The Dark Universe:
What do we really know?

Brussels, Jan.9, 2015

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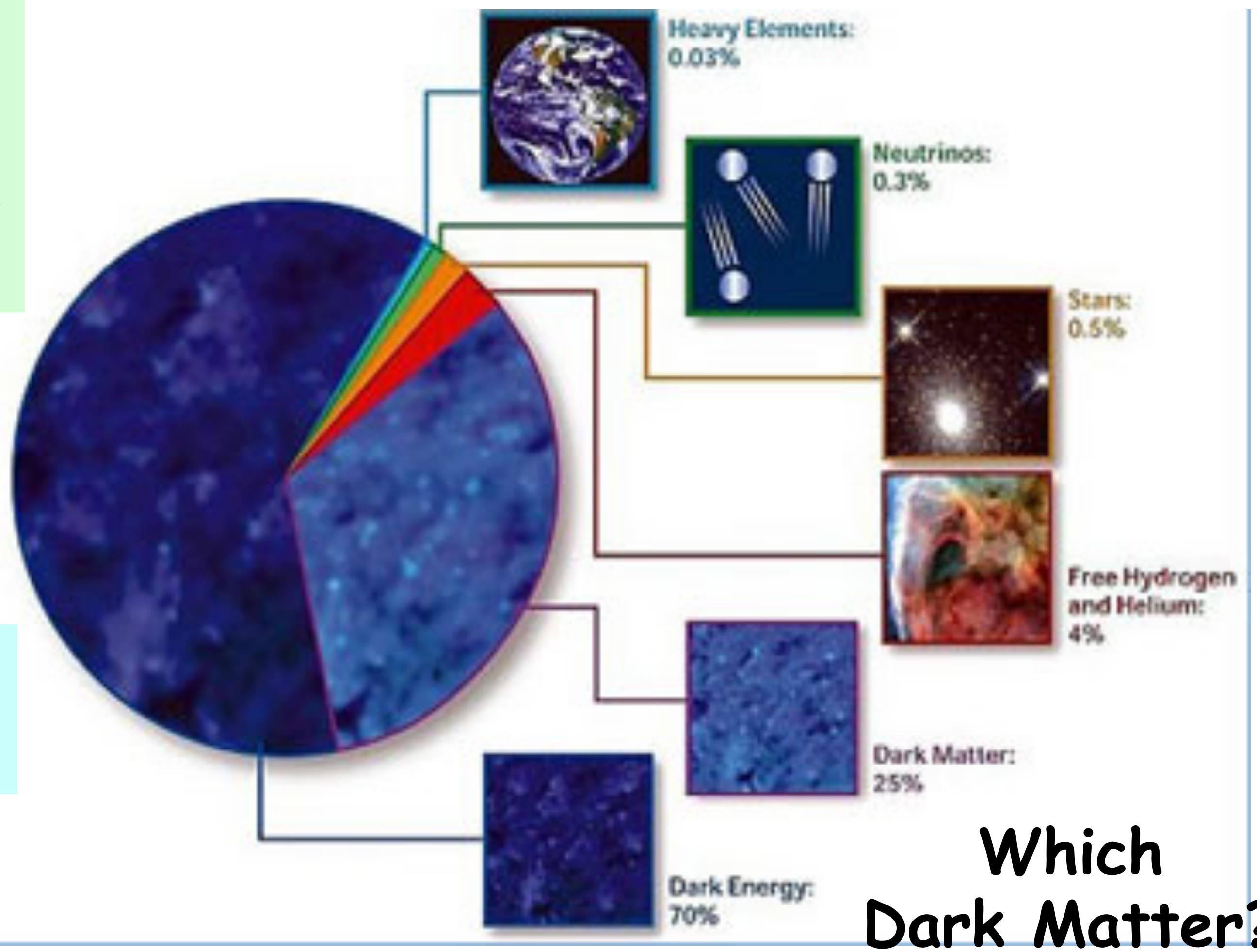
- Director of research CNRS-CPPM, Marseille, France
- Director Tsinghua Center for Astrophysics, Beijing, China

- From experimental particle physics to cosmology and astronomy

- Always a "cleaning lady" : cleaning dust in gaseous particle detectors to galactic dust in supernovae/quasar/CMB spectra

A mysterious Universe

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



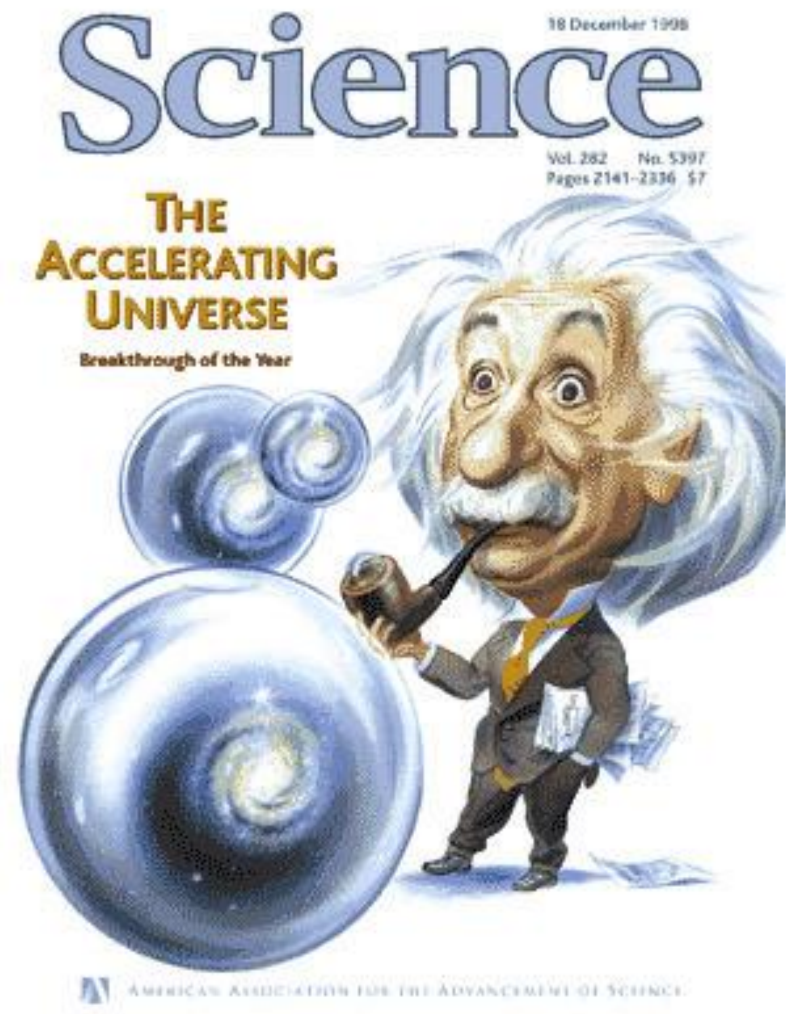
What is Dark Energy?

Which Dark Matter?

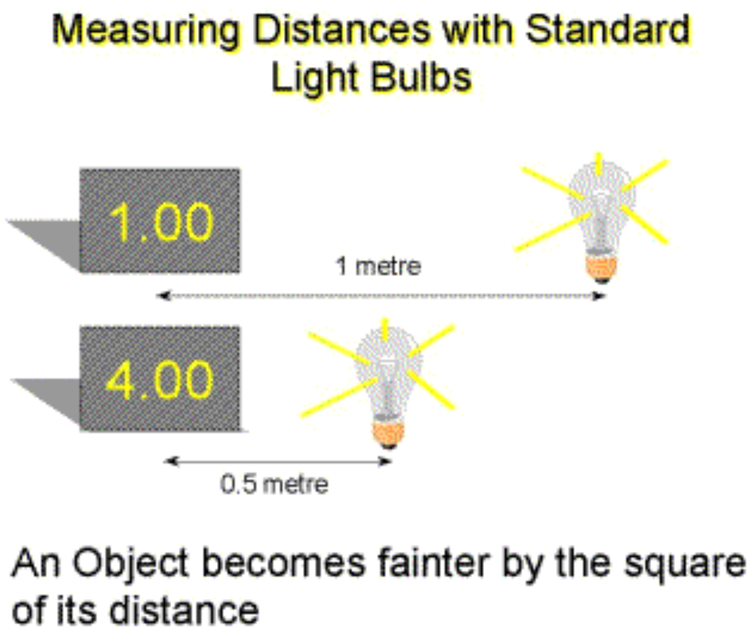
Graph source: Wikipedia

Surprise 1998:
An accelerating Universe!

2 Collaborations with SNIa
SCP +HST



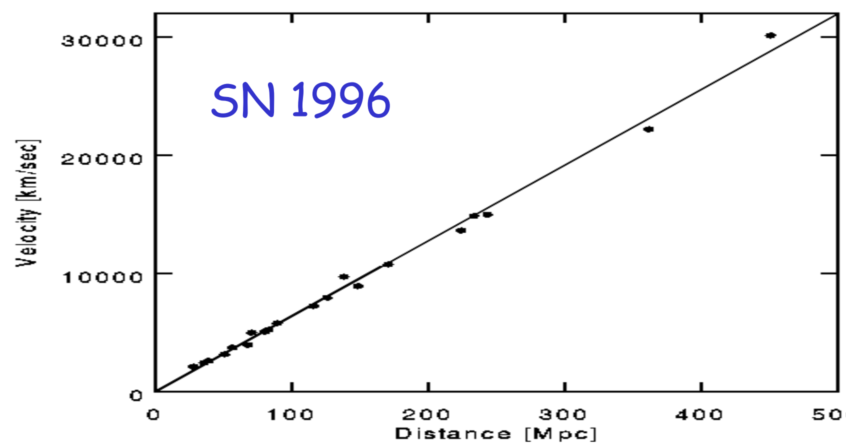
Cosmology: Measuring distances with standard candles



Cosmology: additional a(t) scale factor

$$D(t) = a(t)\ D(t_0)$$

$$a(t) = a_0(1 + H_0 t - 1/2\ q_0\ (H_0 t)^2 + \ \ldots)$$



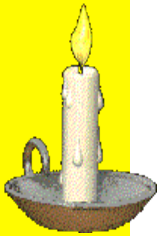
H_0 = Hubble parameter measures the expansion rate of the Universe

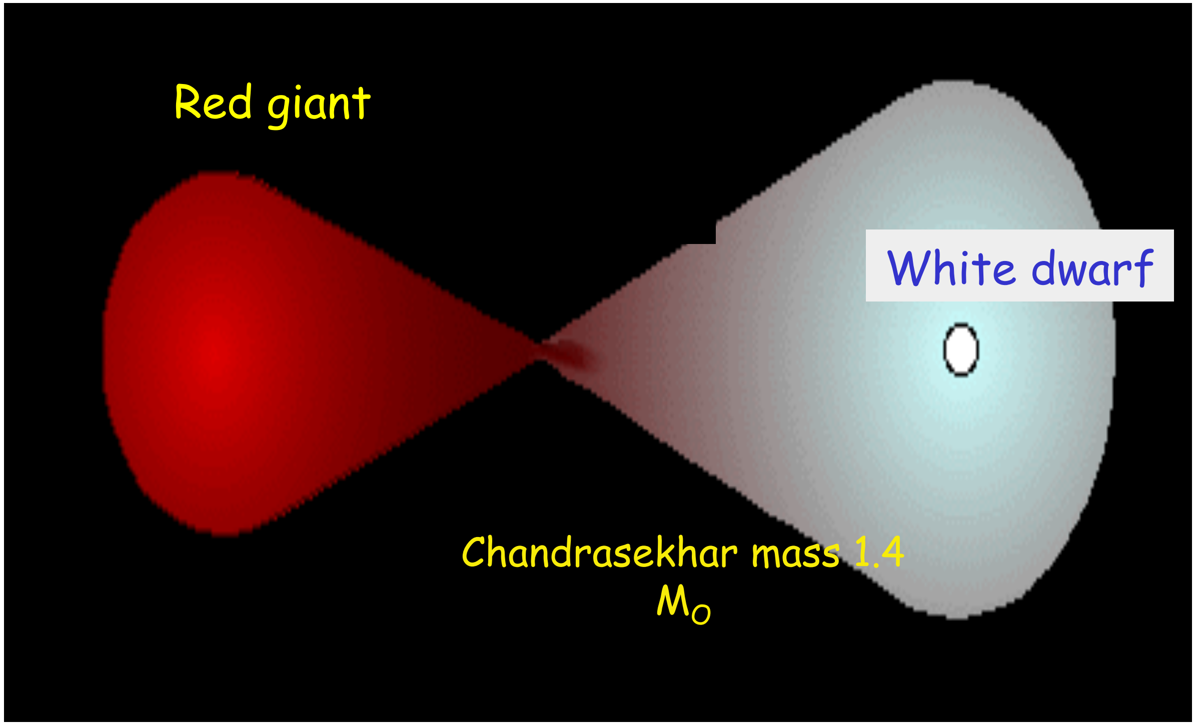
$H_0 = (\dot{a}/a)_0 = 100\ h$ km/s/Mpc h= 0.71 +/- 0.025 (?)

q_0 = deceleration parameter

A Universe with only matter is expected to decelerate

Supernovae type Ia
Best known « standard » candles





SNIa : 2 stars accretion (a white dwarf +…)

➔

Chandrasekhar mass 1.4 M_O

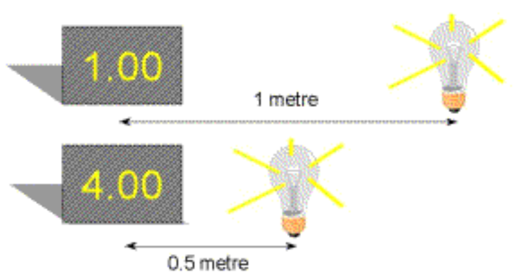
Detailed explosion physics not clear yet. Worth studying!

Different SNIa progenitors?

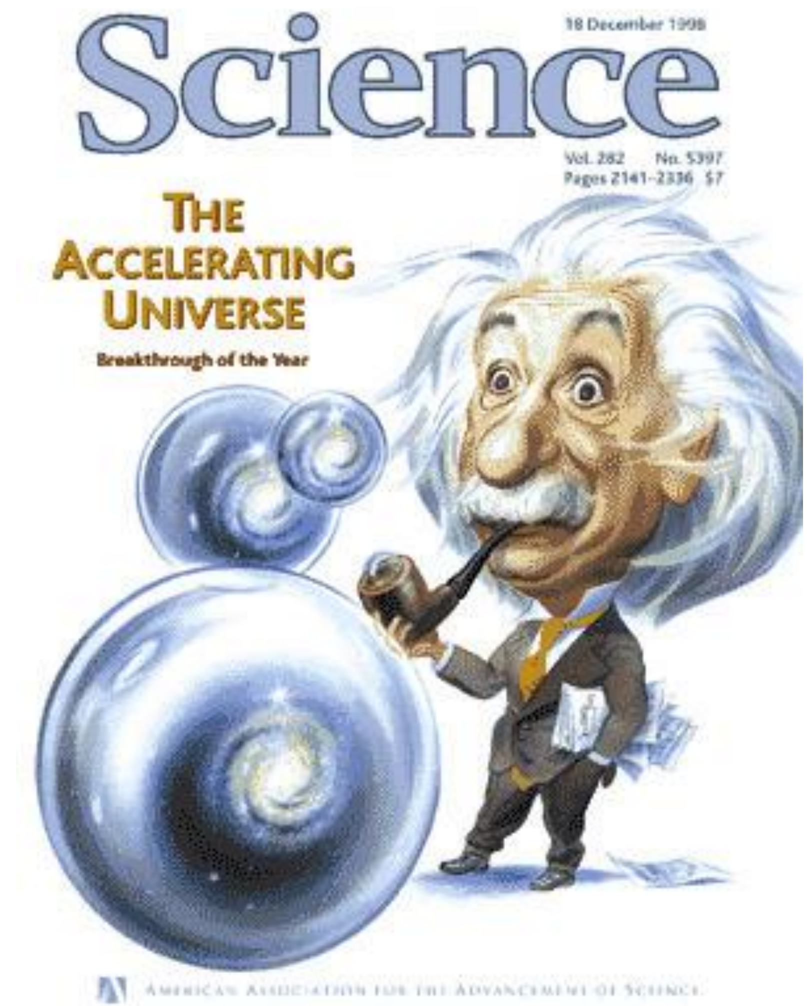
Surprise 1998:
An accelerating Universe!

2 Collaborations with SNIa
SCP +HST

Measuring Distances with Standard Light Bulbs



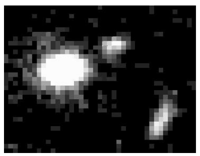
An Object becomes fainter by the square of its distance

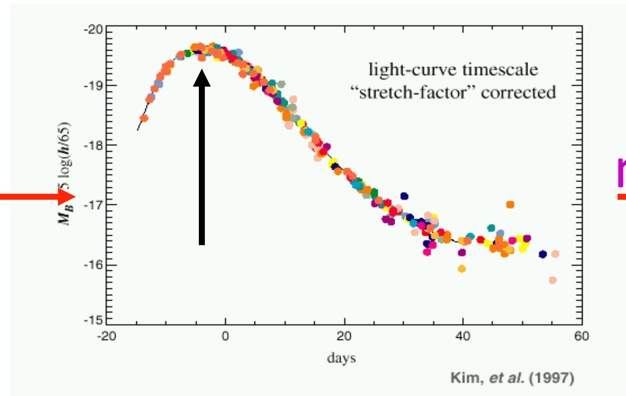


Measure q_0 negative!!!

SN observation methods

Images



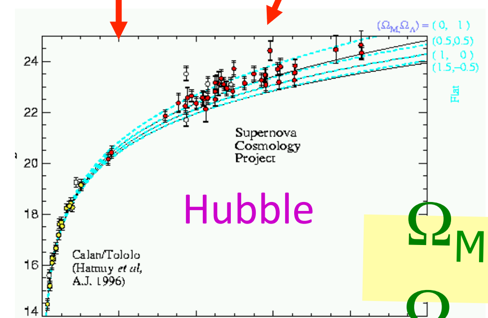


magnitude

galaxy

spectrum

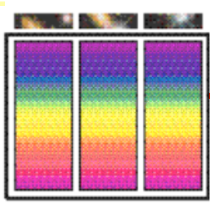
z(redshift)



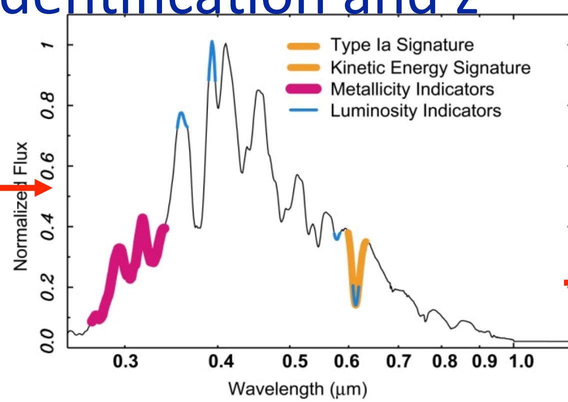
Hubble

Ω_M , Ω_Λ

Spectrum



identification and z

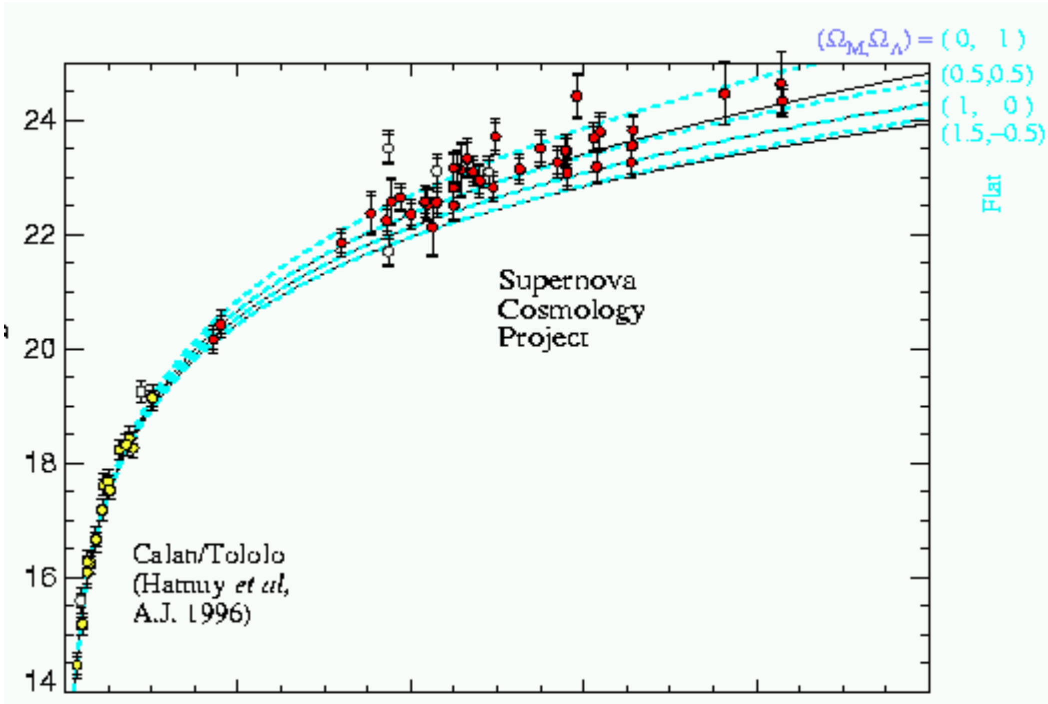


Ia

data → analysis → physics

Determination of cosmological parameters

Hubble Diagramme



Different possible parametrisations

$w(z) = p/\rho$

$= w_0 + w' z$

$= w_0 + w_1 z$

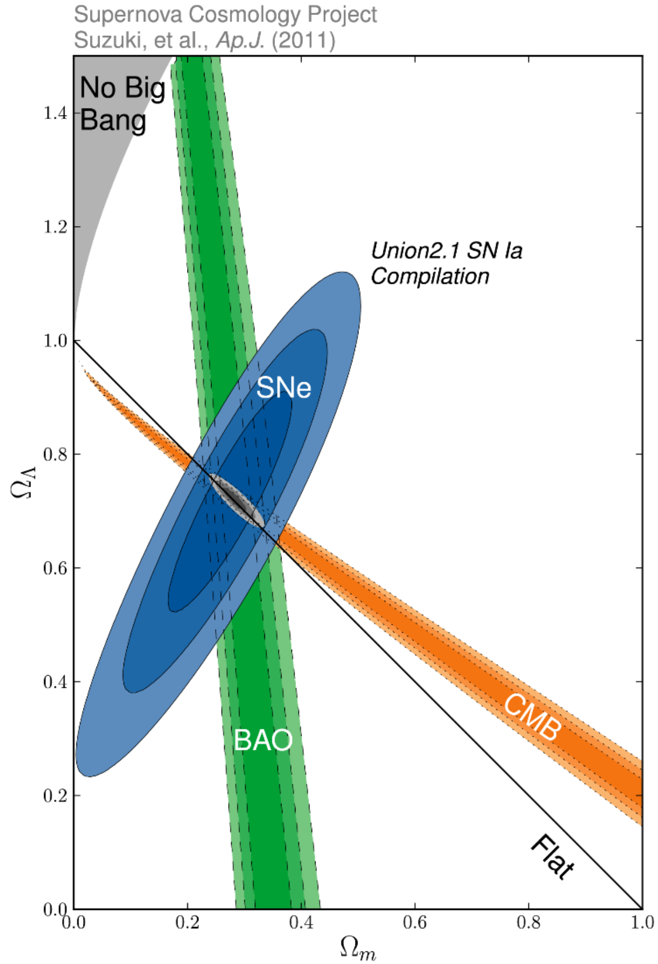
$= w_0 + w_a z/(1+z)$

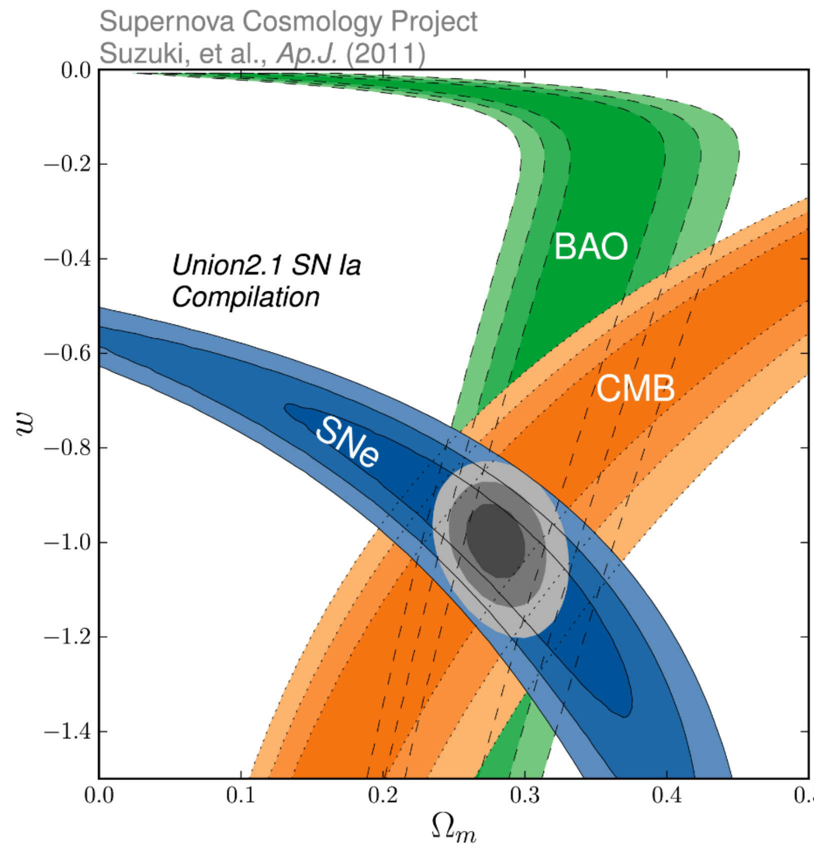
- **Cosmological Fit**
  - From Hubble diagramme , one can find the best cosmological model parameter agreeing with observations :

→ determines then the parameters characterising DE

Ω_Λ, or (Ω_X, w, w') and matter density Ω_M

Combination of probes to constrain cosmological parameters





Concordance Λ−CDM model !

Lambda: Cosmological Constant

Eisntein's equations $$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

$$R_{\mu\nu} - 1/2\, g_{\mu\nu}(R - \Lambda) = 8\pi\, G\, T_{\mu\nu}$$

The most general form of Einstein's equations
has a constant,
a priori arbitrary

Introduced by Einstein in 1917 paper NOT to keep the Universe constant
But to define limiting conditions at infinity!

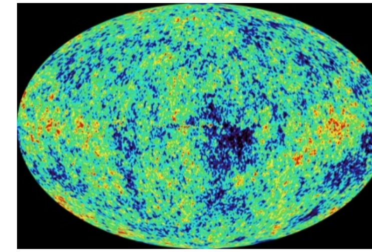
The concordance model stands quite strong!

CMB

Snapshot at ~400,000 yr, viewed from z=0

Angular diameter distance to z~1000

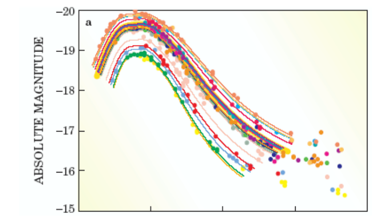
Growth rate of structure (from ISW)



Supernovae

Standard candle

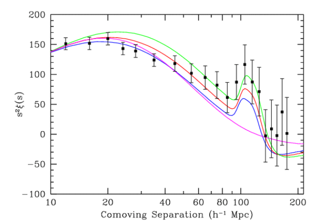
Luminosity distance



Baryon Wiggles

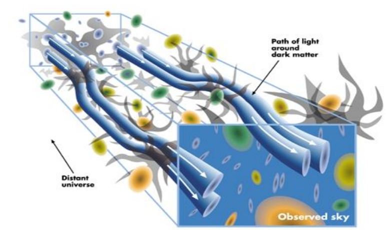
Standard ruler

Angular diameter distance



Cosmic Shear

Evolution of dark matter perturbations
Angular diameter distance
Growth rate of structure

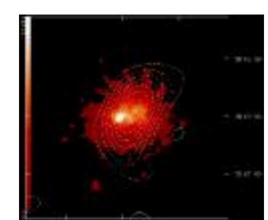


Cluster counts

Evolution of dark matter perturbations

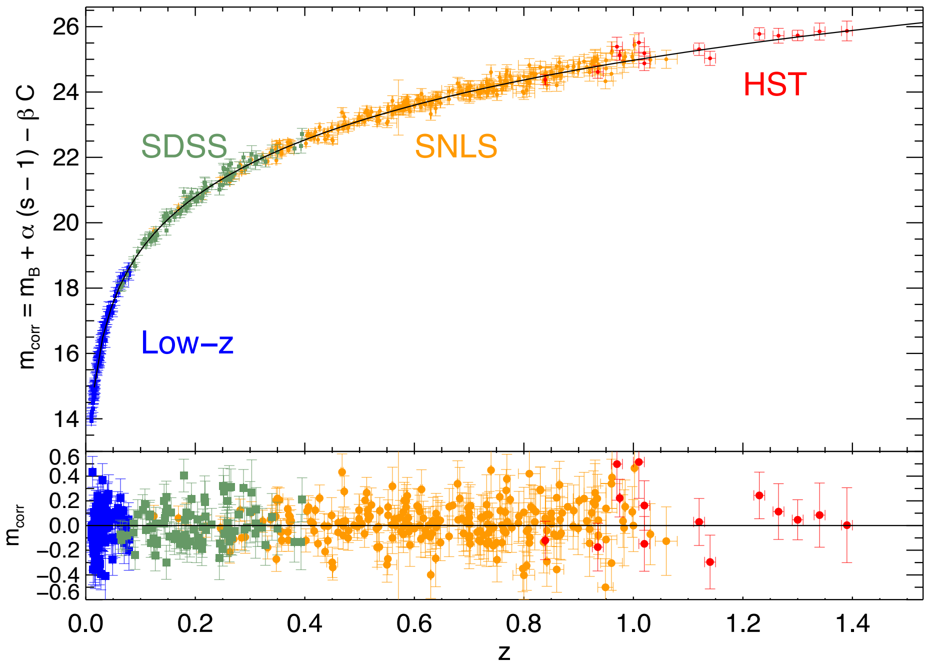
Angular diameter distance

Growth rate of structure

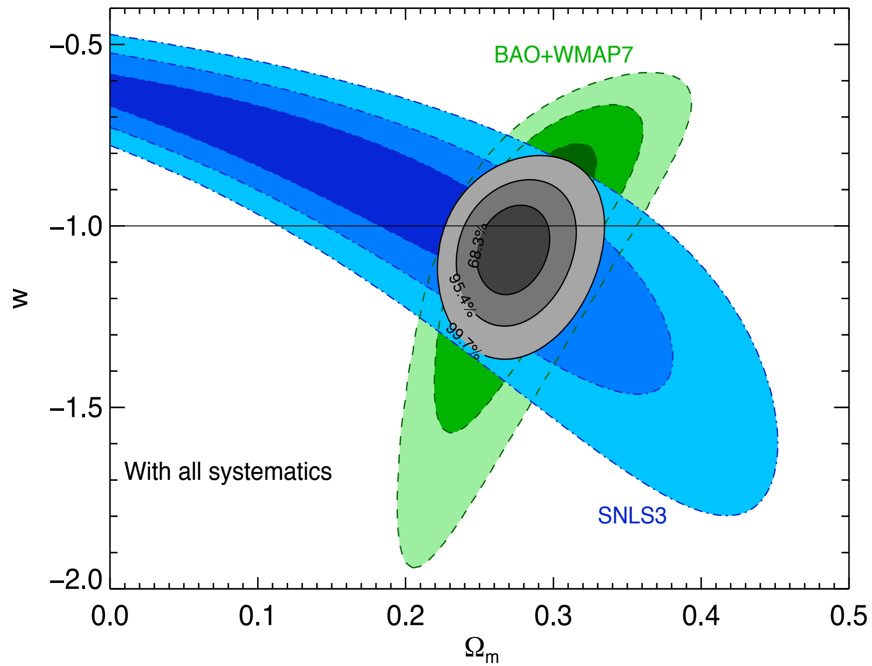


Current SNIa cosmological constraints on DE

Compilation of 472 SNeIa
123 low-z, 93 SDSS, 242 SNLS, 14 HST



$w\ (=P/\rho) = -1.06 +/- 0.07$
(including systematics, assuming flat universe with WMAP7, BAO and H_0 constraints)



SNLS 3-year results (Conley et al 2010, Sullivan et al 2011, Guy et al 2010),

SNIa cosmology

Nearby SN now

- Different classes of SNIa, average magnitude may depend on environment, redshift …

May have impact on precision cosmological parameter determination

- Precision : aim for 1% ➔ calibration issues

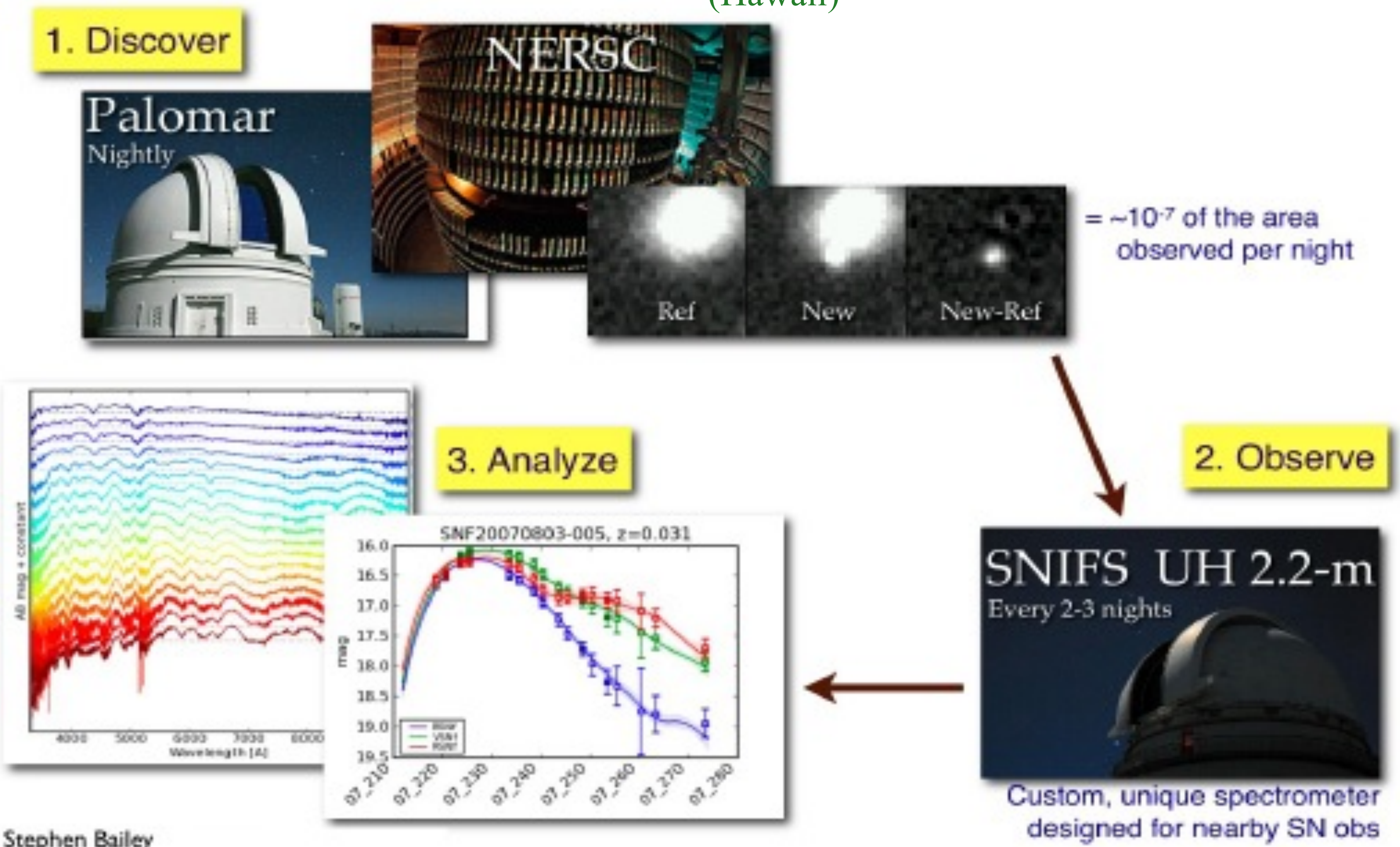
Waiting for SNI thousand SNIa scale **space programs** (**EUCLID** in Europe, WFIRST in US, 2m in China?)

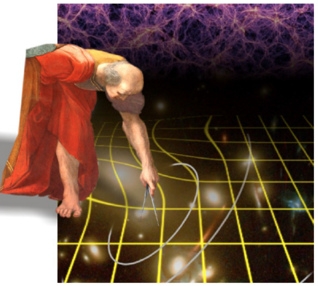
And/or … **Chinese Antarctica Dome A** project?

Nearby SNFactory

National Energy Research
Scientific Computing Center

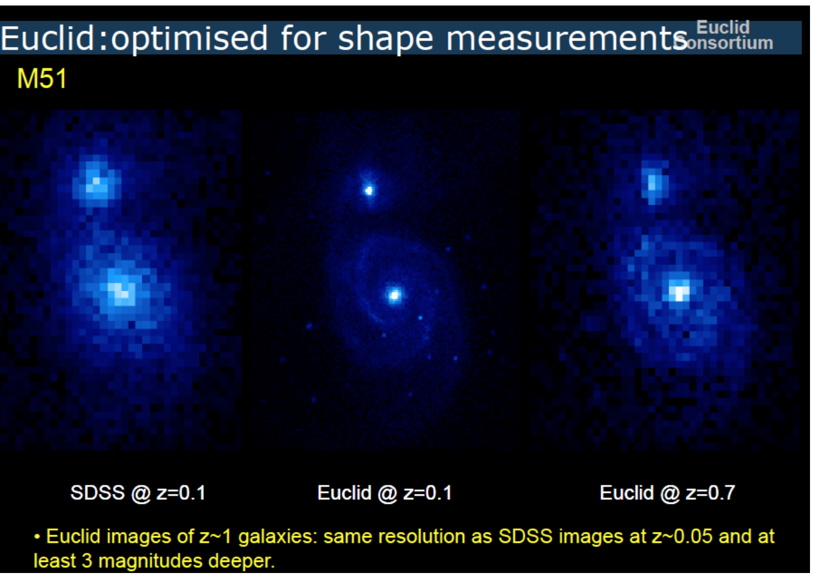
Discovery: Two cameras (one wide field) 1.2 m ground based telescopes: NEAT/QUEST
Lightcurve follow-up with YALO
Photo-spectro follow-up with Field Integral Spectrometre (SNIFS) at UH 2.2m telescope (Hawaii)

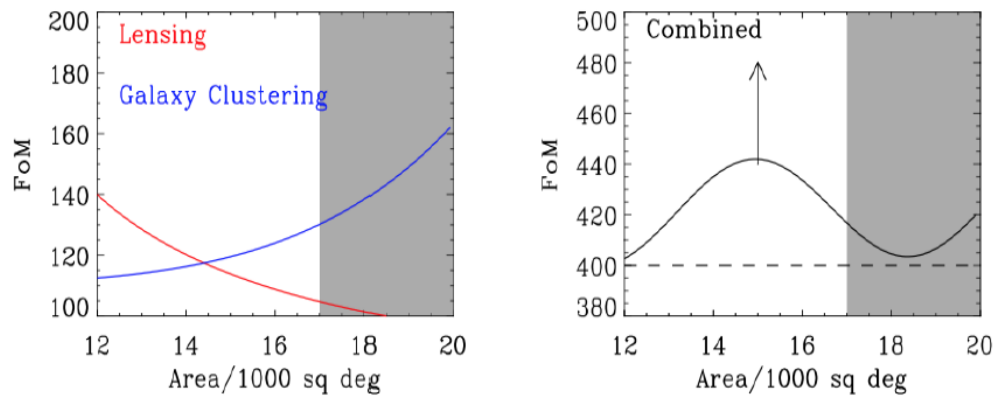




The European EUCLID space project

http://www.euclid-ec.org





- With 15,000 deg^2 for for GC and WL: optimisation for a fixed time survey.
- Allows Euclid to do WL and GC simultaneously on the same area.

Will provide best constraints on DE parameters with multi-probe combination + studies of DM (weak gravitational lensing)

Proposed SNIa DESIRE survey with EUCLID

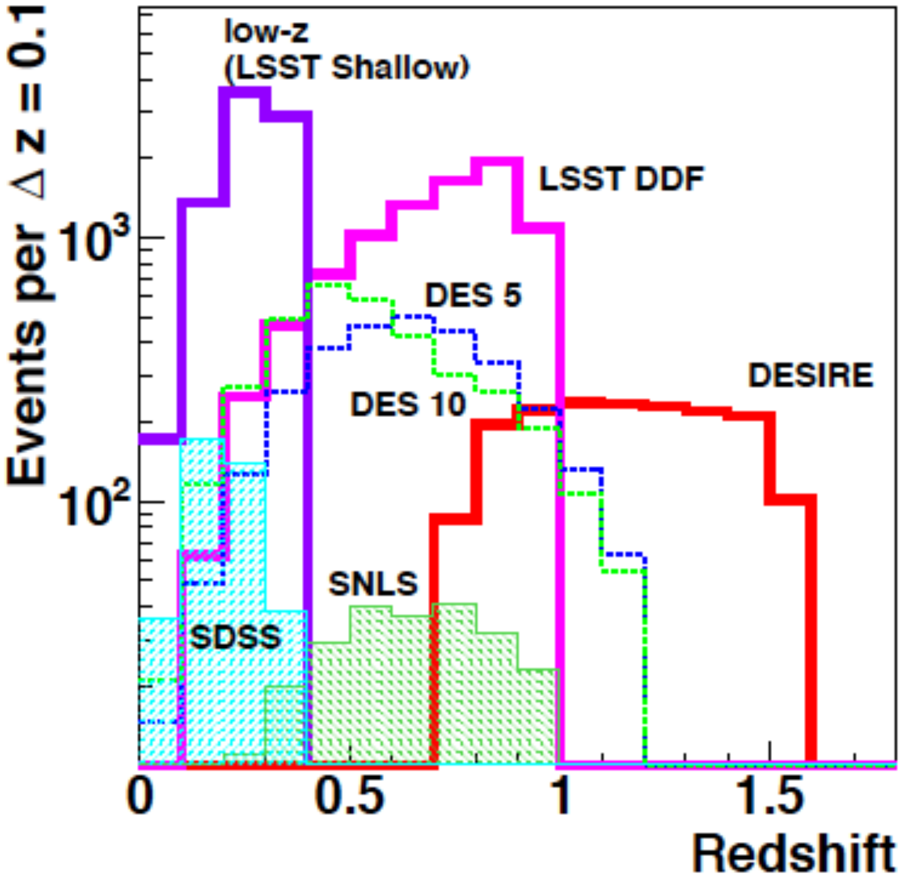


Fig. 12. Redshift distribution of events for various surveys. For th SDSS and SNLS, the distributions sketch the total sample of spectroscopically identified events eventually entering the Hubble diagram. "DES 5" and "DES 10" refer respectively to the "hybrid-5" and "hybrid-10" strategies studied in Bernstein et al. (2012), where the baseline is hybrid-10. "LSST-SHALLOW", "LSST-DDF" and "DESIRE" refer to the three prongs studied in this proposal.

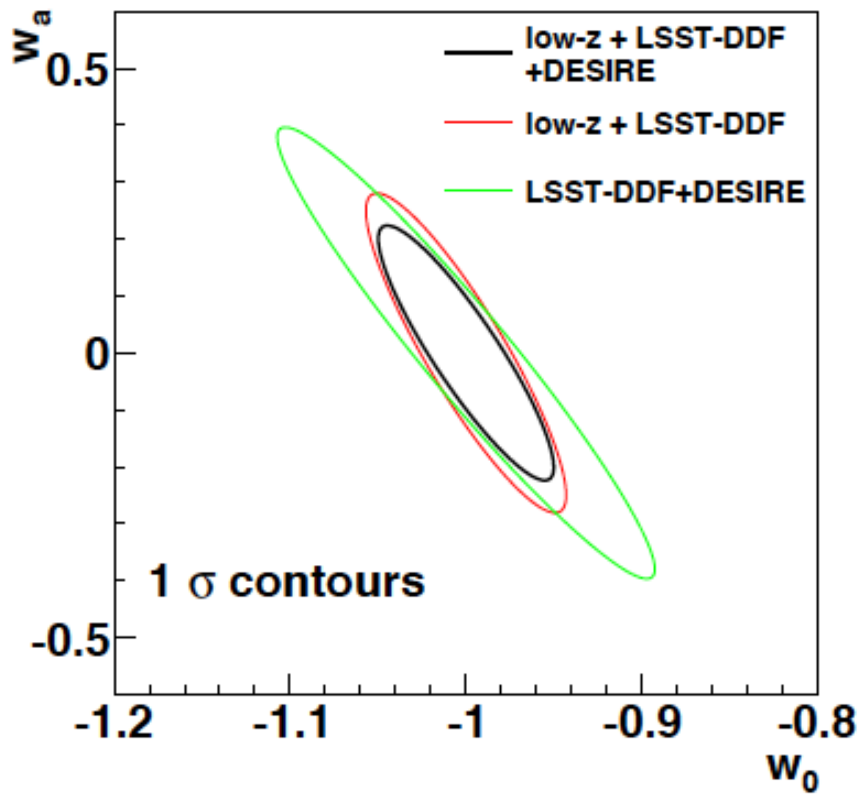


Fig. 9. Confidence contours (at the 1σ level) of the survey combinations listed in Table 5. The assumptions for systematics correspond to the last row of

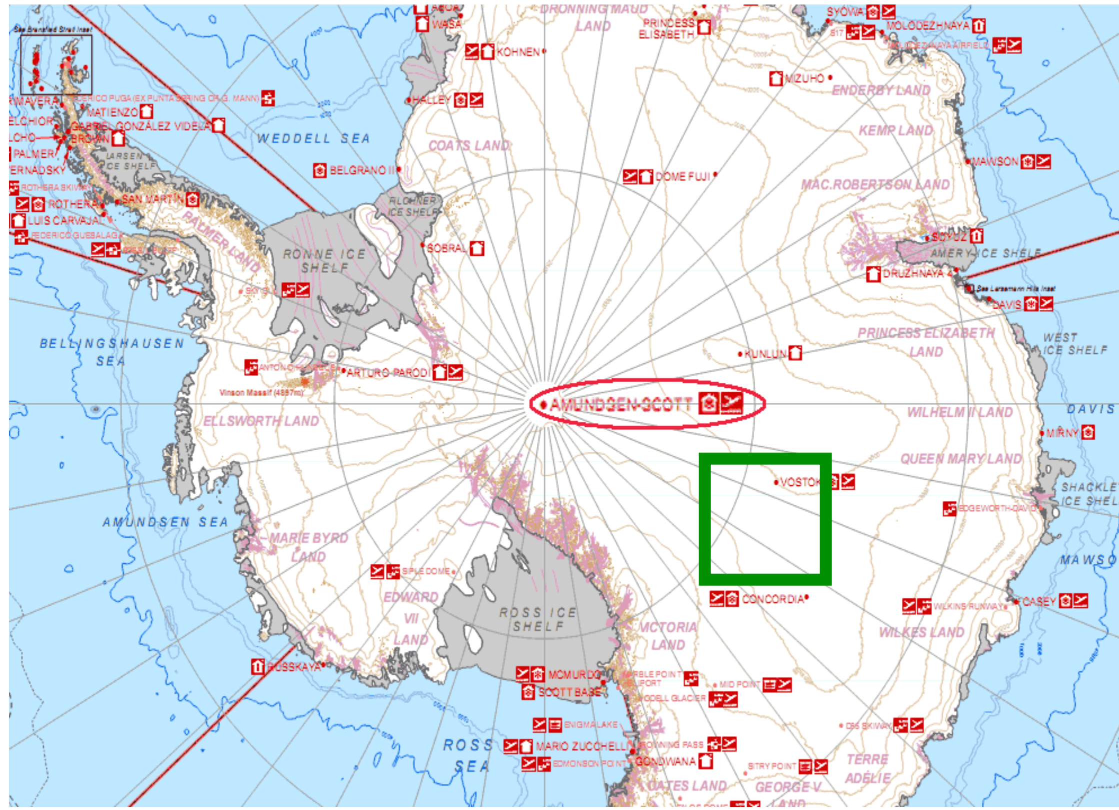
Table 5. Cosmological performance of the simulated surveys.

	$\sigma(w_a)$	z_p	$\sigma(w_p)$	FoM
low-z + LSST-DDF + DESIRE	0.22	0.25	0.022	203.2
low-z + LSST-DDF	0.28	0.22	0.026	137.1
LSST-DDF + DESIRE	0.40	0.35	0.031	81.4

Notes. The FoMs assume a 1-D geometrical *Planck* prior and flatness. z_p is the redshift at which the equation of state uncertainty reaches its minimum $\sigma(w_p)$. The FoM is defined as $[Det(Cov(w_0, w_a))]^{-1/2} = [\sigma(w_a)\sigma(w_p)]^{-1}$ and accounts for systematic uncertainties. The contributions of the main systematics are detailed in Table 6.

C. Tao is co-lead of transients SWG

Dome A Kunlun Telescopes

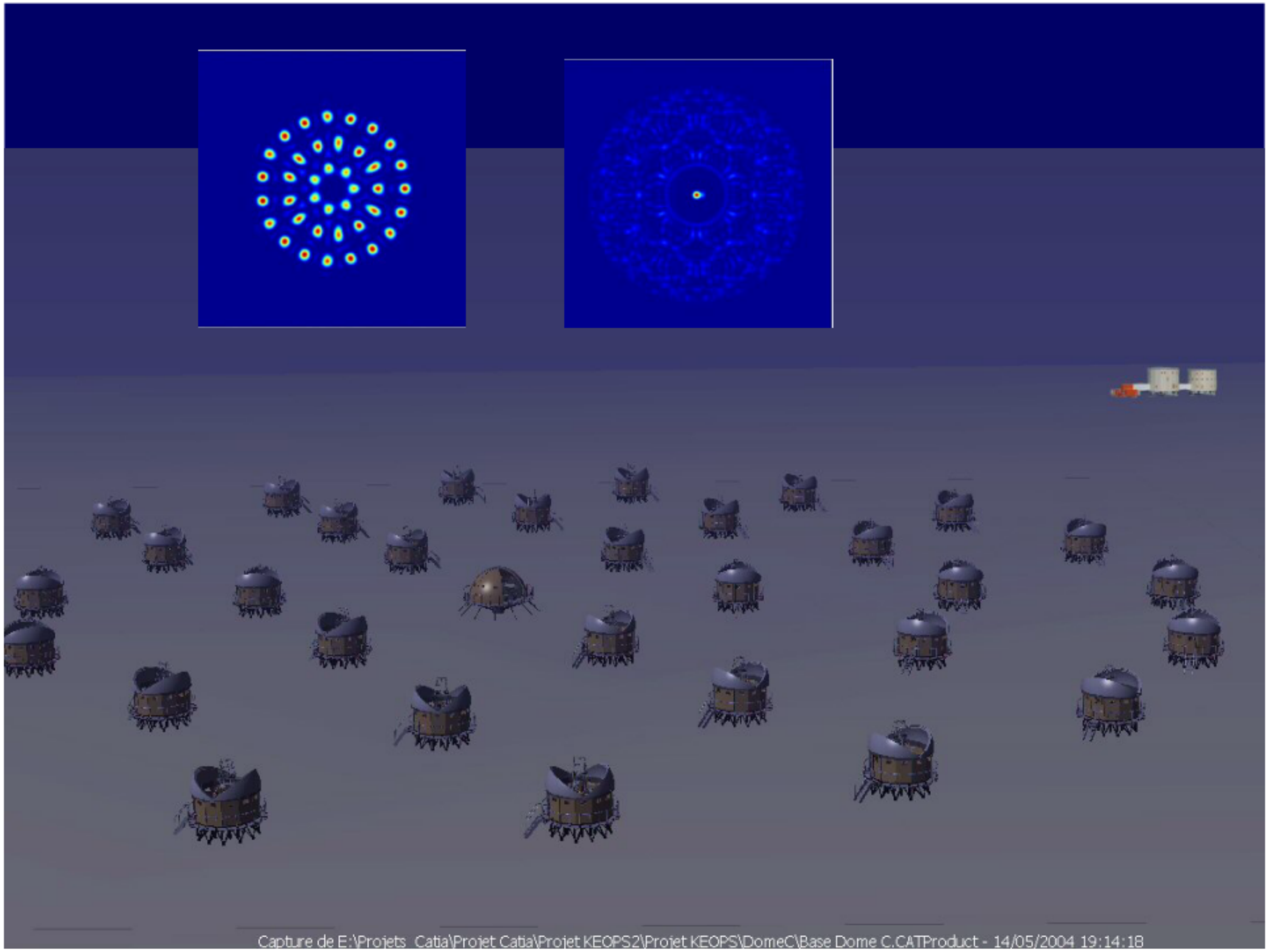


Advantage: great seeing!

Expect: 0.3 arc sec, eg almost

2 – 50cms telescopes being installed right now in Dome A

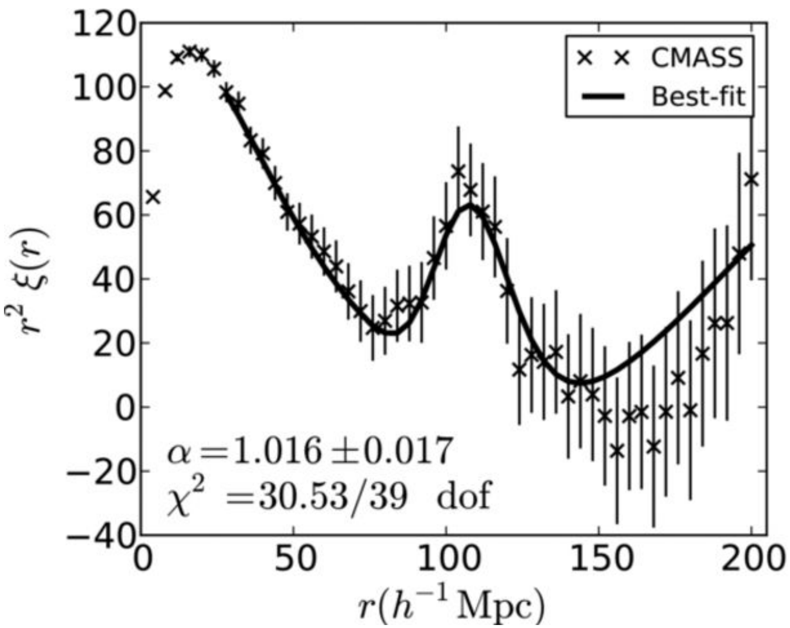
Antarctica
for future science not realistic in space

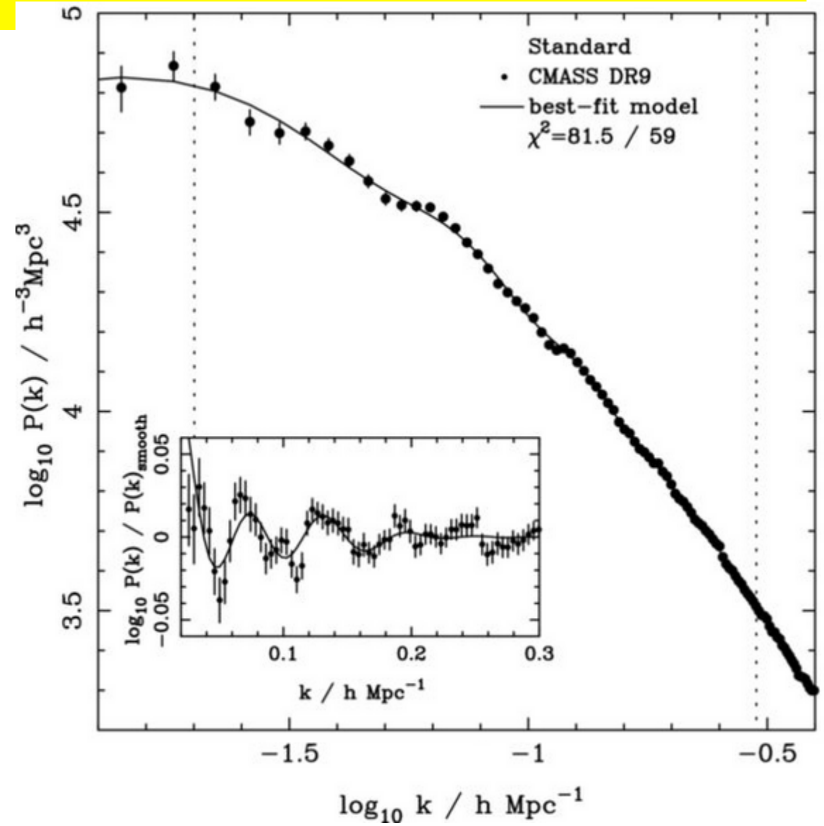


SNIa: Best single probe till 2013

Now BAO (Baryonic Acoustic Oscillations) with SDSS/BOSS results

Large Scale Structures Correlations



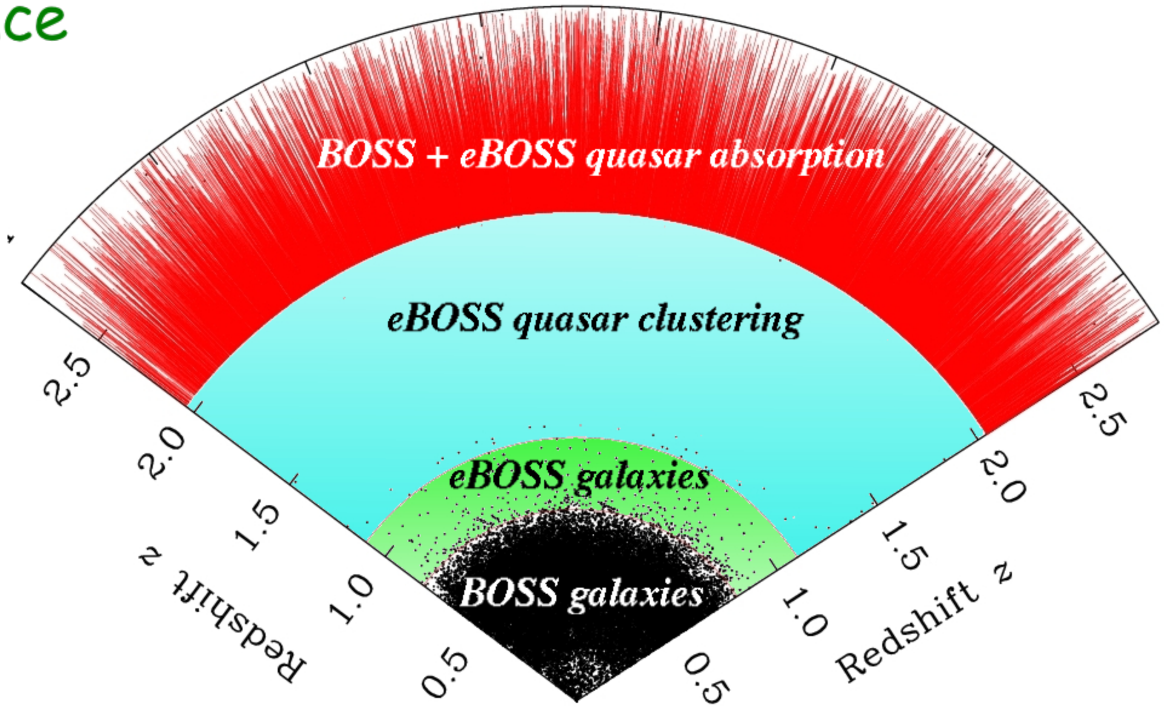


Galaxy-galaxy correlations

Anderson et al, 2012

eBOSS(SDSS4) started in August 2014

- Transition from deceleration to acceleration ($H(z)$)
- Structure growth (test of GR-ΛCDM)
- Neutrinos
- QSO/galaxy science
- …

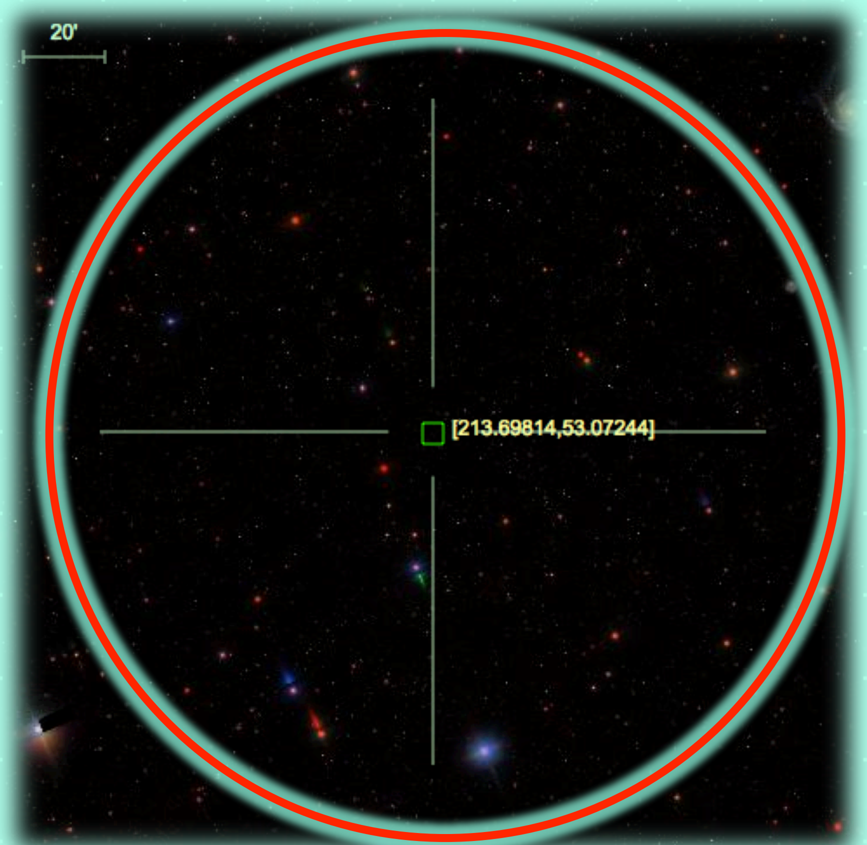


http://www.sdss3.org/future/eboss.php

Quasar reverberation mapping with BOSS/eBOSS

PI: SHEN Yue

- Motivation: expanding the RM AGN sample in both size and luminosity range
- Simultaneous monitoring 849 quasars at 0.1<z<4.5 in a single 7 deg^2 field with the SDSS-BOSS spectrograph
- Dense photometric light curves since 2010-



THCA: C.Tao + Gao Yang + Sun Jiayi +…

AGN and quasars:
a new cosmology probe?

暗物质的天体物理与宇宙学研究

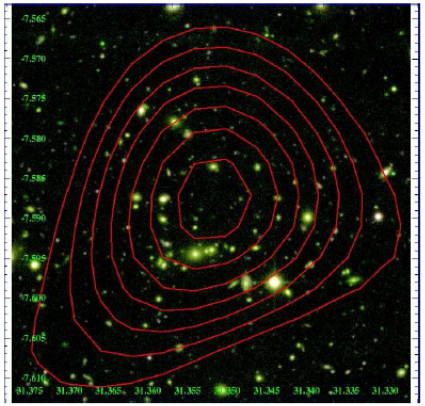
Astrophysical and Cosmological Determinations of Dark Matter

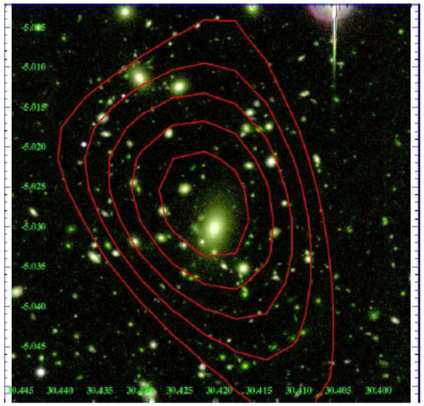
THCA

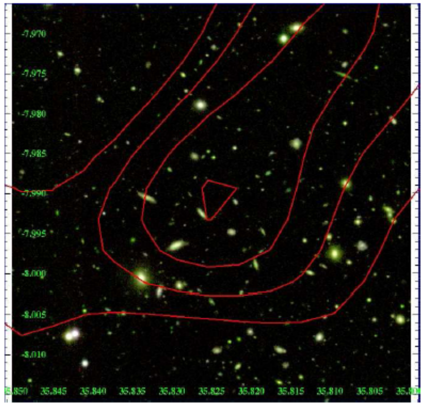
Charling Tao (and Shan Huan Yuan)

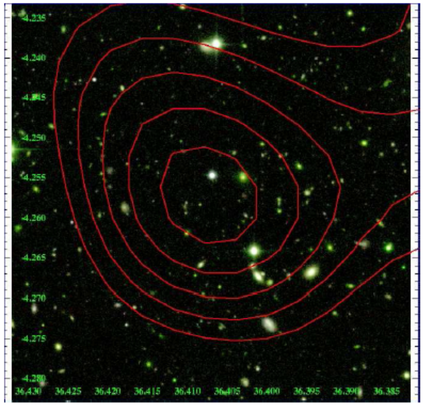
- **Analyze existing CFHT data**
- **Prepare for Large scale surveys. MS-DEsI, LSST, EUCLID, KDUST, …**

Collaboraton with
+ IHEP
+NAOC
+PKU
+…







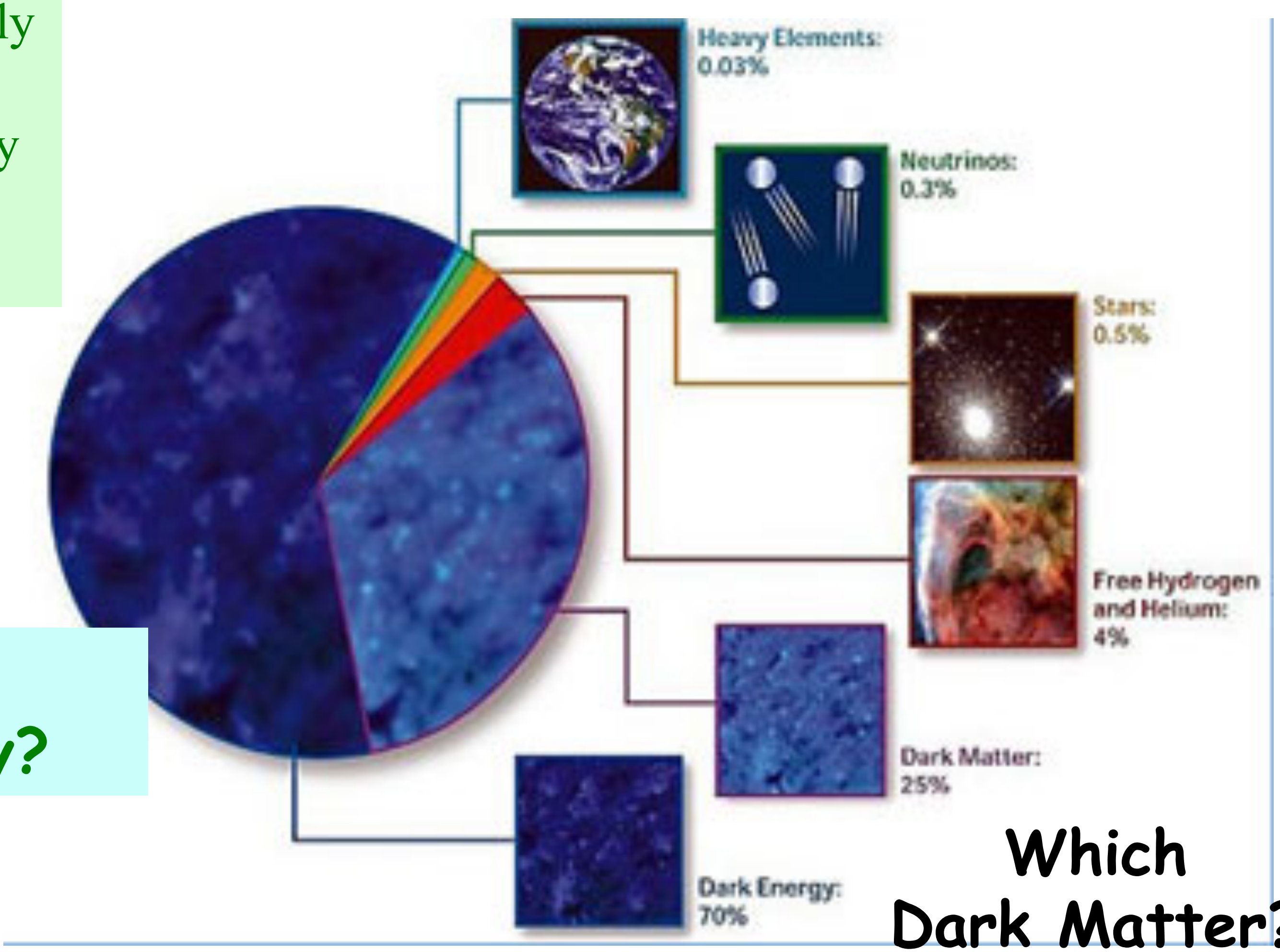


A mysterious Universe !

New Paradigm

Concordance Model ΛCDM

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



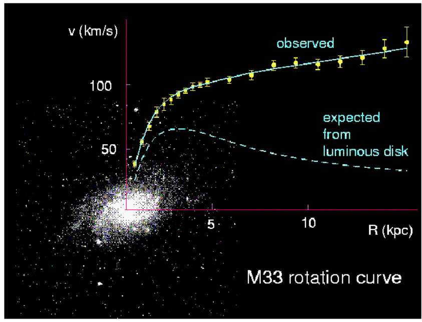
What is Dark Energy?

Which Dark Matter?

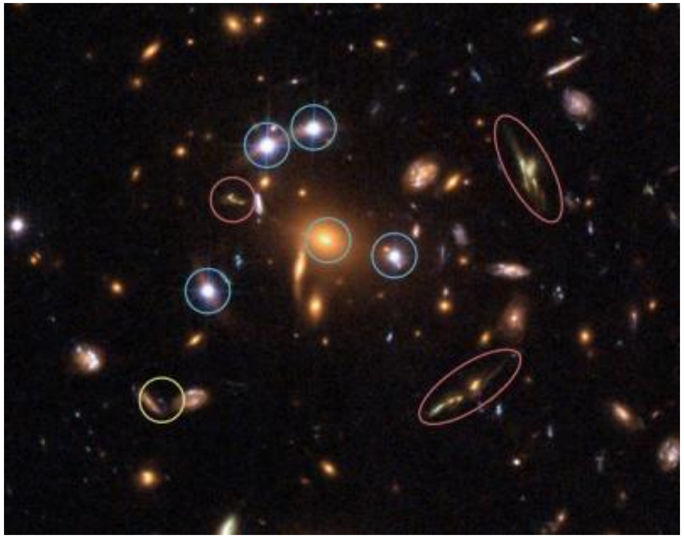
Graph source: Wikipedia

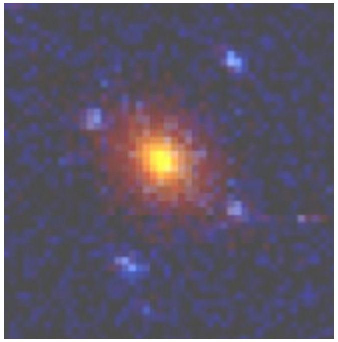
Wealth of evidence for DM is astrophysical

- Galaxy rotation curves (V. Rubin)



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

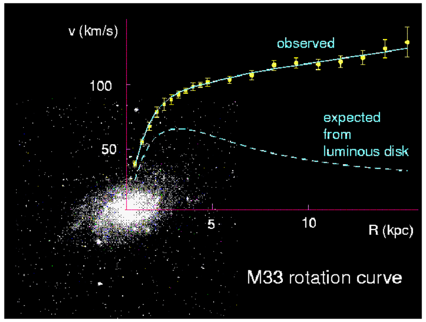




- Bullet cluster (Clowe+,2006)

Wealth of evidence for DM is astrophysical

- Galaxy rotation curves ~~(V. Rubin)~~ HI?



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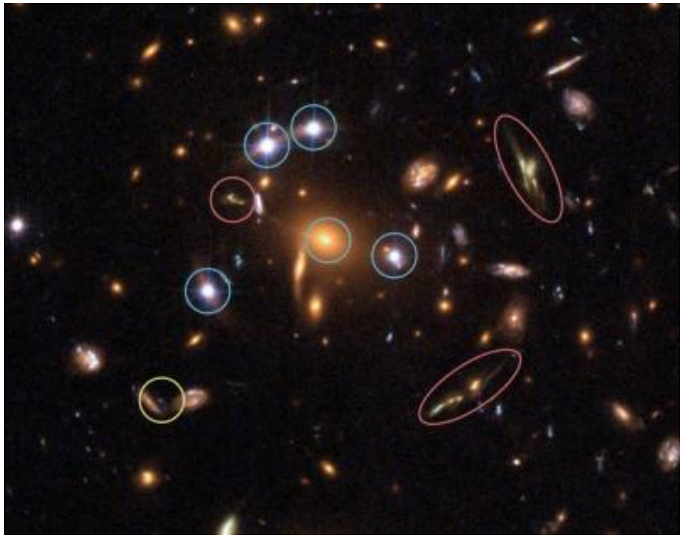
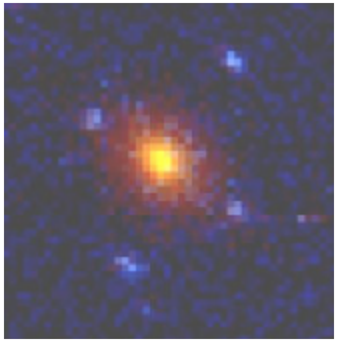
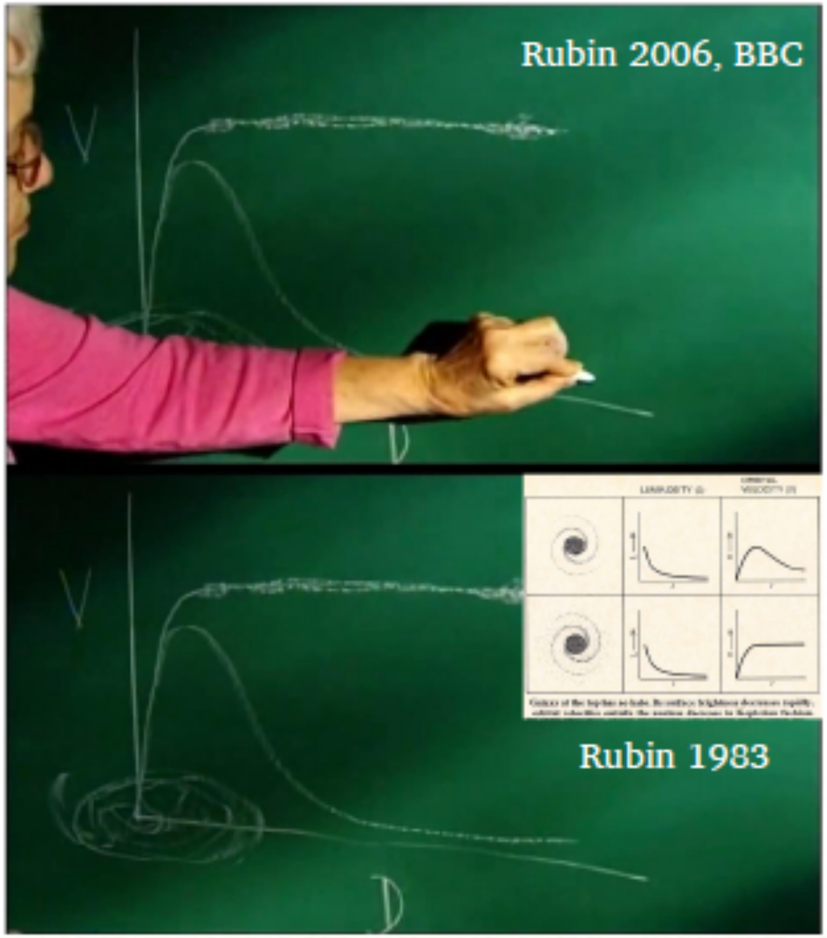


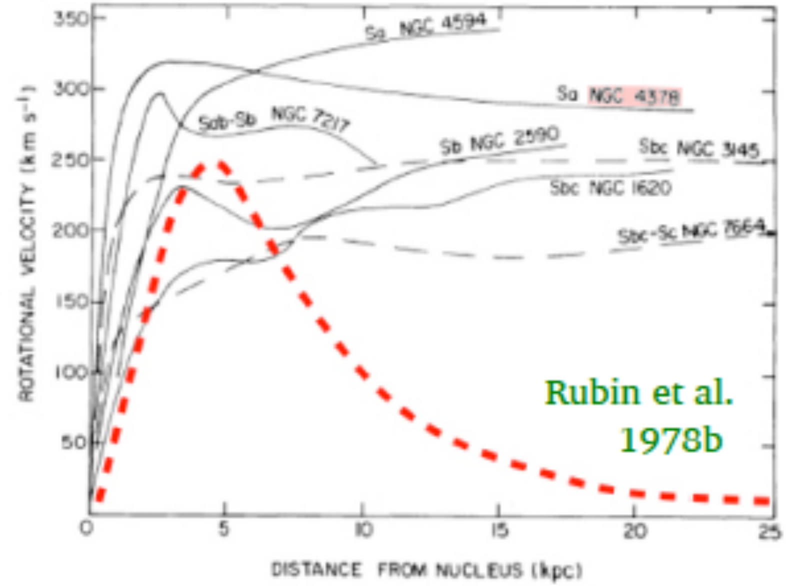


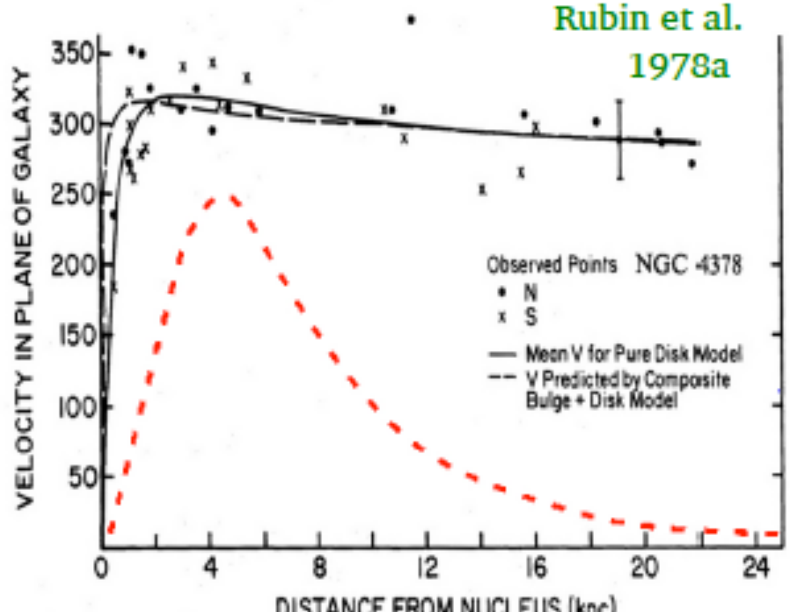
- Bullet cluster (Clowe+,2006)

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.



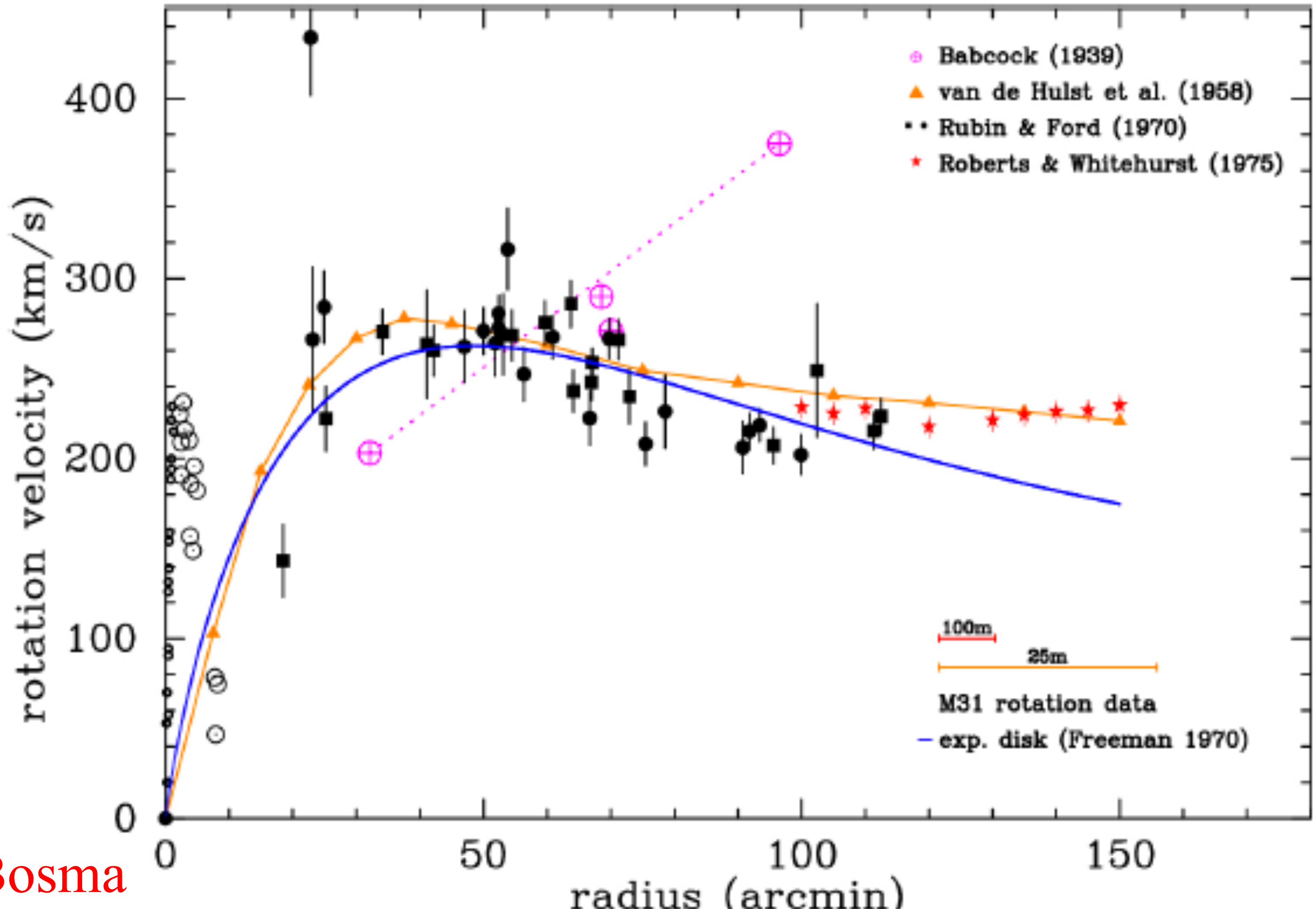


Keplerian behaviour just outside the nucleus can NOT be expected

A. Bosma

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

Rotation curve analysis

From data to mass models

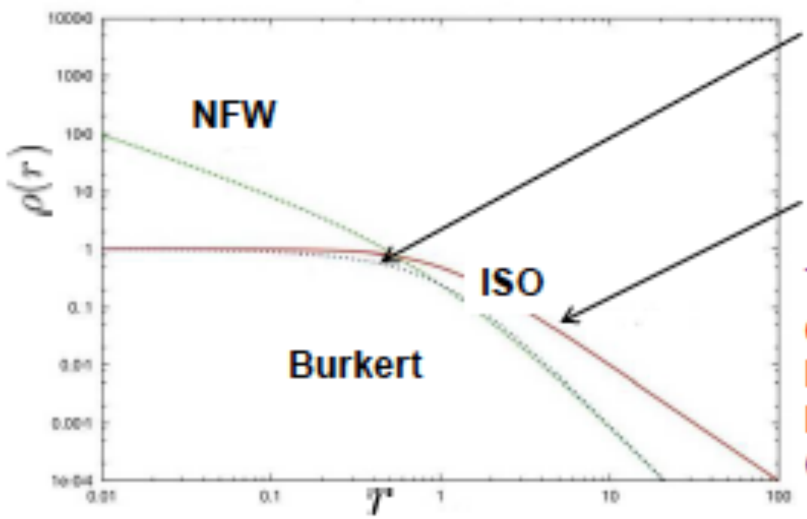
$$V^2(R) = V^2_{halo}(R) + V^2_{HI}(R) + V^2_{disk}(R)$$

observations = model

- V^2_{disk} **from I-band photometry**
- V^2_{HI} **from HI observations**
- V^2_{halo} **different choices for the DM halo density**

Dark halos with central constant density (Burkert, Isothermal)

Dark halos with central cusps (NFW, Einasto)



$$\rho(r) = \frac{\rho_0}{(1 + r/r_0)(1 + (r/r_0)^2)}$$

$$\rho(r) = \frac{\rho_0}{1 + (r/r_0)^2}$$

The mass model has 3 free parameters:
disk mass
halo central density
Halo core radius (length-scale)
Obtained by best fitting method

P. Salucci, NAOC 2014

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_{sun}

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

➔ Local density 0.3- 0.4 GeV/cm3 ~ 10^{-2} Mo/pc^3**?**

Dark Matter:
What do we really know?

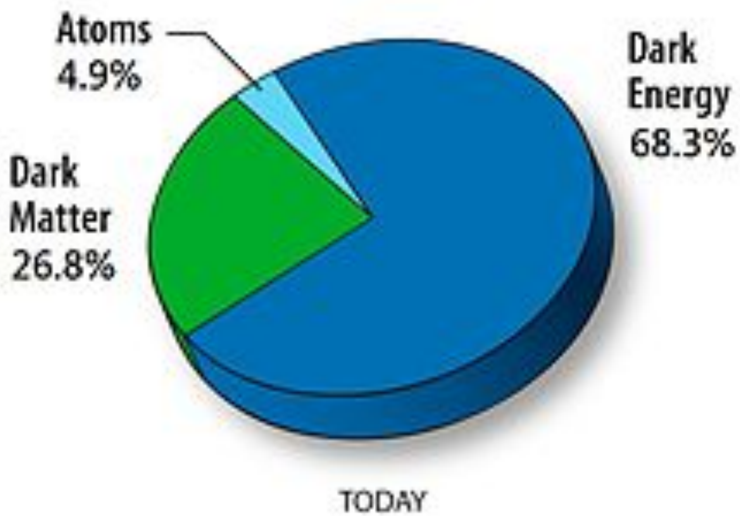
DM: - particle that does not emit observable radiation
- interacts gravitationally…
- non baryonic

DM common paradigm: **it exists!**

- **Contributes to energy density in the Universe,**
- **Measured in clusters and galaxies**

Assuming standard Big bang Cosmology with General Relativity

The Universe energy density content after Planck



% precision

Cf Planck march 2013 papers

Wikipedia

Matter today ~ 31.7%
energy density of the Universe

84.5% of the *matter* is dark matter

12%

13.7 BILLION YEARS AGO
(Universe 380,000 years old)

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

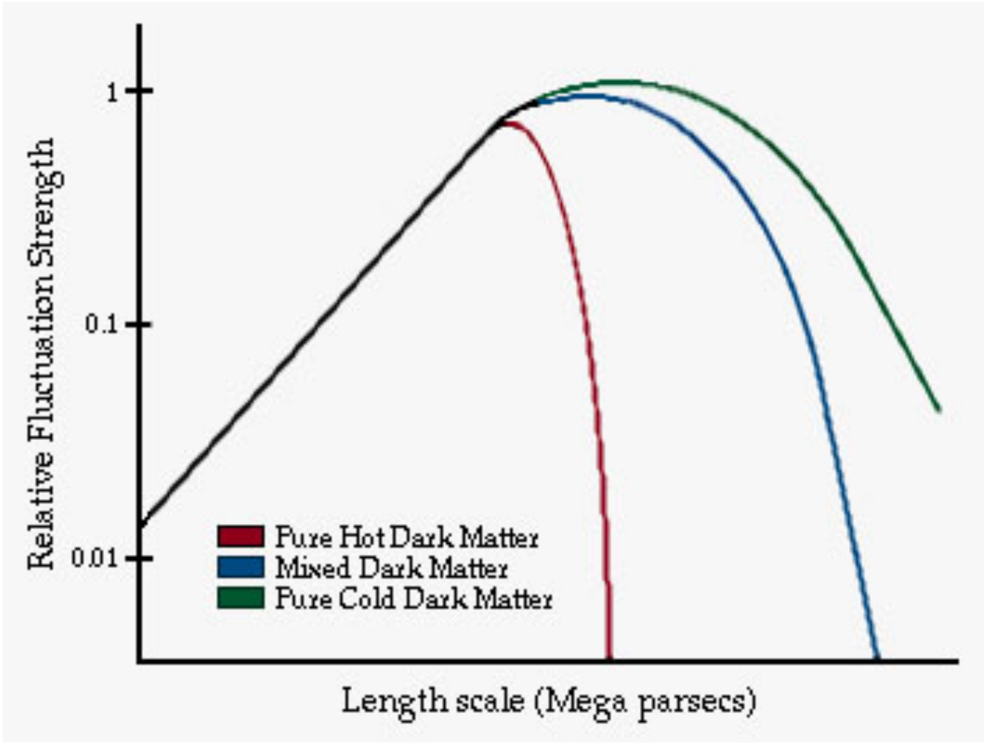
AND

Observations in Astrophysics / Cosmology

<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



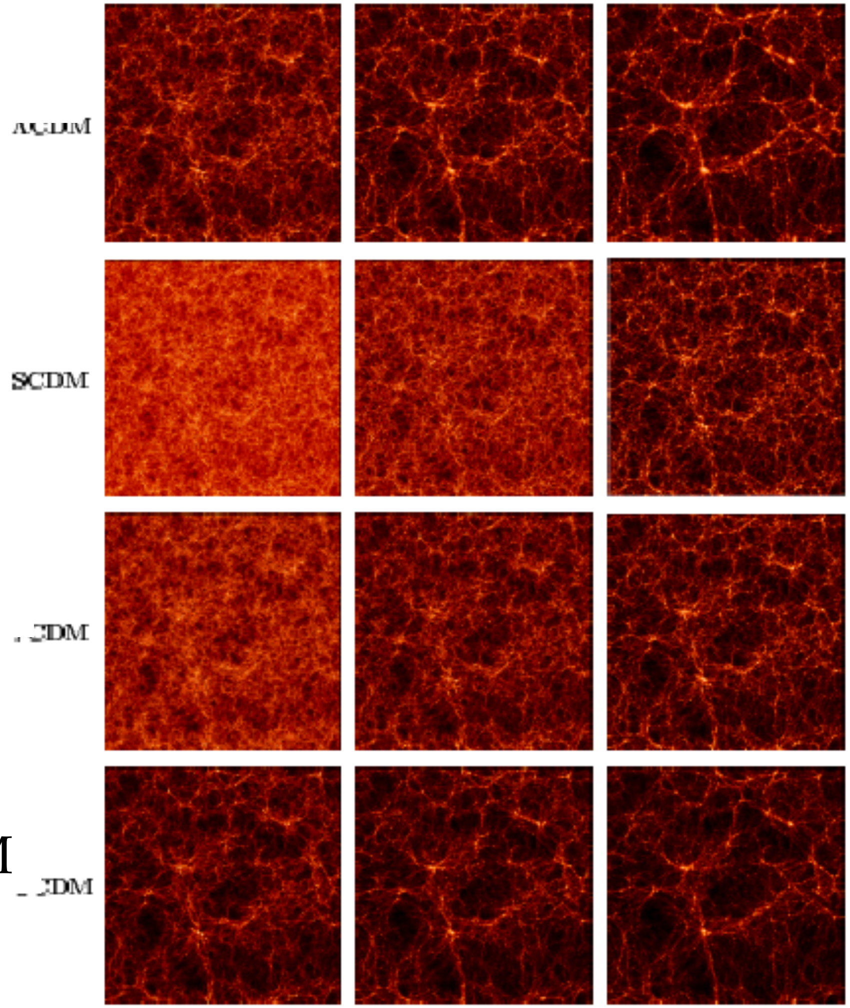
Comparisons of LSS observations with pre-2000 N-body Simulations prefer CDM

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/

N-Body simulations: CDM

Preferred paradigm: CDM

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

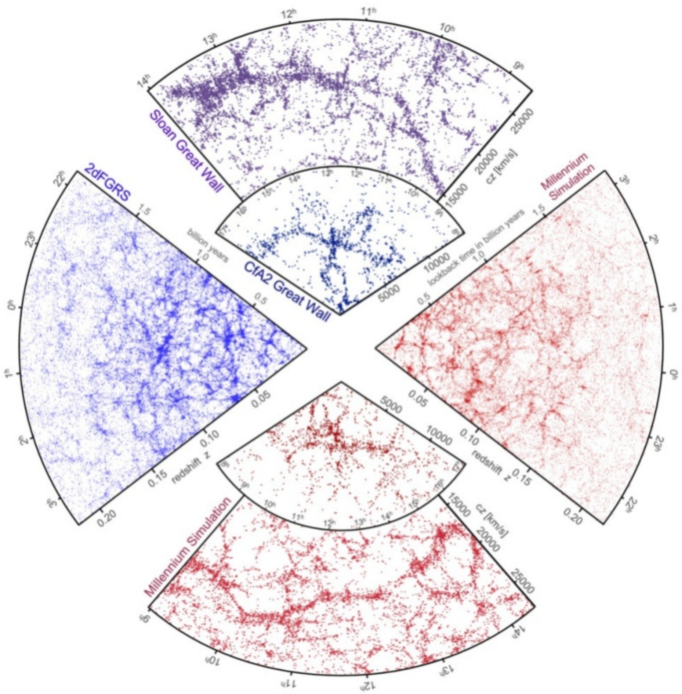
structures evolve, merge and cluster

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

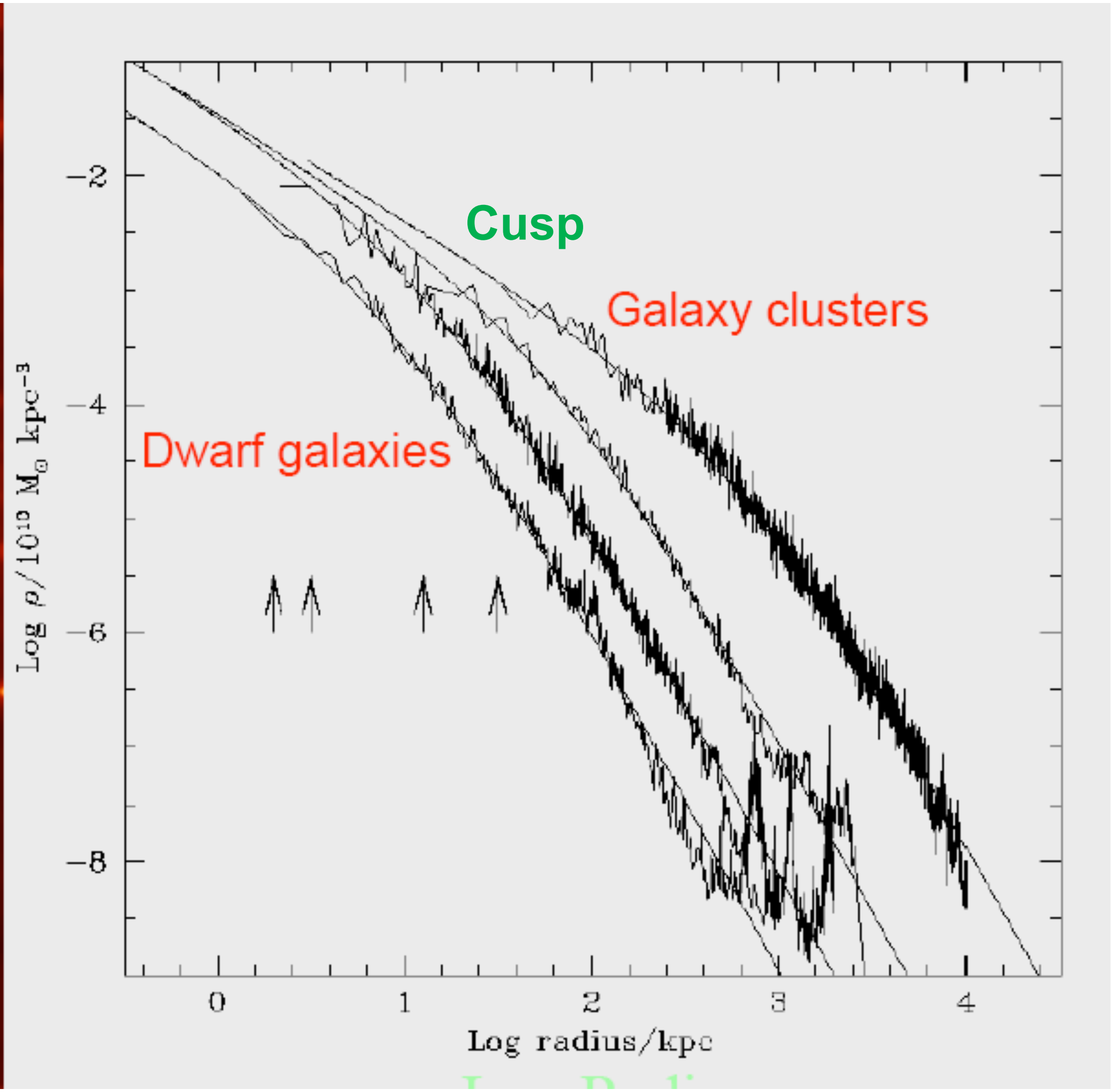
~2000 :Problems with CDM at small scales

Comparing data with N-body Simulations

- Galactic satellites
- cusp/core at GC



Dark matter distribution—Density profiles



Universal Density Profile from N-body simulations

NFW

Navarro, Frenk, White 1996

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

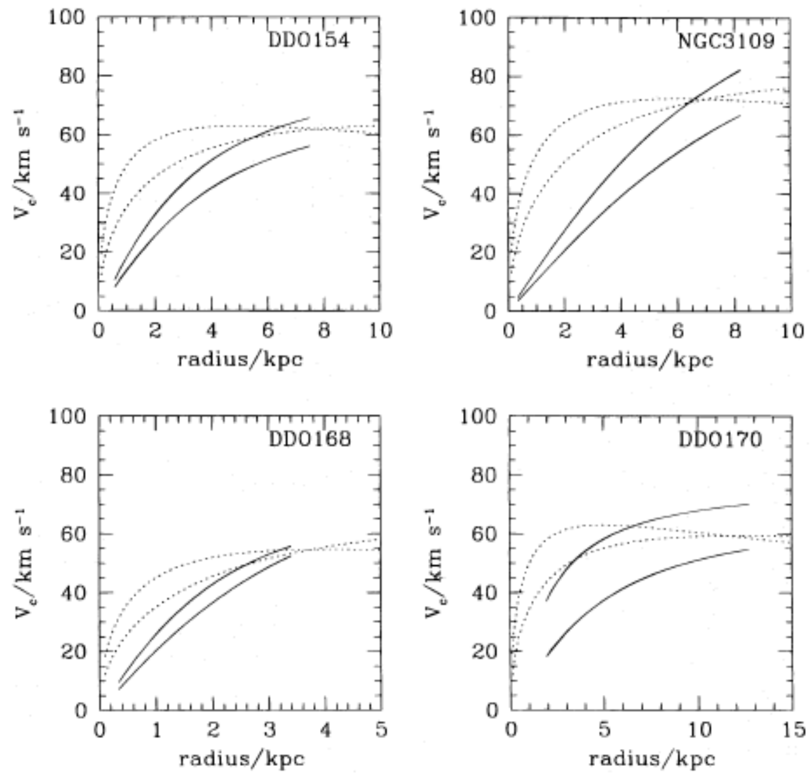
Galaxy profiles prefer core at center

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

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

Problems at smaller scales?

Observations favour
Core profile

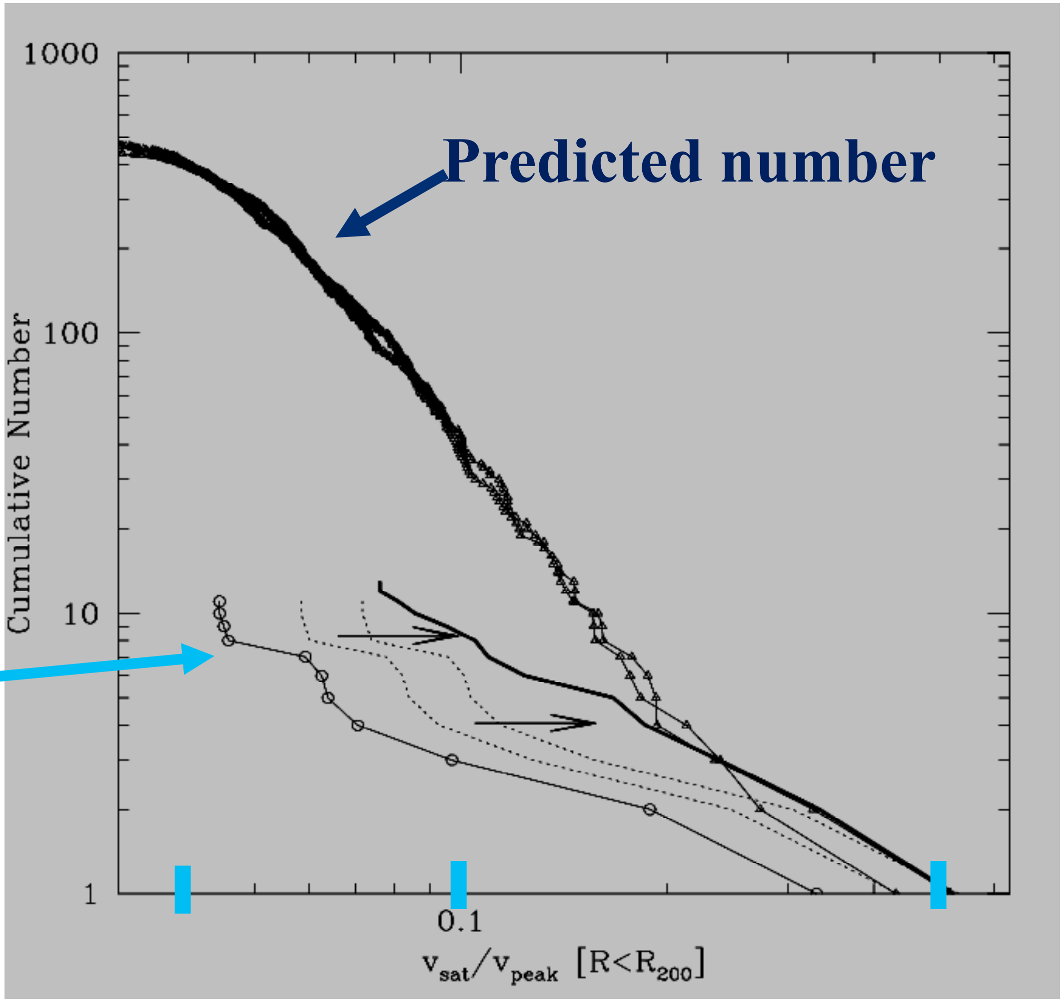


rotation curves

Too low number of visible Satellite galaxies

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

Observed number of luminous satellite galaxies



10km/s 20km/s 100km/s

Alternatives to CDM

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

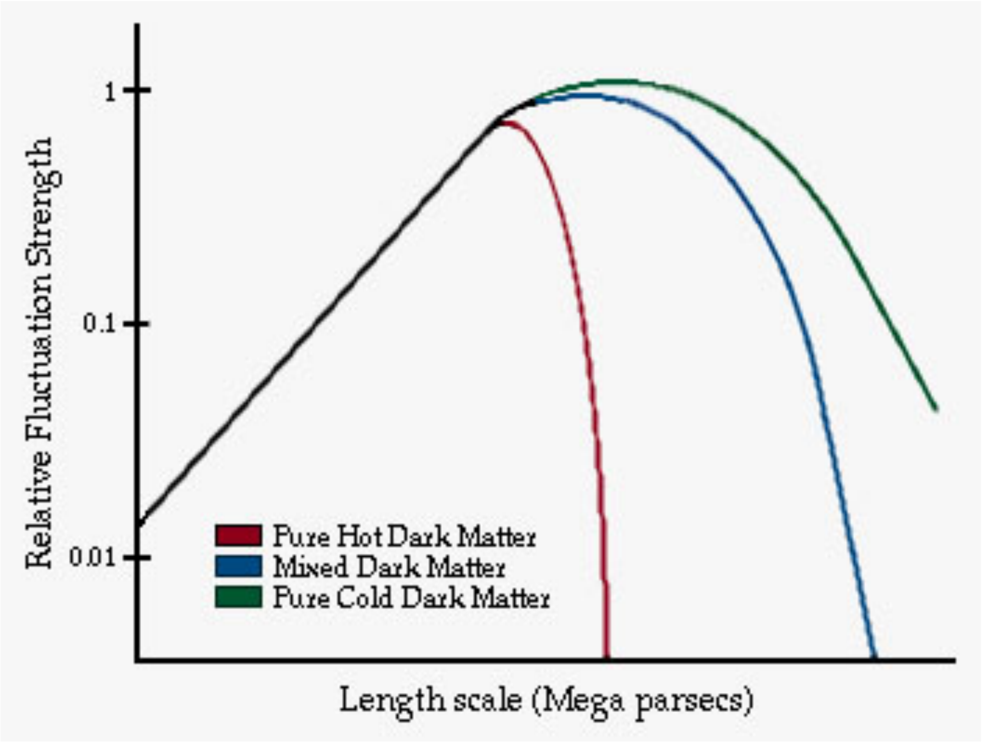
- WDM: reduce the small scale power

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

>2000: 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

Limits on mass of eventual WDM particles

- Stellar dynamics in MW satellites (Boyanovsky, de Vega, Sanchez 2008; de Vega and Sanchez 2009)
- High-z QSO LF (e.g. Song and Lee 2009)
- Ly-alpha forest to constrain P(k) at small scales and different z's (Most popular method: Narayanan et al 2000; Viel et al 2005;2008)
- Ly-a + SDSS results (Boyarsky et al 2009)
- QSO lensing (Miranda & Maccio 2007)
- Abundance of dwarf satellites of MW (Maccio & Fontanot 2010; Polysensky & Ricotti, 2010)

→ Mass WDM ~ 1- 5 keV

A fashionable (?) candidate:
Sterile neutrinos

Sterile neutrinos as dark matter

Can be prouced by the following mechanisms,
color coded by "warmness" vs "coldness",

- Neutrino oscillations off resonance [Dodelson, Widrow] No prerequisites; production determined by the mixing angle alone; no way to turn off this channel, except for low-reheat scenarios [Gelmini et al.]
- Resonant neutrino oscillations [Shi, Fuller]. Pre-requisite: sizeable leptop asymmetry of the universe. (The latter may be generated by heavier sterile neutrinos [Laine and Shaposhnikov])
- Higgs decays [AK, Petrai]. Assumes the Majorana mass is due to Higgs mechanism. Sterile miracle: abundance a "natural" consequence of singlet at the electroweak scale (which itself may not be seen as natural. Also, inflaton decays can also contribute to the population of dark matter [Tkachev,Shaposhnikov]

“Evidence” for WDM ?

•"missing satellite problem",

•"cusp-core problem'’,

• “Too big to fail”

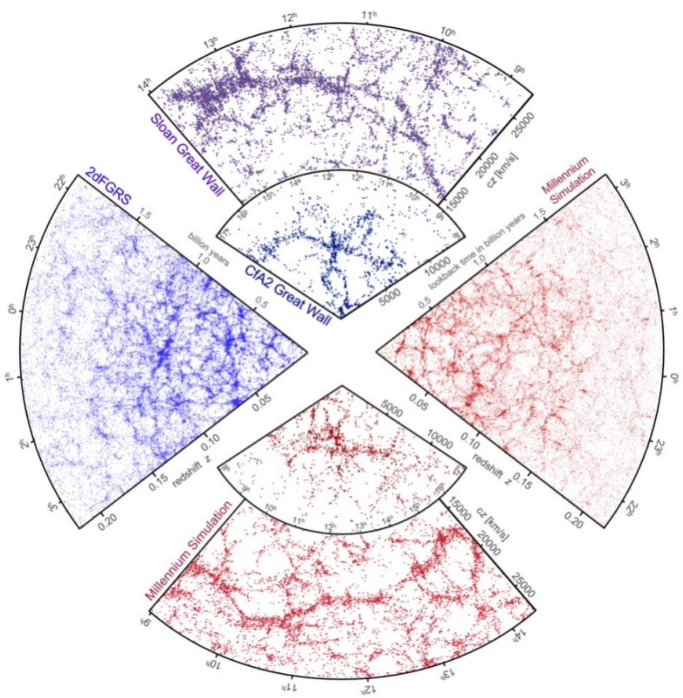
• mini-voids The sizes of mini-voids in the local universe: an argument in favor of a warm dark matter model? Tikhonov et al.

•HI determinations of velocity function profiles
N-Body simulation Comparisons with Virgo results by Arecibo Legacy (ALFALFA)

Problems with CDM at small scales ?

Problems with CDM can perhaps be solved with :

- **New measurements**
- **Better resolution**
- **Additional physics in N-Body simulations (SN, AGN feedback, stellar winds…)**



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

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	$77^\circ \pm 12^\circ$	$215^\circ \pm 20^\circ$
e	0.4 ± 0.1	0.3 ± 0.2
$(m-M)_0$	21^m3	16^m1
$M_{tot,V}$	-5^m0	-1^m2

* Magnitudes are accurate to $\sim \pm 0^m5$ and are corrected for the Galactic foreground reddening.

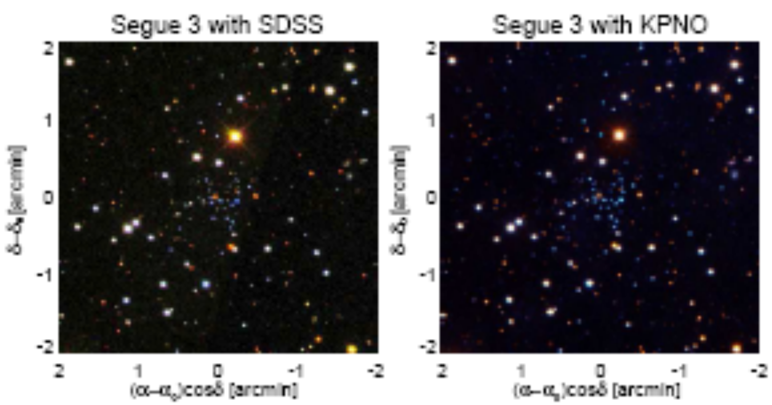


Fig. 4.— Color images covering $4' \times 4'$ region centered on Segue 3 made with SDSS (left) and KPNO (right) data. SDSS image is made with g, r and i band frames. KPNO image is made with g and r band frames.

Einasto vs NFW

CDM Simulations
→ cusps
rather Einasto
profiles than NFW

Ma Chung Pei,
Chang, P.,
Zhang, 2009

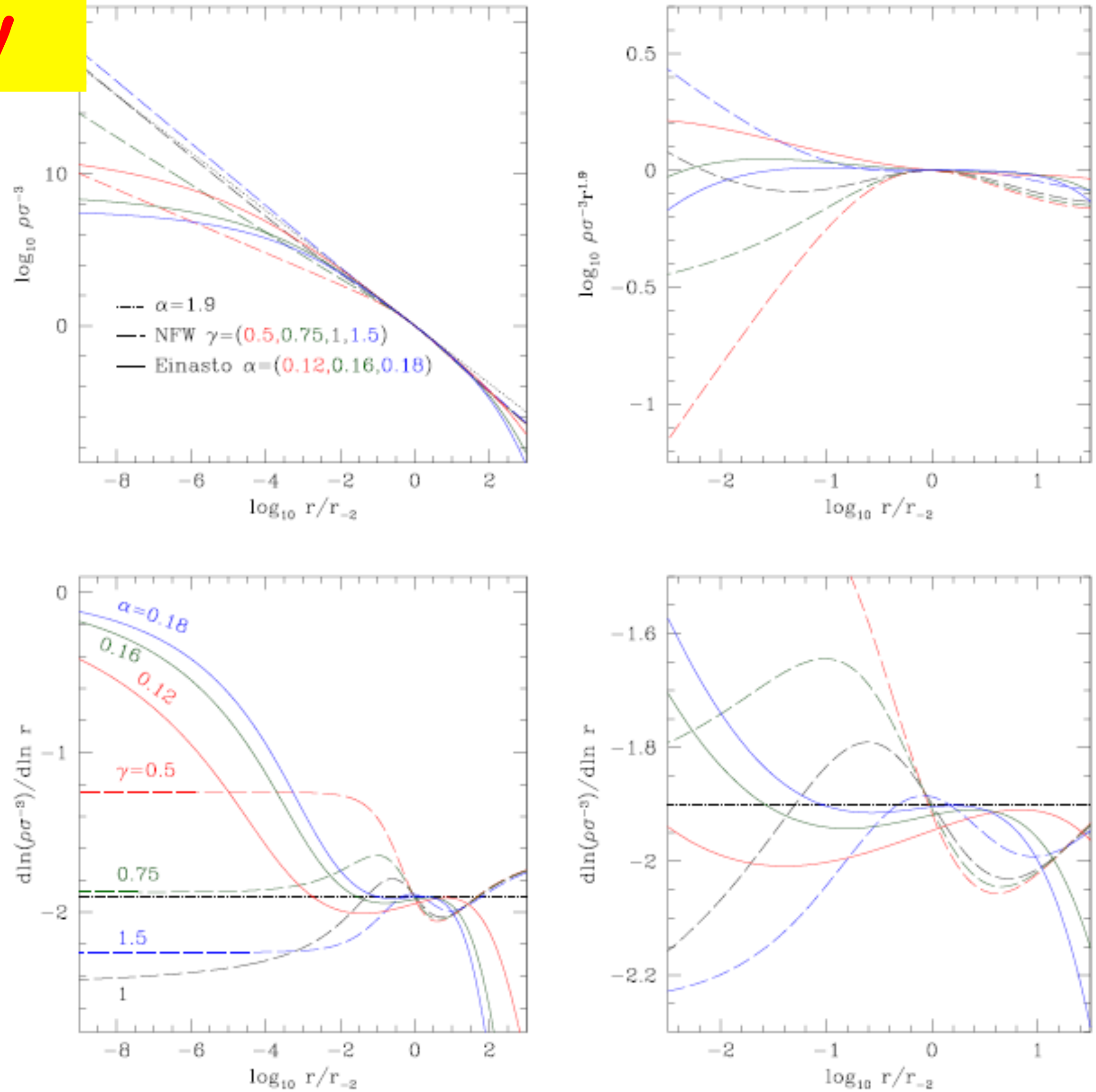


Figure 1. Radial profiles of the pseudo-phase-space density $\rho/\sigma_r^3(r)$ (upper panels) and the corresponding logarithmic slope $d\ln\rho/\sigma_r^3(r)/d\ln r$ (lower panels) obtained from the spherical Jeans equation with $\beta = 0$ for seven input halo density profiles: Einasto (solid) with $\alpha = 0.18$ (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 $r = r_{-2}$.

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 Y. (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 DM
is a challenge for the 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 degenerate

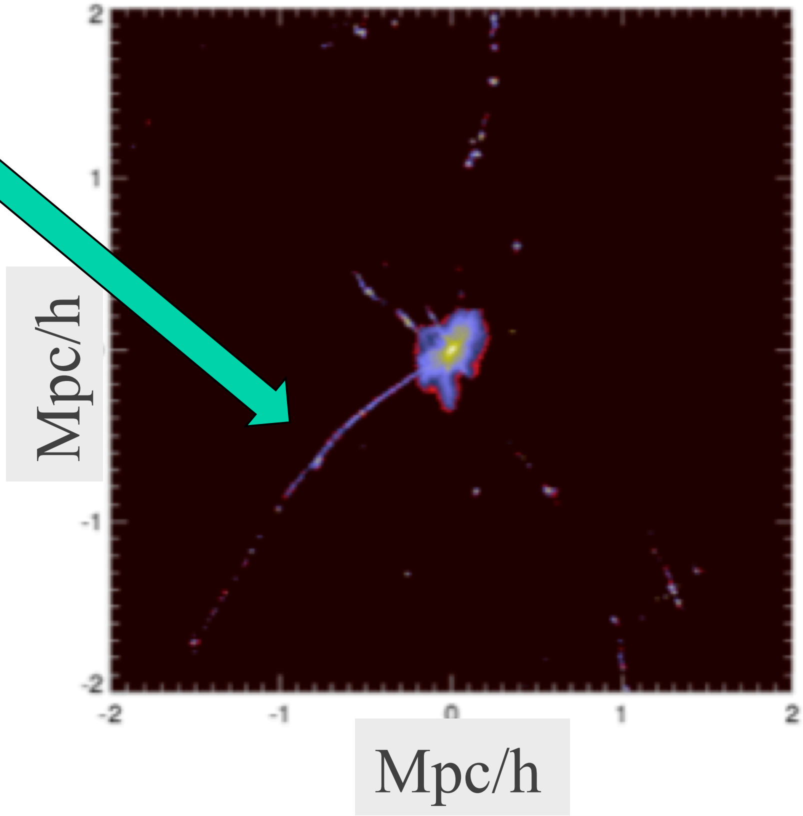
Surroundings of high z galaxies hide important information of the nature of dark matter

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

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

Semboloni+ (2011)

Van Daalen+(2011)

Shale + :OWLS simulation

➔ Consequences on WL cosmological parameters fits

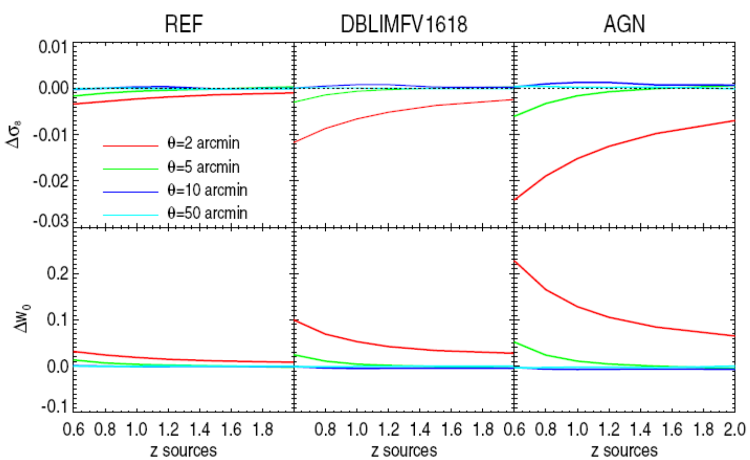


Figure 4. Top (bottom) panels show the deviation of the inferred σ_8 (w_0) from the true reference value $\sigma_{8,\mathrm{ref}} = 0.74$ ($w_{0,\mathrm{ref}} = -1$) as a function of source redshift, when the amplitude of the ellipticity correlation function $\xi_+(\theta)$ is used to estimate the cosmological 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.

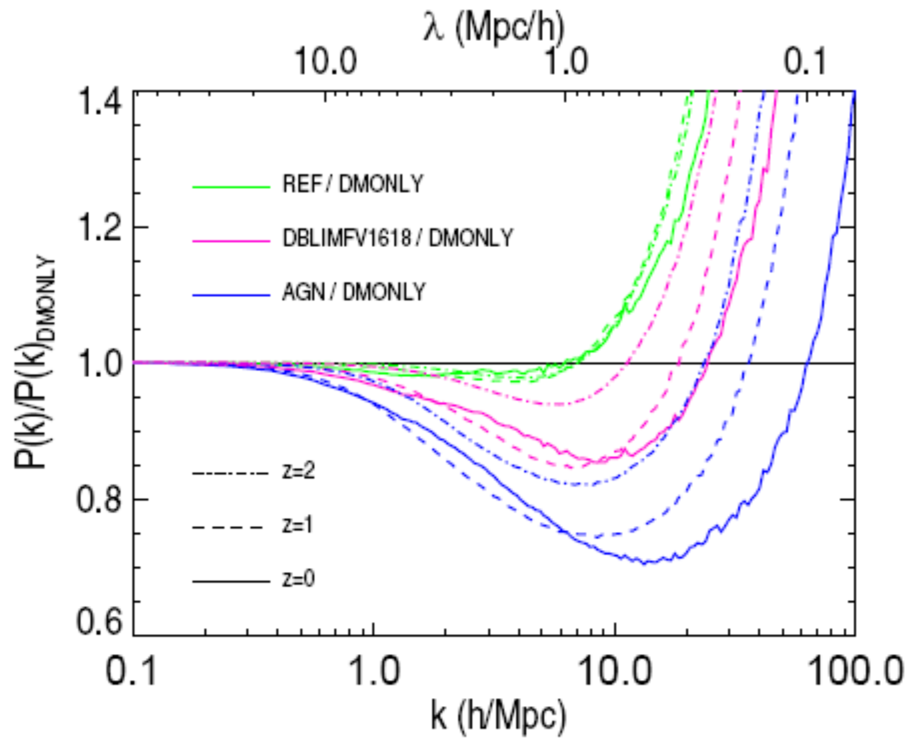
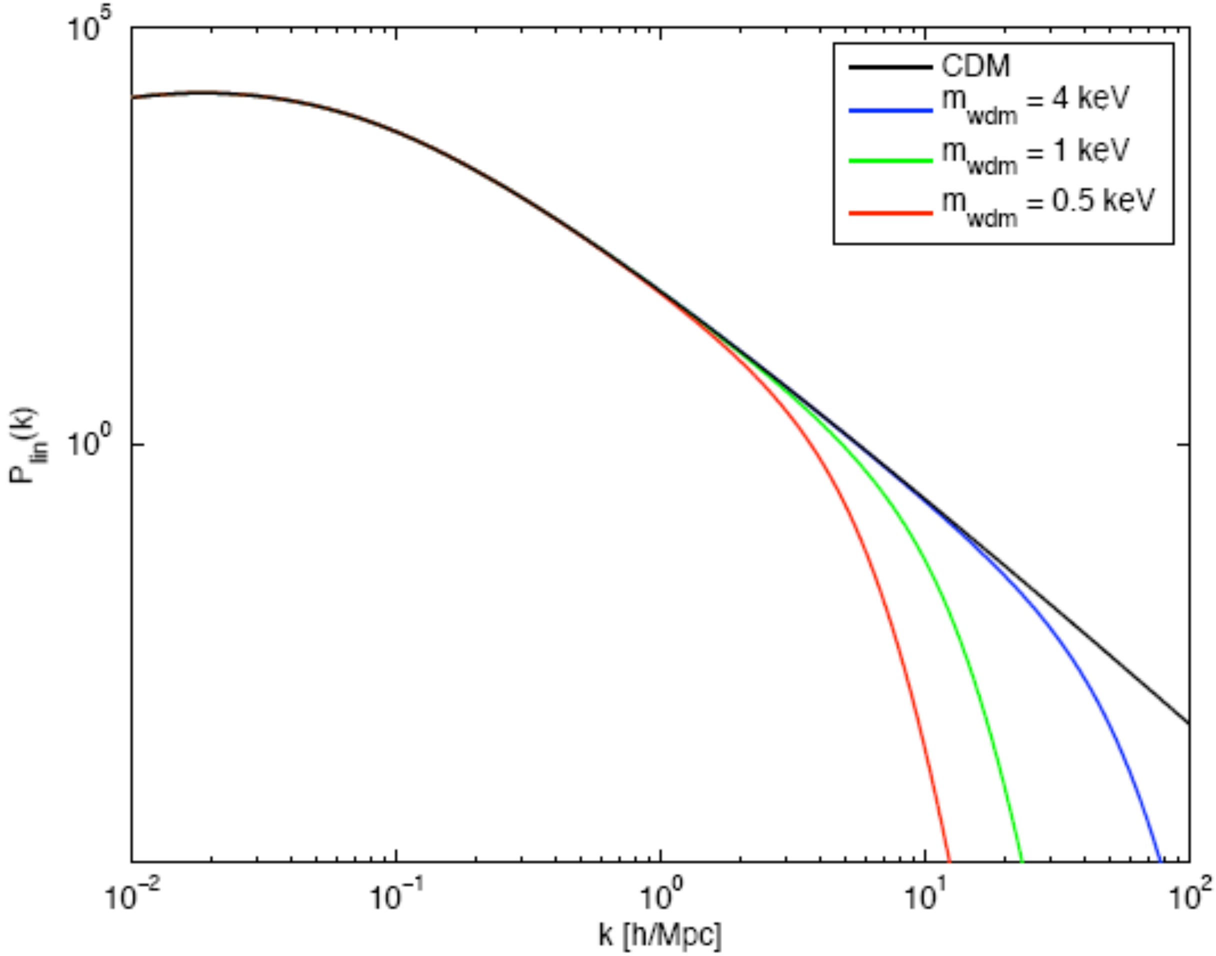


Figure 1. Ratio between the power spectrum of matter fluctuations measured from the simulations with baryons and the one measured from the DMONLY simulation. The ratio for the REF simulation is shown in green, the one for the AGN simulation is shown in blue, and the one for the DBLIMFV1618 model is shown 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

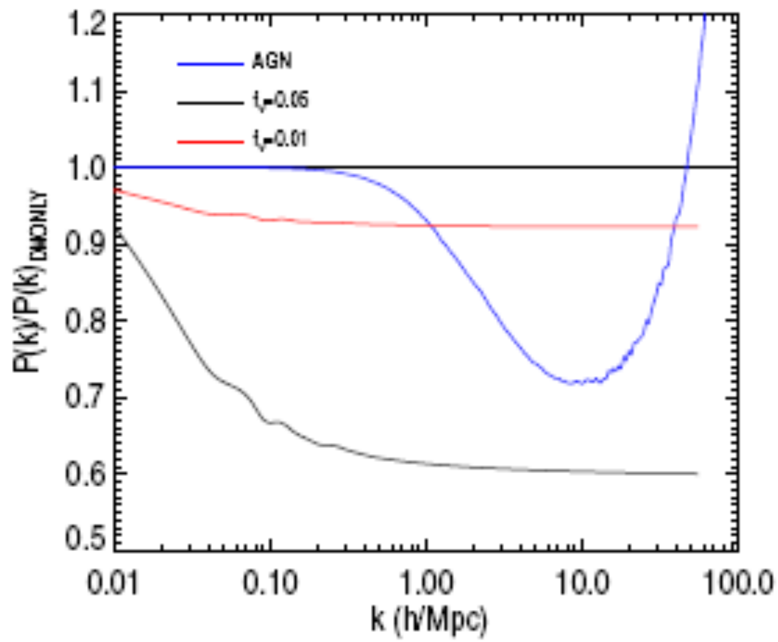


Figure 14. Ratio of the AGN/DMONLY power spectra (blue line), and dark matter power spectra with $f_\nu \equiv \Omega_\nu/\Omega_m = 0.01$ and 0.05, which correspond to neutrino masses of $\sum m_\nu \sim 6.0$ and $\sum m_\nu \sim 1.2$ eV, respectively. The effect of massive neutrinos on the power spectrum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

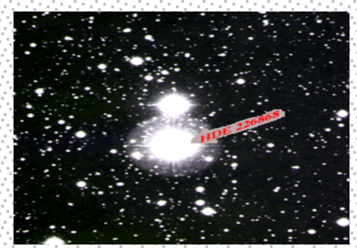
Very different DM candidates

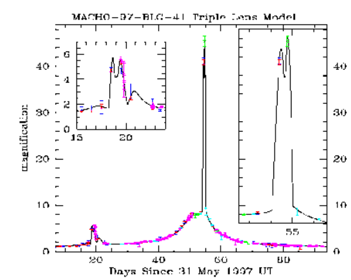
Modified Gravity

Cold Molecular Hydrogen

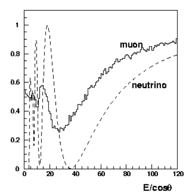
MACHOs

Black holes





SIMPs

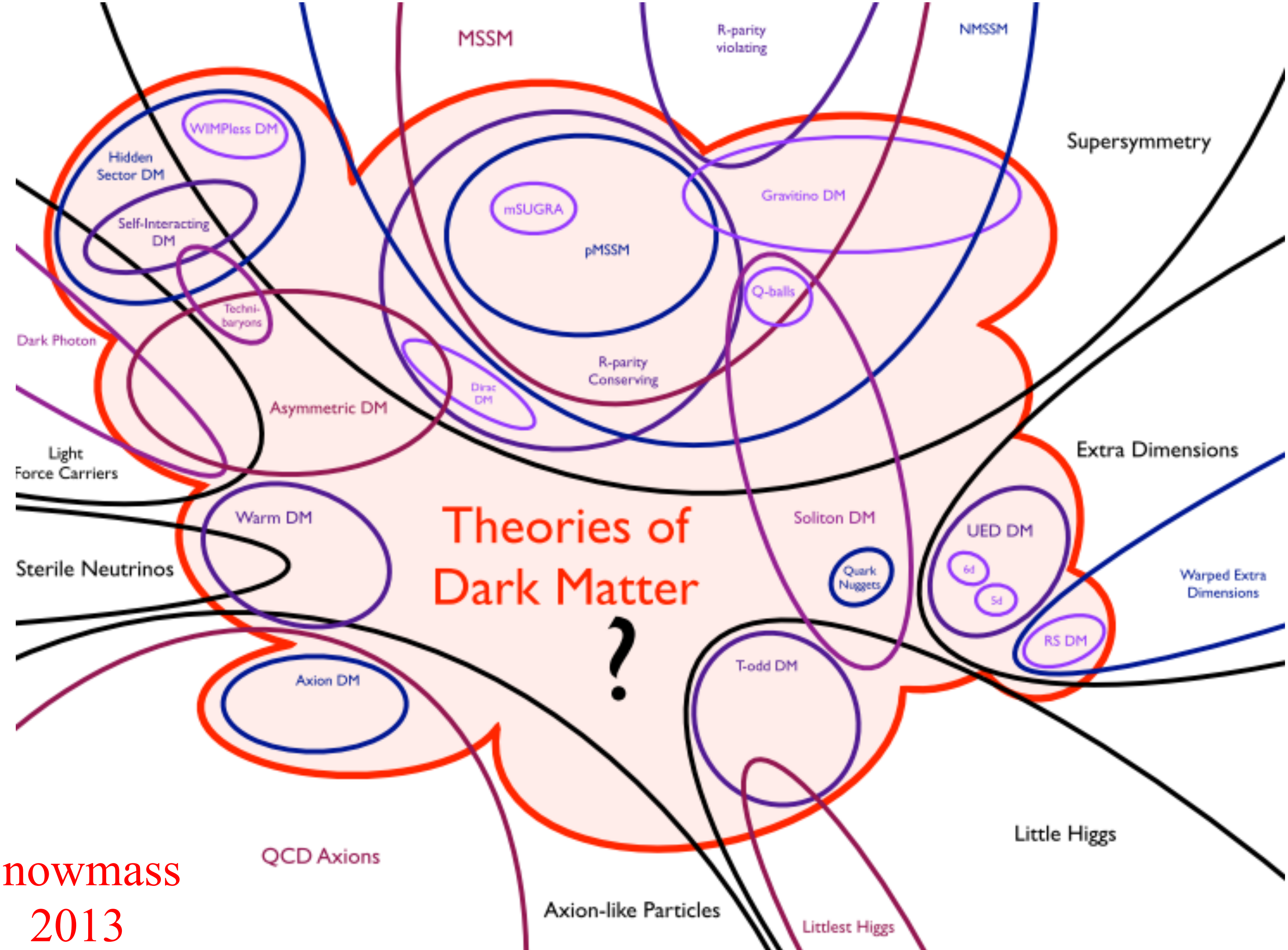


1Neutrino

2. WIMPs
Weakly interacting massive particles
10-1000GeV

3. Light axions

Exotica



Snowmass 2013

Why WIMPs?

“WIMP” = “Weakly Interacting” Massive Particles

G. Altarelli (2013) :
« still most optimal candidates !»

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…

Particle physics preferred DM: SUSY Neutralinos ?

- A natural particle physics solution
- Stable linear combination gauginos and higgsinos (LSP)

$$\chi = \alpha\tilde{\gamma} + \beta\tilde{Z} + \gamma\tilde{H}_1^0 + \delta\tilde{H}_2^0$$

- SUSY > 7 parameters MSSM →
- Experimental Constraints LEP, pp, b-->sγ, + **LHC** ...

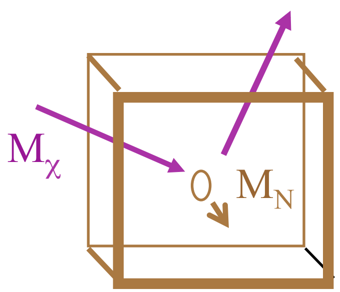
Look everywhere possible !

Direct and Indirect

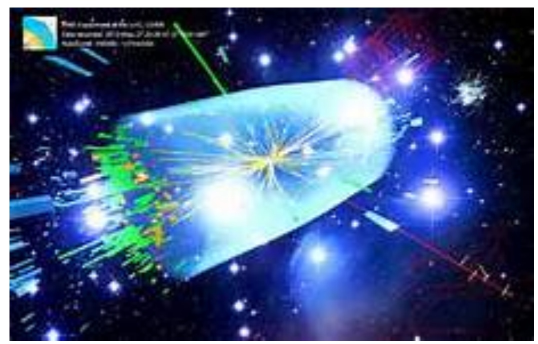
Detections

WIMP searches > 30 years

Direct detection

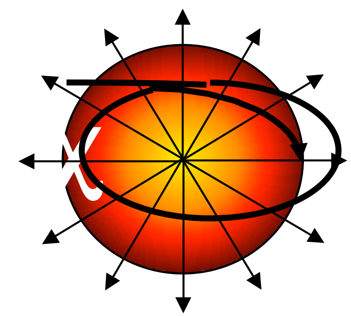


Ge, Si, NaI, LXe, …



Accelerator particle production, eg, LHC

Indirect detection

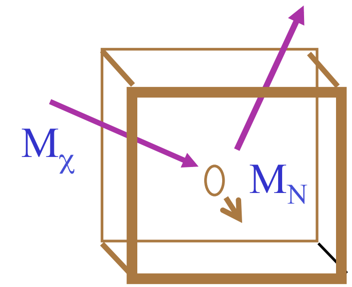


ν, γ, p, e^+

NO convincing signal found yet !

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

- Exponential recoil energy distribution

Ge, Si, NaI, LXe, …

event rate per unit mass

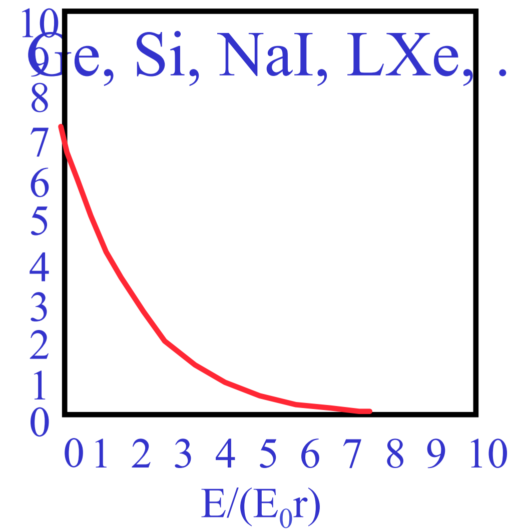
total event rate (point like nucleus)

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

recoil energy

incident energy

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



- Rates: Weak interactions or smaller

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

Differential rate for WIMP elastic scattering

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

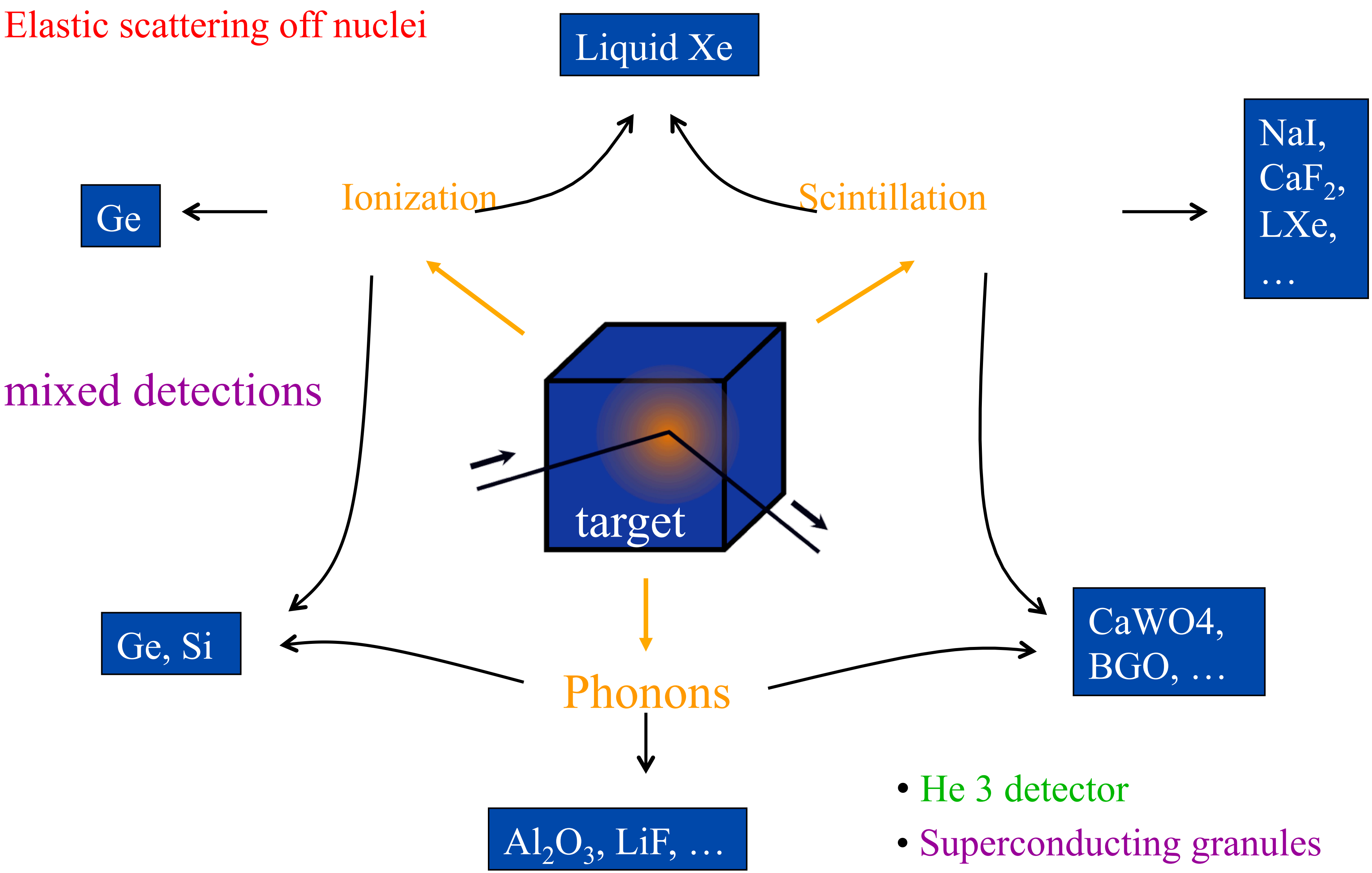
$$v_{\min} = \sqrt{\frac{m_N E_{th}}{2 m_r^2}}, v_{\max} = v_{esc}$$

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

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

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

WIMP direct detection schemes with and w/o background rejection

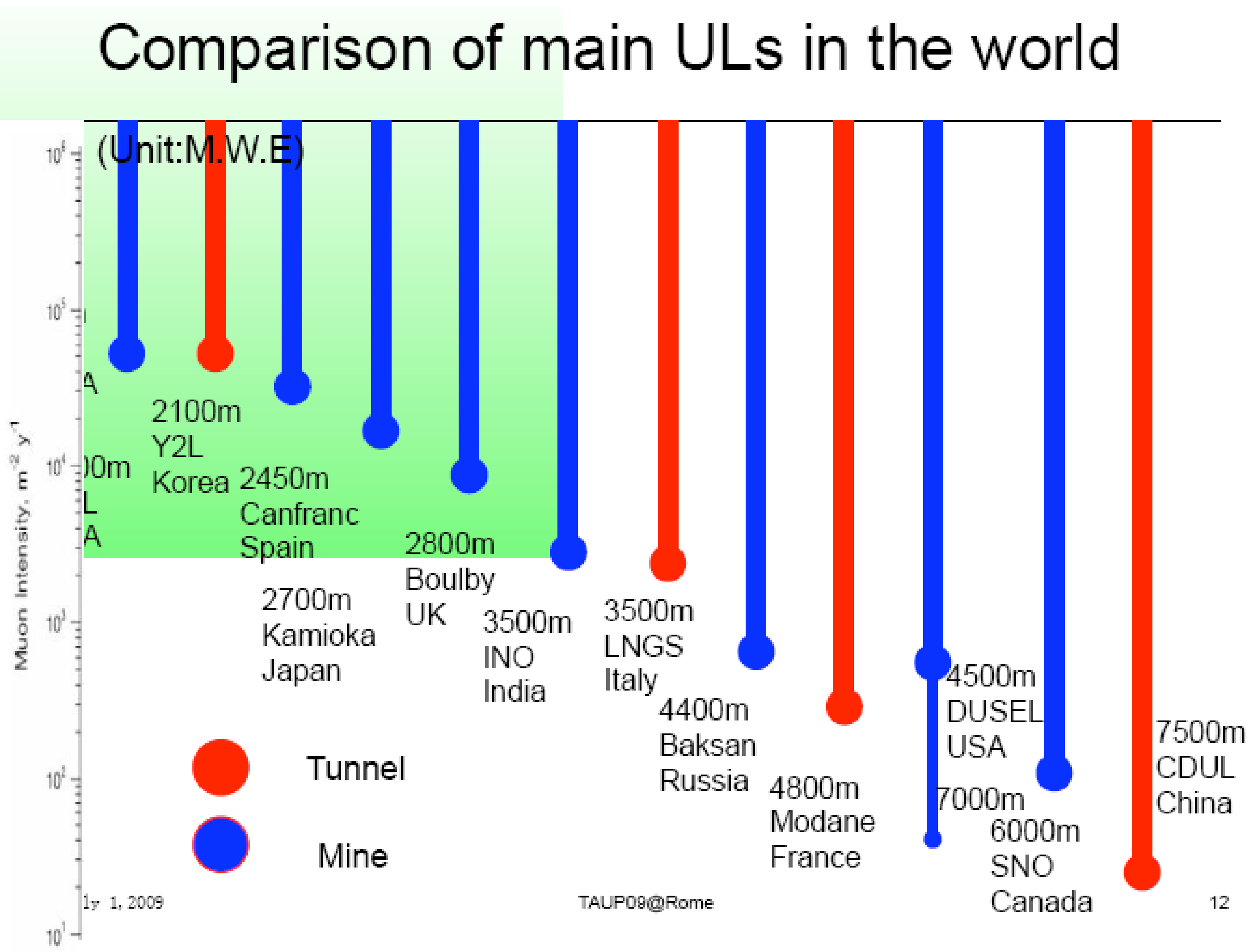


- He 3 detector
- Superconducting granules
- Freon aerogel

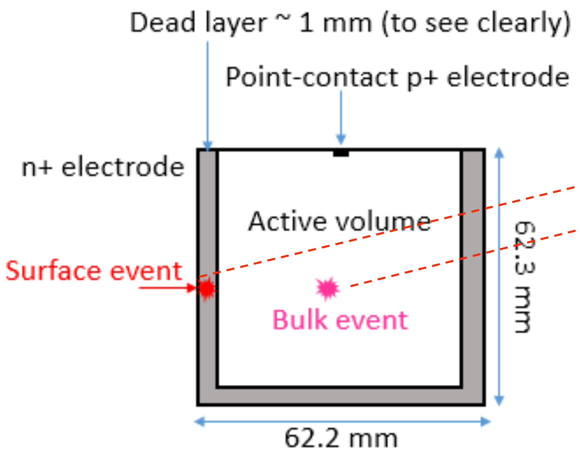
Opportunity in Jinping, Sichuan for direct detection DM detectors

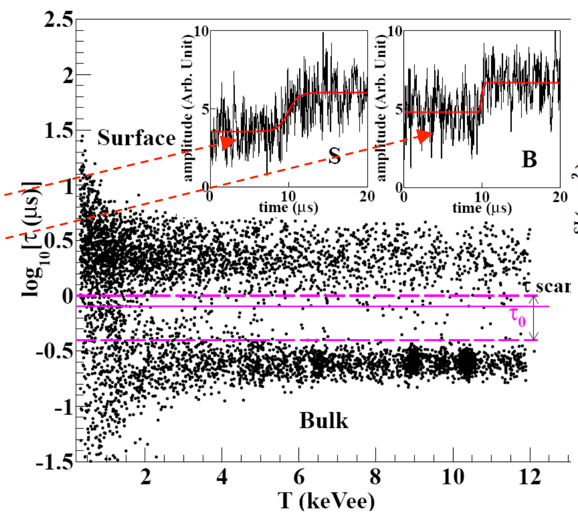
Yue Qian 岳骞

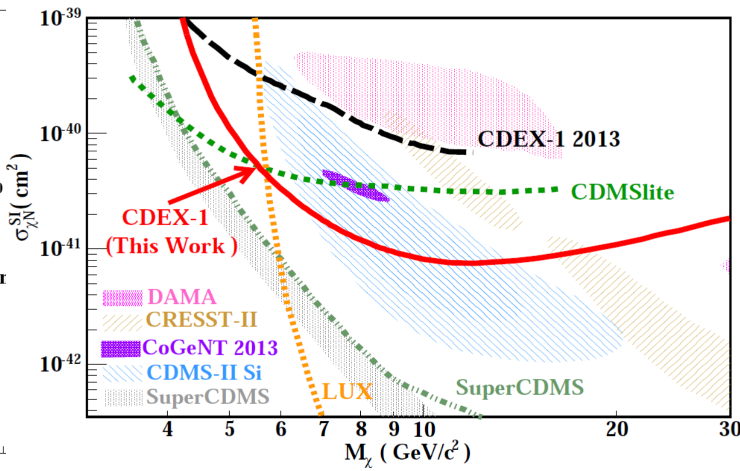
Great mountain coverage



CDEX-1 experiment







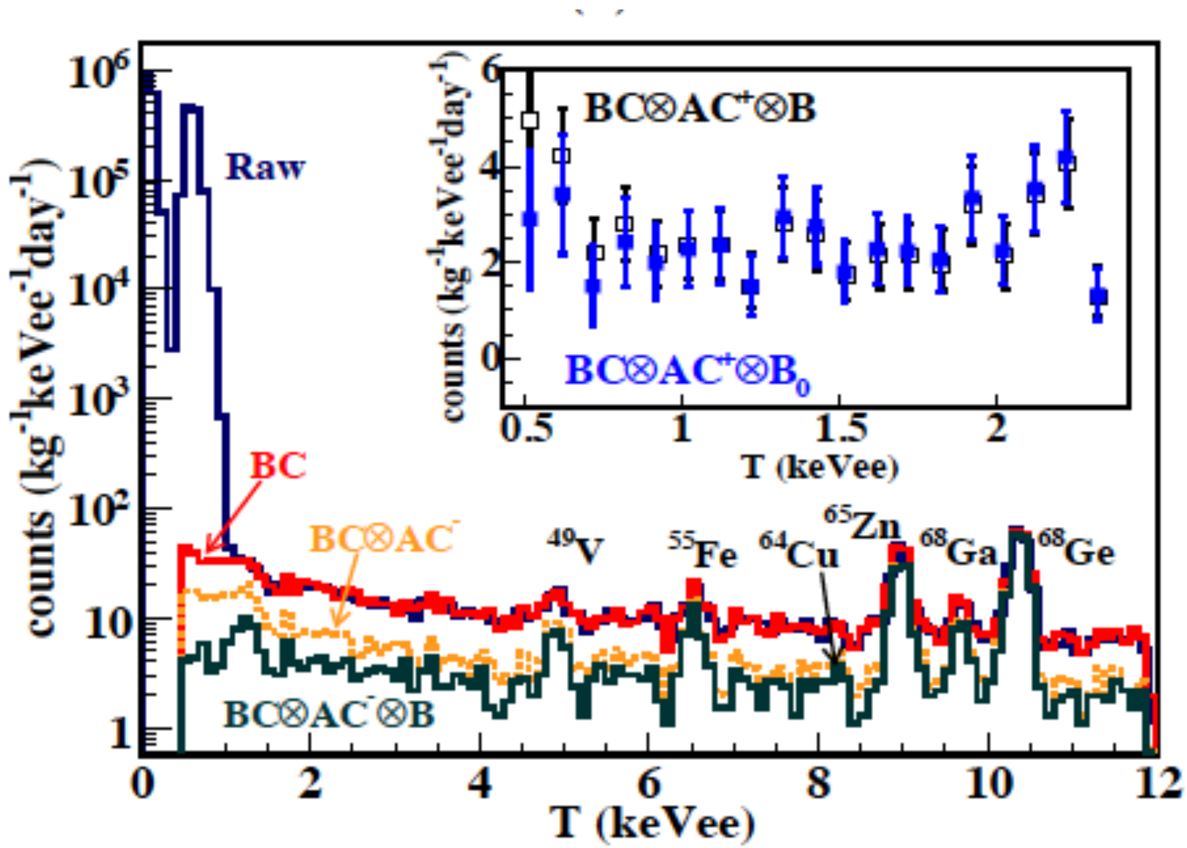
Bulk/Surf Discrimination

C1A 1kg-PPCGe + NaI(Tl)

Q.Yue et al., arXiv:1404.4946. (2014)
Accepted by Physical review D (RC)

- ✓The best sensitivity by PCGe in the world;
- ✓Exclude the regions favored by CoGeNT.

CDEX: reaching best present Ge limits in < 5 years!



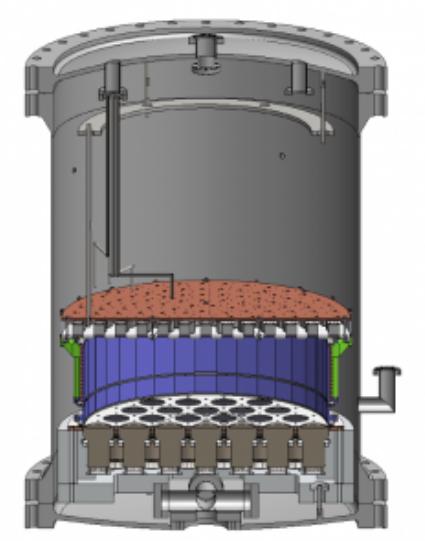
1 kg crystal

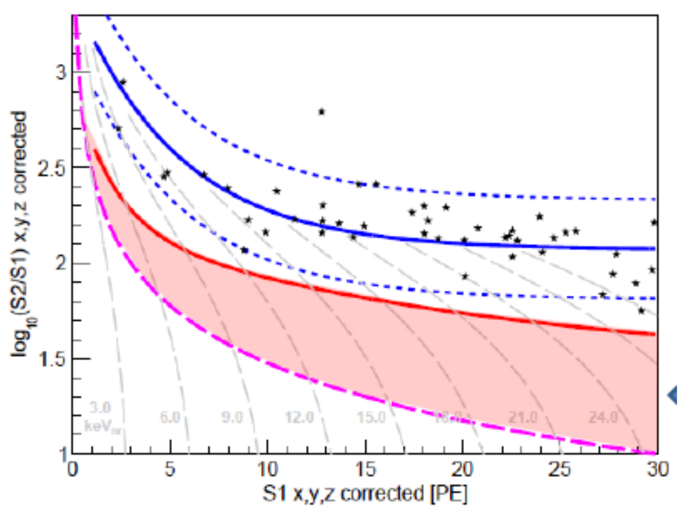
Y.Qian et al., arxiv 1404.4946

Panda-X: inauguration end march 2014

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

Project lead by SJTU



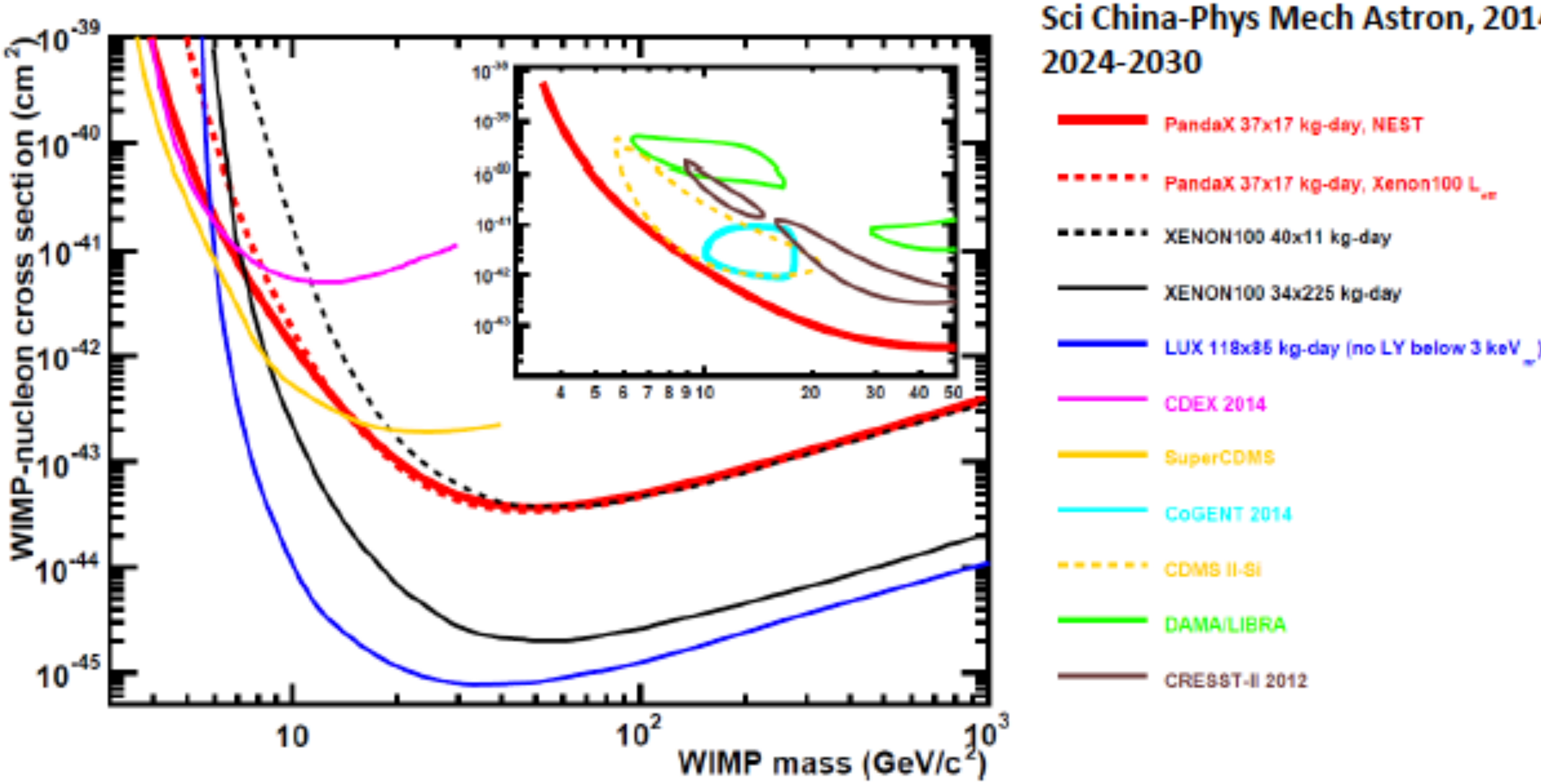


No events found in the DM search region!

Results already in summer 2014

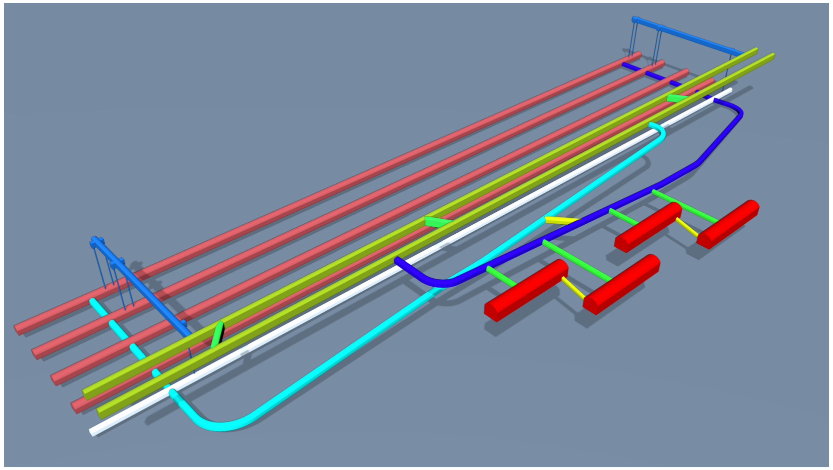
PandaX-I first results

Sci China-Phys Mech Astron, 2014, 57(11): 2024-2030



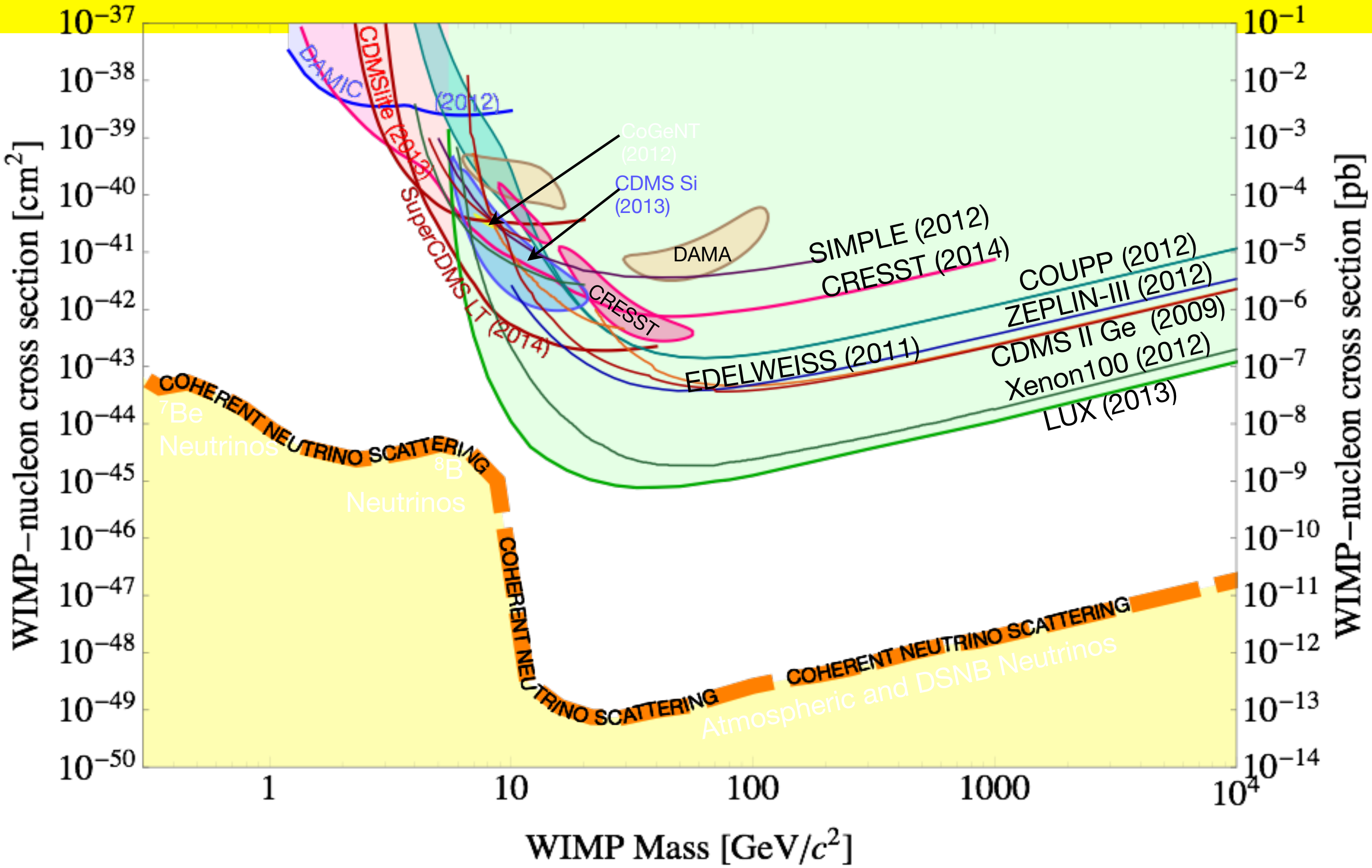
- Our results disfavor previously reported signals
- At low mass region, our results significantly better than XENON100 first results with similar exposure
- Limits similar using NEST or XENON100 L_{eff} at high mass; the latter gives a more conservative limit at low mass

CJPL Extension : 5 more cavities in 2015!



- Four 14m*14m*120m tunnel
- 20 times larger than CJPL-I

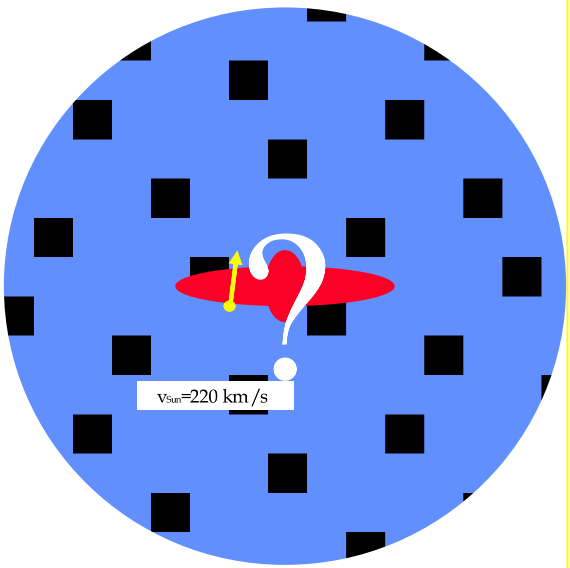
Direct detection Current Situation (Sep 2014)



Some comments, though…

Usual assumptions of DM distribution in our Galaxy

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

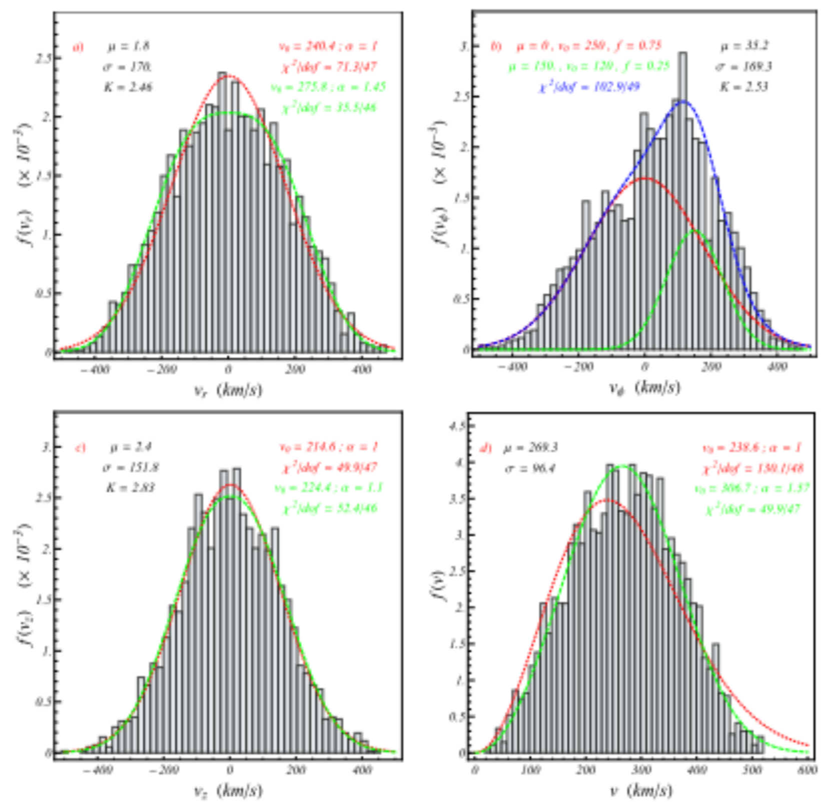


Figure 5: *Velocity distributions of dark matter particles ($N_{ring} = 2,662$) in a ring $7 < R < 9$ kpc, $|z| < 1$ kpc around the galactic plane.*
a) Radial velocity v_r, with Gaussian (red) and generalized Gaussian (green) fits (cfr. Eq. (2.1)).
b) Tangential velocity v_ϕ, with a double Gaussian fit.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

Future: directional detectors?

How to convince ourselves a signal is from galactic DM?

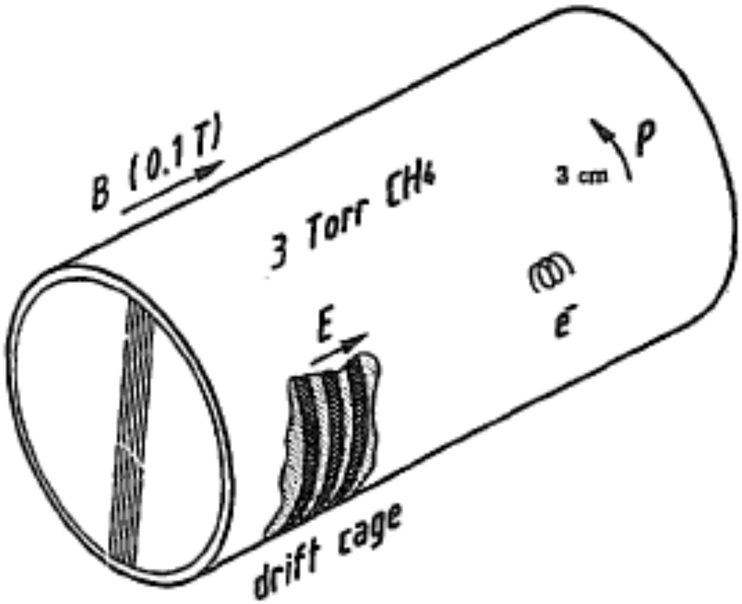
DM signal signatures

- Detection with >2 nuclei
- Correlation with Galactic Center

➔ Directionality important

Can help with solar neutrino floor!

And 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

Best Directional DM detector project todate:

MIMAC $1m^3$ in preparation

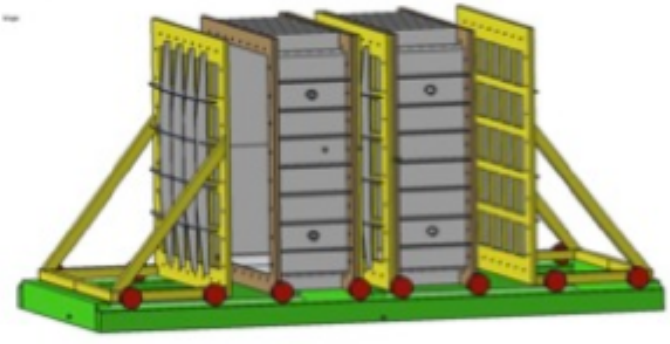
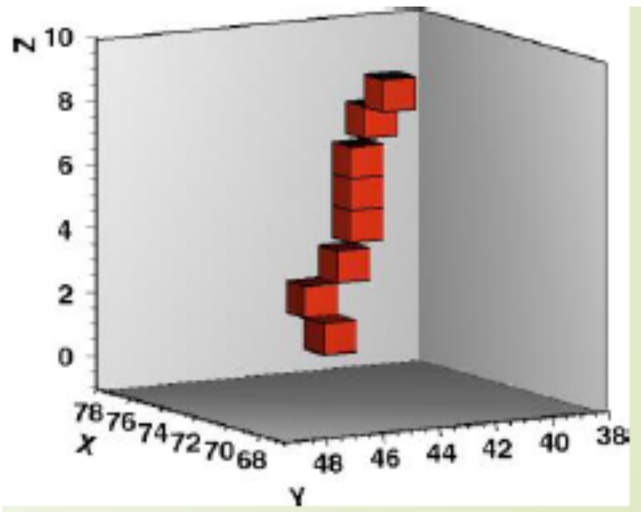


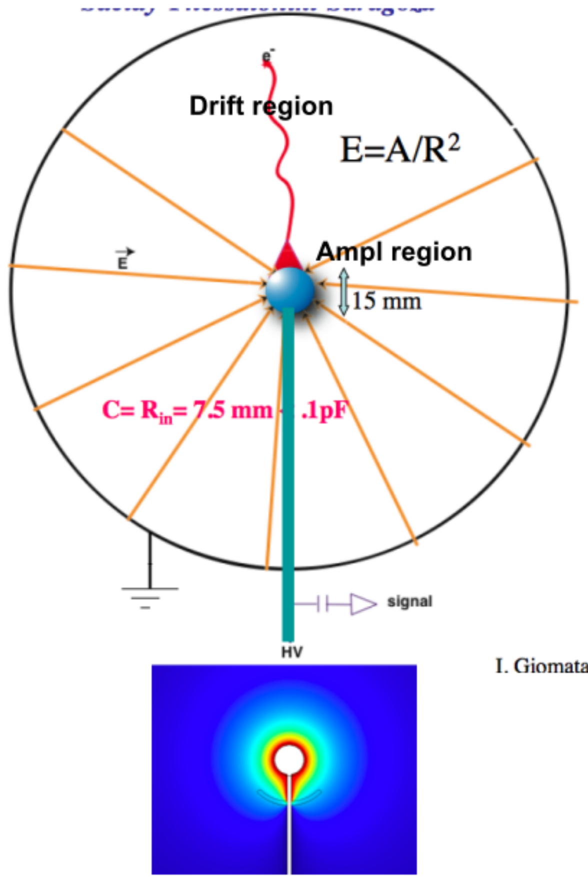
Figure 5. The preliminary mechanical design of the demonstrator of MIMAC -1 m^3 .



Grenoble Daniel Santos et al...

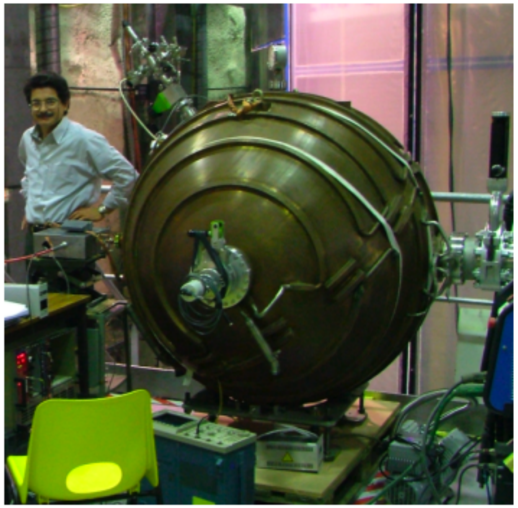
Tsinghua + IHEP + Europe + Canada collaboration for neutrino and DM

Spherical Proportional Counter

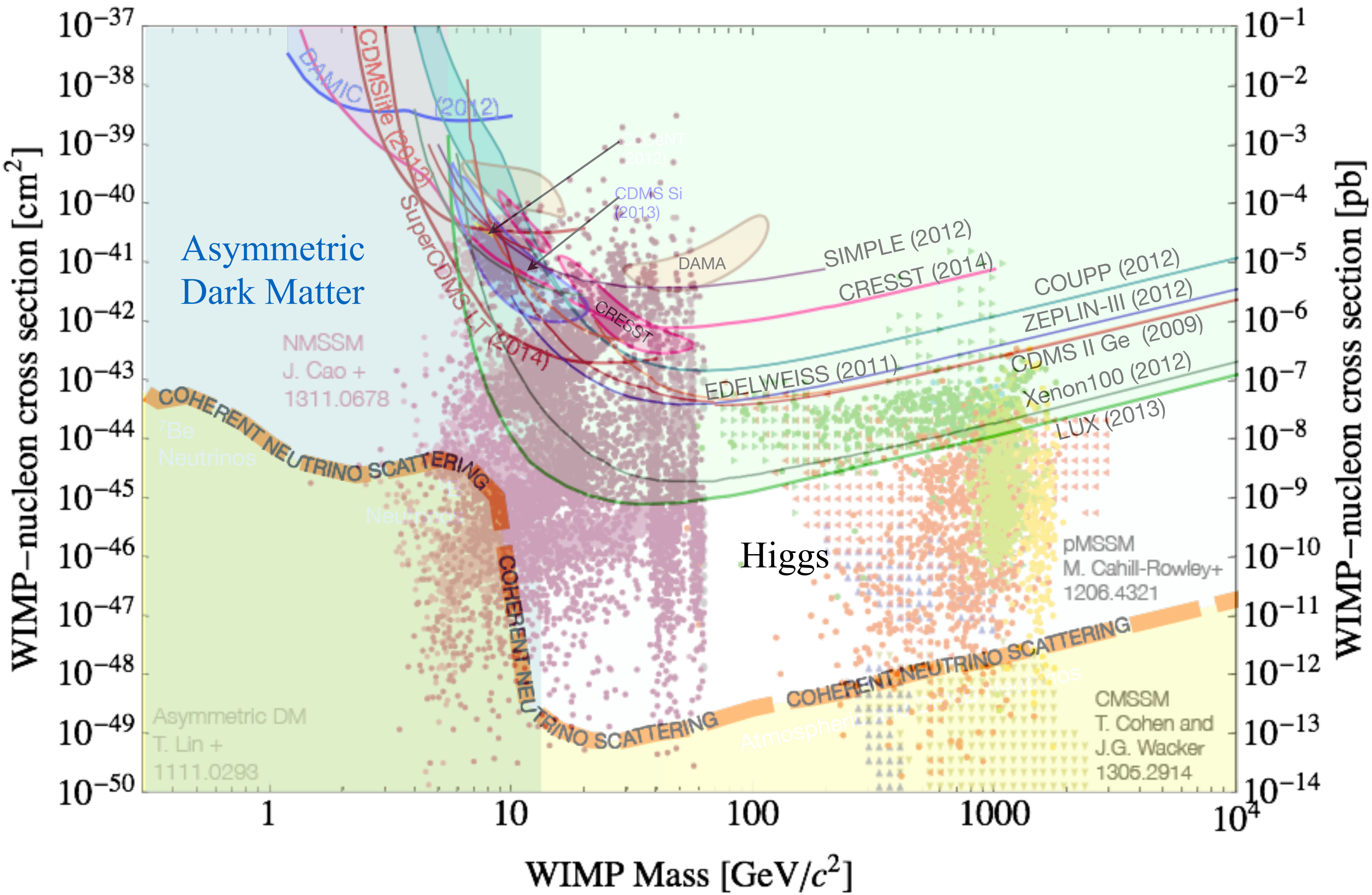


I. Giomataris

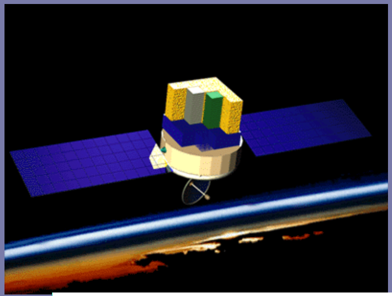
- Low threshold (low C)
- Fiducial selection (risetime)
- Flexible (P, gaz)
- Robust
- Simple/cheap
- 2 LEP cavity tested 1.3 m Ø

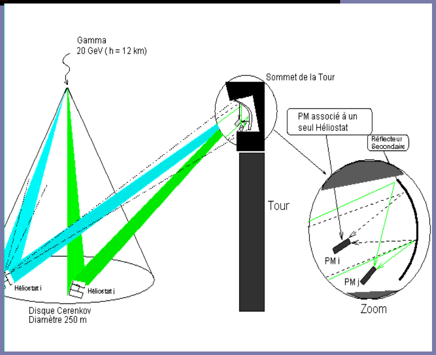


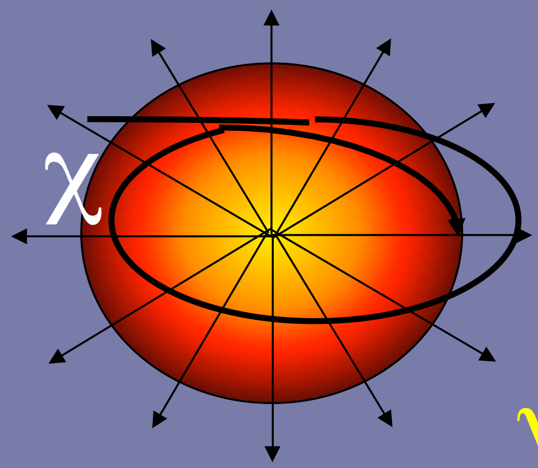
Direct detection Current Situation (Sep 2014)

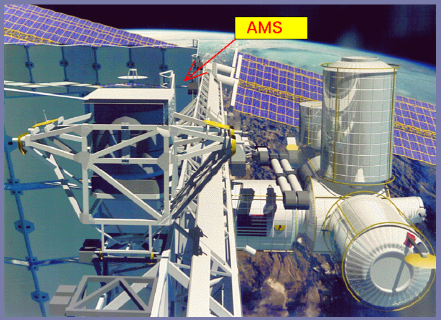


WIMPs Indirect Detection

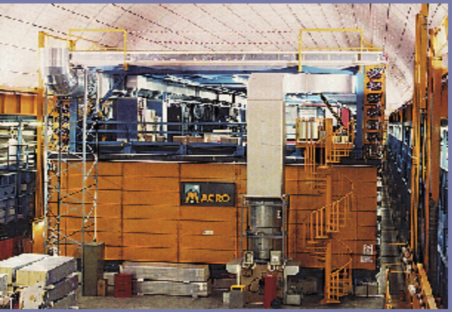


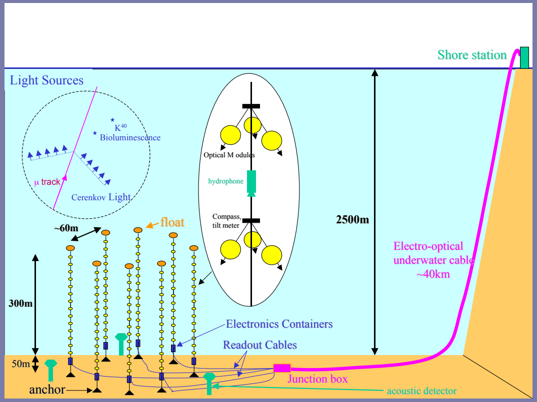


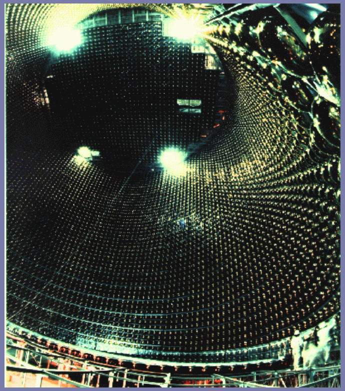


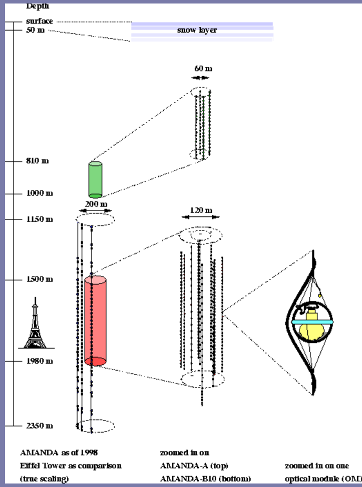


$\nu, \gamma, \bar{p}, e^{+}$





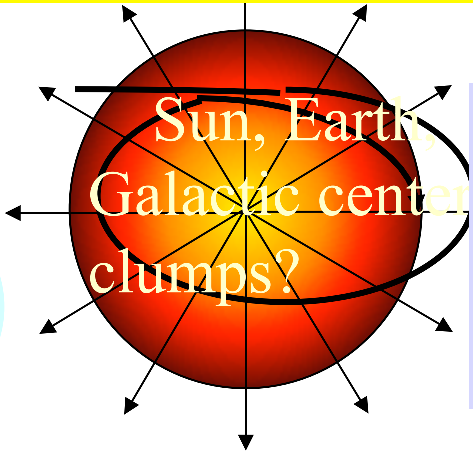




Indirect Detection: Principle

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 ?

DM searches: a summary

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

  need confirmation 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!!!

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 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

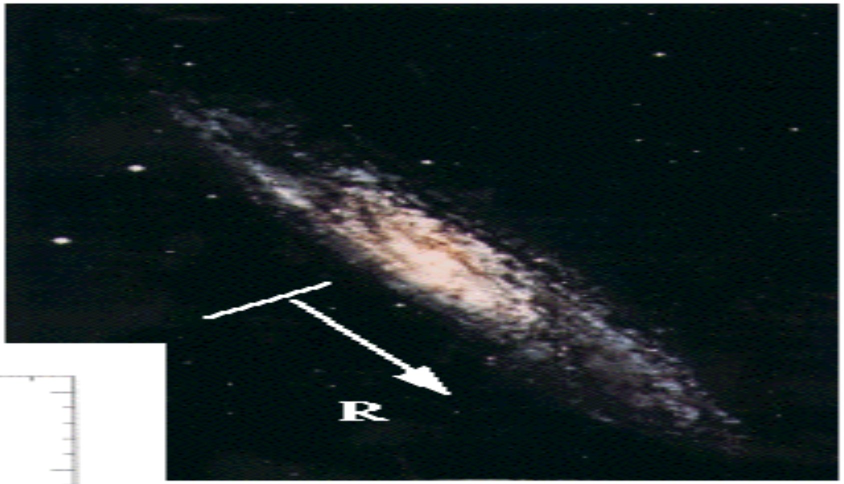
Famaey & Mc Gaugh

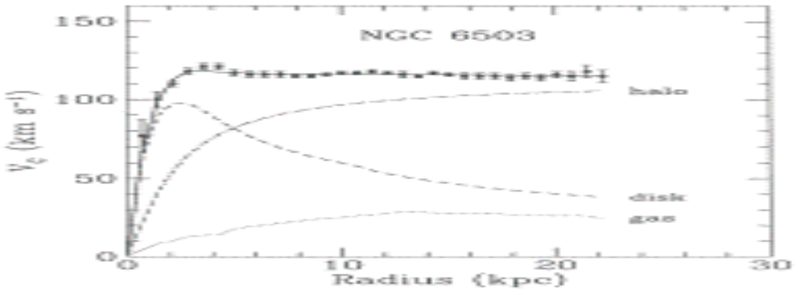
- **MOND-** Milgrom /TEVES-Beckenstein needs neutrinos to explain Bullet Cluster…
- **MOG** : Moffat and collaborators

  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

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...

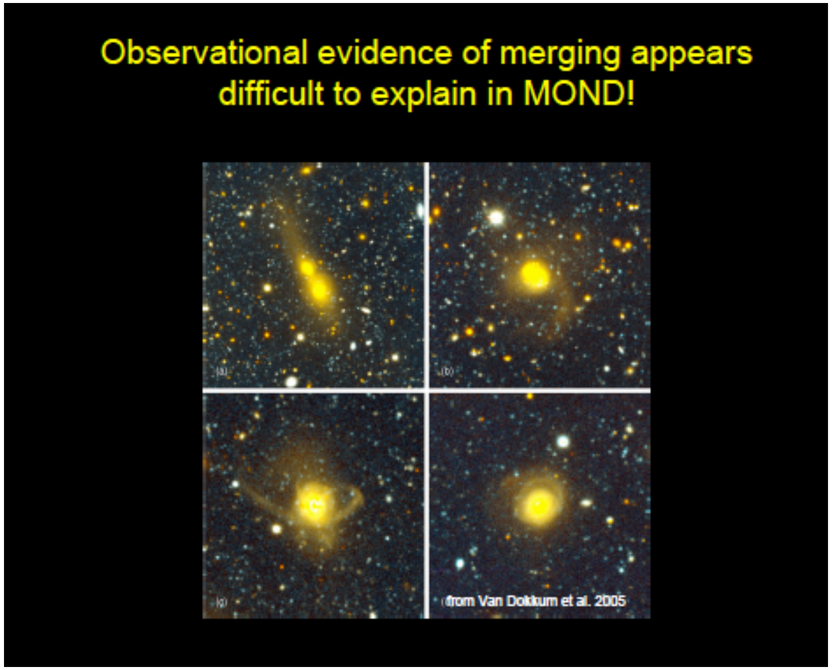
N-body simulations with no DM?

- Modified gravity f(R) simulations often have DM

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

  Status?

- Torsion model, etc…?



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 ?

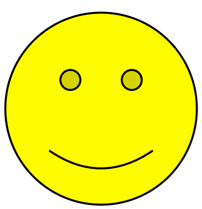
- More work on baryonic N-body simulations needed!

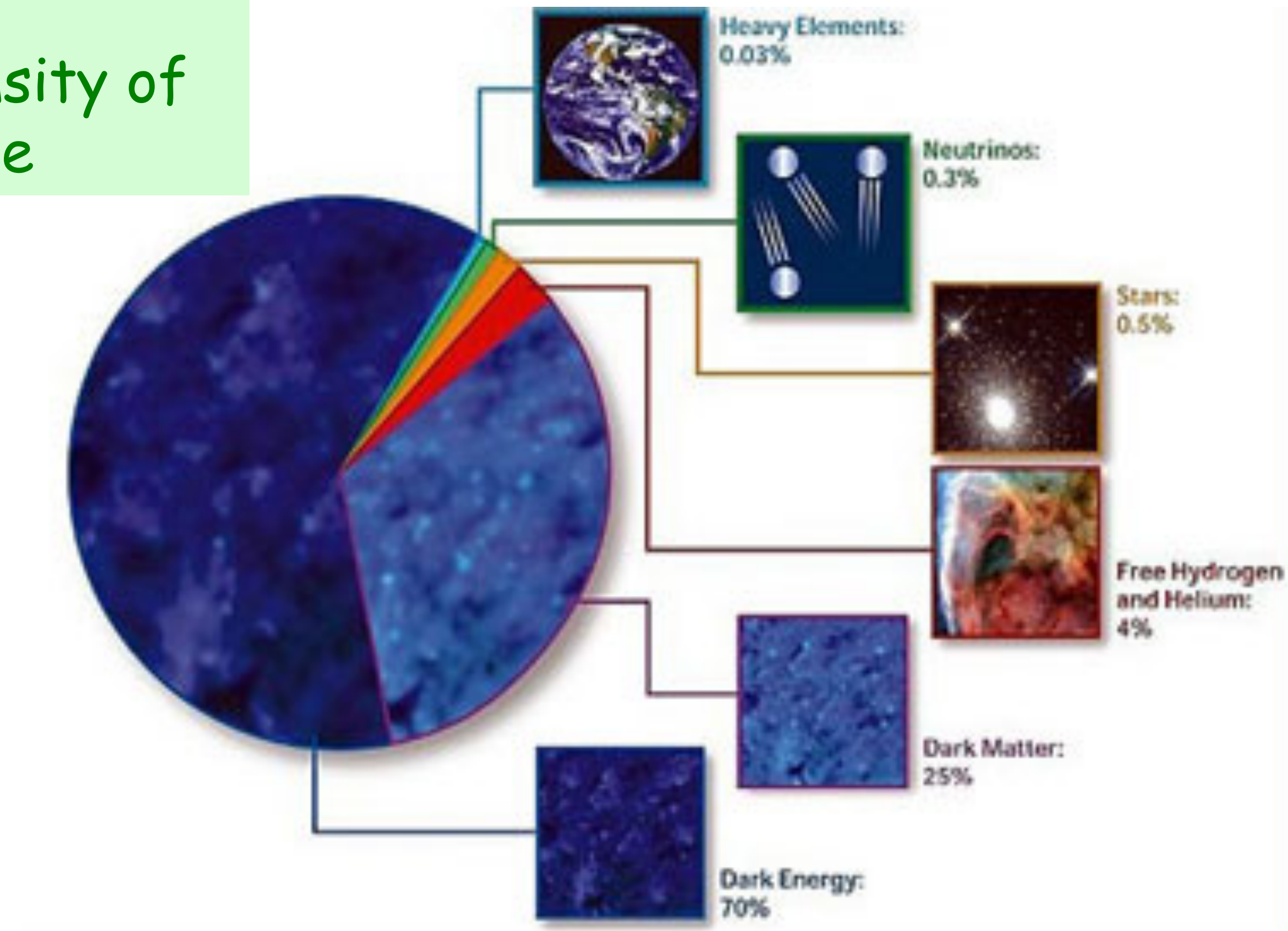
Particle physicists love CDM
but need to find CDM
in
accelerators and DD/ID experiments!

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 !



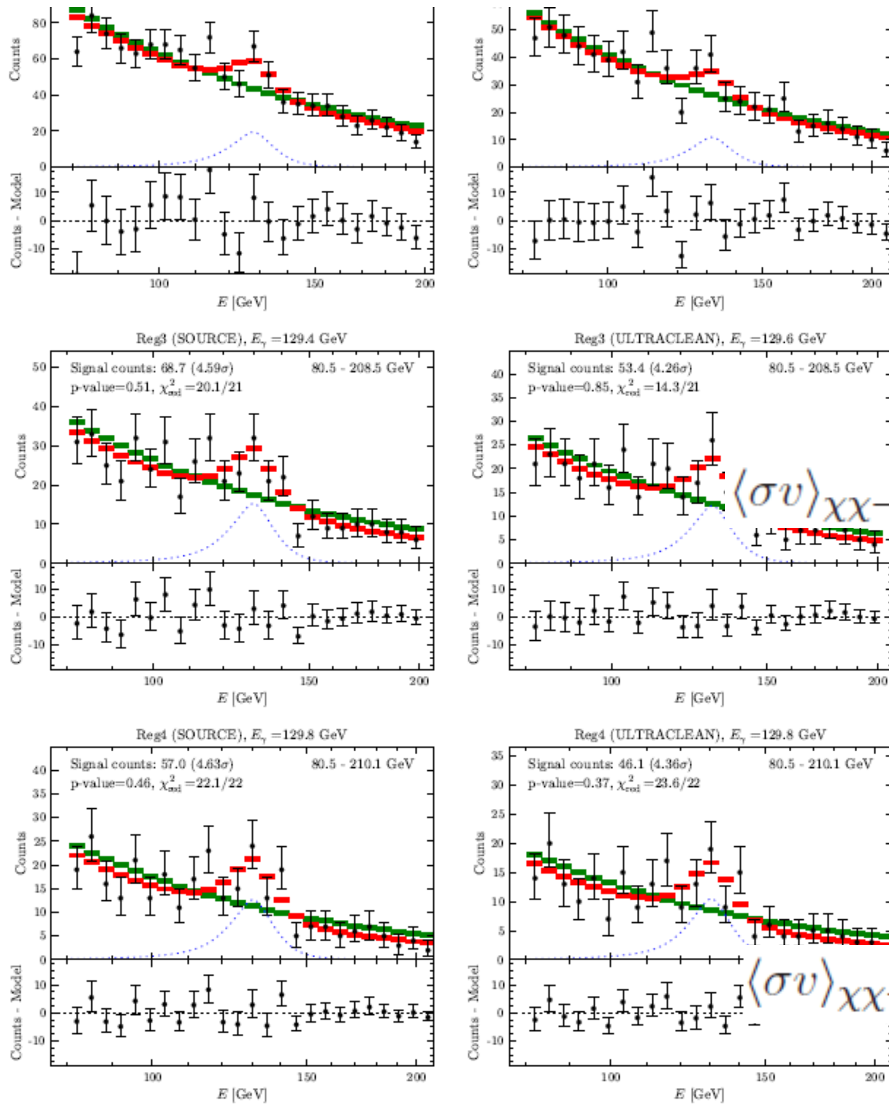


Graph source: Wikipedia

Thank you for your attention !

Dankjewel !

Fit to the data with line spectra for different DM density profile



Weniger, arXiv: 1204.2791

Einasto

$$\rho_{\rm dm}(r) \propto \exp\left(-\frac{2}{\alpha_E}\frac{r^{\alpha_E}}{r_s^{\alpha_E}}\right)$$

$$\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = (1.27 \pm 0.32^{+0.18}_{-0.28}) \times 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$$

NFW

$$\rho_{\rm dm}(r) \propto \frac{1}{(r/r_s)^{\alpha}\,(1+r/r_s)^{3-\alpha}}$$

$$\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = (2.27 \pm 0.57^{+0.32}_{-0.51}) \times 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$$

The line feature (120-140GeV) is clear in the spectrum. Excesses is around the GC.

Fit data with two lines gives marginally better result.

SU, Finkbeiner, arXiv:1205.

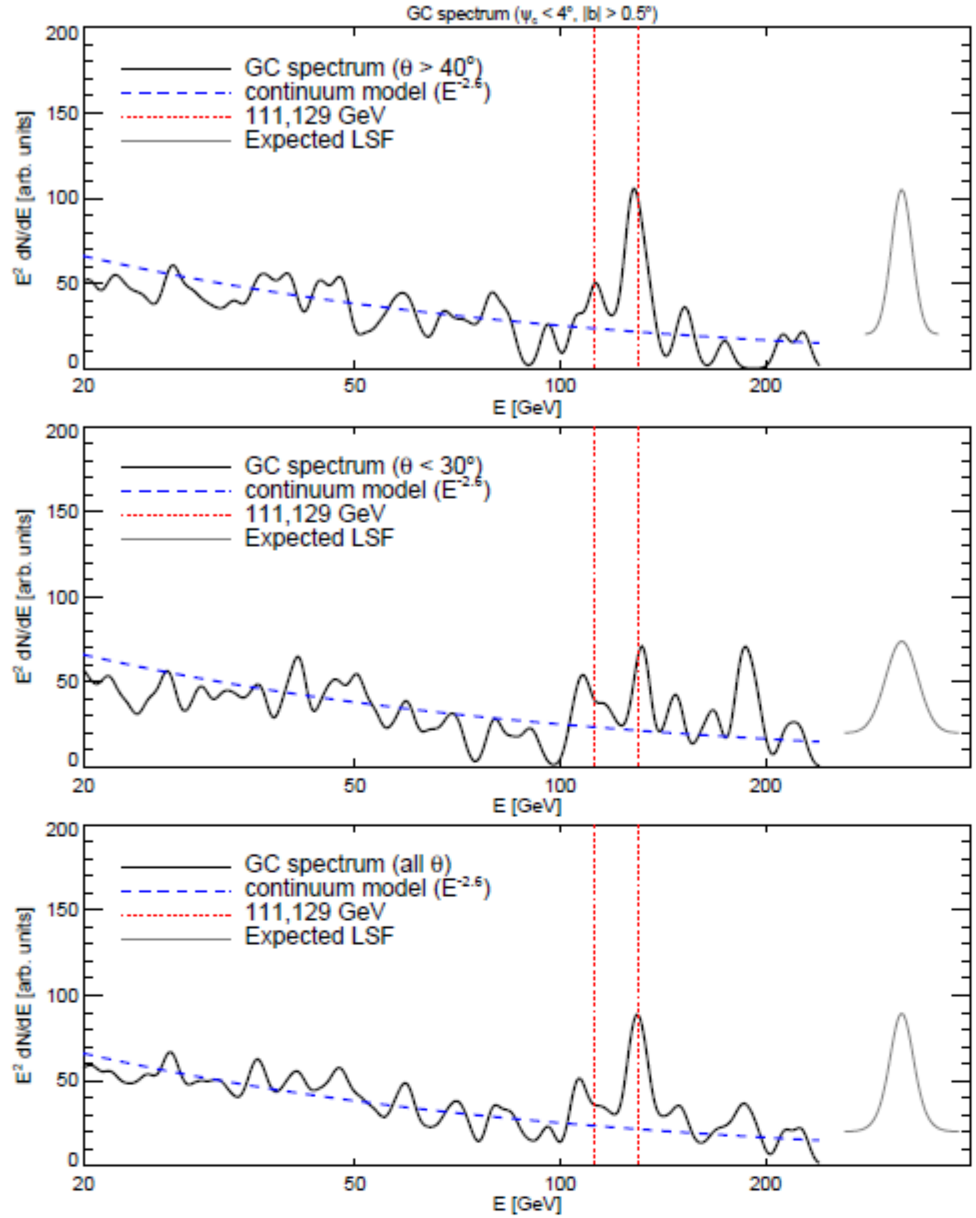
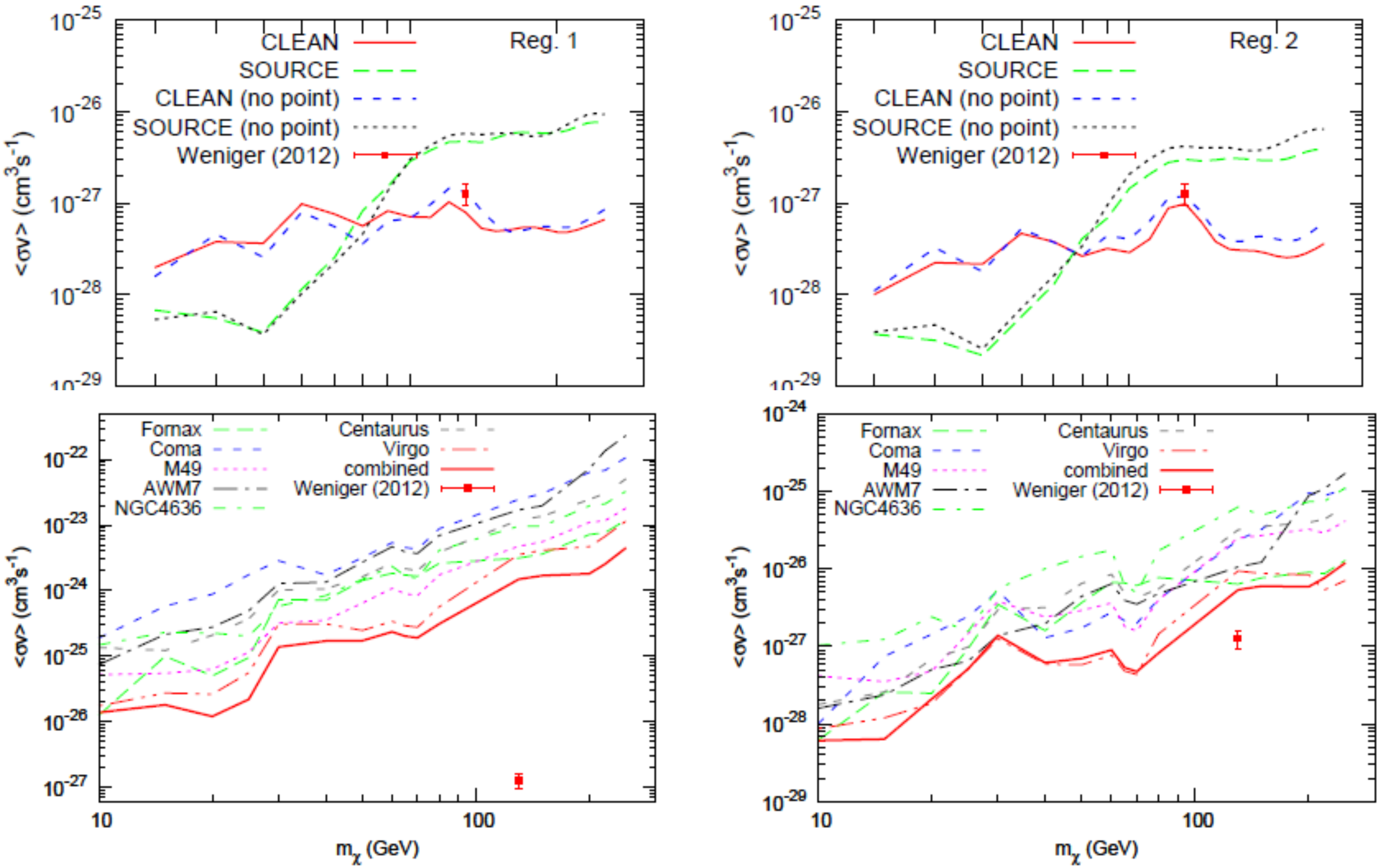


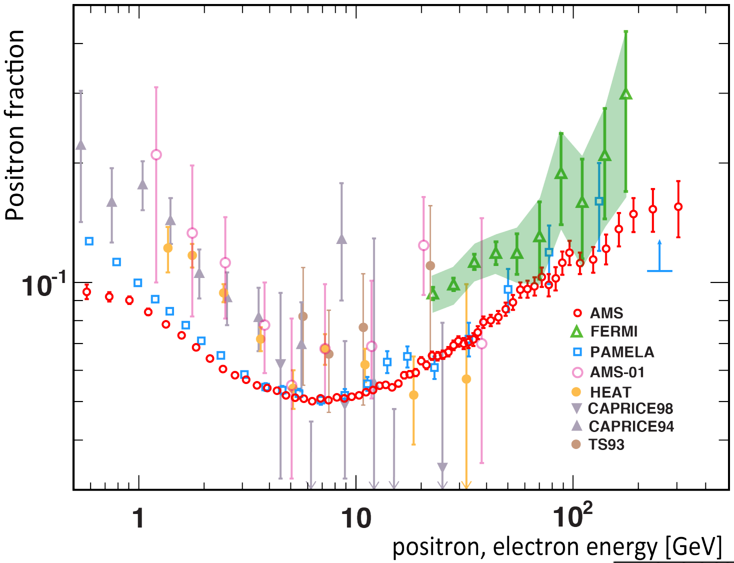
Fig. 18.— Spectrum of emission within 4° of the cusp center $(\ell, b) = (-1.5, 0)$, excluding $|b| < 0.5°$. High-incidence angle events (*upper panel*) have a factor of ~ 2 better energy resolution than those that enter the LAT close to normal incidence (*middle panel*) or the whole sample (*lower panel*). All three spectra have been

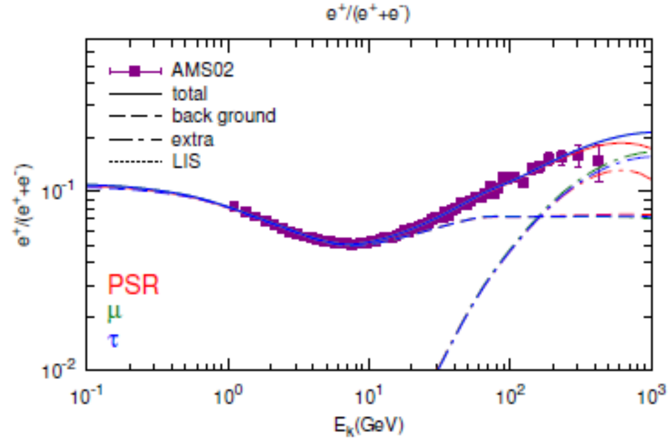
Constraints on the line emission

Huang, Yuan, Yin, Bi, Chen, JCAP1204, 030

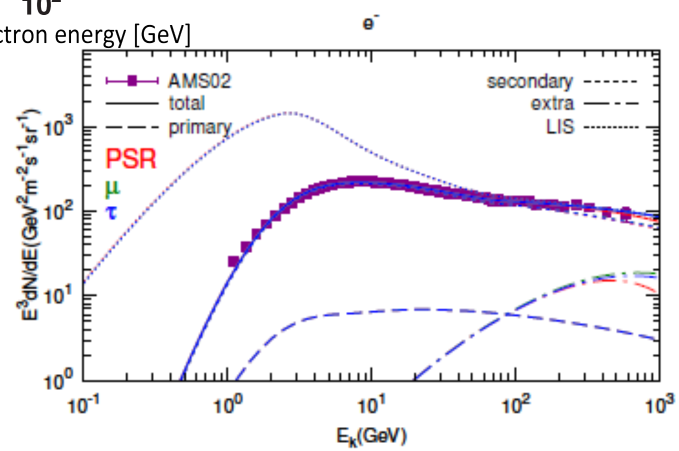
From halo, cluster and dwarf

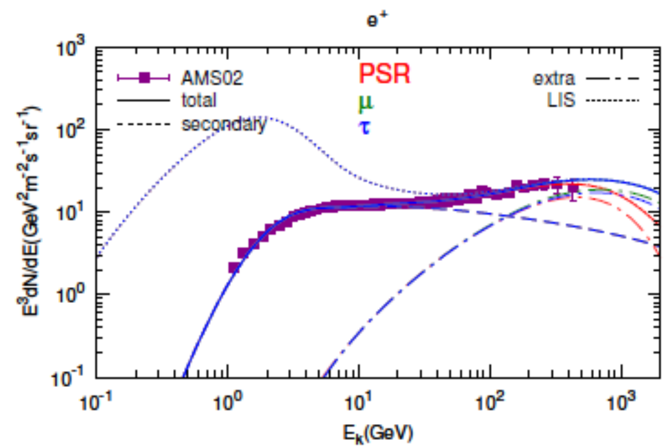






AMS





Updated positron fraction and electron/positron spectra are Sep. 2014.

Observations of a 3.55 keV signal in clusters?

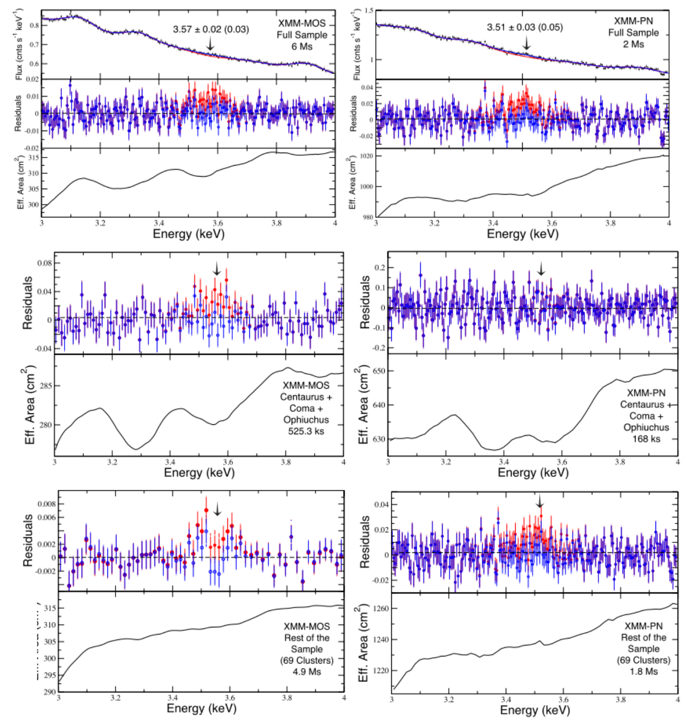
v1 [astro-ph.CO] 10 Feb 2014

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul[1,2], Maxim Markevitch[2], Adam Foster[1], Randall K. Smith[1] Michael Loewenstein[2], and Scott W. Randall[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.
Submitted to ApJ, 2014 February 10

ABSTRACT

We detect a weak unidentified emission line at $E = (3.55 - 3.57) \pm 0.03$ keV in a stacked XMM spectrum of 73 galaxy clusters spanning a redshift range $0.01 - 0.35$. MOS and PN observations independently show the presence of the line at consistent energies. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is seen at $> 3\sigma$ statistical significance in all three independent MOS spectra and the PN "all others" spectrum. The line is also detected at the same energy in the *Chandra* ACIS-S and ACIS-I spectra of the Perseus cluster, with a flux consistent with *XMM-Newton* (however, it is not seen in the ACIS-I spectrum of Virgo). The line is present even if we allow maximum freedom for all the known thermal emission lines. However, it is very weak (with an equivalent width in the full sample of only ~ 1 eV) and located within 50–110 eV of several known faint lines; the detection is at the limit of the current instrument capabilities and subject to significant modeling uncertainties. On the origin of this line, we argue that there should be no atomic transitions in thermal plasma at this energy. An intriguing possibility is the decay of sterile neutrino, a long-sought dark matter particle candidate. Assuming that all dark matter is in sterile neutrinos with $m_s = 2E = 7.1$ keV, our detection in the full sample corresponds to a neutrino decay mixing angle $\sin^2(2\theta) \approx 7 \times 10^{-11}$, below the previous upper limits. However, based on the cluster masses and distances, the line in Perseus is much brighter than expected in this model, significantly deviating from other subsamples. This appears to be because of an anomalously bright line at $E = 3.62$ keV in Perseus, which could be an Ar XVII dielectronic recombination line, although its emissivity would have to be 30 times the expected value and physically difficult to understand. In principle, such an anomaly might explain our line detection in other subsamples as well, though it would stretch the line energy uncertainties. Another alternative is the above anomaly in the Ar line combined with the nearby 3.51 keV K line also exceeding expectation by factor 10–20. Confirmation with *Chandra* and *Suzaku*, and eventually *Astro-H*, are required to determine the nature of this new line.



ure 5. Top panels: 3−4 keV band of the stacked MOS (left panel) and stacked PN (right panel) spectra of the samples. The figures v the energy band where the new spectral feature is detected. The Gaussian lines with maximum values of the flux normalizations of K I and Ar XVII estimated using AtomDB were included in the models. The red lines in the top panels (shown only for the full sample) v the model and the excess emission. The blue lines show the total model after another Gaussian line is added, representing the new Middle panels shows the residuals before (red) and after (blue) the Gaussian line is added. The bottom panels show the effective area es (the corresponding ARF). Redshift smearing greatly reduces variations of the effective area in the high-z sample.

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]
[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland
[3]Bogolyubov Institute of Theoretical Physics, Metrologichna Str. 14-b, 03680, Kyiv, Ukraine
[4]National University "Kyiv-Mohyla Academy", Skovorody Str. 2, 04070, Kyiv, Ukraine
[5]Leiden Observatory, Leiden University, Niels Bohrweg 2, Leiden, The Netherlands

] 17 Feb 2014

We identify a weak line at $E \sim 3.5$ keV in X-ray spectra of the Andromeda galaxy and the Perseus galaxy cluster – two dark matter-dominated objects, for which there exist deep exposures with the XMM-Newton X-ray observatory. Such a line was not previously known to be present in the spectra of galaxies or galaxy clusters. Although the line is weak, it has a clear tendency to become stronger towards the centers of the objects; it is stronger for the Perseus cluster than for the Andromeda galaxy and is absent in the spectrum of a very deep "blank sky" dataset. Although for individual objects it is hard to exclude the possibility that the feature is due to an instrumental effect or an atomic line of anomalous brightness, it is consistent with the behavior of a line originating from the decay of dark matter particles. Future detections or non-detections of this line in multiple astrophysical targets may help to reveal its nature.

So many signals come and go!!!

Future Measurements of DM properties with lensing

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

DARK ENERGY SURVEY

KDUST?

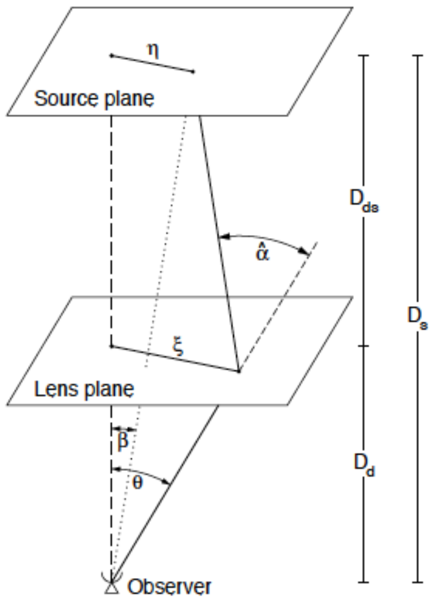
LSST Large Synoptic Survey Telescope

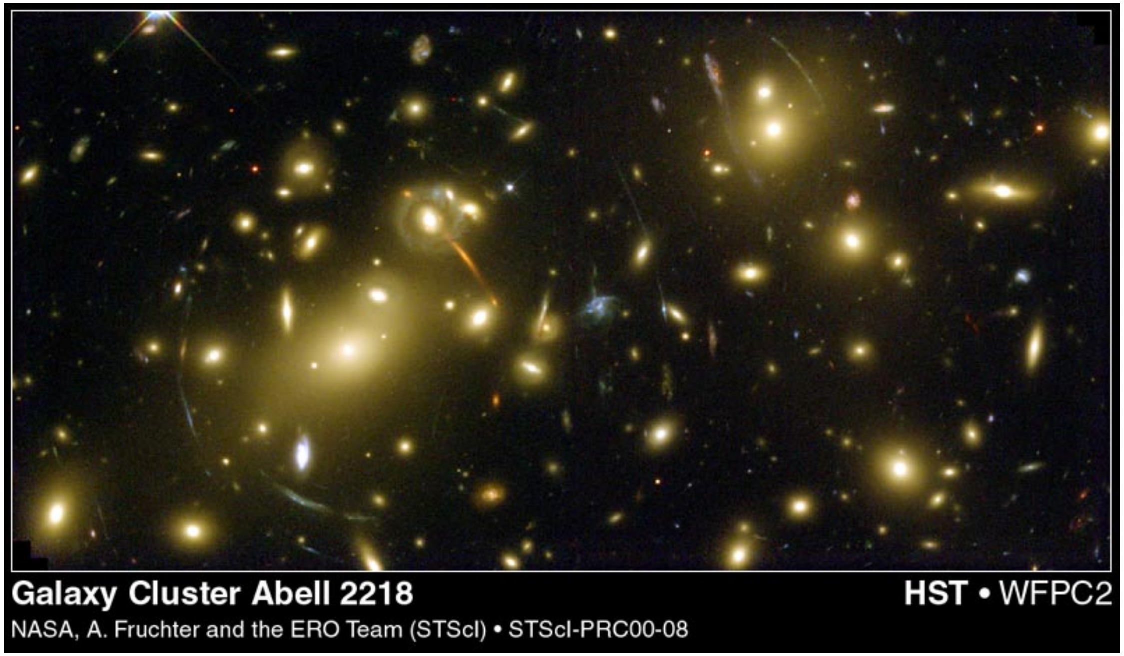
Euclid Consortium

WFIRST?

MS-DESI can provide 3D

Progress in Gravitational Lensing



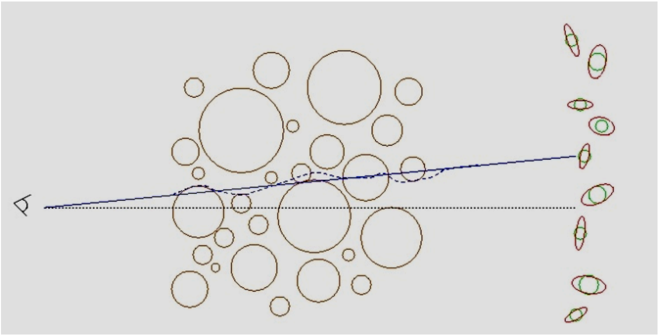


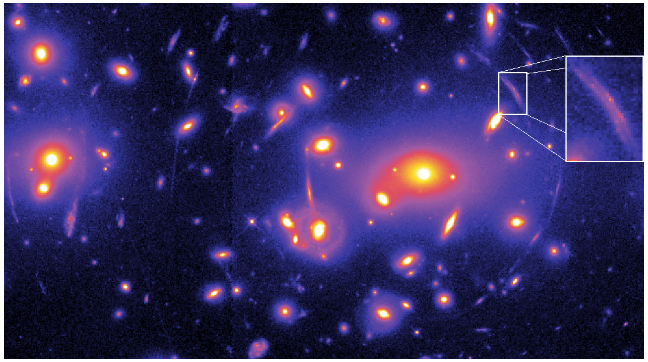
$$\alpha = \frac{4GM}{c^2\xi} = \frac{4\pi\langle v_{\|}^2\rangle}{c^2}$$

$$\theta_E = \alpha\frac{D_{ds}}{D_s}$$

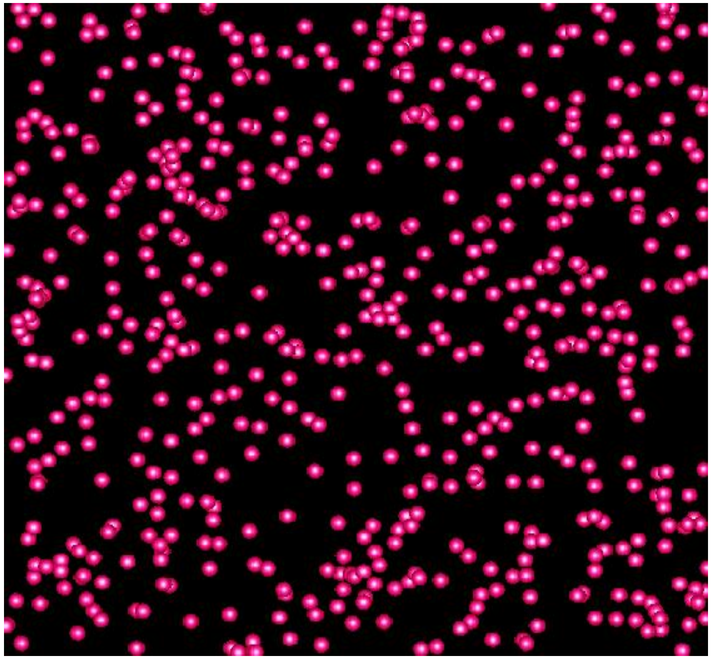
- Strong lensing arclets
- Weak lensing
- Flexion

"Weak Lensing"

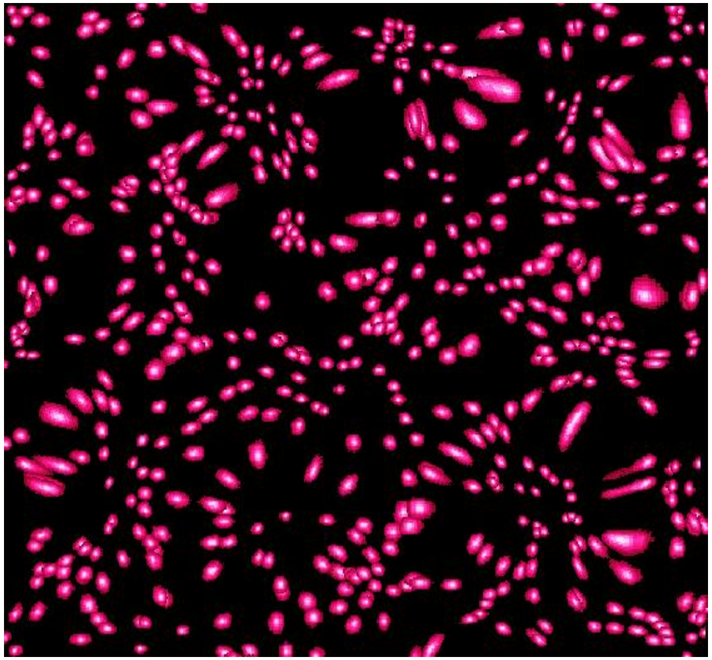




Distorsion of galaxy shapes by foreground matter

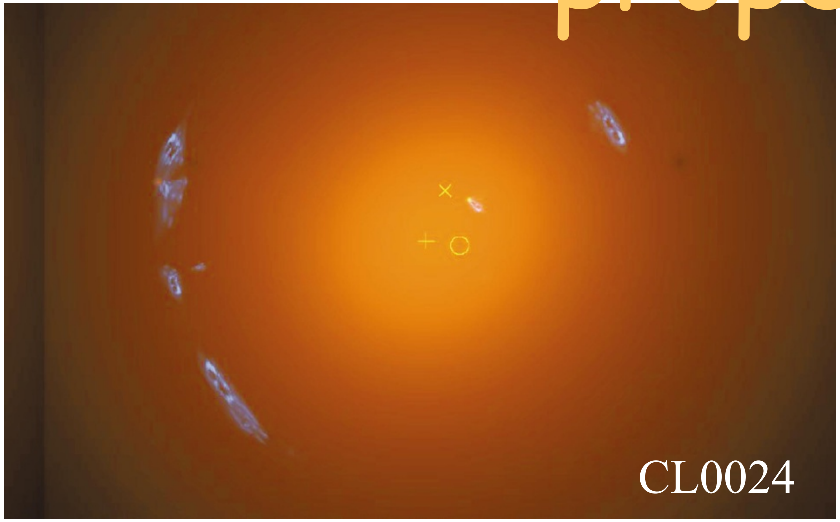


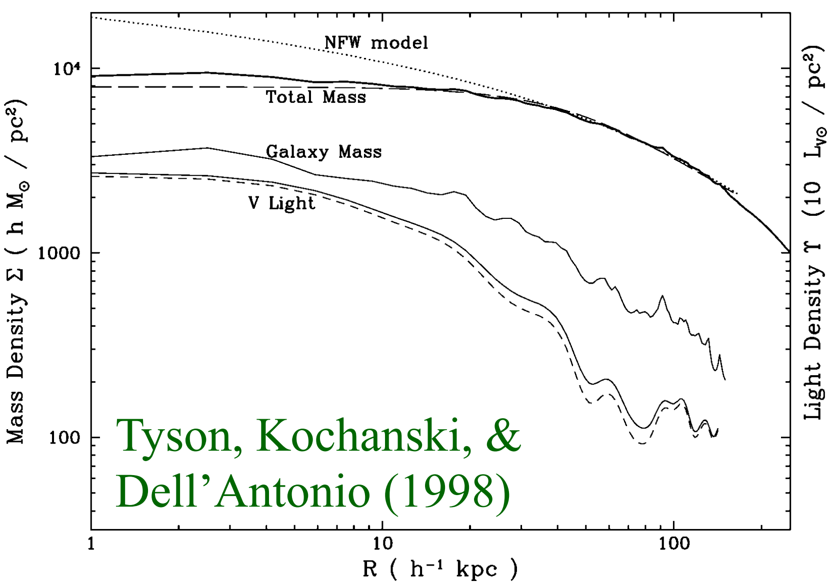
without lensing



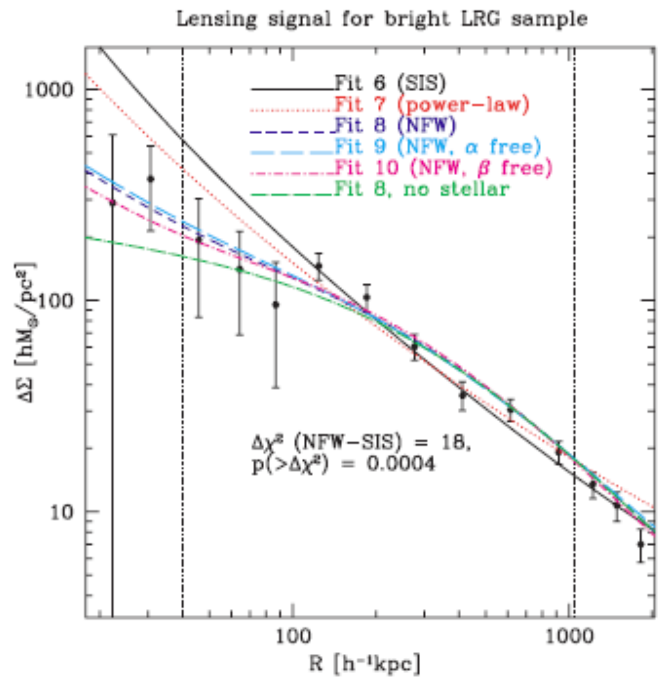
Lensing effect

Probing DM Particle properties





Tyson, Kochanski, & Dell'Antonio (1998)



Mandelbaum et al. (2006)

Stacked galaxy—galaxy weak lensing signal fit with various profiles.

CFHTLenS: Combined probe cosmological model comparison using 2D weak gravitational lensing

Dec 2012

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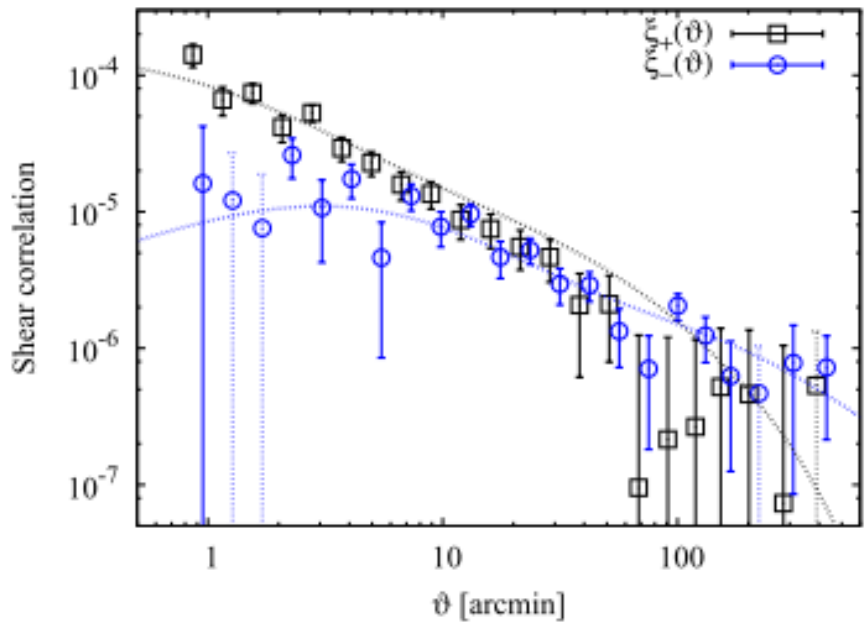
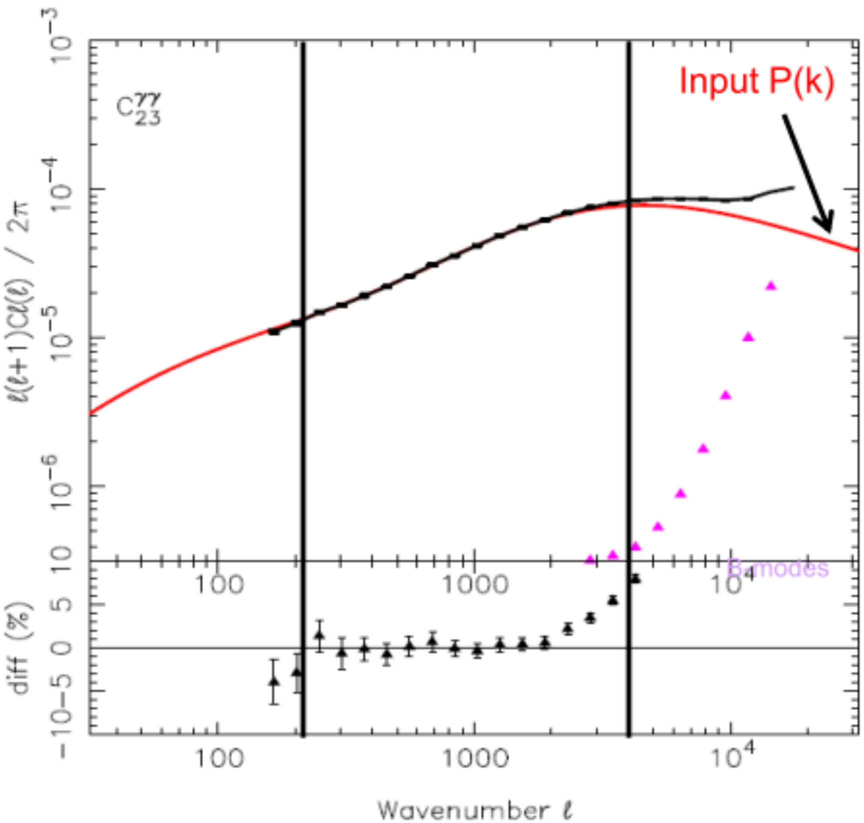
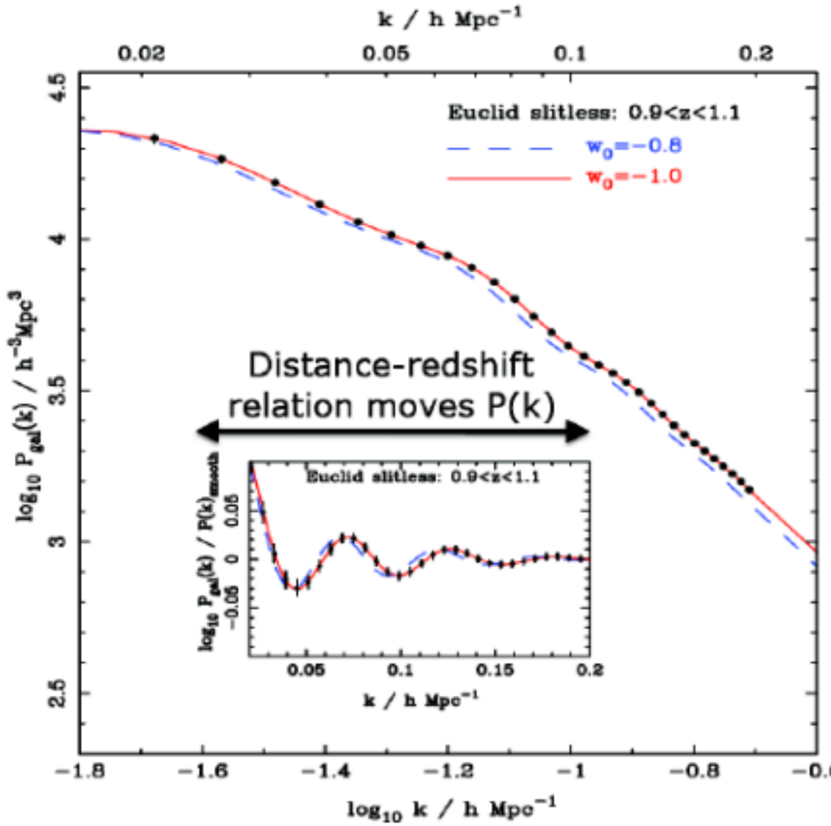


Figure 6. The measured shear correlation functions ξ_+ (black squares) and ξ_- (blue circles), combined from all four Wide patches. The error bars correspond to the total covariance diagonal. Negative values are shown as thin points with dotted error bars. The lines are the theoretical prediction using the WMAP7 best-fitting cosmology and the non-linear model described in Sect. 4.3. The data points and error bars are listed in Table B1.

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

Euclid Consortium





- 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% .

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

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

Ref: Euclid RB arXiv:1110.3193