Search For Dark Matter With Picasso

CPPM

Marseille

October 26, 2009

Viktor Zacek, Université de Montréal

Search For Dark Matter With Picasso

Project in Canada to Search for Supersymmetric Objects

Projet d'Identification de Candidats Supersymétriques SOmbres

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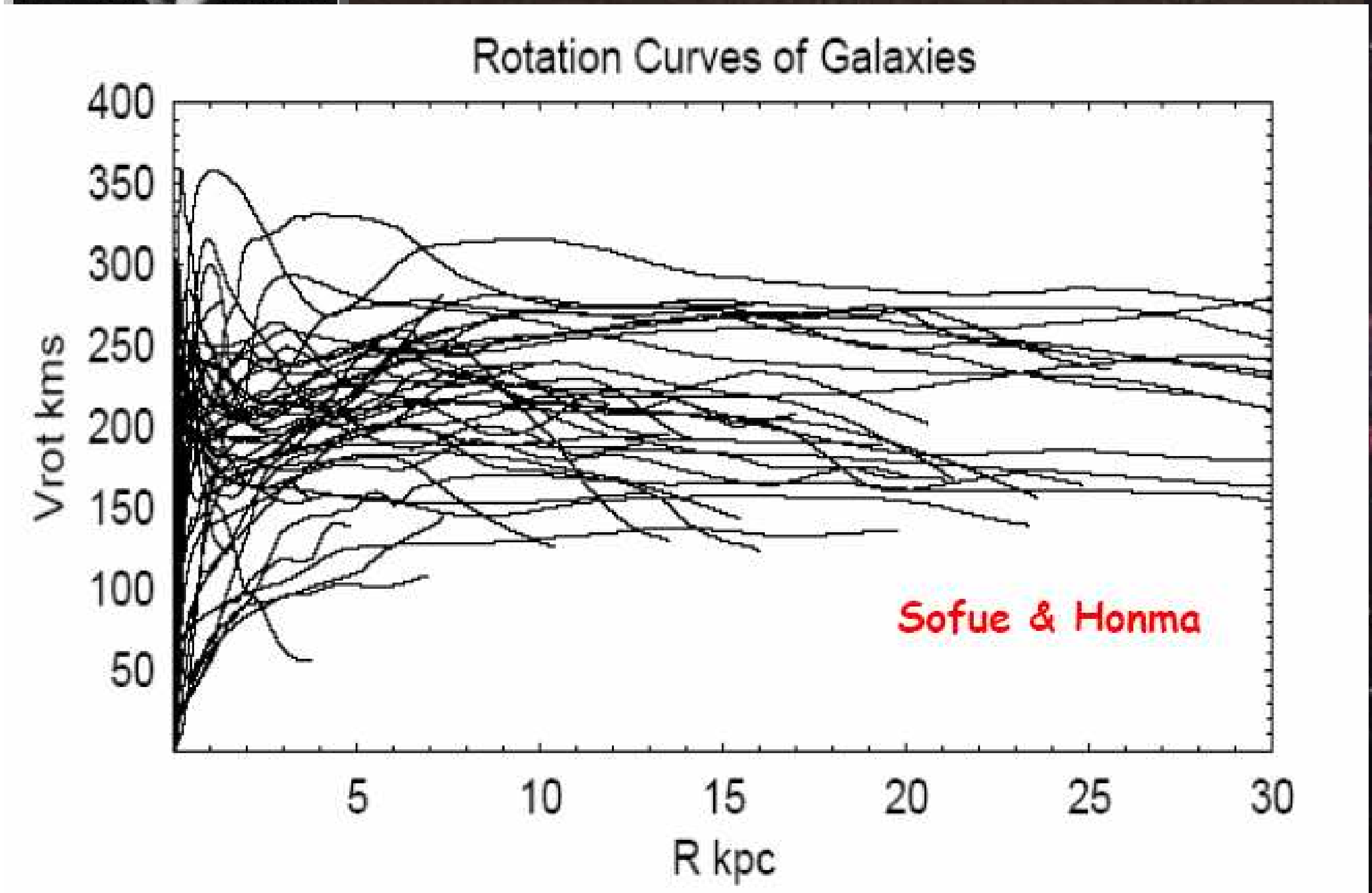
THE DARK MATTER PROBLEM - FIRST INDICATIONS

Fritz Zwicky, 1937

- Studies kinetic energies of 8 galaxies of the Coma Cluster
- finds velocities are much larger than expected
- apparently Coma cluster contains 200 x more mass than is visible in form of galaxies

The "hidden mass" problem becomes a "key problem" of modern cosmology

DARK MATTER & GALACTIC ROTATION CURVES



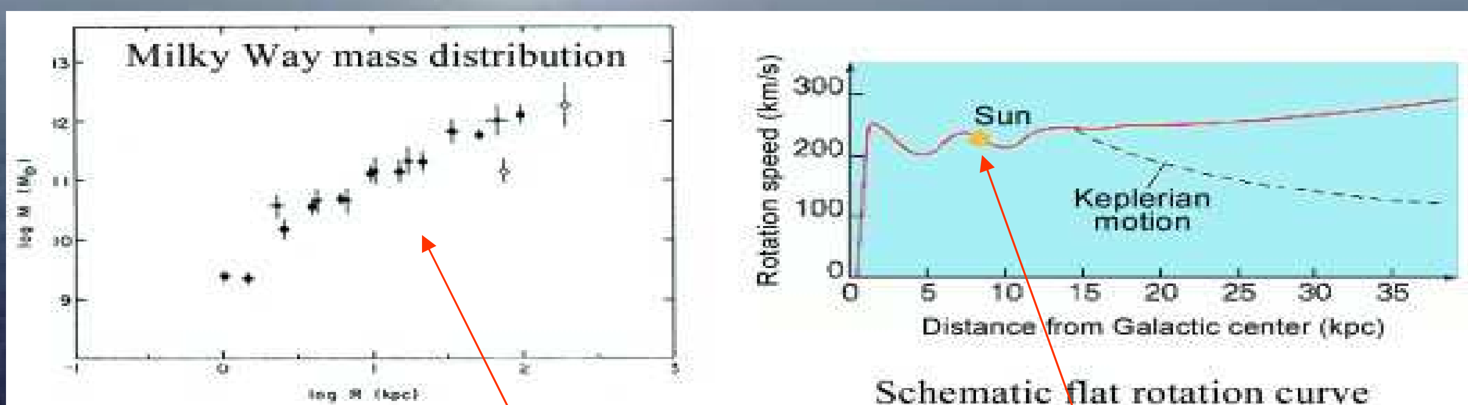
v_{rot} = const.

$M(r) \propto r$

Doppler shift of star light and of H- emission

$M_{halo} > 10 \times (M_{lum} + M_{gas})$

DARK MATTER IN OUR MILKY WAY



Mass increases up to 200 kpc

Schematic flat rotation curve for the Milky Way galaxy

1kpc = 3.259 10^3 Ly

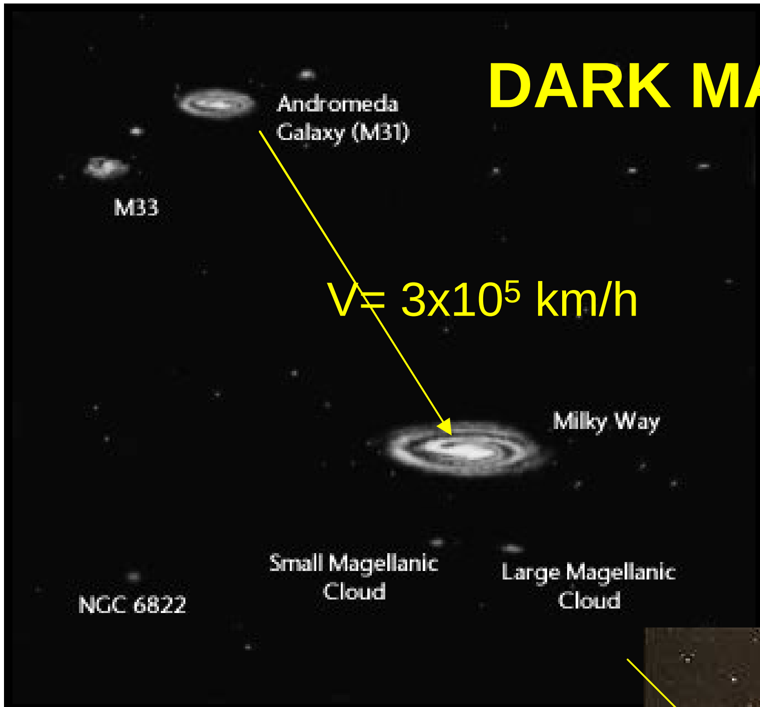
$$M(r) = \frac{v_{rot}^2 r}{G}$$

$\rho_{DM} \sim 0.3\ m_p/cm^3$

2MASS two Micron All Sky Survey

…only 5-10% of matter visible!

DARK MATTER IN OUR NEIGHBORHOOD

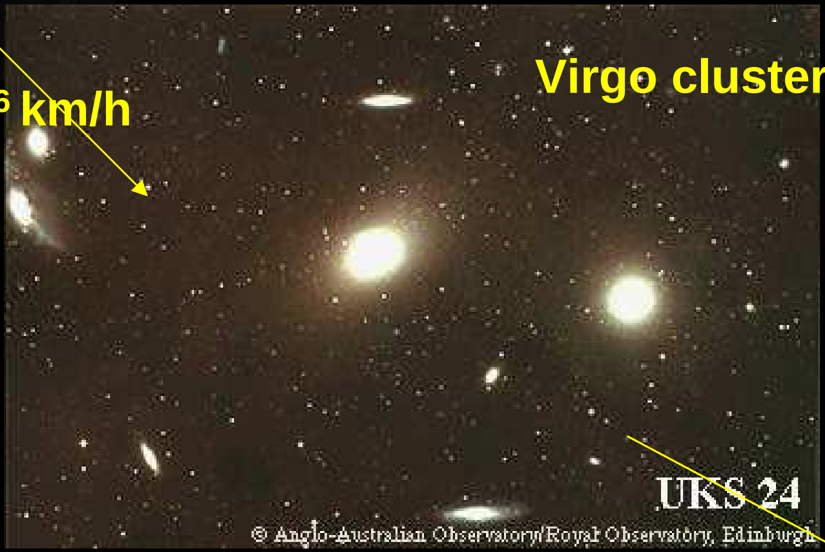


$V = 3 \times 10^5$ km/h

- **Size of Local group 2.2 MLy**
- **MW & M31 dominate Local Group**
- **Enormous gravit. pull between the two galaxies**
- **Invisible mass > 10 x M_{MW}**
- **Local group at fringe of Virgo cluster**

v ~ 1.6×10^6 km/h

Virgo cluster

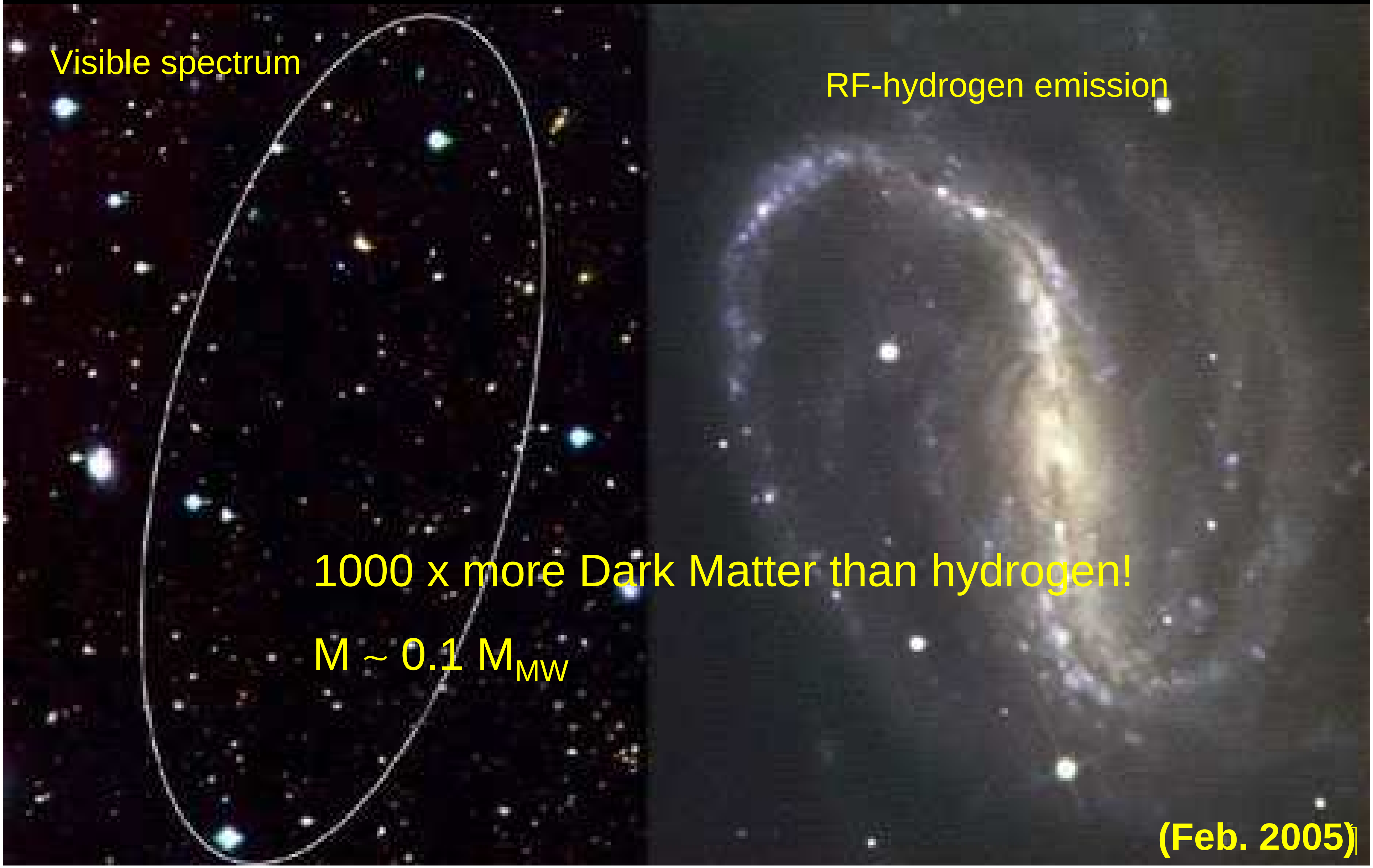


v ~ 2×10^6 km/h

- **Size of Virgo cluster 50MLy**
- **Local group pulled towards Virgo cluster**
- **invisible mass > 10 x M_{vis}**

Virgo Cluster pulled towards an invisible "Great Attractor"

VIRGOHI21: A GALAXY OF DARK MATTER ! (50 M Ly)

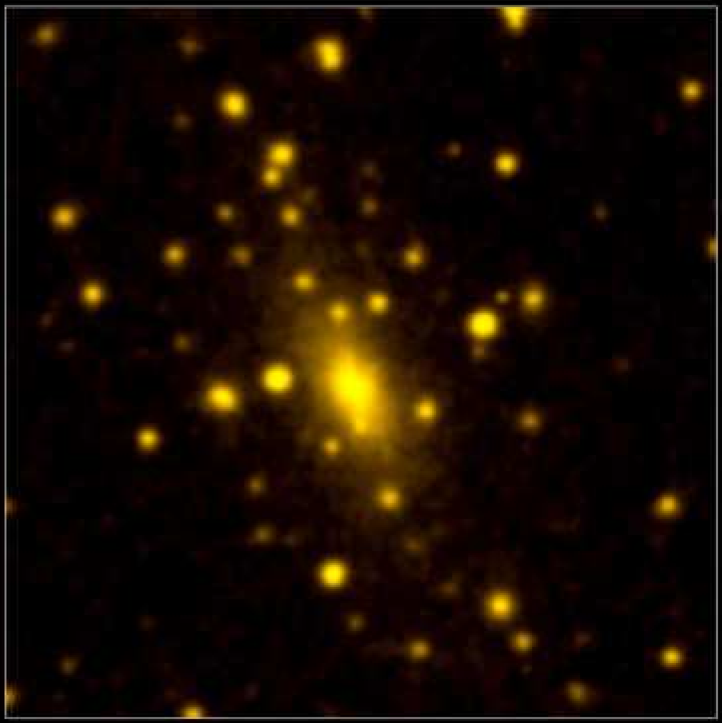


1000 x more Dark Matter than hydrogen!

$M \sim 0.1\ M_{MW}$

(Feb. 2005)

DARK MATTER AROUND OTHER GALAXIES

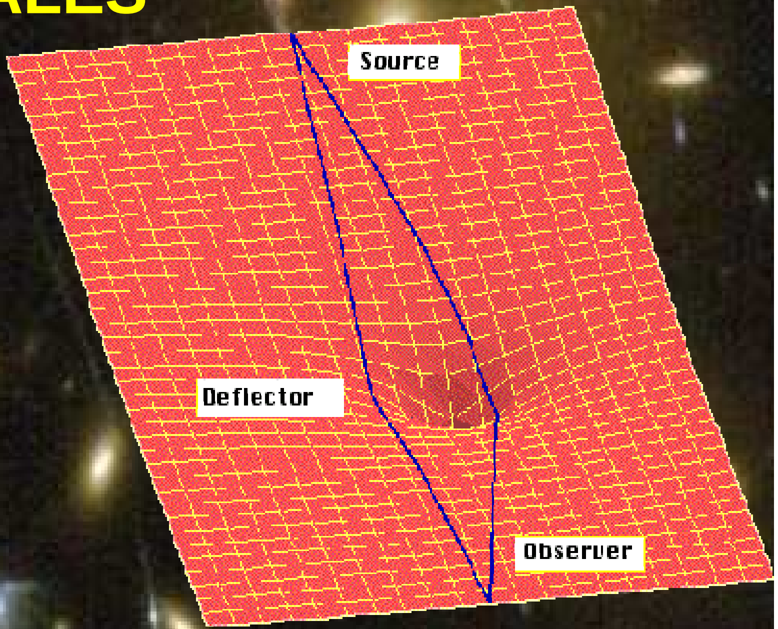


Abell 2029

- a cluster of thousands of galaxies
- surrounded by gigantic clouds of hot gas
- T~ 10^6 K

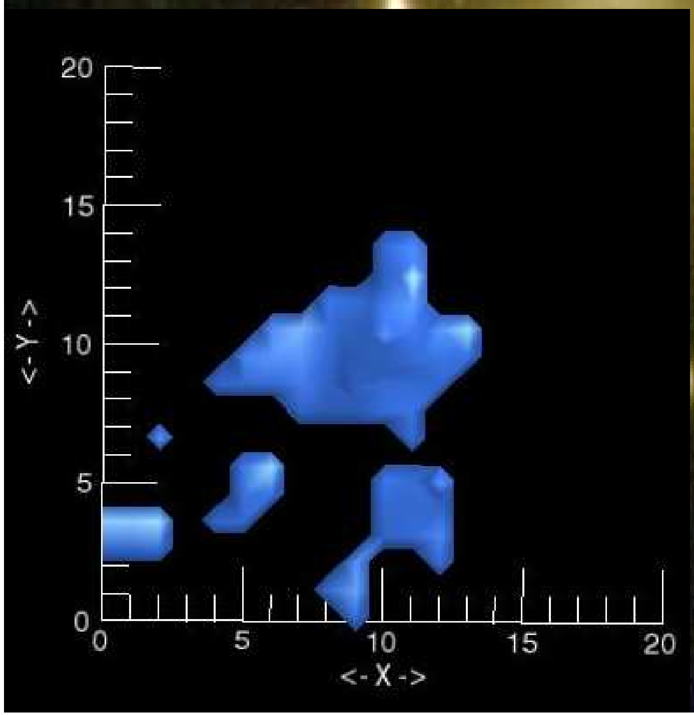
$M_{Tot} > 10\ M_{vis}$

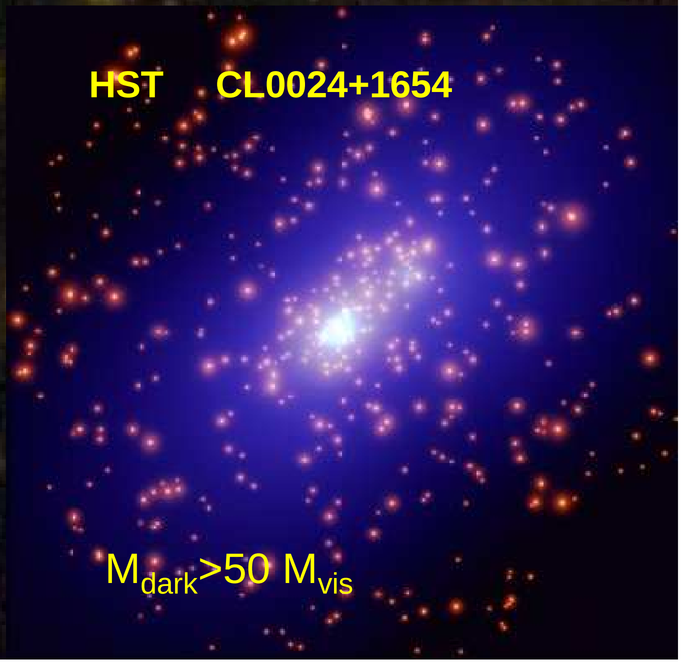
DARK MATTER AT AT LARGE SCALES



Gravitational lensing

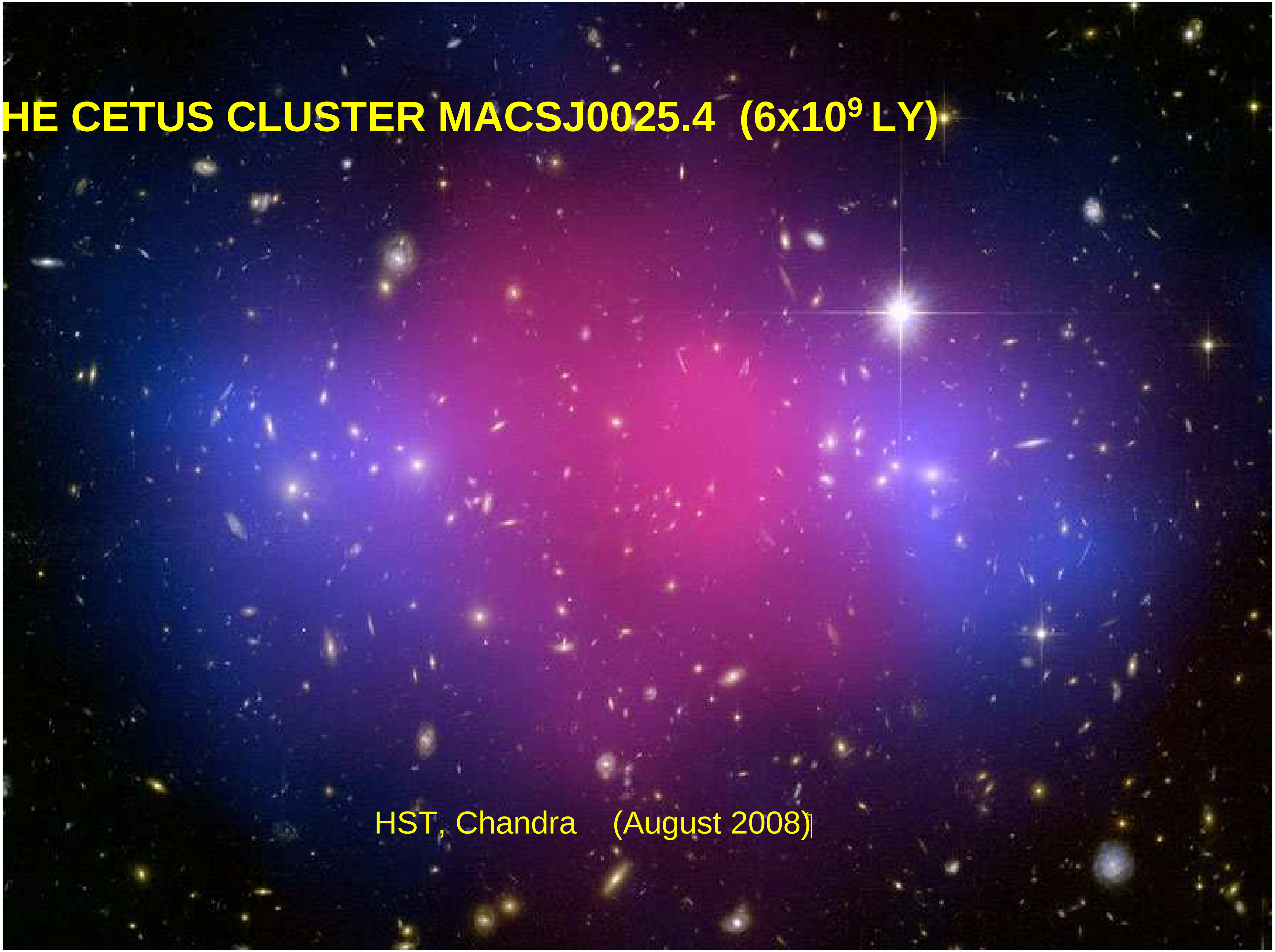
- **provides evidence of large masses between source and MW**
- **recently 3D reconstruction of clusters of Dark Matter**





THE BULLET CLUSTER IE0657-56 (3.4 10^9 LY)

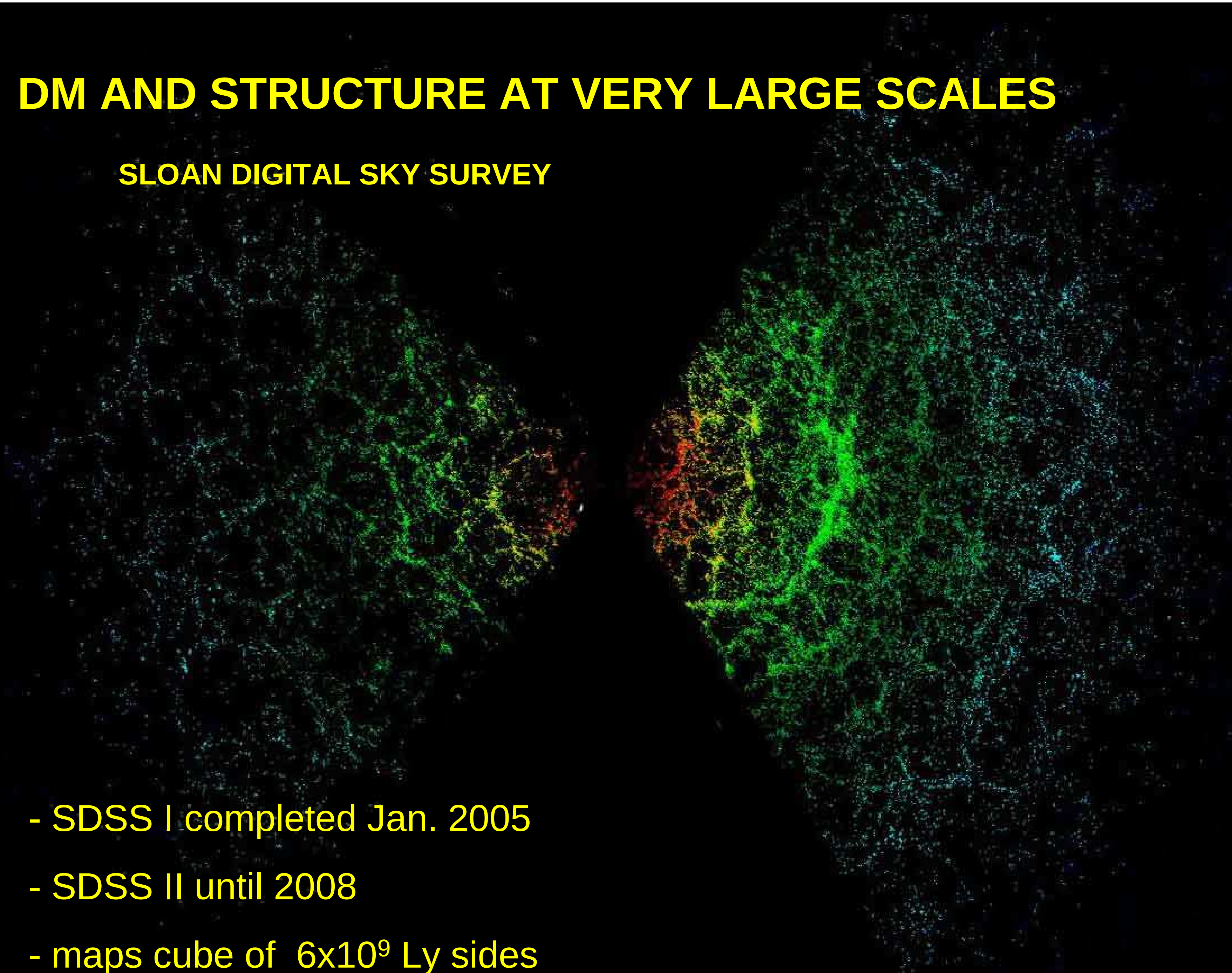
HE CETUS CLUSTER MACSJ0025.4 (6x10^9 LY)



HST, Chandra (August 2008)

DM AND STRUCTURE AT VERY LARGE SCALES

SLOAN DIGITAL SKY SURVEY

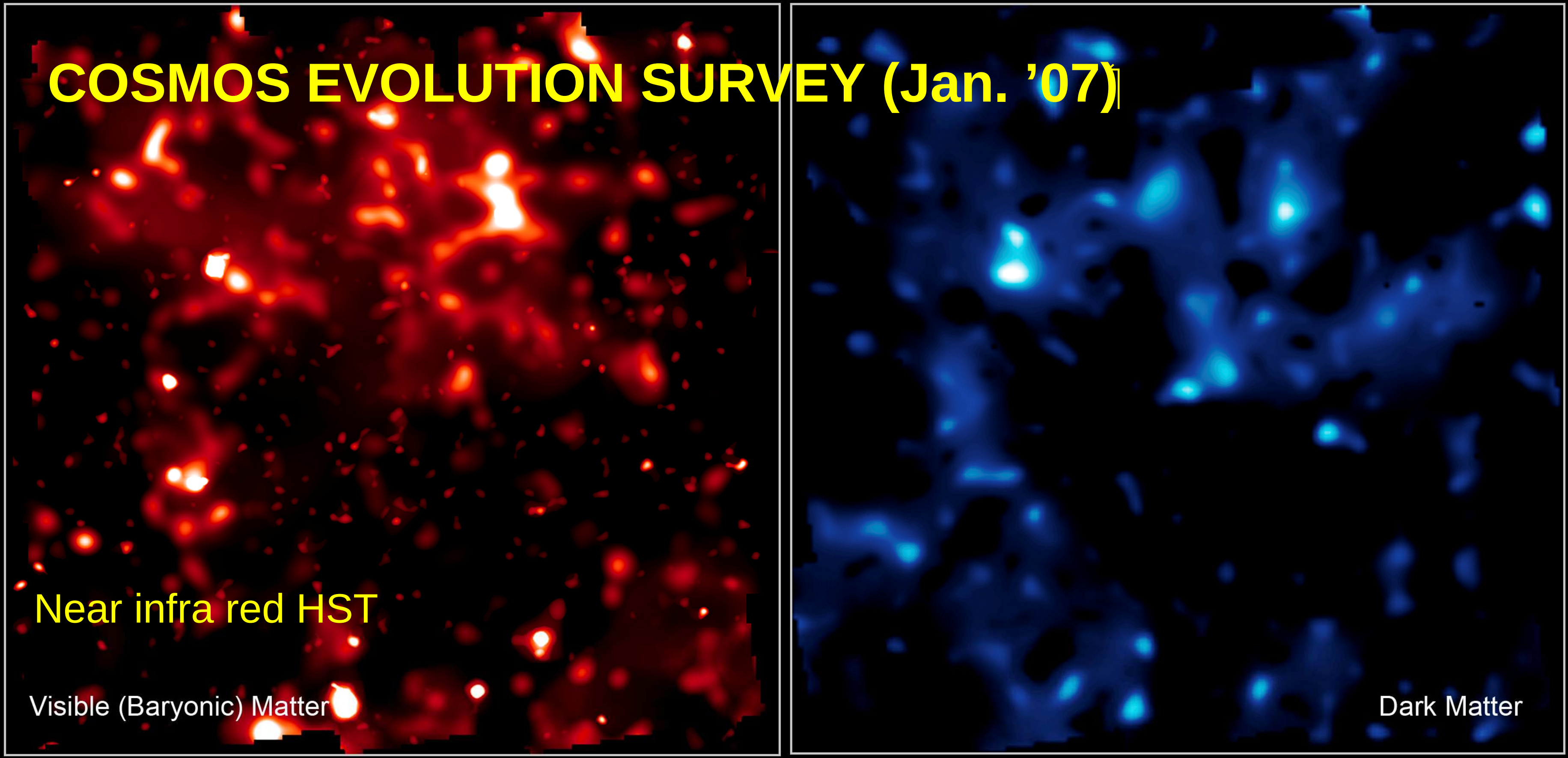


- SDSS I completed Jan. 2005
- SDSS II until 2008
- maps cube of $6\text{x}10^9$ Ly sides

DM & DEVELOPMENT OF STRUCTURE

- BB creates DM + ord. Matter
- DM decouples early
- Clumps
- Ordinary matter flows in
- Galaxies form
- Galaxies trace DM distribution

COSMOS EVOLUTION SURVEY (Jan. ’07)

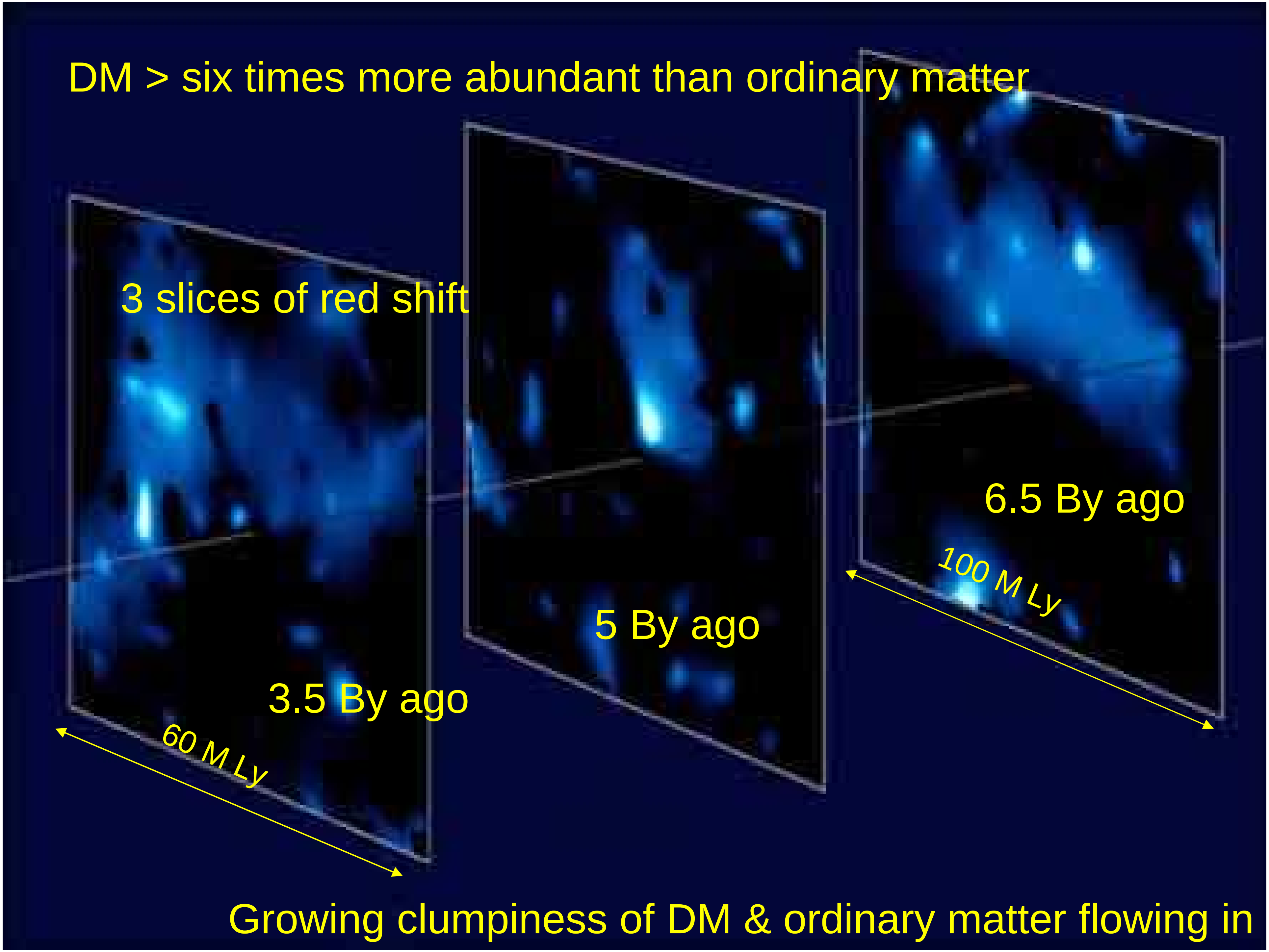


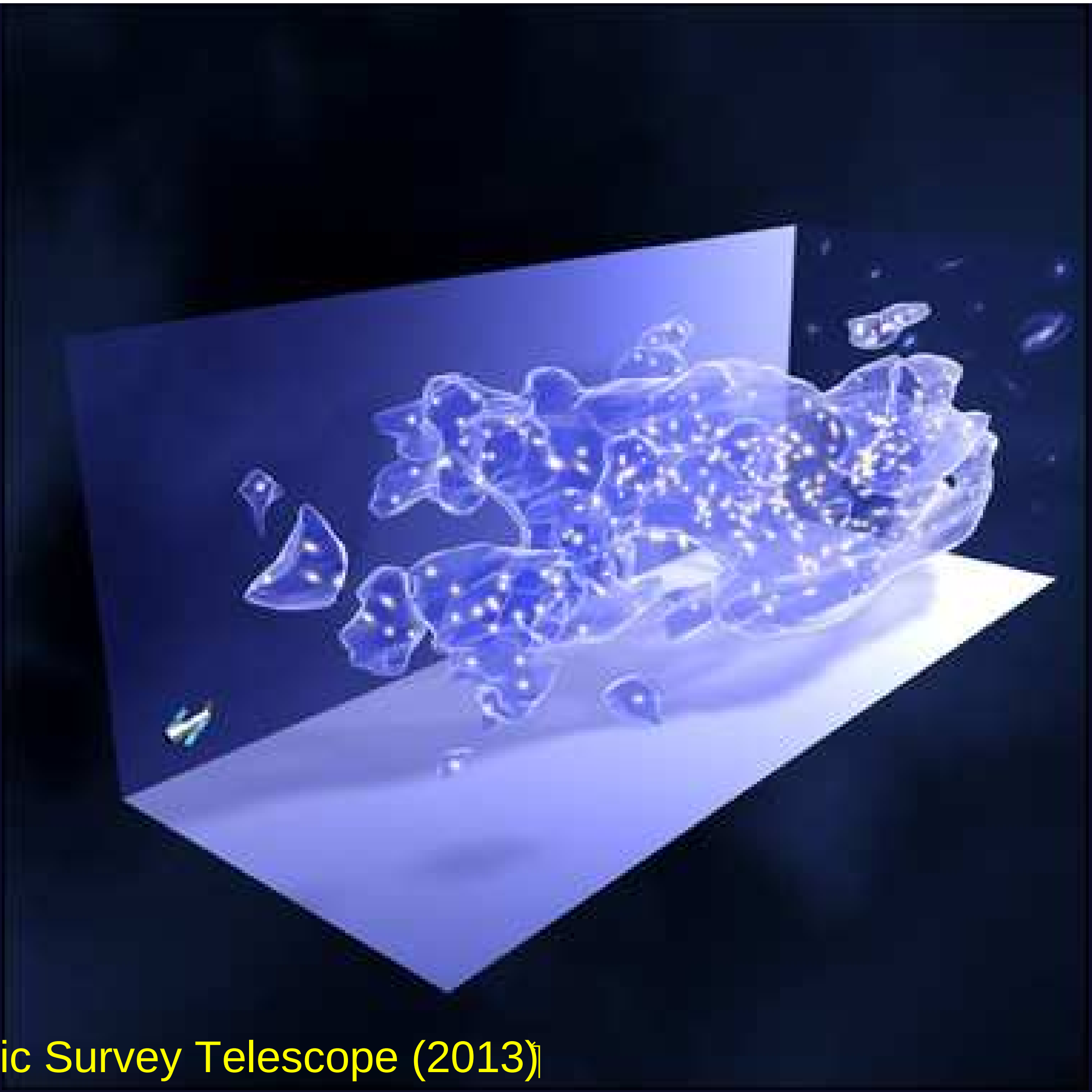
-First large scale 3D reconstruction of DM distribution

-Hubble Space Telescope: largest picture mosaic ever 1.4^0 x 1.4^0 (size of moon)

- Distance by red shifts: ESO VLT (Chile), Magellan (Chile), Subaru (Hawaii), CHT (Hawaii)

--X-ray mapping of gas in galaxies: XMM Newton


DM > six times more abundant than ordinary matter
3 slices of red shift
6.5 By ago
100 M Ly
5 By ago
3.5 By ago
60 M Ly
Growing clumpiness of DM & ordinary matter flowing in



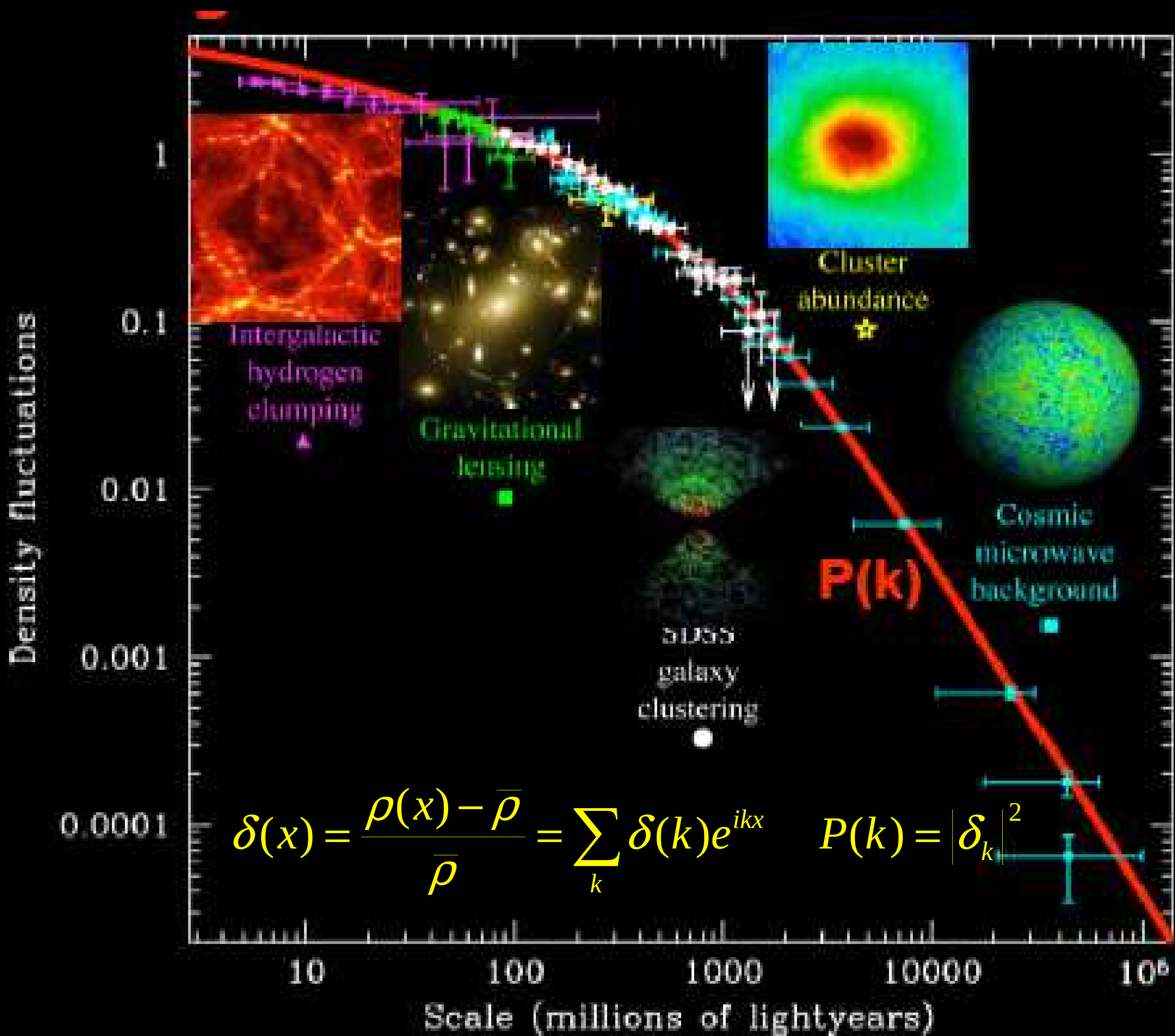
Next: Large Synoptic Survey Telescope (2013)

8.4 m diameter mirror

30 Tbyte/night

Google participates in organizing data analysis (New Scientist Jan. 2007)

LARGE SCALE STRUCTURE



$$\delta(x) = \frac{\rho(x) - \bar{\rho}}{\bar{\rho}} = \sum_k \delta(k) e^{ikx} \qquad P(k) = |\delta_k|^2$$

Max Tegmark

Best fit:

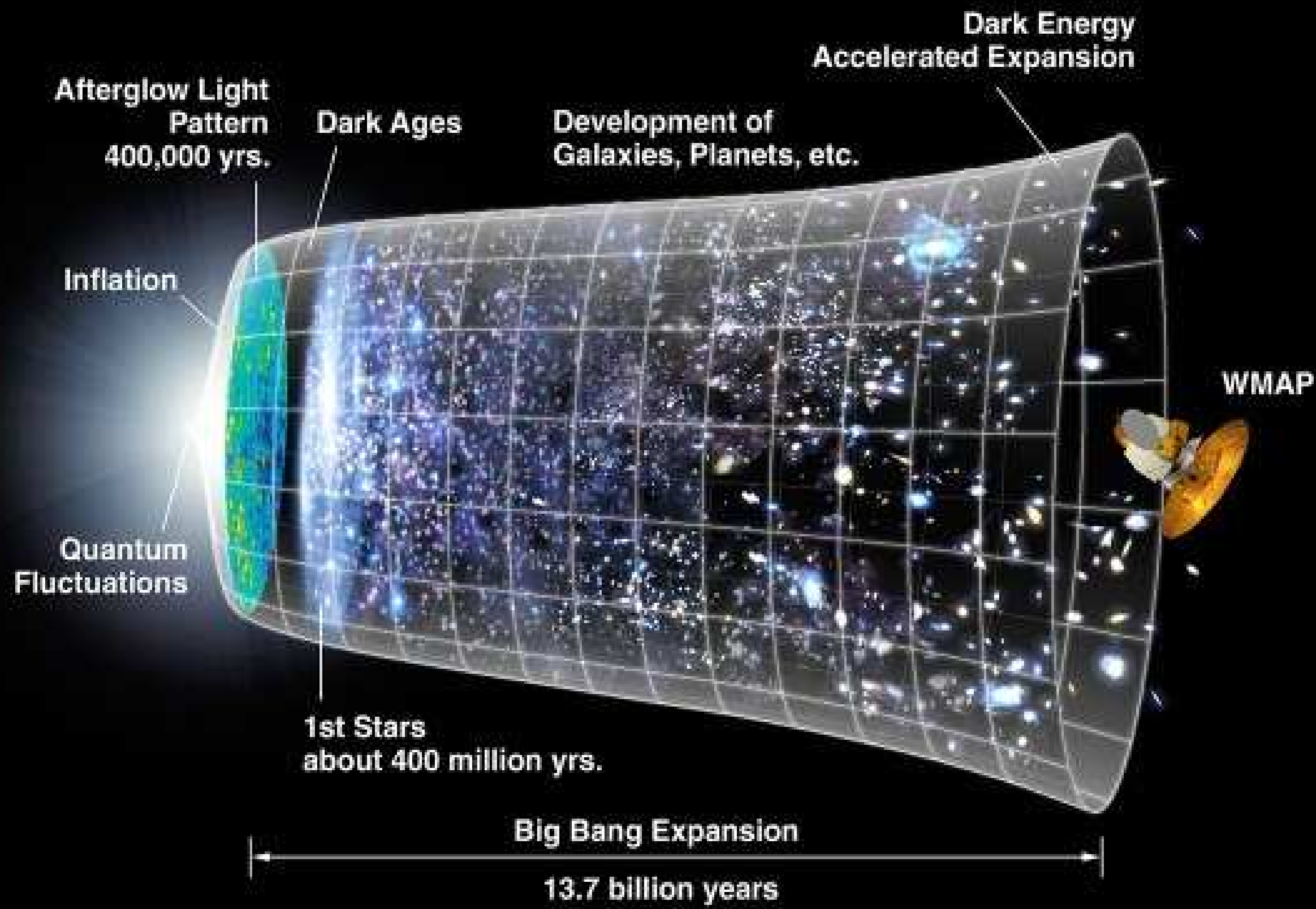
Ω_b=5%

Ω_{dm}=25%

Ω_Λ =70%

The larger the scale we average the more uniform becomes the Universe!

WMAP – PRECISION COSMOLOGY!



INFLATION* : $\Omega_{tot} = 1$

*** Phase change @T ~10^{-35}s with x 10^{50} → flat space**

NASA/WMAP Science Team

WMAP RESULTS:

$\Omega_{tot} = 1.02 \pm .02$

$\Omega_b = 0.04 \pm 0.004$

$\Omega_m = 0.27 \pm 0.04$

$\Omega_\Lambda = 0.73 \pm 0.04$

Other :

Inflation : $\Omega_{tot} = 1$

BBN: $\Omega_b = 0.039$

clusters of galaxies, grav. lensing
hot x-ray gas : $\Omega_m = 0.3$

SN1a –redshift : $\Omega_\Lambda = 0.7$

THE NEUTRALINO: A CDM CANDIDATE

- χ_1 can be lightest stable super symmetric particle – LSP
- Majorana particle
- interaction with matter electro-weak
- can provide closure density
- relic population from early BB

$$\chi_1 = \underbrace{N_{11}\tilde{\gamma}}_{\text{“photino”}} + \underbrace{N_{12}\tilde{Z}}_{\text{“zino”}} + \underbrace{N_{13}\tilde{H}_1^0}_{\text{higgsino”}} + \underbrace{N_{14}\tilde{H}_2^0}_{\text{“higgsino”}}$$

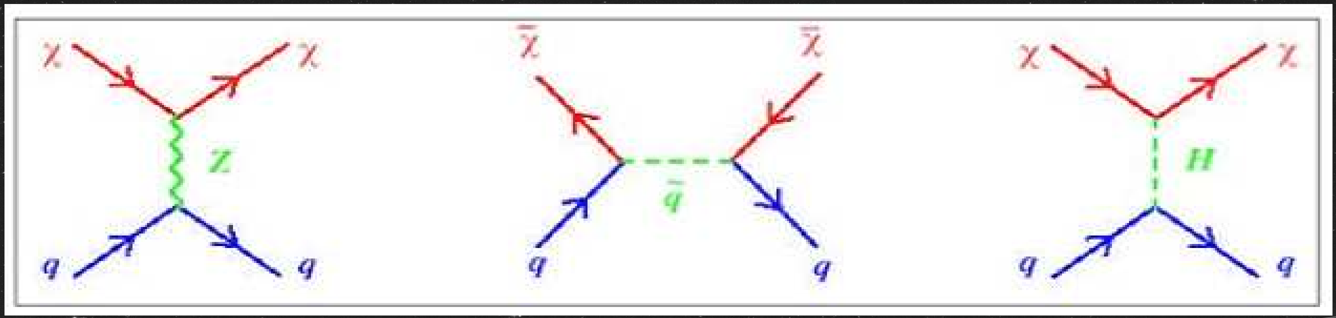
45 GeV < Mχ < 600 Gev - 7 TeV

Acceleleerators

SUSY structure

cosmology

NEUTRALINO INTERACTION CROSS SECTIONS



Spin-dependent

Spin-independent

General form of cross sections:

Enhancement factor

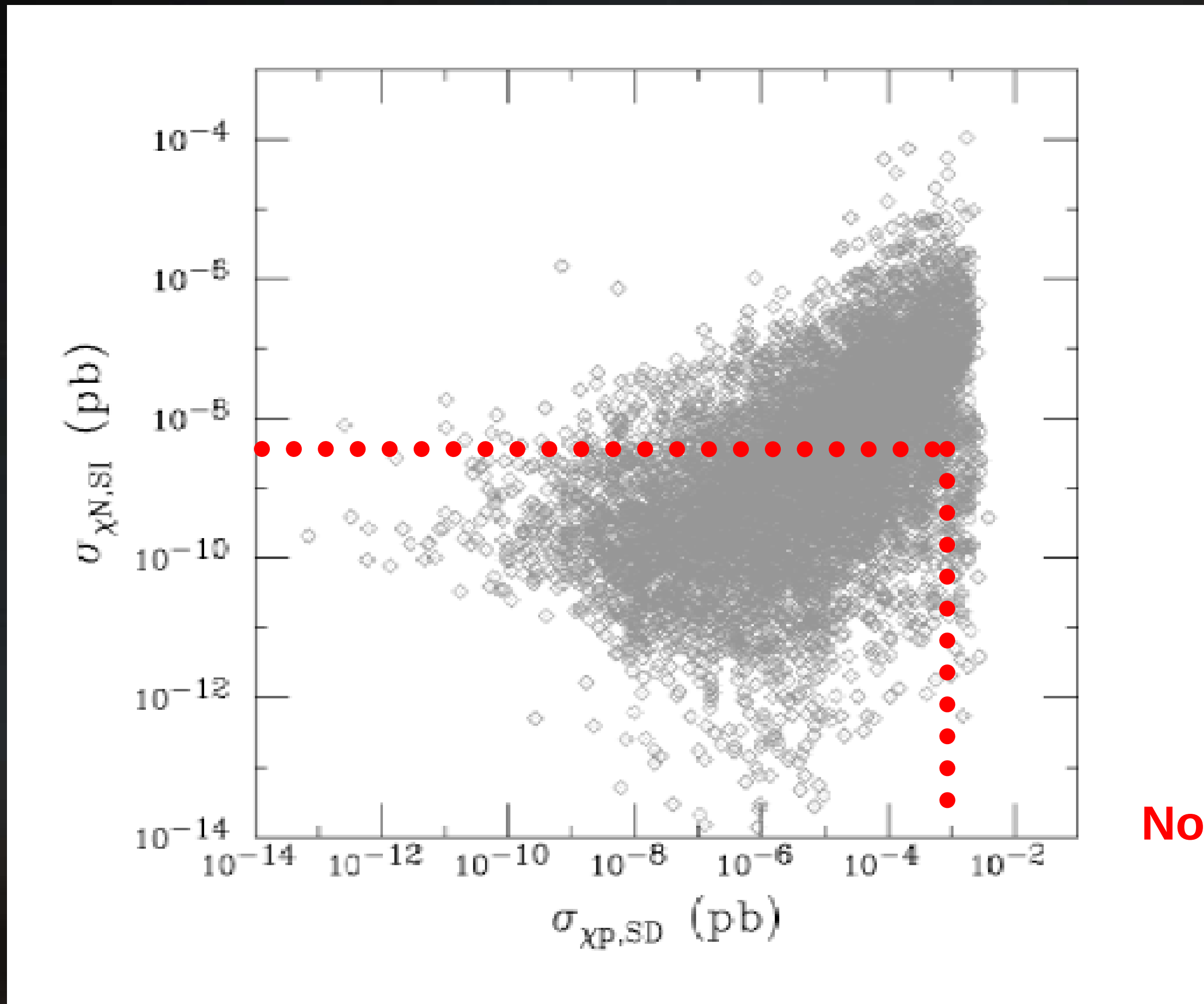
$$\sigma_A = 4G_F^{\,2}\left(\frac{M_\chi M_A}{M_\chi + M_A}\right)^2 C_A F(q^2)$$

C_A^{SI} : Spin independent – coherent interaction $\propto A^2$

C_A^{SD} : Spin dependent interaction $\propto \langle S_{p,n}\rangle^2$

$F(q^2)$: nucl. form facor $\rightarrow$ important for large q^2 and large A

SPIN DEPENDENT - SPIN INDEPENENT



Spin independent

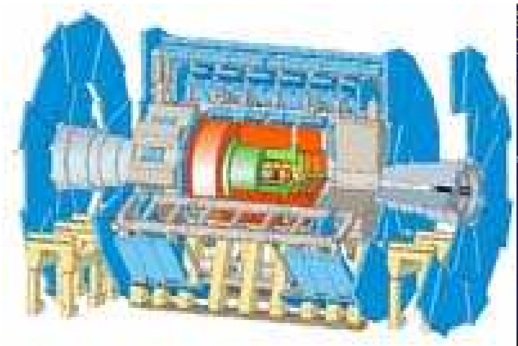
No correlations

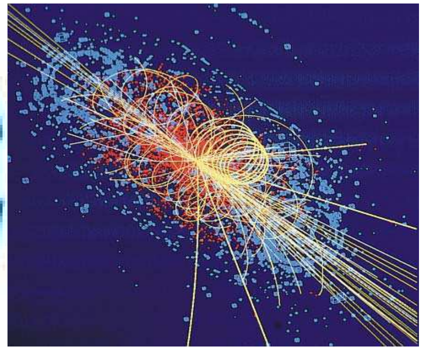
Spin dependent

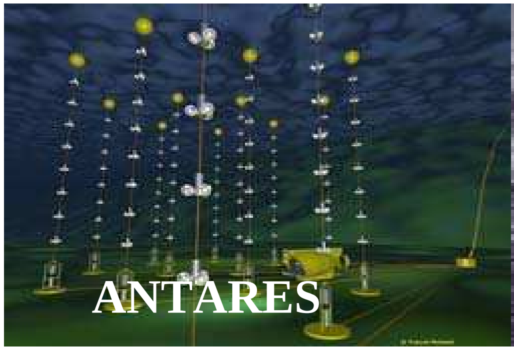
Large SD x - sections possible for small SI x-sections !

Searches for DM Particles

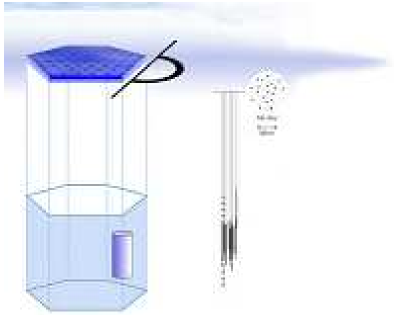
Production in situ at accelerators





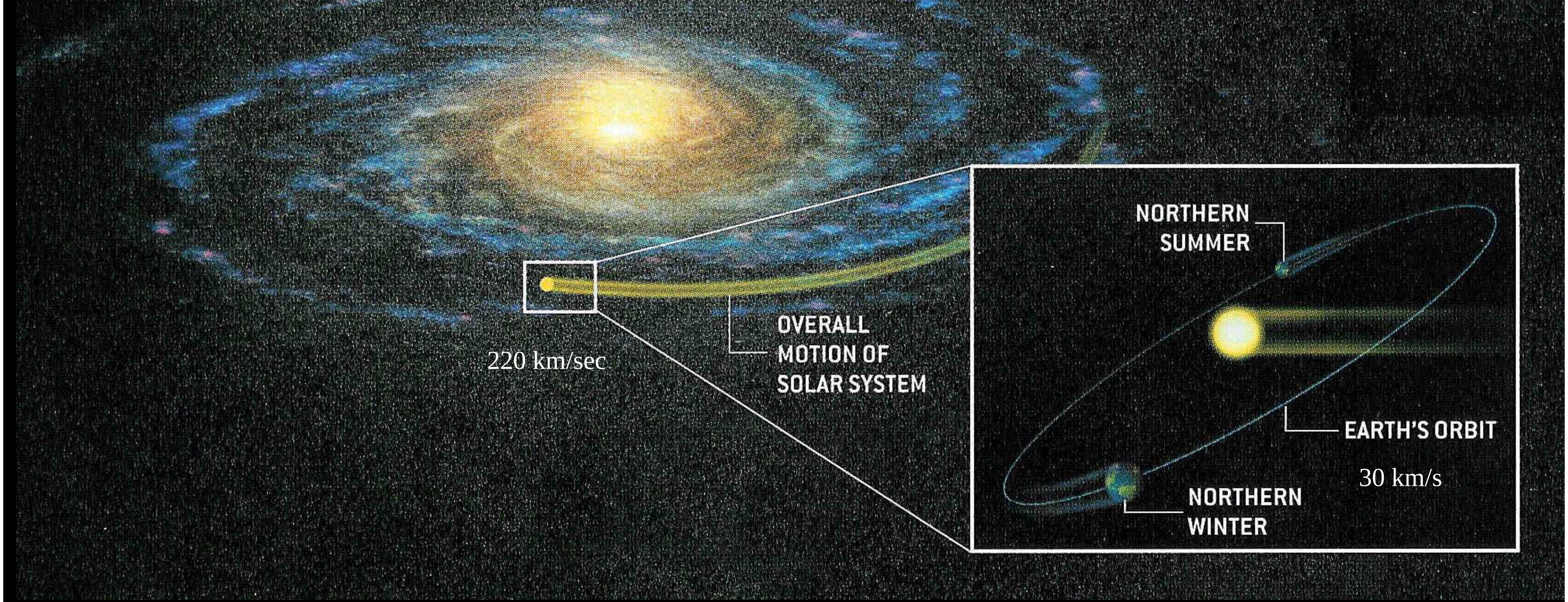


Indirect detection via DM annihilation in Sun, Earth, Galaxy
ν, γ-rays, anti-protons , positrons

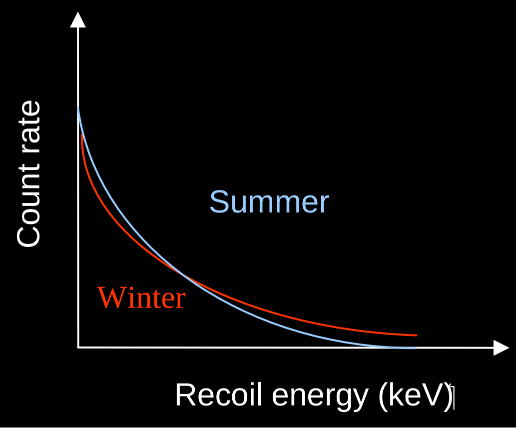


Direct detection in u/g laboratories

DIRECT DETECTION OF CDM PARTICLES



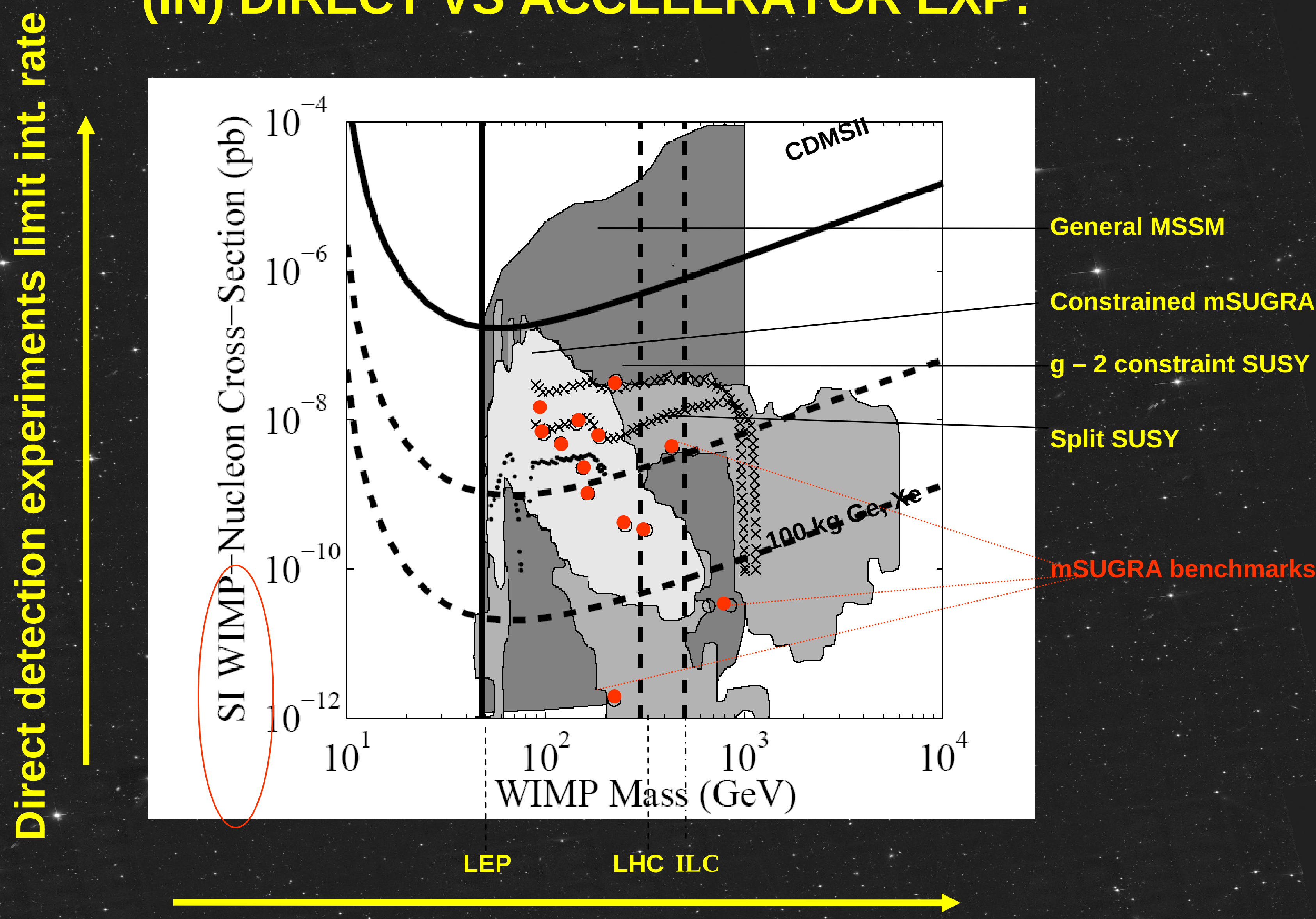
~ 10^{10} particles traverse us on earth per second!



- Recoil energyies: < 100 keV
- Rates: << 0.1 count /kgd
- Annual rate modulation ≈ 5 – 7%

A. Drukier, K. Freese, Spergel PRD 33(86)3495

(IN) DIRECT VS ACCELERATOR EXP.



R.W. Schnee astro-ph/061256

DIRECT SEARCHES

- lab detectors interact with galactic WIMPS
- *fast WIMPS* produce measurable recoils
- probe χ- halo density / structure at solar system
- no signal $\rightarrow$ limits on X-section
- $\rightarrow$ constraints on MSSM parameter space

INDIRECT SEARCHES

- gravitational trapping (sun, galactic centre etc)
- annihilating of *slow WIMPS*
- detection of annihil. products: pairs of γ, μ, ν, Z's
- probe χ abundance elsewhere
- no signal $\rightarrow$ limits on X-section
- $\rightarrow$ constraints on parameter space

χ - CDM ?

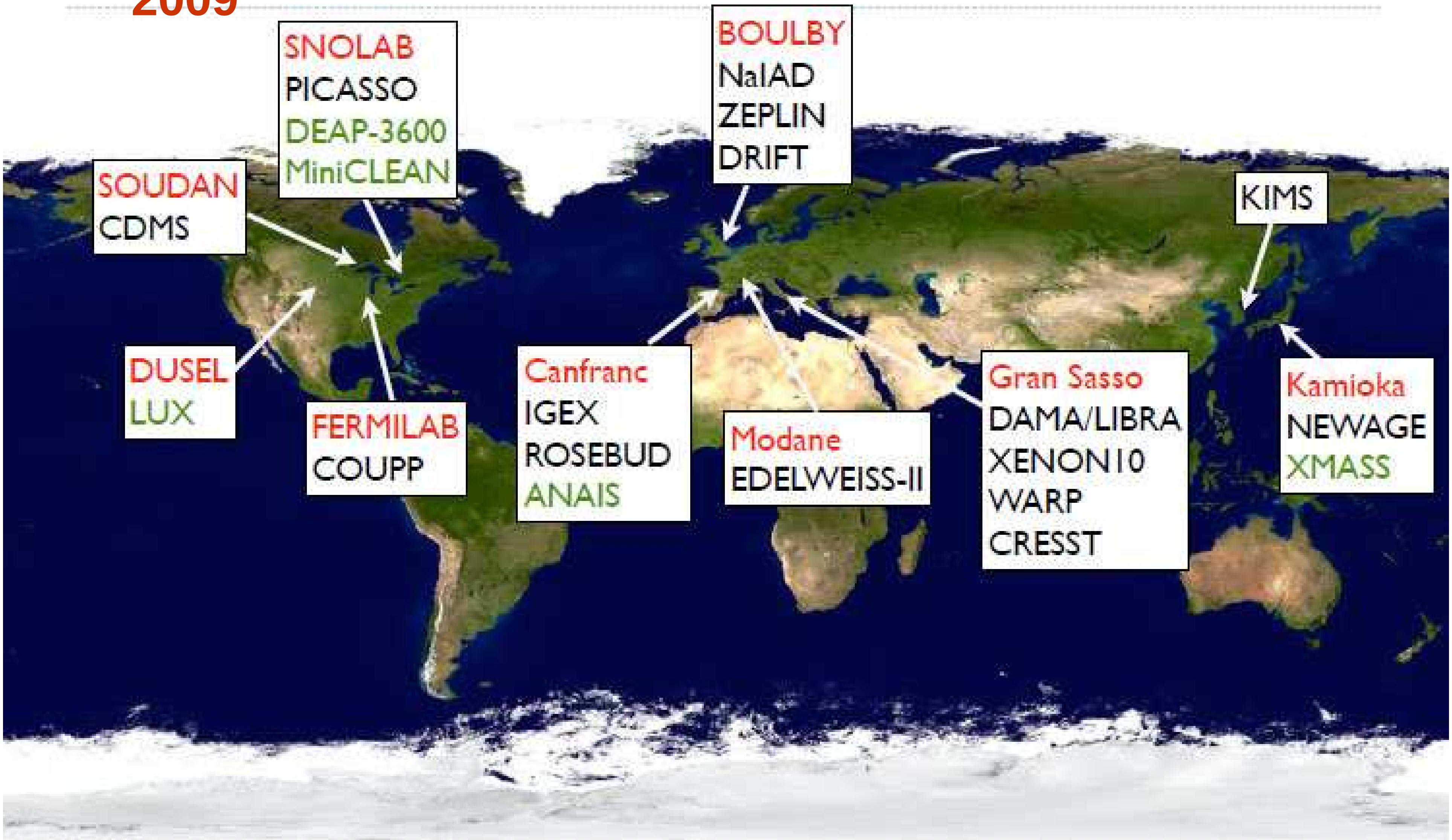
ACCELERATOR SEARCHES

- no signal $\rightarrow$ limits on mass range
- cannot tell if WIMP is stable
- $\rightarrow$ constraints on MSSM parameter space

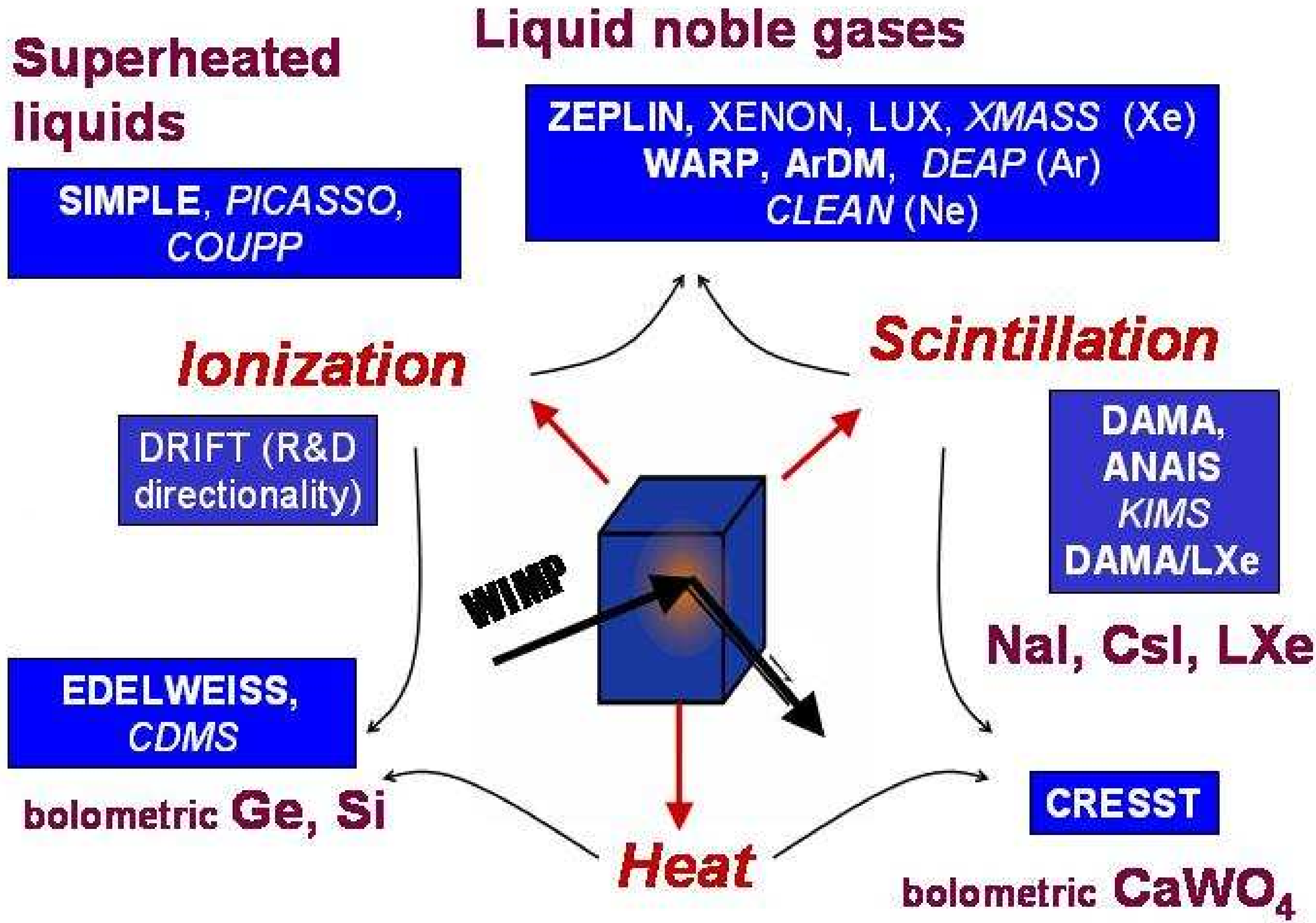
Complementarity !!!

- Discovery of cosmol. WIMP does not prove yet SUSY $\rightarrow$ accelerator searches
- LHC signal does not yet prove CDM discovery $\rightarrow$ (in) direct searches

SUMMARY DIRECT DETECTION ACTIVITIES - 2009



Black: running green: starting soon

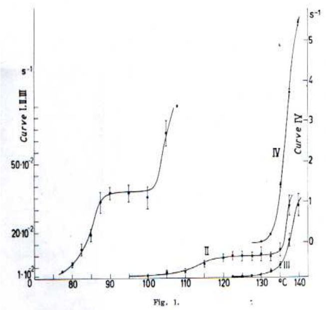

Superheated liquids
SIMPLE, PICASSO, COUPP
Liquid noble gases
ZEPLIN, XENON, LUX, XMASS (Xe)
WARP, ArDM, DEAP (Ar)
CLEAN (Ne)
Ionization
Scintillation
DRIFT (R&D directionality)
DAMA, ANAIS KIMS DAMA/LXe
WIMP
NaI, CsI, LXe
EDELWEISS, CDMS
bolometric Ge, Si
Heat
CRESST
bolometric CaWO4


Picasso
Project in Canada to Search for Supersymmetric Objects
Projet d'Identification de Candidats Supersymétriques SOmbres
Université de Montréal, Queen's University, University of Alberta, Laurentian University, University of Indiana, South Bend, Saha Institute for Nuclear Physics, Kolkata, SNOLAB, CTU Prague, Bubble Technology I.

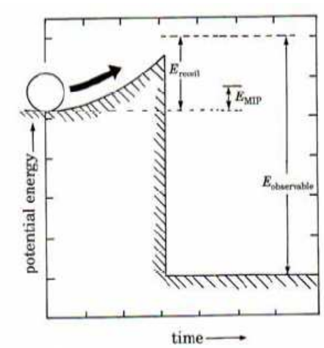
Superheated Liquids For Particle Detection

1952 Donald Glaser: “Some Effects of Ionizing Radiation on the Formation of Bubbles in Liquids” (Phys. Rev. 87, 4, 1952)

1958 G. Brautti, M. Crescia and P. Bassi: “A Bubble Chamber Detector for Weak Radioactivity” (Il Nuovo Cimento, 10, 6, 1958)



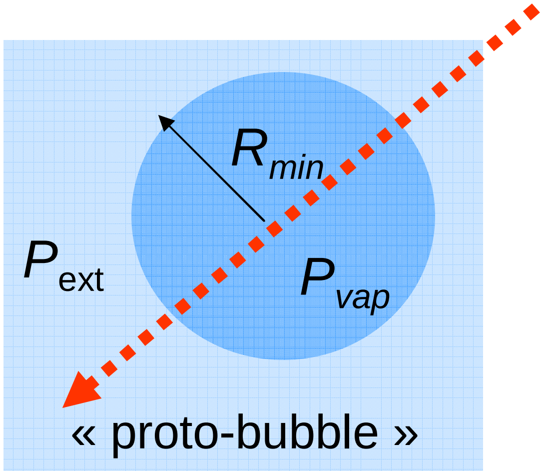
1960 B. Hahn and S. Spadavecchia “Application of the Bubble Chamber Technique to detect Fission Fragments” (Il Nuovo Cimento 54B, 101, 1968)



1993 Picasso “Search for Dark Matter with Moderately Superheated Liquids” (V.Z., Il Nuovo Cimento, 107, 2, 1994)

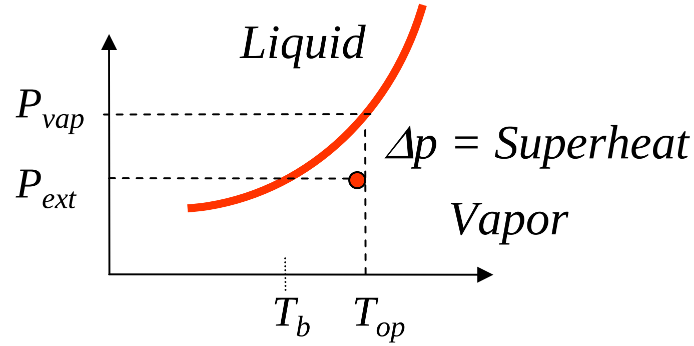
Superheated Liquids & Dark Matter: SIMPLE, COUPP, PICASSO

The Seitz Theory of Bubble Chambers



A bubble forms if:

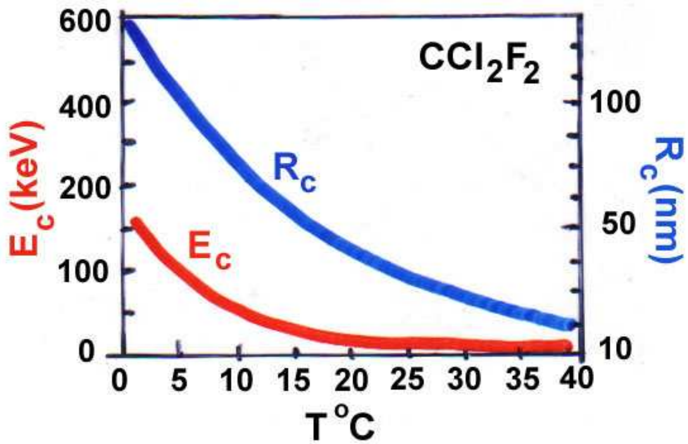
- particle creates a heat spike
- with enough energy E_{min}
- deposited within R_{min}



$$E_{dep} = \frac{dE}{dx} \cdot R_{\min} \geq E_{\min}$$

$$R_{\min} \equiv \frac{2\gamma(T)\varepsilon}{\Delta P(T)}$$

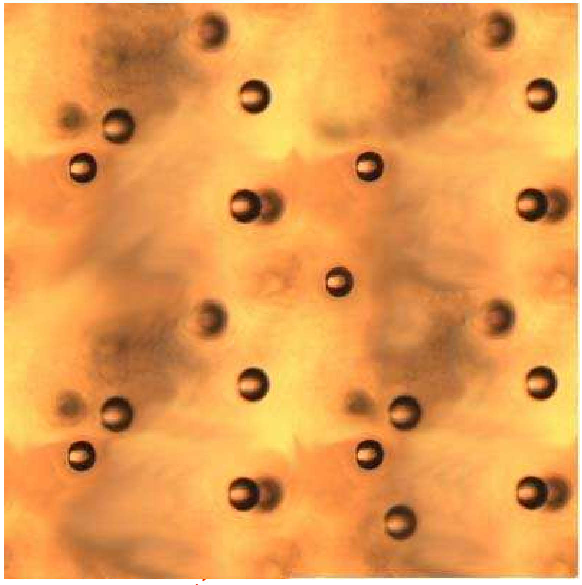
$$E_{\min} \equiv \frac{16\pi}{3\times\eta} \frac{\gamma^3(T)}{(\Delta P(T))^2}$$

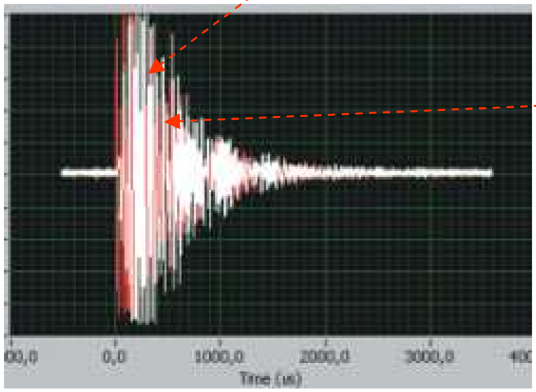


ΔP(T) = superheat
γ(T) = Surface tension
ε = critical length factor
η = energy convers. efficiency

F. Seitz, Phys. Fluids I (1) (1958) 2

- Superheated droplets at ambient T & P *
- 150μm droplets of carbofluorides dispersed in polymerised gel
- Active liquid: C_4F_{10} T_b= - 1.7 °C)
- Radiation triggers phase transition
- Events recorded by piezo-electric transducers





* Inspired by personal neutron dosimeters @ Bubble Technology Industries, ON

Main Features

- each droplet is an independent "clean" Bubble Chamber

- keV threshold for DM induced recoils

- with full efficiency for nuclear recoils

- excellent gamma & MIP at E_{rec}= 5 keV

- continuous operation 30h

- recompression recycles burst droplets

- low cost, with potential for a large DM experiment

- in house fabrication

1st generation: 10 mL

2nd generation : 1L

3rd generation : 4.5L

Active Target C_4F_{10}

Neutralino interaction with matter:

$$\sigma_A = 4G_F^{\,2}\left(\frac{M_\chi M_A}{M_\chi + M_A}\right)^2 C_A$$

Enhancement factor

Depending on the type of target nucleus and neutralino composition

Spin independent interaction ($C_A \propto A^2$)

Spin dependent interaction

$$C_A = (8/\pi)(\underbrace{a_p\langle S_p\rangle + a_n\langle S_n\rangle}_{\lambda})^2(J+1)/J$$

Isotope	Spin	Unpaired	λ^2
^{7}Li	3/2	p	0.11
^{19}F	1/2	p	0.863
^{23}Na	3/2	p	0.011
^{29}Si	1/2	n	0.084
^{73}Ge	9/2	n	0.0026
^{127}I	5/2	p	0.0026
^{131}Xe	3/2	n	0.0147

Spin of the nucleus is approximately the spin of the unpaired proton or neutron

Ho to make Picasso Detectors

R&D in collaboration with BTI, Chalk River

- Start with monomer matrix solution

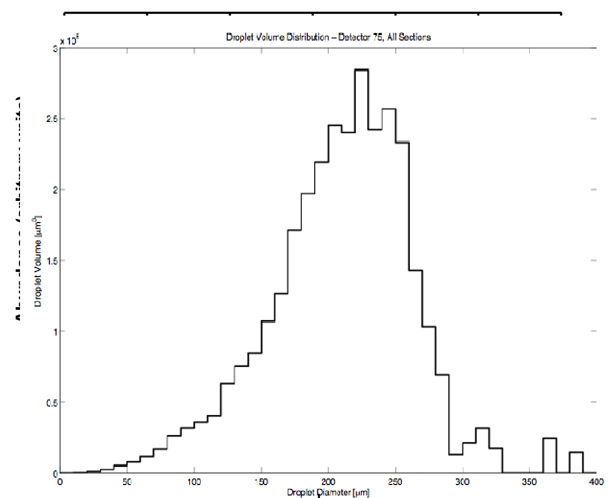
- Add heavy CsCl solution to match density of active gas (ρ = 1.6 g/cm^3)

- add active gas in liquid form

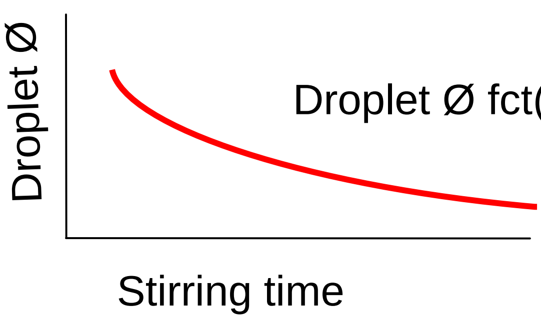
- magnetic stirring to disperse droplets

- polymerize matrix

- all done in clean room to avoid U/Th, Rn

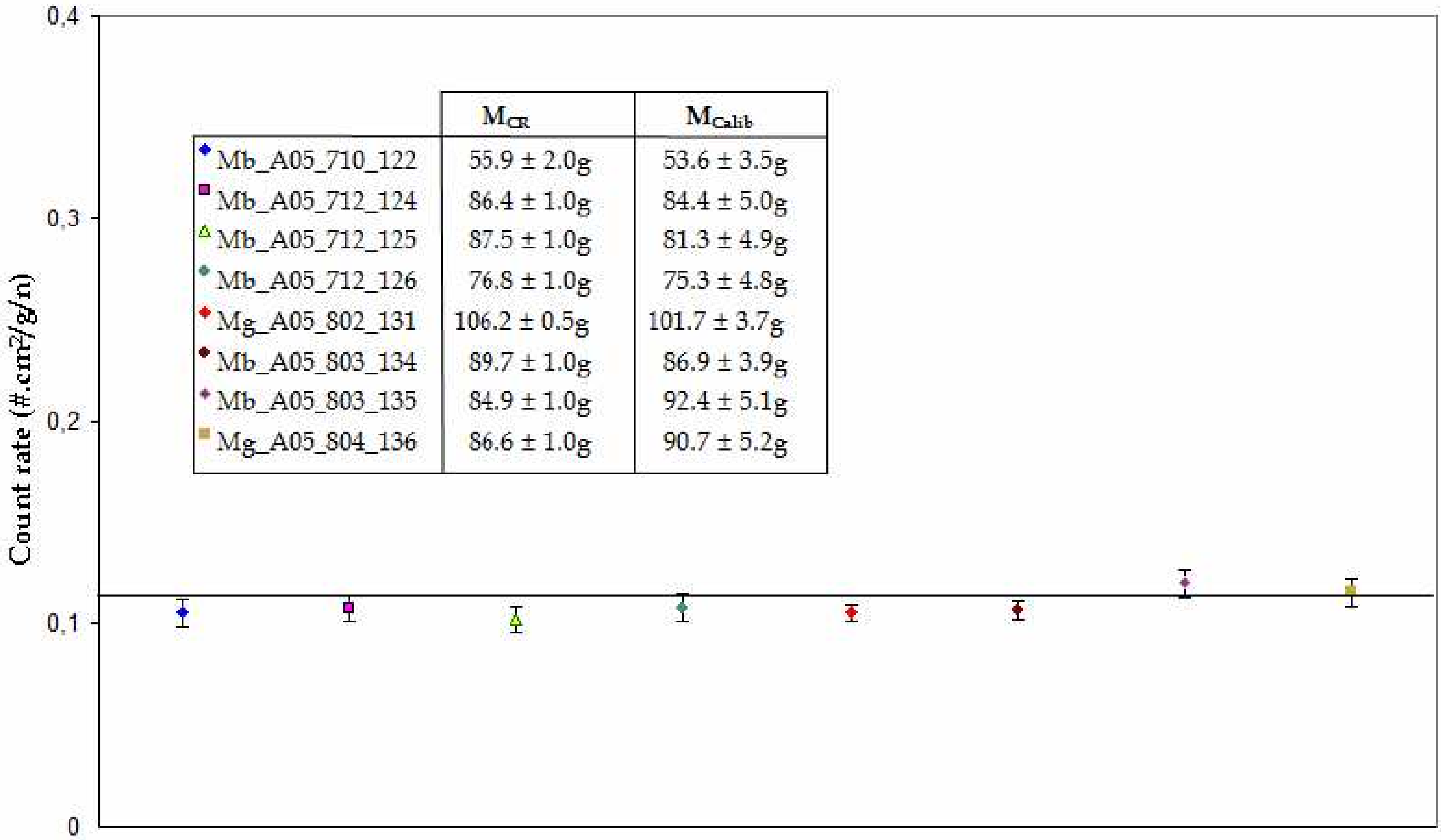


200µmØ



Determination of the acive mass

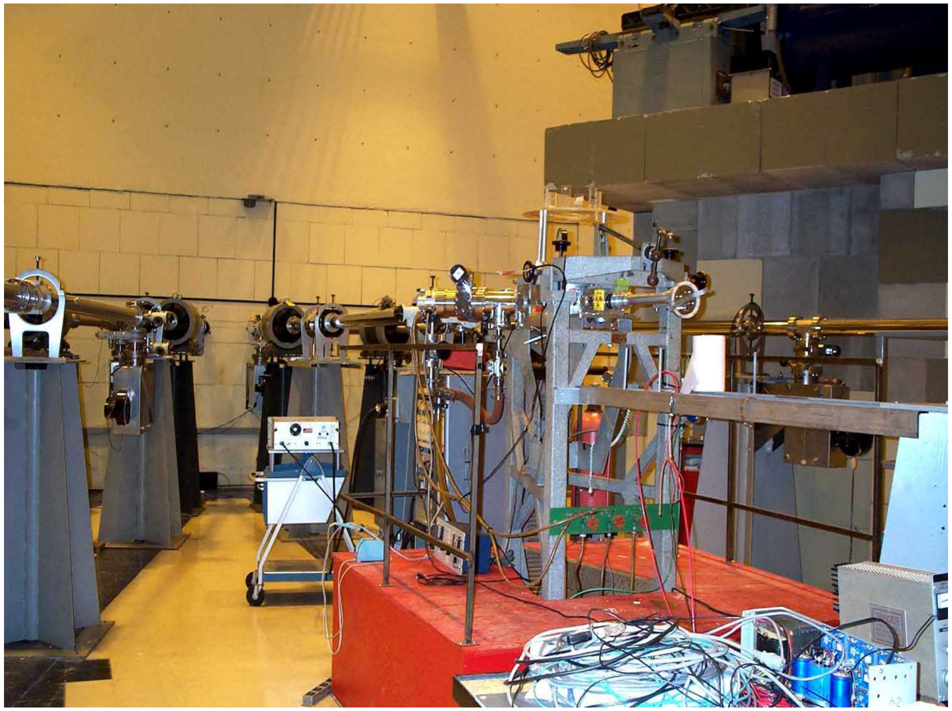
- Weighing of C_4F_{10} during detector fabrication
- Control of active mass by calibration in know AcBe neutron flux



	M_{CR}	M_{Calib}
Mb_A05_710_122	55.9 ± 2.0g	53.6 ± 3.5g
Mb_A05_712_124	86.4 ± 1.0g	84.4 ± 5.0g
Mb_A05_712_125	87.5 ± 1.0g	81.3 ± 4.9g
Mb_A05_712_126	76.8 ± 1.0g	75.3 ± 4.8g
Mg_A05_802_131	106.2 ± 0.5g	101.7 ± 3.7g
Mb_A05_803_134	89.7 ± 1.0g	86.9 ± 3.9g
Mb_A05_803_135	84.9 ± 1.0g	92.4 ± 5.1g
Mg_A05_804_136	86.6 ± 1.0g	90.7 ± 5.2g

Detection of Nuclear Recoils

- Calibration with mono-energetic neutrons
- neutron induced nuclear recoils similar to WIMPS
- at low energies only s-wave scattering important
- Reaction: $^{7}Li(p,n)^{7}Be$, $^{51}V(p,n)^{51}Cr$ reaction at 6 MV UdeM-Tandem

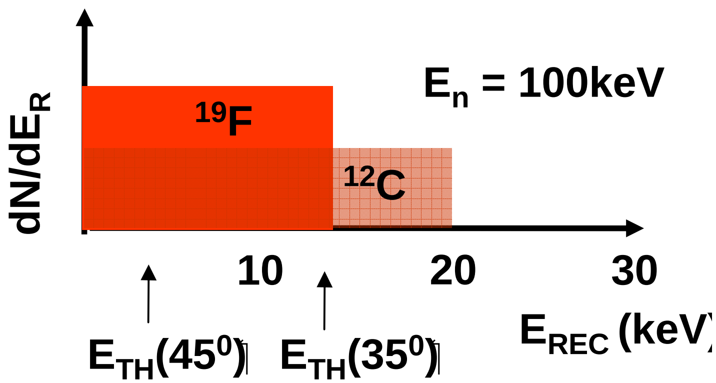


- Recoil detection efficiency
- Control of active mass in detectors
- Comparison of different liquids

Ideal tool for calibrating droplet detectors!

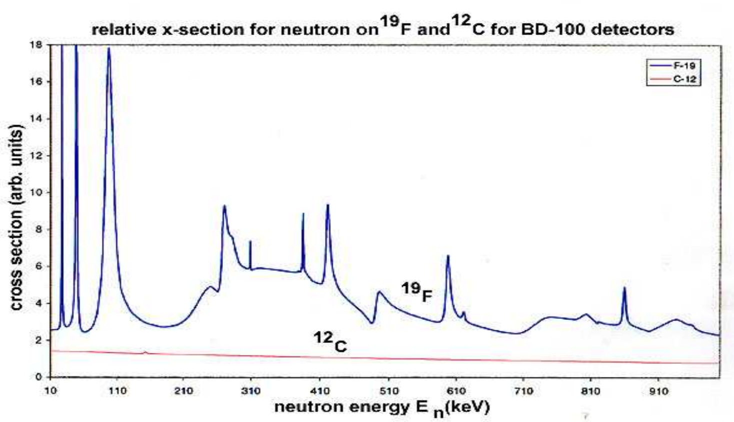
Droplet Detectors are Threshold Detectors…

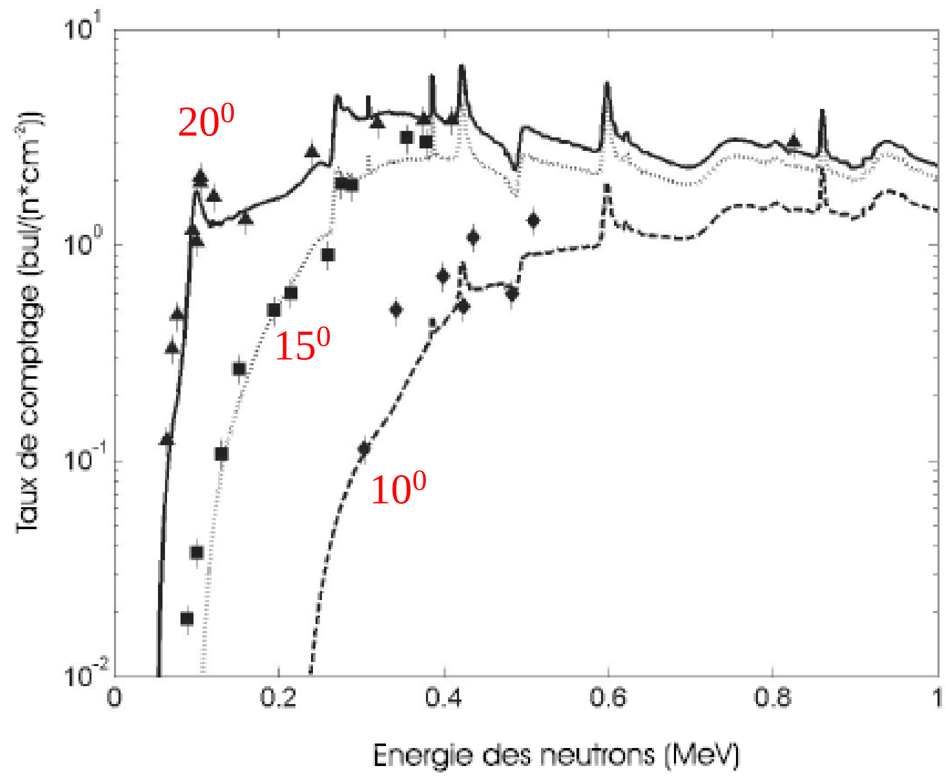
Determine energy response as a function of T & P $\rightarrow$ superheat!



$$E_{Rec} = E_n \frac{2A}{(A+1)^2}(1-\cos\theta)$$

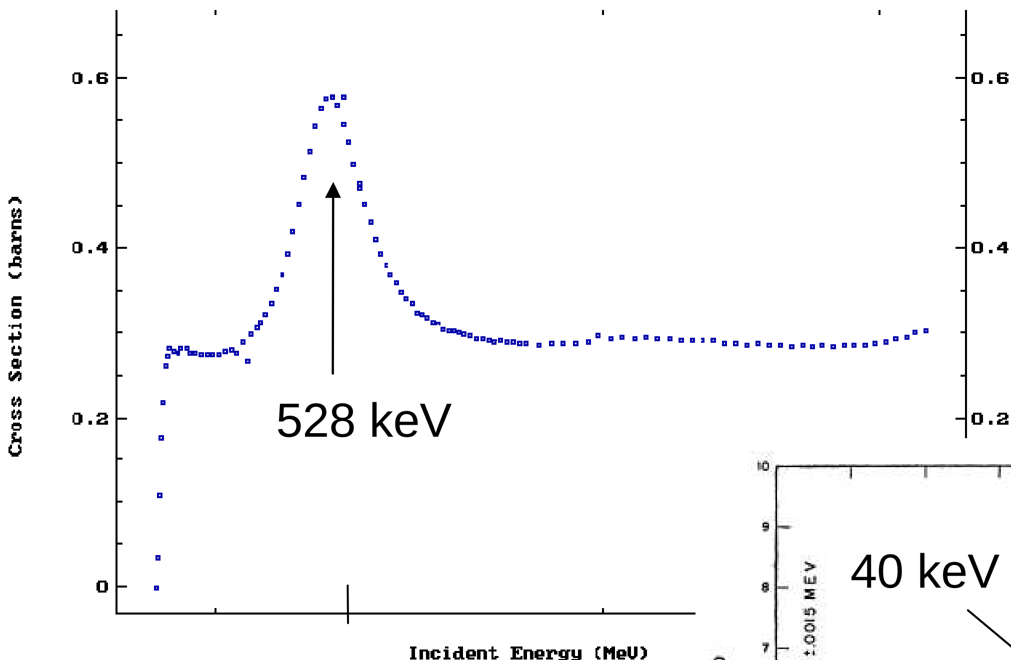
Cross sections well known:





Target selection

Lithium (^{7}Li)



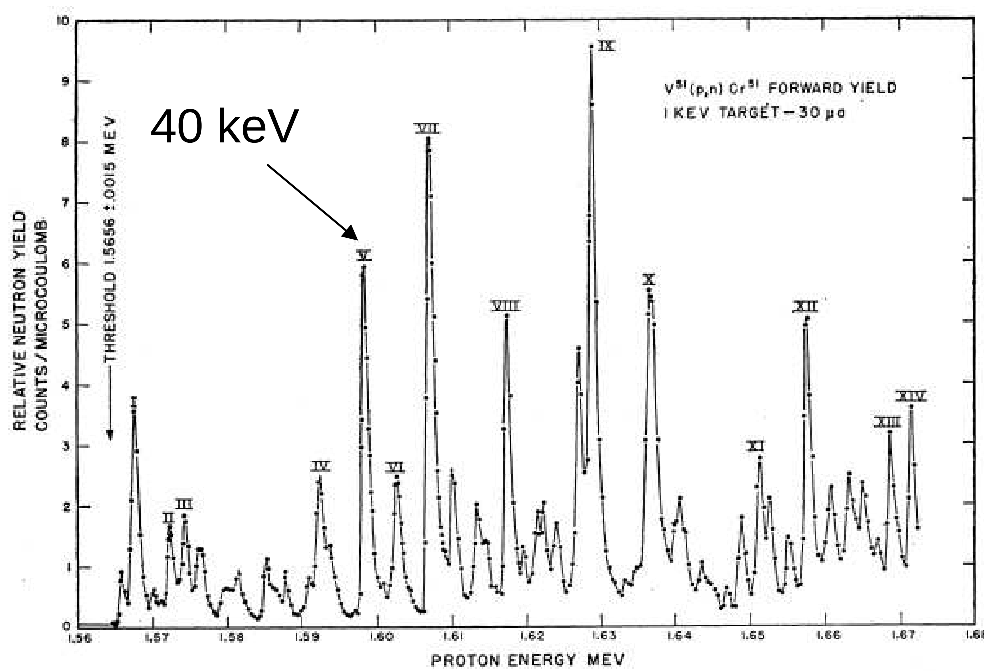
2.28 MeV

Previous measurements:

^{7}Li target

200 keV < E_n < 5000 keV.

Vanadium (^{51}V)

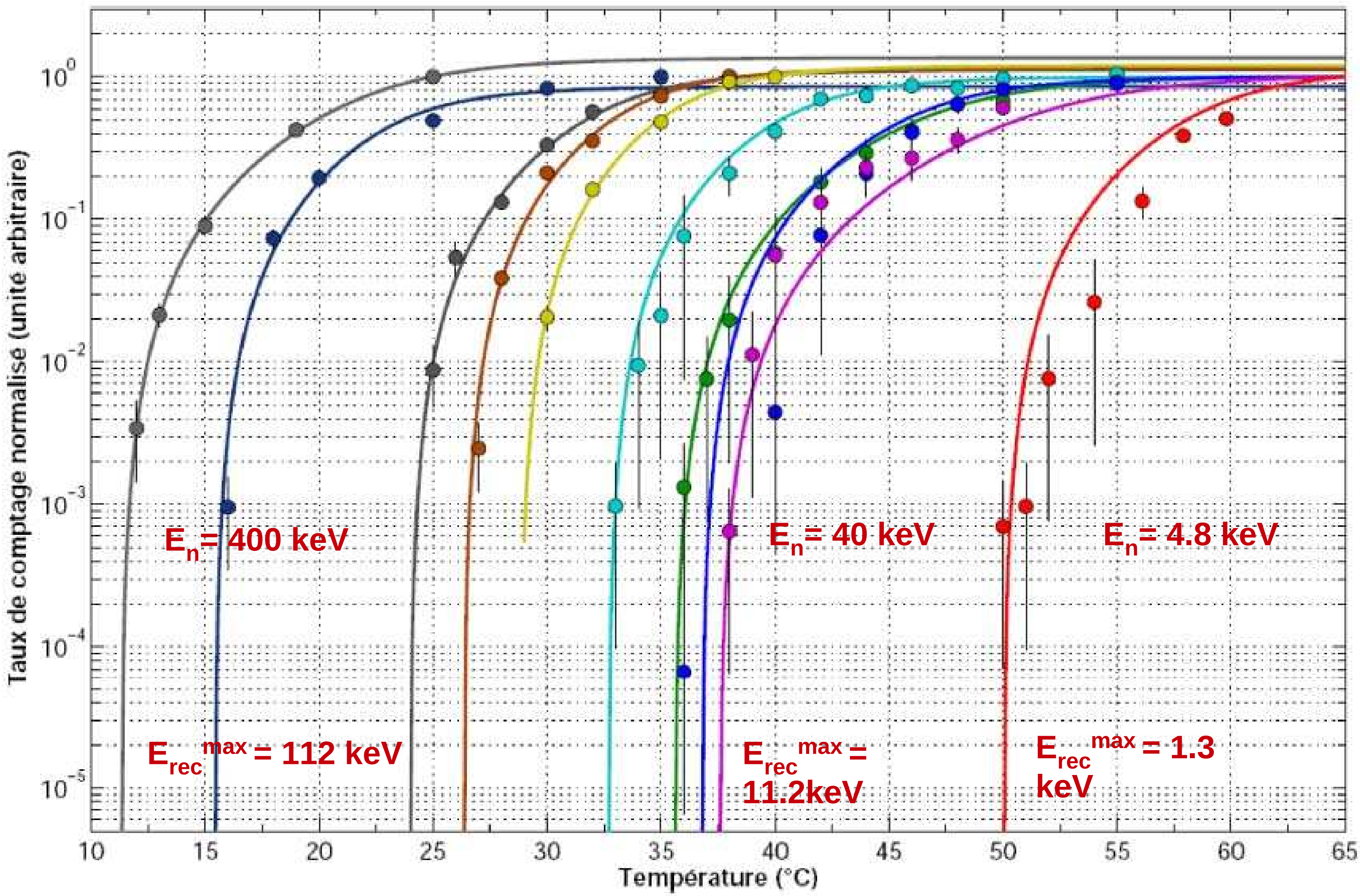


New measurements:

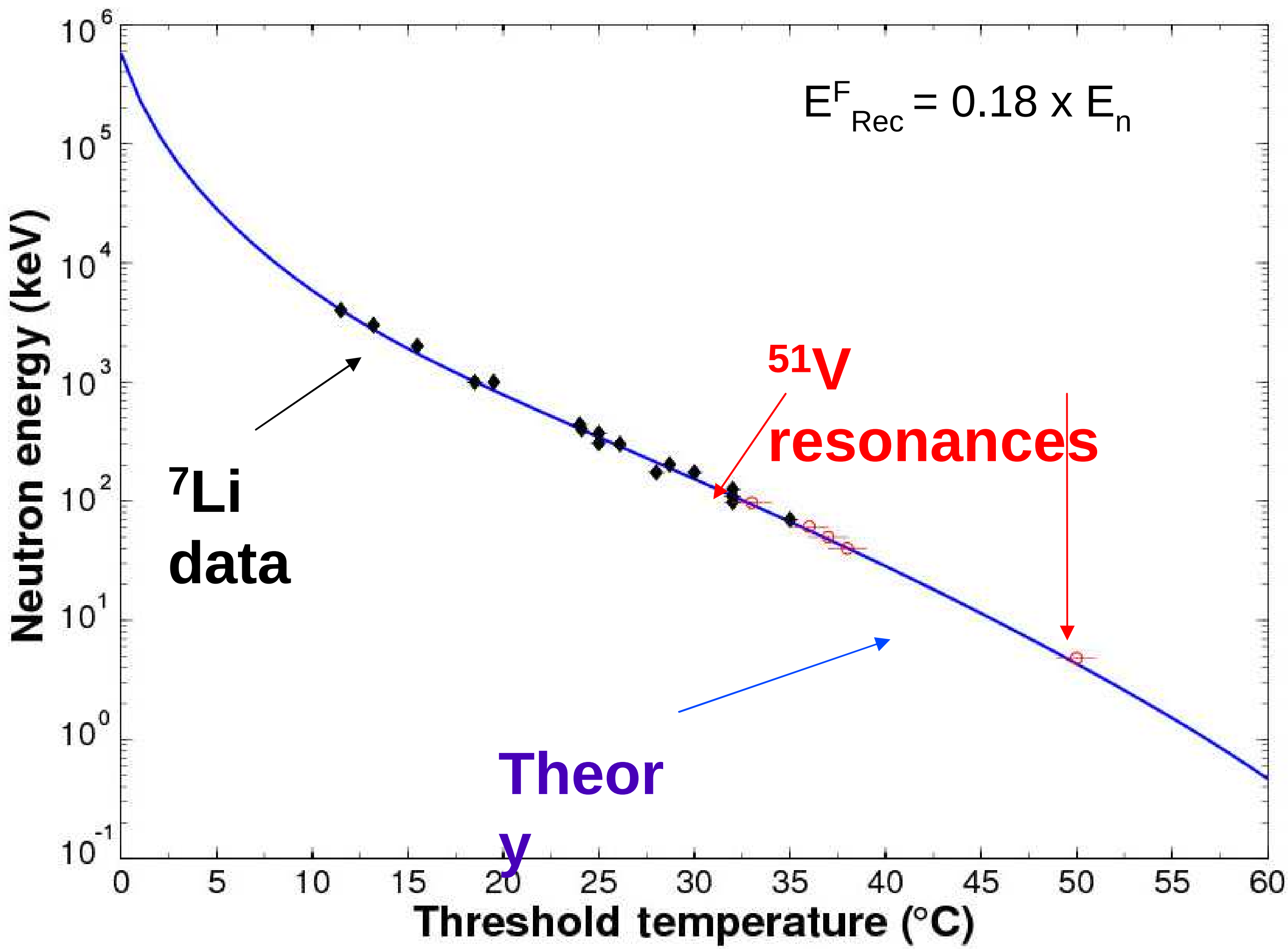
^{51}V target

5 keV < E_n < 90 KeV

Neutron Beam Calibration

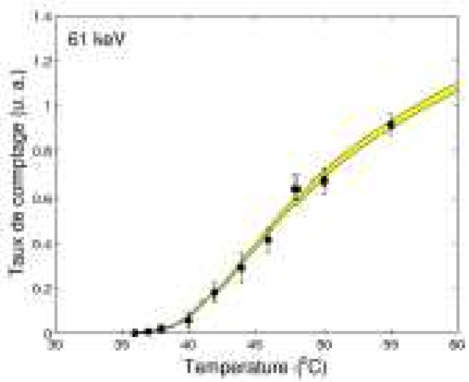


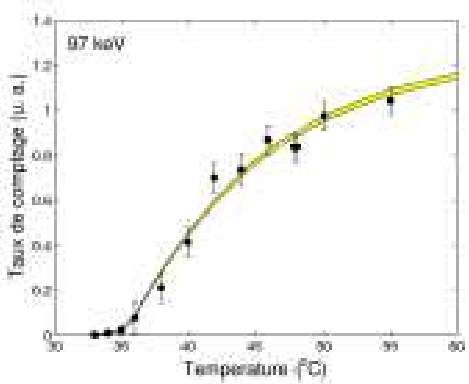
Calibration of the Detector Response



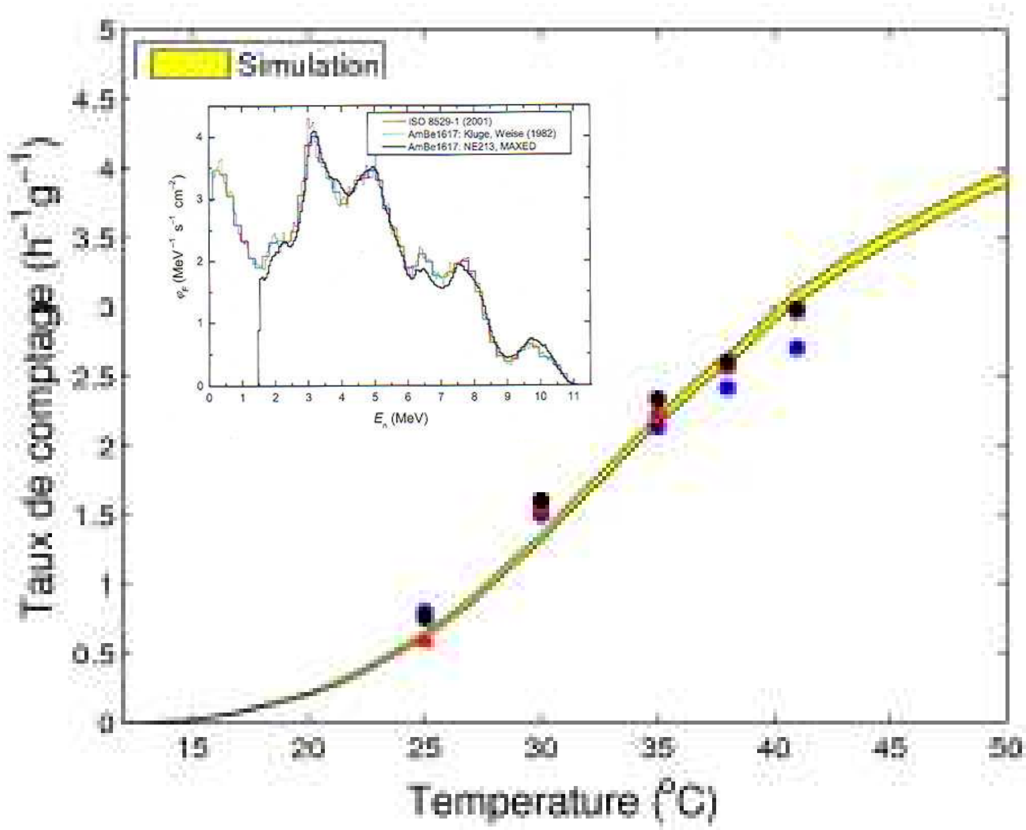
Monte Carlo Simulations

Test beam





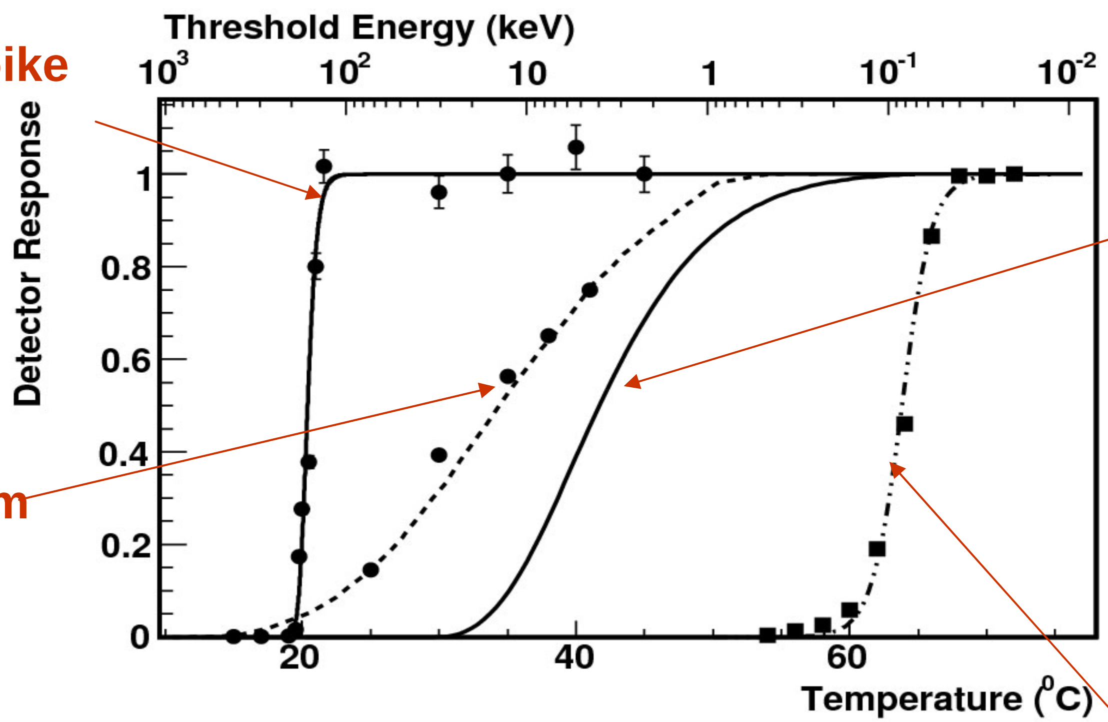
AmBe source (u/g calib.)



- Response at threshold not a step function! $P(E,E_{th}) = 1 - \exp a(1 - E/E_{th})$
- *a* - increases with neutron energy! New!

Detector Response

α - particles
from ^{226}Ra spike



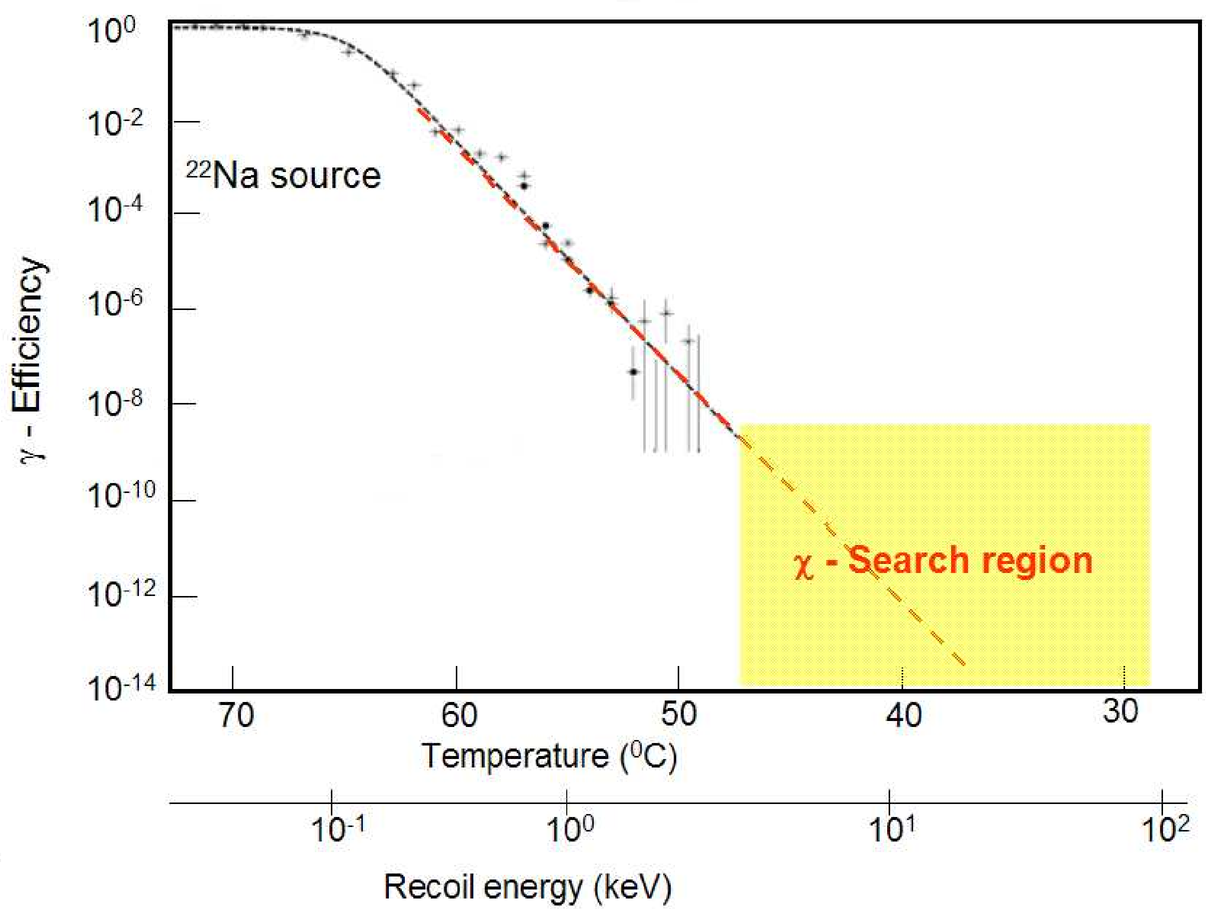
Reoil nuclei from
50 GeV /c^2 WIMP

Neutrons from
AcBe source
(data +MC)

γ's from ^{22}Na & MIP's

Gamma & MIP rejection better 10^{10} above E_{rec}= 10 keV!

Background Reduction

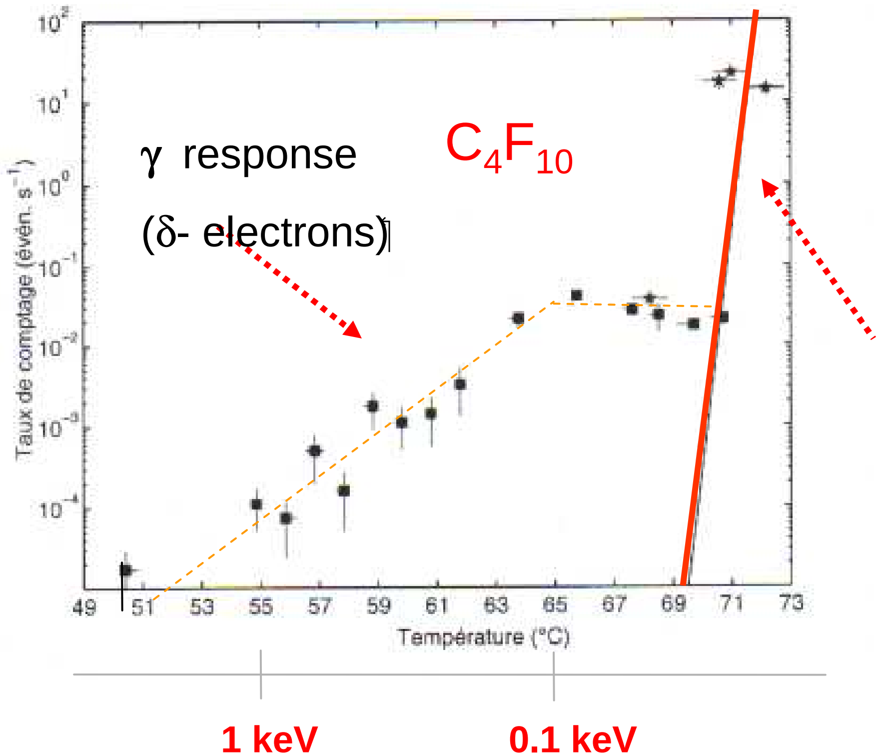


Gamma & MIP rejection better 10^{10} above E_{rec}= 10keV!

Limit of Stability: Homogeneous Nucleation

- Limit of stability when thermal fluctuations deposit E_{min} within R_{mib}
- Theory predicts instability of liquid phase at app. 90% T_c

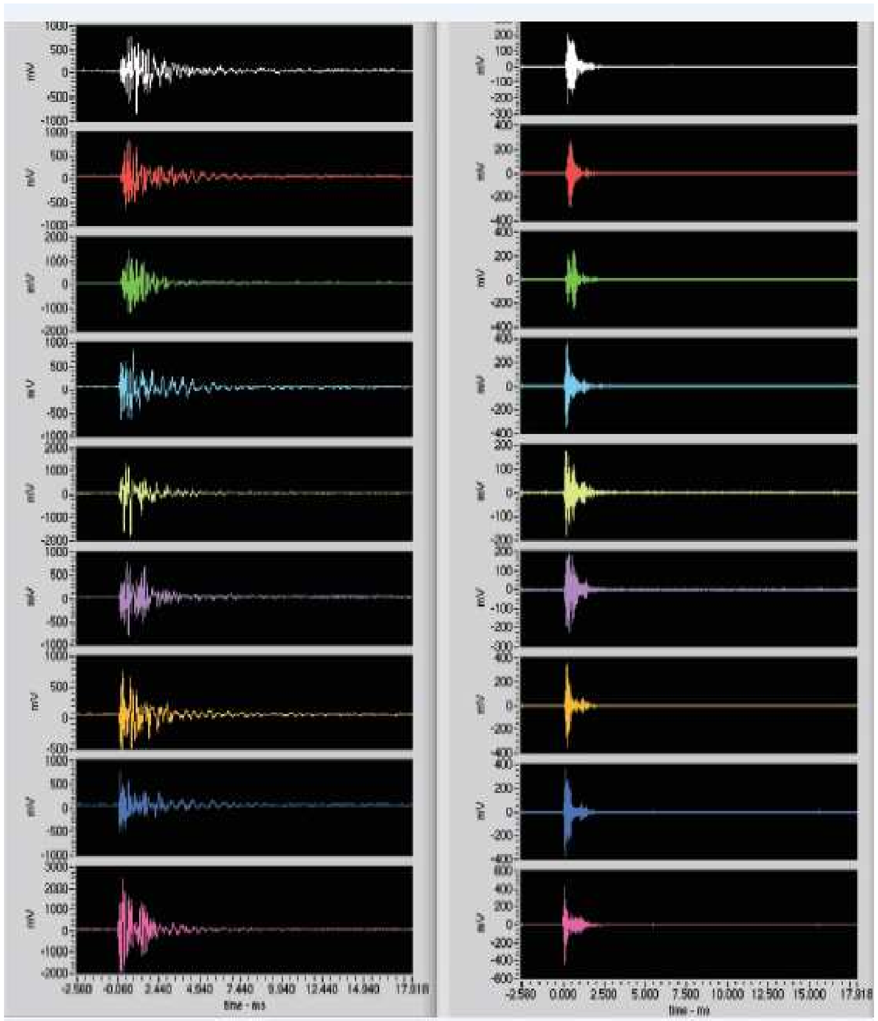
$$P(s^{-1}cm^{-3}) \propto \exp(-\frac{E_c(T)}{kT})$$



Future applications:

coherent neutrino scattering?

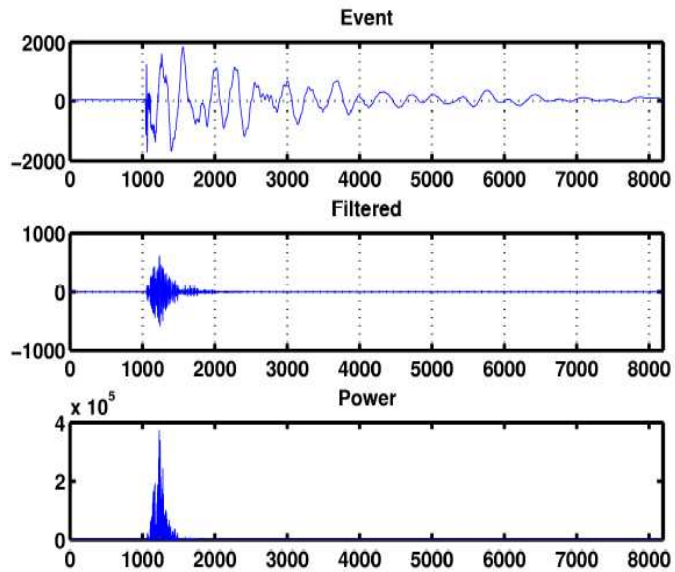
Treatment of Signal Waveforms



Raw

>18 KHz

- filter events (high pass)
- Integrate amplitude
- $\rightarrow$ Variable $\propto$ to Signal energy “pvar”

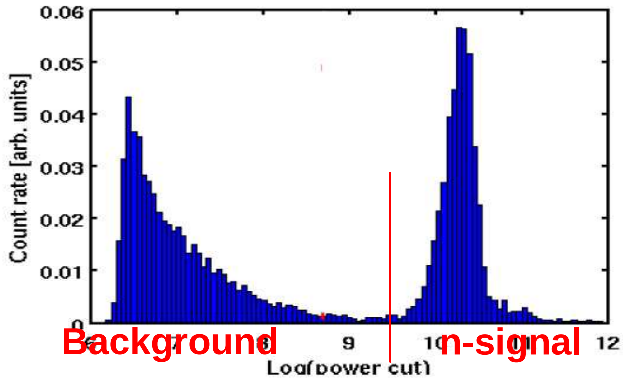


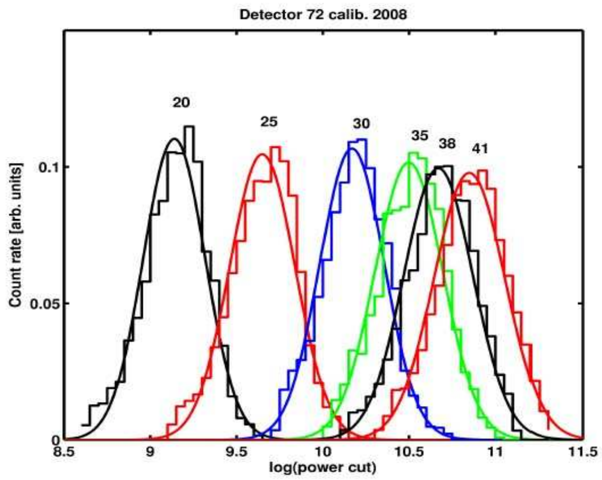
- time frequency analyis
- Fourier transform variable “fvar”
- spike cuts

The Energy Variable "Pvar"

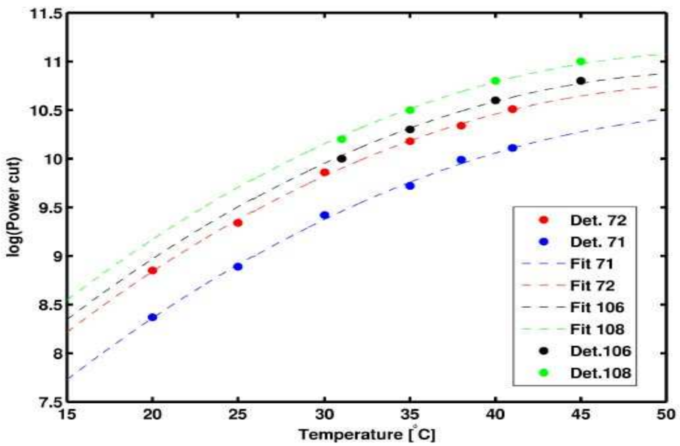
Power cut variable discriminates:
- « Non-particle » induced events
- Air bubbles
- Fractures...

Cut value is temperature dependent!



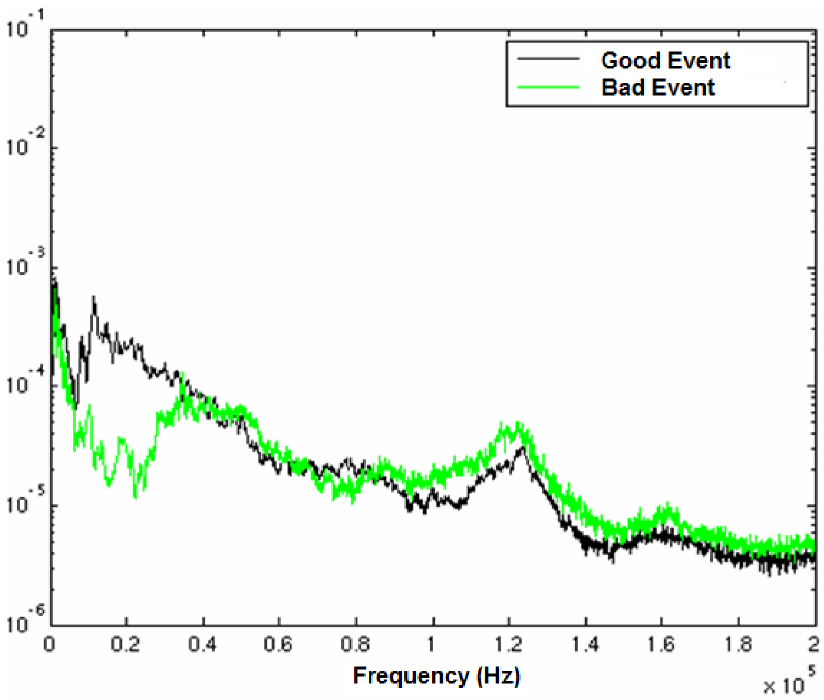


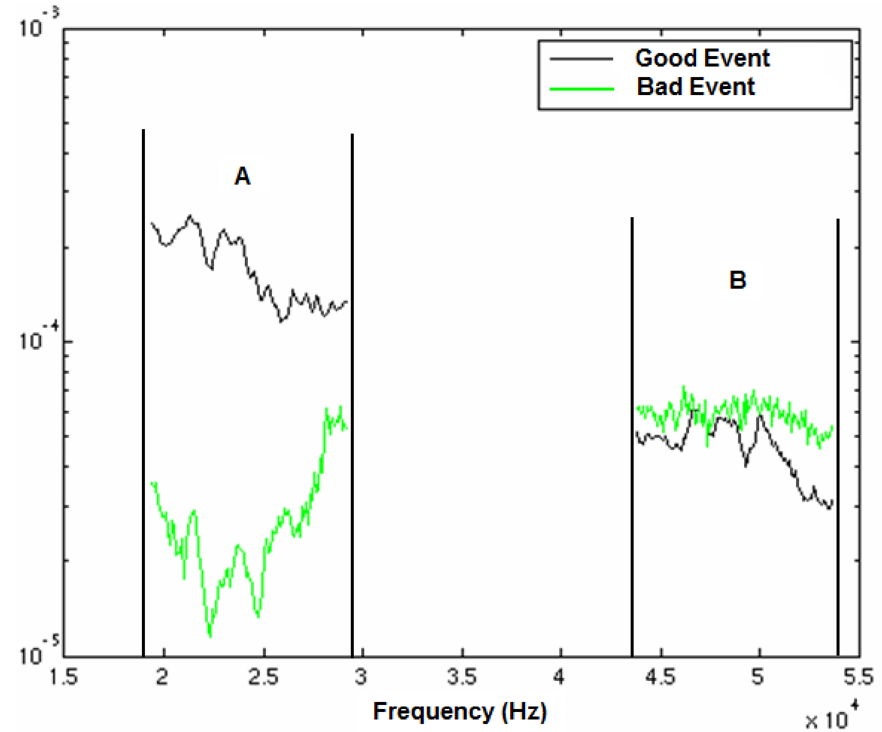
Neutron-calibration (AcBe)



Temperature interpolation

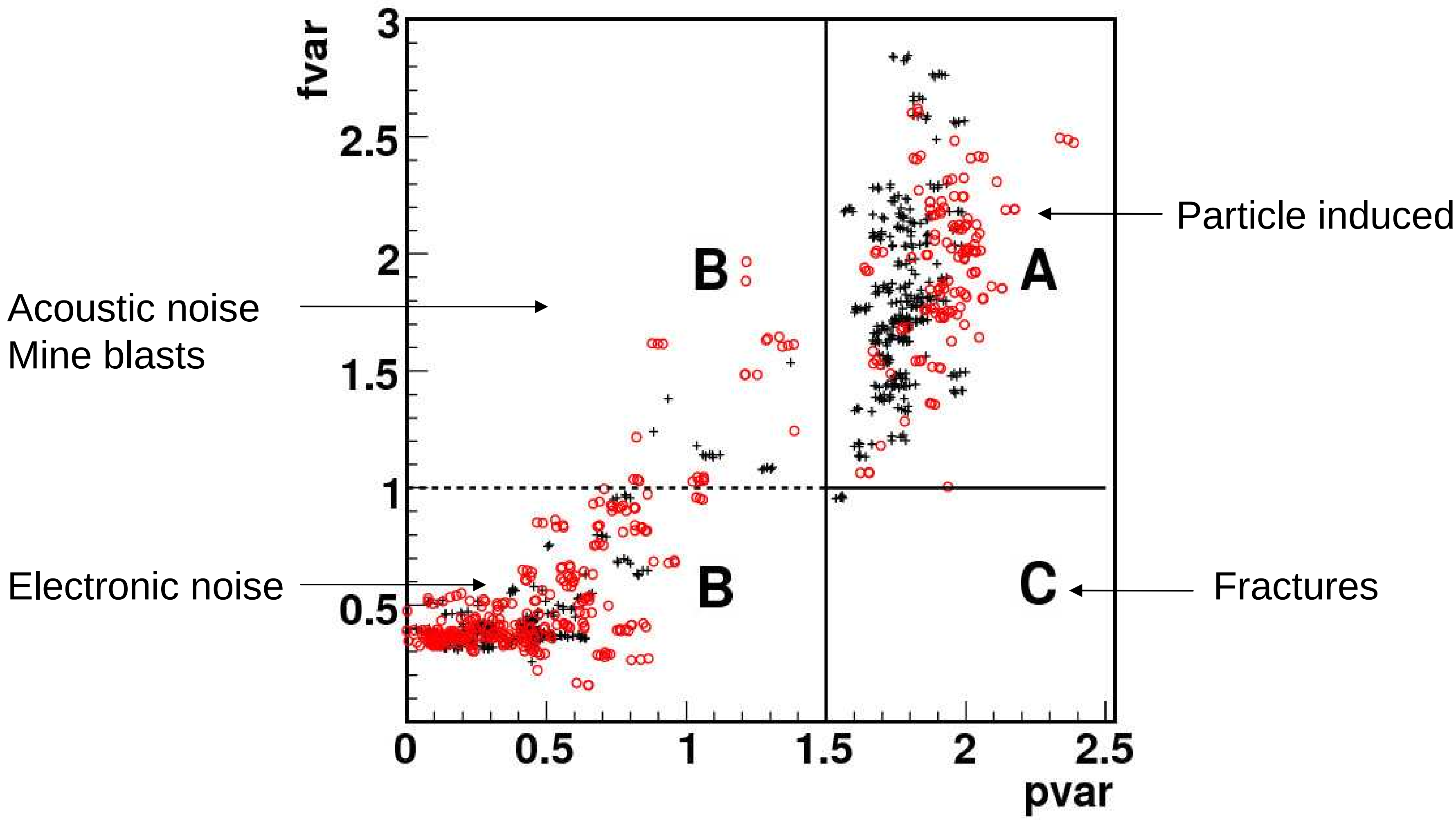
The Frequency Variable "Fvar"





- Construct Fourier Transform
- Ratio of region A / region B → "Fvar"

Pvar vs. Fvar → Background Discrimination!



Black: n- calibration run

Red: background run

Discrimination of Nuclear Recoils from Alpha Particles

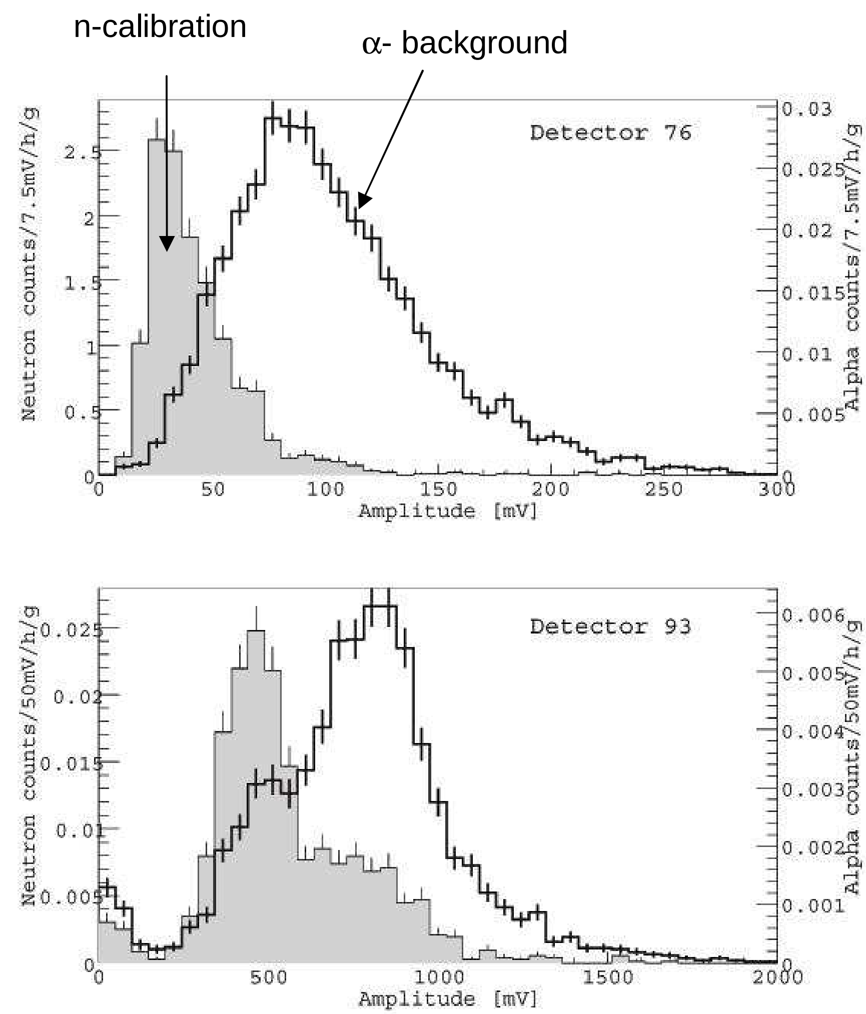
PICASSO discovered a significant difference between amplitudes of neutron and α- particle induced events !

New Journal of Physics 10(2008)103017 arXive: 0807.1536

Average of peak amplitudes of nine transducers / detector

High pass filter with cut-off at 15 KHz

Signals carry information about first moment of bubble formation



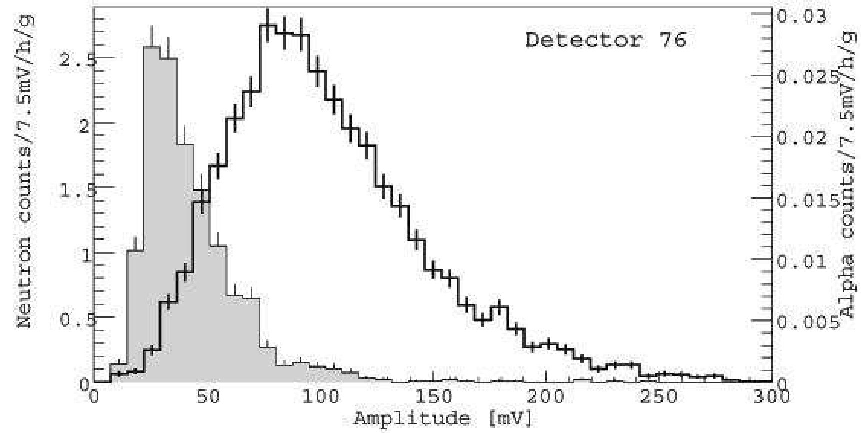
Discrimination of Nuclear Recoils from Alpha Particles

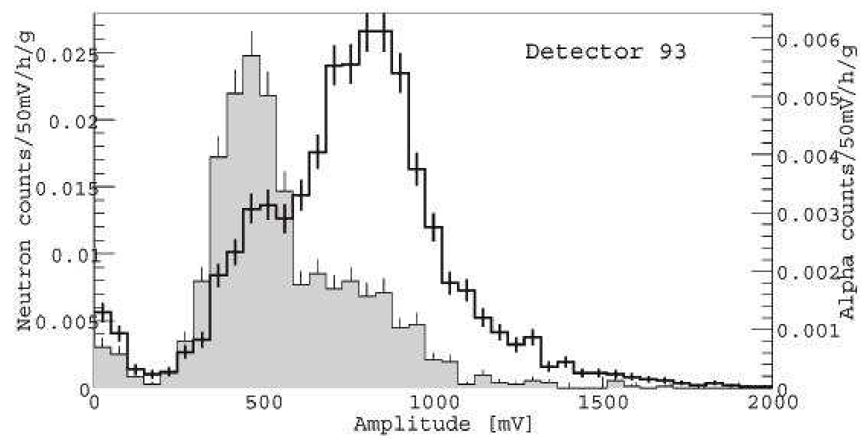
PICASSO discovered a significant difference between amplitudes of neutron and α- particle induced events ! New Journal of Physics 10(2008)103017 arXive: 0807.1536

Why not observed earlier?

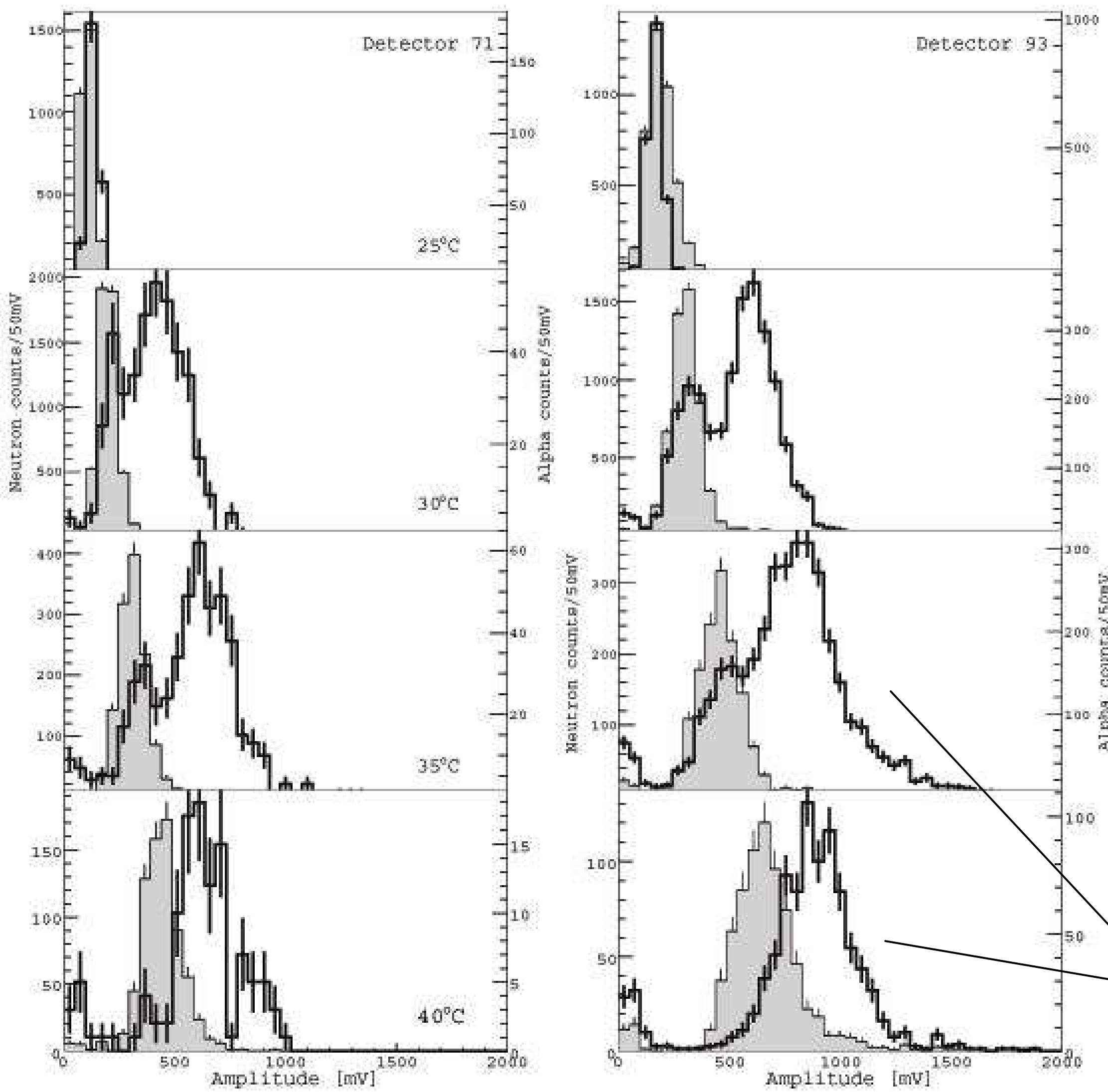
Previous detector had smaller droplets!

- now 200 μm compared to < 10 μm
- range of nuclear recoils < L_c
- but range of alphas >> L_c
- many bubbles can form on α track (depend on temperature)





α - n Discrimination: Temperature Dependence

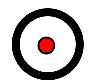


Strong saturation of raw signals above 30^{0}C!

α - n Discrimination: a tentative explanation

Nuclear recoil: point like, strong ionisation

# of primary bubbles



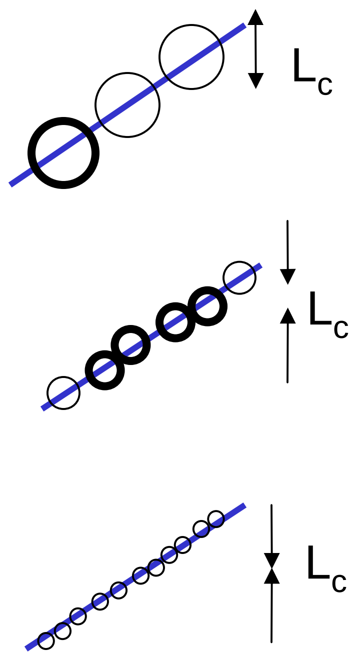
α-particles: ionization on 35μm track

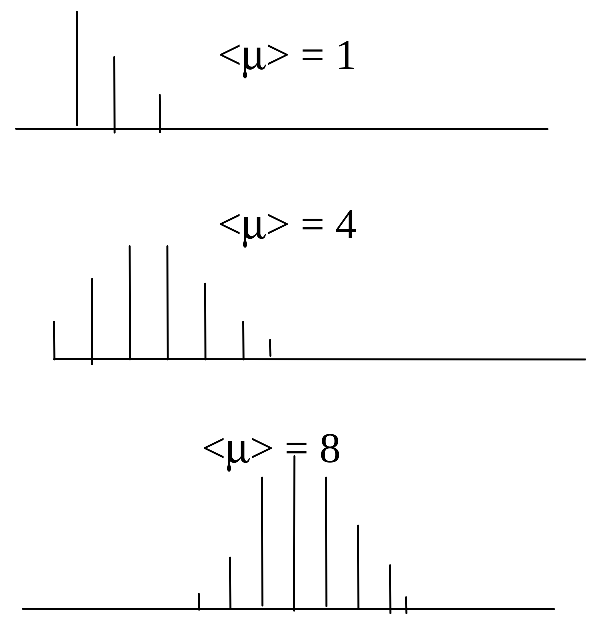
prim. bubbles *Poisson* distributed !

$T = 30^0C$

$T = 40^0C$

$T = 50^0C$





# of bubbles created

(in MIP sensitive region: $T = 60^0$ C $\rightarrow$ > 20 bubbles)

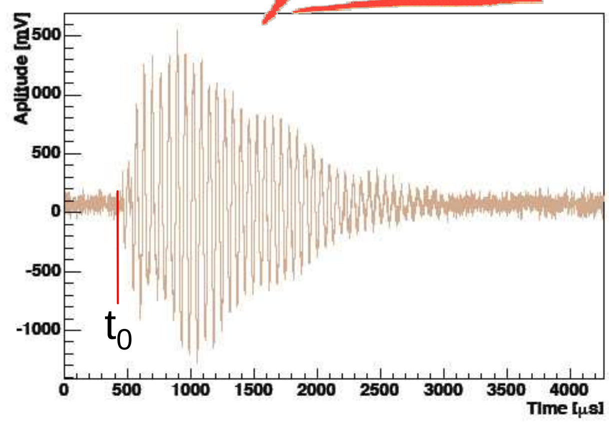
EVENT LOCALIZATION

Reconstruction of event position very promising

Allows suppression of hot spots or surface events

Determine t_0 from wave form

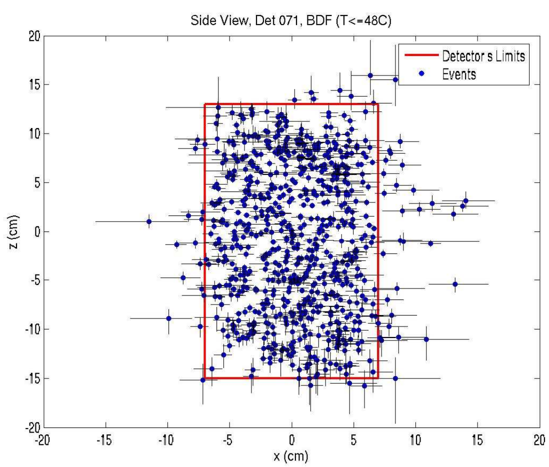
Reconstruction efficiency > 80%

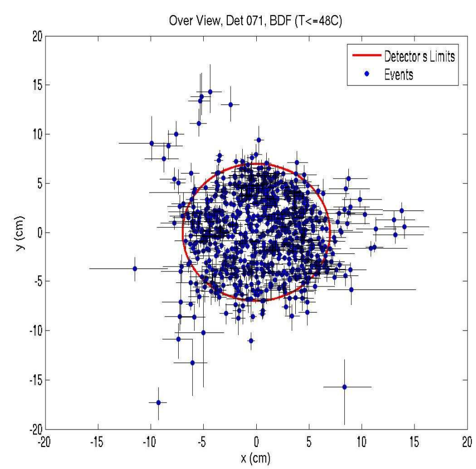


$$\chi^2 = \sum_{i=0}^{8} \left(\frac{(th_i - th_0) - (t_i - t_0)}{\sigma_i} \right)^2$$

th_i : Calculated time from the fitted point to the i^{th} piezo.

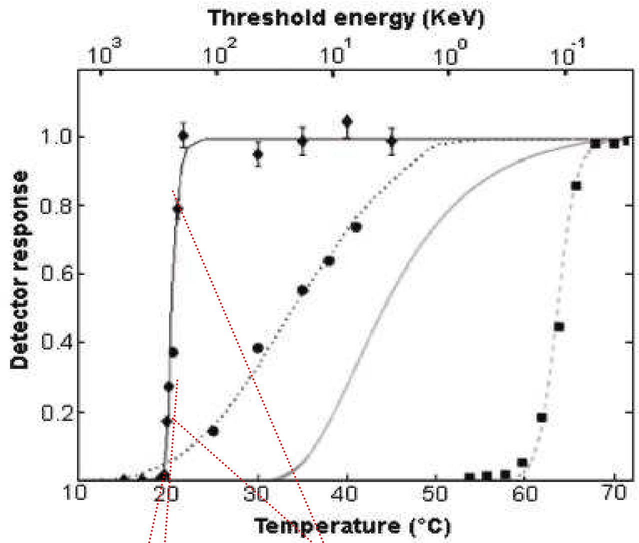
t_i : Measured time of the beginning of the event on the i^{th} channel.



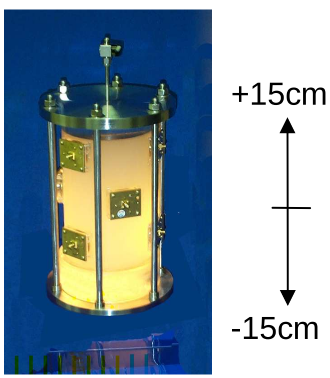


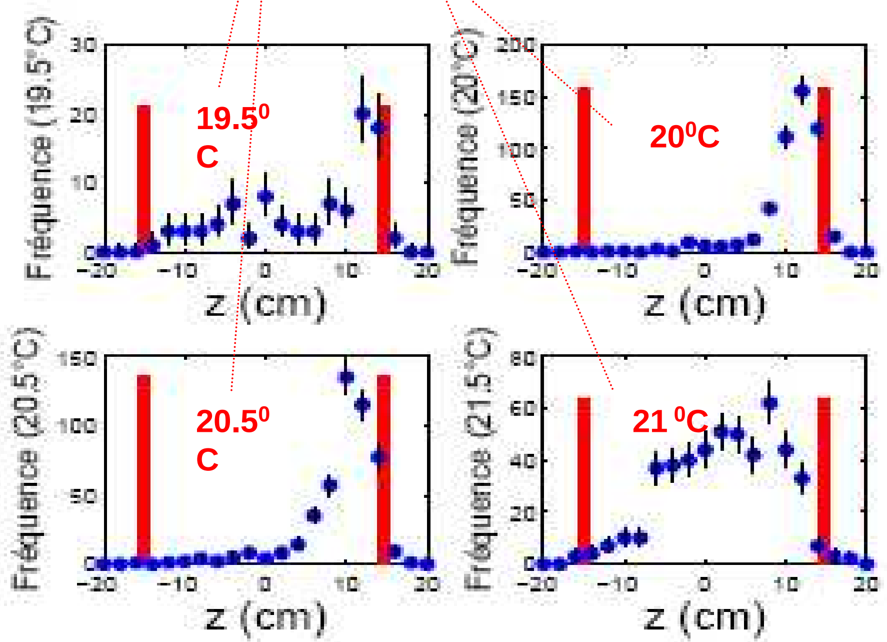
3D- distribution of background events

A Curiosity: The Amazing Steepness of the α-Threshold!



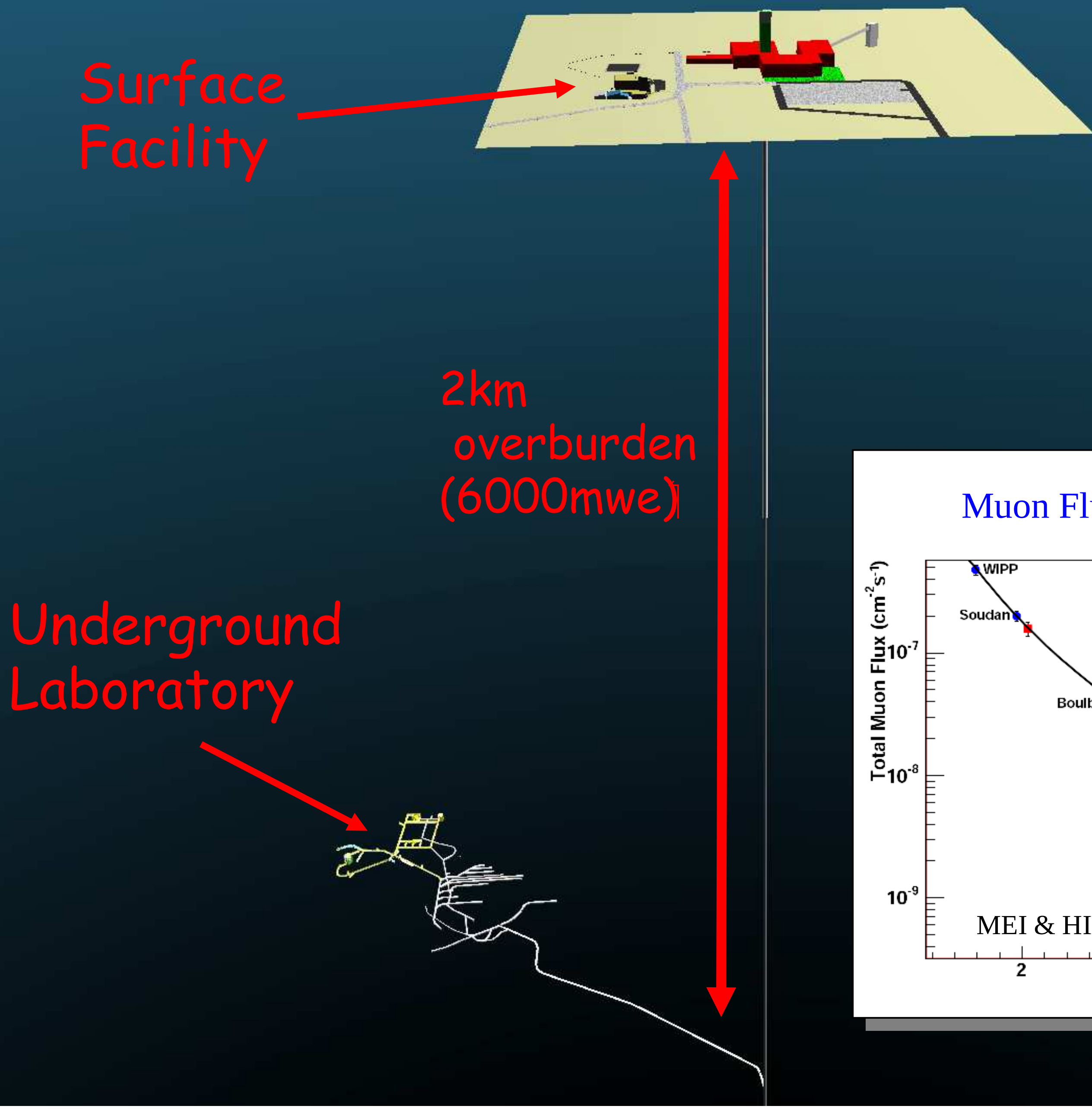
Localization of events in an alpha-spiked detector...

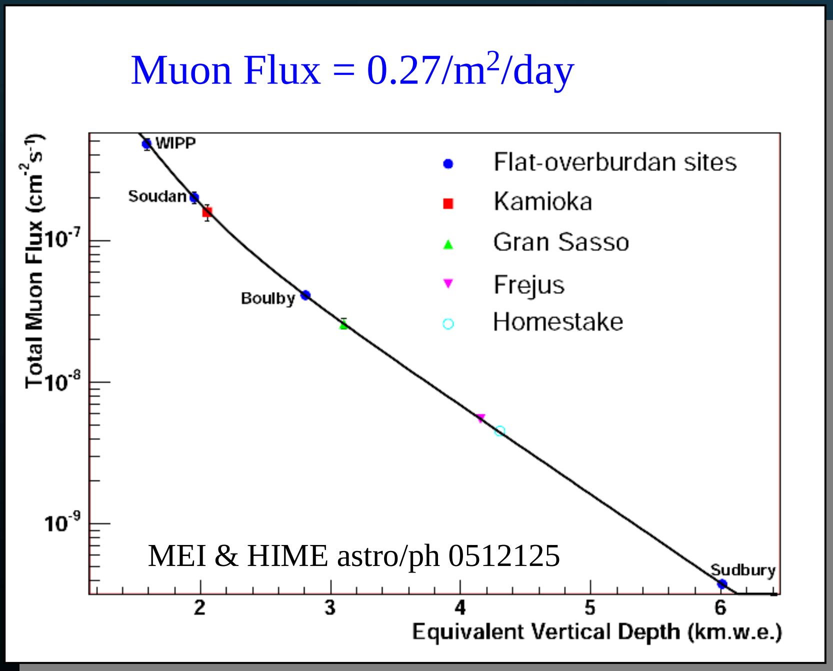




Hydrostatic pressure change over deetctor: $\Delta p/p = 4.7\%$

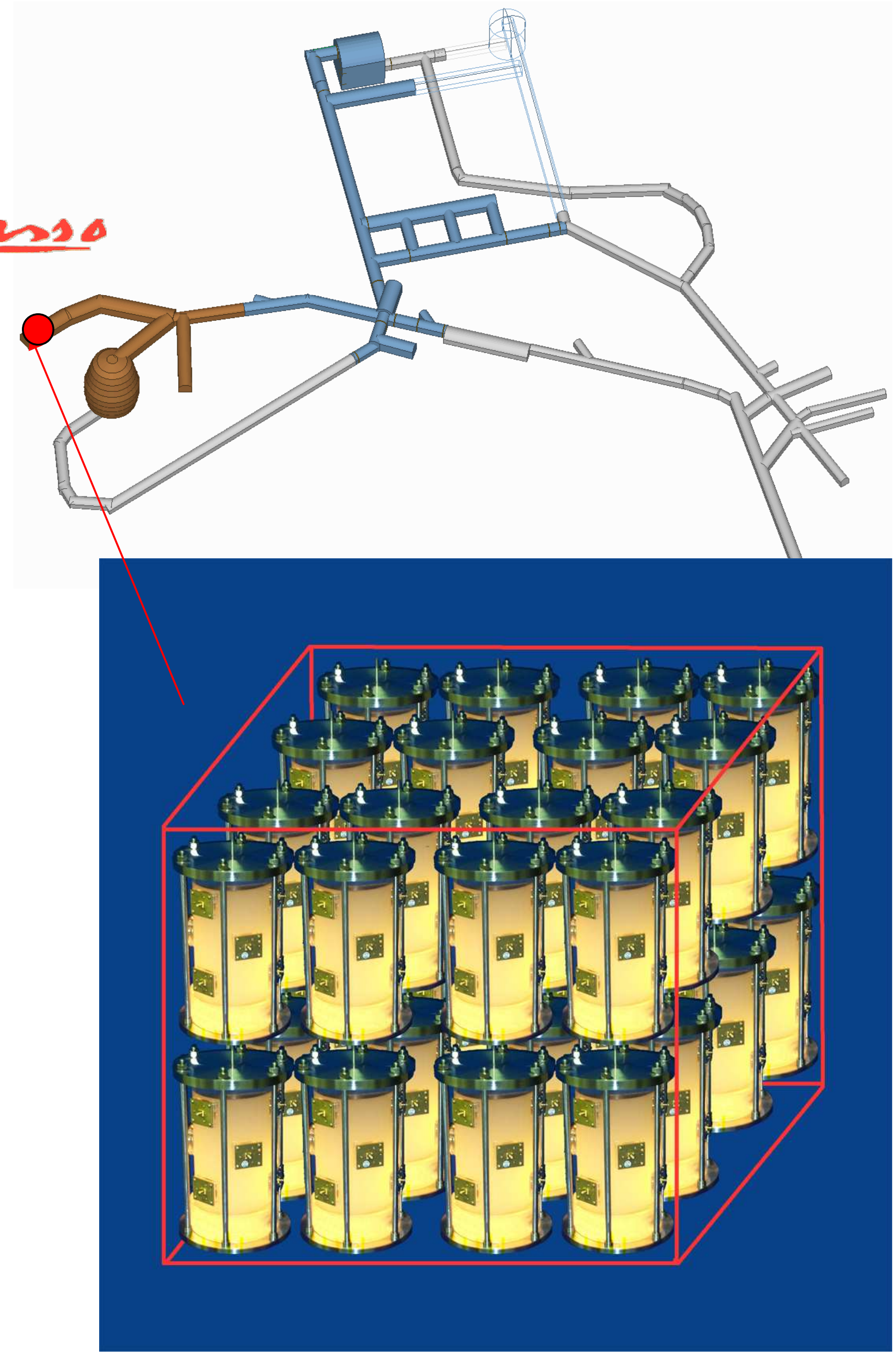
SNOLAB


Surface Facility
2km overburden (6000mwe)
Underground Laboratory


Muon Flux = 0.27/m^2/day
Total Muon Flux (cm^{-2}s^{-1})
Equivalent Vertical Depth (km.w.e.)
10^{-7}
10^{-8}
10^{-9}
2
3
4
5
6
WIPP
Soudan
Boulby
Sudbury
Flat-overburdan sites
Kamioka
Gran Sasso
Frejus
Homestake
MEI & HIME astro/ph 0512125

The Ongoing 2.6 kg PHASE

Picasso



- 32 detectors $\rightarrow$ 2.6 kg of C_4F_{10}
- 288 acoustic R/O channels
- 3D event localization
- 32 detectors running
- Control via Internet
- analysis in progress

Mb_A05_709_114
AMPOULODOIT

Picasso

Temperature & Pressure Control System (TPCS)

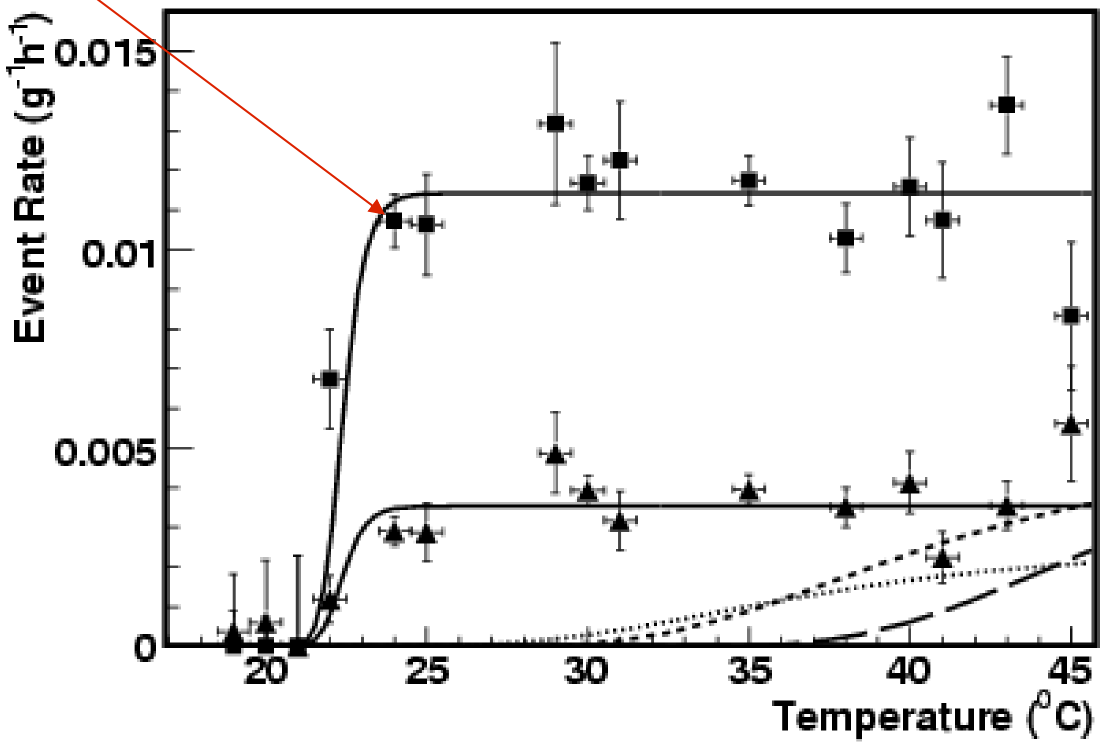
- **TPCS units**
- **temp. precision: ± 0.1^{0}C**
- **4 detectors /TPCS**
- **40 h data taking**
- **15 h recompression**


Picasso

Data Analysis

Example : Det. 71, 72 (subset of data)
Rates normalized to ^{19}F mass

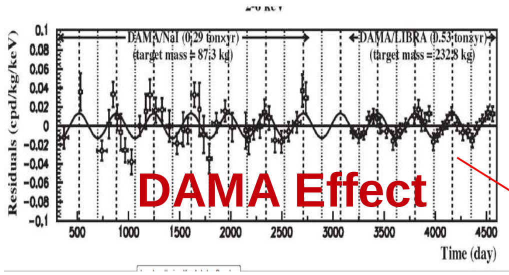
α - background



σ_p = 1pb
M_W = 10, 30 100 GeV /c^2

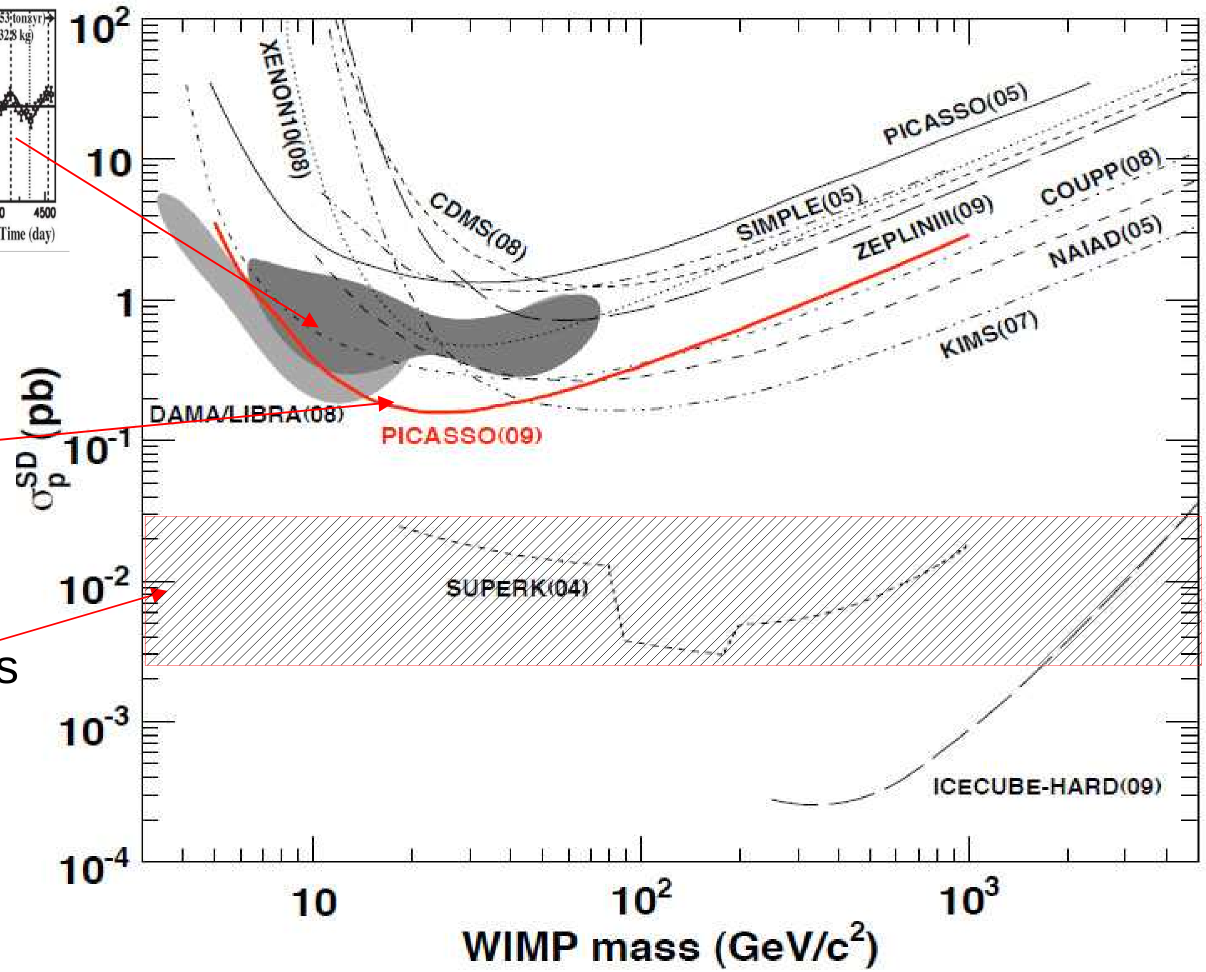
Fitting to known backgrounds $\rightarrow$ determine χ- limits

Status: Spin Dependent WIMP Interactions



Pilot analysis* with
2- detectors
134 g ^{19}F
13.75 ± 0.48 kgd

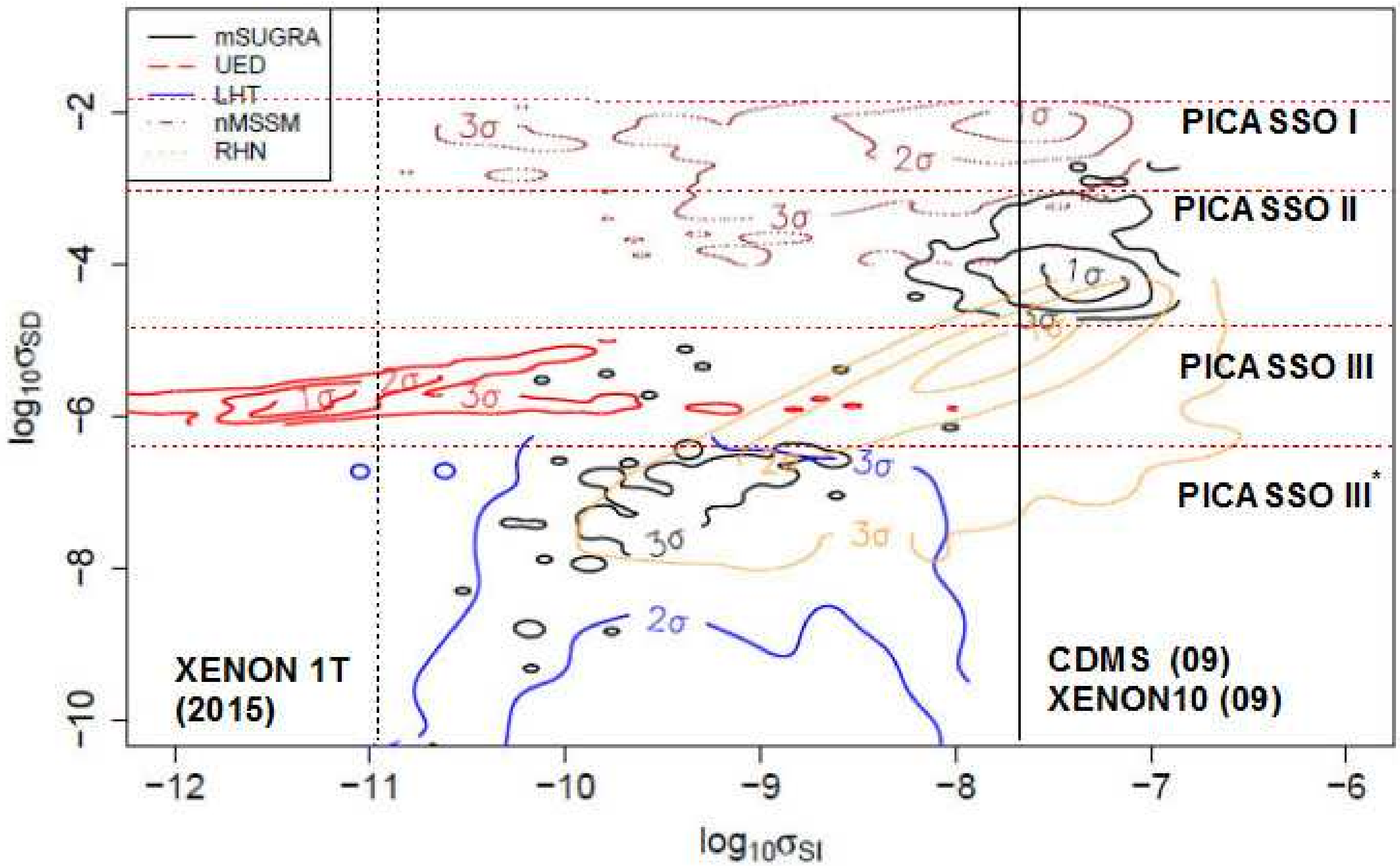
In prep.: full analysis
32 detectors
2.6 kg ^{19}F, 144 kgd



*Subm. Phys. Lett B. (arXiv: 0907.0307)

The Future: SI vs. SD Searches

Spin – dependent

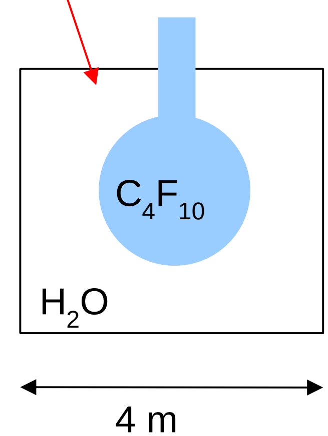


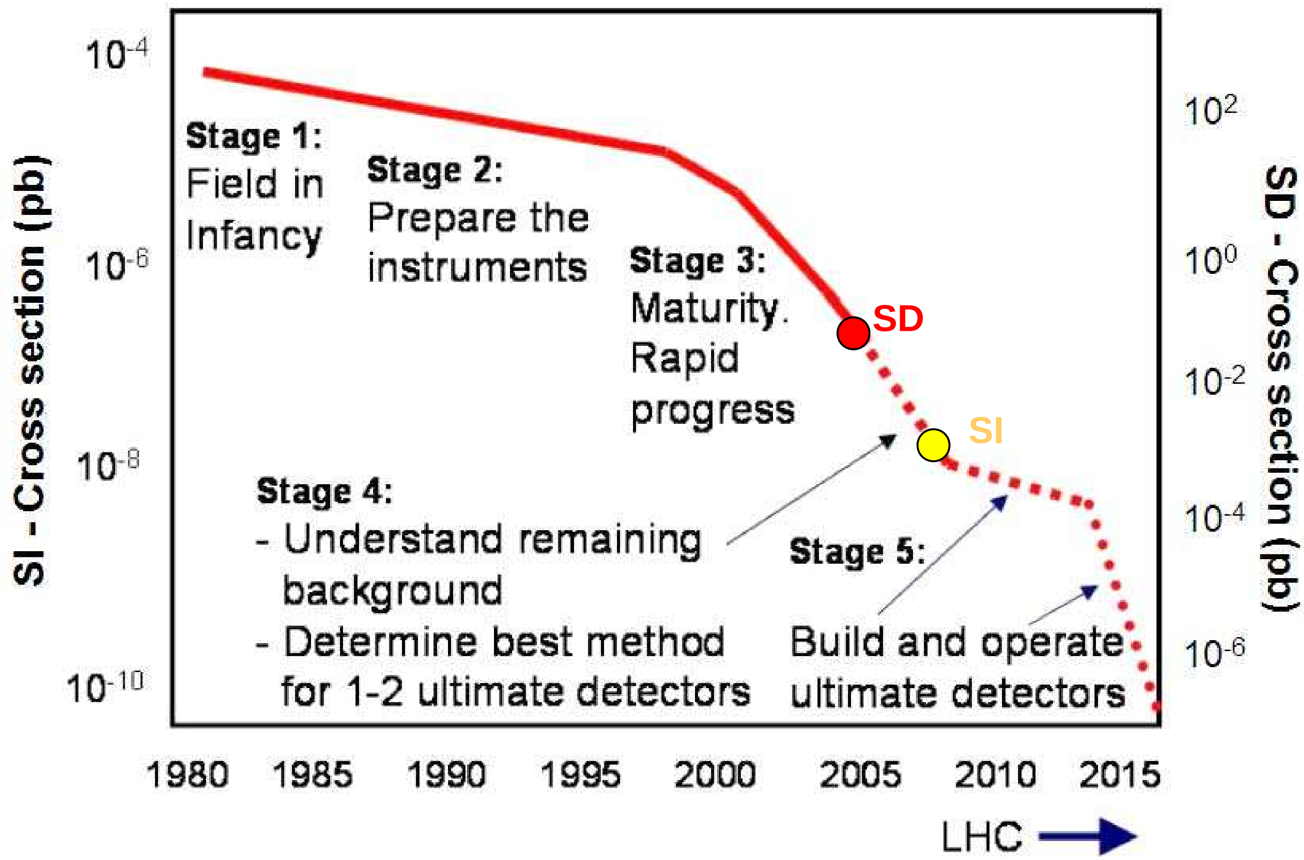
Spin – independent

On-going 2.5 kg

Upgrade to 25 kg

500 kg with full
α -n discrim.




SI - Cross section (pb)
SD - Cross section (pb)
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
1980
1985
1990
1995
2000
2005
2010
2015
LHC
Stage 1: Field in Infancy
Stage 2: Prepare the instruments
Stage 3: Maturity. Rapid progress
SD
SI
Stage 4:
- Understand remaining background
- Determine best method for 1-2 ultimate detectors
Stage 5: Build and operate ultimate detectors

Summary

- 2.6 kg Phase with 32 detectors
- First physics competive results with two detectors only
- Rule out most of DAMA/LIBRA effect in SD sector
- Upgrade gradually with cleaner detectors $\rightarrow$“saltless” detectors
- New discovery of n - α discrimination
- Next: prepare 25 kg phase $\rightarrow$ 7000 kgd