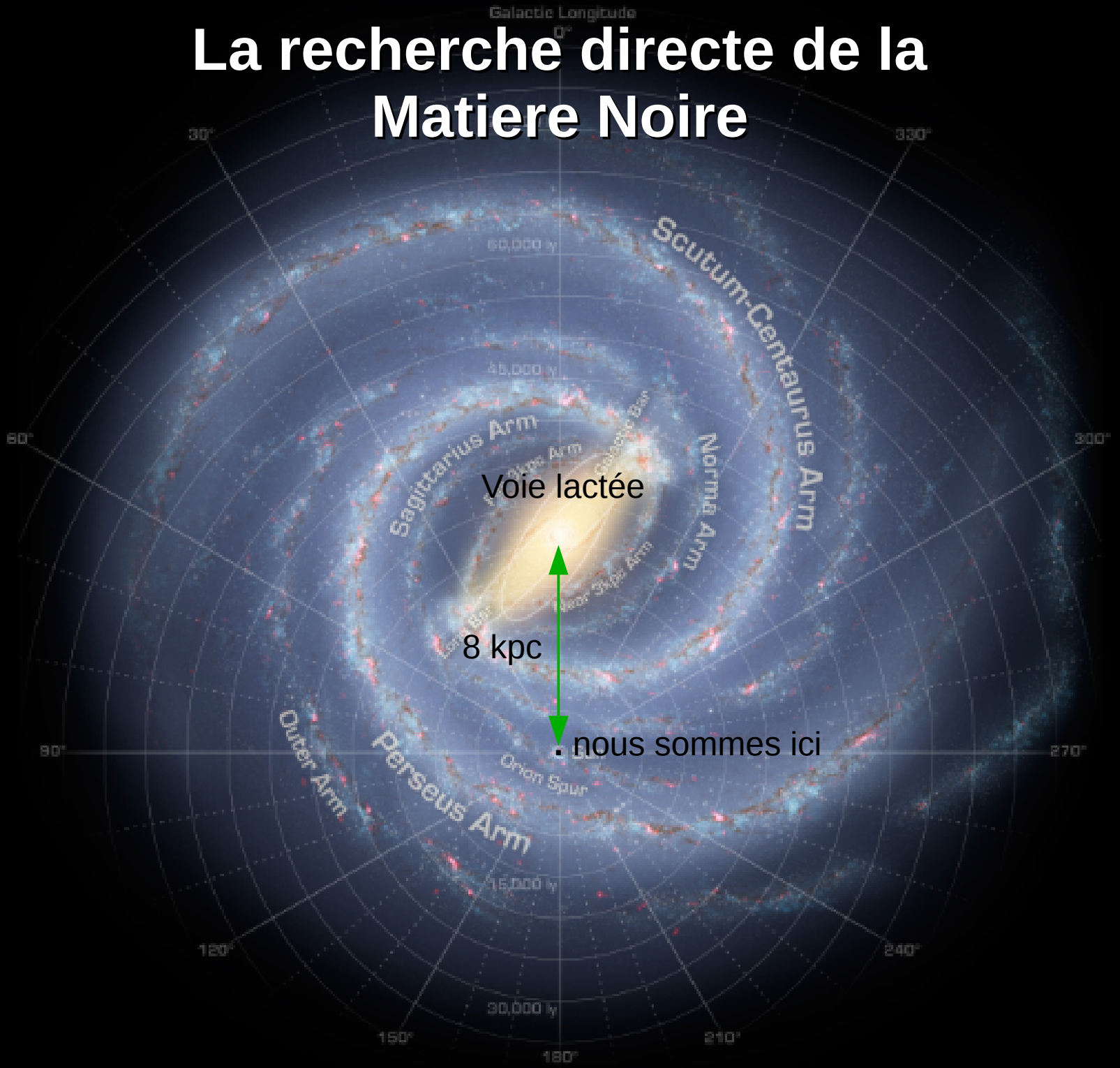
Les perspectives de la recherche directe (mais pas seulement) de la Matiere Noire @ LPNHE

Luca Scotto Lavina
CNRS

Avec le materiel et les idées de Romain, Claudio, Bertrand et apres plein de discussions avec tous

Biennale LPNHE, Montpellier

La recherche directe de la Matiere Noire



Ce que on cherche

Dark Matter is required to be:

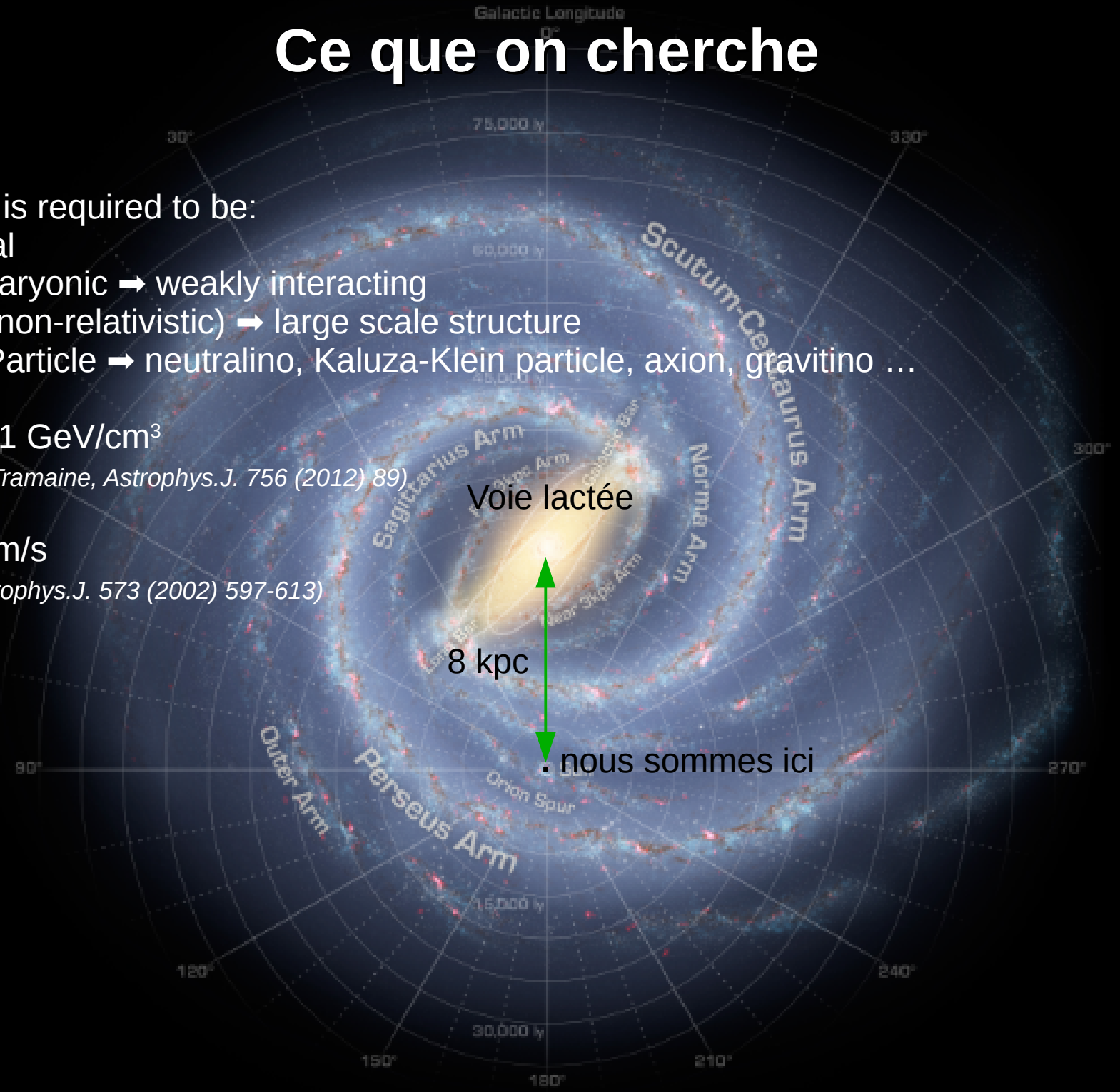
- Neutral
- Non-baryonic ➡ weakly interacting
- Cold (non-relativistic) ➡ large scale structure
- New Particle ➡ neutralino, Kaluza-Klein particle, axion, gravitino …

$\rho_\chi = 0.3 \pm 0.1$ GeV/cm^3

(J. Bovy and S. Tramaine, Astrophys.J. 756 (2012) 89)

$V_{sun} \sim 220$ km/s

(Klypin et al. Astrophys.J. 573 (2002) 597-613)



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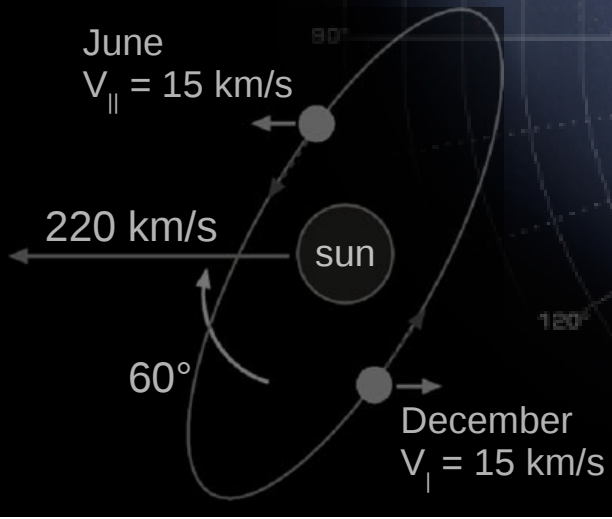
Voie lactée

8 kpc

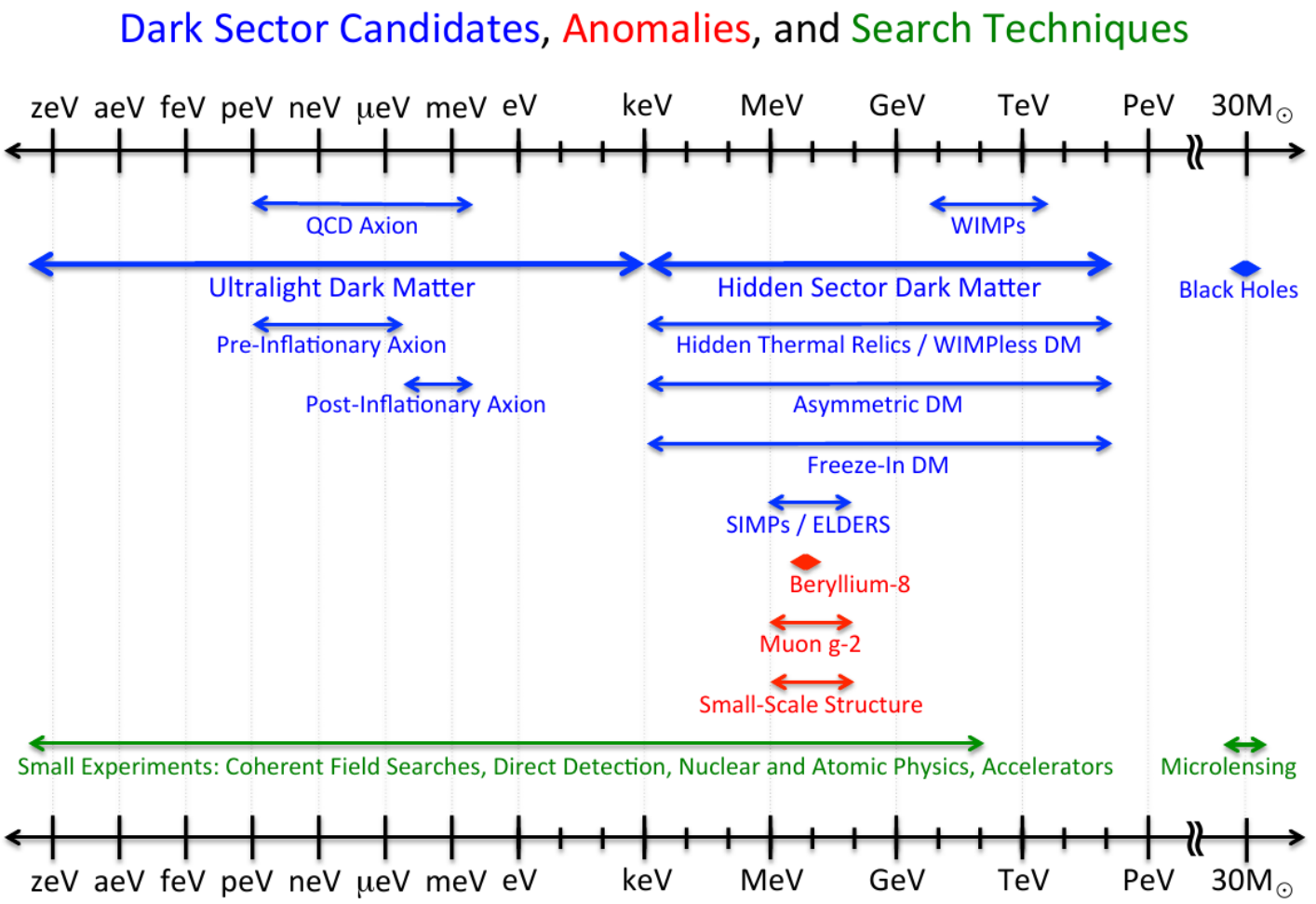
nous sommes ici



Dark Matter might interact with known matter is many ways:

- Spin Independent/Dependent interaction
- With nuclei or with electrons
- Elastically or inelastically

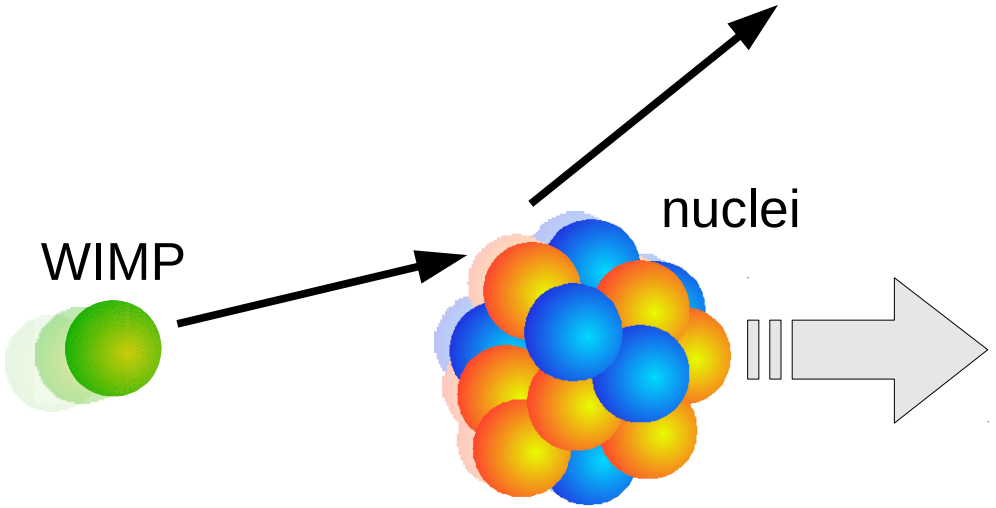
Mass ranges of dark matter



US Cosmic Visions: New Ideas in Dark Matter 2017 arxiv:1707.04591

The direct detection principle

WIMP elastically scatters off nuclei → nuclear recoils



χ + N → χ + N

$v \sim 230\ km/s$

$m_\chi = 10 - 10^4\ GeV/c^2$

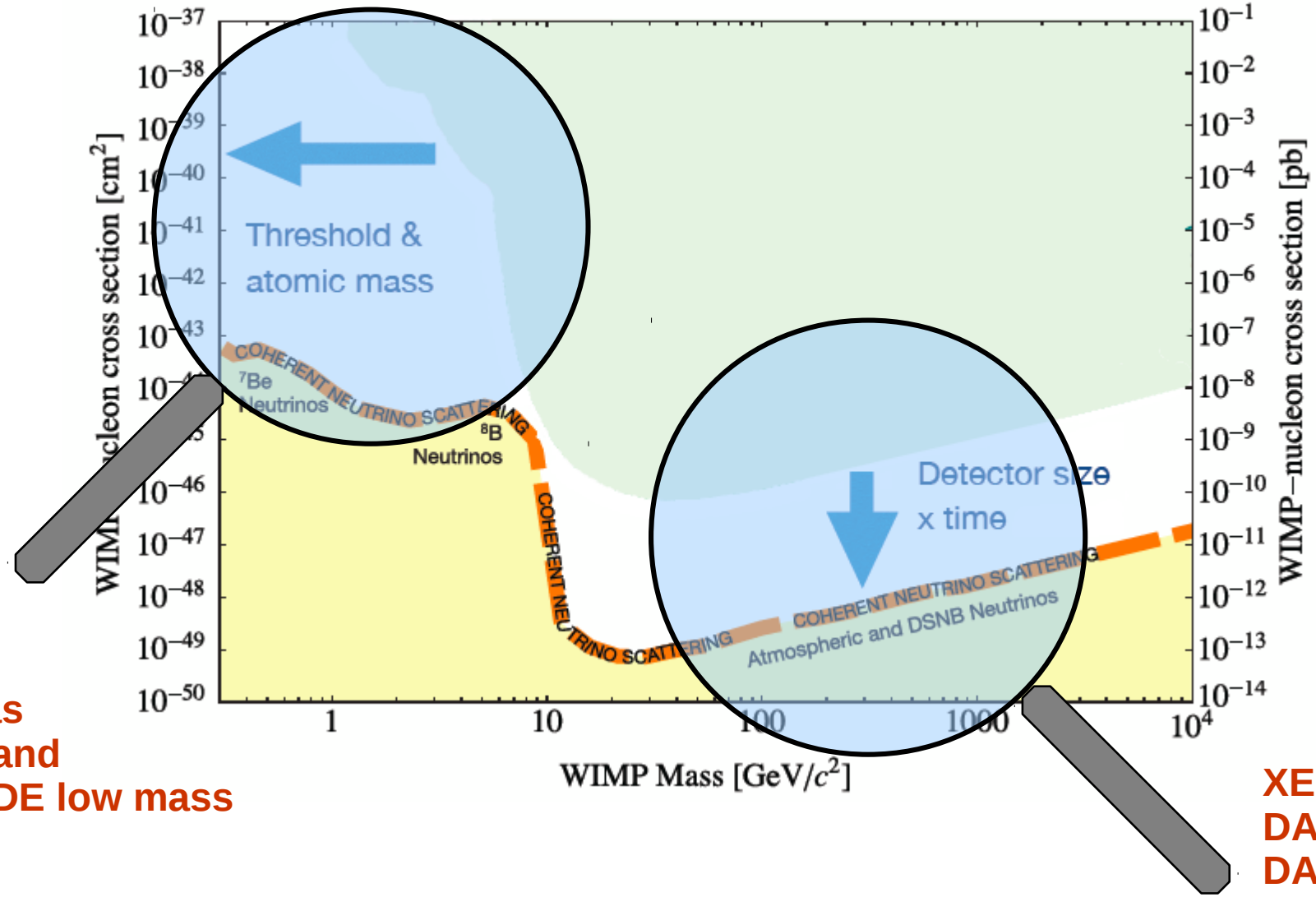
$\rho_\chi \sim 0.3\ GeV/c^2/cm^3$

Small recoil energy $$E = \frac{\mu^2 v^2}{m_N}(1 - cos\theta) \lesssim 100keV$$

Small event rate $$\frac{dR}{dE} = \frac{\rho_\chi}{m_\chi}\frac{\sigma|F(E)|^2}{2\mu_p^2}\int_{v_{min(E)}}^{v_{esc}} d^3v \frac{f_\oplus(\vec{v},t)}{v}$$

Experiences in LPNHE looking for a direct evidence of dark matter

Competition and complementarity !!!



DAMIC

as well as XENON and DARKSIDE low mass

XENON DARKSIDE DARWIN

Today's menu : from current status to perspectives

Current → **Under design/construction** → **Beyond**

1) DAMIC → DAMIC-M → DAMIC 10 kg?

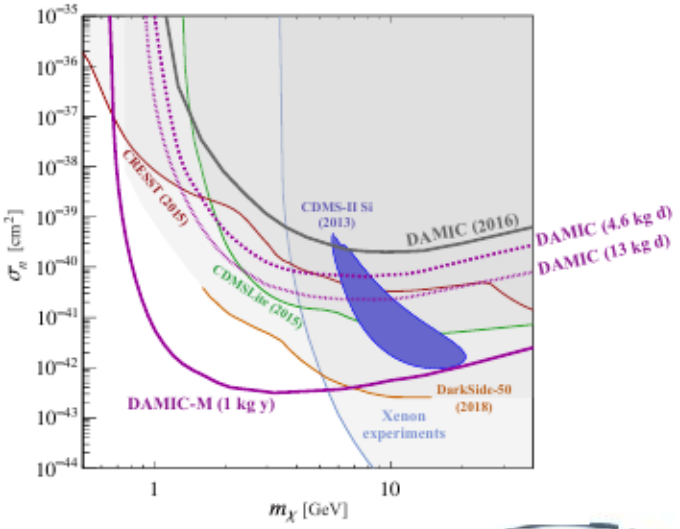
2) DarkSide50 → DarkSide-20k → ARGO

3) XENON1T → XENONnT → DARWIN

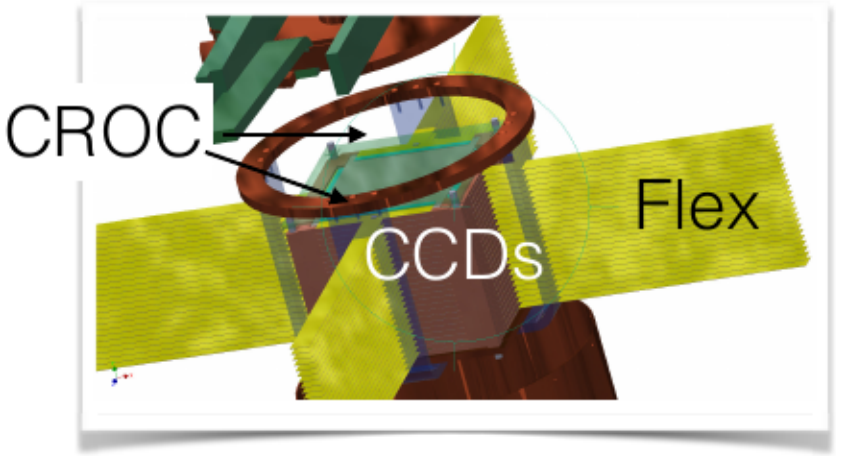
4) nothing...
→ Cryogenic lab
→ Synergy Direct, Indirect, Colliders

DAMIC-M

- **Objectifs scientifiques**
  - WIMP « legeres » (1-10GeV)
  - Secteur caché (compétitif pour plusieurs scenarios)

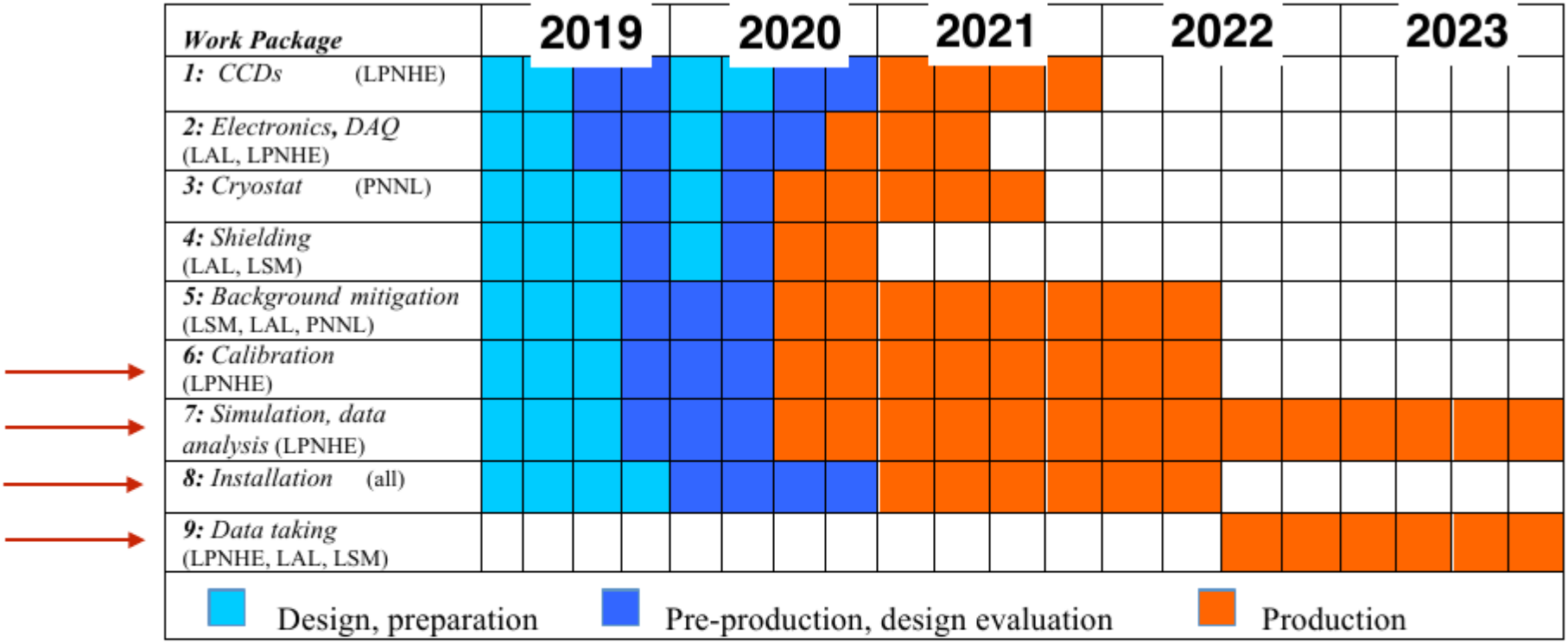


- **Un détecteur innovant**
  - Une grande camera (**1kg** of CCD)
  - Utilisation de la technologie **skipper (bruit < 1e)**
  - Screening radioactif complet
  - Potentiel unique d'identification des chaines
  - Bruit de fond radioactif **< 0.1 d.r.u.**



- **Un projet:** LPNHE PARIS
  - LPNHE porteur de l'ERC
  - Paolo: Spokesperson
  - Antoine: Science coordinator
  - Herve: Electronics Task leader

DAMIC-M schedule



- Exploitation prévue jusqu'à 2023
- Le LPNHE impliqué dans la plupart des WP d'exploitation
- Coordination étroite avec d'autres labos IN2P3 (Nantes, Bordeaux, Orsay, LSM) (besoin d'un soutien au delà de l'ERC)

DAMIC-M calibration and installation

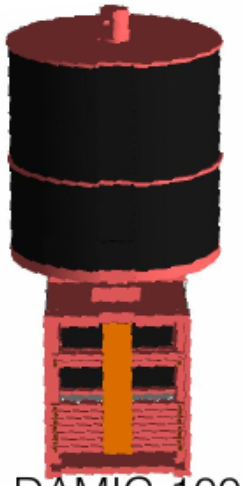
- **Integration du système de lecture (<2022)**
  - Cartes filles (controle / ADC) avec ODILE (carte mere)
  - Hardware/Firware avec DAQ (IPNO)

- **Optimisation du système de lecture (<2022)**
  - Sequence Skipper CCD
  - Bruit d'une fraction d'electron
    - propreté horloges
    - Caractérisation du bruit de l'ampli de lecture
  - optimisation de la temperature du système

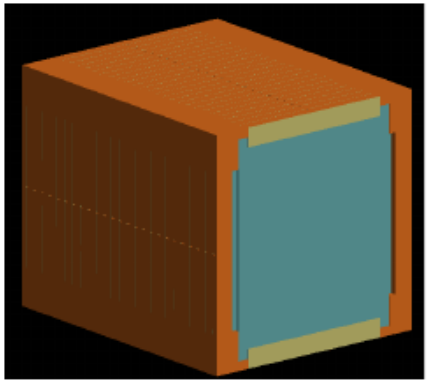
- **Développement d'un système de calibration sur site**
  - Bonding des CCD et CROC (chip de lecture) a Modane
  - Systeme de test / selection à developper

DAMIC-M simulation and data analysis

Simulation

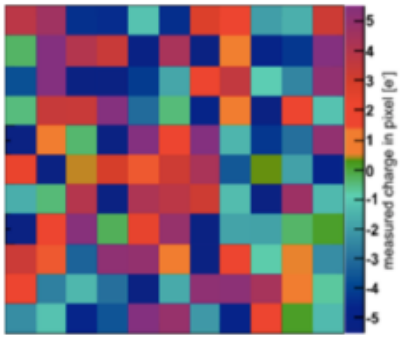


DAMIC-100
(LPNHE)

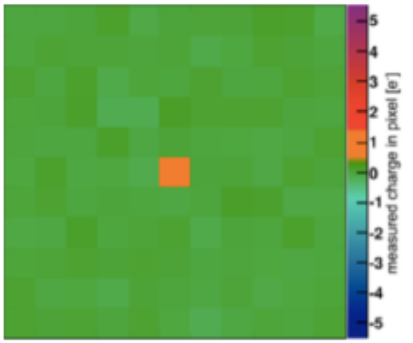


DAMIC-M
(Subatech)

Analyse



avant



après
(skipper)

- Experience avec DAMIC-100 (simu et analyse)
  - nouvelle Geometrie / système de lecture / bruit radioactif plus faible
  - Collaboration avec Subatech
  - nouveau PhD en Novembre au LPNHE

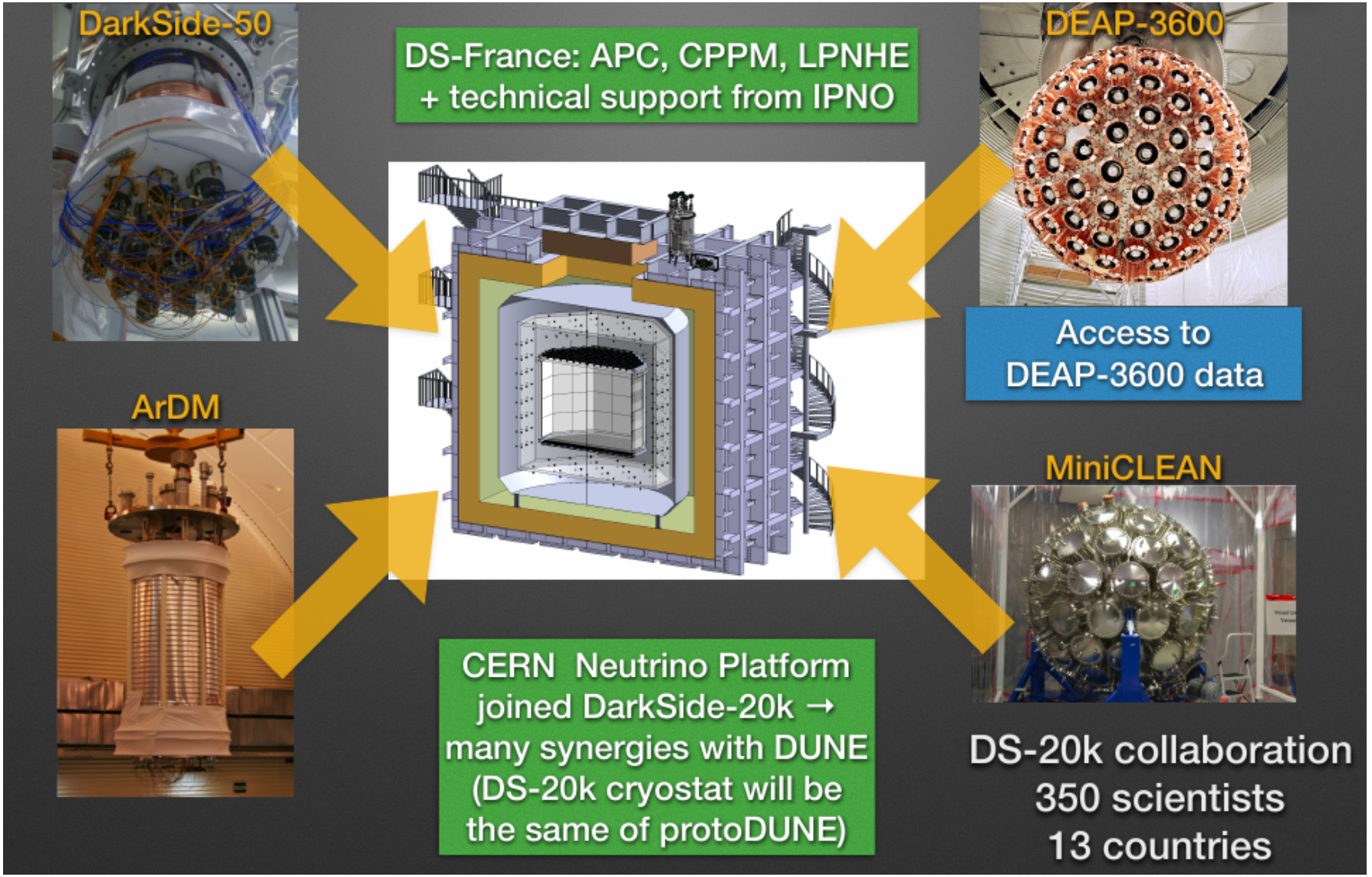
DÉTECTEUR SILICIUM HAUTE GRANULARITÉ BAS BRUIT BAS SEUIL

Efforts lancés (5-10 ans) par le DOE (pour Fermilab) pour les détecteurs Silicium de prochaine generation

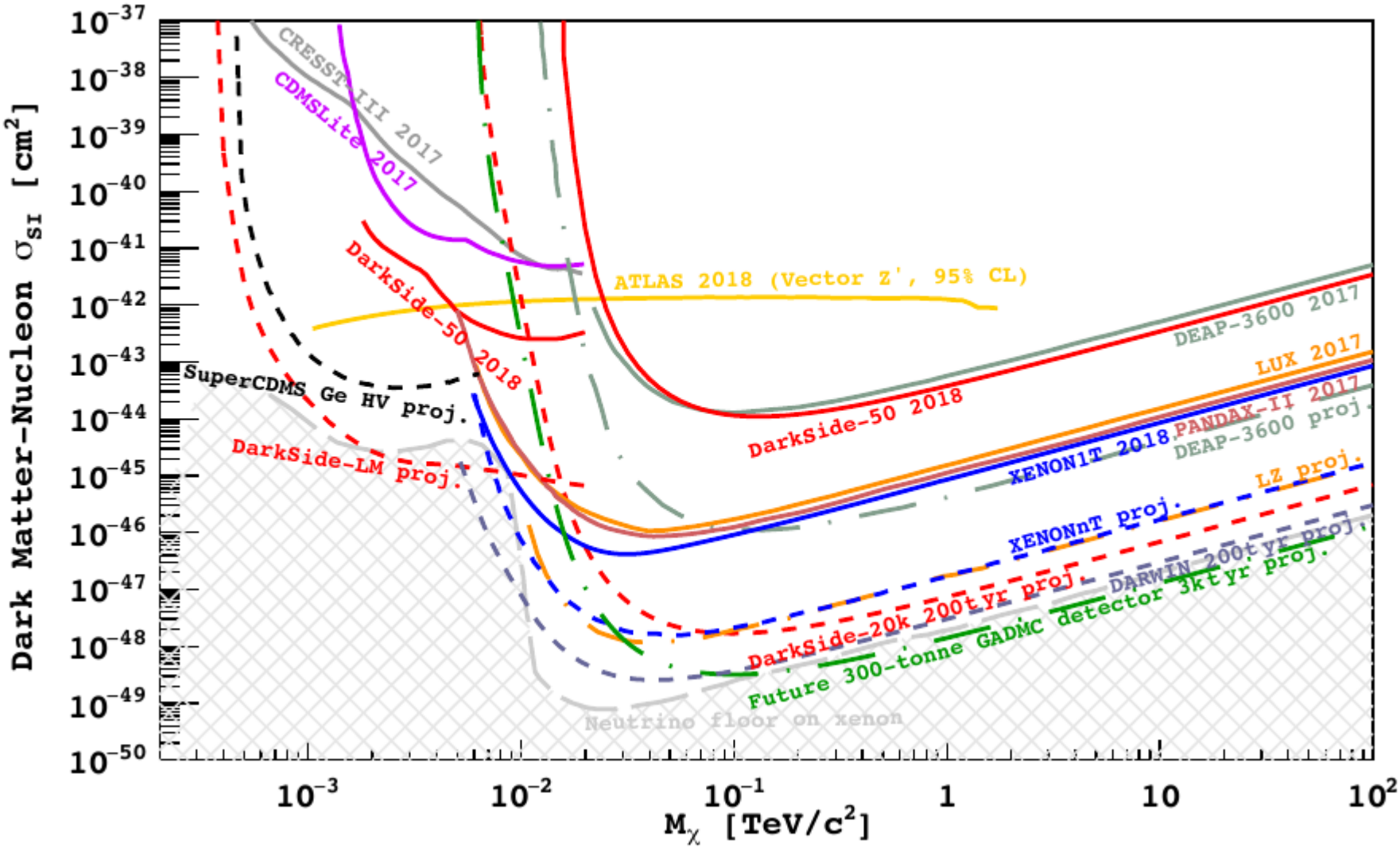
le LPNHE pourrait s'y associer

- DAMIC-10kg ?
- Detection de diffusion coherente de neutrinos
- Autres applications:
  - Nuclear forensic
  - Soft error rate

DarkSide-20k

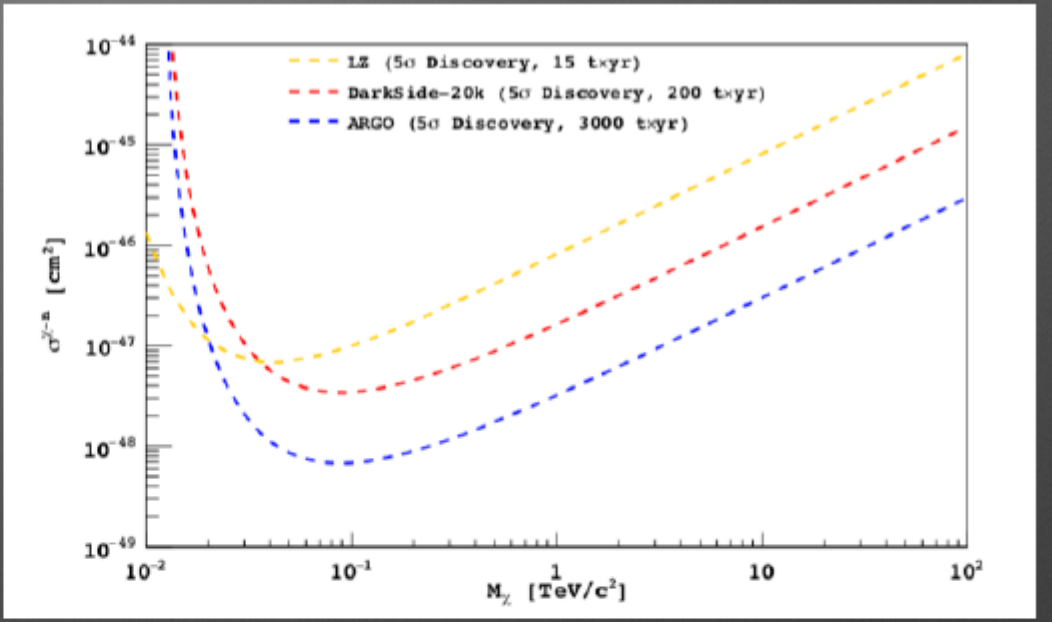


Expected sensitivities



Discovery potential

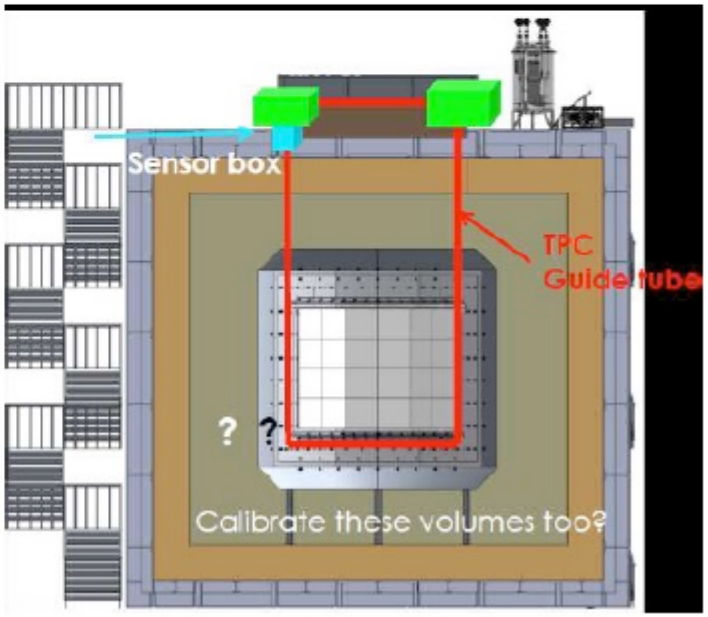
- LAr only technique able to confirm signals seen in Xenon-detectors
- Excellent discovery potential in the next decade



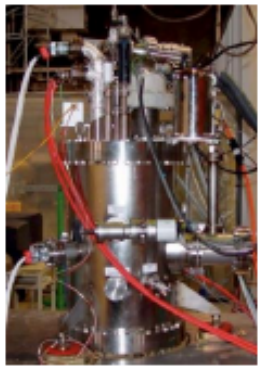
	20-	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
DS-50																		
DS-Proto				DS-LM														
DEAP-3600																		
DS-20k																		
ARGO																		

DarkSide France

- Calibration system being designed by French groups
  - LPNHE: Responsible for simulations (Olivier Dadoun)
  - CPPM: design of the insertion system (Pierre Barillon, Pascal Pralavorio, Fabrice Hubaut)
- Everything has to be inside a LAr bath → cryogenic temperatures
- Need to host ER calibration sources but also a D-D gun for NR calibration
- Design will be presented to the collaboration in June 2019
- Hope to get approval by IN2P3 following positive recommandations from IN2P3 Conseil Scientifique

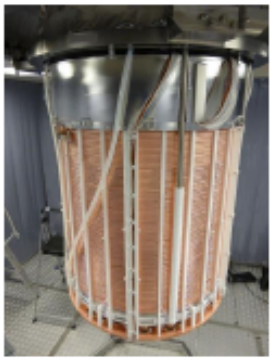


XENON Program

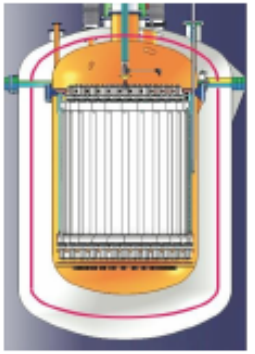


XENON10
Total Xe: 25 kg
Target:14 kg
Fiducial: 5.4 kg
Limit: ~10^{-43}

XENON100
Total Xe: 162 kg
Target: 62 kg
Fiducial: 34/48 kg
Limit: ~10^{-45}

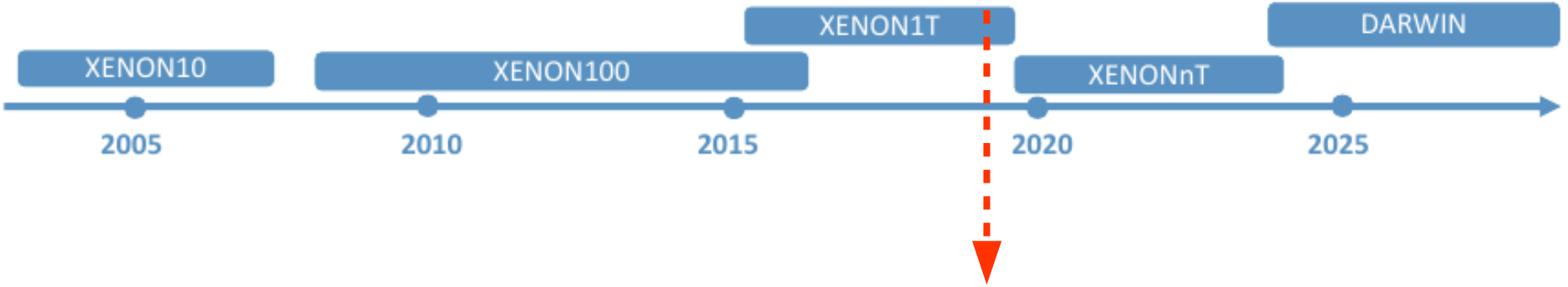


XENON1T
Total Xe: 3.2 ton
Target: 2 ton
Fiducial: 1 ton
Limit: ~10^{-47}



XENONnT
Total Xe: ~8 ton
Target: ~6.5 ton
Fiducial: ~5 ton
Limit: ~10^{-48}

DARWIN
Total Xe: 50 ton
Target: 40 ton
Fiducial: 30 ton
Limit: ~10^{-49}



XENONnT physics studies and LPNHE participation

Many analyses in XENON1T that will be done also in XENONnT:

- Limit on Spin-Independent WIMP-nucleon cross section
- Limit on Spin-Dependent WIMP-nucleon cross section
- Limit on Inelastic cross section
- Search for magnetic inelastic scattering
- Annual modulation
- Low-mass Dark Matter
- S2-only analysis
- Single electrons origins

LPNHE contribution in XENON1T/nT

- Search for SuperWIMPs
- Axions
- Search for double electron capture in ^{124}Xe
- $0\nu\beta\beta$-decay

French contribution in XENON1T/nT

- …

A lot of **analysis work** with XENONnT data !!!

Darwin experiment

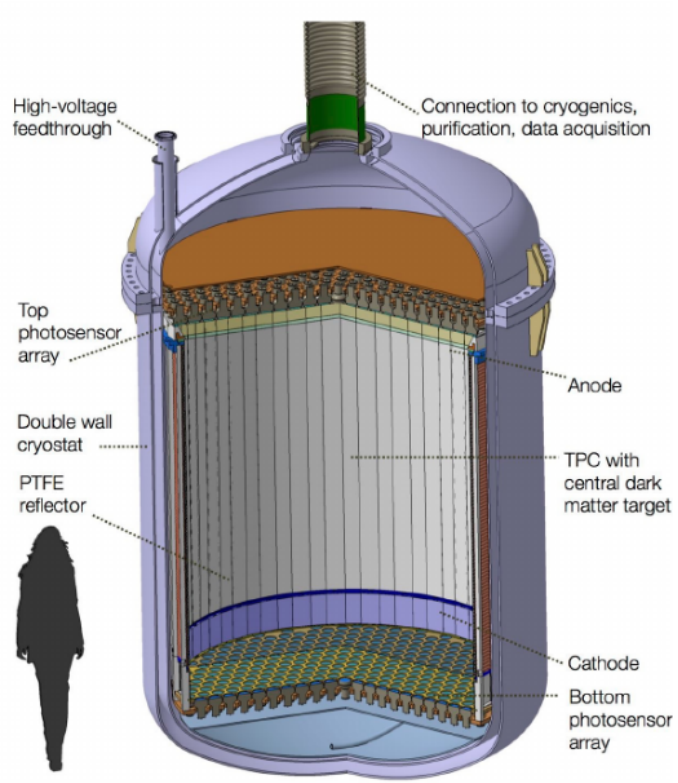
DARWIN

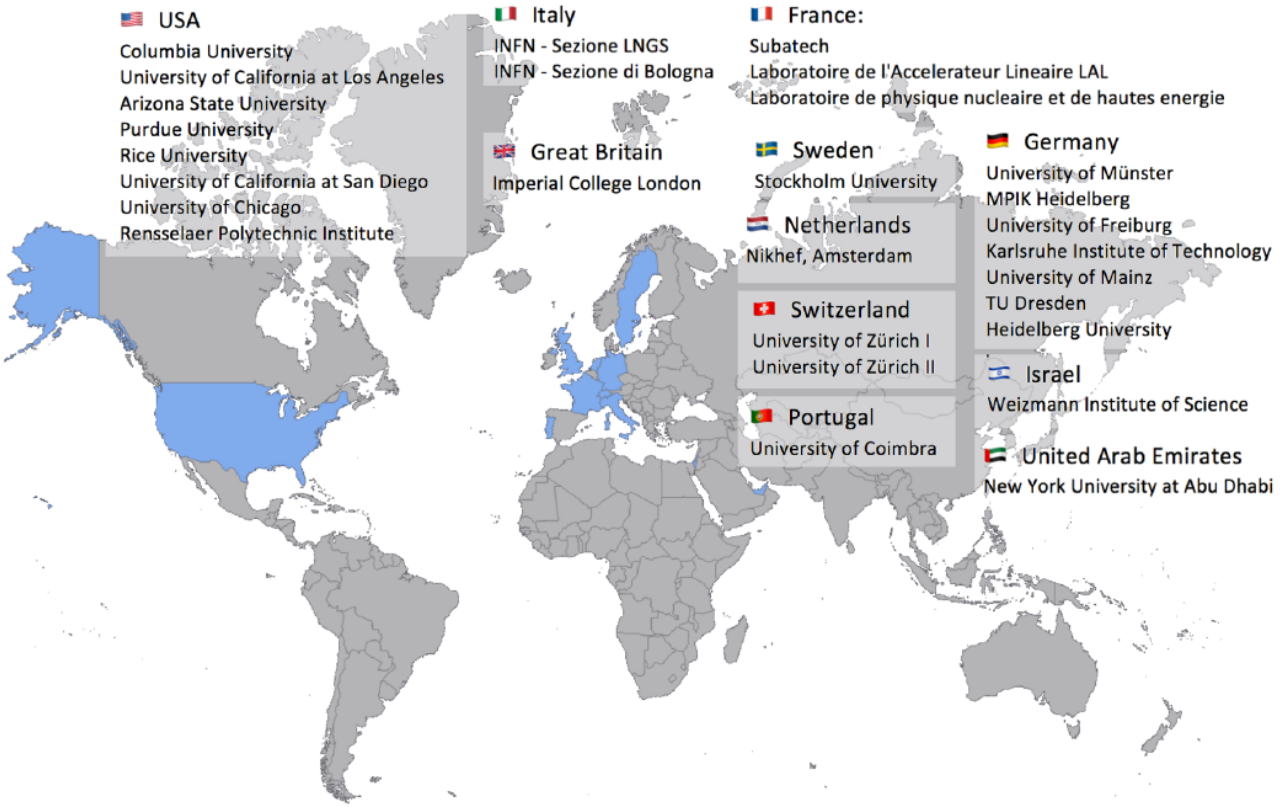
darwin-observatory.org

DARWIN collaboration, JCAP 1611 (2016) 017

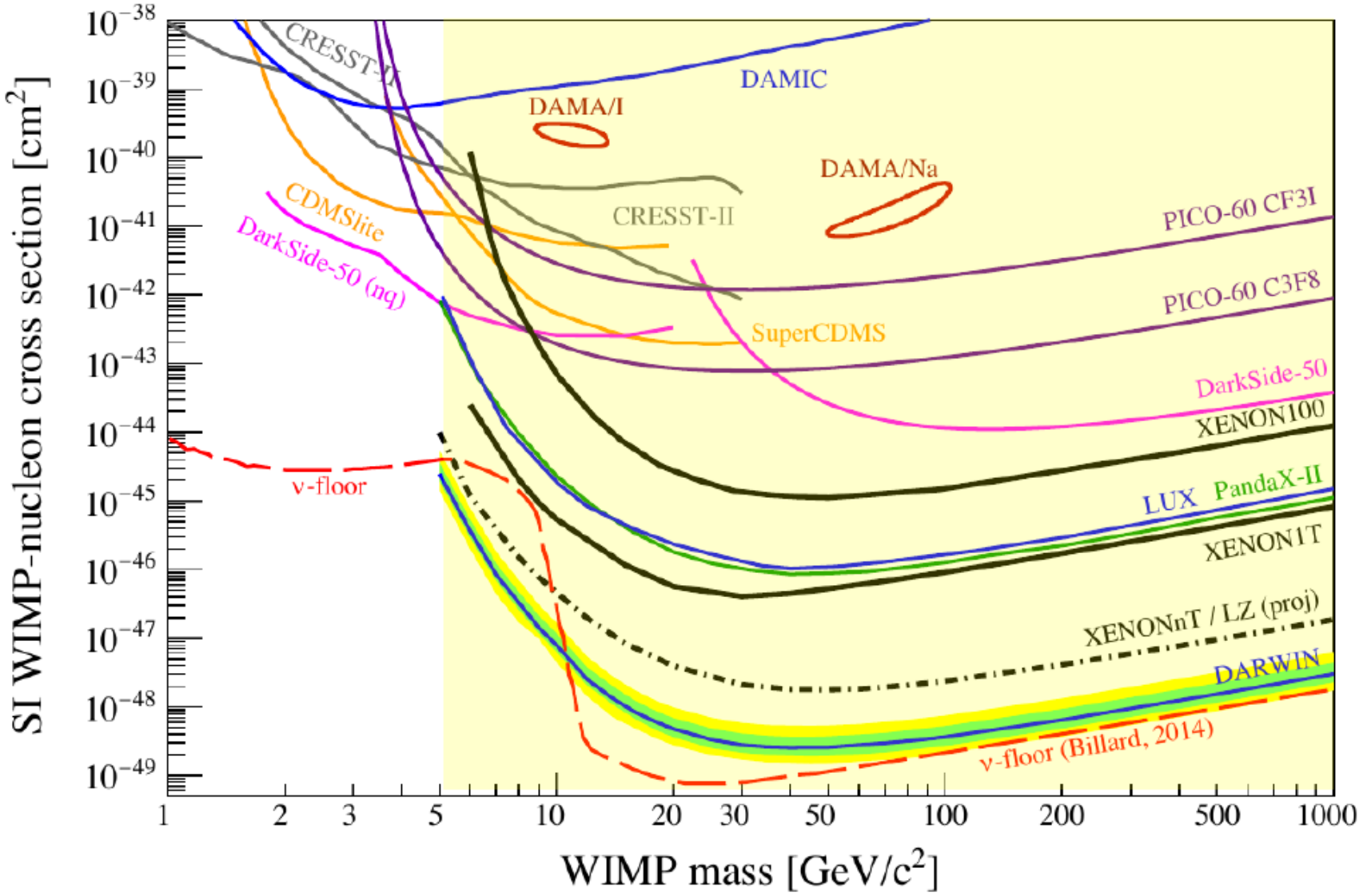
"Ultimate" WIMP detector

50 tonnes liquid xenon





XENON1T limit and expected sensitivity of XENONnT and DARWIN



DARWIN : rich science goal

- Probe WIMP-nucleon interactions for WIMP masses above ~5 GeV/c2
  (via spin-independent, spin-dependent and inelastic interactions)

- Probe even lower WIMP masses by using the charge signal alone (XENON10, XENON100, CDMS, EDELWEISS, DS-50)

- Coherent neutrino-nucleus scattering : ^{8}B neutrinos from sun, galactic supernova neutrinos

- "Leptophilic DM" models : look for signatures of DM scattering off electrons

- Solar neutrinos: pp-neutrinos via nu-e scattering (precision <1% on flux)

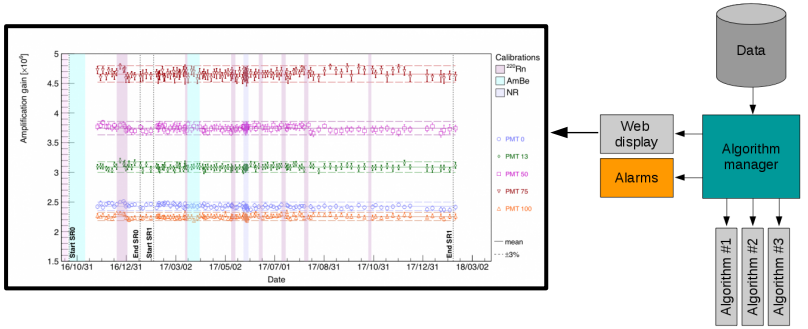
- Search for the neutrinoless double beta decay in ^{136}Xe

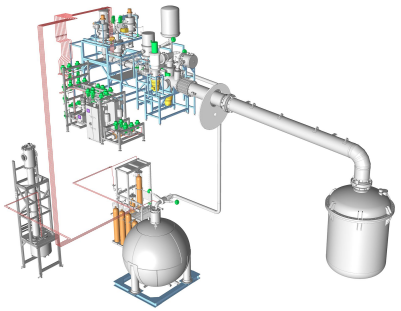
- Probe solar axions and axion-like particles models (axio-electric effect)

- Probe sterile neutrinos with masses in the > 10 keV range

Activities for XENONnT and DARWIN in France

Activity : Offline data quality monitoring tool
Who : LPNHE
Contribution: software development
Goal : run analysis algorithms to datasets and show results in a web interface in order to provide a quick feedback on data quality and trigger alarms in case some observables deviate from standard values.

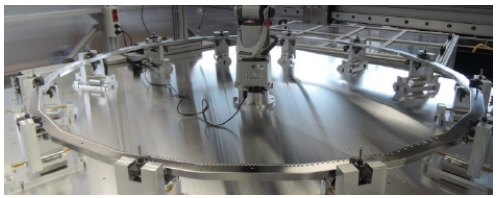




Activity : Cryogenics
Who : LPNHE, LAL, Subatech
Contribution: design, R&D, interaction with industry
Goal : develop the cryogenic network of DARWIN (cooling, storage, purification, distillation, recovery, safety) in collaboration with other groups (mainly Germany and Switzerland)

Activity : Computing
Who : LPNHE (+ CC-IN2P3)
Contribution: analysis hub for the whole Collaboration
Goal : offer to the DARWIN Collaboration a place where to process data and perform analysis remotely

jupyter RUCIO python mongoDB



Activity : Electrodes
Who : LAL (and eventually LPNHE, see next slides...)
Contribution: design, R&D, interaction with industry
Goal : improve the performances of electrodes for larger TPCs, reduce the generation of electrons, performing tests

Common timeline

	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
DAMIC-M											
XENONnT											
DarkSide-20k											
DARWIN											

Today's menu : from current status to perspectives

Current → **Under design/construction** → **Beyond**

1) DAMIC → DAMIC-M → DAMIC 10 kg?

2) DarkSide50 → DarkSide-20k → ARGO

3) XENON1T → XENONnT → DARWIN

4) nothing...
→ Cryogenic lab
→ Synergy Direct, Indirect, Colliders

Cryogenic laboratory in LPNHE

Cryogenie :

Cryostat (Costruzioni Generali)
Xenon bottles (Air Liquide / Orano)
Nitrogen (service Sorbonne)
Heat exchanger (DATE)
Purification system (SAES getter)

TPC :

SiPM and/or PMT

Slow Control :

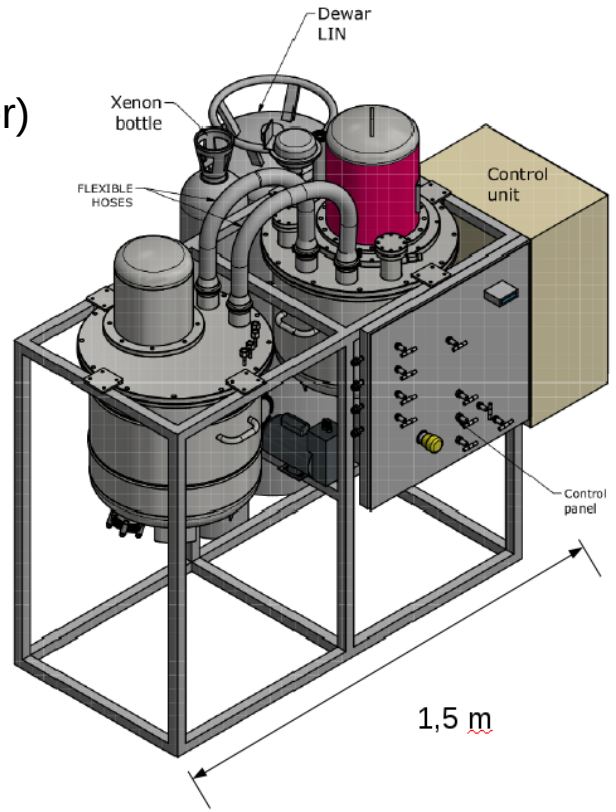
Open source software

DAQ :

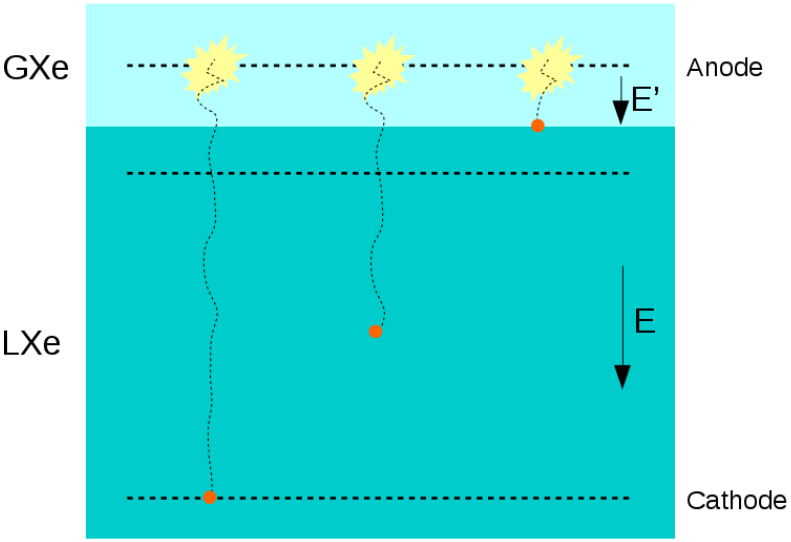
Very simple since not many channels are foreseen

Data processing :

Demanding very low CPU power



Goal: origin of single electrons signal

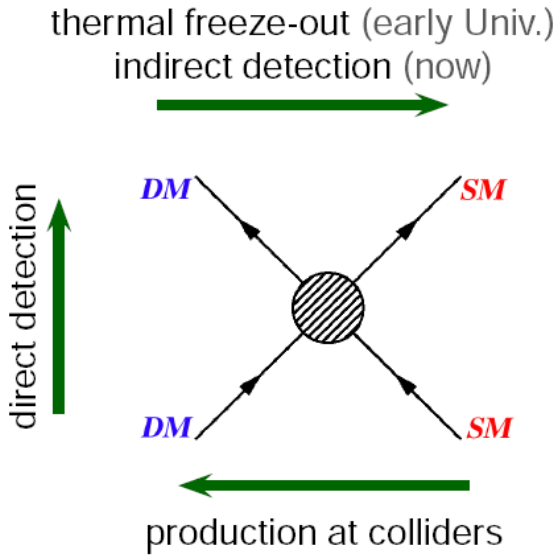


Electrons emitted by:
- **electrodes**
- **impurities**
- **delayed extraction**

- Very important for sub-GeV WIMP studies
- Nobody studied this so far
- Physics case common in xenon and argon
- No major technical challenges
- Sharing technical know-how with other
- activities (LSST, AXIS, DAMIC)
- Allows R&D on electrodes for DARWIN

Synergies between several Dark Matter searches

Dark Matter Search: three different approaches, but (hopefully) the same mechanism



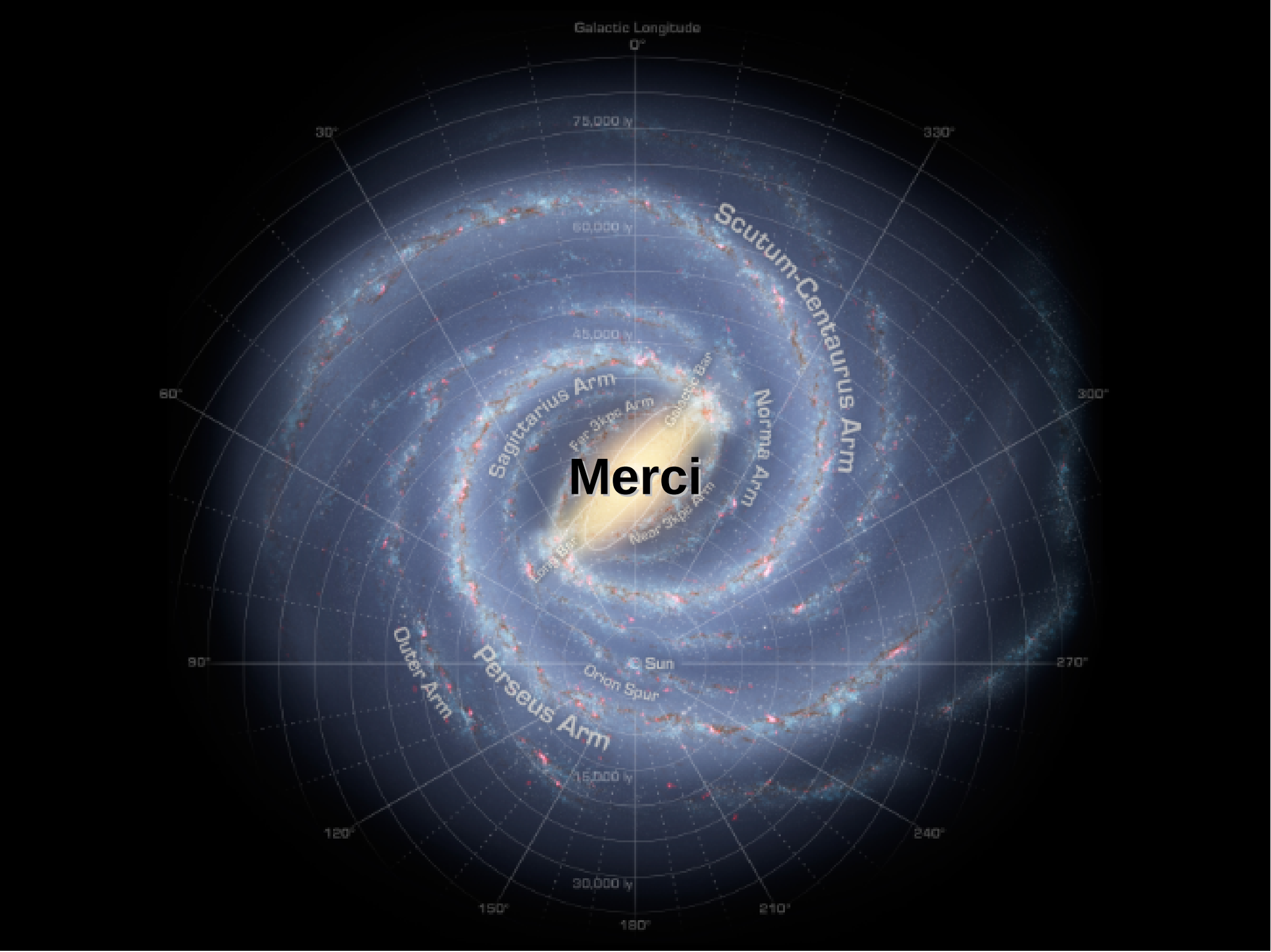
So far no interaction among us, however there are several opportunities:

Phenomenology: better understanding of DM coupling with ordinary matter by cross-constraining science results (a sort of DMfit)

Perspective: developing internal discussions with (internal and external) speakers in order to have a deeper view on future research programs

Outreach: animating a better diffusion on dark matter field in many contexts (*fete de la science*, school lectures, conferences, expositions, but also in our university)

Possible actions :
- initial **brainstorming** (free access, no tickets….)
- monthly **meetings** with all groups working on dark matter
- organize **seminars**, mainly on common topics
- a couple of **discussions** in reunions du vendredi


Galactic Longitude
0°
30°
330°
75,000 ly
60,000 ly
45,000 ly
60°
300°
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Merci
90°
270°
Outer Arm
Perseus Arm
Sun
Orion Spur
15,000 ly
120°
240°
30,000 ly
150°
210°
180°

Backup

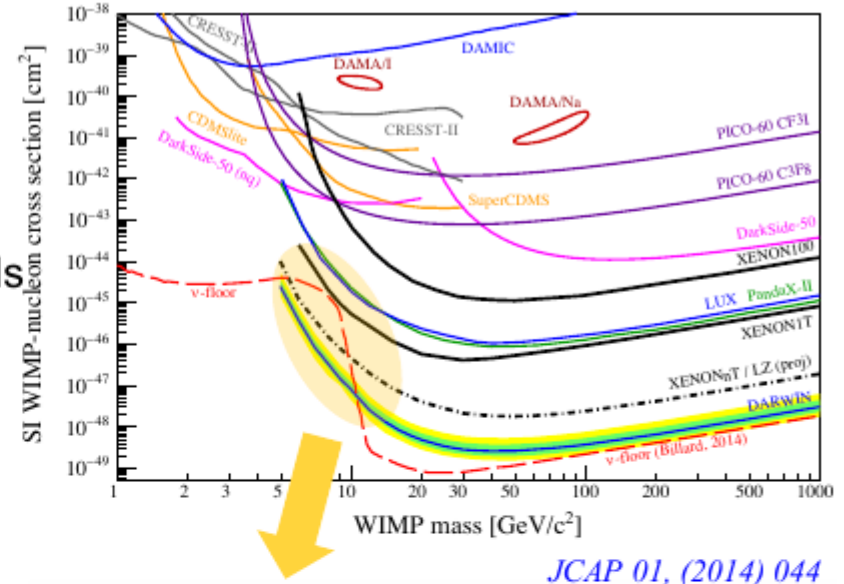
Solar neutrinos as NR background & Science Channel

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) of high E astrophysical neutrinos poses the irreducible background for WIMP searches.

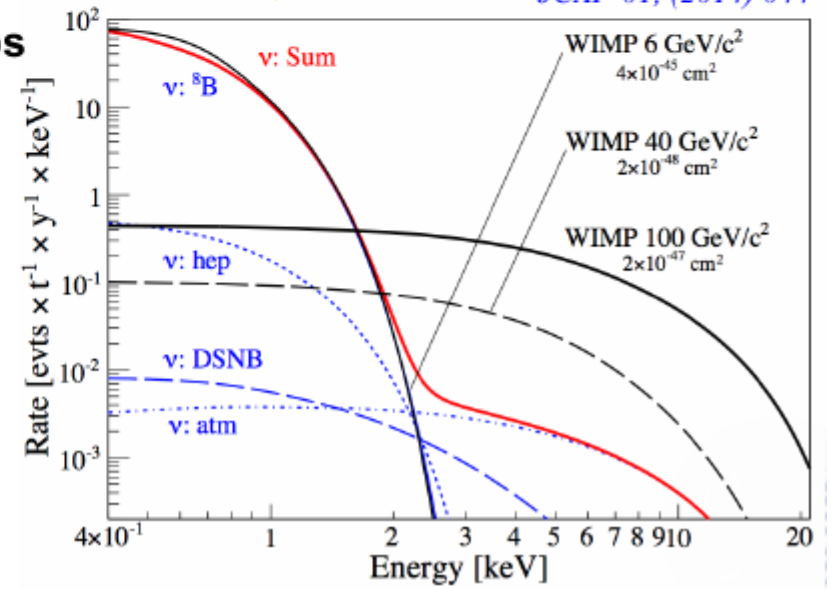
- ^{8}B neutrinos set a strong discovery limit towards low WIMP masses
- atmospheric neutrinos dominate the limit for higher WIMP masses

➔ **Observation of CEvNS by solar ^{8}B neutrinos is a science goal by itself**

DARWIN will observe $\nu_{\text{8B-CNNS}}$ events, expected rate depends strongly on the E_{NR} threshold.



JCAP 01, (2014) 044

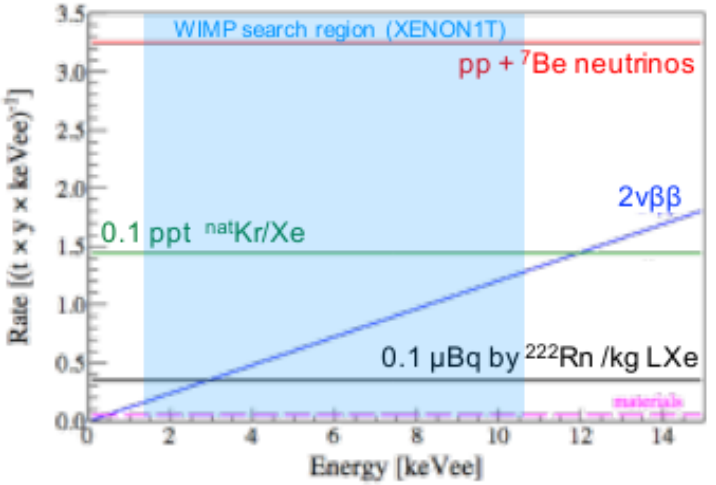


Xenon intrinsic radiogenic background

Goal: radiogenic ER < neutrino induced ER (pp + ^{7}Be)

→ Challenging requirements on the xenon radioactivity:

^{136}Xe ^{nat}Kr ^{222}Rn



^{136}Xe (8.9% nat. ab.) introducing 2νββ background

Spectrum of 2νββ is subdominant in WIMP search region

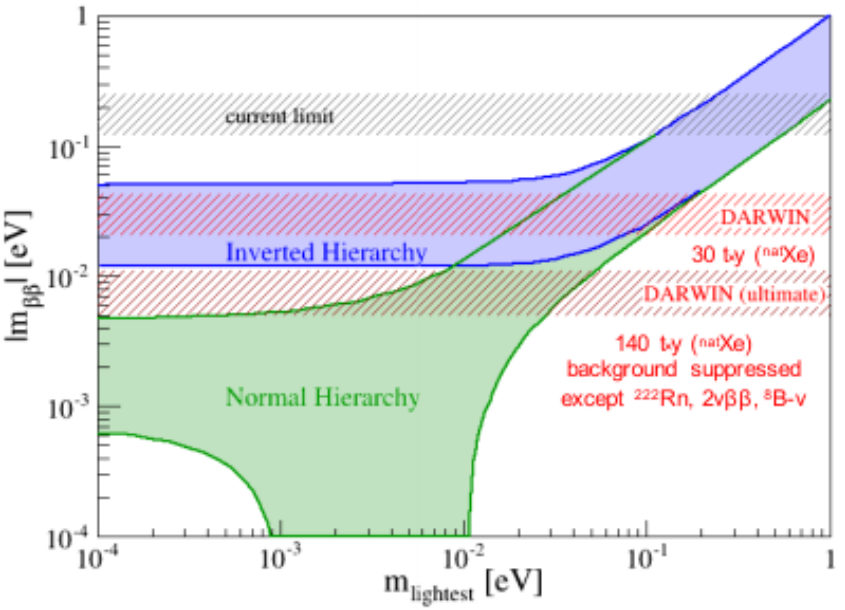
JCAP 11, 017 (2016)

➔ **Major science channel: 0νββ**

- SS vs. MS discrimination (x,y,z reconstruction)
- $\sigma_E|Q_{\beta\beta}$ optimization with extra readout channel

➔ High $T_{1/2}$ sensitivity, due to $m_{\beta\beta}$ > 3.5t, low background + fiducial cut / self shielding

DARWIN will be a competitive **0νββ** experiment, probing <m $_{\beta\beta}$> in IH-range

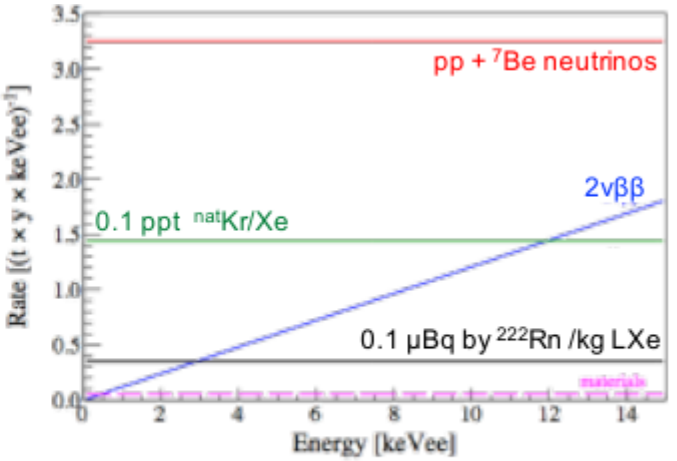


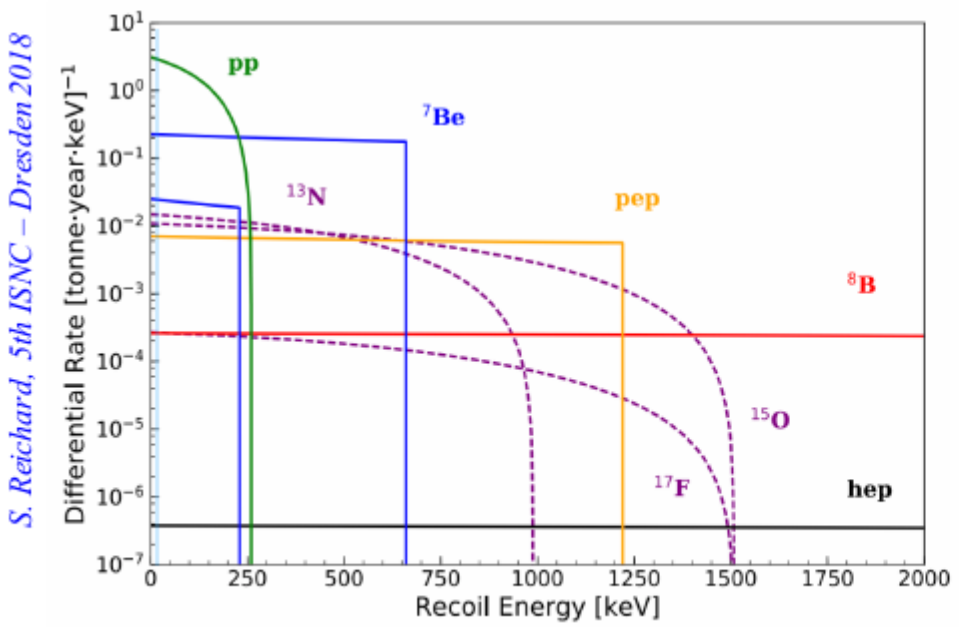
pp+^{7}Be neutrinos as ER background & science channel

ER events from low energetic (pp + ^{7}Be) solar neutrinos remain as background events and must be suppressed

ER/NR discrimination: 99.98% ER rejection
→ estimated 30% NR acceptance
JCAP 10, 016 (2015)

➔ Solar neutrinos are an interesting science channel





- Highest flux from pp and ^{7}Be

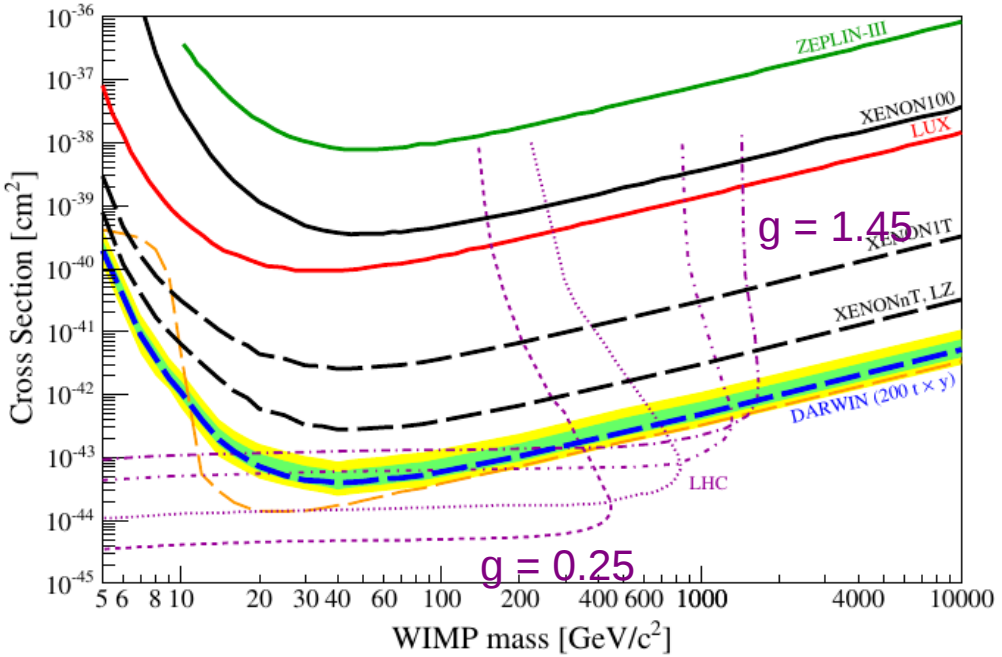
→ Several hundred ν-induced events/year

→ Precision measurement of ϕ_{pp} and ϕ_{7Be} with ±0.3% and ±2.3% accuracy

→ Conclusion on the weak mixing angle and ν-survival probability below 200keV

Science goal : SD WIMP-nucleon interactions

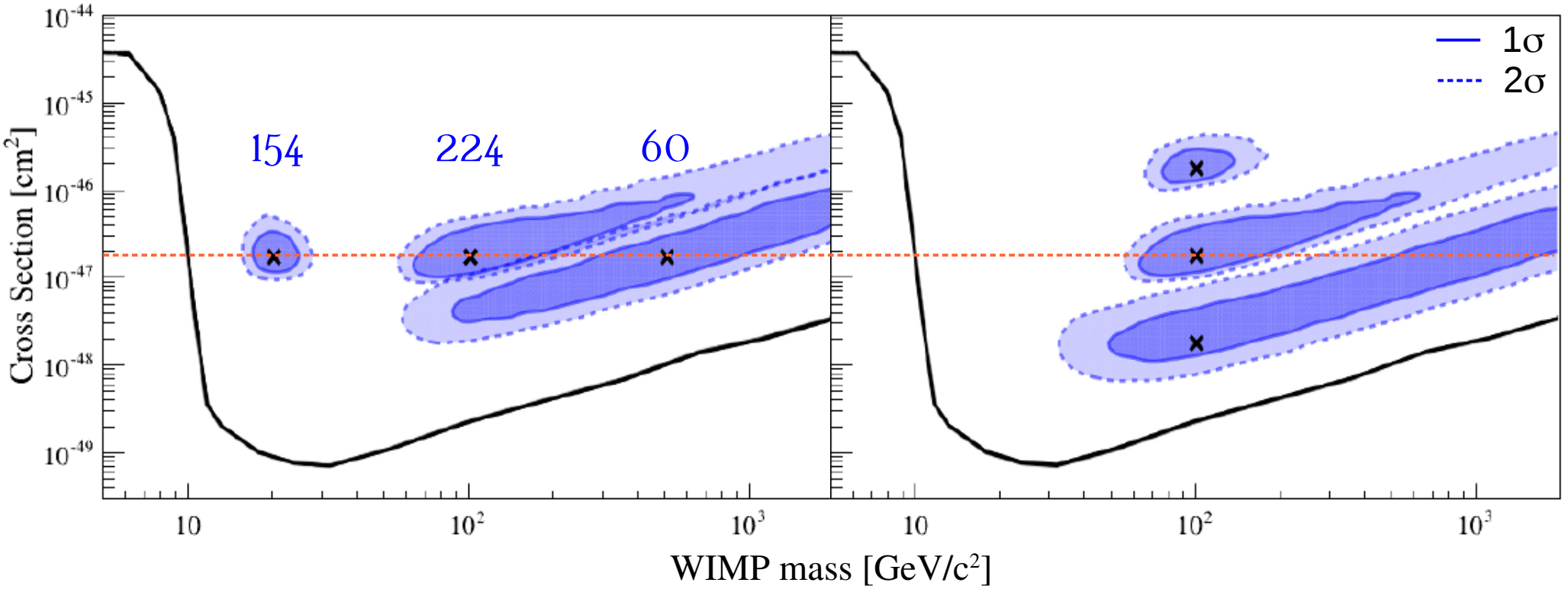
neutron coupling



200 t·y exposure
E = 4-50 keV$_{nr}$
30% NR acceptance
99.98% ER rejection
LY = 8 PE/keV @ 122keV

Complementarity with the LHC:
minimal simplified DM model with Dirac fermion interacting with an axial-vector mediator
$g \equiv g_q = g_{DM}$
S. A. Malik et al., Phys. Dark Univ. 9-10 (2015) 51

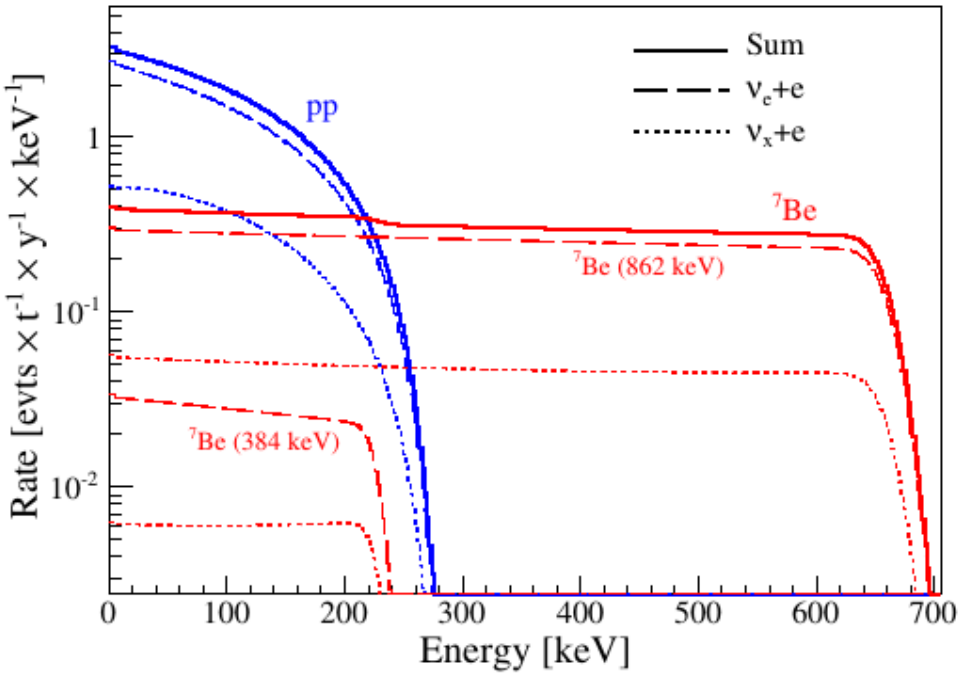
WIMP spectroscopy

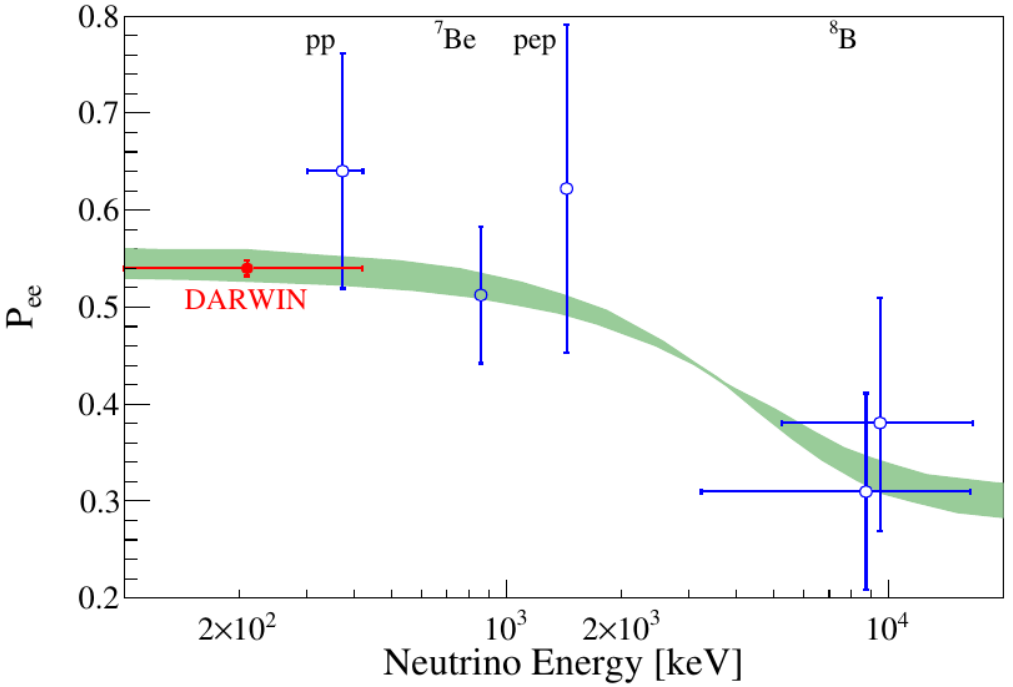


200 t·y exposure
v_{esc} = 544 ± 40 km/s
v_0 = 220 ± 20 km/s
ρ_χ = 0.3 ± 0.1 GeV/cm³

Capability on reconstructing the WIMP mass and cross section for various masses (20, 100, 500 GeV/c2) and cross sections (reference line: XENON1T sensitivity)

Science goal : solar neutrinos





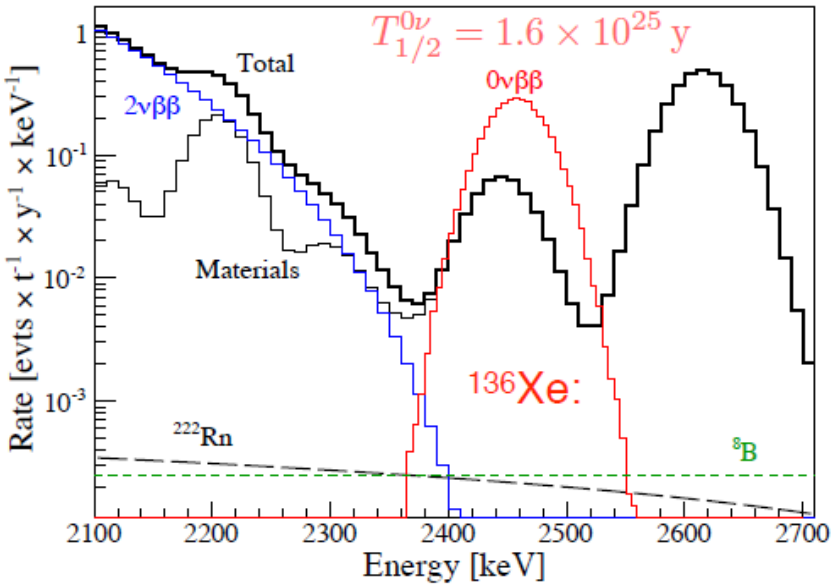
$\nu + e^- \rightarrow \nu + e^-$

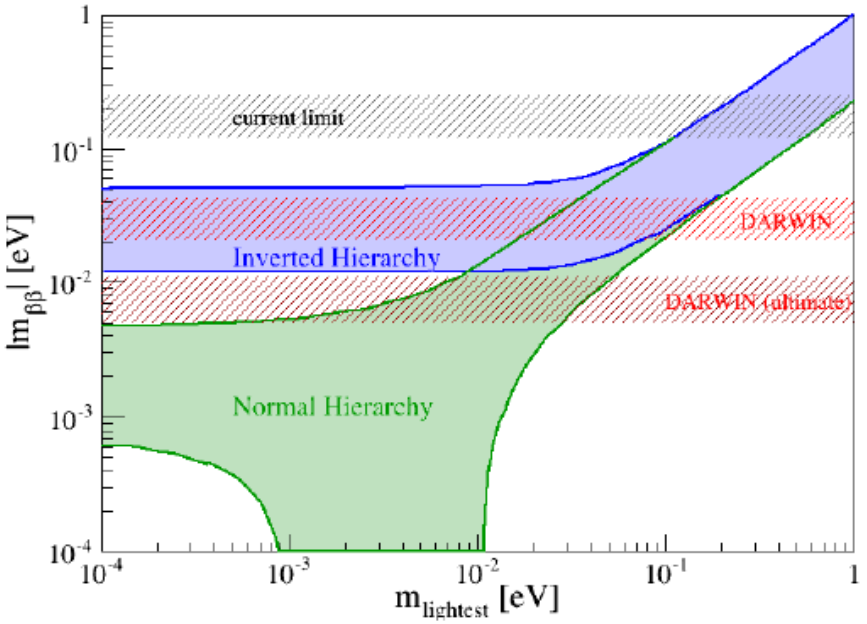
Expected rate at 2-30 keV$_{ee}$

- pp neutrinos : 7.2 events/day
- ^{7}Be neutrinos : 0.9 events/day

More than 2000 neutrino pp events per year
2% precision in a year, 1% after 5 years
Scoping neutrino and solar models

Science goal : double beta decay





^{136}Xe: $Q_{\beta\beta}$ = 2458.7 ± 0.6 keV

Sensitivity to 0νββ by ^{136}Xe:

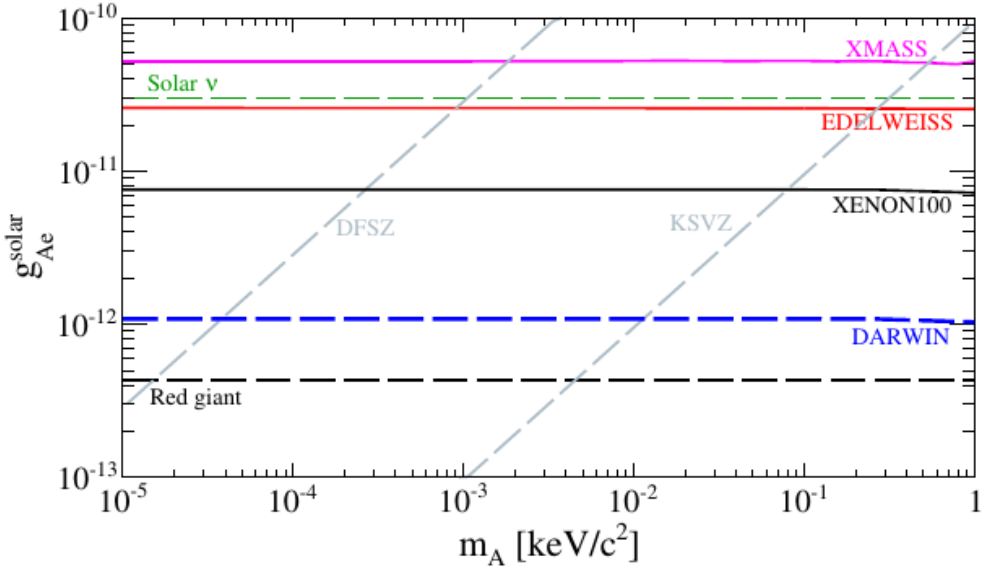
- $T_{1/2} > 5.6 \cdot 10^{26}$ yr (95% CL) in 30 t y
- $T_{1/2} > 8.5 \cdot 10^{27}$ yr (95% CL) in 140 t y

Assumptions:

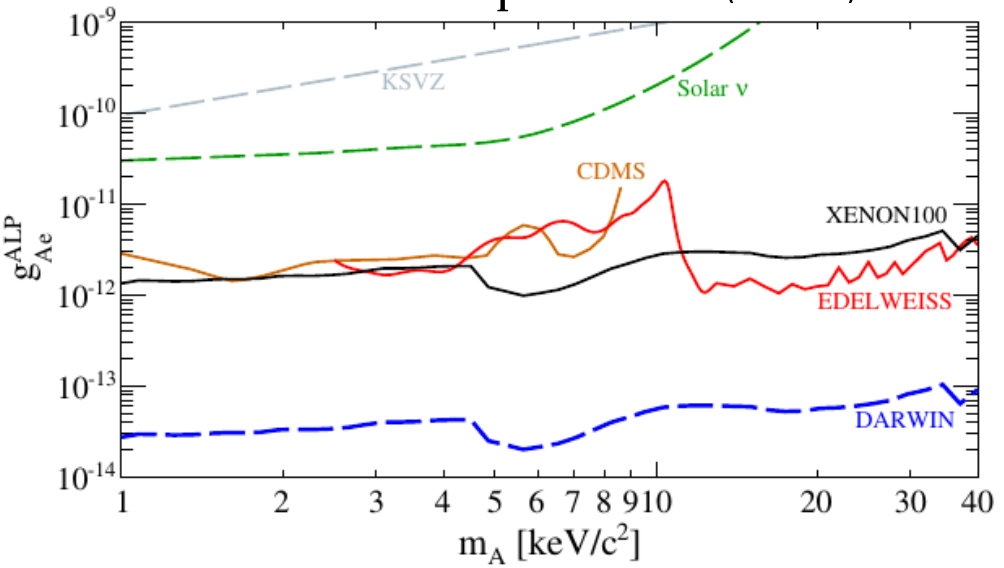
- Fiducial mass 6 t ^{nat}Xe (needed stronger fiducialisation)
- ^{222}Rn: 0.1 μBq/kg (rate compatible with ^{8}B)
- σ_E/E = 1-2% at $Q_{\beta\beta}$
- DARWIN "ultimate" assumes negligible background from detector materials

Science goal : axions and axion-like particles

Solar axions



Axion-like particles (ALPs)



Assumptions:
- 200 t·y exposure
- Similar energy threshold as in XENON100
- 30% better energy resolution

Dependency from exposure:

$G^{solar}_{Ae} \propto (MT)^{-1/8}$

$G^{ALP}_{Ae} \propto (MT)^{-1/4}$

Dominating background: solar neutrinos and $2\nu\beta\beta$ ^{136}Xe