Direct searches for dark matter particles

Eric Armengaud - CEA Saclay

OHP - 28/11/2019

References

- Reviews on WIMPs (phenomenology, a bit old)
  - "Particle Dark Matter: Evidence, Candidates and Constraints", Gianfranco Bertone, Dan Hooper, Joseph Silk, Phys. Rept., 405 :279–390, (2005):arxiv.org/abs/hep-ph/0404175
  - "Dark Matter Candidates from Particle Physics and Methods of Detection", Jonathan L. Feng, Ann.Rev.Astron.Astrophys., 48, 495-545.5(2010):https://arxiv.org/abs/1003.0904

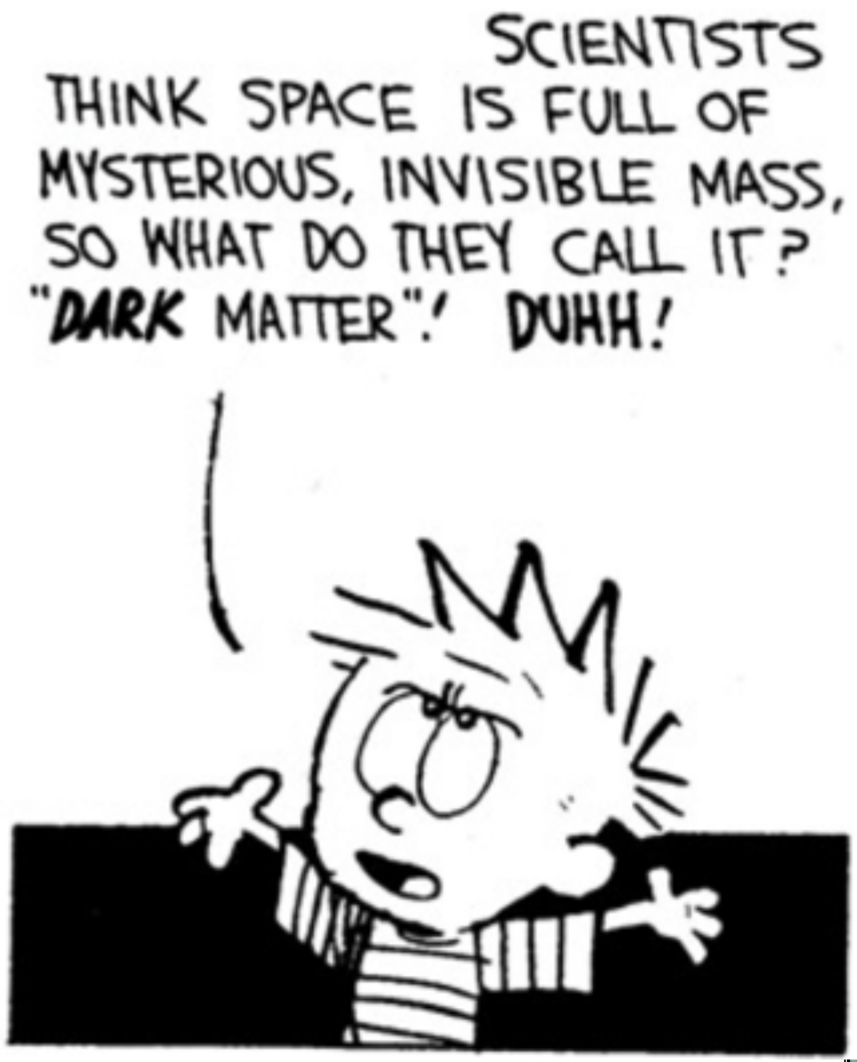
- Experimental review
  - "Dark matter direct-detection experiments", Teresa Marrodan Undagoitia, Ludwig Rauch, J. Phys., J. Phys. G43 (2016) :https://arxiv.org/abs/1509.08767

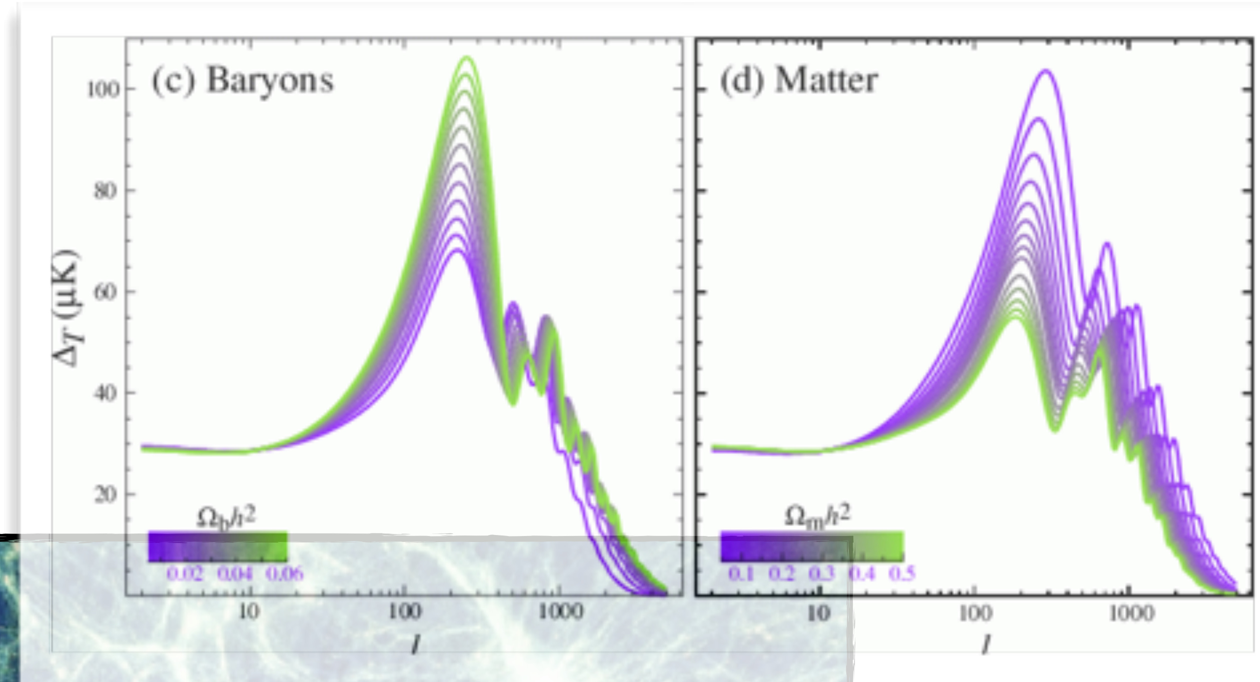
- "Seminal article" on WIMP detection
  - "Detectability of certain dark-matter candidates", Mark W. Goodman and Edward Witten, Phys. Rev. D 31, 3059 (1985) :http://hep.ucsb.edu/people/hnn/susy/goodwit/goodwit.pdf

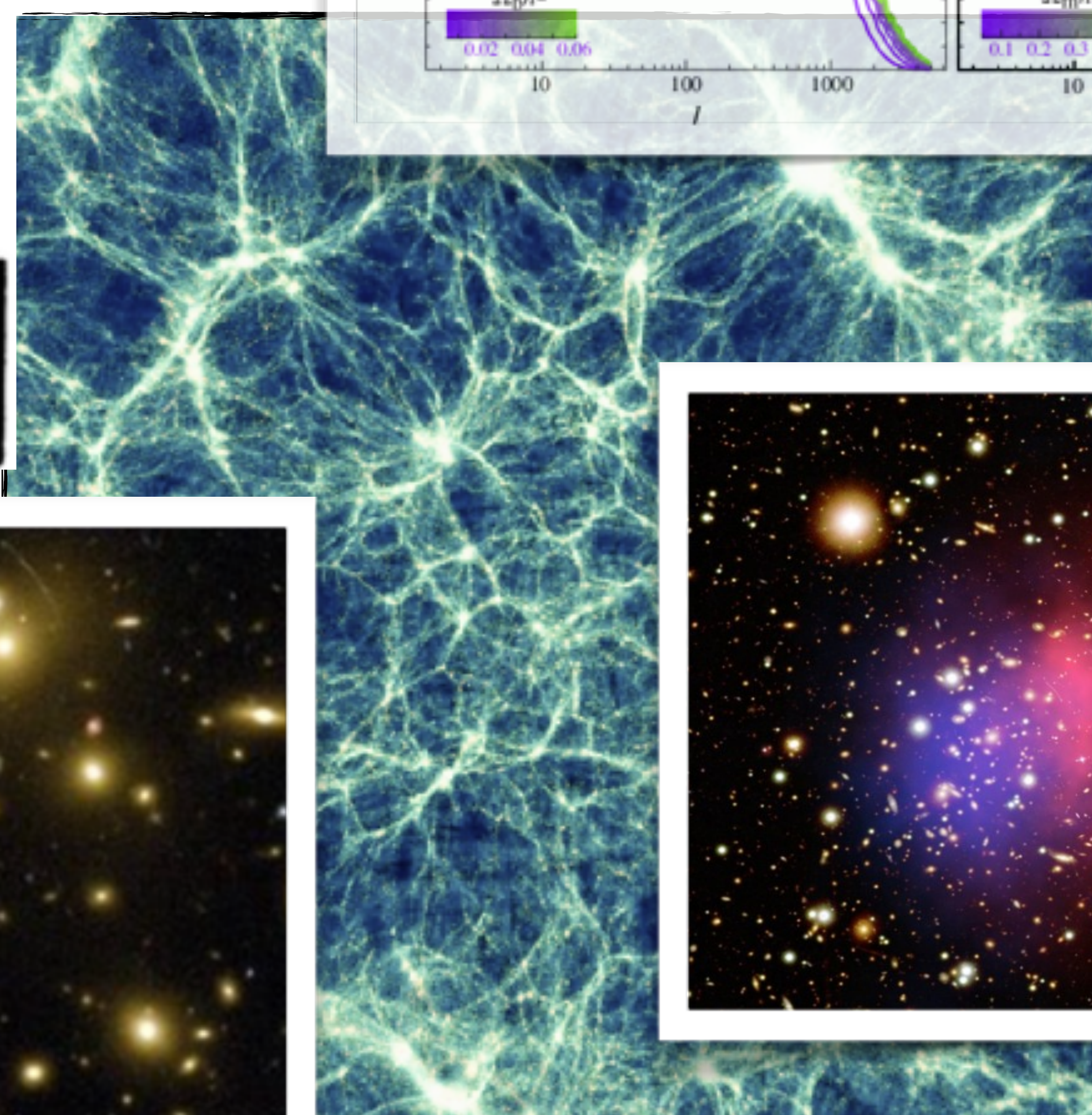
- Currently the best limit on WIMPs (most standard "channel")
  - "Dark Matter Search Results from a One Ton-Year Exposure of XENON1T", E. Aprile et al. (XENON Collaboration) Phys. Rev. Lett. 121, 111302 (2018) :https://arxiv.org/abs/1805.12562

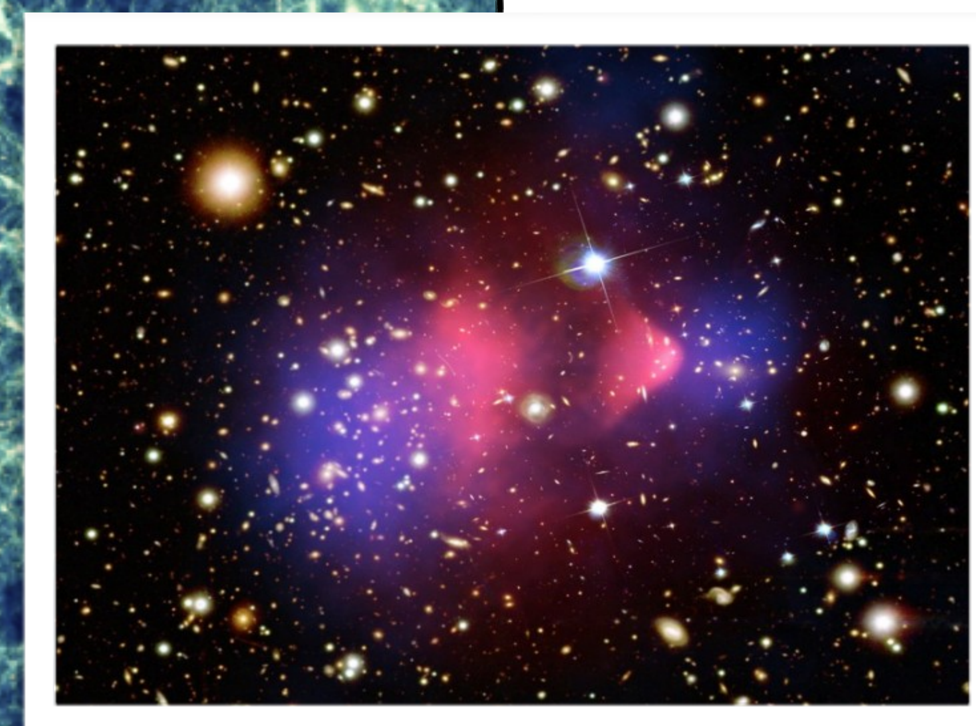
- Prospects for DM search in particular other models than WIMPs
  - "US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report", M Battaglieri et al. Phys. Rev. Lett. 121, 111302 (2018) :https://arxiv.org/abs/1707.04591

- **Dark matter and direct detection**
- WIMP direct detection
    - Principle
    - History and the example of XENON1t
    - Supplementary material
- Low mass dark matter
    - Interactions with nuclei
    - Interactions with electrons
- QCD axions
    - Axion haloscopes


SCIENTISTS THINK SPACE IS FULL OF MYSTERIOUS, INVISIBLE MASS, SO WHAT DO THEY CALL IT? "DARK MATTER"! DUHH!

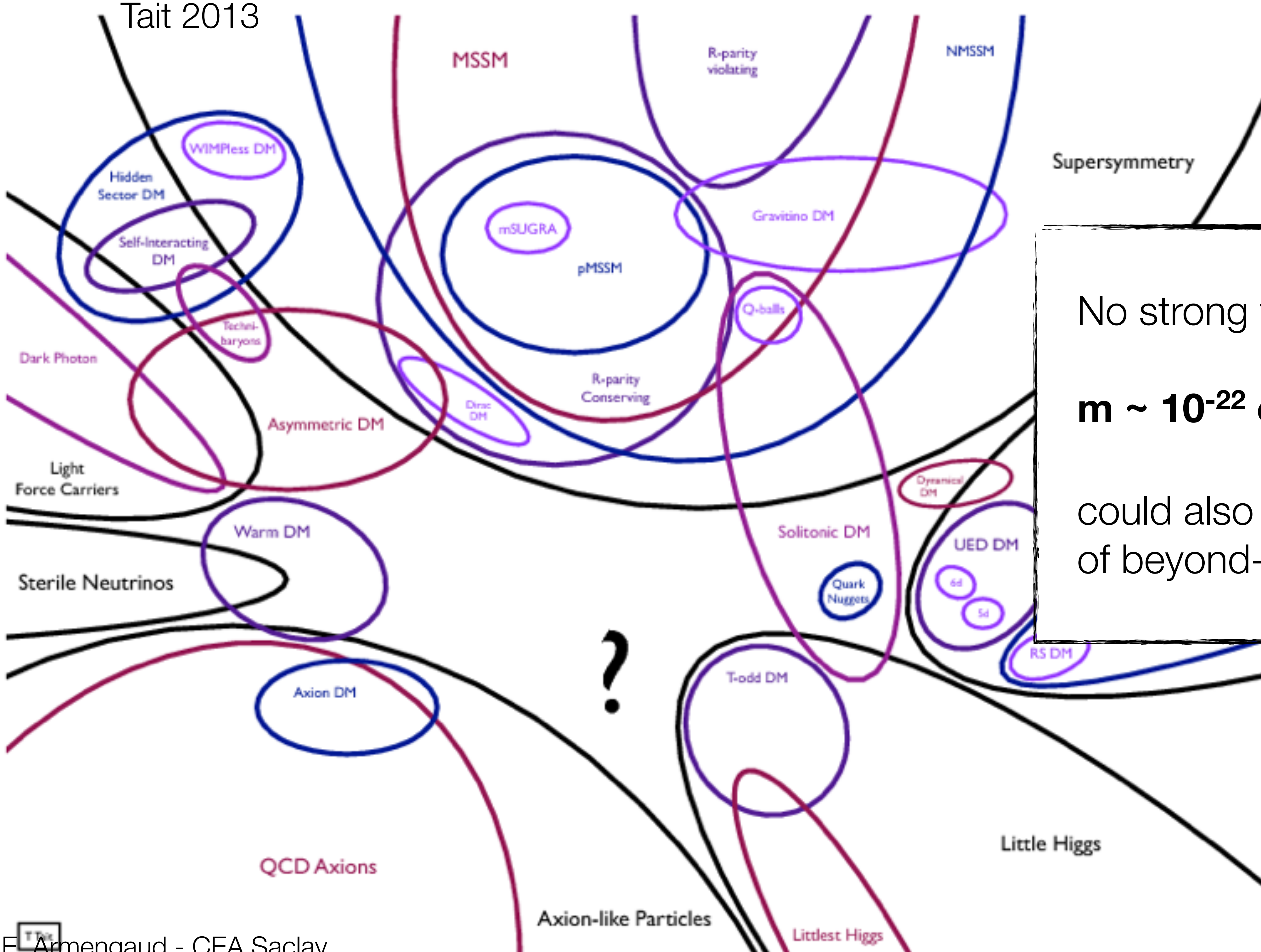

(c) Baryons
(d) Matter
Δ_T (μK)
$\Omega_b h^2$
$\Omega_m h^2$
l





What is Dark Matter ??

Tait 2013



No strong theoretical prior

m ~ 10^{-22} eV - 50 M$_\odot$

could also be a manifestation of beyond-GR gravity

« Direct detection » of dark matter

- The Earth is embed in the Milky Way halo
  local properties of that dark halo not very well measured, but unless simulations / observations are terribly wrong, we know the orders of magnitudes:
  mass density ~ 0.4 GeV / cm^3
  velocity distribution ~ maxwellian v ~ 200 km/s

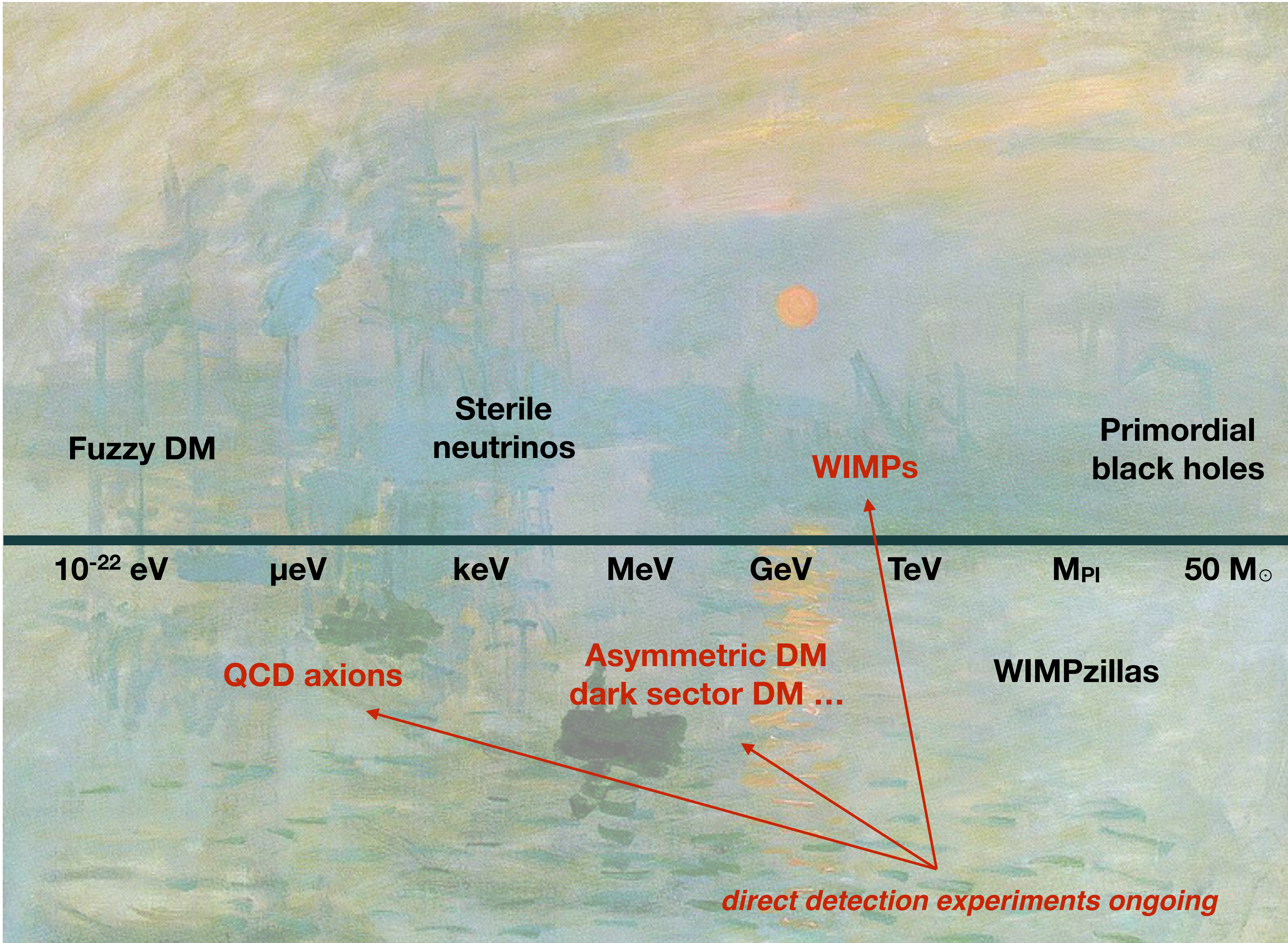
- Assume DM is made of some kind of particles

- In many scenarios, DM particles have **(non-gravitational) interactions with ordinary stuff**
  Ordinary stuff = nuclei, electrons, electromagnetic fields

  DM beam = galactic halo
  target = terrestrial detector

  If lucky enough, these (weak) interactions could be detected !
  Highly risky endeavour, but the stake is high

- Direct detection is model-dependent :
  Terrestrial detectors are designed depending on the DM scenario to be tested


Sterile
neutrinos
Fuzzy DM
WIMPs
Primordial
black holes
10^{-22} eV
µeV
keV
MeV
GeV
TeV
M_{Pl}
50 $M_{\odot}$
Asymmetric DM
dark sector DM …
QCD axions
WIMPzillas
direct detection experiments ongoing

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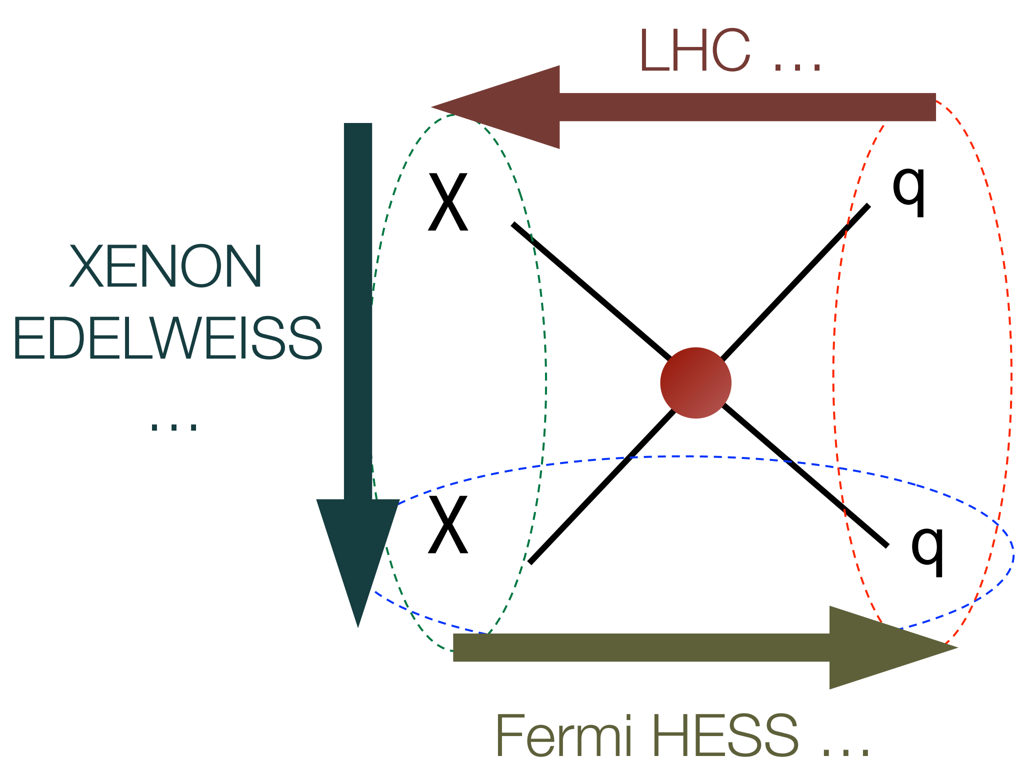
The WIMP paradigm

Assume new physics @ electroweak scale (SUSY, etc…)

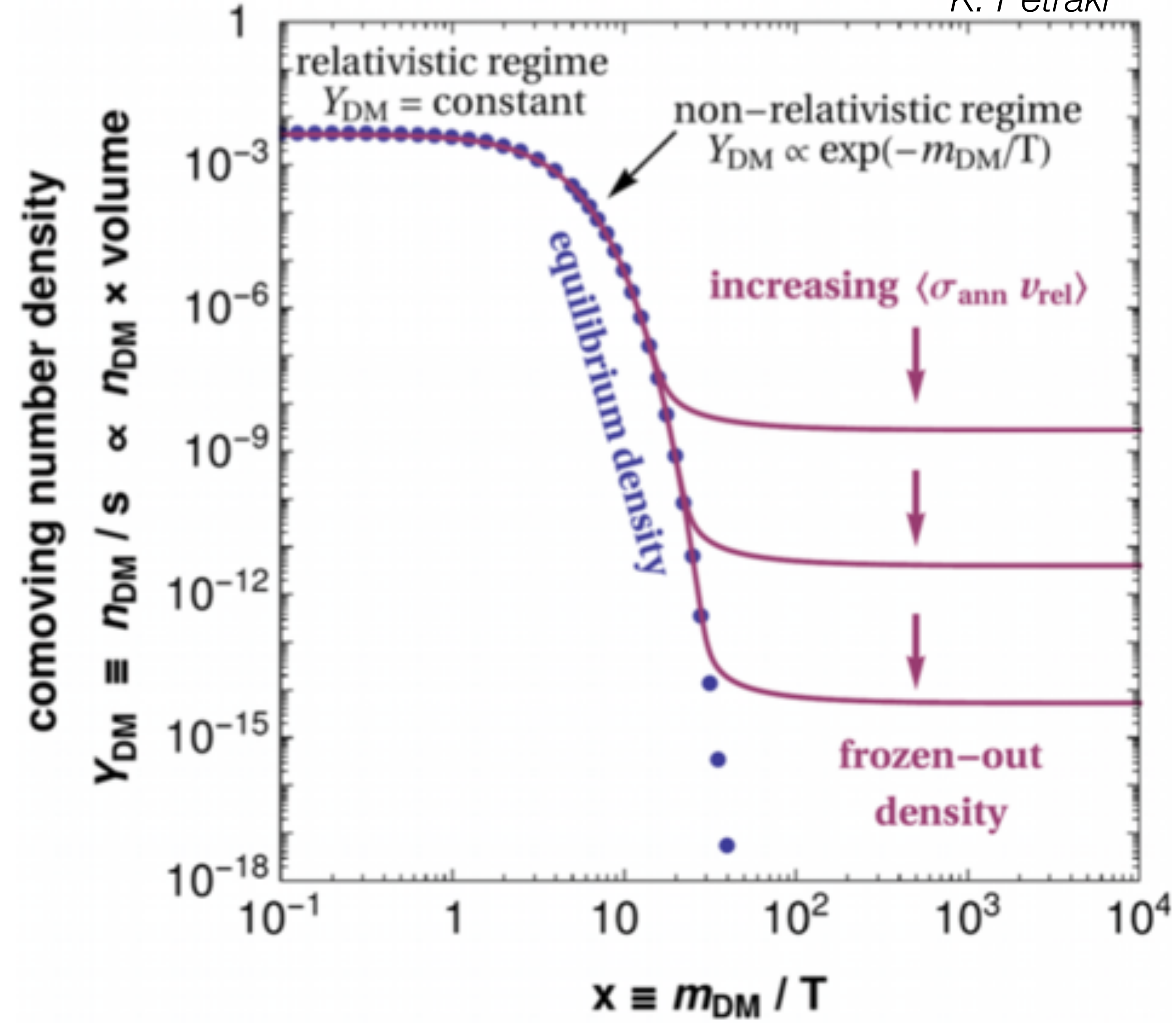
Simple thermal relic calculation
« WIMP miracle »

Collider / direct / indirect detection

Most explored DM scenario 90's - 2010's

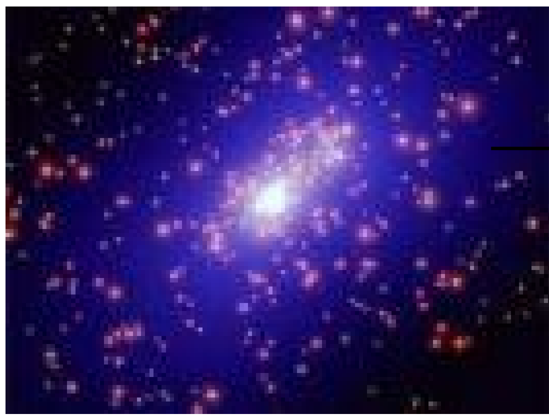


K. Petraki



$$\Omega \simeq 0.26 \times \left(\frac{1pb \cdot c}{\sigma_{ann} v_{rel}}\right)$$

Direct detection of WIMP dark matter



Galactic WIMP → Interaction in a terrestrial detector

velocity v ~ 200 km/s
local density ρ_0

θ_r

Energy deposition
Nuclear recoil E_r

WIMP mass ~ 10s - 100s GeV

$$E_r = \left(\frac{m_\chi}{2} v^2\right) \times \frac{4 m_N m_\chi}{(m_N + m_\chi)^2} \times \cos^2 \vartheta_r$$ ~ 1 - 100 keV

New EW physics + hadron physics

Astrophysics (WIMP velocity distribution and local density)

$$\frac{dR}{dE_r} = \frac{\sigma_0 \rho_0}{2 m_\chi m_r^2} F^2(q) \int_{v_{min}}^{\infty} dv \frac{f_1(v)}{v}$$

Nuclear physics

- Kinetics => search for **interactions with nuclei** (nuclear recoil NR)
- **Energy spectrum** ~ exponential
- Scales with ~ A^2 for spin-independant (SI) coupling
- **Scaling with M_{WIMP}** : low recoil energies at low M_{WIMP}

Direct detection of WIMP dark matter (2)

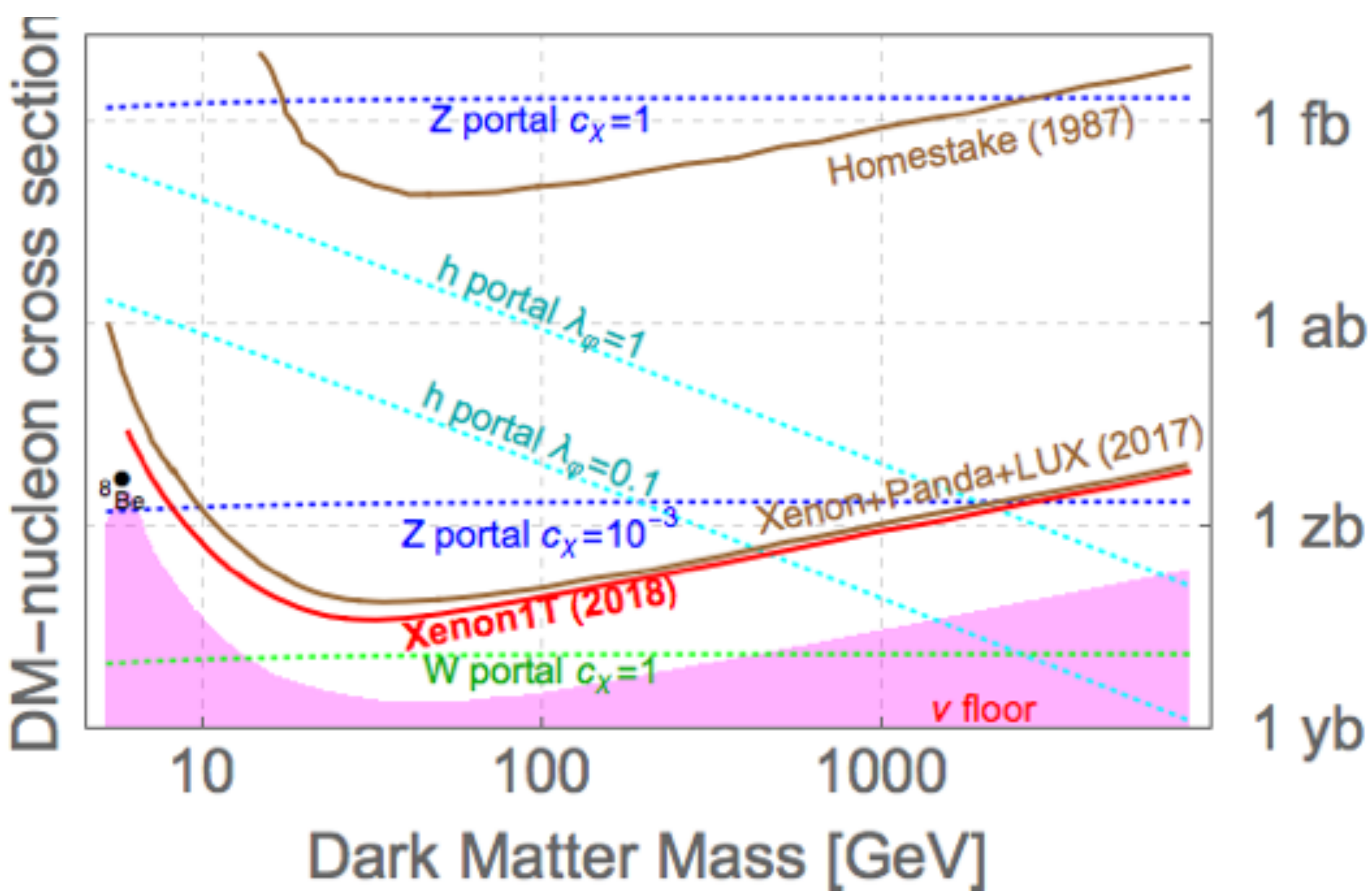
Cross-section : Highly model-dependent (structure of WIMP couplings, mediator mass…)

« spin-independant » (SI)
scales with ~ A^2 : use heavy targets

$$\sigma_A^{SI}(q \to 0) = \frac{4\mu_A^2}{\pi}[Zf_p + (A-Z)f_n]^2 \approx \frac{\mu_A^2}{\mu_p^2}\sigma_p A^2$$

« spin-dependant » (SD)
use specific isotope targets

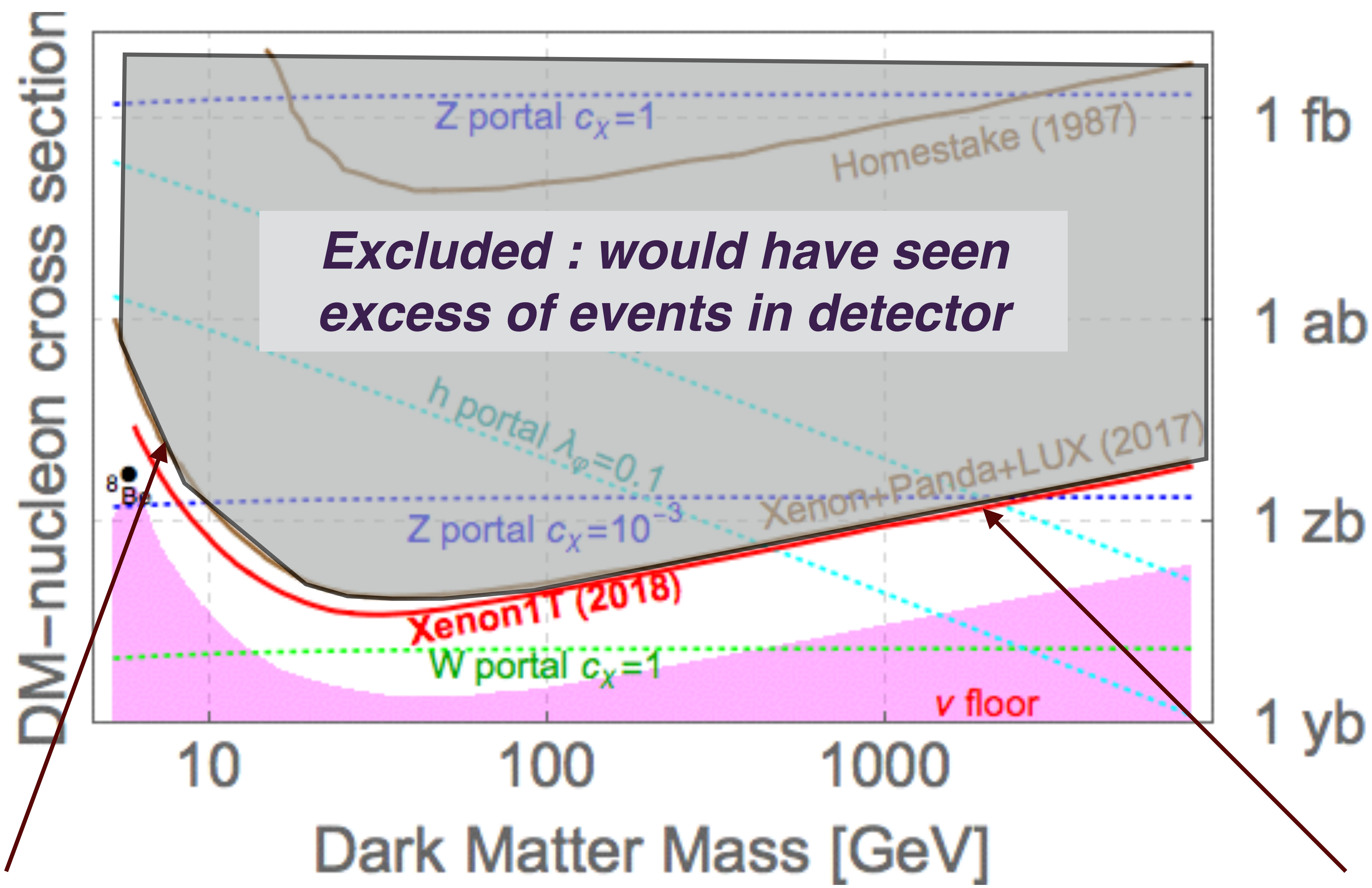
$$\sigma_A^{SD}(q \to 0) = \frac{\mu_A^2}{\mu_p^2}\sigma_{p,n}^{SD}\left[\frac{4}{3}\frac{J+1}{J}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2\right]$$



Z mediator excluded long ago

Now constraining Higgs mediator

Understanding « WIMP exclusion curves »

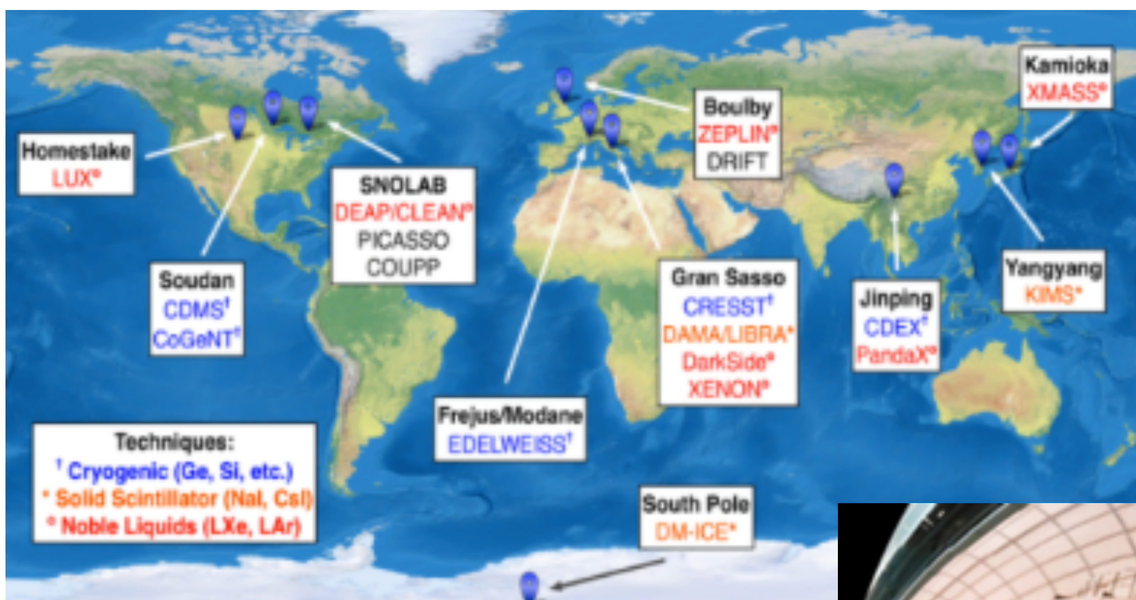


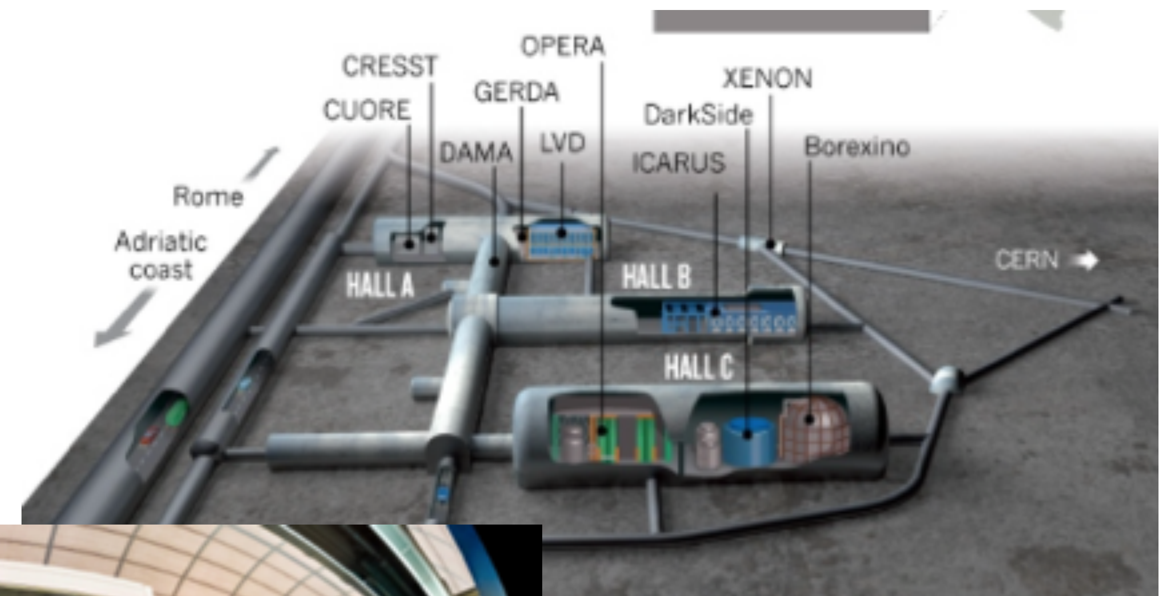
Experimental energy threshold (kinematics)

Local number density decreases when DM mass increases

WIMP detection is hard : signal vs backgrounds

Massive target (kg … tons)
Low detection threshold (~ few keV)
Radioactive backgrounds : gamma-rays, betas, alphas, neutrons...
passive rejection = underground detector, shields and vetos, radiopurity
active rejection = smart detector design





Gran Sasso

XENON1t

A wonderful playground for detector R&D

Noble liquids, cryogenic bolometers, CCDs, gazeous chambers, solid scintillators, bubble chambers…

IGEX HDMS TEXONO CoGeNT CDEX C4

BPRS NaIAD ANAIS DAMA LIBRA KIMS DM-Ice SABRE COSINE-100 PICOLON

CDMS EDELWEISS ROSEBUD CRESST EDELWEISS-II CDMS-II EDELWEISS-III SuperCDMS COSINUS CDMSlite

ZEPLIN ZEPLIN-II XENON-10 ZEPLIN-III XENON-100 LUX XENON1t LZ Panda-X DARWIN XMASS DarkSide-50 WaRP XENONnt ArDM CLEAN DEAP DEAP3600 DarkSide-G2

Newage DRIFT CYGNUS DM-TPC NEWS-dm MiMac DAMIC TREX-DM NEWS-G SENSEI

SIMPLE PICASSO COUPP PICO Paleo-detectors

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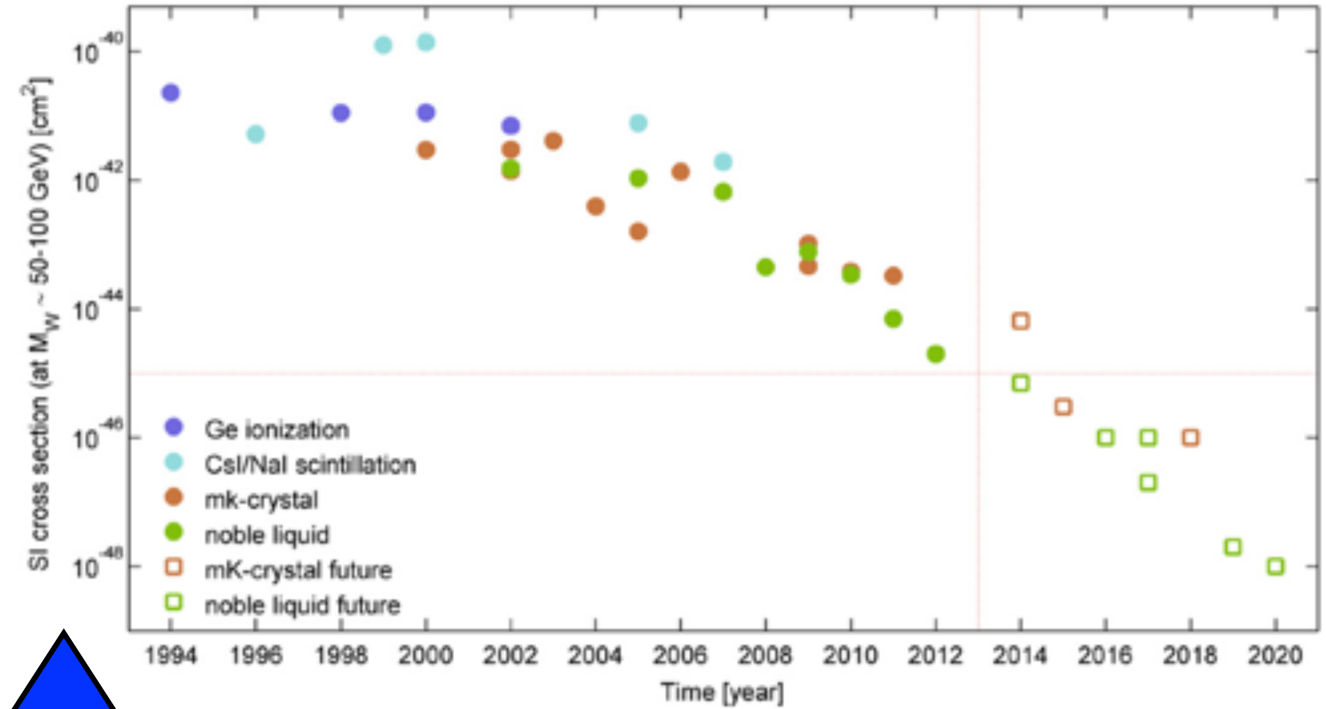
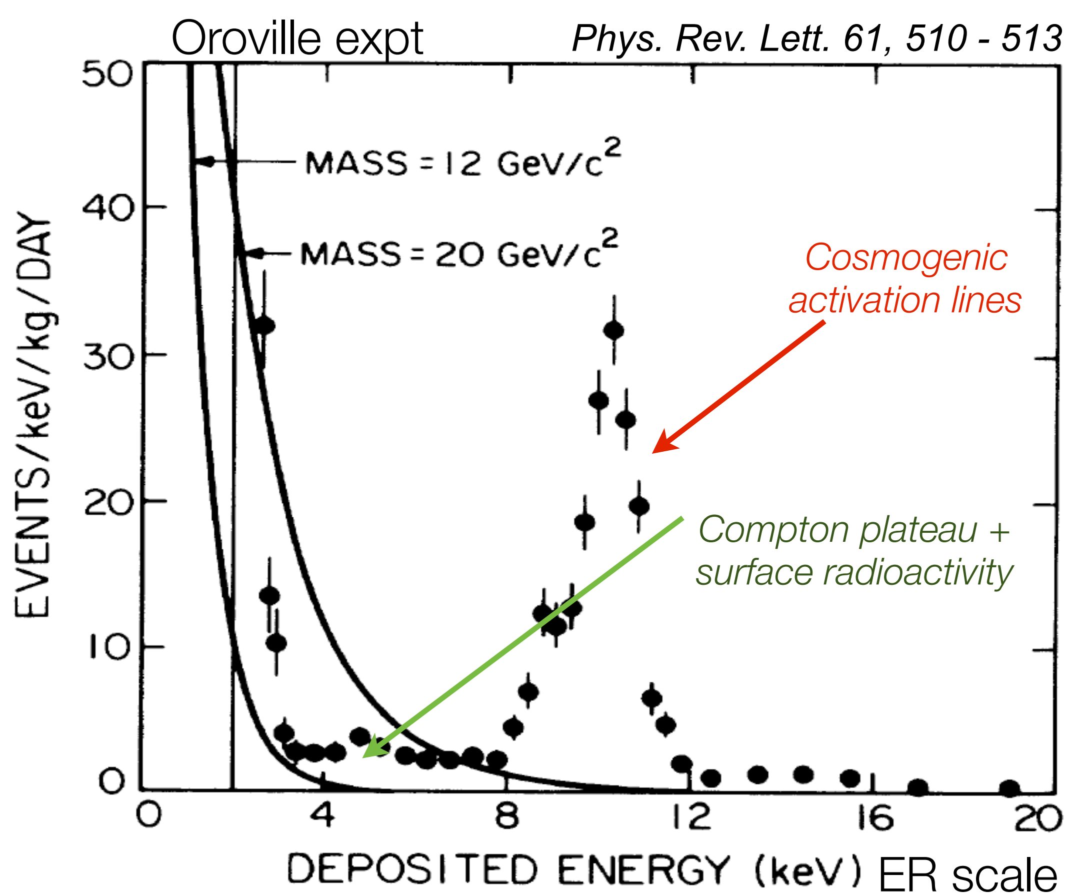
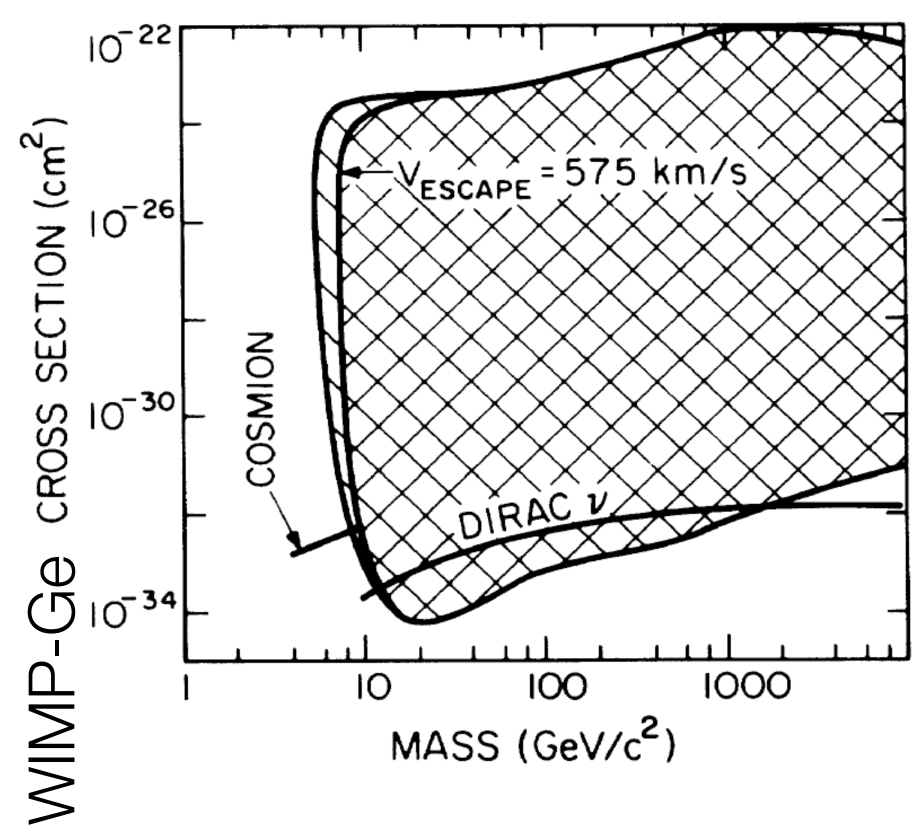
History of sensitivities

Germanium detectors (ionization)

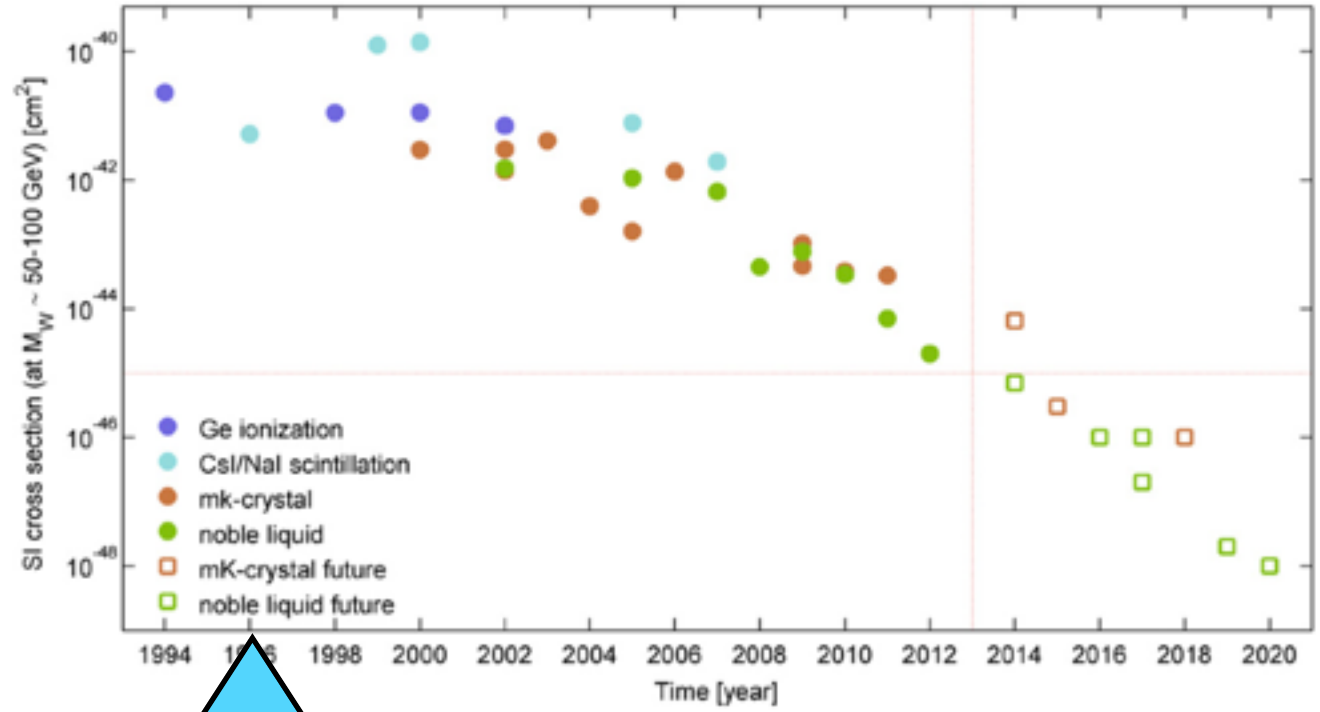
• Measure low-energy background spectrum down to ~ few keV
• **No background discrimination (electron recoils ER)**







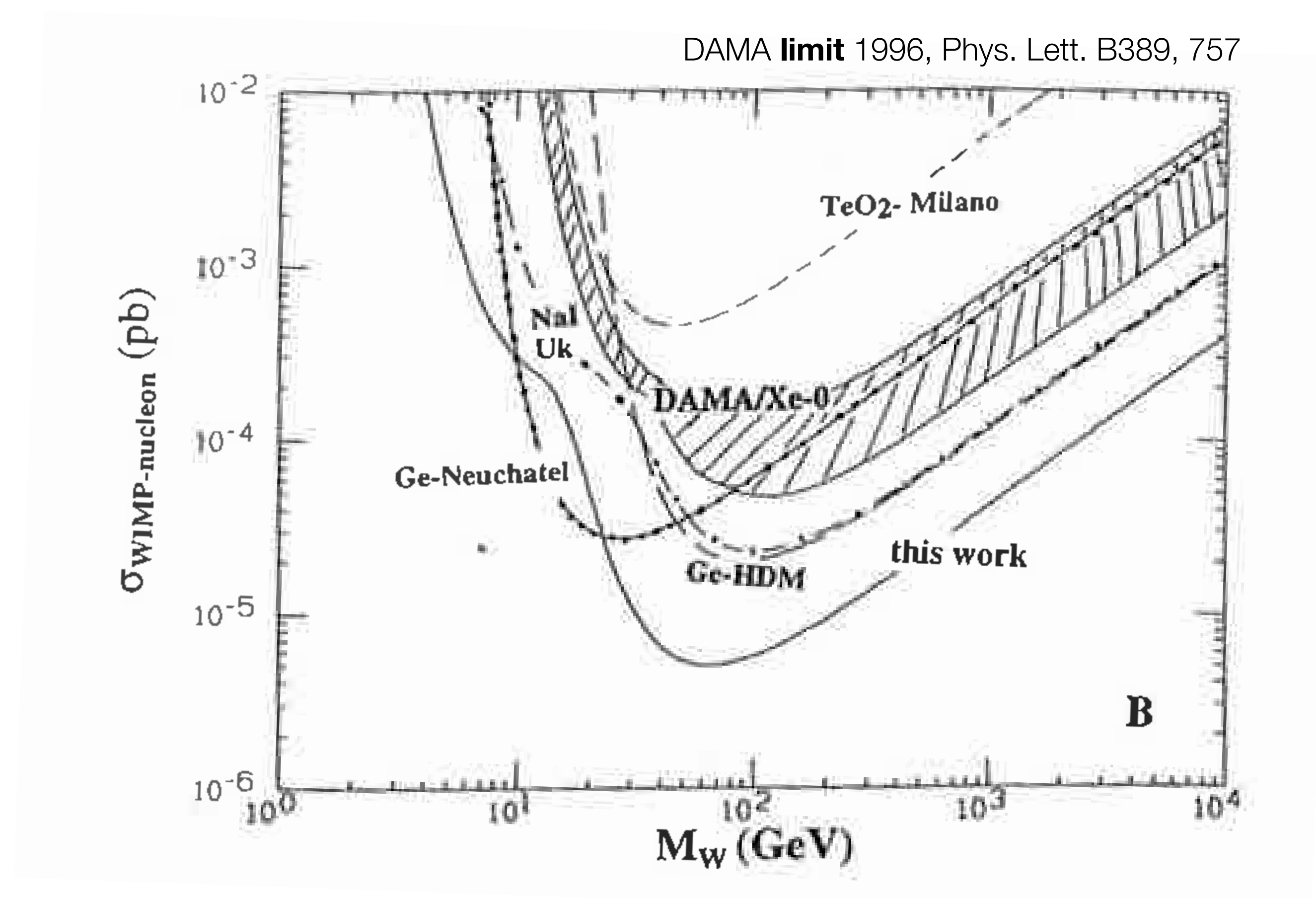
History of sensitivities

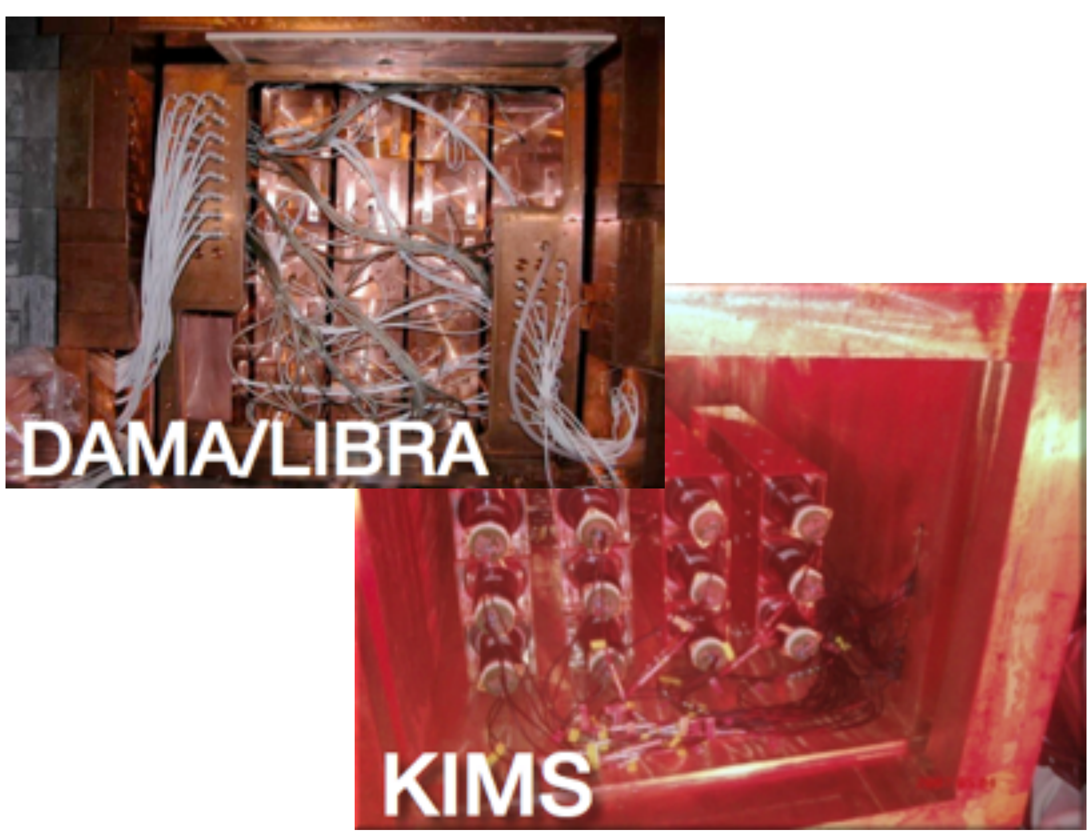


<u>Low-threshold scintillating crystals (NaI, CsI…)</u>

- Goal exploit pulse shape discrimination to reduce the ER background
  - Statistical discrimination only, and hard at low energy
- DAMA : then turned to annual modulation search (presented later)

DAMA **limit** 1996, Phys. Lett. B389, 757





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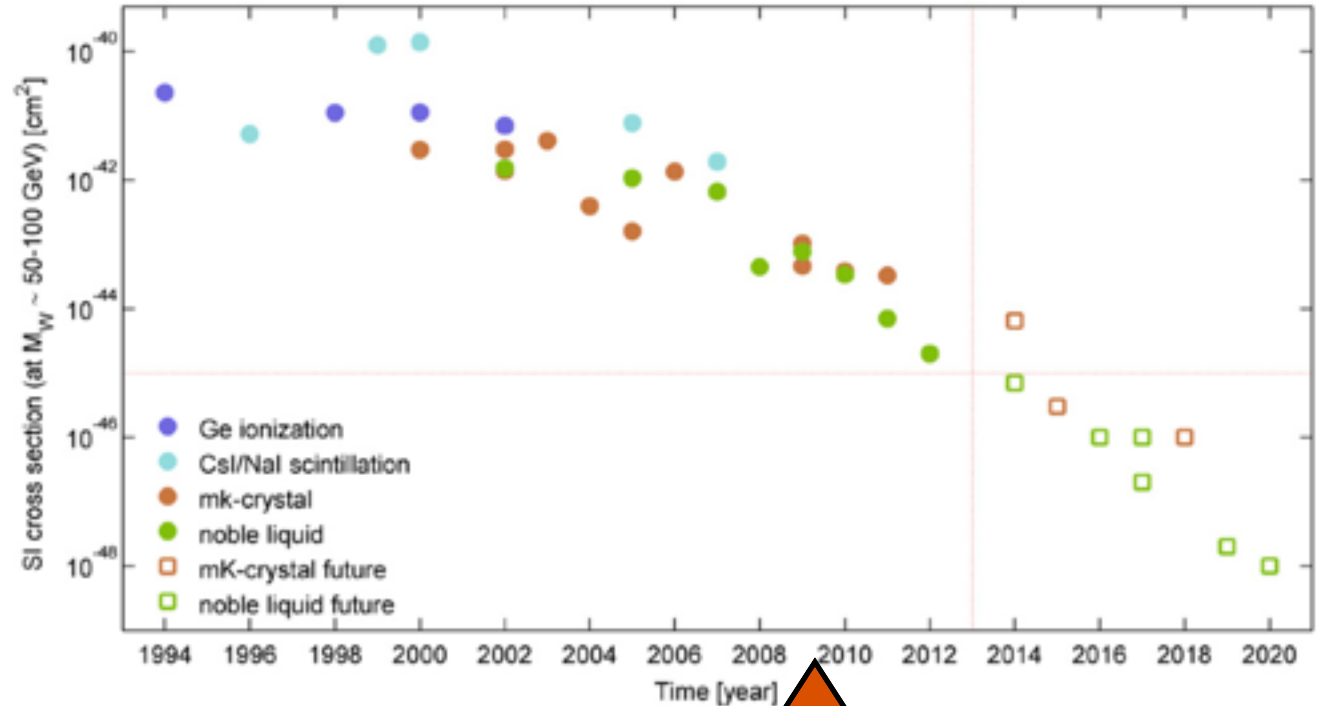
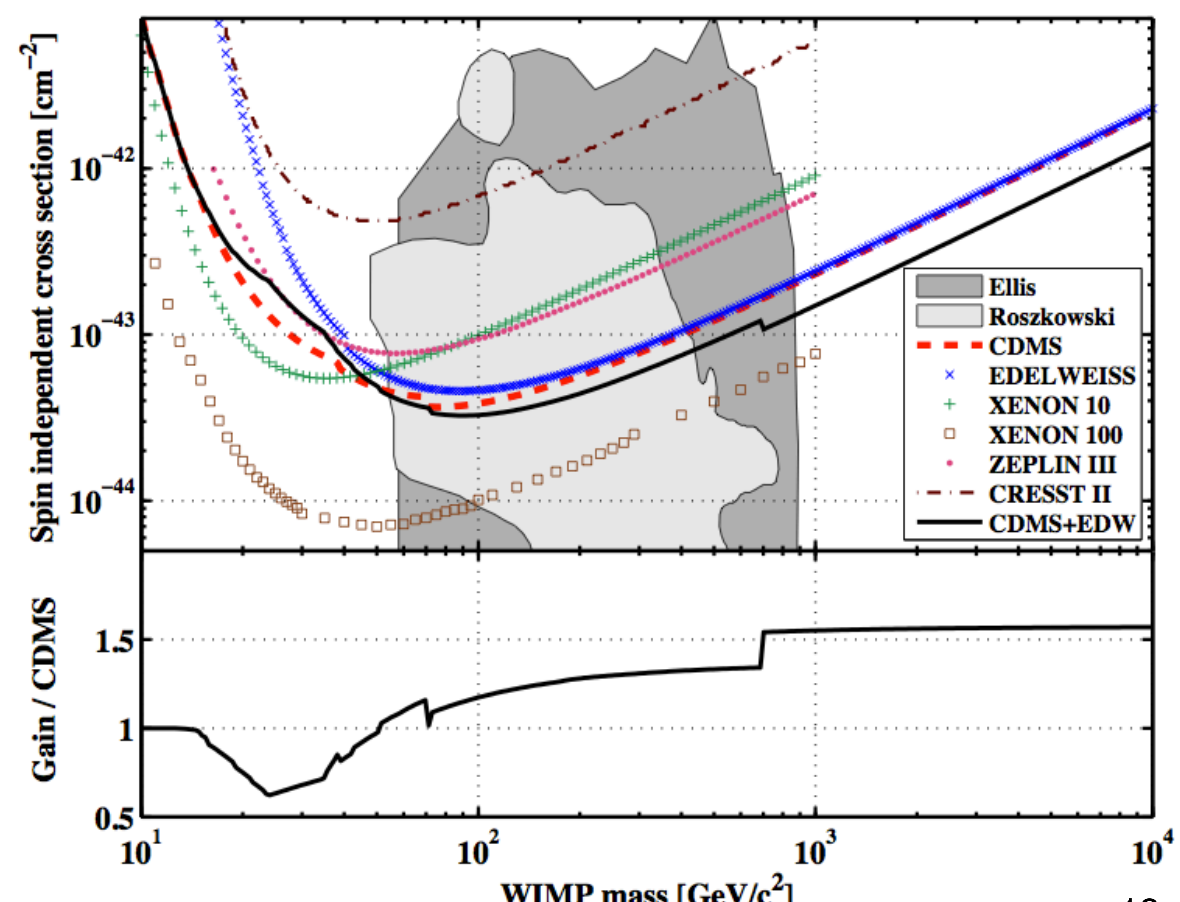


Low-temperature heat-ionization bolometers

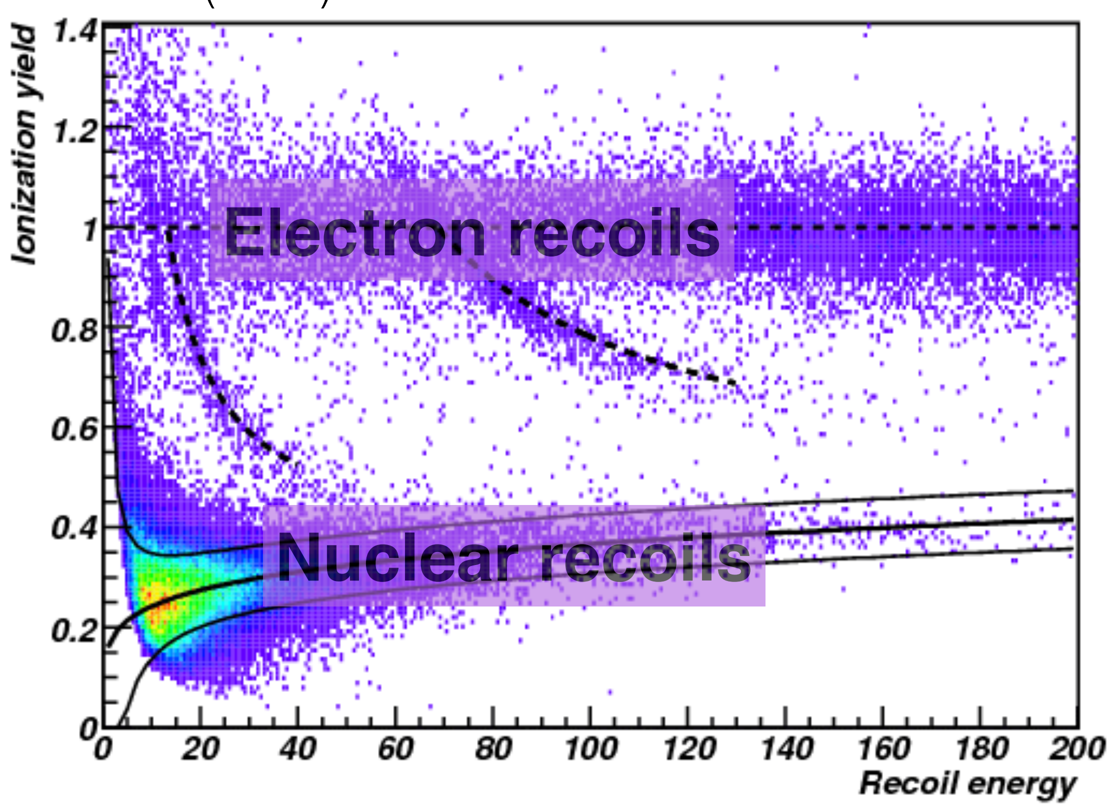
- EDELWEISS - CDMS - CRESST
- Combine phonon (heat) with ionization measurement
  - **Event by event discrimination of ERs vs NRs**
- Orders of magnitude improvement in sensitivity

EDELWEISS-II + CDMS-II, PRD 84, 011102



PLB 702 (2011) 329

EDELWEISS-II neutron calibration



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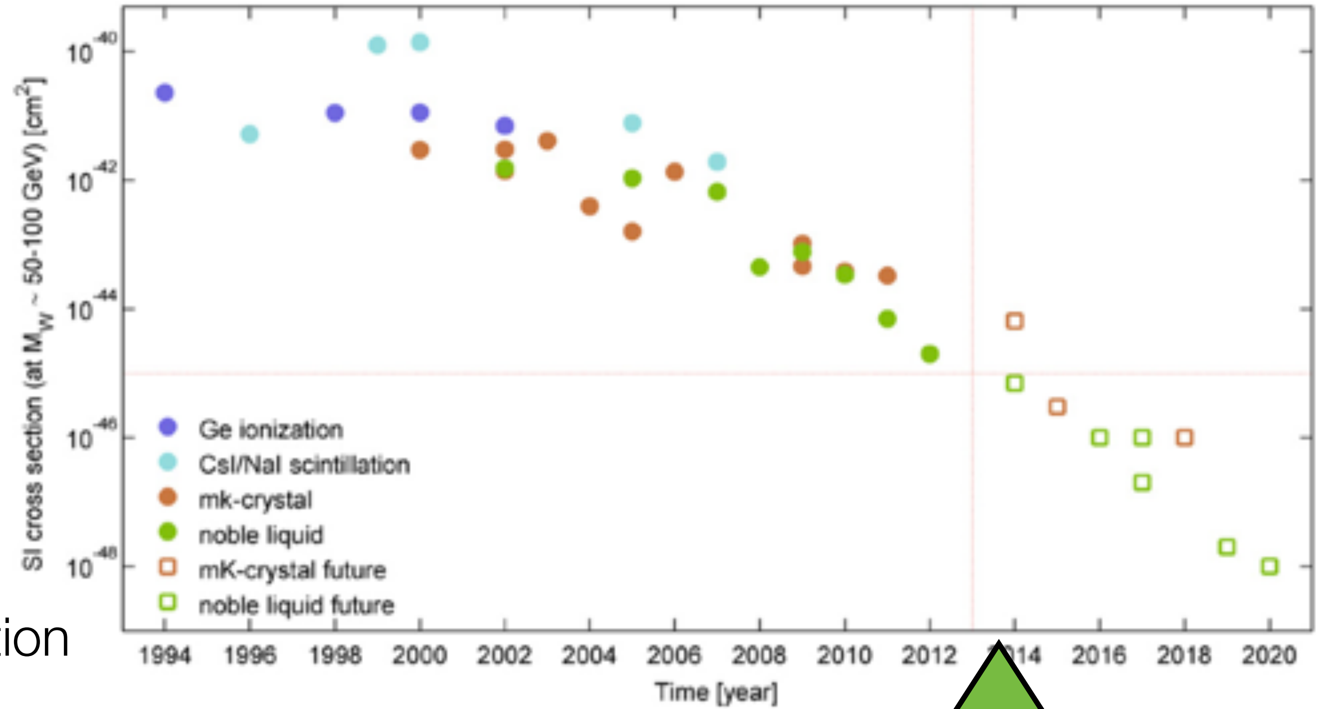
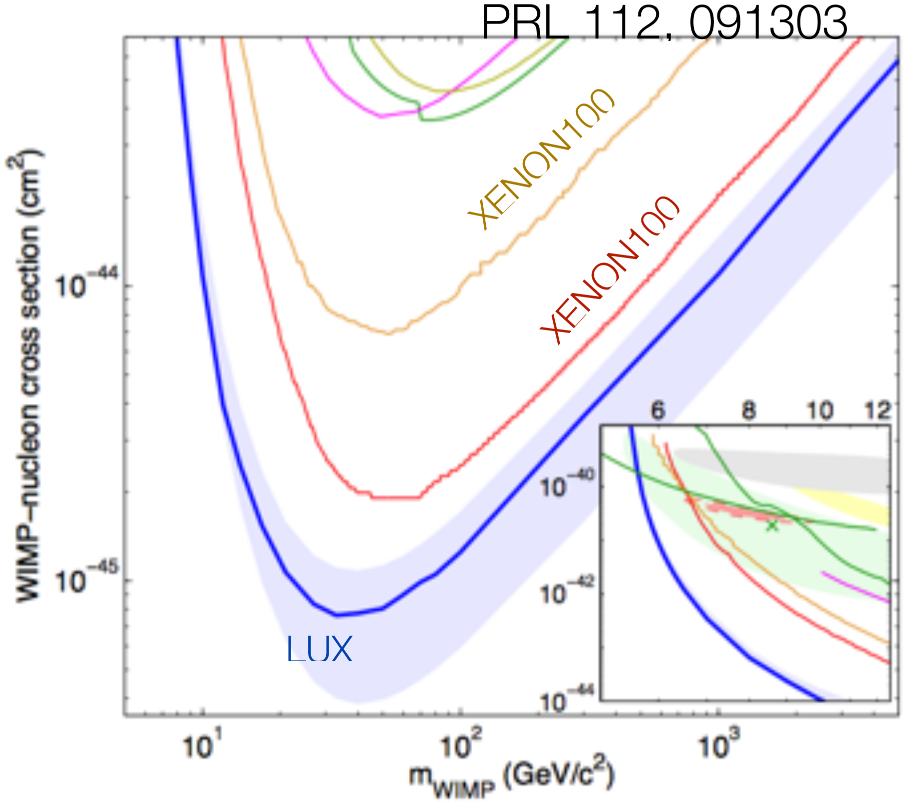


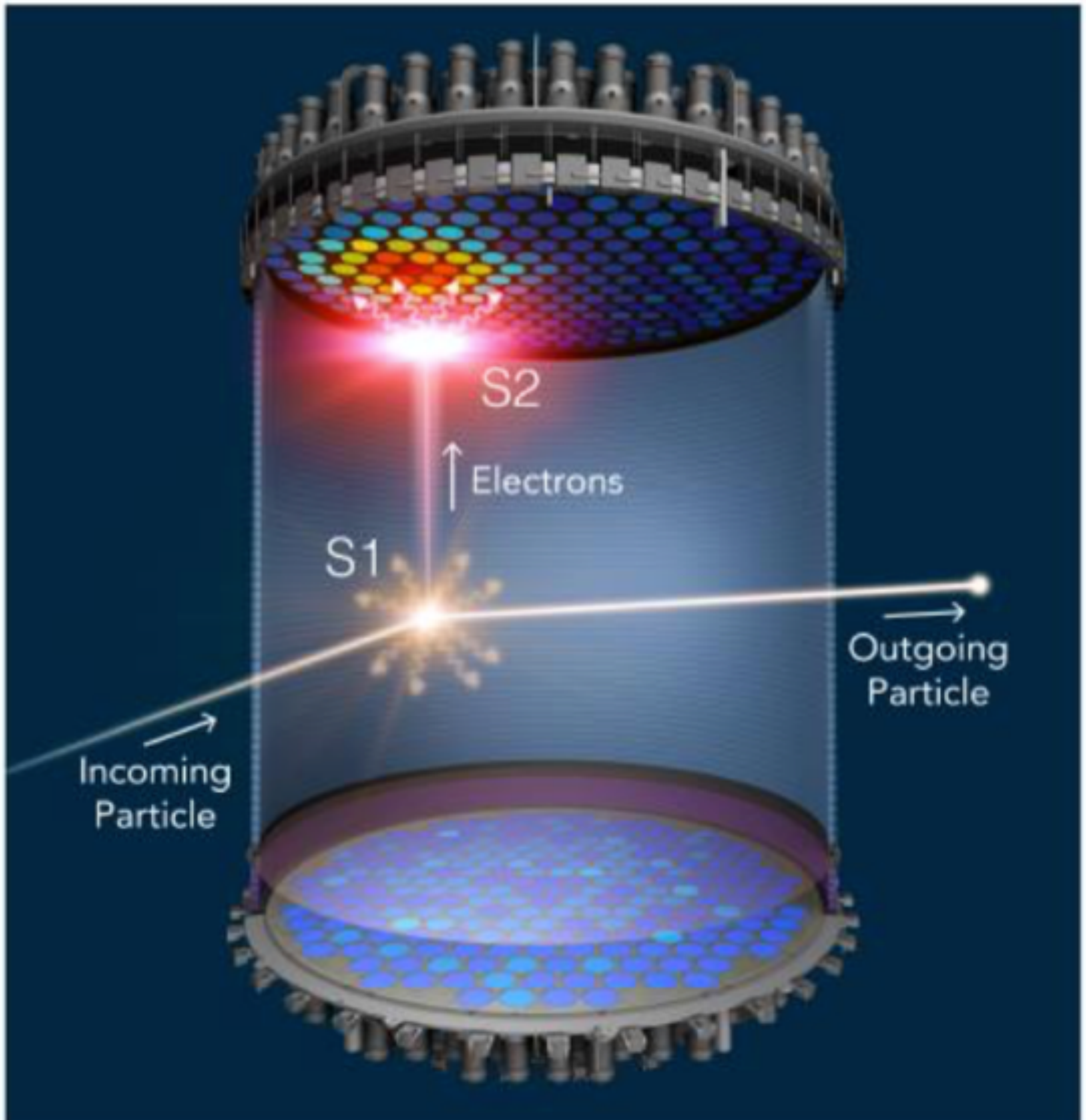
<u>Dual-phase Xenon TPCs</u>

• XENON - LUX - etc
• Discriminate ERs vs NRs with scintillation + ionization measurement
• **Scale to large volume (self-shieding) + radiopurity of Xenon : very low intrinsic bg**
• *Calibration and low-threshold now quite mature*
• *Leading technology since ~ 2011*

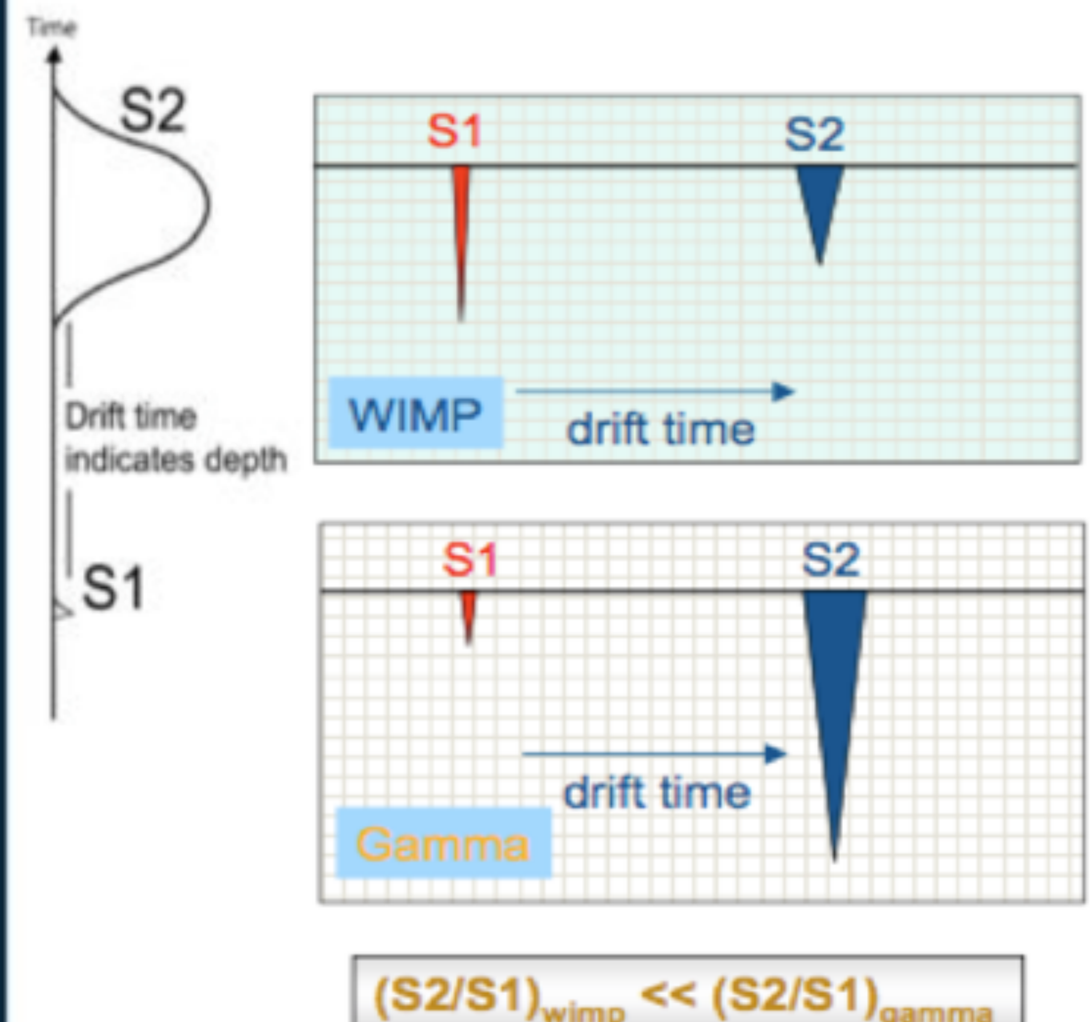
PRL 112, 091303



Example - dual-phase Xenon TPC



« S1 » = direct light, <u>scintillation</u>
« S2 » = light emitted when electrons are accelerated in the gas phase, <u>ionization</u>

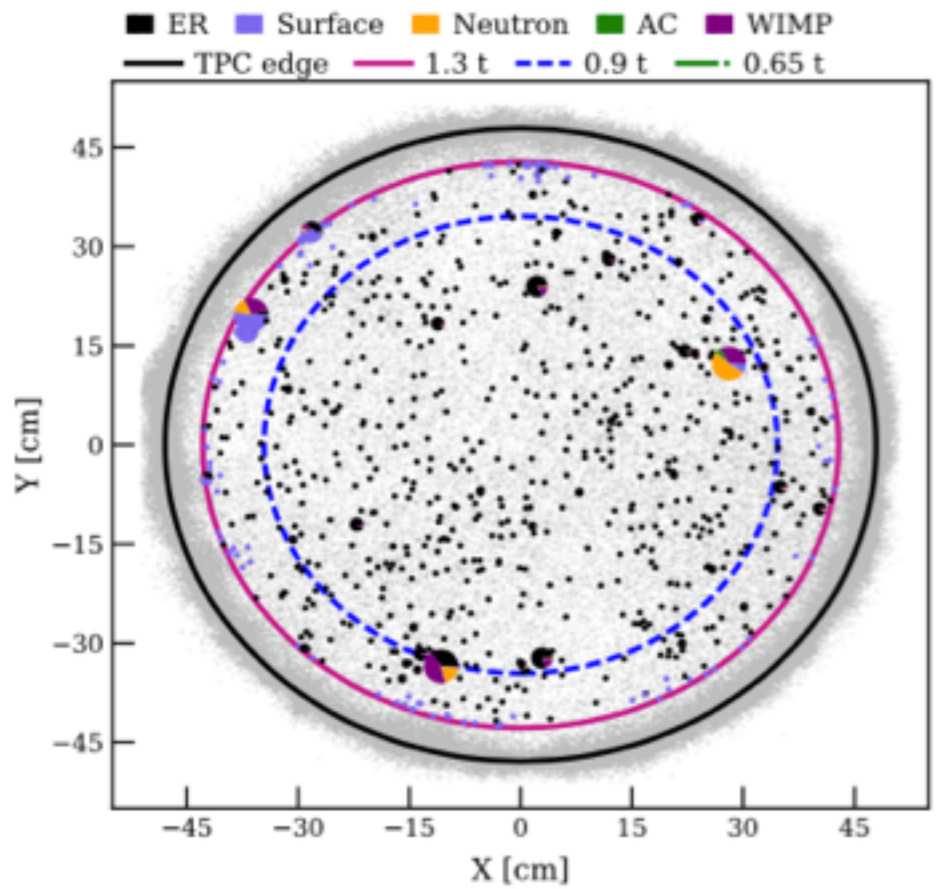


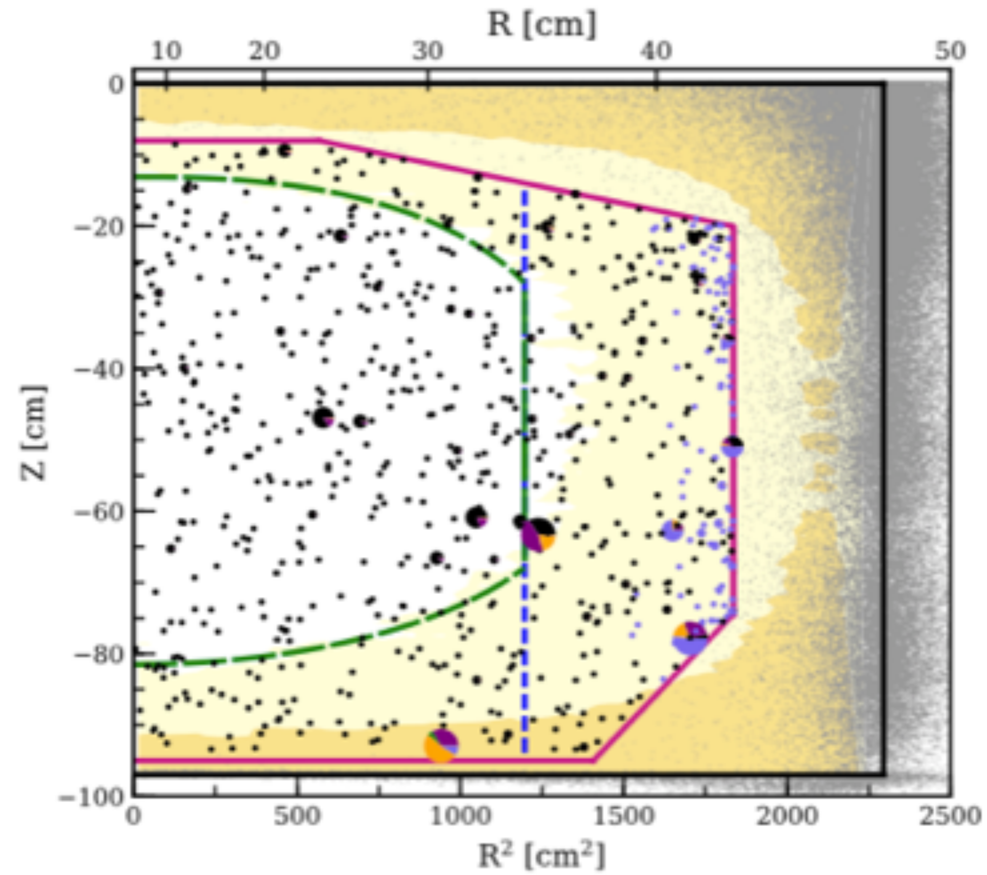
XENON1t result PRL121, 111302 (2018)

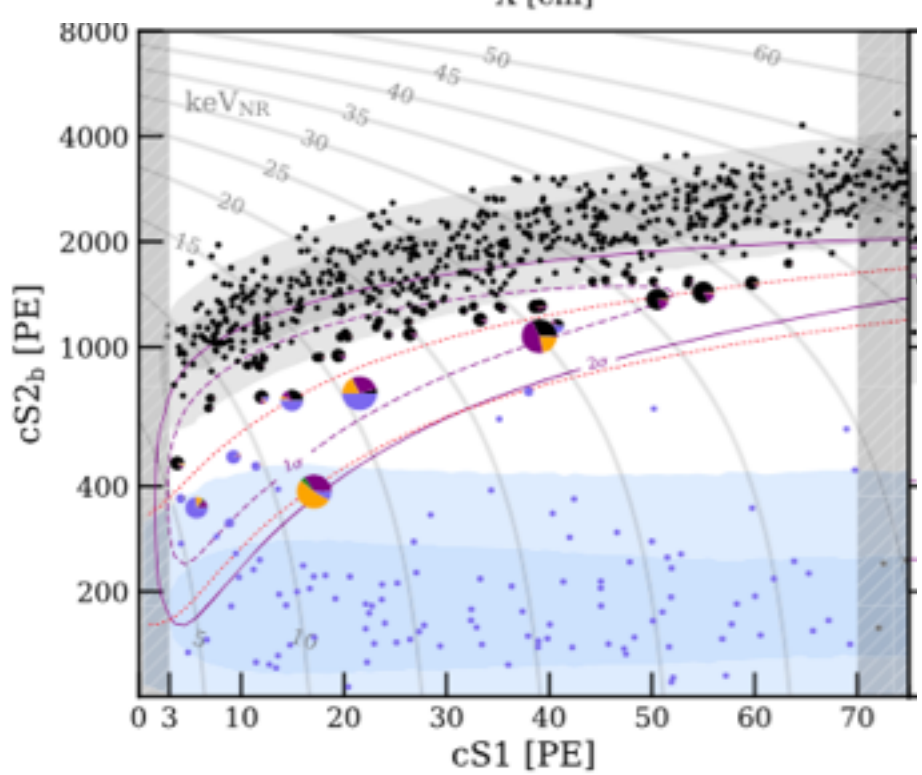
~1.3 ton Xe fiducial (~3ton total Xe)   ~1m diameter detector, 250 PMTs

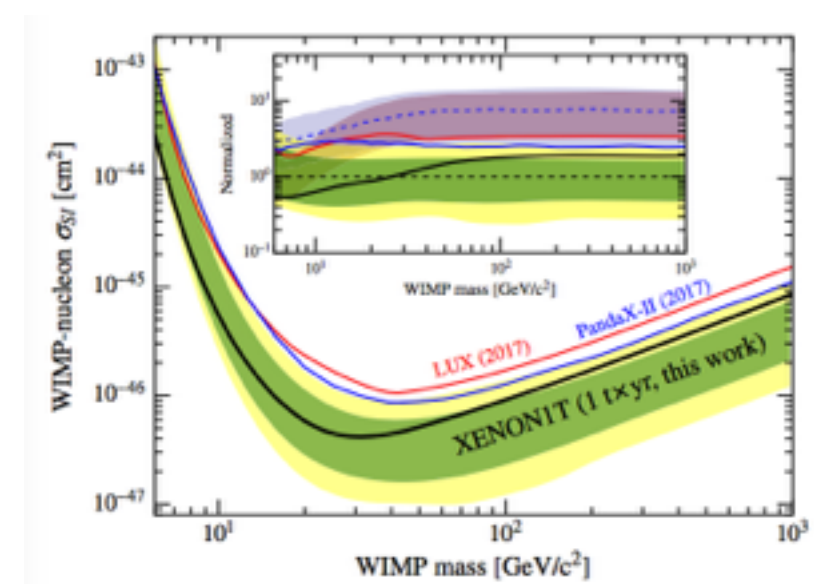
HUGE effort : material and Xe radiopurity, shielding, optimal operation of TPC

280 days exposure   profile likelihood analysis







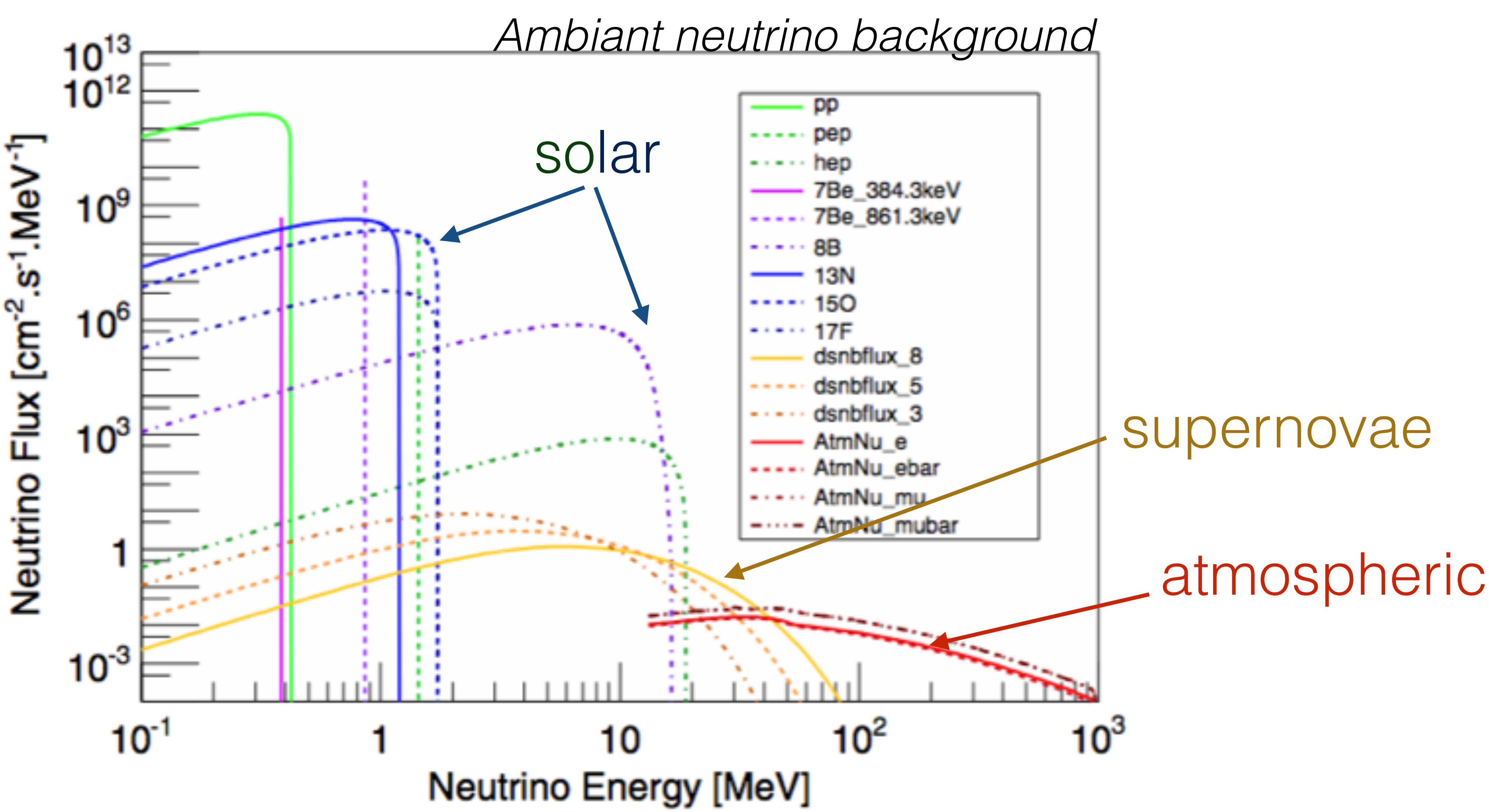


Projects with Xenon or Argon …

Where we will stop : The neutrino floor

Coherent scattering of neutrinos on nuclei

Low-energy NRs : irreducible background for WIMP direct detection
Sets a natural « target » for experiments
Eventually detectors will do neutrino physics



Where we will stop : The neutrino floor

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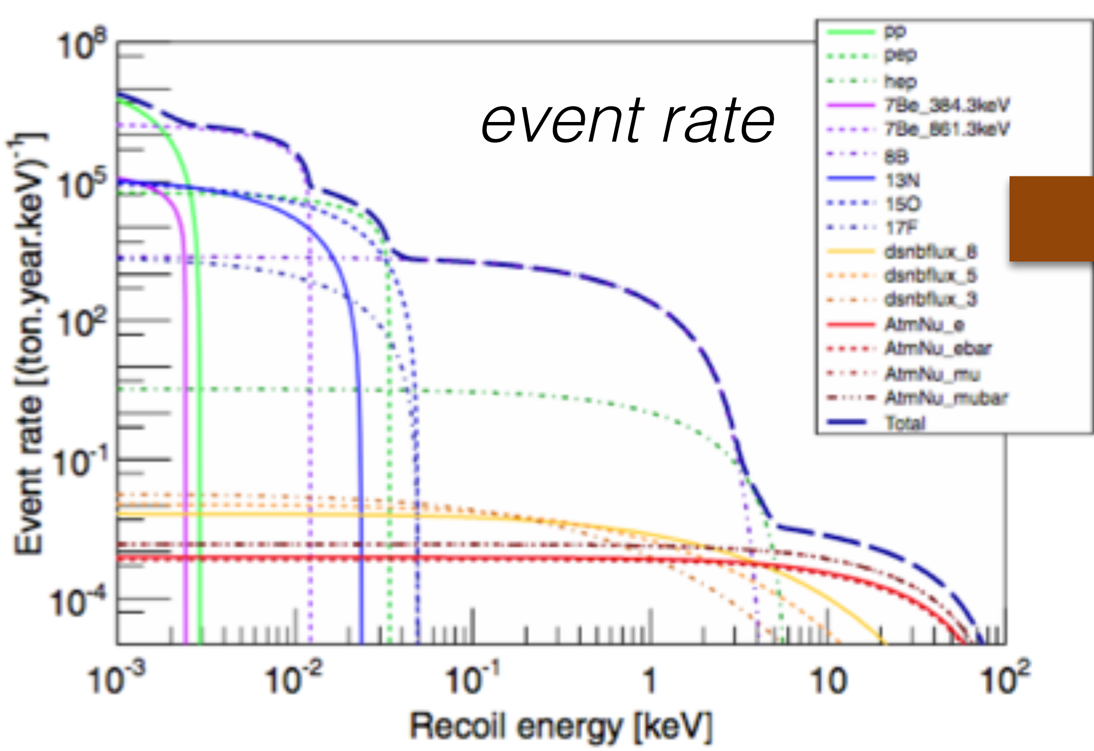
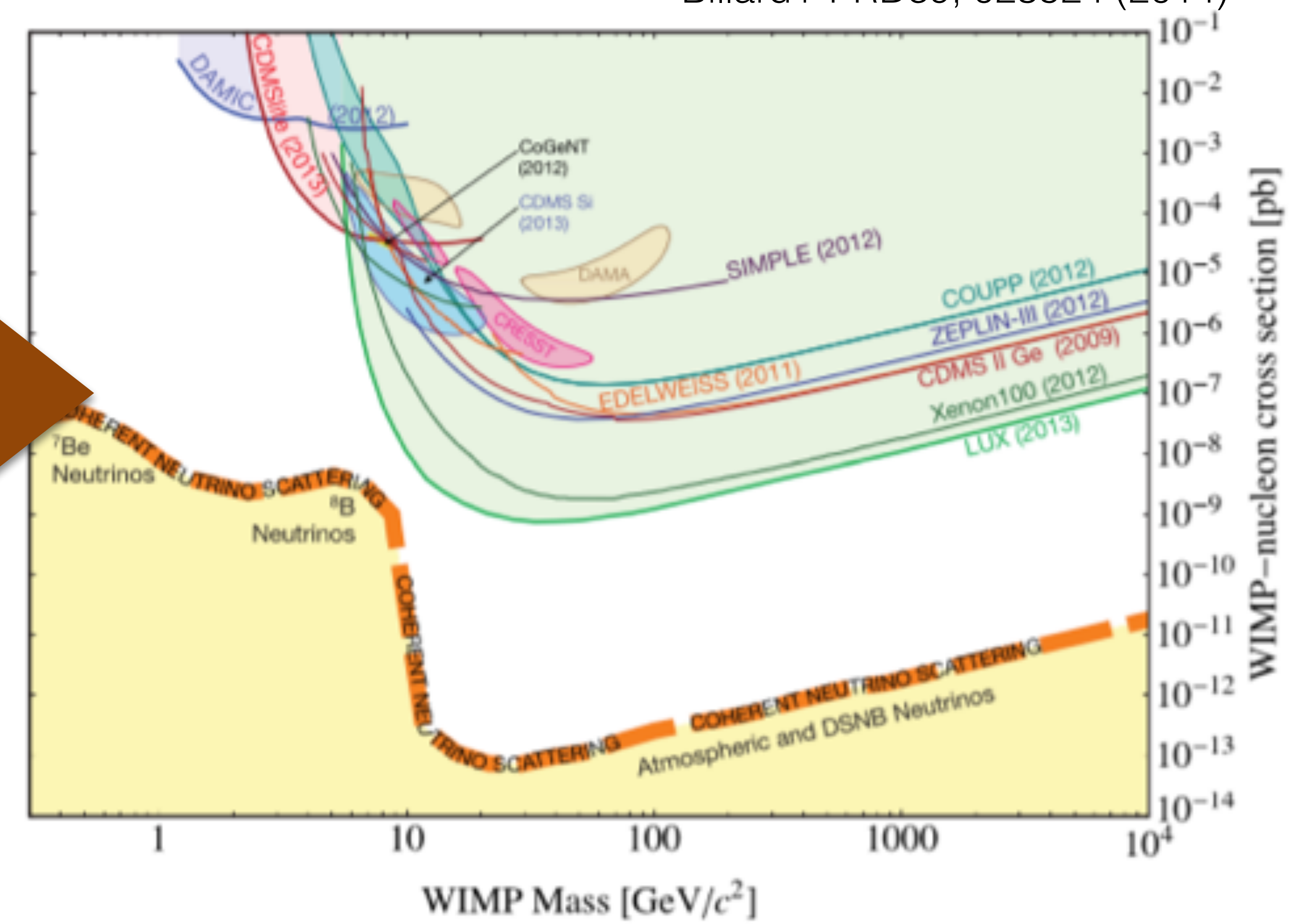
$$\frac{d\sigma(E_\nu, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_w^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F^2(E_r),$$

$$Q_w = N - (1 - 4\sin^2\theta_w)Z$$



Billard+ PRD89, 023524 (2014)



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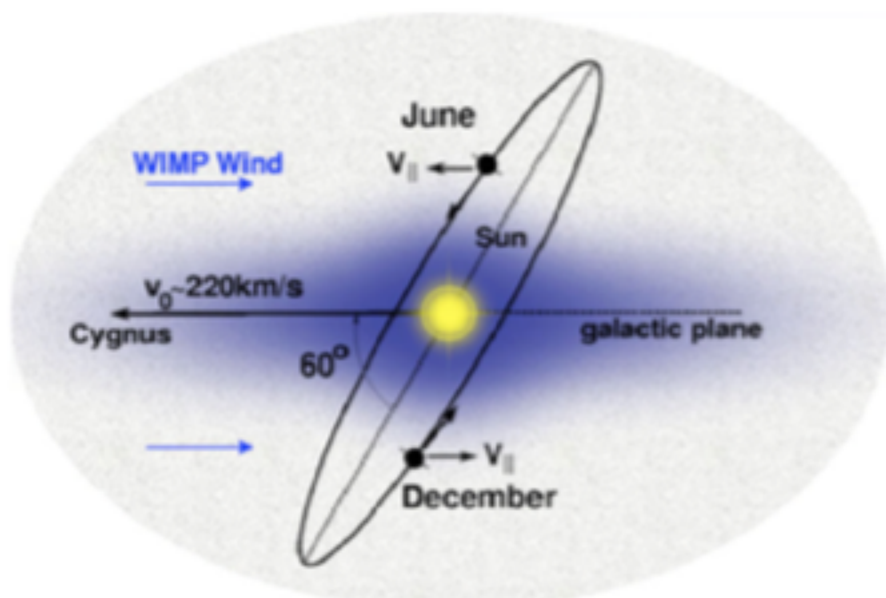
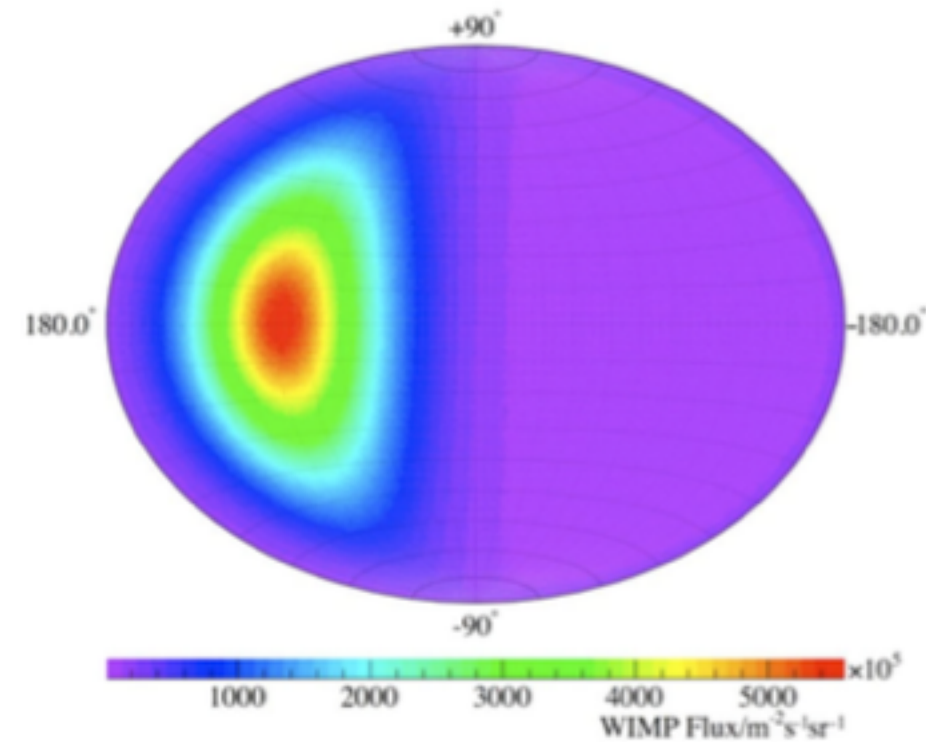
« Astrophysical » signatures

Detector motion with respect to DM halo





1) **Prefered recoil direction from Sun motion wrt halo** [Spergel+ PRD 37,1353 (1988)]
Large effect O(1) dipole-like
Technical challenge : track length ~1mm in gaz

2) **Annual modulation from Earth rotation**
~ O(7%) effect

The annual modulation signal of DAMA

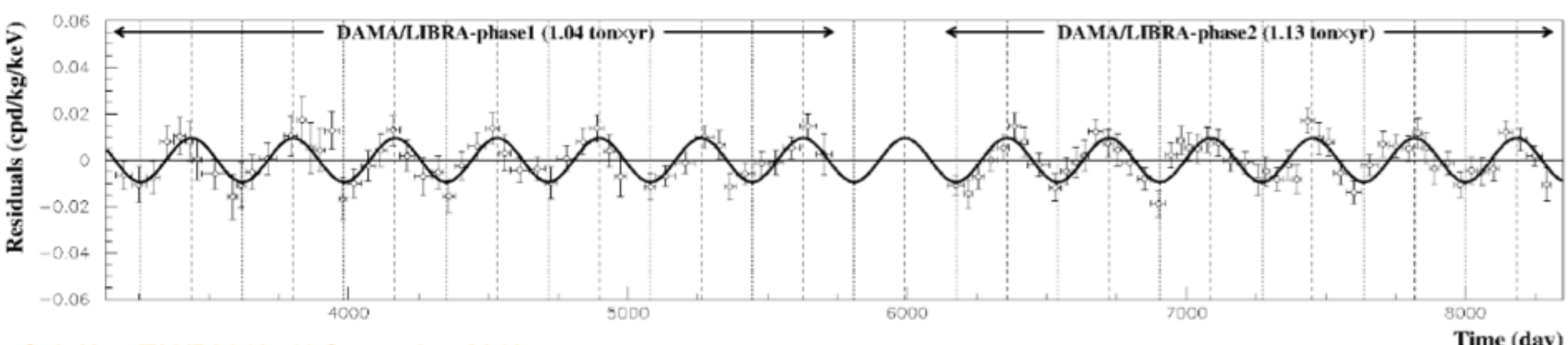
NaI scintillating crystals (no rejection of ER bckgd)

- DAMA/NaI 1995-2002 9x9.7 kg
- DAMA/LIBRA (2003-2010) 25x9.7 kg
- DAMA/LIBRA phase 2 (2011-2018) new PMTs (1 keV threshold)

Large statistical significance

Near threshold signal, backgrounds not modeled

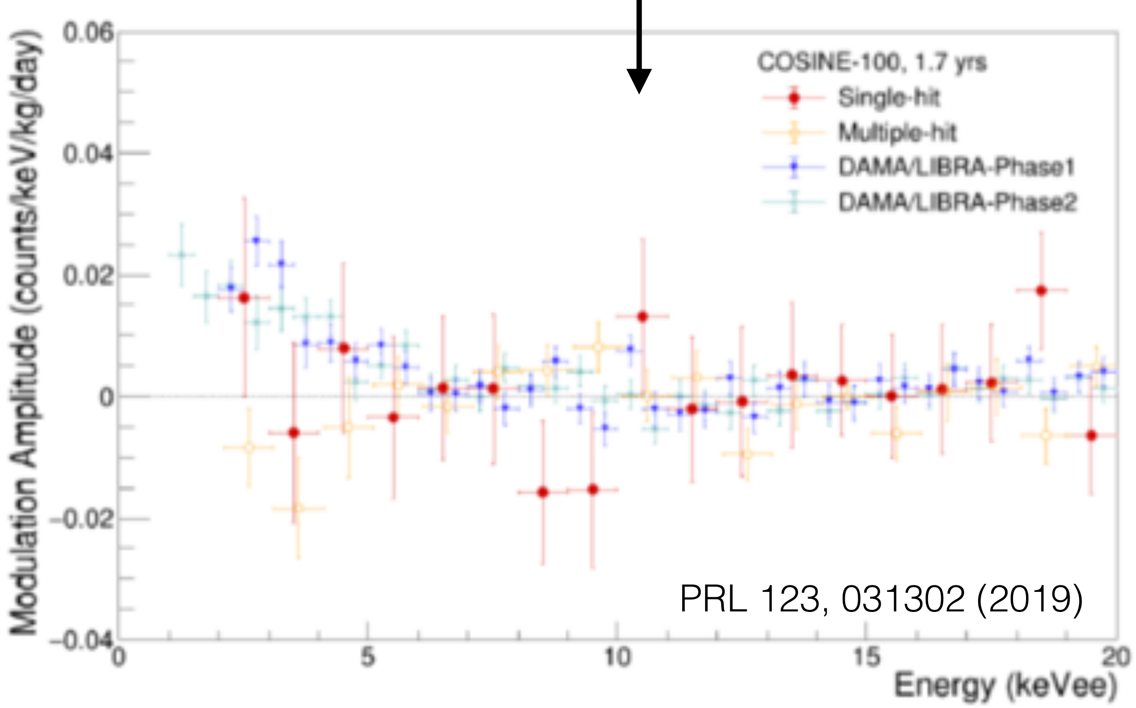
Still a mystery after 20 years …



S. Cebrián, TAUP2019, 11 September 2019

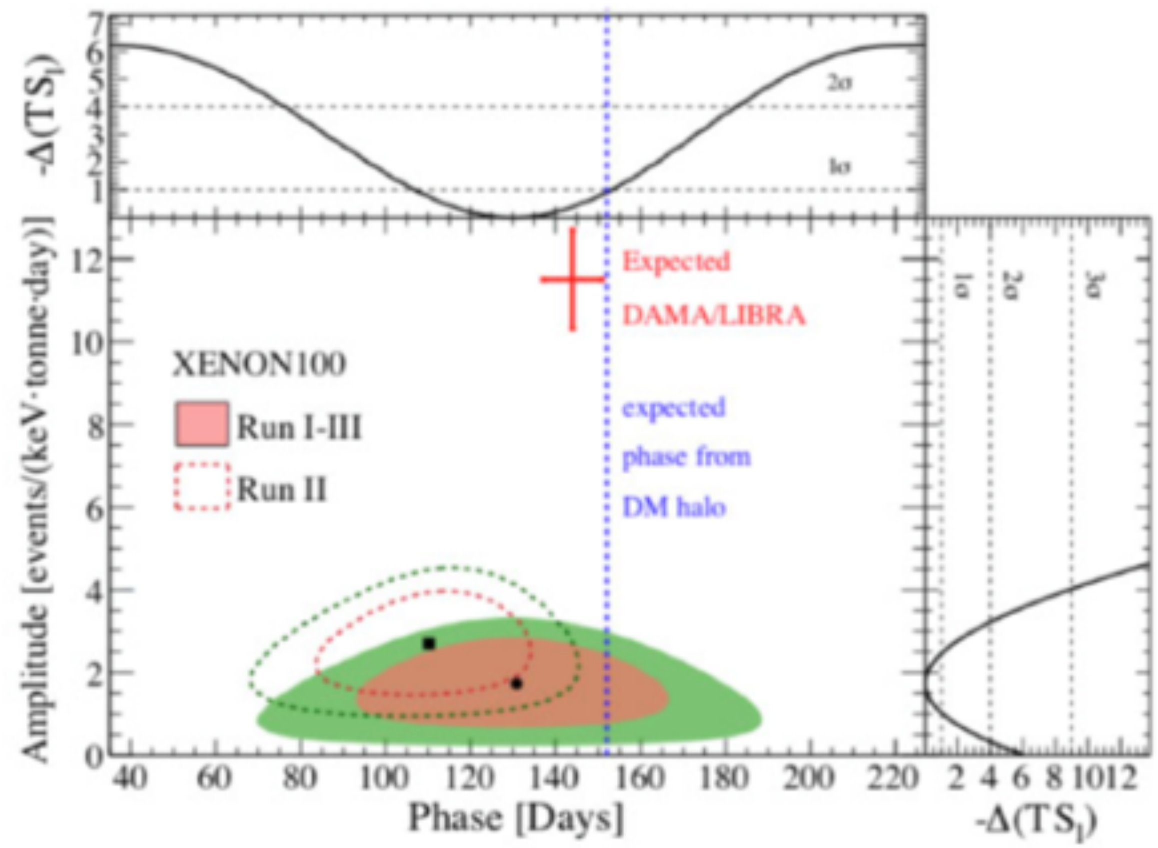
Testing the potential DAMA signal

- « Standard » WIMP events : excluded by many experiments
- Electron recoil interpretation : excluded by Xenon experiments
- Redo exactly the same experiment … : ongoing



PRL 123, 031302 (2019)

Aprile+ PRL 118, 101101 (2017)

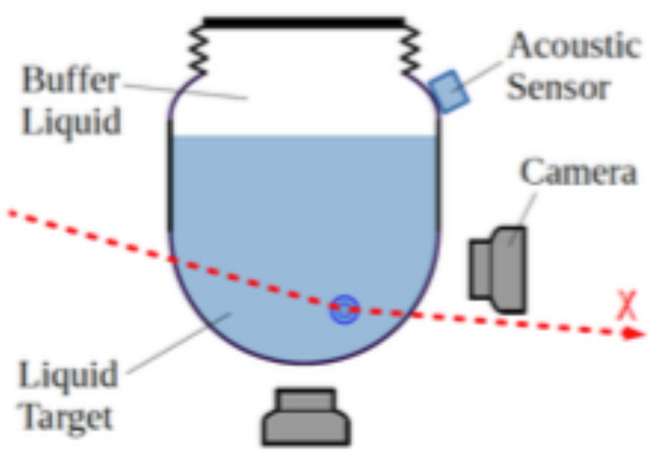


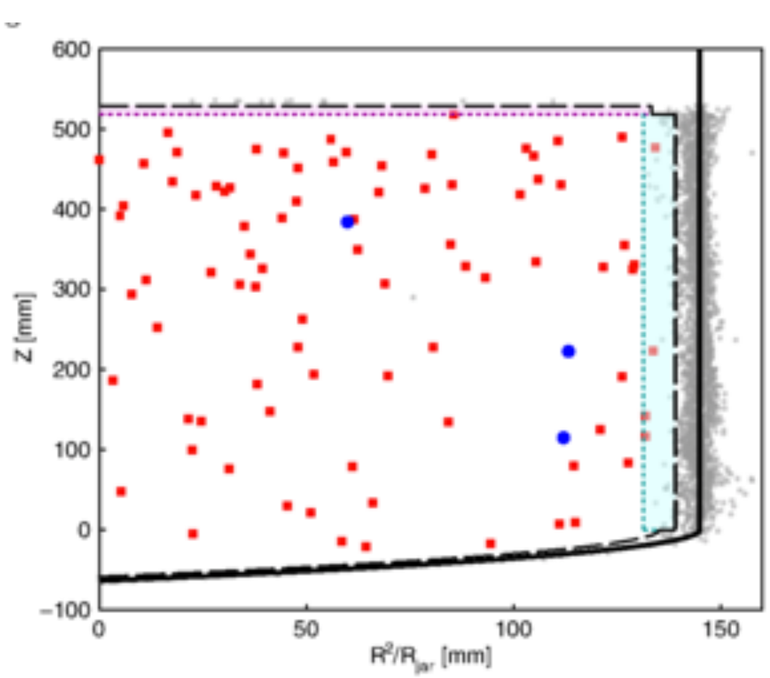
=> The final word
should come soon…

« Spin-dependent » WIMP scattering

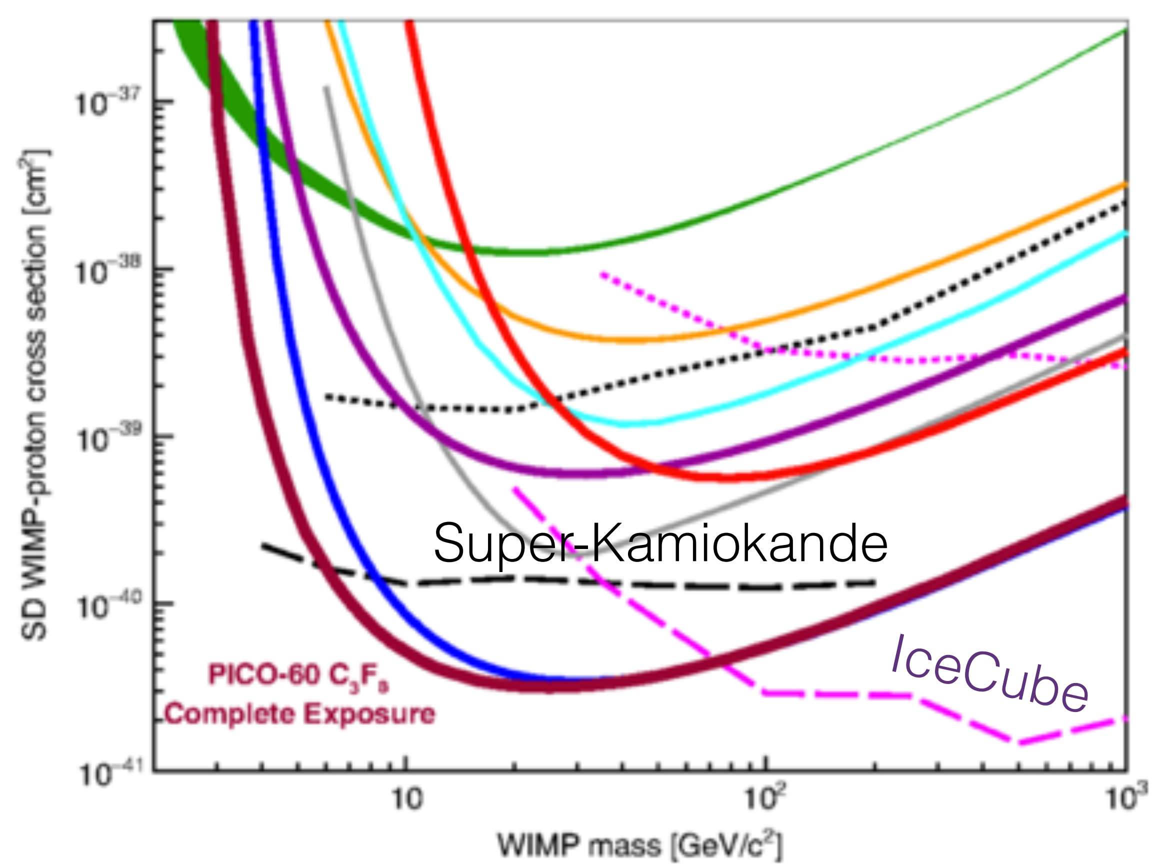
Case of WIMP-proton coupling :

- *Can compare directly with searches for neutrinos from the Sun*
- Leading sensitivity : bubble chamber-like technology





PRD100 022001 (2019)
52 kg bubble chamber



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Beyond WIMPs

Many viable models exist for « light » DM with various masses and couplings to ordinary matter

Probably (much) less motivated than WIMPs, but still plausible

Underlying theories often invoke « dark sectors », ie new interactions (hidden photon, hidden QCD…)

May explain some astrophysical features

eg. $\Omega_b \sim \Omega_m$ for asymmetric DM scenarios

eg. DM « small-scale problems » for hidden-QCD-like DM scenarios

Kinematics :

M > 100 MeV : nuclear scattering

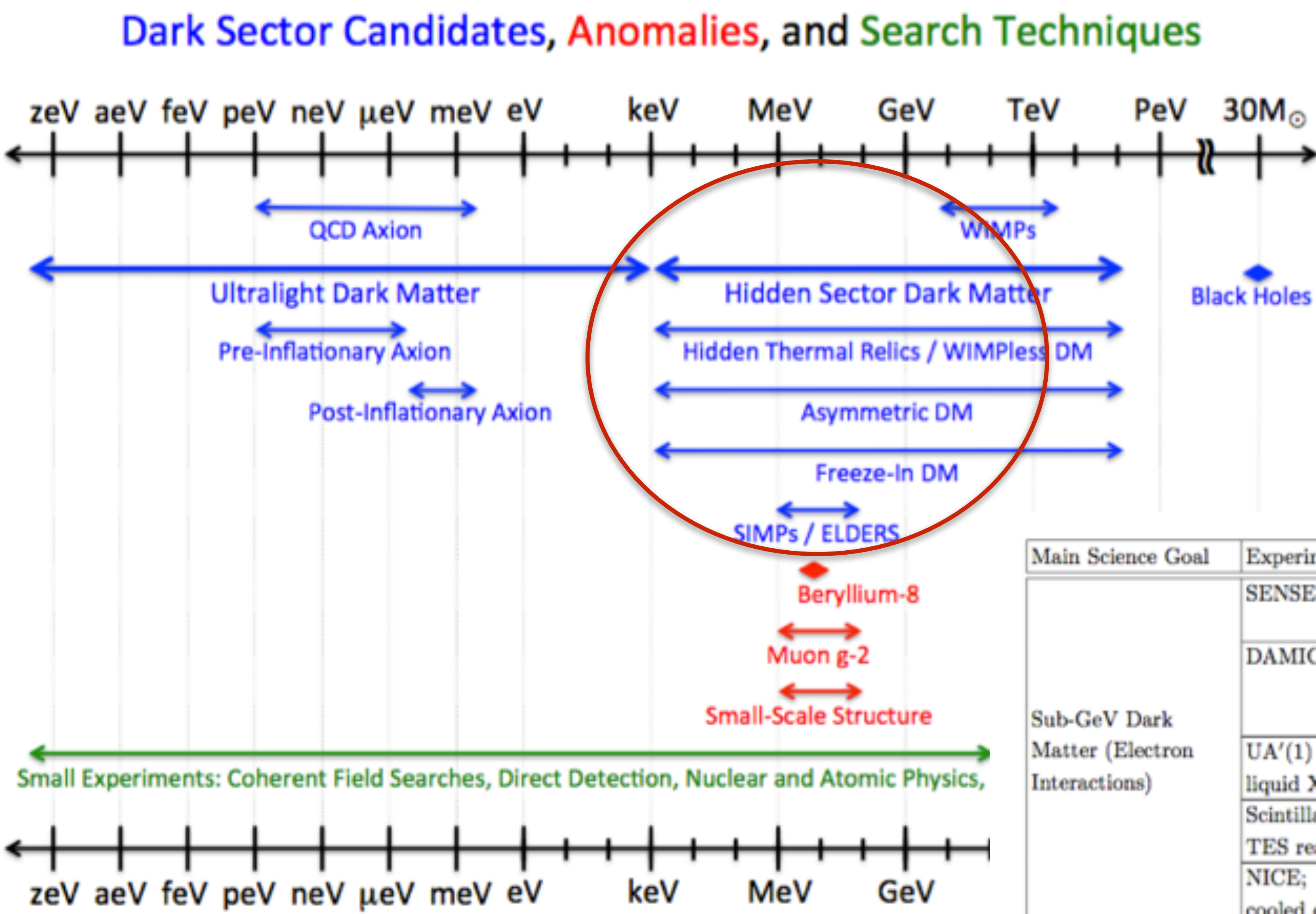
M < 100 MeV : electron scattering

Very low energy depositions in detectors

Signal intensity :

DM - ordinary matter coupling can be surprisingly strong

Need dedicated devices, or tricks…



US Cosmic Visions 2017
(1707.04591)

Main Science Goal	Experiment	Target	Readout	Estimated Timeline
Sub-GeV Dark Matter (Electron Interactions)	SENSEI	Si	charge	ready to start project (2 yr to deploy 100g)
	DAMIC-1K	Si	charge	ongoing R&D 2018 ready to start project (2 yr to deploy 1 kg)
	UA′(1) liquid Xe TPC	Xe	charge	ready to start project (2 yr to deploy 10kg)
	Scintillator w/ TES readout	GaAs(Si,B)	light	2 yr R&D 2020 in sCDMS cryostat
	NICE; NaI/CsI cooled crystals	NaI CsI	light	3 yr R&D 2020 ready to start project
	Ge Detector w/ Avalanche Ionization Amplification	Ge	charge	3 yr R&D 1 yr 10kg detector 1 yr 100kg detector
	PTOLEMY-G3, 2d graphene	graphene	charge directionality	1 yr fab prototype 1 yr data
	supercond. Al cube	Al	heat	10+ yr program
Sub-GeV Dark Matter (Nucleon Interactions)	Superfluid helium with TES readout	He	heat, light	1 yr R&D; 2018 ready to start project; 2022 run
	Evaporation & detection of He-atoms by field ionization	superfluid helium, crystals with long phonon mean free path (e.g. Si, Ge)	heat	3 yr R&D; 2020 ready to start project R&D
	color centers	crystals (CaF)	light	R&D effort ongoing
	Magnetic bubble chamber	Single molecule magnet crystals	Spin-avalanche (Magnetic flux)	R&D effort ongoing

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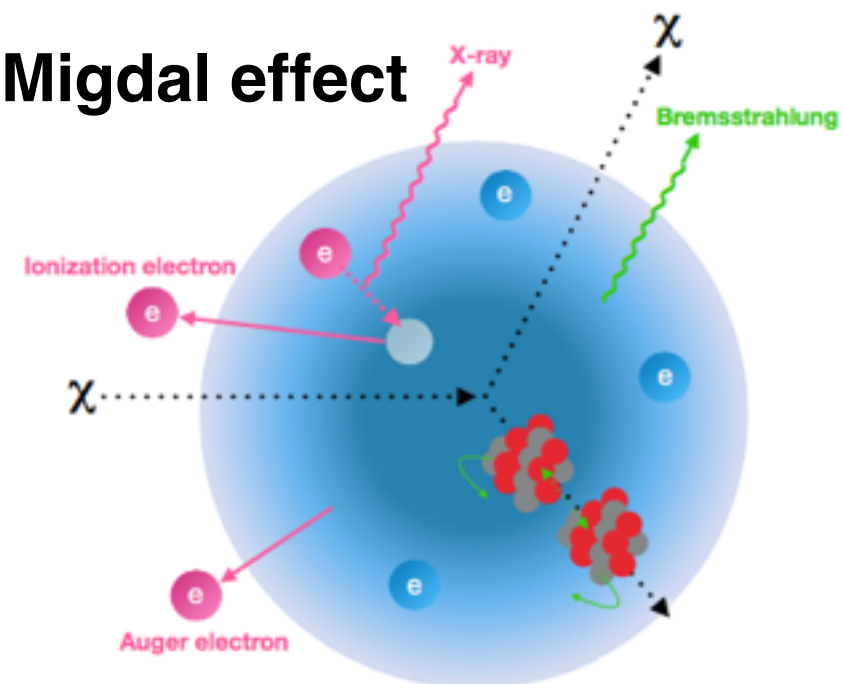
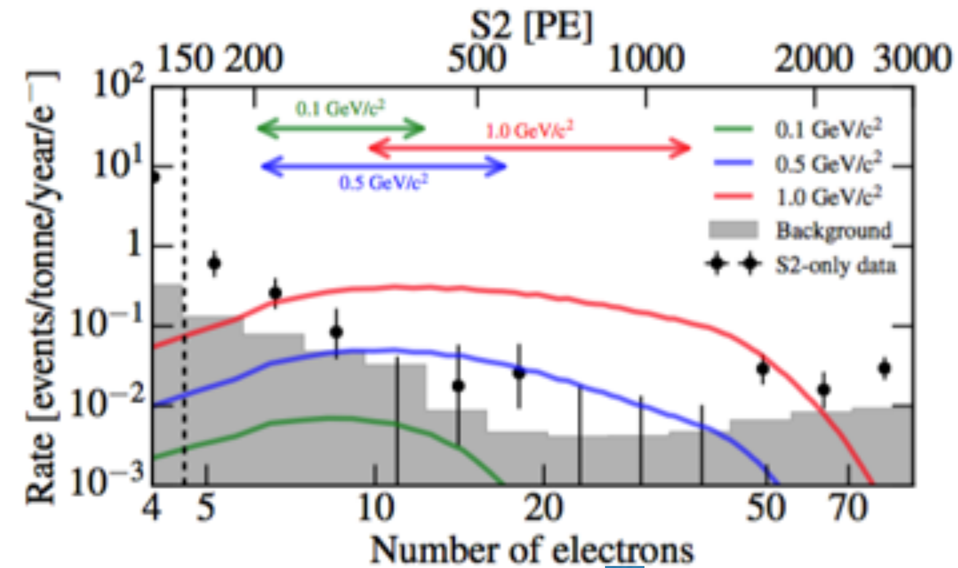
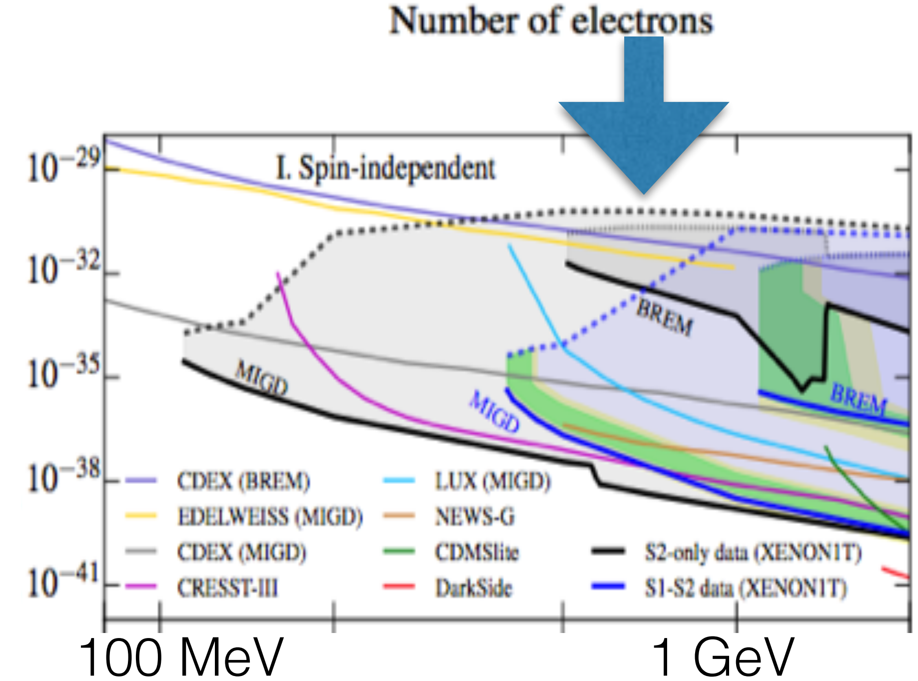
Trick 1 for M>100 MeV : use atomic physics

Migdal effect



XENON1t (1907.12771)
ER signal (ionization)





Ibe+, JHEP 03, 194 (2018)
Excitation / ionization of recoiling atom

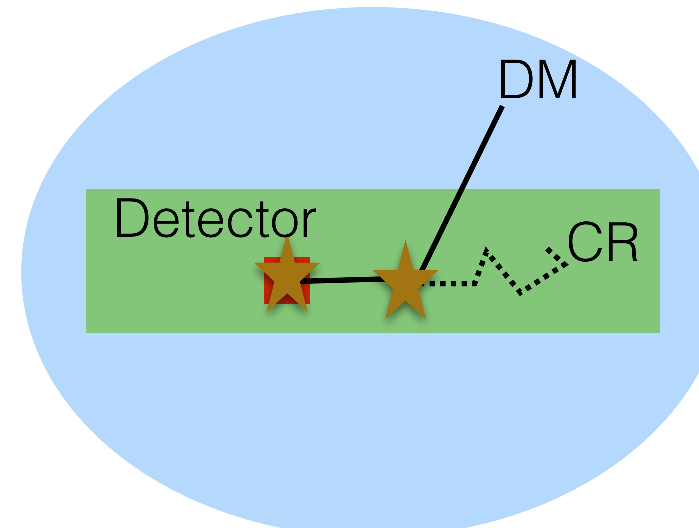
Still to be calibrated

$$\frac{dR}{dE_{\rm ER}} \simeq \int dE_{\rm NR} dv \frac{d^2R}{dE_{\rm NR}dv} \times \frac{1}{2\pi}\sum_{n,l}\frac{d}{dE_{\rm ER}} p^c_{q_e}(n,l\to E_{\rm ER}-E_{n,l})$$

atomic physics

Trick 2 : use cosmic rays !

DM - cosmic ray scattering
Rather strong interactions + large DM density (light DM)



=> changes CR flux [Cappiello+ PRD 99, 063004 (2019)]
=> secondary high energy DM flux: easier to detect !
[Bringmann Pospelov PRL 122, 171801 (2019)]

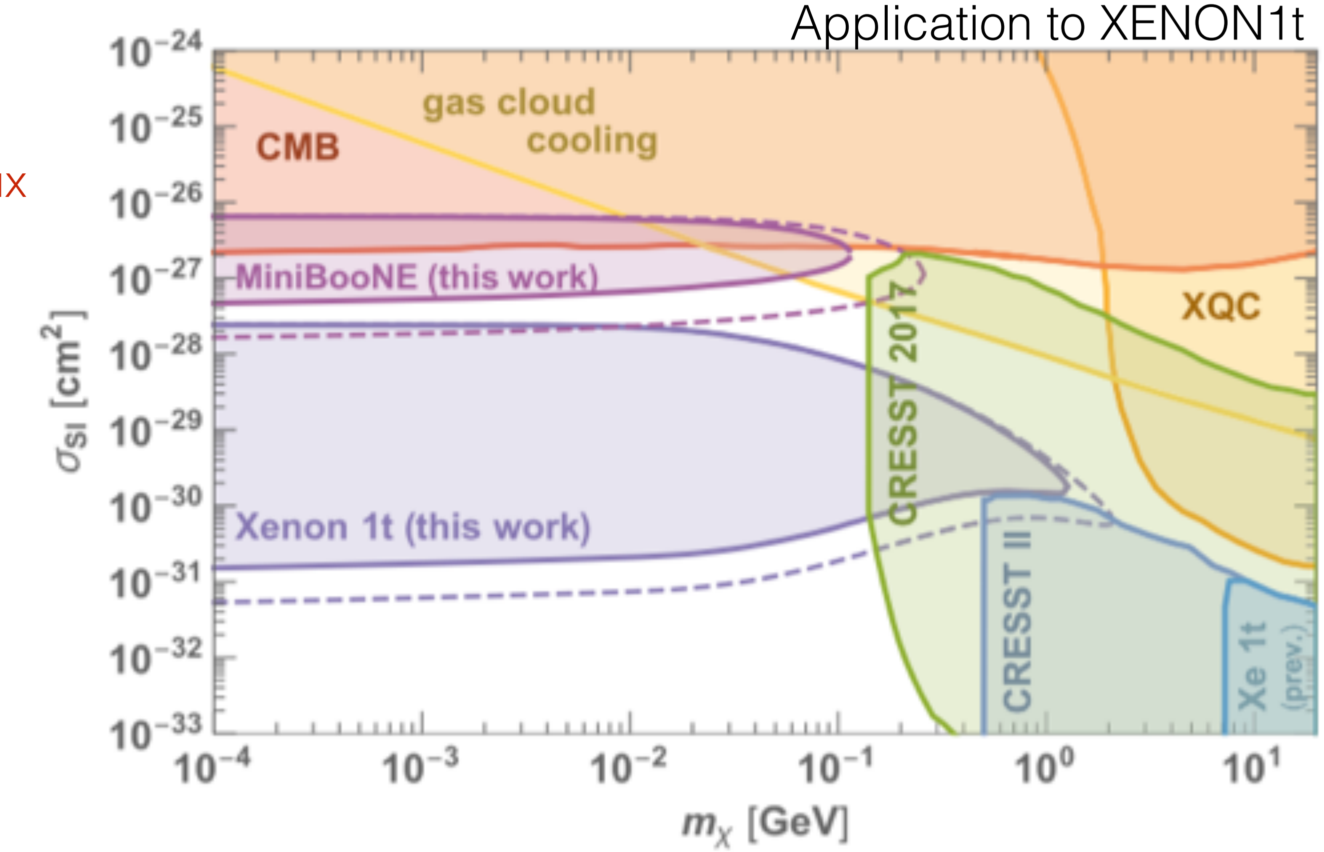
$$\frac{d\Phi_\chi}{dT_\chi} = D_{\rm eff}\frac{\rho_\chi^{\rm local}}{m_\chi} \times \sum_i \sigma^0_{\chi i} G_i^2(2m_\chi T_\chi)\int_{T_i^{\min}}^{\infty} dT_i \frac{d\Phi_i^{\rm LIS}/dT_i}{T_\chi^{\max}(T_i)}.$$

CR flux

size of CR halo

particle physics

Application to XENON1t

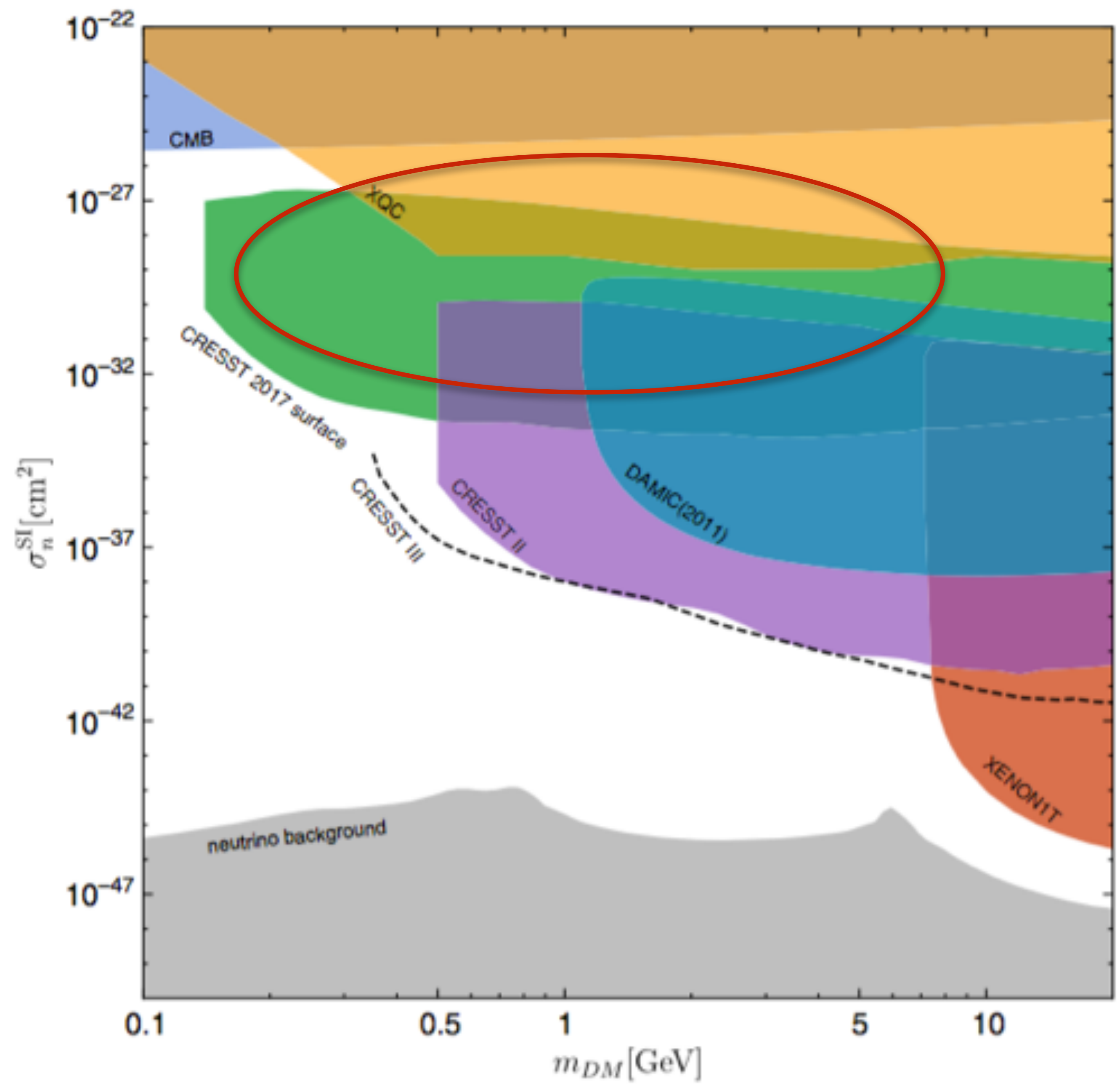


Additional difficulty when probing light DM / large cross-sections : Earth shielding effect

eg. Emken Kouvaris PRD97 115047 (2018)

Need involved calculations for DM propagation / energy losses in the Earth crust and/or atmosphere

Some parameter space can only be probed with experiments above ground or above the atmosphere



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M < 100 MeV : search for DM - electron interactions

Scattering

$$\frac{d\langle\sigma_{ion}^{nl}v\rangle}{d\ln E_{er}} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\left|f_{ion}^{nl}(k',q)\right|^2\left|F_{DM}(q)\right|^2\eta(v_{min})\,dq$$

Detector physics (electron orbitals)

DM physics (mediator mass)

Essig et al. 2012

Requires to measure eV-scale energy depositions

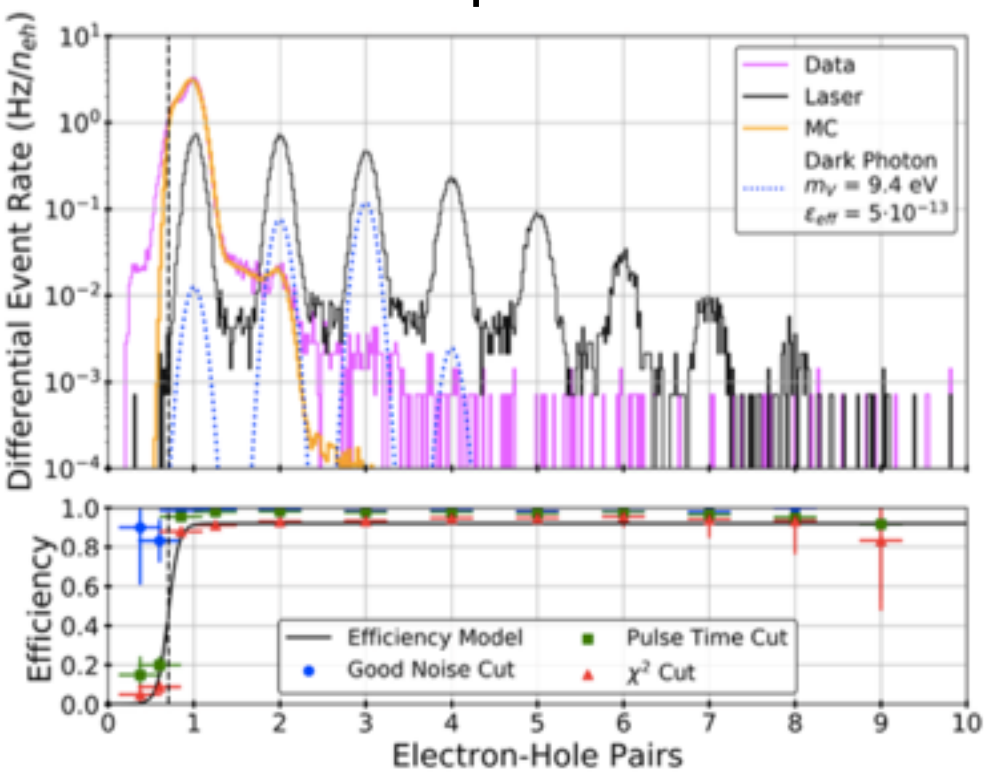
Absorption

Only for bosonic DM

NB DM must be bosonic for m<100 eV (phase-space density in halos)

Analog to photoelectric effect

Pospelov+ 2008



CDMS 2018 : see individual electrons (0.5g detector)

M < 100 MeV : search for DM - electron interactions

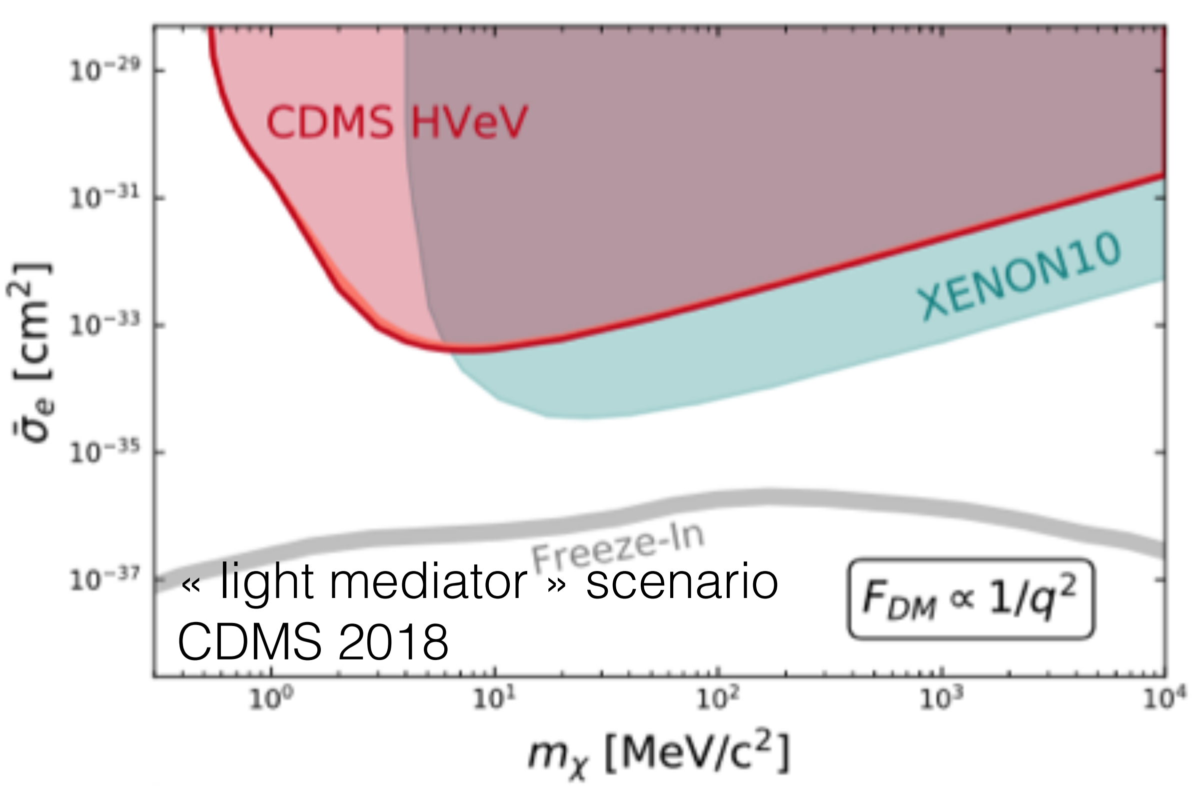
Scattering

$$\frac{d\langle\sigma^{nl}_{ion}v\rangle}{d\ln E_{\rm er}} = \frac{\overline{\sigma}_e}{8\mu^2_{\chi e}}\int q\left|f^{nl}_{ion}(k',q)\right|^2\left|F_{\rm DM}(q)\right|^2\eta(v_{\rm min})\,dq$$

Detector physics (electron orbitals) → $f^{nl}_{ion}(k',q)$

DM physics (mediator mass) → $F_{\rm DM}(q)$

Essig et al. 2012



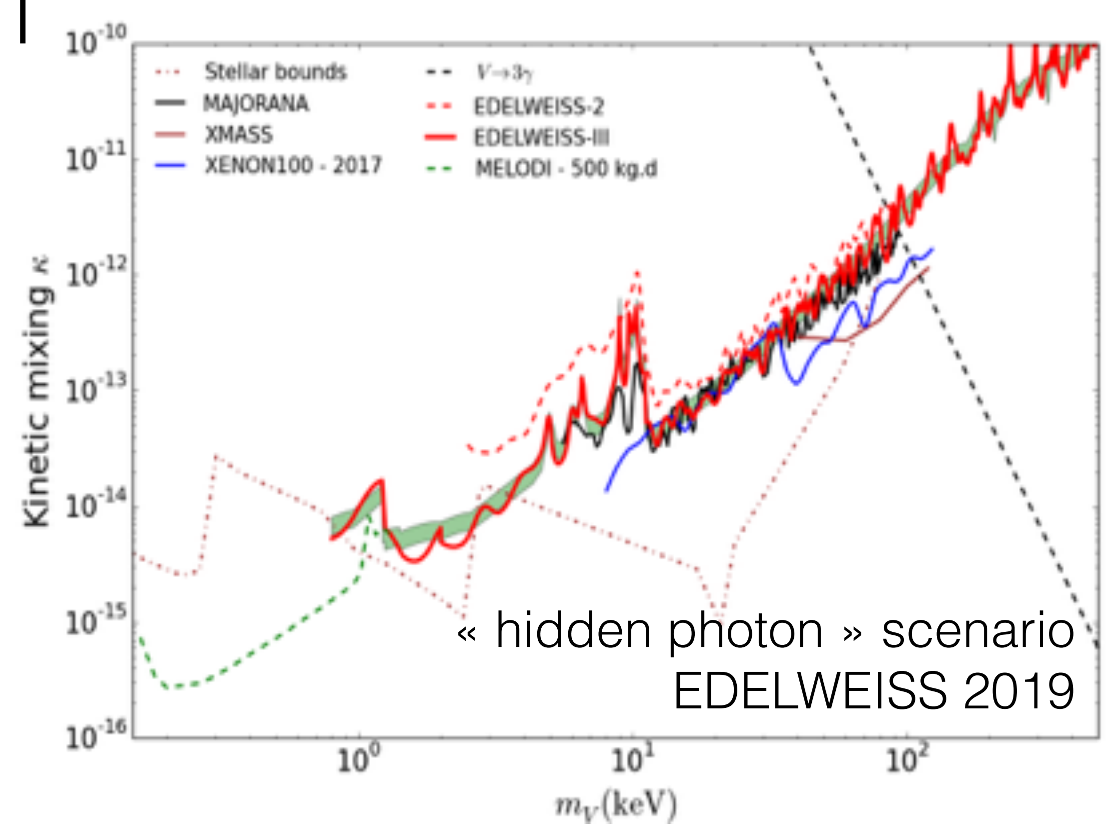
Absorption

Only for bosonic DM

NB DM must be bosonic for m<keV (phase-space density in halos)

Analog to photoelectric effect

Pospelov+ 2008



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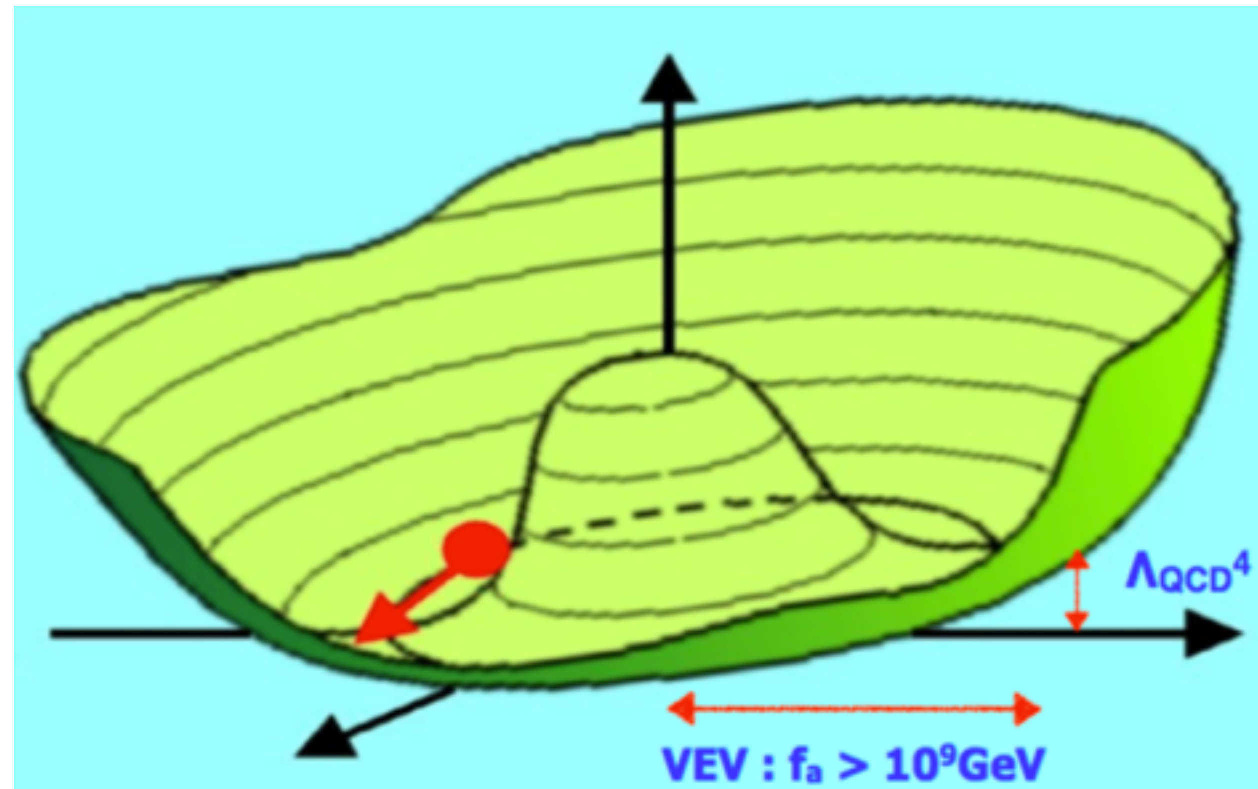
The QCD axion paradigm

Assume new physics @ very high energy scale
some complex field with U(1) symmetry breaking @ scale f_a (Peccei-Quinn)

Massless Goldstone boson = axion
angle $\theta_a = a/f_a$

Coupling to QCD
After QCD phase transition :
- axion gets a mass $m_a \sim \Lambda^2_{QCD} / f_a$
- **no CP violation in the QCD sector**

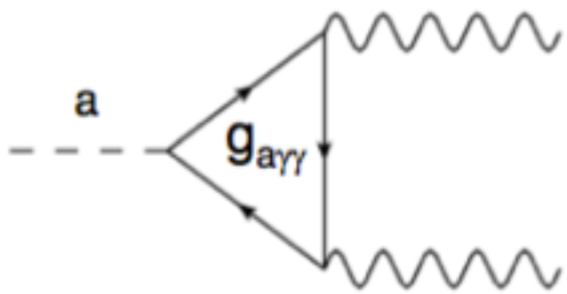


Oscillations after QCD transition :
misalignment mechanism
the axion field behaves like dark matter

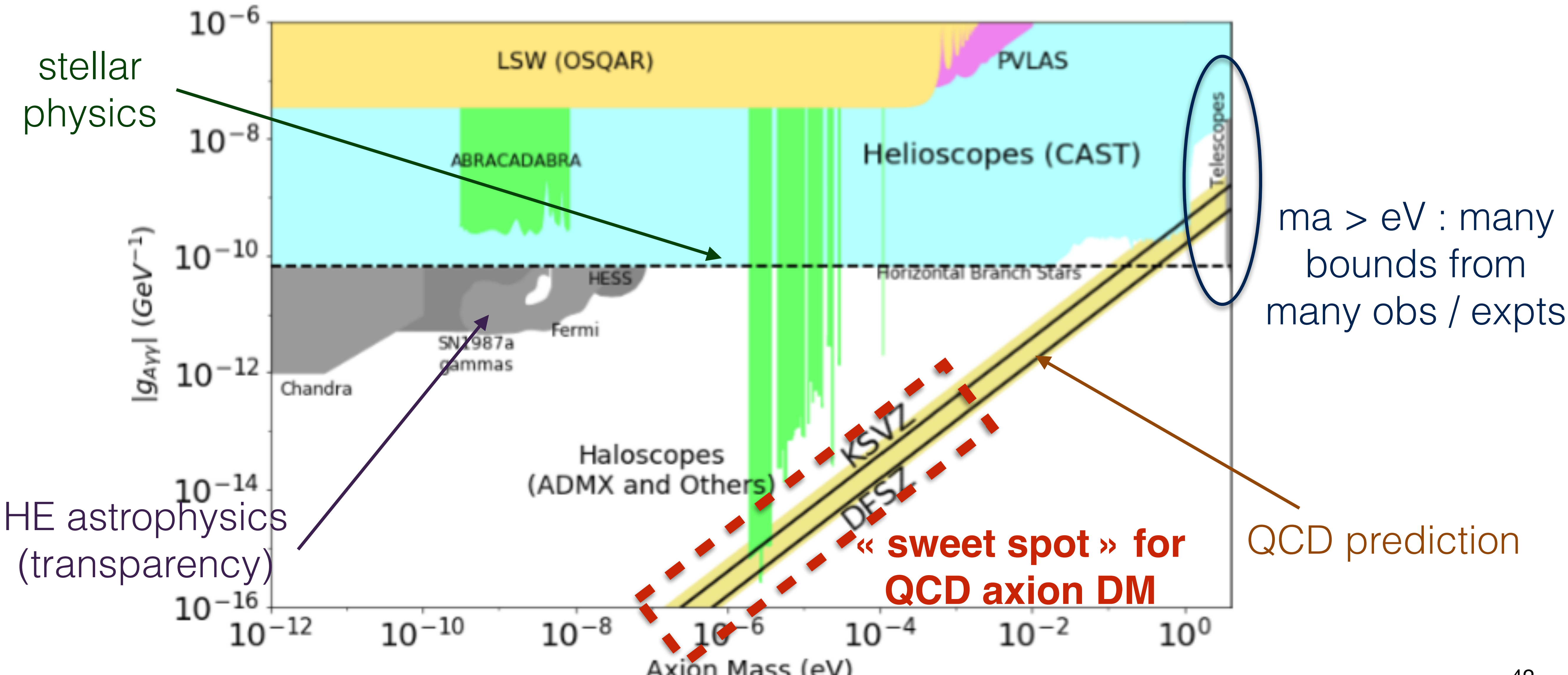
$$\Omega_a \sim 0.36 \left(\frac{10\ \mu\text{eV}}{m_a}\right)^{1.184}$$

(simplest case)

The axion interacts with photons



Effective coupling ~ $g_{a\gamma\gamma}$. a . (E . B)
depends on axion model
but for QCD axion $g_{a\gamma\gamma} \sim 1/f_a \sim m_a$



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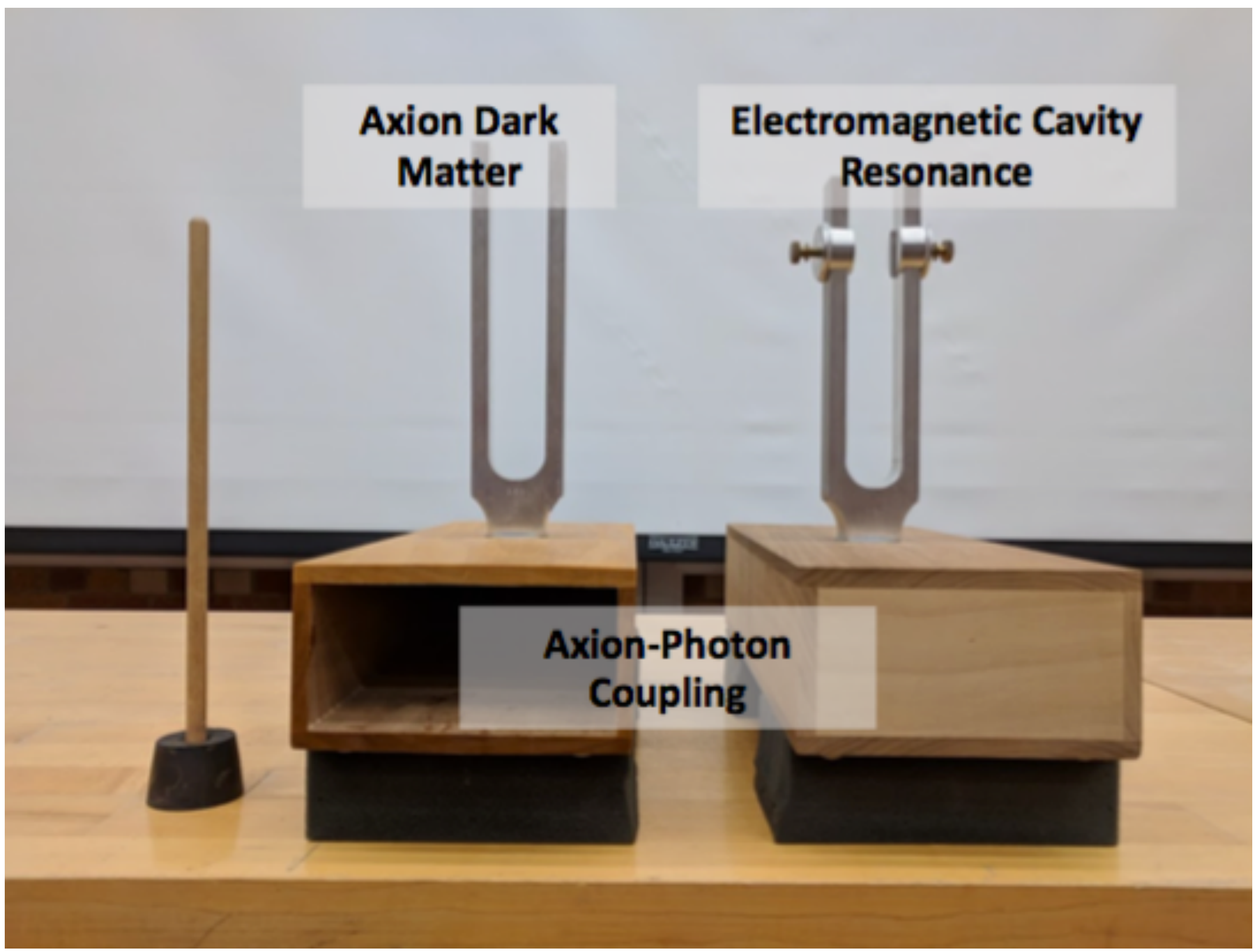
Axion « haloscopes » : principle

P. Sikivie 80s

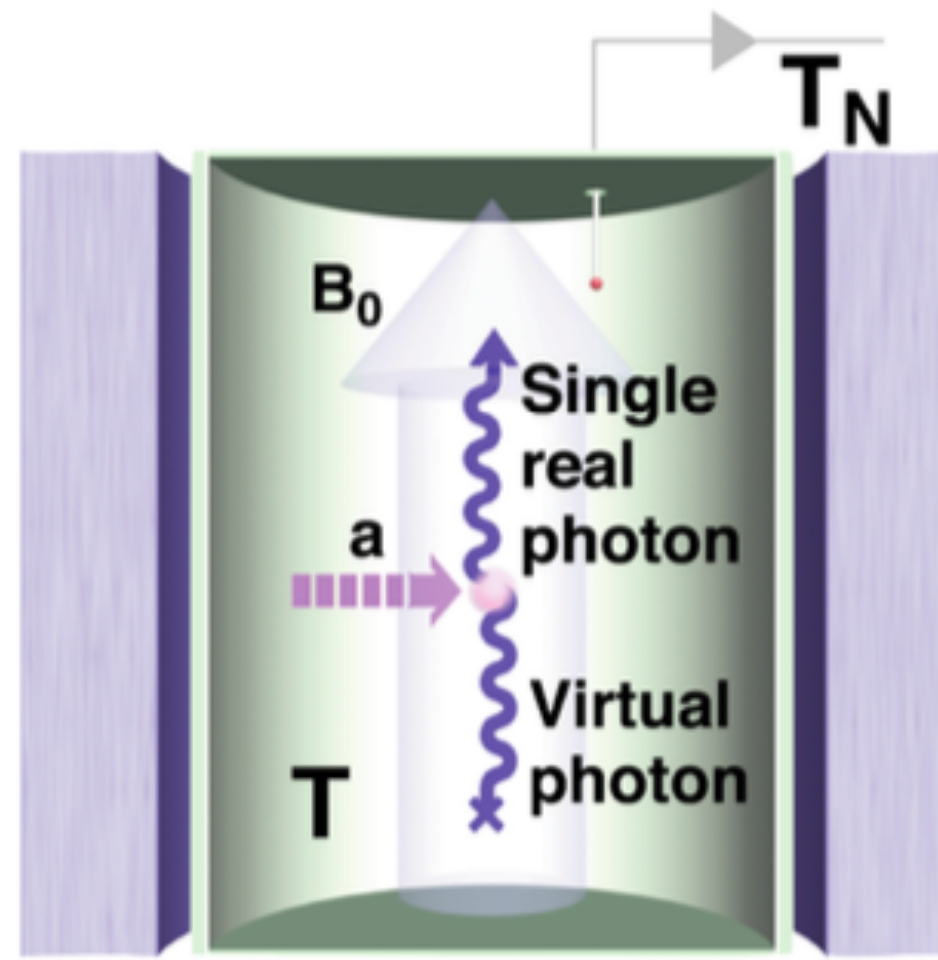
Effective coupling ~ $g_{a\gamma\gamma}$. a . (E . B)

a : axion from DM halo, oscillates @ $\omega = m_a$

B : magnet (static) ==> detect E @ $\omega = m_a$

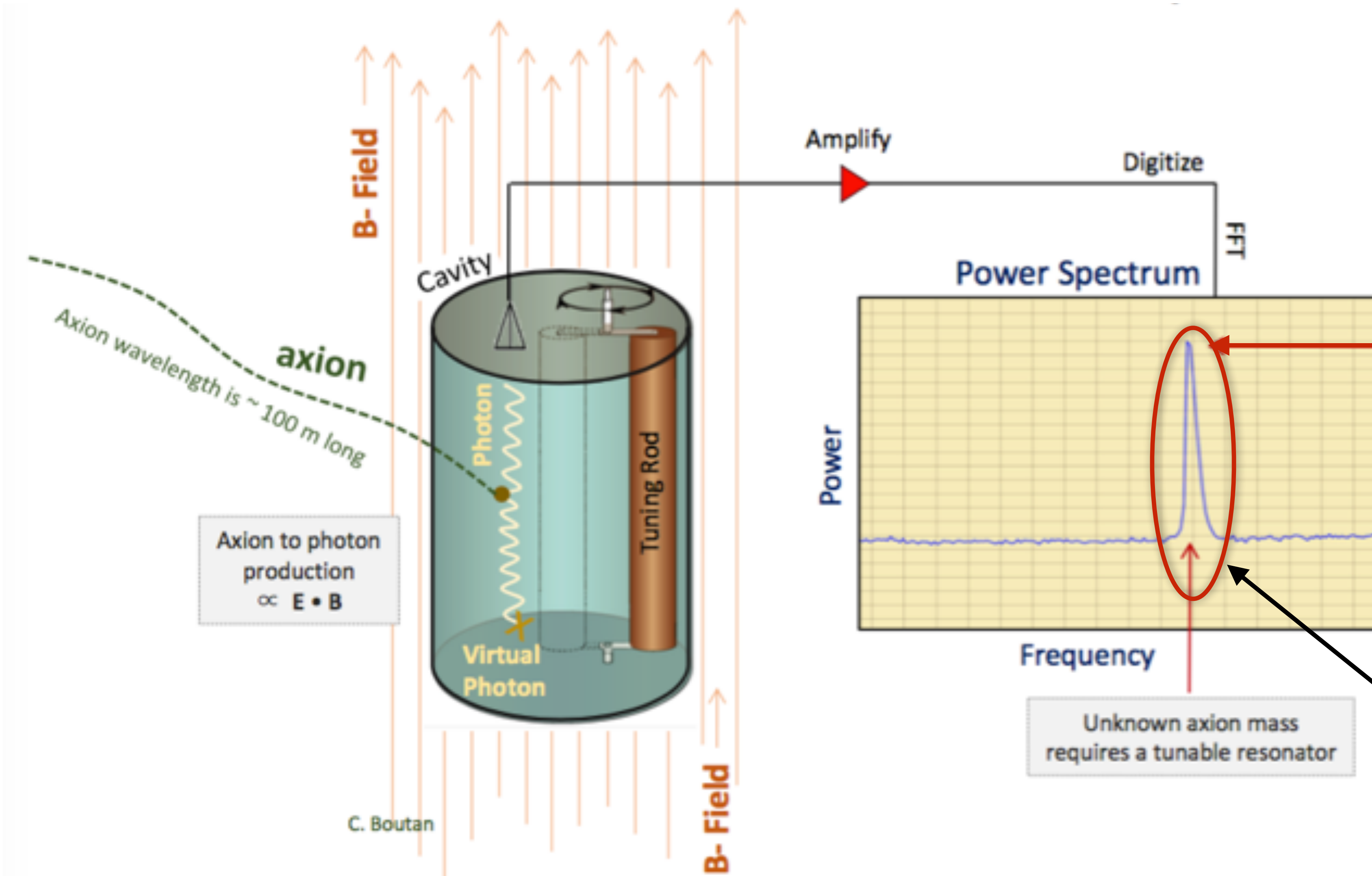


field



particle

Axion haloscope (2)



ω = m_a (1+1/2 v^2)
==> can directly reconstruct the local DM velocity distribution

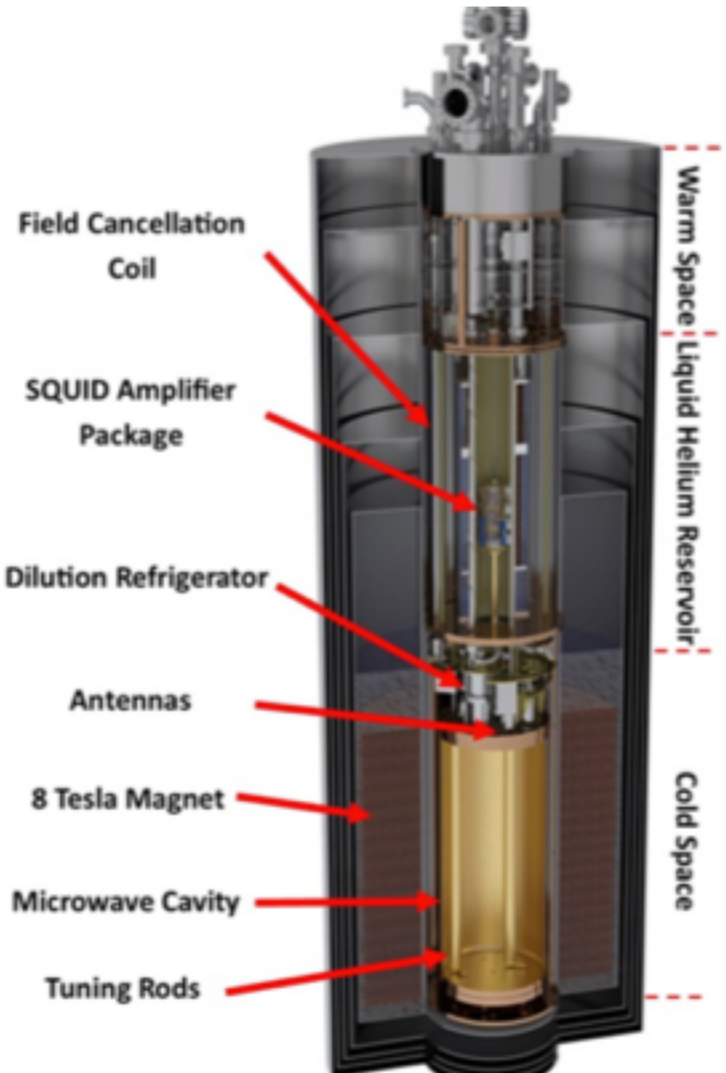
$$\frac{S}{N} = \frac{P_{\rm axion}}{k_B T_{\rm sys}} \sqrt{\frac{t}{b}}$$

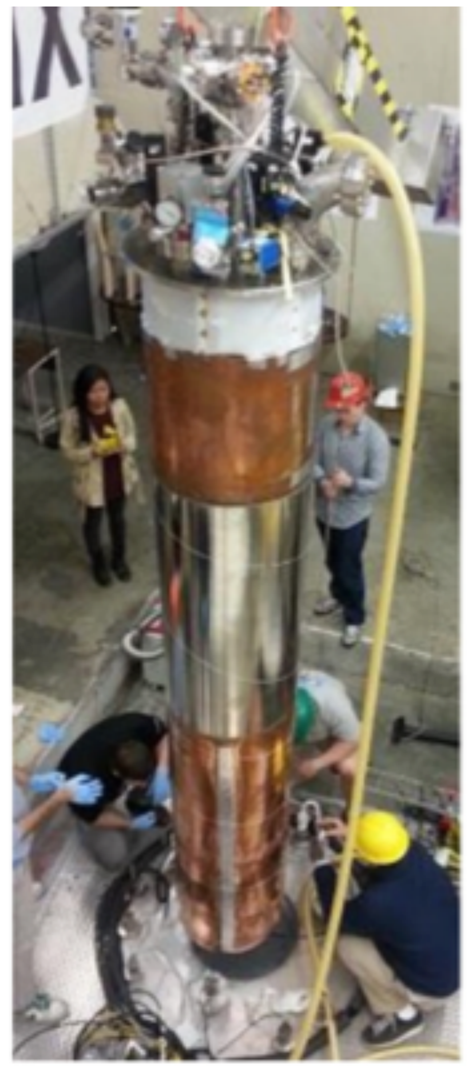
Resonator Volume, Form Factor, Dark Matter Density, Resonator Quality

$$P_{a\rightarrow\gamma} = 1.52\times10^{-21}\,\mathrm{W}\left(\frac{V}{220\,l}\right)\left(\frac{B}{7.6\,\mathrm{T}}\right)^2 f_{nlm}\left(\frac{g_\gamma}{0.97}\right)^2\left(\frac{\rho_a}{0.45\,\mathrm{GeV/cc}}\right)\left(\frac{f_a}{750\,\mathrm{MHz}}\right)\left(\frac{Q}{70,000}\right)$$

Power in haloscope, Magnetic Field, Model Coupling, Frequency

(Main) example : ADMX axion search



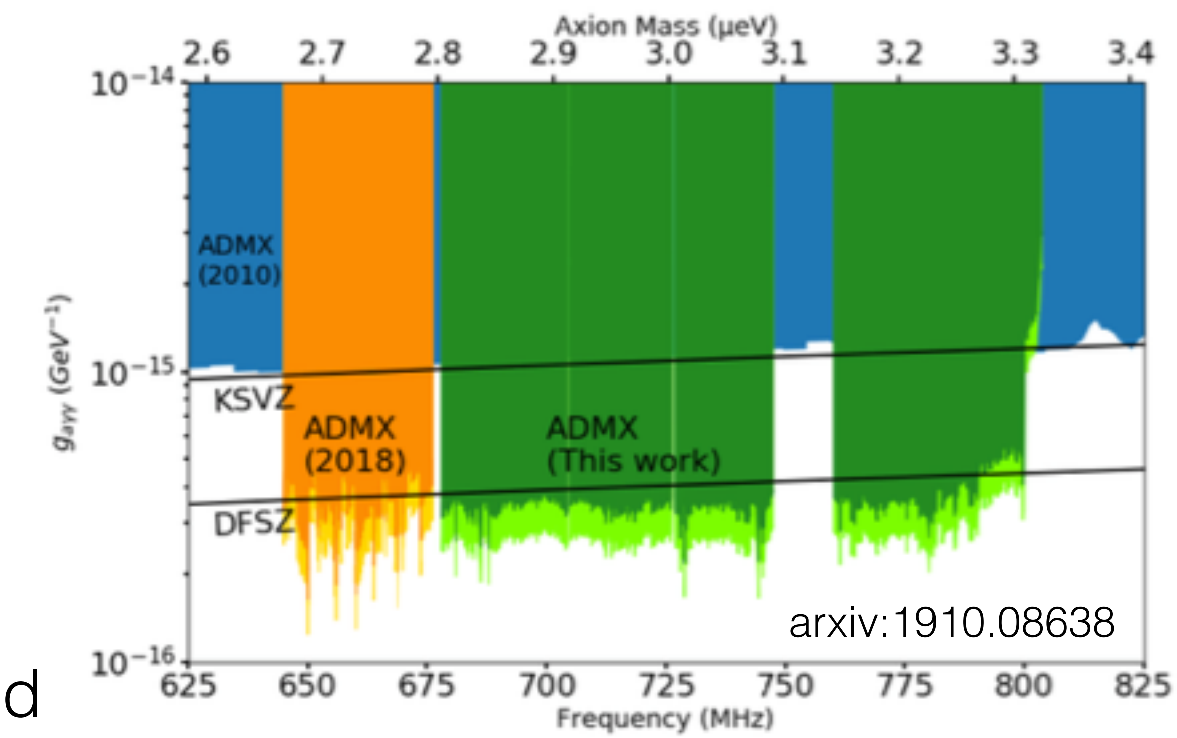


Key technologies:

-millikelvin cryogenics

-ultralow noise quantum amplifiers

scan over frequency

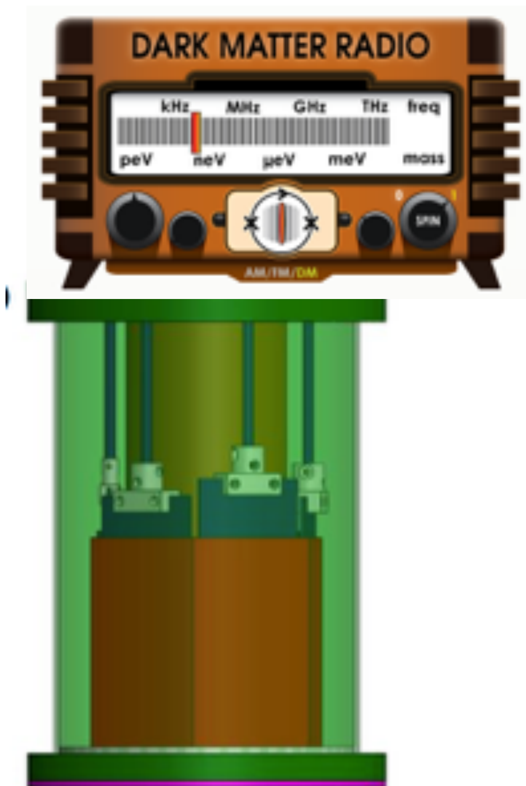


arxiv:1910.08638

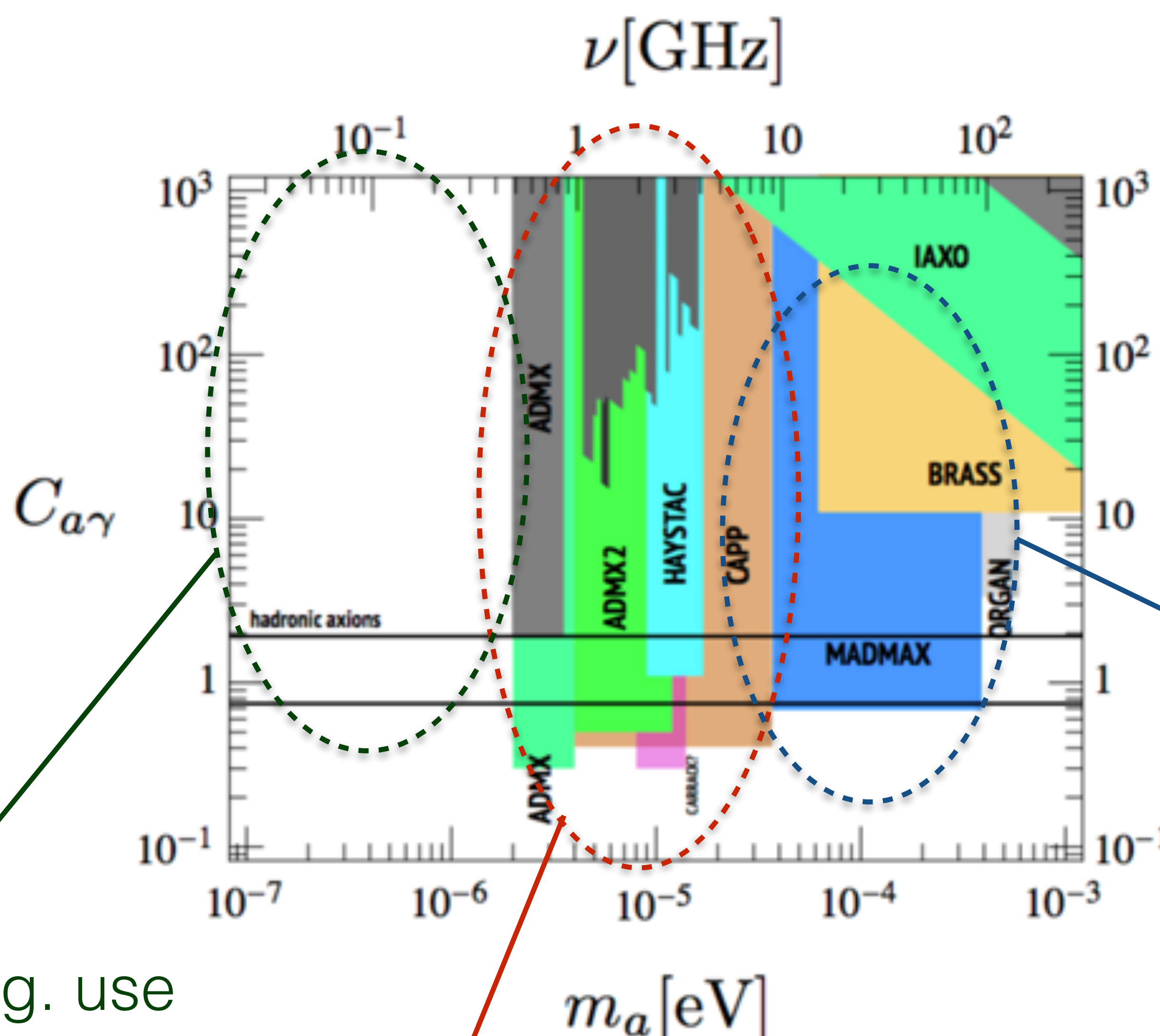
narrow QCD axion mass range excluded

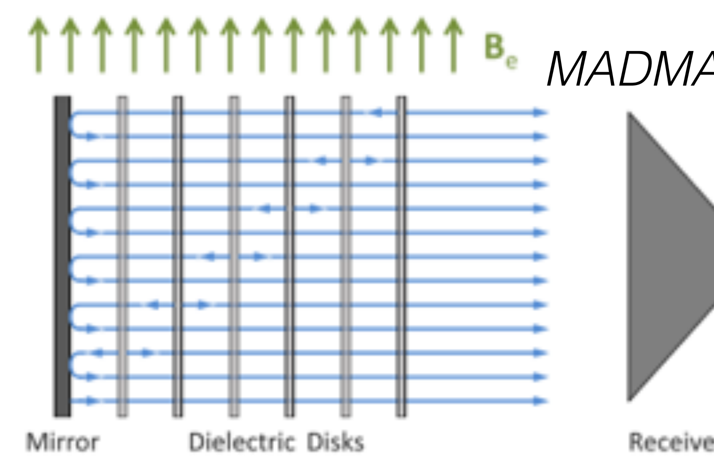
QCD axion searches : the future

Many R&D started in the past years to cover a wide range of mass
First prototypes exist. Will take years to reach QCD sensitivity



DM-radio





MADMAX

high frequency eg. use closely packed dielectric disks

low frequency eg. use LC-like resonators

ADMX-like (optimize scan speed / sensitivity)

Conclusions

DM direct search is a long, risky endeavour

Only works in certain DM scenarios
Driven by technological developments, R&Ds have possible applications in other branches of science

The WIMP scenario

Originally strongly motivated on phenomenological grounds
Technology : from nuclear / particle physics
Mature, large-scale experiments see no signal, in line with LHC / Fermi / …
Experiments will continue : go down to nu floor, do neutrino physics

« Low-mass » DM scenarios

Some phenomenological motivations
Technology : from material science / quantum devices
Currently small-scale experiments, progressing fast

QCD axions

Strong phenomenological motivation
Technology : radiometer-like
Experiments will probably explore most interesting scenarios in coming decade(s)