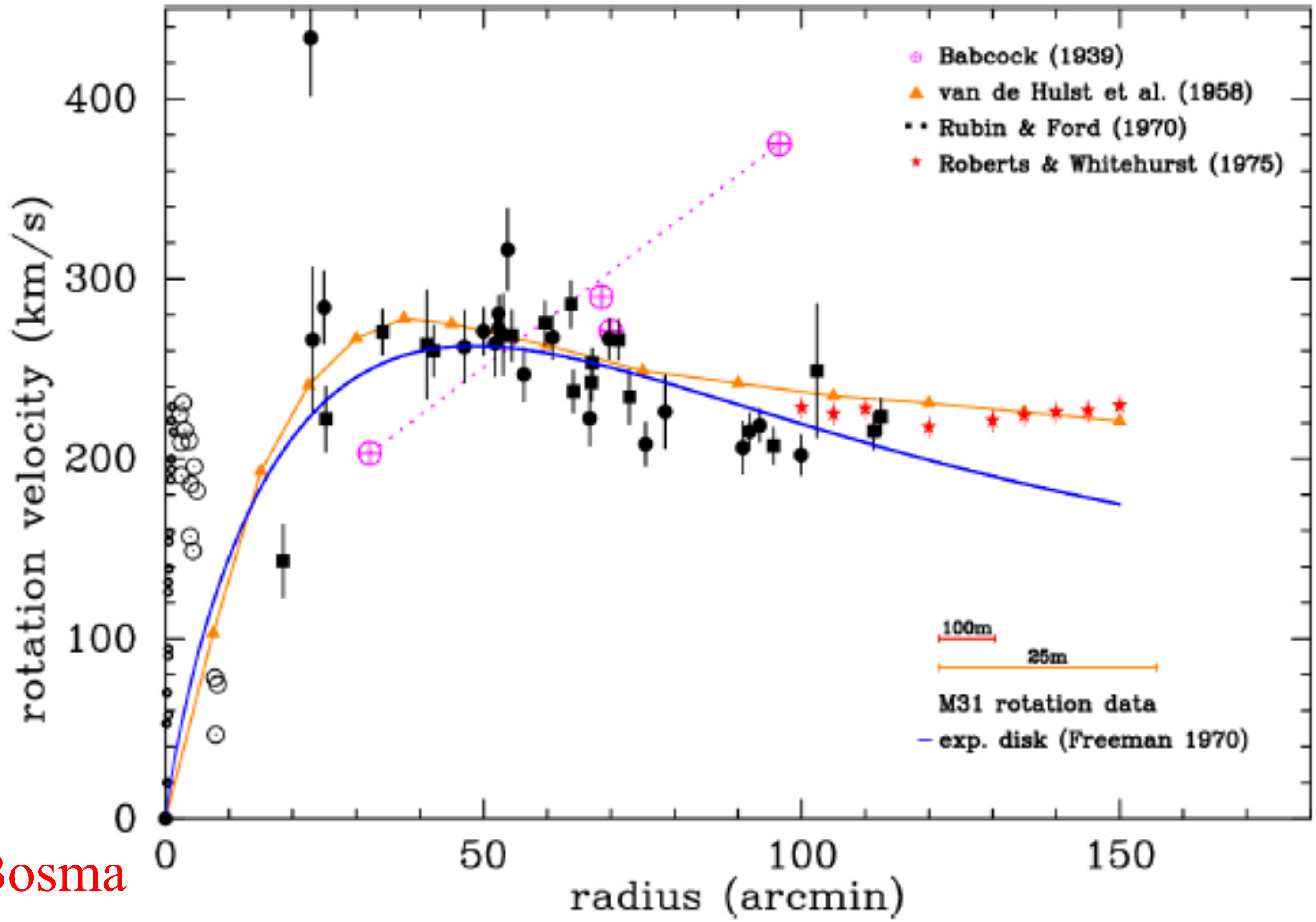




A. Bosma (LAM)

Freeman 1970, appendix For NGC 300 and M33, the 21-cm data give turn-over 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.

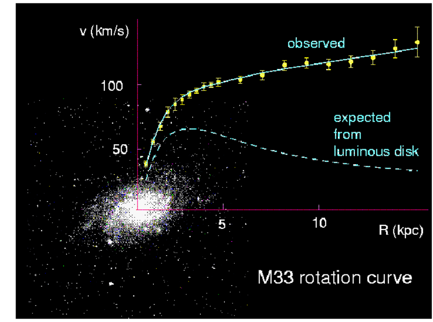
M31 – Need for dark matter based on radio data

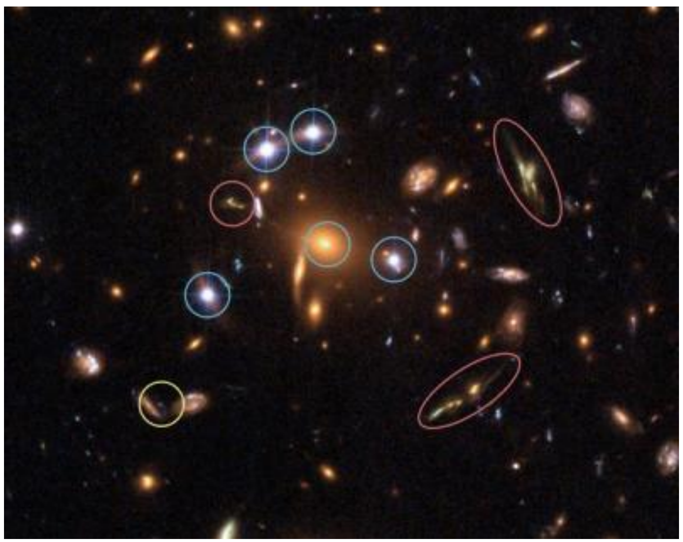


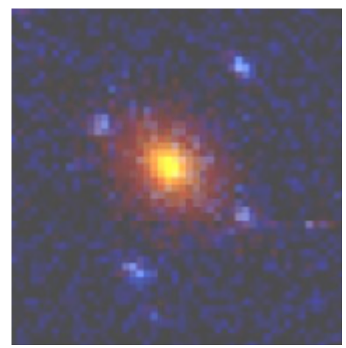
A. Bosma

Wealth of Evidence for DM

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

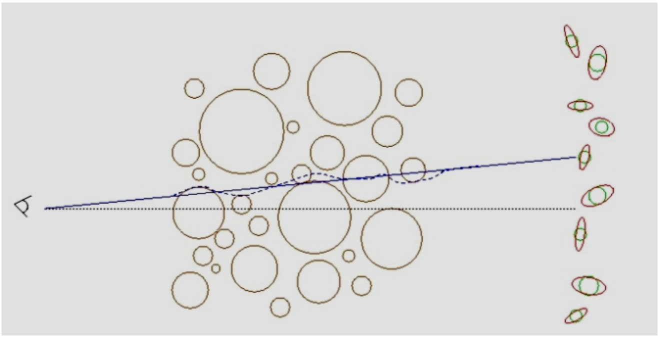


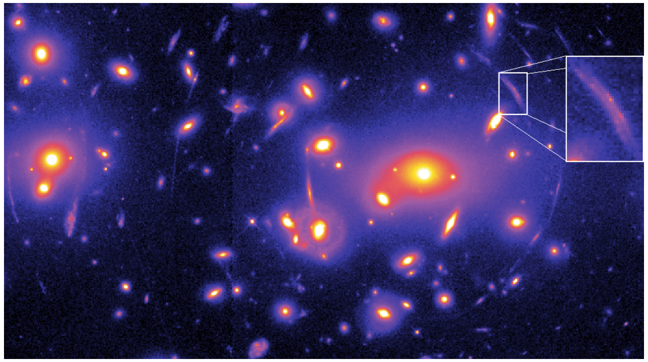




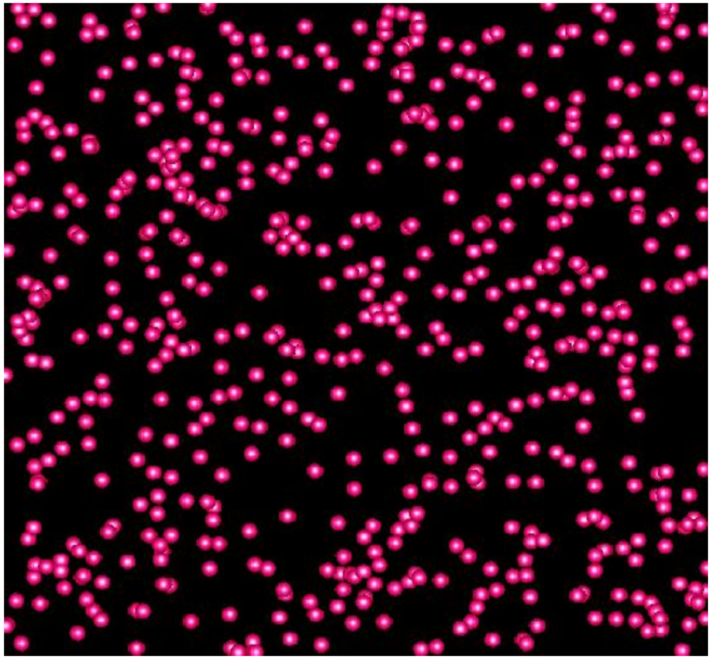
- Bullet cluster (Clowe+,2006)

Weak Lensing

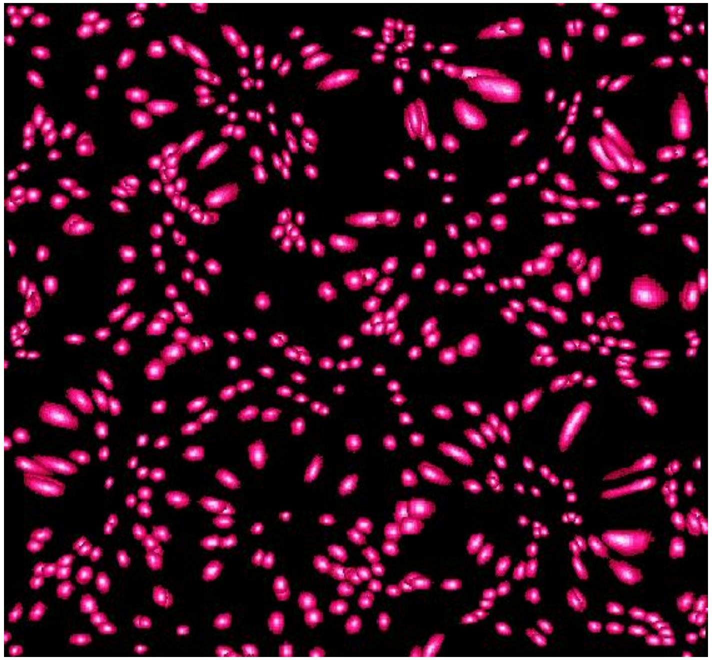




Distorsion of galaxy shapes by foreground matter



without lensing

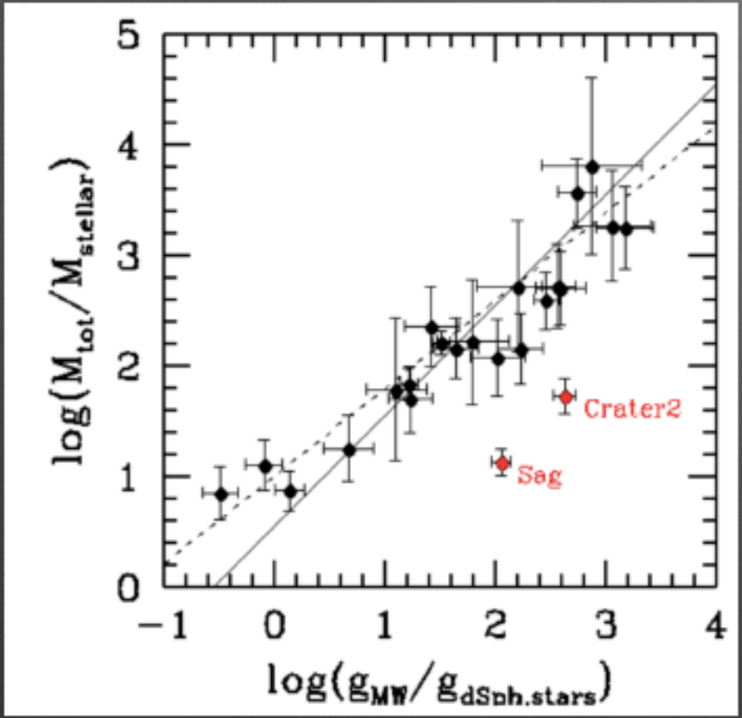


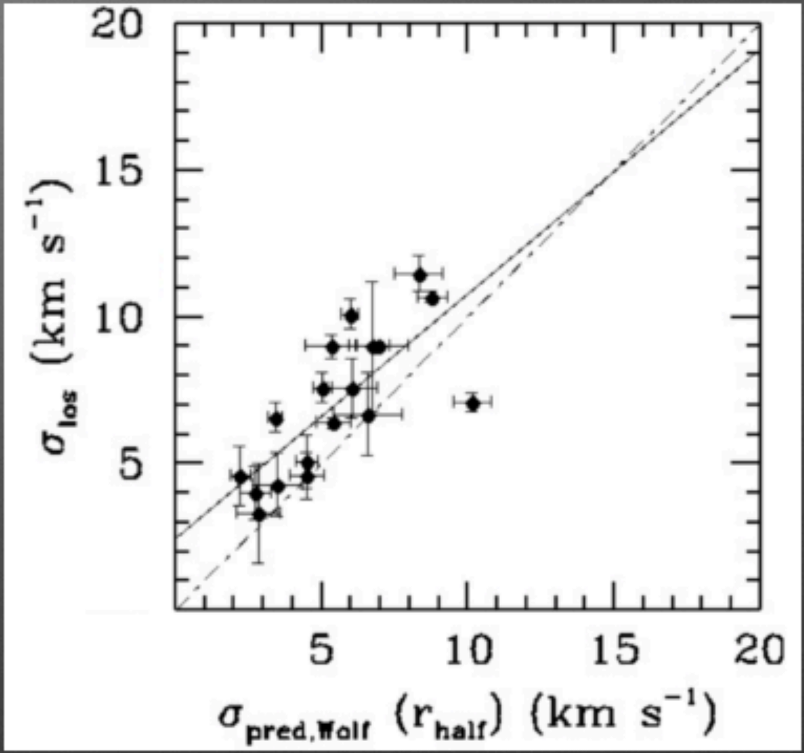
Lensing effect

Galactic forces rule dynamics Milky Way dwarf galaxies

Yang Yanbin Yunnan Sino French meeting Nov 2018

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

➔ **Evidence for DM? (against modified gravity)**

ΛCDM : Dominant theory of Structure formation and evolution

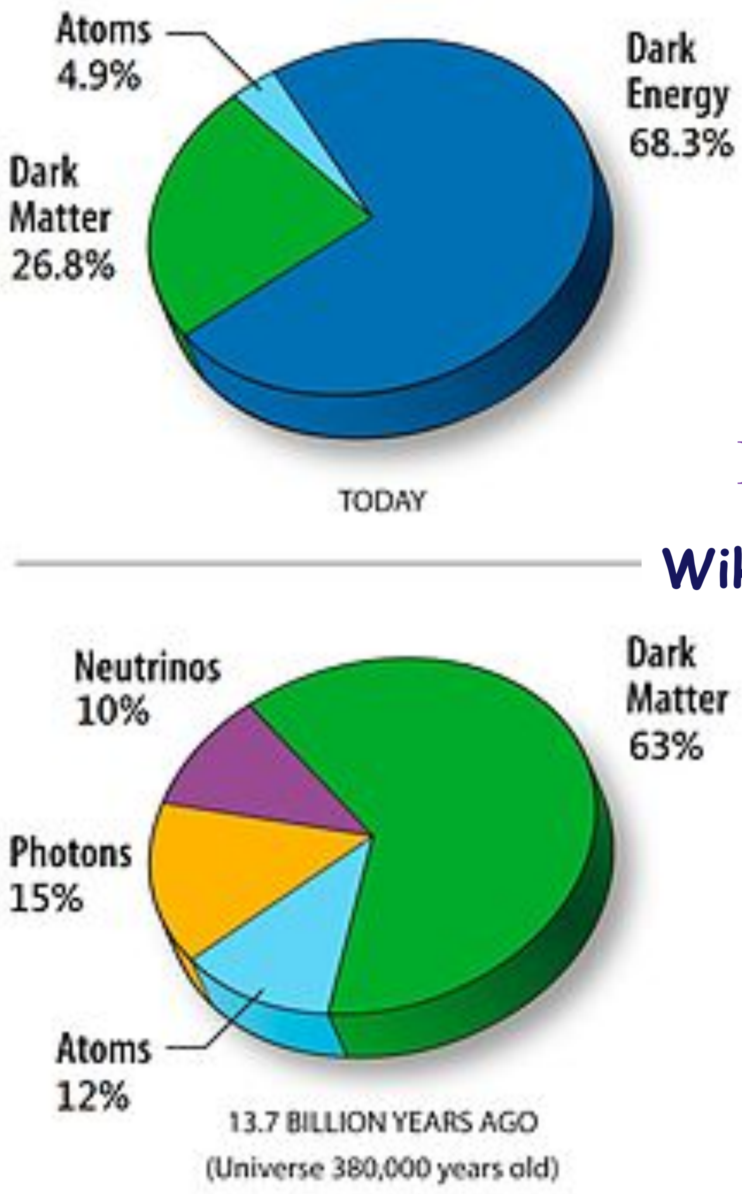
- Primordial Universe: Vacuum ? Inflation?

- 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?

The Universe energy density content after Planck



Wikipedia

% precision

Cf Planck march 2018 papers

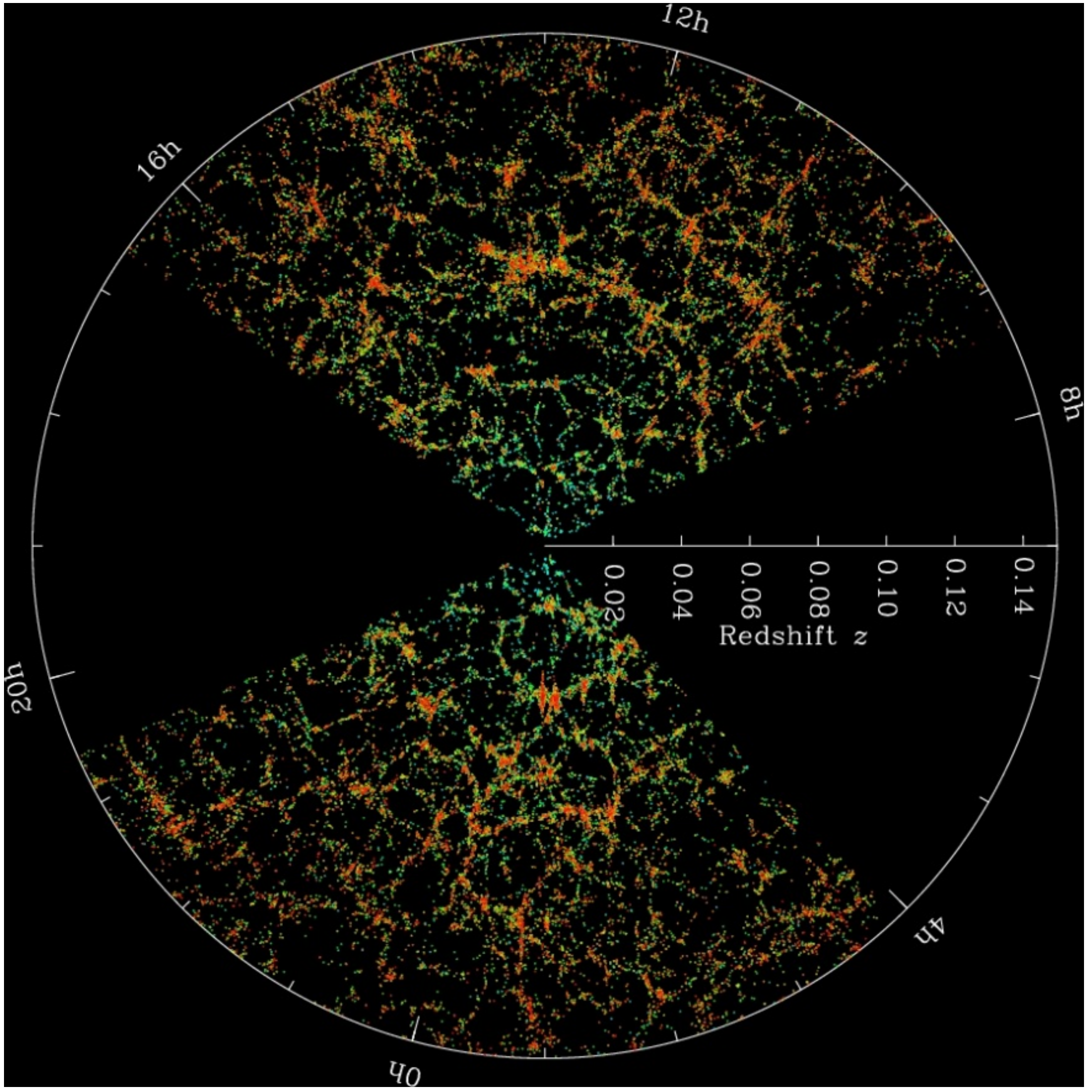
For Λ or DE, cf another seminar!

Matter today ~ 32% energy density of the Universe

85% of the matter is dark matter

Cosmic Web: Knots, Filaments, Sheets and Voids

From large scale structure surveys, eg, data in redshift



Voids = low density regions in space

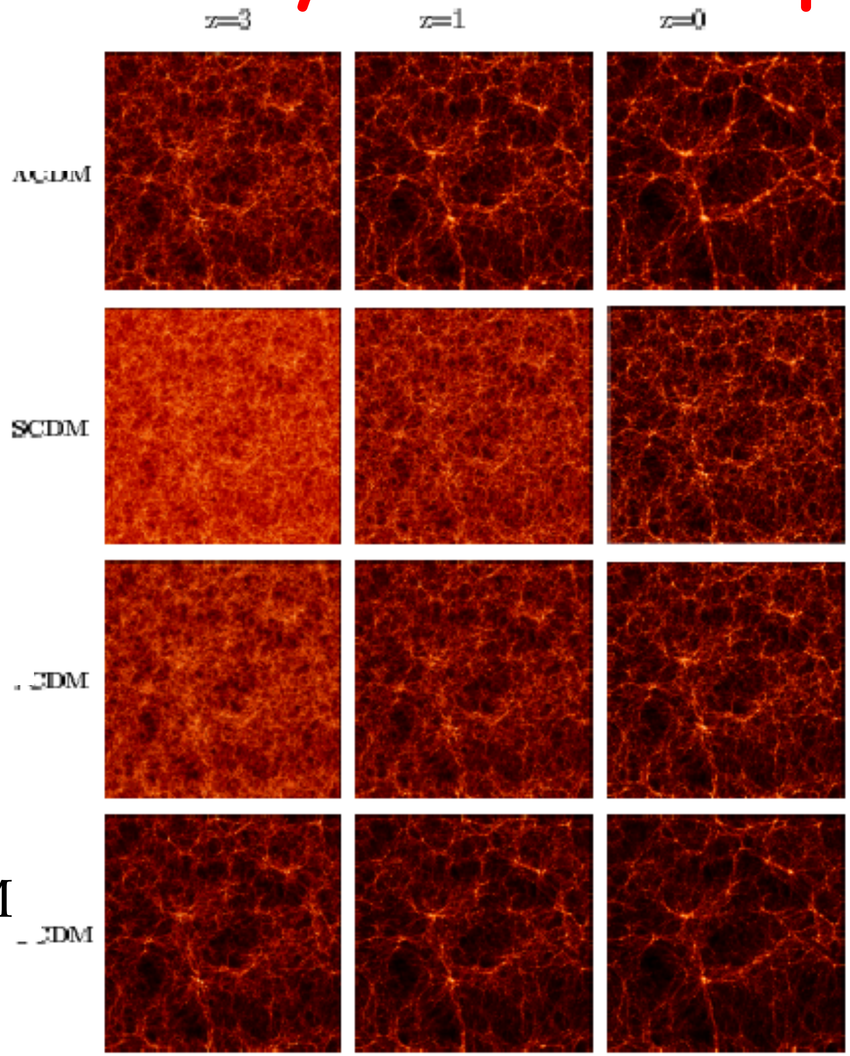
Comparisons of LSS observations with pre-2000 N-body Simulations prefer CDM

ΛCDM

SCDM

τCDM

OCDM



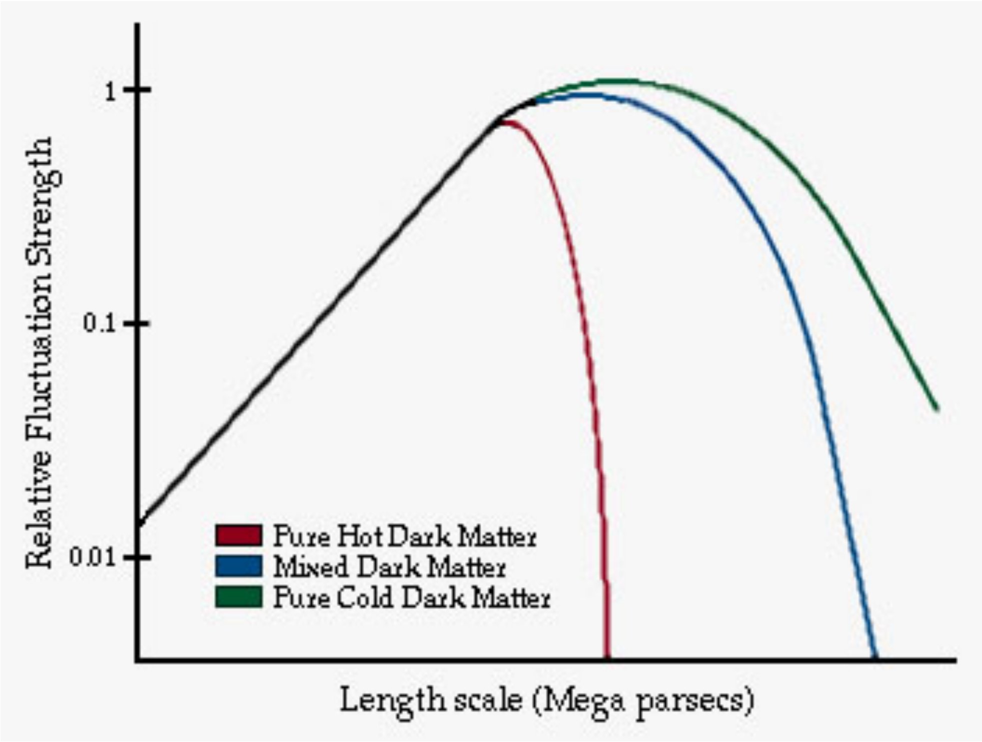
OMEGA = 0.3
LAMBDA = 0.7
H0 = 70 km/(Mpc sec)
Sigma8 = 0.9

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

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

<2000: Nature of DM
Hot or Cold?

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



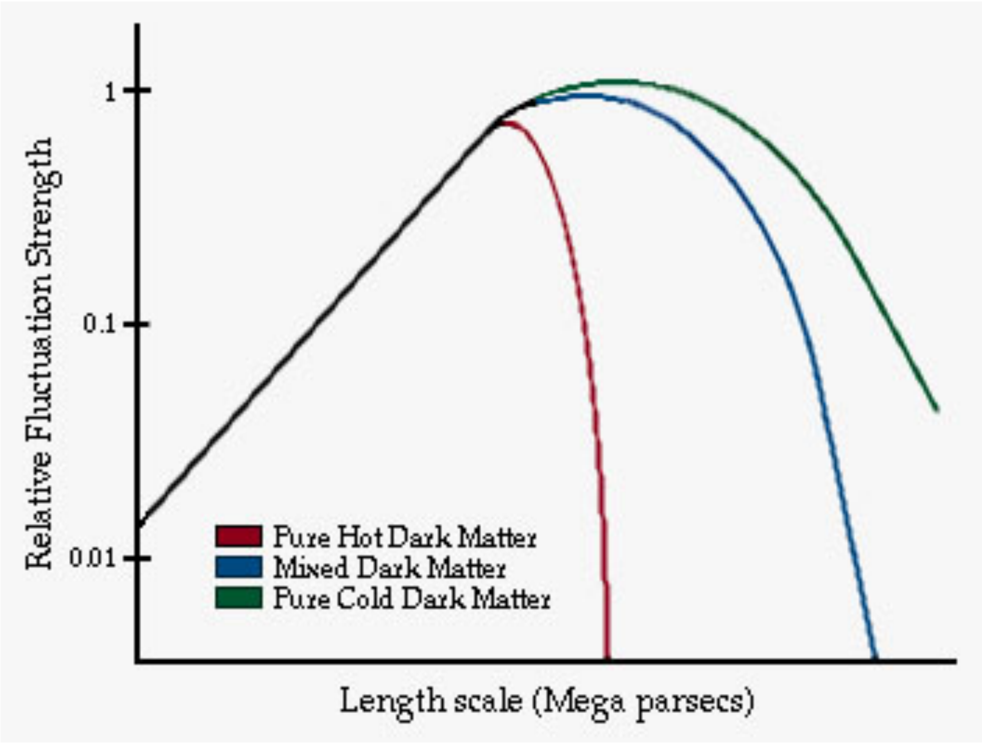
HDM is tightly bound by observations and LSS formation

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



N-Body simulations: CDM

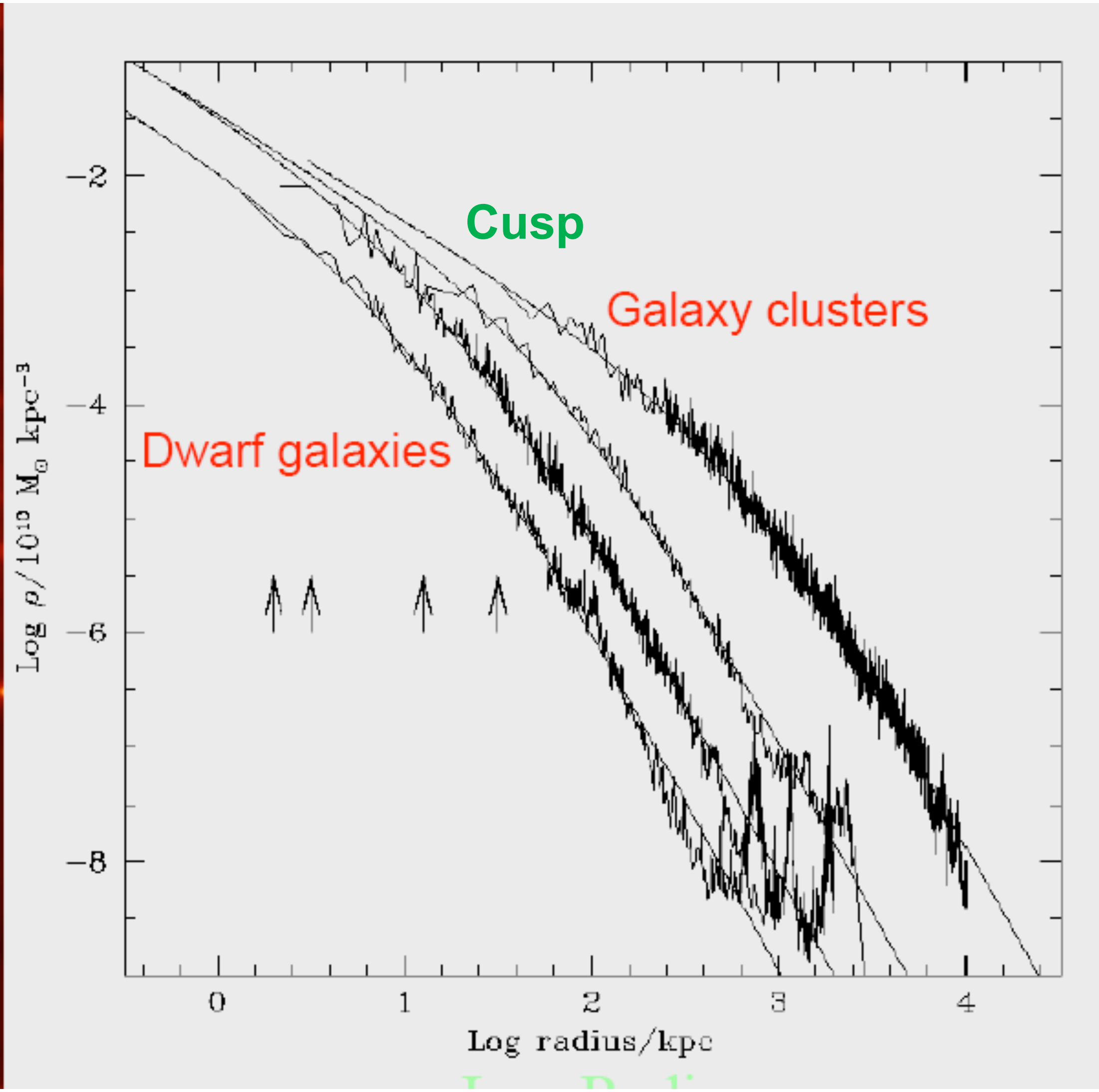
Preferred paradigm: CDM

Most N-Body simulations use stable CDM halos as seed for structures:

structures evolve, merge and cluster

- Properties of CDM halos
  - cuspy density profiles,
  - Triaxial halos
  - central density depends on the mass of the halo.

Dark matter distribution—Density profiles



Universal Density Profile from N-body simulations

NFW

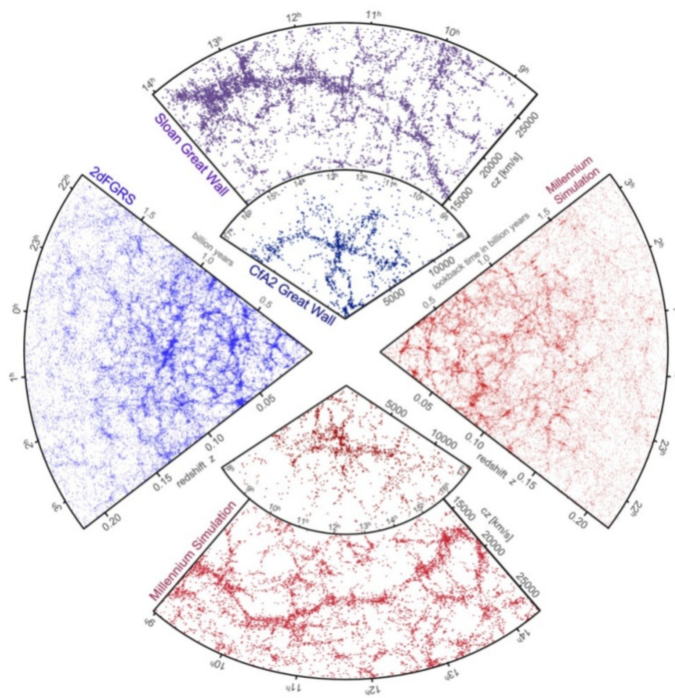
Navarro, Frenk, White 1996

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

~2000 :Problems with CDM at small scales

Comparing data with N-body Simulations

- Galactic satellites
- cusp/core at GC



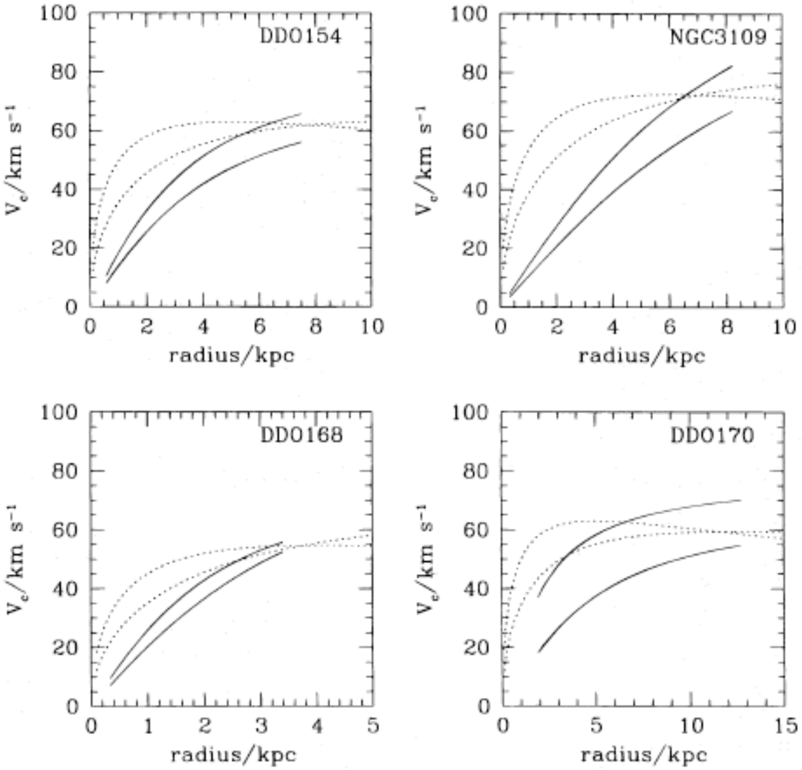
Galaxy profiles prefer core at center

CDM Simulations → cusps
(Navarro, Frenk, White 1996):

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2},$$

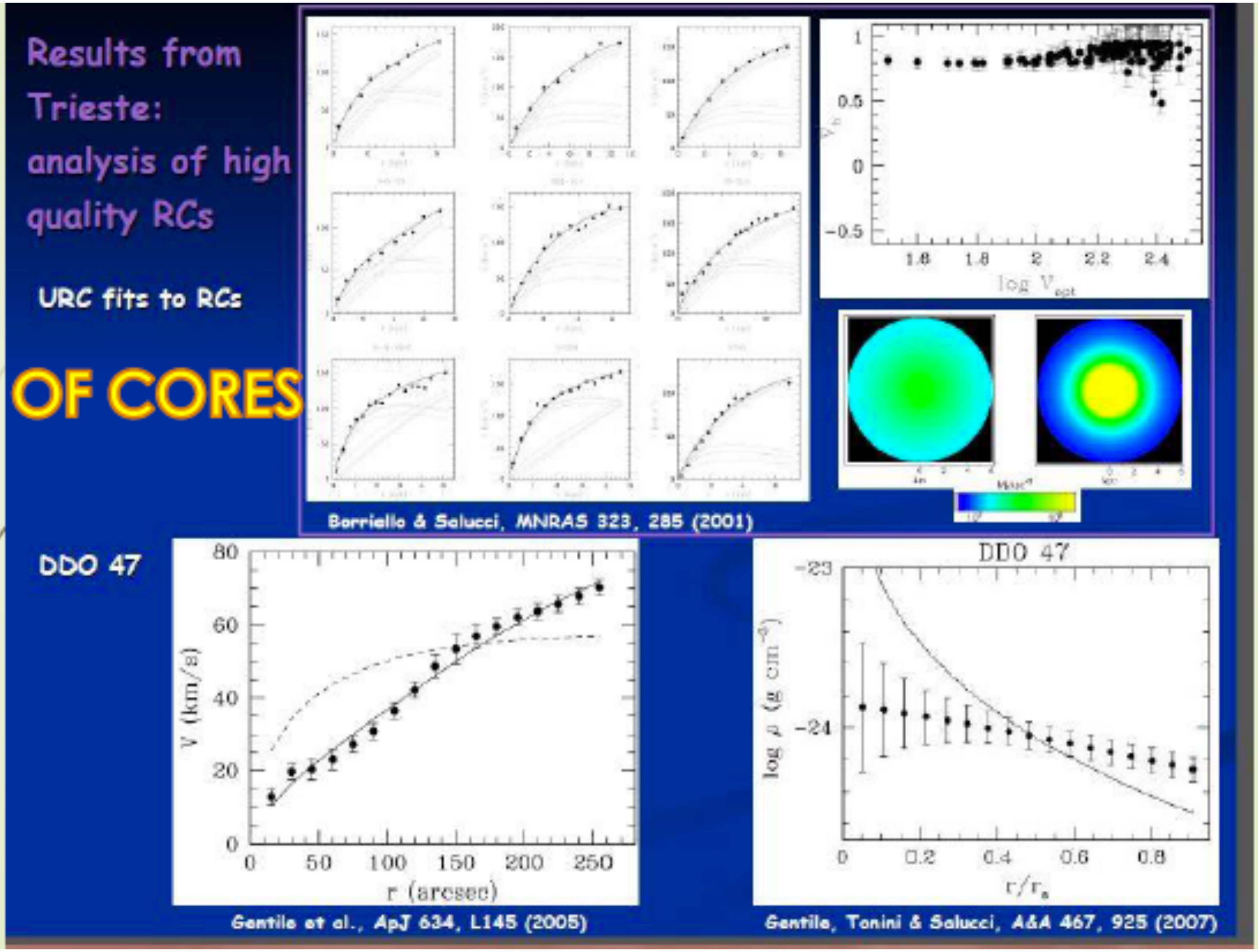
Problems at smaller scales?

Observations favour
core profile



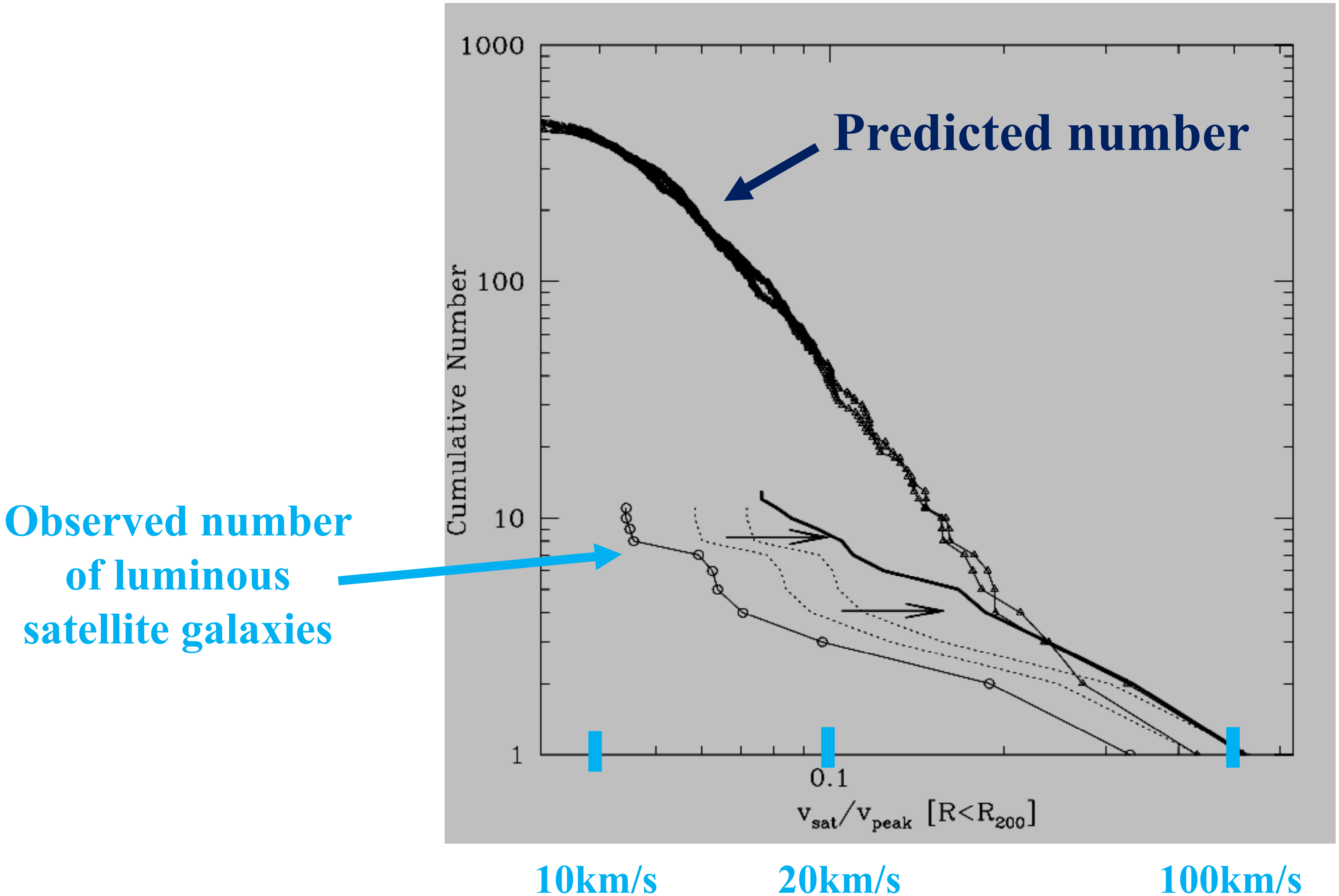
rotation curves

PROOFS OF CORES



Too low number of visible Satellite galaxies

Satellite galaxies are seen in Milky Way, e.g. Saggittarius, MCs



Alternatives to CDM

- Self-Interacting Dark Matter (Spergel & Steinhardt 2000)
- Strongly Interacting Massive Particle
- Annihilating DM
- Decaying DM (eg. Zhang XM+)
- …

- **WDM: reduce the small scale power**

Norma G.Sanchez, Hector J. de Vega+… Chalonge series

“Evidence” for WDM ?

•"missing satellite problem",

•"cusp-core problem'’,

• “Too big to fail”

• mini-voids The sizes of mini-voids in the local universe: an argument in favor of a warm dark matter model? Tikhonov et al.

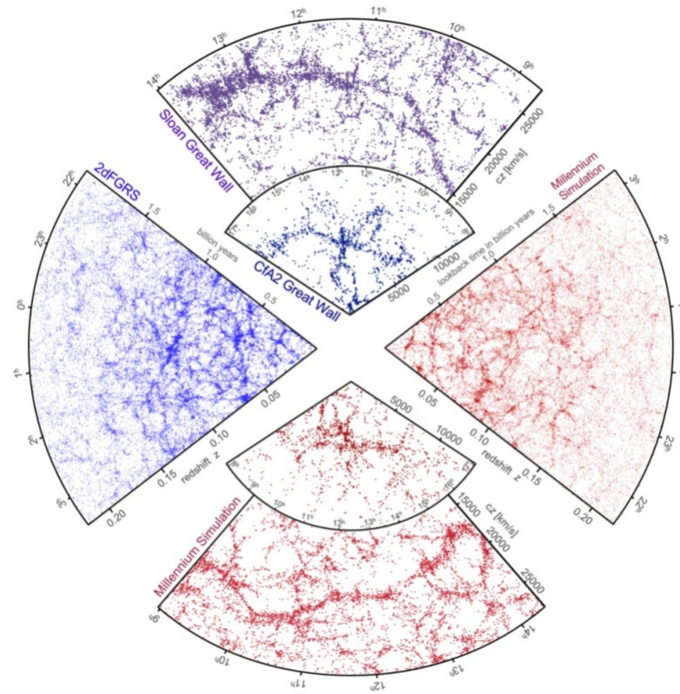
•HI determinations of velocity function profiles

N-Body simulation Comparisons with Virgo results by Arecibo Legacy (ALFALFA)

Solutions to CDM Problems at small scales ?

- New measurements
- Better si resolution

-Additional physics in N-Body simulations (SN, AGN feedback, stellar winds…)



Einasto vs NFW

CDM Simulations

➔ cusps

rather Einasto

profiles than NFW

Ma Chung Pei,

Chang, P.,

Zhang, 2009

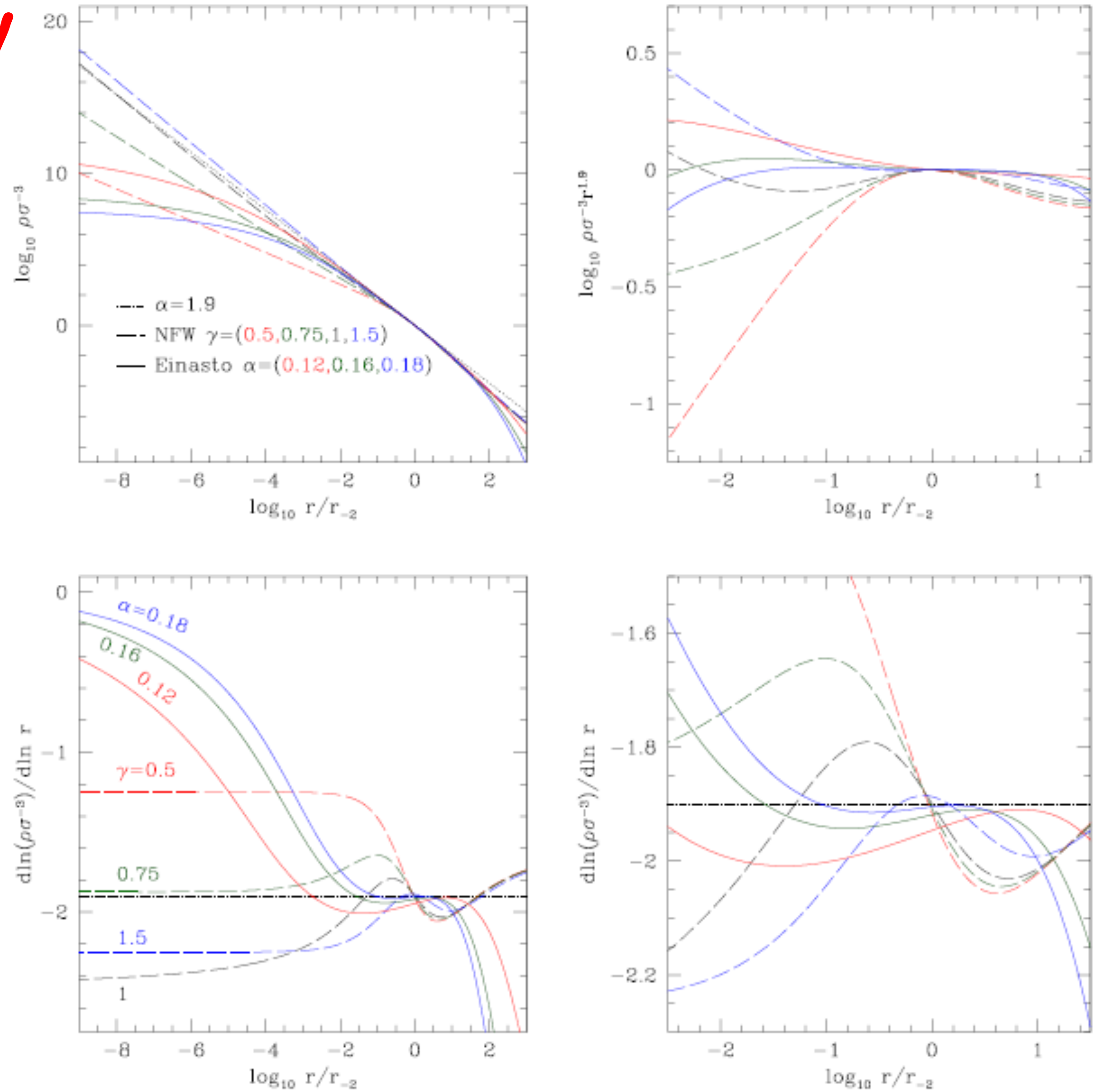


Figure 1. Radial profiles of the pseudo-phase-space density $\rho/\sigma_r^3(r)$ (upper panels) and the corresponding logarithmic slope $d\ln\rho/\sigma_r^3(r)/d\ln r$ (lower panels) obtained from the spherical Jeans equation with $\beta = 0$ for seven input halo density profiles: Einasto (solid) with $\alpha = 0.18$ (blue), 0.16 (green), and 0.12 (red), and GNFW (dashed) with $\gamma = 1.5$ (blue), 1 (black), 0.75 (green), and 0.5 (red). The left panels show the behavior of $\rho/\sigma_r^3(r)$ over 12 orders of magnitude in r, while the right panels show zoom-in views of the region $0.01 \lesssim r/r_{-2} \lesssim 10$, which corresponds to the range resolvable by the latest N-body simulations. For ease of comparison with a power-law, the light dotted straight lines indicate the critical case $\rho/\sigma_r^3 \propto r^{-1.9}$, and the y-axis in the upper right panel plots the logarithm of the ratio of $\rho/\sigma_r^3(r)$ to $\rho/\sigma_r^3 \propto r^{-1.9}$. All curves are scaled to have $\rho/\sigma_r^3 = 1$ at $r = r_{-2}$.

More faint or dark galaxies discovered

Eg, Belokurov et al, 2010

BIG FISH, SMALL FISH: TWO NEW ULTRA-FAINT SATELLITES OF THE MILKY WAY

V. Belokurov[1], M. G. Walker[1], N. W. Evans[1], G. Gilmore[1], M. J. Irwin[1], D. Just[2], S. Koposov[1], M. Mateo[3], E. Olszewski[2], L. Watkins[1], L. Wyrzykowski[1]

TABLE 1
Properties of Pisces II and Segue 3

Parameter	Pisces II	Segue 3
RA (J2000)	$22:58:31 \pm 6$	$21:21:31 \pm 4$
Dec (J2000)	$+05:57:09 \pm 4$	$+19:07:02 \pm 4$
Galactic ℓ	$79.21°$	$69.4°$
Galactic b	$-47.11°$	$-21.27°$
r_h (Plummer)	$1'.1 \pm 0'.1$	$0'.65 \pm 0'.1$
θ	$77° \pm 12°$	$215° \pm 20°$
ϵ	0.4 ± 0.1	0.3 ± 0.2
$(m-M)_0$	$21^m.3$	$16^m.1$
$M_{tot,V}$	$-5^m.0$	$-1^m.2$

* Magnitudes are accurate to $\sim \pm 0^m.5$ and are corrected for the Galactic foreground reddening.

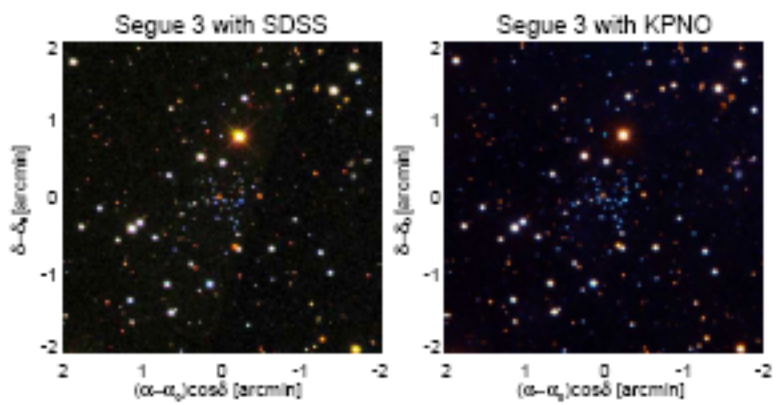


Fig. 4.— Color images covering $4' \times 4'$ region centered on Segue 3 made with SDSS (left) and KPNO (right) data. SDSS image is made with g, r and i band frames. KPNO image is made with g and r band frames.

Missing satellites: CDM way out

- satellites do exist, but star formation suppressed (after reionization?)
- satellites orbit do not bring them to close interaction with disk, so they will not heat up the disk.
- Local Group dwarf velocity dispersion underestimated
- Galaxies may not follow dwarves

Halo substructures may be probed by
- Lensing
- local Milky Way structures

Nature of dark matter or astrophysics process?

REPORTS

Stellar Feedback in Dwarf Galaxy Formation

Sergey Mashchenko,* James Wadsley, H. M. P. Couchman

Dwarf galaxies pose substantial challenges for cosmological models. In particular, current models predict a dark-matter density that is divergent at the center, which is in sharp contrast with observations that indicate a core of roughly constant density. Energy feedback, from supernova explosions and stellar winds, has been proposed as a major factor shaping the evolution of dwarf galaxies. We present detailed cosmological simulations with sufficient resolution both to model the relevant physical processes and to directly assess the impact of stellar feedback on observable properties of dwarf galaxies. We show that feedback drives large-scale, bulk motions of the interstellar gas, resulting in substantial gravitational potential fluctuations and a consequent reduction in the central matter density, bringing the theoretical predictions in agreement with observations.

N-Body simulations with baryons

Jing Yipeng (2005)

More recent comparisons of WDM and CDM simulations.

eg Gao+, Jing+ , Guo Qi, Yepes+ ,

- Non-linear collapse of WDM structures

Caveat: Strong Reliance on N-body simulations might be misleading!

Some Issues

- **Galaxy evolution alters DM halos and the matter power spectrum .**

Rudd, Zentner & Kravtsov, Effects of Baryons and Dissipation on the Matter Power Spectrum (2008);

Pedrosa,Tissera, & Scannapieco, The joint evolution of baryons and dark matter halos, (2010);

Scannapieco +, The Aquila Comparison Project: The Effects of Feedback and Numerical Methods on Simulations of Galaxy Formation, arXiv:1112.0315.

- **Most of the simulations (even today) are DM-only**

- DM halos extremely sensitive to the implementation of the galaxy physics in the codes.

- DM halo morphologies and galaxy properties need resolutions: giant molecular cloud (GMC) sized regions .

But a lot of concern/work in the last years

(leading contributions from Chinese astrophysicists!)

What we know:

Comparisons of observations with N-body Simulations today prefer

Non-Hot DM

Cold or Warm is a challenge for next years...

eg, Gao Liang NAOC Oct 2014
Sino French meeting

Missing satellite problem: solutions degenerated

Core/Cusp: seems not relevant to the nature of dark matter

Too big to fail problem: solutions also degenerated

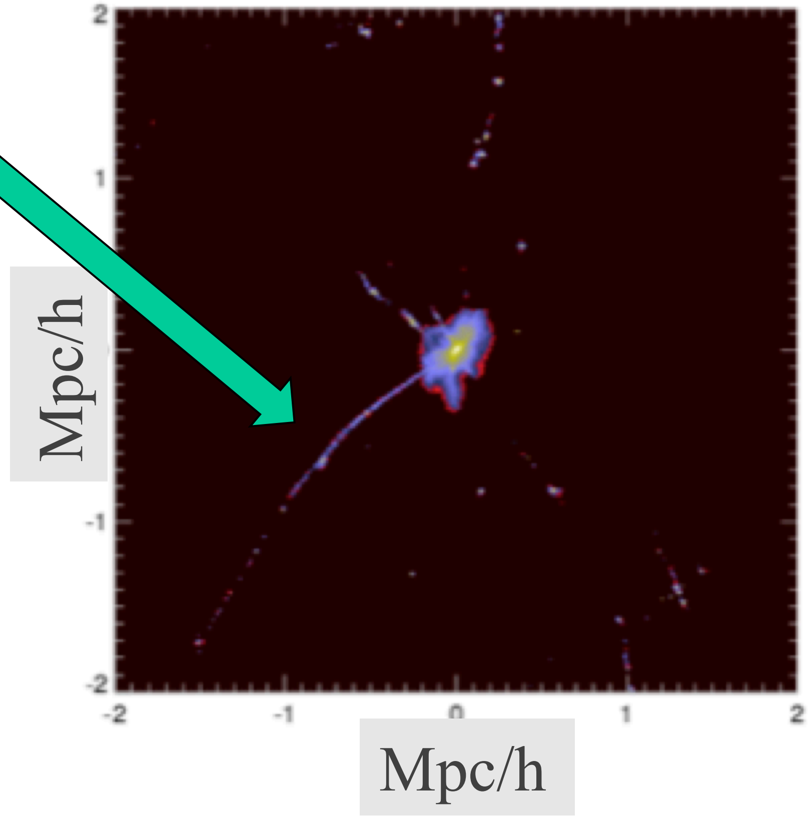
Surroundings of high z galaxies hide important information of the nature of dark matter

Gao Liang NAOC Oct. 2014

Observations of a stringy appearance of high z galaxies will rule out CDM

This star formation model Is NOT included in any current galaxy formation models.

Many arguments against WDM should be revised. (Reionisation, Lya PS, satellites abundance …)



Gao, Theuns, Springel, 2014

GAMA find “tendrils” in voids !

arxiv 1401.4064

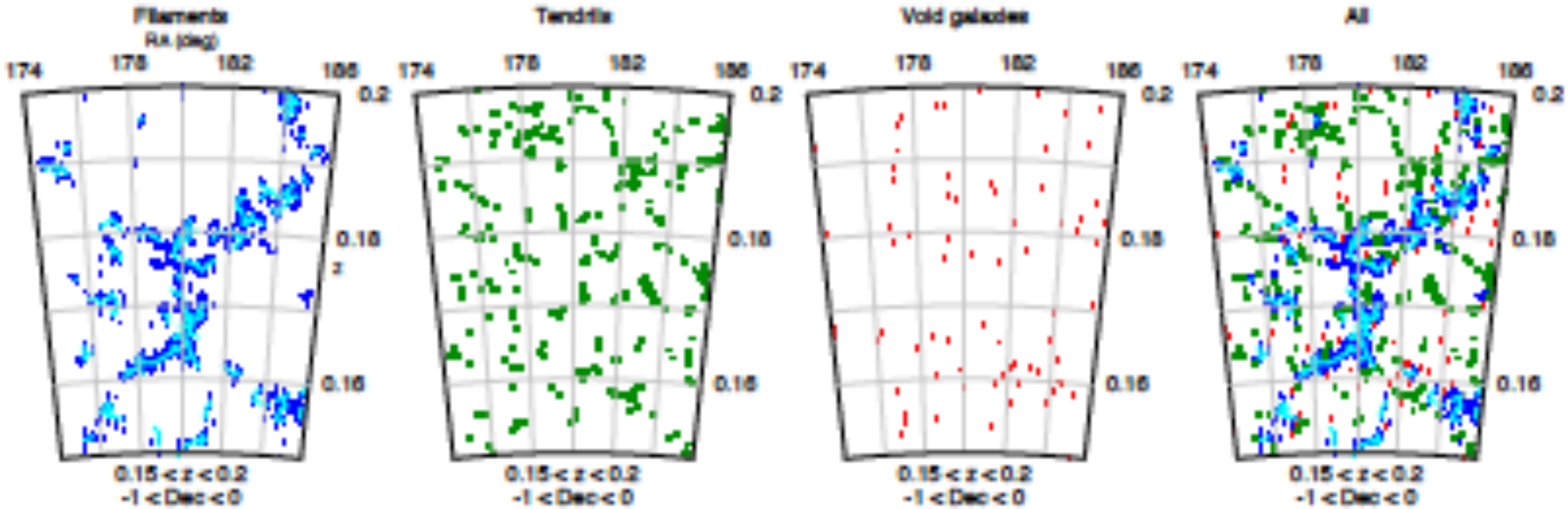
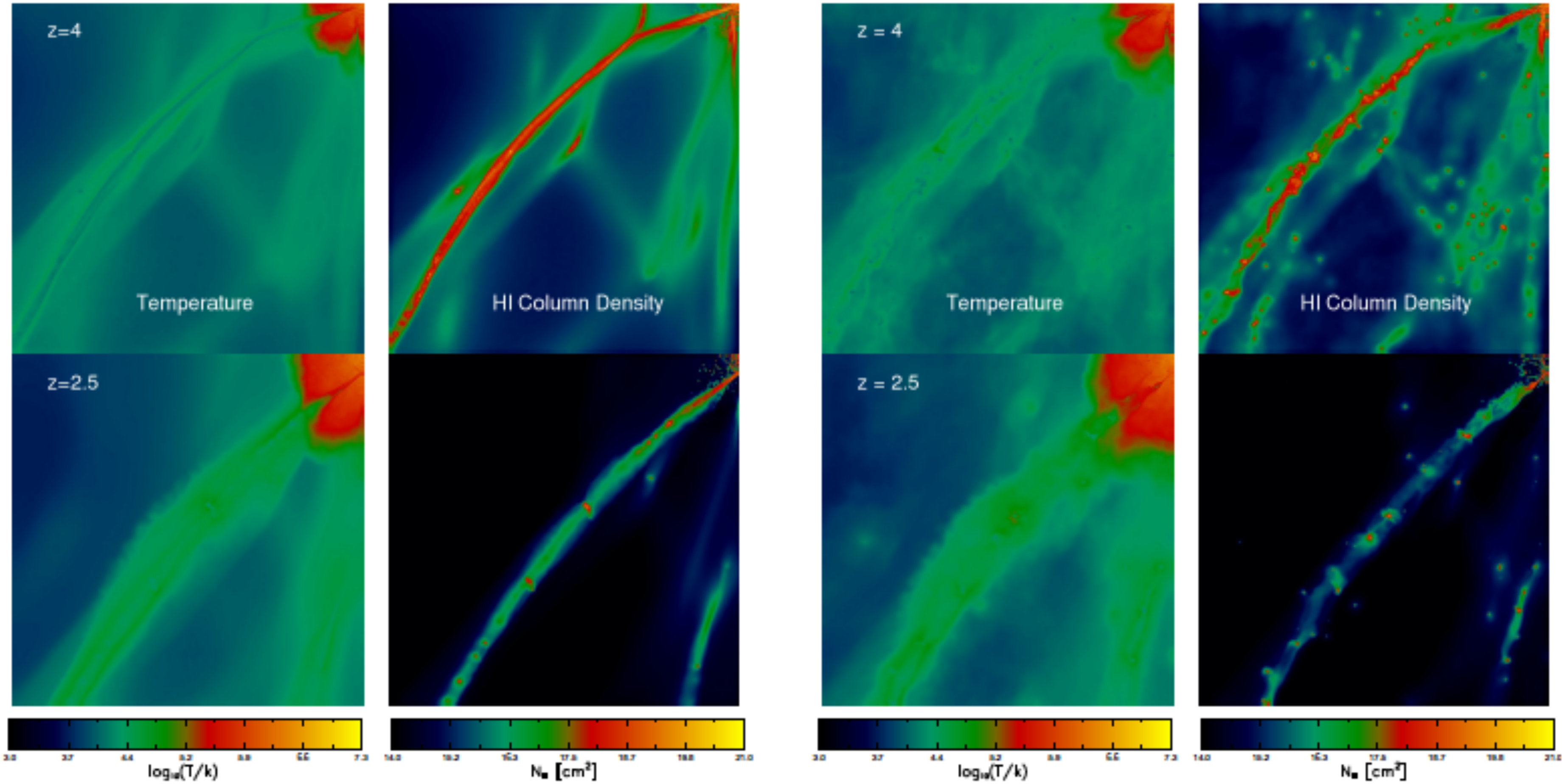


Figure 1. A section of the G12 field with different galaxy populations shown in each panel. From left to right the populations shown are galaxies in filaments with the filament minimal spanning tree (blue and cyan respectively); galaxies in tendrils (green); galaxies in voids (red); and all three populations in their respective colours.

Thin filaments found !

WDM/CDM hydrodynamic simulations
star formation

Gao, Theuns, Springel 2014



NB: Box size: 1.5 Mpc/h

N-body simulations more recent

- The cold dark matter content of Galactic dwarf spheroidals: no cores, no failures, no problem: Fattahi, Navarro et al... 1607.06479

with APOSTLE LCDM hydro simulations with baryons

- The low abundance and insignificance of dark discs in simulated
Milky Way galaxies: Schaller, Frenk et al... 1605.02770
only 1/24 has significant dark disk!

No simulation can replace measurements!

Warm or Cold DM?

- More work is necessary!

  Need more Baryons simulations

  And more and better data

CDM is not dead!

Future Measurements of DM properties with lensing

From 100 sq deg scale at CFHT
to 5000 - 20000 sq deg sky surveys

DARK ENERGY SURVEY

KIDS

HSC

LSST
Large Synoptic Survey Telescope

Euclid
Consortium

WFIRST?

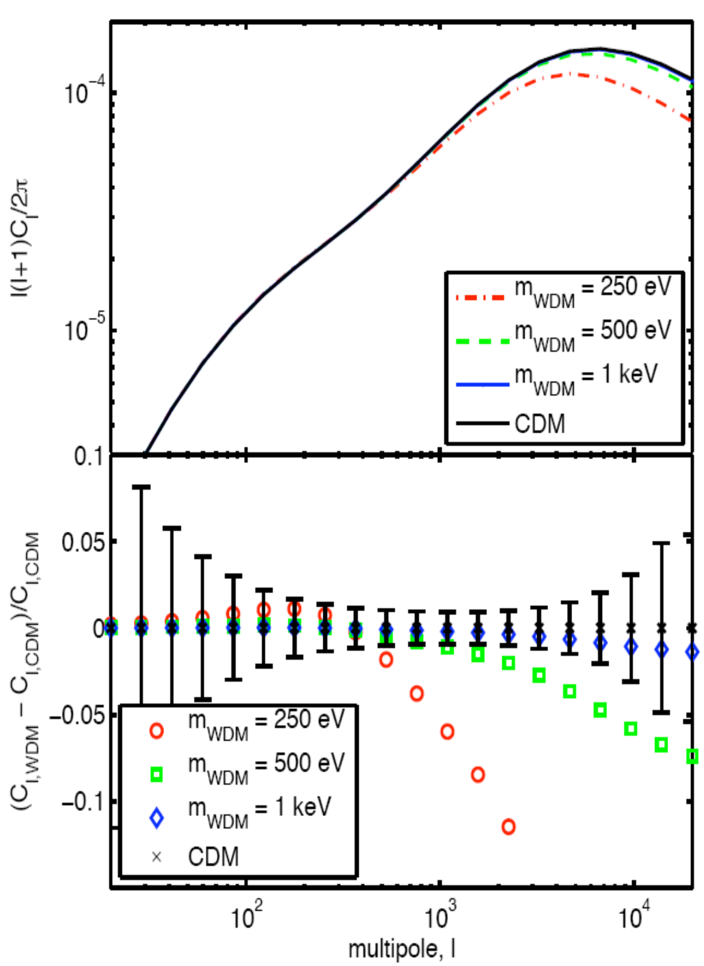
CSS-OS

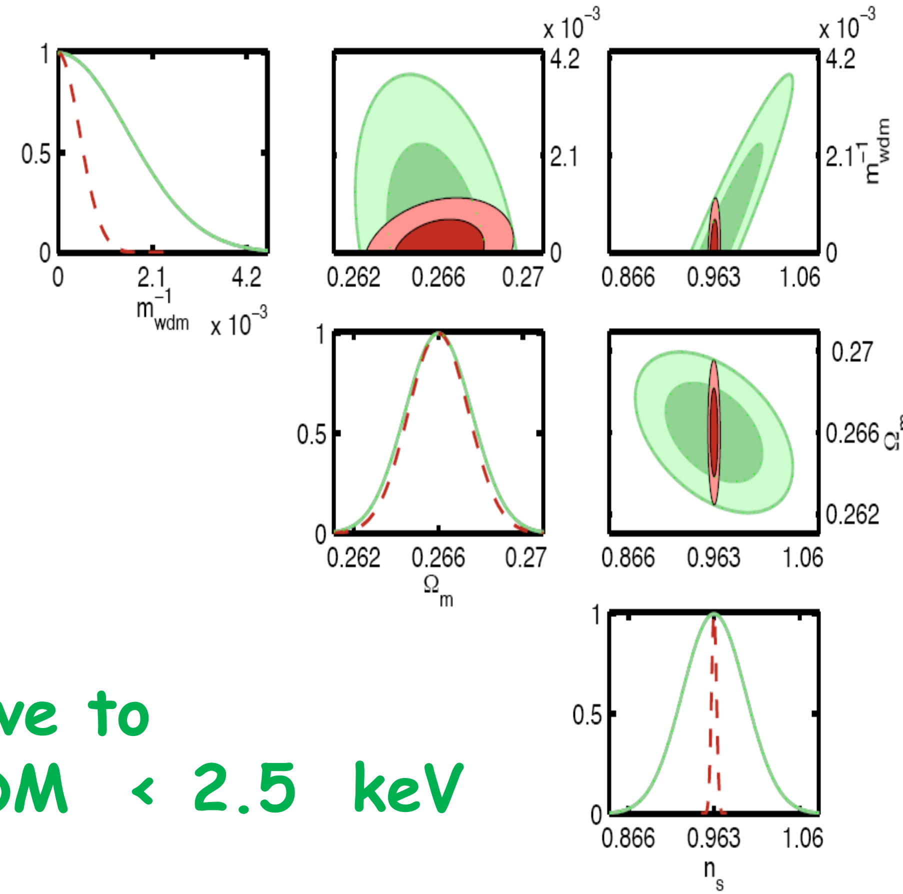
MS-DESI can provide 3D

Cosmic shear power spectra

Markovic et al. 2010 Euclid-like DE space survey +Planck:

Integral effects → better than matter power spectrum

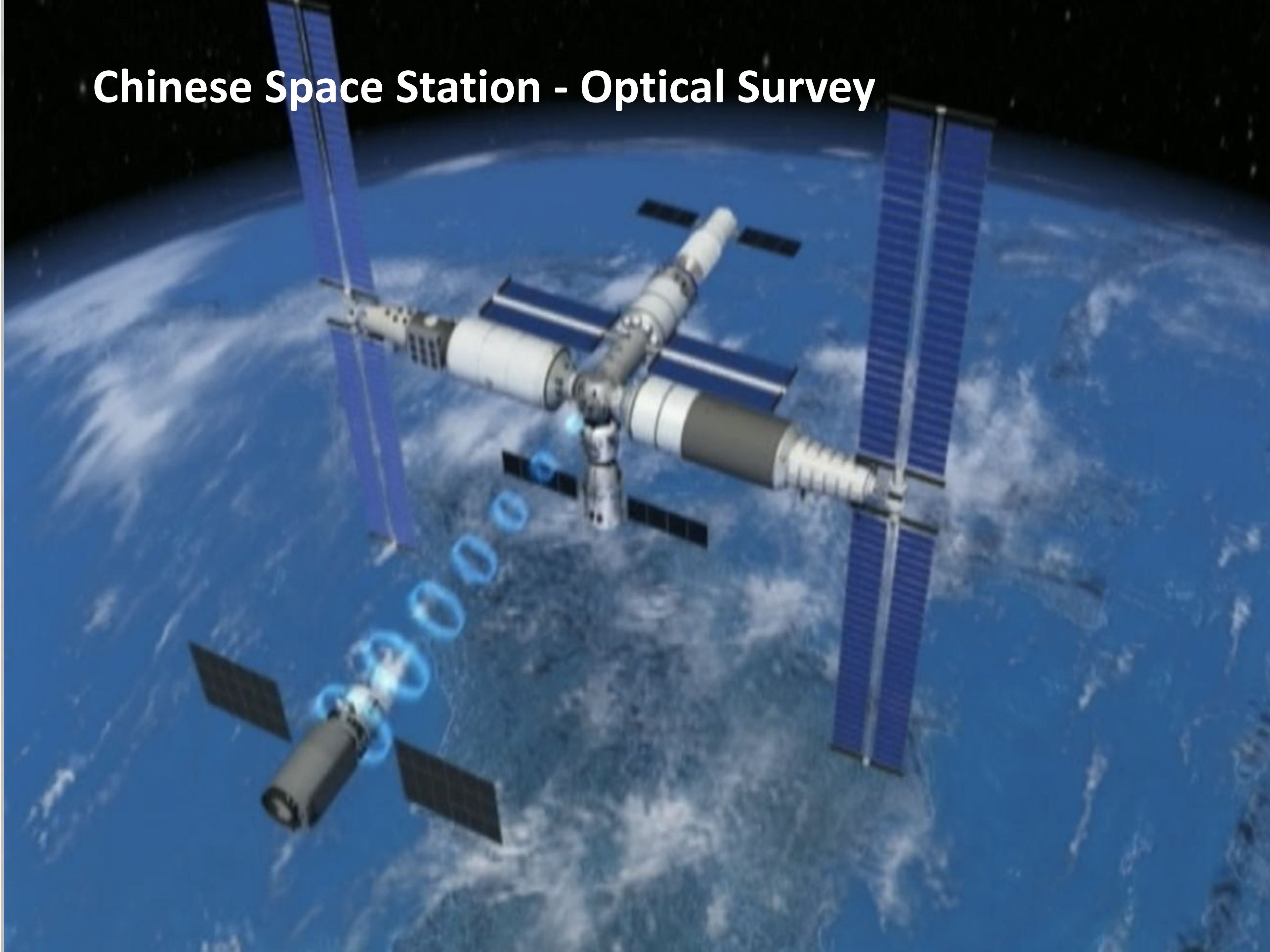




Sensitive to m_WDM < 2.5 keV

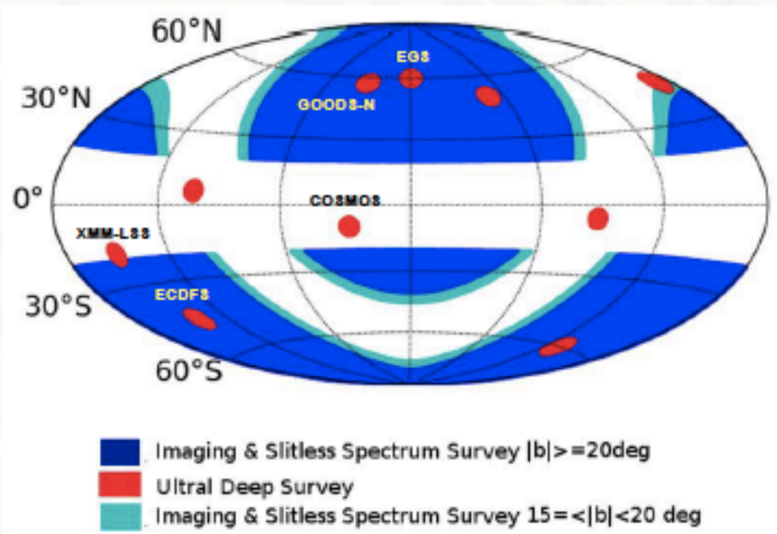
Excluded by Ly α?

Chinese Space Station - Optical Survey



Survey Specs

- **17500□° imaging : 255-1000nm, ≥6 filters, avg ≥25.5^m (5σ, point source, AB mag);**
- **17500□° slitless spect: 255-1000nm, R≥200, ≥20-21^m/res;**
- **400□° deep imaging & spect: at least 1^m deeper.**



Ecliptic Coord.
Deep fields will be finalized later; sim results for demo only.

Science

Cosmology: dark energy, dark matter, gravity, large-scale structure, neutrinos, primordial non-Gaussianity…

AGNs: high-z AGNs, clustering, dual AGNs, variability, UV excess, host galaxies…

Galaxies: formation & evolution, mergers, high-zs, dwarfs, LSBs, near field, halos properties…

Milky Way: structure, satellites, dust, extinction…

Stellar science: formation, dwarfs, metal poor…

Solar system (high inclination): TNO、NEA…

Astrometry: reference frame, star clusters…

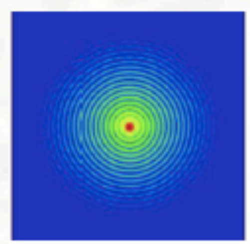
Comparison with Other Surveys

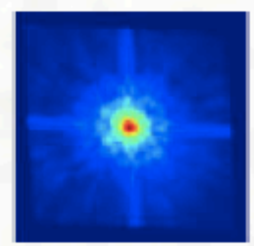
Project	Site/ orbit	Launch /op	FoV	R_{EE80}	Num pixels	Area	Wavelength	Num Filters	Spect
			deg^2	″	10^9	deg^2	nm		
CSS-OS	LEO	~2024	1.1	0.15 0.074/pix	2.5	17500	255—1000	≥6	yes
Euclid	L2	2022	0.56 0.55	>0.2 pix lmt	0.6 0.07	15000	550—920 1000—2000	1 3	no yes
WFIRST	L2	>2025	0.28	>0.2	0.3	~2000	927—2000	4	yes
LSST	Chile	2022	9.6	~0.5	3.2	18000	320—1050	6	no

R_{EE80}: radius encircling 80% energy

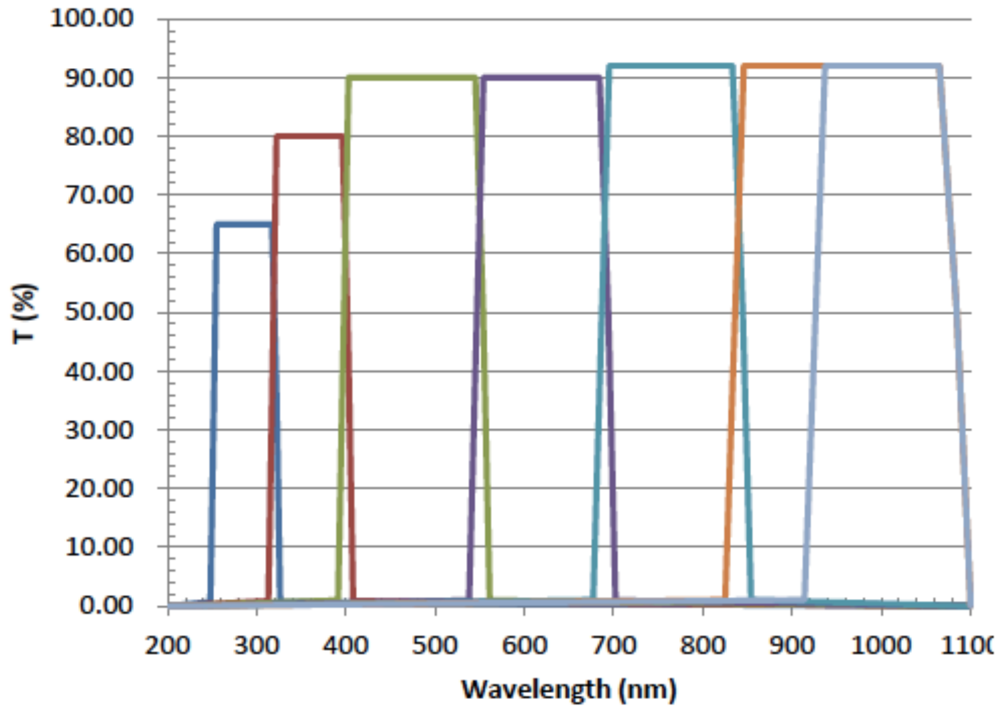
	CSS-OS	HST/ACS WFC	Euclid	WFIRST
R_{EE50}	0.1"	0.06"	0.13"	0.12"
R_{EE80}	0.15"	0.12"	~0.23"	~0.24"

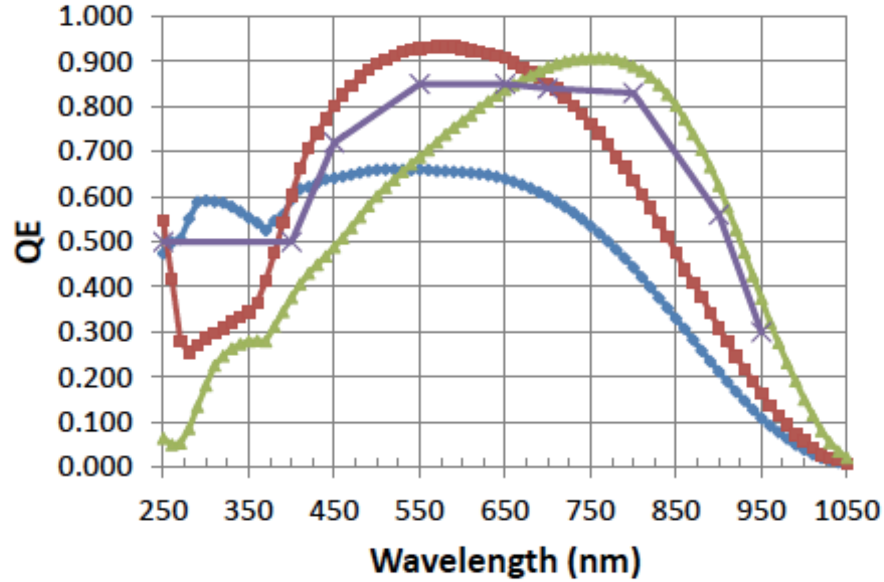
Dynamic sims: R_{EE80} ~0.13"


CSS-OS


HST

Filters & Limiting Mags



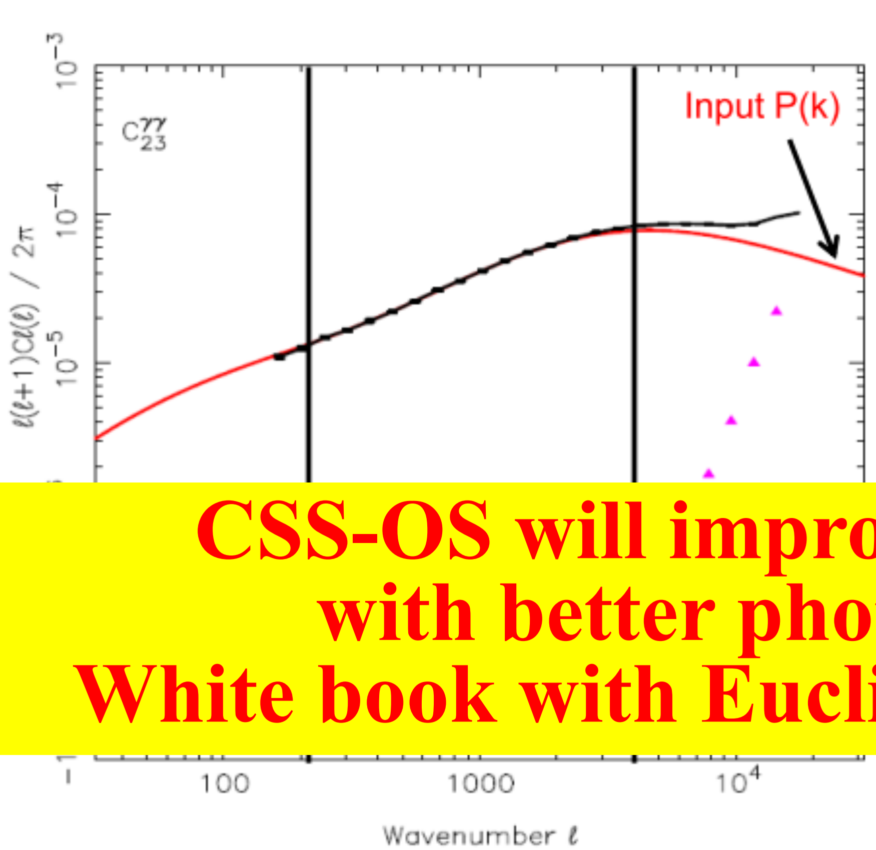


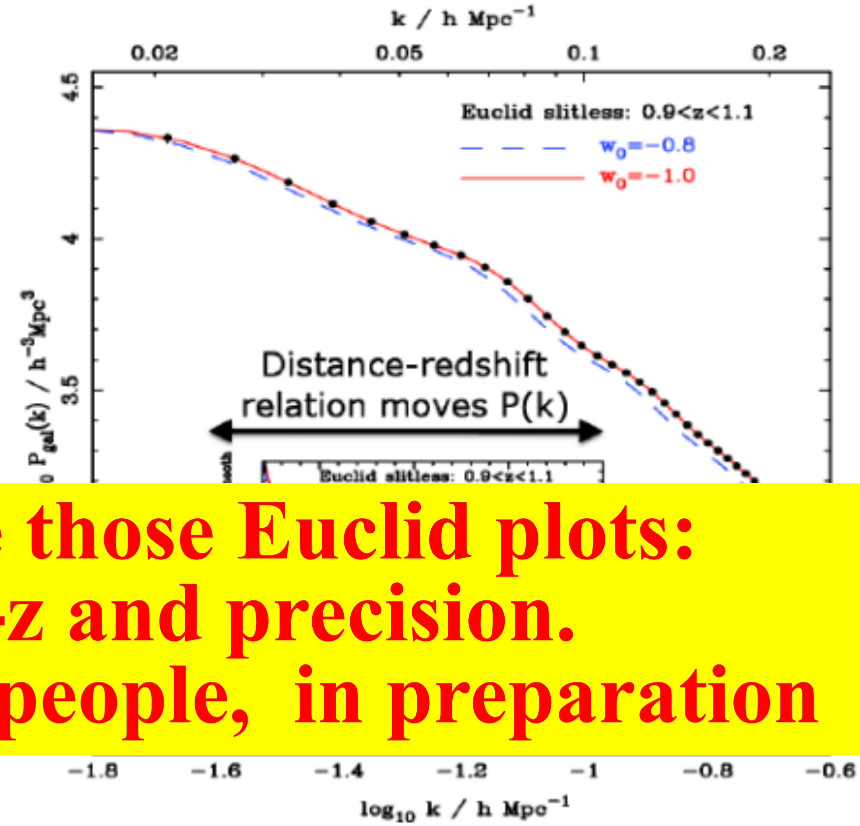
	Exp.	NUV	u	g	r	i	z	y
17500□°	2×150s	25.4	25.4	26.3	26.0	25.9	25.2	24.4
400□°	8×250s	26.7	26.7	27.5	27.2	27.0	26.4	25.7

NUV:u:g:r:i:z:y=2:1:1:1:1:1:2

Euclid WL GC: DM and Gal. reconstructed P(k)

Euclid Consortium





CSS-OS will improve those Euclid plots: with better photo-z and precision. White book with Euclid people, in preparation

- Tomographic WL shear cross-power spectrum for 0.5 < z < 1.0 and 1.0 < z < 1.5 bins.

- Percentage difference [*expected* – *measured*] power spectrum: recovered to 1% .

- $V_{eff} \approx 19\ h^{-3}\ Gpc^3 \approx$ 75x larger than SDSS
- Redshifts 0<z<2

- Percentage difference [*expected* – *measured*] power spectrum: recovered to 1% .

Ref: Euclid RB arXiv:1110.3193

Euclid Consortium

Baryon physics (eg.,AGN feedback) affects Matter Power Spectrum

Semboloni+ (2011)

Van Daalen+(2011)

Shale + :OWLS simulation

➔ Consequences on WL cosmological parameters fits

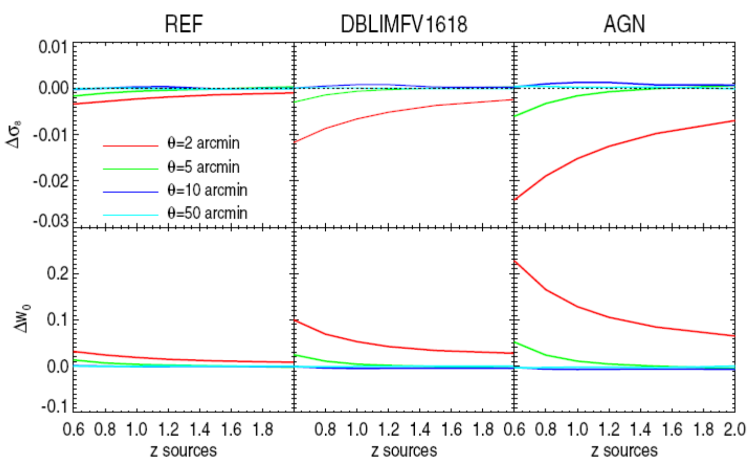


Figure 4. Top (bottom) panels show the deviation of the inferred σ_8 (w_0) from the true reference value $\sigma_{8,\mathrm{ref}} = 0.74$ ($w_{0,\mathrm{ref}} = -1$) as a function of source redshift, when the amplitude of the ellipticity correlation function $\xi_+(\theta)$ is used to estimate the cosmological parameter of interest (while the other parameters are kept at their reference values) and when we use halofit models (see text for details). The deviation depends on the angular scales that is used and is smaller for larger scales. The left panels show the results for the REF scenario, the middle panels for the DBLIMFV1618 and the right panels for the AGN scenario, which results in the largest biases.

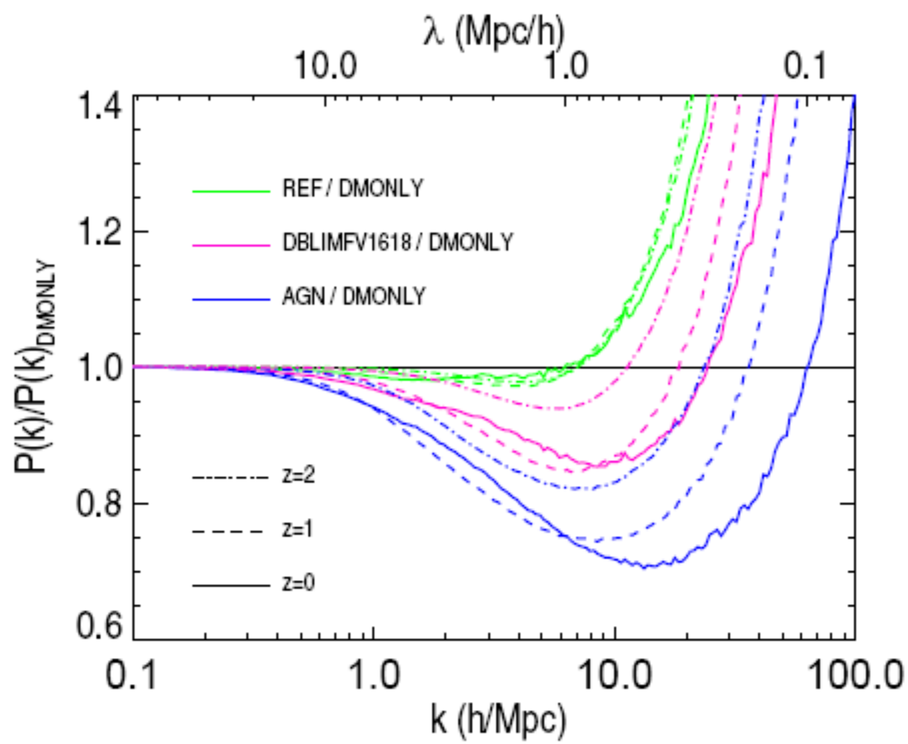
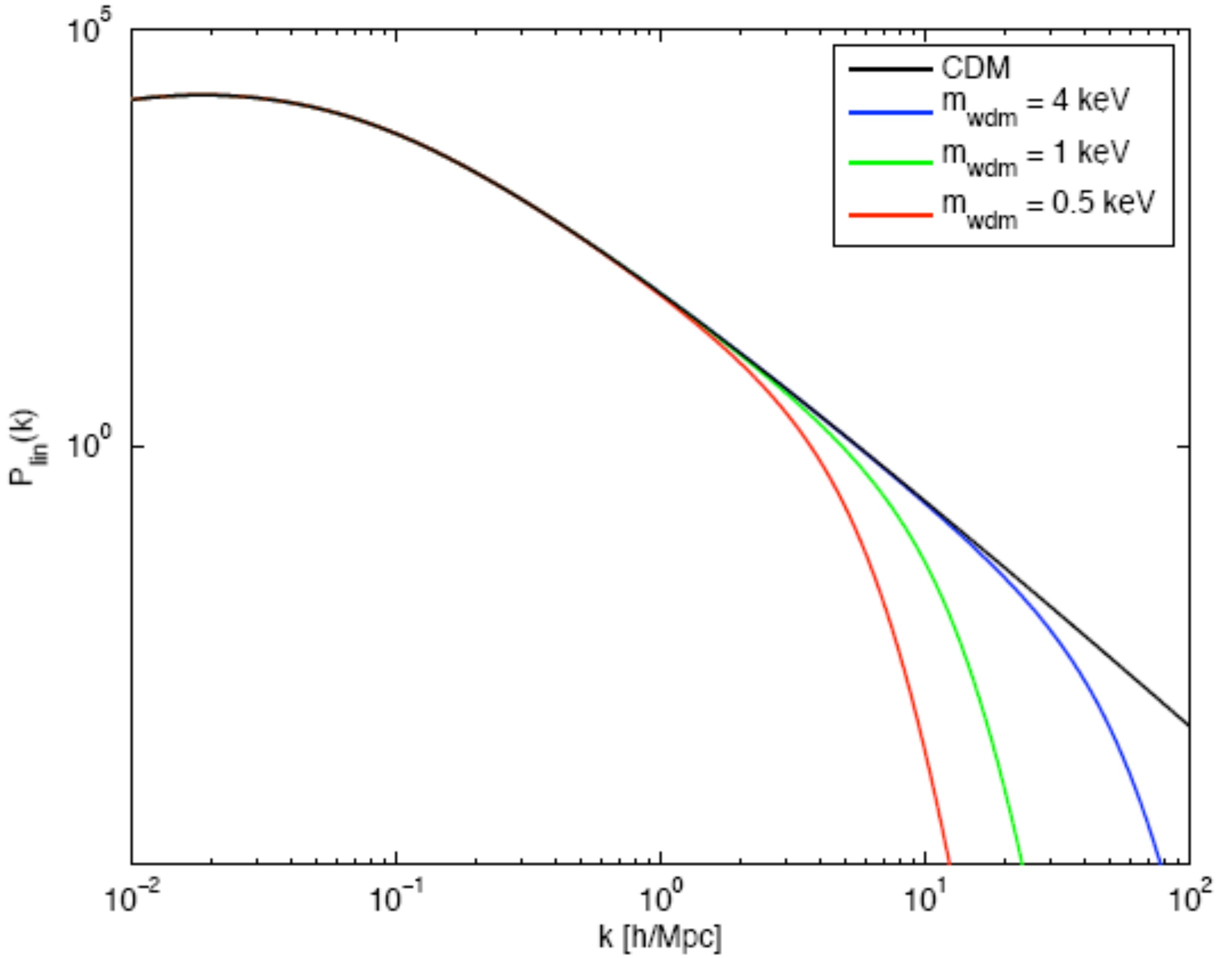


Figure 1. Ratio between the power spectrum of matter fluctuations measured from the simulations with baryons and the one measured from the DMONLY simulation. The ratio for the REF simulation is shown in green, the one for the AGN simulation is shown in blue, and the one for the DBLIMFV1618 model is shown in pink. Since the simulations have been carried out using the same initial conditions, deviations of the ratio from unity are due to the differences in baryon physics.

keV WDM effect around k=10 h/Mpc



Baryon effects different from low mass standard model neutrino effects

Semboloni et al. 2011

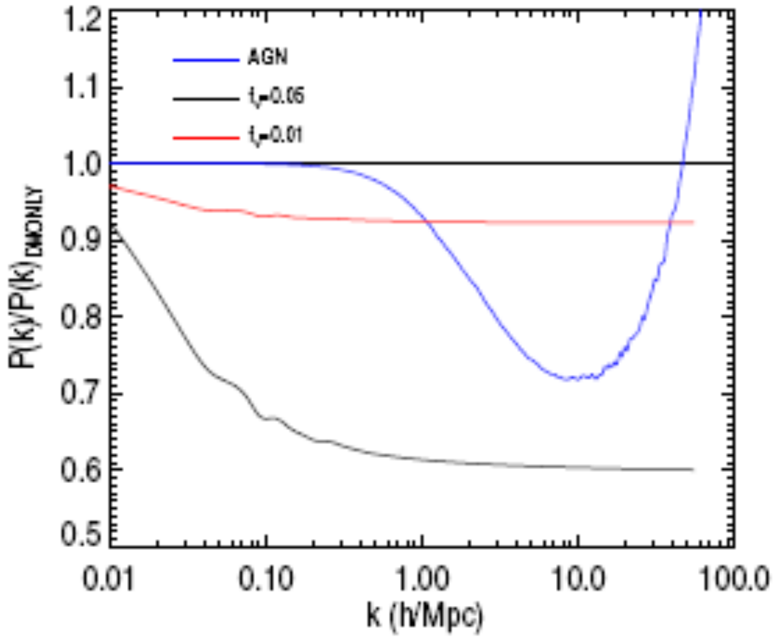


Figure 14. Ratio of the AGN/DMONLY power spectra (blue line), and dark matter power spectra with $f_\nu \equiv \Omega_\nu/\Omega_m = 0.01$ and 0.05, which correspond to neutrino masses of $\sum m_\nu \sim 6.0$ and $\sum m_\nu \sim 1.2$ eV, respectively. The effect of massive neutrinos on the power spectrum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

What do we know about the nature of DM?

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

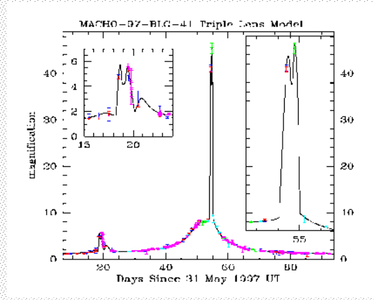
Constraints from non-observation in direct/indirect/LHC searches
AND
Observations in Astrophysics / Cosmology

Very different DM candidates

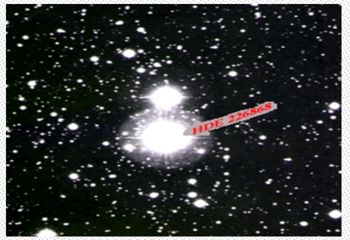
Modified Gravity

Cold Molecular Hydrogen

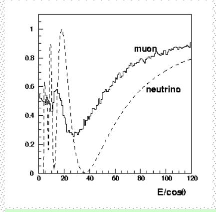
MACHOs



Black holes



SIMPs

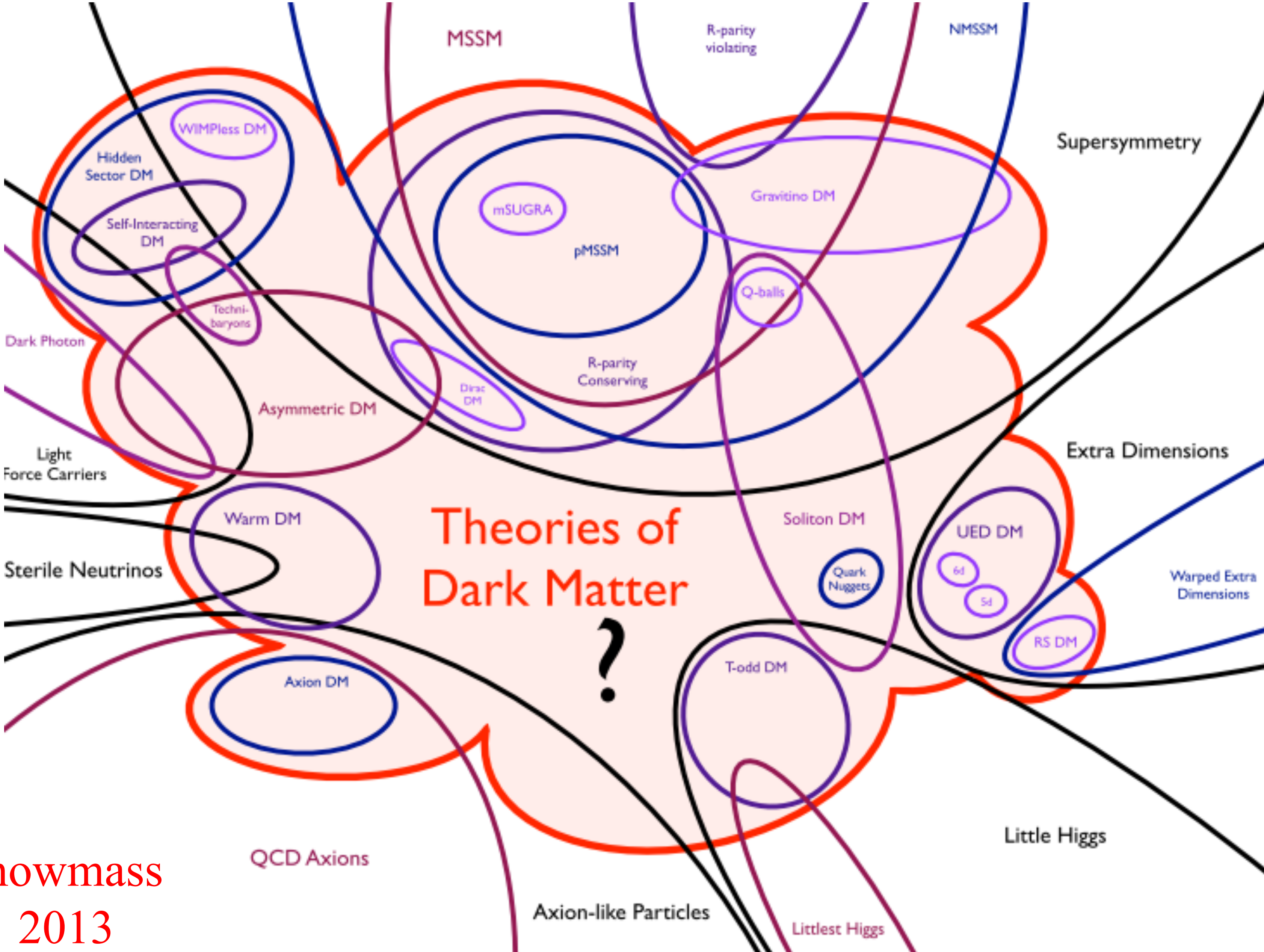


1Neutrino

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 spectr

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'

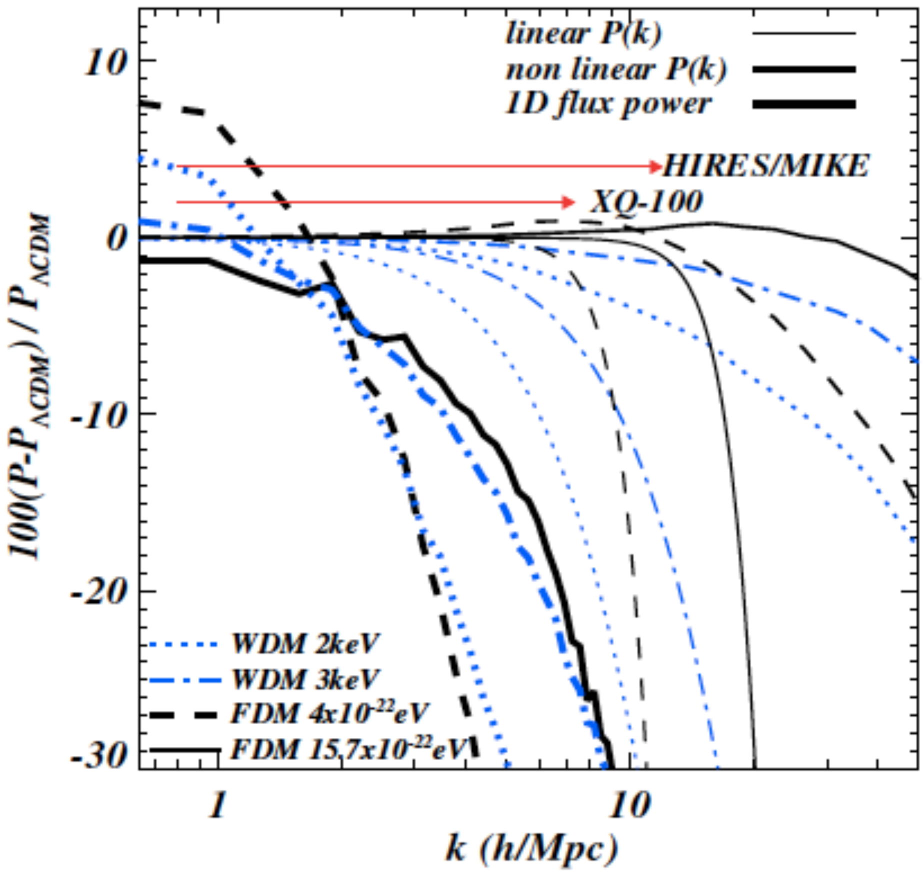


FIG. 1: Power spectrum relative to ΛCDM at $z = 5.4$ (in per cent). Linear matter, non-linear matter and flux power spectra are represented by the thin, thick and very thick curves, respectively. Black (blue) curves are for FDM (WDM) models with $m_{FDM} = 5.7, 15.7 \times 10^{-22}$ eV ($m_{WDM} = 2,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

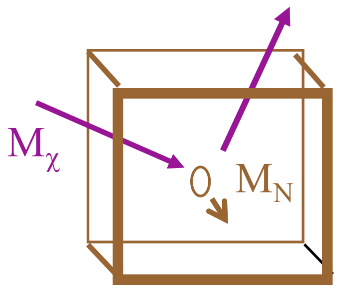
Detections


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!
?

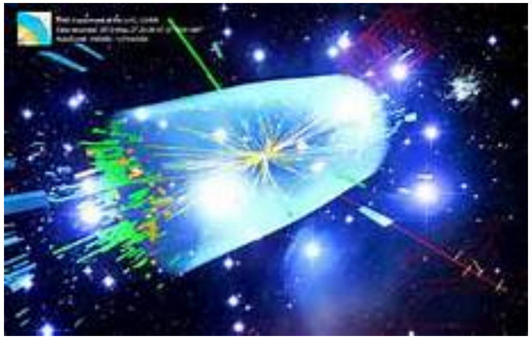
Fisher (1942)

WIMP searches

Direct detection

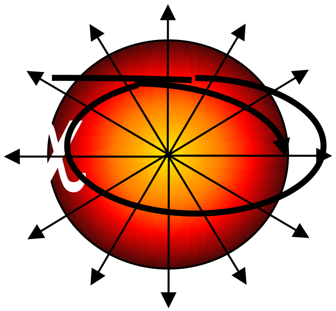


Ge, Si, NaI, LXe, …



Accelerator particle production, eg, LHC

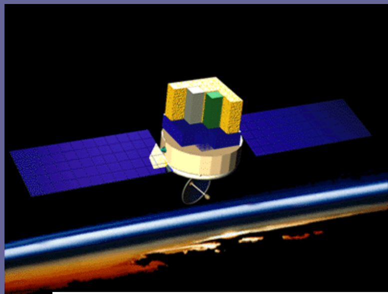
Indirect detection

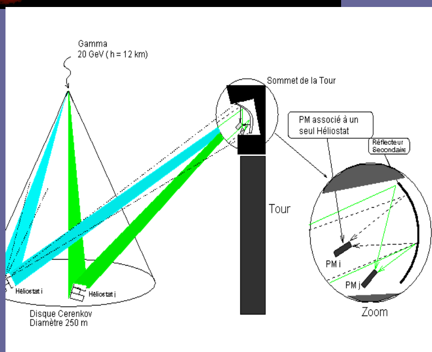


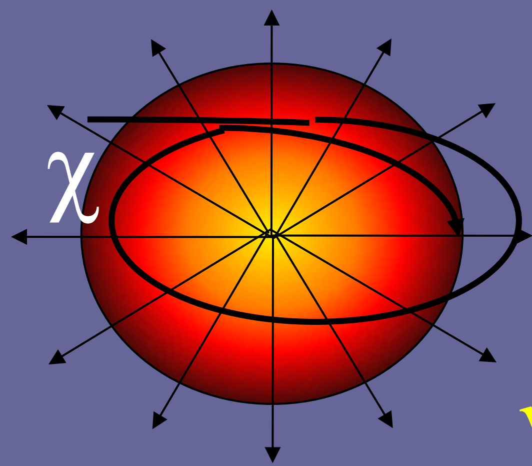
ν, γ, p, e^+

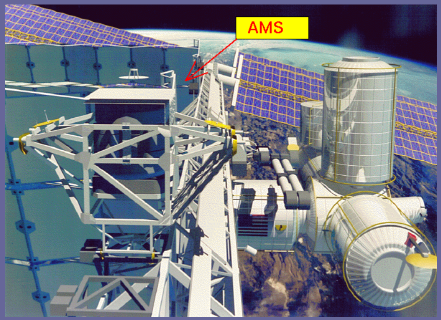
+ Galactic, cluster, Universe scales…

WIMPs Indirect Detection

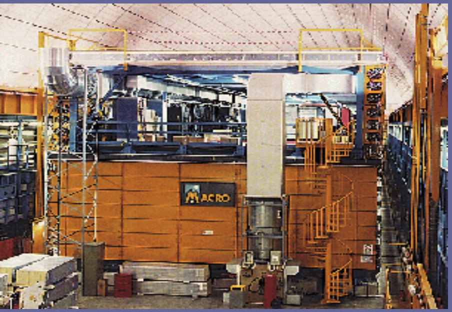


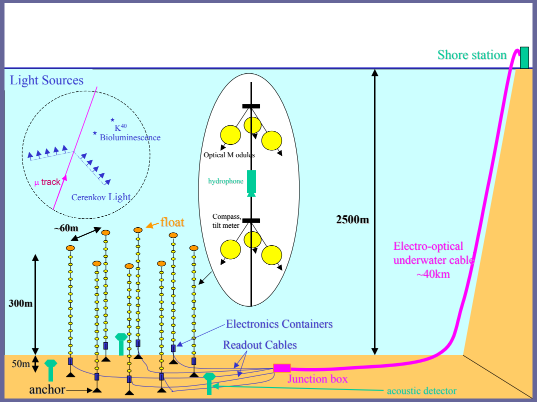


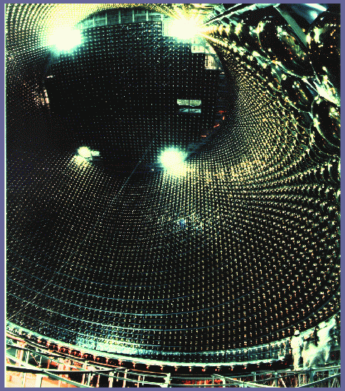


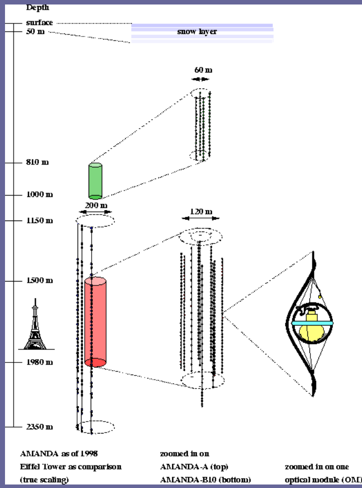


$\nu, \gamma, \bar{p}, e^+$



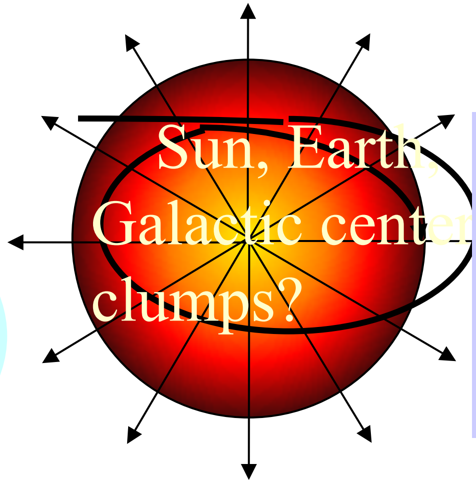






Indirect Detection: Principle

SUSY



SMMG

Accumulation

+

Annihilation

Possible final states: $\tau^+\tau^-$, lepton pairs, qq, WH, ZH, WW, ZZ ; Hadronisation and decay

Astroparticle detectors:
positrons, antiprotons, antideutons
gammas, neutrinos

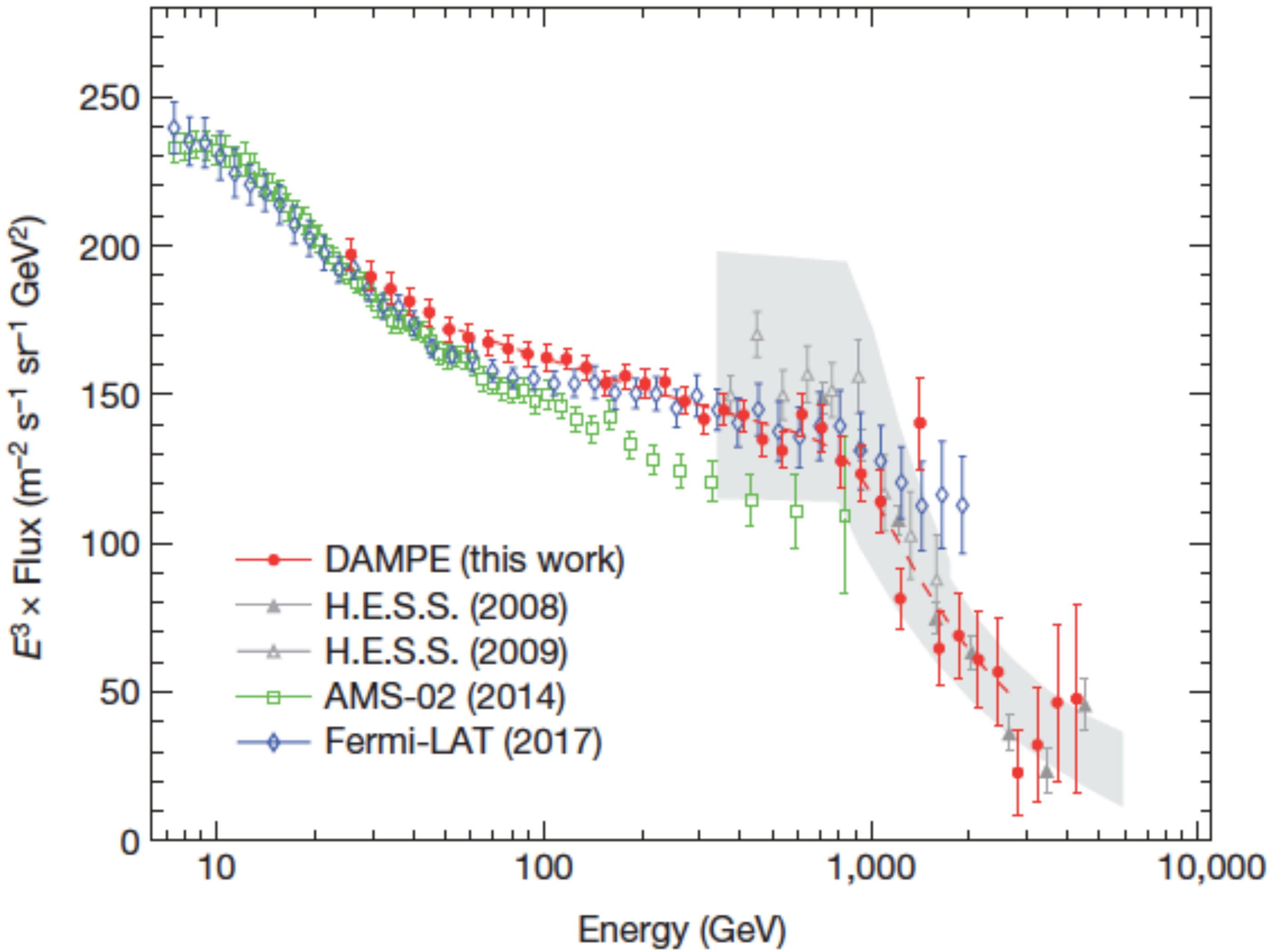
Astrophysical origin of observed signals,eg, AMS, are hard to exclude

Need discovery at accelerators!

Still hope at LHC ?

Indirect Detection e- & e+

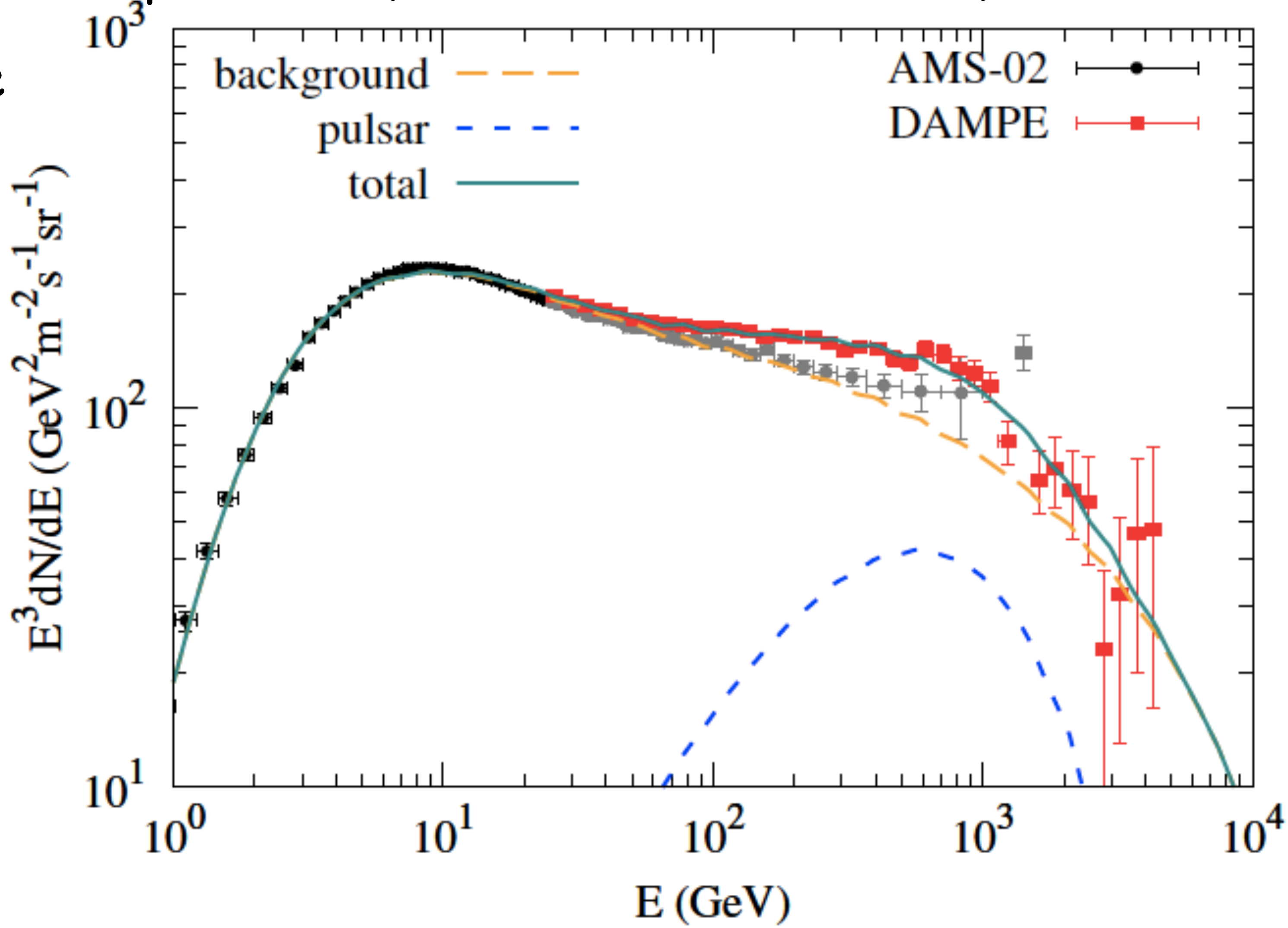
eg, DAMPE, Nature Nov 29, 2017



Indirect Detection e- & e+

DM or pulsar? (Yuan et al., 1711.10989)

Log scale

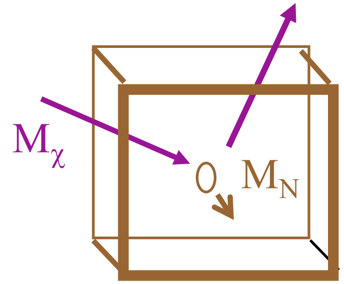


WIMP searches: Direct detection

- **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, …

WIMP searches: Direct detection

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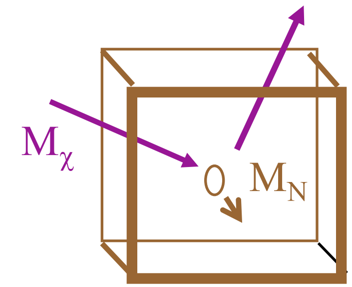


Ge, Si, NaI, LXe, …

- **Exponential recoil energy distribution**

event rate per unit mass

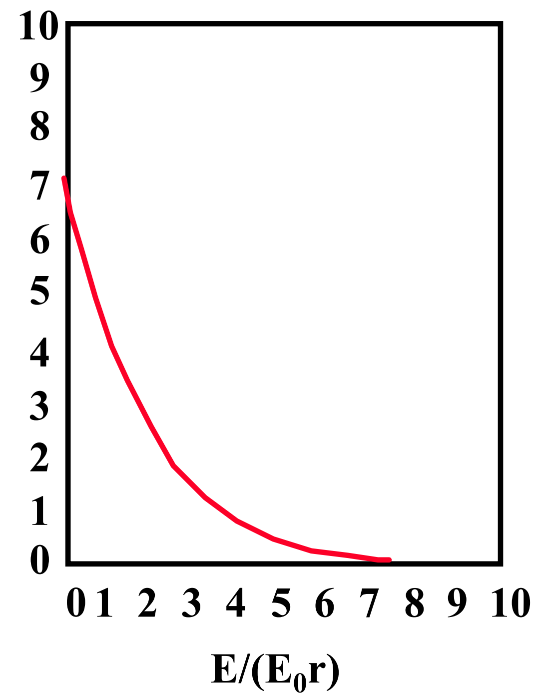
total event rate (point like nucleus)

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

recoil energy

incident energy

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



- **Rates**: **Weak interactions or smaller**

Differential rate for WIMP elastic scattering

$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_W} \int_{v_{\min}}^{v_{\max}} d\vec{v}\, f(\vec{v}) v \frac{d\sigma}{dE_R}$$

$$v_{\min} = \sqrt{\frac{m_N E_{th}}{2 m_r^2}}, v_{\max} = v_{esc}$$

$$f(v)\, dv = 4\pi \left(\frac{3}{2\pi \bar{v}^2} \right)^{3/2} v^2 \exp\left(-\frac{3v^2}{2\bar{v}^2} \right) dv, \bar{v} \approx 270\, km/s$$

$$E_R = \frac{m_r^2 v^2 (1 - \cos\vartheta)}{m_N}$$

$$\frac{d\sigma}{dE_R} = \frac{\sigma_0}{E_R^{\max}} F^2(E_R),\ \sigma_0 = \frac{1 + m_W / m_p}{1 + m_W / m_N} A^2 \sigma_{scalar}^{nucleon}$$

Direct detection: Interaction rates

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 <u>Nature of WIMP and cross-sections</u>

σ_χ

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

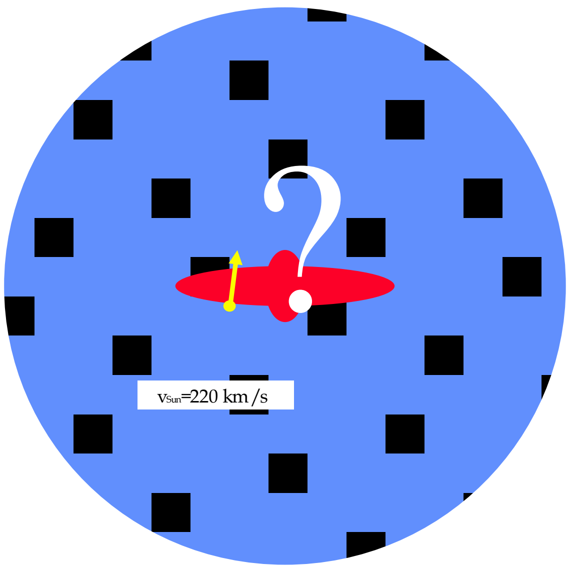
Neutralinos are a linear combination of higgsinos and gauginos

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?

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

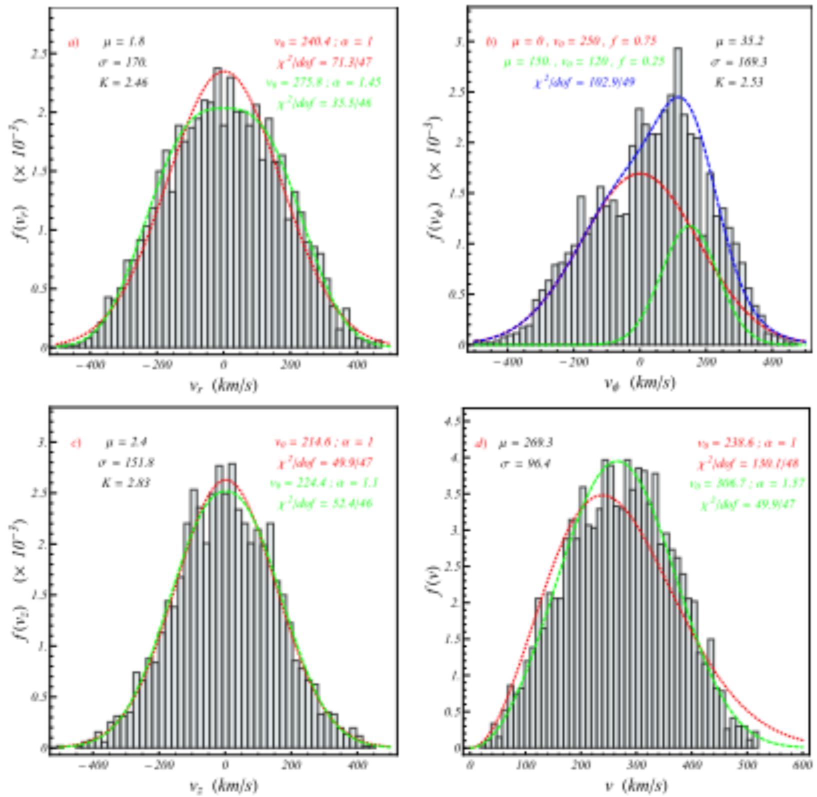


Figure 5: *Velocity distributions of dark matter particles ($N_{ring} = 2,662$) in a ring $7 < R < 9$ kpc, $|z| < 1$ kpc around the galactic plane.*
a) Radial velocity v_r, with Gaussian (red) and generalized Gaussian (green) fits (cfr. Eq. (2.1)).
b) Tangential velocity v_ϕ, with a double Gaussian fit. 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).

Some numbers ...

A galaxy like the Milky Way or Andromeda has a total visible mass of about 6×10^{10} M_{sun}.

- rotation velocity is ~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/cm3)

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

Analysis of Gaia results

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

1) GD-1 stream from Gaia ➔a new level of precision in simulating a stream-dark-matter encounter (A. Bonaca et al., 2019).

Need a clump of 10^7Mo!

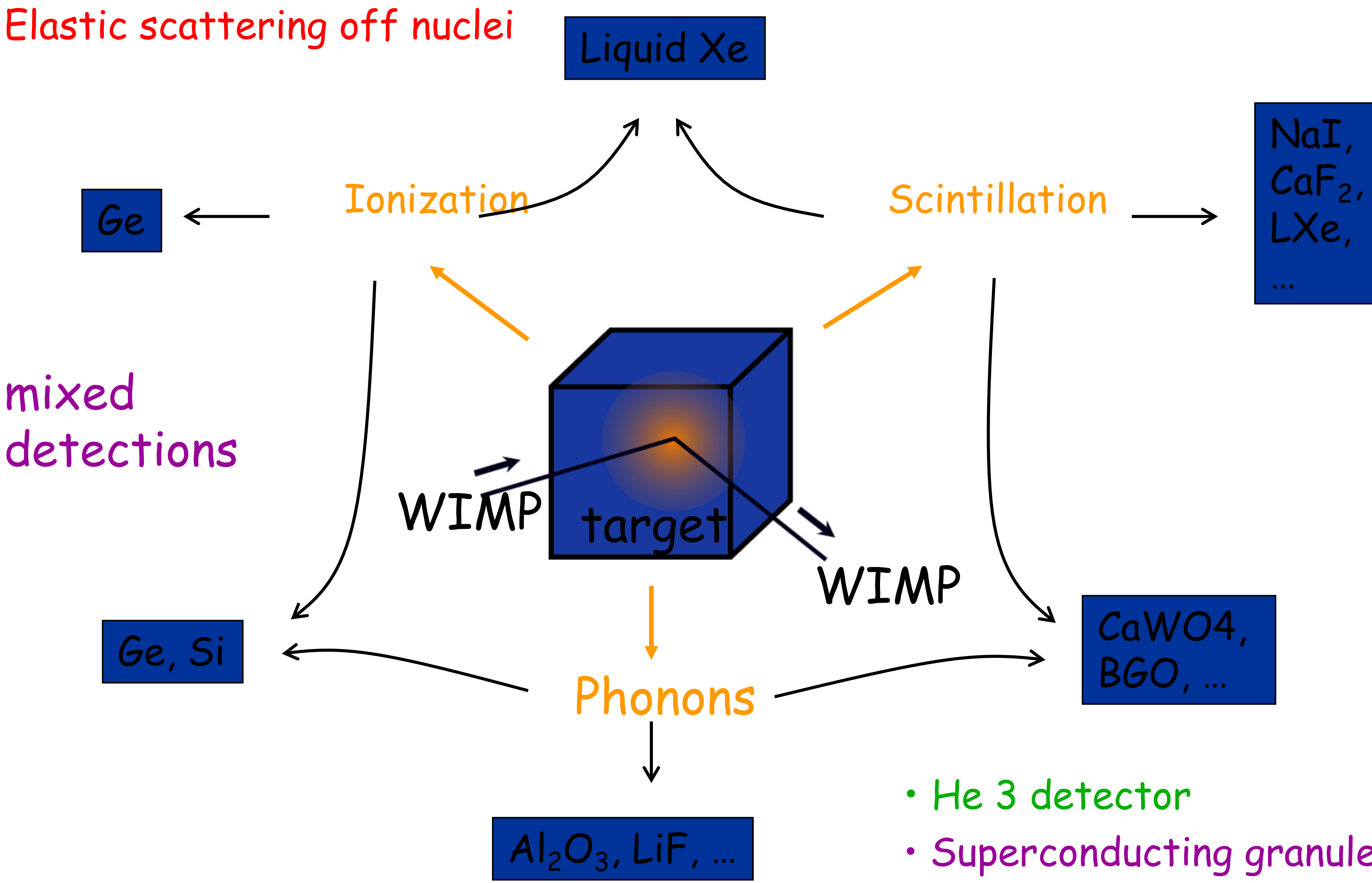
2) Lisanti et al 2019: 2 non disk populations of stars :

i) Old, isotropic velocity distributions

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

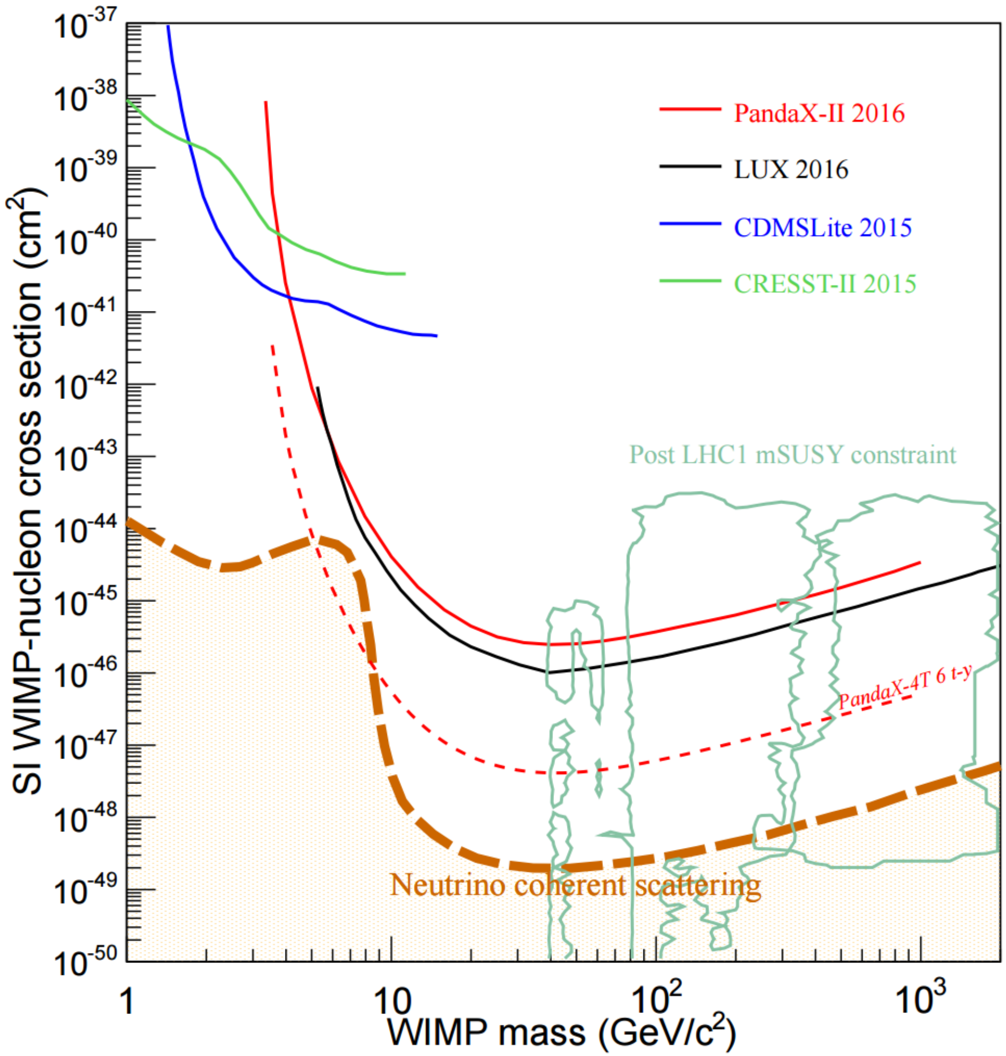
Each should have its own DM population!!!

WIMP direct detection schemes with and w/o background rejection



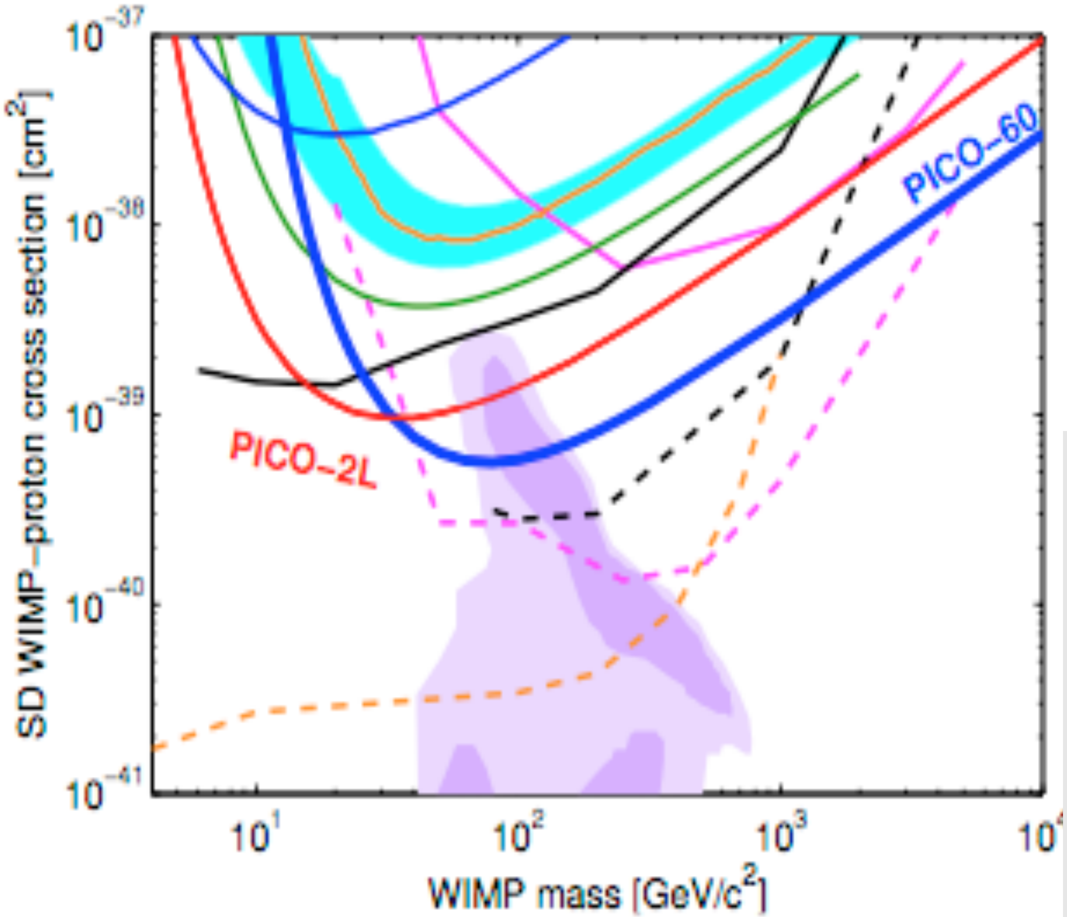
- He 3 detector
- Superconducting granules
- Freon aerogel

Present limits: Spin Independent coupling



From
Ji Xiangdong,
Dec 2016

Present Spin Dependent Exclusion plots



90% C.L. of PICO-2L plotted along with limits from PICO-60
COUPP-4: light blue region,
PICASSO: dark blue,
SIMPLE: thin green,
XENON100: orange,
IceCube: dashed and solid pink,
SuperK: dashed and solid black
CMS: dashed orange

Best results are not direct and need assumptions!

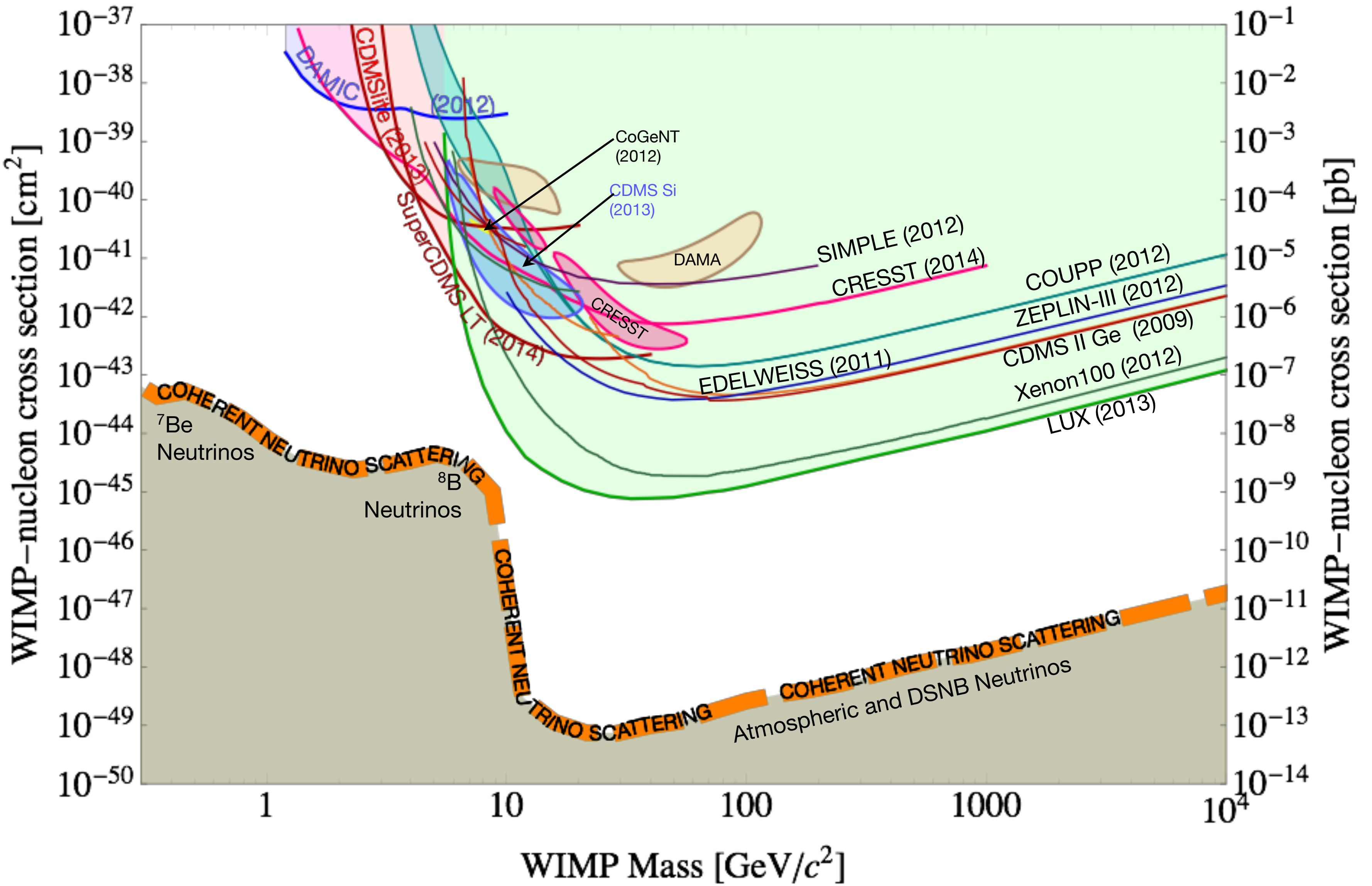
IceCube and SuperK :

- dashed lines: annihilation to W pairs
- solid lines : annihilation to b quarks.

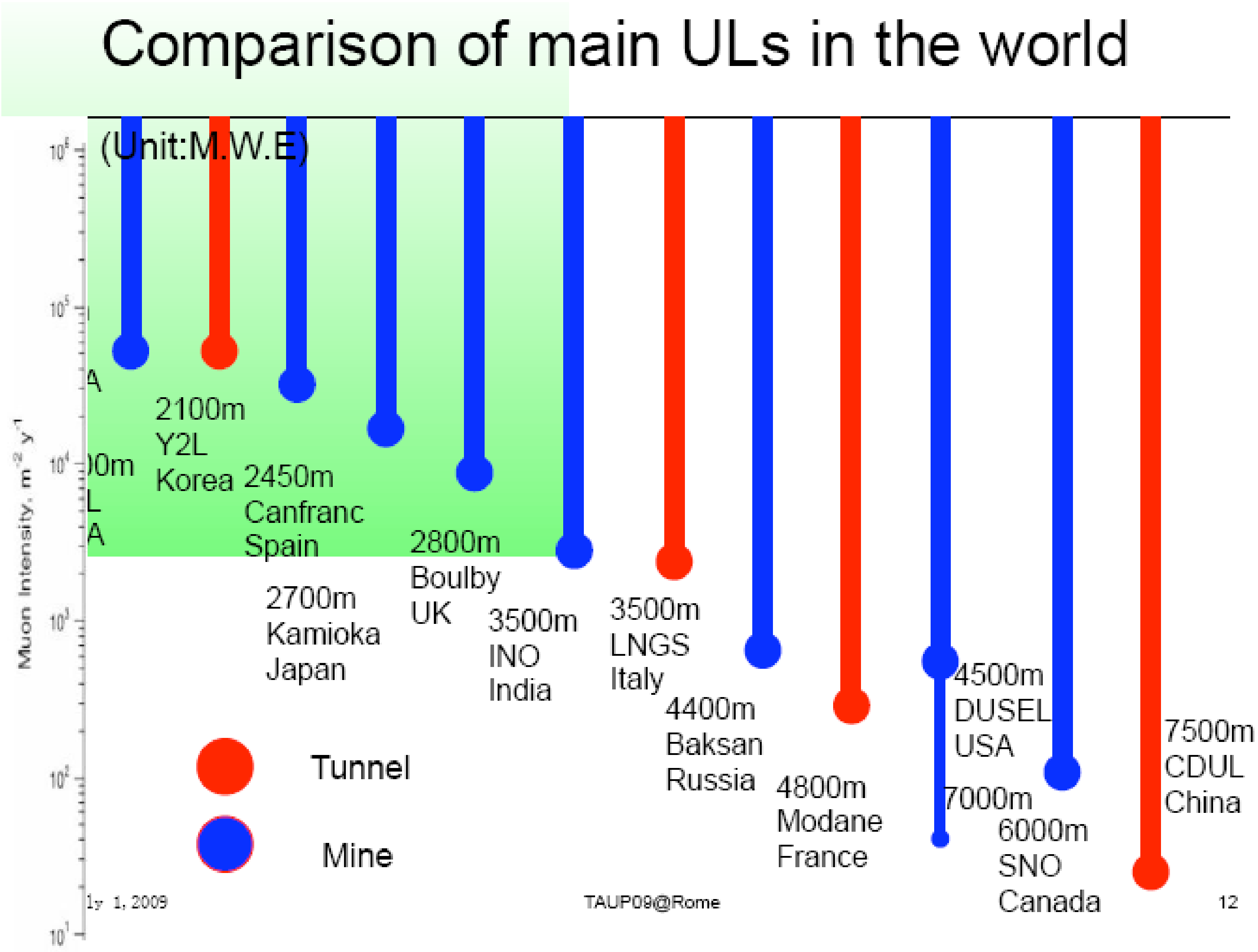
Comparable limits ANTARES, Baikal and Baksan neutrino telescopes

CMS/ATLAS limit : monojet search with effective field theory

Direct detection Situation



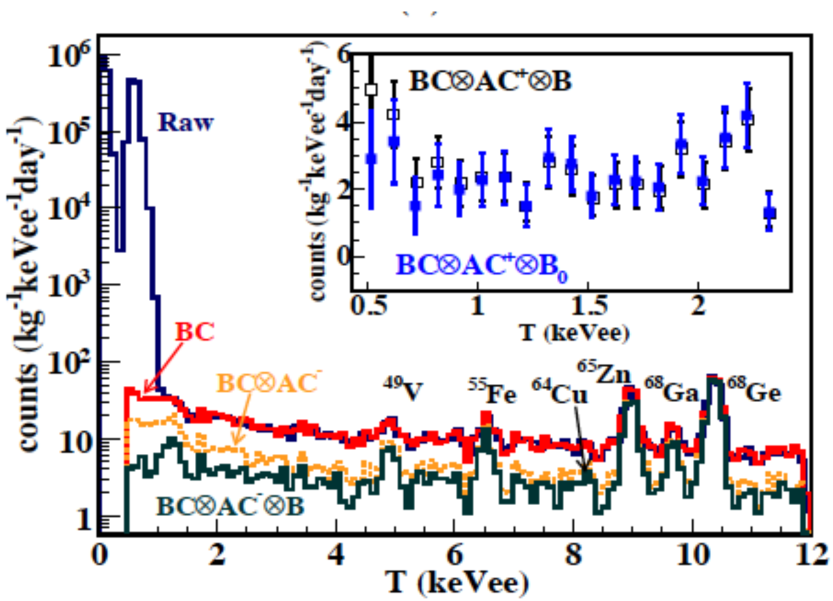
Great mountain coverage



Chinese Underground Laboratory in Jinping CJPL

Road and Tunnel

CDEX: reaching best present Ge limits in 5 years!



10 kg crystal

Y.Qian et al., arxiv 1404.4946

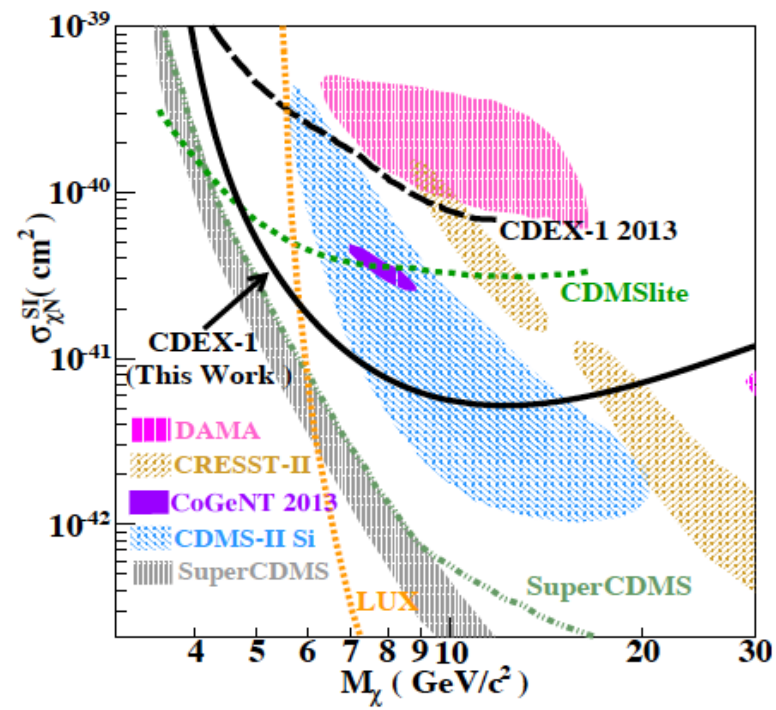


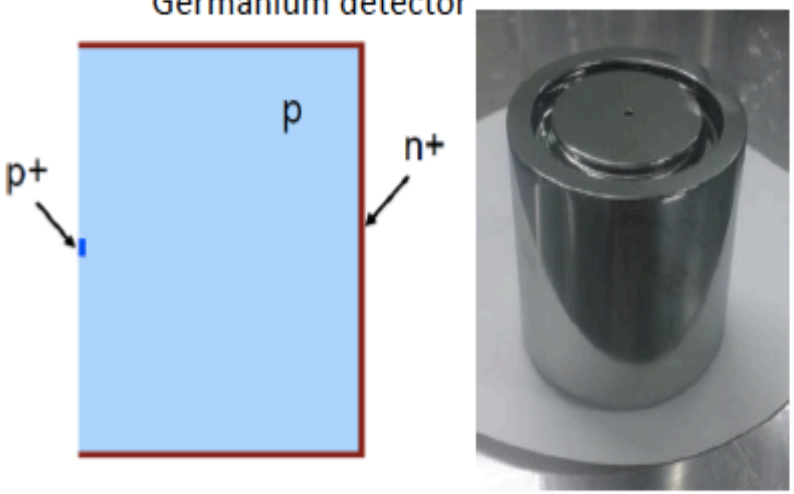
FIG. 4: The 90% confidence level upper limit of spin-independent χN coupling derived from this work, superimposed with the results from other benchmark experiments [2–5, 7, 9, 10, 14].

Cosmogenics Ge-68 has 270.8 days half-life!

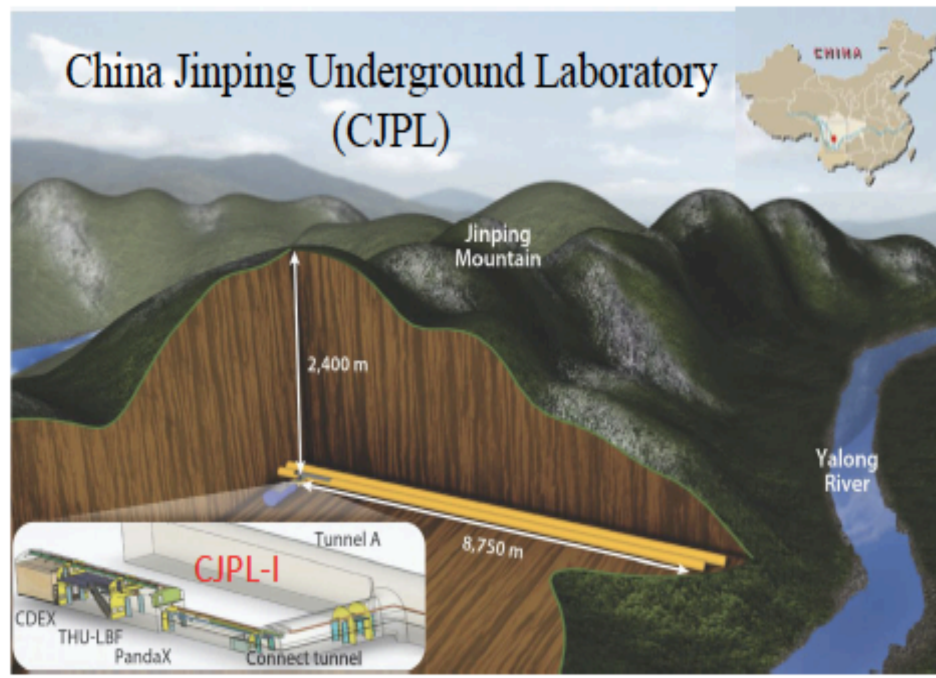
CDEX stages

- DM detection w/ Ge prepared since 2003 and started in 2005 in Y2L (5g);
- CDEX-1: Development of PPC Ge detector, bkg understanding, since 2011;
- CDEX-10: Performances of Ge array detector immersed in LN_2, since 2016;
- CDEX-10X: Home-made Ge detector and Ge crystal growth;

P-type Point-Contact(PPC)
Germanium detector

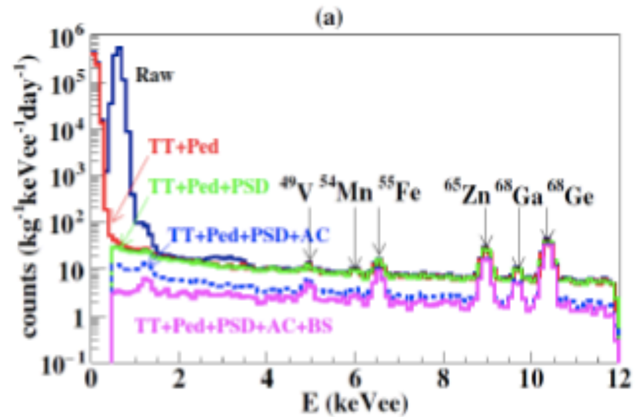


Direct detection of low-mass WIMPs w/ Ge detector at CJPL.



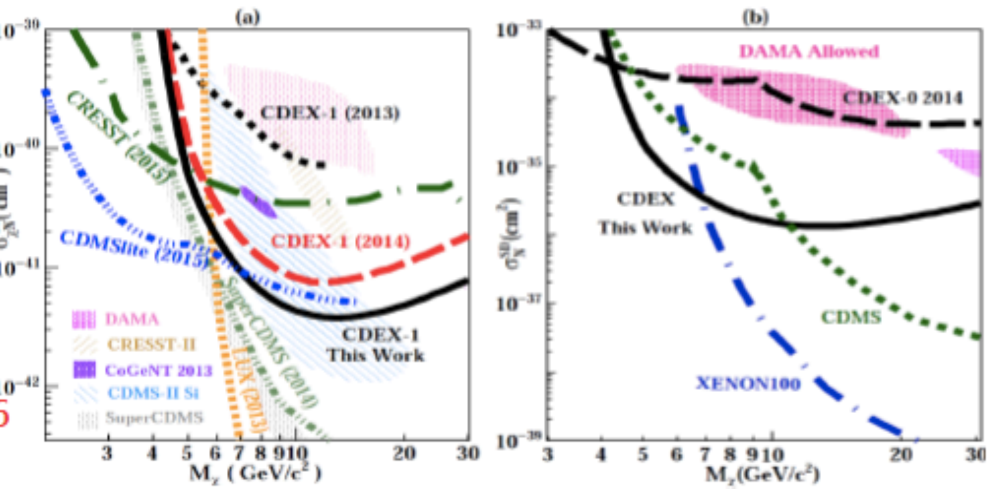
CDEX 2016 Results

- >500 days run, ~336 d·kg dataset;
- Energy threshold: 475 eVee;
- Bulk/Surface disc. to cut events with slow rise-tim and partial charge collection;
- K/L X-rays from Cosmogenic nuclides to trace crystal history;



- SI sensitivity improved;
- SD best below 6 GeV then;

PRD93, 092003, 2016

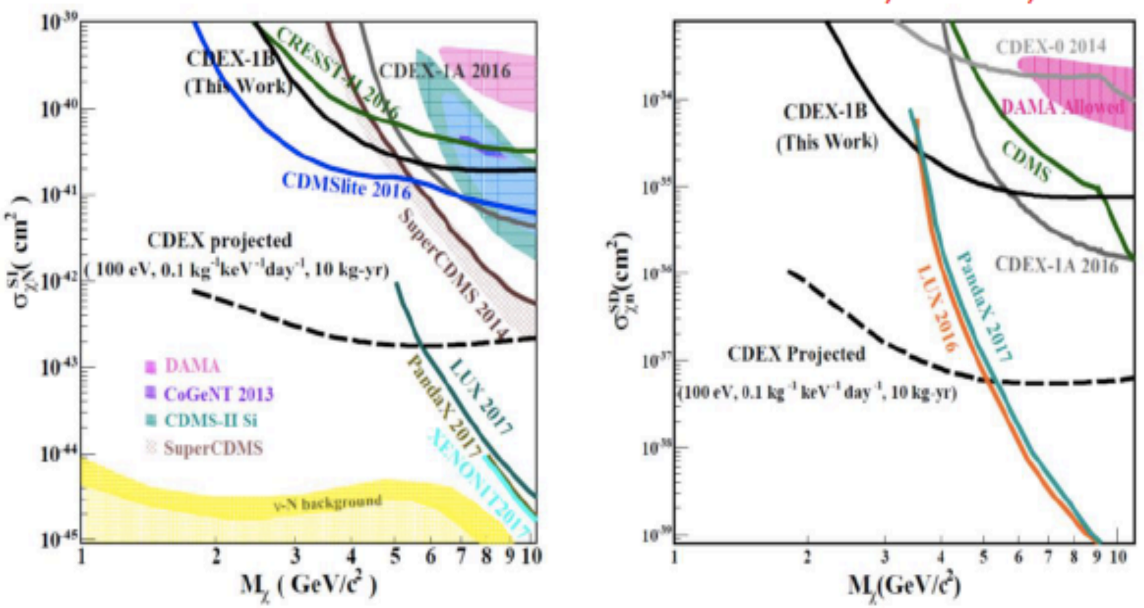


CDEX 2018 Results

- Detector upgraded w/ lower JEFT noise and material bkg;
- Run 3.3 years, totally 737.1 kg·d exposure;
- Achieving 160 eVee energy threshold;
- Sensitivity improved and extending to 2 GeV/c^2.

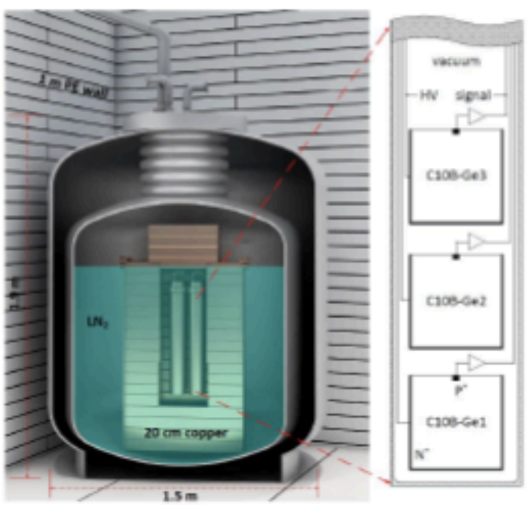
Detector	FWHM of pulser
CDEX-1A	130 eVee
CDEX-1B	80 eVee

CPC 42, 023002, 2018

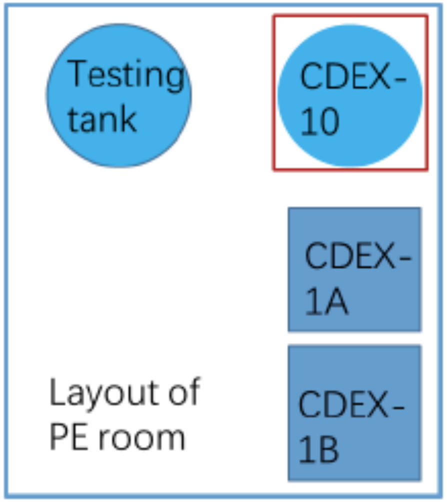


CDEX-10

- Array detectors: 3 strings with 3 det. each, ~10kg total;
- Direct immersion in LN_2;
- Prototype system for future hundred-kg to ton scale experiment
  - Light/radio-purer LN_2 replacing heavy shield i.e. Pb/Cu;
  - Arraying technology to scalable capability;



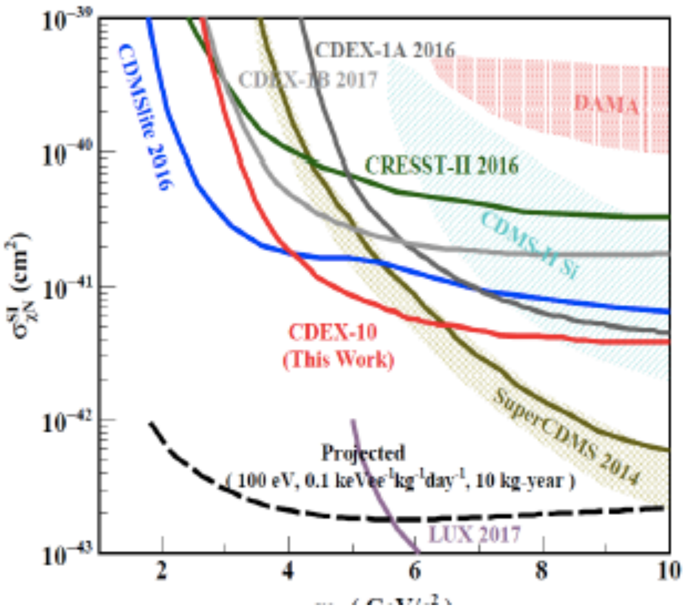
CDEX-10: ~10kg PPC Ge array

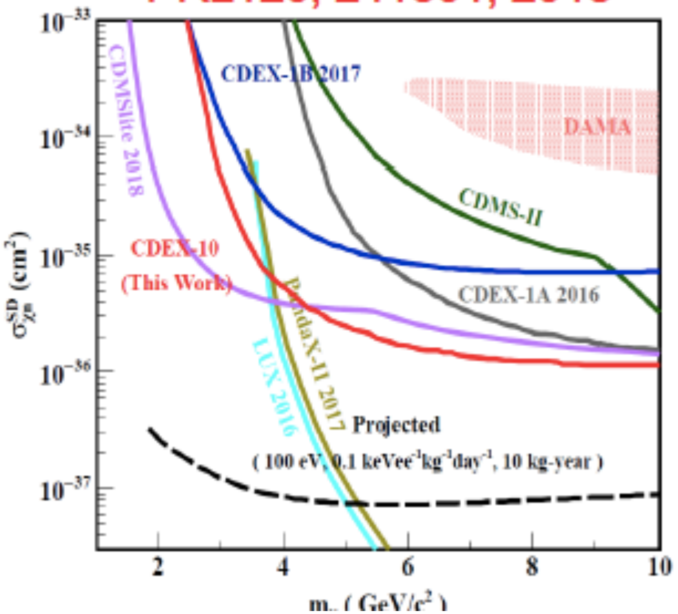


CDEX-10 first results

- First results from 102.8 kg·day exposure w/ E_{th}=160eV;
- Bkg level: 2 cpkkd @ 2-4 keV;
- New SI limit on 4-5 GeV/c^2.

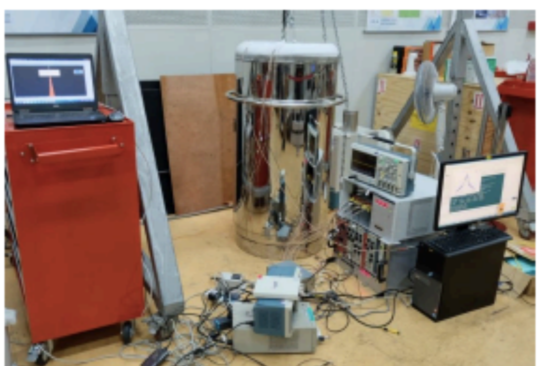
PRL120, 241301, 2018



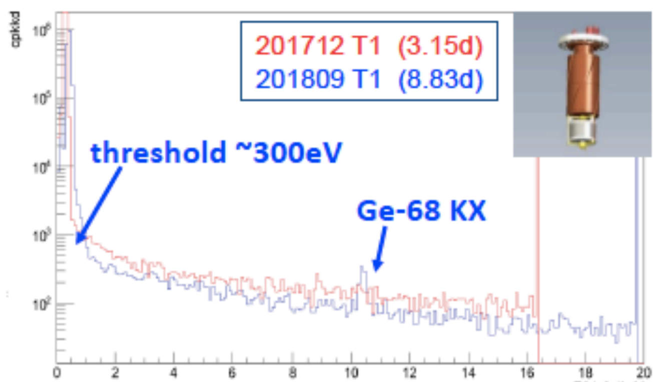


CDEX-10X (T1)

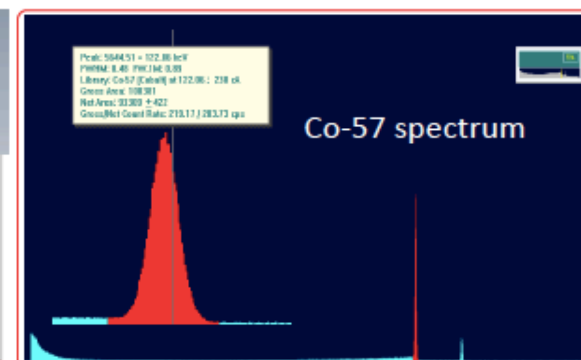
- Commercial Ge crystal + stainless steel canister;
- T1 detector: 500g Ge(φ50×50mm) + CMOS ASIC preAmp;
- Works, and Performance expected;
- Going on to improve bkg, low-noise electronics…



Tested in CJPL-I



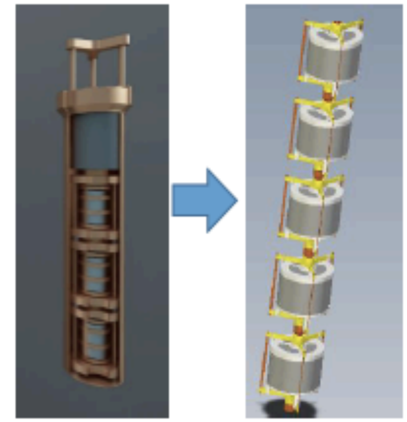
Background spectrum @CJPL

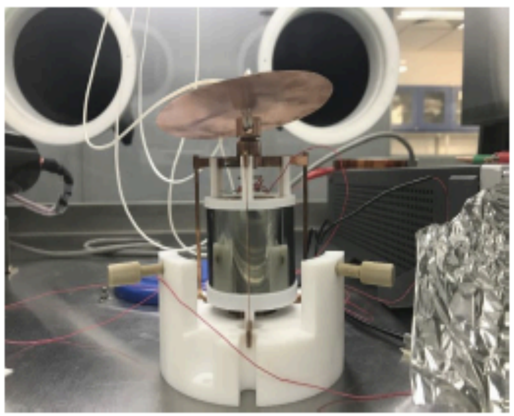


FWHM=0.48keV@122keV_Co57

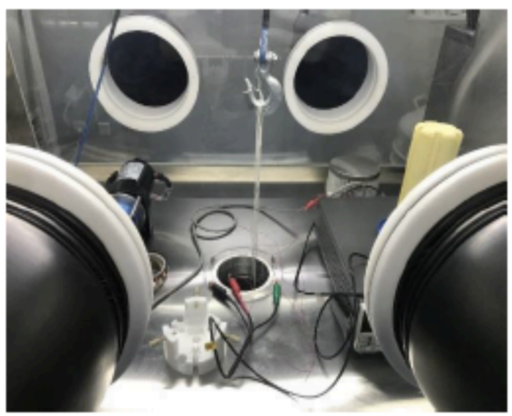
Bare HPGe in LN2

- Vacuum chamber, structure materials, not conducive to further reduce the radioactive background;
- ASIC-based preamplifiers can work well in liquid nitrogen;
- ✓ Develop bare HPGe detectors immersed into LN_2!
- ✓ Immerse the detector into liquid nitrogen for about 8 hours, we got a stable leakage current ~10 pA for 1000V bias voltage.



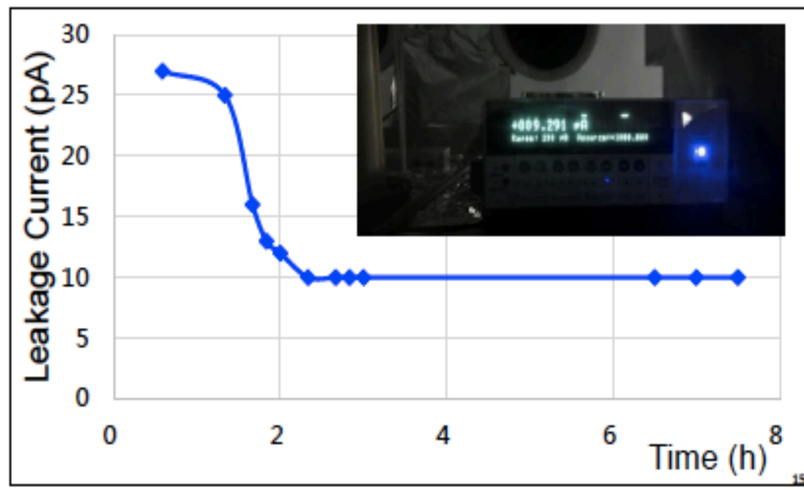


Bare HPGe detectors



Bare HPGe in LN_2

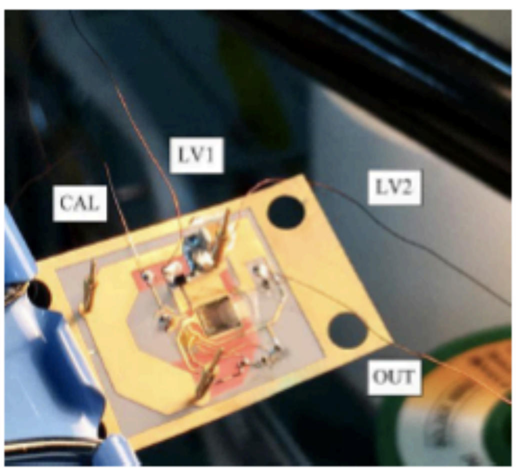
PPC: ϕ50mm x 50mm, Depleted voltage: ~800V

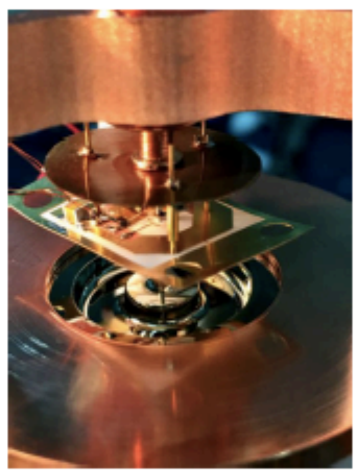


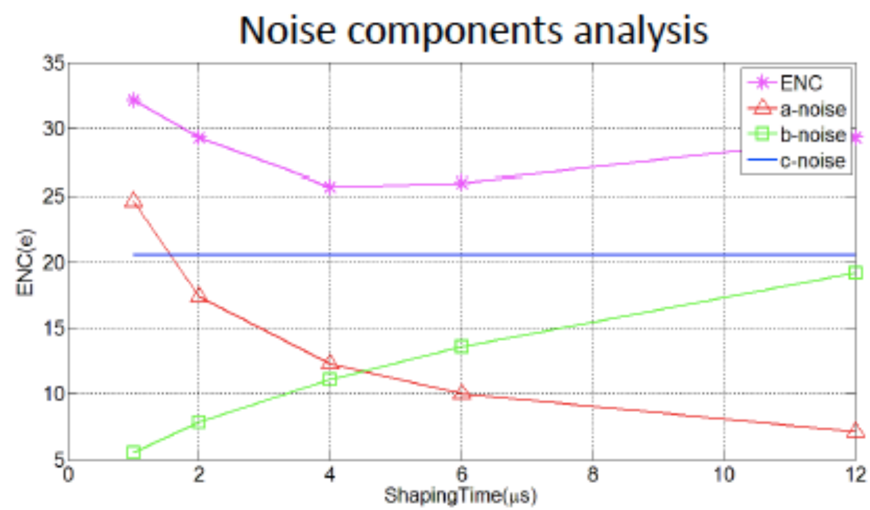
CMOS ASIC Front end electronics

- Light DM search →low noise/threshold (low capacity, etc)
- Very close to Ge detectors →low bkg(radiopure, low-mass, etc)
- ASIC preamplifier @ 77K
  - PCB material: PTFE(Rogers 4850);
  - ENC ~26e(<200eV) w/ 4μs shaping time, mainly from 1/f noise (~21e);

JINST (2018) 13: 8019

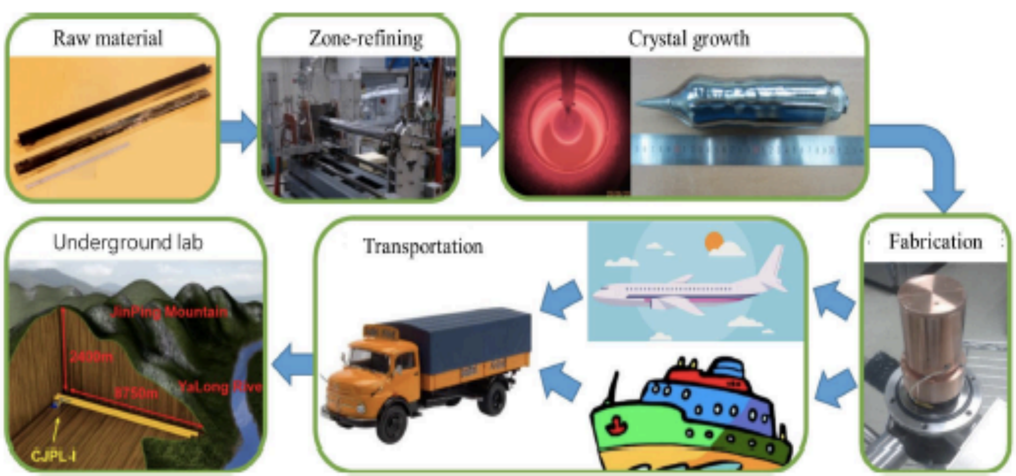






Planned developments

- New detectors cooperated with commercial companies
  - 3kg from BSI, 2kg from ORTEC, planning 5kg from CANBERRA/ORTEC;
  - Particular control of detector fabrication process above ground;
- Home-made detectors
  - Improve T1 w/ low bkg material and low noise electronics;
  - Set up underground fabrication and testing facility;



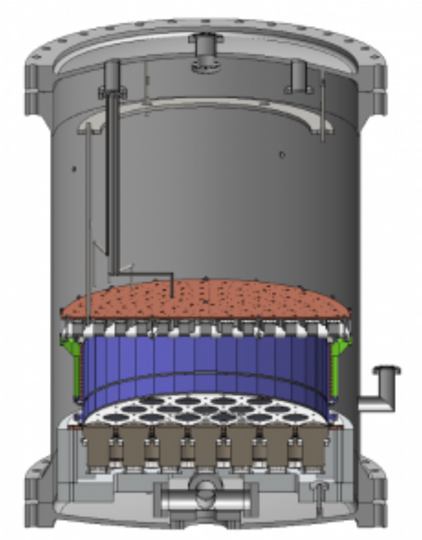
Detector production: 45days +
Ground transportation: 60 days +
Underground cooling: 180days →

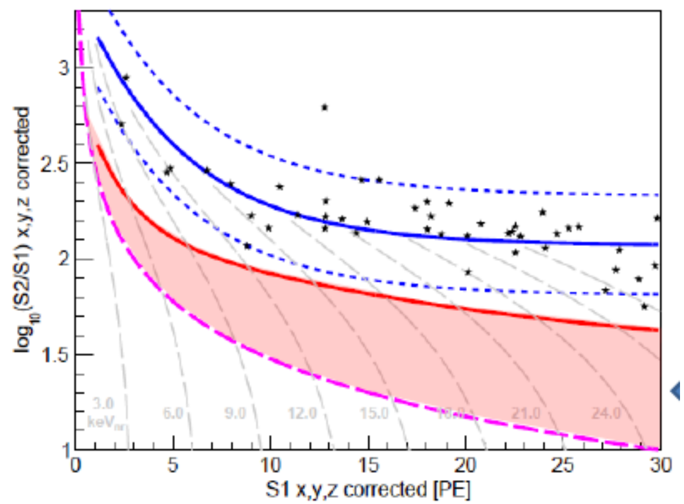
<u>Cosmogenic bkg: 0.03cpkkd(sim.)</u>.

Pandax: inauguration
end march 2014 –results 2016

Ton scale liquid Xenon two phase (liquid and gas) TPC

Project lead by SJTU



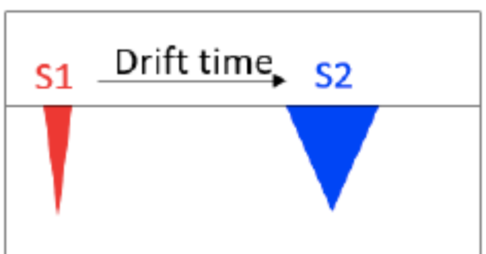


No events found in the DM search region!

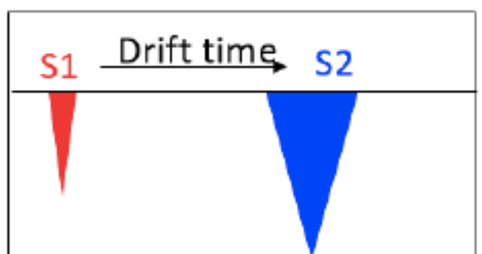
PandaX WIMP direct detection

- **PandaX-I**: 2009-2014
- **PandaX-II**: 2014-2018
  - 60 cm x 60 cm dual-phase xenon TPC
  - 580 kg LXe in sensitive volume
- Dual-phase xenon detectors:
  - Large monolithic target
  - 3D reconstruction and fiducialization
  - Good ER/NR rejection
  - Calorimeter capable of seeing a couple of photons/electrons

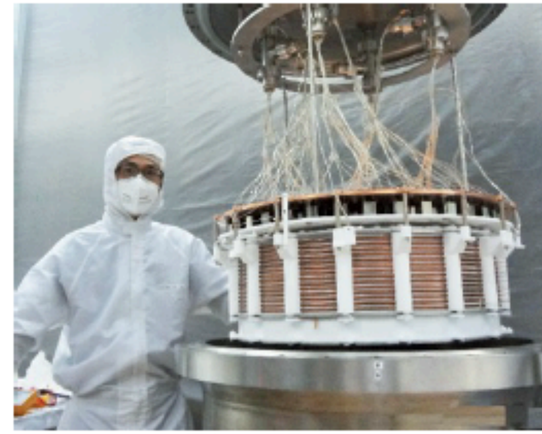
Dark matter: nuclear recoil (NR)



γ background: electron recoil (ER)



$$(S2/S1)_{NR} << (S2/S1)_{ER}$$

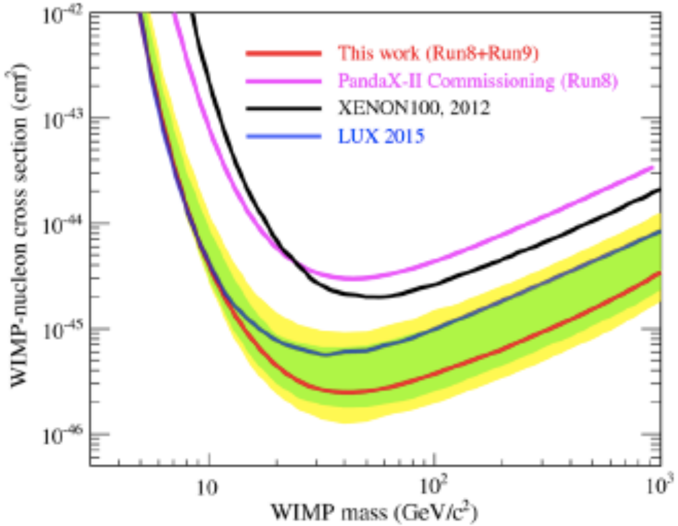


Phase I: 120 kg
2009-2014

Phase II: 580 kg
2014-2018

Highlights of PandaX-II Results

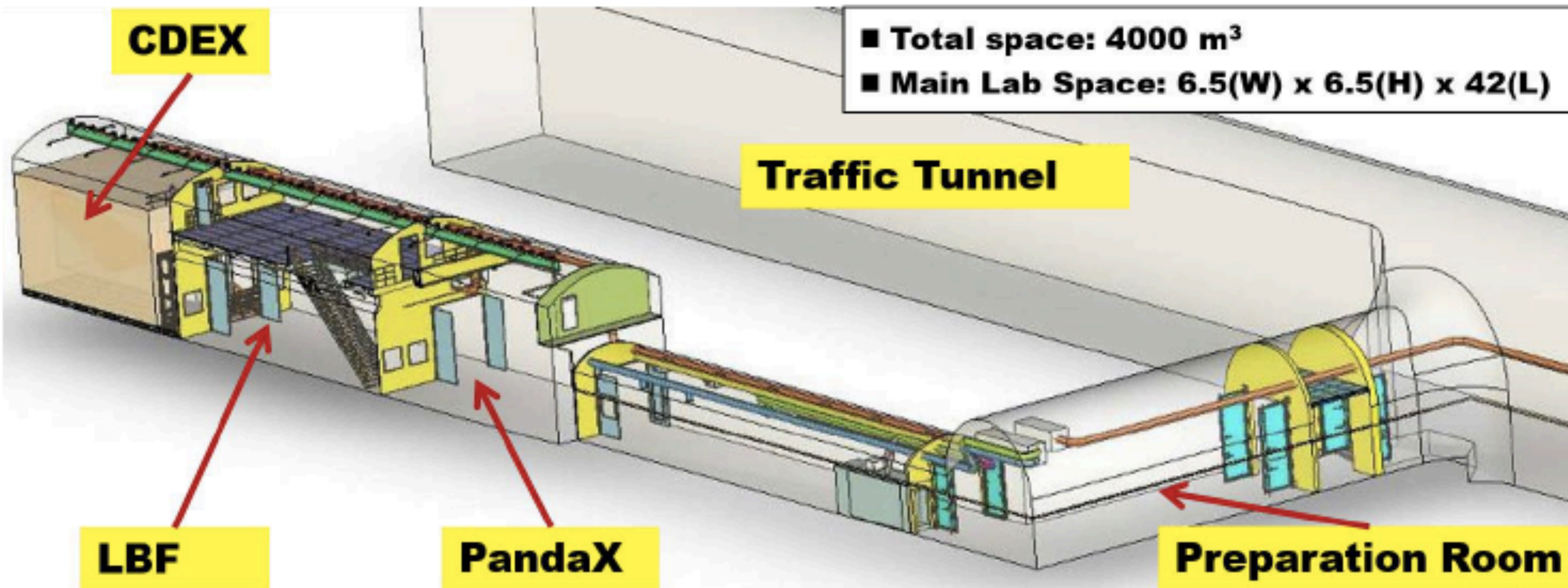
- 33 ton-day: spin independent search, **PRL 117, 121303 (2016)**



- 33 ton-day: spin dependent search, **PRL 118, 071301 (2017)**
- 27 ton-day: inelastic scattering search, **PRD 96, 102007 (2017)**
- 27 ton-day: Axion and ALP search, **PRL 119, 181806 (2017)**
- 54 ton-day: spin independent search, **PRL 119, 181302 (2017)**
- 54 ton-day: light mediator search, **PRL 121, 021304 (2018)**
- 54 ton-day: general EFT and spin-dependent search, **PLB 792, 193(2019)**

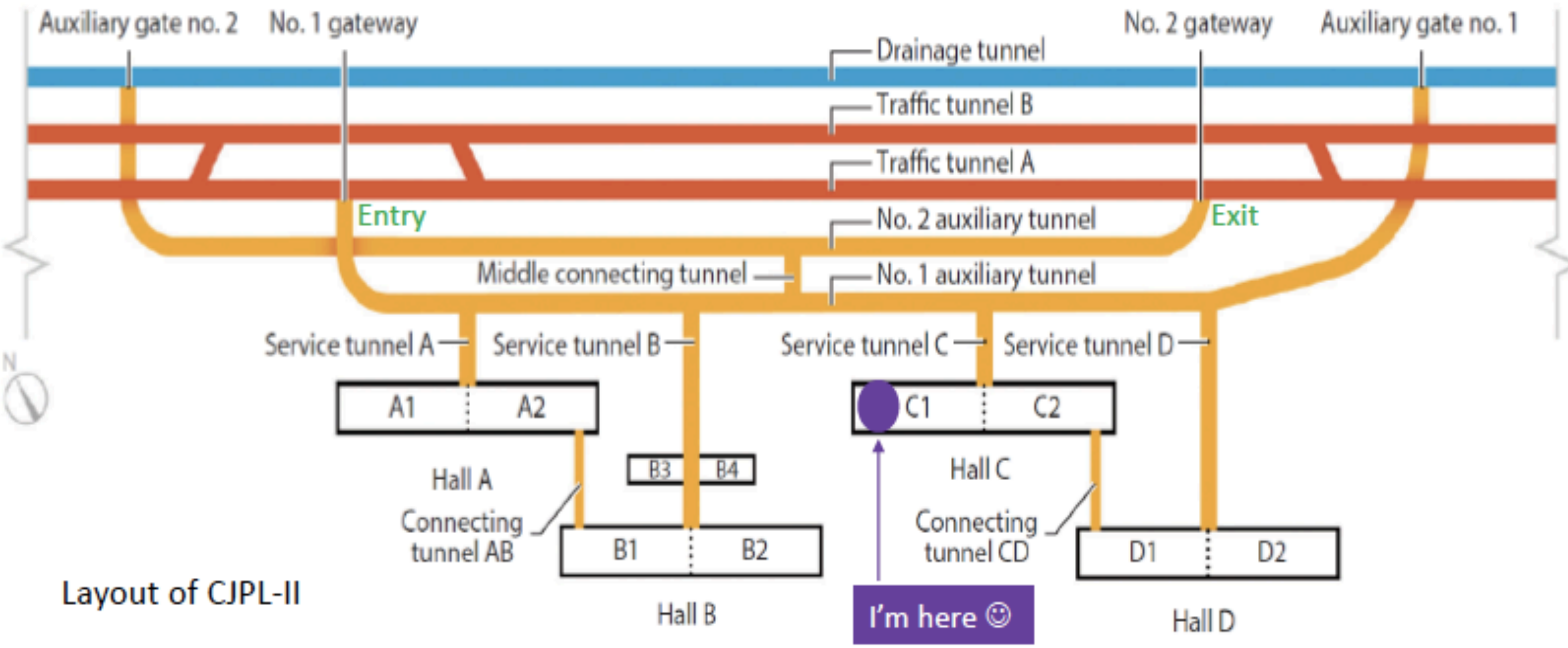
CJPL I

- CJPL-I
  - Volume: 4000 m³
  - 1 main hall (6.5x6.5x42m)



From CJPL-I to CJPL-II

- CJPL-I to CJPL-II
  - Volume: 4000 m^3 to 300,000 m^3;
  - 1 main hall (6.5x6.5x42m) to 8 main halls (14x14x60m each);
  - Additional pit for next-generation CDEX;



Layout of CJPL-II

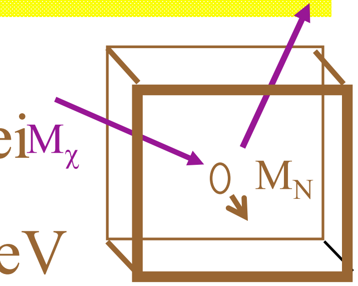
Why a Directional Dark Matter detector?

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

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

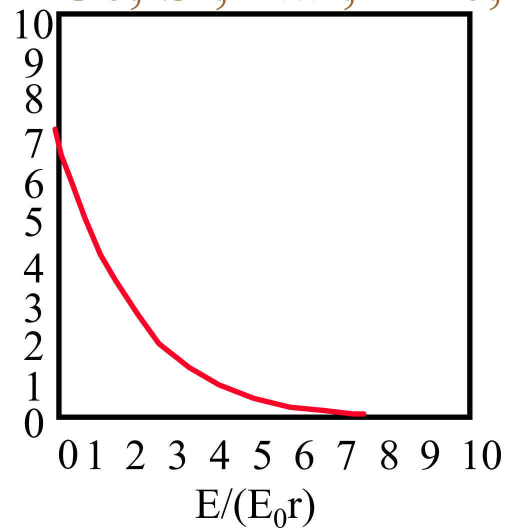
event rate per unit mass

total event rate (point like nucleus)

recoil energy

incident energy

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



- 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

*A*ll experiments

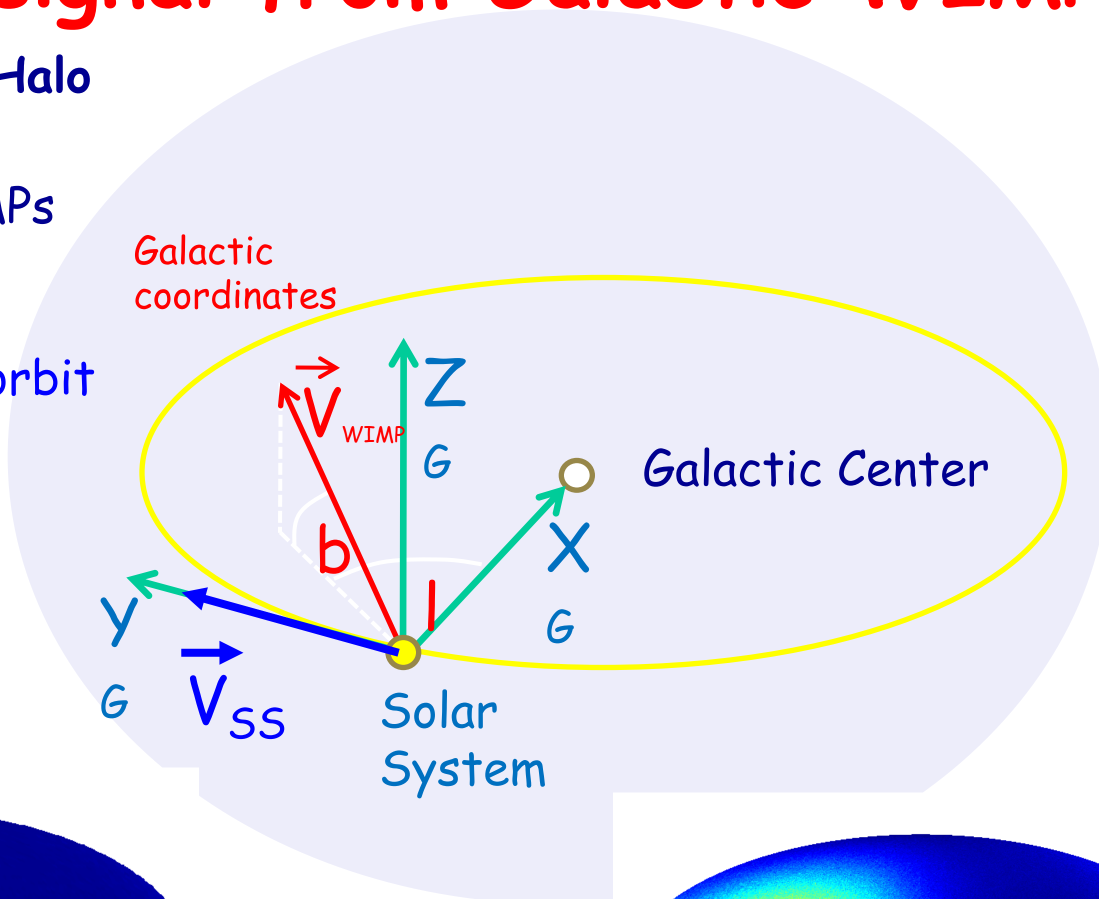
not in competition

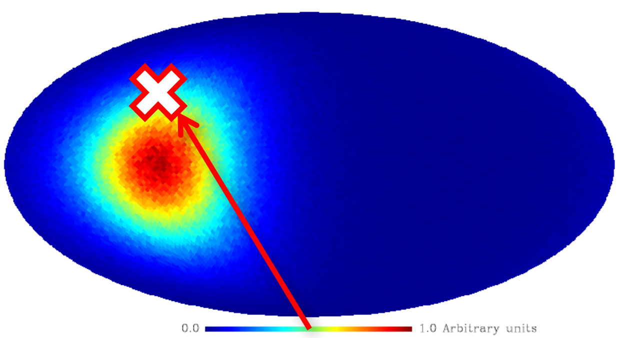
but **complementary!**

Expected signal from Galactic WIMPs

Dark matter Halo
=
gaz of WIMPs

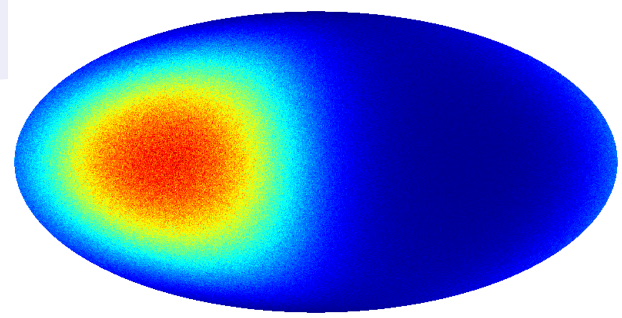
Solar System's orbit





Cygnus Constellation (l = 90°,b = 0°)

After collision



WIMP signal
ected

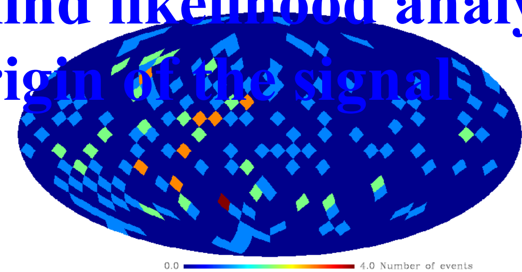
J. Billard *et al.*, PLB 2010
J. Billard *et al.*, arXiv:1110.6079

Phenomenology: Discovery

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

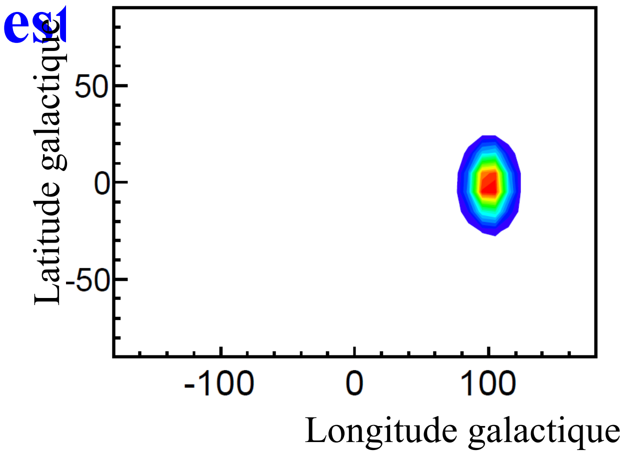
Proof of discovery: **Signal pointing toward the Cygnus constellation**

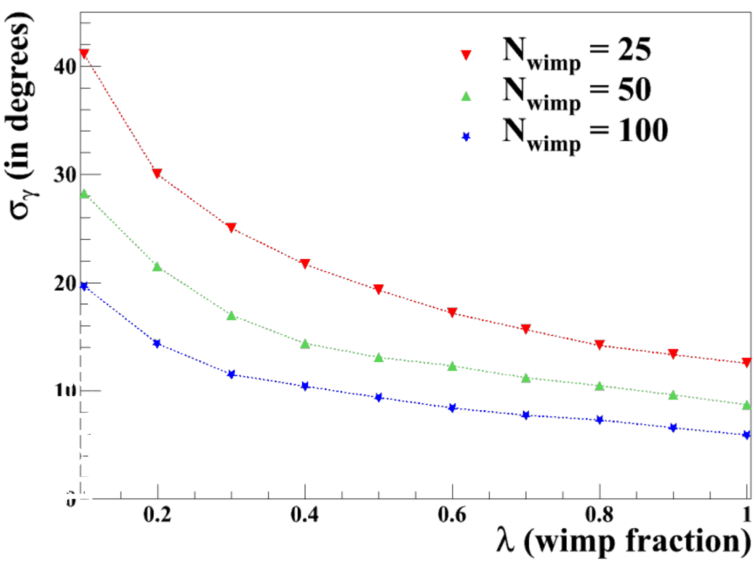
Blind likelihood analysis in order to est
origin of the signal



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

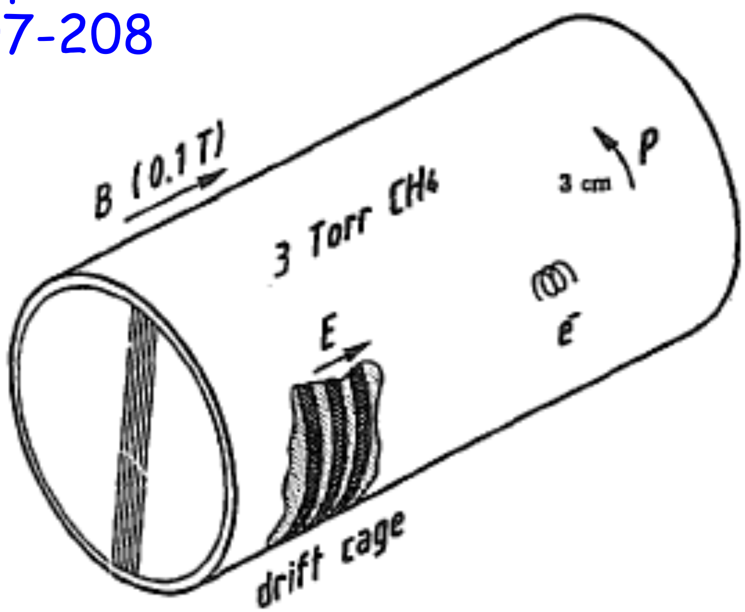
- Measurable track length
- Measurable directionality
- Head-tail separation
- Ion/electron separation
- Quenching factor
- Reconstruction of initial recoil angle
- ,…

The MIMAC project

An old idea:
Dark matter detection with hydrogen proportional counters

G. Gerbier, J. Rich, M. Spiro, C. Tao

Nuclear Physics B - Proceedings Supplements
Volume 13, February **1990**, Pages 207-208



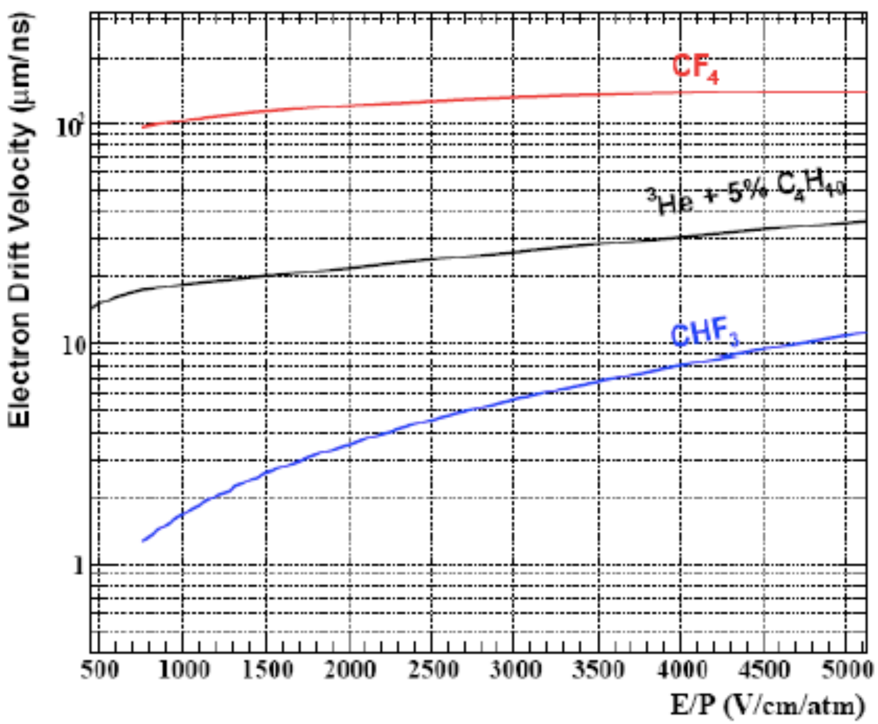
Problems: - technical : low pressure, short track length expected
- Is DM Cold? N-body simulations issues

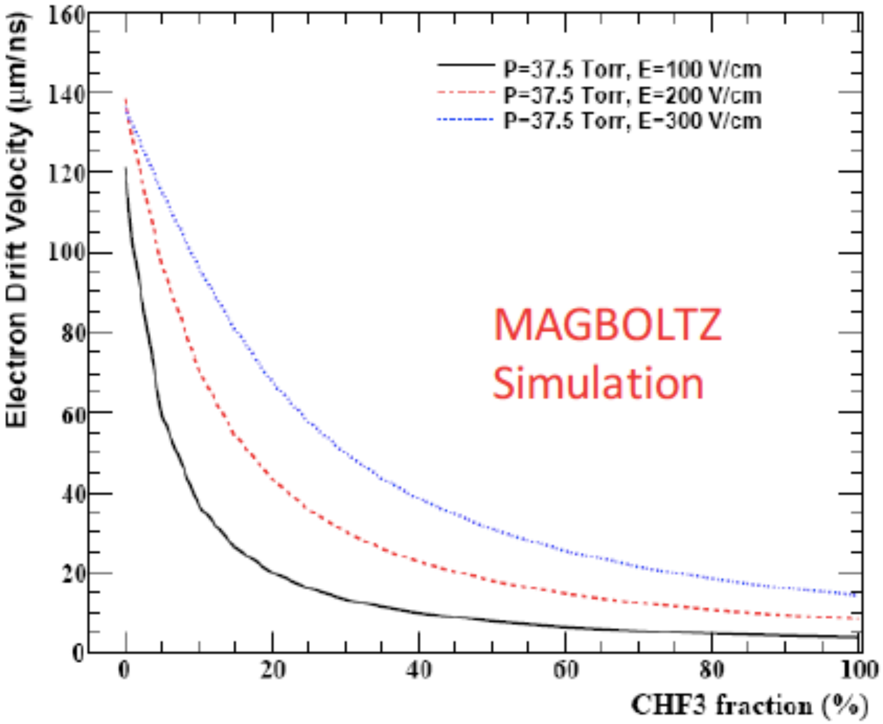
➔ **Astrophysics**

Special gaz mixture

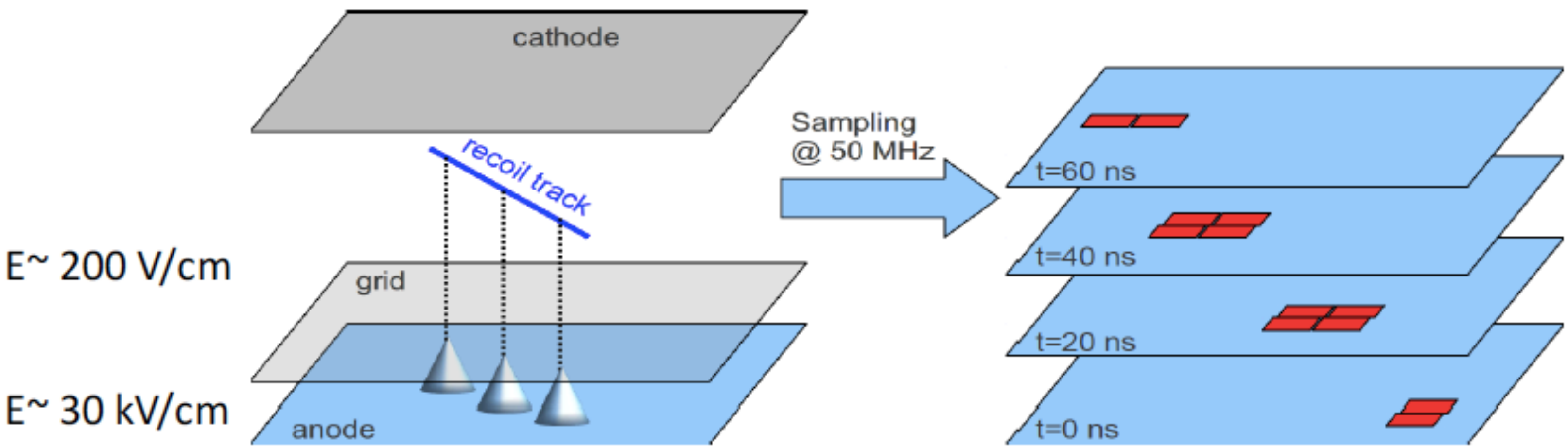
· 70% CF_4 + 28% CHF_3 + 2% iC_4H_{10}

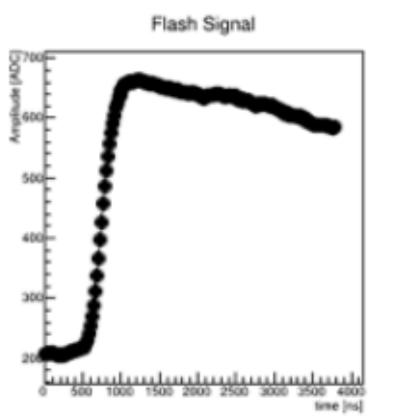
- Reduces electron drift velocity
- Operating at low pressure

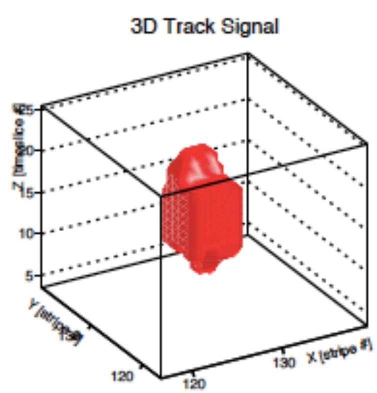


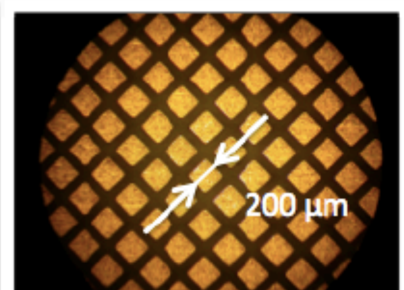


MIMAC strategy



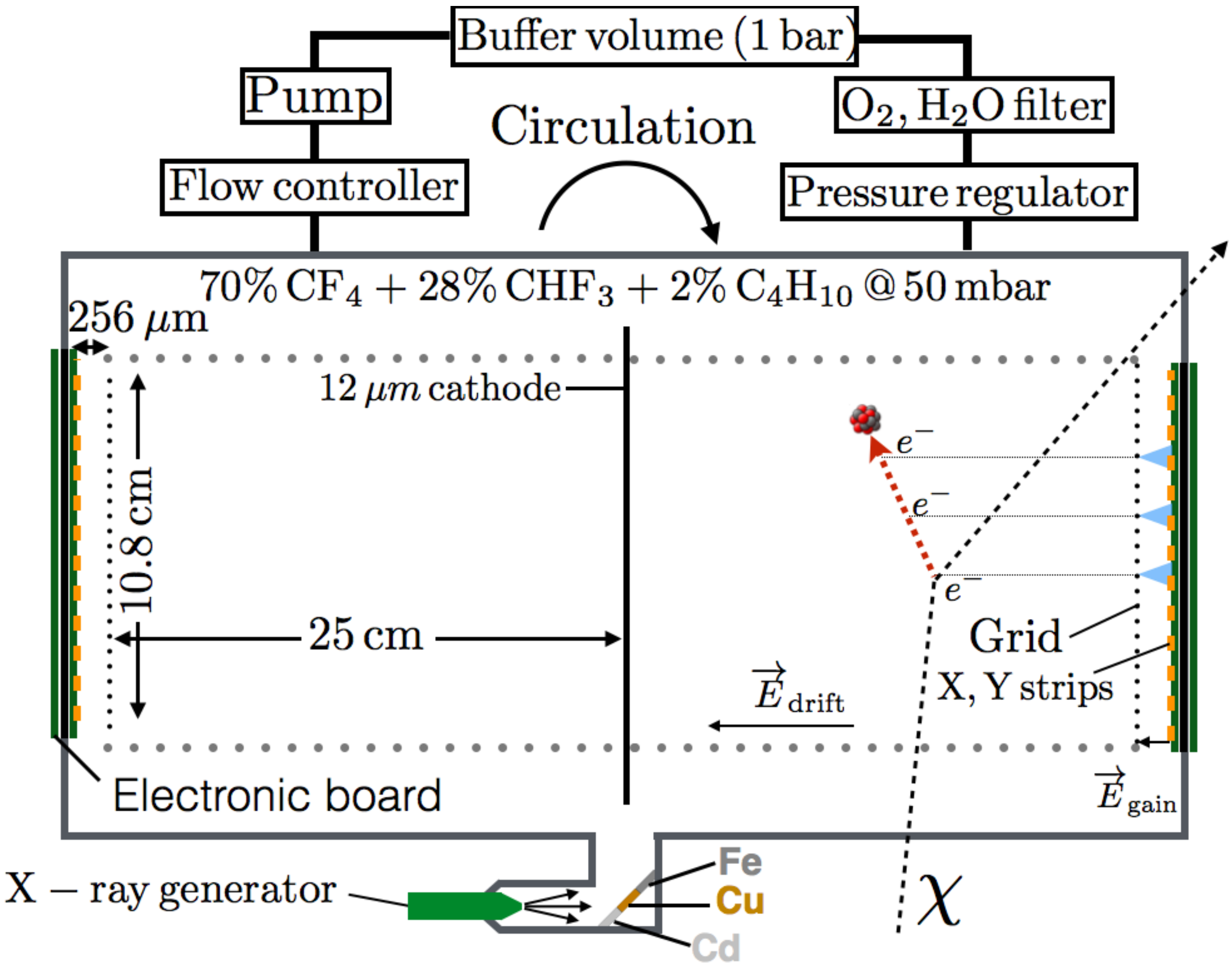


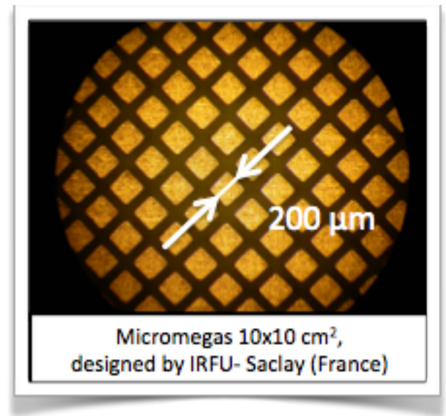




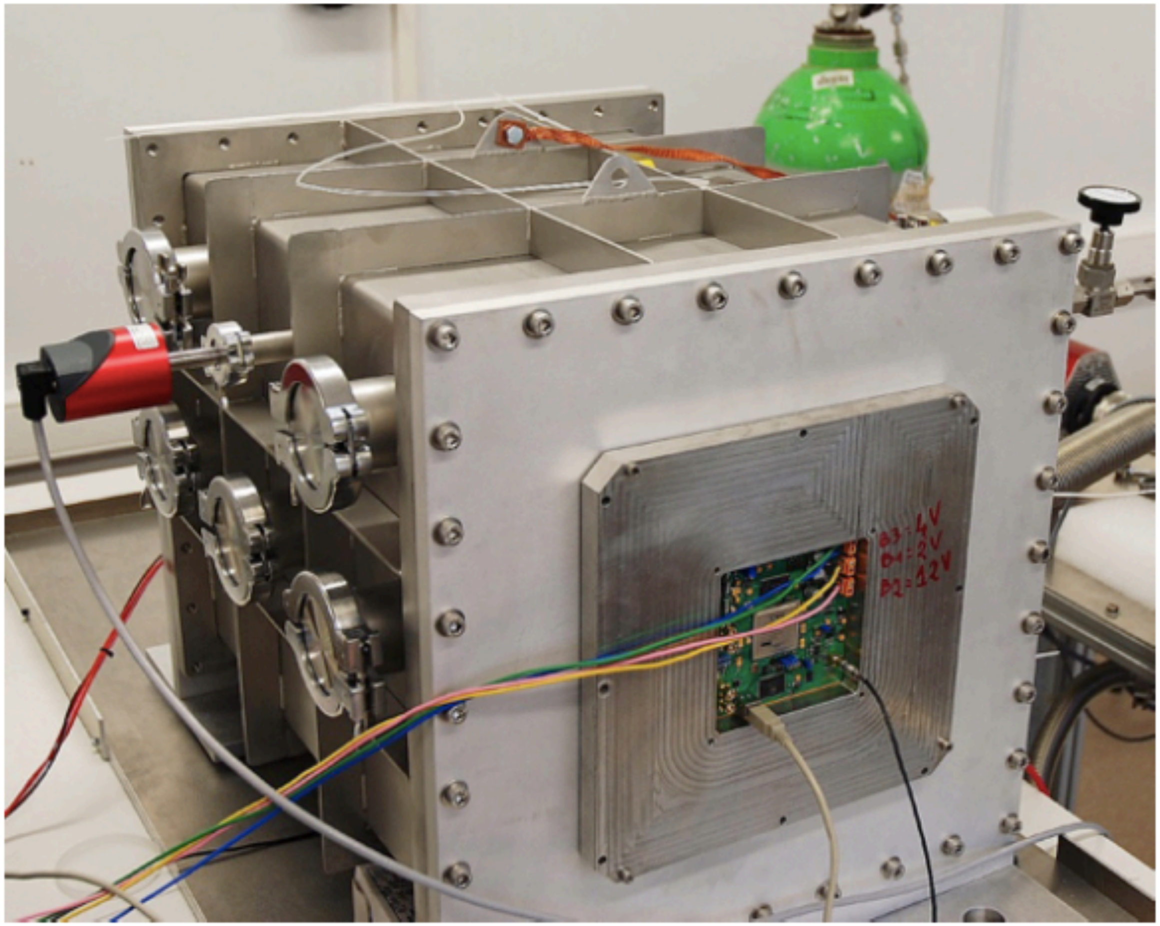
Micromegas 10x10 cm^2,
designed by IRFU- Saclay (France)

MIMAC-bi-chamber module prototype





MIMAC Bi-chamber



- Energy
- 3D track

2 x (10.8 x 10.8 x 25 cm^3)

9 keV ion track in Mimac prototype

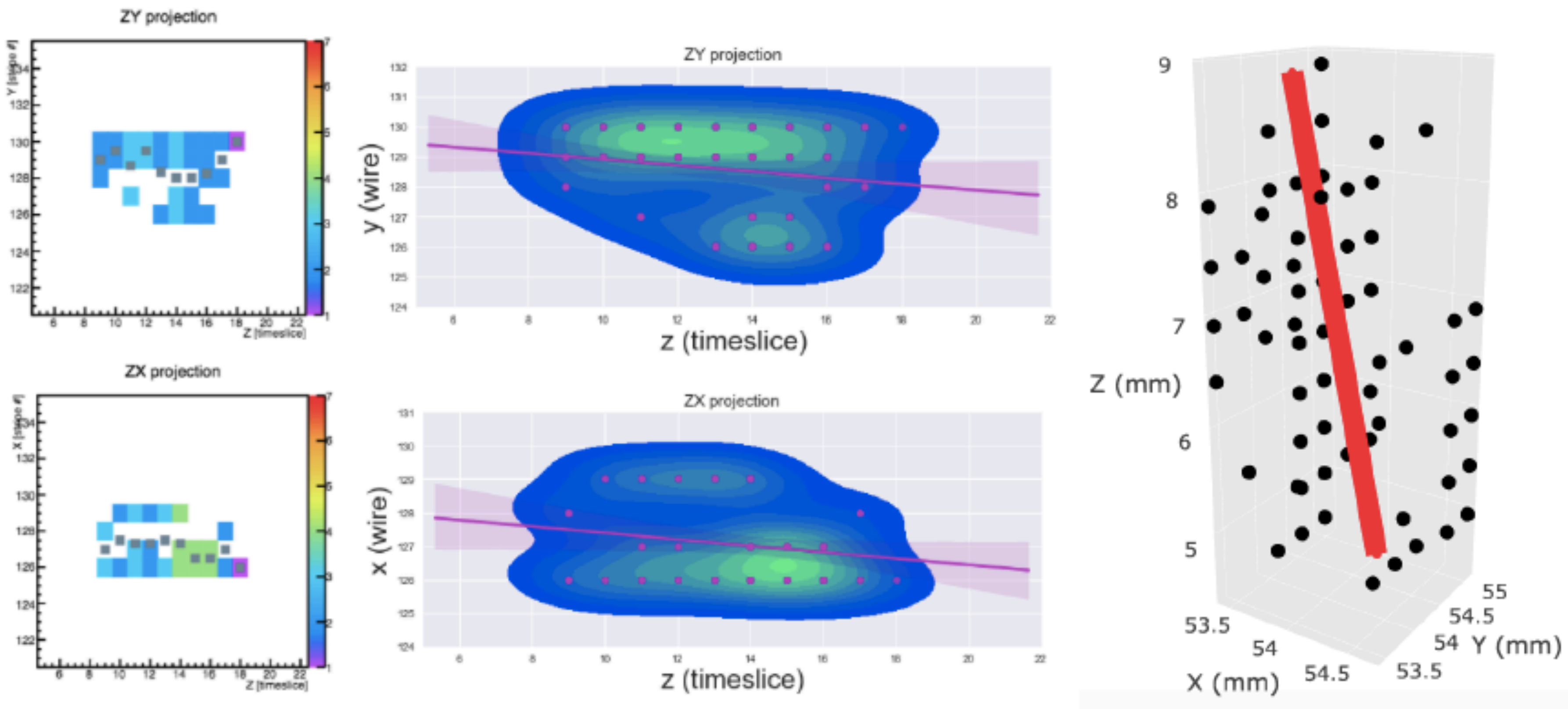
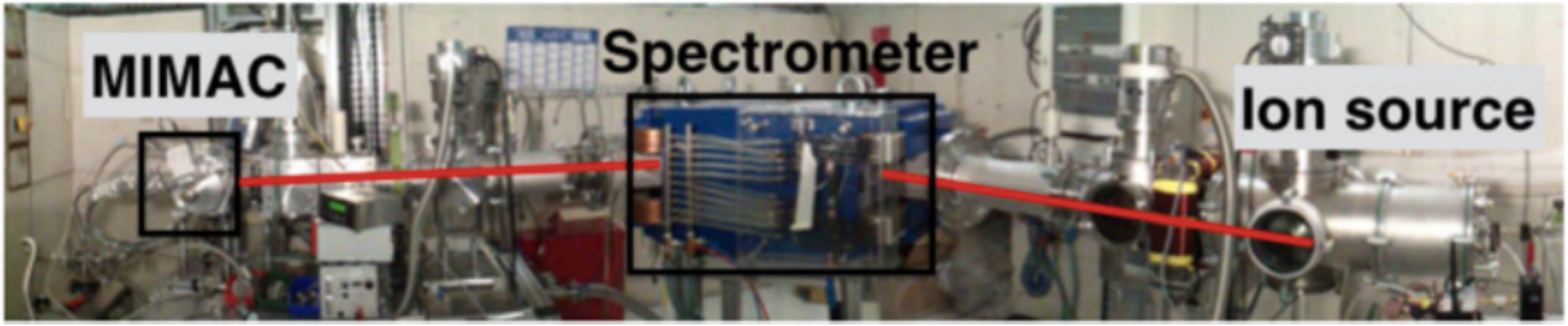


FIG. 4. Example of an ion track in ZX and ZY projection using barycenter representation (left), triggered wires and 2D fit (middle) and 3D (right) for an ion of kinetic energy of 9.32 keV.

Specially developed keV ion beams

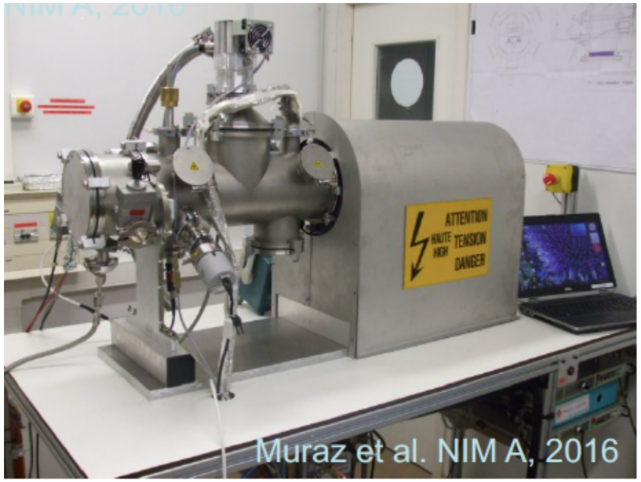
LHI facility in Grenoble



COMIMAC – a portable ion source

Quenching factor measurement facility

Our targets: ^{19}F, H, He,...

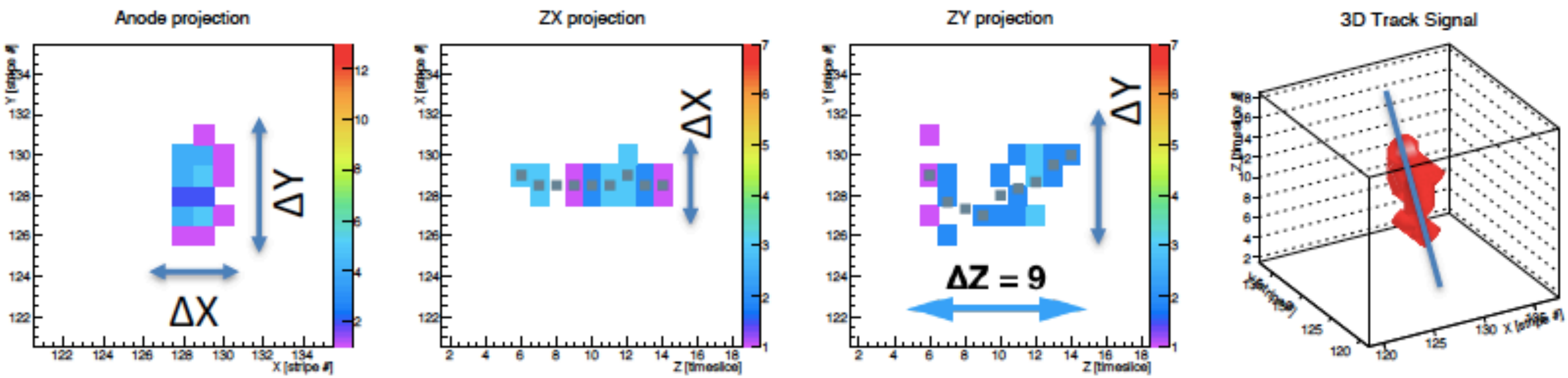


Directional experiments around the world

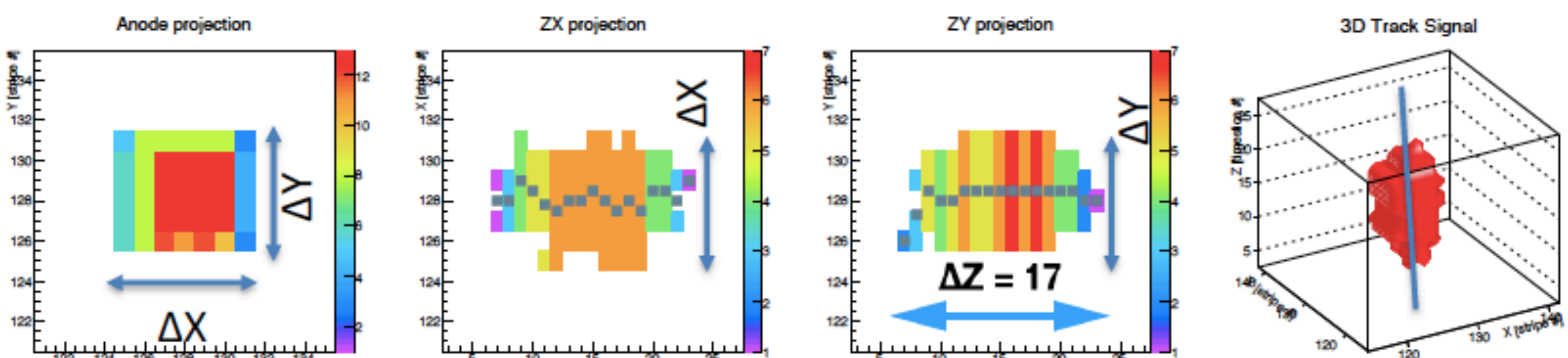
Running in an Underground Laboratory

MIMAC: the only experiment that has shown 3D reconstructed tracks

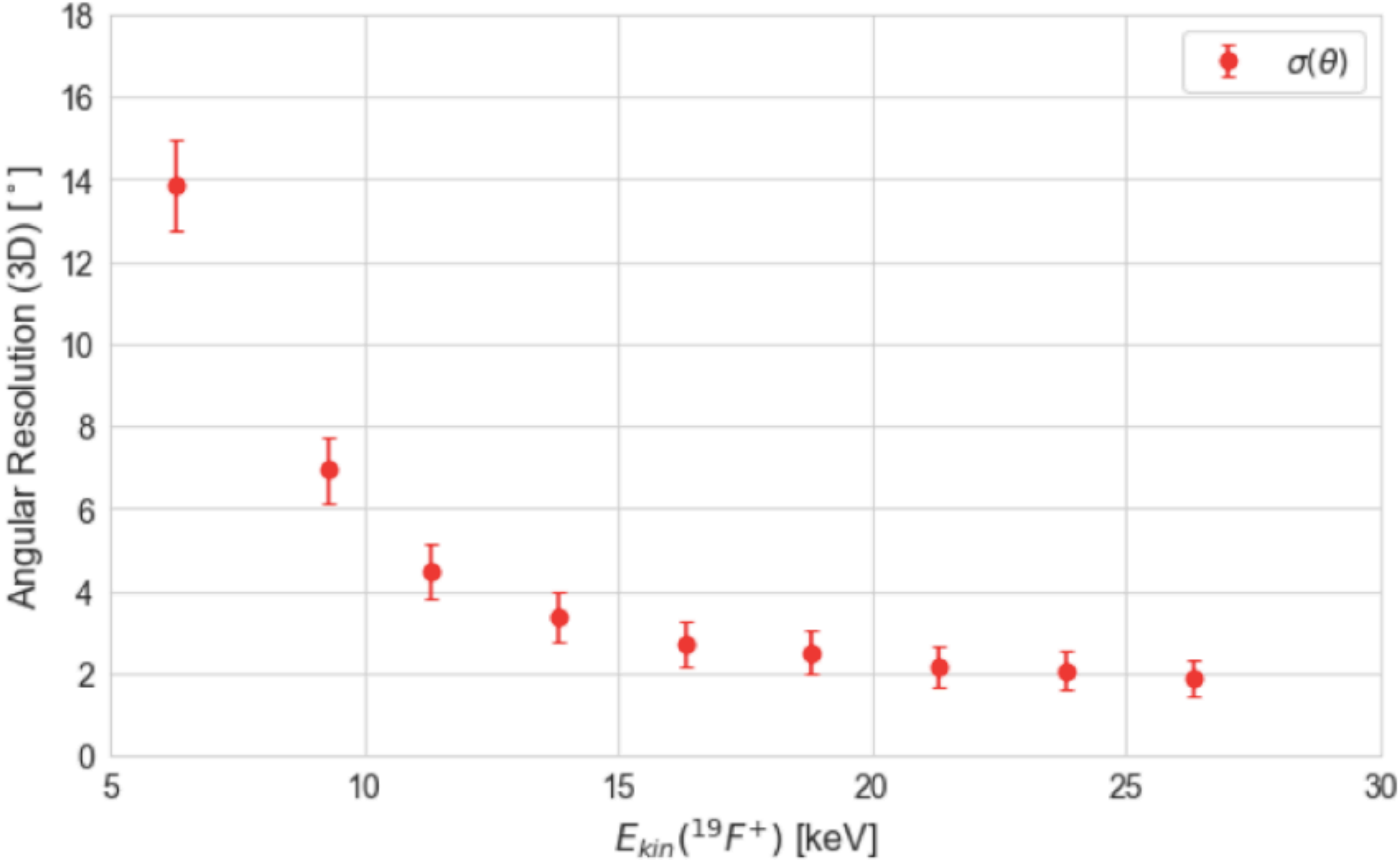
Fluorine 6.3 keV (~2 keVee)



Fluorine 26.3 keV (~9 keVee)



Angular resolution:
better than required 20deg !



Y. Tao *et al.*, arXiv: 1903.0215

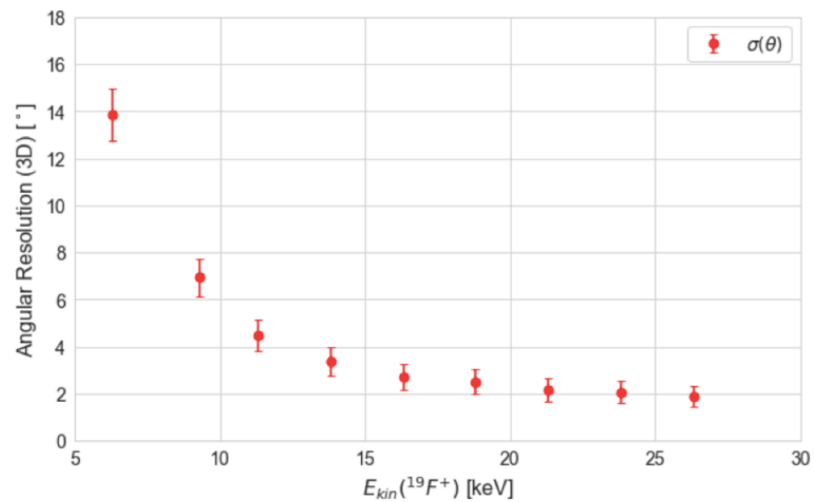
Summary for MIMAC R&D

i) A new directional detector of nuclear recoils at low energies has been developed giving a lot of flexibility on targets, pressure, energy range…

ii) Ionization quenching factor measurements have been determined experimentally and they can be checked in-situ.

iii) MIMAC bi-chamber module has been installed at Modane Underground Laboratory in June 2012. An upgraded versions in June 2013 and June 2014 and it shows an excellent gain stability. For the first time the 3D nuclear recoil tracks from Rn progeny have been observed.

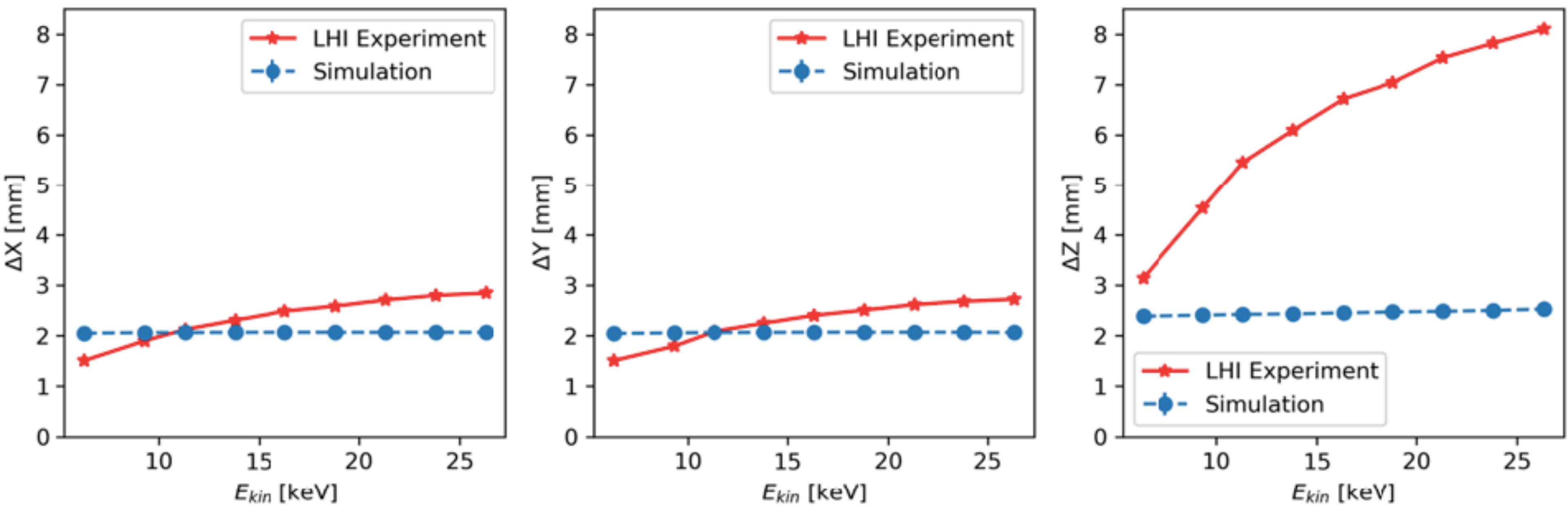
iv) Angular resolution and directional studies of 3D tracks are now possible with COMIMAC and the angular resolution aim of less than 10 deg has been shown down to 8 keV



Y. Tao *et al.*, arXiv: 1903.02159

Comparison data- simulation

Width X Width Y Depth Z



Large discrepancy !!

Molecular effect ?

Need to be understood!

MIMAC 1m^3 in preparation

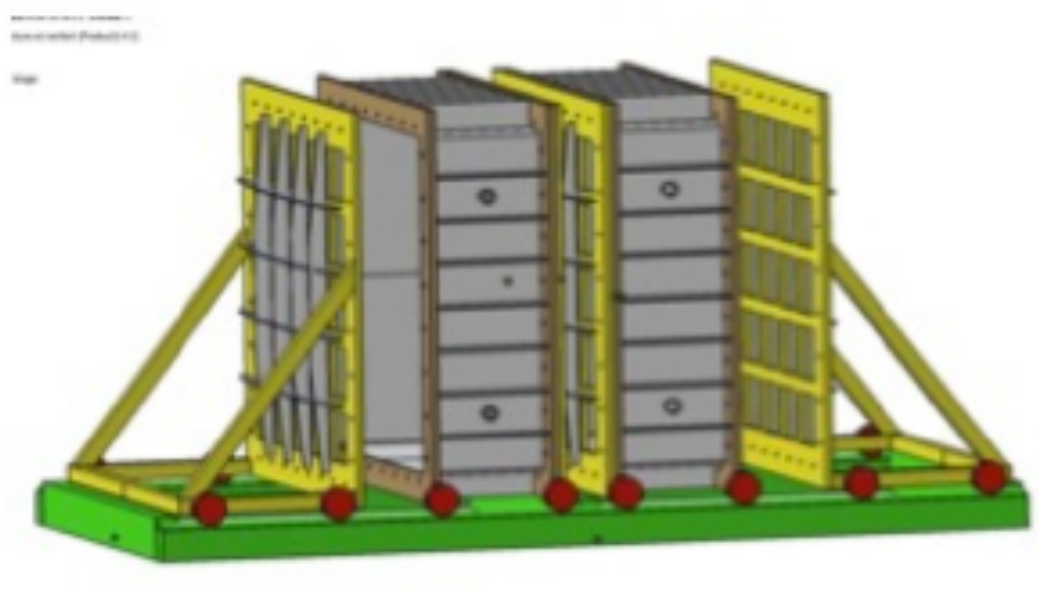


Figure 5. The preliminary mechanical design of the demonstrator of MIMAC -1 m^3 .

Fully funded

(< 1 Meuros including manpower)

Installation in 2020-2021 in LSM

Towards an international DMDD ?

Initiative led by Neil Spooner with Japanese, Italian, Australian, US, Chinese, French, +…

MIMAC -based technology? only detector which has shown < 10 keV tracks

- Low radioactivity issues
- Which underground lab(s) ? One or many?

Alternatives to Gaseous detectors

eg DAMIC DM detection with CCD

- Low energy threshold of a few tens of eV
- High spatial resolution

Figure 5: Candidate β decay sequence found in data. The first cluster had 114.5 keV of energy. A second cluster, with energy 328.0 keV, was observed in an image taken 35 days later. Both tracks appear to originate from the same point (yellow star) in the CCD x-y plane.

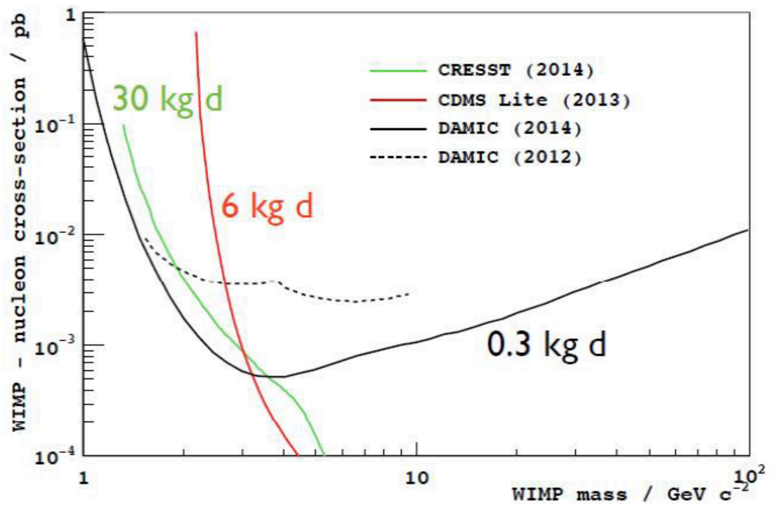


Figure 6: Cross section exclusion limit at 90% CL for the DAMIC 2014 results (solid black) compared to DAMIC 2012 (dashed black) [9], CRESST 2014 (solid green) [18] , CDMSlite 2013 (solid red) [17].

SRIM simulations

Couturier et al.   1607.08157

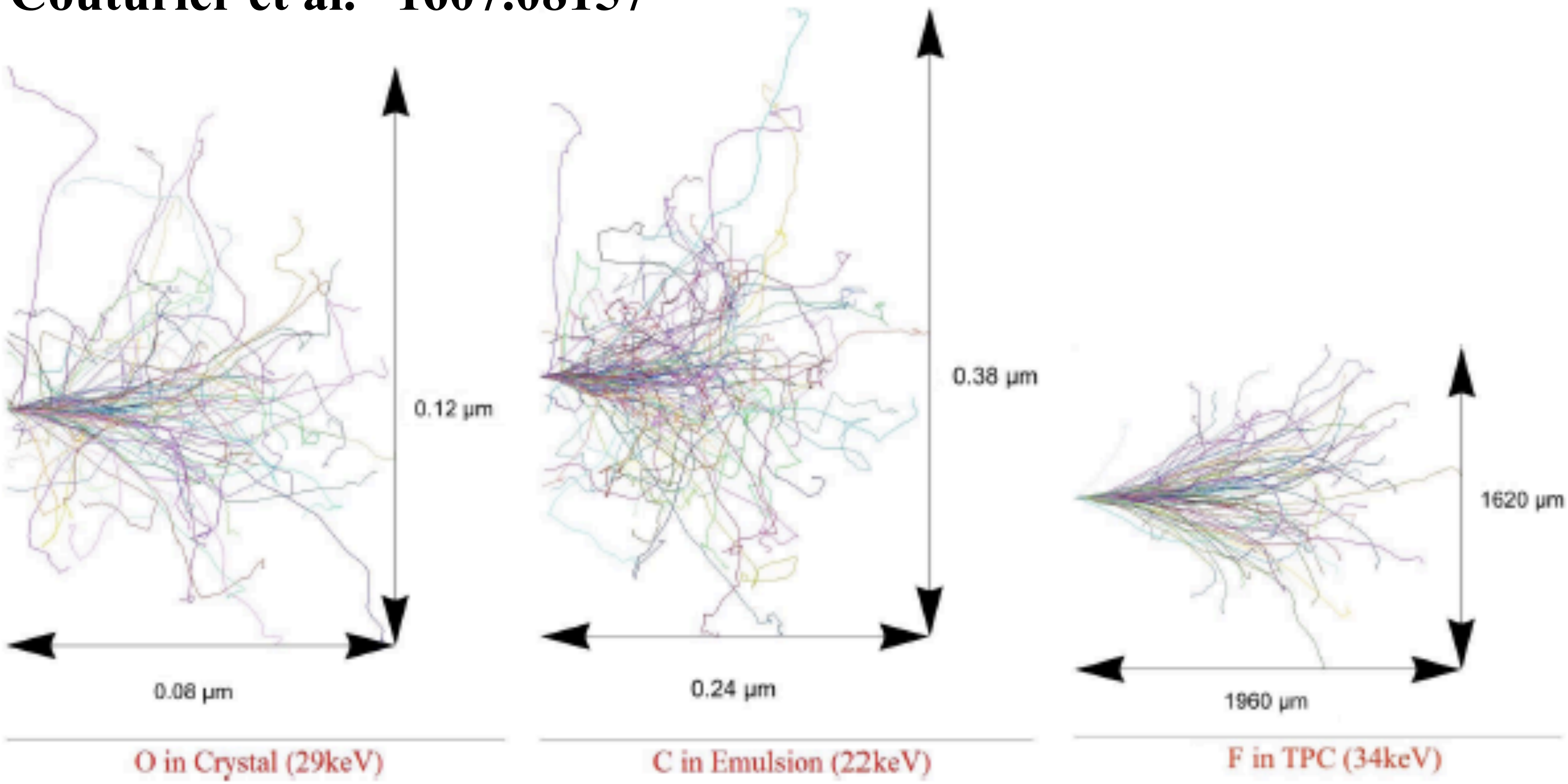


Figure 1. Development of the tracks of recoils with the maximum kinetic energy induced by a 1000 GeV/c^2 WIMP. From left to right: ^{16}O of 29 keV in $ZnWO_4$, ^{12}C of 22 keV in Emulsion, ^{19}F of 34 keV in the TPC gas mix. (SRIM simulations)

For solids, need submicron resolutions!

WIMP DM searches

- **No convincing signal todate !**
- Exclusion/discovery plots are interpretation dependent!
- Once a signal is found (ie > 5σ statistics)

  but also confirmed by different signatures !

- Direct Detection: floor from solar neutrino scattering
- Indirect Detection: many signals –

  Cannot exclude easily conventional astrophysics solutions

- Beware of assumptions for absolute exclusions!!!

Axion DM

- Some types can be found in existing WIMP detectors
- More connexion to advanced technology?

Axion DM and advanced technology

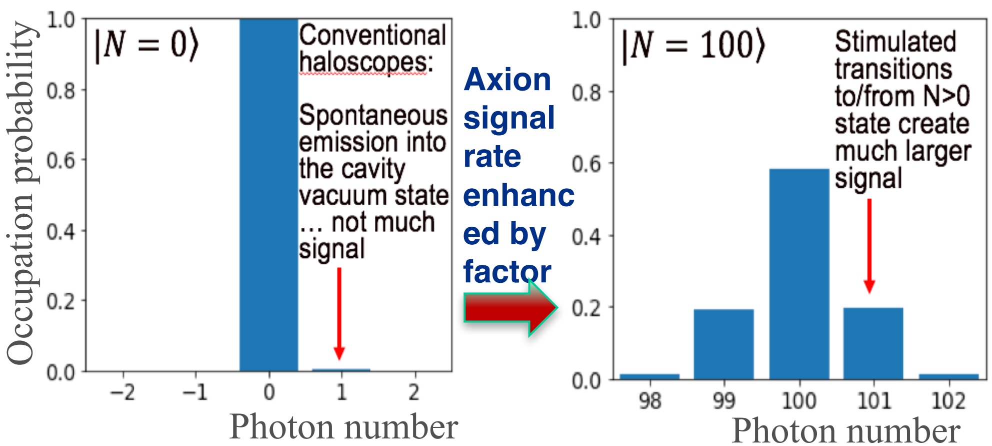
NIST JILA, U. Chicago, and Fermilab

Use Fock states to stimulate emission from DM axions into cavity photons

Use qubits to load individual quanta into detection RF cavity

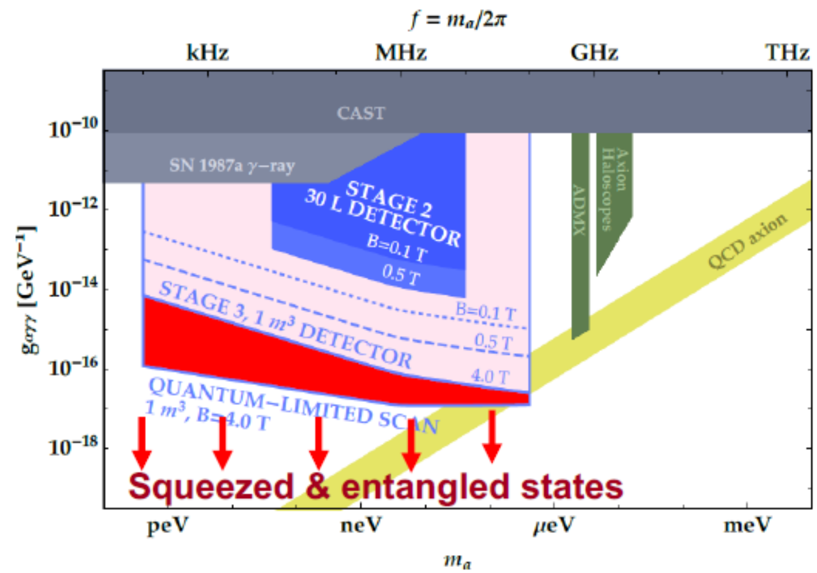
Resulting large N Fock state is a quantum superposition of all possible oscillation phases

Enhanced response to all possible signal phases



Konrad Lehnert (NIST JILA), David Schuster (U. Chicago), Aaron Chou (FNAL)

Collaboration between SLAC, KIPAC, and Heising-Simons quantum sensors to dramatically enhance sensitivity to axions



Zeesh Ahmed (SLAC)

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

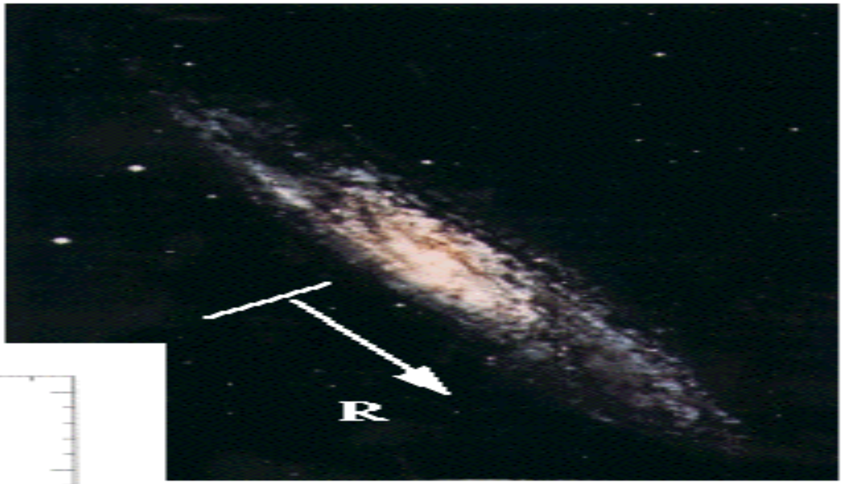
Famaey & Mc Gaugh

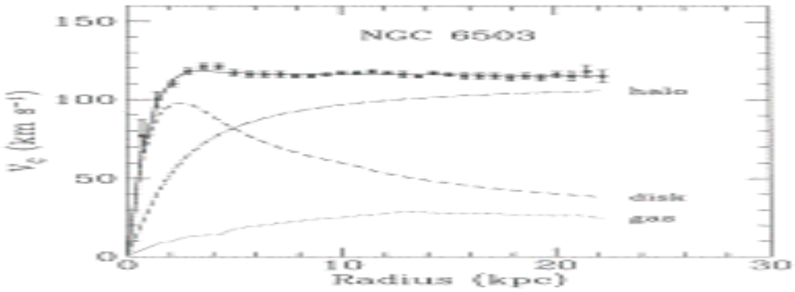
- **MOND-** Milgrom /TEVES-Beckenstein needs neutrinos to explain Bullet Cluster…
- **MOG** : Moffat and collaborators

  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,

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

$a_0 \sim 1.2\ A/s^2$

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

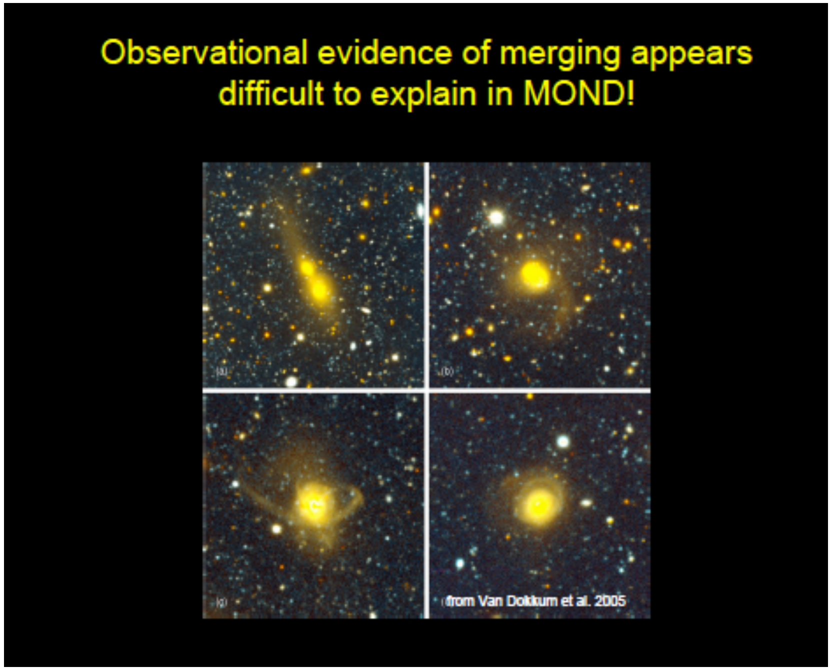
N-body simulations with no DM?

- 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 ?

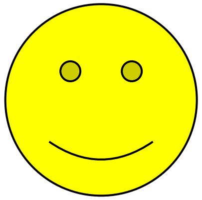
- **More work on baryonic N-body simulations needed!**

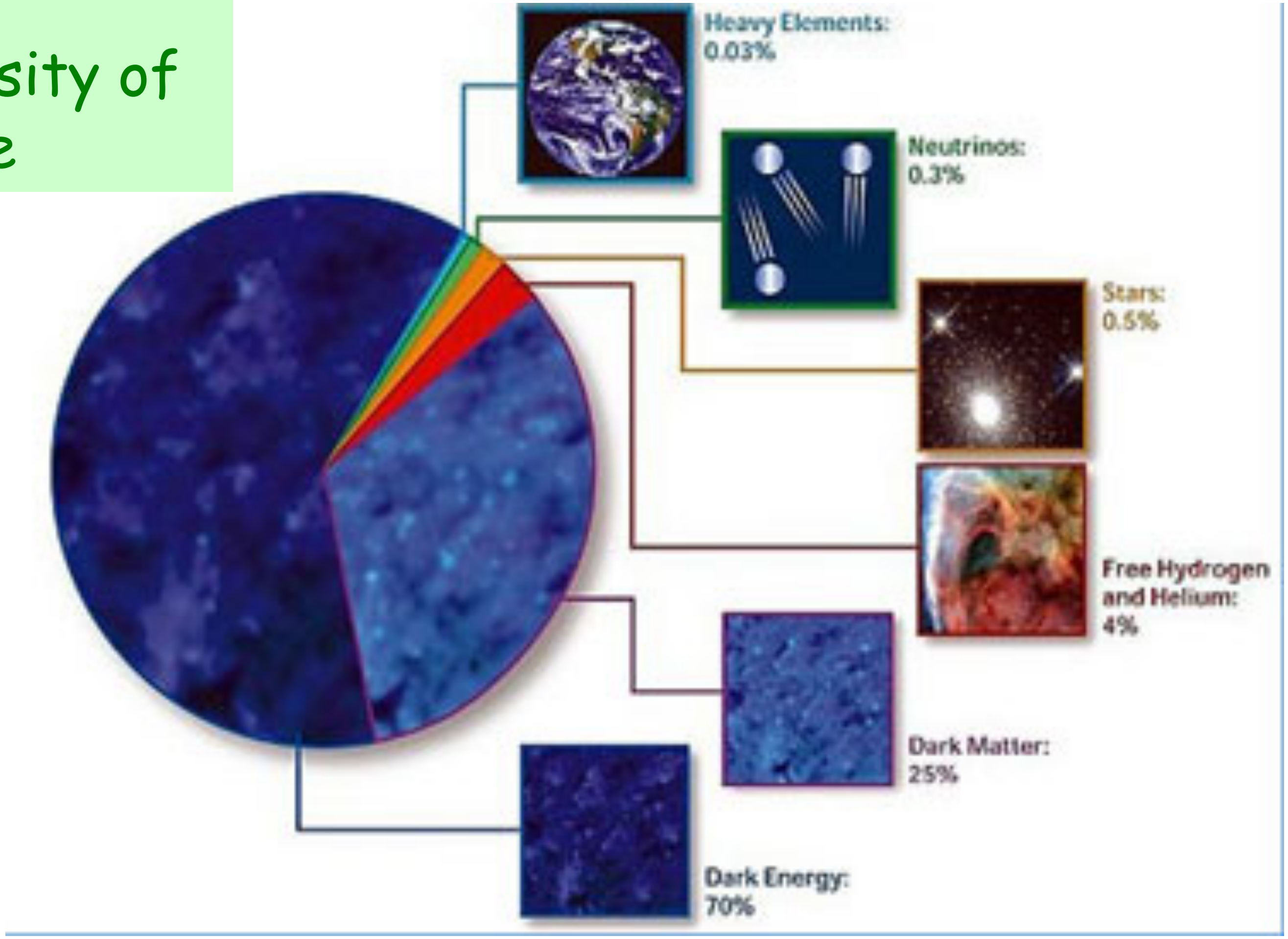
Need to find **DM**
in
accelerators and DD/ID experiments!

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