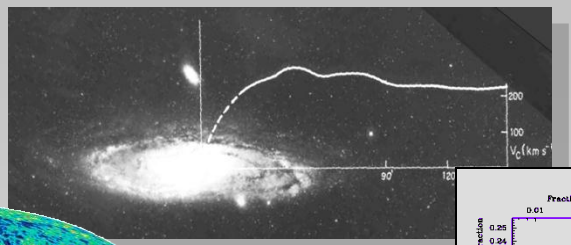
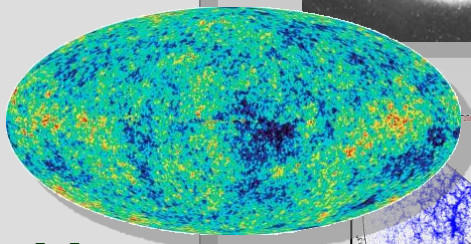
Direct Search for Dark Matter

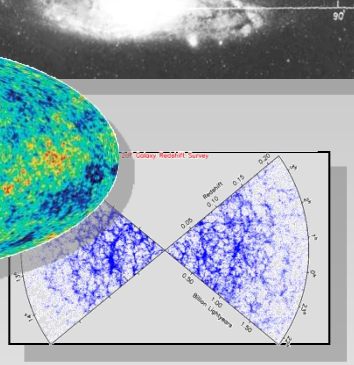
Dark Matter in the Universe $\Omega = 0.23$

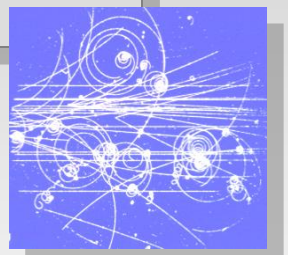
- non-baryonic
- not neutrinos

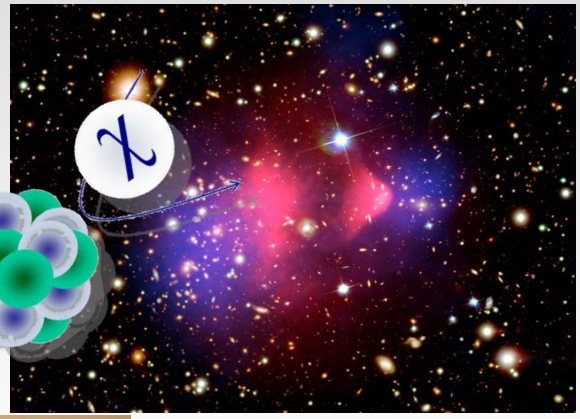
$\Rightarrow$ **physics beyond the standard model**











thermal relics from Big Bang
weakly interacting
in the mass range ~(10 – 1000) GeV
could nicely explain Dark Matter

$\Rightarrow$ can be detected by direct detection
elastic scattering off nuclei
$\Rightarrow$ could be supersymmetry

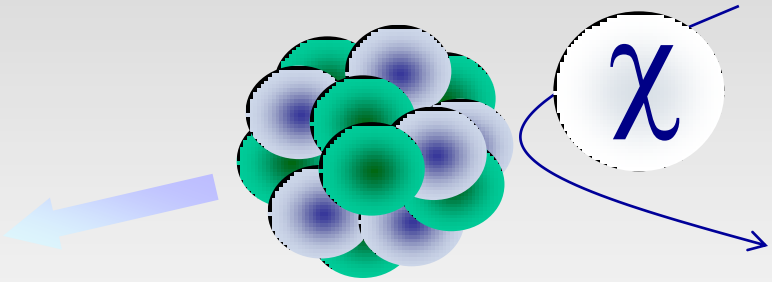
WIMP – Direct Detection

W**eakly **I**nteracting **M**assive **P**articles = **WIMPs

Elastic Scattering off Nuclei

- **Nuclear Recoils:** reduced efficiency for charge- or light-production

  - Mass GeV - ~ $1000\ GeV$
  - relative speed $270\ km/s$
    (~ oprbital speed in Milky Way)



$\Rightarrow$ only a few keV of energy

- cross section $\sigma_\chi < 10^{-36} cm^2$
- local WIMP-Density $\rho_\chi = 0.3\ GeV / cm^3$
  - *corresp. 3 WIMPs$^{(100GeV)}$ / Liter*
  - *75000 /s /cm^2*

$\Rightarrow$ very very rare scattering events(< 1 / Week / kg)

Today's sensitivity < 1 / year / kg

Direct DM Searches - Worldwide

Direct
Dark Matter Search

COVENTIONAL
NaI, CsI, Ge

run 250kg NaI
run 100kg CsI

DAMA
Italy

KIMS
Korea

run ~1kg Ge

COGENT
US

CRYOGENIC

run
~ 10kg, 2012
plan
~ 1t, 2015

CRESST
Germany, UK, Italy

EDELWEISS
France, Germany, UK, Russia

CDMS
US, Can., Switzerlnd

prototypes

Rosebud
France, Spain

LIQUID NOBLE GASES

XENON

run ~ 30kg
2012
plan
~ 1t, 2014

XENON
USA, Switzerl. Italy, Japan, Portugal, Germ. France, China

run
~ 100kg

XMASS
Japan

prepare
~ 100kg

LUX
10 US institutions, Moscow

ARGON

prepare
~ 100kg–1t
plan
> 1t

ArDM
Switzerland, Spain, UK, Poland

DARK SIDE
US, Italy, Rus, Poland China, Ukraine, UK

DEAP/ CLEAN
Canada, US

finsihed

WARP
Italy, US

DROPLETS

runs 4kg
starts 60kg
prepares 500kg

COUPP
USA

runs 2kg

PICASSO
Canada, USA, Czeck

very good spin dependent limits

DIRECTIONAL

first runs

DRIFT
UK, US

DM-TPC
US

NEWAGE
Japan

prototypes

MIMAC
France

Direct DM Searches

remarkable progress

x 100 improvement in sensitivity
in 10 yrs

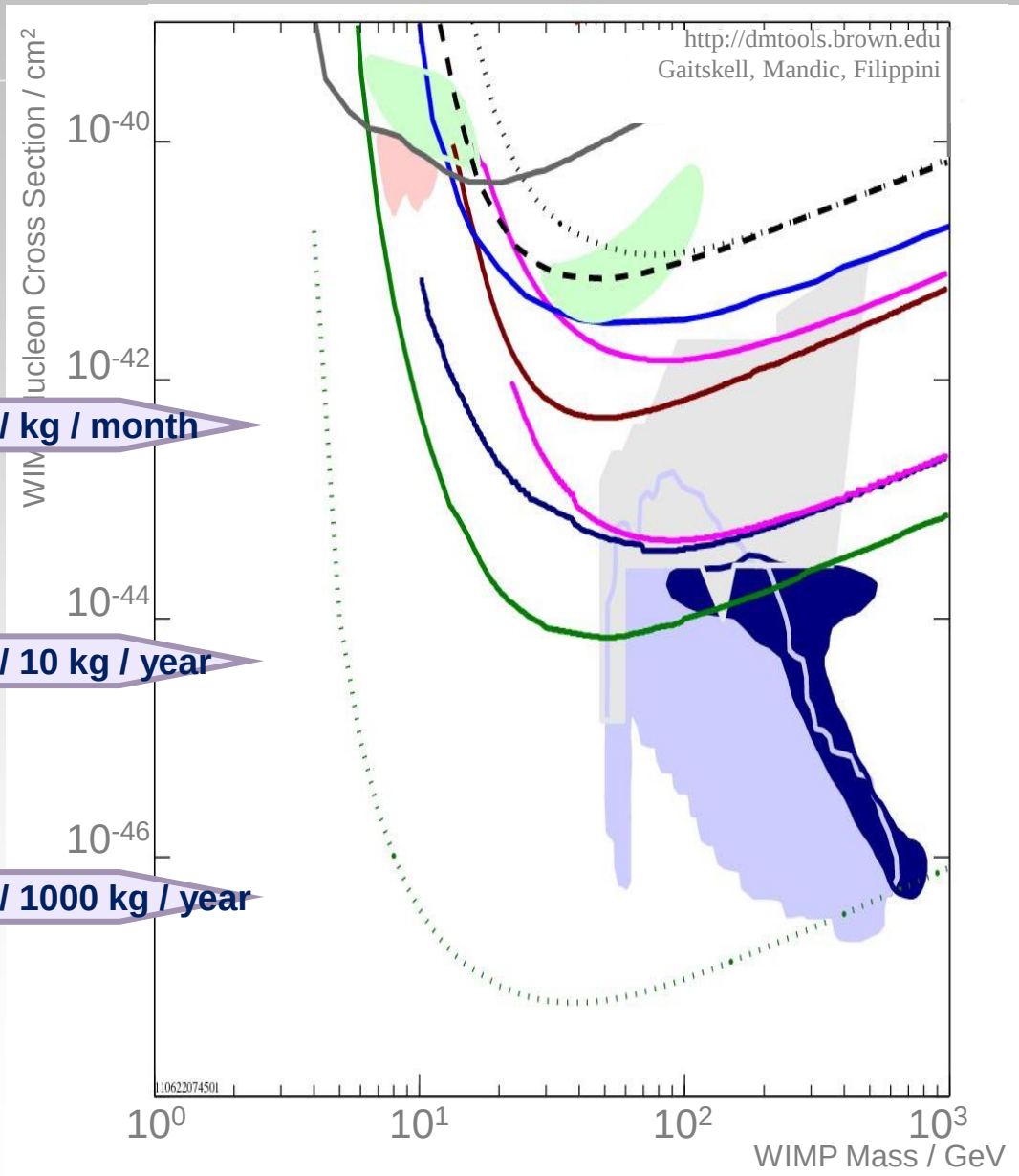
present best sensitivities
(for spin independent WIMP scattering)

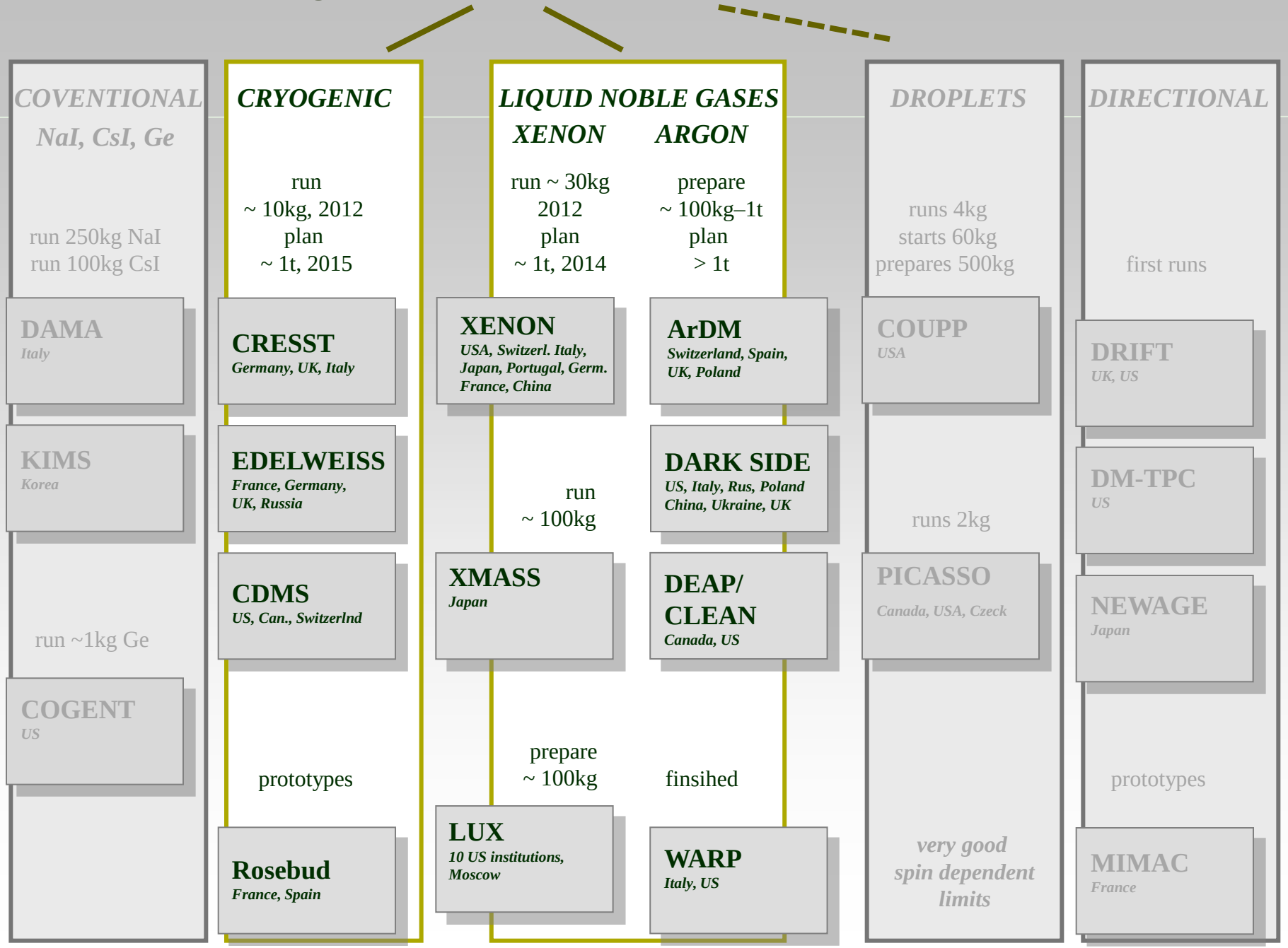
- cryogenic
- liquid Xenon

+ other techniques
(doing better for spin dependent WIMP scattering)

we have different techniques
with promising sensitivity

simultaneously
LHC is starting
and will march upward in mass




distinguish nuclear recoils / electron recoils
COVENTIONAL
NaI, CsI, Ge
run 250kg NaI
run 100kg CsI
DAMA
Italy
KIMS
Korea
run ~1kg Ge
COGENT
US
CRYOGENIC
run
~ 10kg, 2012
plan
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CRESST
Germany, UK, Italy
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France, Germany,
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CDMS
US, Can., Switzerlnd
prototypes
Rosebud
France, Spain
LIQUID NOBLE GASES
XENON
ARGON
run ~ 30kg
2012
plan
~ 1t, 2014
prepare
~ 100kg–1t
plan
> 1t
XENON
USA, Switzerl. Italy,
Japan, Portugal, Germ.
France, China
ArDM
Switzerland, Spain,
UK, Poland
run
~ 100kg
XMASS
Japan
DARK SIDE
US, Italy, Rus, Poland
China, Ukraine, UK
DEAP/
CLEAN
Canada, US
prepare
~ 100kg
LUX
10 US institutions,
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runs 4kg
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USA
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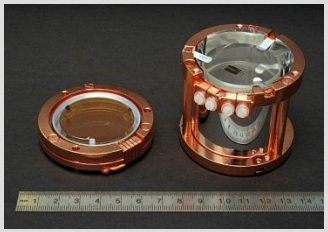
Canada, USA, Czeck
very good
spin dependent
limits
DIRECTIONAL
first runs
DRIFT
UK, US
DM-TPC
US
NEWAGE
Japan
prototypes
MIMAC
France

Particle Identification by Combination of Channels

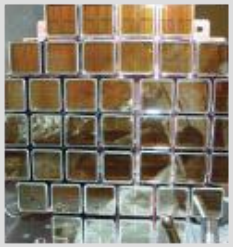
cryogenic charge / phonon

EDELWEISS
CDMS,
EURECA

cryogenic light / phonon



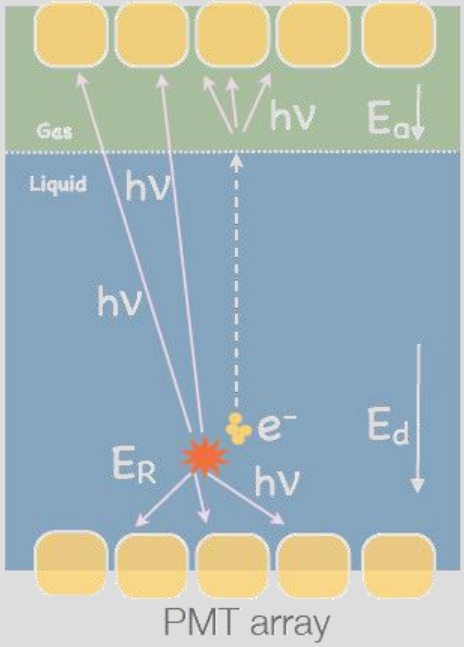
CRESST
EURECA

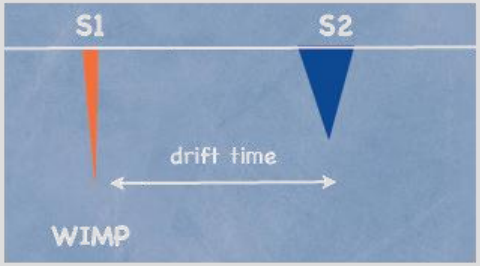


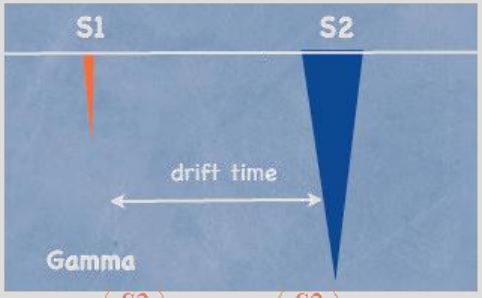
liquid noble gas light / charge

XENON
WARP, ArDM,
LUX, ZEPLIN

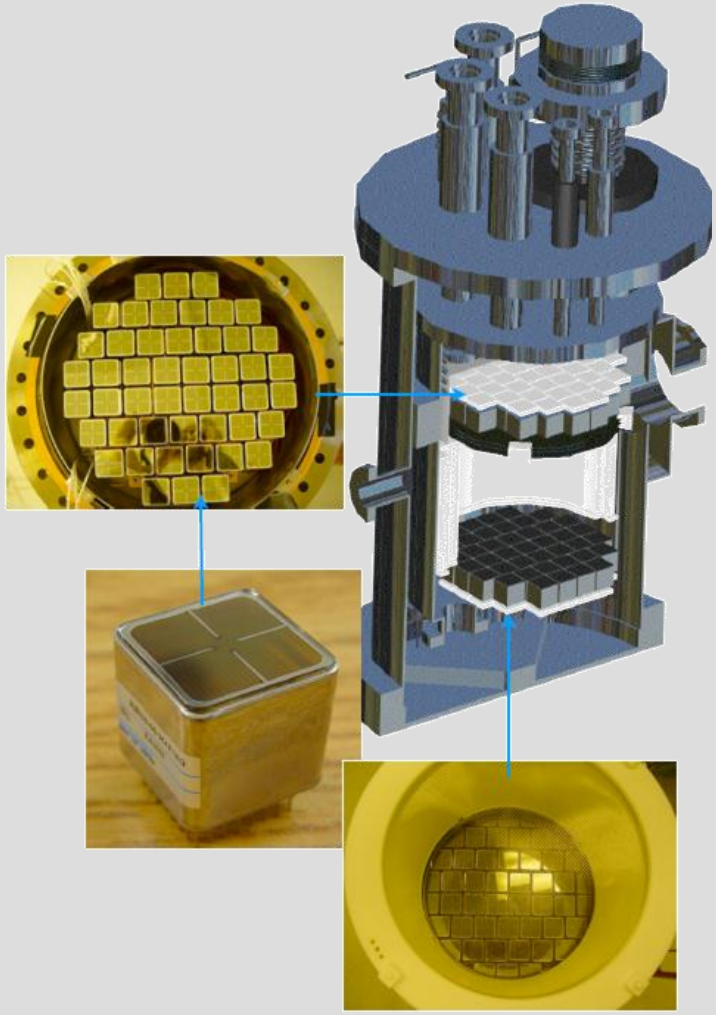
Liquid Noble Gases
Background Rejection by Light vs. Charge

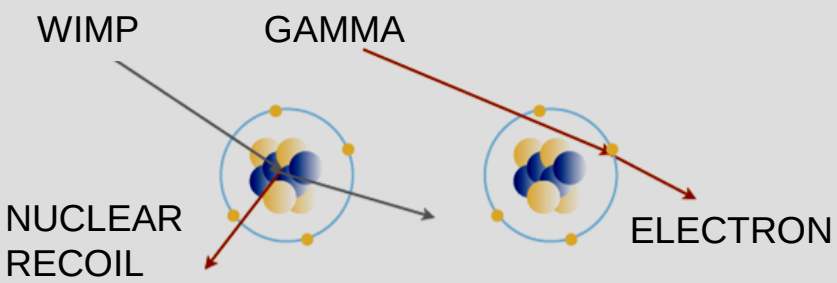






$$\left(\frac{S2}{S1}\right)_{WIMP} \ll \left(\frac{S2}{S1}\right)_{gamma}$$





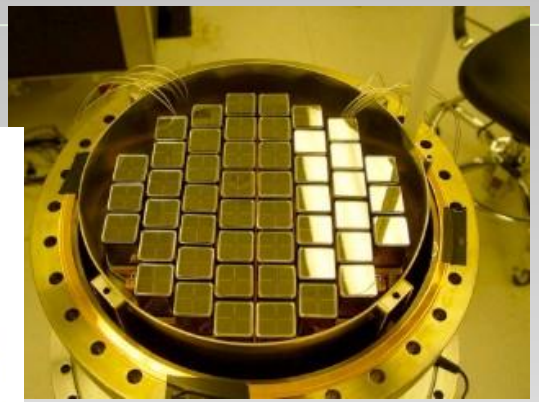
Liquid Xenon *Charge + Light*

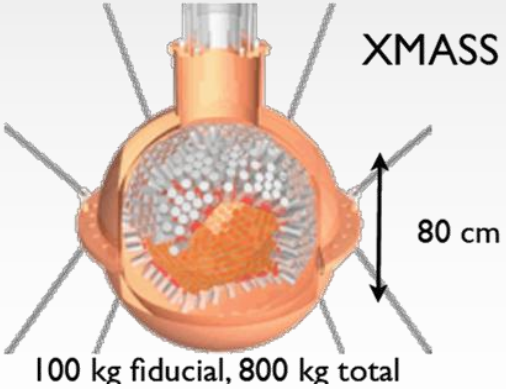
XENON
USA, Switzerland, Italy, Portugal, Germany, France, Japan, China

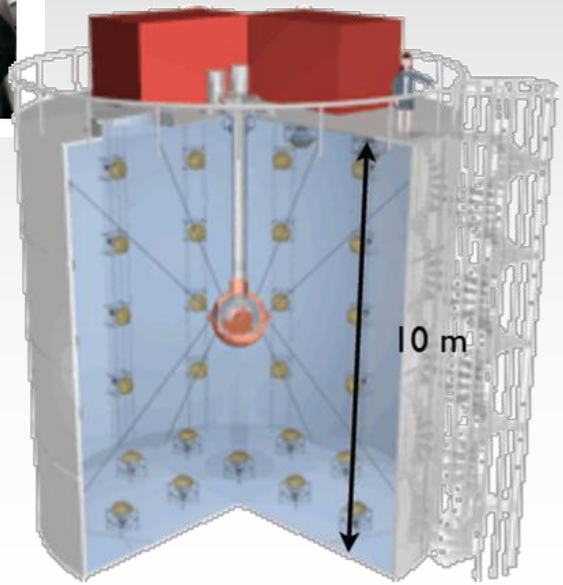
LUX
10 US institutions, Moscow
- planned 100 kg fiducial
- prototype tested
- July 2012 moved to Sanford Lab

XMASS
10 institutions from Japan
- at Kamioka
- 1 phase, 850 kg total

⇒self shielding 100 kg fid.
- larger bckgr. than expected
- new physics run in 2013







Liquid Xenon *Charge + Light*

XENON
USA, Switzerland, Italy, Portugal, Germany, France, Japan, China

Charge + Light, FV

at Gran Sasso
- 34 / 48 kg fiducial / 62 kg total
- starting end of 2009

- achieved 2010:
  ~ 7 x 10^{-45} cm^2
- **achieved 2012:**
  ~ 2 x 10^{-45} cm^2

XENON *Charge + Light*

July 2012

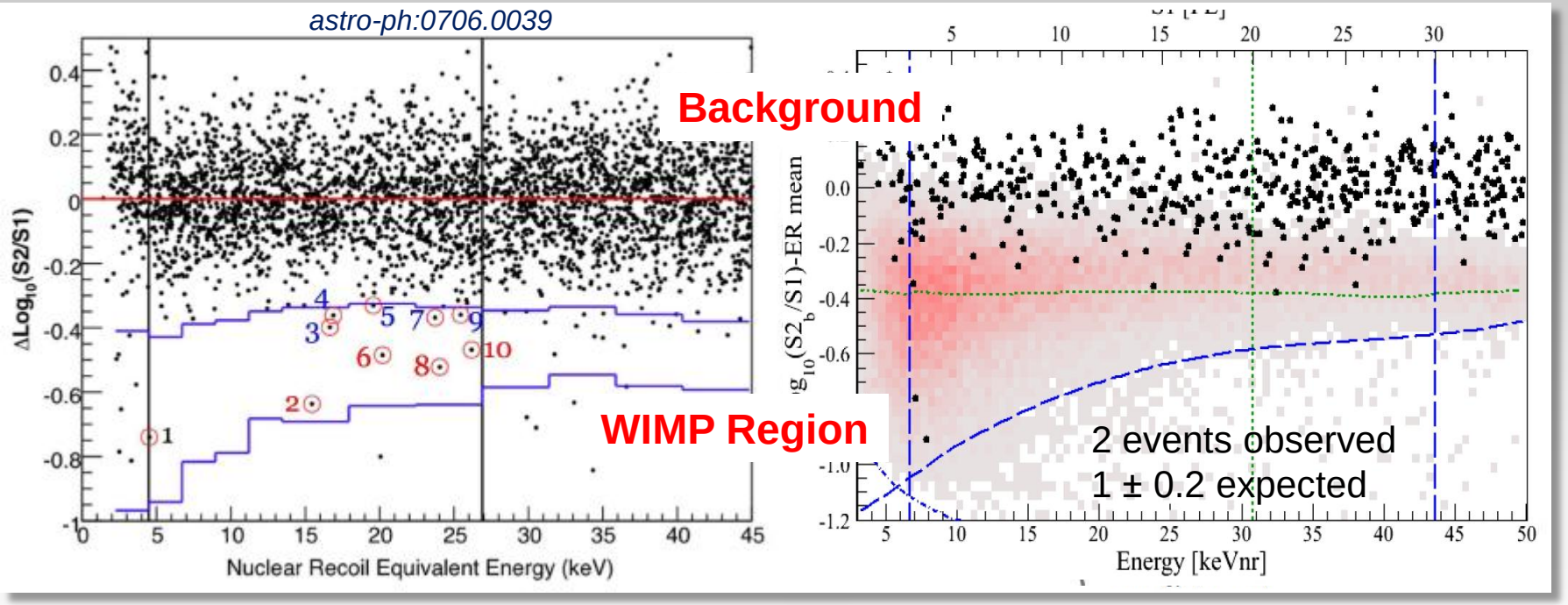
XENON10 *2007*

5.5 kg target,
58.6 kgd exposure
10 background events
~1 cts / 6 kgd

XENON100

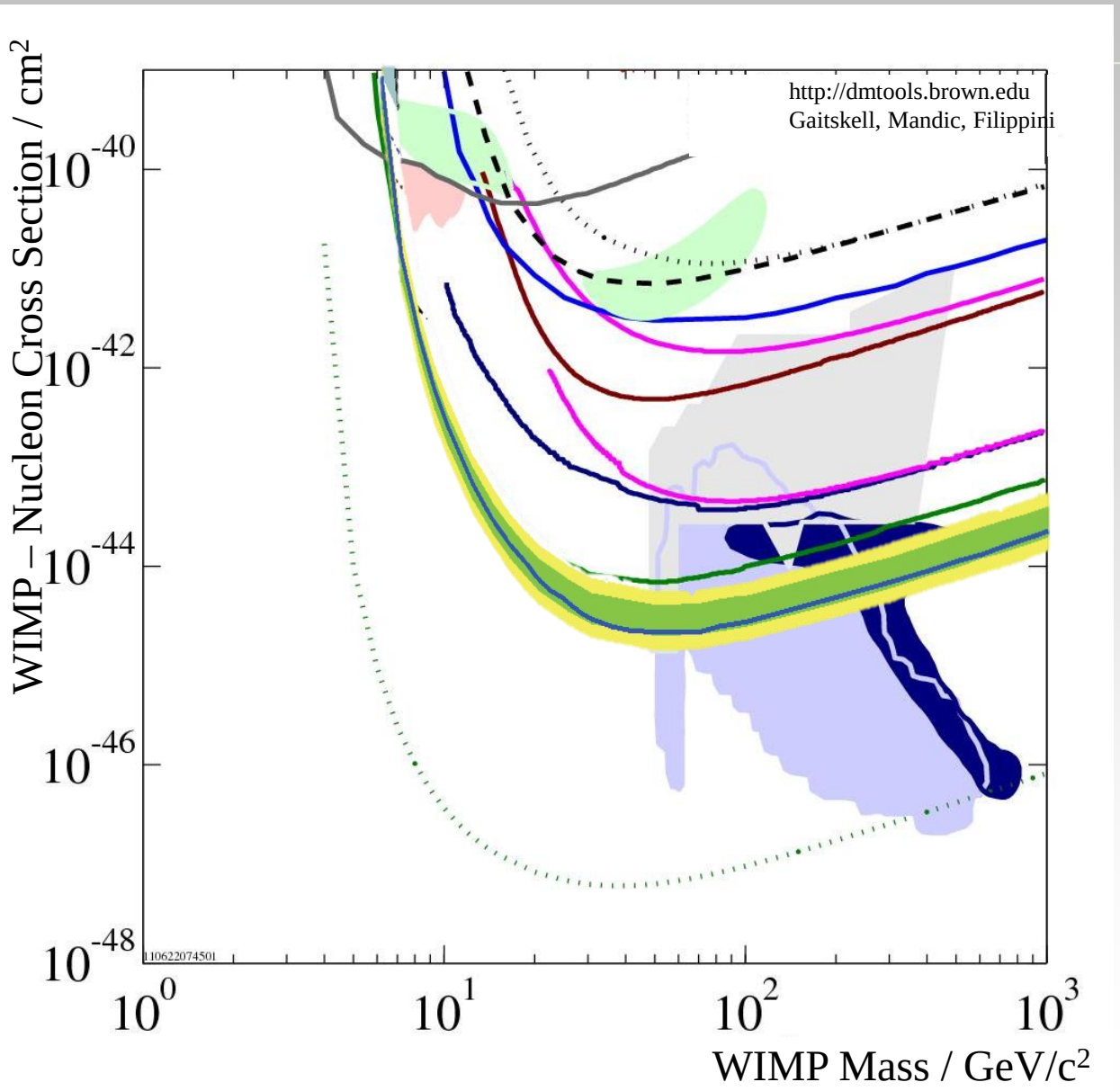
34 kg target,
~2500 kgd exposure
2 background events
~ 1 cts / 1500 kgd , ~ 1 cts/ 4 kg years
γ bckgrnd ~ 250 x lower

astro-ph:0706.0039



no indication for WIMP signal

Large improvement on background



Heidelberg Moscow 1996
IGEX 1998
DAMA 1998 / LIBRA 2008
CDMS 2000
EDELWEISS 2002
CRESST 2009
EDELWEISS 2011
CDMS 2011
XENON 2011
XENON 2012

~ 0.00003 cts / kg / d / keV

Baltz, Gondolo MSSM 2001
Baltz, Gondolo 2004
Trotta et al CMSSM 2008

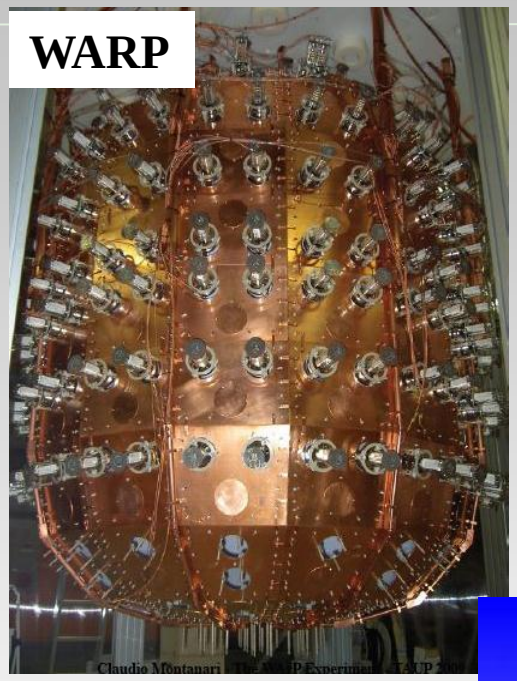
Liquid Argon *Charge + Light*

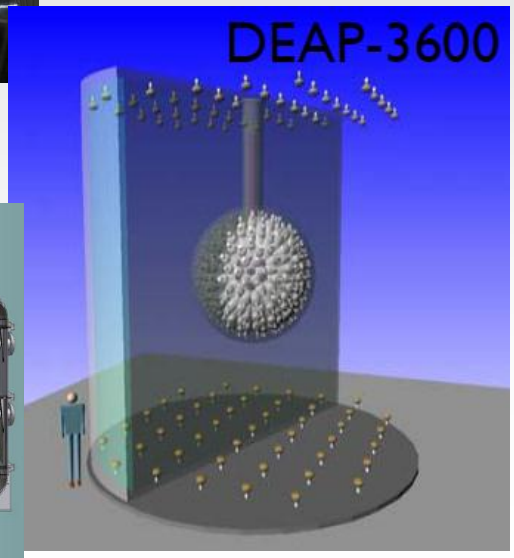
WARP
Italy, US
• at Gran Sasso
• stopped (technical problems)

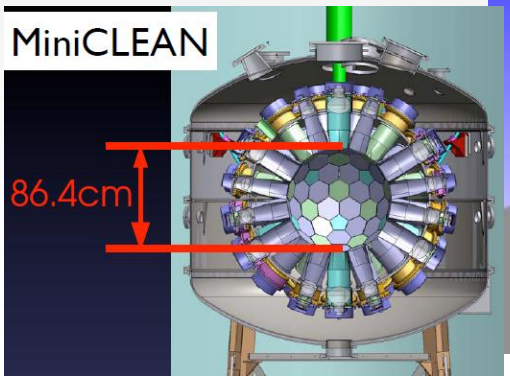
ArDM
Switzerland, Spain, UK, Poland
•1000 kg R & D, prototype
• set up at Canfranc start 2012

DarkSide
US, Rus, I, P, China, Ukr., UK
• proposed, depleted Ar

DEAP / CLEAN
Canada, US
• 1-phase, SNOLAB
•1000 kg fid. start set up 2012





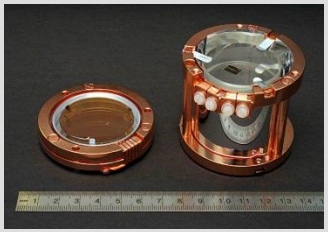


Particle Identification by Combination of Channels

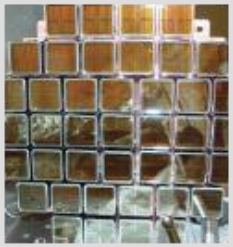
cryogenic charge / phonon

EDELWEISS
CDMS,
EURECA

cryogenic light / phonon



CRESST
EURECA



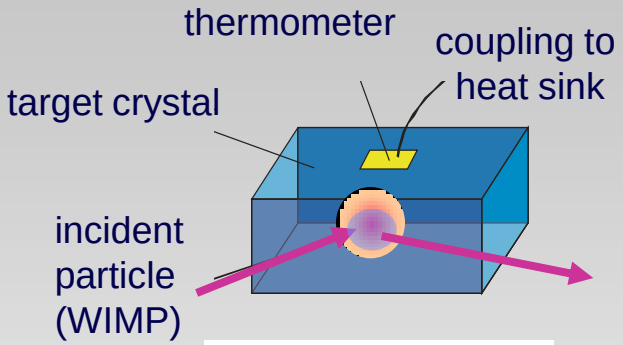
liquid noble gas light / charge

XENON
WARP, ArDM,
LUX, ZEPLIN

Calorimetry – measure total energy *(heat- or phonon- signal)*

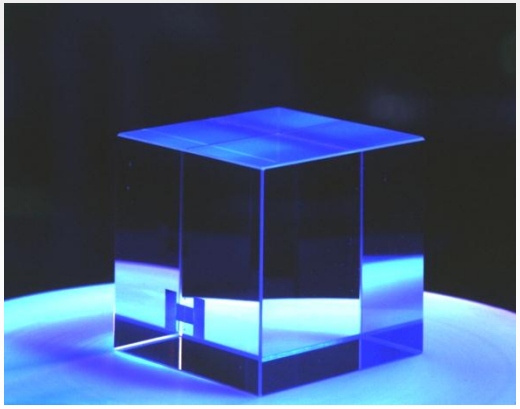
Energy deposition
by scattering

=> temperature rise



$$\Delta T \propto E/C$$

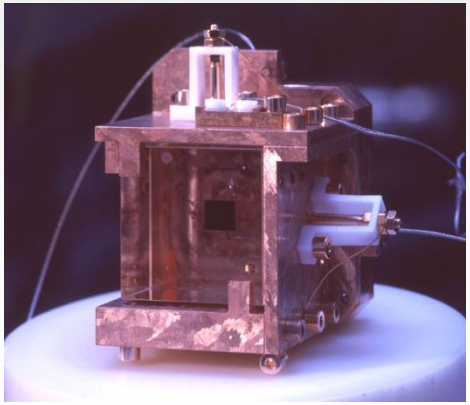
at very low temperature (~20mK)
=> high sensitivity, small C



thermometer:

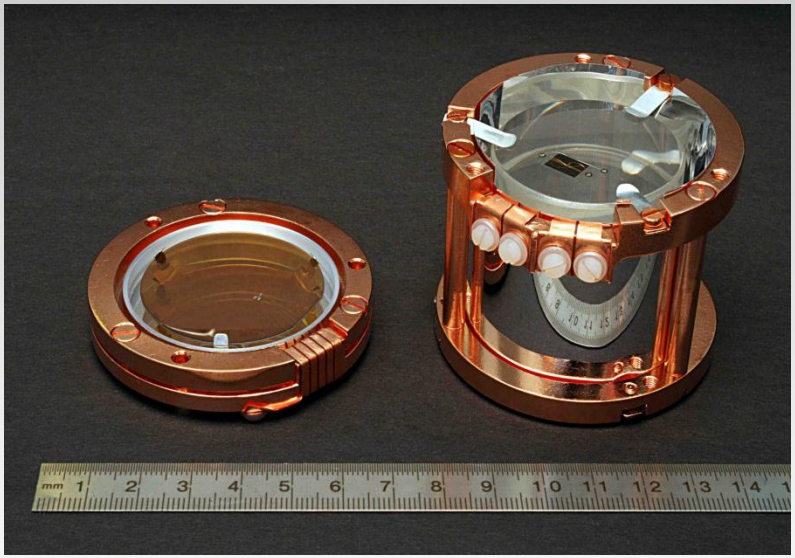
superconducting
phase-transition-thermometer

NTD semicondutors



Calorimeter for Dark Matter Search

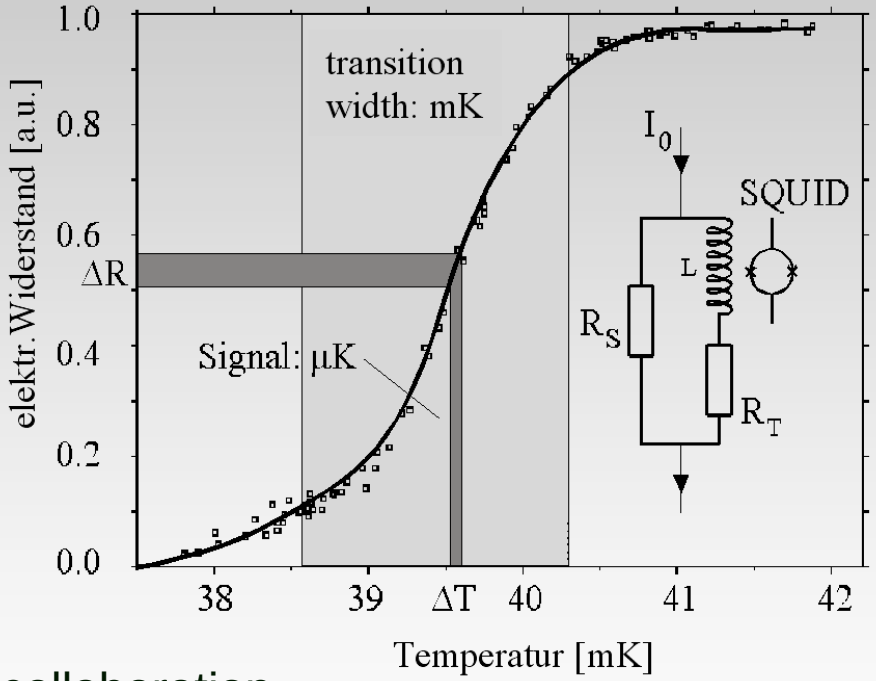
Superconducting Phase-Transition-Thermometer (SPT)
e.g. Wolfram $T_c \approx 15mK$



z.B. $CaWO_4$ -Absorber

300gr, 4cm x 4cm

Heat Capacity Sapphire 250gr
3.4 MeV / K @ 25mK
220 GeV / K @ 1K



CRESST-collaboration

(Cryogenic Rare Event Search with Superconducting Thermometers)

Max-Planck-Institut München, TU München
Universität Tübingen, Oxford University, Gran Sasso Labor

Phonon + Light or Phonon + Charge

CDMS
Cryogenic Dark Matter Search
US Kollaboration

Charge+ Phonon
(semiconductor Ge, Si)

EDELWEISS
Experience pour DEtecter Les Wimps En SIte Souterrain
France and Germany

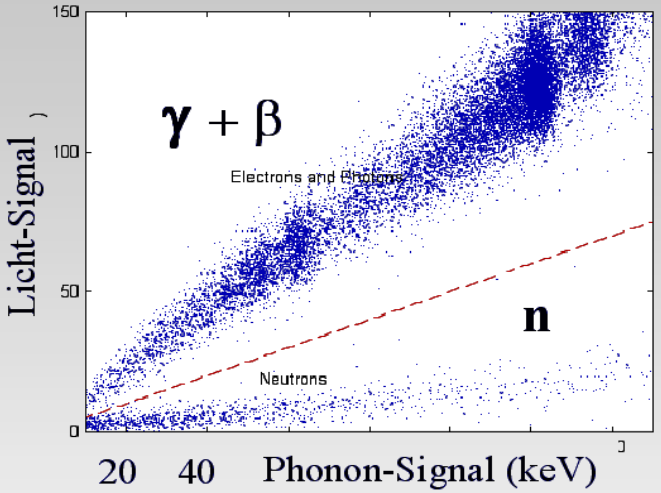
Charge + Phonon
(semiconductor Ge, Si)

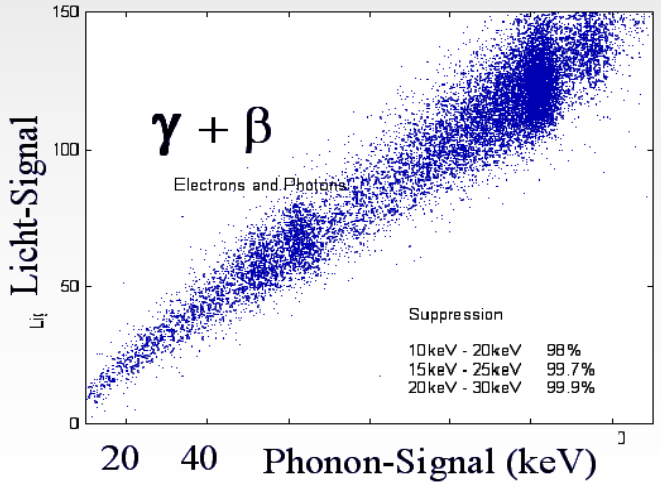
CRESST
Cryogenic Rare Event Search with Superconducting Thermometers

Max-Planck-Institut München, TU München
Universität Tübingen, Oxford University, Gran Sasso

ROSEBUD
Cryogenic Rare Event Search with Superconducting Thermometers

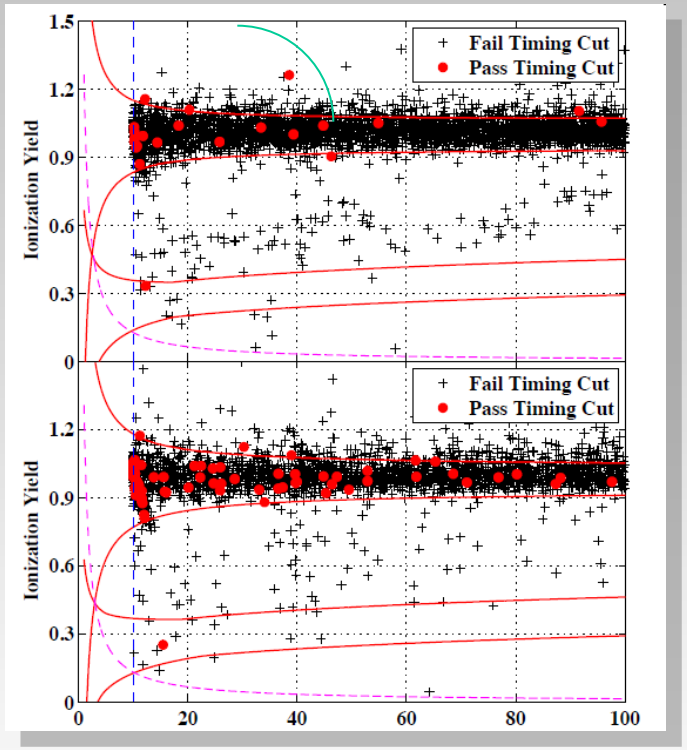
Zaragoza, Paris

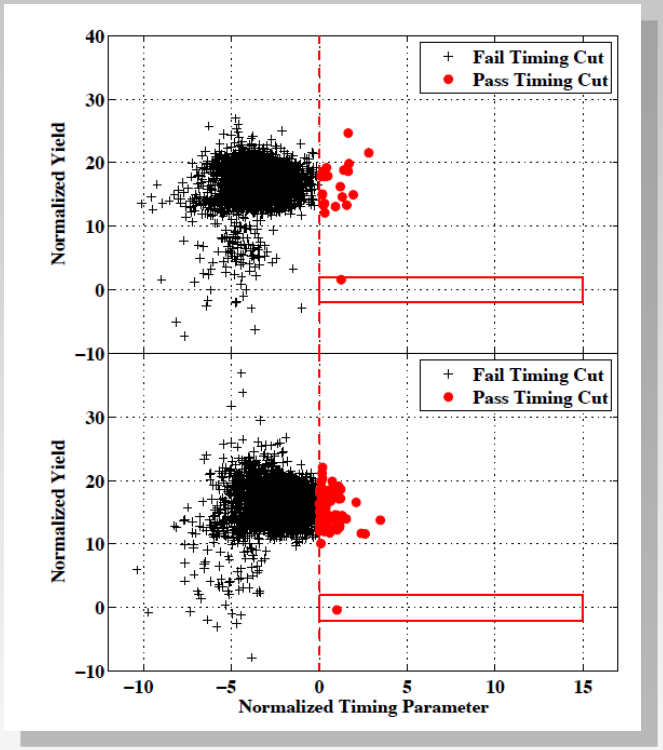




CDMS results

no indication for WIMP signal





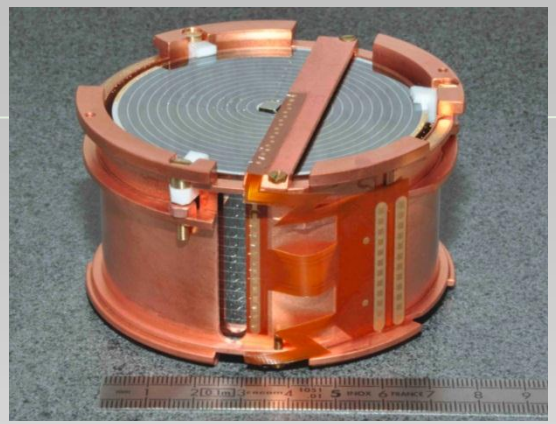
612 kg-days raw exposure

194.1 kg-days spectrum-averaged equivalent exposure @ 60 GeV

23% probability of observing two or more background events

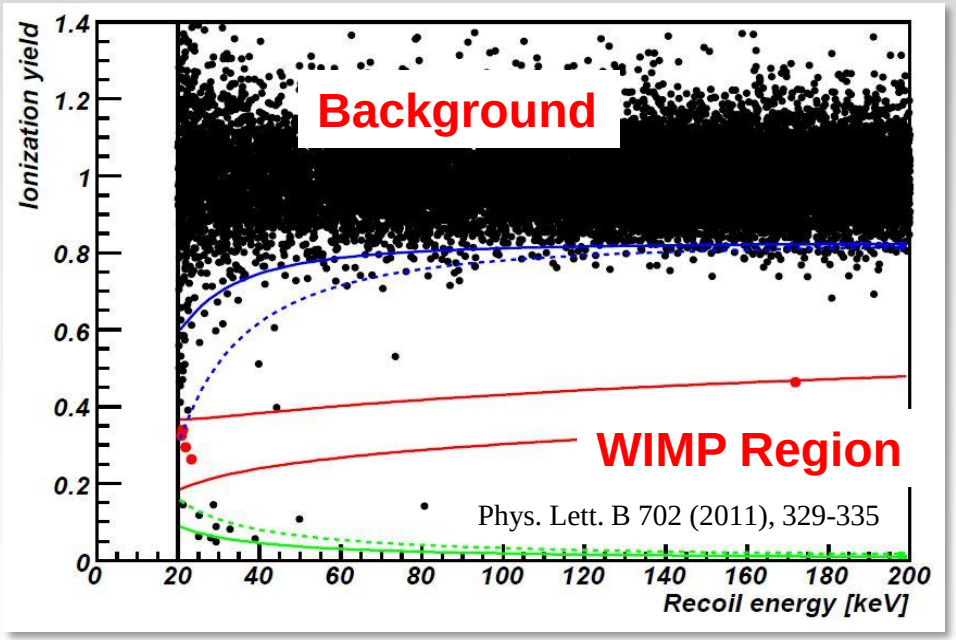
$3{,}8 \times 10^{-44}$ cm^2 upper limit on spin-independent cross-section @ 70 GeV, 90% CL
+ improved limits for low WIMP masses

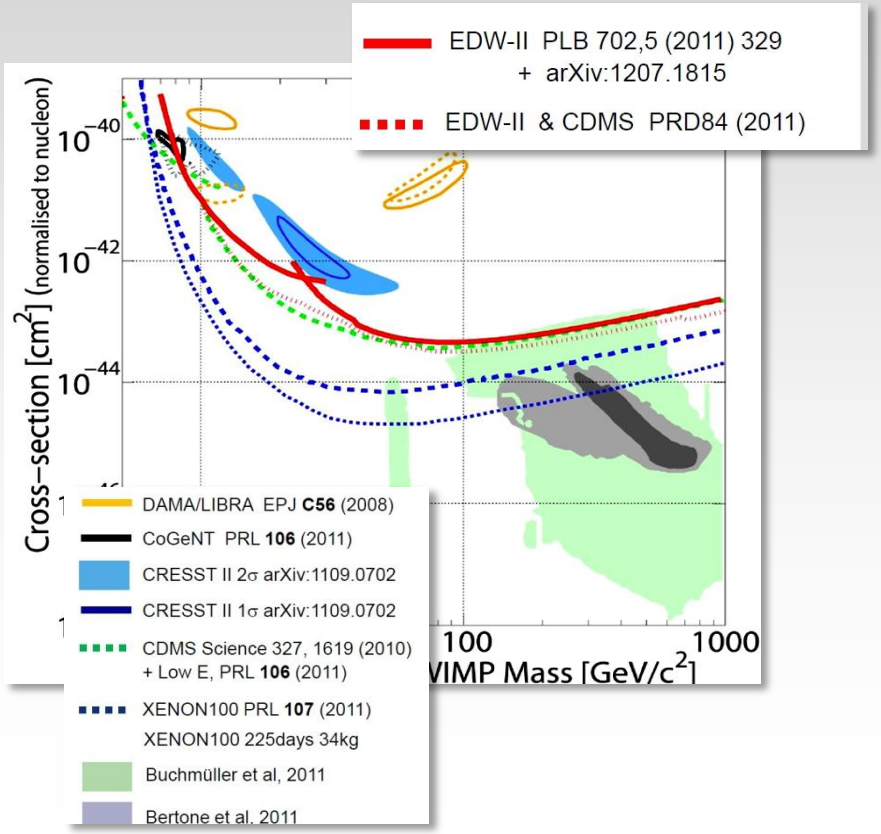
EDELWEISS – Charge / Phonon



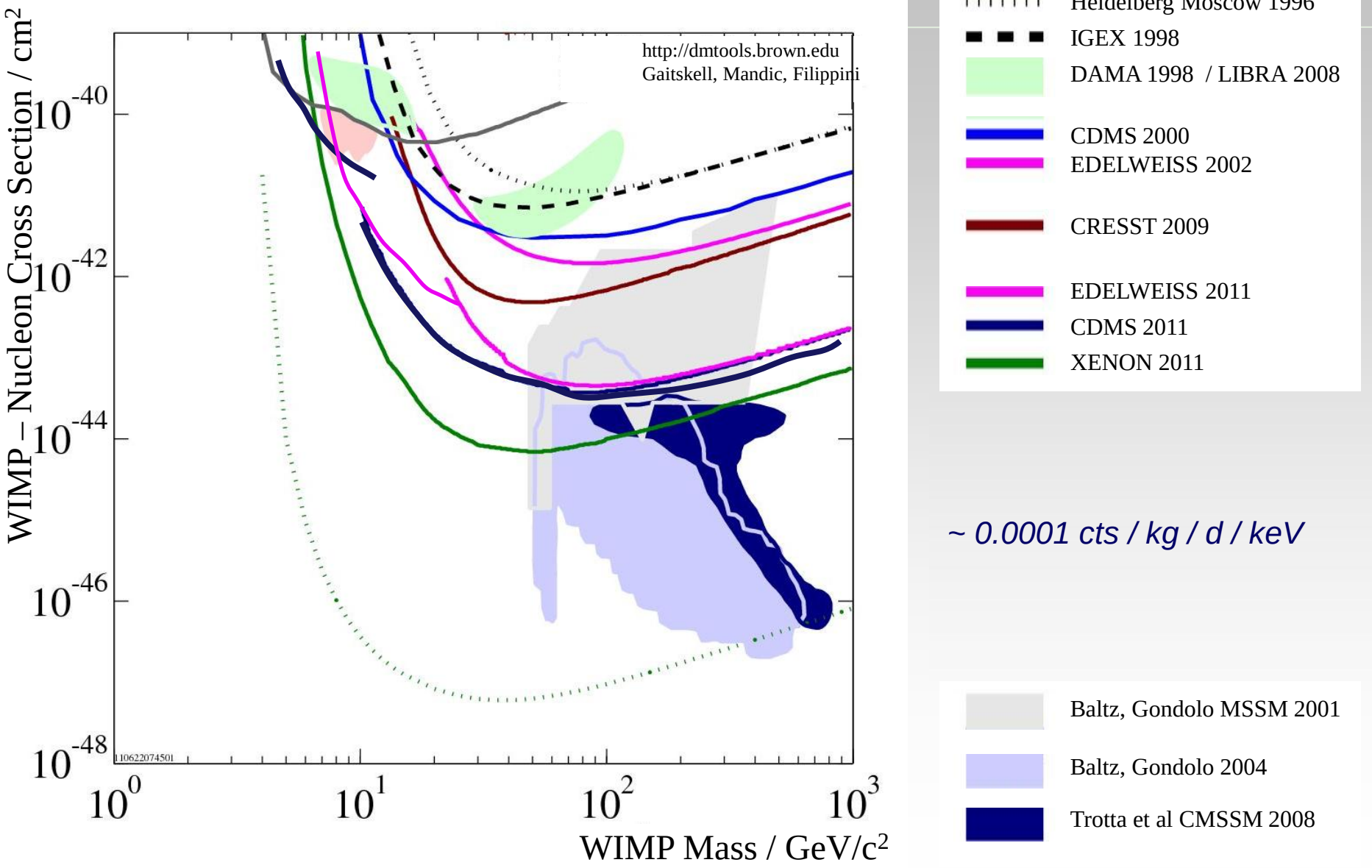
- continous data taking
- 384 kg d published
- one of the best limits
- 3000 kg d expected 2013

- *1 cts / 80 kg day*

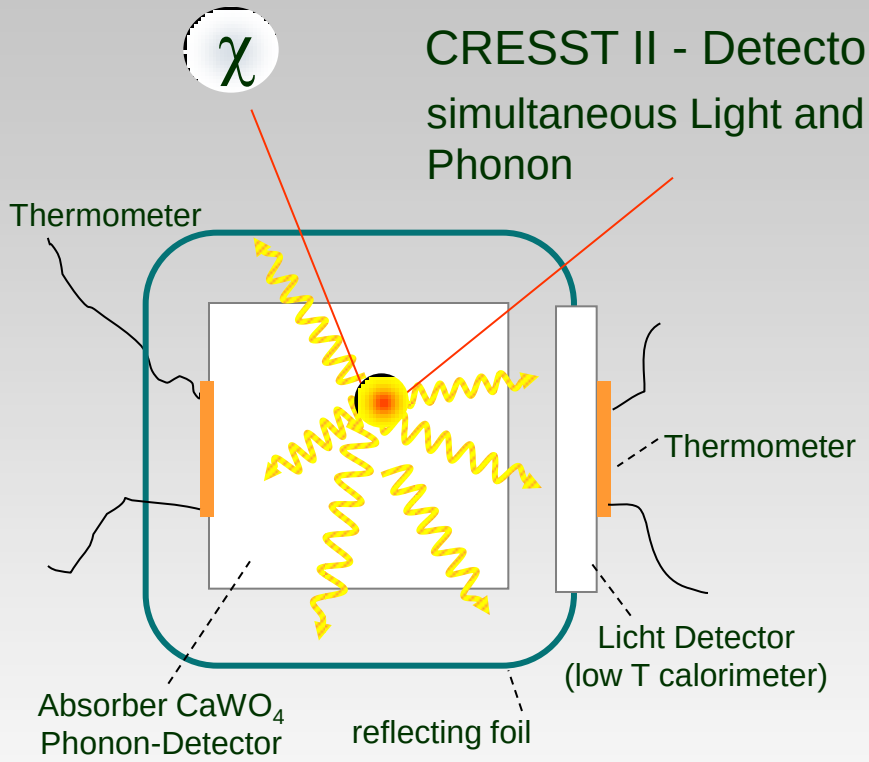


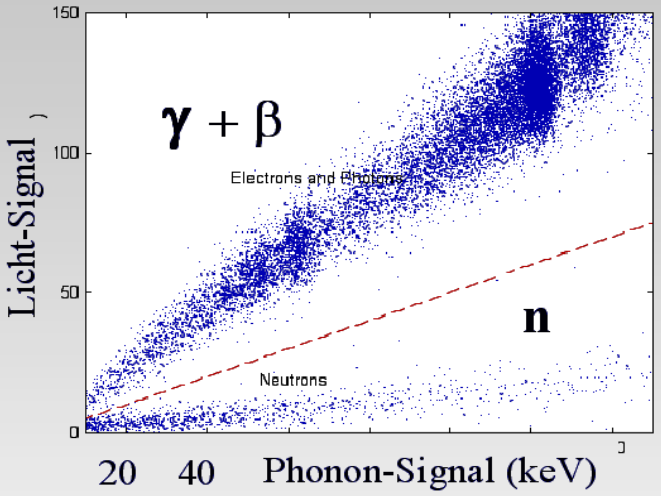


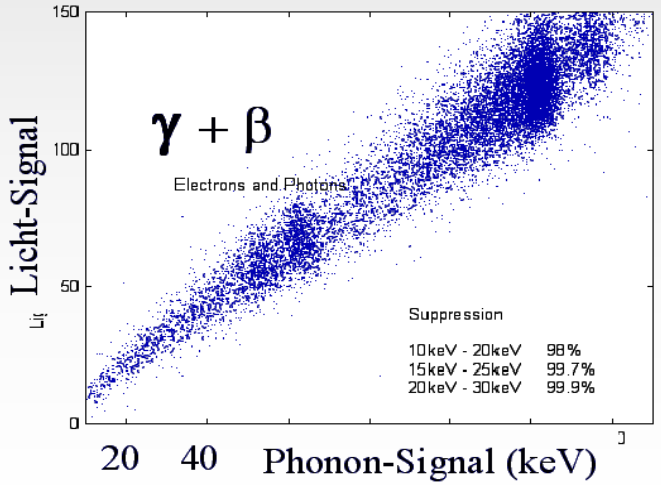
no indication for WIMP signal


http://dmtools.brown.edu
Gaitskell, Mandic, Filippini
WIMP – Nucleon Cross Section / cm²
10^-40
10^-42
10^-44
10^-46
10^-48
10^0
10^1
10^2
10^3
WIMP Mass / GeV/c²
Heidelberg Moscow 1996
IGEX 1998
DAMA 1998 / LIBRA 2008
CDMS 2000
EDELWEISS 2002
CRESST 2009
EDELWEISS 2011
CDMS 2011
XENON 2011
~ 0.0001 cts / kg / d / keV
Baltz, Gondolo MSSM 2001
Baltz, Gondolo 2004
Trotta et al CMSSM 2008

CRESST: Phonon + Light





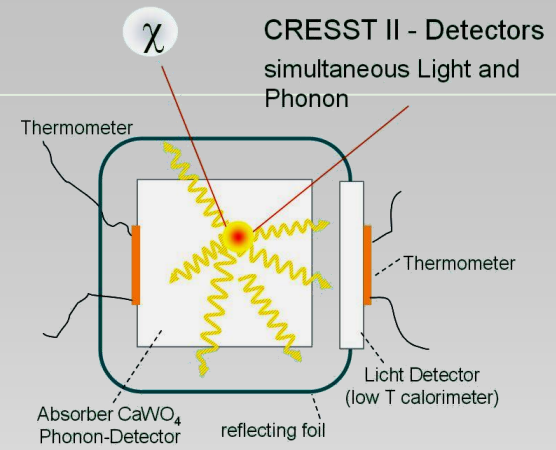


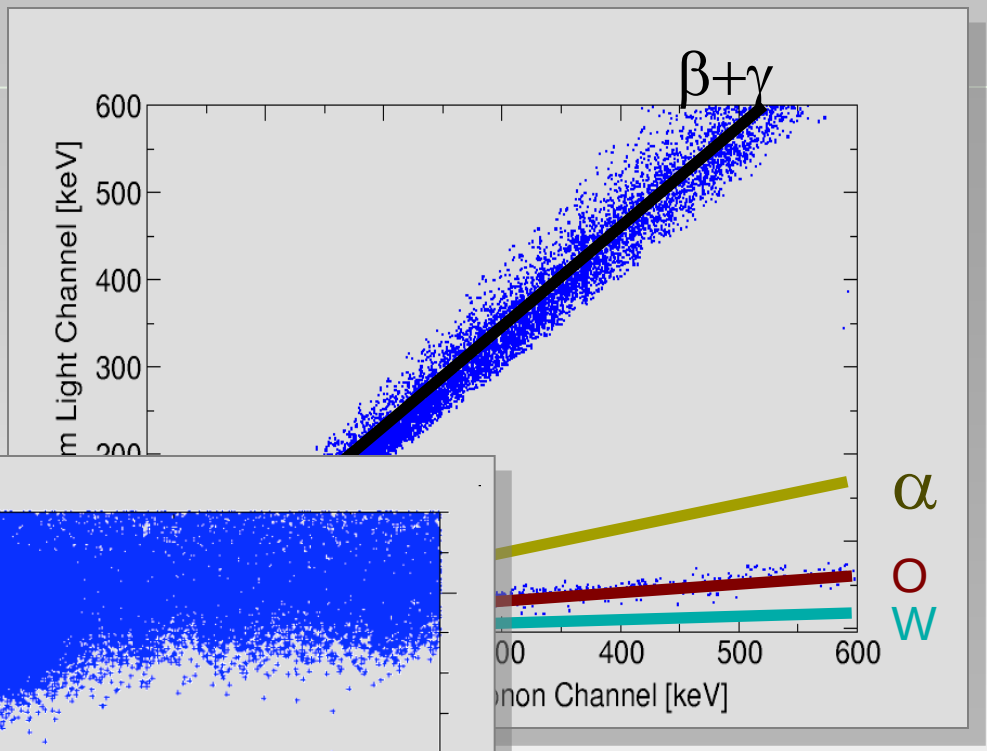
CRESST

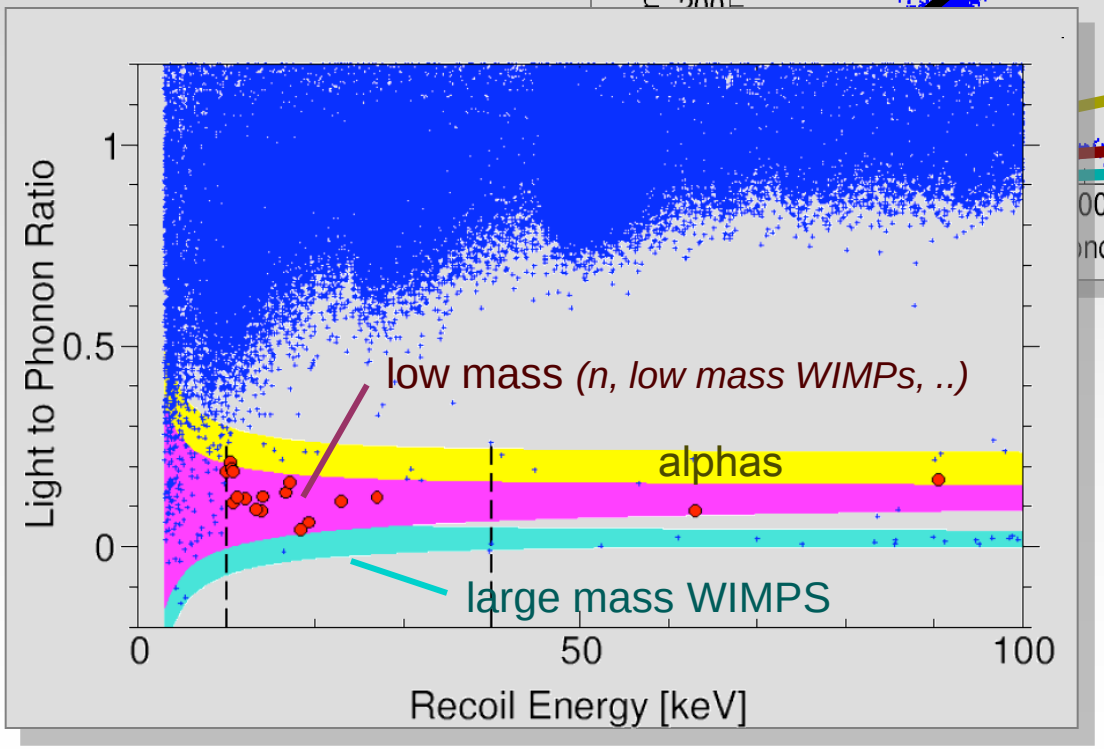
Cryogenic Rare Event Search with Superconducting Thermometers

Max-Planck-Institut München, TU München
Universität Tübingen, Oxford University, Gran Sasso

CRESST – Light / Phonon – $CaWO_4$ Target

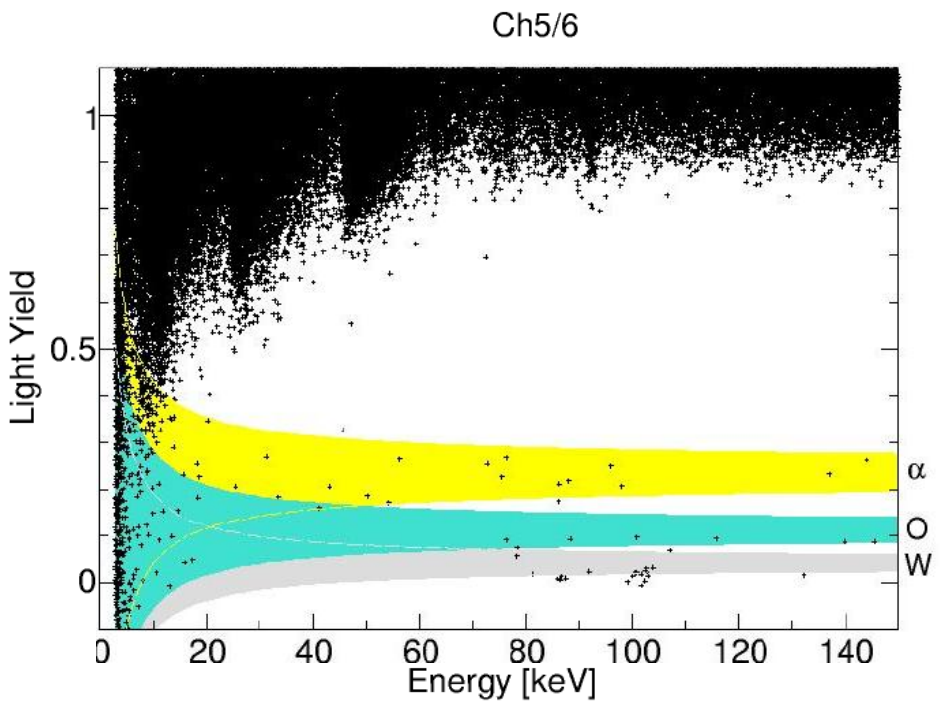






several target nuclei 'special feature' of CRESST

CRESST Data



- **Measurement 2009 - 2011**
- **8 detectors**
- results from 730 kgd exposure

⇒ **67 events in nuclear recoil acceptance region**

too many to be explained by known backgrounds

e / γ : 1 event per detector expected by threshold definition
α leakage or Pb-recoils: very unlikely, overlap to acceptance region too small
Neutrons: very unlikely, rate too high, multiplicities wrong

+ energy spectrum, + light-yield spectrum

low mass WIMPs : who knows?

CRESST Run 2009 – 2011: Likelihood Analysis

Contributions from all backgrounds + possible WIMP signal

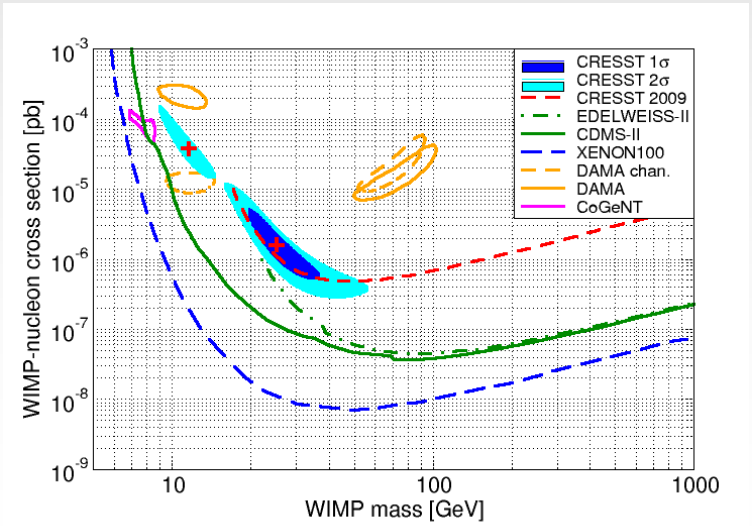
uses full information of distribution in energy and light-yield

takes into account different resolutions and thresholds

takes into account statistical uncertainties

Likelihood function shows two maxima

	M1	M2
e/γ-events	8.00 ± 0.05	8.00 ± 0.05
α-events	$11.5^{+2.6}_{-2.3}$	$11.2^{+2.5}_{-2.3}$
neutron events	$7.5^{+6.3}_{-5.5}$	$9.7^{+6.1}_{-5.1}$
Pb recoils	$15.0^{+5.2}_{-5.1}$	$18.7^{+4.9}_{-4.7}$
signal events	$29.4^{+8.6}_{-7.7}$	$24.2^{+8.1}_{-7.2}$
m_χ [GeV]	25.3	11.6
σ_{WN} [pb]	$1.6 \cdot 10^{-6}$	$3.7 \cdot 10^{-5}$



Considered backgrounds not sufficient to explain the data

⇒ **additional source needed**

CRESST Run 2009 – 2011

Considered backgrounds not sufficient to explain the data

$\Rightarrow$ additional source needed

background contributions still large

next run:

reduction of α- and Pb-background by new clamps

more detectors

internal neutron shield

starting spring next year

Clarification if excess persists or not

Likelihood function shows two maxima

	M1	M2
e/γ-events	8.00 ± 0.05	8.00 ± 0.05
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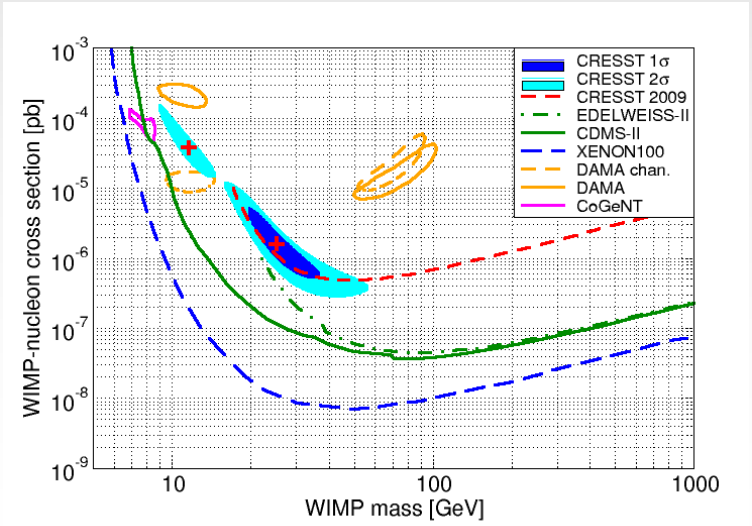

COVENTIONAL
NaI, CsI, Ge

run 250kg NaI
run 100kg CsI

DAMA
Italy

KIMS
Korea

run ~1kg Ge

COGENT
US

CRYOGENIC

run
~ 10kg, 2012
plan
~ 1t, 2015

CRESST
Germany, UK, Italy

EDELWEISS
France, Germany, UK, Russia

CDMS
US, Can., Switzerlnd

prototypes

Rosebud
France, Spain

LIQUID NOBLE GASES

XENON

run ~ 30kg
2012
plan
~ 1t, 2014

XENON
USA, Switzerl. Italy, Japan, Portugal, Germ. France, China

run
~ 100kg

XMASS
Japan

prepare
~ 100kg

LUX
10 US institutions, Moscow

ARGON

prepare
~ 100kg–1t
plan
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Switzerland, Spain, UK, Poland

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US, Italy, Rus, Poland China, Ukraine, UK

DEAP/ CLEAN
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finsihed

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very good spin dependent limits

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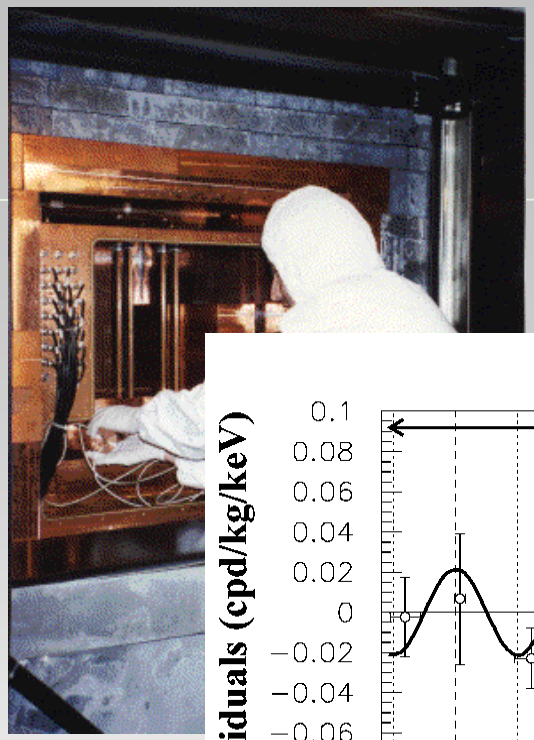
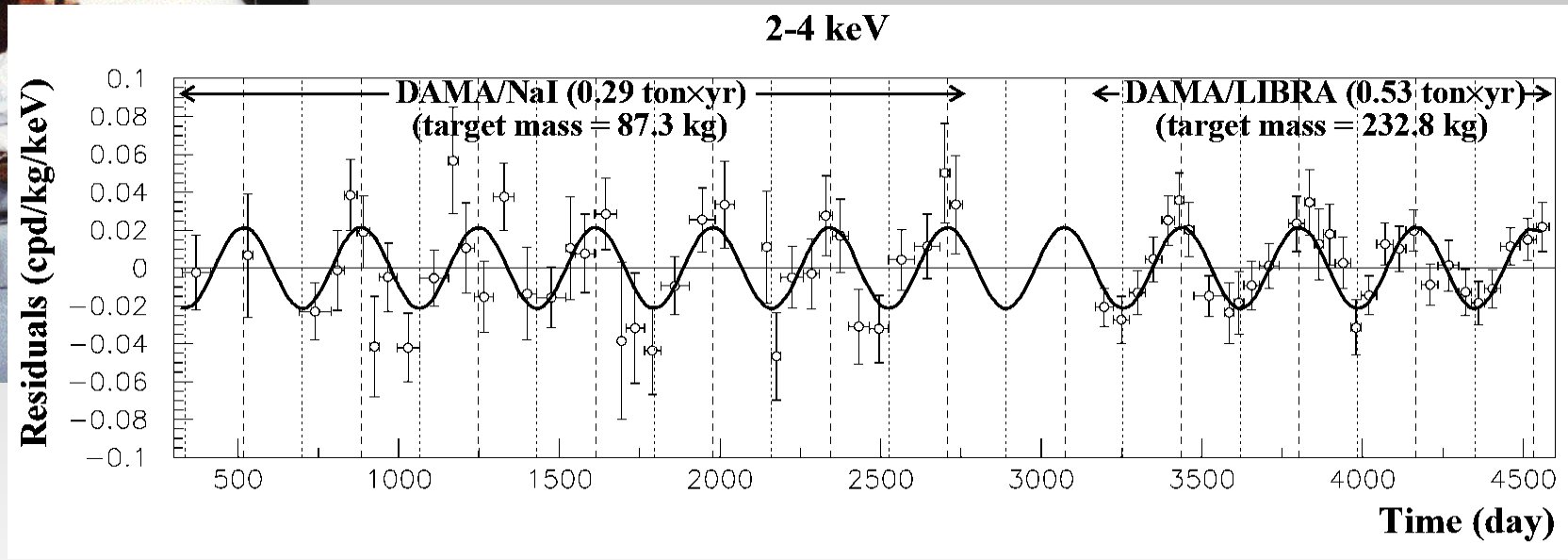
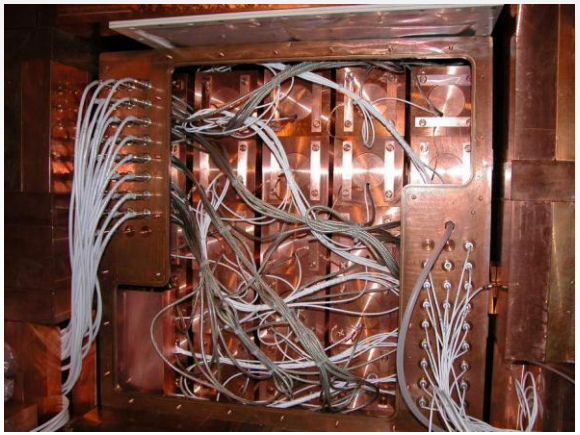


Annual Modulation

DAMA Exp. – Gran Sasso – Ital.Collab.

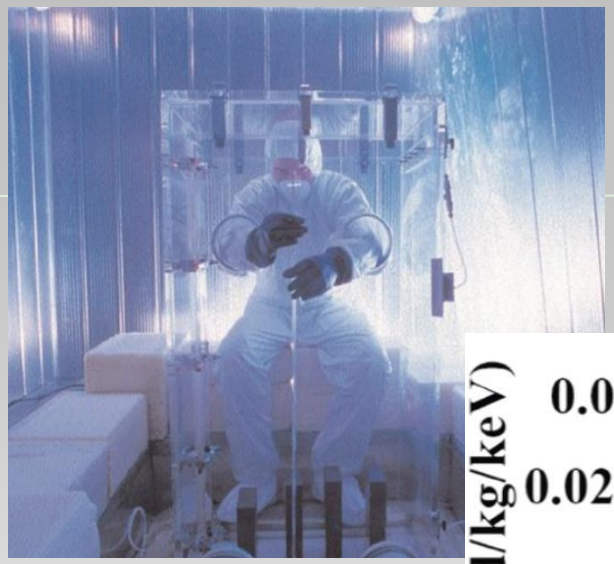
DAMA - Experiment:
first hint to WIMPs ?





up to today 11 years of data taking
(~ 300.000 kg x days, 0.8 ton x year)

Modulation eith 8σ Confidence
Riv.N.Cim. 26/1 (2003), 1-73



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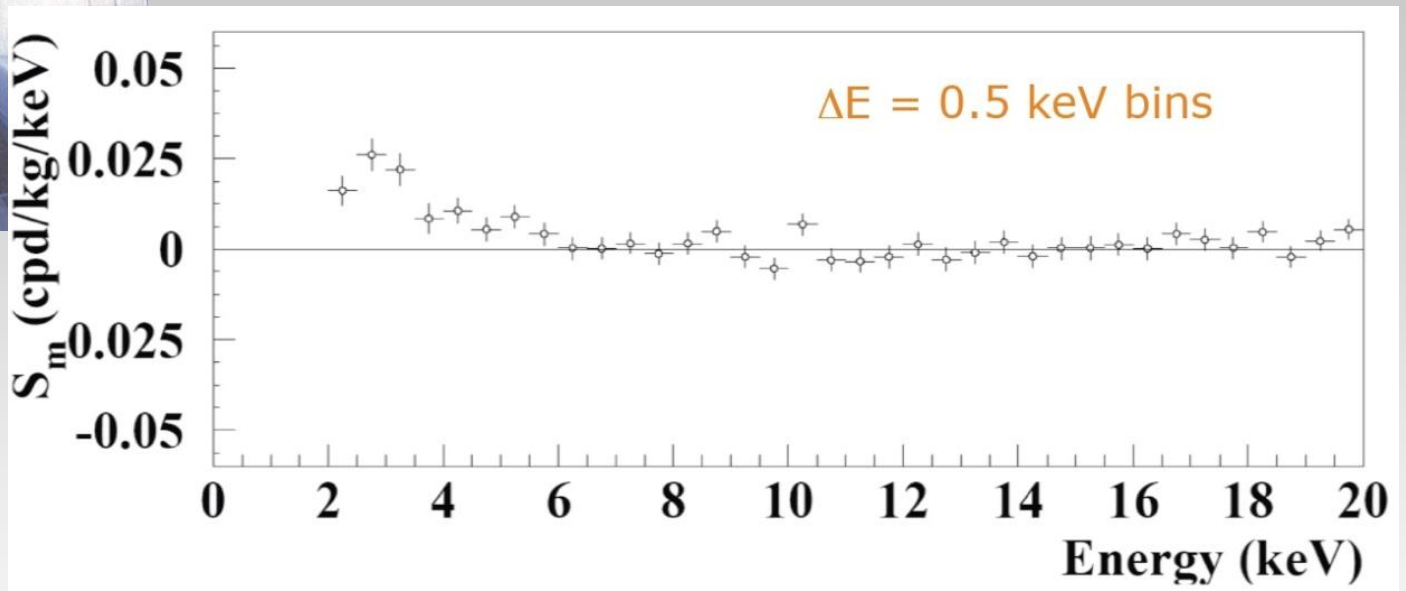

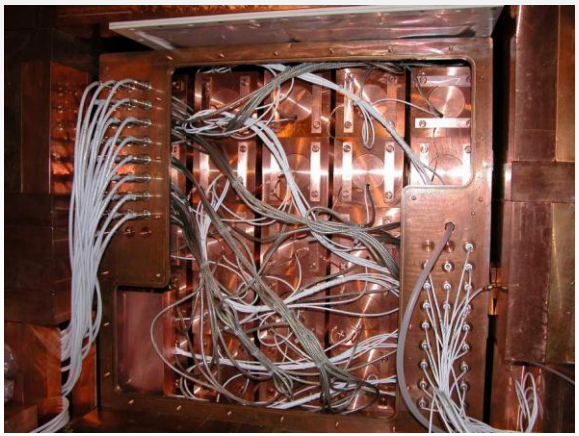

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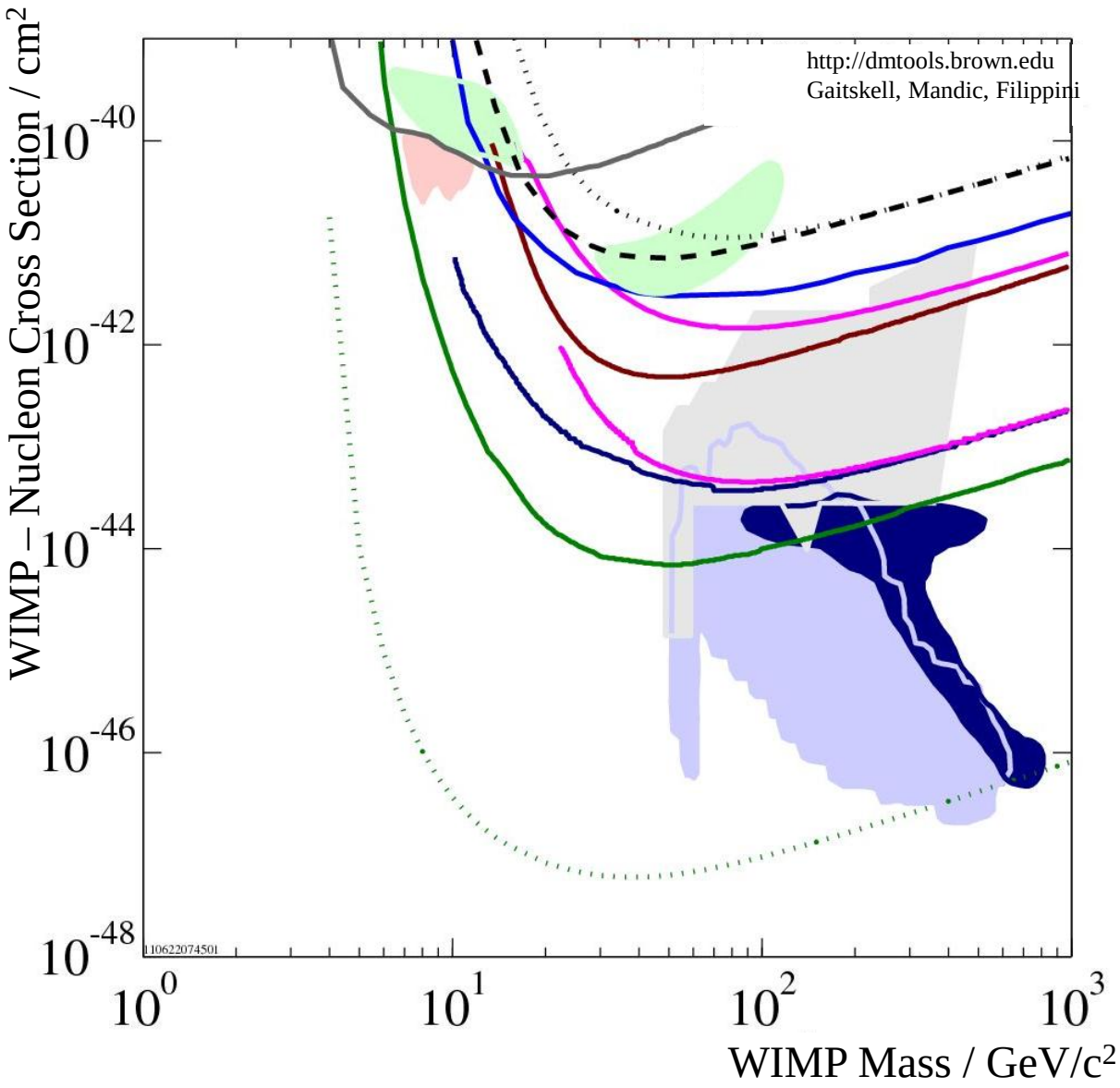
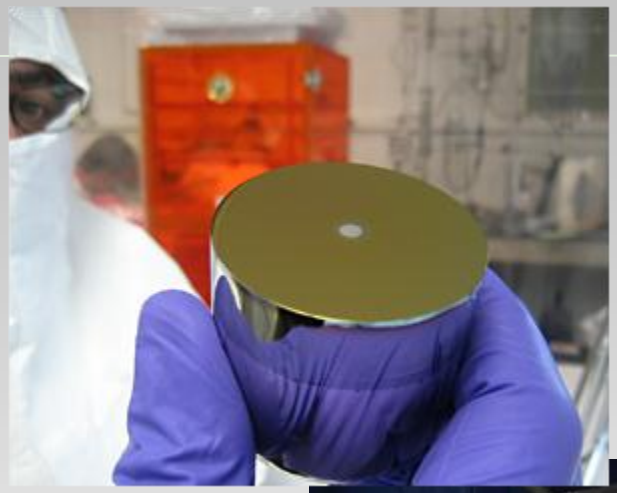

http://dmtools.brown.edu
Gaitskell, Mandic, Filippini
WIMP – Nucleon Cross Section / cm²
10^-40
10^-42
10^-44
10^-46
10^-48
10^0
10^1
10^2
10^3
WIMP Mass / GeV/c²
Heidelberg Moscow 1996
IGEX 1998
DAMA 1998 / LIBRA 2008
Baltz, Gondolo MSSM 2001
Baltz, Gondolo 2004
Trotta et al CMSSM 2008

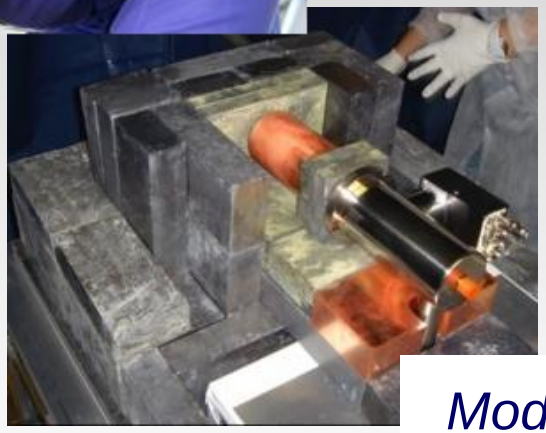
COGENT

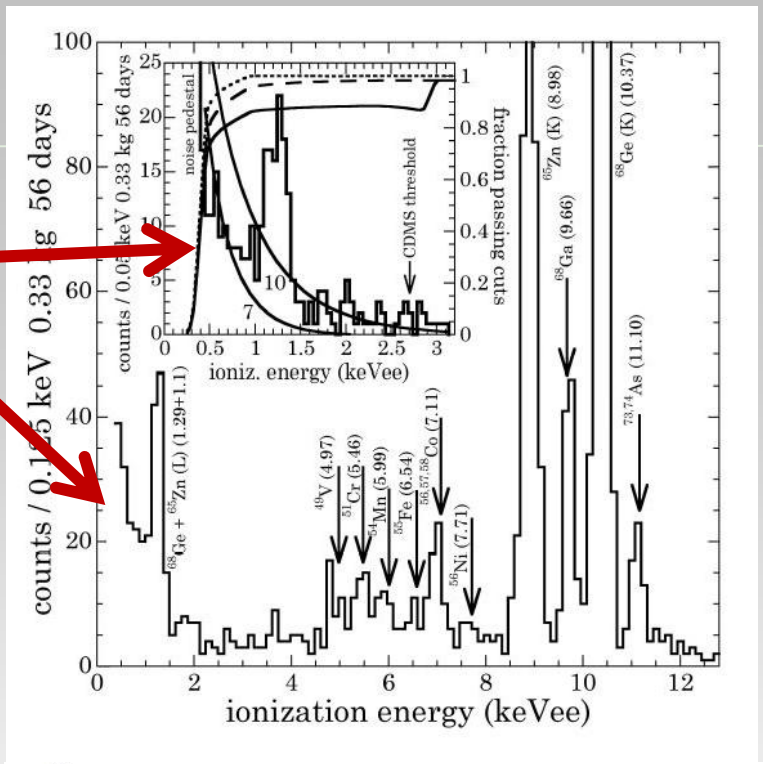
Soudan Mine
US Collaboration



low energy excess

low mass WIMPs?

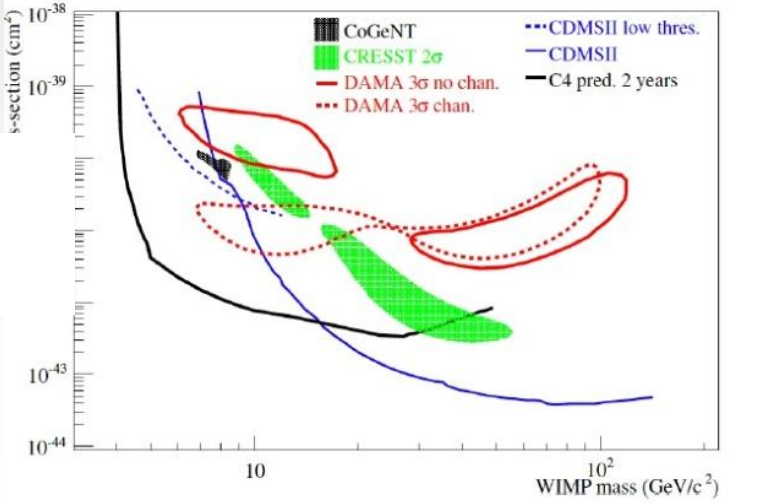




Ge detectors

Ionisation only

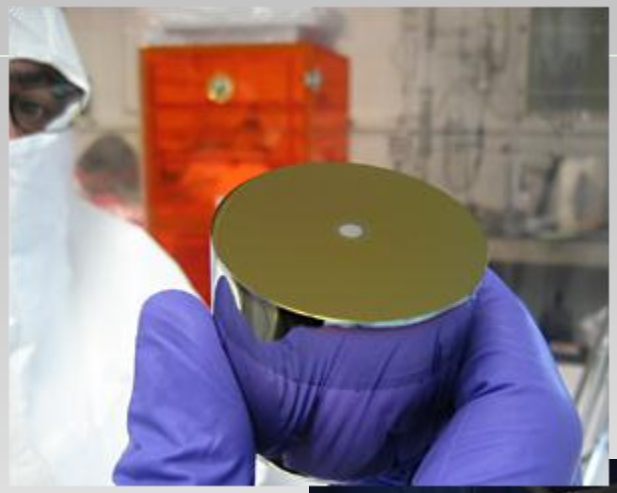
Modulates ?
(2.8 sigma)



Point contact detectors
⇒ Very low threshold
⇒ Good to look for light WIMPs

COGENT

Soudan Mine
US Collaboration



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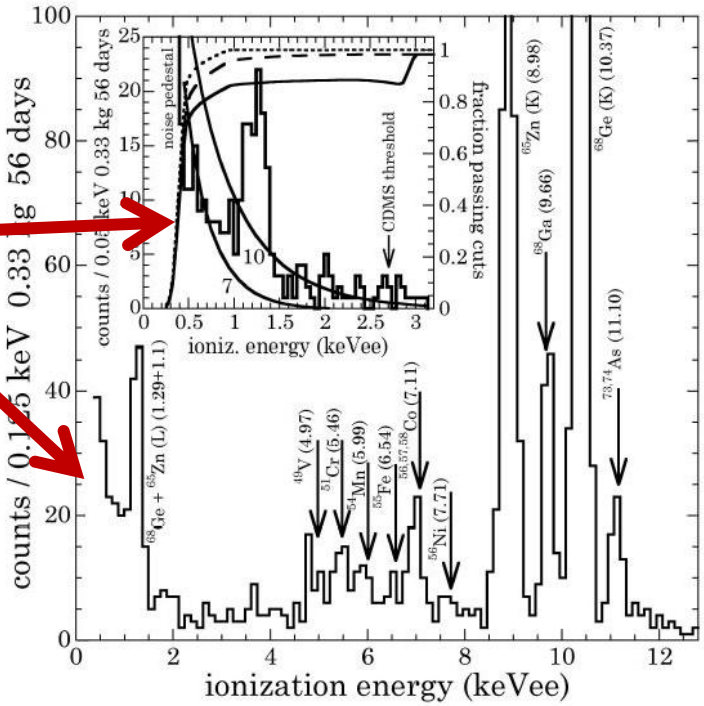
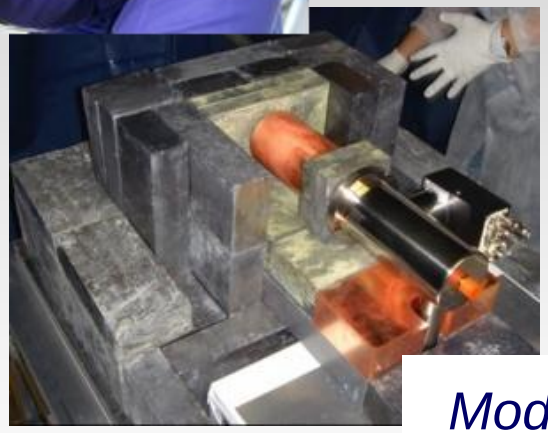




Ge detectors

Ionisation only

Modulates ?
(2.8 sigma)

Point contact detectors
⇒ Very low threshold
⇒ Good to look for light WIMPs

July 2012
IDM Conference

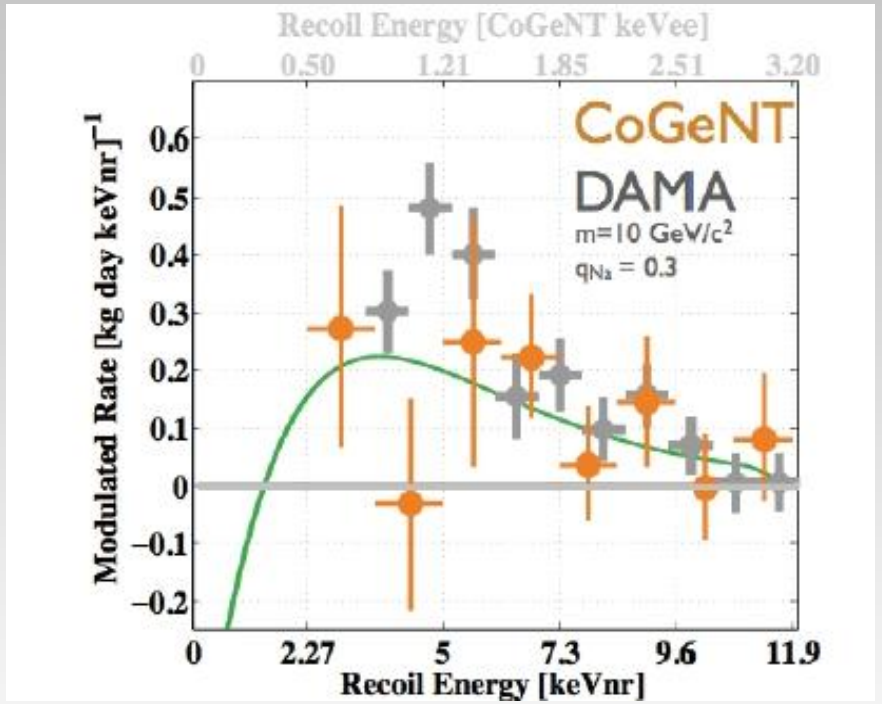
”

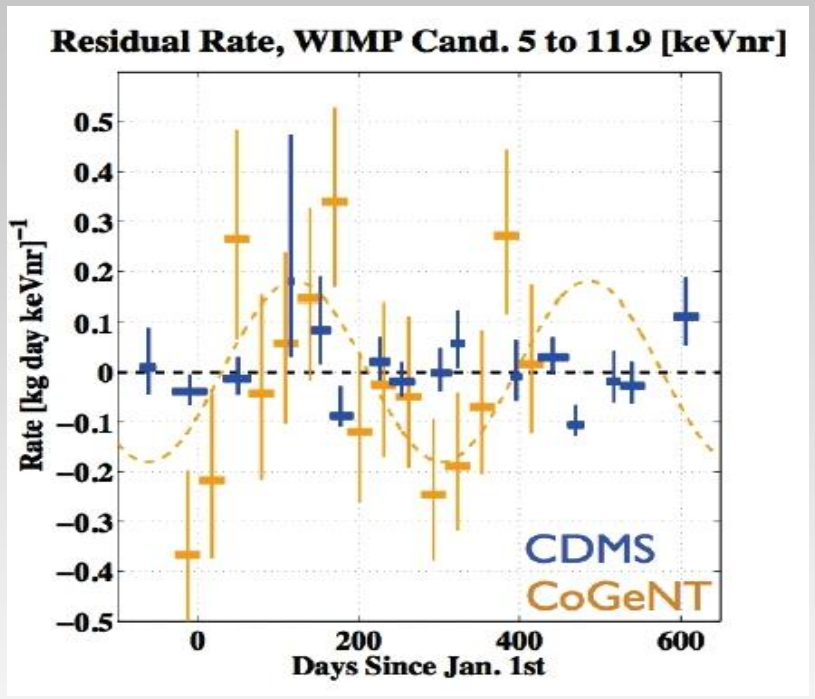
- Low-energy excess still there.
- Rates look flatter on second year.

Optimist: to be expected, the modulation was too large.
Pessimist: to be expected, the modulation was a fluke.

”

Modulation Signals DAMA - COGENT - CDMS





5.0-11.9 keVnr

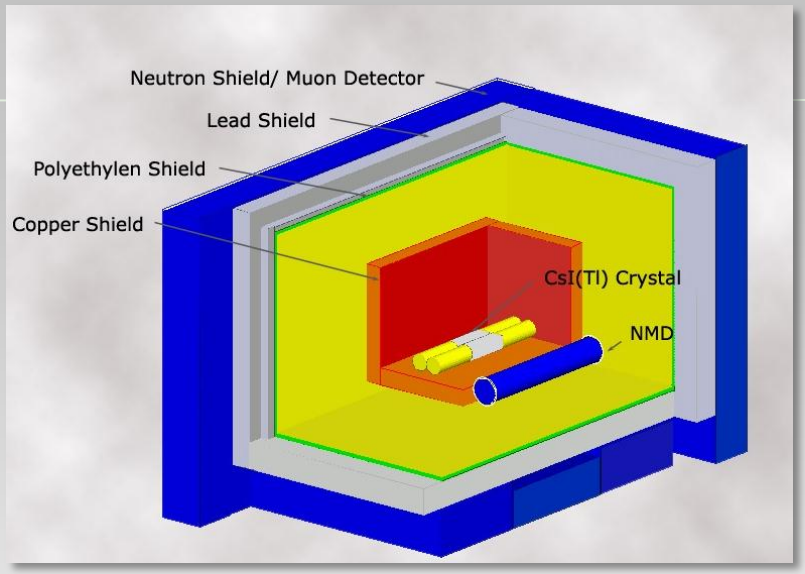
CDMS Modulation Analysis

$R_{mod} < 0.06$ **[keV$_{nr}$ kg day]$^{-1}$** (99% CL)

inconsistent with CoGeNT (>98% CL)

KIMS

Korea



CsI(Tl) detectors, ~ 100kg

scintillation only

exposure ~ 25000 kg days

continues

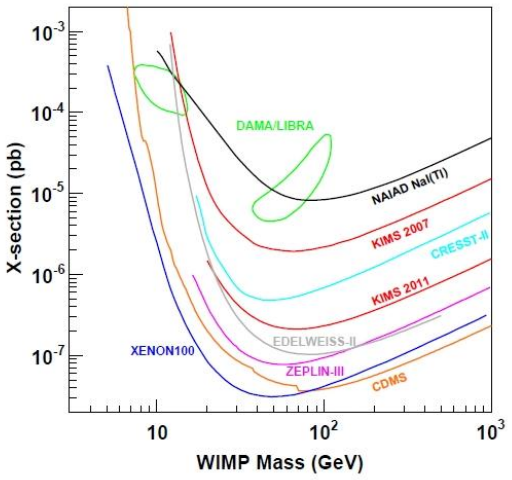
competitive SD and SI limits

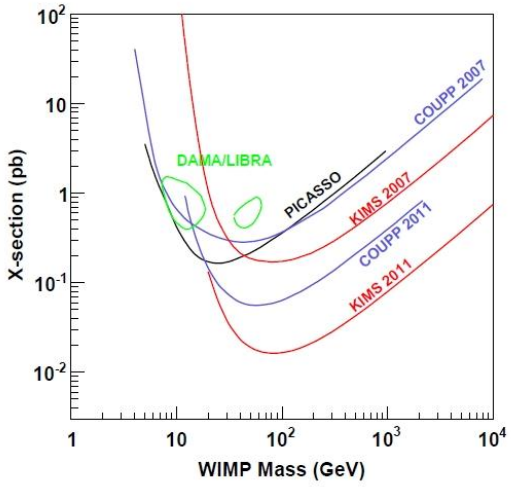
nuclear recoil rate

smaller than

DAMA Modulation amplitude !!!

the same for
CDMS, EDELWEISS, CRESST, XENON
but
KIMS most similar to DAMA





Modulation Signals

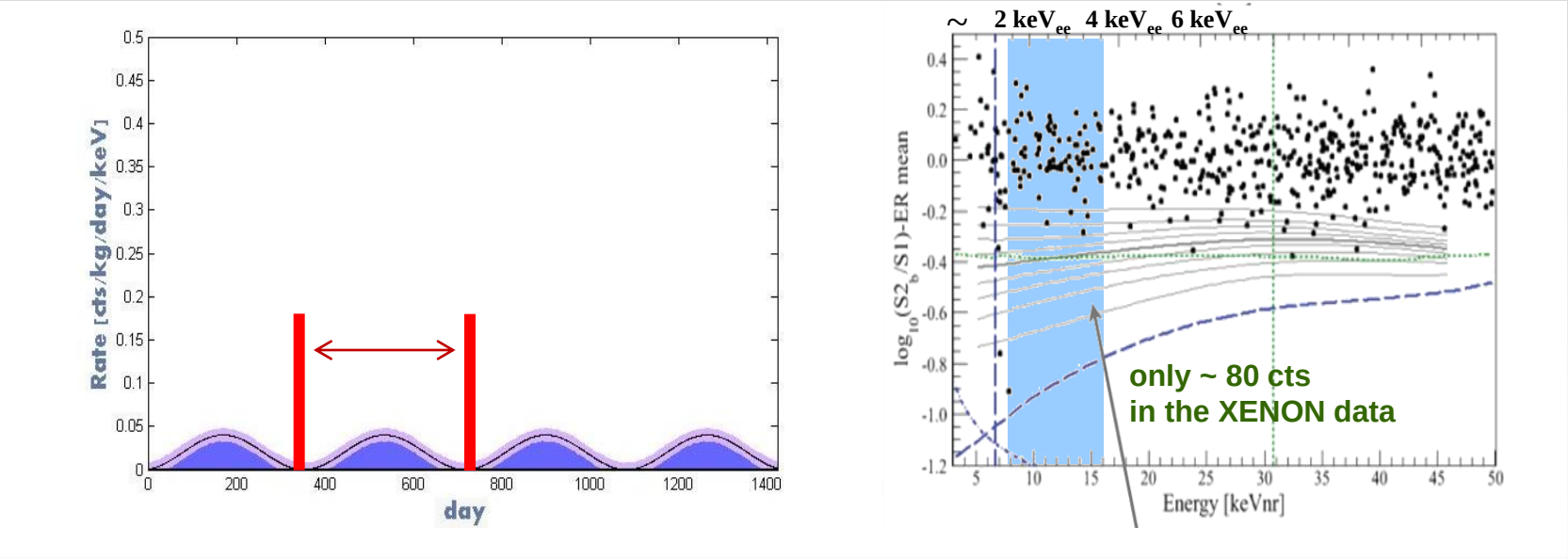
assume most extreme case, signal fully modulates, no bulk rate

in any model, modulation is the minimum you must see

expected rate from DAMA signal in (2-4) keV:

if nuclear recoils:
1500 cts/year in KIMS *(most similar to DAMA in mass and material)*, **but measured < 800 cts/year**

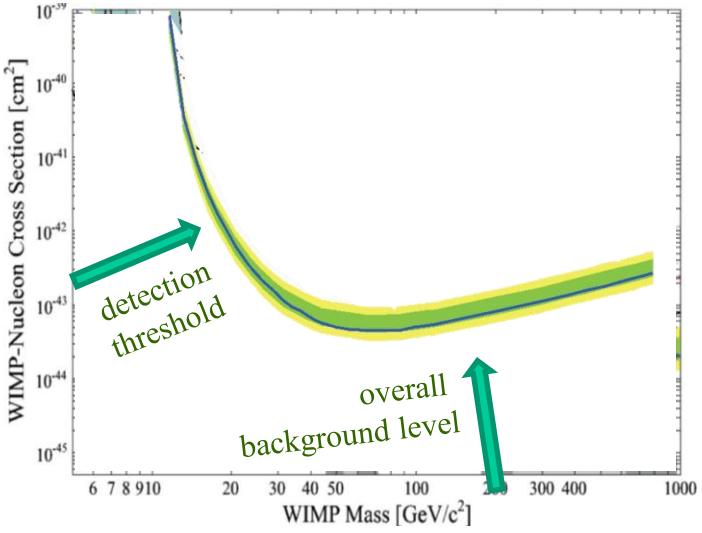
if electron recoils:
500 cts/year in XENON, but measured ~ 80 cts/year

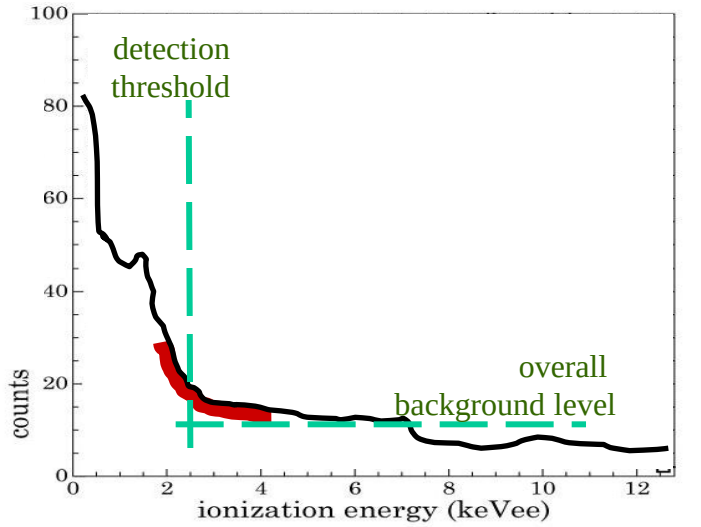


this conflict is model independent (halo: $v_{galaxy} - v_{earth}$; WIMP: electronic-nuclear recoils)

caveat left: XENON-keV$_{ee}$ energy scale, so far calibrated only above 40keV ! needs to be done down to keV range !

Low Mass WIMPs ?





limit curves
= limit of detector sensitivity

where statistics is too low
and
background comes in

any background or other technical problem interpreted as WIMP

shows up along this line

background usually rises towards lower energy
⇒ ***first background to sneak in***
is background at threshold

⇒ ***low mass limit is the most difficult to control***
+ ***low mass WIMP the most likely to get by background***

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NaI, CsI, Ge

run 250kg NaI
run 100kg CsI

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KIMS
Korea

run ~1kg Ge

COGENT
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run
~ 10kg, 2012
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~ 1t, 2015

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run
~ 100kg

XMASS
Japan

prepare
~ 100kg

LUX
10 US institutions, Moscow

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prepare
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Switzerland, Spain, UK, Poland

DARK SIDE
US, Italy, Rus, Poland China, Ukraine, UK

DEAP/ CLEAN
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finsihed

WARP
Italy, US

DROPLETS

runs 4kg
starts 60kg
prepares 500kg

COUPP
USA

runs 2kg

PICASSO
Canada, USA, Czeck

very good spin dependent limits

DIRECTIONAL

first runs

DRIFT
UK, US

DM-TPC
US

NEWAGE
Japan

prototypes

MIMAC
France

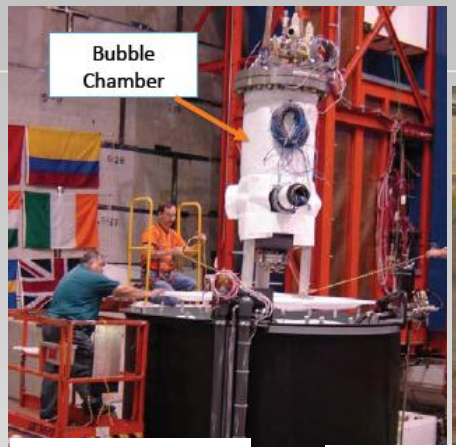
Superheated Droplets COUPP

similar to bubble chamber

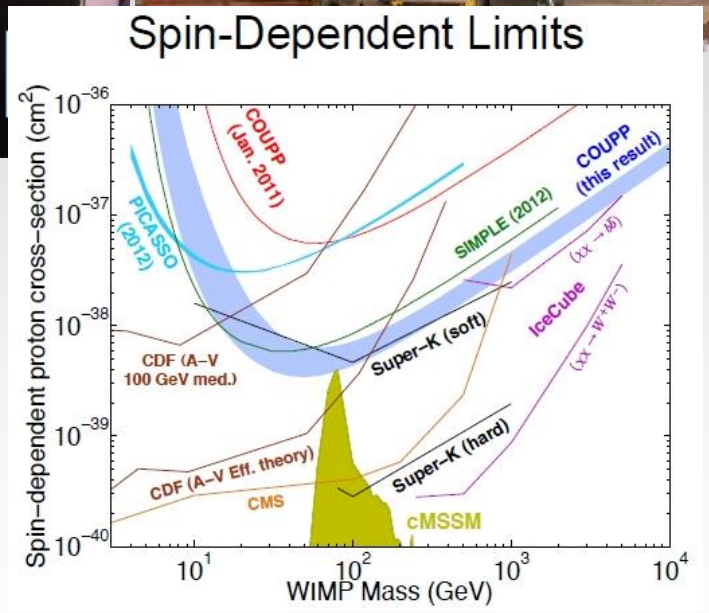
P and T set to be sensitive only to nuclear recoils and alphas

recognize alphas by pulse shape

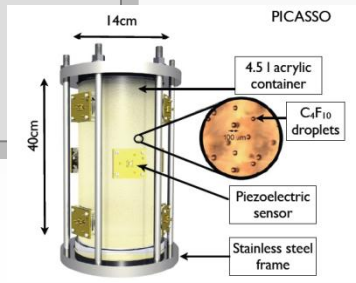
COUPP
USA
- 4kg running at SNOLAB
- 60kg running at Fermilab
  moving to SNOLAB
  physics run start 2012
- 500kg in preparation



COUPP
60-kg detector
surface test



PICASSO
•***Canada, USA, Czeck***
1.9 kg running since 2009
• new SD constraints from
• moved to larger lab
within SNOLAB



COUPP 4kg
best direct detection
spin dependent limit

Superheated Droplets PICASSO

similar to bubble chamber

P and T set to be sensitive only to nuclear recoils and alphas

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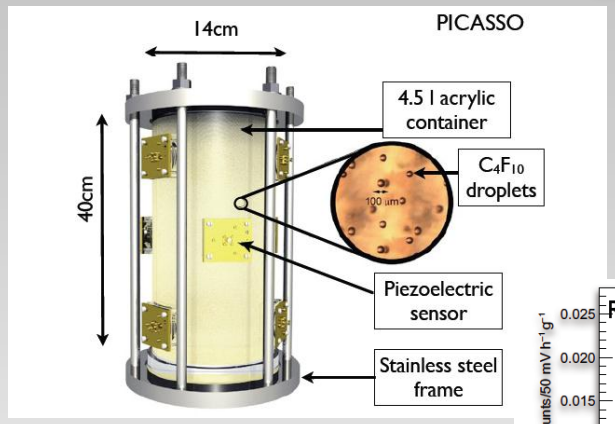

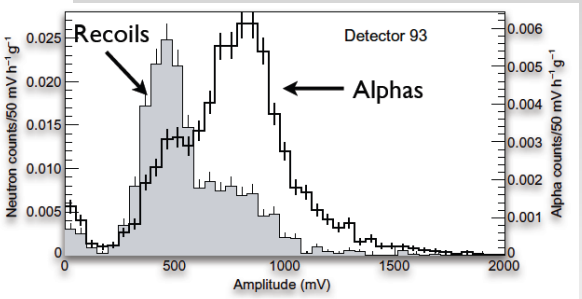

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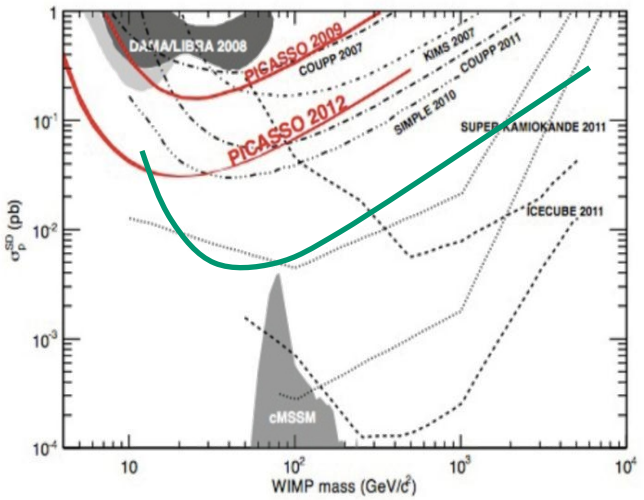
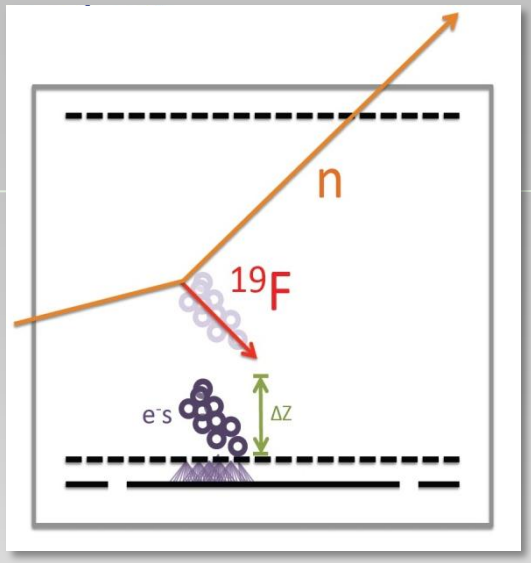


Directional



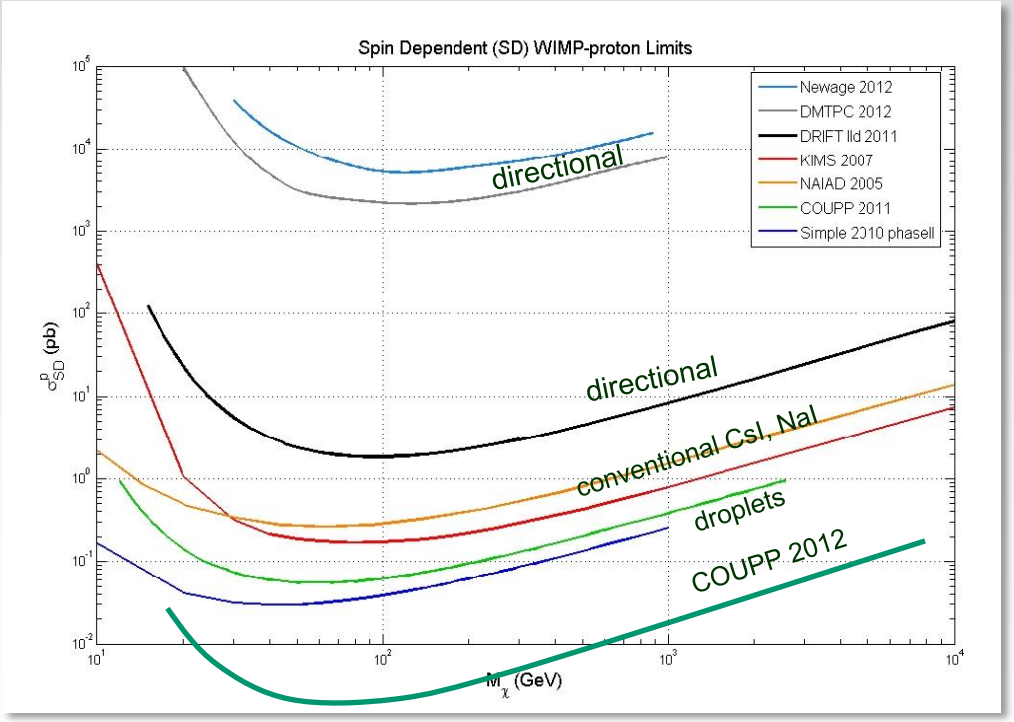
WIMPs come from certain direction (Cygnus)

=> measure direction of recoil

needs gas target
thin => low mass,
CF good for spin dependent

and track read out

DMTPC – *US*
MIMAC – *France*
DRIFT – *UK, US*
NEWAGE - *Japan*



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Germany, UK, Italy

EDELWEISS
EURECA
France, Germany, UK, Russia

CDMS
Super CDMS
US, Can., Switzerlnd

prototypes

Rosebud
France, Spain

LIQUID NOBLE GASES

XENON

run ~ 30kg
2012
plan
~ 1t, 2014

XENON
USA, Switzerl. Italy, Japan, Portugal, Germ. France, China

run
~ 100kg

XMASS
Japan

prepare
~ 100kg

LUX
10 US institutions, Moscow

ARGON

prepare
~ 100kg–1t
plan
> 1t

ArDM
Switzerland, Spain, UK, Poland

DARK SIDE
US, Italy, Rus, Poland China, Ukraine, UK

DEAP/
CLEAN
Canada, US

finsihed

WARP
Italy, US

DROPLETS

runs 4kg
starts 60kg
prepares 500kg

COUPP
USA

runs 2kg

PICASSO
Canada, USA, Czeck

very good spin dependent limits

DIRECTIONAL

first runs

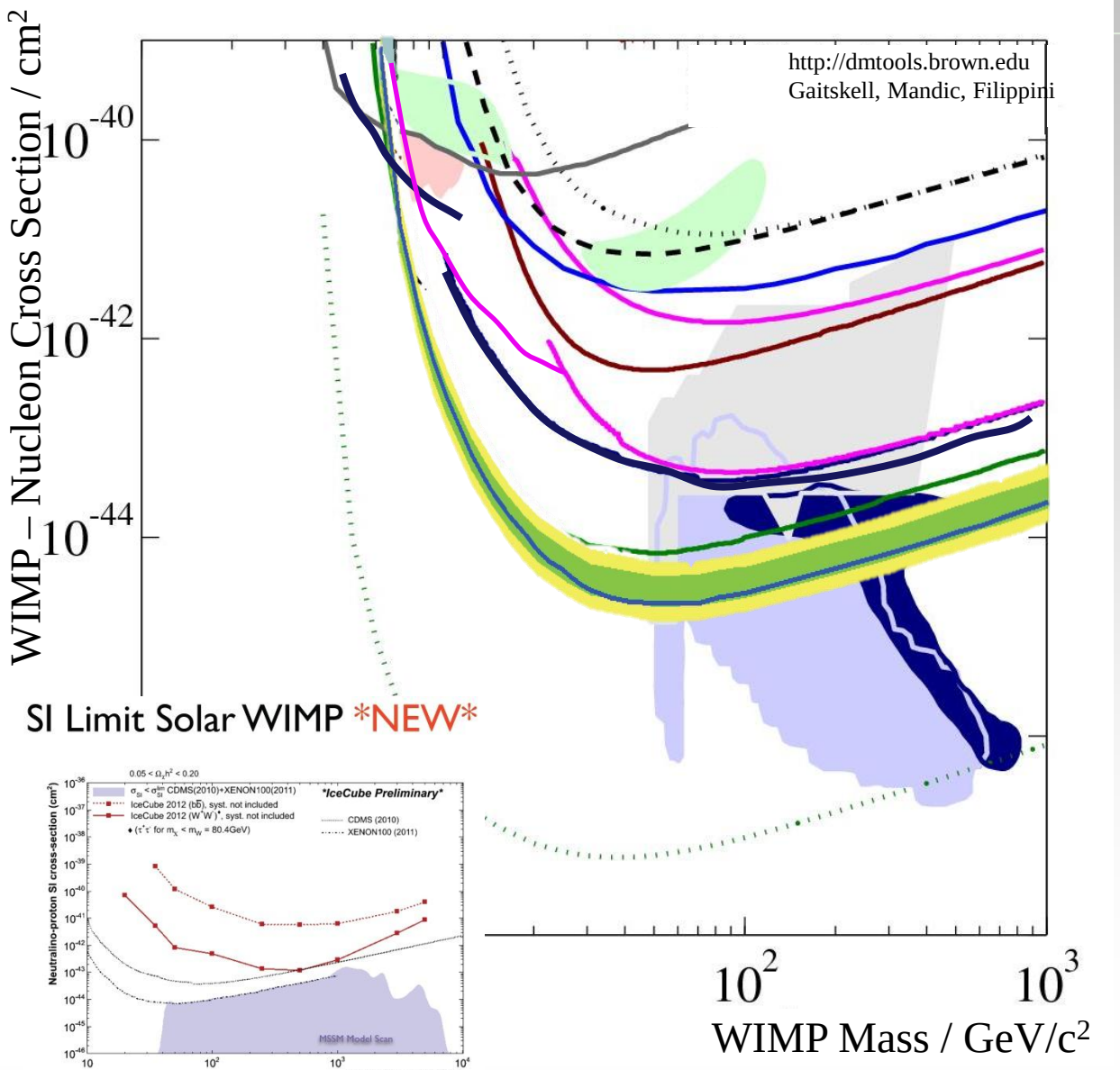
DRIFT
UK, US

DM-TPC
US

NEWAGE
Japan

prototypes

MIMAC
France


WIMP – Nucleon Cross Section / cm²
10⁻⁴⁰
10⁻⁴²
10⁻⁴⁴
http://dmtools.brown.edu
Gaitskell, Mandic, Filippini
SI Limit Solar WIMP *NEW*
10²
10³
WIMP Mass / GeV/c²
Heidelberg Moscow 1996
IGEX 1998
DAMA 1998 / LIBRA 2008
CDMS 2000
EDELWEISS 2002
CRESST 2009
EDELWEISS 2011
CDMS 2011
XENON 2011
XENON 2012
~ 0.00003 cts / kg / d / keV
Baltz, Gondolo MSSM 2001
Baltz, Gondolo 2004
Trotta et al CMSSM 2008
IceCube Preliminary
CDMS (2010)
XENON100 (2011)
MSSM Model Scan
Neutralino mass (GeV)
Neutralino-proton SI cross-section (cm²)

Direct DM Searches

remarkable progress

x 100 improvement in sensitivity
in 10 yrs

present best sensitivities
(for spin independent WIMP scattering)

- cryogenic
- liquid Xenon

+ other techniques
(doing better for spin dependent WIMP scattering)

we have different techniques
with promising sensitivity

simultaneously
LHC is starting
and will march upward in mass