The Dark Universe

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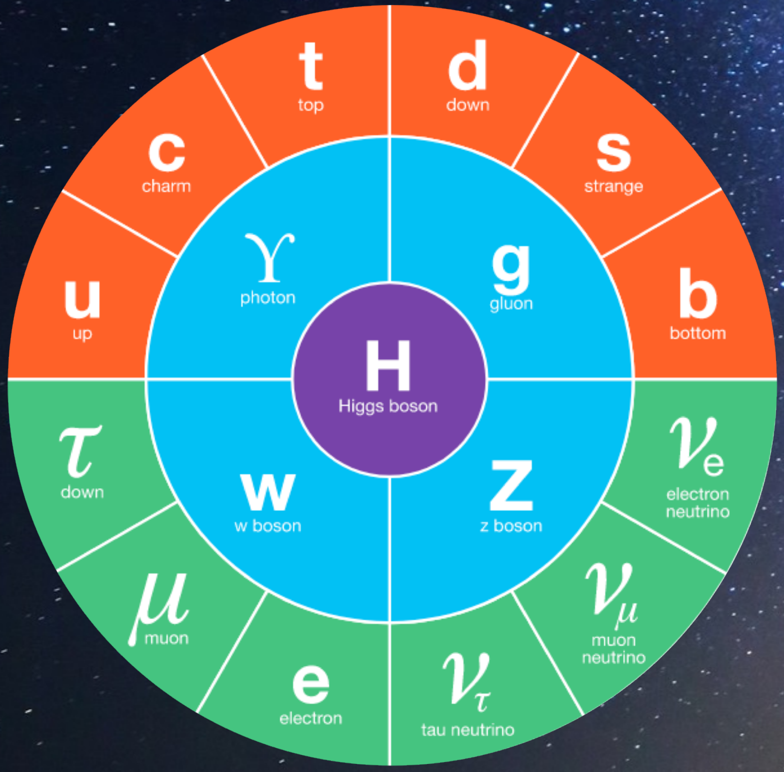
Giornate in ricordo di Milla Baldo Ceolin

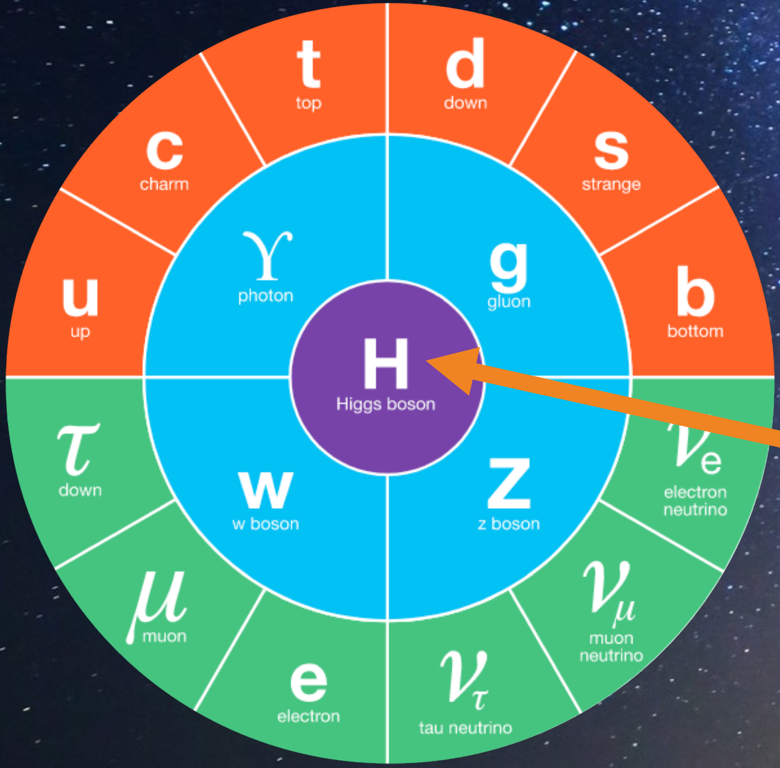
Nov, 25 2021
via remote

MAX-PLANCK-INSTITUT
FÜR PHYSIK

Ordinary Matter

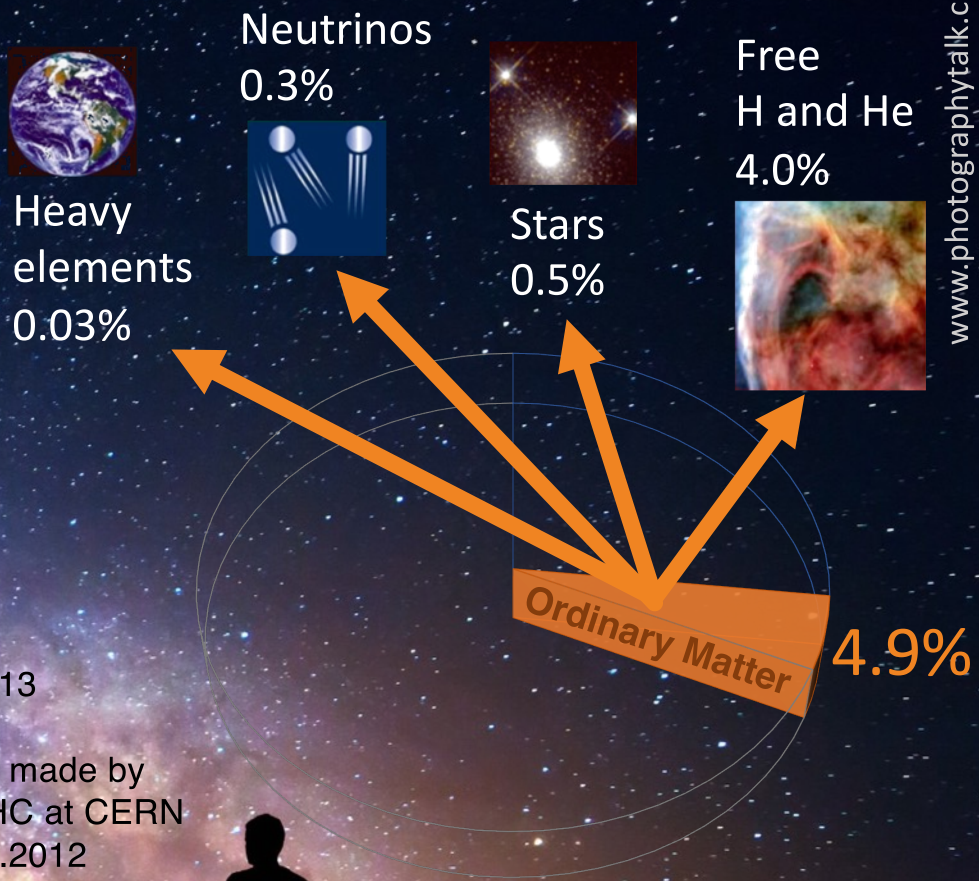


Ordinary Matter



Prof. Peter Higgs
Nobel prize winner, 2013

First observations was made by ATLAS and CMS at LHC at CERN and announced on 4.7.2012



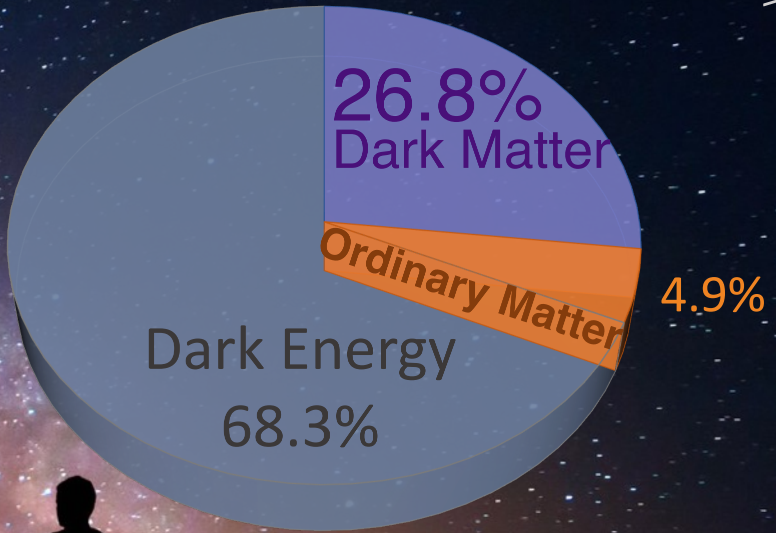
Dark Matter

+ **add extra and new ingredient**

→Physics beyond the Standard Model

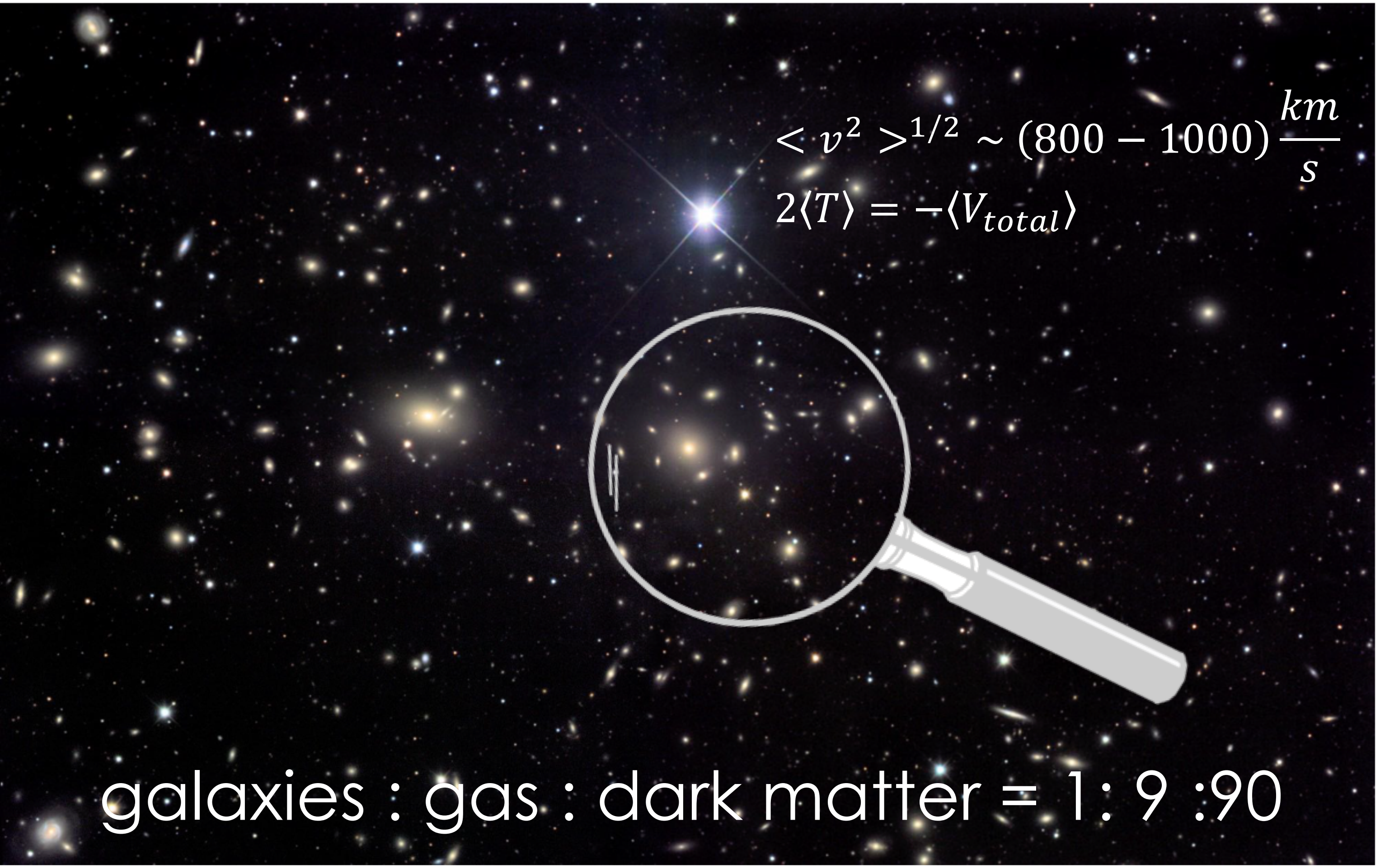
Dark Energy

Taken from Dragone



Galaxy clusters

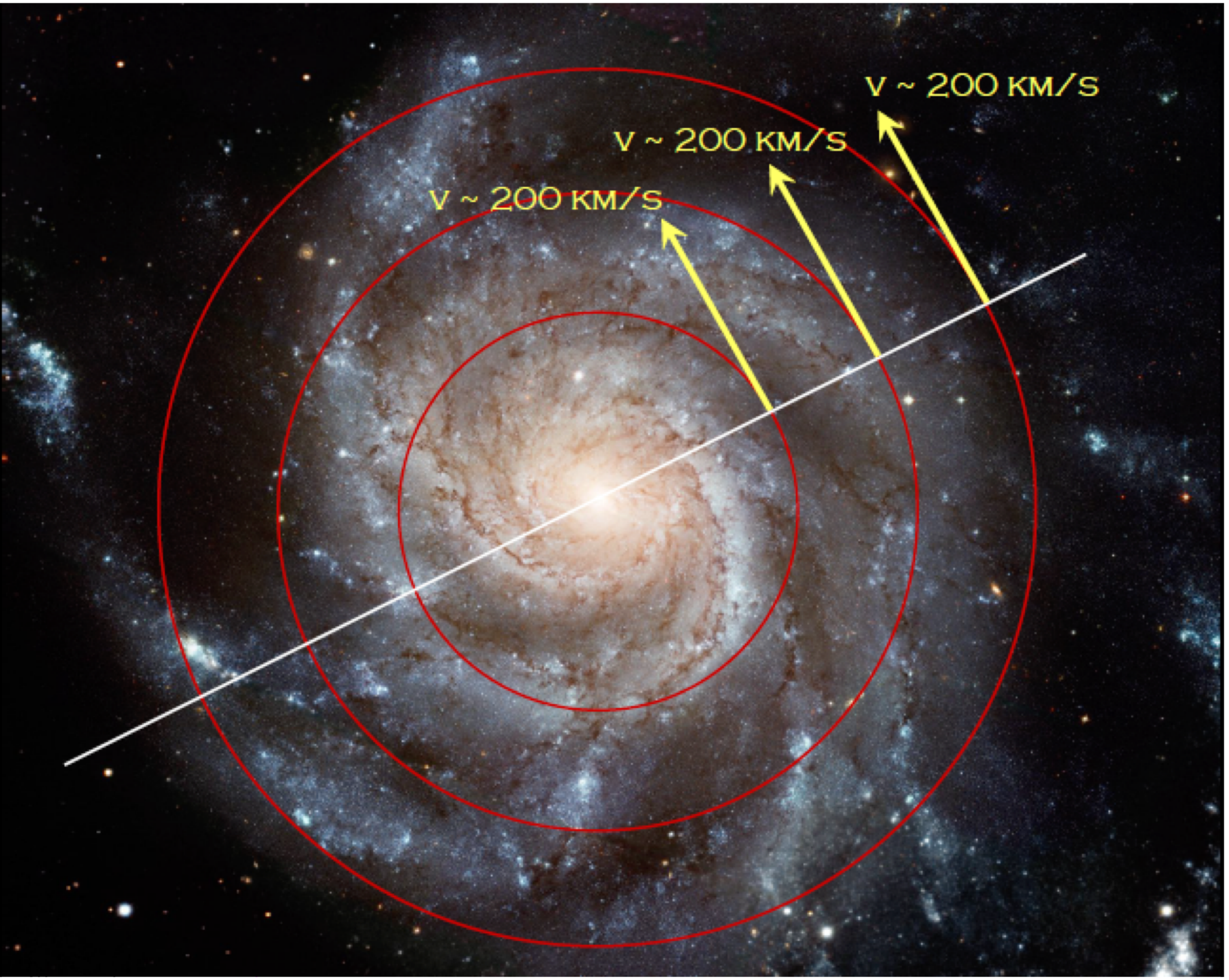
Zwicky 1933



Velocity dispersion of galaxies in the cluster is too large:

→ cluster would not be gravitally bound system and "evaporate"

Rotational curves of galaxies **Rubin 1970**

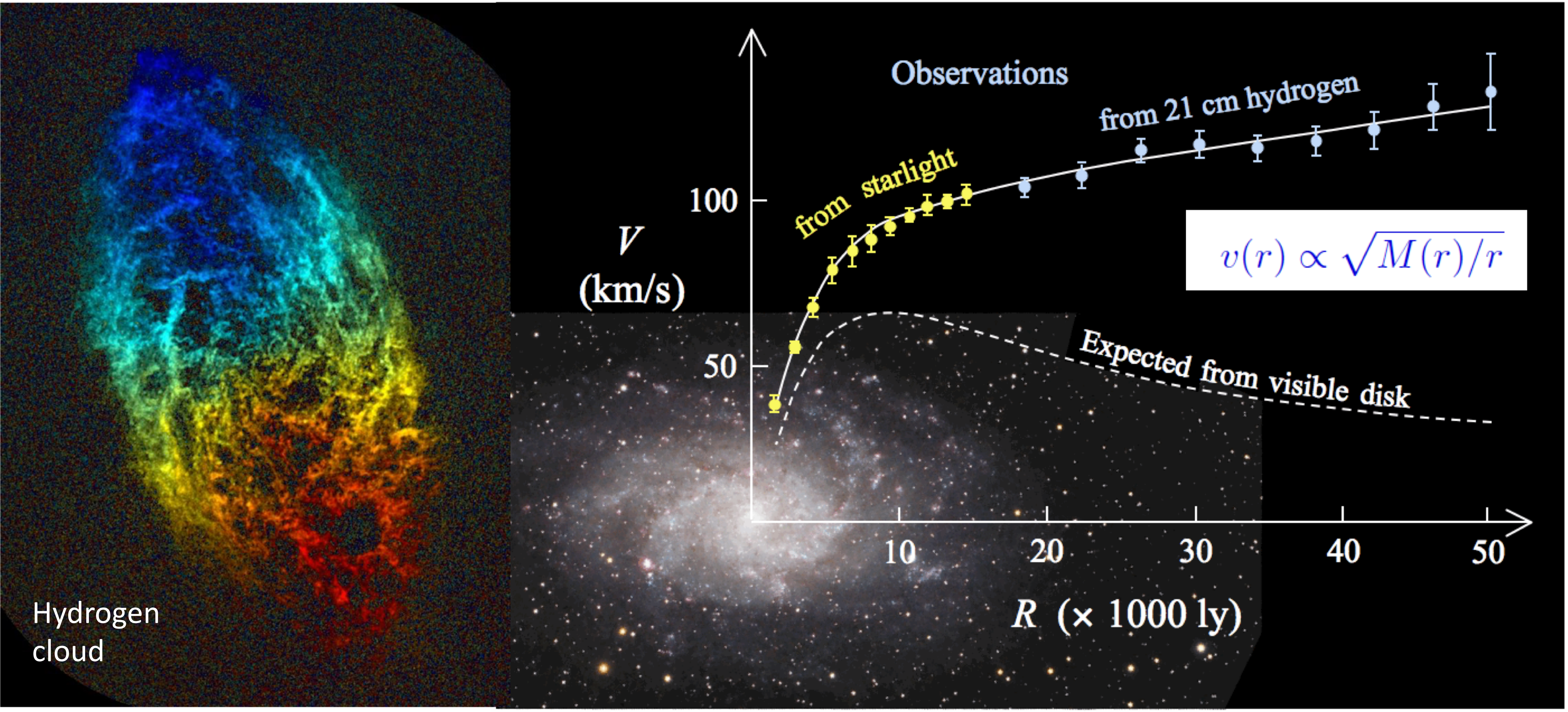


Credits N. Fornengo

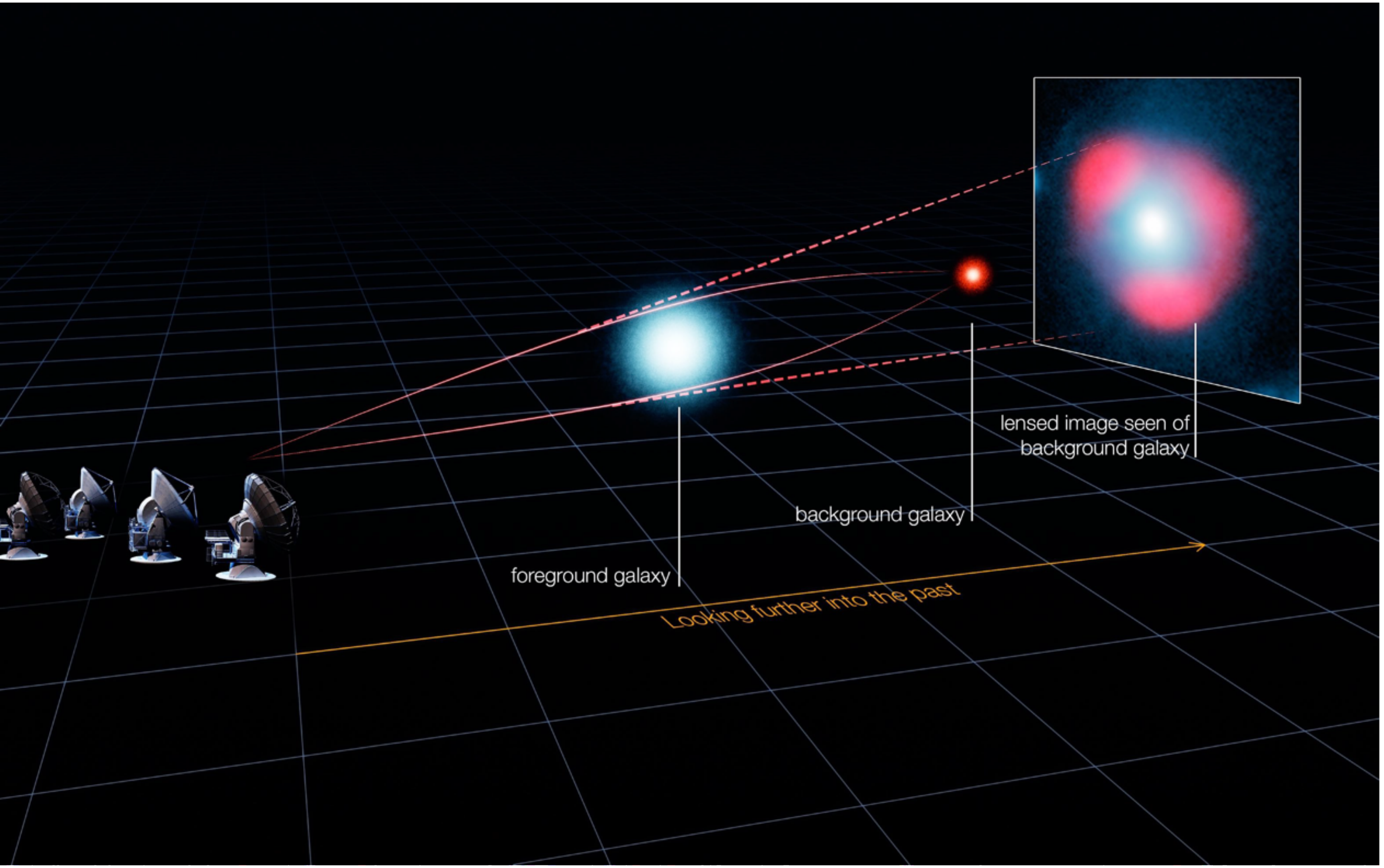
Stars in the outer arms are faster than expected

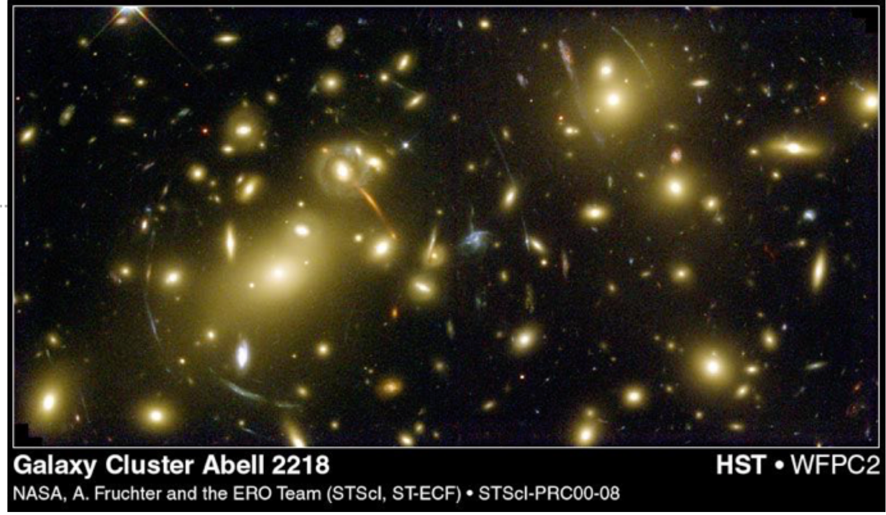
→ much more mass present than luminous mass only

Rotational curves of galaxies of M33

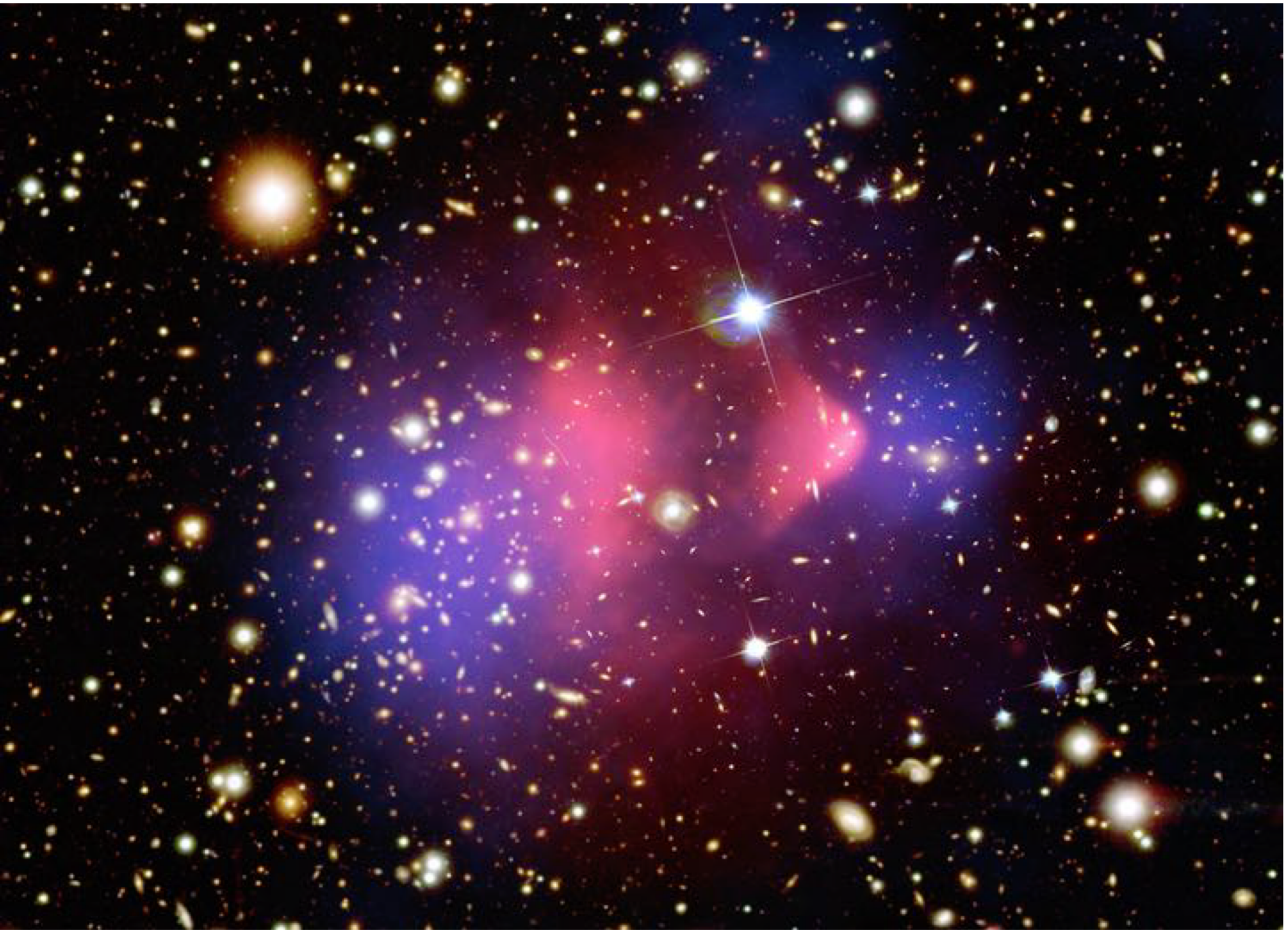


Gravitational lensing effect





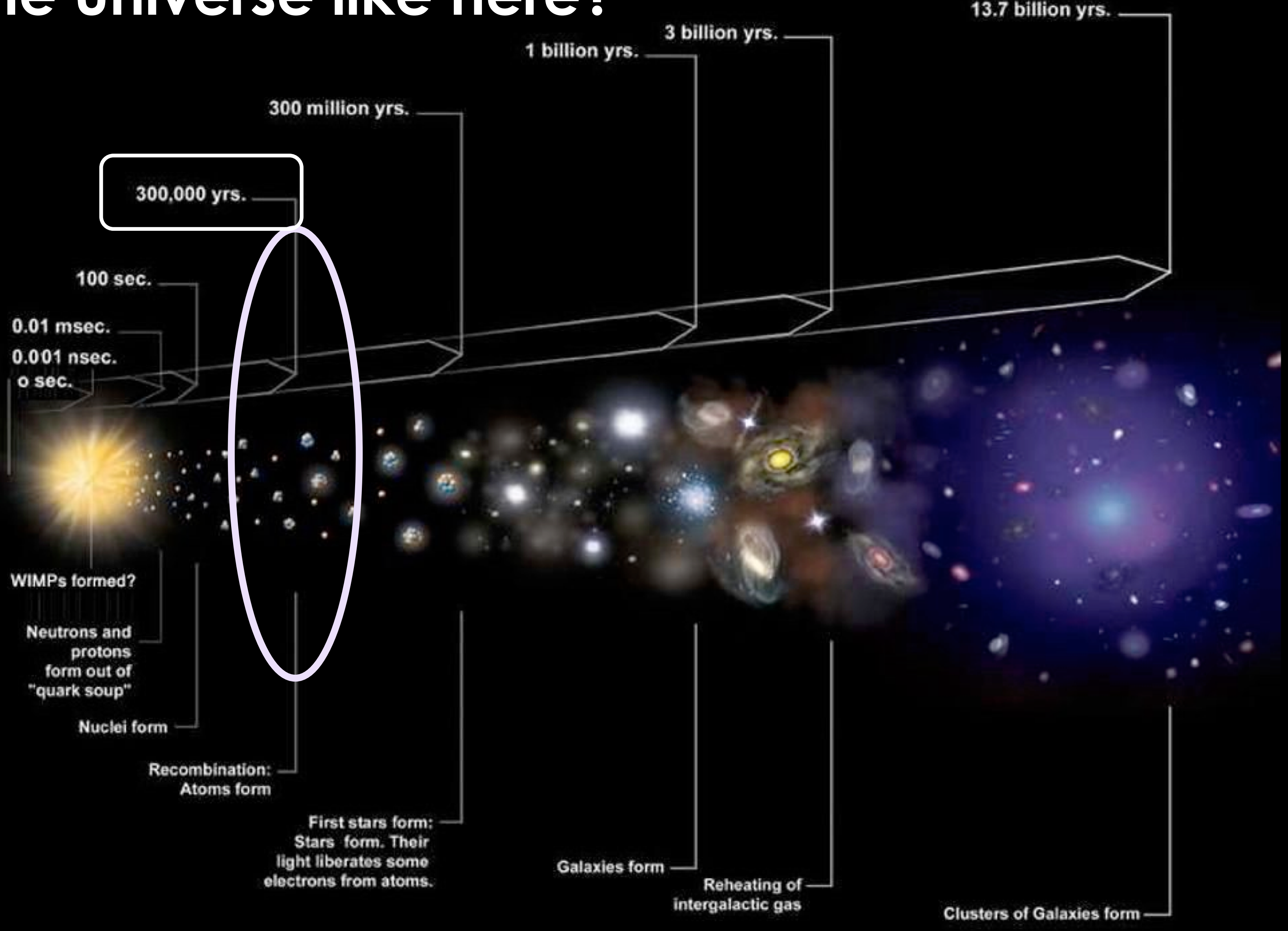
Bullet Cluster – collision of two galaxy clusters



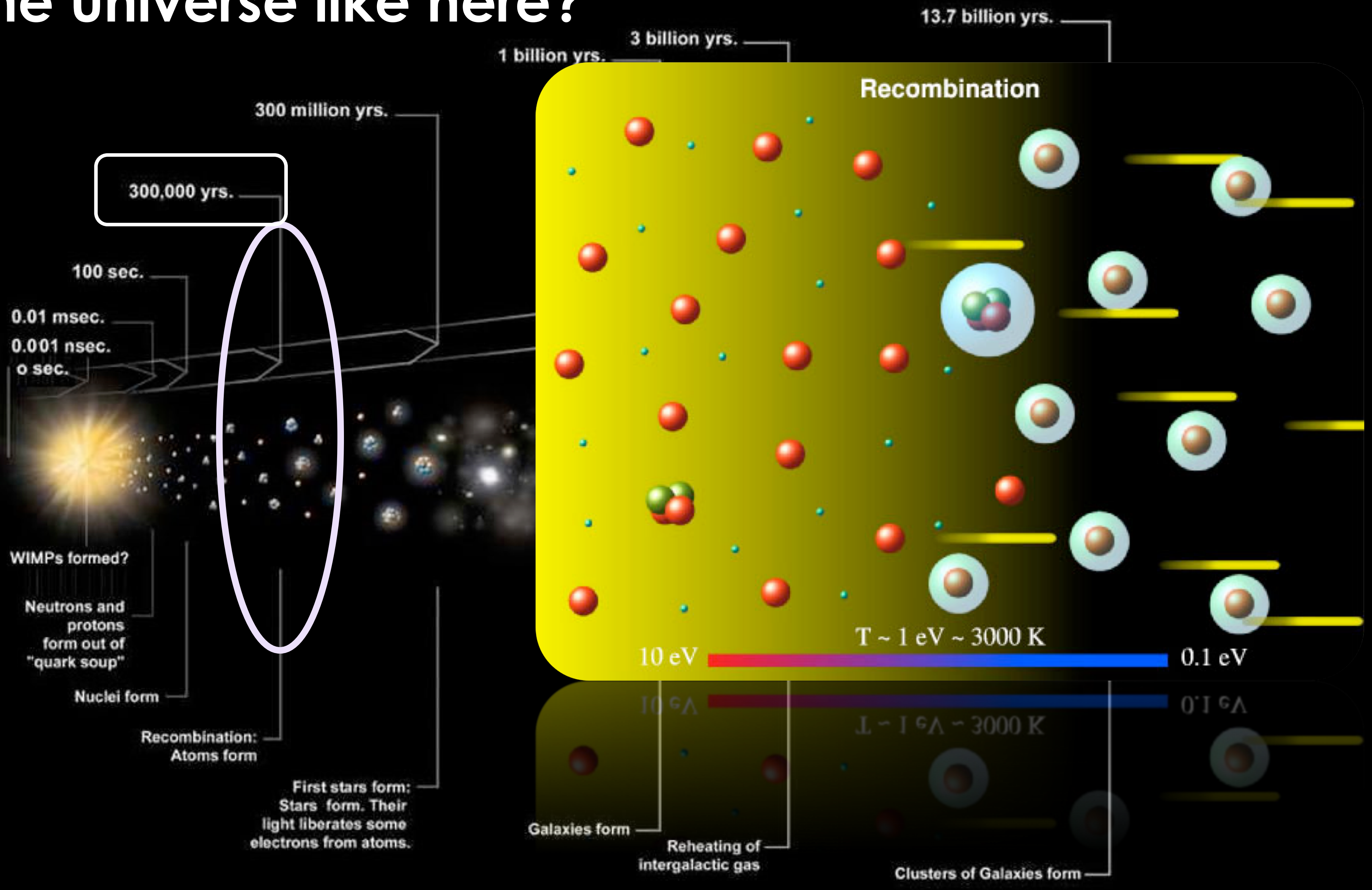
- best current evidence for the nature of dark matter

- spatial offset of the center of the total mass from the center of the baryonic mass peaks cannot be explained with an alteration of the gravitational force law alone

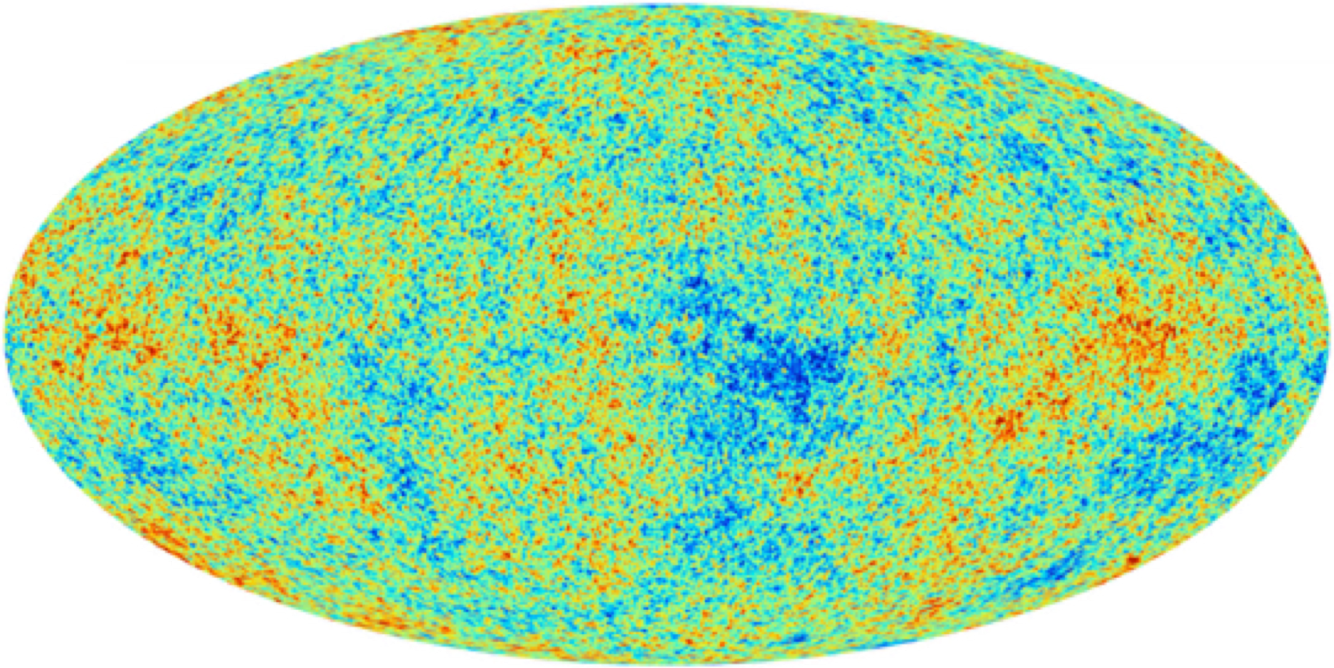
What is the universe like here?



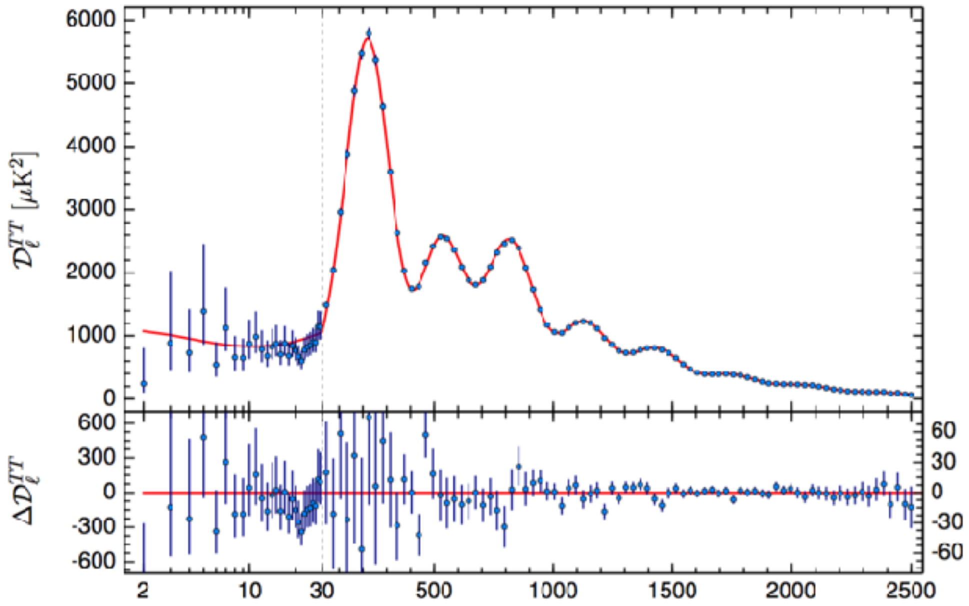
What is the universe like here?



PRECISION COSMOLOGY: Cosmic Microwave Background

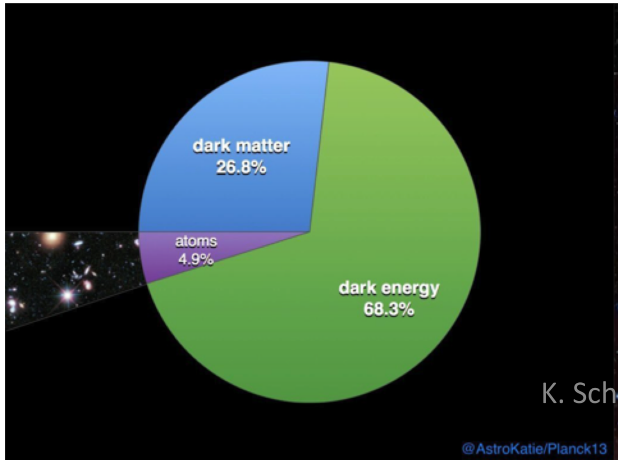


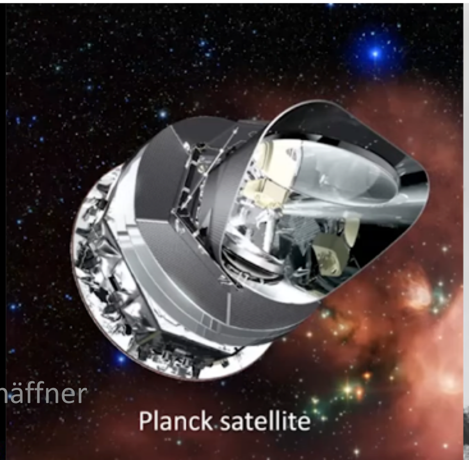
Planck, but also ACT, SPT, and in the near future S4 and SO

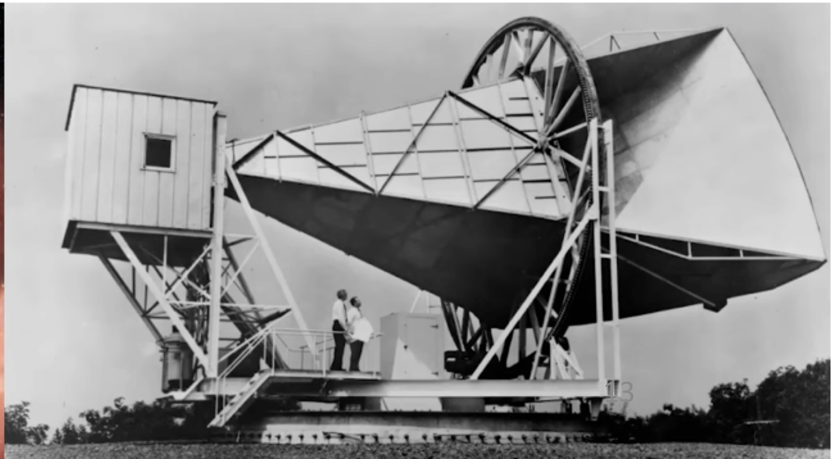


Planck collaboration

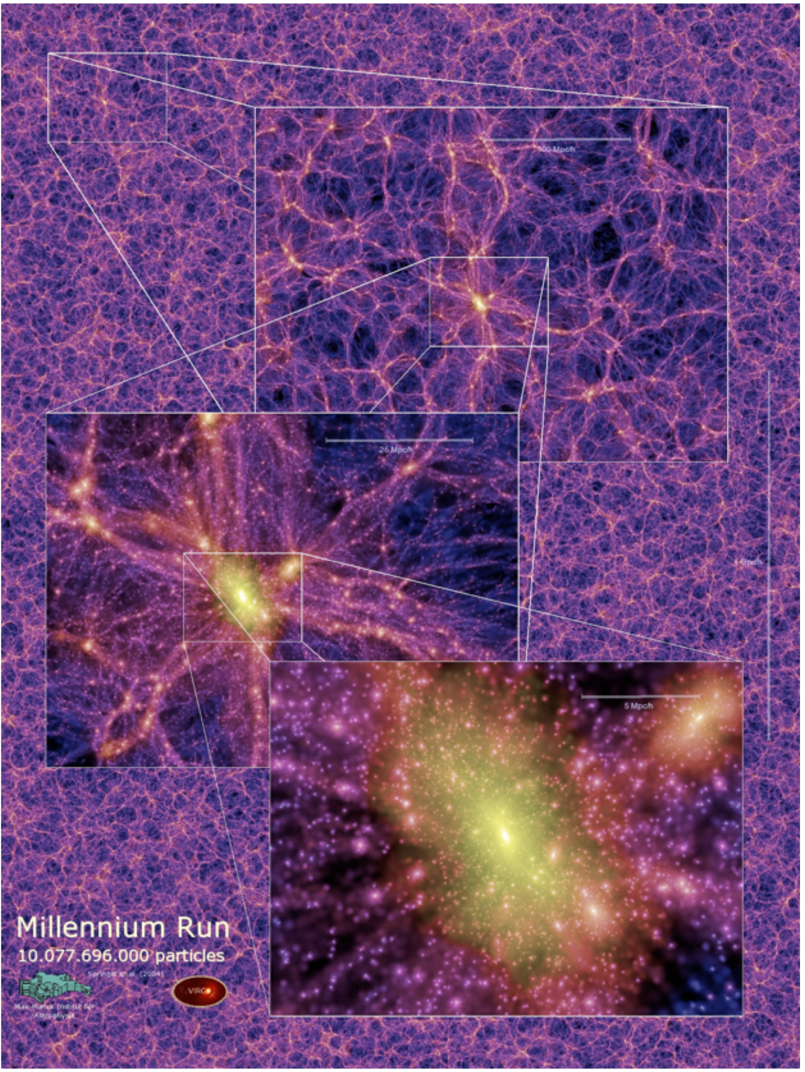
Temperature and polarization anisotropies allow to extract energy/matter content of the Universe





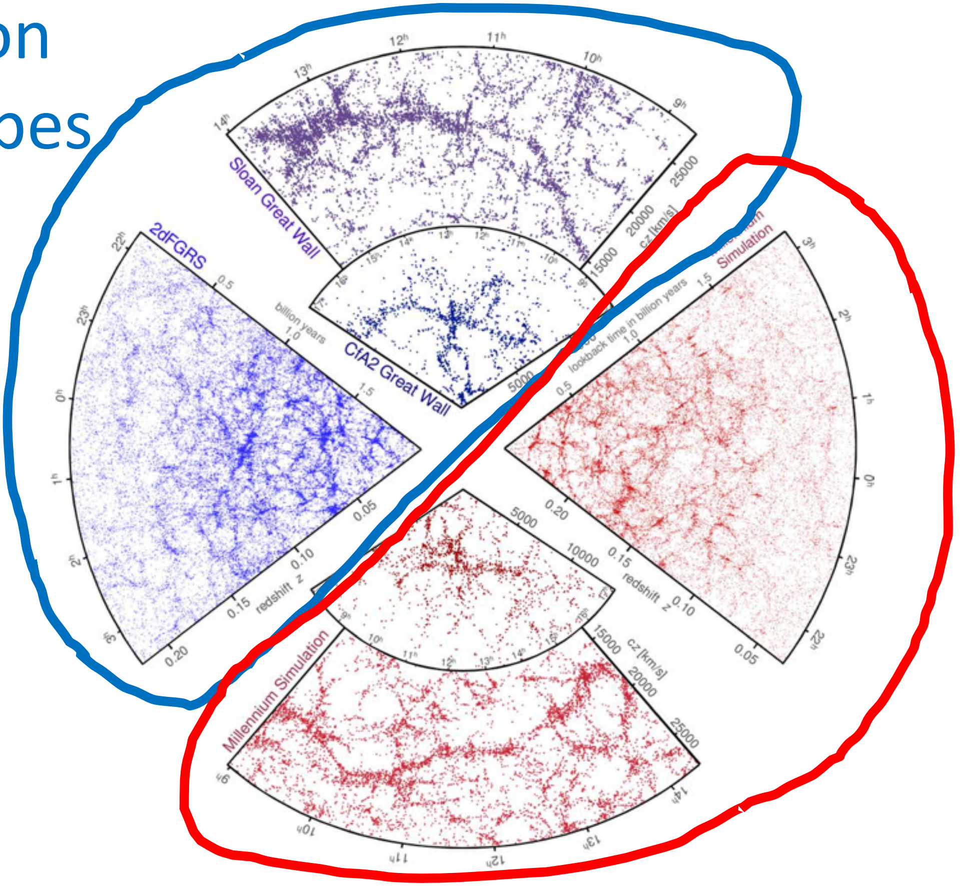


Large Scale Structure formation



Dark matter seeded galaxy formation

Observation by telescopes



Prediction by simulation

TAKE HOME MESSAGE

Our cosmological observations are based on **gravitational interaction only** and only make sense if the largest fraction of matter is **non-baryonic** (cold-ish)

+ add (≧1) extra and new ingredient (=Dark Matter)

→ **new fundamental physics beyond SM**

→ **explains huge interest in community**

+ add general relativity

MODIFIED GRAVITY

- Is dark matter just a relic from the early Universe?

  → new elementary particle, beyond SM

- Do we need to modify General Relativity?

  → MOND, higher-derivative gravity, TeVeS, ...

Any extension can provide a new puzzle to the dark matter mystery

BUT:

→ General relativity acts at any scale (solar system to cosmological length scales)
→ General relativity predicts a large number of phenomena (Expansion, structure formation, black holes, gravitational lensing, gravitational waves, …)

→ → to date not a unique consistent extension on the market that explains dark matter and works at any scale

CHALLENGE FOR DM DETECTION

Gravity is universal:
no chance for particle identification

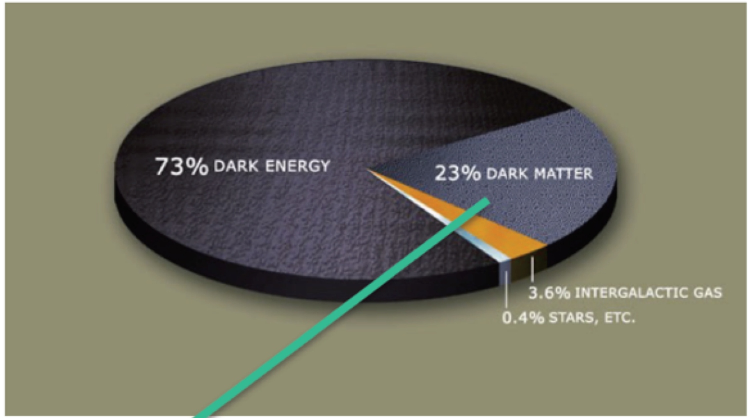
Particle physics framework:
evidence via other channels is mandatory
e.g. weak interaction or beyond

BUT:

→What you search for is **model-dependent**!

→(*hardest part*: other channel is **not** guaranteed, DM could also be only gravitationally coupled to Standard Model particles)

Why identifying dark matter is difficult



Av. Density ~
0.3 GeV/cc – not a lot

L_{exp}~few * 10^2 cm

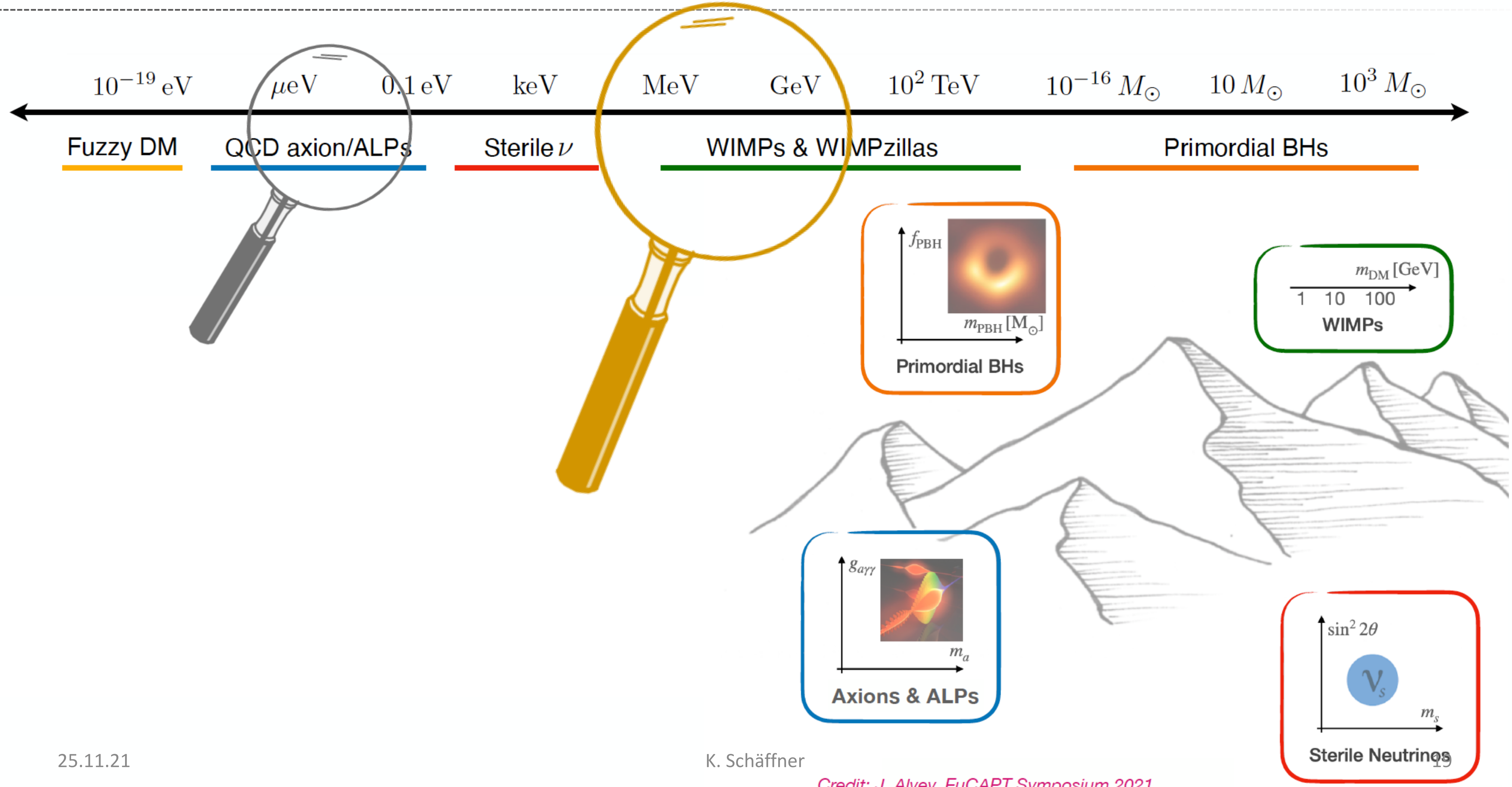
$L_{min} \sim 10^{21}$ cm

We need to extrapolate
19 orders of magnitude!
Theory is the first step!

Credits to Maxim Pospelov (TAUP 2021)

2

Dark matter candidates



Credit: J. Alvey, EuCAPT Symposium 2021

AXION as dark matter candidate

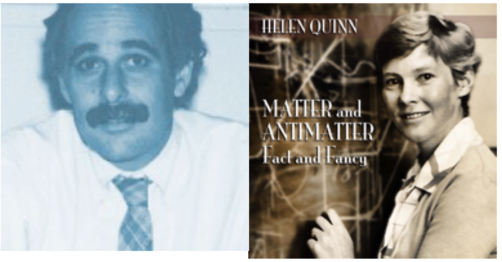
MOTIVATION: "Strong CP problem"

- No reason for QCD to conserve P and CP
- Measurement of neutron electric dipole moment
  → very small P and CP

- 1977: postulation of a new symmetry by Peccei & Quinn
  → axion when symmetry is spontaneously broken

Production in the early Universe:

Axions are born non-relativistically, are non-thermal relics
→ **cold dark matter candidate** $m_a \sim 1 - 1000 \mu eV$

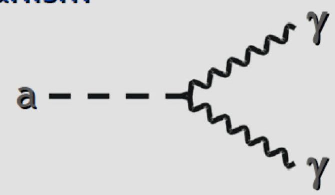


PRL 38, 1440 (1977)

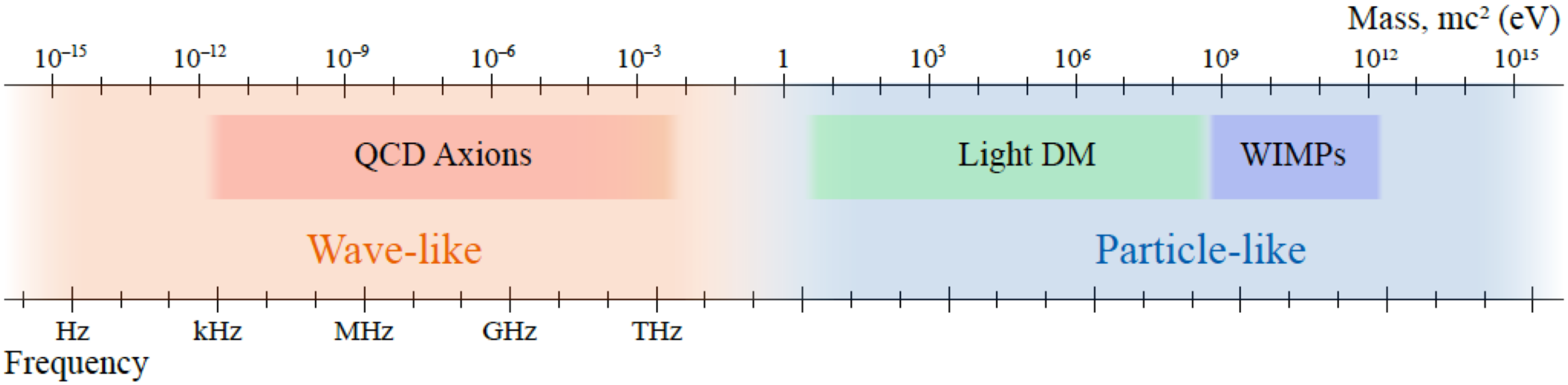
CP conservation in QCD by Peccei-Quinn mechanism

→ Axions $a \sim \pi^0$

$m_\pi f_\pi \approx m_a f_a$



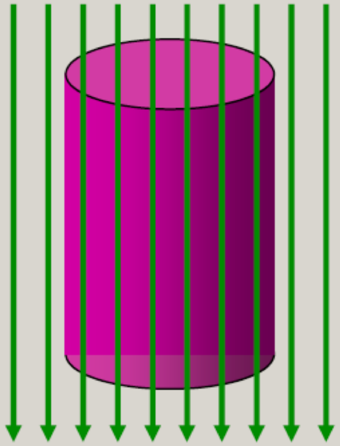
For $f_a \gg f_\pi$ axions are "invisible" and very light



arXiv:2111.08875v1

SEARCH FOR AXION DARK MATTER

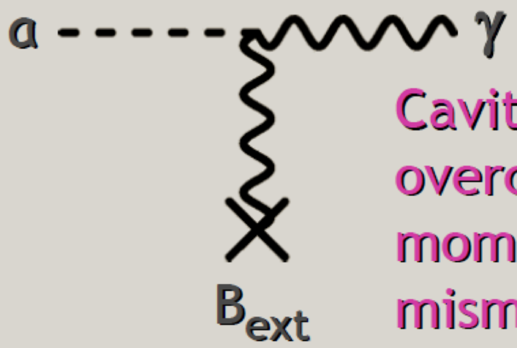
Axion Haloscope (Sikivie 1983)



$B_{ext} \approx 8$ Tesla

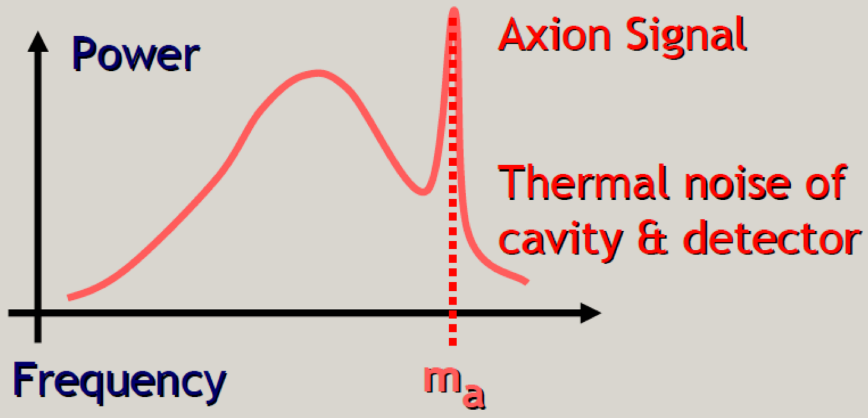
Microwave Resonator
$Q \approx 10^5$

Primakoff Conversion



Cavity overcomes momentum mismatch

DM axions	m_a = 10-3000 μeV
Velocities in galaxy	$v_a \approx 10^{-3}$ c
Energies therefore	$E_a \approx (1 \pm 10^{-6})\, m_a$



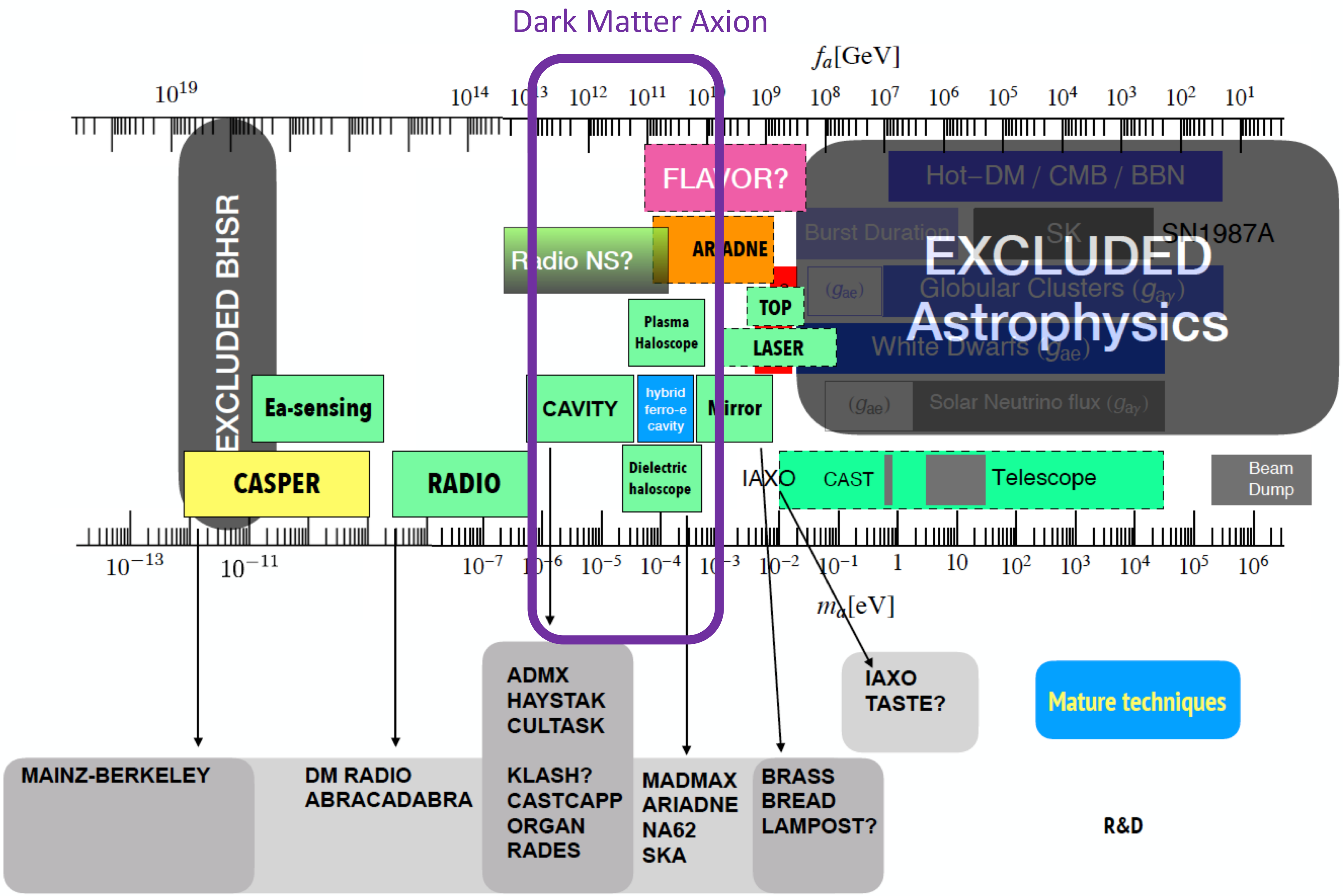
Credits to G. Raffelt

Microwave energies

$1\ GHz \sim 4\ \mu eV$

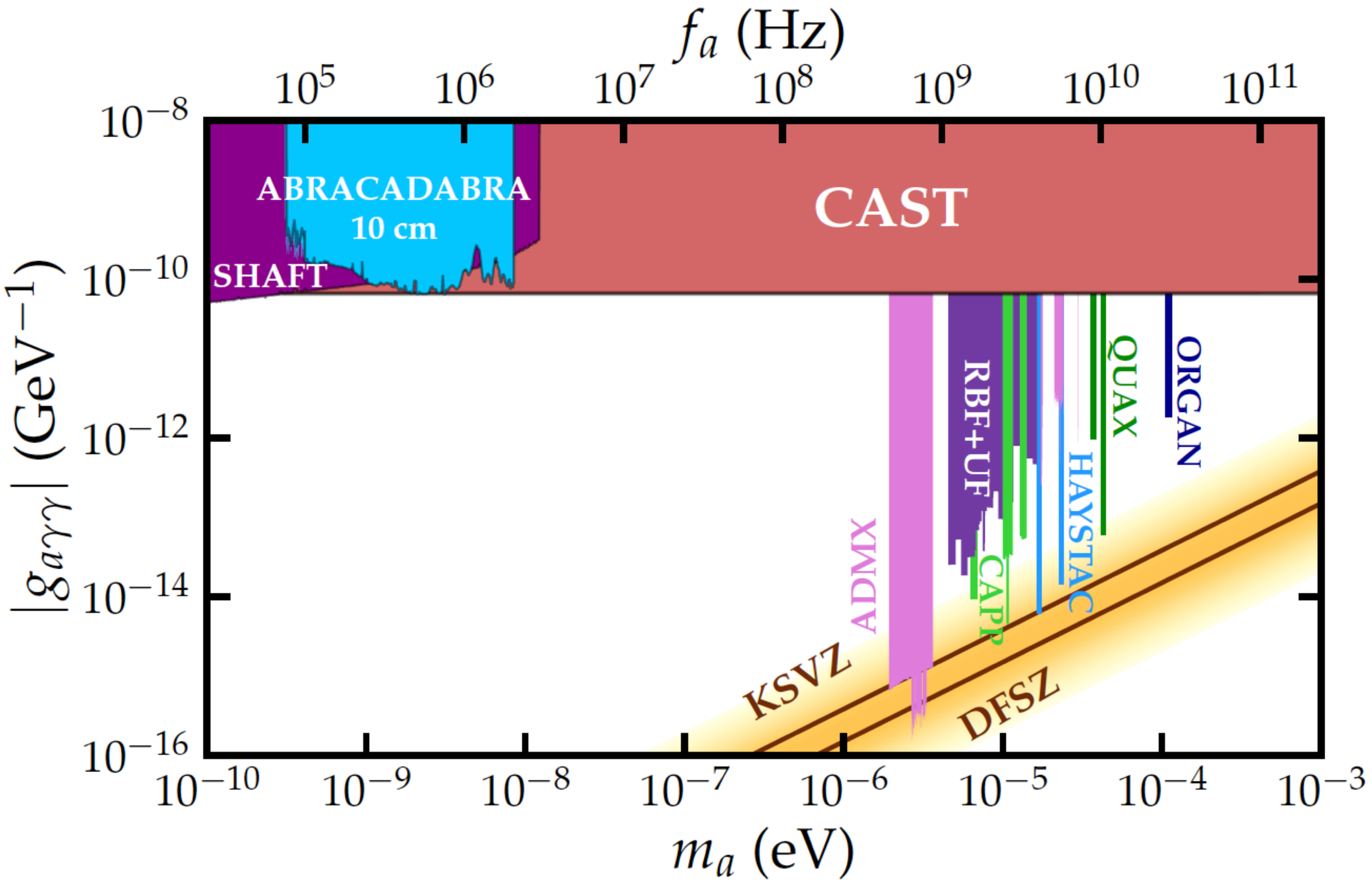
Experimental Landscape

DM nonDM



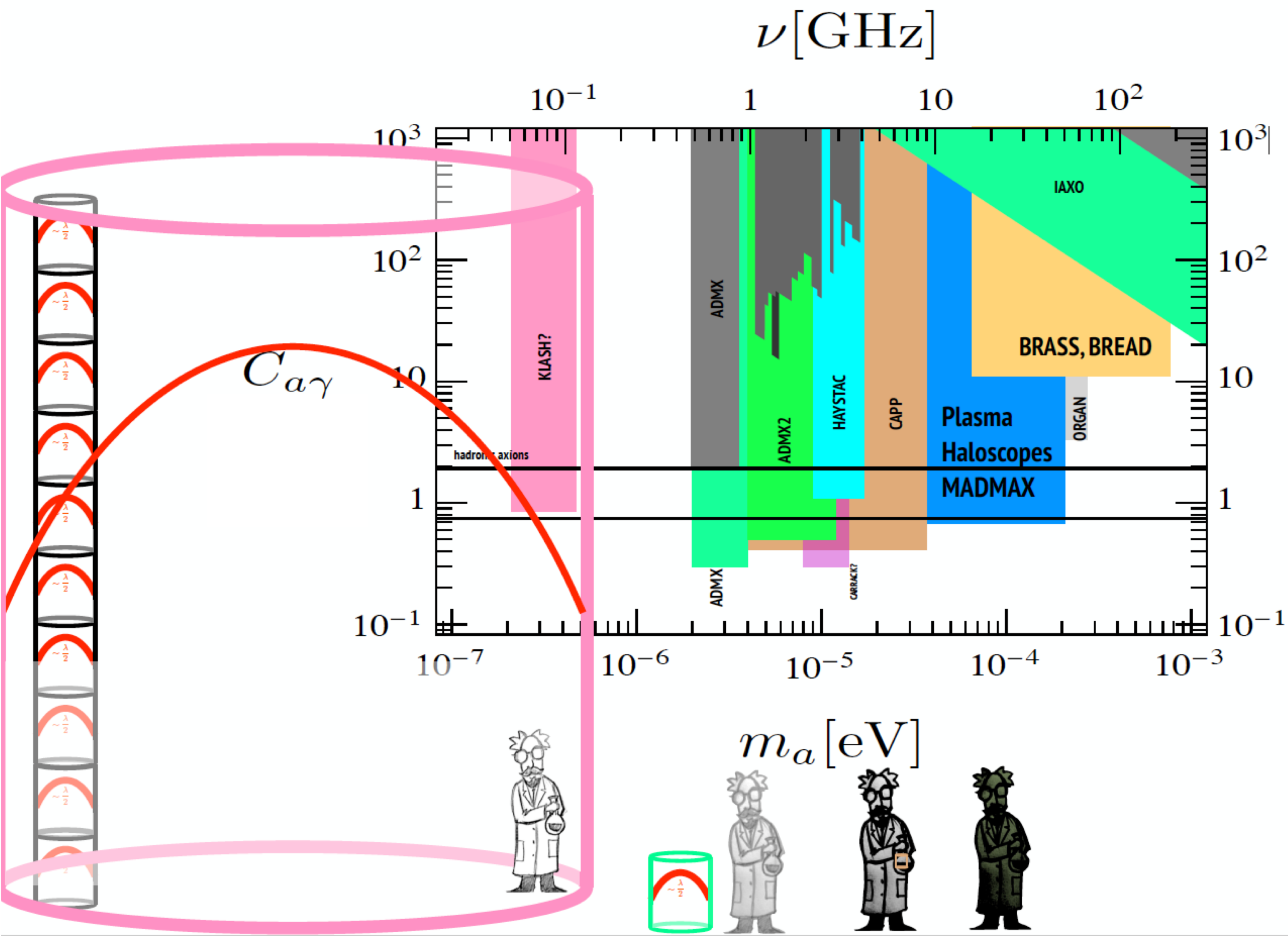
Credits to J. Redondo, TAUP 2021

AXION LANDESCAPE



arXiv:2111.08875v1

Prospects, issues, solutions



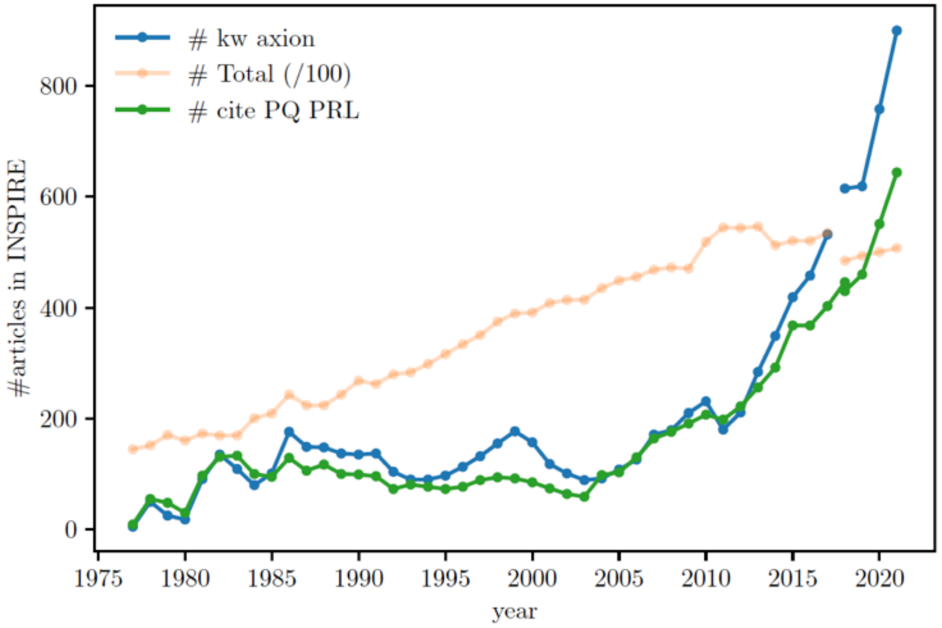
- Use HE particle physics tech
- B-fields and cavities

- 20-30 T fields with HTC superconductors
- QL detectors, mK Temperatures
- SC cavities to reach Q~10^6
- new photon counters
- add up signal from many cavities

- Huge volume experiments
  - Photonic band gap
  - Brain cavities
- new photon counters?
- ALTERNATIVES
  - Dielectric haloscopes (res. + large Area)
  - Dish antenna (BRASS, BREAD)
  - Plasma Haloscopes (enhace E_a)

Credits to J. Redondo, TAUP 2021

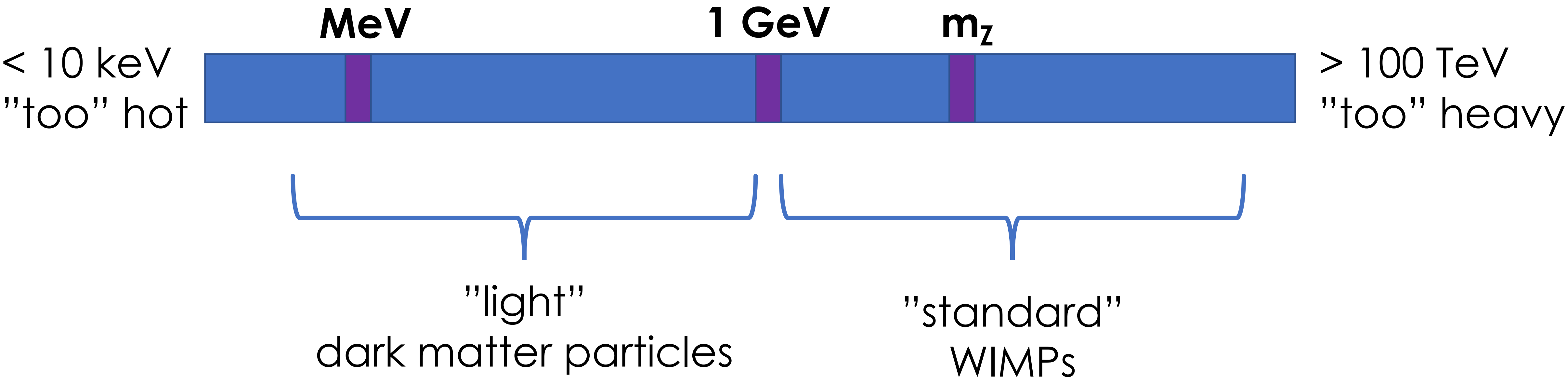
AXION CONCLUSION



Credits to J. Redondo

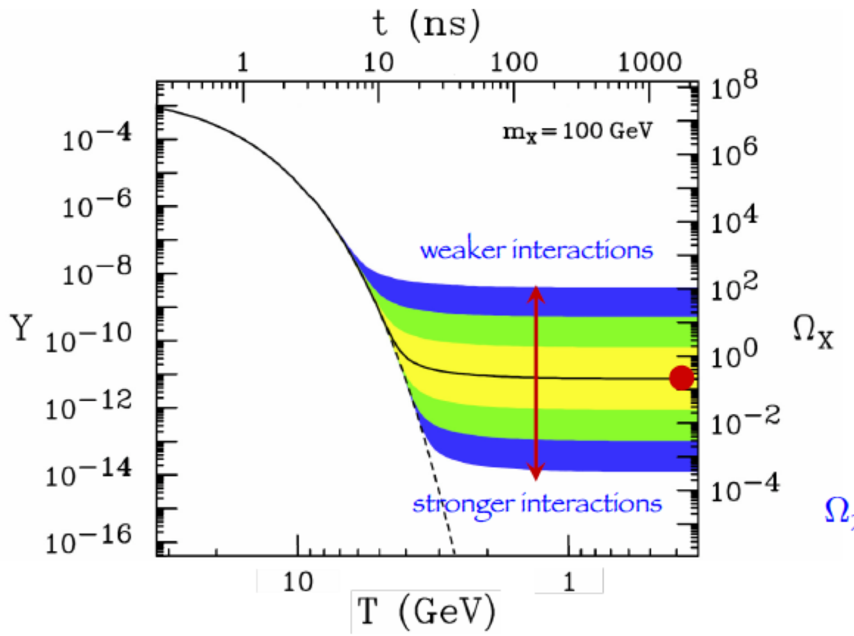
- The axion would solve the strong CP problem and would be an cold dark matter candidate
- Motivation comes from physics beyond the SM and simplicity
- A prediction of the axion DM mass is possible in the post-inflationary scenario
  → guide for experimentalists
- Detection is challenging but experiments underway in all the mass range

DARK MATTER AS A THERMAL RELIC



Weakly Interacting Massive Particles

Credits N. Fornengo



$\Omega_\chi = \frac{\rho_\chi}{\rho_C}$

The universe cools down — abundance today (relic)

$m_\chi \sim (\text{GeV} \div \text{TeV})$

$\langle \sigma_{\text{ann}} v \rangle \sim (\xi G_F)^2 \, m_{\text{DM}}^2 \quad \sim 10^{-10} \xi^2 \left(\frac{m}{\text{GeV}}\right)^2 \text{GeV}^{-2}$

weak type

$\langle \sigma_{\text{ann}} v \rangle \sim \frac{10^{-10}}{(\Omega h^2)_{\text{CDM}}} \sim 10^{-9} \ \text{GeV}^{-2}$

naturally $\Omega_\chi h^2 \sim 0.1$

$x_f \sim (10 \div 30)$

WIMP → dark matter particle with mass in the sub-GeV to few TeV and weak scale interaction

→ consistent with observed abundance and structure of the Universe
  → WIMP "**miracle**" (Lee and Weinberg)

→ SUSY neutralino long time favored WIMP candidate
  → absence of hints at LHC now lead to shift to other "minimalistic" options

HUNT FOR DARK MATTER

INDIRECT

Annihilation

$\chi\bar{\chi} \rightarrow \gamma\gamma, q\bar{q}, \ldots$

HUNT FOR DARK MATTER

INDIRECT

Annihilation

$\chi\bar{\chi} \rightarrow \gamma\gamma, q\bar{q}, \ldots$

COLLIDERS

production

e.g. $p + p \rightarrow \chi\bar{\chi} + X$

HUNT FOR DARK MATTER

INDIRECT

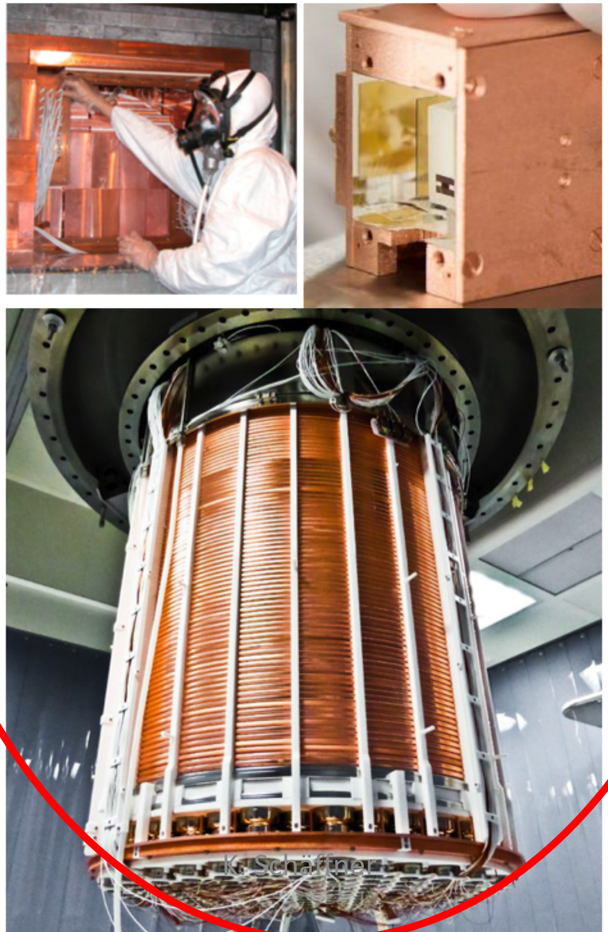
Annihilation

$\chi\bar{\chi} \rightarrow \gamma\gamma, q\bar{q}, \ldots$

DIRECT

scattering

$\chi\,\mathrm{N} \rightarrow \chi\,\mathrm{N}$



COLLIDERS

production

e.g. $p + p \rightarrow \chi\bar{\chi}$ + products

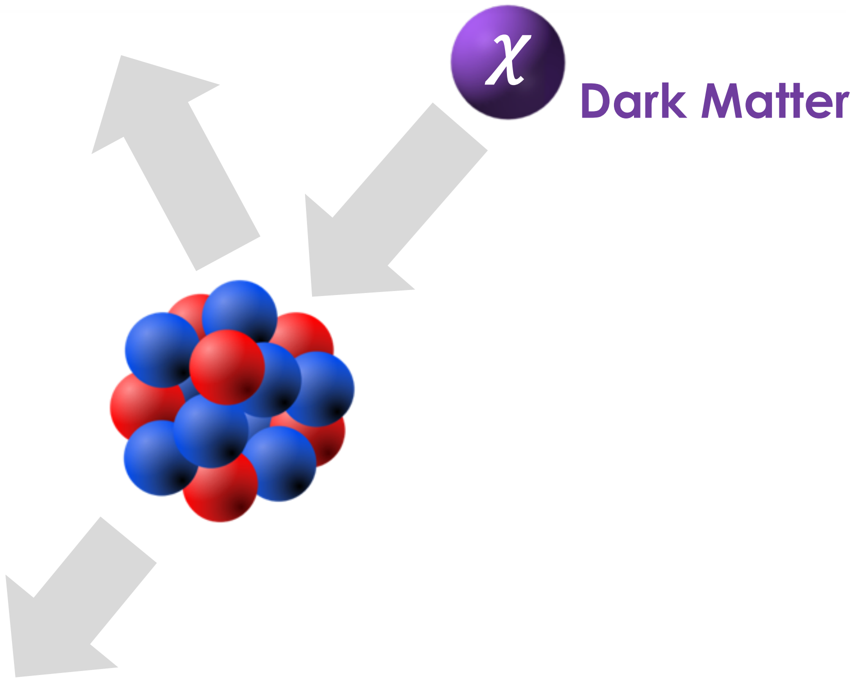
DIRECT DARK MATTER INTERACTION

Assumption

Particle-like dark matter which interacts with Standard Model particles

Most common

Dark matter particle scatters off the nucleus and induces a nuclear recoil

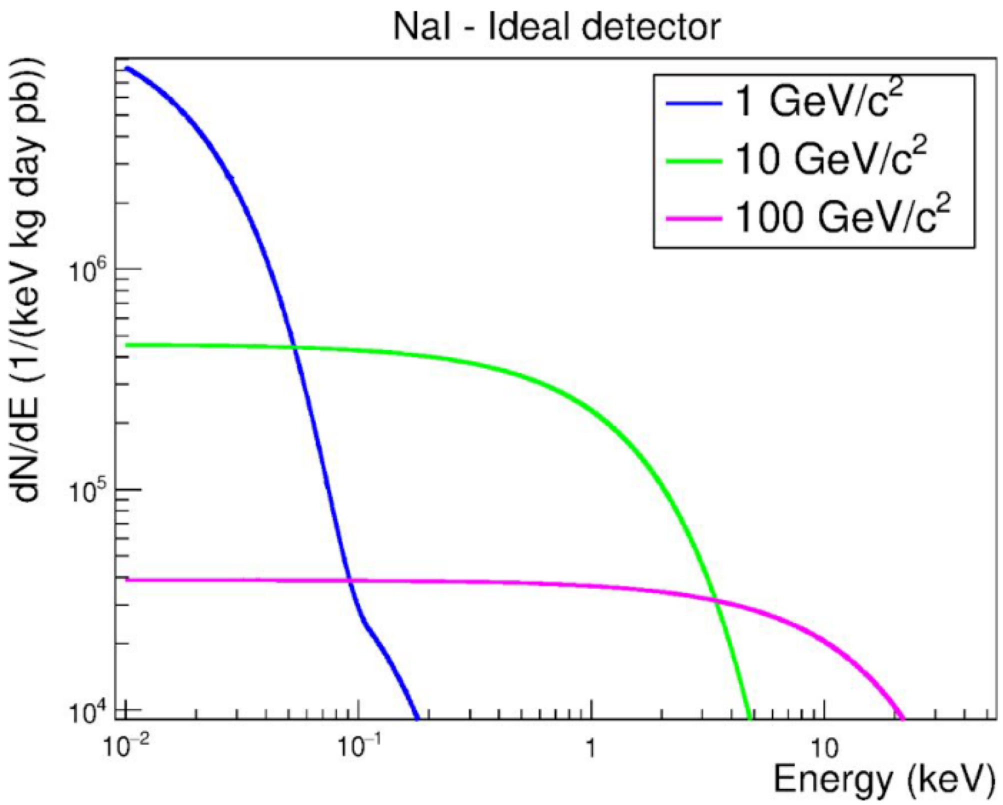


also:

Electron recoils ? !

EXPECTED NUCLEAR RECOIL **SPECTRUM**

rate and shape of recoil spectrum depend on target material



extremely rare interaction rate

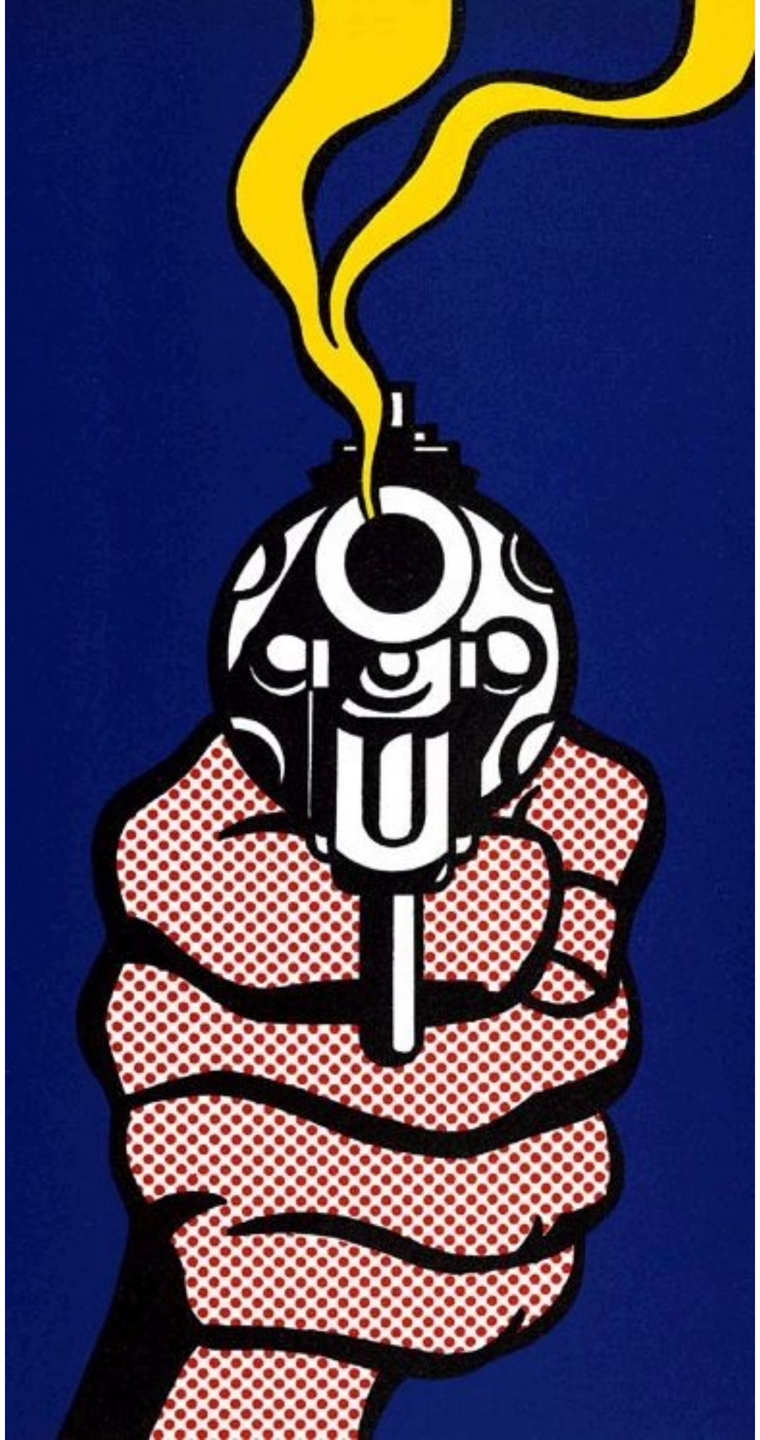
current limit: $\mathcal{O}$ **(0.01) counts/(keV tonne year) ***

small recoil energies of few ~ **keV range**

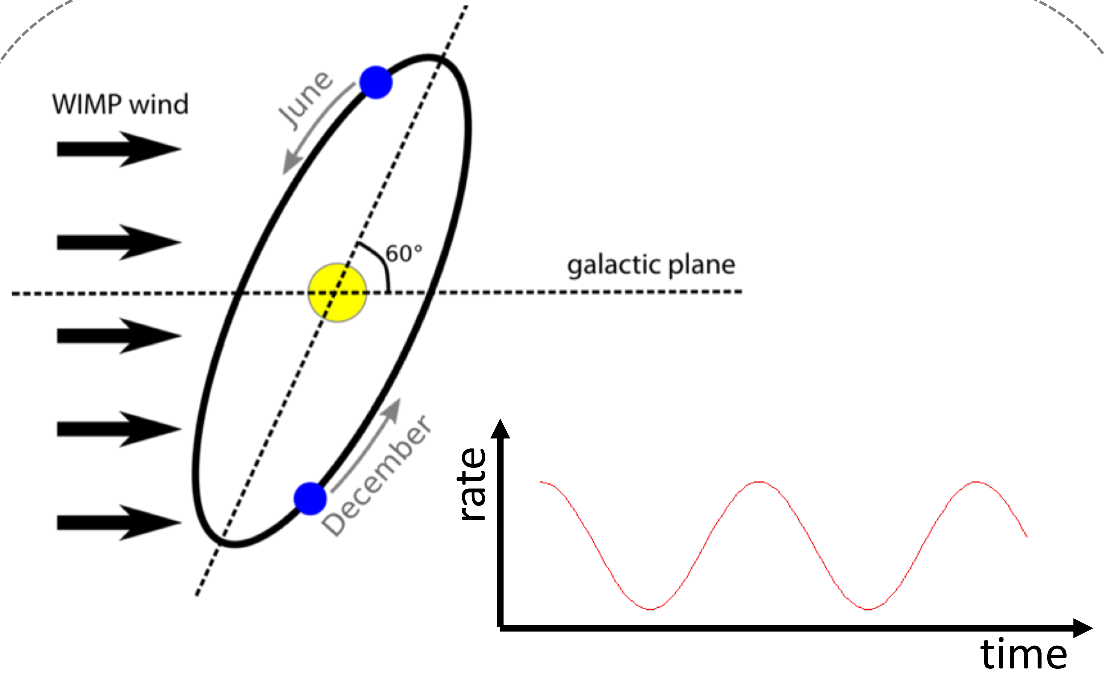
flat and **featureless** spectrum !!

* Xenon1t: Phys. Rev. Lett. 121, 111302

Is their a smoking gun signature in direct dark matter searches ?



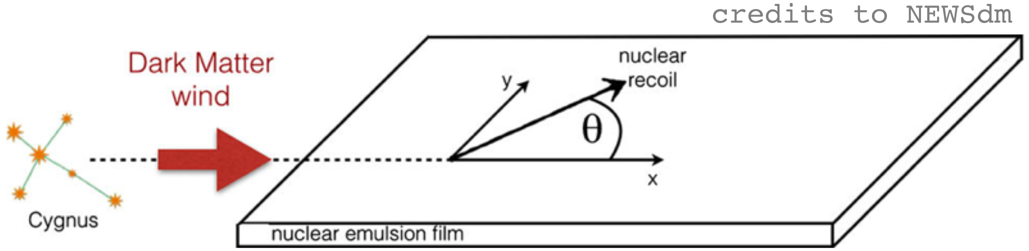
MODULATION

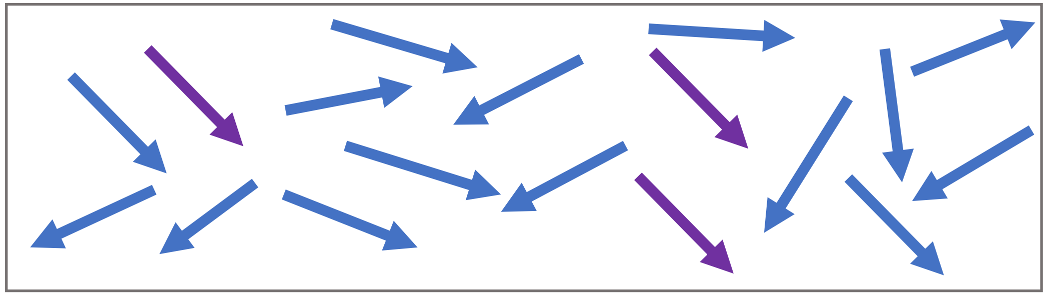


motion of the Earth causes relative modulation of velocity

→ **annual variation in the rate**

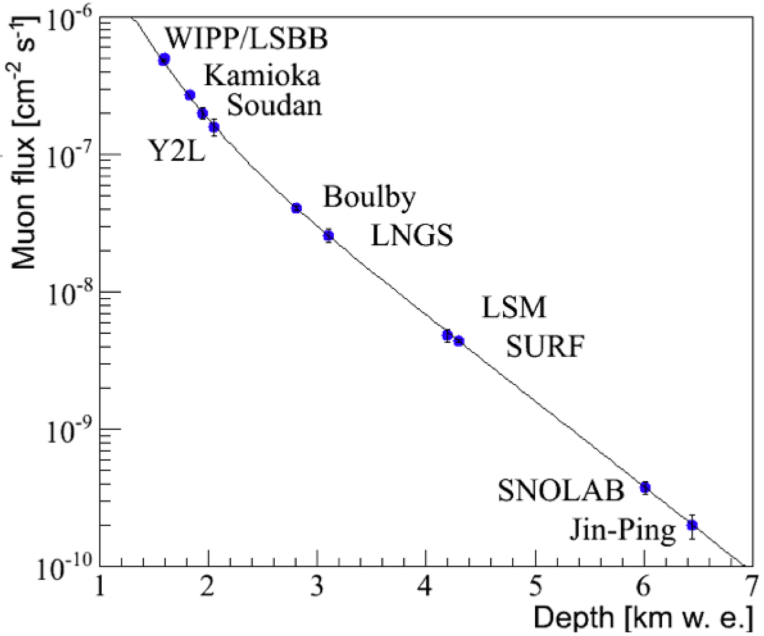
DIRECTIONALITY





→ directional dependence of nuclear recoils

BACKGROUNDs



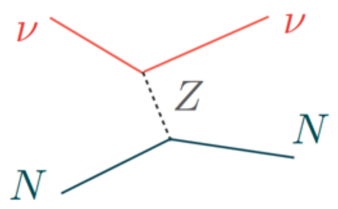
- **External neutrons**:
  muon-induced,
  (α, n) and from fission reactions → **underground sites!**

- **External γ's:** from natural radioactivity

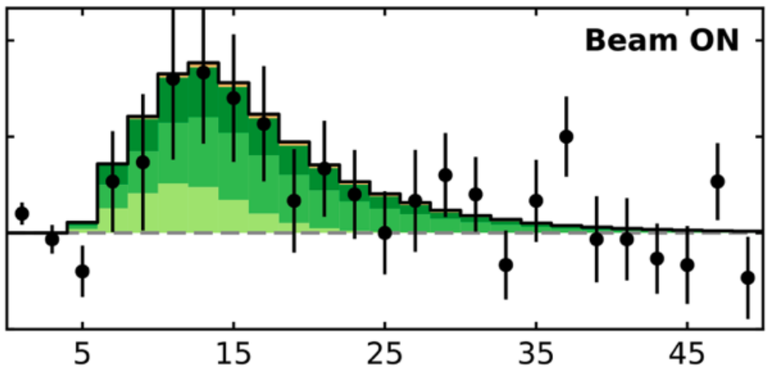
- **Internal backgrounds**:
  Liquid targets: ^{85}Kr and Rn-emanation from surrounding materials
  Solid targets: activation / surface events from α- or β–decays

- **Neutrinos:** neutrino coherent nucleus scattering
  from the Sun, atmospheric and from supernovae

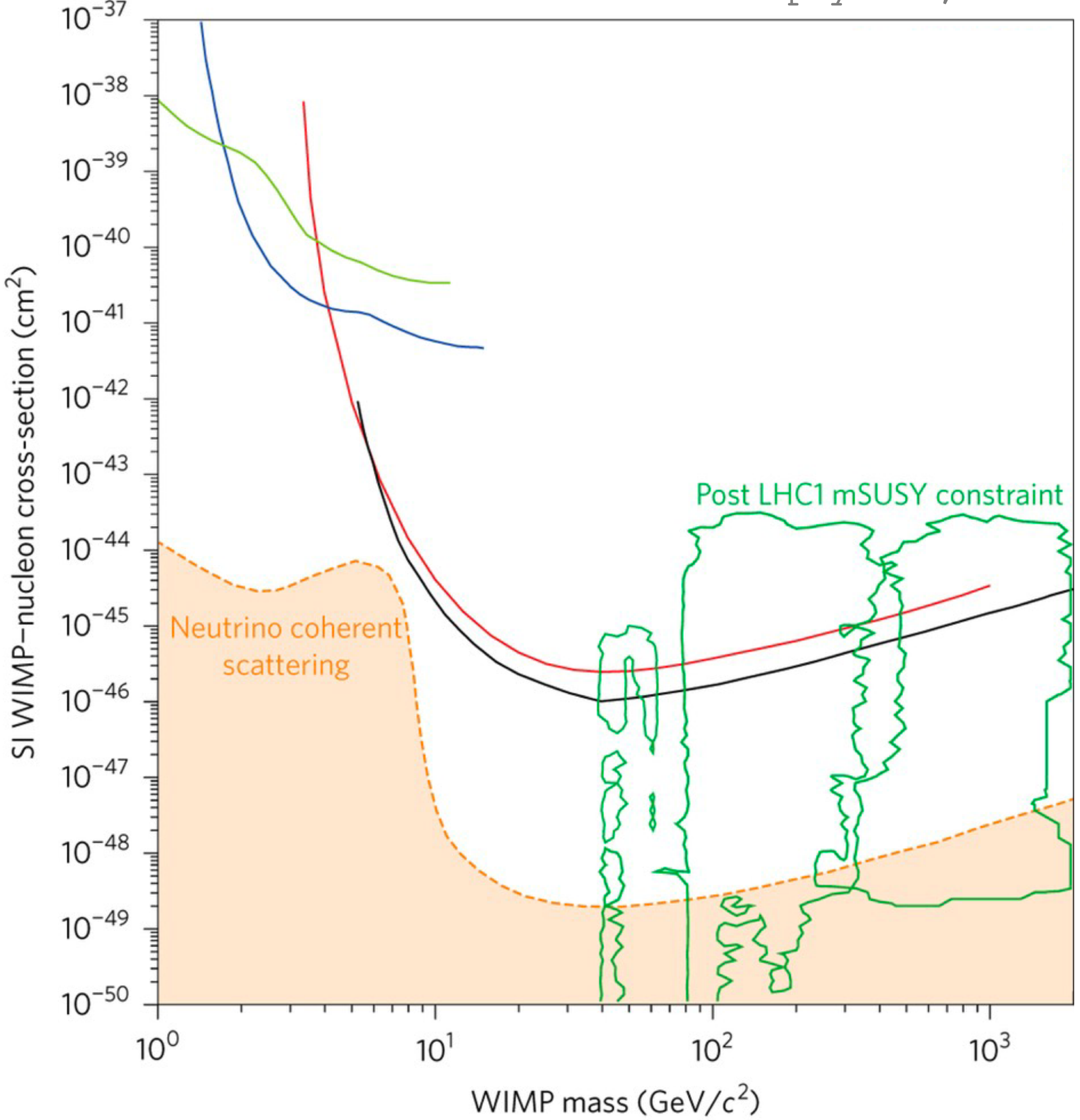
Background of today can be the signal of tomorrow !



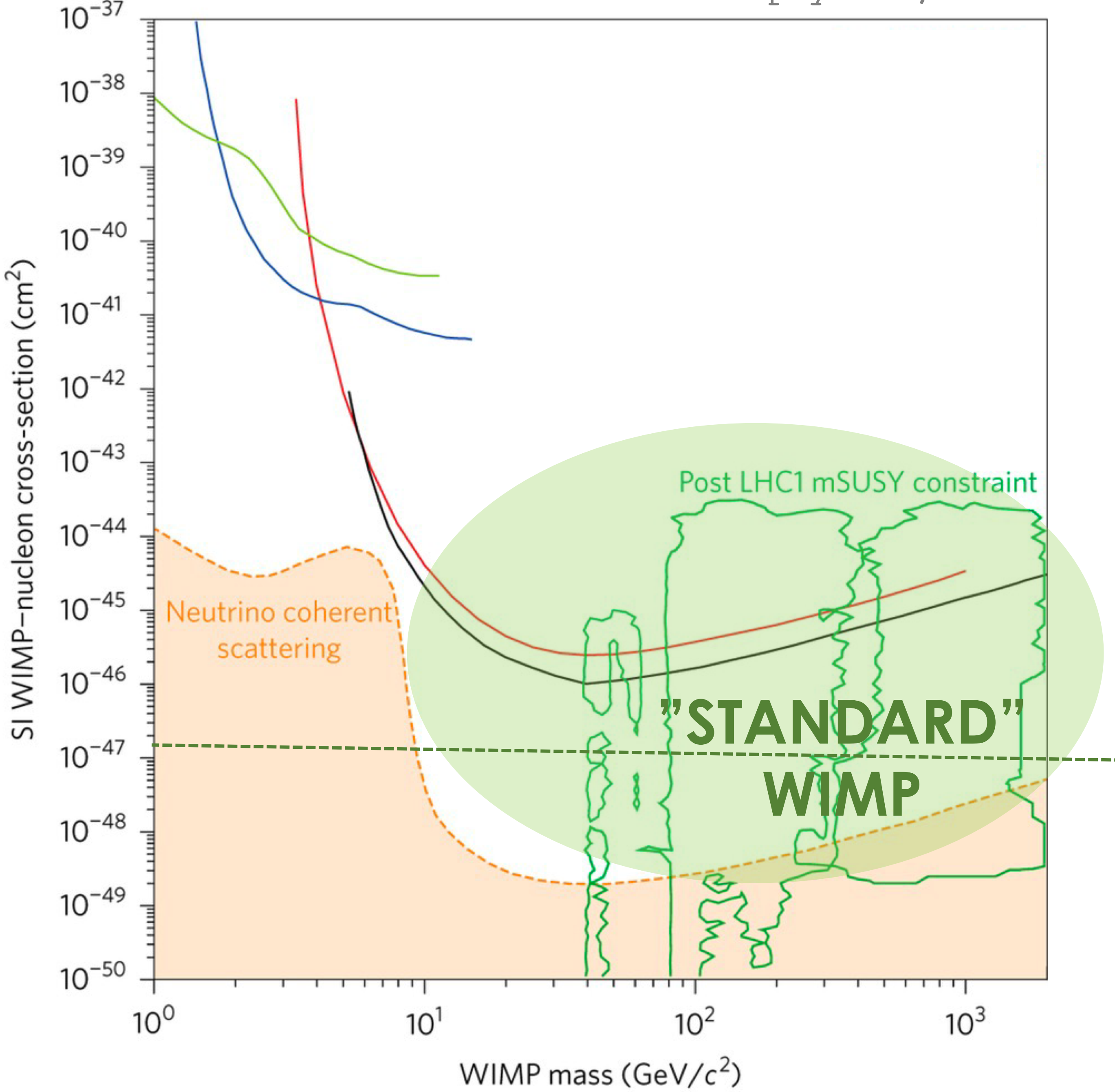
COHERENT, Science, 2017



Nature physics, 2017



Nature physics, 2017



large target

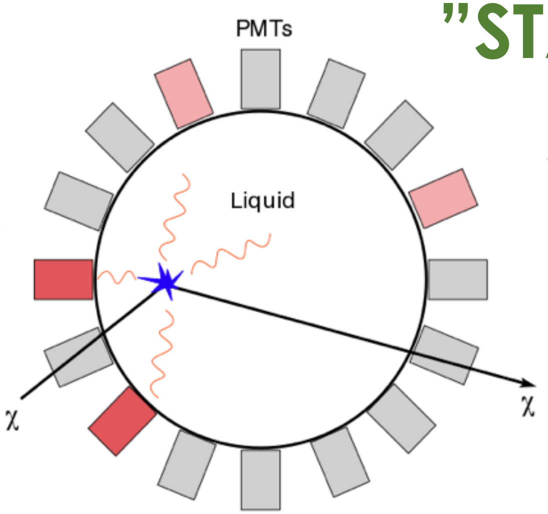
→ exposure

mainly liquid noble gases

~ 1 event/ tonne-year

SINGLE PHASE LIQUID NOBELS

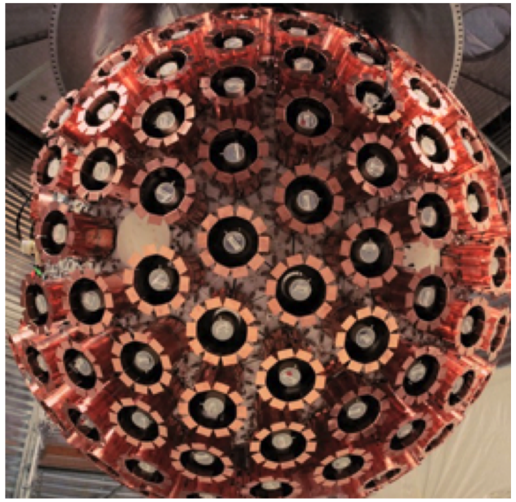
"STANDARD" WIMP



- high light yield using 4π PMT coverage
- pulse shape discrimination from scintillation

DEAP-3600
@ SNOLAB, Canada

PRD 100, 022004 (2019)



- LAr detector
- 3600 kg total mass
  → new results
- 1 ton FV
- 10^{-8} discrimination above 25 keV_{ee}

XMASS
@ Kamioka, Japan

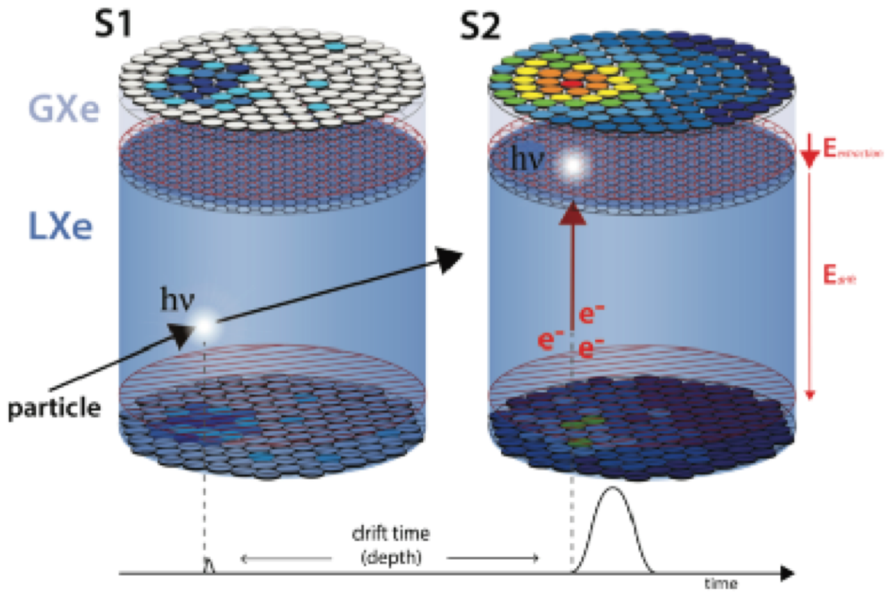
PLB 789, 45 (2019)

- LXe detector
- 1000 kg total mass
- 832 kg FV
- high light yield: 14.7 PE/keV_{ee}

DUAL PHASE LIQUID NOBELS

Time projection chambers:

- 3D position resolution via light (S1) & charge (S2) → fiducialization
- electron/ nuclear recoil discrimination



LAr EXPERIMENT

DarkSide-50
@ LNGS, Italy

46 kg depleted argon

ALSO:
sensitivity for low mass dark matter

→ **threshold: 100eV$_{ee}$**

PRL, 121, 081307 (2018)
PRD 98, 102006 (2018)

LXe EXPERIMENTS

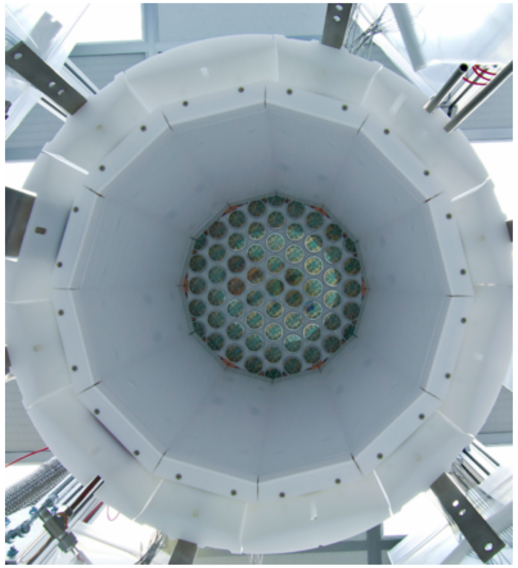
"STANDARD" WIMP

LUX @ SURF

250 kg fiducial mass
(370 kg total)

- exposure: 33.5 tonne days
- decommissioned

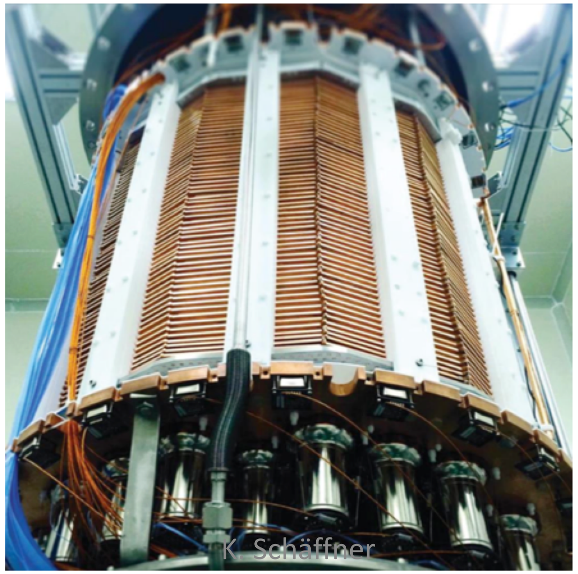
PRL 118, 021303 (2017)
PRL 122, 131301 (2019)



PANDAX-4T @ CJPL

- 3.7t active target
- exposure: 0.63 ton year
- running

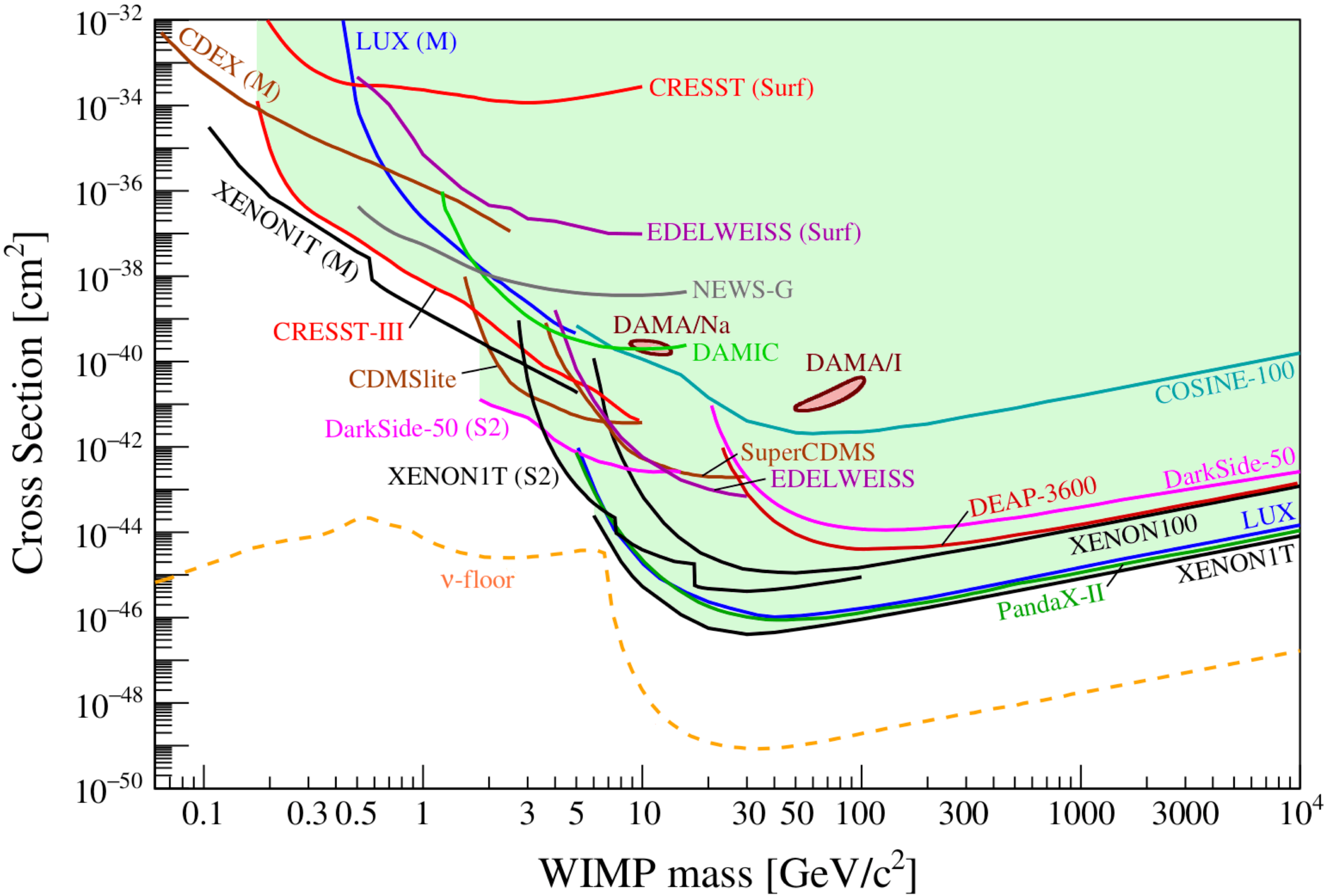
PRL 119, 181302 (2017)
arXiv:2107.13438



XENON1T @ LNGS

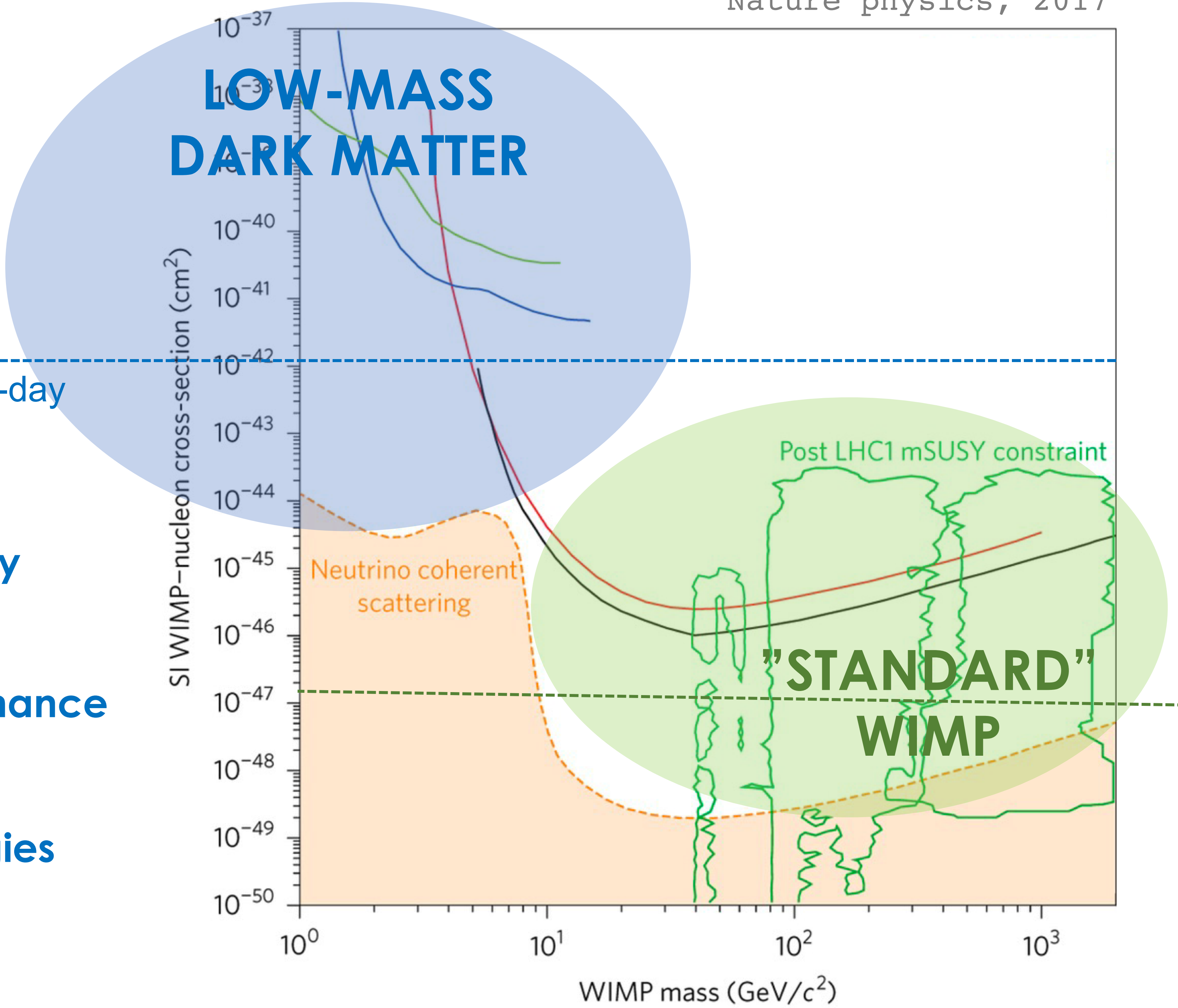
- 2000 kg fiducial mass
- (3.2 t total)
- exposure: 0.6 ton year
- upgrade to XENONnT

PRL 121, 111302 (2018)
PRL 123, 241803 (2019)
PRL 123, 251801,(2019)
PRL 126, 091301 (2021)



Cross Section [cm^2]
10^{-32}
10^{-34}
10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
0.1
0.3 0.5
1
3
5
10
30 50
100
300
1000
3000
10^4
WIMP mass [GeV/c^2]
CDEX (M)
LUX (M)
CRESST (Surf)
XENON1T (M)
EDELWEISS (Surf)
NEWS-G
CRESST-III
DAMA/Na
DAMIC
DAMA/I
CDMSlite
COSINE-100
DarkSide-50 (S2)
SuperCDMS
XENON1T (S2)
EDELWEISS
DarkSide-50
DEAP-3600
LUX
XENON100
XENON1T
PandaX-II
ν-floor

Nature physics, 2017



~ 1 event/ kg-day

low energy threshold

→ performance

diverse technologies

large target

→ exposure

mainly liquid noble gases

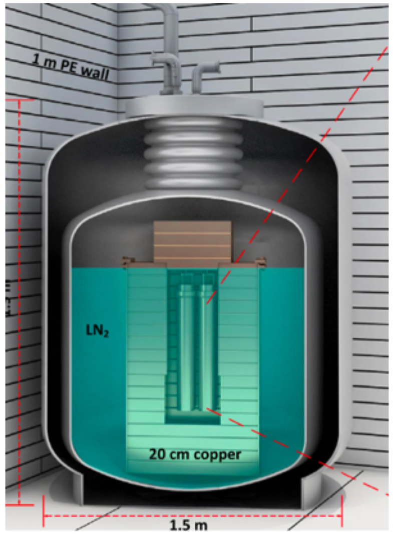
~ 1 event/ tonne-year

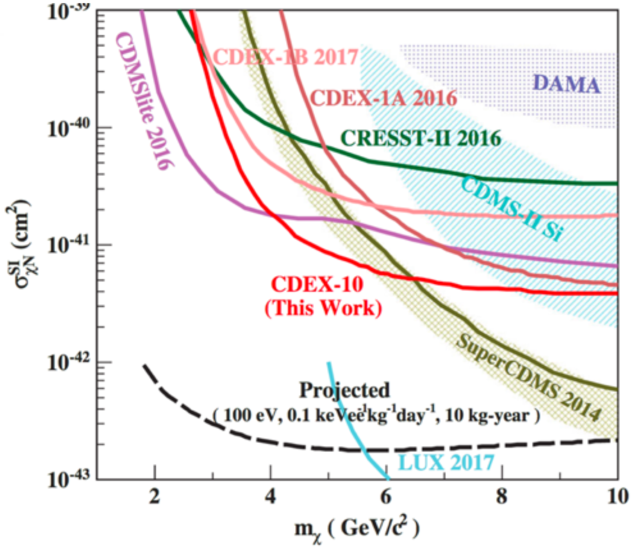
LOW MASS DM - TECHNOLOGIES

Ge-DETECTORS: CDEX-10 @ CJPL

- 10 kg p-type point contact Ge
- exposure: 102.8 kg-days
- analysis threshold: 160 eV_{ee}

PRL 123, 161301 (2019)





improved limit on WIMP mass of 5 GeV/c^2

lower mass reach extended to 2 GeV/c^2.

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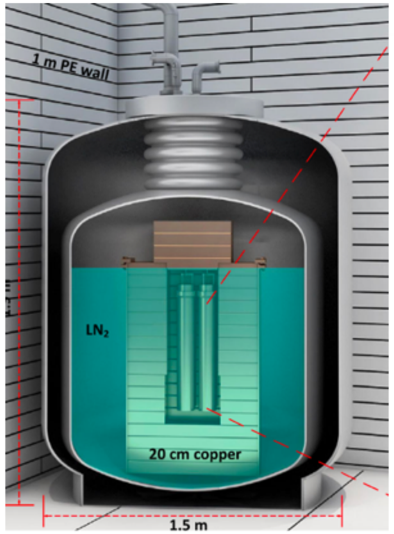
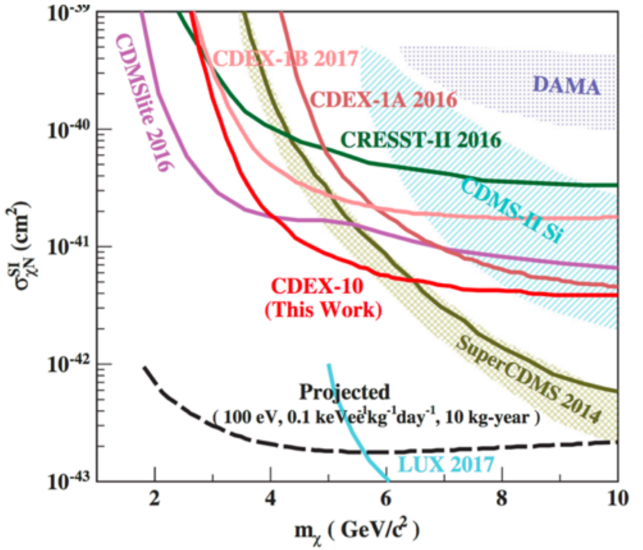


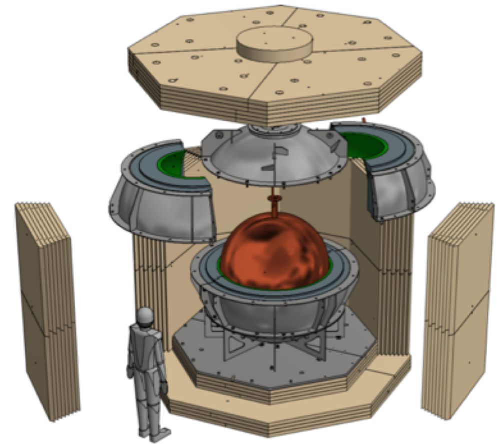


improved limit on WIMP mass of 5 GeV/c^2

lower mass reach extended to 2 GeV/c^2.

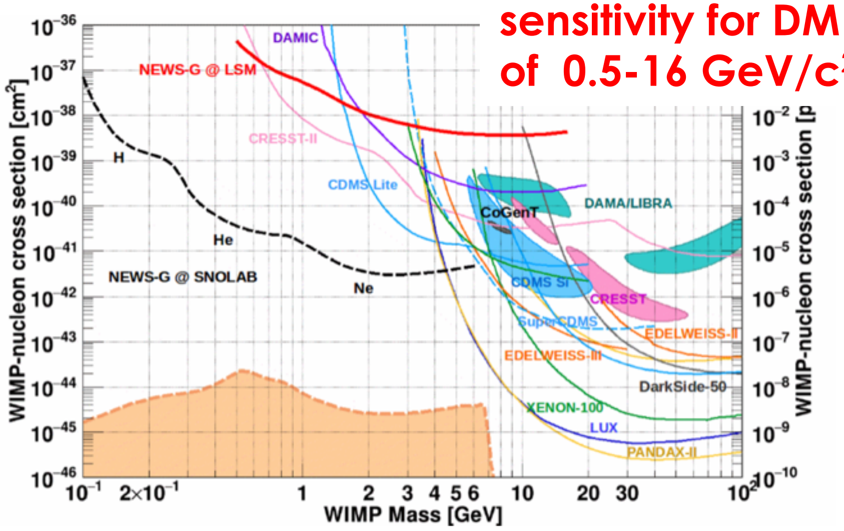
SPHERE GAS DETECTOR NEWS-G @ LSM/SNOLAB

- light target: Ne, (He, H)
- sensitivity for single electrons
- energy threshold: 36 eV_{ee}



Astr. Part. Phys. 97 (2018) 54-62

sensitivity for DM mass of 0.5-16 GeV/c^2



CRYOGENIC DETECTORS

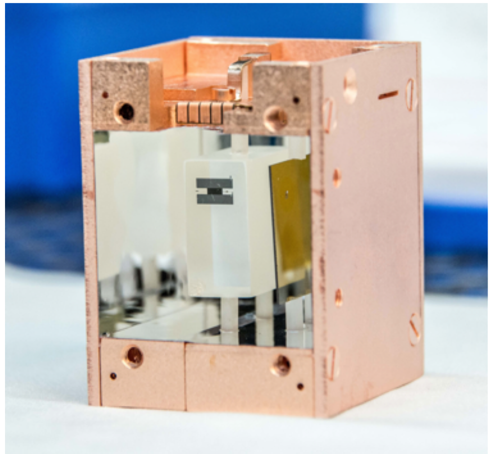
LOW MASS DARK MATTER

CRESST @ LNGS

- 24g $CaWO_4$ crystals
- nuclear recoil

threshold: 30.1 eV_{nr}

PRD 100, 102002 (2019)

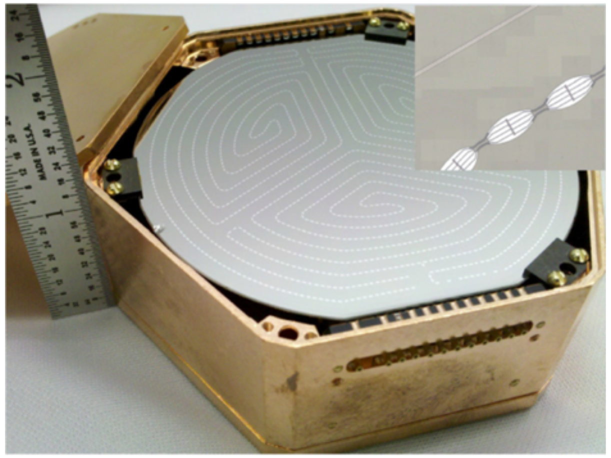


SuperCDMS @ SNOLAB

CDMSlite: 600g Ge
energy threshold = 70 eV

→ moving to SNOLAB
future detectors: Ge: 25 kg
Si: 3.6 kg

PRD 97, 022002 (2018)
PRD 99, 062001 (2019)

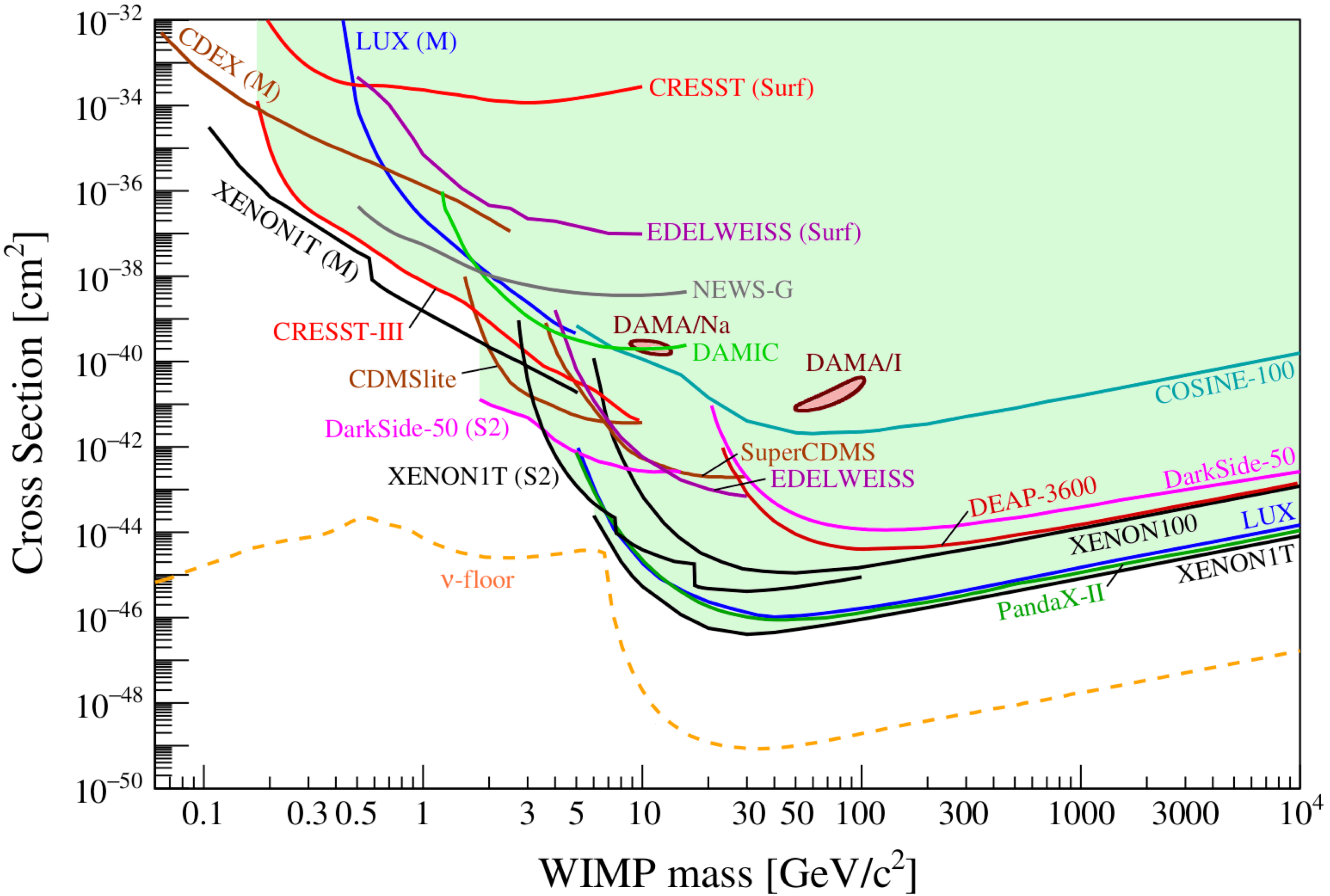


EDELWEISS @ LSM

20 kg Ge mass

+ improved low threshold detectors of 50 eV_{ee}

PRD 97 (2018) 022003



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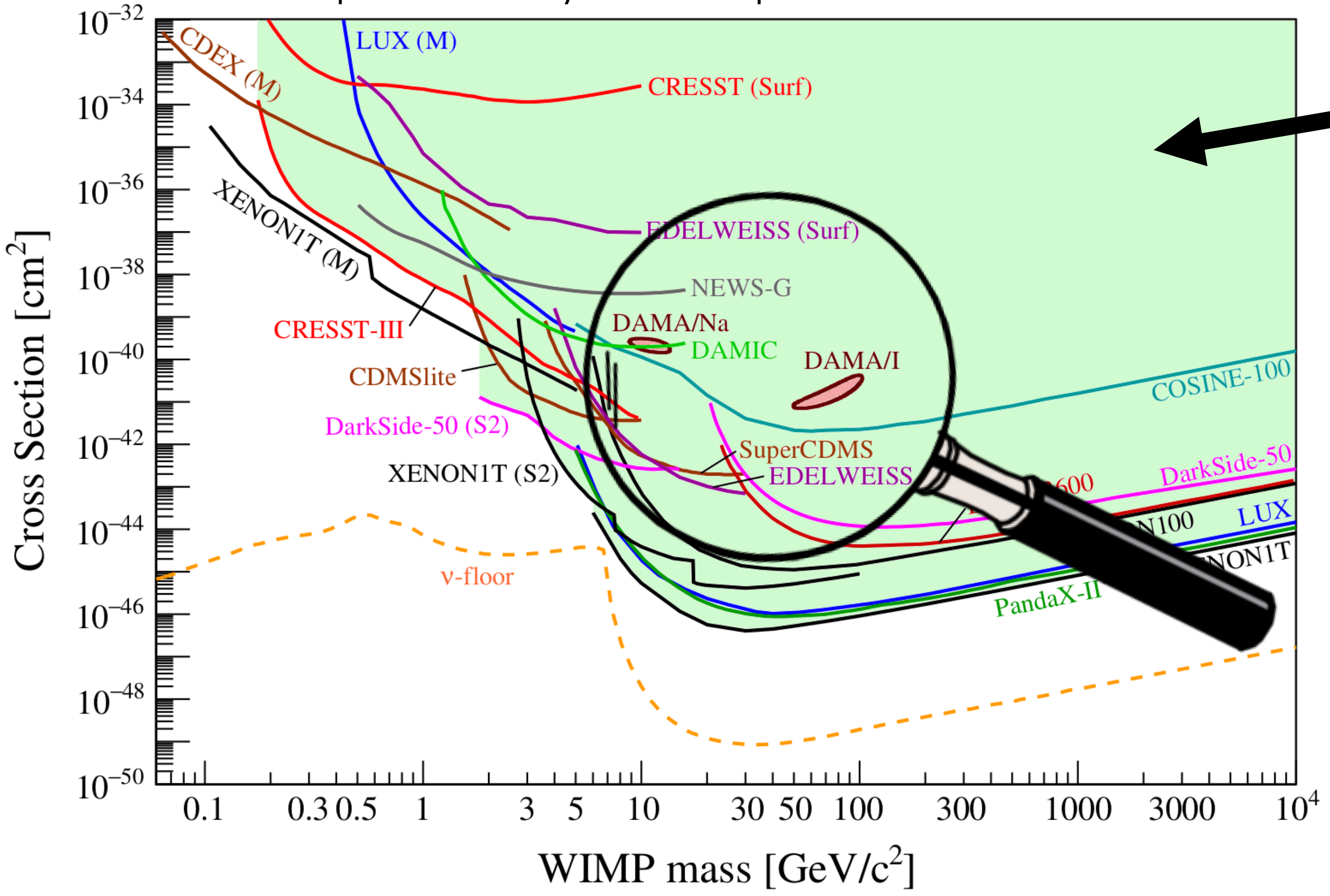
DEAP-3600
LUX
XENON100
XENON1T
PandaX-II
ν-floor

"STANDARD" WIMP

There is one exception …

DIRECT DARK MATTER DETECTION LANDSCAPE

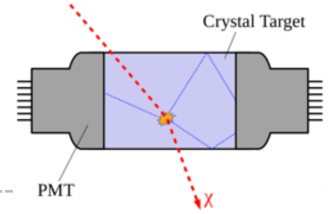
Astroparticle Physics European Consortium APPEC, v1.02



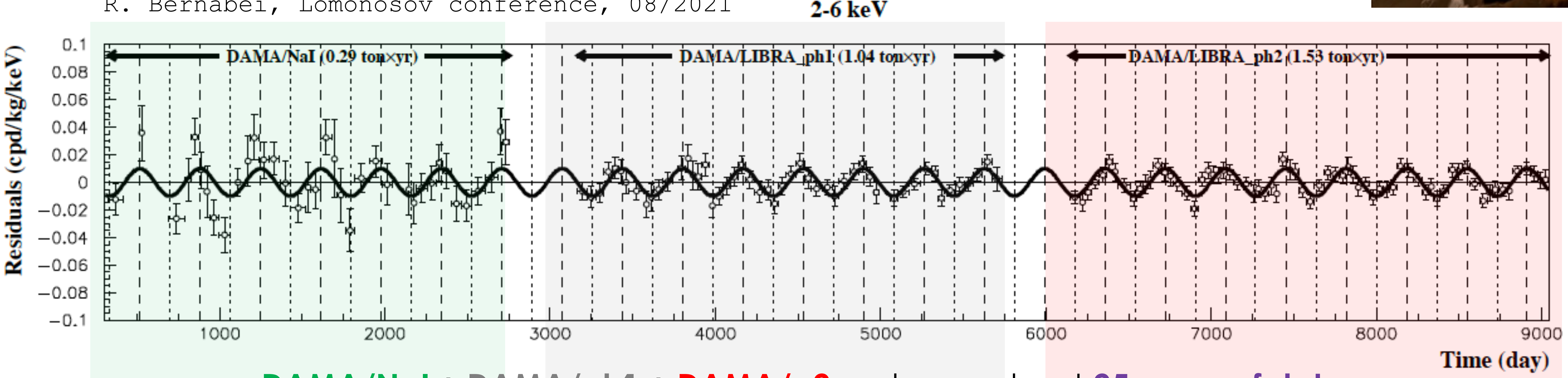
Excluded area

Positive evidence reported by DAMA

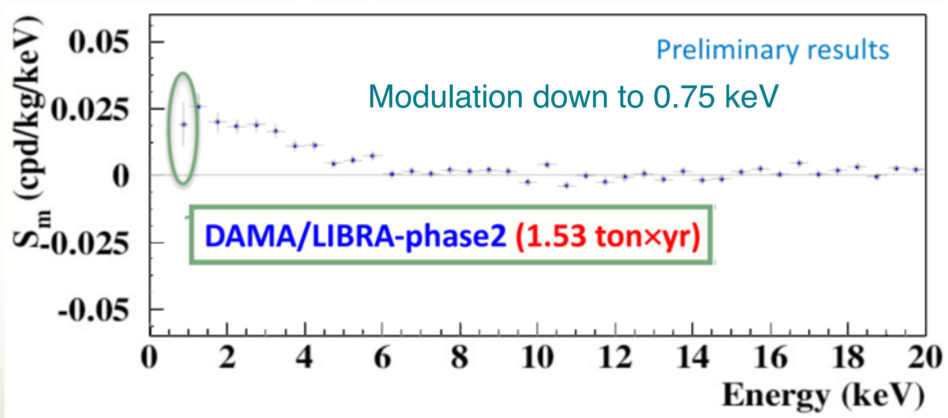
DAMA/LIBRA: **TIME DISTRIBUTION**



R. Bernabei, Lomonosov conference, 08/2021



DAMA/NaI + **DAMA/ph1** + **DAMA/p2** make up about **25 years of data**



Total exposure: 2.86 tonne years

Statistical significance: 13.7 σ

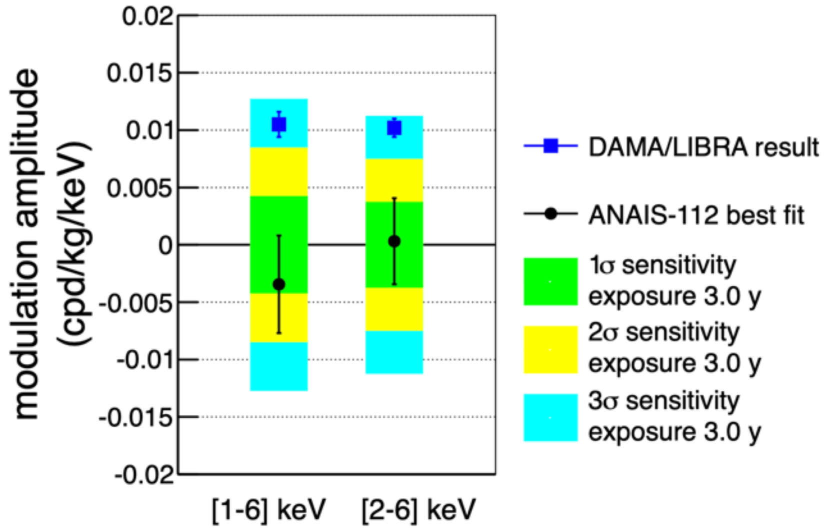
Claim: positive evidence for the presence of DM particles in the galactic halo

ANAIS-112

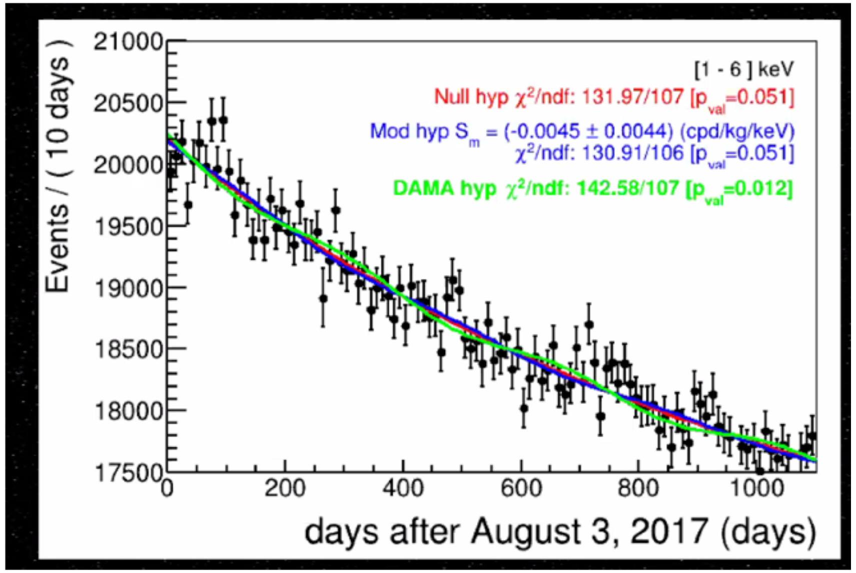
PRD 103.10 (2021): 102005

No modulation observed

incompatible with DAMA at 3.3σ [1-6 keV]



3 years of data = 314 kg year

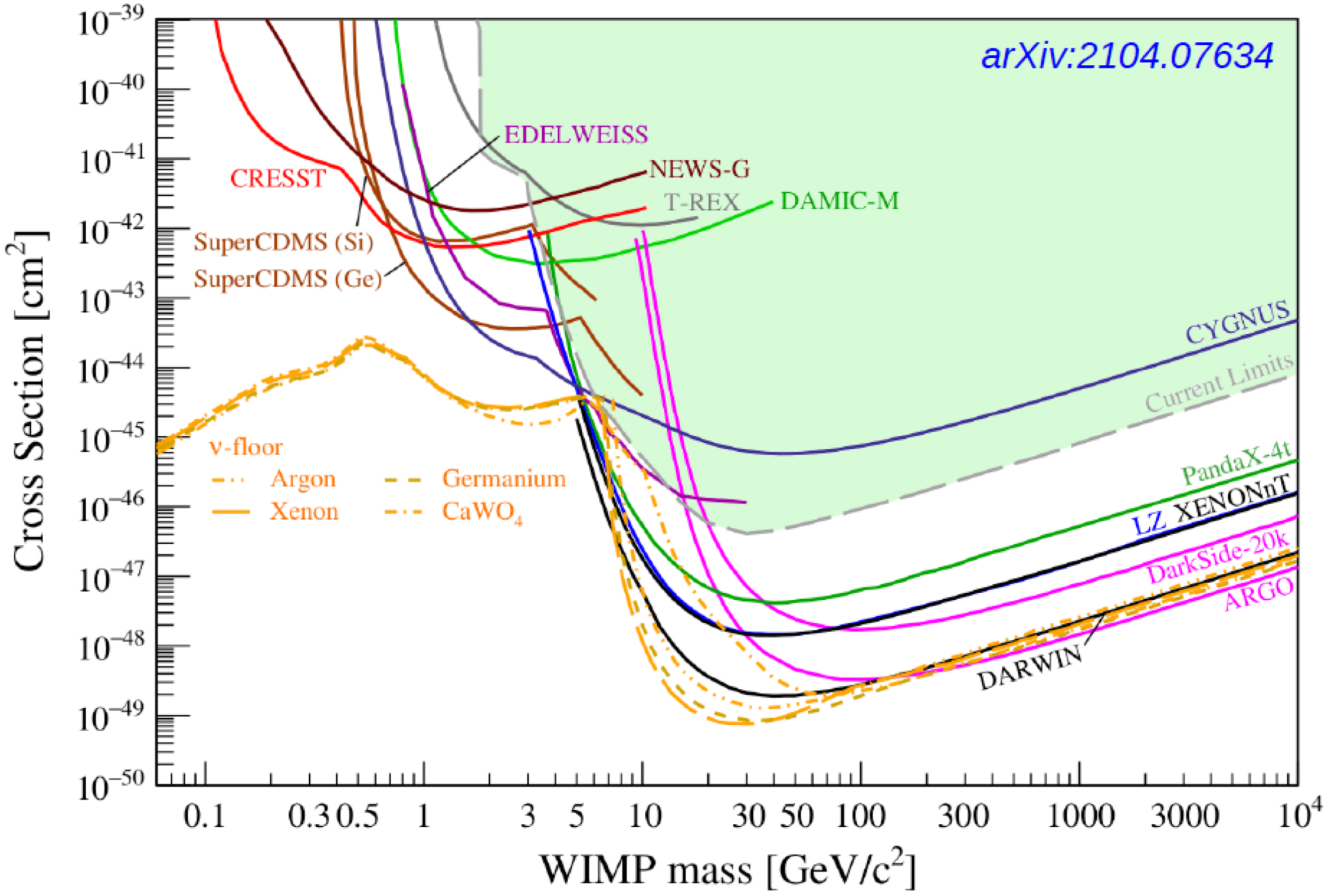


Moriond 2021: M.L. Sarsa

COSINE-100

- excludes DAMA interpreted as SI interaction with standard halo model
  Nature 564, 83 (2018)
  PRL 123, 031302 (2019)
- Modulation analysis of 3 years of data (173 kg year) is consistent both with and without modulation
  arXiv:2111.08863

Whats next in direct detection?



- Very rich and diverse experimental landscape
- Different technologies allow to probe a very wide parameter space
- Next generation of experiments aim for closing the parameter space in the next decade(s)

SUMMARY

- We are just at the beginning of having an understanding of our Universe and the nature of dark matter is still an open and pressing mystery

- Dark matter searches employ a huge variety of detection technologies

- Sensitivity of direct detection experiments improved tremendously in the last decades
  → next generation detectors will cover full parameter space down to the neutrino-floor and clarify the DAMA/LIBRA claim

- Recent strategy given null-results for WIMPs: "***probe what we can probe***"
  → low mass (sub-GeV) DM searches, DM-electron scattering and new ideas (+exotics)

- Rich non-WIMP physics program: Axion dark matter searches are on the way

Thank you for your attention