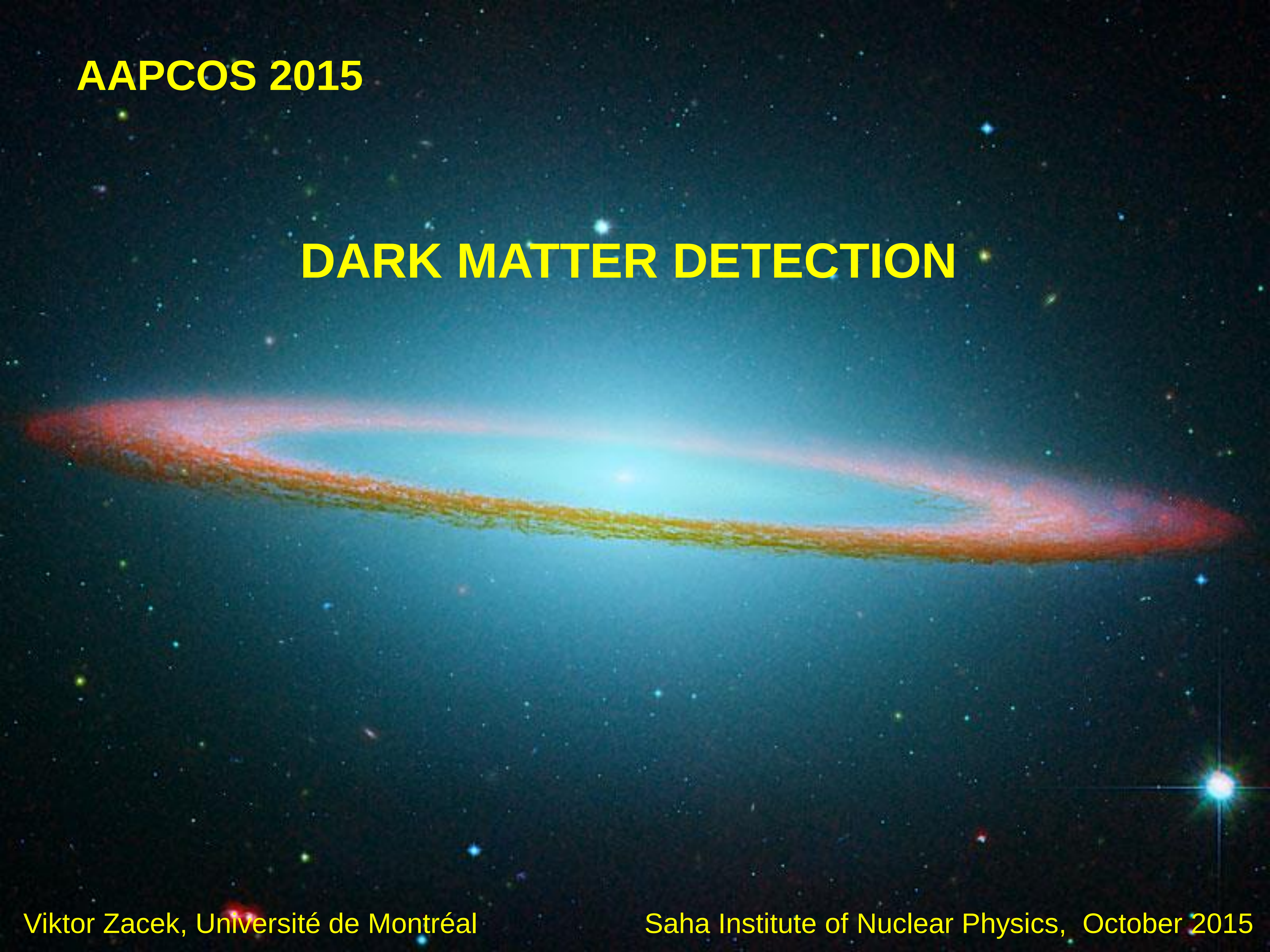


AAPCOS 2015

DARK MATTER DETECTION

Viktor Zacek, Université de Montréal

Saha Institute of Nuclear Physics, October 2015

Lecture I

- Evidences for Dark Matter
- Present knowledge of the matter content of the Universe
- Dark Matter and structure of the Universe
- What Dark Matter can and cannot be

Lecture II

- DM detection – rates and limits
- Backgrounds and their mitigation
- A guided tour through SNOLAB
- Status of direct search experiments

Lecture III

- Status of indirect search experiments
- Accelerator searches
- Other candidate searches
- Future directions

GENERAL STRATEGY FOR DARK MATTER SEARCH

Requirements

- Very low, threshold $\rightarrow$ keV
- Very small intrinsic and induced background $\rightarrow$ < 0.1 cts/kg/d
- Located in underground laboratories in radio-pure environment
- Screened from neutrons
- With capability to discriminate signal from background
- Superb stability and control of systematics
- Large detector mass $\rightarrow$ 100kg

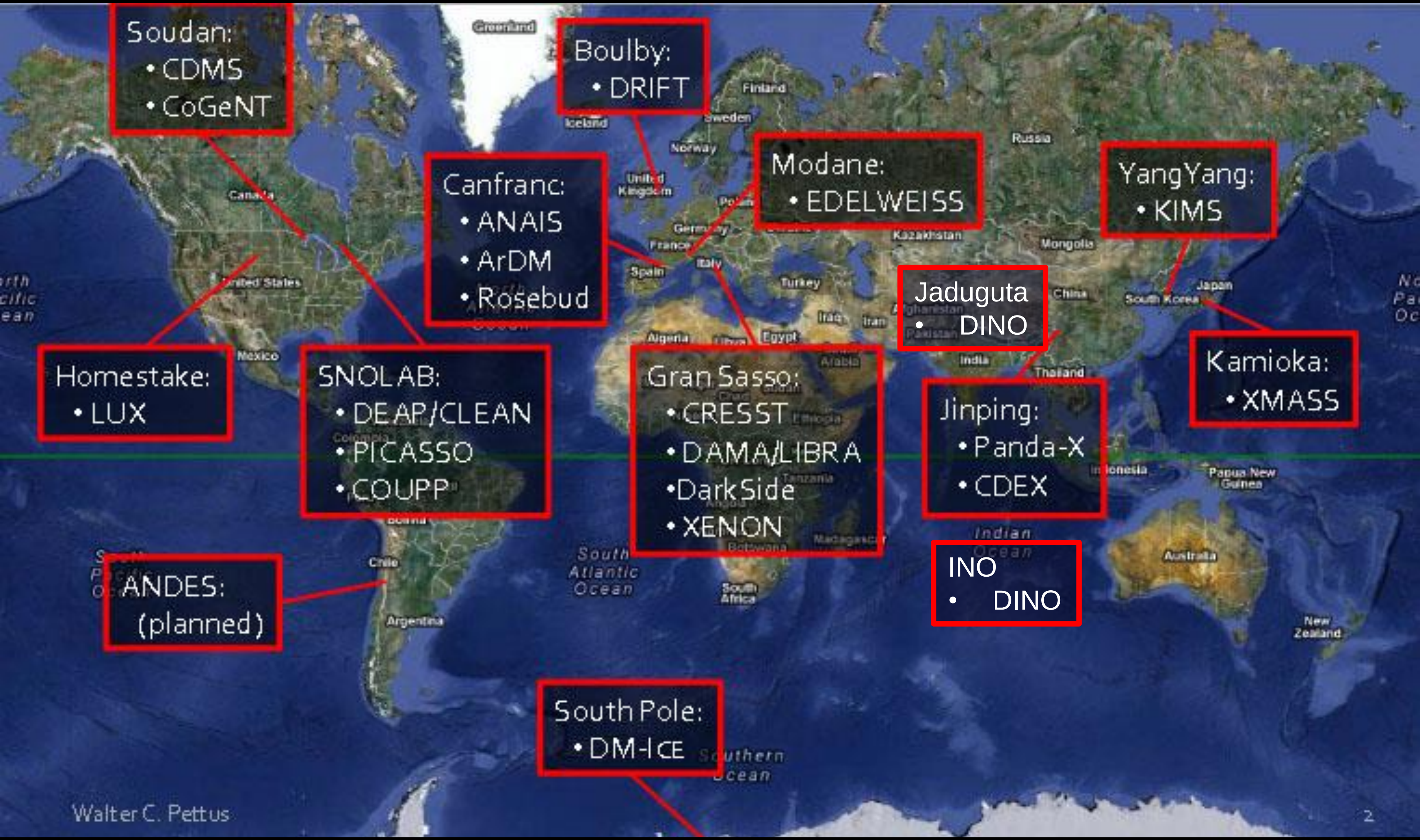
GENERAL STRATEGY FOR DARK MATTER SEARCH

Signatures

- **Annual / daily modulation → statistics!**
- **Dependence on target A (SI) or target spin (SD)**
- **Directionality (Cygnus) → statistics, low pressure**
- **Absence of multiple events (neutrons) → detector arrays**

WIMPs scatter only once !!!

(Incomplete) World Wide Activities in U/G Labs

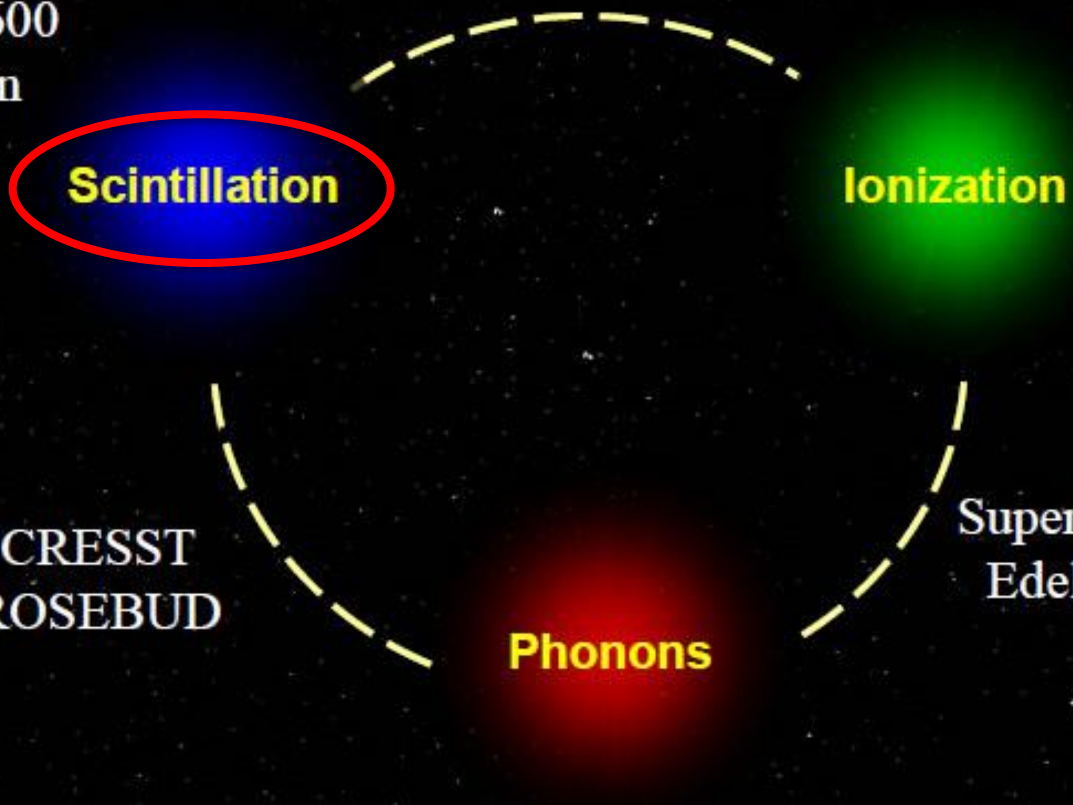


Dark Matter Strategies

Zeplin III Xe
Xenon 100 Xe
LUX Xe
ArDM Ar

NaI Dama/Libra
Ar DEAP-3600
Ar/Ne MiniClean
Xe Xmass

DRIFT CS_2
CoGeNT Ge
DM-TPC CF_4



$CaWO_4$ +... CRESST
ROSEBUD

SuperCDMS
Edelweiss
Ge

COURE TeO_2
PICASSO C_4F_{10}
COUPP CF_3I
SIMPLE CCl_2F

= PICO

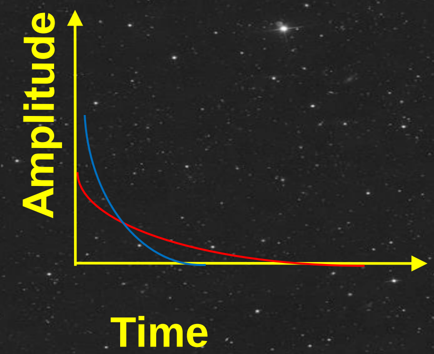
Unknowns:
- Particle type
- Mass,
- Kind of interaction (SI,SD)

A. Noble ICRC2013

SCINTILLATOR EXPERIMENTS

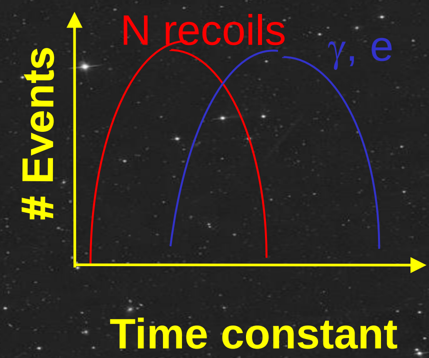
Principle:

- crystals (NaI, CsI), Liquids (Xe, Ar, Ne, CaF_2(Eu)) emit light if hit by radiation (T_{room})
- light collected by photomultiliers ($\varepsilon \sim 15\%$) or photo-diodes
- ΔE / photon ~ 15 eV
- light gain ~ 2-8 phe/keV



Background rejection:

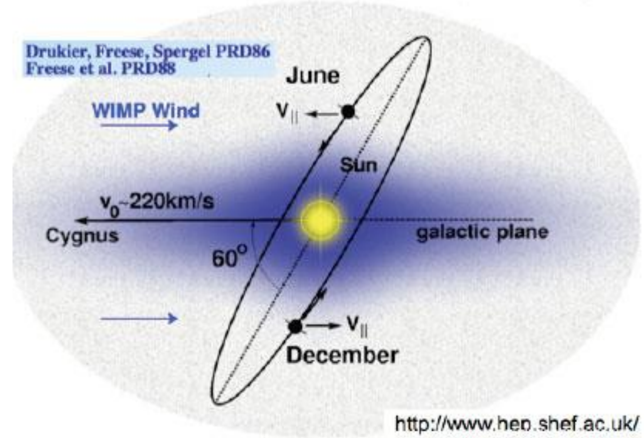
- different pulse shape (time constant) for nuclear recoil or e, gamma induced events



Experiments:

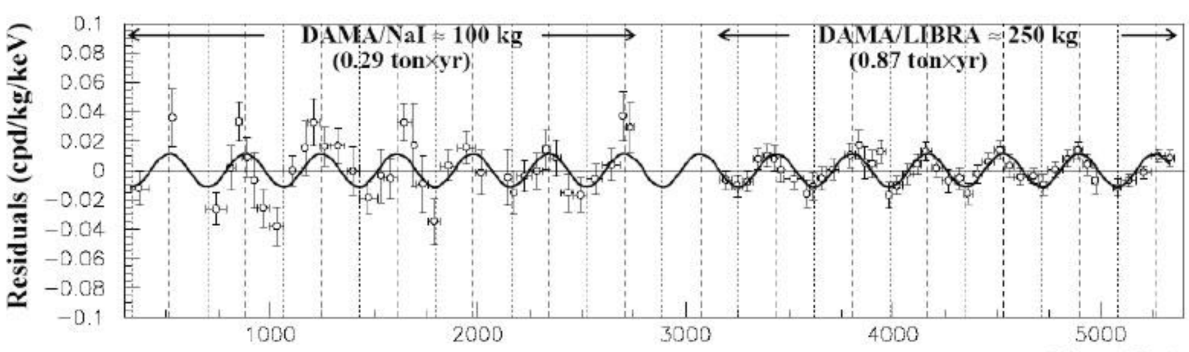
DAMA, NAIAD, ANAIS, KIMS, DEAP…

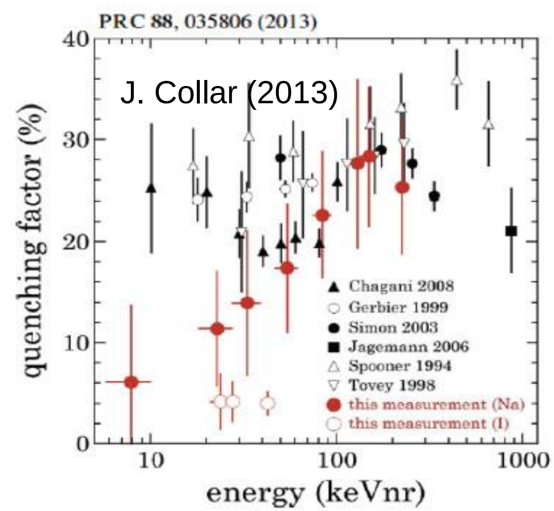
DAMA / LIBRA NaI (Gran Sasso)



- 250 kg of NaI crystals
- > 13 annual cycles show a modulation at 8.9σ
- period T=1.00 $\pm$ 0.01 y; A = 0.0195 $\pm$ 0.003 cts/kg/d/keV
- modulation at low energies 2-6 keV
- total exposure 1.17 ton y
- **Signal: $M\chi \sim 10 - 50$ GeV/c^2; $\sigma_{SI} \sim 10^{-6}$ pb**

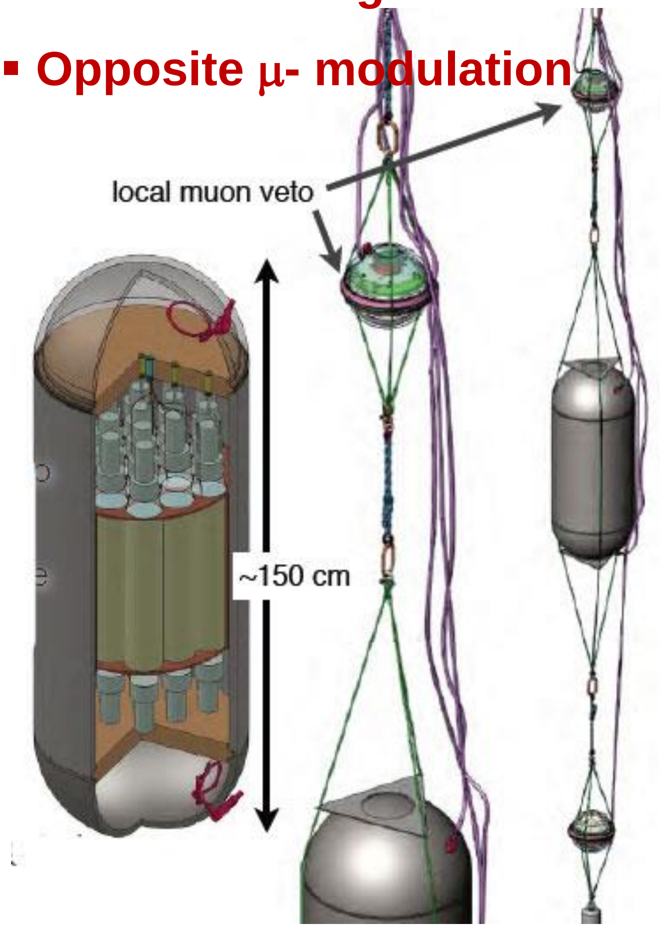
R. Bernabei et al.; PLP 24(1998) 195, R. Cerulli, IDM2012

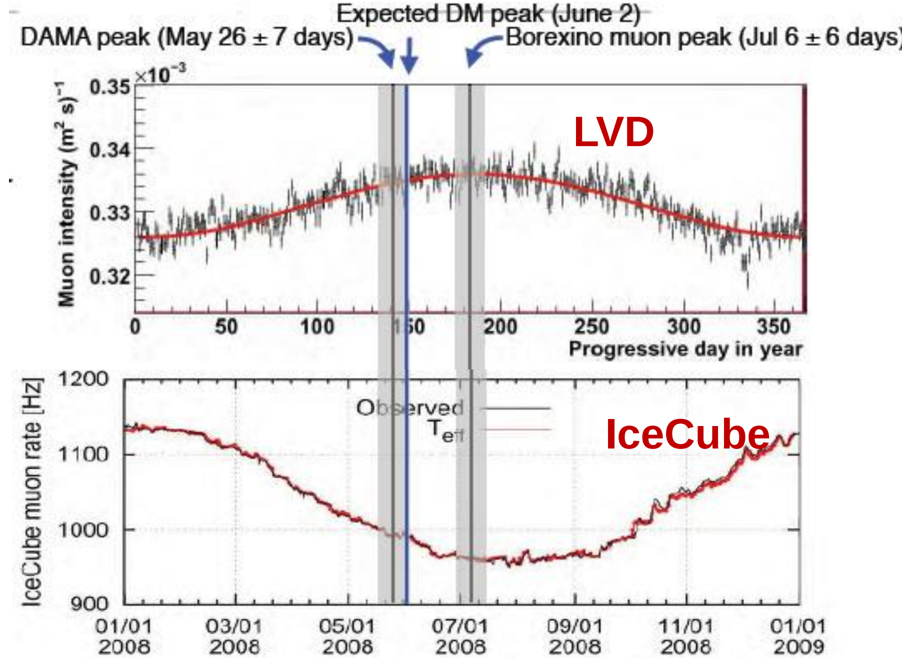




DM - ICE (South-pole)

- **Same detector as DAMA**
- **Addressing diff. systematic effects**
- **Different background**
- **Opposite μ- modulation**





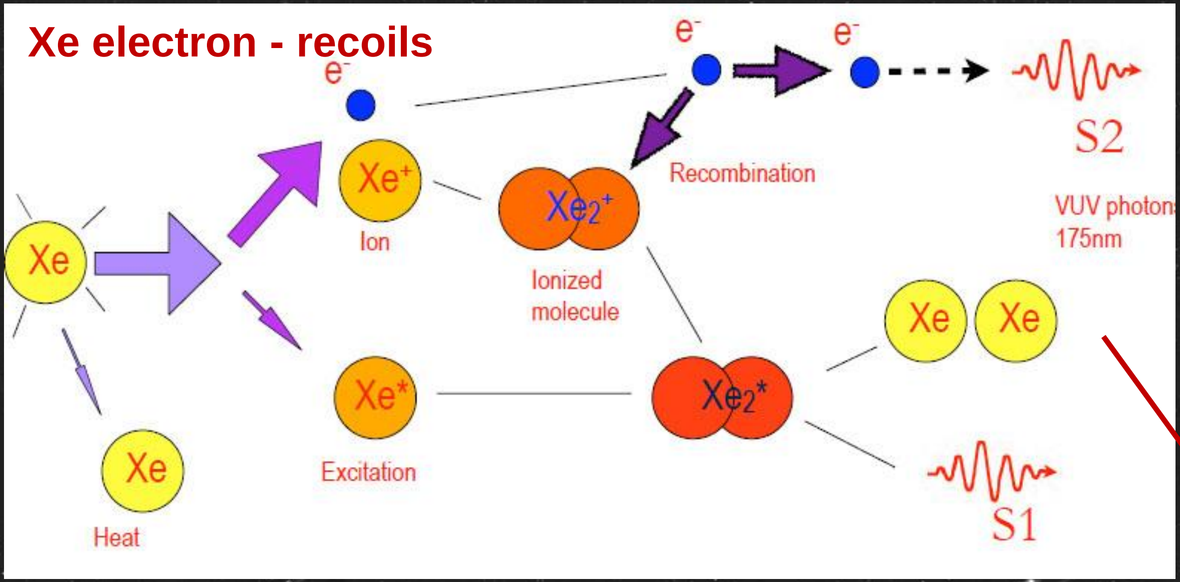
- 17 kg of Na(Tl) part of NaIAD (since 2011)
- 2500 m depth in the ice
- Near the center of IceCube for additional veto
- Data transmitted by satellite
- **Analysis under way!!**
- Next 250 kg on Northern hemisph.

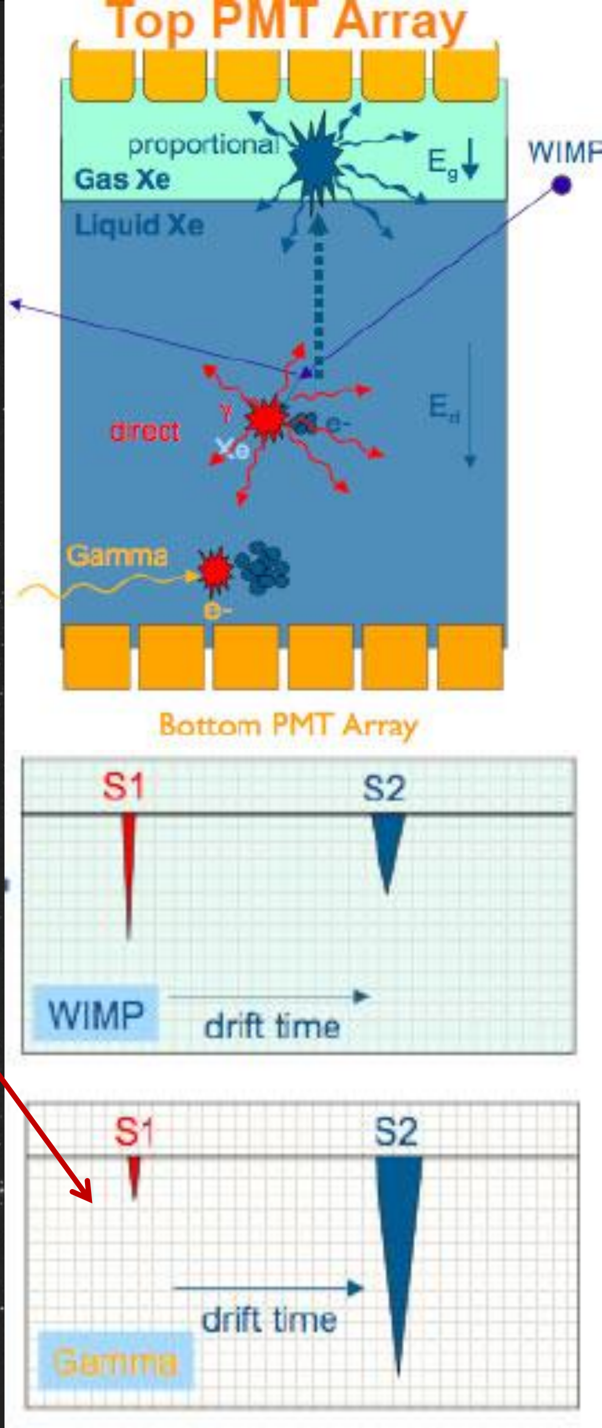
First data: arXiv:1401.4804

LIQUID NOBLE GASES

Principle

- Single phase: LXe,LNe, LAr $\rightarrow$ scintillation
- Dual phase liquid /gas $\rightarrow$ scintillation + ionisation





LIQUID NOBLE GASES

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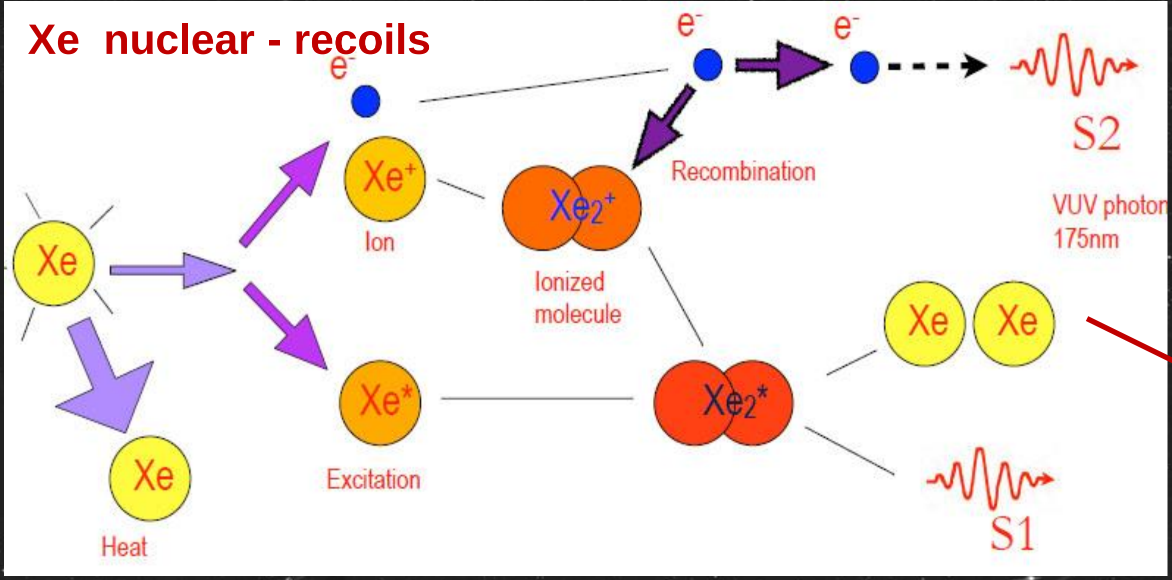
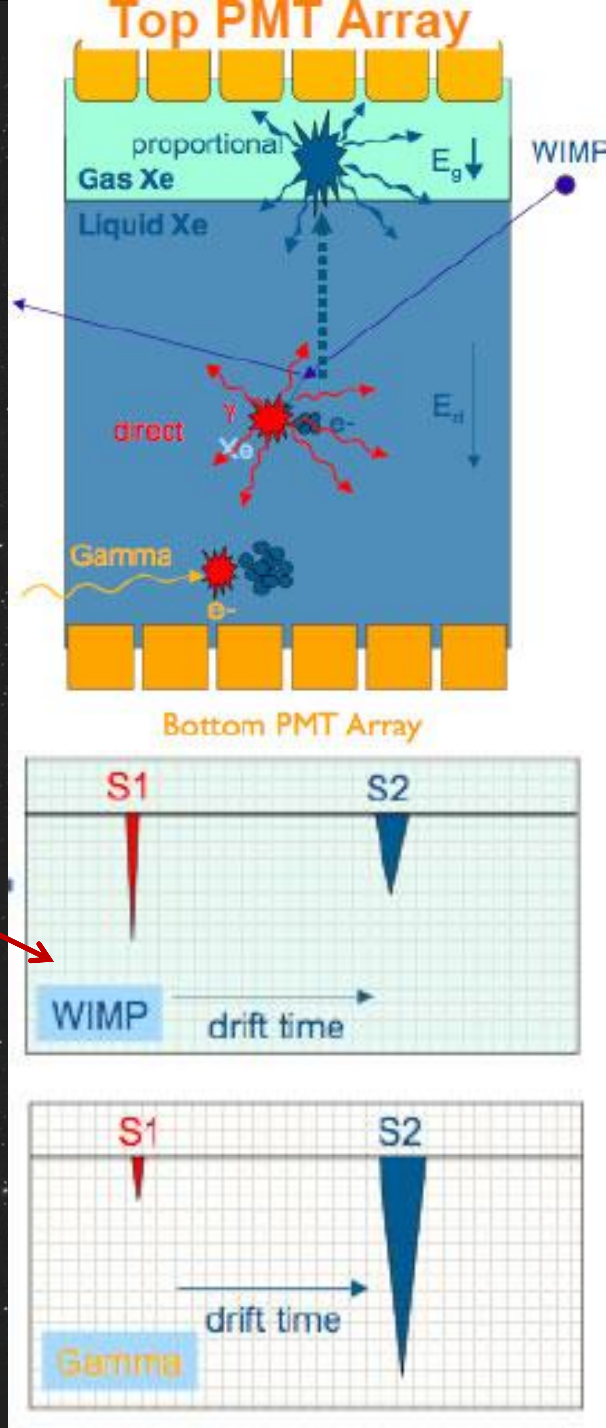




LIQUID NOBLE GASES

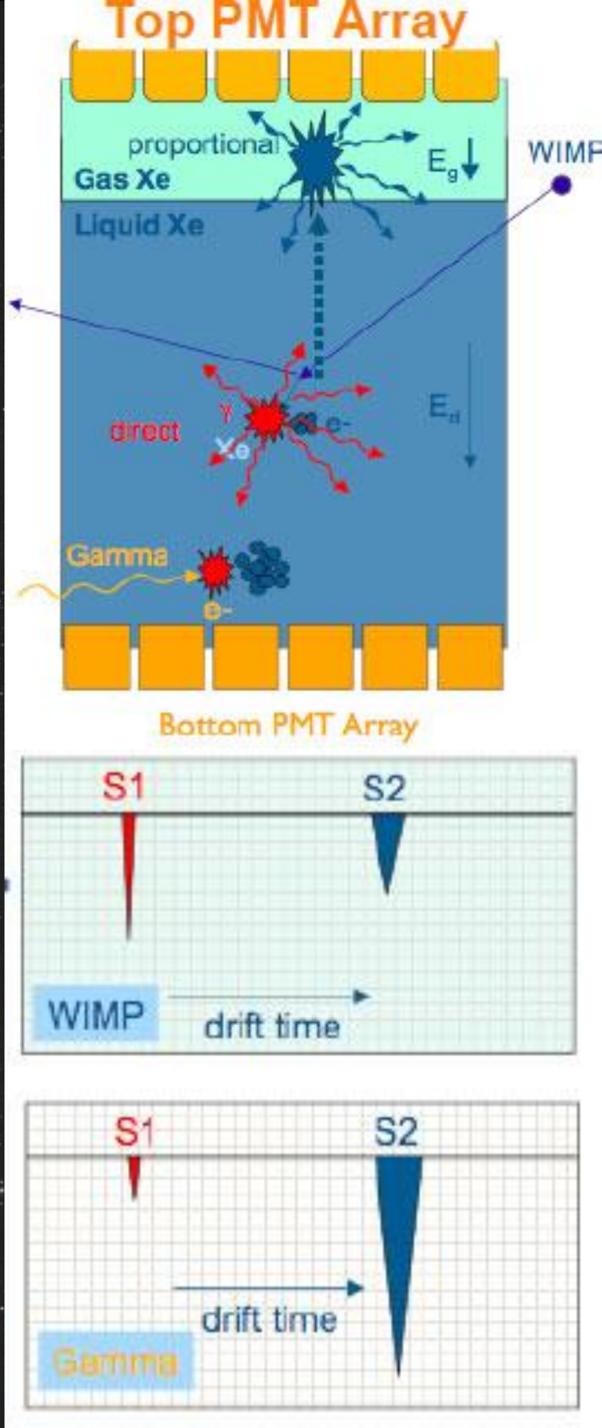
Principle

- Single phase: LXe,LNe, LAr $\rightarrow$ scintillation
- Dual phase liquid /gas $\rightarrow$ scintillation + ionisation

Advantages:

- large mass
- Re-purification
- Good particle ID

Gas	Single phase	Double phase
Xenon	ZEPLIN I, XMASS	ZEPLIN, XENON, LUX
Argon	DEAP, CLEAN	WARP/ DarkSide, ArDM
Neon	CLEAN	SIGN



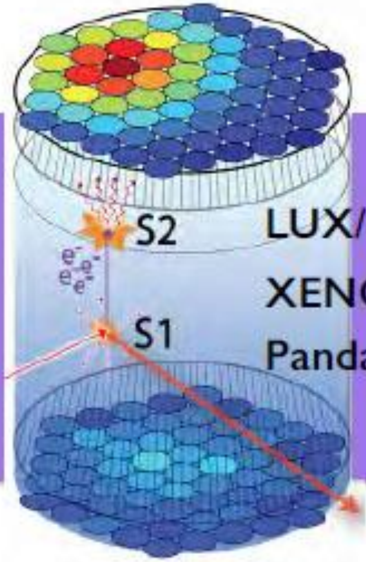
SINGLE PHASE

DOUBLE PHASE

DEAP
MiniCLEAN

DarkSide
ArDM

XMASS



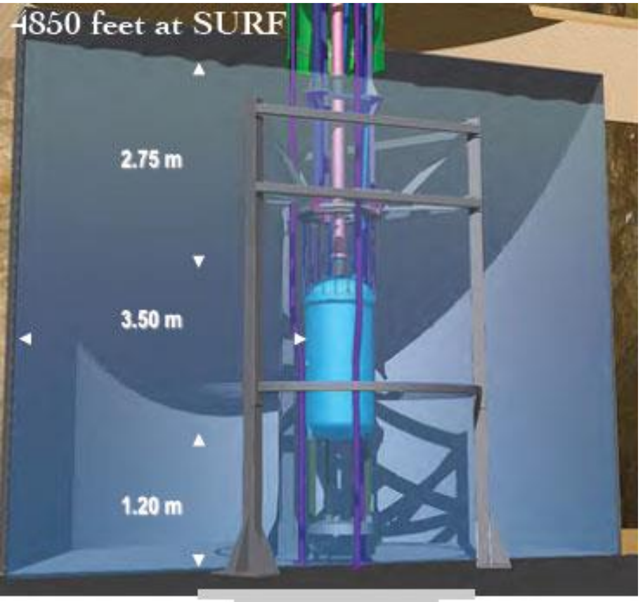
LUX/LZ
XENON-100/1T/nT
Panda-X

discharge tubes from
http://periodictable.com

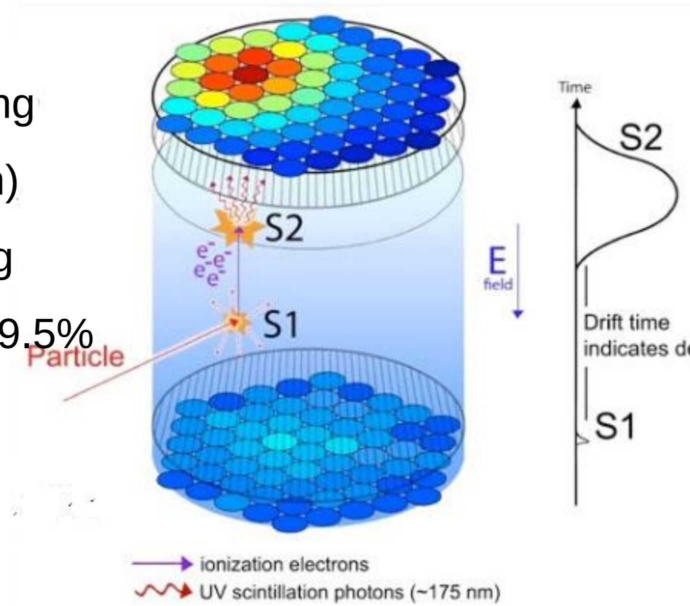
LIQUID NOBLE GASES

LUX (SURF Homestake)

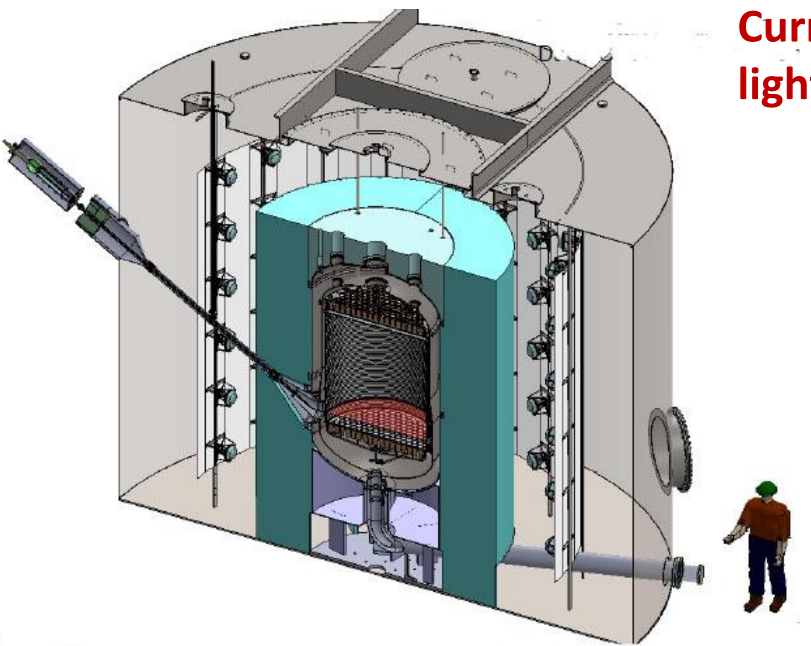
SI



- Two phase detector
- 300 kg LXe
- Z- position from S1-S2 timing
- 3D imaging (mm resolution)
- γ, n – bckg. by self shielding
- Beta - gamma rejection > 99.5%



Currently best limits
light WIMPS ruled out

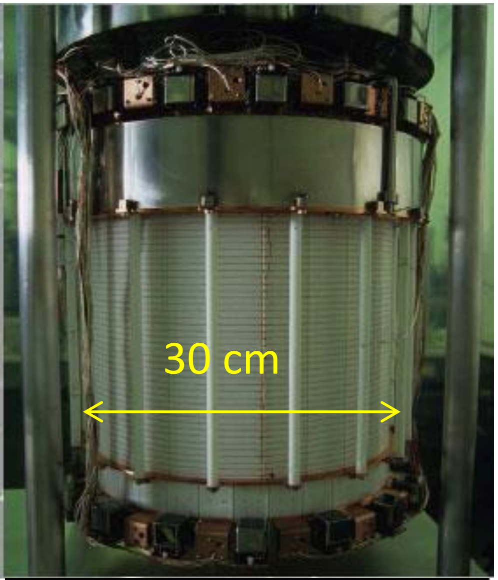


LZ at SURF

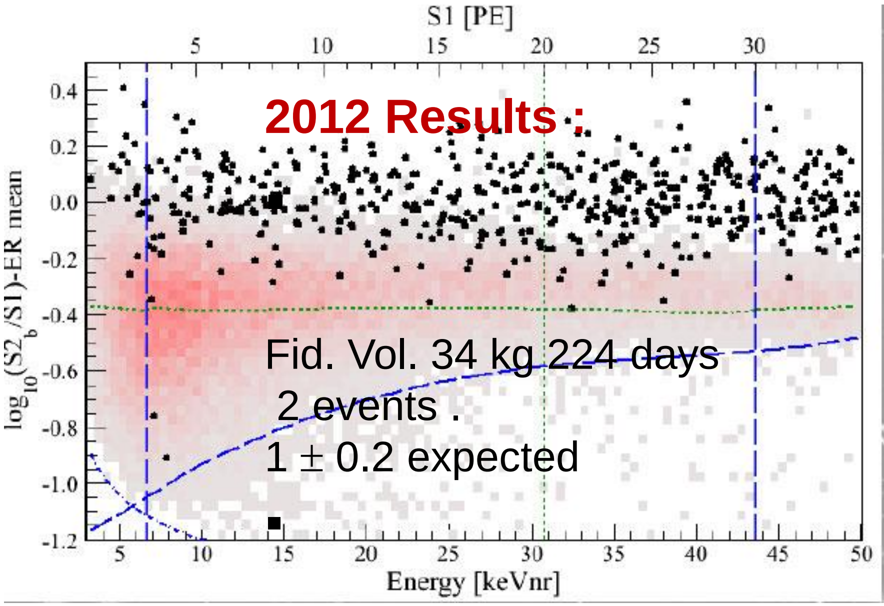
- Merger of LUX & ZEPLIN
- 7 tonne (fiducial) Xenon

LIQUID NOBLE GASES

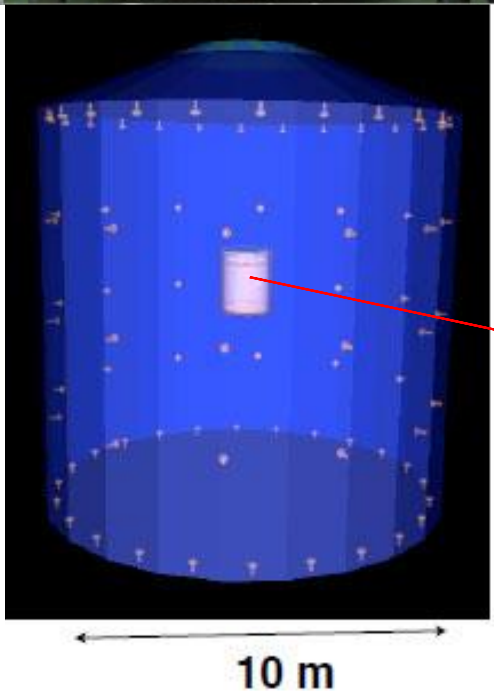
XENON 100 (Gran Sasso)

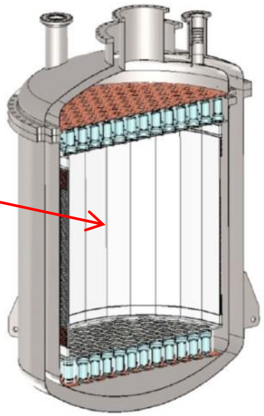


- 2-phase Xe TPC
- 162 kg LXe (A=131)
- 241 1” PMT
- LXe veto around
- Kr: 19 ppt



XENON 1t





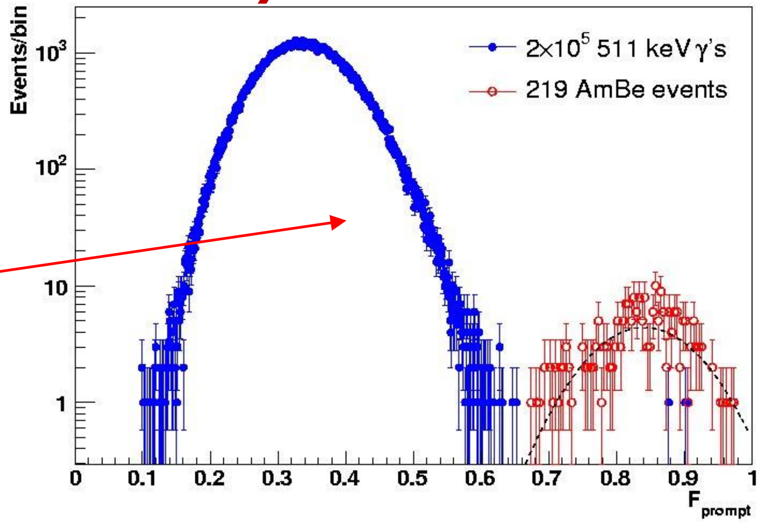
- 100x reduction in bkg beyond XENON 100
- 1 tonne fiducial
- Water Cerenkov μ - veto
- Under construction
- Data taking 2015

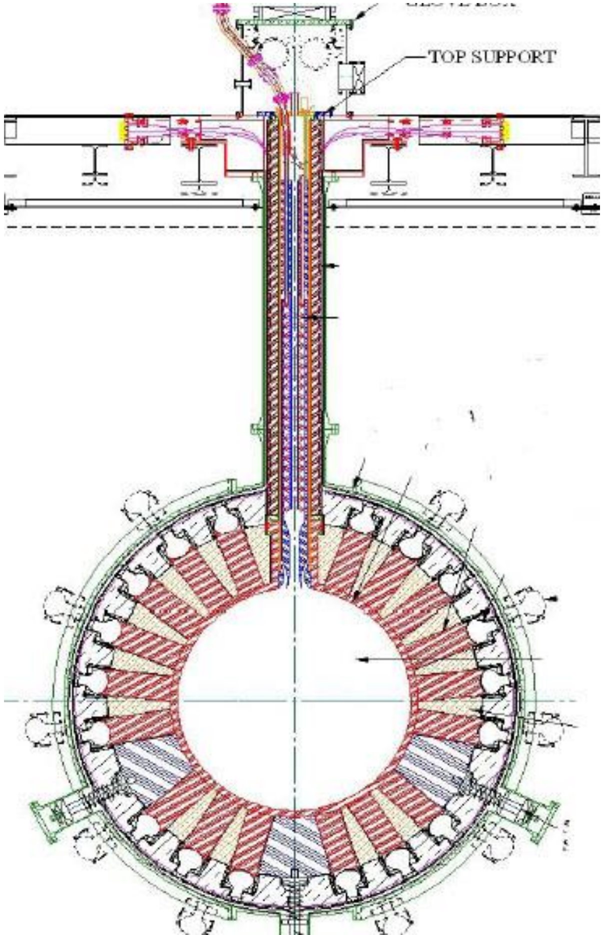
Later → XENON nt , DARWIN 20t

LIQUID NOBLE GASES

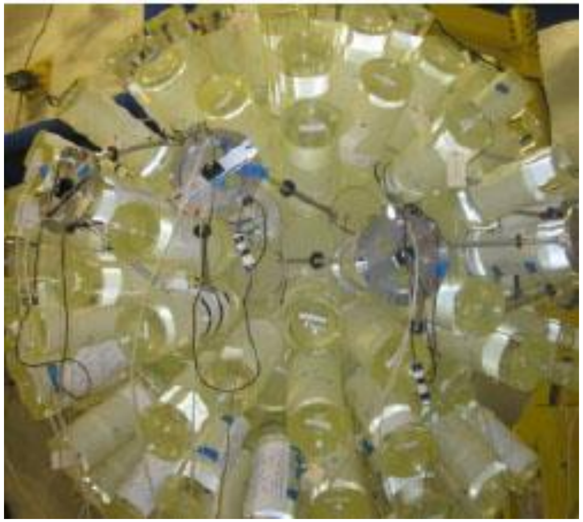
DEAP 3600 (SNOLAB)

- Scintillation light in LAr at 85K
- Threshold ~ 60 keV$_r$
- Excited Ar^*_2 lifetimes depend on ionisation (e, n)
- Bckg. rejection by pulse shape x10^{-9}





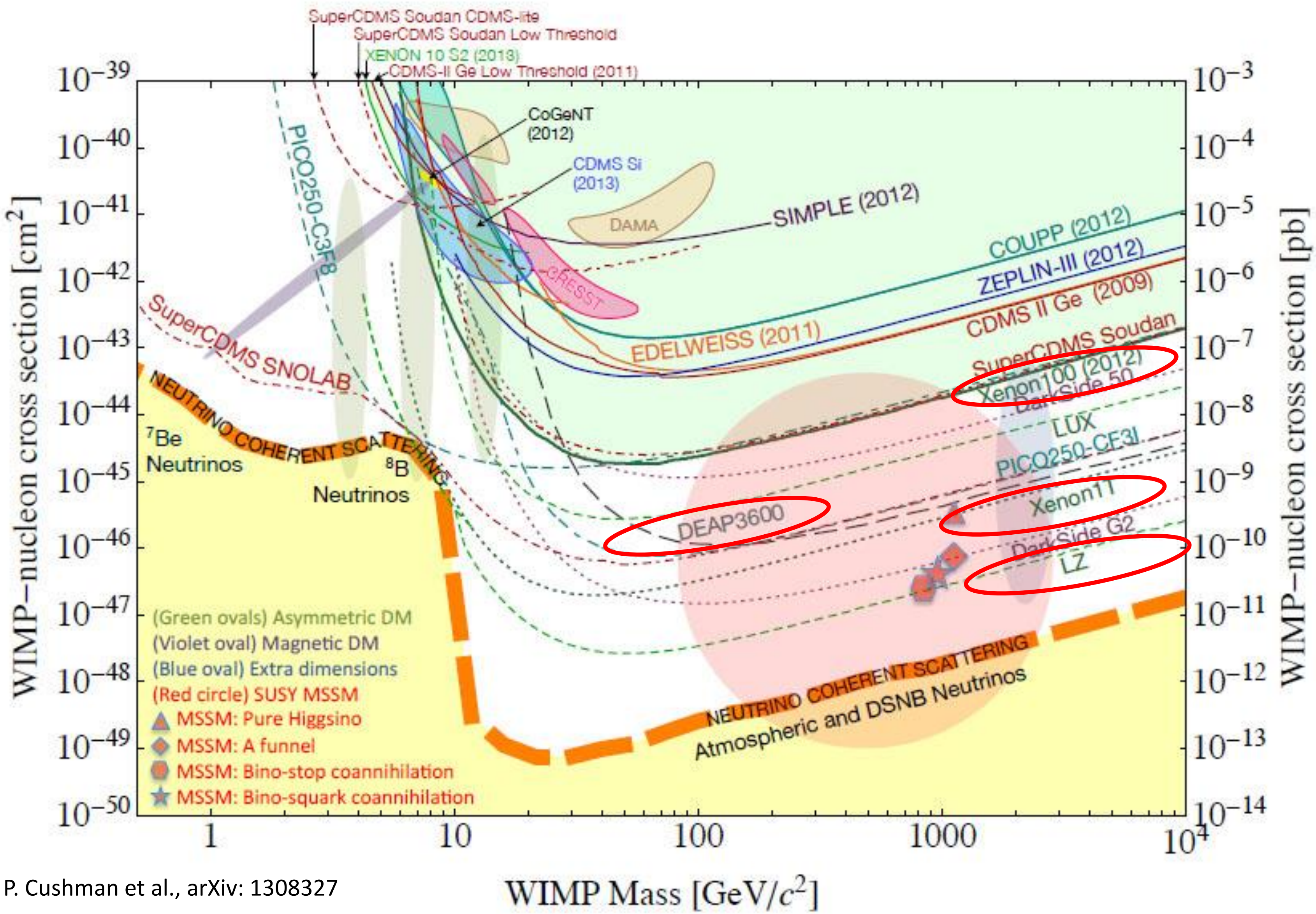
- 3600 kg LAr, 1000 kg fid.
- 50 cm light guides
- 253 PMT's →75% coverage
- Resurfaced in situ (Rn)
- Detector in 8m water shield



About to take data…

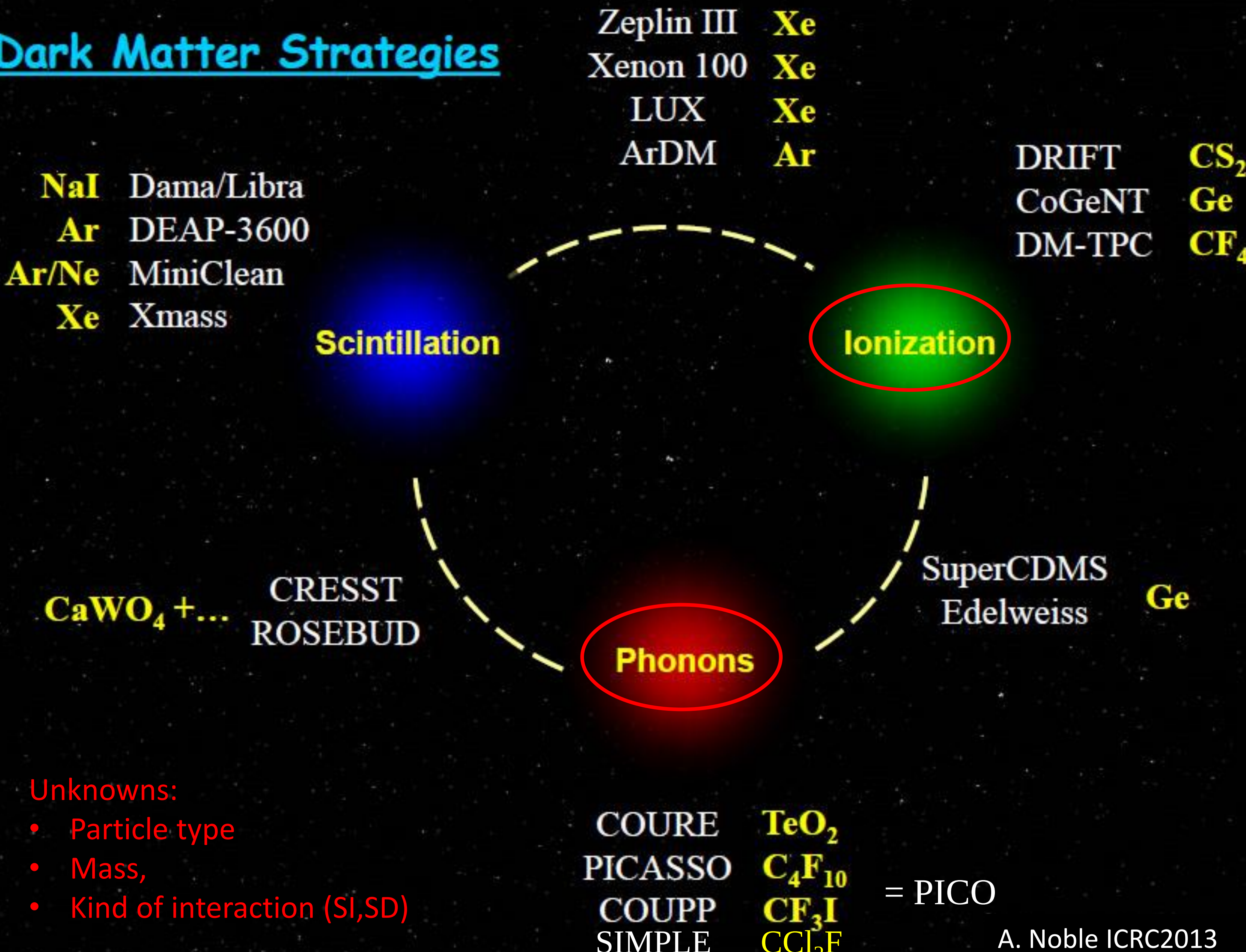

SNOLAB
DEAP-3600
Under assembly
3.6 t LAr
Data 2014!
MiniCLEAN
Under assembly
360 kg LAr
39Ar spike
Later LNe
Courtesy F. Duncan

Liquid Noble Gases – Independent Searches



P. Cushman et al., arXiv: 1308327

Dark Matter Strategies



Unknowns:

- Particle type
- Mass,
- Kind of interaction (SI,SD)

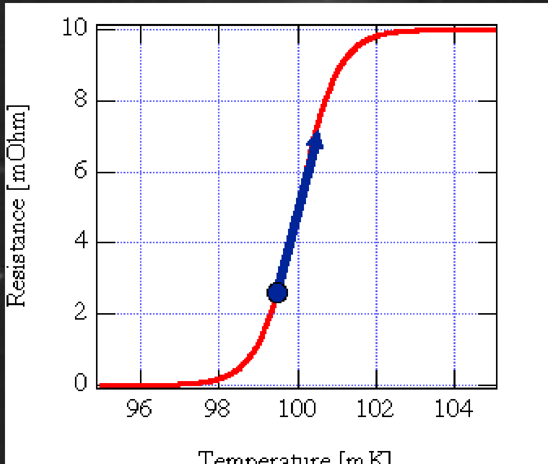
A. Noble ICRC2013

CRYOGENIC EXPERIMENTS (SI)

- Crystals (Al_2O_3, Ge, Si, $TeO_{2)}$ at low temperatures sev. mK
- Energy per phonon ~ meV FWHM 4.5 eV @ 6 keV_x
- Particle interaction produces phonons (heat)
- Temperature rise measured by semi/superconducting thermometers

Why low temperatures? Specific heat: $$C(T) = \frac{dE}{dT} \propto T^3$$

$$\Delta T = \frac{\Delta E}{C(T)}$$

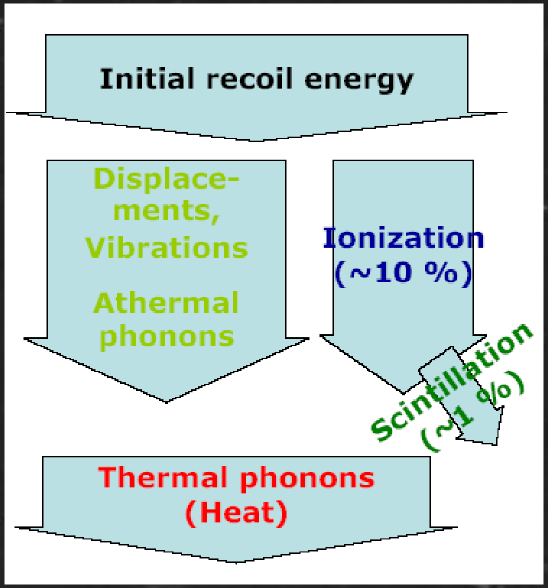


CRYOGENIC EXPERIMENTS (SI)

Background rejection:

• Ionization / scintill. light yield depends on recoiling particle

• Compare phonon with ion. / scintill. signal



Experiments:

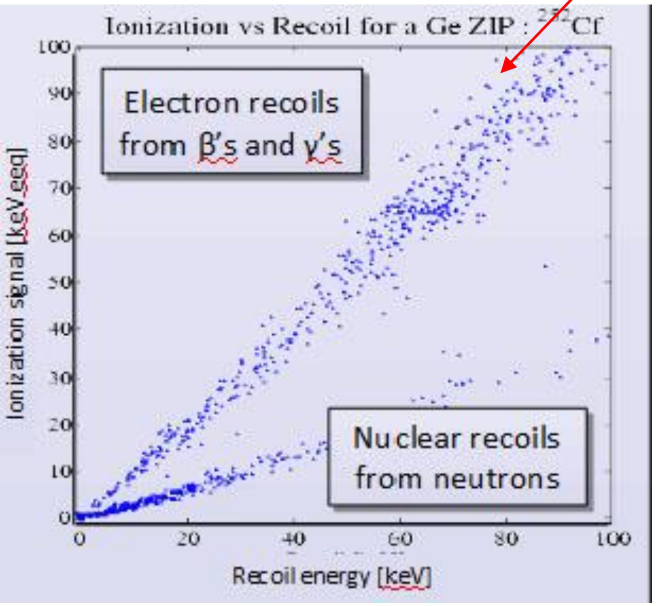
CDMS, CRESST, ROSEBUD, CUORE, EDELWEISS, New: DINO @ INO !

CRYOGENIC DETECTORS

CDMS & SuperCDMS (SOUDAN)

- Ionisation + phonons + risetime
- 250 g Ge, Si ZIP detectors at 50 mK
- Total mass 4.5 kg Ge, 1.1 kg Si
- γ rejection > 99.9998 %, 99.75 for β's

ZIP: Z-sensitive ionisation phonondetector



CDMS Lite

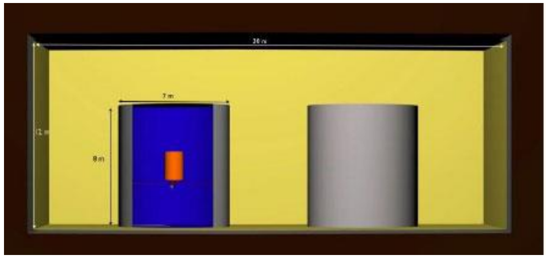
- Luke Neganov amplification
- $\rightarrow E_{th}$ <170 eV
- 0.6 kg sensitivity < 4 GeV

Apply large potential across crystal

G2 approval !

SuperCDMS (SNOLAB)

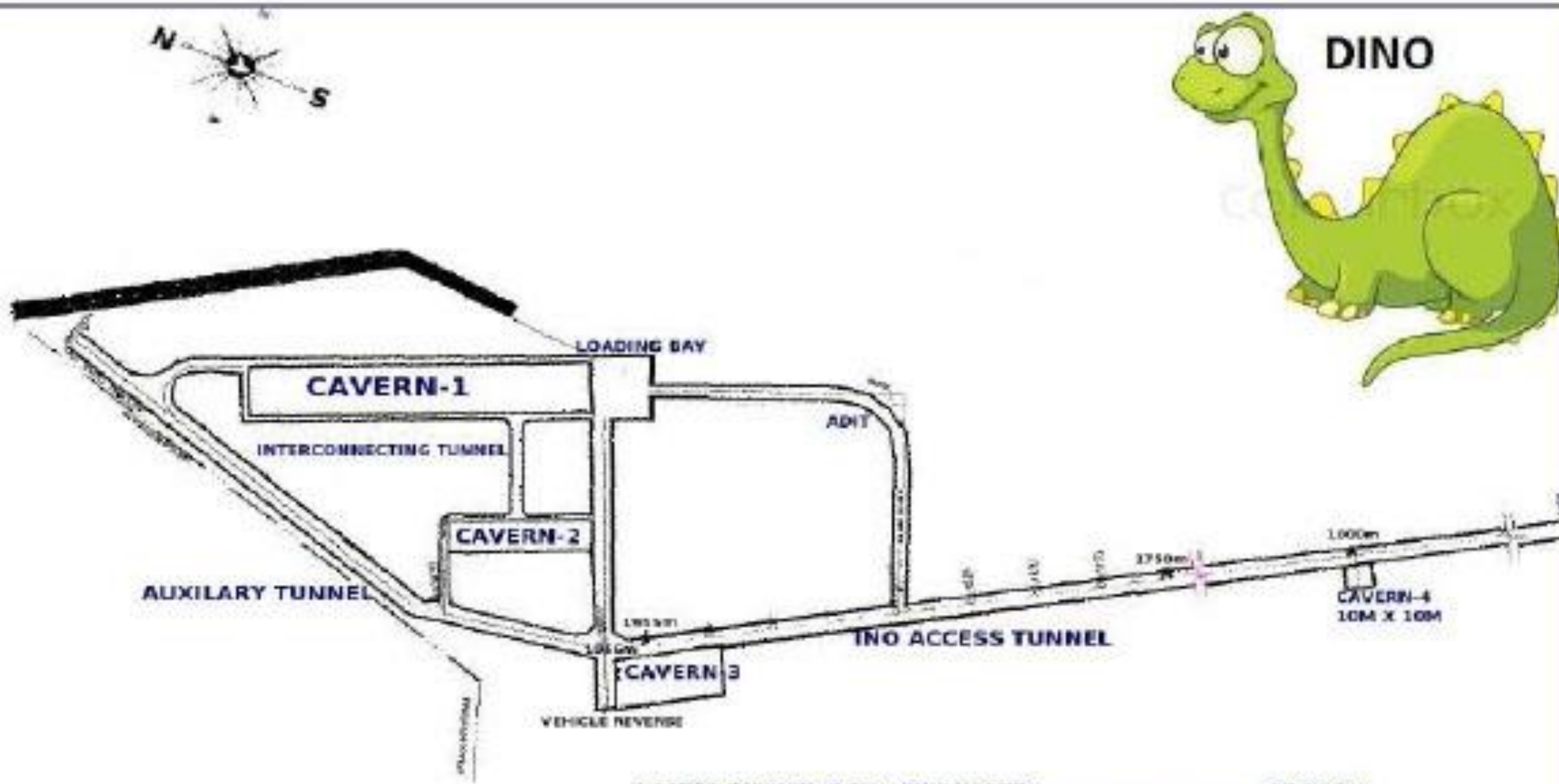
- 92 kg Ge, 11 kg Si
- 7 kg low thresh. Ge/Si



Combined with Eureka $\rightarrow$200 kg?

CDMS, CRESST (scint), ROSEBUD (scint.), CUORE, EDELWEISS, **DINO** …

Dark-matter@INO (DINO) Ton-scale 2020



ACCESS TUNNEL 7.5m, 'D' SHAPED :1966.0m
ADDITIONALLY DRIVEN INT. TUNNEL 5.5m 'D' SHAPED: 175.4m
AUXILARY TUNNEL 7.5m 'D' SHAPED : 224.6m
INTERCONNECTING TUNNEL 3.5m 'D' SHAPED : 72.5m
ADDITIONAL TUNNEL 7.5m 'D' SHAPED (future expn) : 50.0m

- **INO Lab Depth 1.3km**

CAVERN -1 : 132m x 26M x 32.5m
CAVERN -2 : 55m x 12.5m x 8.6m
CAVERN -3 : 40m x 10m x 10m
CAVERN -4 : 10m x 10m x 10m

Pottipuram in Bodi West hills

Mini-DINO @ UCIL-Jaduguda Mines

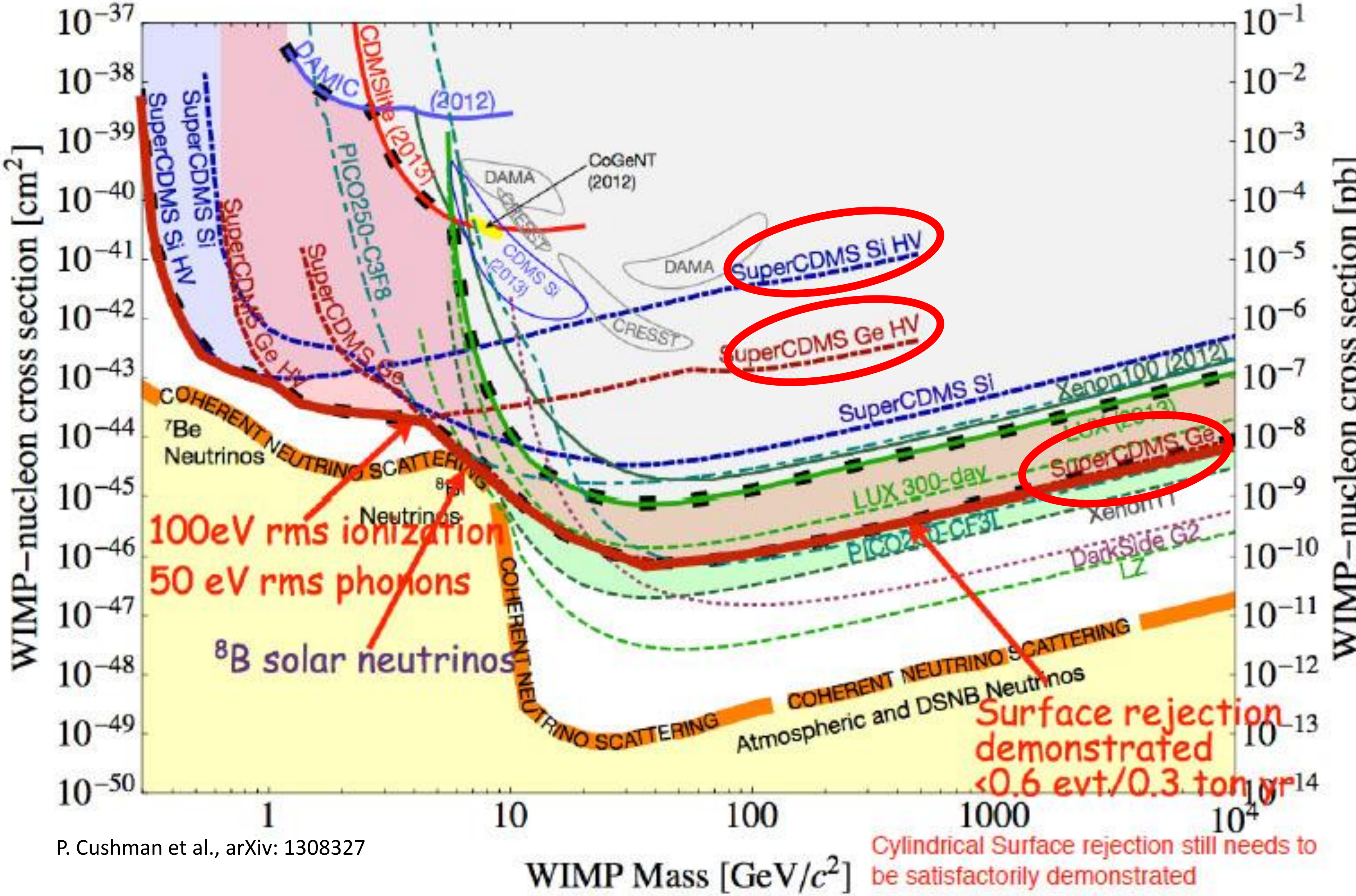
- A 15-30 kg Si/Ge detector for low-mass ($\lesssim$ 10 GeV) WIMPs
- Two possibilities being explored:
  (i) Use only ionization signal — can operate at 77 K or 4 K with few keV threshold.
  No phonon sensors (which would require TES operating at mK temperatures).
  (ii) Use both ionization and phonon signals at sub-keV threshold
- New iZIP detector technology developed at TAMU: can pick up low-ionization events due to nuclear recoils.
- Discrimination against high-ionization events due to electron recoils possible by pulse-shape-based analysis (R&D going on at SINP & TAMU)

Multi-institutional collaborative effort:

SINP (Kolkata), Texas A&M (TAMU, USA), NISER (Bhubaneswar), TIFR, IoP-Bhubaneswar, PRL-Ahmedabad, . . .

Thanks to Bernard Sadoulet

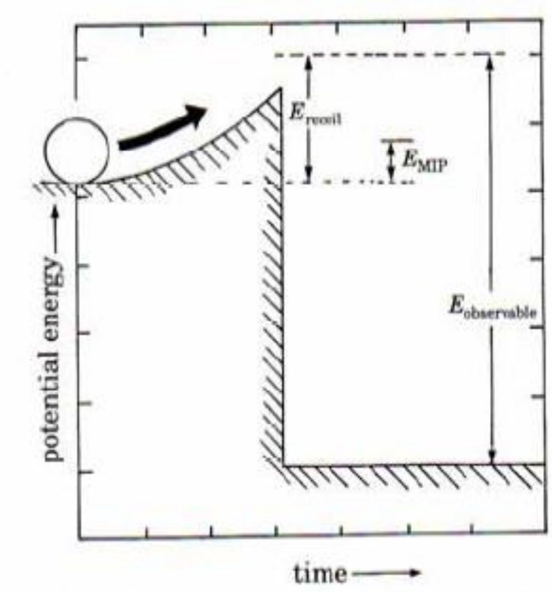
Summary Spin Independent Searches



P. Cushman et al., arXiv: 1308327

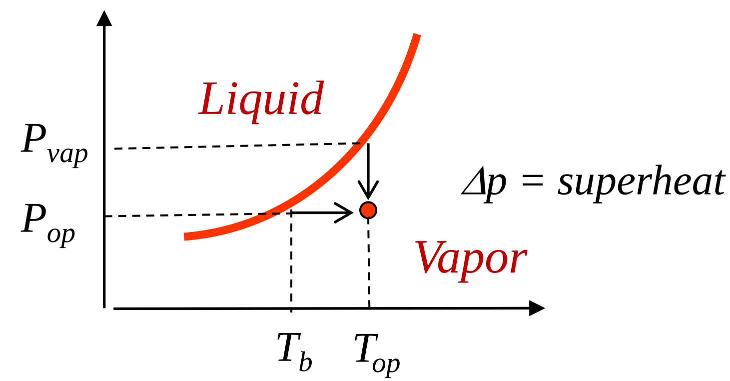
Cylindrical Surface rejection still needs to be satisfactorily demonstrated

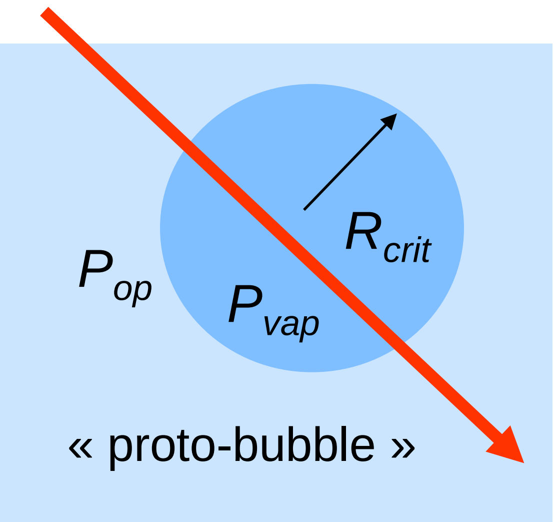
Superheated Liquids as Threshold Detectors



Idea:

- SHL is a fluid in a metastable state
- which can be quenched by energy depositions of particles
- Tiny energy deposition $\rightarrow$ Macroscopic phase transition
- ....but γ's cannot or almost!



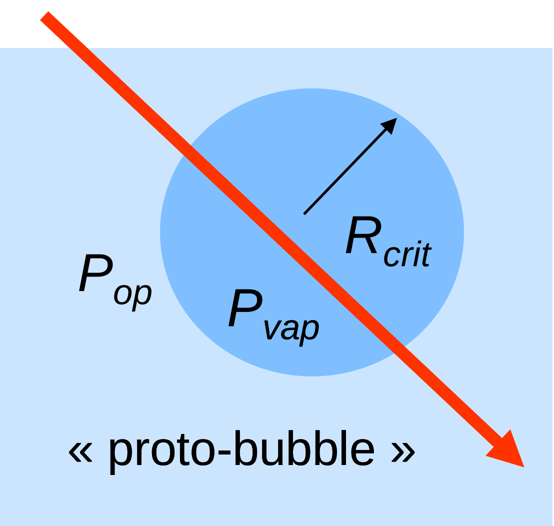


Bubble chamber principle: (D. Glaser, 1952)

- $E_{dep} < E_{thr}$ within $R_{crit} \rightarrow$ proto-bubble collapses
- $E_{dep} > E_{thr}$ within $R_{crit} \rightarrow$ irreversible bubble expansion!

Superheated Liquids as Threshold Detectors

Much simpler for DM search!



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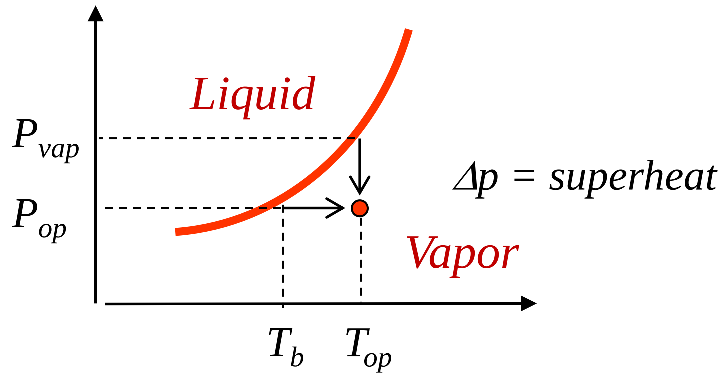

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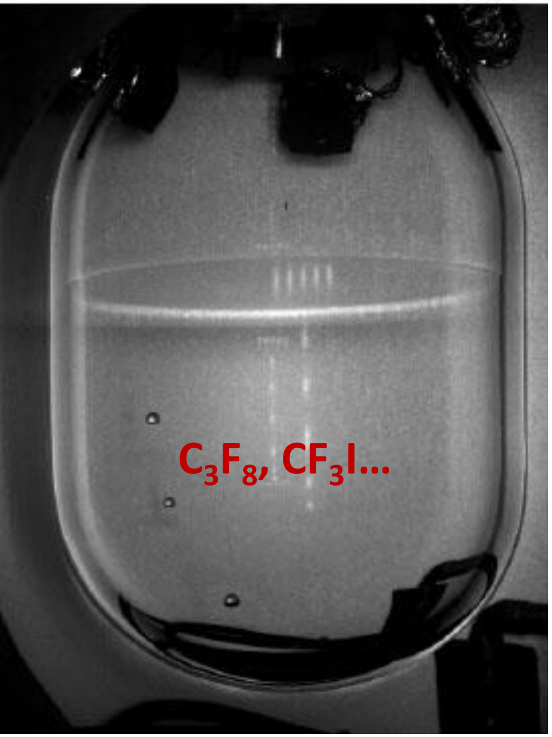
Superheated Liquids as Threshold Detectors



Fluids of choice: Fluorinated halocarbons → SD, SI

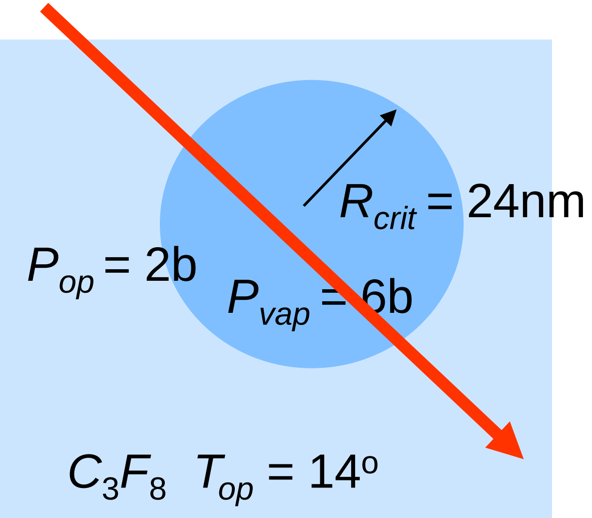
- C_4F_{10}, C_5F_{12}, C_3F_8, CF_3I,… (right surface tension)
- But in principle any liquid

What does it take to create a bubble ?

Surface tension

$$R_c = \frac{2\sigma}{\Delta p} \qquad E_{thr} = 4\pi R_c^2\left(\sigma - T\frac{\partial\sigma}{\partial T}\right) + \frac{4}{3}R_c^3\rho_v h$$

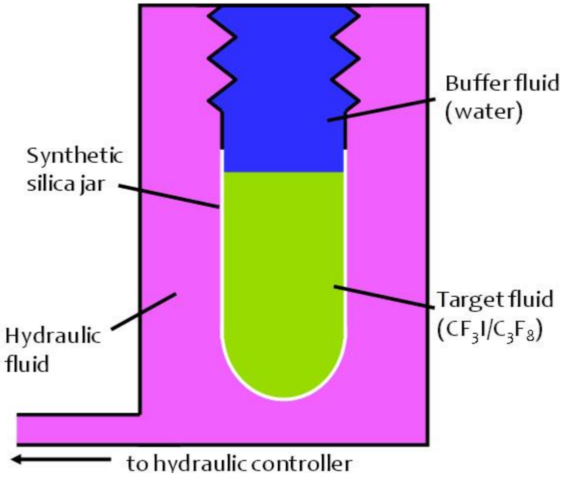
Crit. Radius (24 nm) | Surface energy (1.53 keV) | Latent heat (1.81 Kev)



$$\boxed{E_{dep} = \frac{dE}{dx}\cdot R_{crit} \geq E_{thr}}$$

Threshold energy E_{thr} is set by varying (T_{op}, P_{op})

Technical Realizations

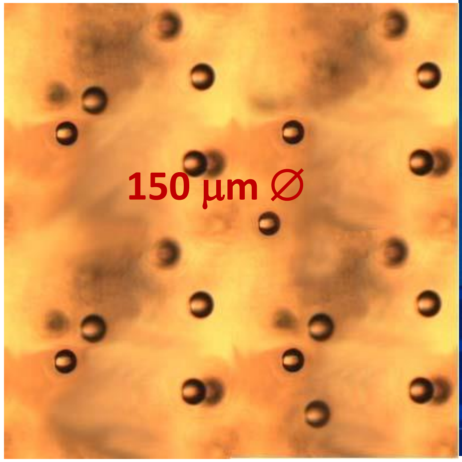


Bubble chambers

Acoustic & optical read out

Droplet detectors

Acoustic read out



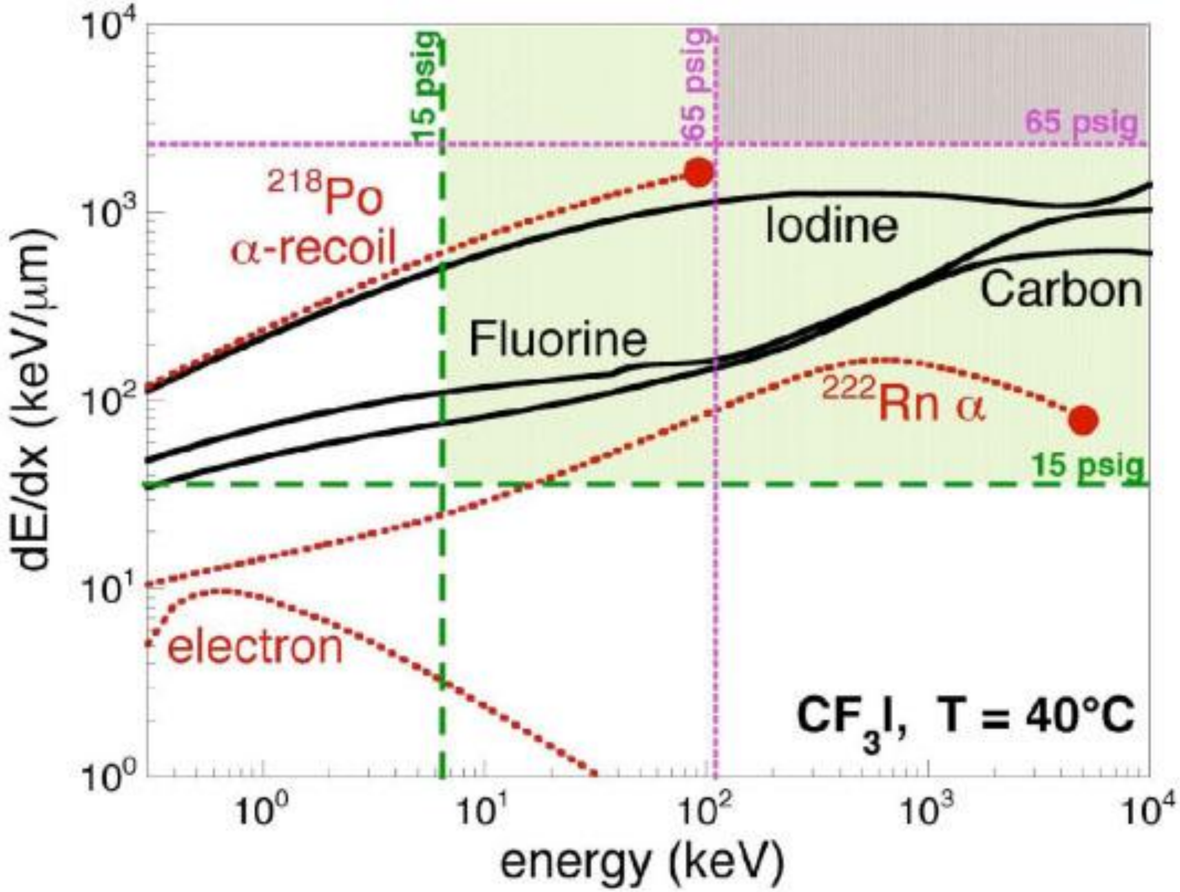
Condensation chambers "Geyser"

Acoustic & optical read out

Particle Discrimination in Superheated Liquids

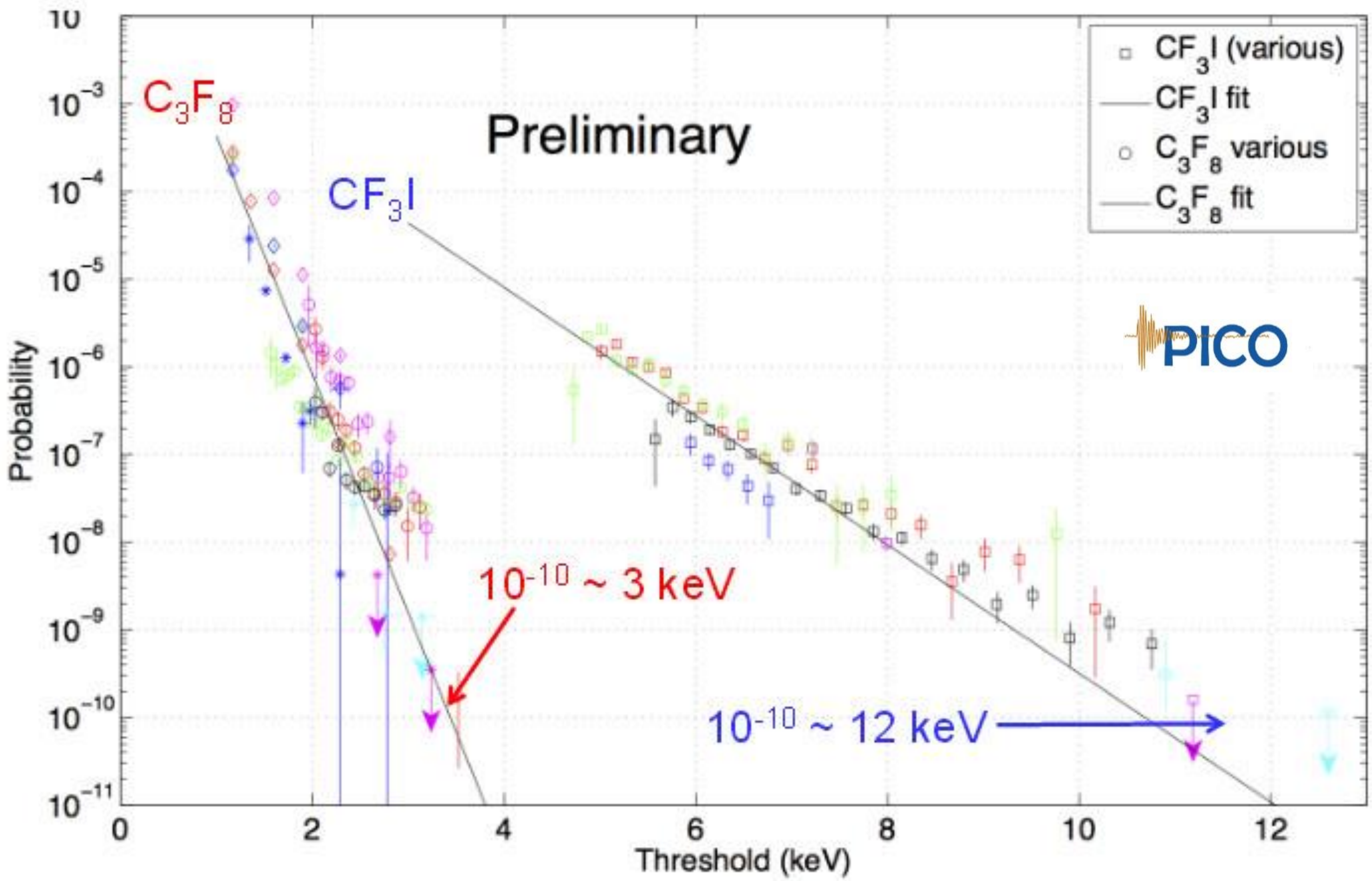
$$E_{dep} = \frac{dE}{dx} \cdot R_{crit} \geq E_{thr}$$

- Energy deposition depends on particle type.
- Can tune detector to be sensitive to certain types only
- Better than 10^{-10} rejection of electron recoils (β, γ)



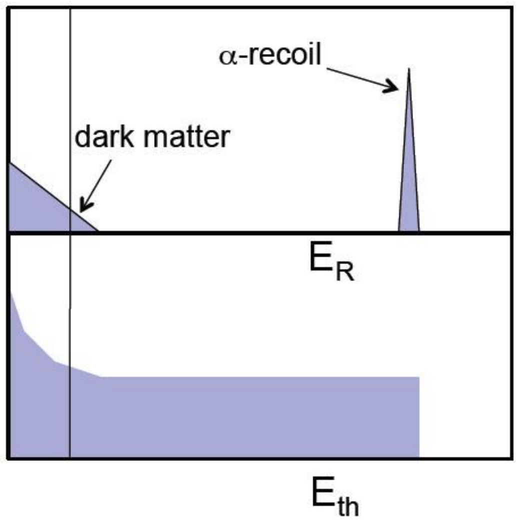
Superheated Liquids and Gamma Rejection

Can set superheat parameters (T, P) such that detector is blind to electronic recoils



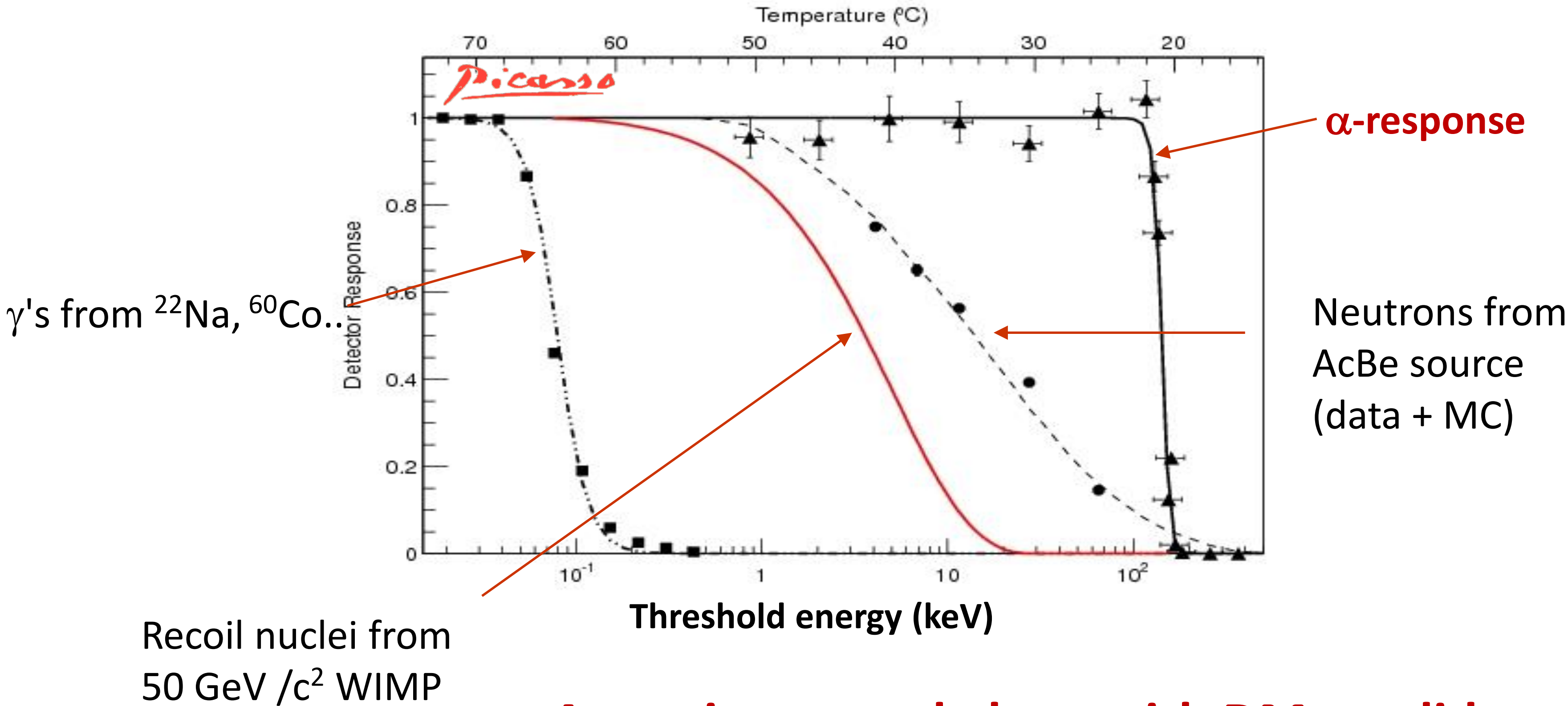
10^{-10} rejection or better!

Particle Responses



Threshold device with integrating response

$$R(T,P) = \int_{E_{th}}^{\infty} \frac{dN}{dE_R} dE_R$$

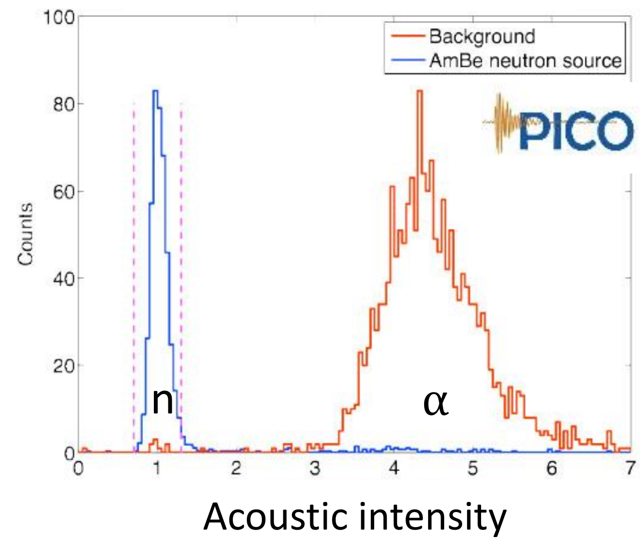


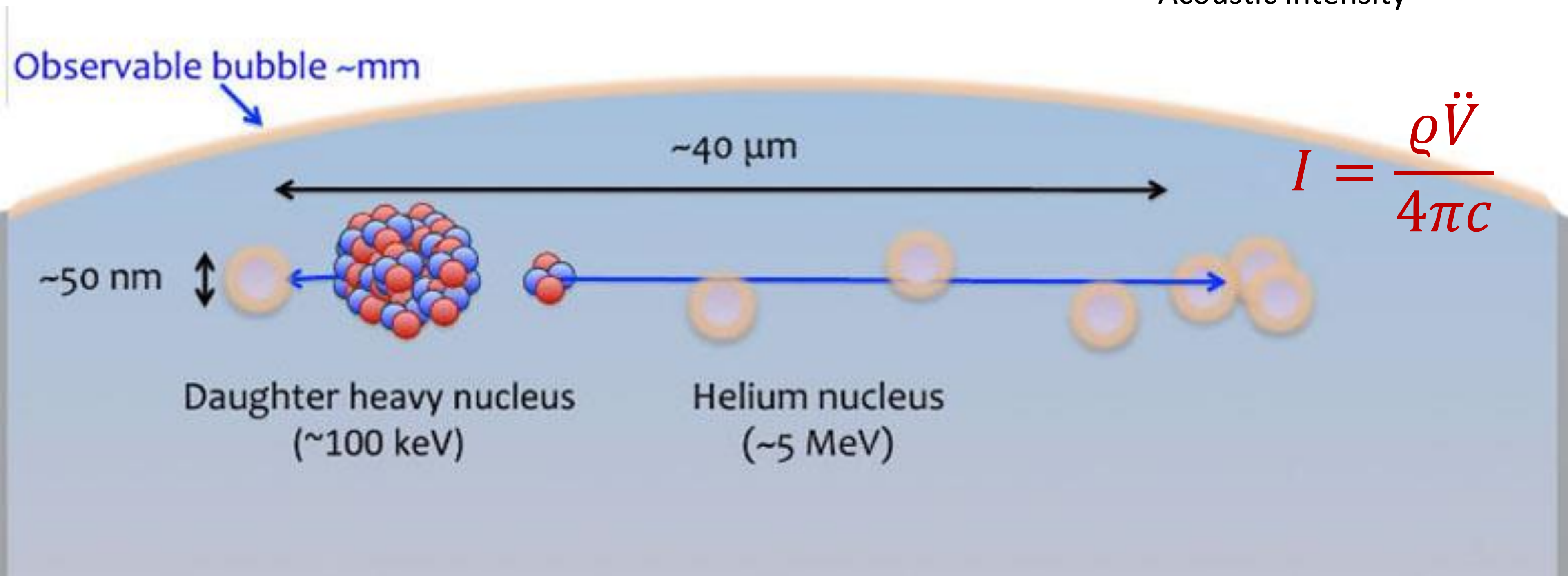
Any α is counted along with DM candidates!

Acoustic Alpha Discrimination

Discovery of acoustic discrimination against alphas by PICASSO (Aubin et al, New J. Phys 10:103017, 2008)

- Alphas deposit energy over tens of microns
- Nuclear recoils deposit theirs in tens of nanometers
- Alphas are several times louder !
- Alpha rejection> 98.2%

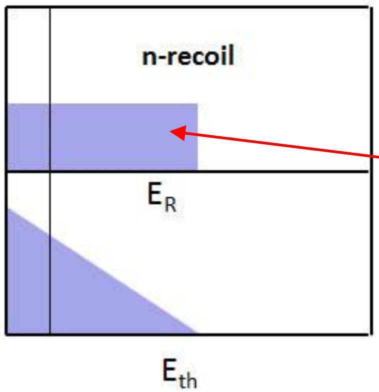




$$I = \frac{\varrho \ddot{V}}{4\pi c}$$

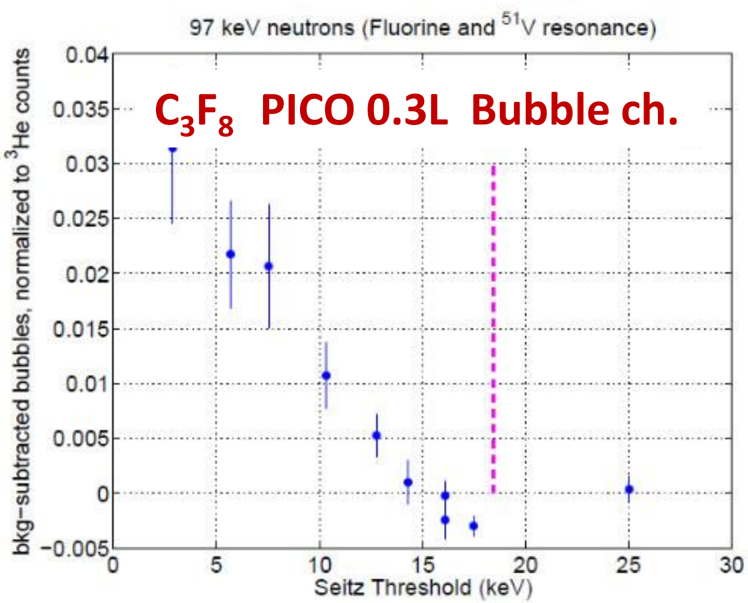
Calibration of Energy Threshold

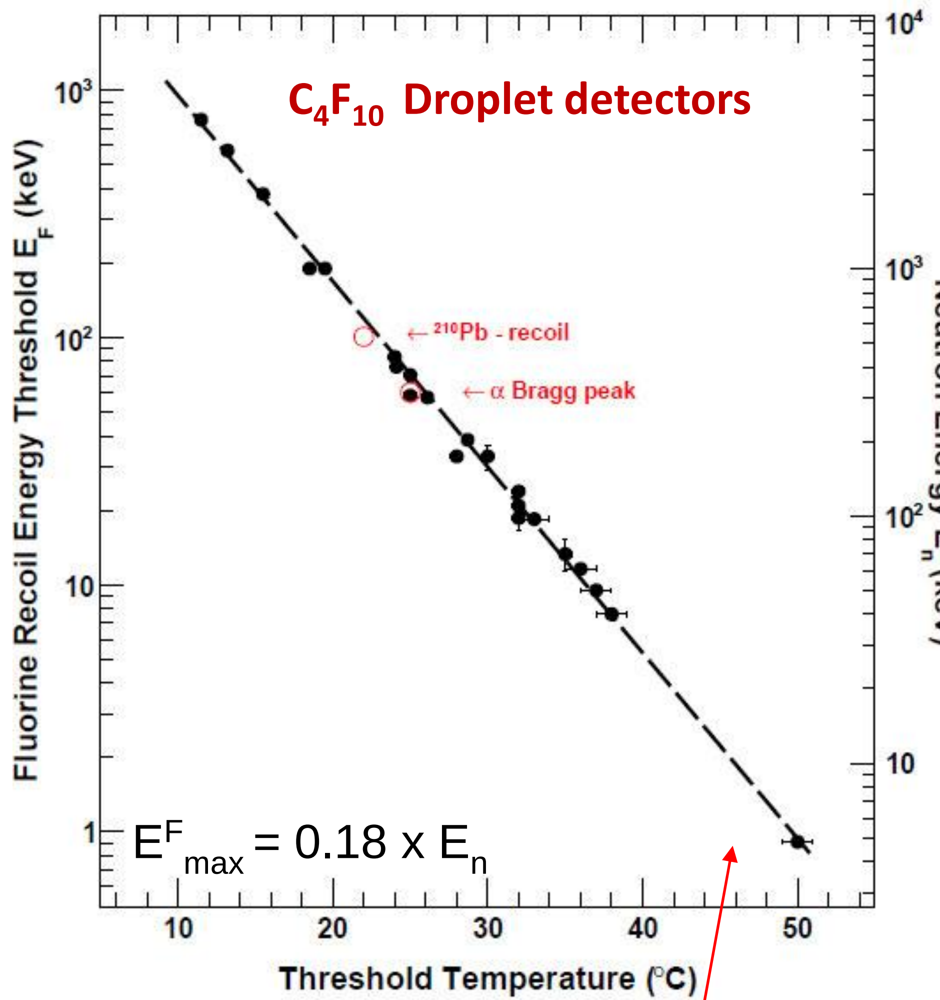
Mono-energetic n-test beam @ Montréal tandem accelerator



Recoil spectrum for mono-energetic neutrons

$E^F_{max} = 0.18 \times E_n$





E_{rec} = 0.86 keV

+ Y/Be source U-Chicago
+ Am/Be sources SNOLAB/Montreal

PICO

Merger of PICASSO and COUPP Collaborations

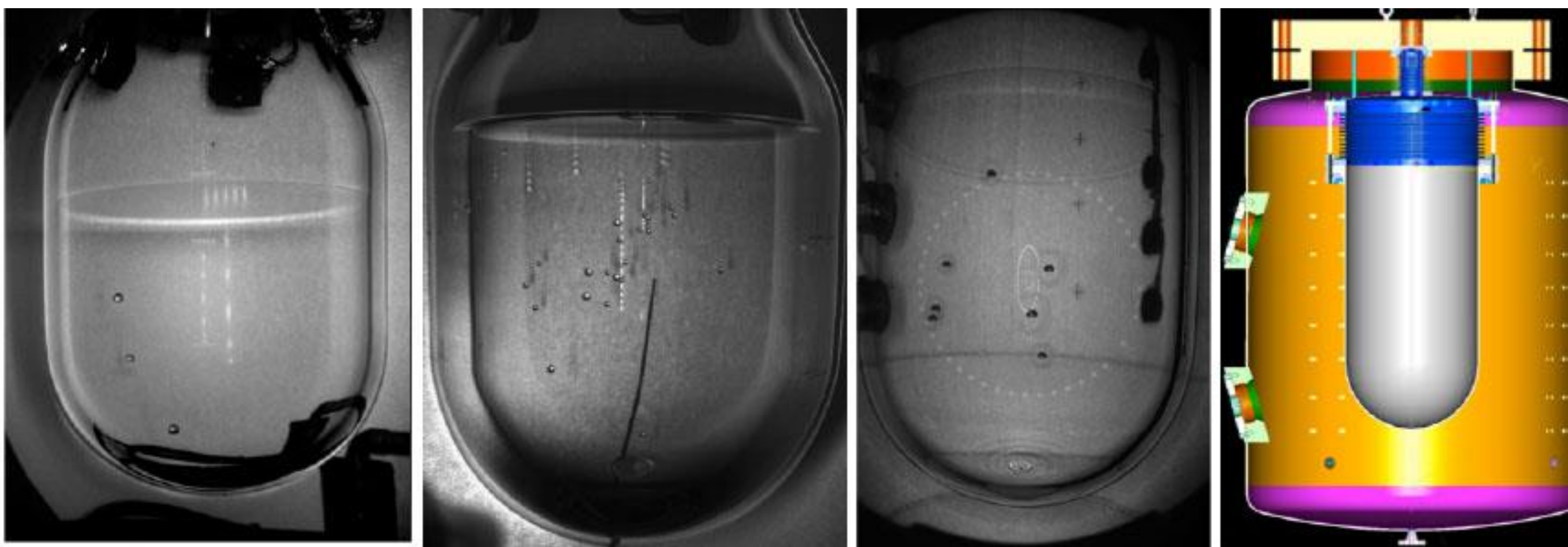
Queen's, Valencia, PNNL, Northwestern, Saha, FNAL, Toronto, Chicago, Montreal, Laurentian, SNOLAB, Alberta, Mexico, Drexel

- Develop the BC technology with the ultimate goal of building a **tonne scale detector** at SNOLAB

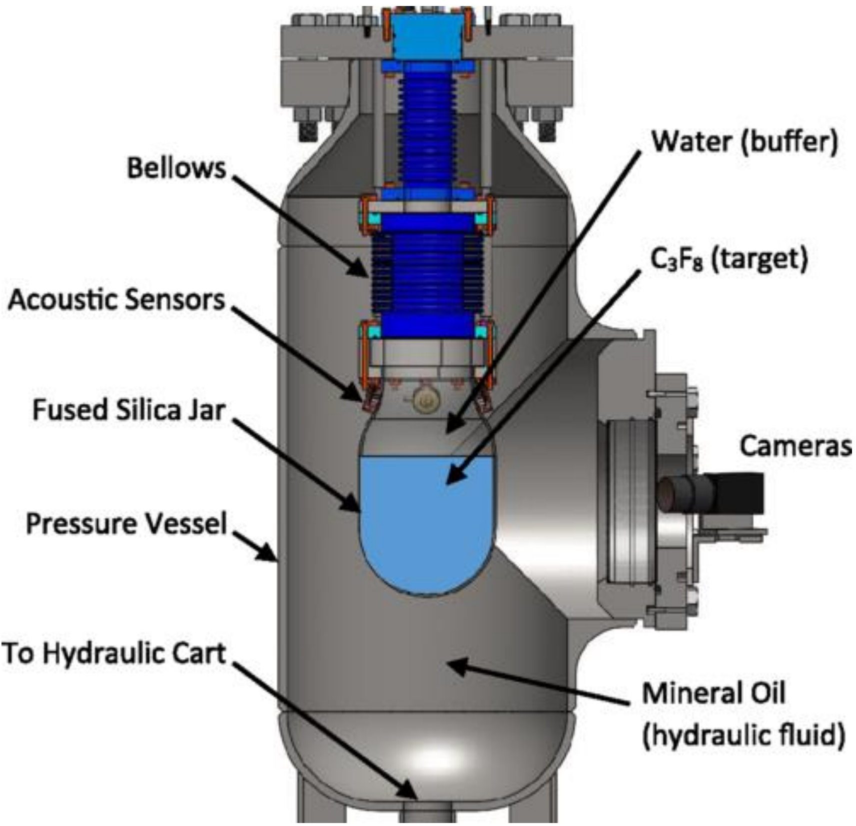
- Fully explore the **Spin-Dependent** sector with F-loaded targets and particular sensitivity to **low mass WIMPs**

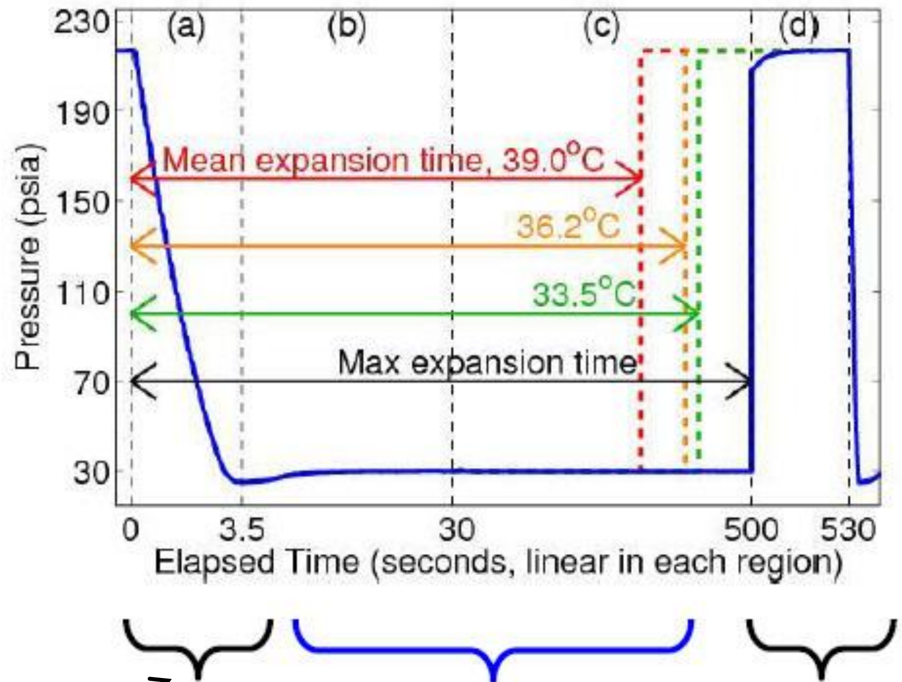
- Exploit the **multi target** capacity of this approach (C_3F_8, CF_3I…)

PICO 2L → PICO 60 L → PICO 250 L



Operation Principle of PICO Chambers





Pressure drop to superheat state

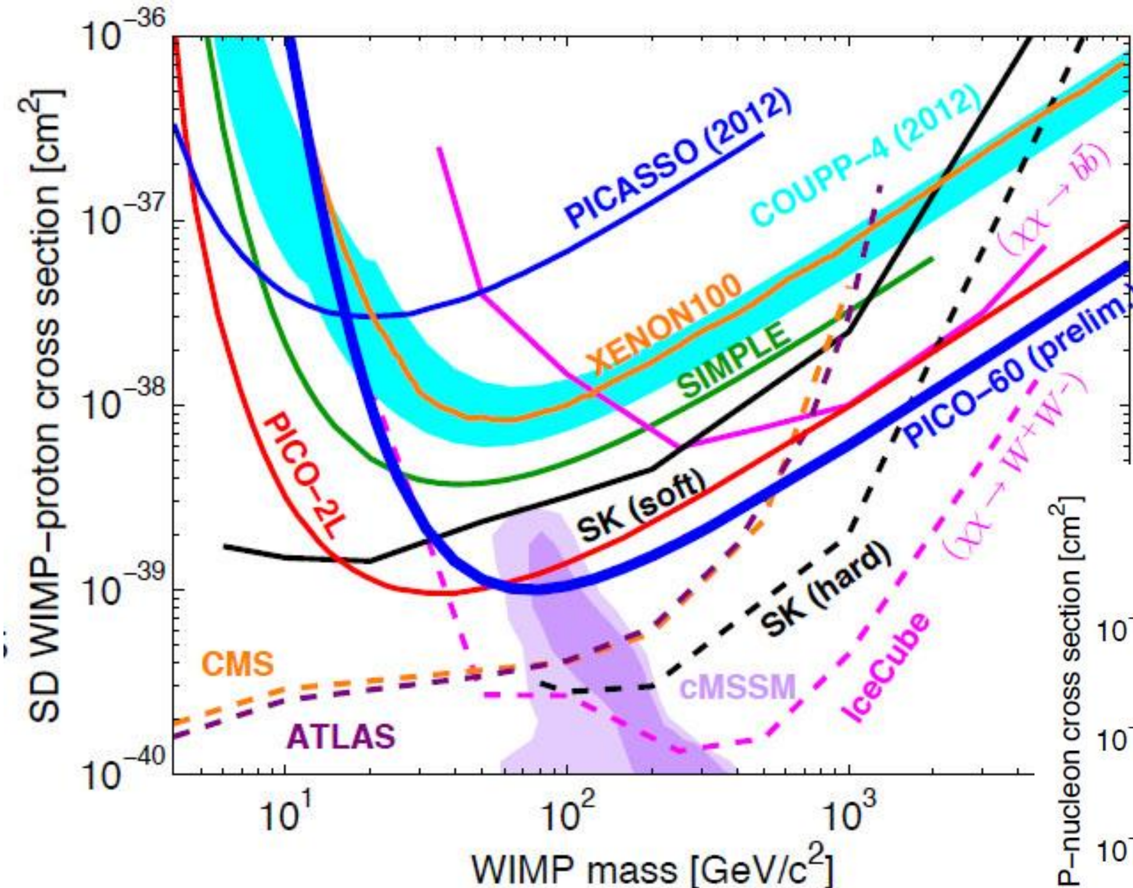
Bubble event: Cameras trigger, record position, Microphones record acoustic traces

Raise pressure to stop bubble growth (100ms), reset chamber (30sec)

PICO 2L : COUPP4 with C_3F_8

PICO 2L @ SNOLAB – Run1

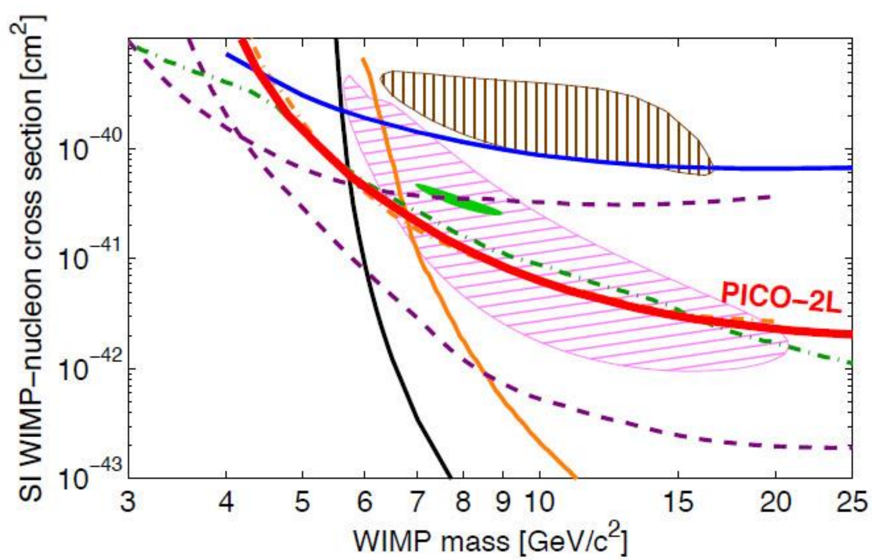
C. Amole et al.: Phys. Rev. Lett. 114, 231302 (2015)



World best Spin Dependent WIMP-proton limits for direct detection!

- 212 kgd exposure of C_3F_8
- 4 thresholds (3 – 8 keV)
- 12 anomalous nucl. recoil events
- Timing not random!
- Rejected by optim. interval analysis

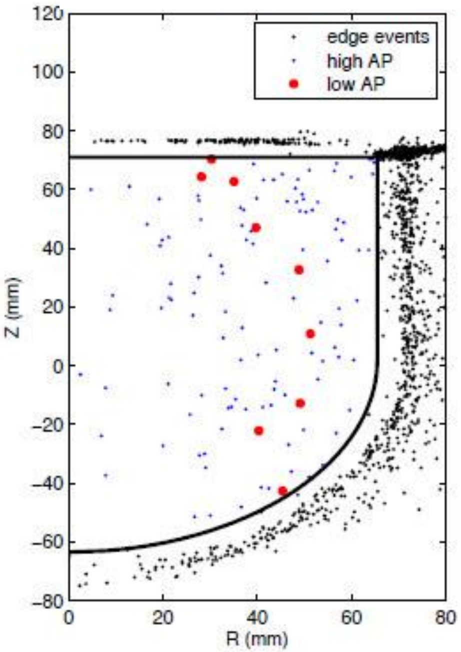
No DM signal detected!



Spin Independent results challenge signal claims!

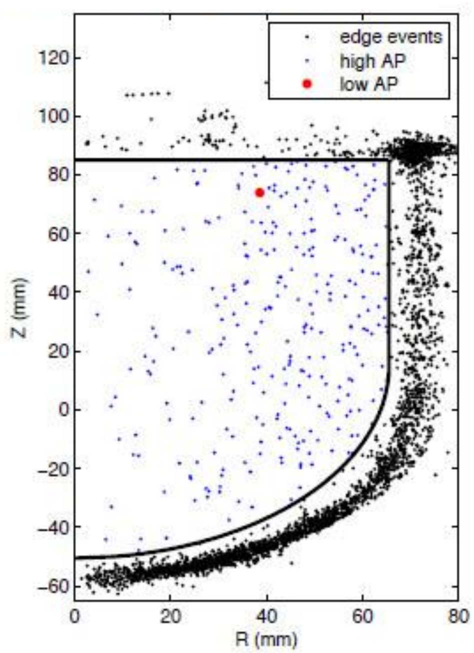
PICO 2L @ SNOLAB – Run2 (ongoing)

RUN1



Run-1 3.2keV data
- 32 live days
- Est. neutron bkgd $0.9^{+0.2}_{-0.7}$ events

RUN 2

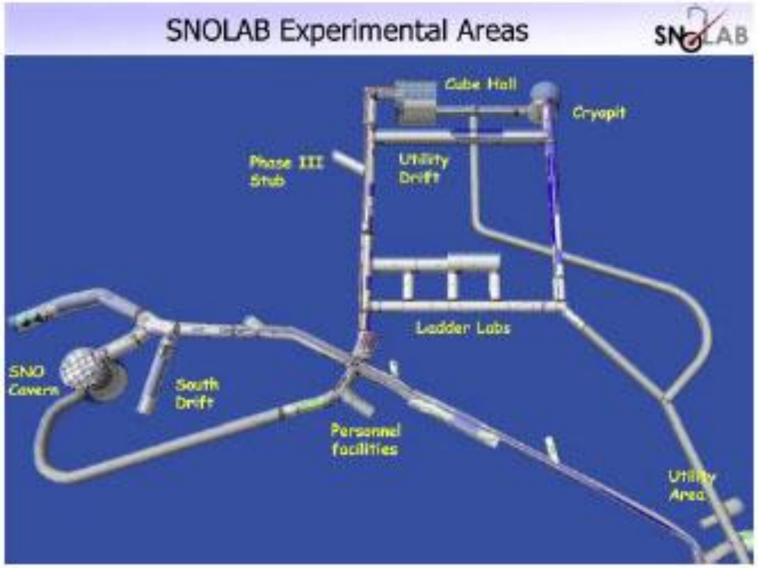


Run-2 3.2keV prelim. data
- ~51 live days and counting
- Est. neutron bkgd $1.5^{+0.3}_{-1.1}$ events

- Nat. quartz flange replaced by fused silica
- Enhanced procedures against part. contamination
- Physics run 2: since 06/15

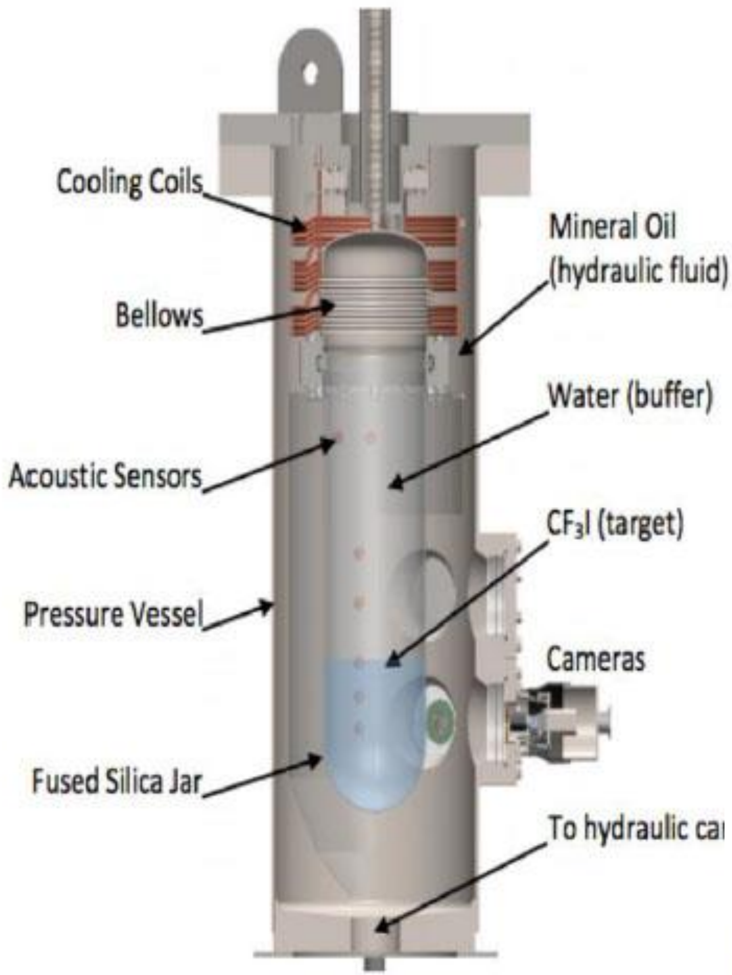
New Run 2 consistent with n-background !!!

PICO 60 CF_3I @ SNOLAB



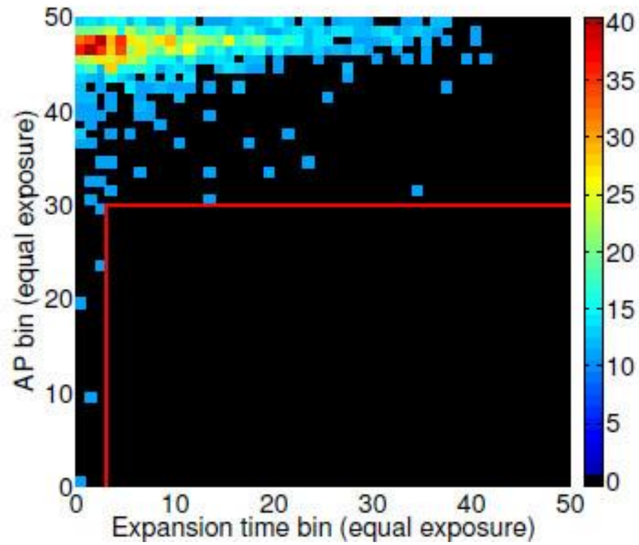
June 2013 – May 2014 (3415 kgd)

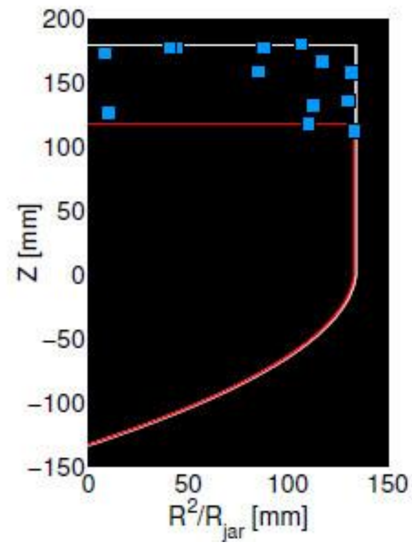
PICO 60 CF_3I @ SNOLAB



- Largest Dark Matter BC ever
- Run Start at SNOLAB April 2014
- 36.8 kg of CF3I & 3415 kgd exposure
- Threshold 9 - 25 keV
- Anomalous recoil events due to particulates

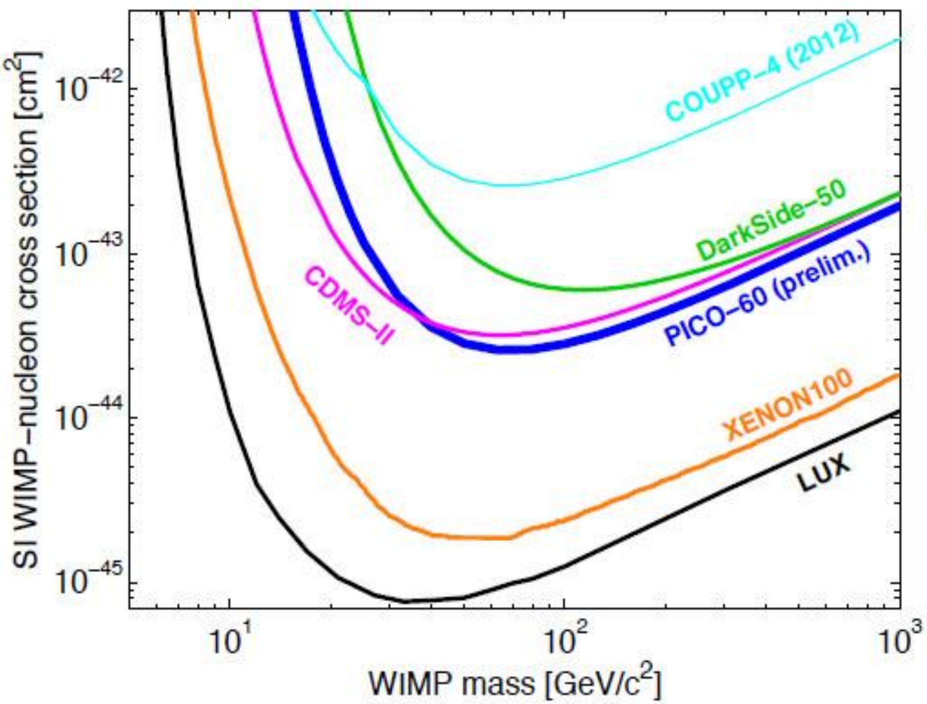
After cuts no DM candidates remaining!

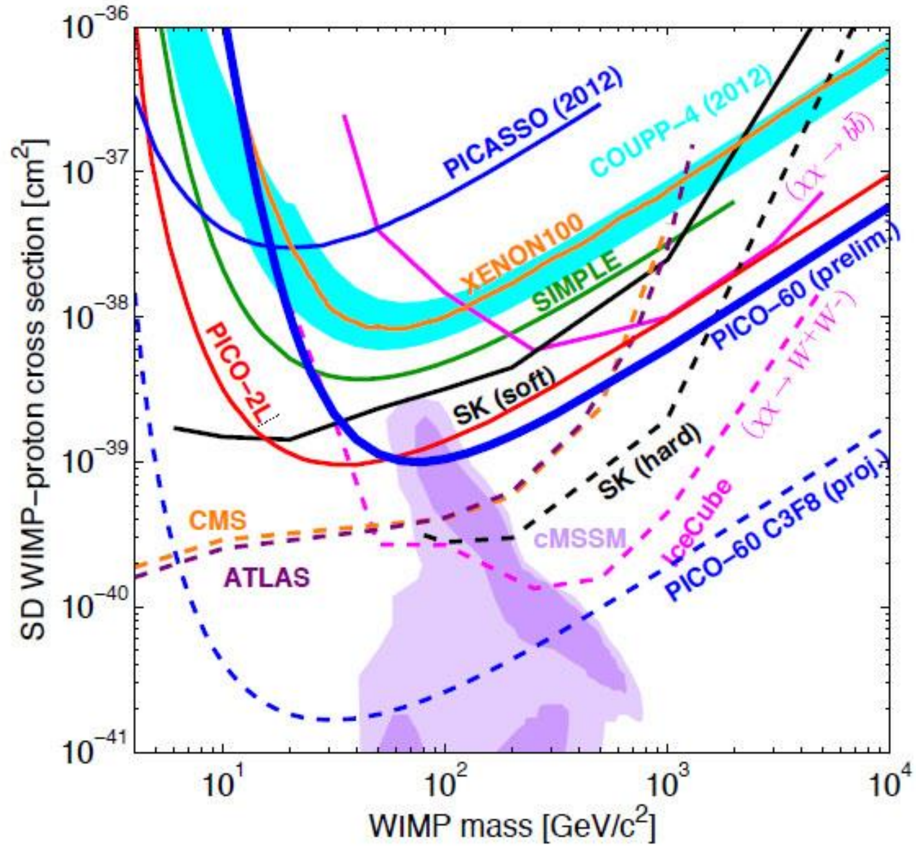




PICO 60 CF_3I @ SNOLAB

Preliminary Limits

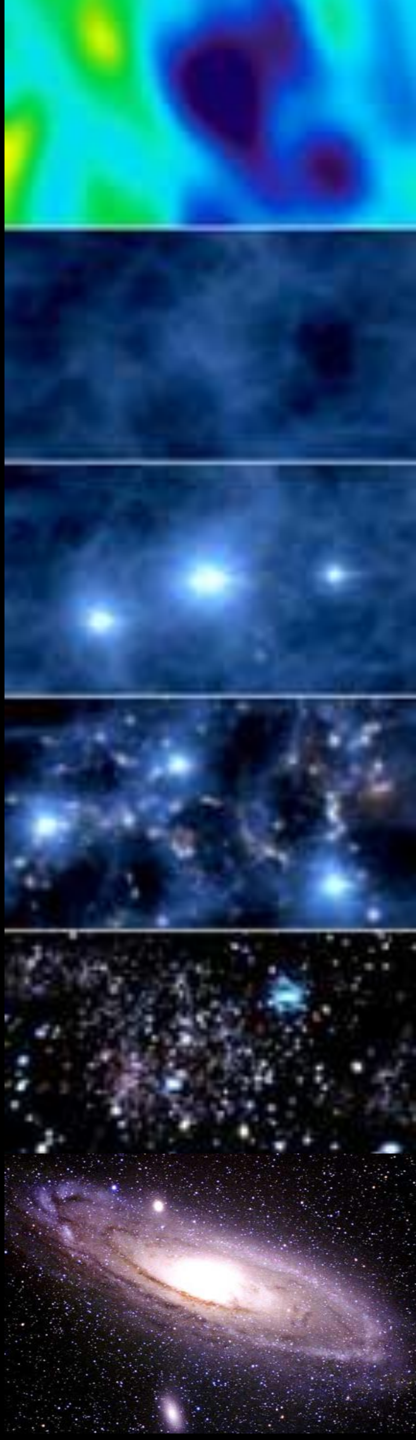


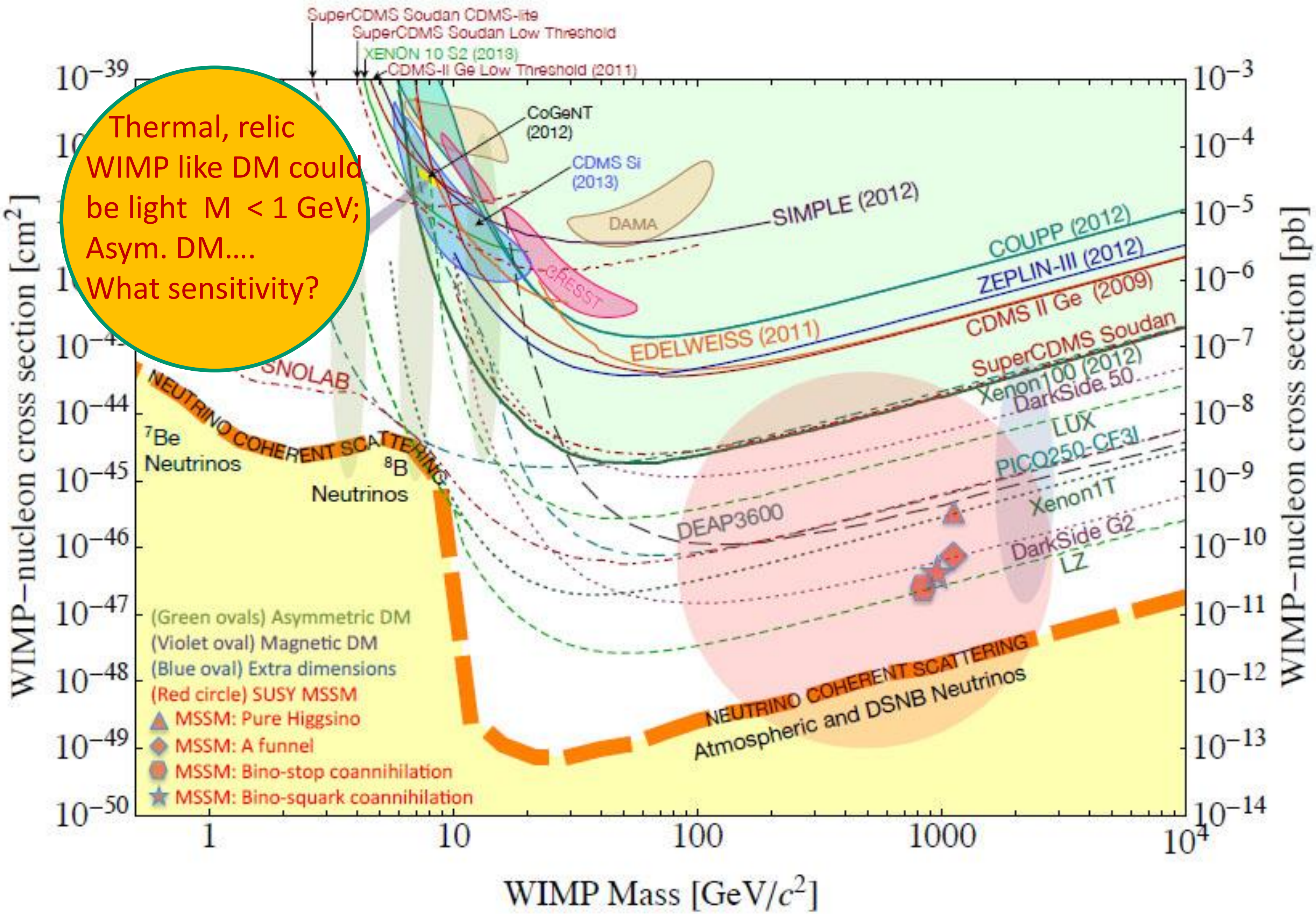


Next:

- PICO 60 with $C_3F_8 \rightarrow$ SD sensitivity
- New fused silica vessel, recirculation/filtering
- Staged array of 60L modules

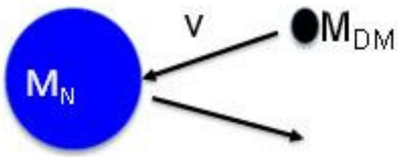
…extending the low mass frontier



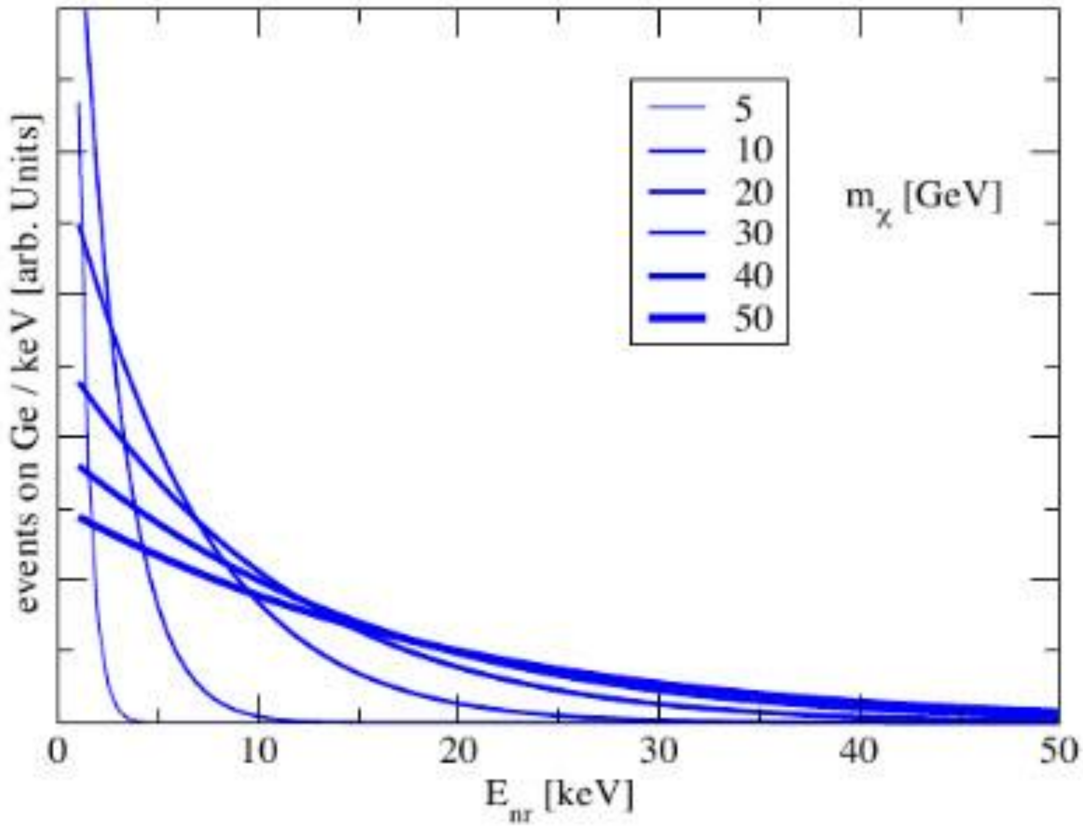


Thermal, relic WIMP like DM could be light M < 1 GeV; Asym. DM…. What sensitivity?
SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
DEAP3600
SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]

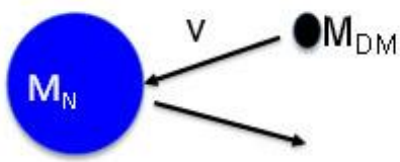
THE LOW MASS WIMP DIRECT DETECTION CHALLENGE



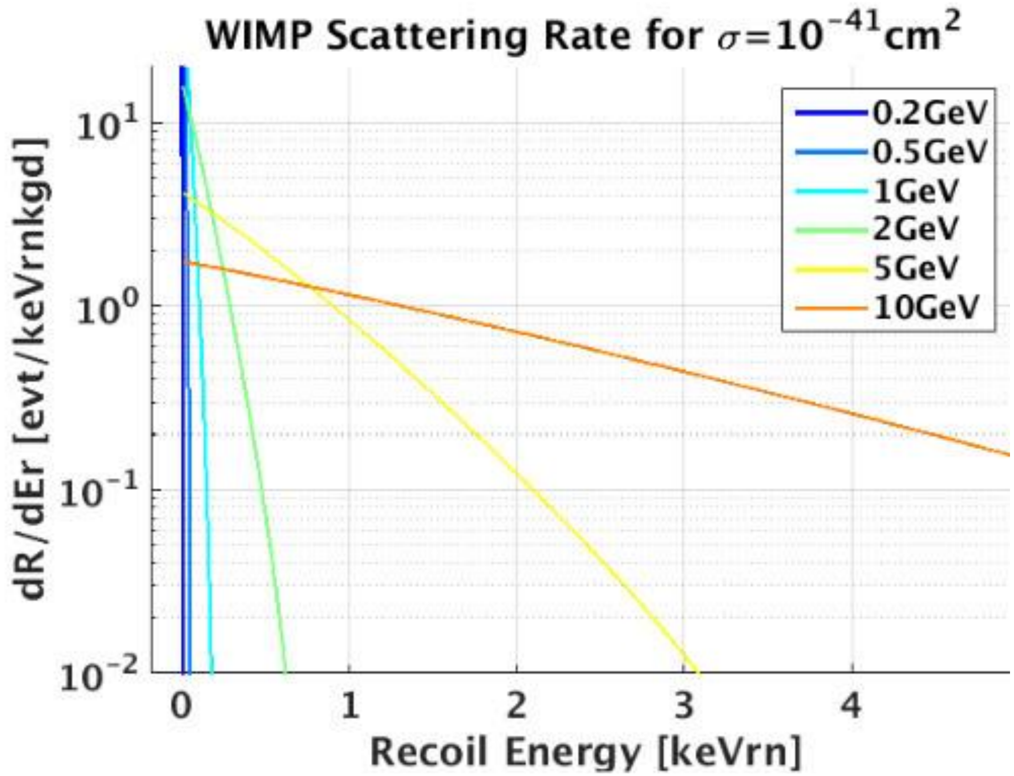
$$\Delta E = \frac{\Delta P^2}{2M_N} \sim \frac{2M_{DM}^2 v^2}{M_N}$$



THE LOW MASS WIMP DIRECT DETECTION CHALLENGE



$$\Delta E = \frac{\Delta P^2}{2M_N} \sim \frac{2M_{DM}^2 v^2}{M_N}$$

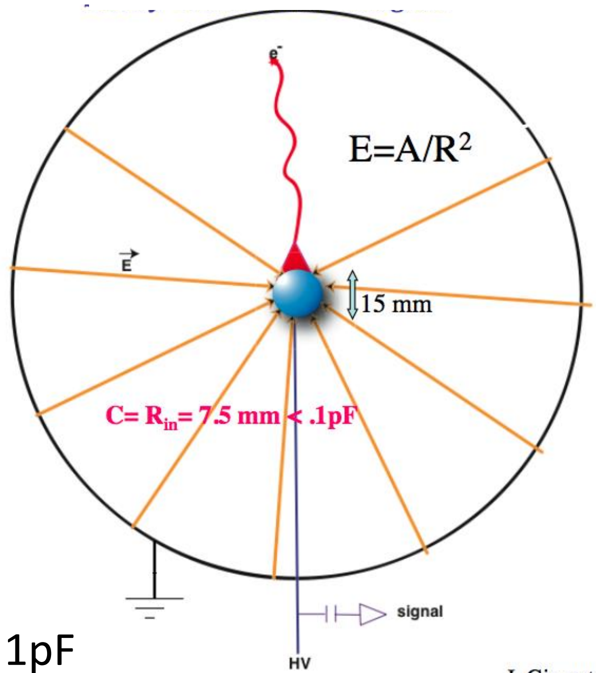


Conventional detectors $\rightarrow$ small or zero sensitivity

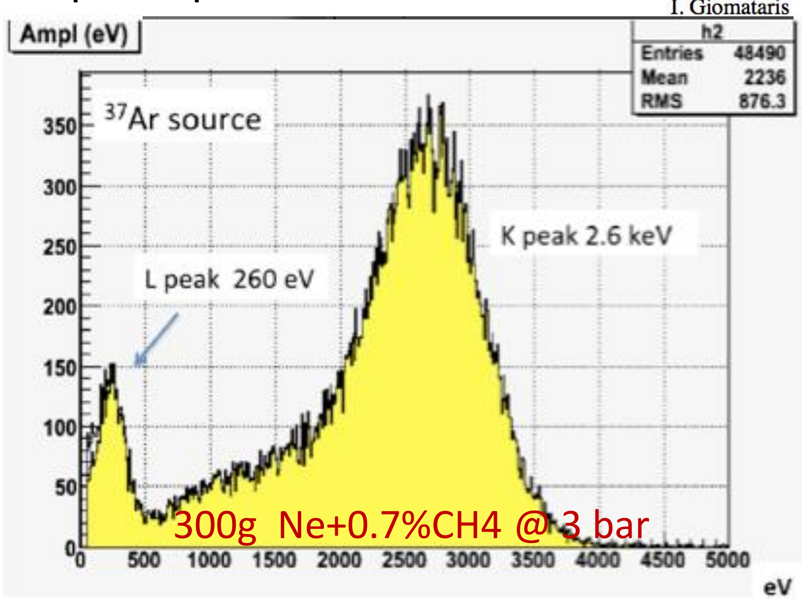
for slow moving cosmological WIMPS !

New Experiments With Spheres

Queen's, SNOLAB, Saclay, LSM, Tessaloniki, Grenoble, Munich

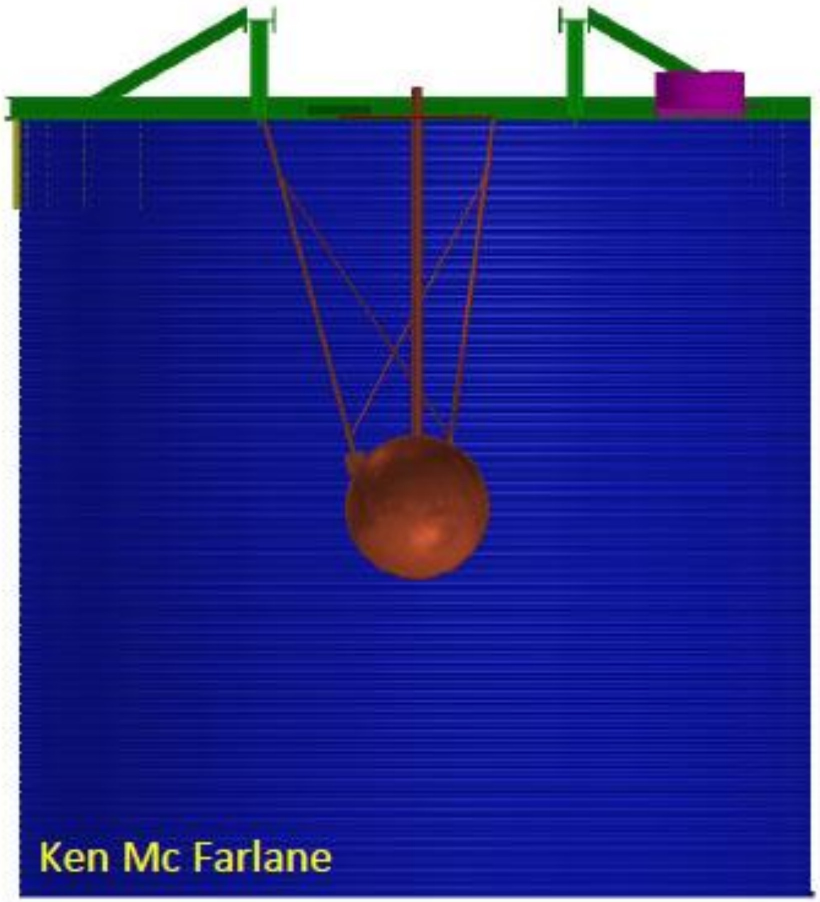


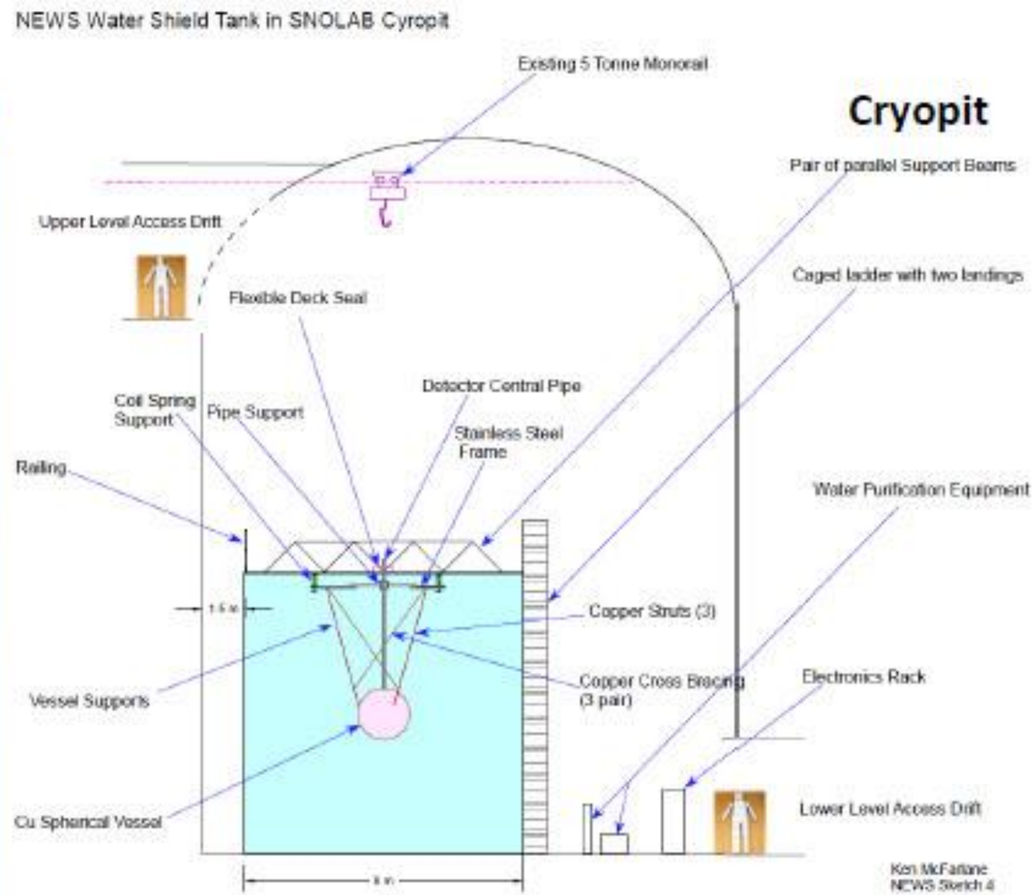
- Spherical cavity + sensor
- Proportional counter mode
- Target: Ar, Ne, He, H (CH4)
- Large volume/mass (30g)
- Single channel R/O
- Low threshold – low cap. < 1pF



- E_{thr} = 120 eV demonstrated in Ne @3b
- Localisation by rise time
- 2 LEP cavities with 130 cm ∅ tested
- SEDINE @LSM: low activity 60 cm Ø module

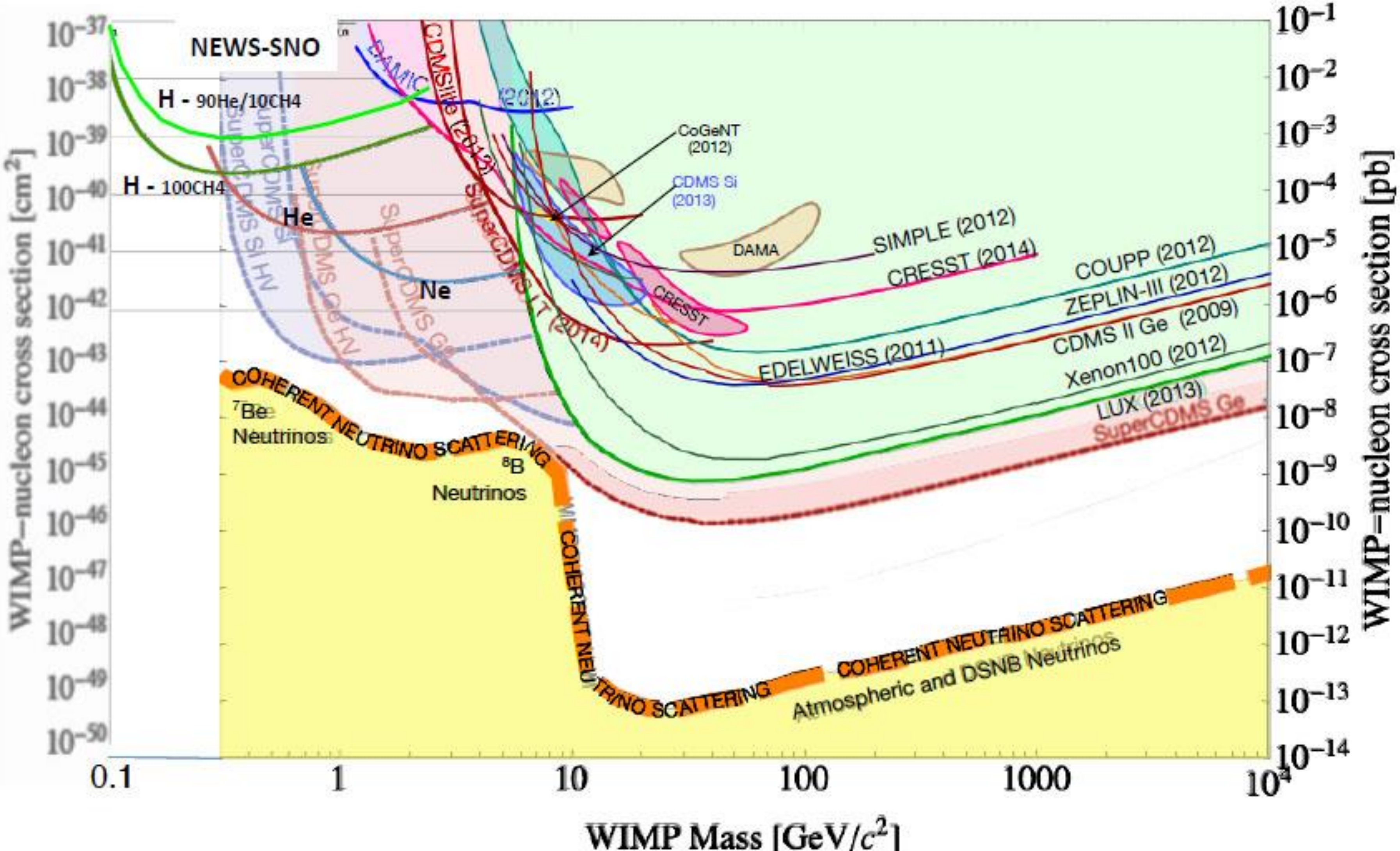
NewS @ SNOLAB !





- 1.4 m ∅ sphere in 8 m ∅ Water tank
- Ne fill 10 b $\rightarrow$ 12.5 kg   (also He, CH4)
- Design, construction, commissioning 2015 – 2017

Projected SI Limits vs Current & Future Competitors



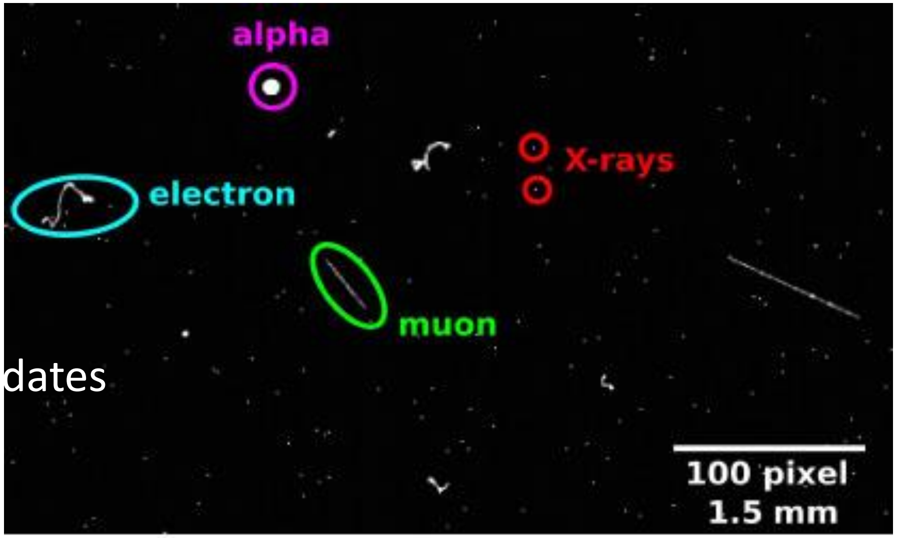
100 kgd; E_{thr} = 100 eVNR

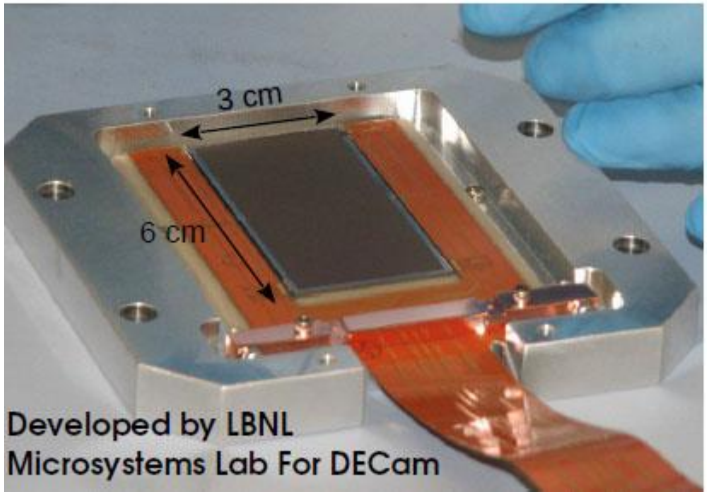
Other physics: low mass spin dependent WIMPS (H-target) - KK axions – Coh. ν scatt.

DAMIC: DArk Matter In CCDs

Fermilab, Chicago, Zûrich, Michigan, UNAM, FIUNA, CAB

- Science-grade CCDs as particle detectors
- Low threshold < 50 eV_{ee} (-140 C)
- Energy resol. : 63 eV RMS @ 5.9 keV
- 3-D reconstruction (diffusion)
- Search for low Mass WIMPs and other candidates



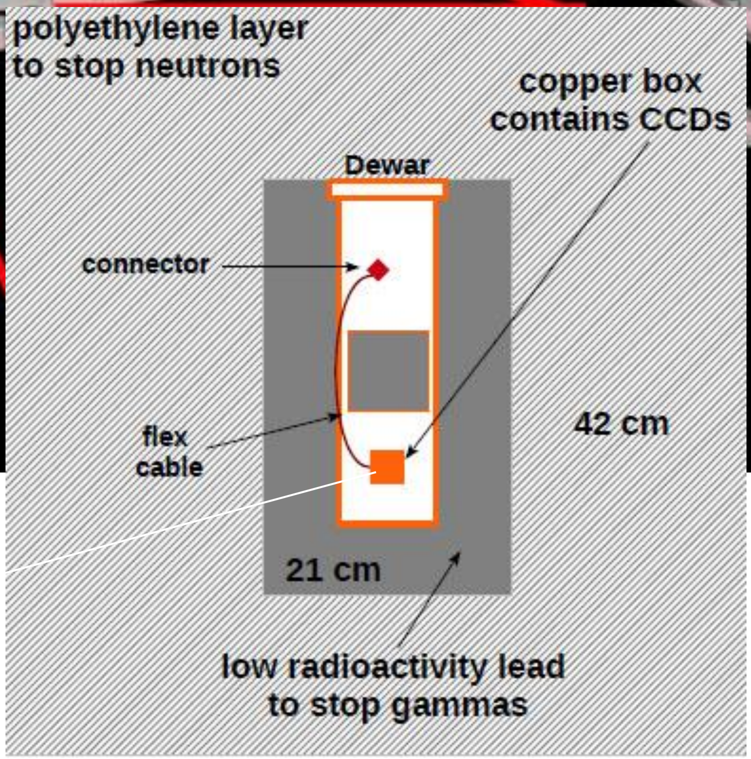


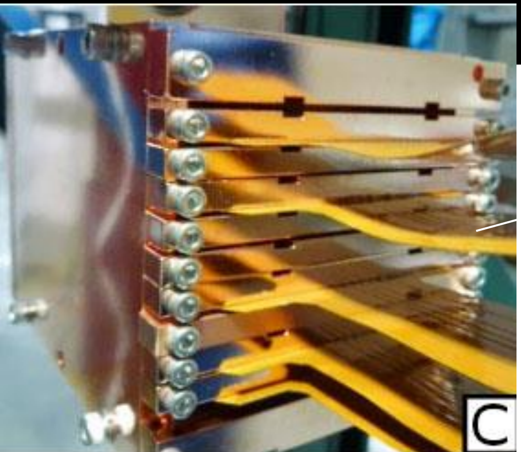
Pixel size:	15μm x 15 μm
# pixels:	8 Mpix / 16 Mpix
Thickness:	250 μm / 675 μm
Mass:	1g / 5.8g

2012 installed at SNOLAB

Snolab

Installed Dec 2012
at ~2 km underground, J-Drift Hall





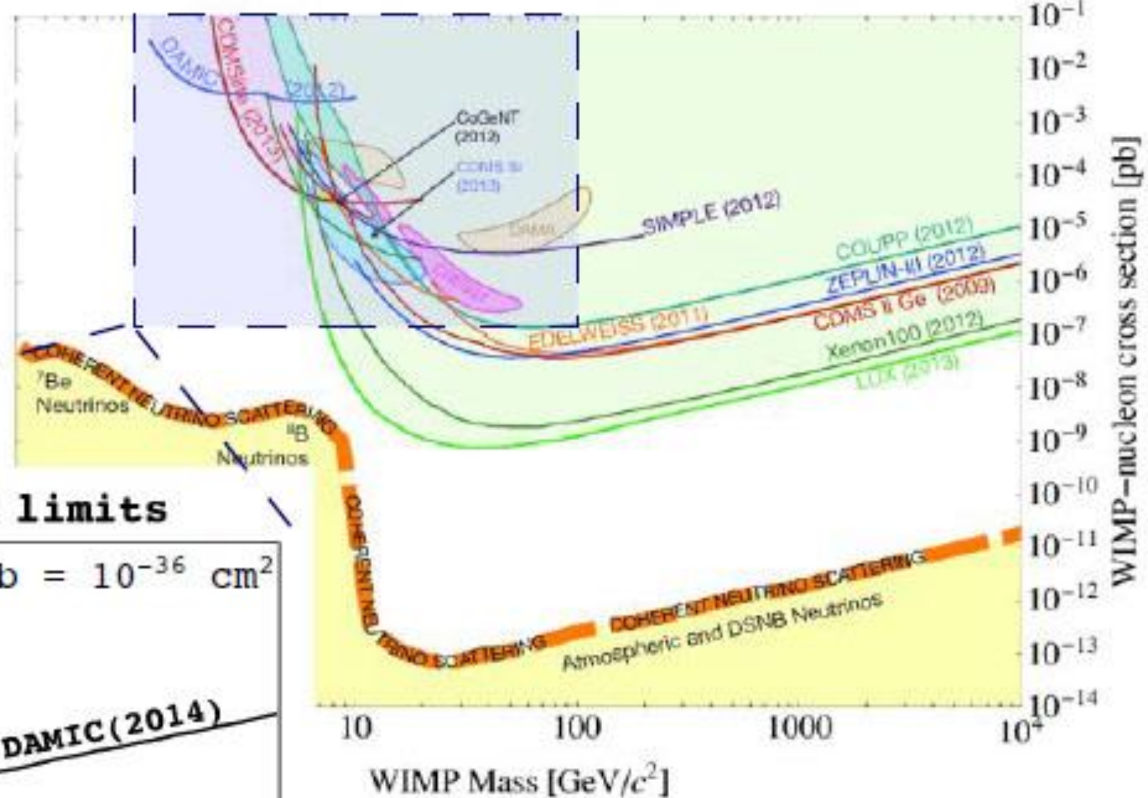
Towards DAMIC 100

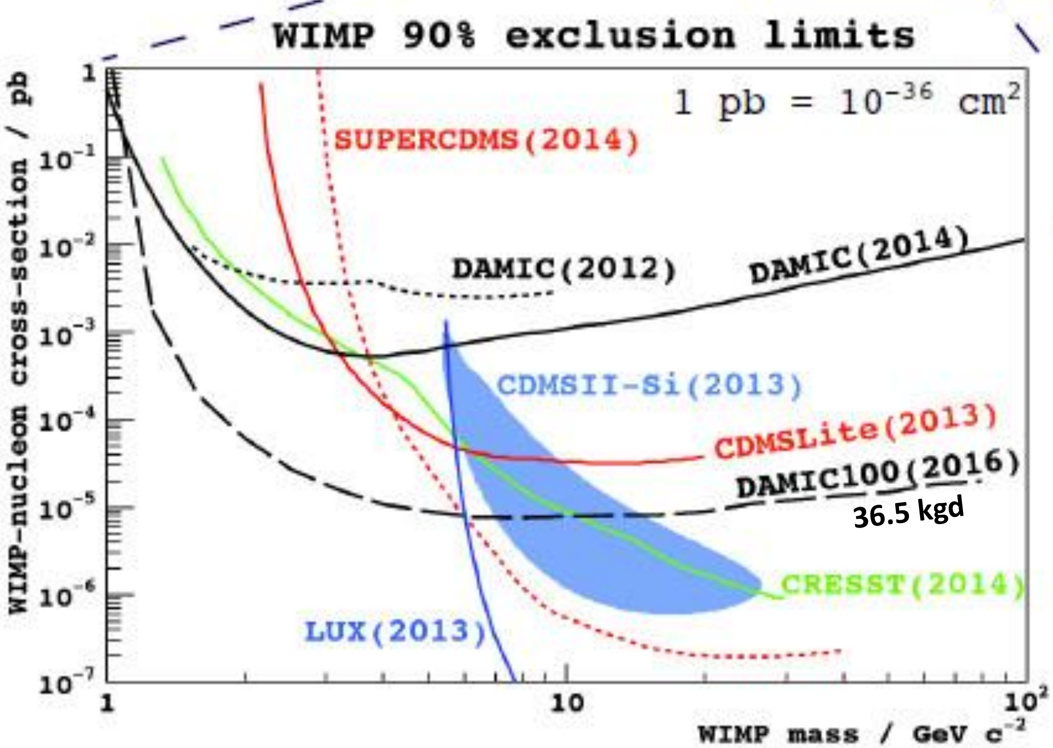
DAMIC

Results:

2012 Exposure 107 gd (FNAL)

2014 Exposure 0.3 kgd (SNOLAB)

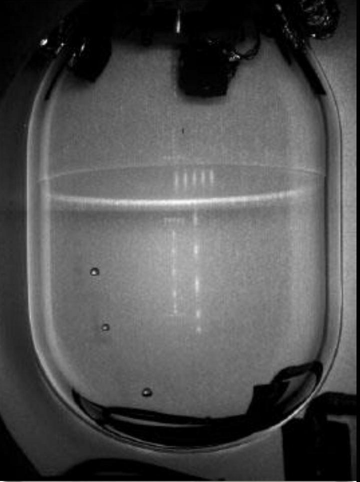




Coming up:

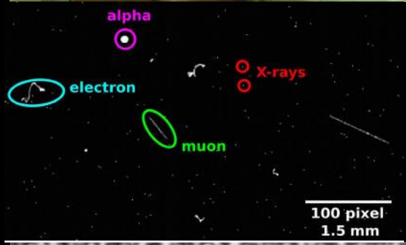
- DAMIC 100: 100 g of Si (18 modules)
- 2015: 1 x 16 Mpix CCD installed
- Data taking started
- Adding gradually more modules

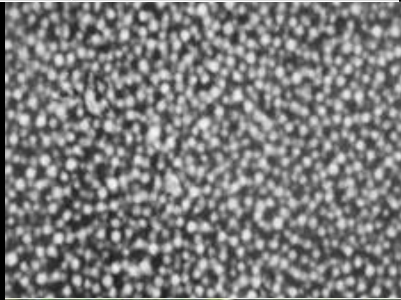
A. Aguilar-Arévalo, Vail Conf., May 2015



New Techniques…

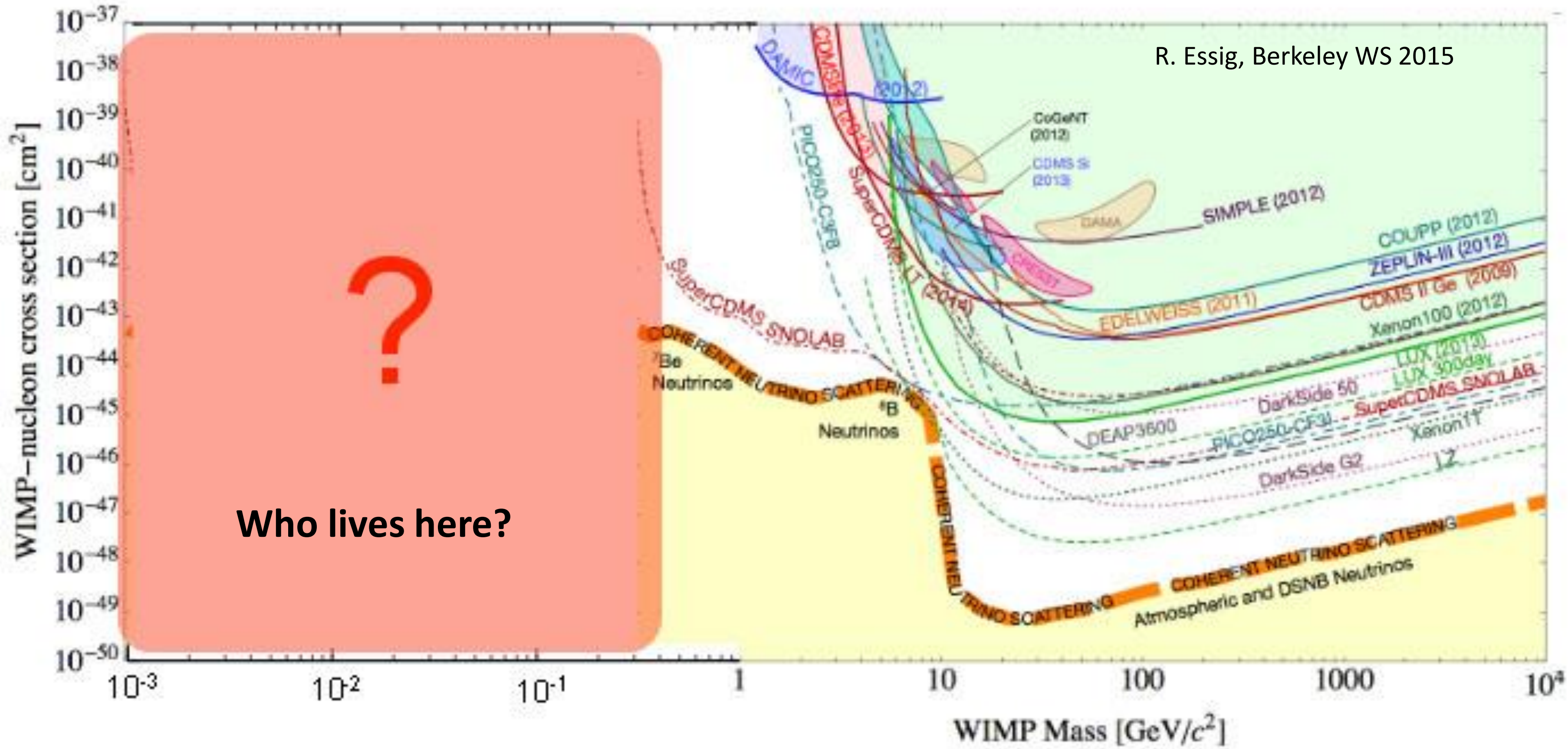
…to explore the dark sector



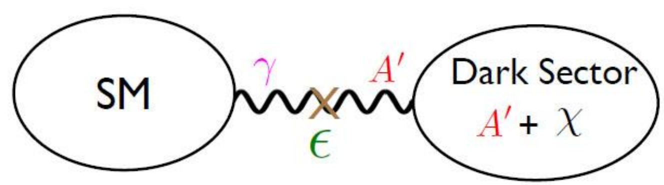


Moving Beyond the standard WIMP …

Boehm, Fayet; Pospelov, Ritz, Voloshin; Batell, Pospelov, Ritz; Lin, Yu, Zurek; Izaguirre, Krnjaic, Schuster, Toro; …



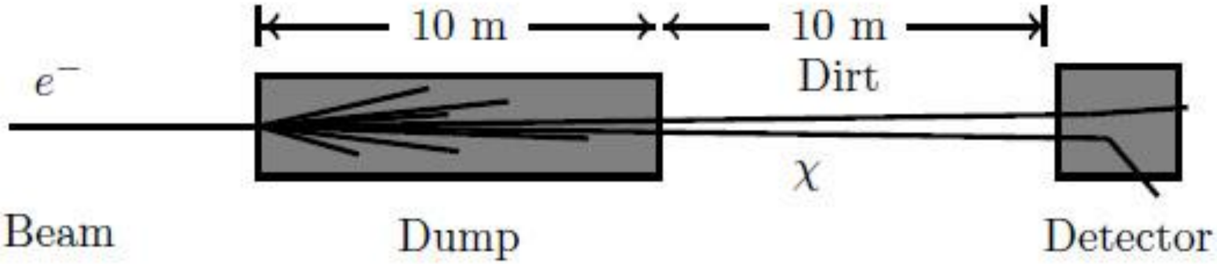
- Actually MeV Dark Matter well motivated !!!
- Interaction with ord. matter by "dark force" A'
- Gauge boson A' which mixes kinetically with γ
- Light vector mediator decays to low mass WIMPs



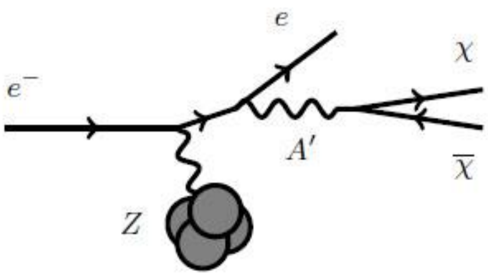
BDX: Search For DM in the Dumps!

Genova, Jlab, Perimeter, Bari, Sassari, Catania, Ferrara, Roma, Frascati, Padova, Torino, Durham, Glasgow, Washington, Hampton, Norfolk, Edinburgh, Athens

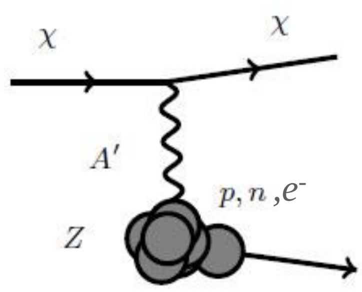
- Production of a DM beam @ CEBAF / Jefferson Lab
- 11 GeV electron beam, 100 μA



Production



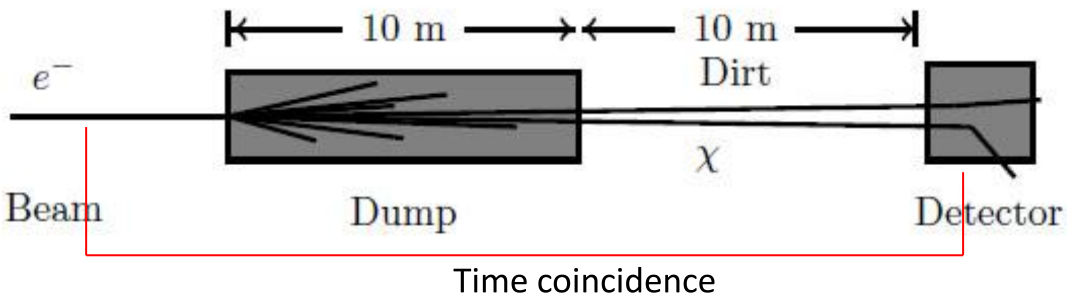
Detection:

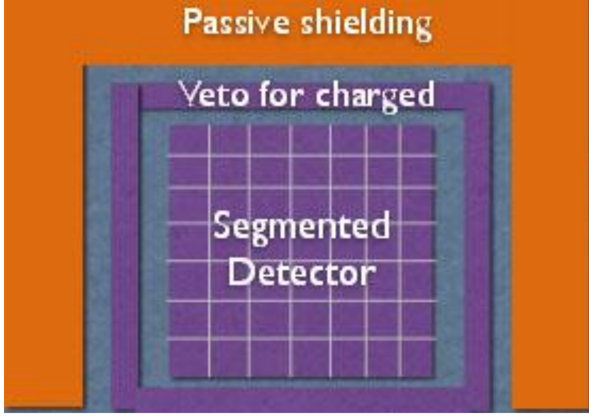


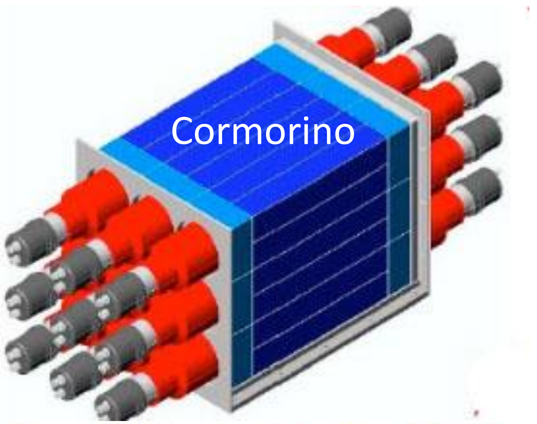
- Elastic $\chi \to$ N, e-scattering
- Senitivity to MeV nucleon recoils
- Sensitivity to GeV e.m. – showers
- Main backg. cosmic n, μ

see Izaguirre, Krnjaic, Schuster, Toro; Diamond, Schuster; Battaglieri et.al.

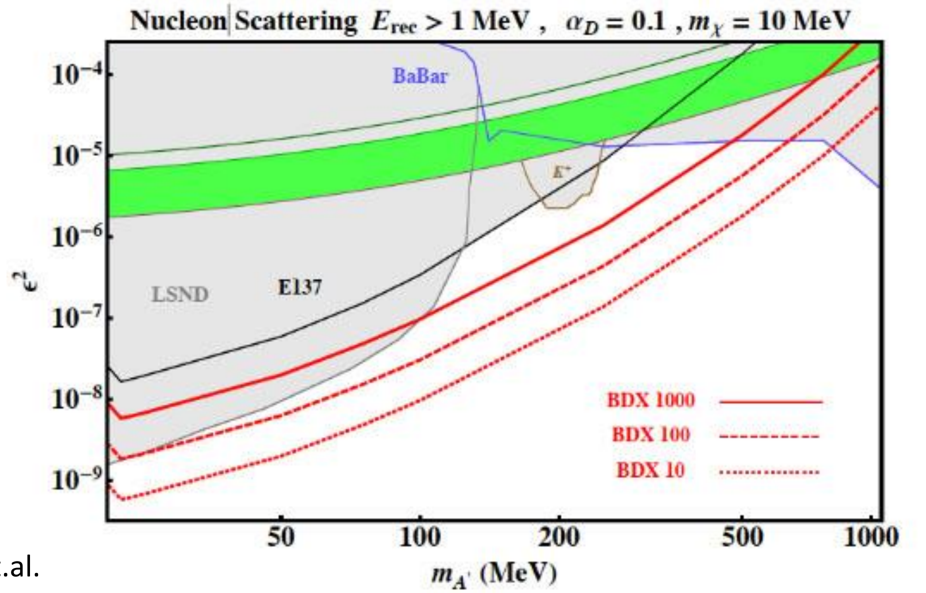
BDX: Experimental Technique







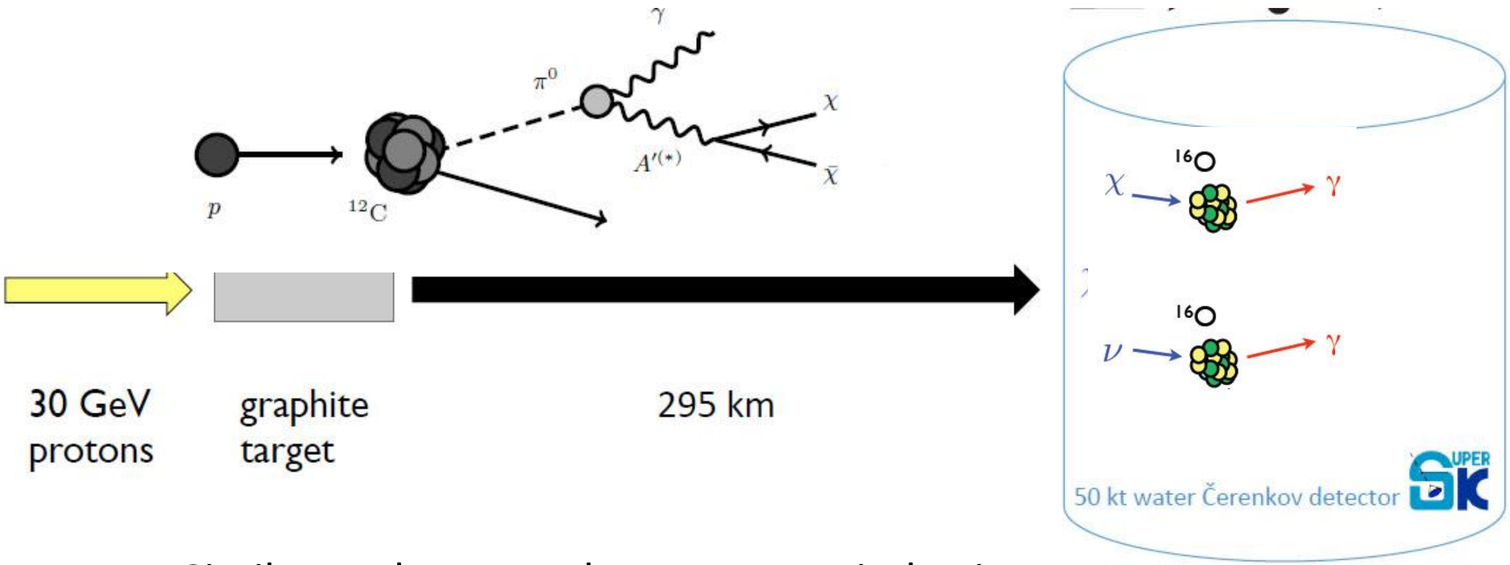
- Good time resolution (beam-uncorr. BG)
- 1 m^3 segmented array of plastic scintillators + Pb-foil
- ~ MeV threshold for nucleon recoil
- EM showers detection (> 100 MeV)
- Basic module 40 x 30 x 30 cm
- Full detector: 30 modules in a row



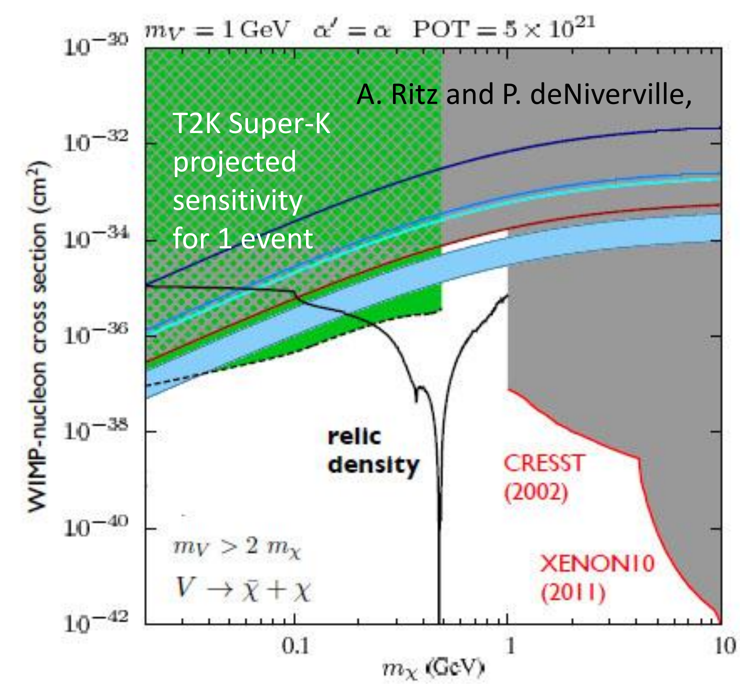
- Also: LSND, BaBar, MiniBoone, E137
- Future: DAEDALUS, SHiP, COHERENT, CENNS
- Complemented by searches for dark photons

see Izaguirre, Krnjaic, Schuster, Toro; Diamond, Schuster; Battaglieri et.al.

Low Mass DM in the T2K Neutrino Beam

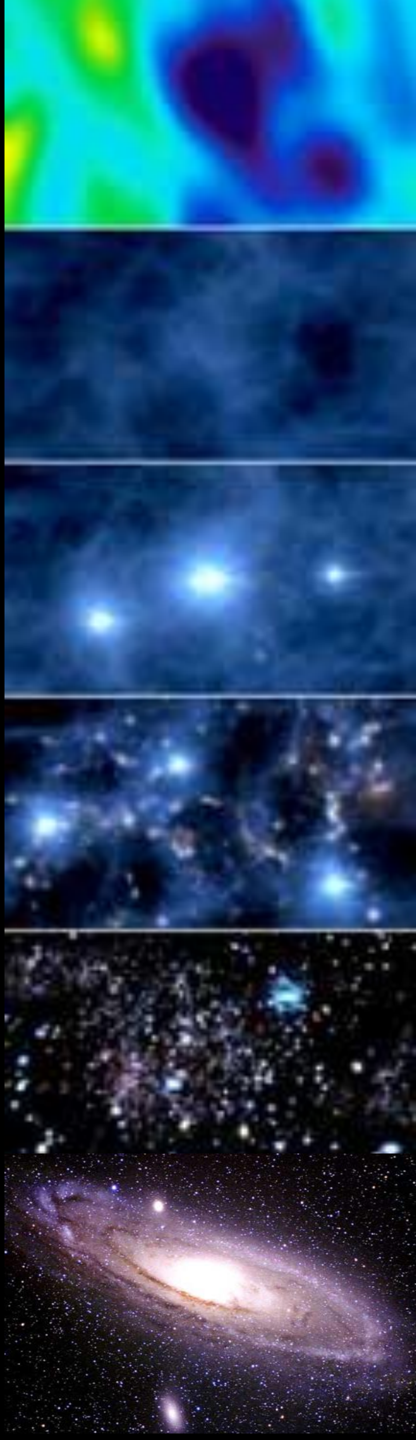


- Similar to the neutral-current quasi-elastic neutrino-oxygen interaction
- 6 MeV de-excitation γ in Super-K after ν - ^{16}O NCQE
- Quasi-elastic nuclear knockout followed by secondary γ's
- **χ - ν discrimination using time of flight**



C. Nantais, CAP Congress, Laurentian U., 2014

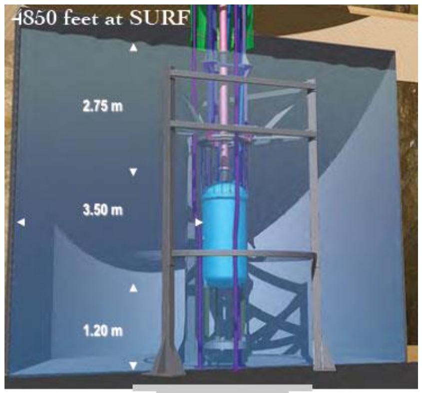
…the future of direct searches



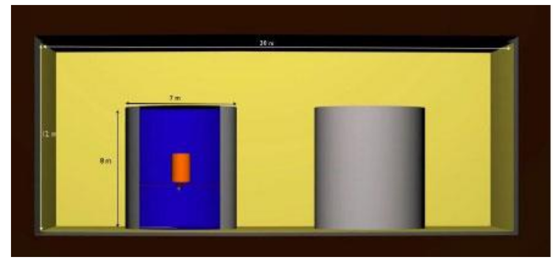
THE FUTURE OF DIRECT DM - SEARCHES

Trend towards a few very large experiments....

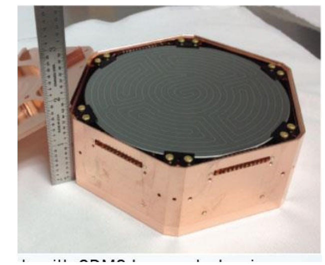
ArDM 850 kg



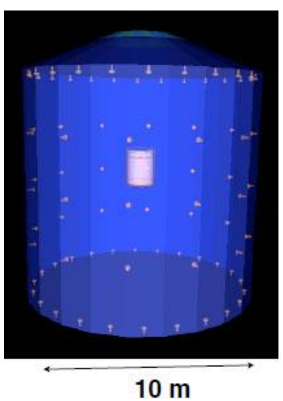
LUX 350 kg Xe



EURECA 0.1 -1t

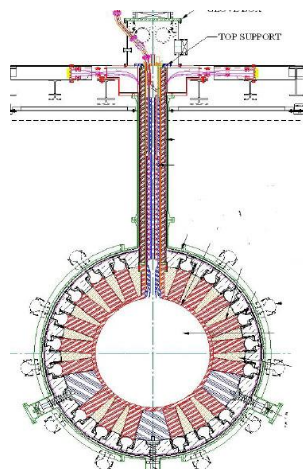


Super CDMS 0.2 t Ge
→ GEODM 1.5t Ge

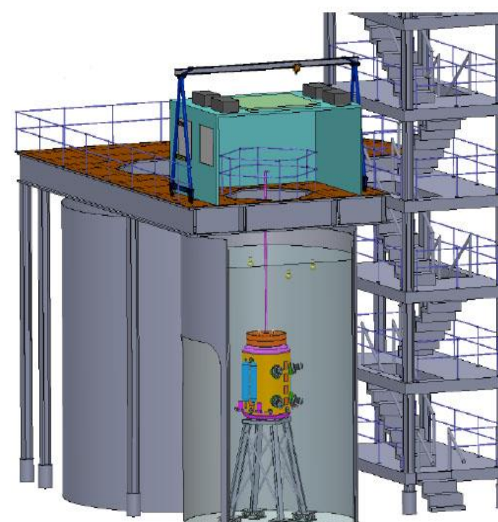


XENON 1t

DARWIN 20t Xe / Ar

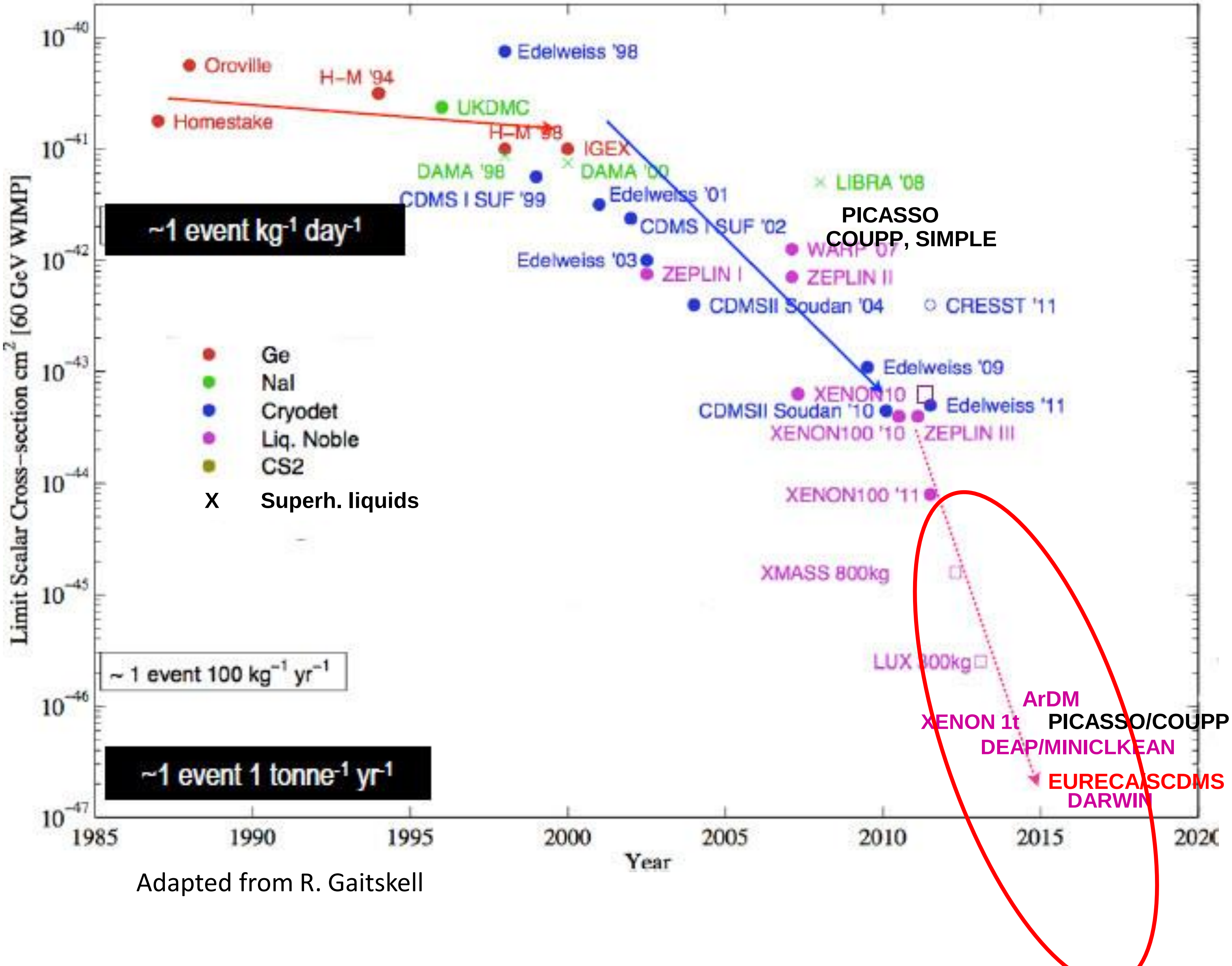


DEAP 3.6 t Ar



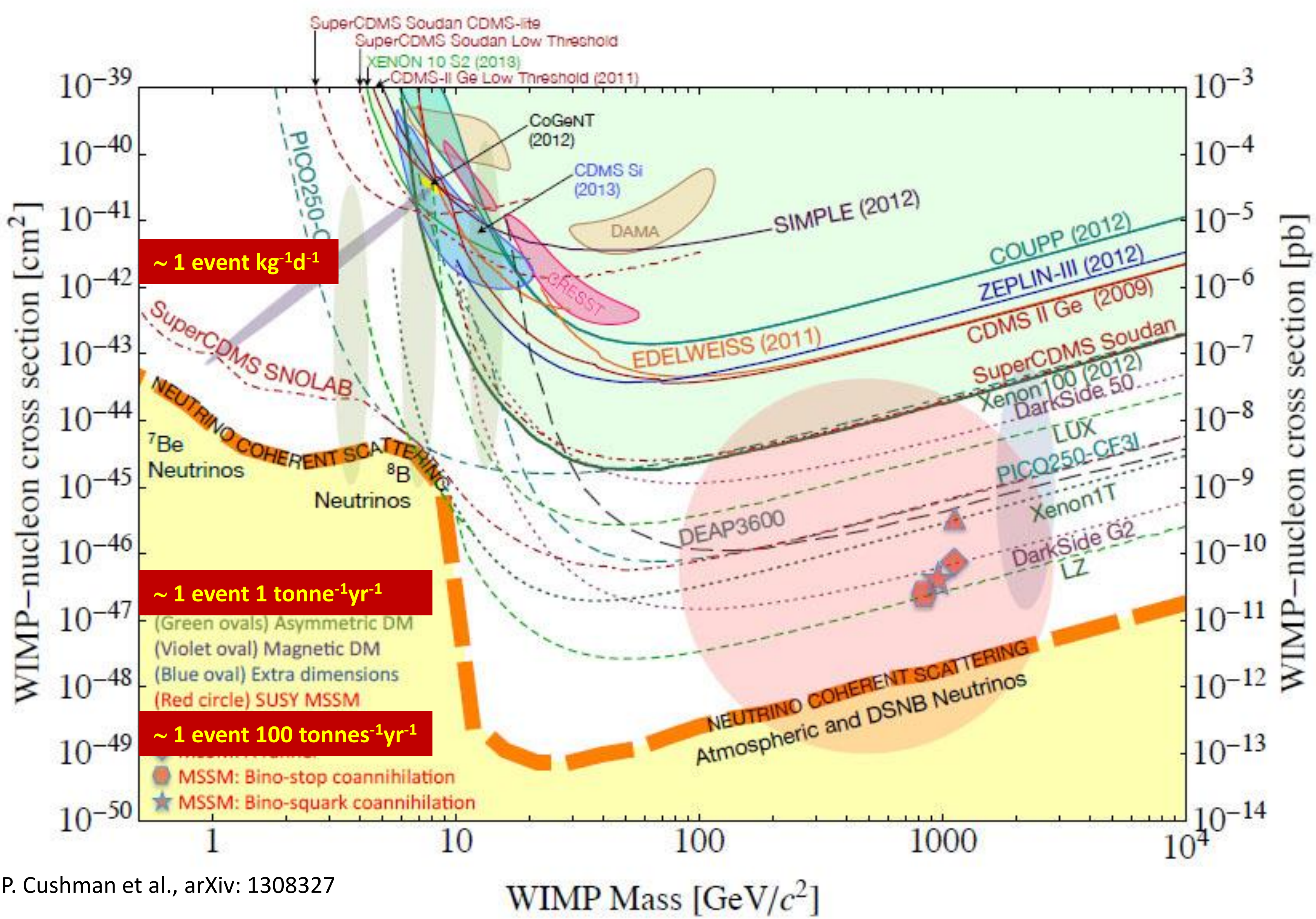
PICO 1t

THE FUTURE OF DIRECT DM SEARCHES



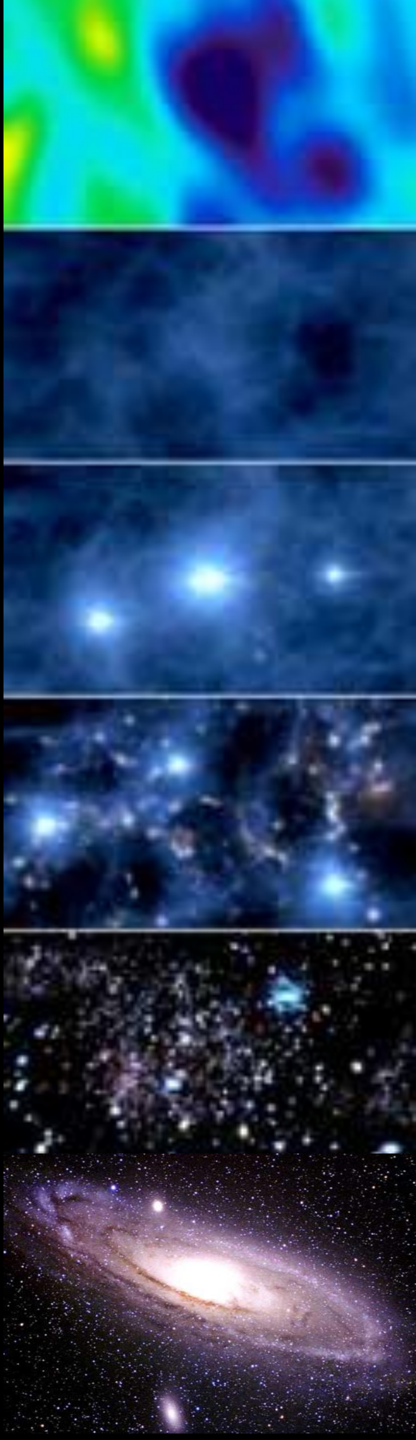
Adapted from R. Gaitskell

Present & Future WIMP Searches (SI)

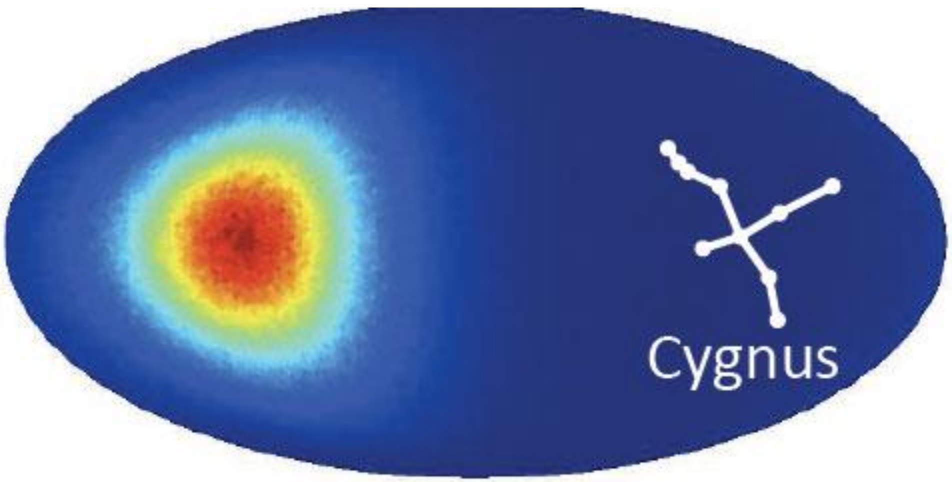


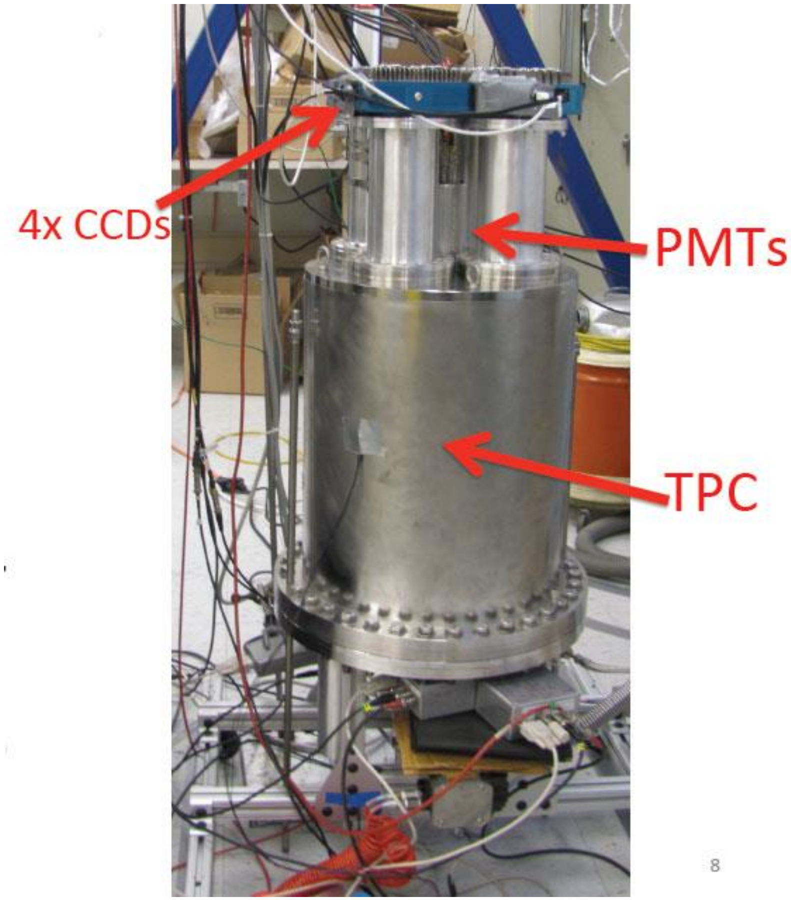
P. Cushman et al., arXiv: 1308327

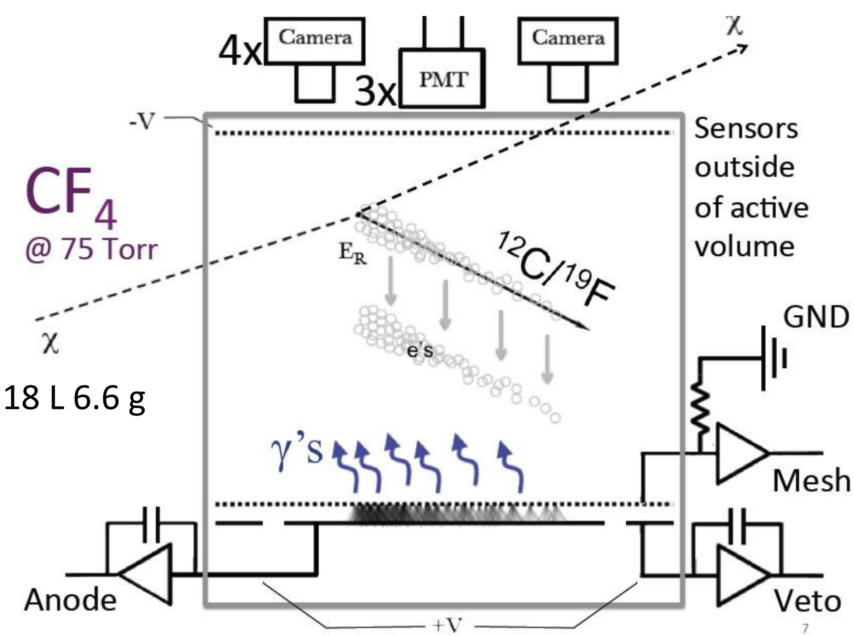
…and if we hit the Neutrino Limit?



DMTPC: Directional WIMP Detection with CF_4



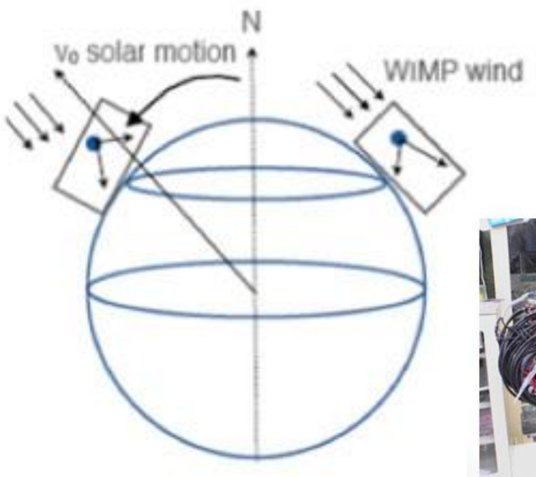




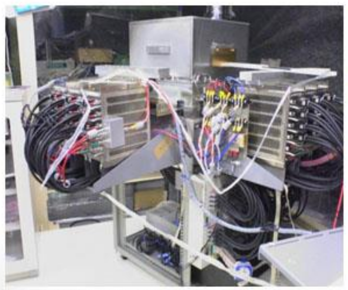
- **Strong day/night modulations expected**
- **Funded to build a 1m^3 TPC at WIPP**

+ DRIFT, MIMAC, NEWAGE

Exploit Directionality !



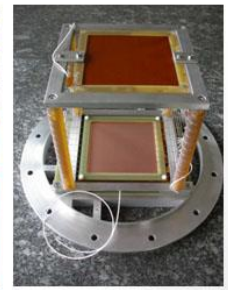
- Strong day/night modulations expected / Cygnus!
- Low pressure TPC's CF_4, CS_2....
- Powerful backg. rejection



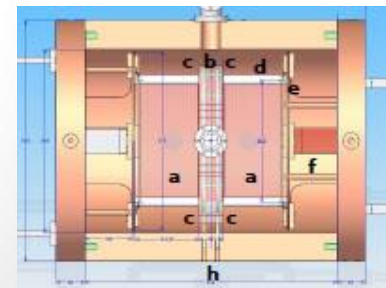
NEWAGE@ Japan

DM-TPC@ USA

DRIFT @ UK



MIMAC@ France

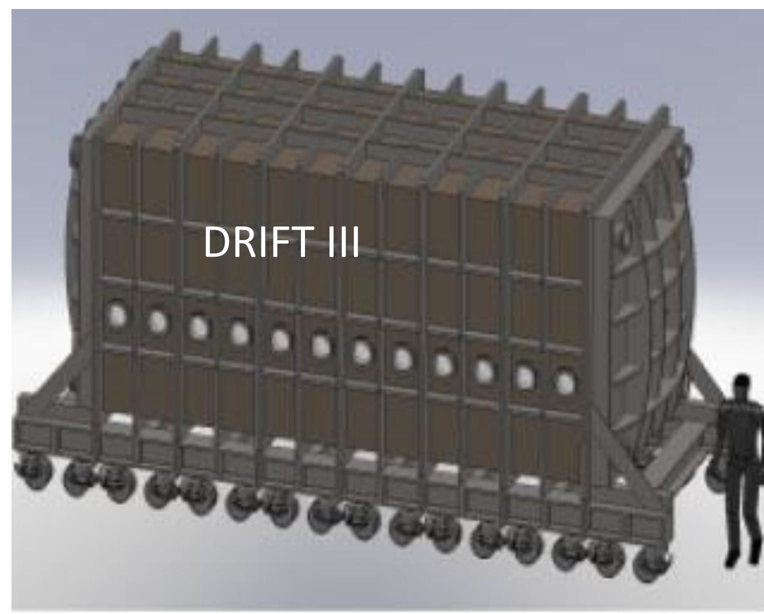


Trex@Spain

- Up to now small mass (100g)
- Huge det. volumes required > 1000 m^3
- Scale up from ~ $1m^3$ modules (DMTPC et al.)

But:

- Important to consolidate WIMP signals
- Important follow-up experiment



NEWS: Nuclear Emulsion Wimp Search

See N. DiMarco's talk

Napoli, LNGS, INFN, Bari, Nagoya

Dir. search on equatorial telescope → Cygnus

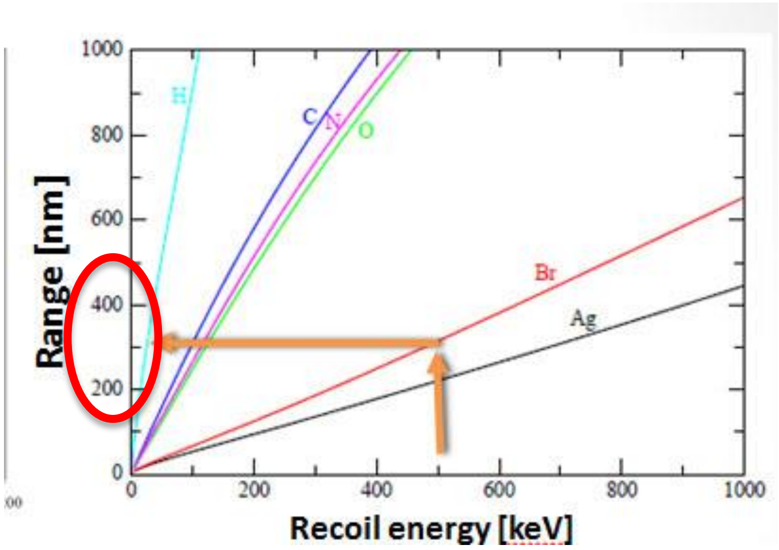
Solid target 3.2 g/cm^3 → 100 kg – 1ton

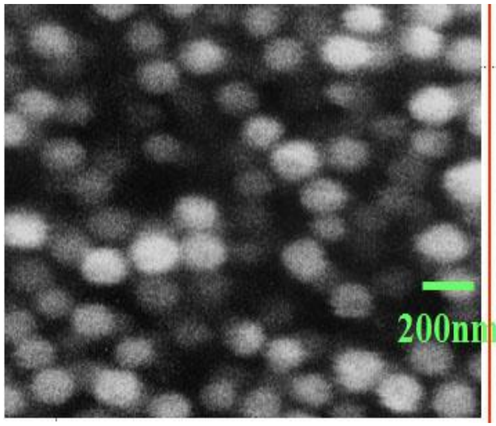
Small recoil track length O(100 nm)

Opera emulsion grains too large (x5 needed)

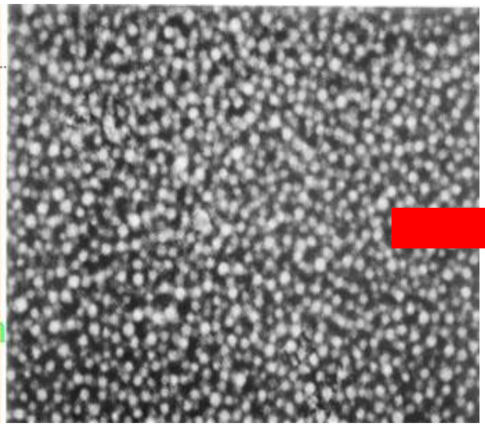
High resolution emulsion R&D at Nagoya

→ Nano Imaging Tracker (NIT)

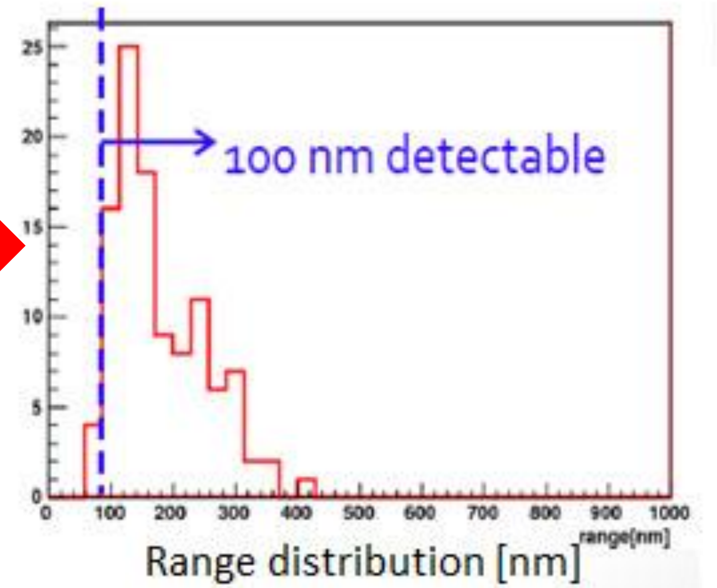




OPERA: AgBr crystal ~200nm



NIT: AgBr crystal ~40nm



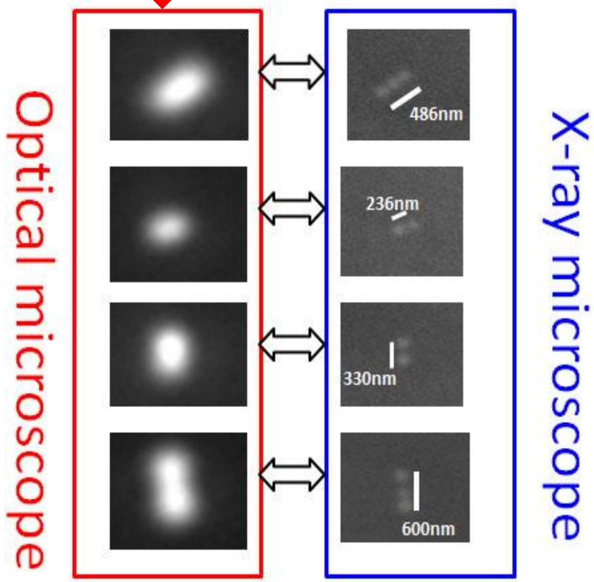
N. Tatsuhiro, Cosmic Frontier WS, SLAC March 2013

See N. DiMarco's talk

NEWS: Nuclear Emulsion Wimp Search

Read Out Step1

Optical shape scan (20 cm^2/s)

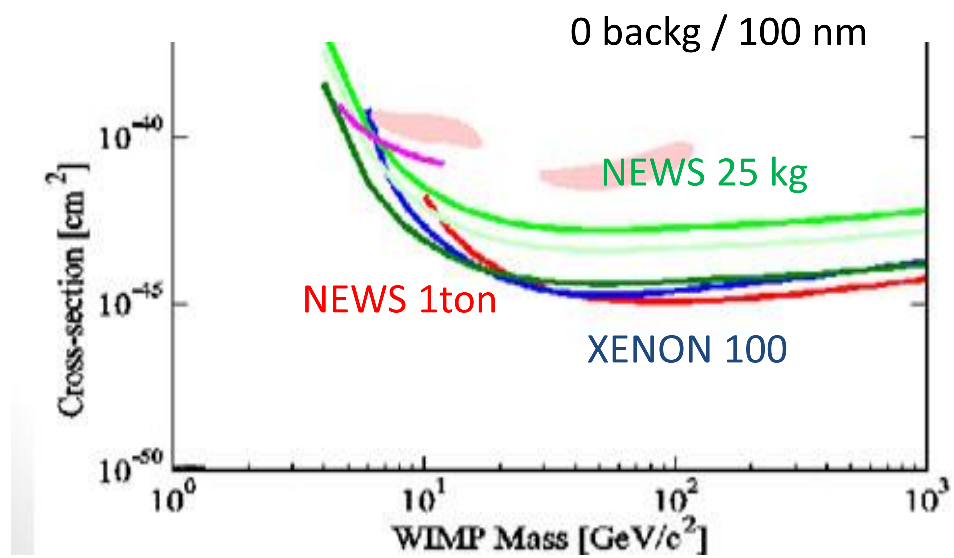


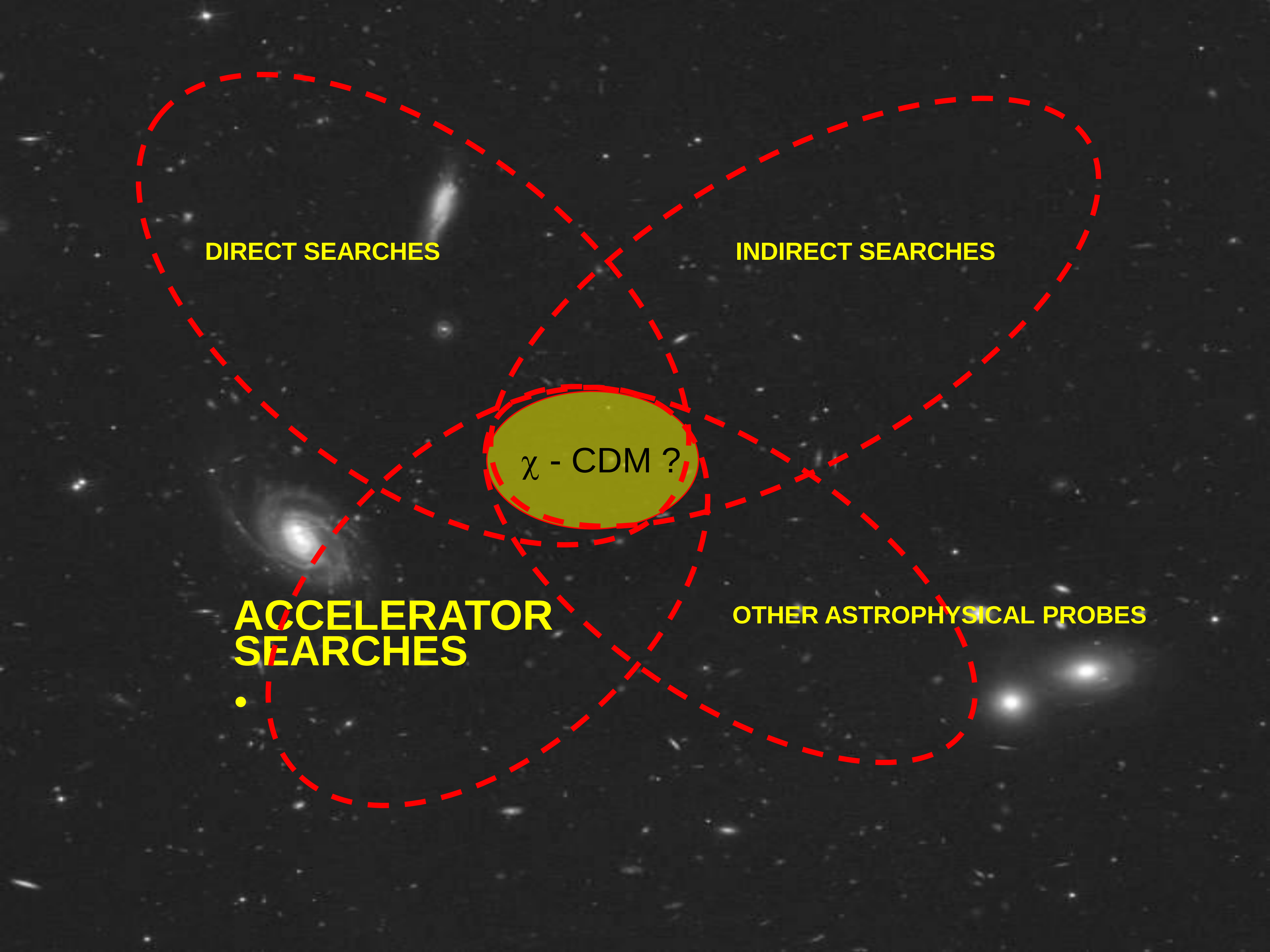
Read Out Step2

Optical confirmation w. pol. Light O(10 nm)

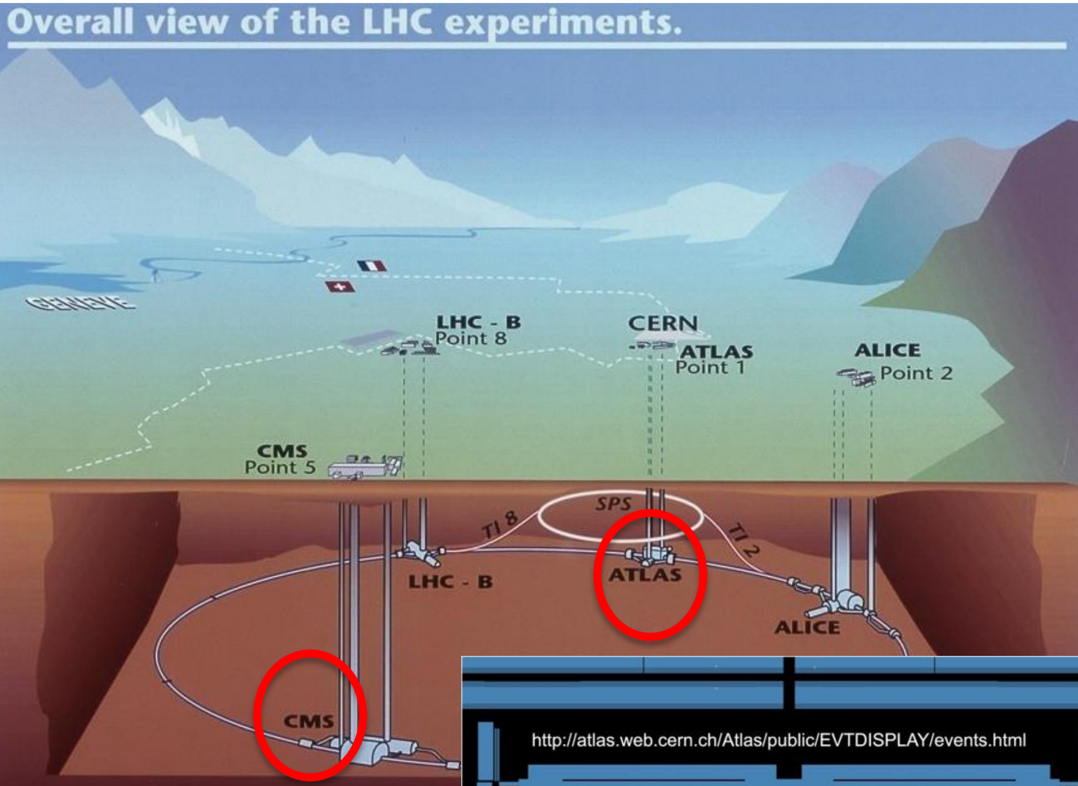
X –ray scan: ang. resol. ~17^0 @ 400 keV Kr

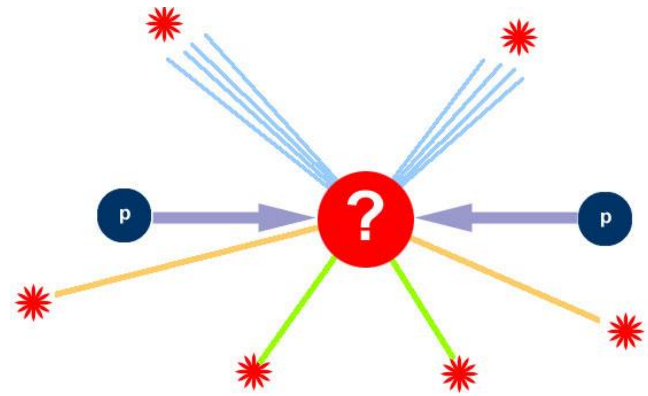
- Optical (autom.) and X-ray R/O systems ready
- Readout efficiency > 80 % @ for 200 nm C- tracks

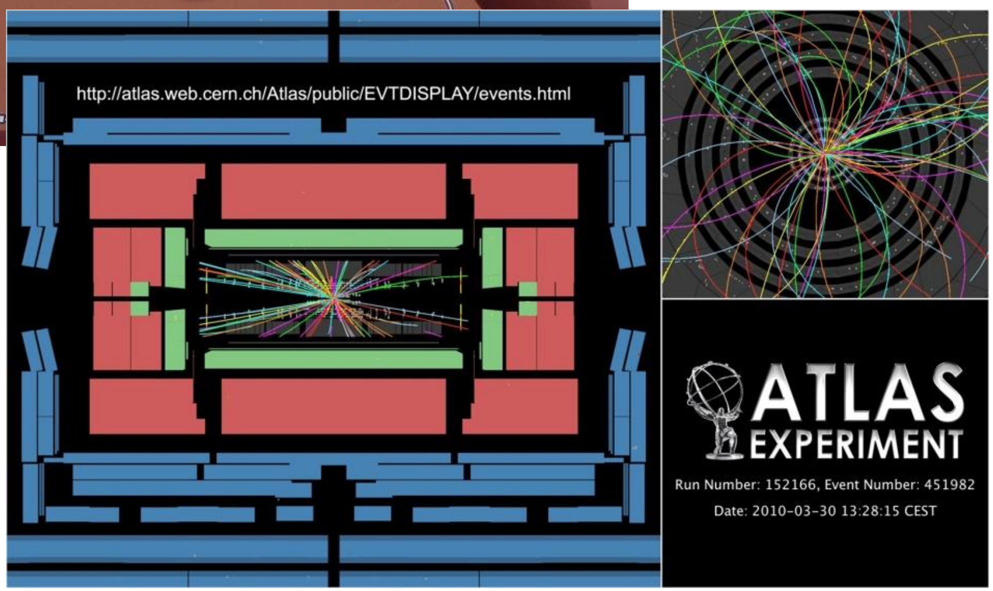



DIRECT SEARCHES
INDIRECT SEARCHES
χ - CDM ?
ACCELERATOR SEARCHES
OTHER ASTROPHYSICAL PROBES

Search for Dark Matter at the LH



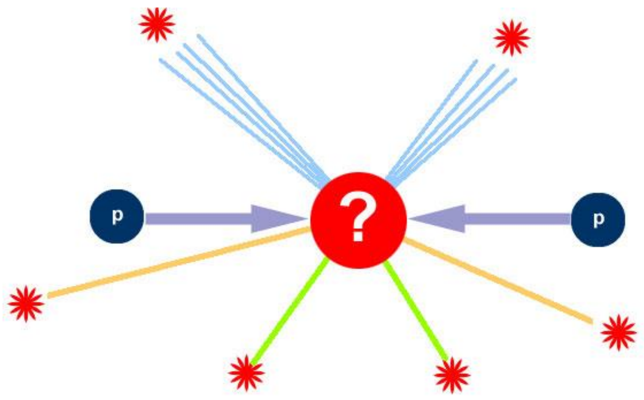




...+ CMS

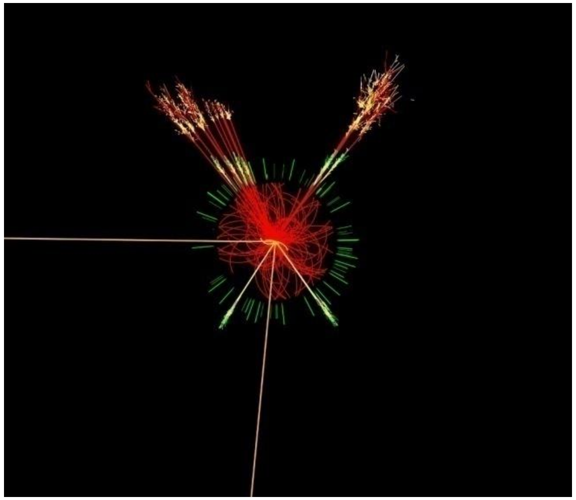
Comment trouver les nouvelles particules?

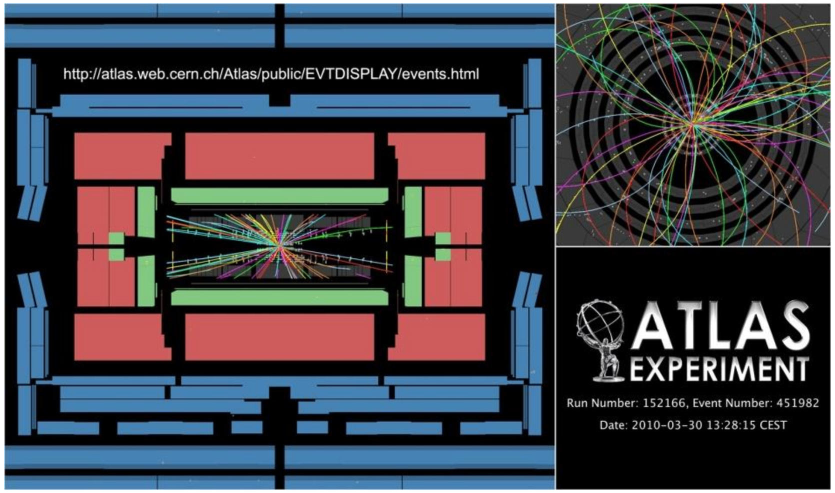
Un diagramme schématique



Produits de la collision à détecter

...et la réalité

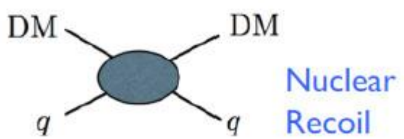




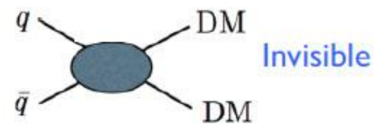
Les détecteurs consistent de composants différents spécialisés pour capturer les signaux et les produits des collisions

Le LHC a commencé ses opérations le 30. mars 2010

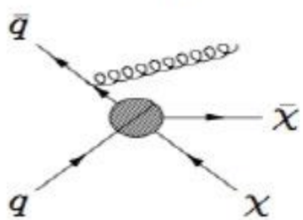
DIRECT DETECTION & LHC → MONO-JETS

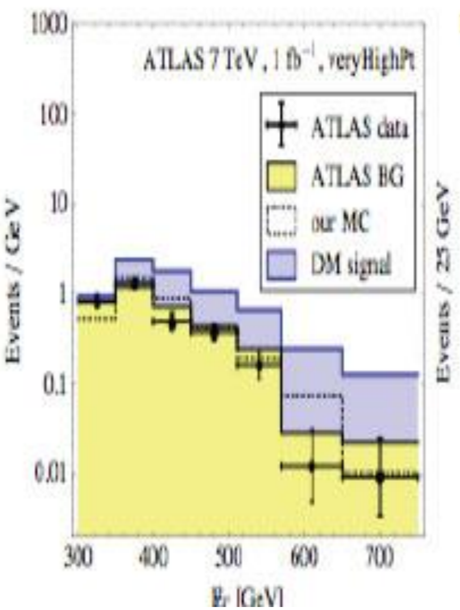


Direct searches (non-relativistic)



LHC searches (highly relativisic)



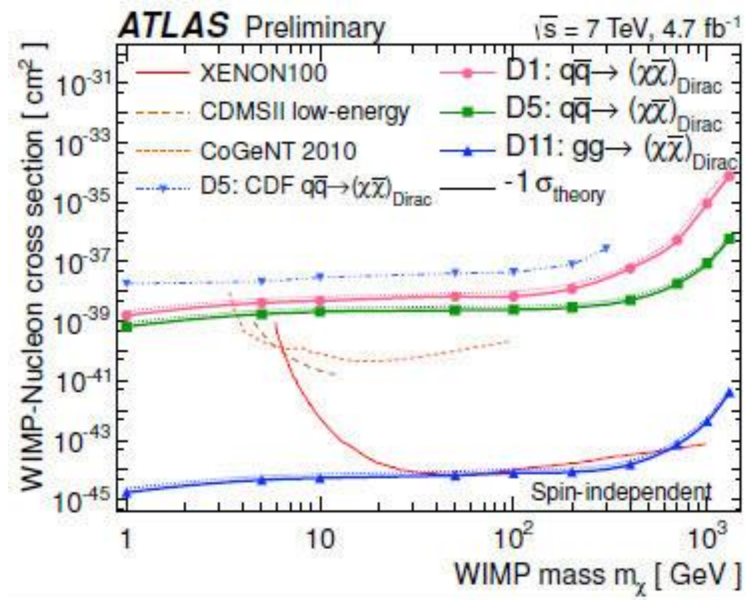


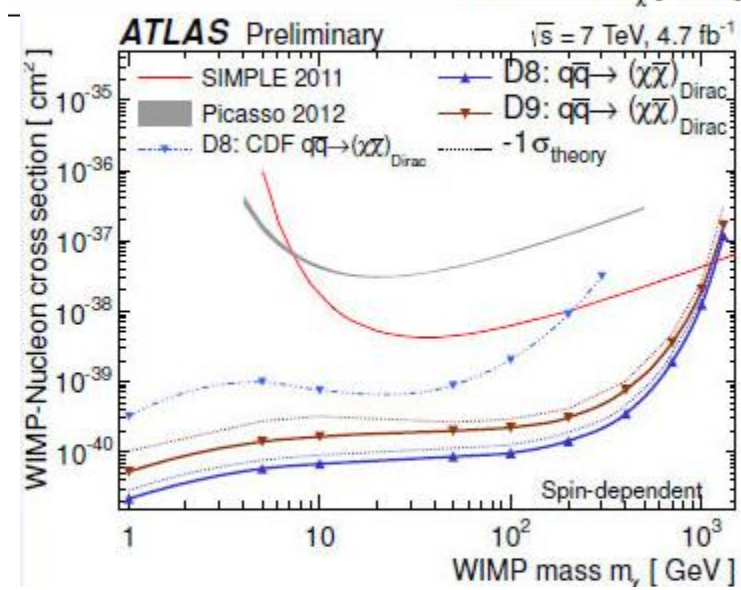
- Tagging by j / γ + E_t^{miss}
- Search for excess
- Suppose contact interaction
- Relate to direct $\sigma_{SI,\ SD}$

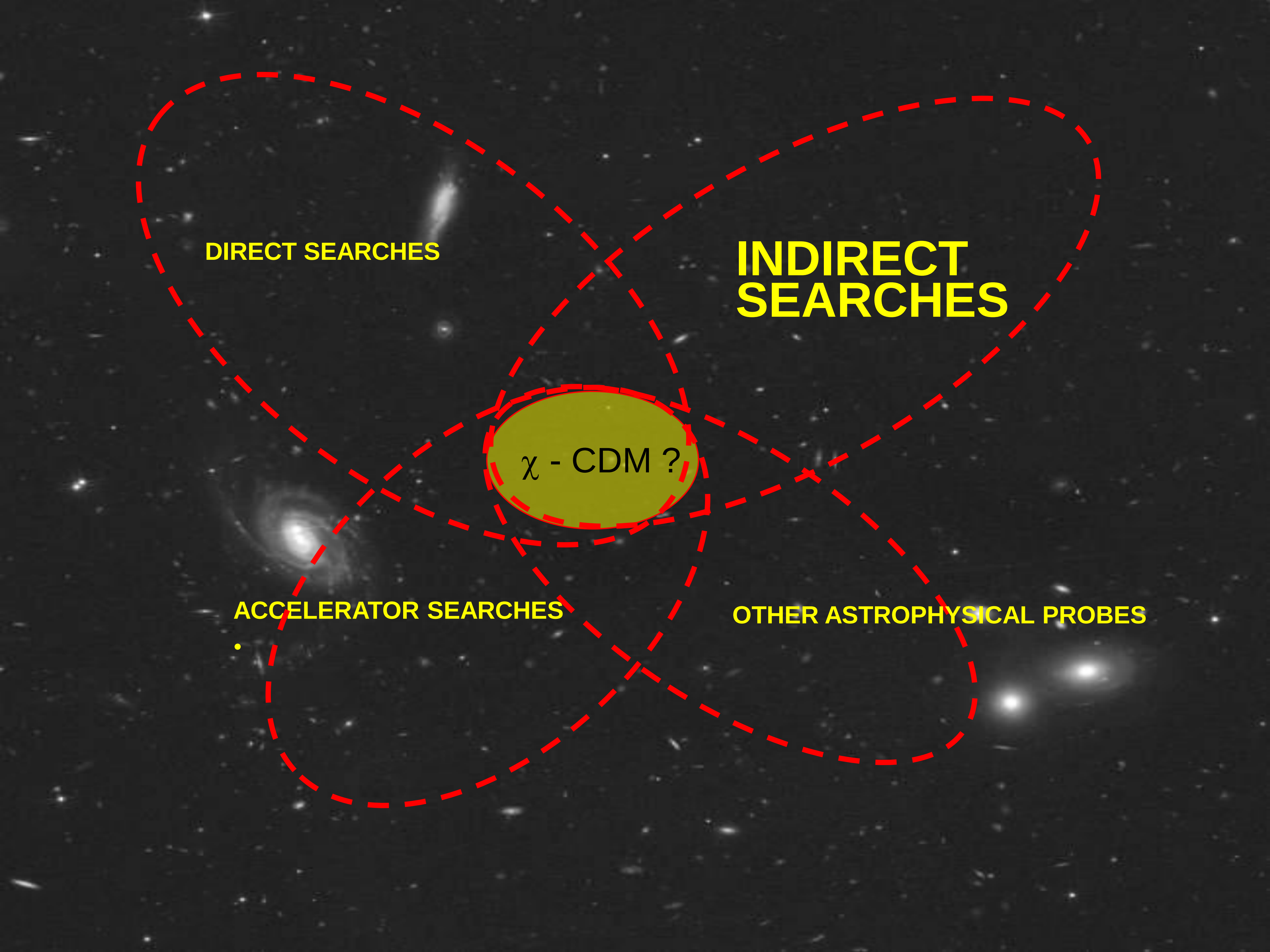
Impressive limits….

BUT:

...works only well for mediator masses > few TeV






DIRECT SEARCHES
INDIRECT SEARCHES
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INDIRECT SEARCHES

Principle:

- Observation of annihilation products
- γ- rays from galactic centre
- Anti-matter from galactic halo
- ν's from the sun etc

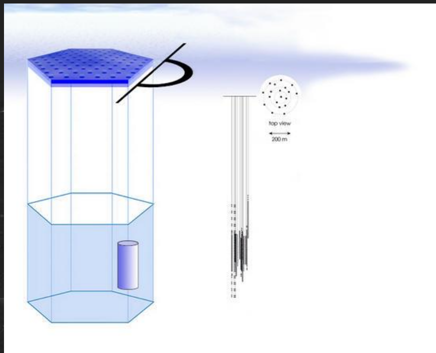
Observable quantities:

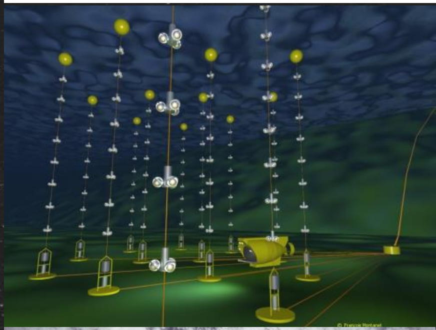
- Neutralino mass M_{χ},
- annihilation cross section σ_{ann}
- annihilation modes $b\bar{b}, W^{+}W^{-}, t\bar{t}, \tau^{+}\tau^{-}$
- elastic scattering X- sections $\sigma_{SD,SI}$
- $\rightarrow$ MSSM parameters

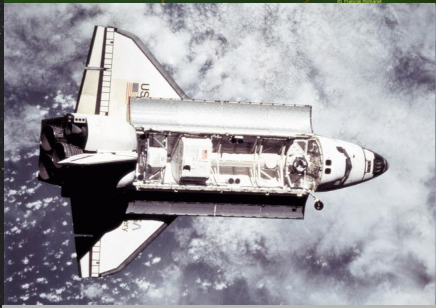
Experiments:

In space: AMS, EGRET, GLAST, PAMELA, FERMI…

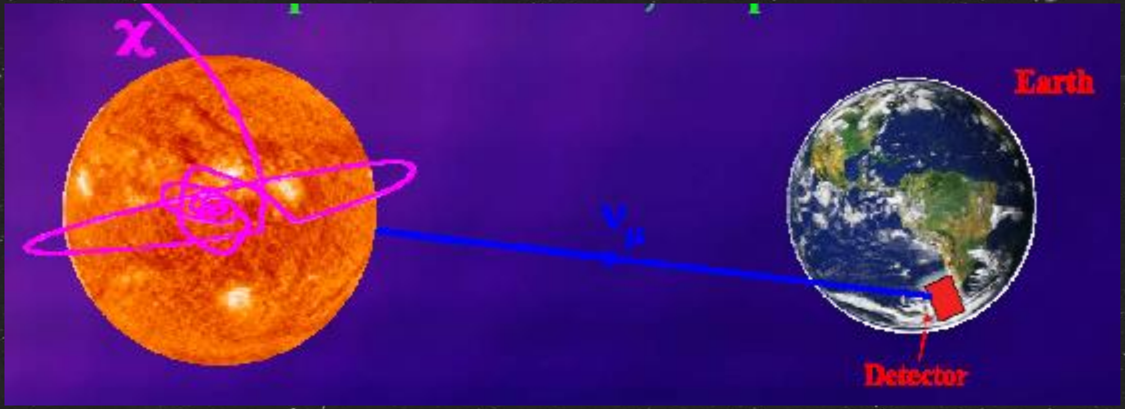
On Earth: Amanda, Antares, IceCube, Nestor, Hess,HEAT, SuperK, VERITAS,







NEUTRALINO ANNIHILATION IN THE SUN



- χ's scatter off protons by elastic scattering in the sun $\rightarrow \sigma_{SD,SI}$
- loose energy and are trapped in the sun's central region

$$R_c\left(\sec^{-1}\right) \approx 10^{18}\left(\frac{\sigma_{\chi p}}{10^{-8}\,pb}\right)\left(\frac{100GeV}{M_\chi}\right)^2$$

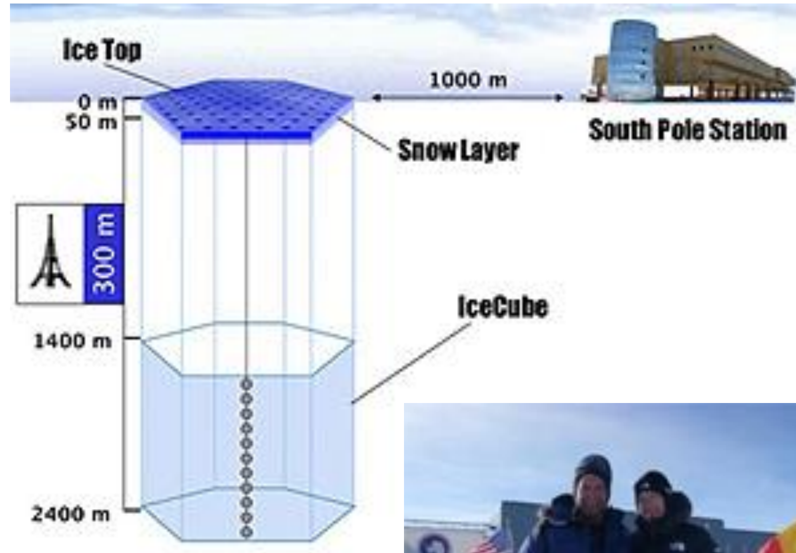
After billions of years annihilation & capture rates in equilibrium

$\rightarrow$ Only neutrinos escape the sun's interior!

ICE CUBE

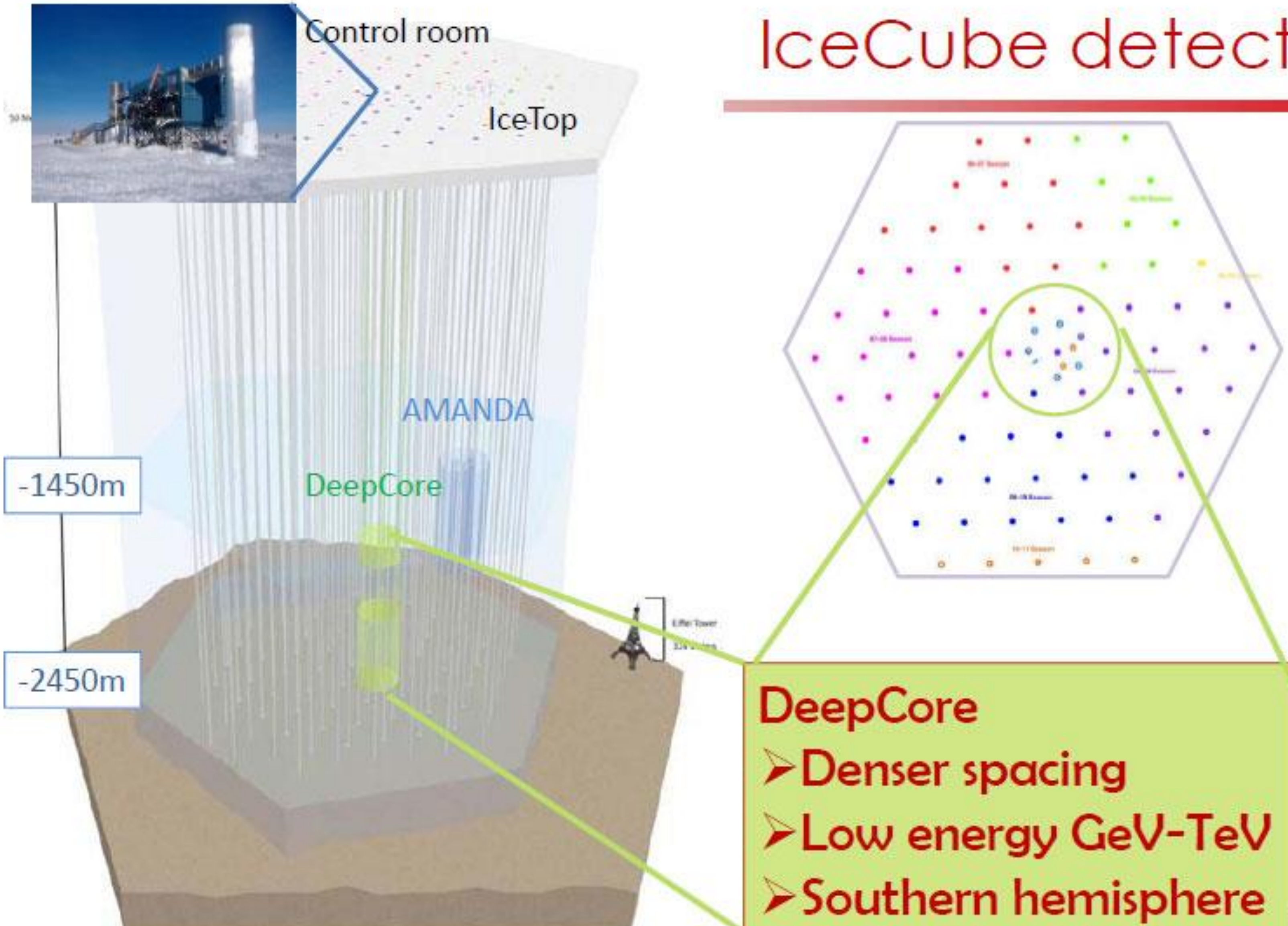
Ice Cube at the south pole

In flight to antarctica ~ 48h from Los Angeles



- Study of high energy neutrinos
  but from « Down Under »

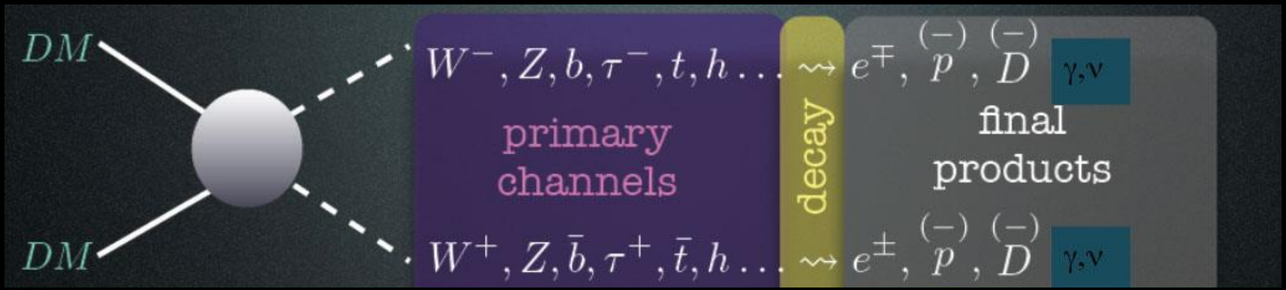
IceCube detector

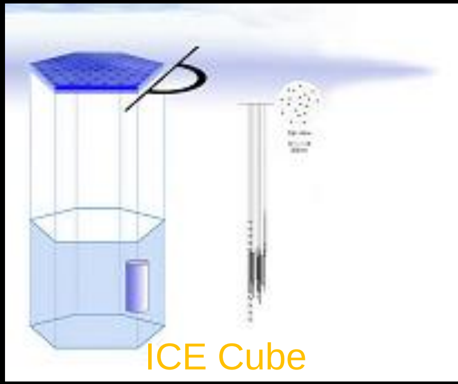


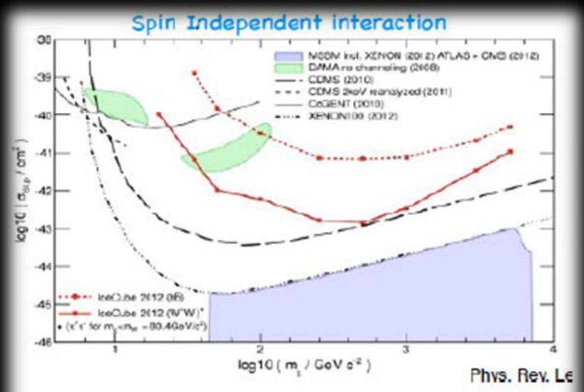
DeepCore

- Denser spacing
- Low energy GeV-TeV
- Southern hemisphere

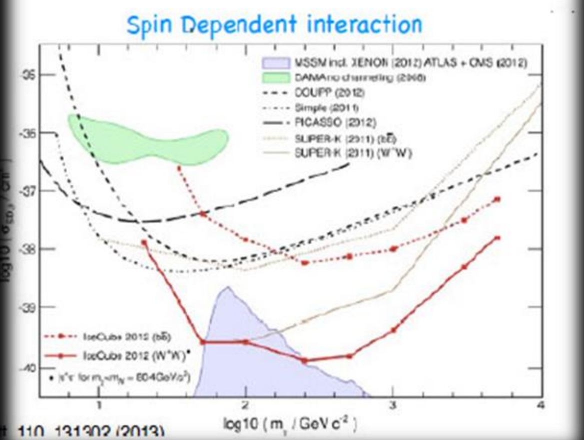
ICECUBE – ANTARES -MAGIC- HESS - VERITAS….



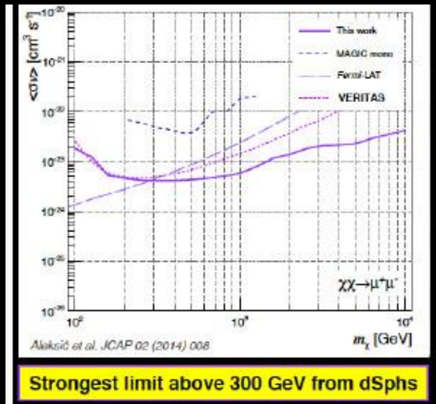


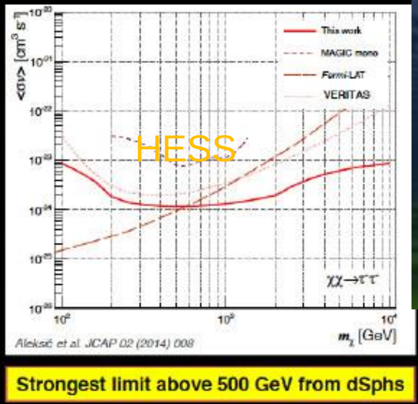


ICECUBE

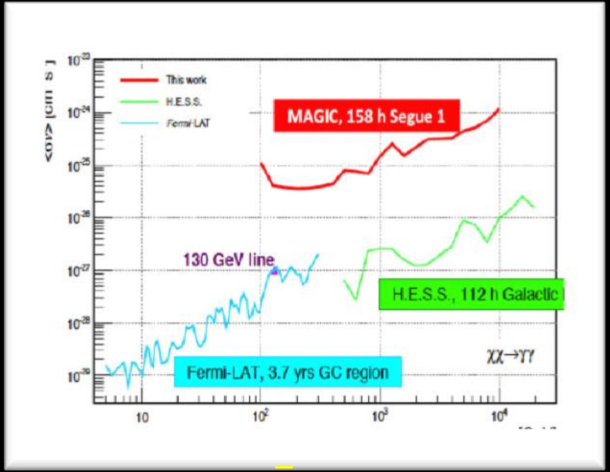


$\chi\bar{\chi} \rightarrow \ldots \nu\bar{\nu}$

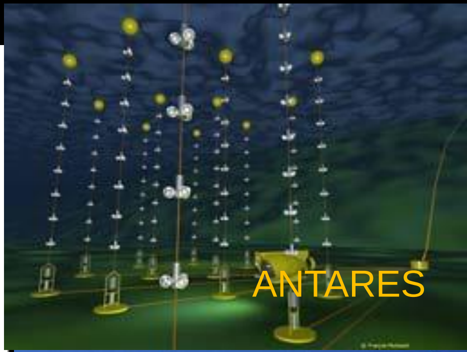




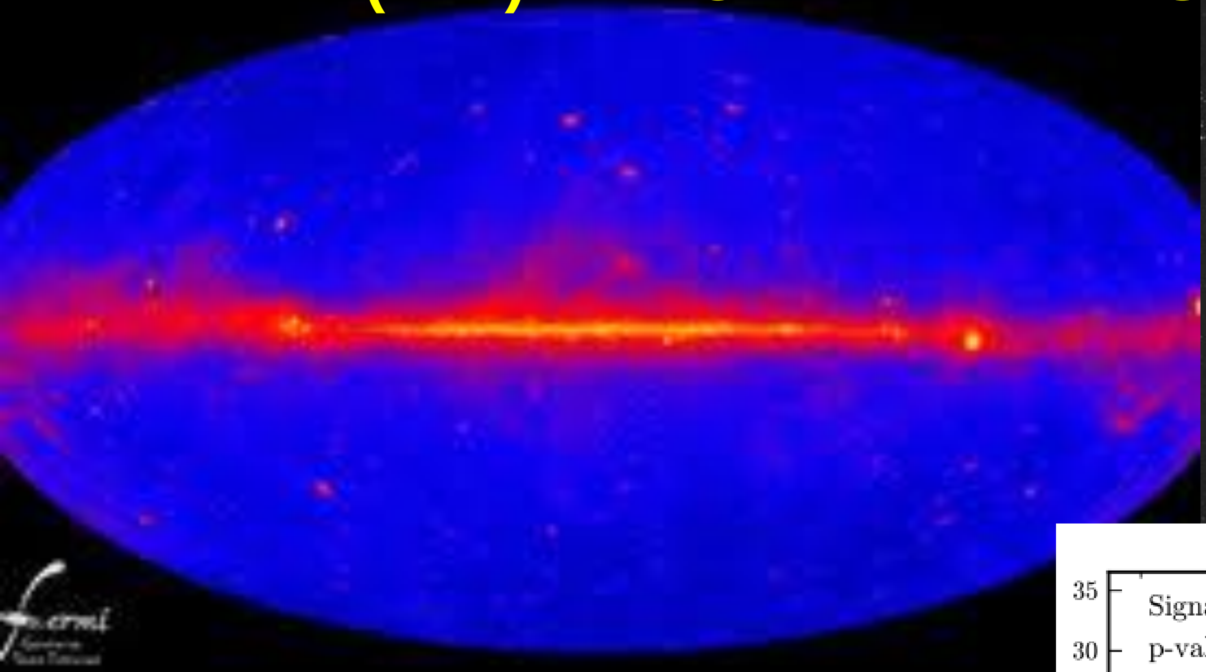
$\chi\bar{\chi} \rightarrow \mu^+\mu^-$ $\chi\bar{\chi} \rightarrow \tau^+\tau^-$



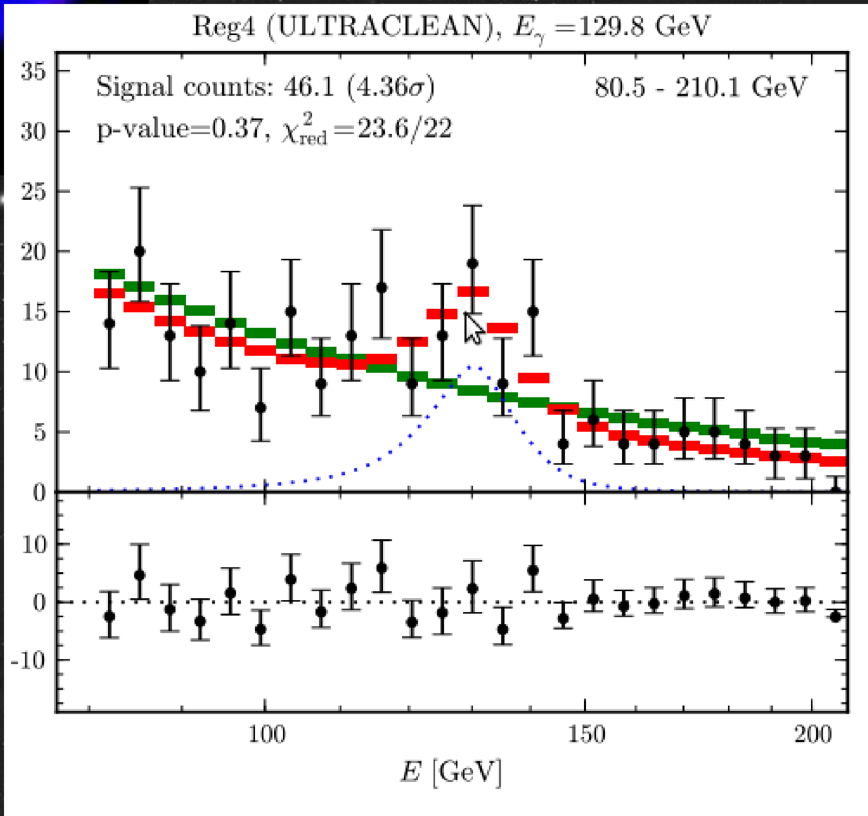
$\chi\bar{\chi} \rightarrow \gamma\gamma$



FERMI (LAT) LARGE AREA TELESCOPE

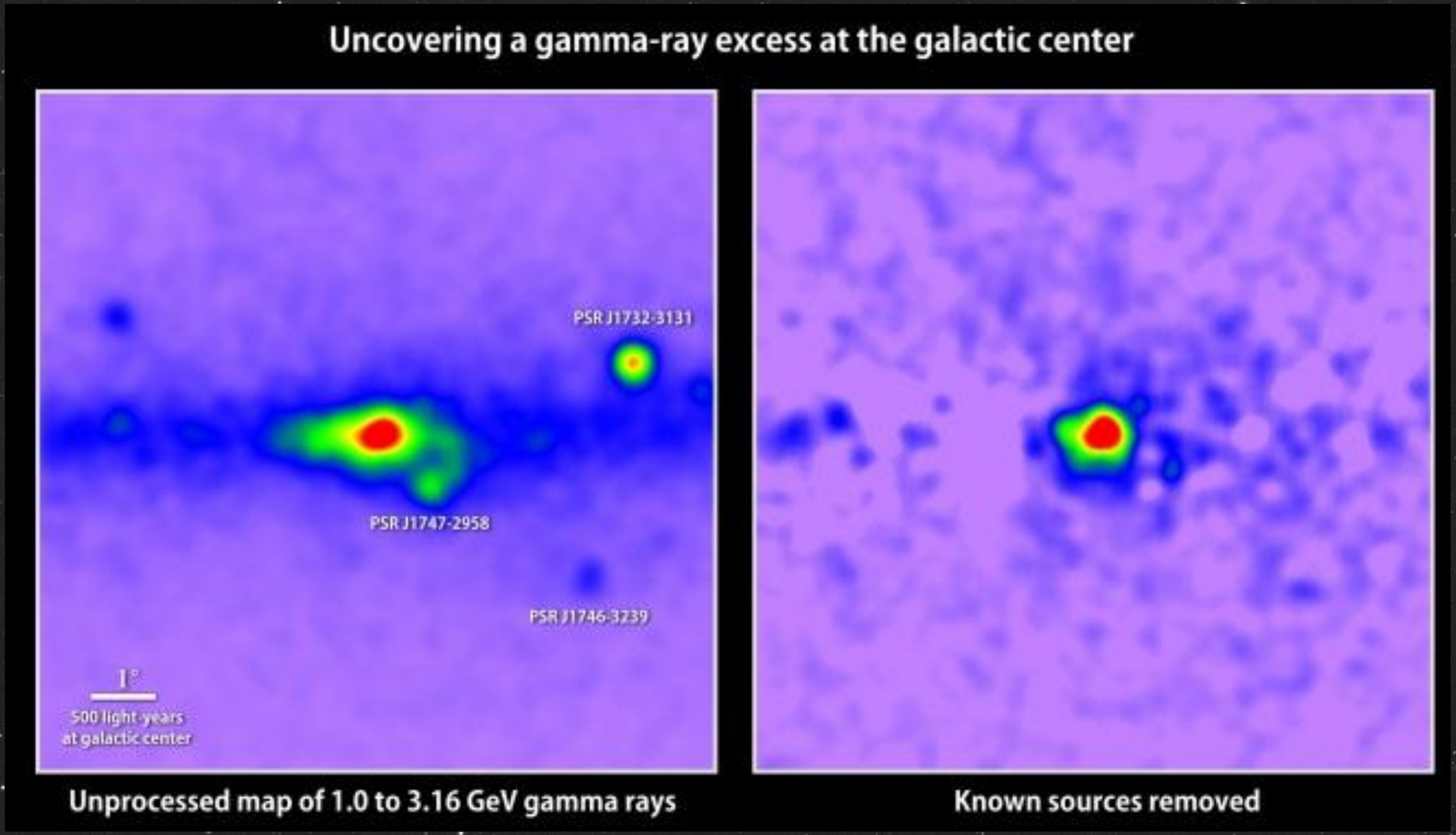


- HE γ-ray spectrometer
- Launched in 2008



- Nov. 2012 spike at 130 GeV -> gal. center
- Reanalysis: CR induced γ's in earth atm. ?
- Effect seems to fade away?

FERMI (LAT) LARGE AREA TELESCOPE

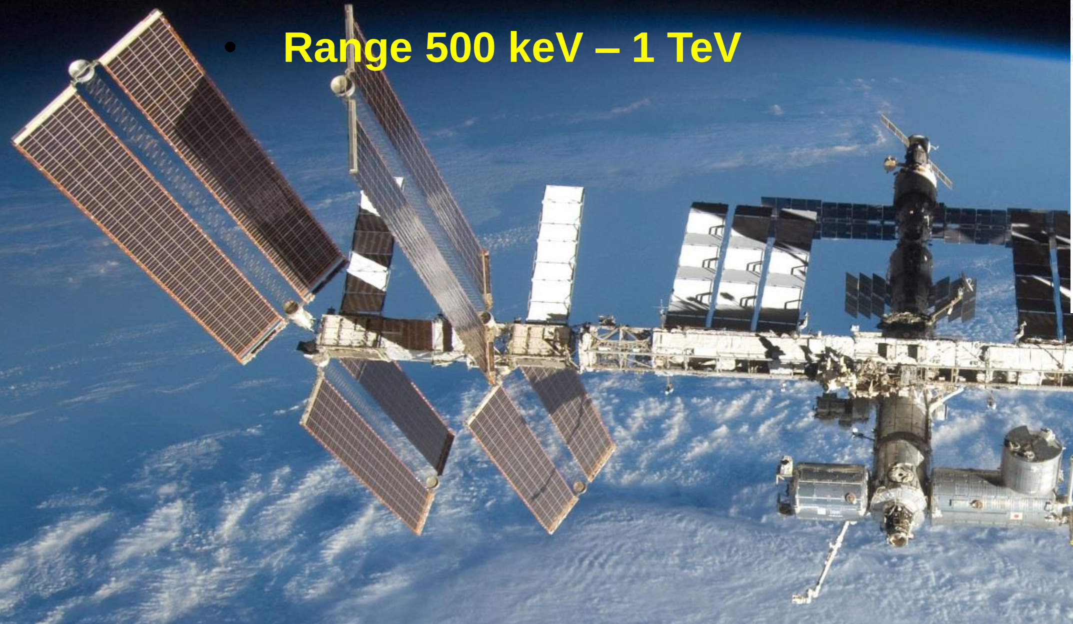


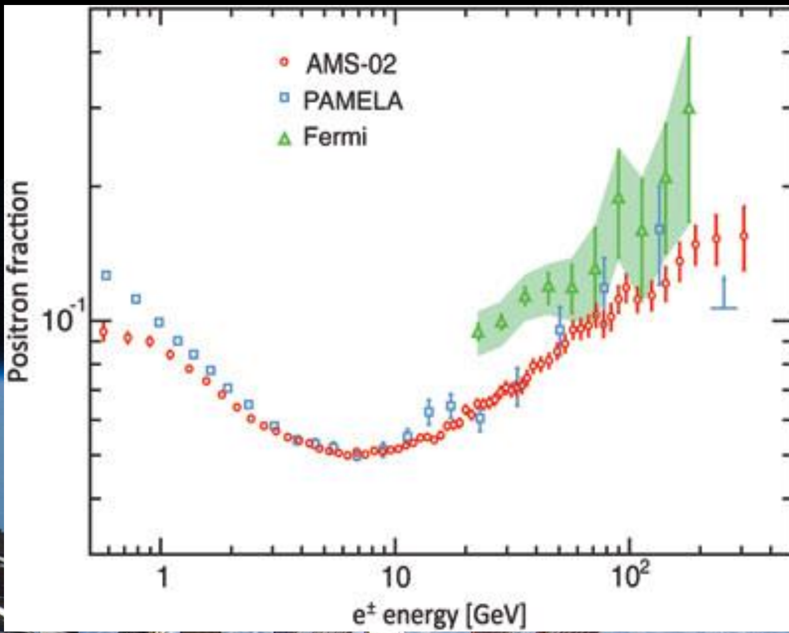
- γ rays peaked at gal. center with 7-12 GeV
- Consistent with thermal relics
- Emission distributed $\rho \sim r^{-1.3}$
- Spectrum not consistent w. msec pulsers and other backgrounds

D. Hooper et al.; arXiv: 1110.0006

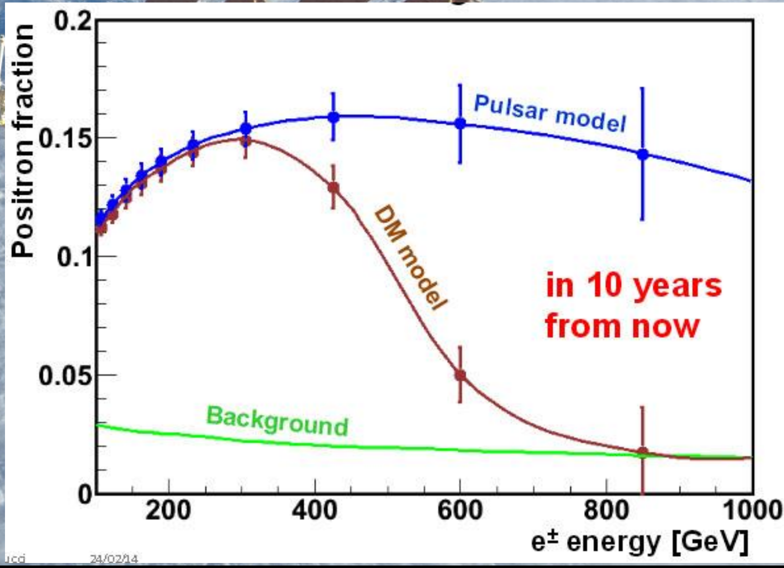
ALPHA MAGNETIC SPECTROMETER (AMS)

- Search for antimatter, $\bar{p}, e^{+}, \ldots$
- Since 2012 installed on ISS
- E.m. spectrometer 7.5t
- Supraconducting magnet 1m Ø
- Range 500 keV – 1 TeV

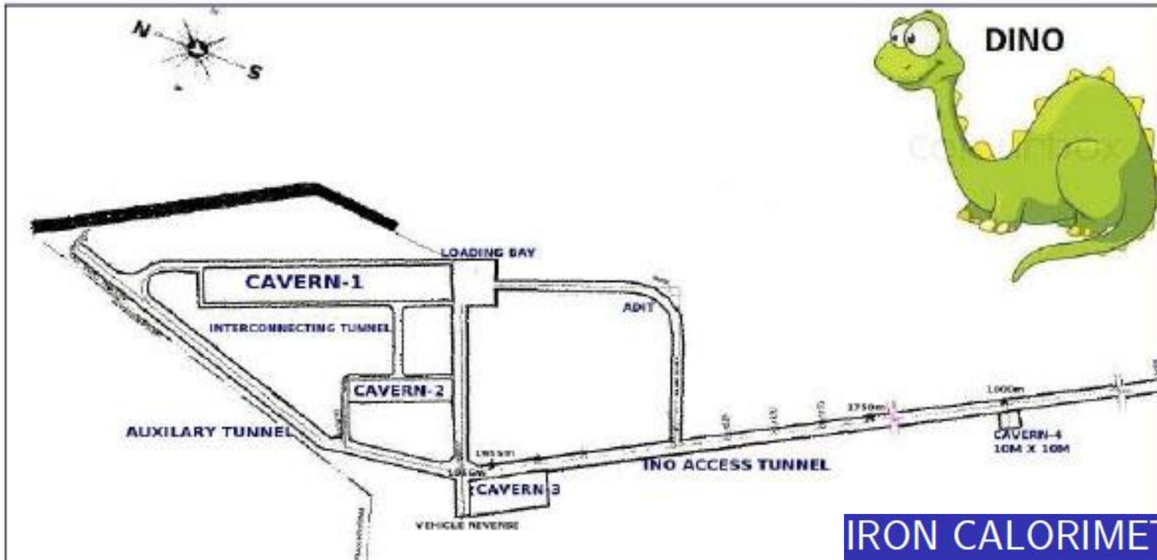




- April 4, 2013: excess of e^{+} announced
- Confirmed 09/2014
- Rate slope decreases > 20 GeV
- implies a heavy DM WIMP of ~ 1 TeV
- or a new mechanism of acceleration in pulsars



Dark-matter@INO (DINO) Ton-scale 2020



ACCESS TUNNEL 7.5m, 'D' SHAPED
ADDITIONALLY DRIVEN INT. TUNNEL 5.5m
AUXILARY TUNNEL 7.5m 'D' SHAPED
INTERCONNECTING TUNNEL 3.5m 'D' SHAPE
ADDITIONAL TUNNEL 7.5m 'D' SHAPED (futu

- **INO Lab Depth 1.3km**

CAVERN -1 : 132m x 26M x 32.5m
CAVERN -2 : 55m x 12.5m x 8.6m
CAVERN -3 : 40m x 10m x 10m
CAVERN -4 : 10m x 10m x 10m

Pott
hills

IRON CALORIMETER

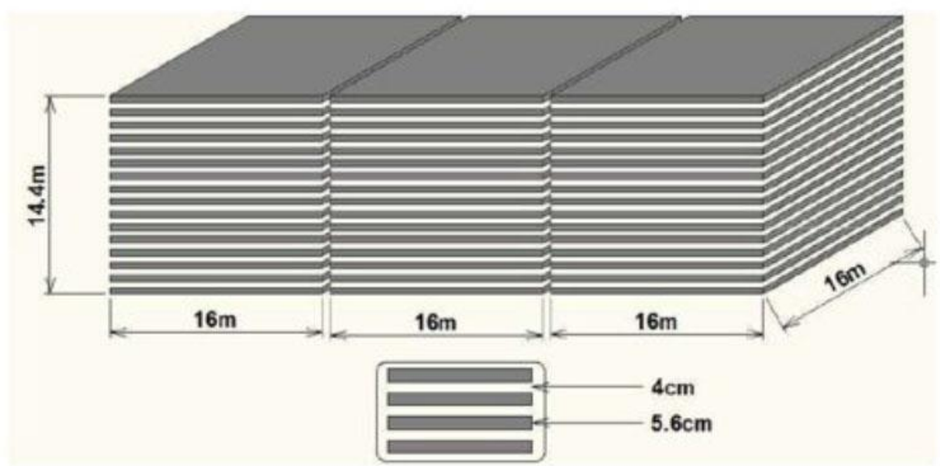
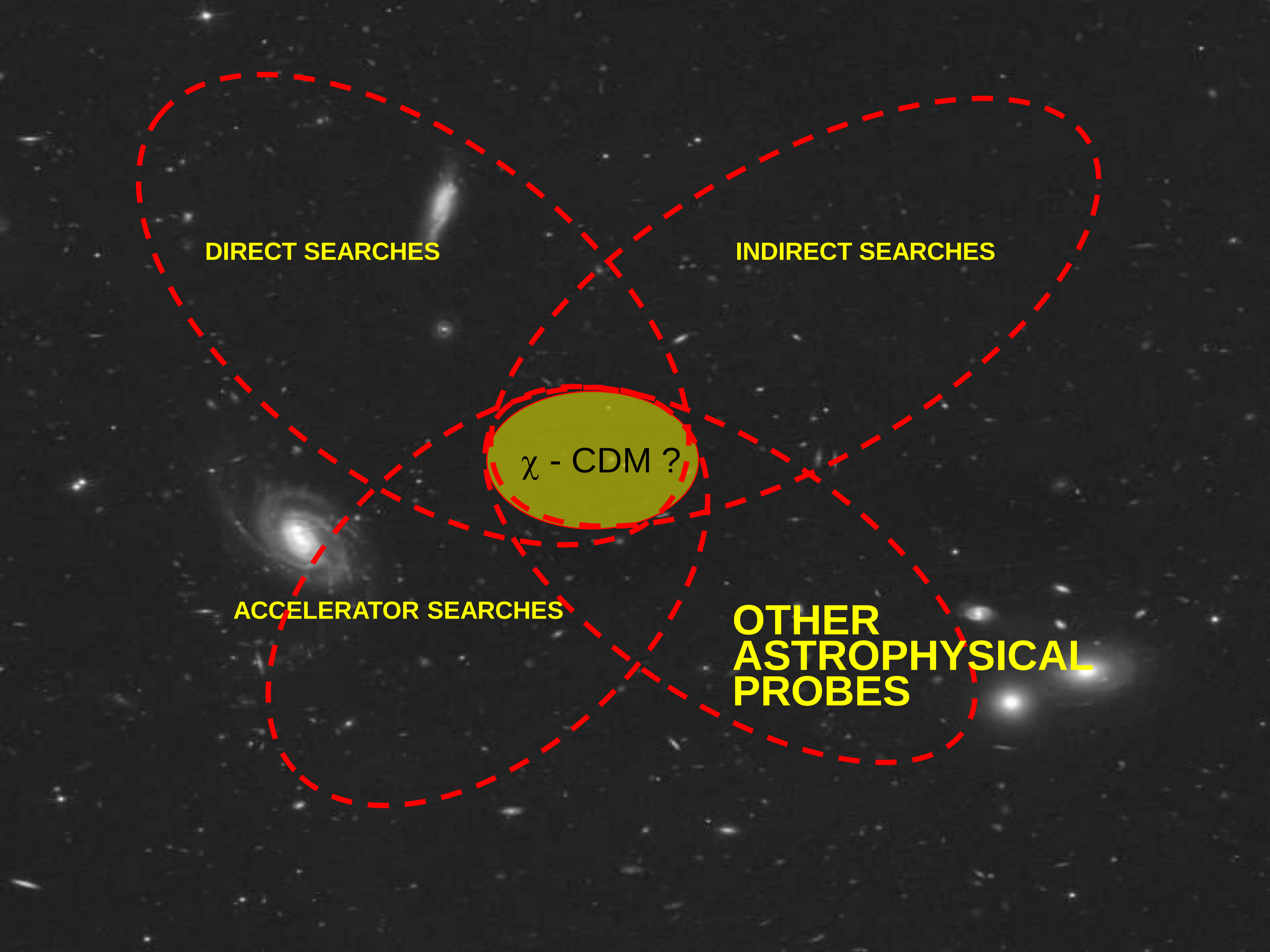


Figure: Figure Iron Calorimeter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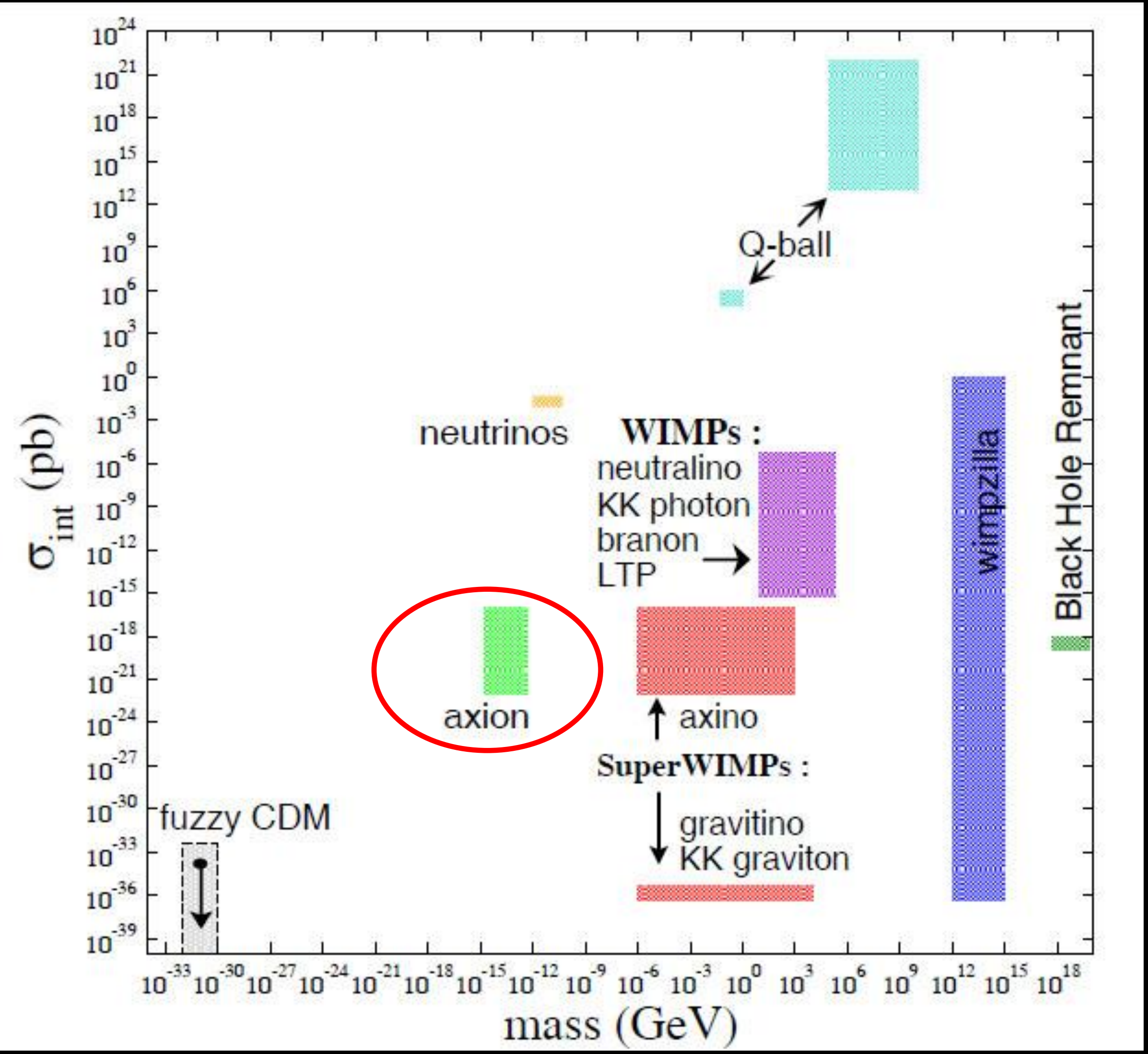
ASTROPHYSICAL
PROBES

….and search for other Candidates !

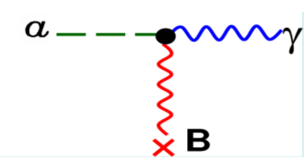


Axions !

- Solution to strong CP problem
- Early U. produced at QCD phase transition /string decays
- Form a Bose condensate
- $m_a \approx 10^{-6} – 10^{-4}$ eV
- extremely weakly interacting
- couple to e.m. field $\rightarrow$ astrophysics, lab experiments
- axion DM can resonantly decay into 2 photons

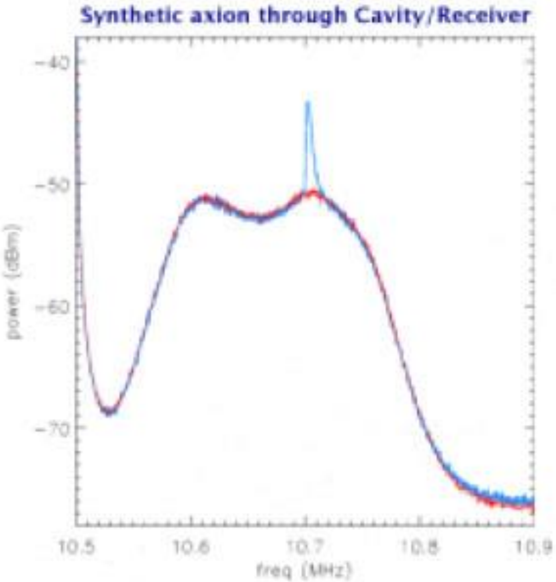
Axion Dark Matter Experiment (ADMX)

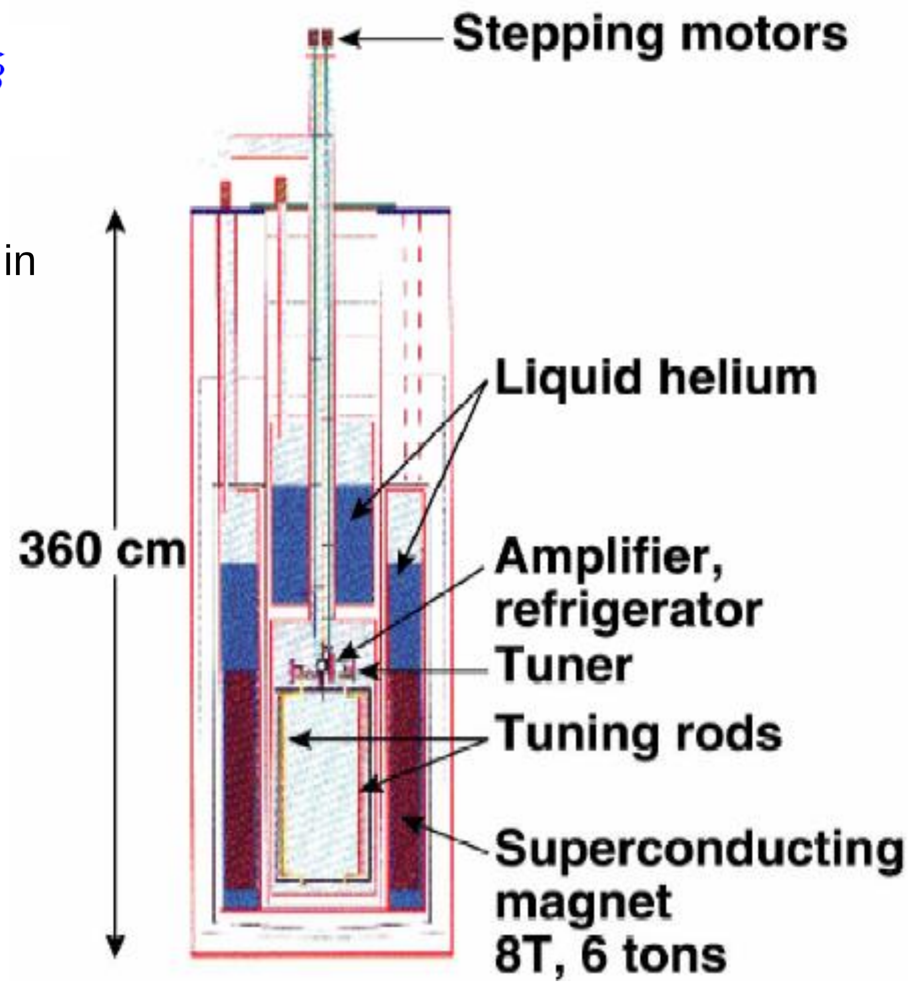
- Search for axions of the galactic halo (0.3-0.5 GeV/cm³)
- Axions couple to E & B field in a resonance cavity



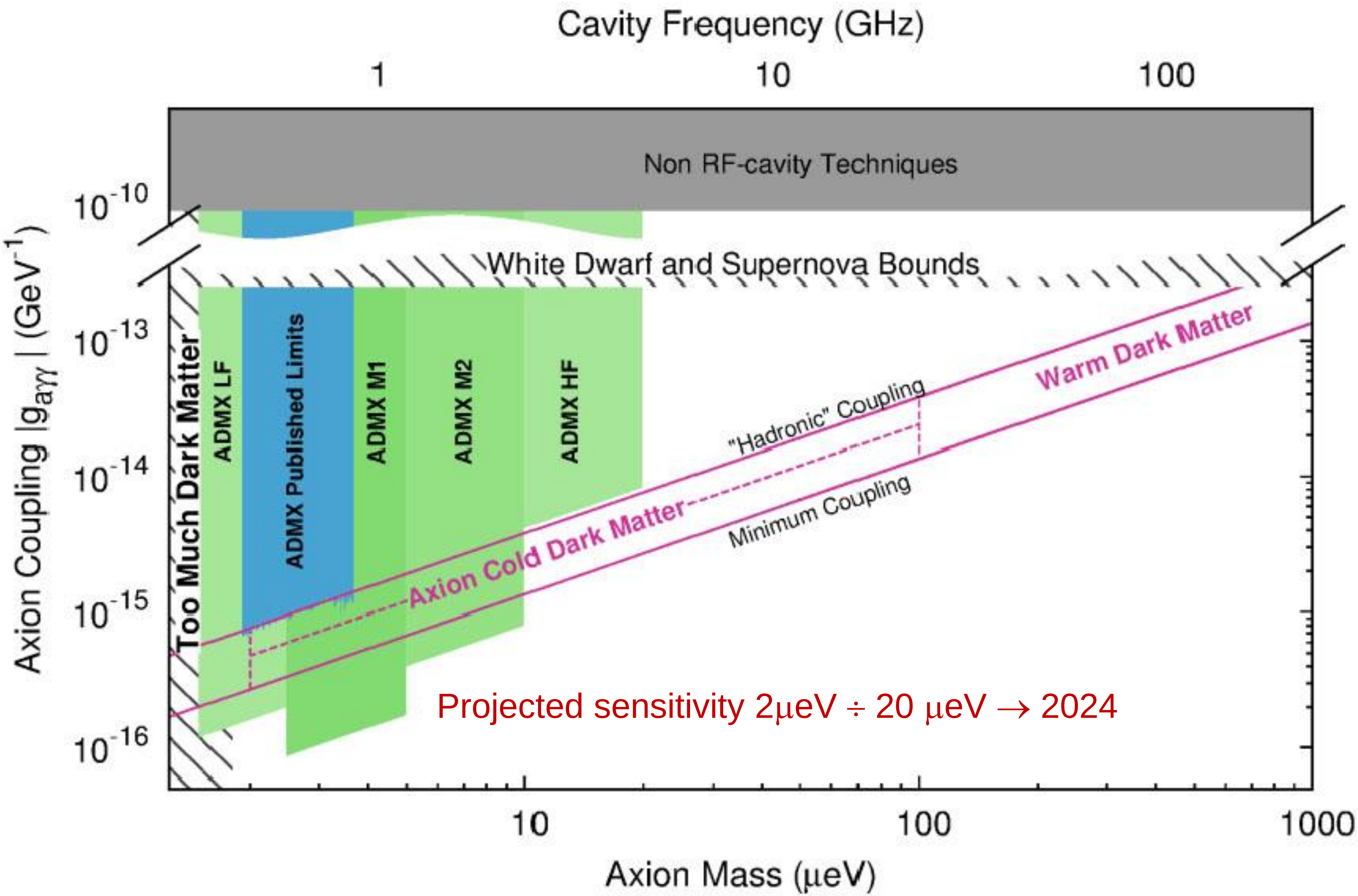
$$L_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi} \frac{a}{f_a} \vec{E} \cdot \vec{B}$$

Signal is excess power if the mode frequency in the cavity is close to the mass of the axions





AXIONS: Well Defined Search Window!



…and many other fascinating ideas:

Noble liquids threshold 10 eV sensitive to 10 MeV (Xe10)

Semiconductor targets 1ev (band gap) sensitive to 1 MeV R&D needed

Superfluid LHe

NEXT / OSPREY TPC Xenon/TMA

Anisotropic scintillators (dir. Det)

DNA detector (dir. Det.)

….

…

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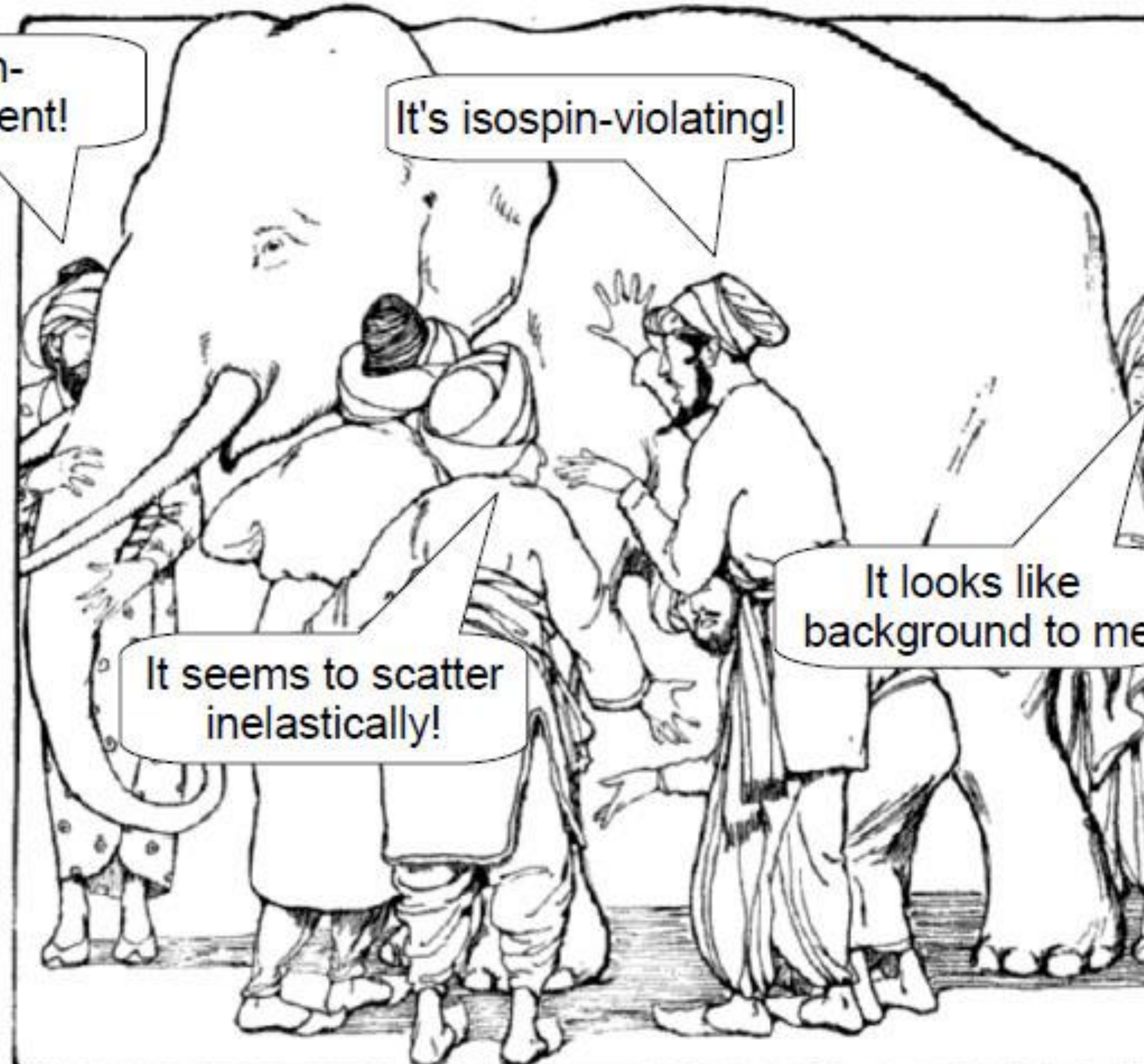
Multiple targets are critical



Scott Oser, CAP Sudbury, 2014

Summary and Caveats

- Rapid progress in field
- Direct detection most promising
- Complementarity (collider, direct, indirect searches)
- Maybe DM not as simple as thought !
- Light WIMPS theoretically well motivated !
- New paradigms (asym DM, hidden sector, axions…)
- Need different techniques & targets
- Lots of astrophysical uncertainties (halo composition)
- ….but discovery possible any time!