Direct searches for Dark Matter

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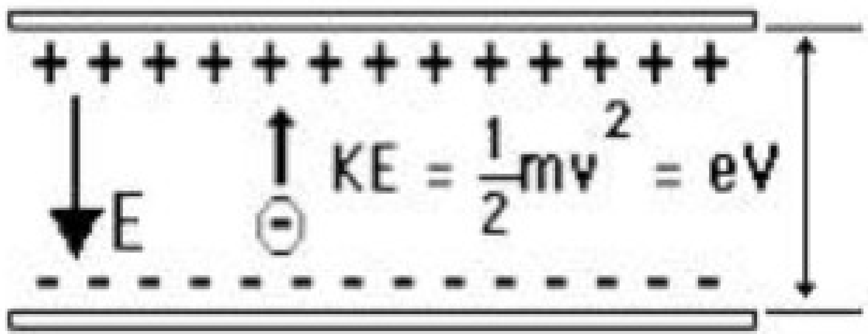
1- Preamble (10')
2- What is dark matter and what it is made of ? (20')
3- Direct detection of dark matter (40')
4- Conclusions

Energy (Mass) Unit: Electron Volt

$$E = qV = (1.6 \times 10^{-19}\ C)(1\ \frac{J}{C})$$

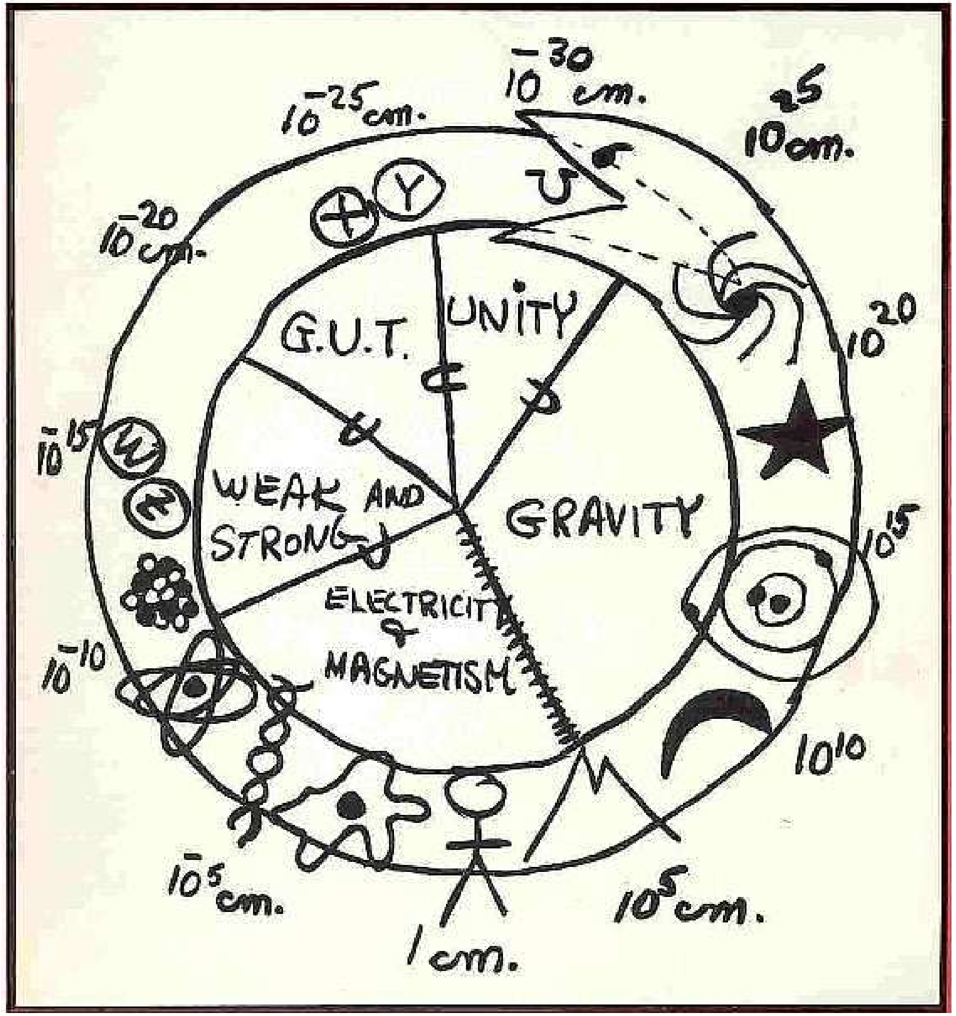
$$1 \text{ electron volt} = 1.6 \times 10^{-19}\ J$$



e = electron charge = 1.6×10^{-19} C
V = voltage

Will talk about μeV, eV, keV, GeV

Lesson from XXth century

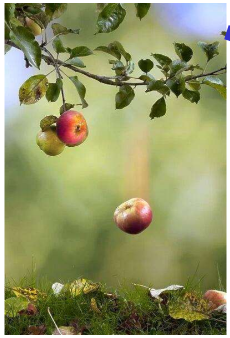


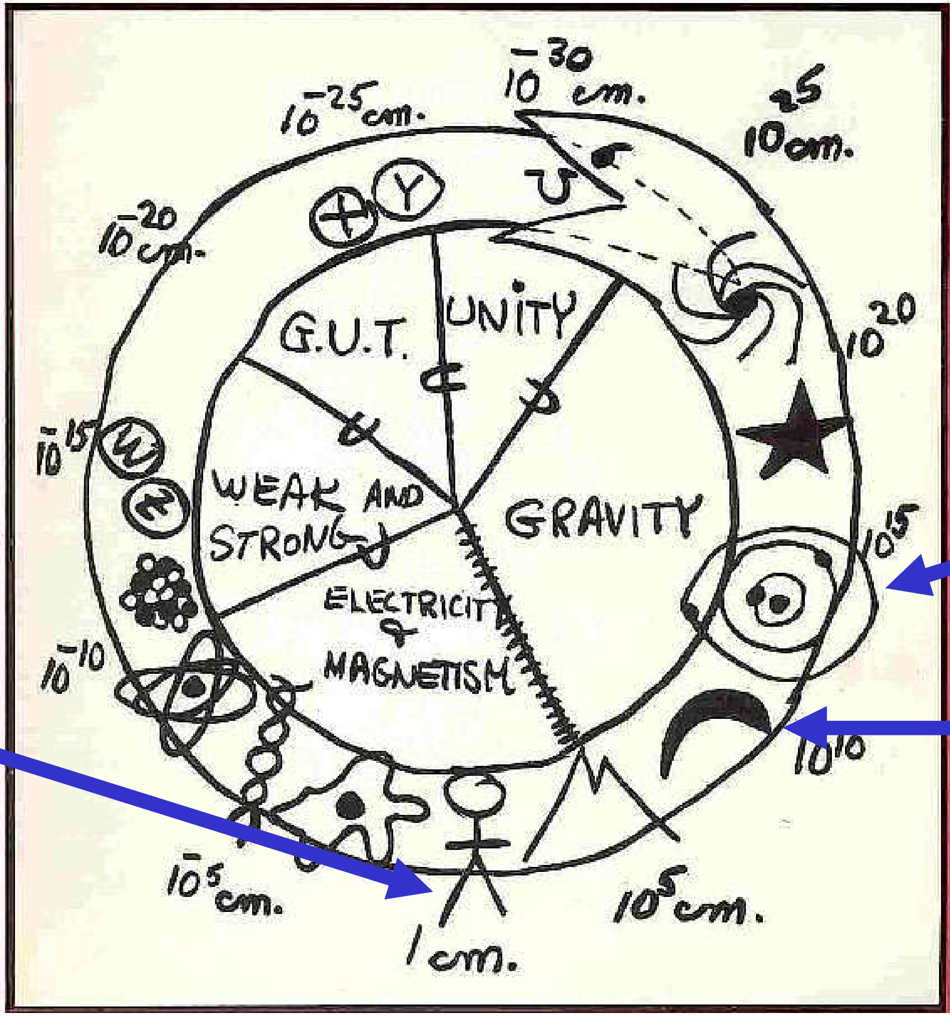
S. Glashow serpent swallowing its tail
New York Times Magazine, Sept. 26, 1982, p. 40

Two infinites (micro and macro) deeply interconnected

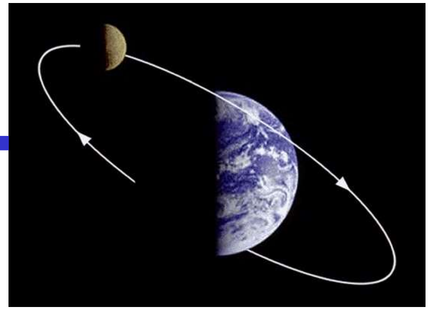
Gravity

Fairly simple experimental set-up !





Fairly simple detector !

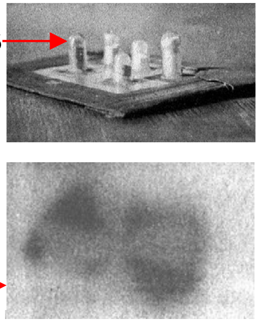


Instantaneous **gravity explains all (1688) !**

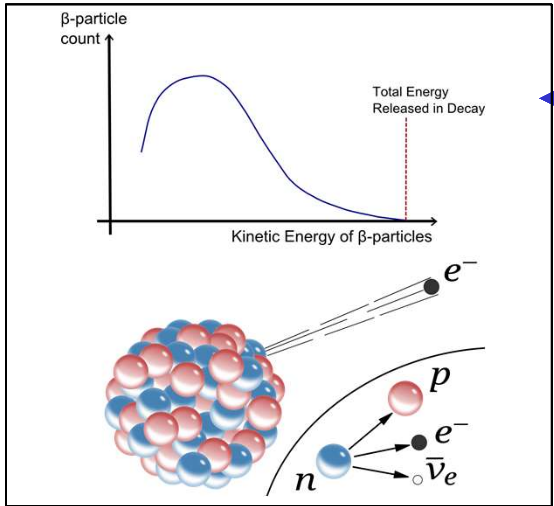
Neutrino from the Sun

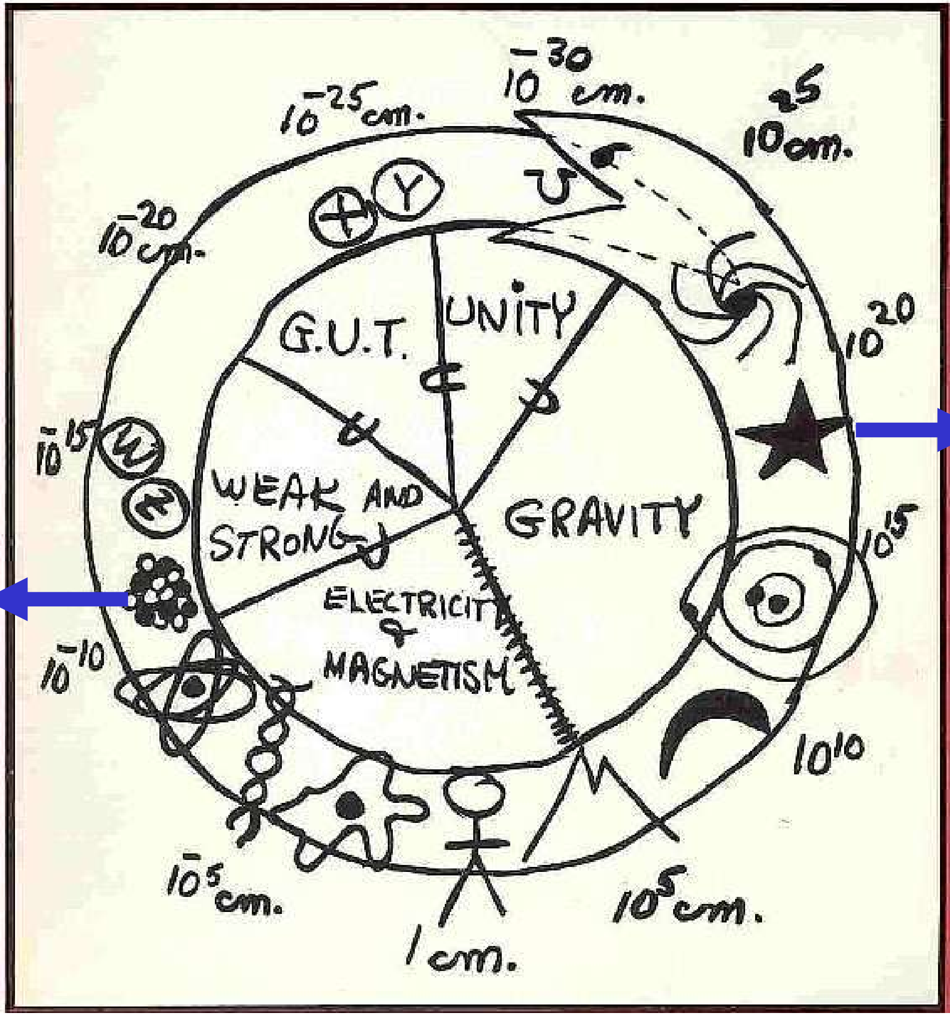
Radioactivity β⁻ (1896)

Uranium salts leave fingerprints on a photographic plate

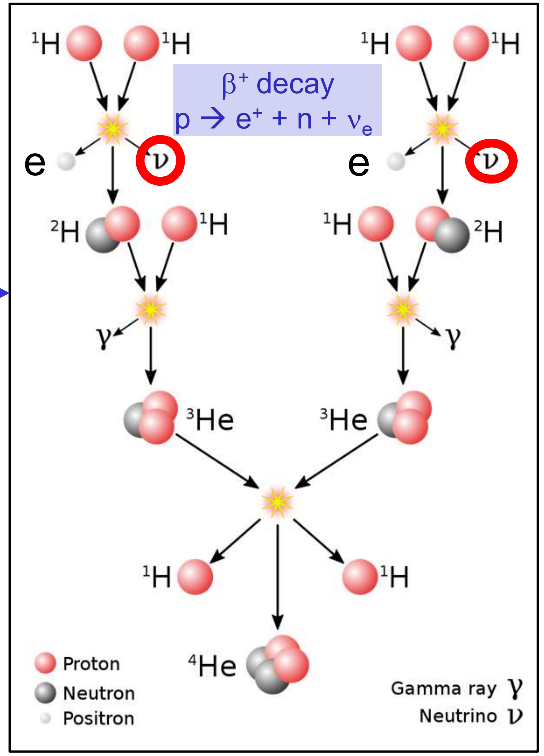


Hypothetical ν (1930)





Hydrogen fusion in the sun (1939)



Sun should emit neutrinos

Neutrino from the Sun

Radioactivity β⁻ (1896)

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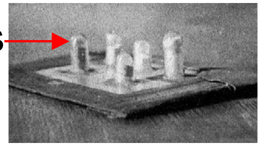

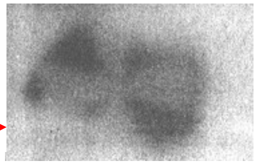

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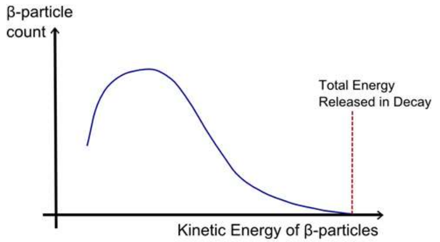
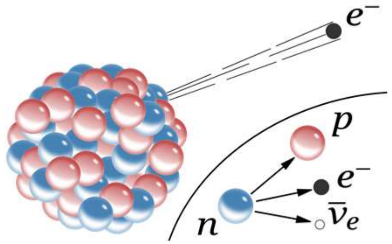
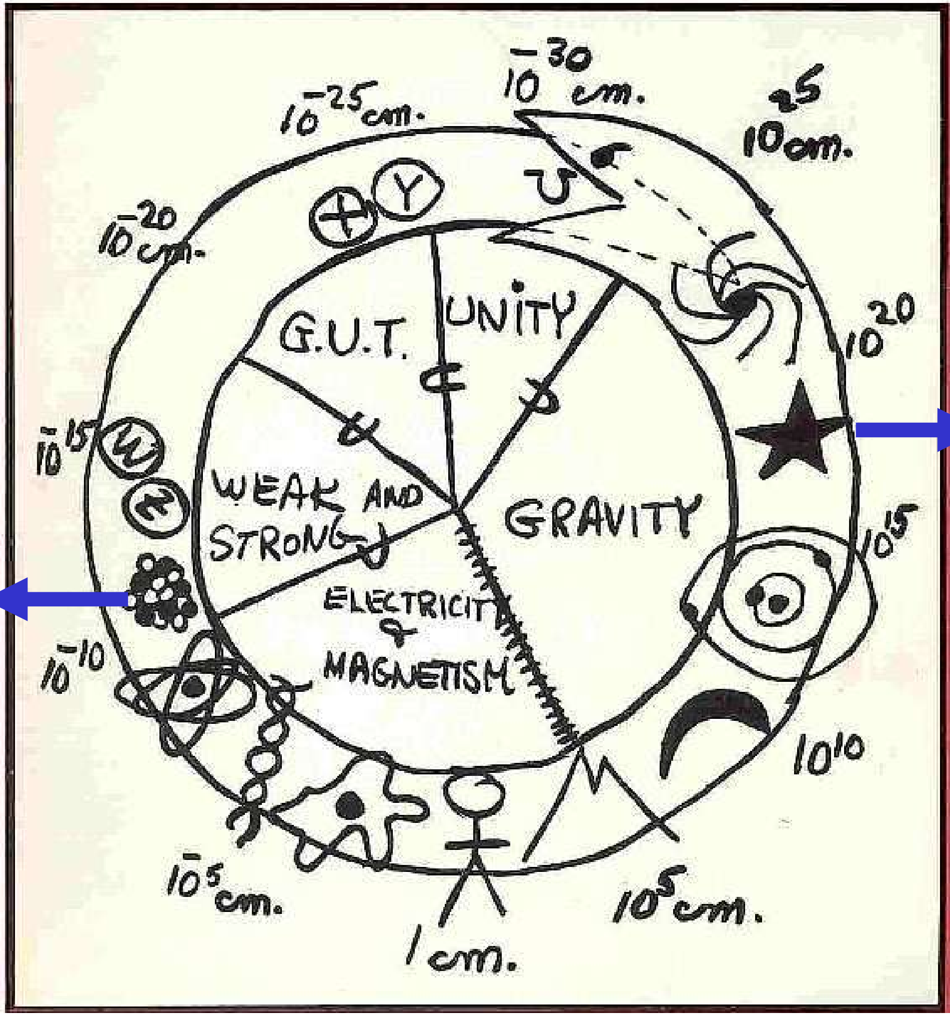






Compute the solar neutrino flux (1964)

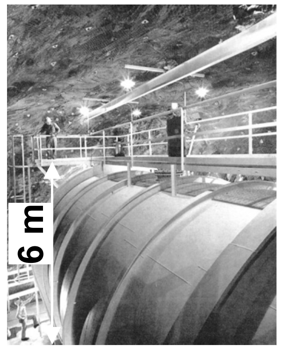
70x10⁹ neutrino/cm²/s

Build experiment 1.4km underground in USA

Tank containing 1200 tons of Chlorine fluid

$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$

(n) (Sun) (p) (det)



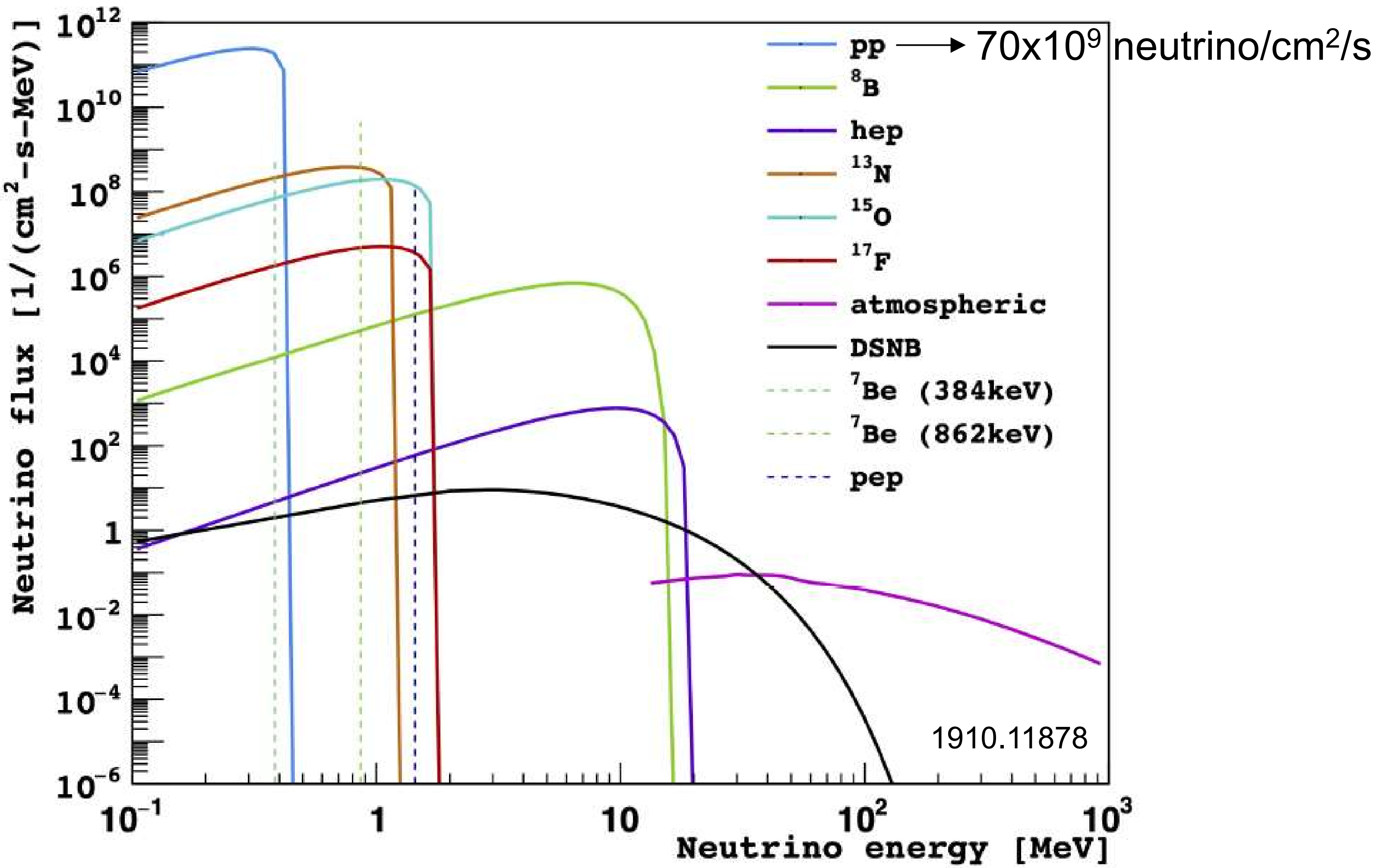
Count ~**6** **new ^{37}Ar per month** (1969)

Neutrino could have been discovered by looking at the Sun !

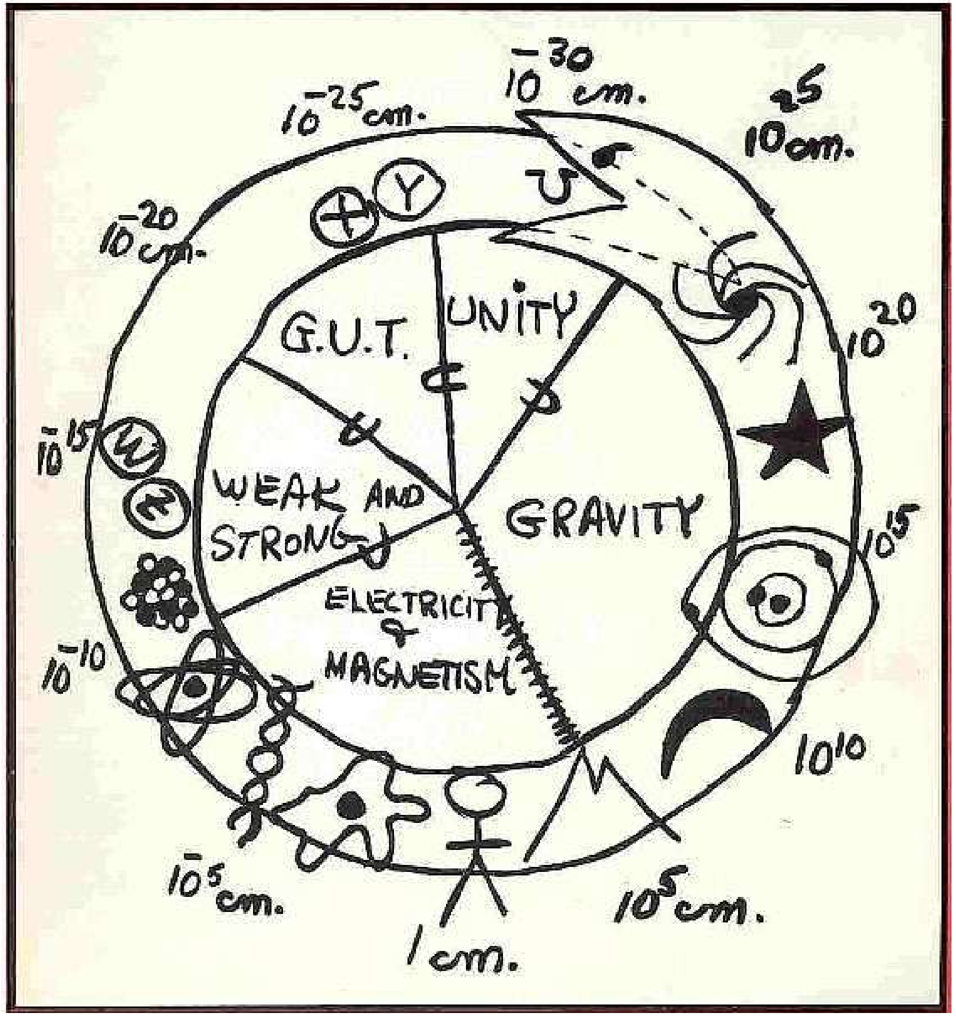
[Discovered in 1956 by looking at a nuclear plant]

Neutrino flux today

❑ **One of the main background for dark matter searches !**



Dark Matter (Part I)



2- Particle physics:
status and open questions.
New hypothetic particles ?

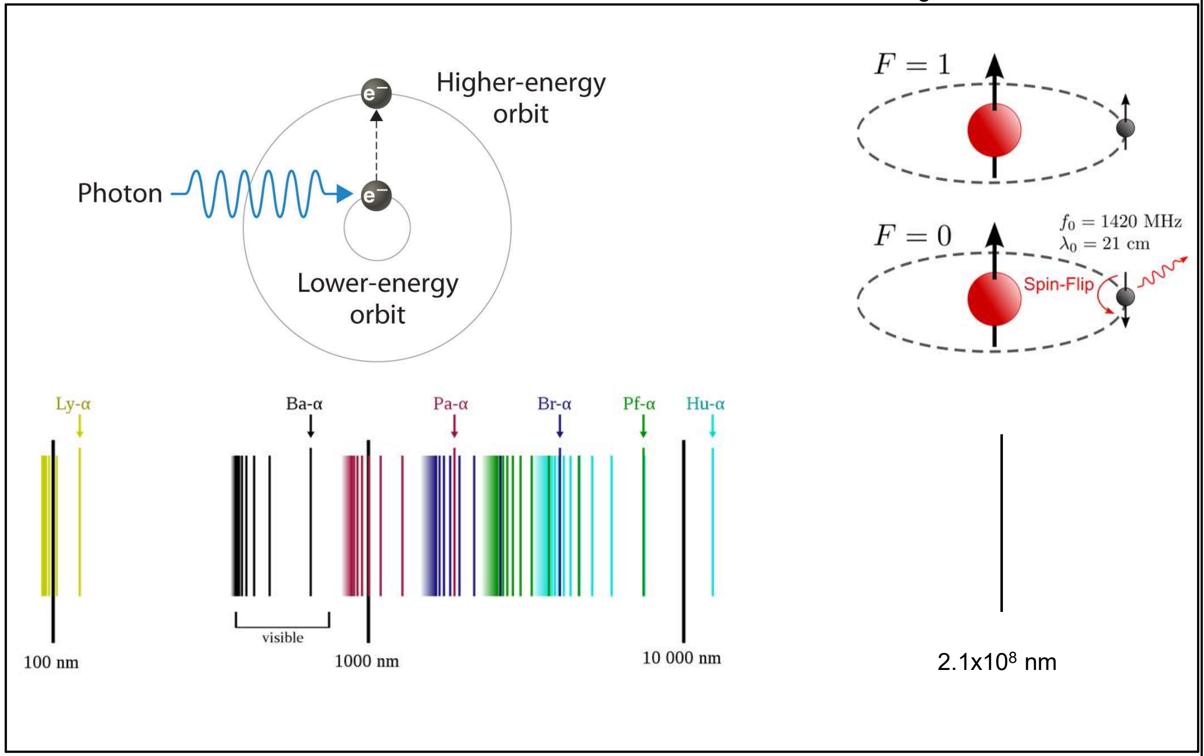
1- Observations of Dark matter in cosmology and astrophysics :
characteristics of Dark matter

3- What is Dark Matter made of ?

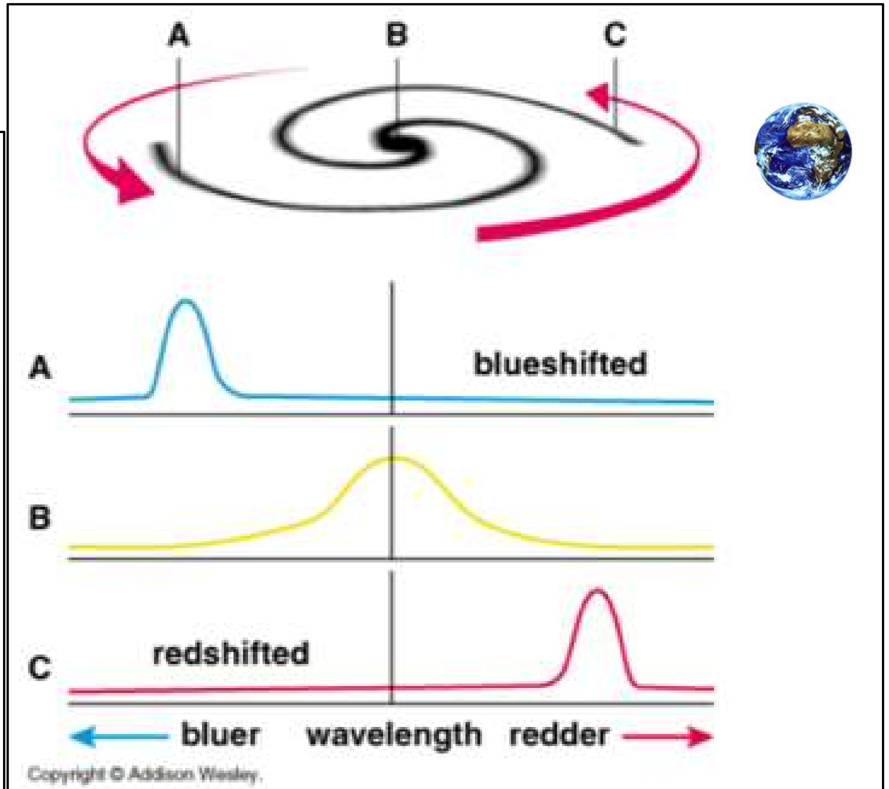
Galaxy rotation curve

- Well-known spectral lines → Doppler shift → velocity curve of stars

Hydrogen spectral lines (f_0)



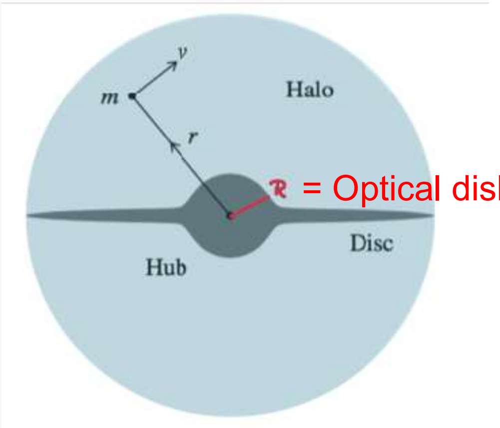
Galaxy rich in Hydrogen gaz



$$\Delta f = \frac{\Delta v}{c} f_0$$

Galaxy rotation curve

❑ **Well-known spectral lines → Doppler shift → velocity curve of stars**

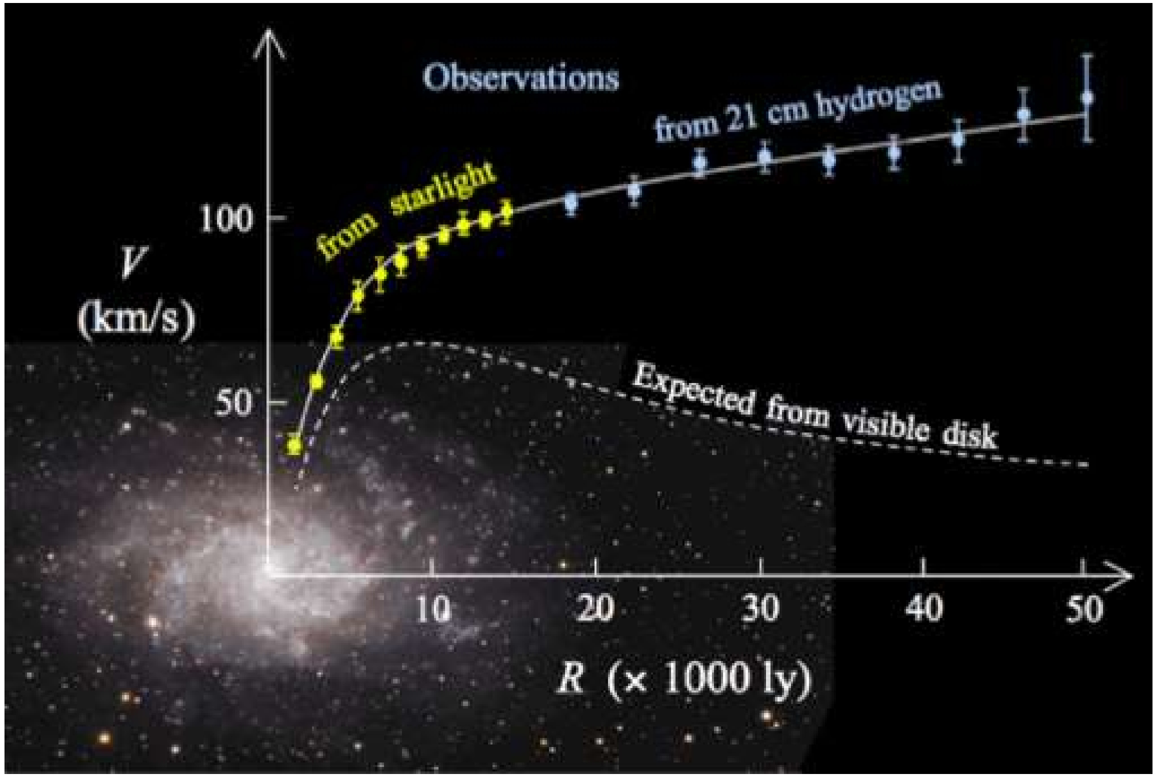


Prediction: $\frac{mv^2}{r} = \frac{mM(r)G}{r^2} \rightarrow v = \sqrt{\frac{GM(r)}{r}}$

Bulk: $r < R$: $M(r) \propto r^3 \Rightarrow v \propto r$ ✔

Disk: $r > R$: $M(r) = const \Rightarrow v \propto \frac{1}{\sqrt{r}}$ X

Observed: $r > R$: $v \sim const \Rightarrow M(r) \propto r$

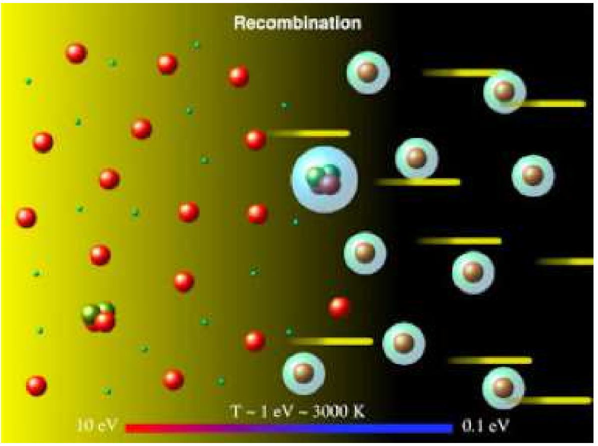


"*Mass, unlike luminosity, is not concentrated near the center of spiral galaxies*" (Vera Rubin)

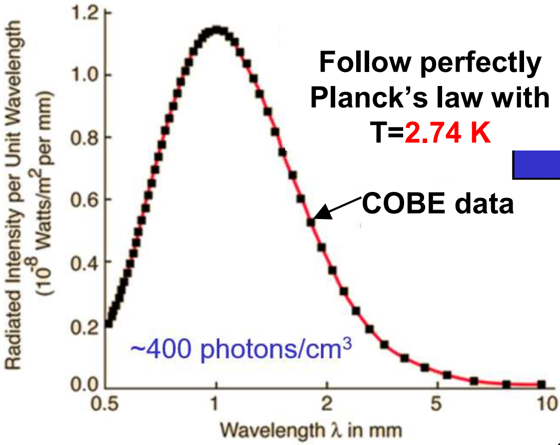
Dark matter halo in the galaxy ?

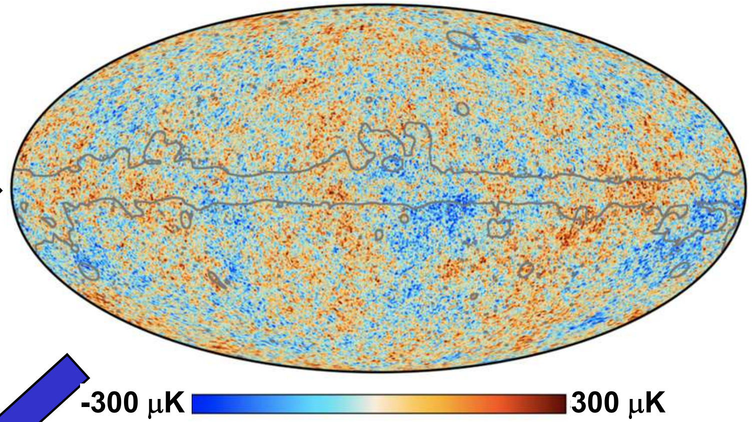
Cosmic microwave background

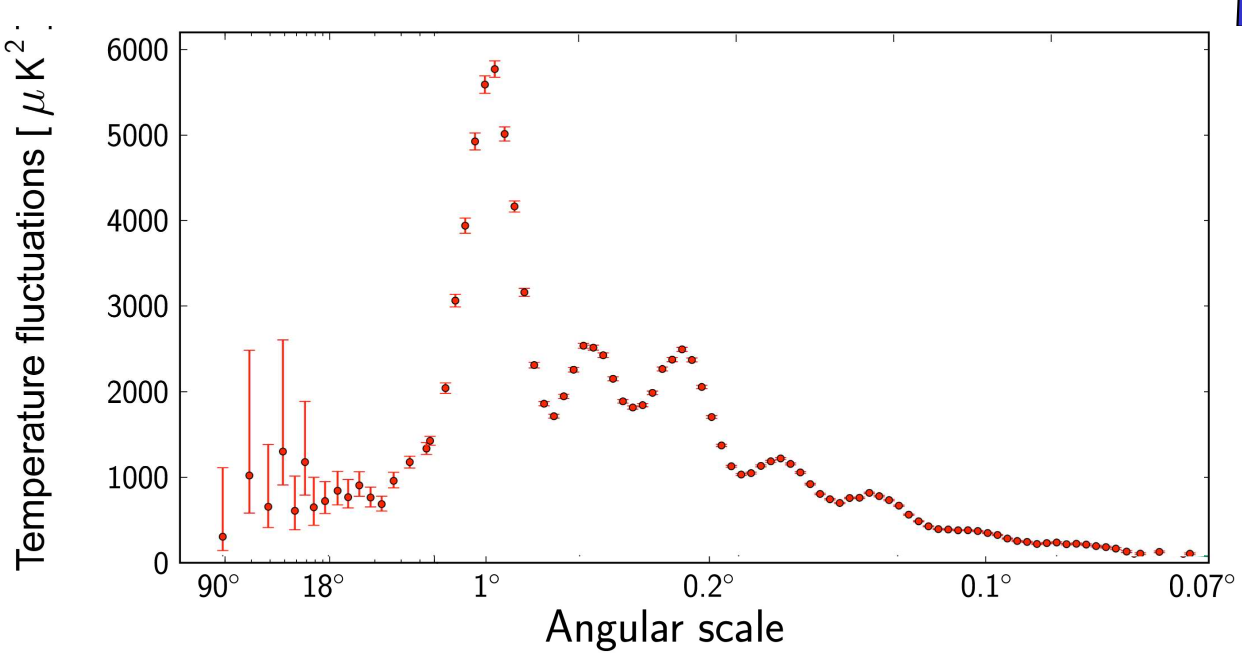
380 000 years after Big Bang



As measured today *13.7 Byr red-shifted*







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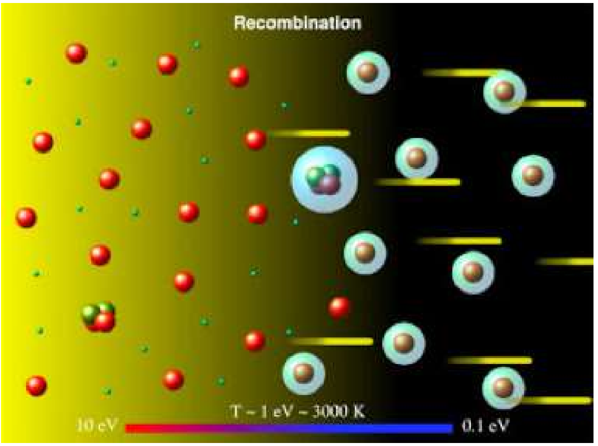
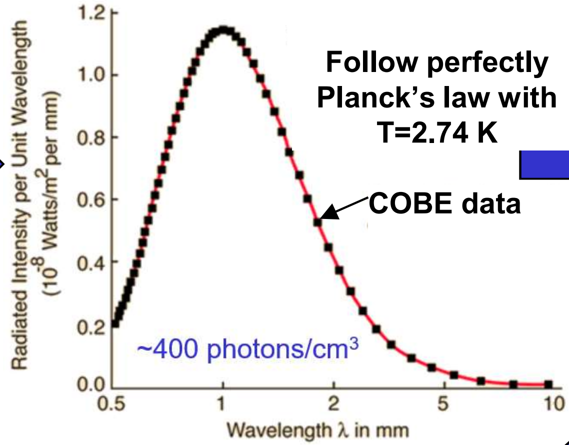
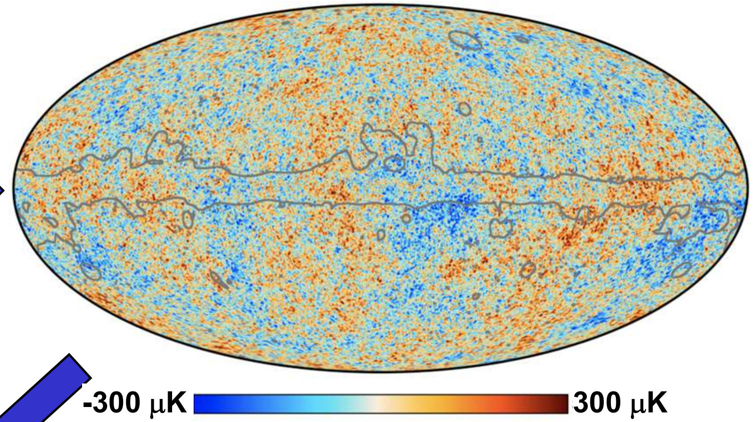
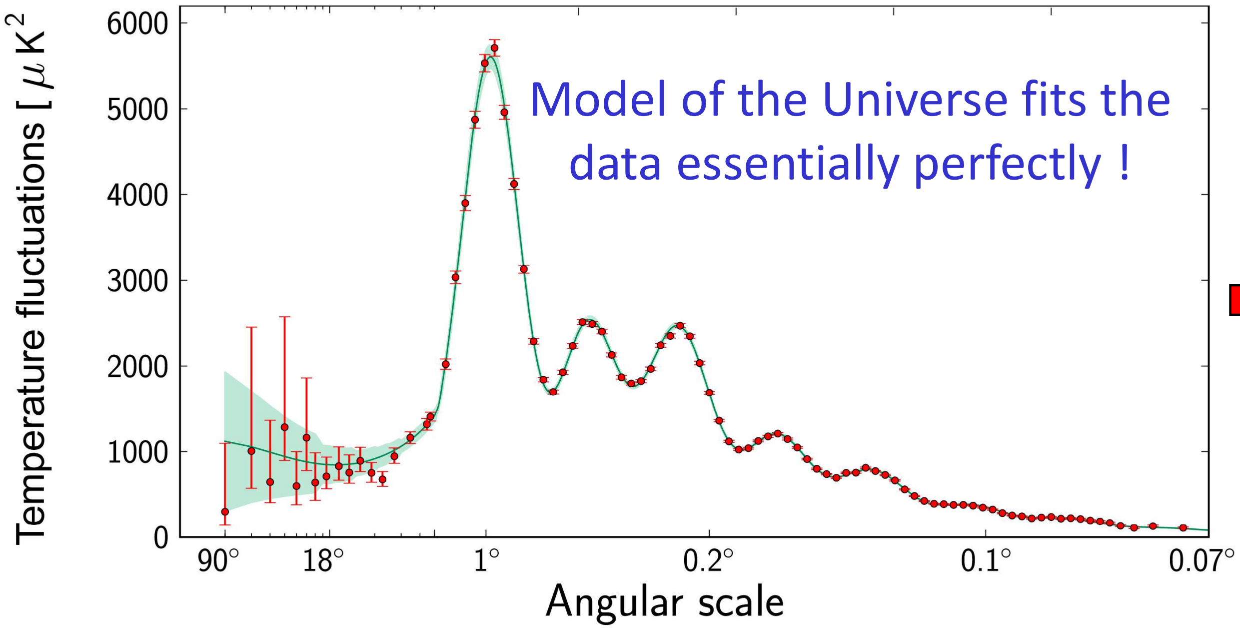


As seen today *13.7 Byr red-shifted*

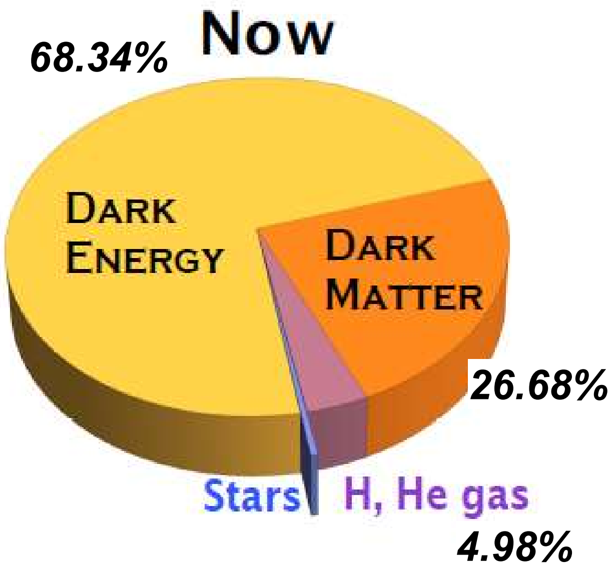


Follow perfectly Planck's law with T=2.74 K



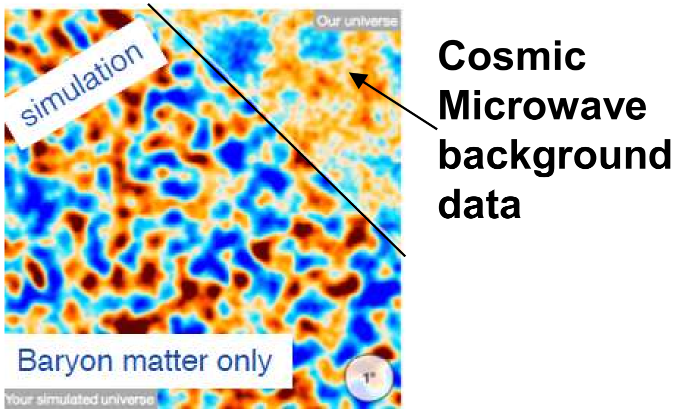


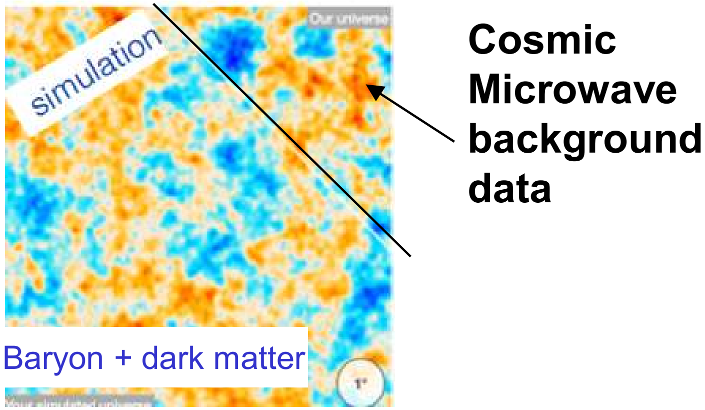
Model of the Universe fits the data essentially perfectly !



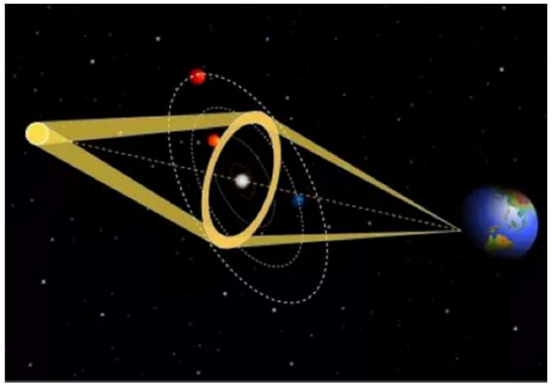
Other proofs

- Galaxy formation, evolution, collision





- Gravitational lensing



- Absence of massive objects made of baryonic matter

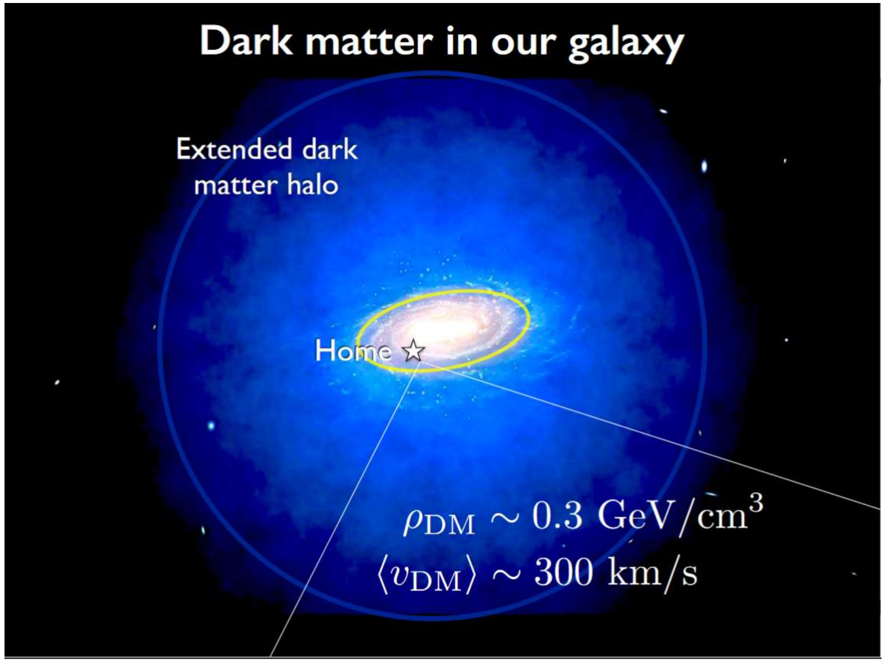
All proofs point towards dark matter

Dark Matter from cosmology

❑ Main characteristics

- Dark matter exists (!)
  - ✓ **Massive**: Interact with gravitational forces
  - ✓ **Form a halo** in our galaxy → favorable for direct exploration → **part II**

- If it is a new particle it should be
  - ✓ **Neutral** (dark)
  - ✓ **Stable** or very long-lived (Big Bang)
  - ✓ **Very weakly interacting with known particles**
  - ✓ **Non relativistic** to form galaxies

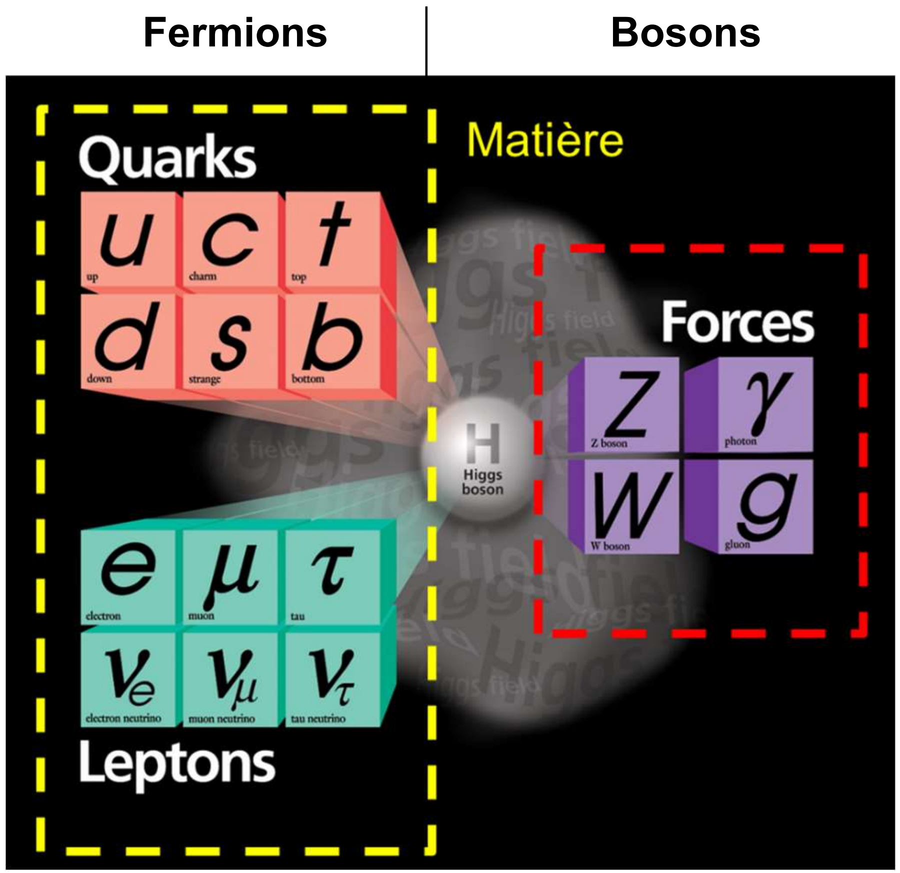


What is the nature of Dark matter ?

Particle physics

- ✓ Massive
- ✓ Neutral
- ✓ Stable
- ✓ Weakly interacting
- ✓ Non relativistic

❑ Elementary particles in a Standard Model (1970's)



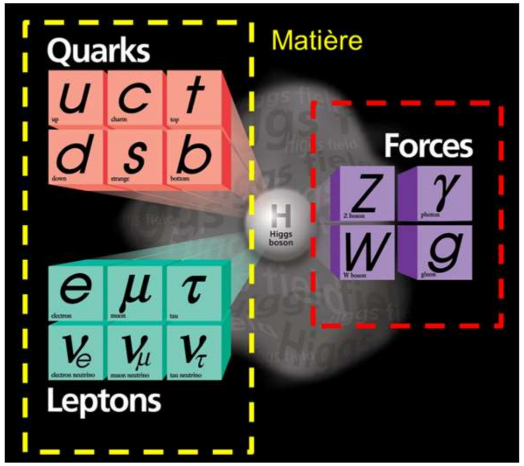
None of them has the required characteristics to be a dark matter particle

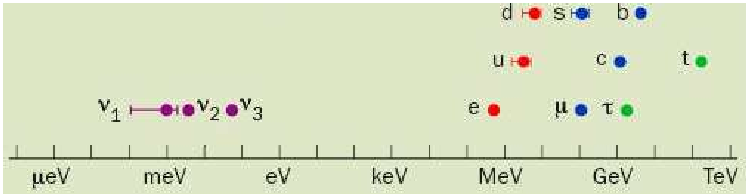
→ Dark Matter calls for New physics

Particle physics

❑ Standard Model status

- **26** free parameters* (21 **measured**) → *5 not measured*
  - ✓ **12 fermion masses (9)** → *ν masses*
  - ✓ **8 weak angles (7)**: 6 mixing (**6**), 2 CP phases δ (**1**) → *ν CP phase*
  - ✓ **1 strong angle (0)**: 1 CP phase θ → Θ_{strong}
  - ✓ **3 coupling constants (3)**: α_{EM}, G_F, α_S
  - ✓ **2 Higgs parameters (2)**: m_H, f_{EWSB}





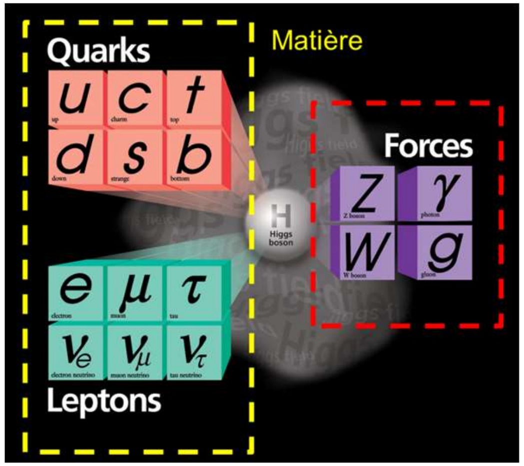
- Some parameters look strange
  - ✓ **m_ν < eV** while m(charged fermion) > 0.5 MeV: why ? → **ν mass origin problem**
  - ✓ **$|\Theta_{strong}| < 10^{-10}$**: why ? → **strong CP problem**
  - ✓ **Higgs Mass**: very high radiative corrections → **gauge hierarchy problem**

We need new particles to solve these problems

* Assuming ν Dirac particles (if Majorana, add 2 other phases)

Particle physics

❑ Standard Model status



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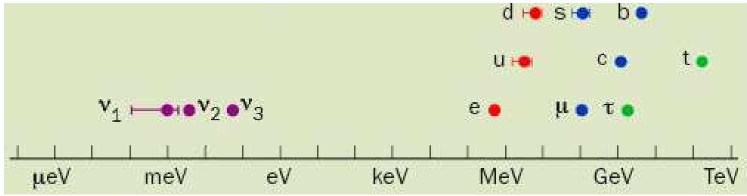


- Some parameters look strange
  - ✓ **m_ν < eV** while m(charged fermion) > 0.5 MeV: why ? → **Sterile Neutrino**
  - ✓ **$|\Theta_{strong}| < 10^{-10}$**: why ? → **Axion**
  - ✓ **Higgs Mass**: very high radiative corrections→**Weakly Interacting Massive Particle (WIMP)**

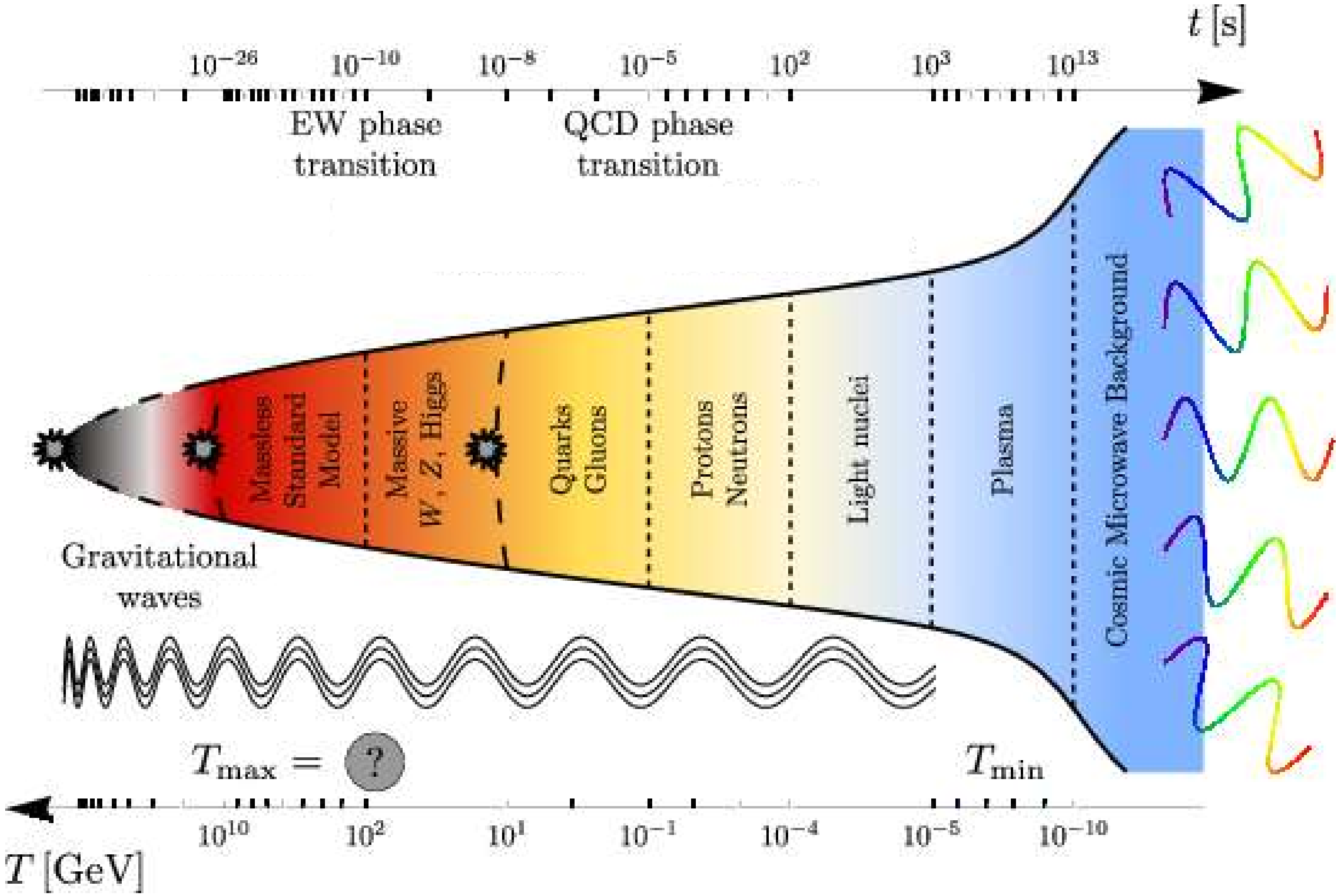
3 candidates fulfilling the dark matter criteria !

- ✓ Massive
- ✓ Neutral
- ✓ Stable
- ✓ Weakly interacting
- ✓ Non relativistic

* Assuming ν Dirac particles (if Majorana, add 2 other phases)

History of the Universe

- Reconciling particle physics and (early) cosmology ?



History of the Universe

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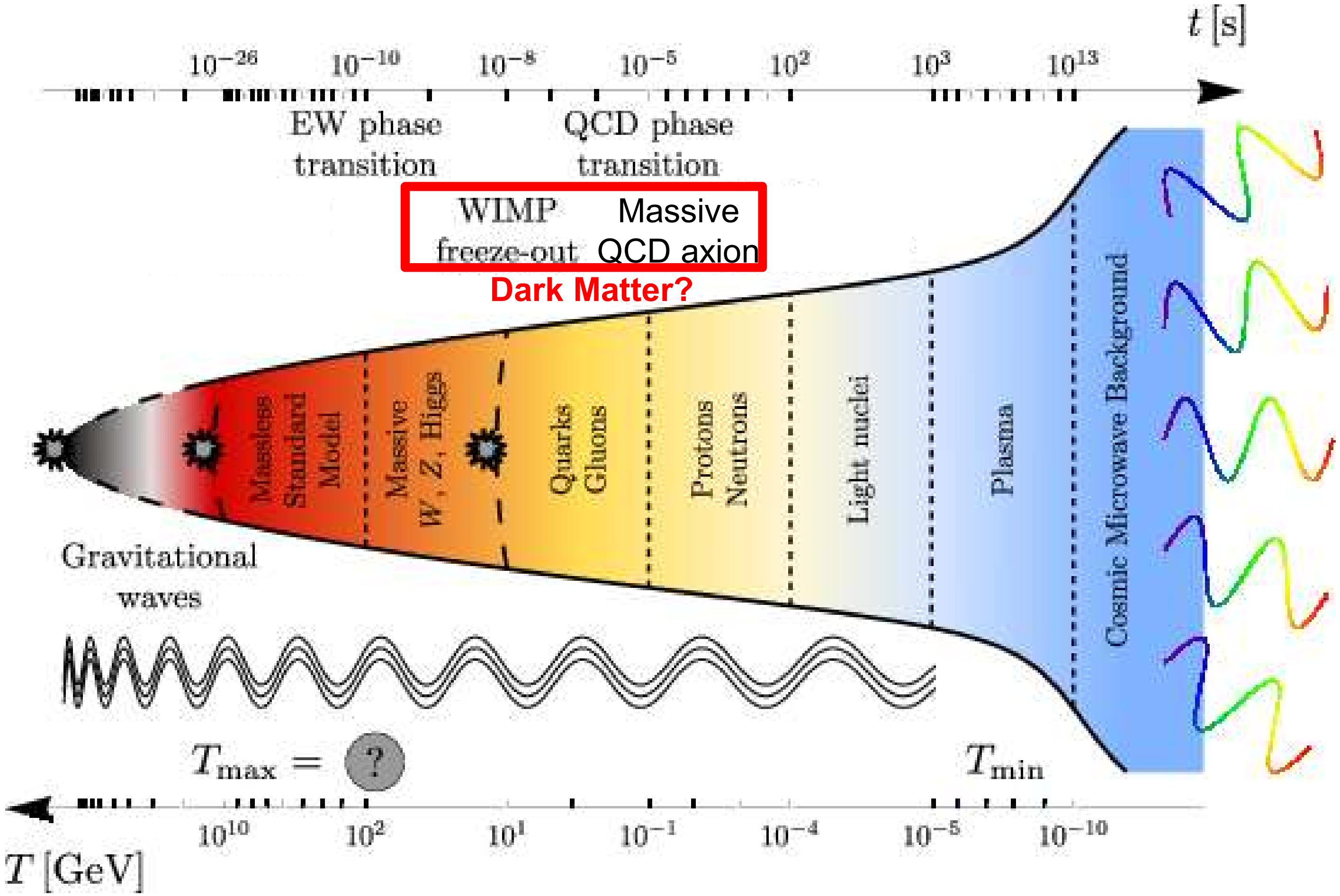
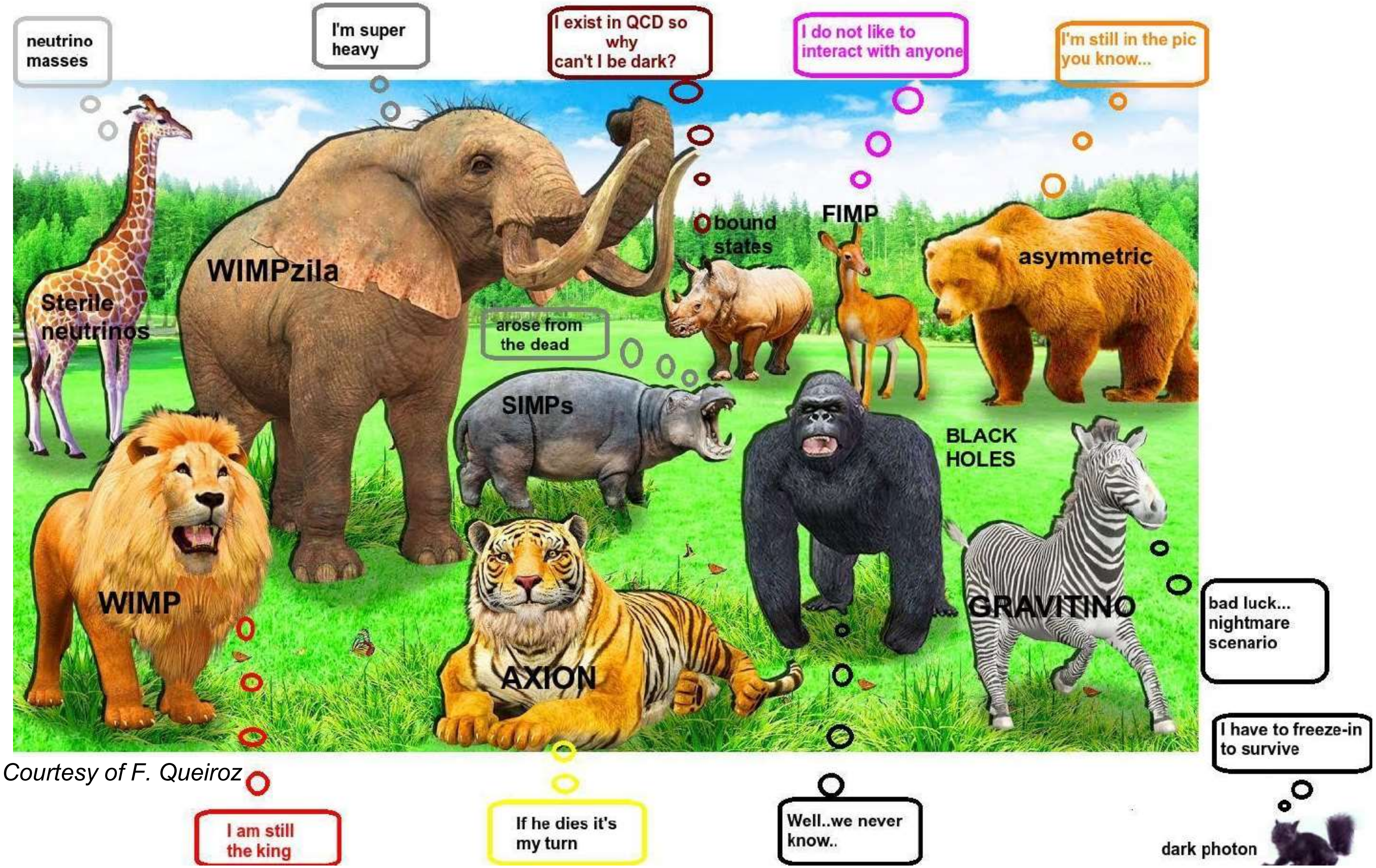
❑ Reconciling particle physics and (early) cosmology ?



Dark Matter appears at the very early instant of the Universe ?

WIMP or axion t <1 s

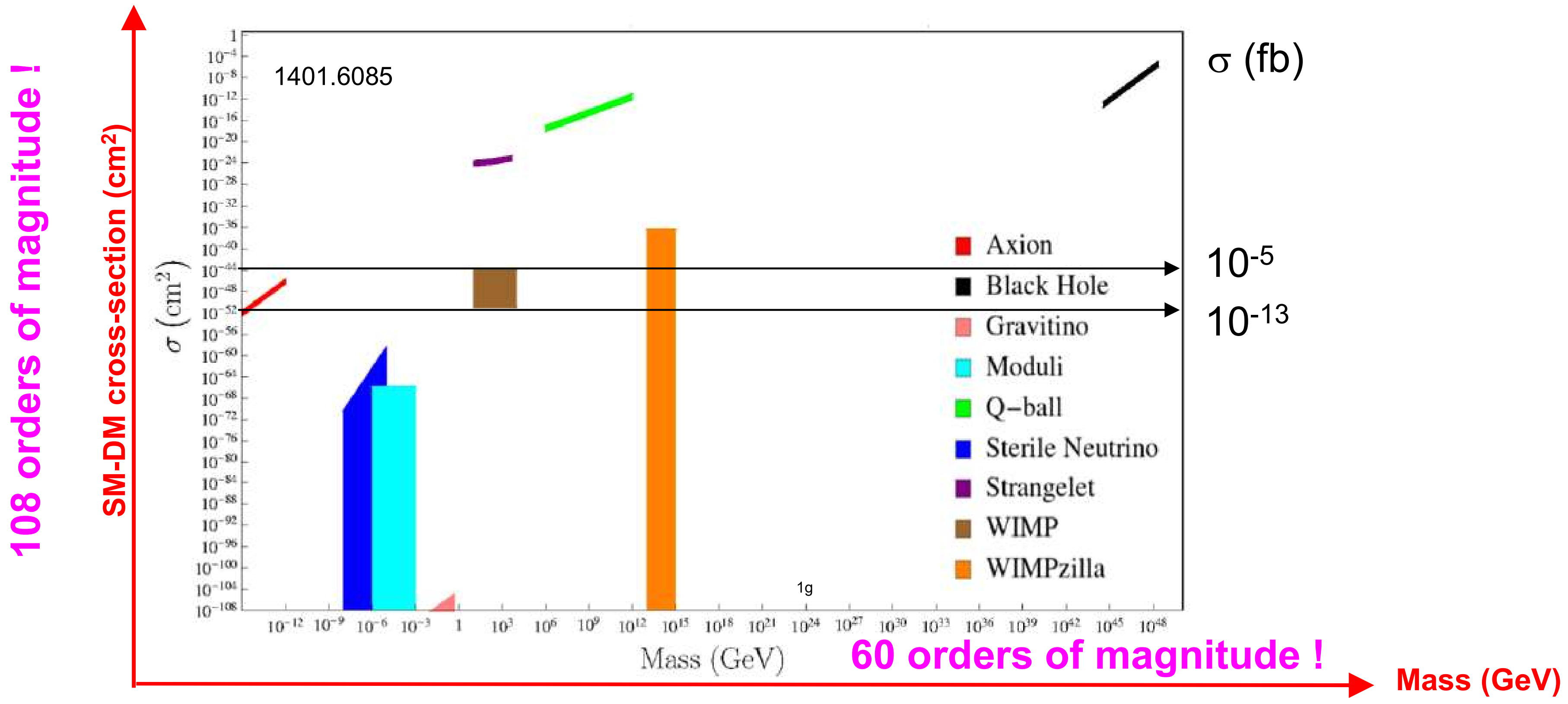
Dark Matter (Part II)



Courtesy of F. Queiroz

Nature of Dark Matter

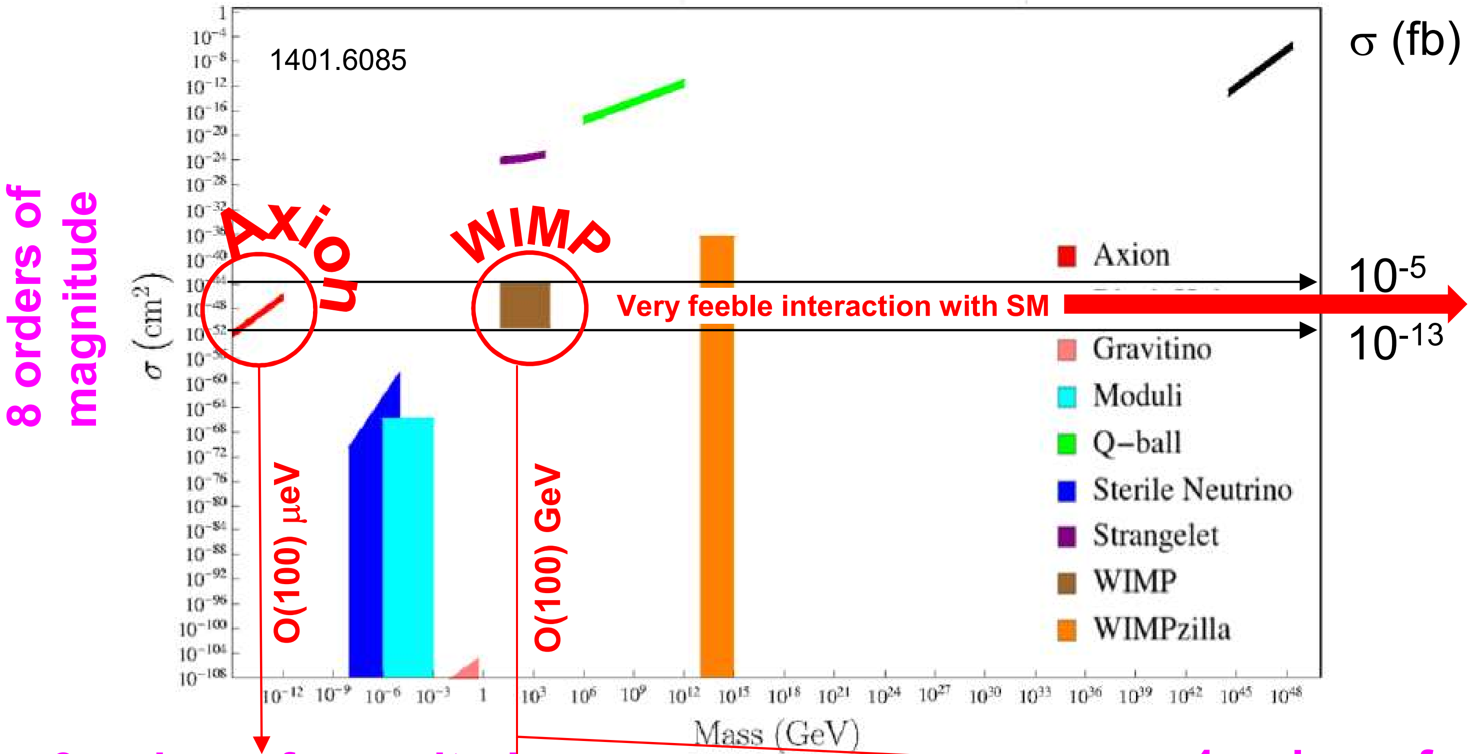
- ❑ **Many dark matter candidates in a gigantic phase space**

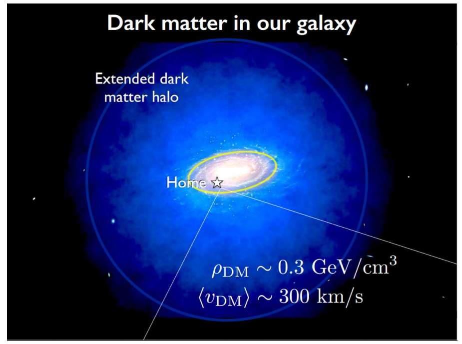


Direct searches are restricted to 2 well-motivated spots: WIMPs, axions

Nature of Dark Matter

❑ Experimental challenges of direct searches





… balanced the abundance of DM particles* in the galaxy halo → 0.3 GeV/cm^3 moving at v=10^{-3}c wrt earth

*produced in very early Universe

3 orders of magnitude

- O(10^{12})/cm^3 ~ gaz → high occupancy
- Tiny mass & interaction → **very feeble signal**

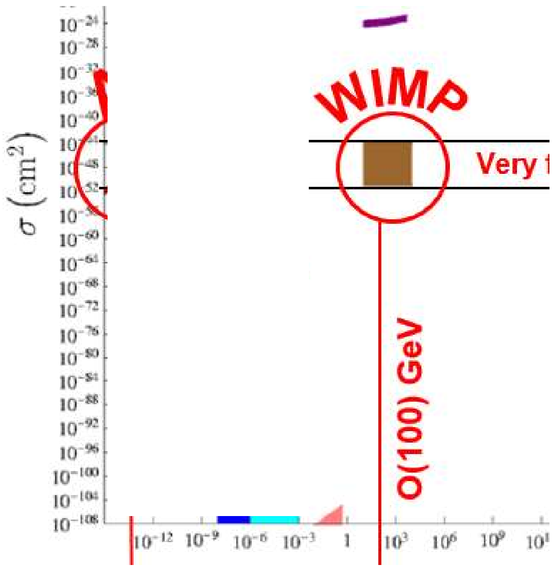
➔ **Boost the signal, very low background**

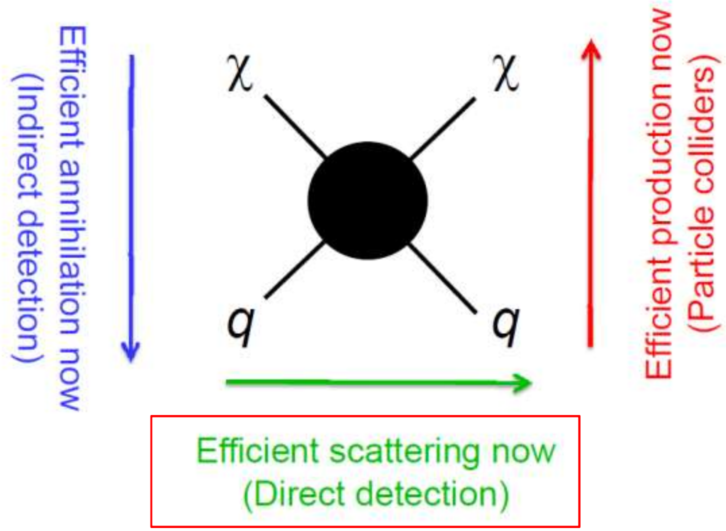
4 orders of magnitude

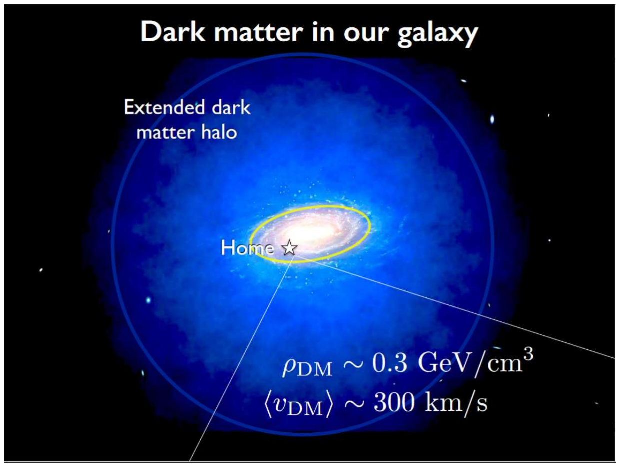
- High mass → visible signal
- O(10^{-3})/cm^3 → **low occupancy** (1 / coffee mug)
- Large detector → **background under control**

➔ **Large volume, very low background**

Direct detection of WIMP







$\chi \rightarrow \gamma$

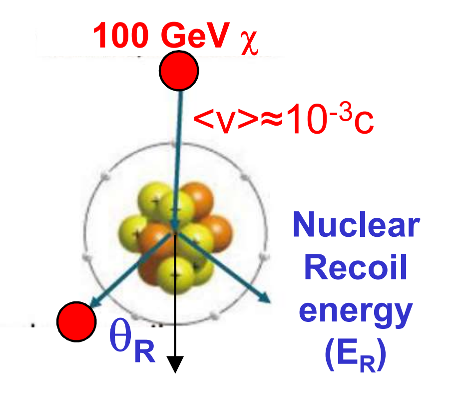
Dark Matter → Detectable Light

WIMP Detection

❑ Event rate expected in the detector

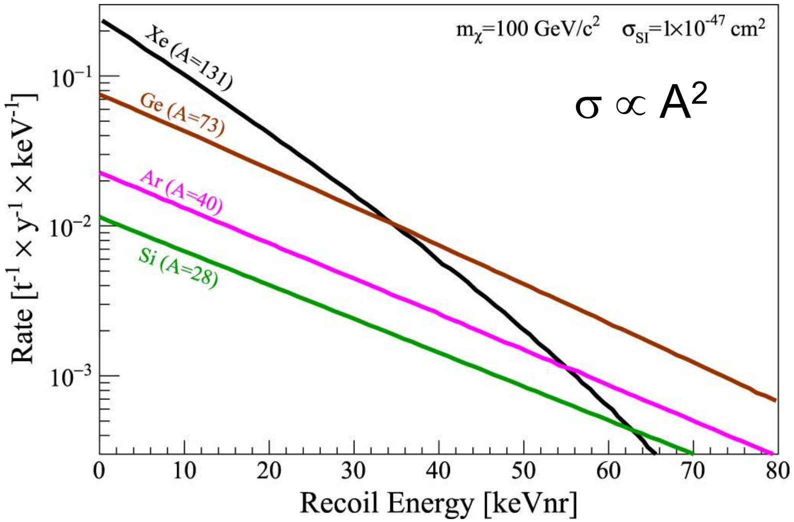
- Galactic halo WIMP elastically scatters on a target nucleus (Xe, Ar, Ge, Na)

Elastic scattering



$$E_R = \left(\frac{m_\chi m_A}{m_\chi + m_A}\right)^2 \frac{v^2}{m_A}(1-\cos\theta_R)$$

$\langle E_R \rangle \approx 40$ keV



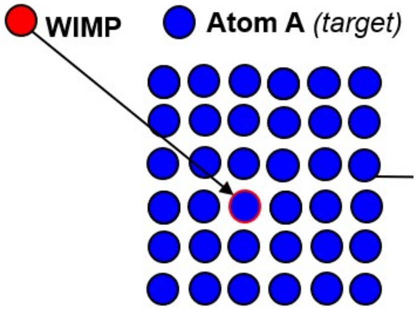
40 keV is very very low : 6.4 10^{-15} J !

- For a detector filled with 1 ton of Ar, taking data during one year and $\sigma_{\chi N}=10^{-47}$cm^2, we get **R ≈ 1 evt / (ton.year)**

Very low number of event expected per year !

WIMP Detection

- ❑ **How to measure the nuclear recoil energy ?**



WIMP Detection

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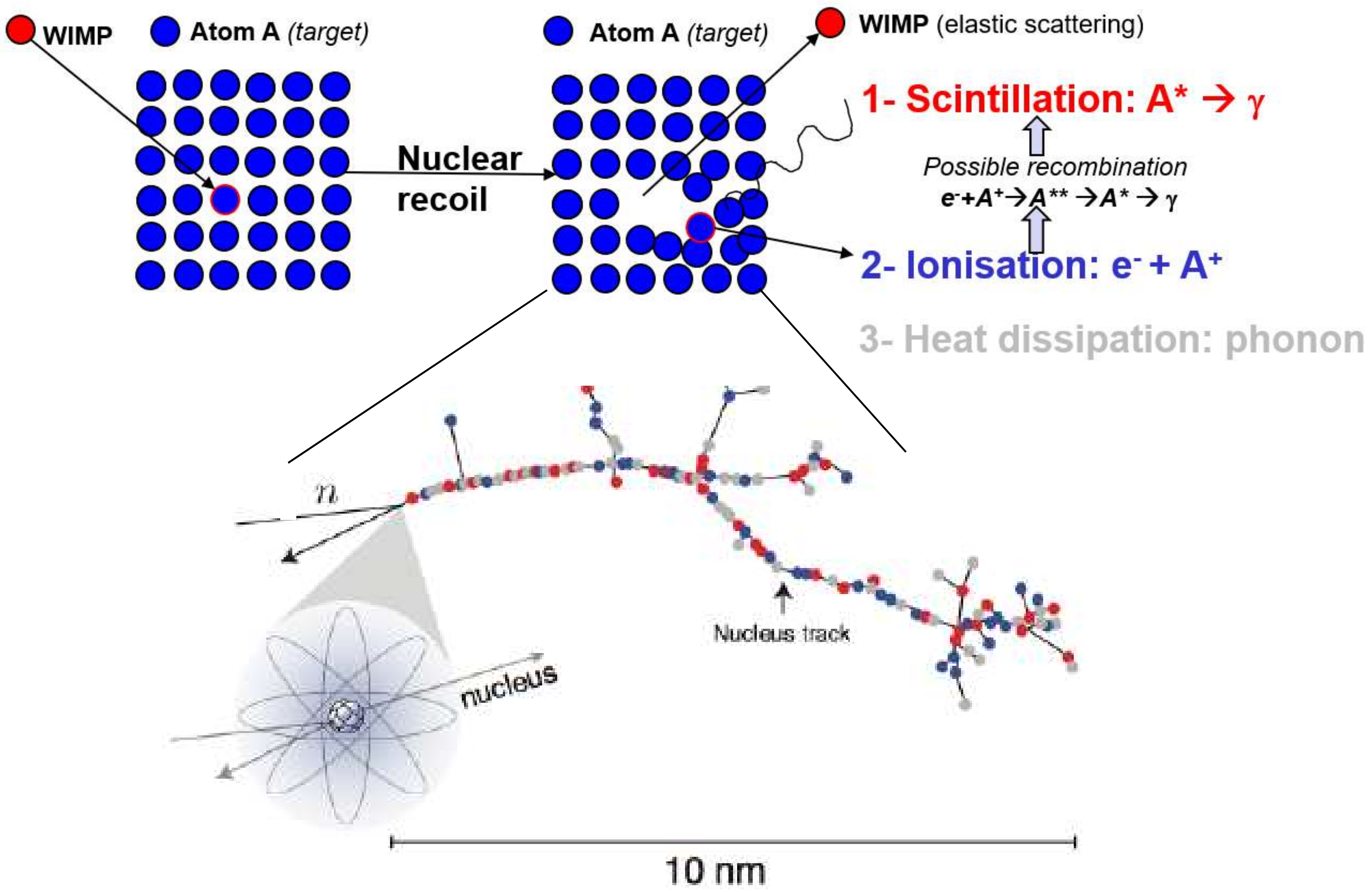
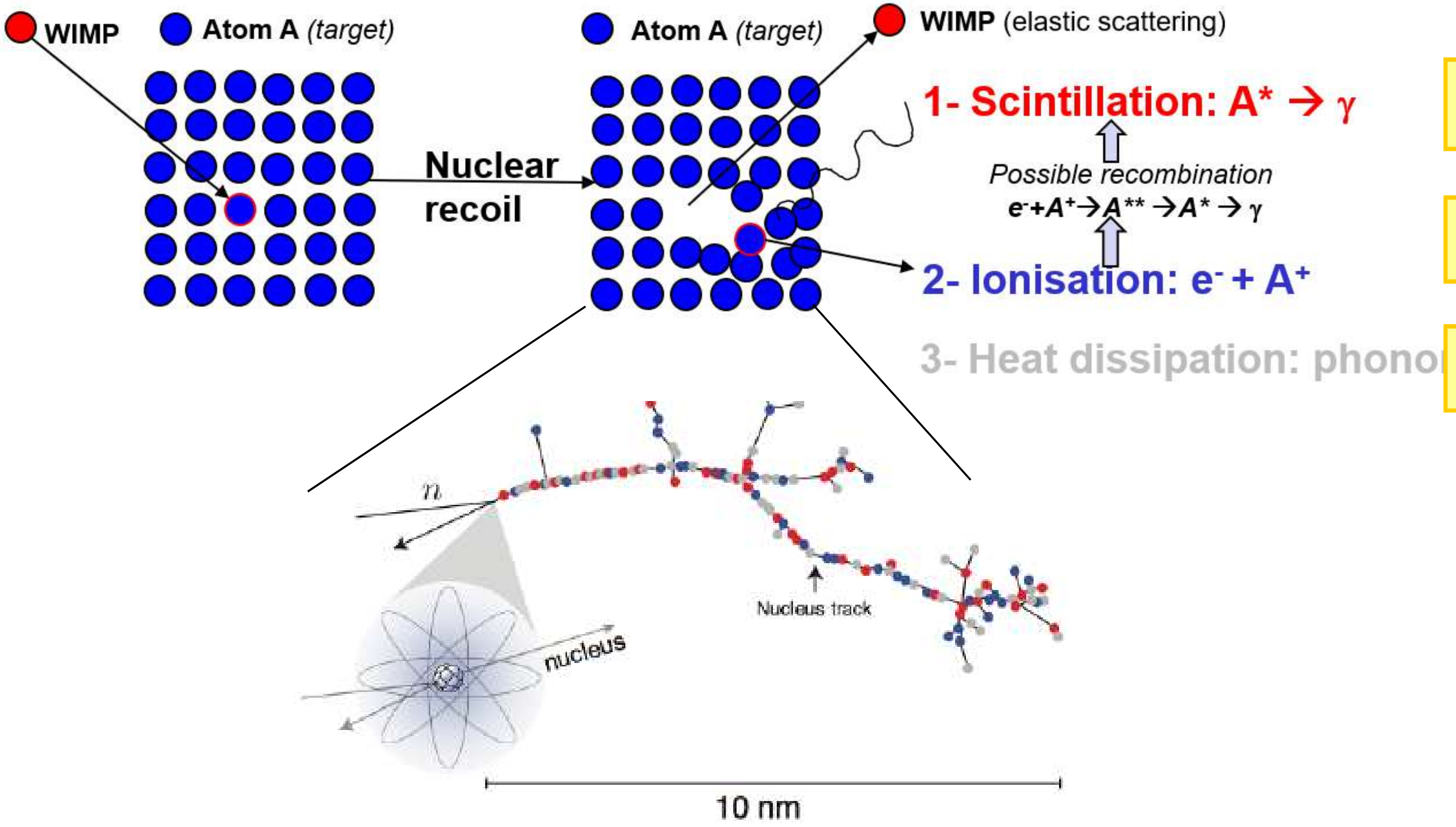


WIMP Detection

- How to measure the nuclear recoil energy ?

Exp. constraints



PhotoMultipliers *(single γ)*

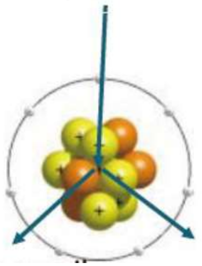
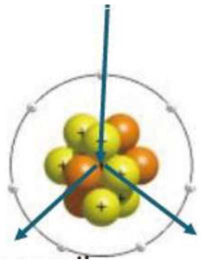
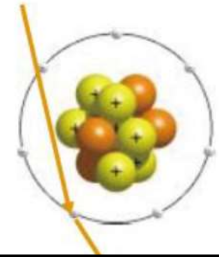
High Electric Field *(kV/cm)*

Very low temperature *(mK)*

WIMP search rich in experimental challenges

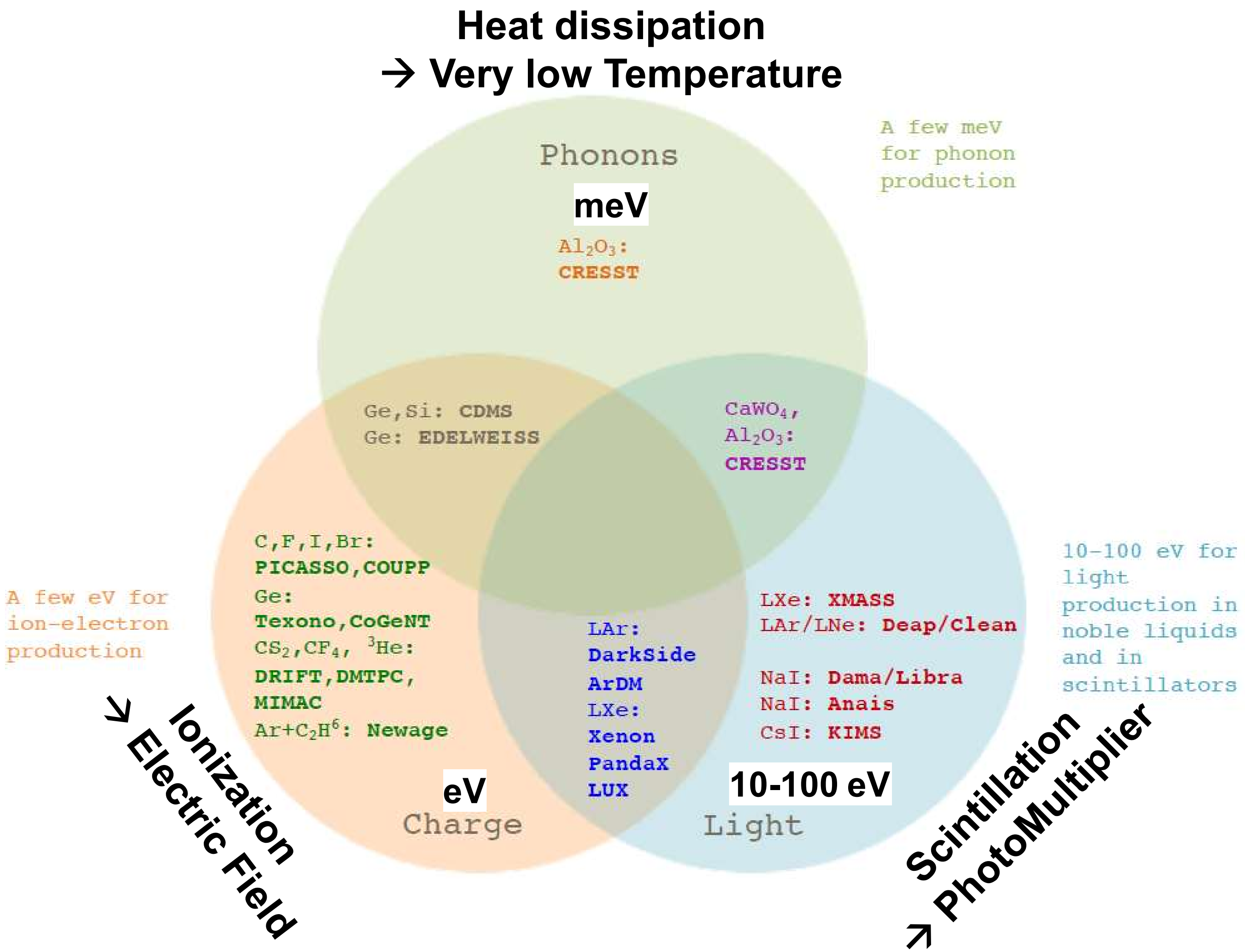
WIMP Detection

❑ Background and its mitigation

	GeV WIMP 	MeV Neutron  100 keV Gammas / Electrons 
Sources	Galactic Halo	✓ Cosmic rays and cosmogenic isotopes ✓ **Natural** (^{238}U, ^{232}Th, ^{235}U, ^{222}Rn) and **anthropogenic** (^{85}Kr, ^{137}Cs) radioactivity ✓ Neutrinos (solar, atmospheric, supernovae !)
Detector constraints	✓ Very low background ➔ careful material selection, **shielded** detector ✓ Low energy detection threshold ➔ low **noise** electronics ✓ Very large volume ➔ **scalable** technologies	

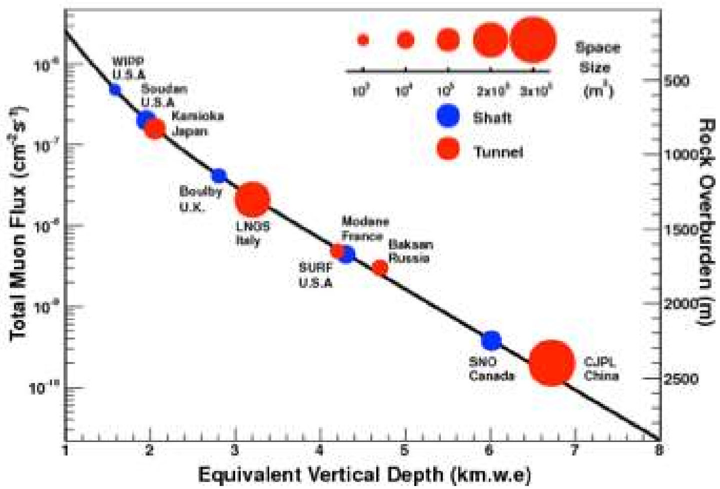
WIMP Detection

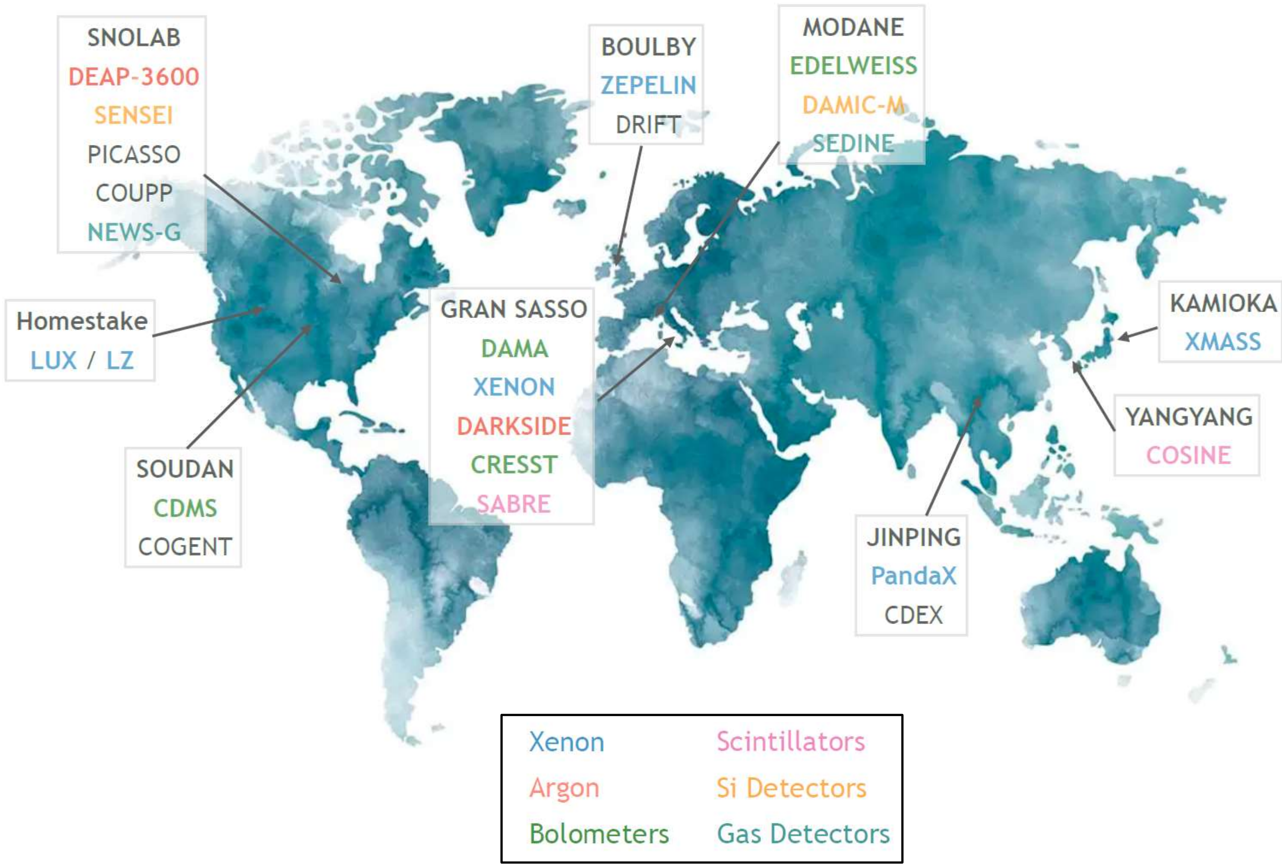
❑ **Detector trying to combine two signals** (higher background rejection)



WIMP Detection

- All experiments located in deep (>0.5 km) underground laboratories



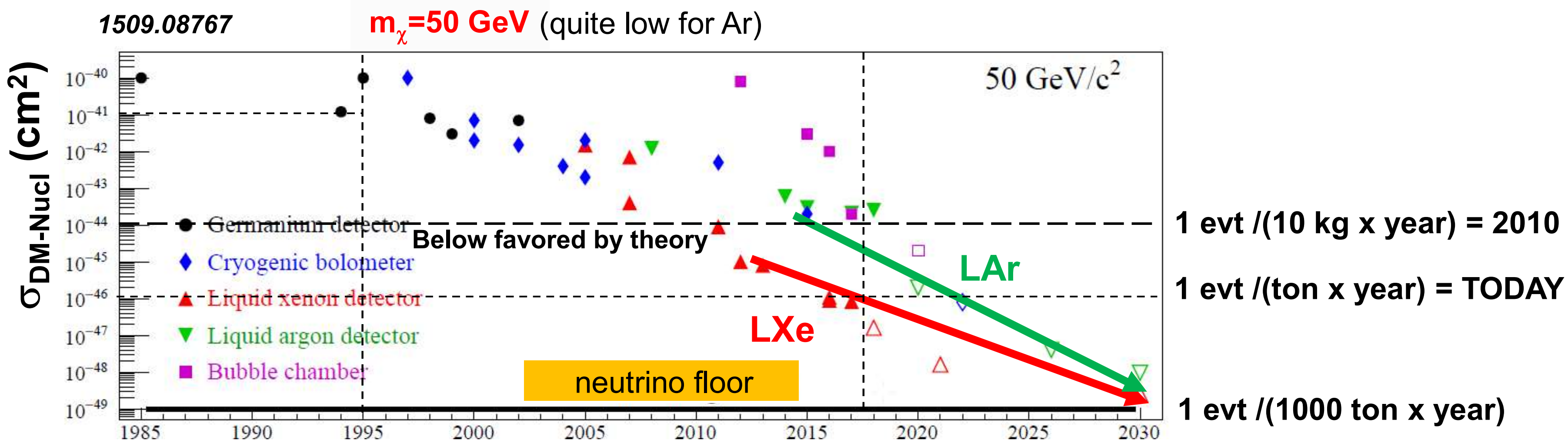


Very high scientific competition !

Status of WIMP search

❑ Direct detection of Dark Matter WIMPs

- Since 30 years, try several technologies :



Leading techno: Ge Bolo LXe LXe+LAr Year

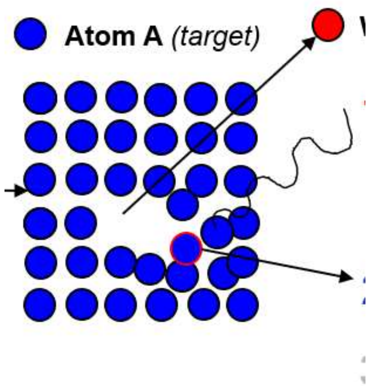
- Gained 5 orders of magnitude in sensitivity in last 20 years
- Next decade: reach irreducible background (neutrino elastic scattering)

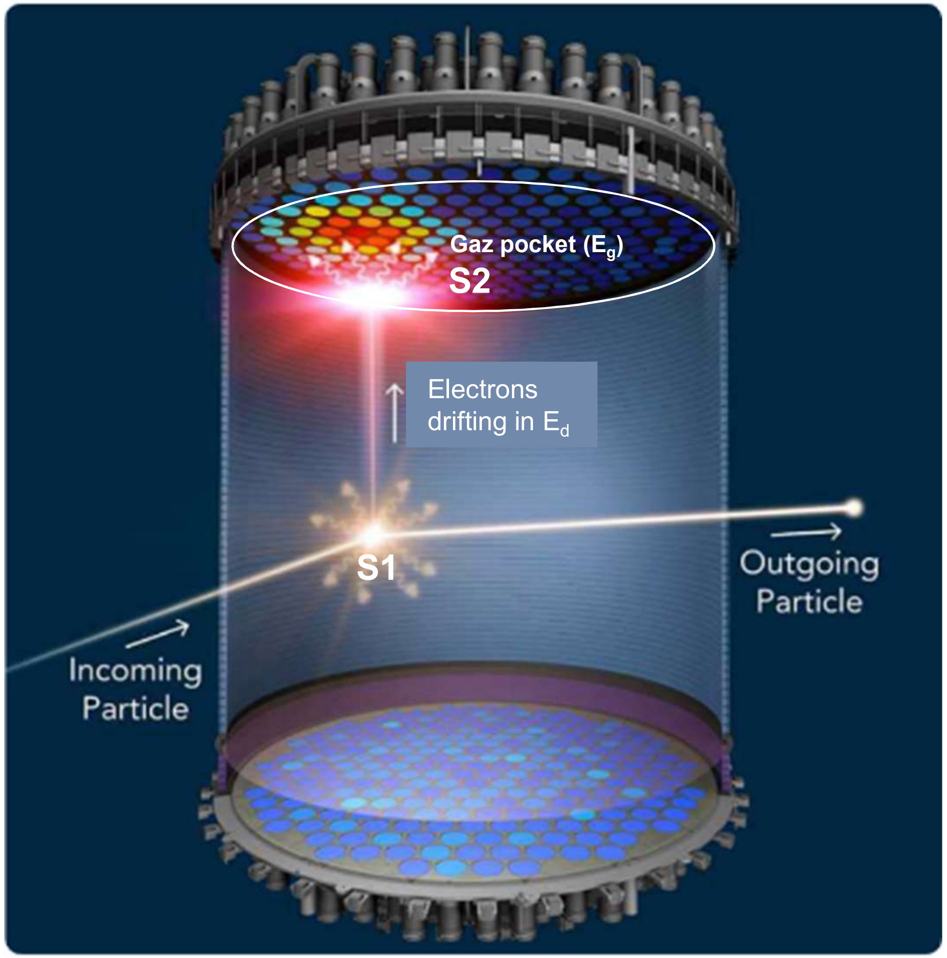
Liquid Xe / Ar dual phase TPC are now leading the race

[Time Projection Chamber]

Status of WIMP search

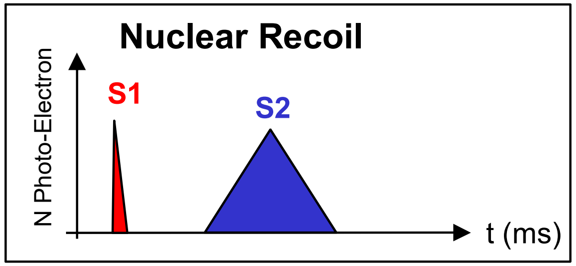
- **How does the "king of the WIMP research" works ?**
  - Combining two signals: prompt **scintillation** (S1) and delayed **ionization** (S2)





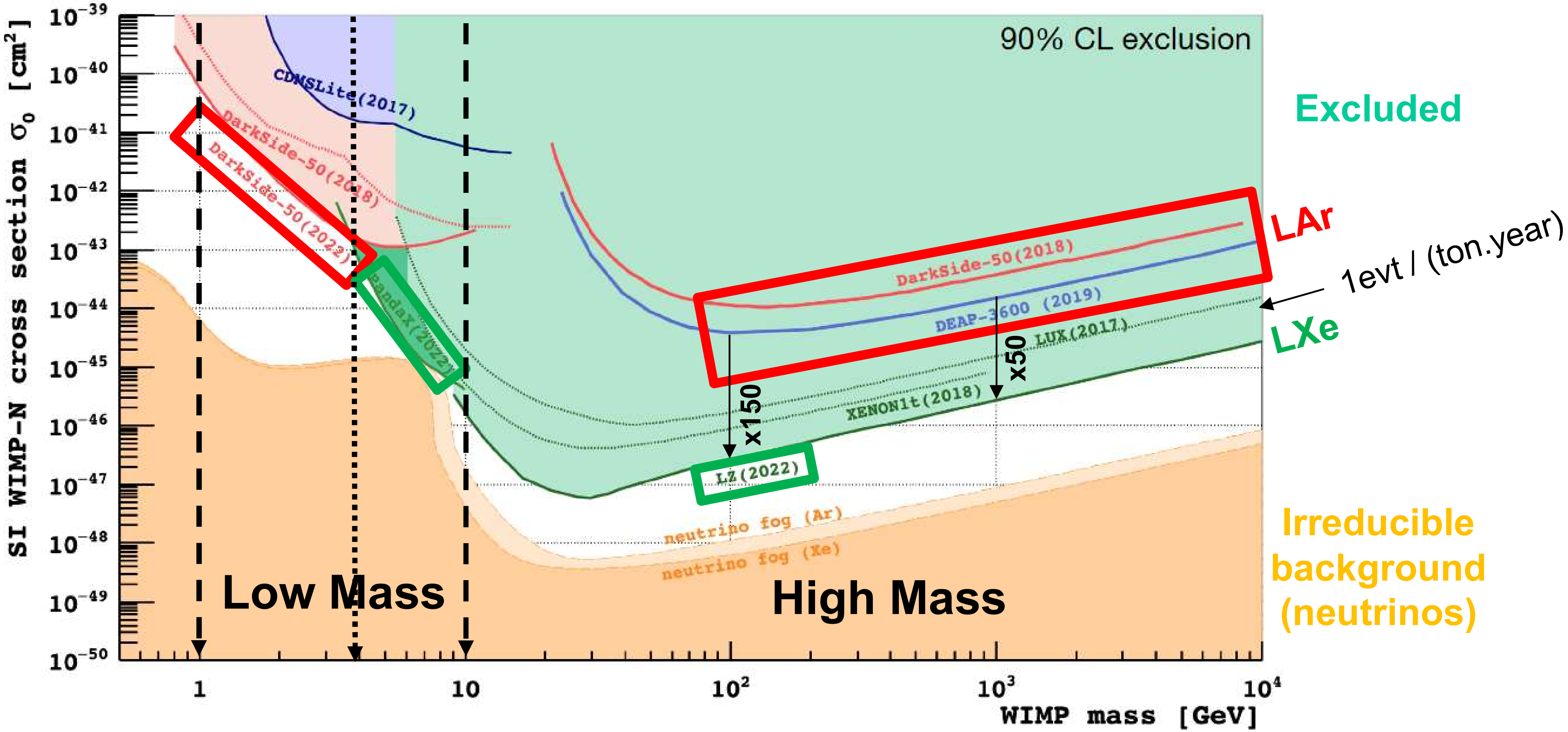
E_g~3kV/cm

E_d=200 V/cm



Status of WIMP search

❑ Direct detection of Dark Matter WIMPs

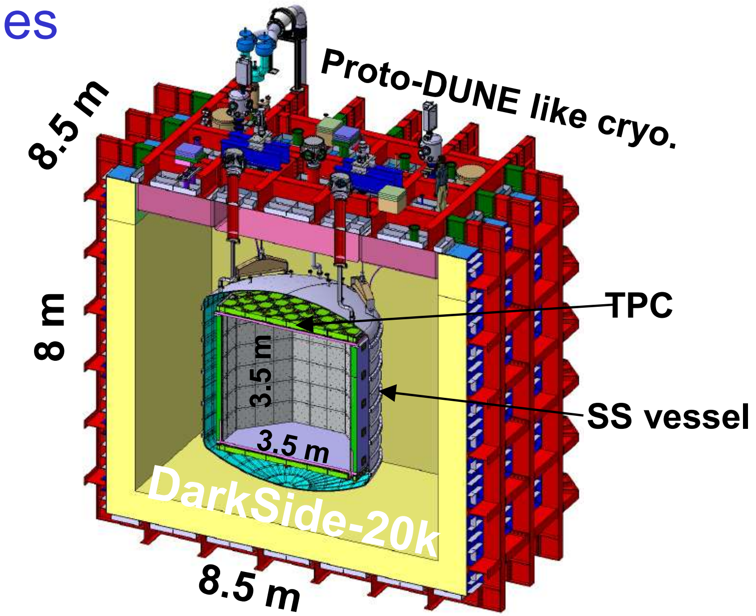


All the white space is well motivated by theory and still to explore !

DarkSide (LAr)

❑ LAr Technology is scalable and mature

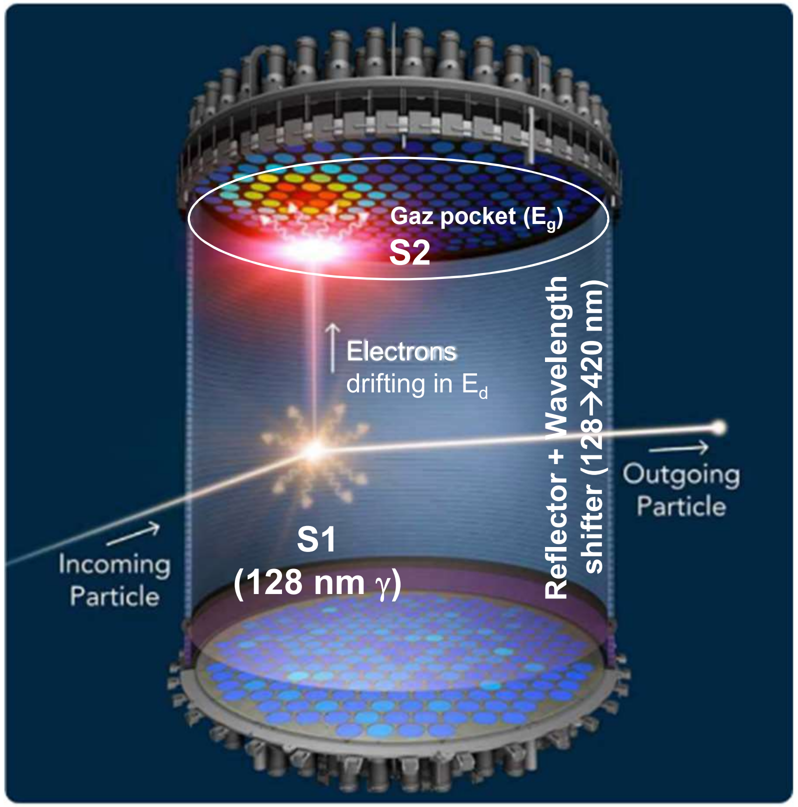
- One world-wide collaboration (GADMC): 300 people
- DarkSide-20k profit from best G1 and G2 technologies



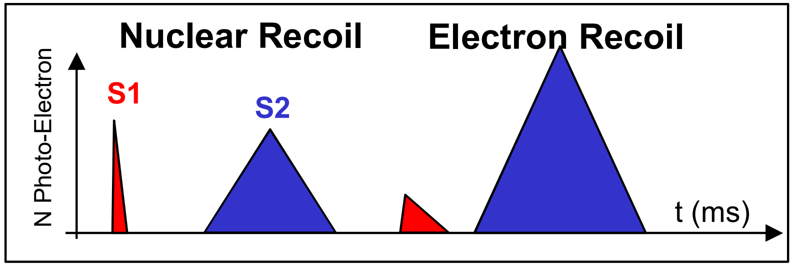
Lab (fid. data)	LNGS (0.05 ton.year)	SNOLab (10 ton.year)	LNGS (200 ton.year)
TPC target	50 kg purified Ar → x70	3.6 t *Atmosph. Ar* → x14	50 t purified Ar
TPC wall	*Stainless Steel*	Acrylic	Acrylic
TPC nb ch.	*38 PMT* → x7	*255 PMT* → x8	200k **SiPM** → 2100 channels
TPC techno	Dual Phase	*Single Phase*	Dual Phase
Veto	*Scint (30 t) + Water (1000 t)* [inner] [outer]	*Water (250 t)*	LAr in vessel (50 t) + **ProtoDUNE** (650 t) [inner] [outer]

DarkSide (LAr)

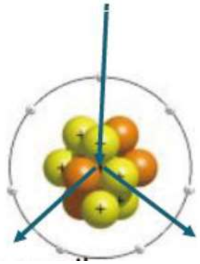
❑ DS-20k can be optimized to be background free



E_d=200 V/cm [E_g~3kV/cm]



GeV WIMP



E_{NR}=1-100 keV

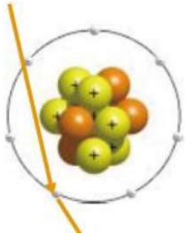
WIMP signal

Nuclear Recoil (NR):
- fast scintillation (6ns)
- few ionization electrons
- large quenching (loss in elastic nuclei collisions)

---

100 keV

Gammas / **Electrons**



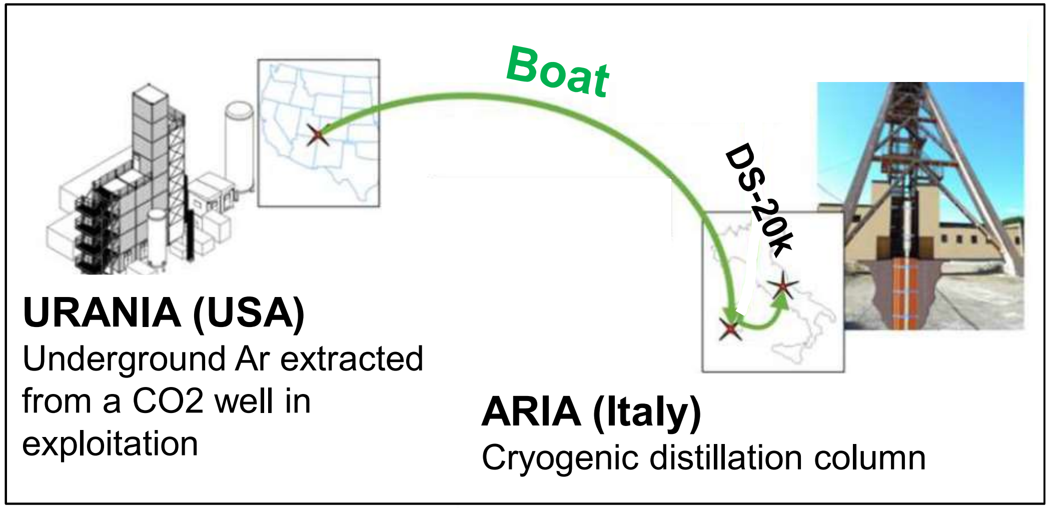
ER bkg ≠ WIMP Signal

Electron recoil (ER):
- slow scintillation (1600 ns >>NR)
- many ionization electrons (>NR)
- no quenching (<NR)

DarkSide (LAr)

❑ DS-20k background removal strategy

1- Purified argon *(depleted in ^{39}Ar cosmogenic argon)*

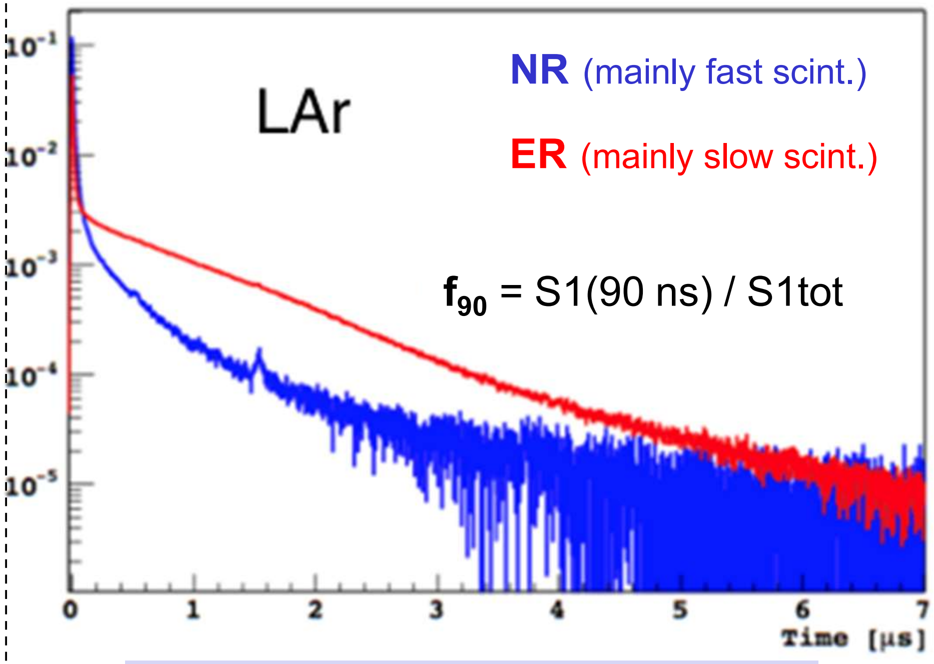


Residual ^{39}Ar activity ~30 Hz in DS-20k TPC

½ of the TPC ER background before PSD

2- S1 pulse shape discrimination

ER rejection measured **$R_{ER}>10^8$ (90% ε_{sig})**

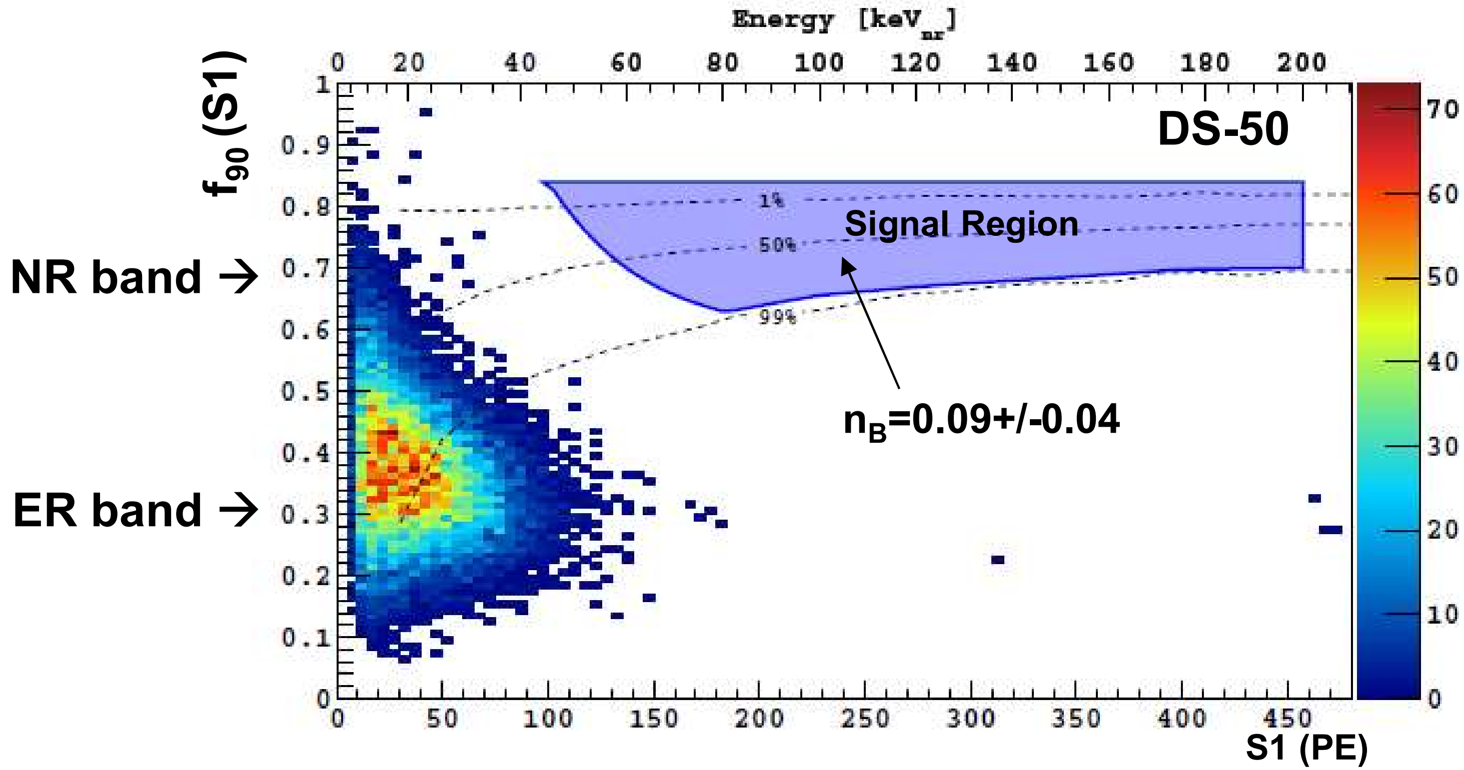


Unique discriminating power
(intrinsic to Ar, not present for Xe)

DarkSide (LAr)

❑ DS-20k overall background

- DS 50 results validates the strategy with **0.05 ton.year**

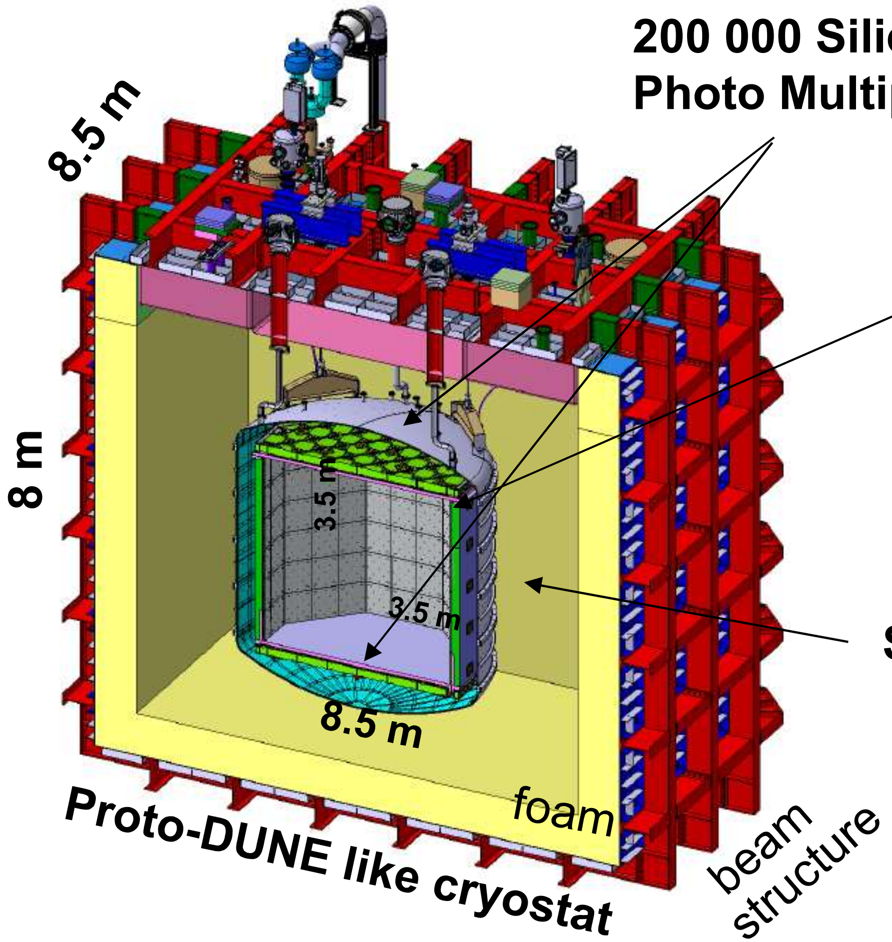


Expect ~0.1 bkg* event in 10 years of running *(200 ton.year)*

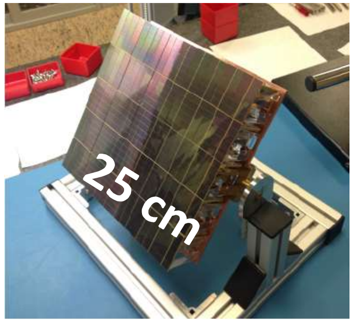
** Note: expect ~3 irreducible evts from ν NR*

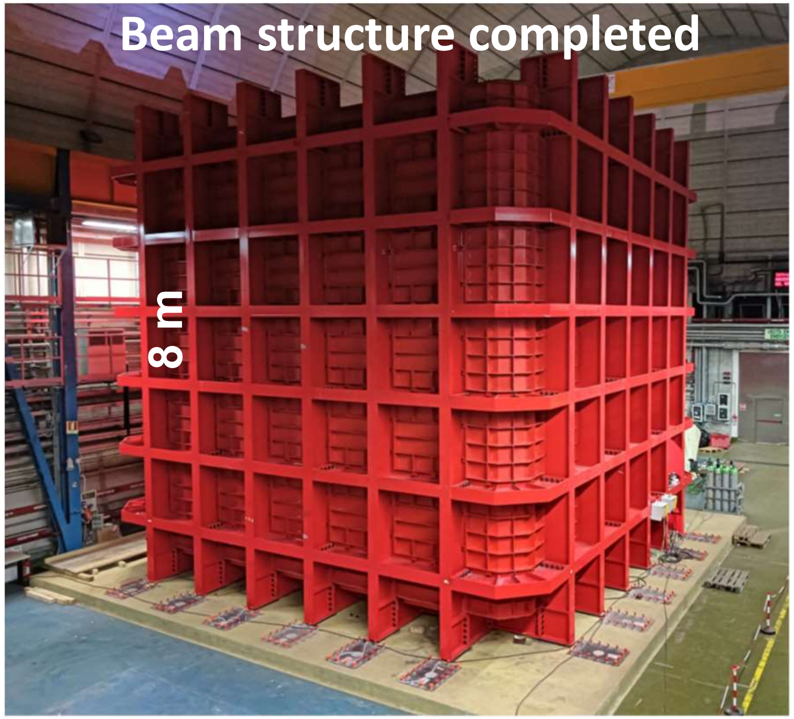
DarkSide (LAr)

❑ **Assembly in Gran Sasso laboratory (Italy)**



400 SiPM grouped in one PDU

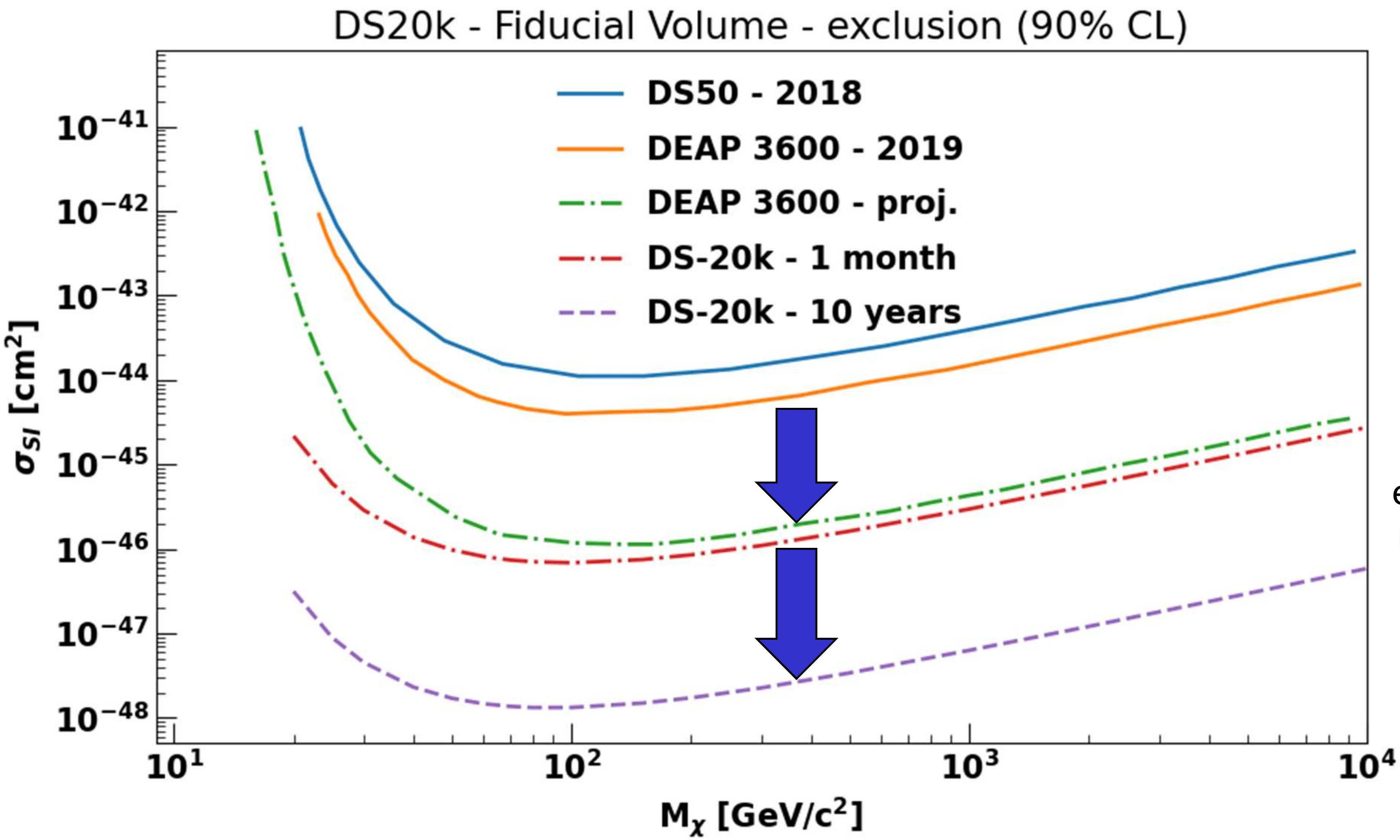




3 years of construction ahead before data daking (2027)

DarkSide (LAr)

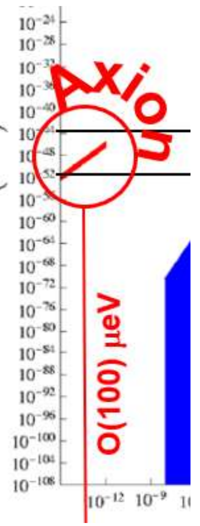
❑ Physics Perspectives

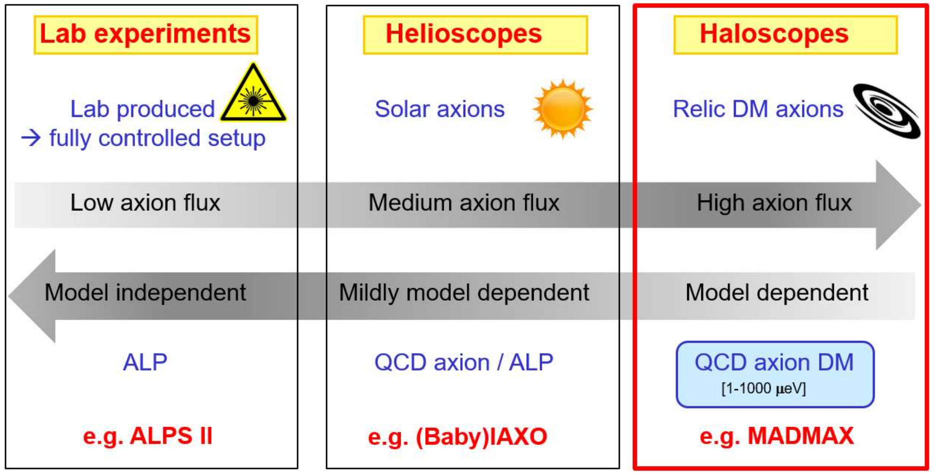


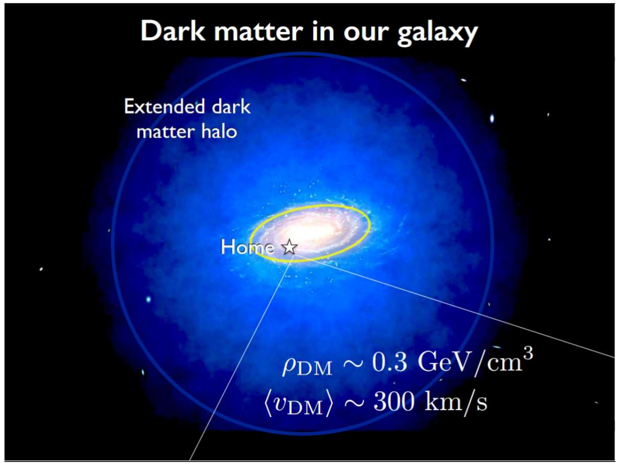
DS-20k needs one day to be the most sensitive LAr TPC

After few years of exploitation it will be most sensitive TPC

Direct detection of axions







a → γ

Dark Matter → Detectable Light

Axion Conversion to E-field

1 eV = 1.6 10^{-19} J, h = 6.6 10^{-34} J.s^{-1}

$\lambda_a^{dB} = h/mv$

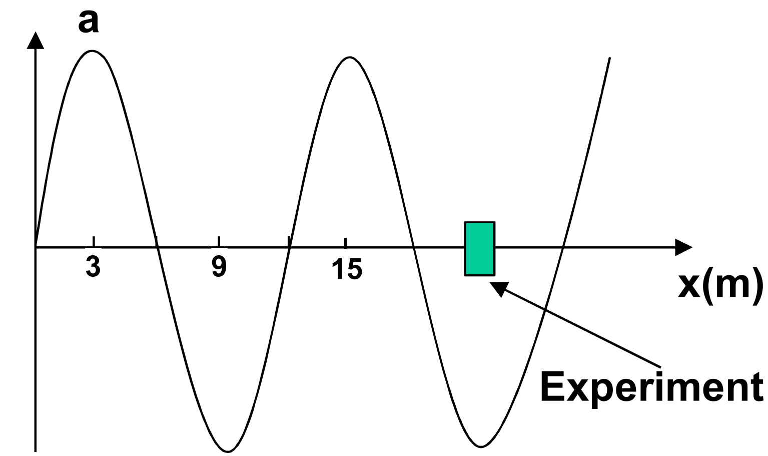
$m_a c^2 = hf_a$, $f_a = m_a c^2/h$

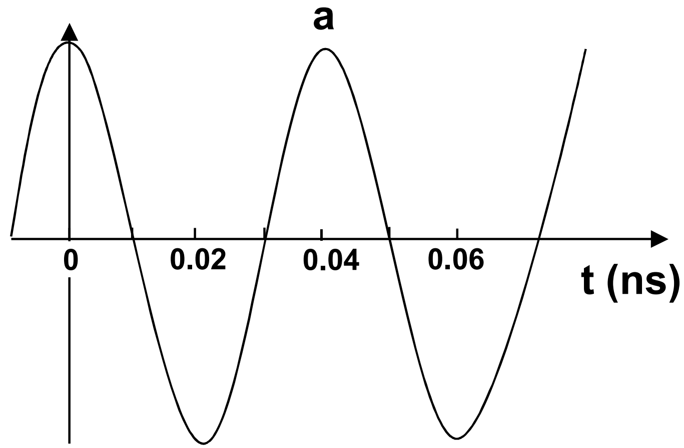
m_a = 100 μeV/c^2 → λ_a = 12 m

→ f_a = 25 GHz

"Invisible" axion

(classical field)





The axion field is not propagating in **space** and is spatially constant in the region of the experiment

The axion field is oscillating in **time**

$a(t) = a_0 \cos(2\pi f_a t)$

$|a_0| = \sqrt{(2\rho_{DM})}/m_a$

Axion Conversion to E-field

$\lambda_a^{Compton} = \lambda_\gamma = c / f_a$

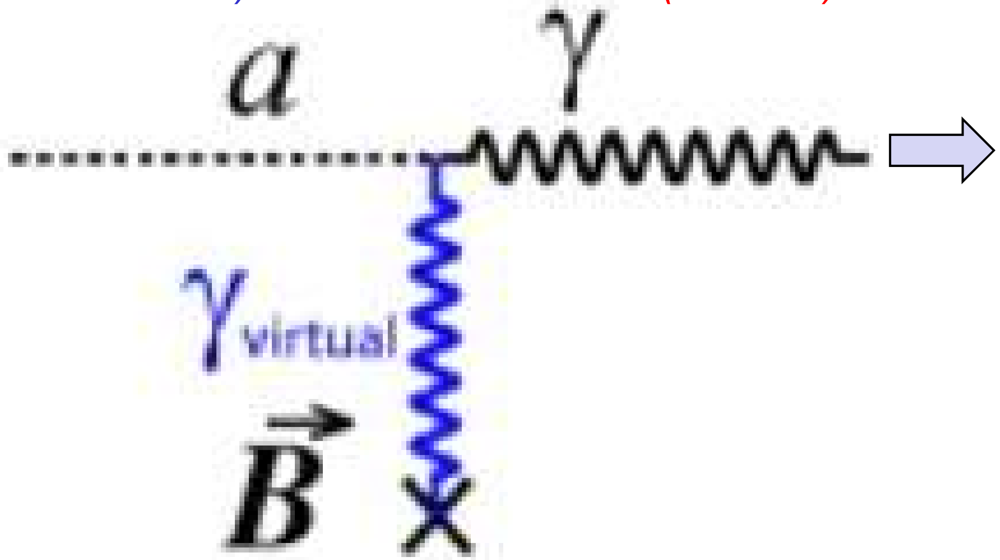
$m_a = 100\ \mu eV \rightarrow f_a = 25$ GHz → $f_\gamma = 25$ **GHz** → $\lambda_\gamma = 1.2$ **cm**

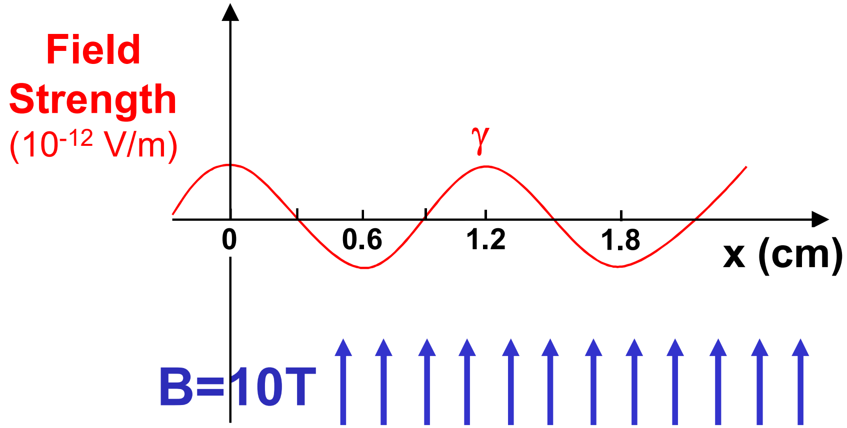
$$E_\gamma(t) = -g_{a\gamma}/\varepsilon\ B\ a(t) = -E_0/\varepsilon \cos(2\pi f_a t)$$

$$E_0 = 1.3 \times 10^{-12}\ \mathrm{V/m}\ \frac{B_e}{10\ \mathrm{T}}$$

"Invisible" axion ↔ **Photon**

(classical field) *(EM field)*





Energy density $\frac{1}{2} E_0^2 / |\epsilon|^2$

Power $2.2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_e}{10\ \mathrm{T}} \right)^2$

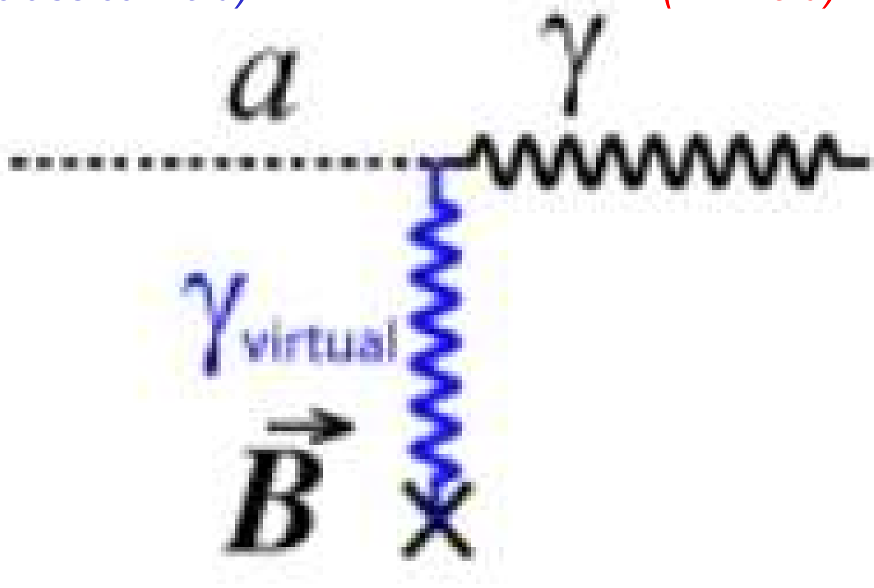
In vaccum (ε=1):

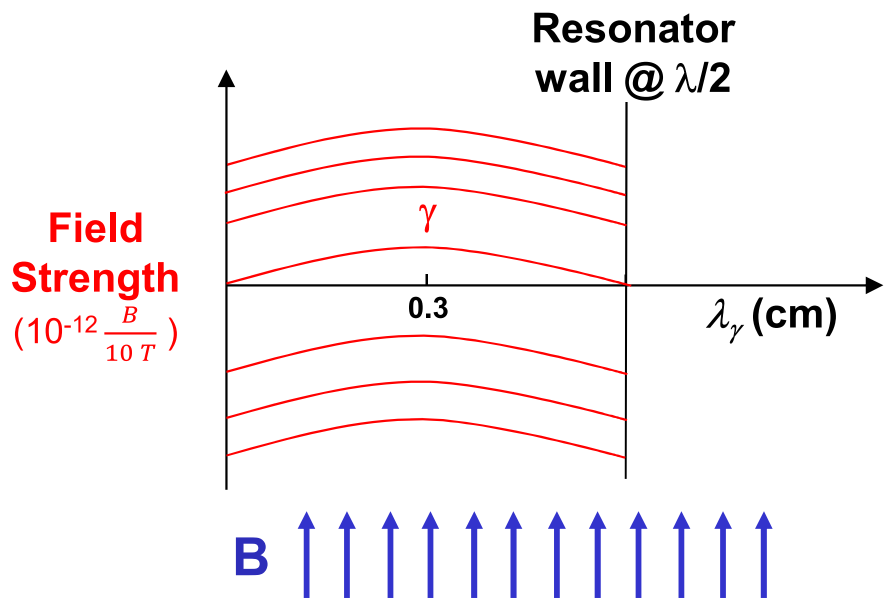
A very very faint E_{field} should appear

Boost E-field with resonant cavity

m_a = 100 μeV→ f_a = 25 GHz → **f_γ = 25 GHz → λ_γ = 1.2 cm**

"Invisible" axion *(classical field)* ↔ **Photon** *(EM field)*





Constructive interference → Boost

Power 10^{-27} W → 10^{-22} W

A resonator will enhance the very very faint signal

Axion Detection

- Convert it to photon in a magnetic field

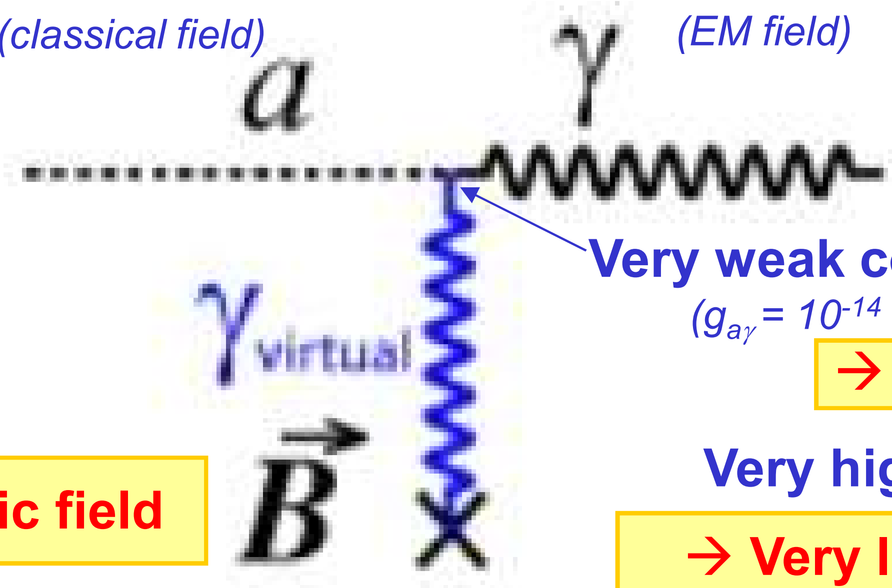
Exp. constraints

μeV ≈ 10^{-15} M(proton)
"Invisible" axion
(classical field)

↔

GHz
Photon
(EM field)

≈ RF, micro-wave



Very weak coupling: feeble signal
($g_{a\gamma} = 10^{-14}$ GeV^{-1} for m_a = 100 μeV)

→ Need boost

High Magnetic field

Very high Background

→ Very low temperature
→ Low Noise Amplifier

Axion search very rich in experimental challenges

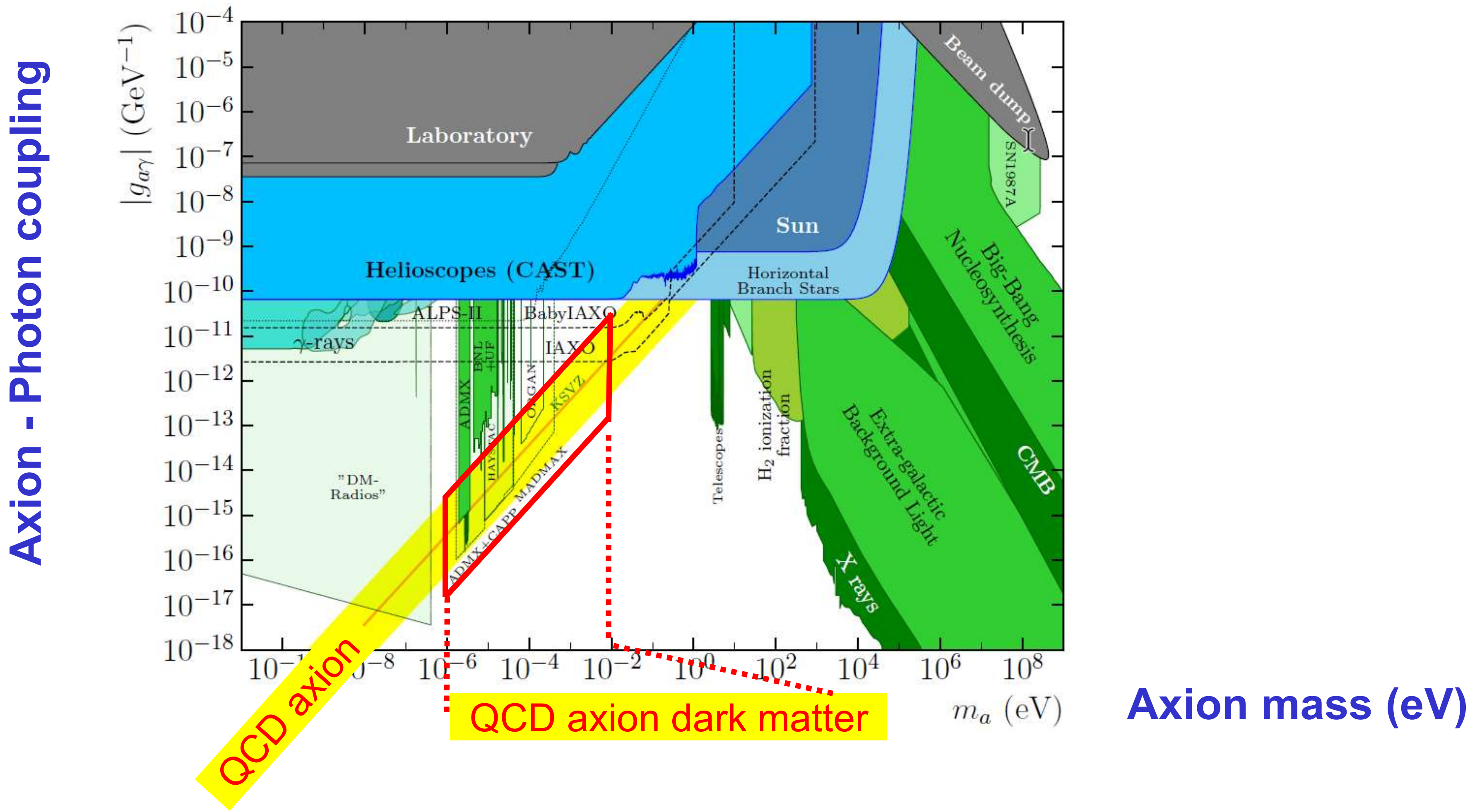
Axion Detectors

- Lots of new axion experiment in the last 10 years …

Very high scientific competition !

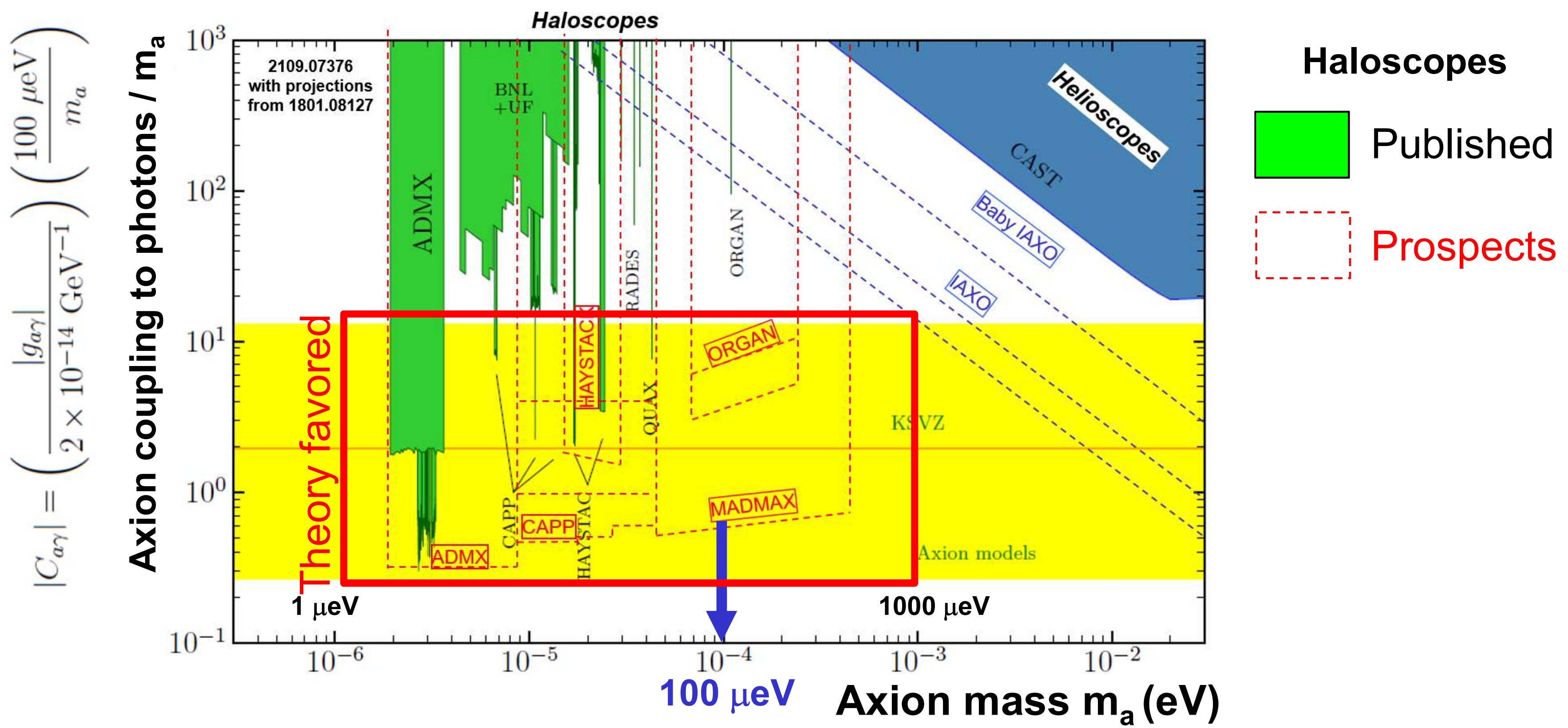
Axion Detectors

- ❑ …but very few can attack the theory favored region !



Axion Detectors

- …but very few can attack the theory favored region !

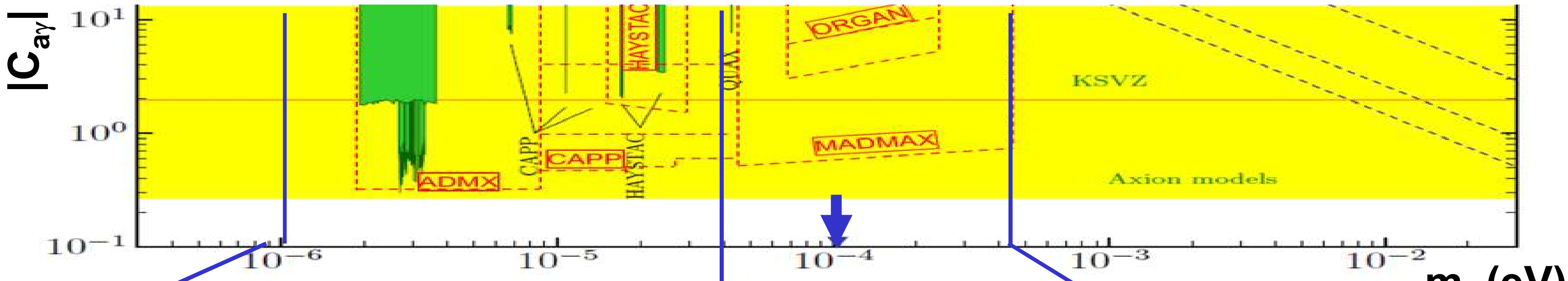


Few experiments can search for QCD axion ≈100 μeV *(favored by theory)*

Axion Detectors

❑ Challenges for haloscopes

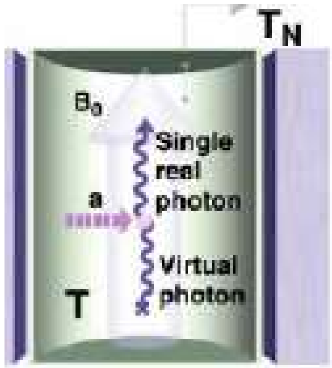
- Convert axions into photons *[E field of O(10^{-12}. $\frac{B}{10\,T}$) V/m]* ➔ **high B_{field}** *[B >> 1T]*
- Boost E_{field} *[up to detectable P~10^{-22} W]* ➔ **resonant** set-up
- Scan over range of axion mass ➔ **tunable** set-up *[precision mecanics]*



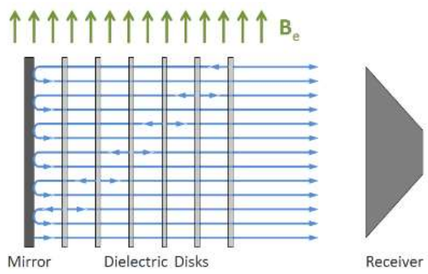
1 μeV [0.25 GHz] **40 μeV** [10 GHz] **400 μeV** [100 GHz] [$\nu_a = \nu_\gamma$]

Cavities

[baseline concept **1983**]



Cavity too small + high noise



MADMAX

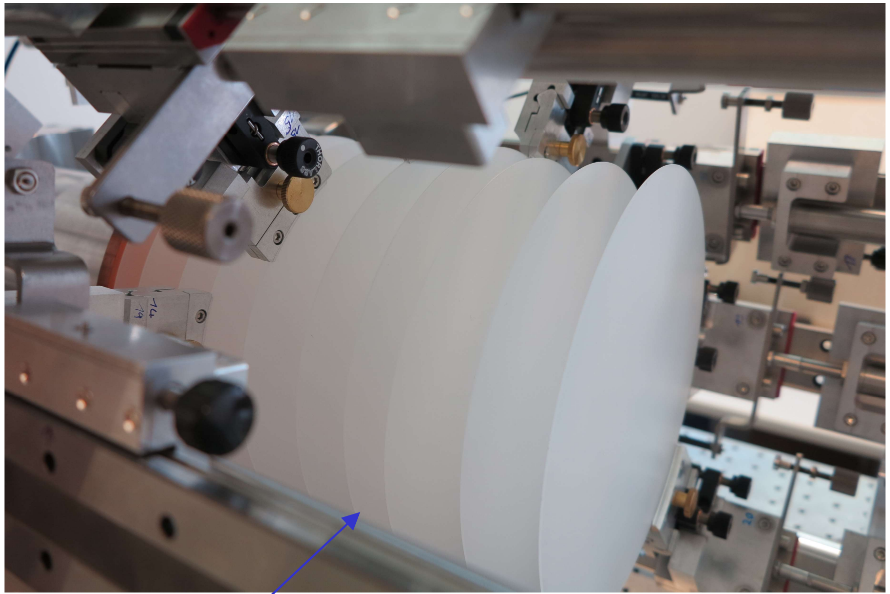
e.g. Dielectric haloscopes

[novel concept **2013**]

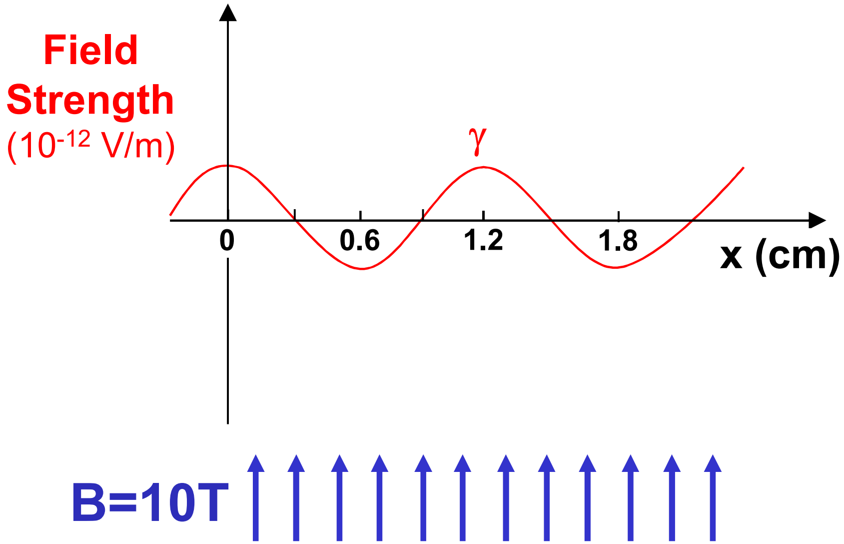
MADMAX

❑ A novel experimental concept

- **Constructive interference** of photon emitted at dielectric surfaces boost signal (β^2)



Dielectric disk in sapphire



MADMAX

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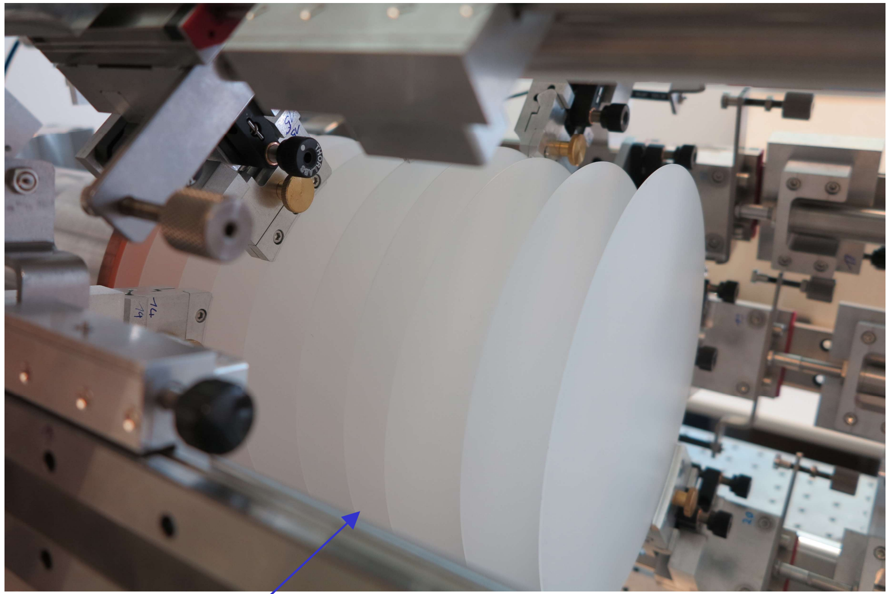
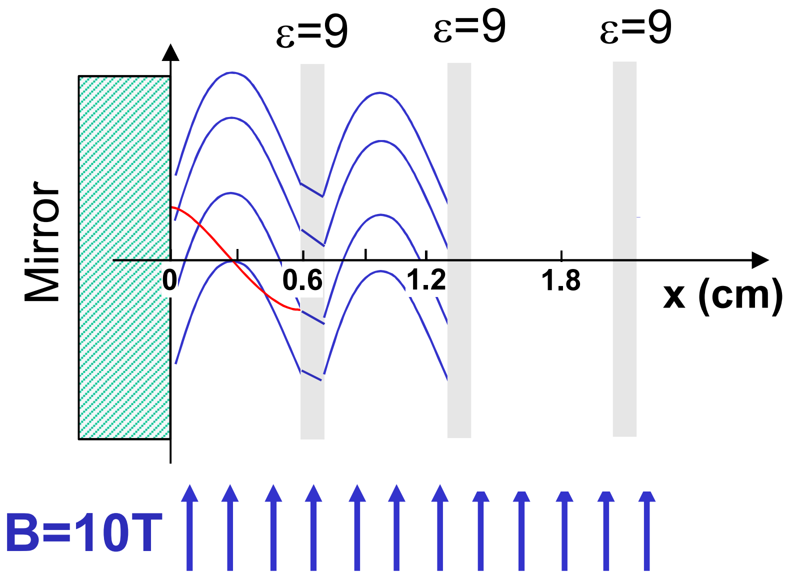
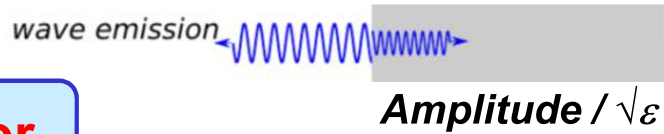


Dielectric disk in sapphire



EM waves emission perpendicular to the surface of the disk because of sudden ε change

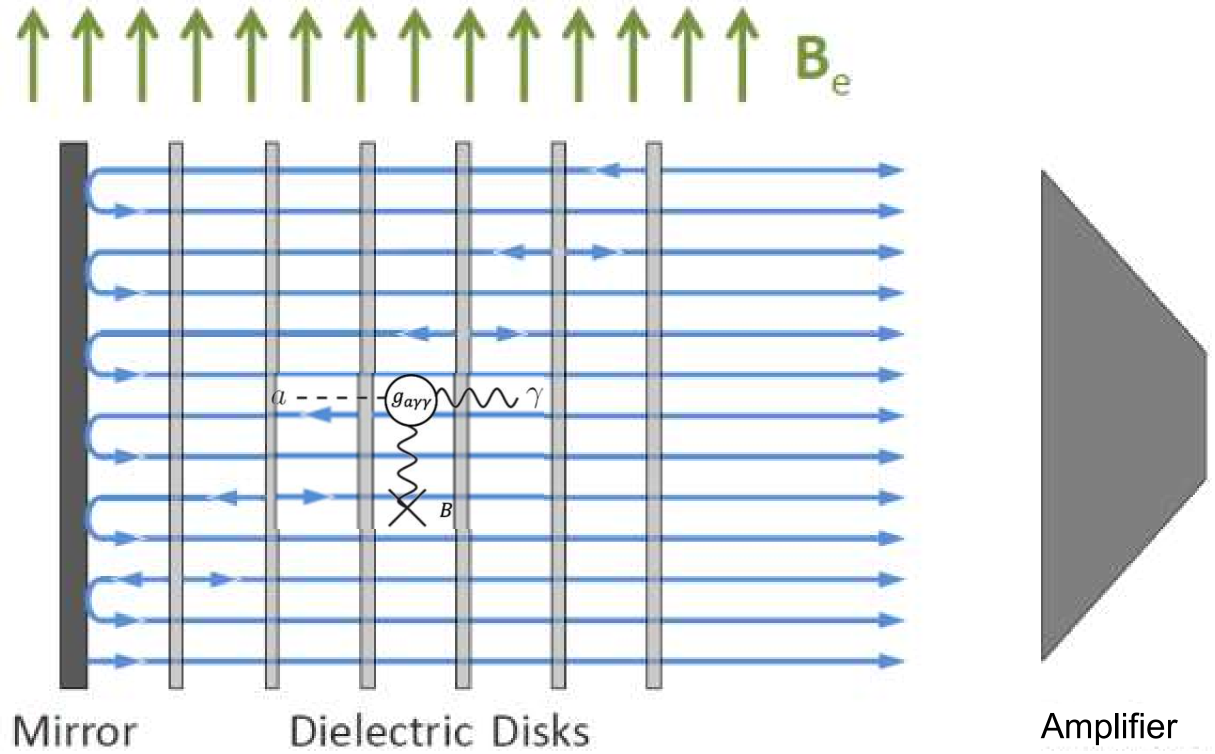


Multi "leaky" resonator

MADMAX

❑ A novel experimental concept

- **Constructive interference** of photon emitted at dielectric surfaces boost signal (β^2)



$$P_{sig} = 10^{-22}\ \mathrm{W} \times \left(\frac{\beta^2}{50000}\right) \times \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 \times \left(\frac{A}{1\ \mathrm{m}^2}\right) \times C_{a\gamma}^2$$

MADMAX

❑ A novel experimental concept

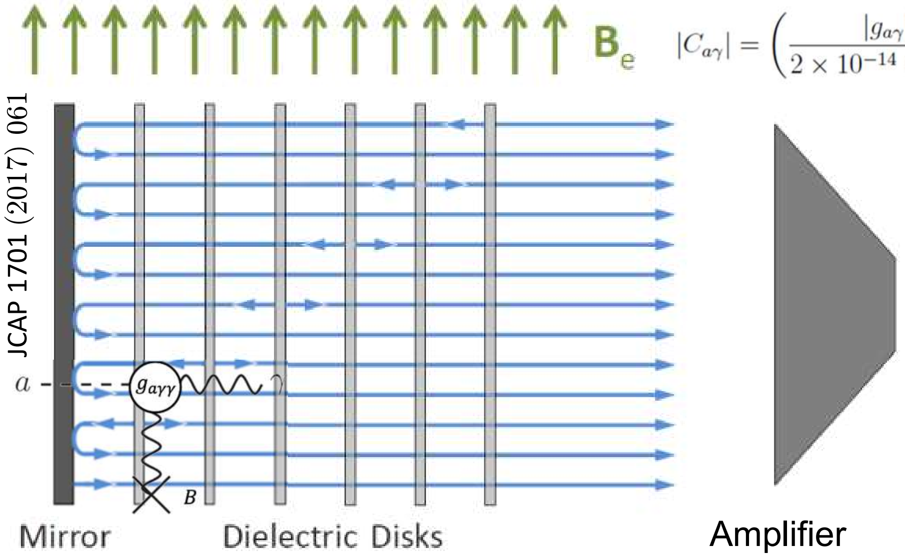
- **Constructive interference** of photon emitted at dielectric surfaces boost (β^2) signal

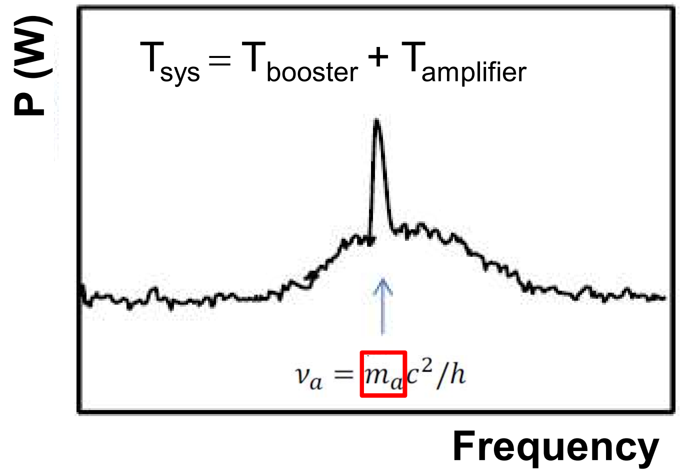
$$P_{sig} = 10^{-22}\ \mathrm{W} \times \left(\frac{\beta^2}{50000}\right) \times \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 \times \left(\frac{A}{1\ \mathrm{m}^2}\right) \times C_{a\gamma}^2$$

$$P_{sig}^{\text{detect.}} = 10^{-22}\mathrm{W} \times \left(\frac{SNR}{5}\right) \times \left(\frac{T_{sys}}{4\ \mathrm{K}}\right) \times \left(\frac{4\ \text{days}}{t}\right)^{1/2}$$

Thermal Noise

$$|C_{a\gamma}| = \left(\frac{|g_{a\gamma}|}{2 \times 10^{-14}\ \mathrm{GeV}^{-1}}\right)\left(\frac{100\ \mu\mathrm{eV}}{m_a}\right)$$





MADMAX

❑ A novel experimental concept

- **Constructive interference** of photon emitted at dielectric surfaces boost (β^2) signal

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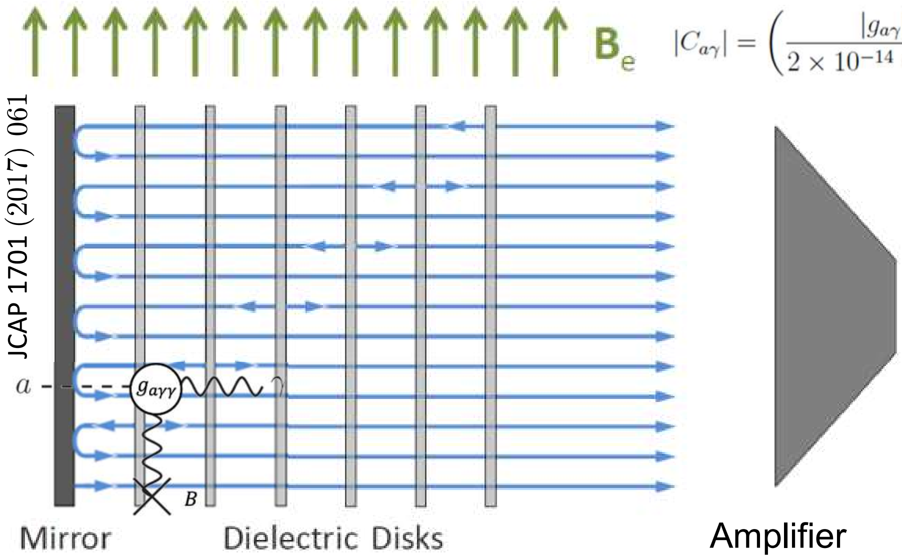

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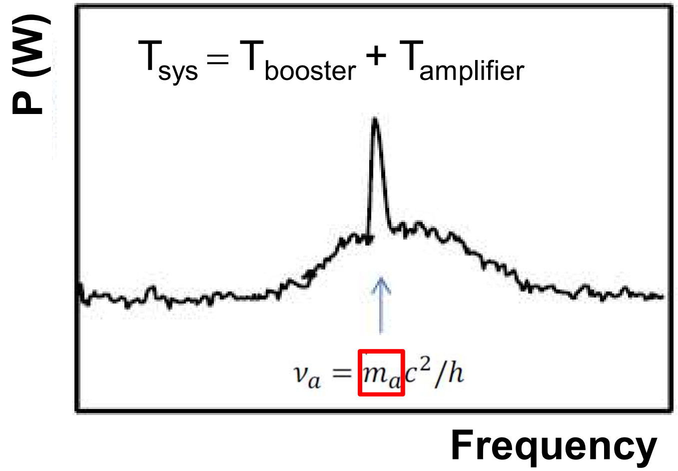
Thermal Noise

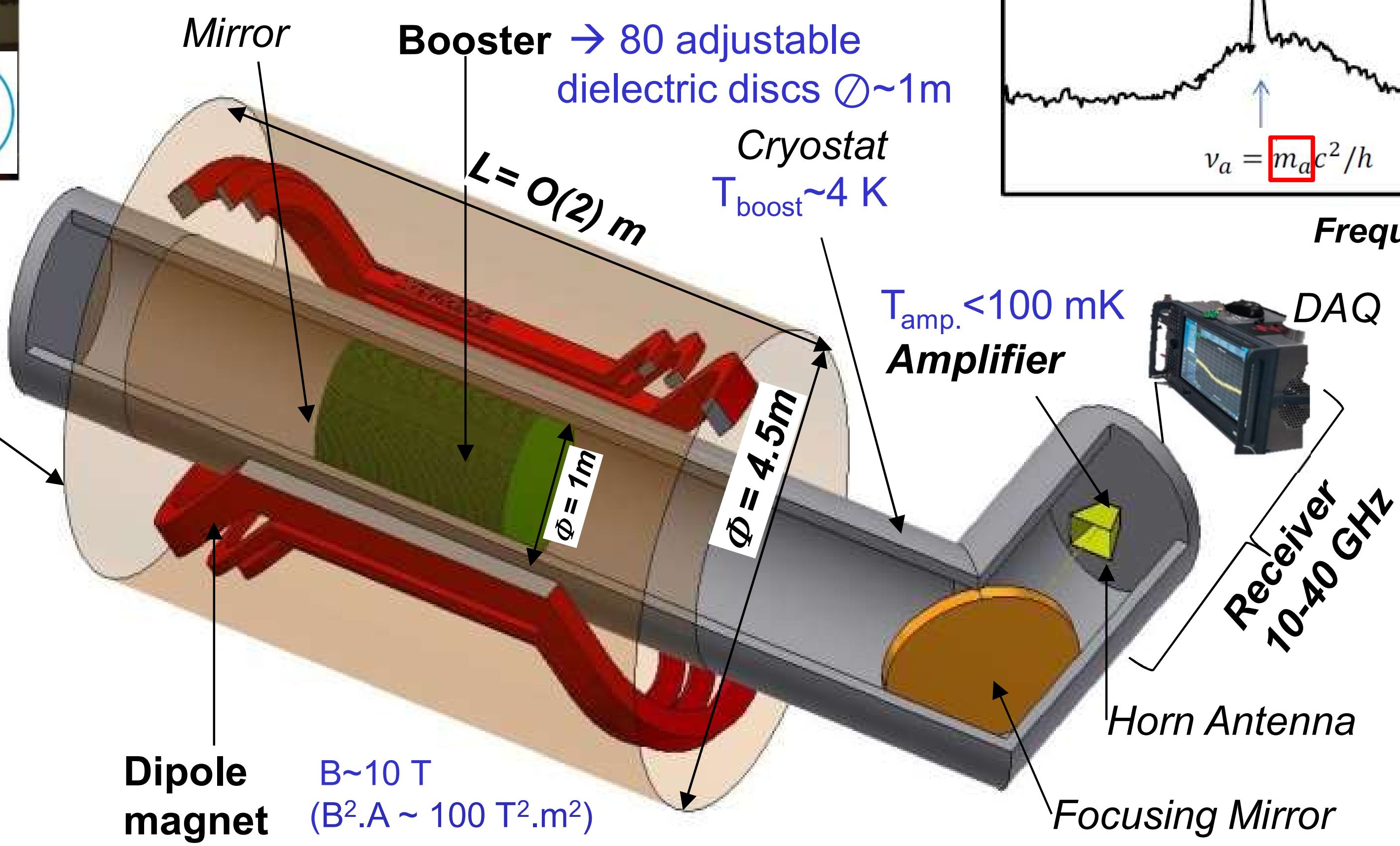


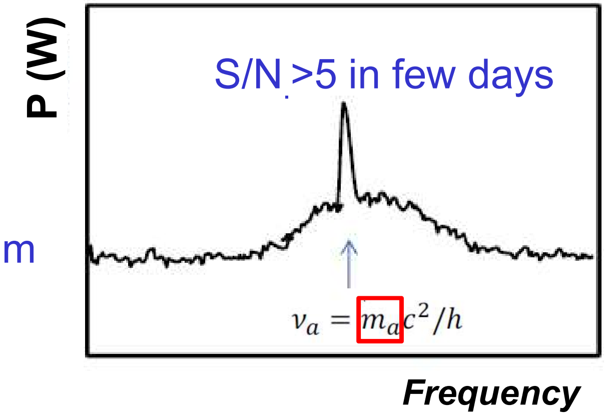
- **Axion mass scan**: move discs with piezo motors *(μm prec.)* at 4K and 10 T *(50 MHz step)*

Final MADMAX

Formed in 2017. 10 institutes: French (2), German (6), Spanish (1) and US (1) → ~50 people

Experiment location: HERA in former H1 iron yoke

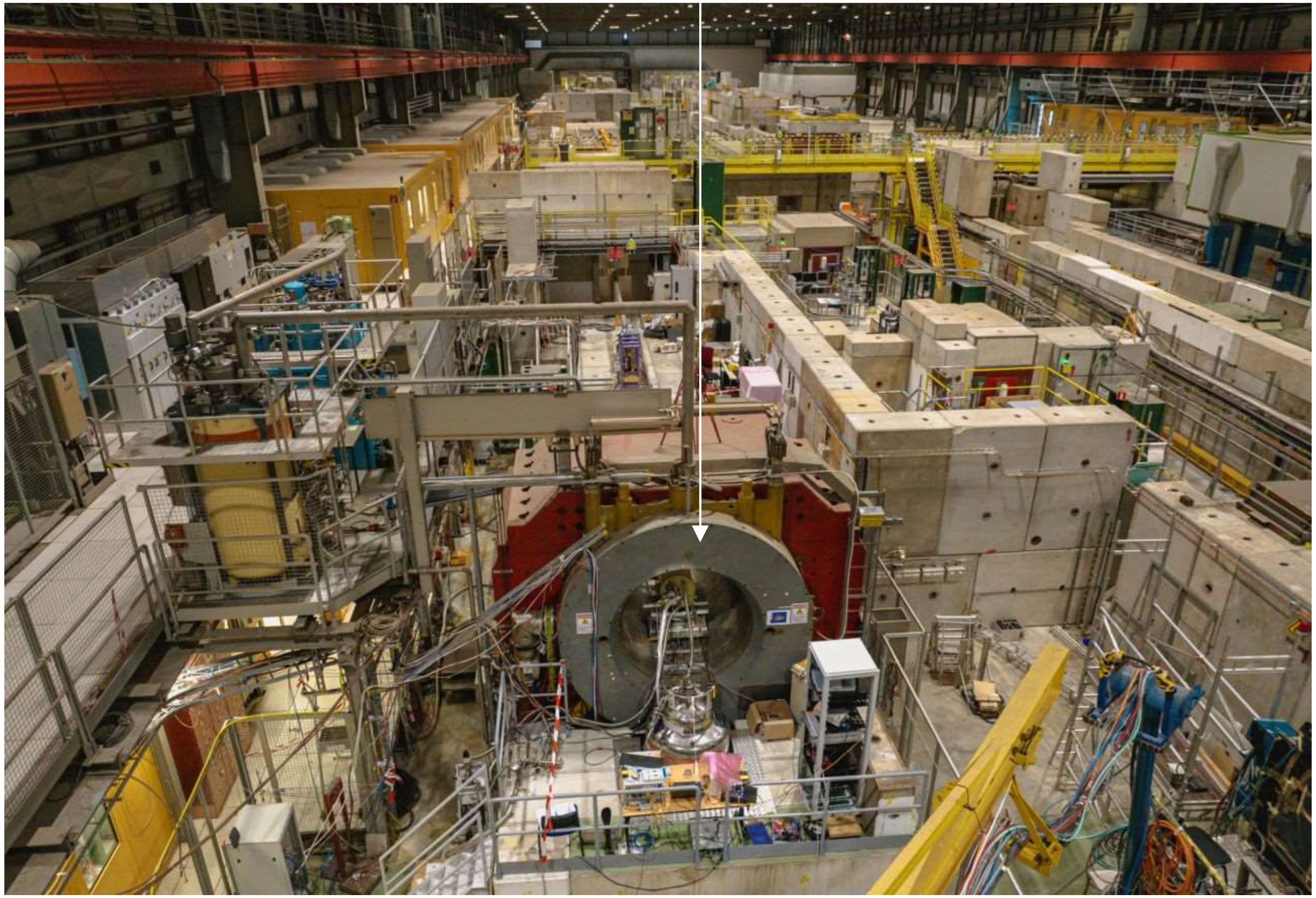




→ Start with prototyping phase to validate concept: cutting-edge R&D

MADMAX recent tests

Morpurgo magnet in the CERN North Area (500 m x 50 m x 8 m)



Article in CERN Bulletin
https://home.cern/news/news/experiments/madmax-forefront-search-axions

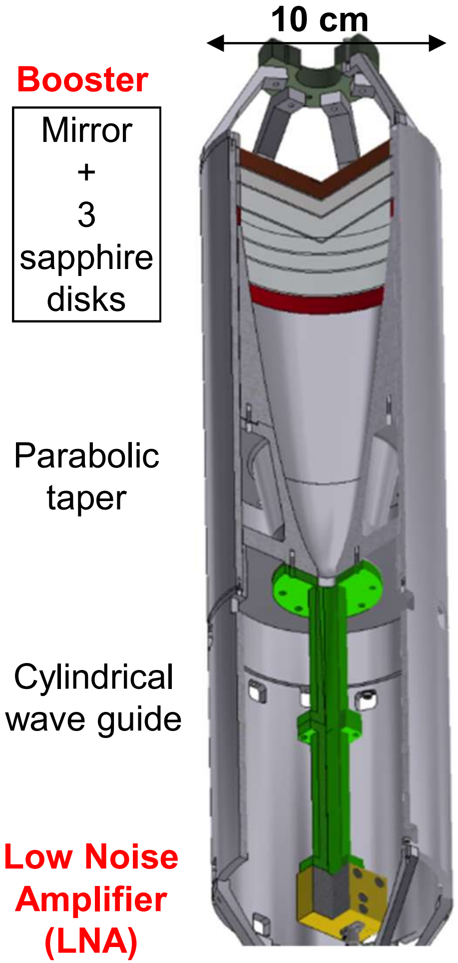
MADMAX recent tests

MADMAX Cryostat in the Morpurgo magnet

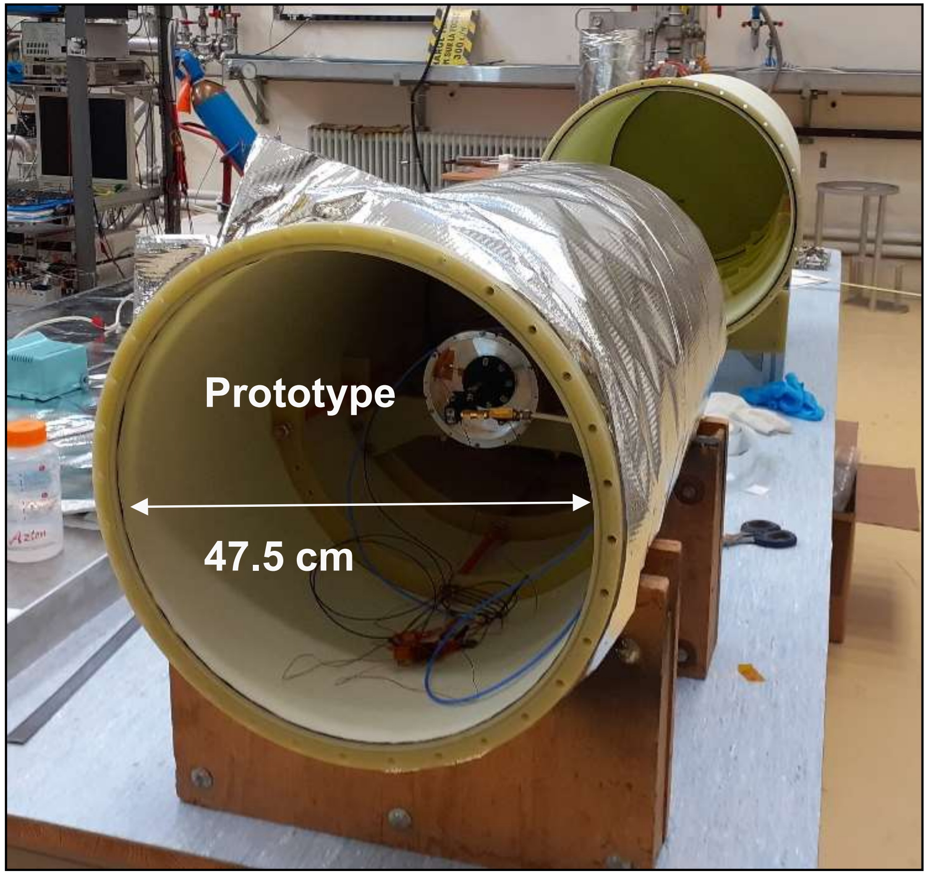
Liquid Helium Bottle

MADMAX recent tests

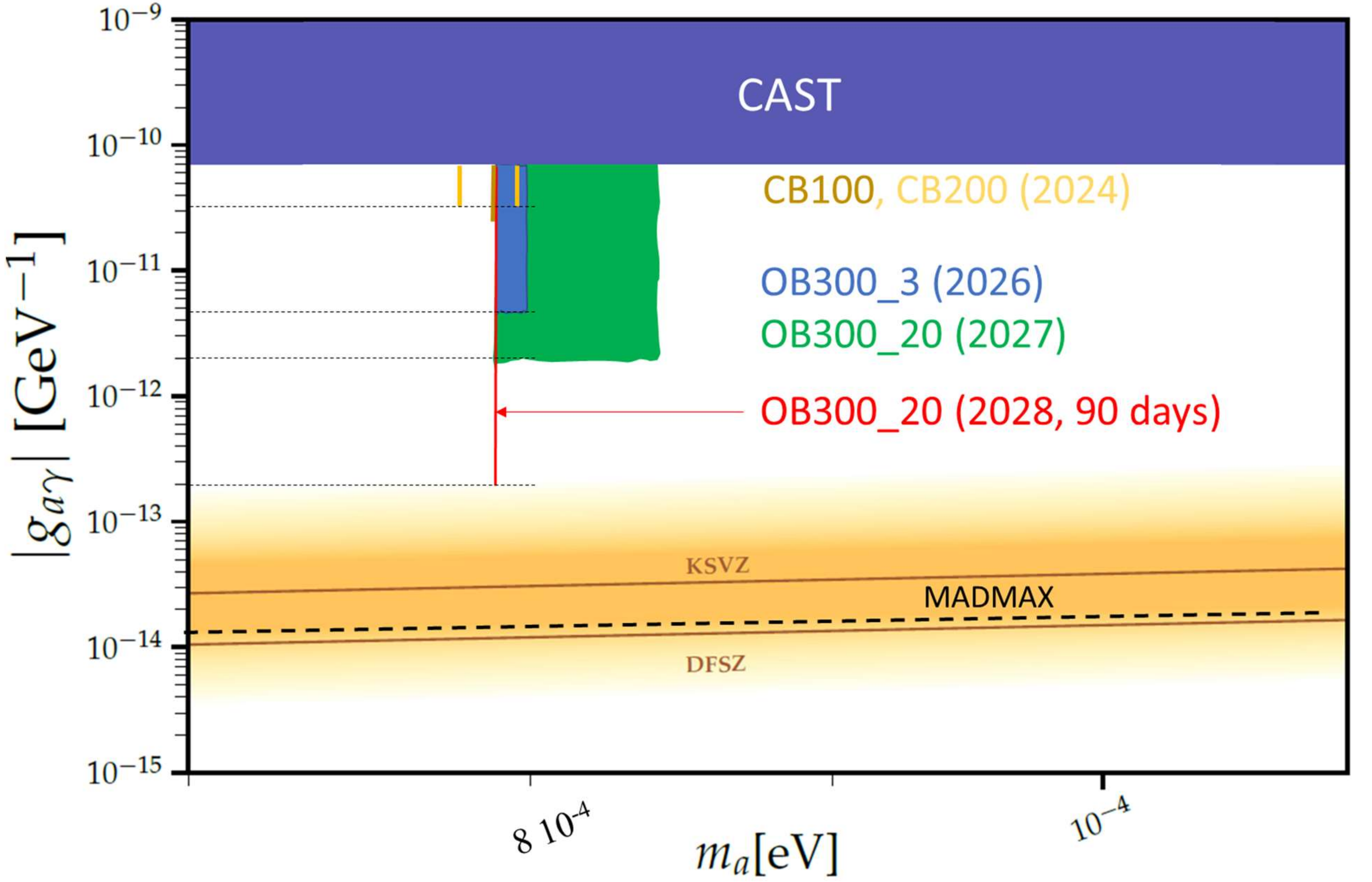
MADMAX Prototype



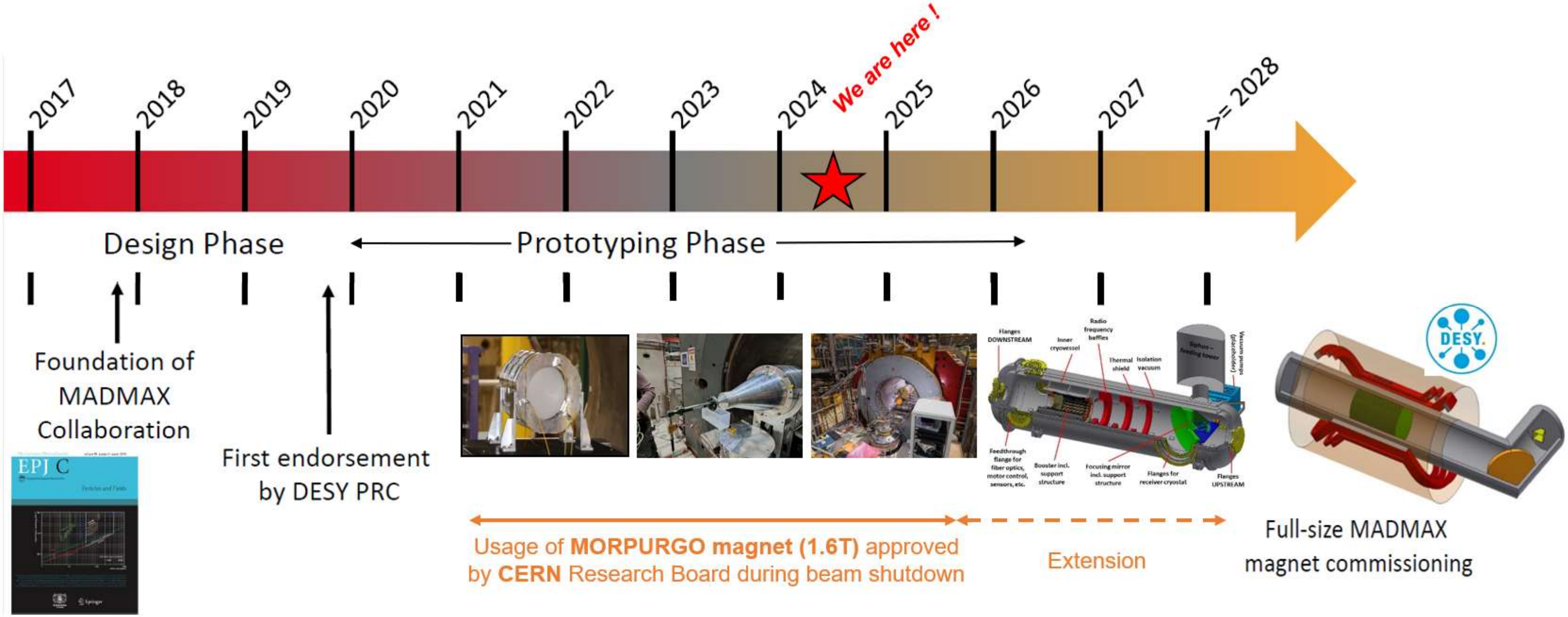
MADMAX cryostat



MADMAX foreseen results



MADMAX Timeline

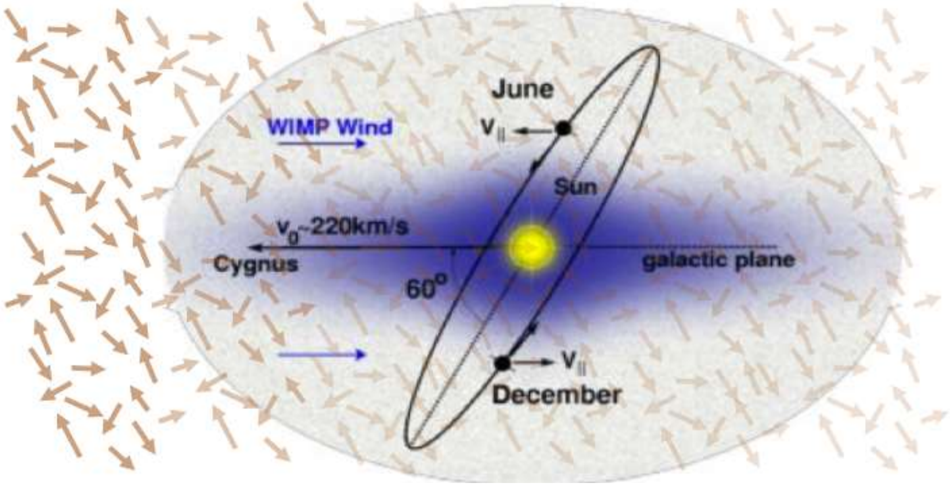


Last Important point

- How to be sure it is really dark matter ?

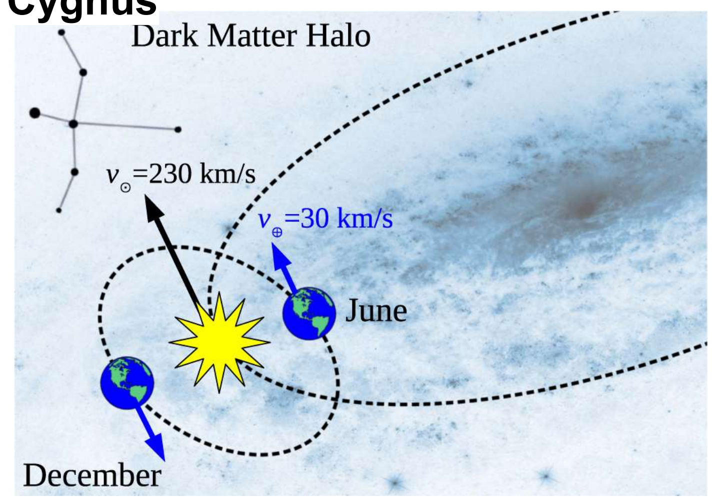
Annual Modulations

Earth rotation around the Sun => largest speed of the dark matter particles in the Milky Way halo relative to the Earth around June 2nd and smallest in December
Expected seasonal variation at 2-10% level



Directionality

The recoil rate, in the Galactic rest frame, is highly anisotropic: the rate in the forward direction is roughly an order of magnitude larger than that in the backward direction



For now, none of the detector presented can be sensitive to this

Conclusions

- **Dark matter is a central question of fundamental physics**
  - Evidence of dark matter (gravitational) existence over many different scales
  - So dark matter exists but what is it made of ?
  - XX^{th} physics suggests it could be a particle(s)

- **Dark Matter direct searches: very dynamic research field**
  - WIMP and axion are two hypothetic particles, very well motivated by particle physics with the required dark matter properties *(massive, neutral, stable, weakly interacting, non relativistic)*
  - Searches are entering the phase space favored by theory
    - ✓ Couples with lots of very challenging technological developments
    - ✓ Very high scientific competition with lots of new experiments
  - Large discovery potential in the next 10 years !

Short term Opportunities (**scientific & technical**) on a **fundamental question** of particle physics with a **strong discovery potential**

Readings

General, cosmology and particle physics

- M. Cribier, D. Verkindt, D. Vignaud, "*History of the neutrino*", https://neutrino-history.in2p3.fr
- A. De Rujula, "*The dark Side of the Universe*", arXiv:2108.01691

- S. Carroll, "*Cosmology for particle physicist*", https://indico.cern.ch/event/417992/
- K. Schmitz, "*Modern Cosmology, an Amuse Gueule*", arXiv:2203.04757

- J. Woithe et al, "*Let's have a coffee with the SM of particle physics!*", Phys. Educ. **52** (2017)
- G. Altarelli, "*Collider Physics within the Standard Model: a Primer*", arXiv:1303.2842
- G. P. Salam et al., "*The Higgs boson turns ten*", arXiv:2207.00478
- N. Craig, "*Naturalness: a Snowmass white paper*", arXiv:2205.05708

Direct dark matter detection (WIMPs, axions)

- K. Garrett, G. Duda , "*Dark Matter: A primer*", arXiv:1006.2483
- M. Schumann, "*Direct detection of WIMP dark matter: concepts and status*", arXiv:1903.03026
- J. Cooley, "*Dark Matter direct detection of classical WIMPs*", arXiv:2110.02359

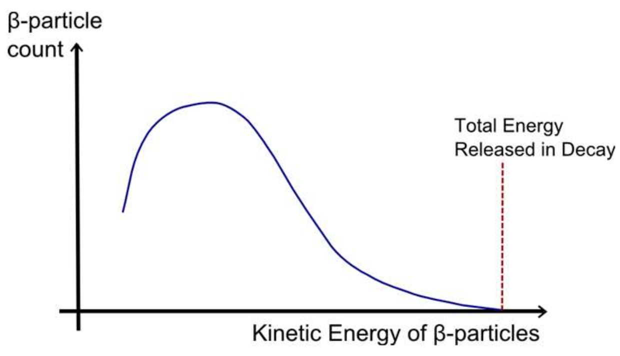
- D. J. E. Marsh, "*Axions for amateurs*", arXiv:2308.16003
- I. Irastorza, "*An introduction to axions and their detection*", arXiv:2109.07376

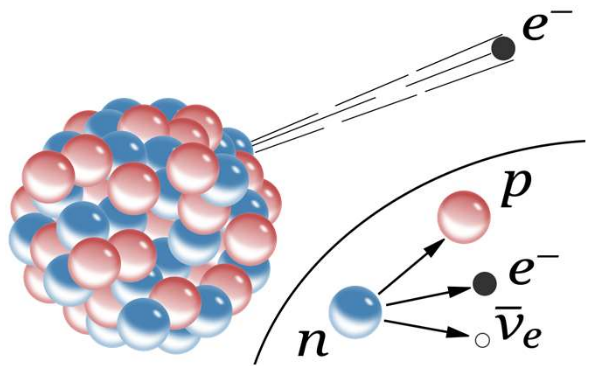
SPARE

β radioactivity

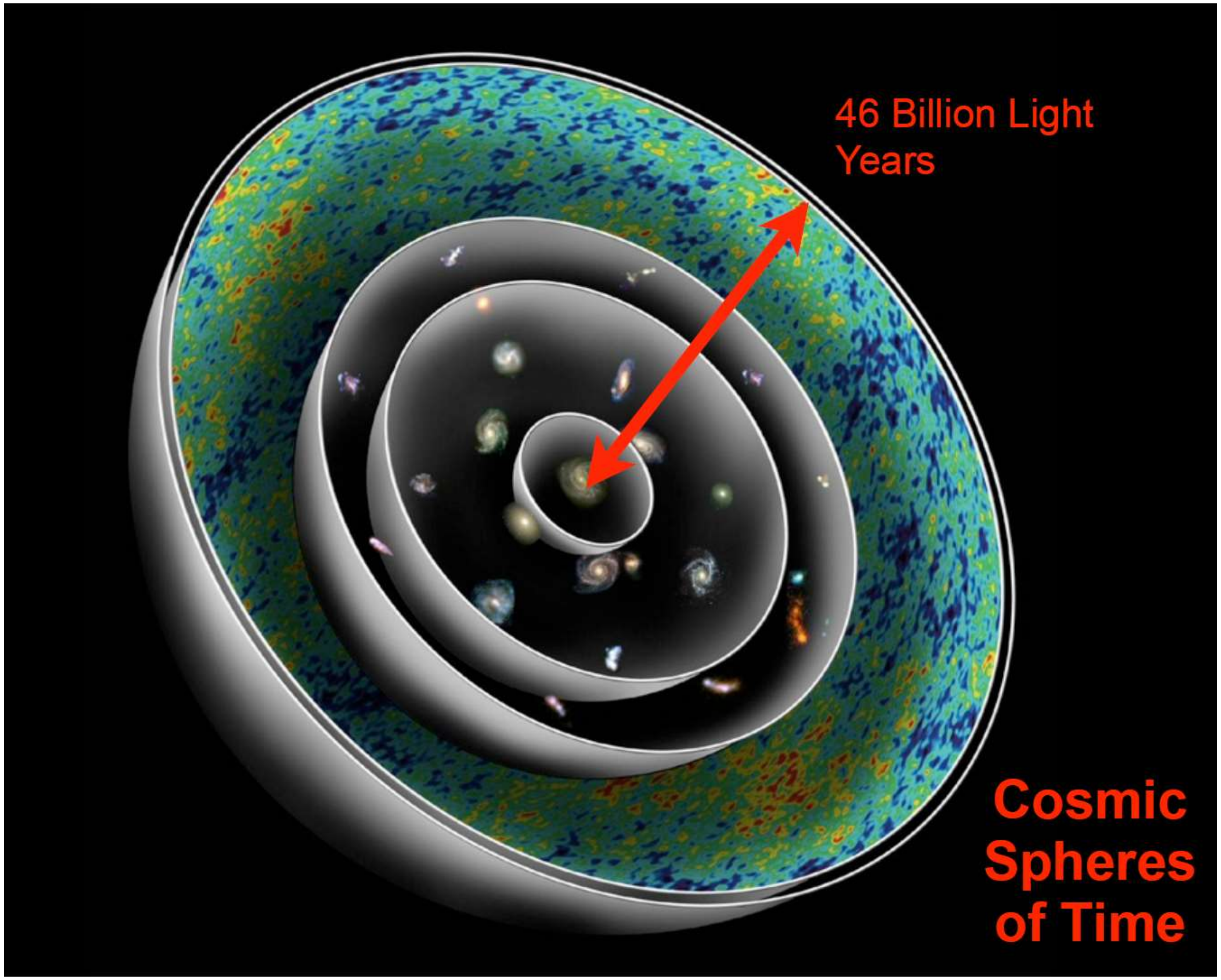
❑ Historical evolution

- <1930, only aware of Nucleus1→Nucleus2 + e^- *(did not know about neutrino and neutron)*
  - ✓ Natural conclusion: e- is in the nucleus → Nucleus = protons + electrons
  - ✓ New particle carrying part of the energy, present in the nucleus (Pauli, 1930) ?
  - ✓ Observe violation of Energy conservation → Violation at quantum level (Bohr, 1931-38) ?
- Discover of the neutron, n (Chadwick, 1932)
  - ✓ n=p-e^- bonded states ? Introduce a new symmetry called isospin (n ≈ p) (Heisenberg)
- Theory of weak interaction (Fermi, 1934): $n \rightarrow p + e^- + \nu_e$
  - ✓ A new particle is created → called it neutrino
  - ✓ Coupling constant $G_F \approx 300000\ GeV^{-2}$ → New physics scale: $\Lambda_F = 1/\sqrt{G_F} \approx 500$ GeV



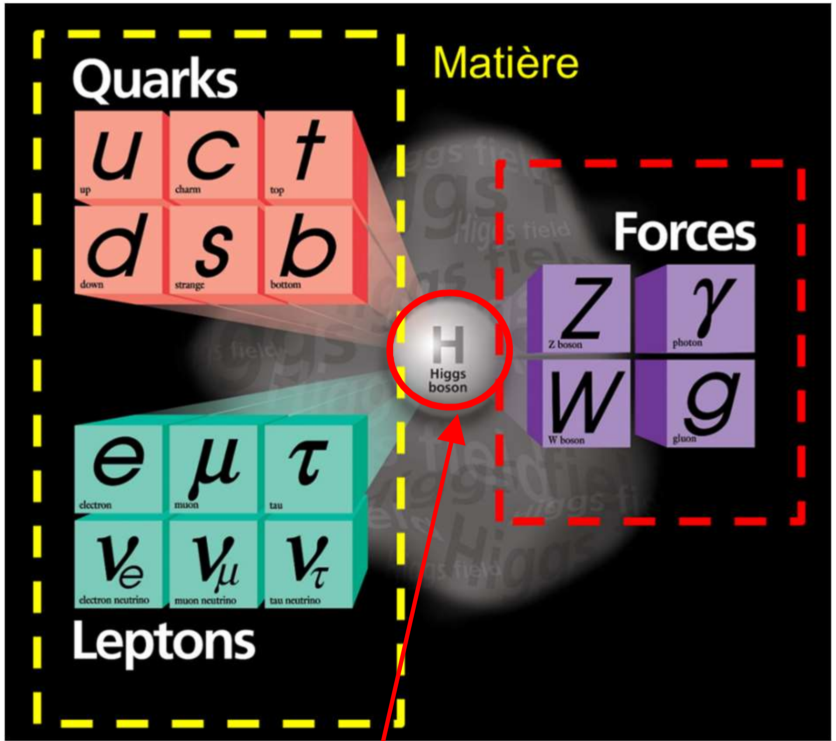


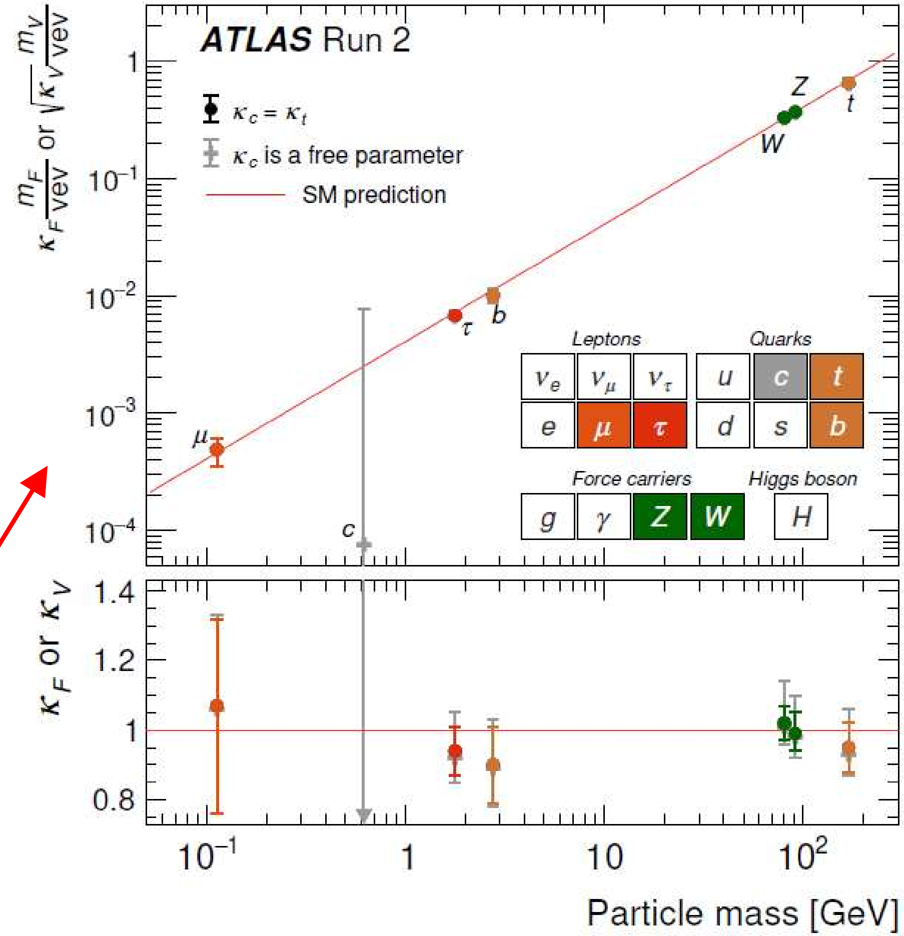
CMB



Particle physics: end ?

❑ **After LHC run II, Standard Model (SM) is stronger than ever !**

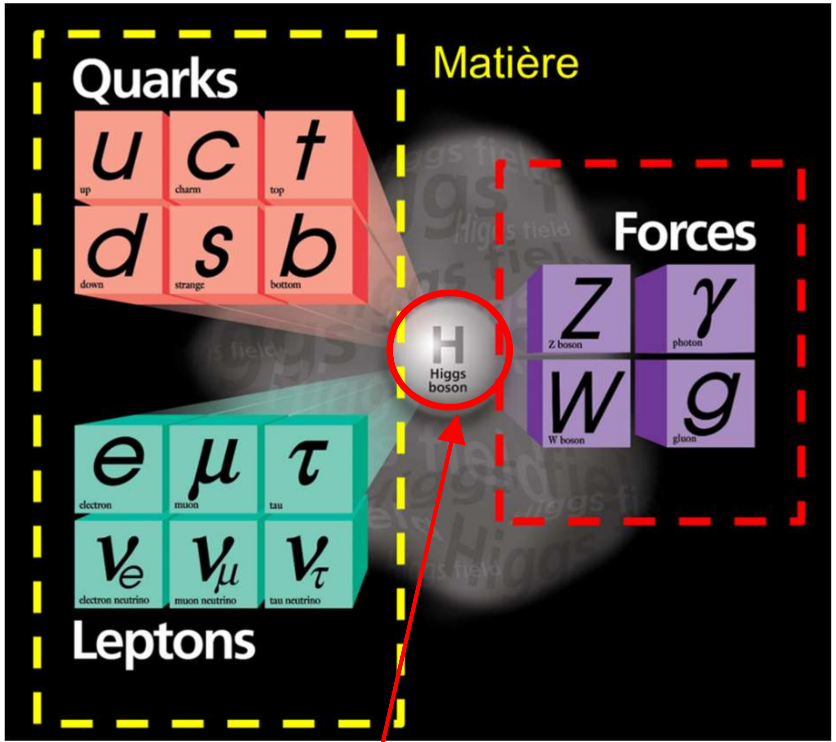


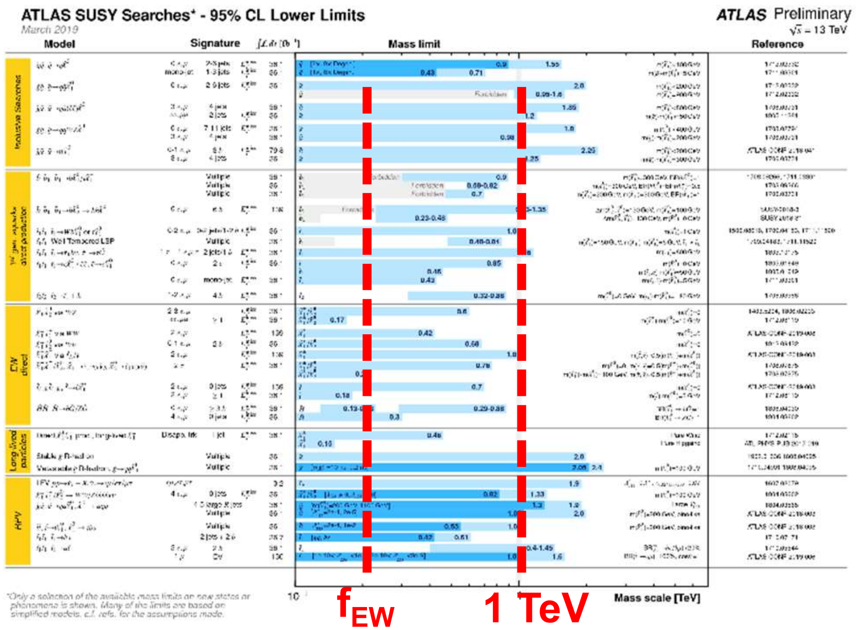


- Higgs discovery in 2012 : SM complete
- Precision measurements of the Higgs couplings agrees with the Standard Model

Particle physics: end ?

- After LHC run II, Standard Model (SM) is stronger than ever !

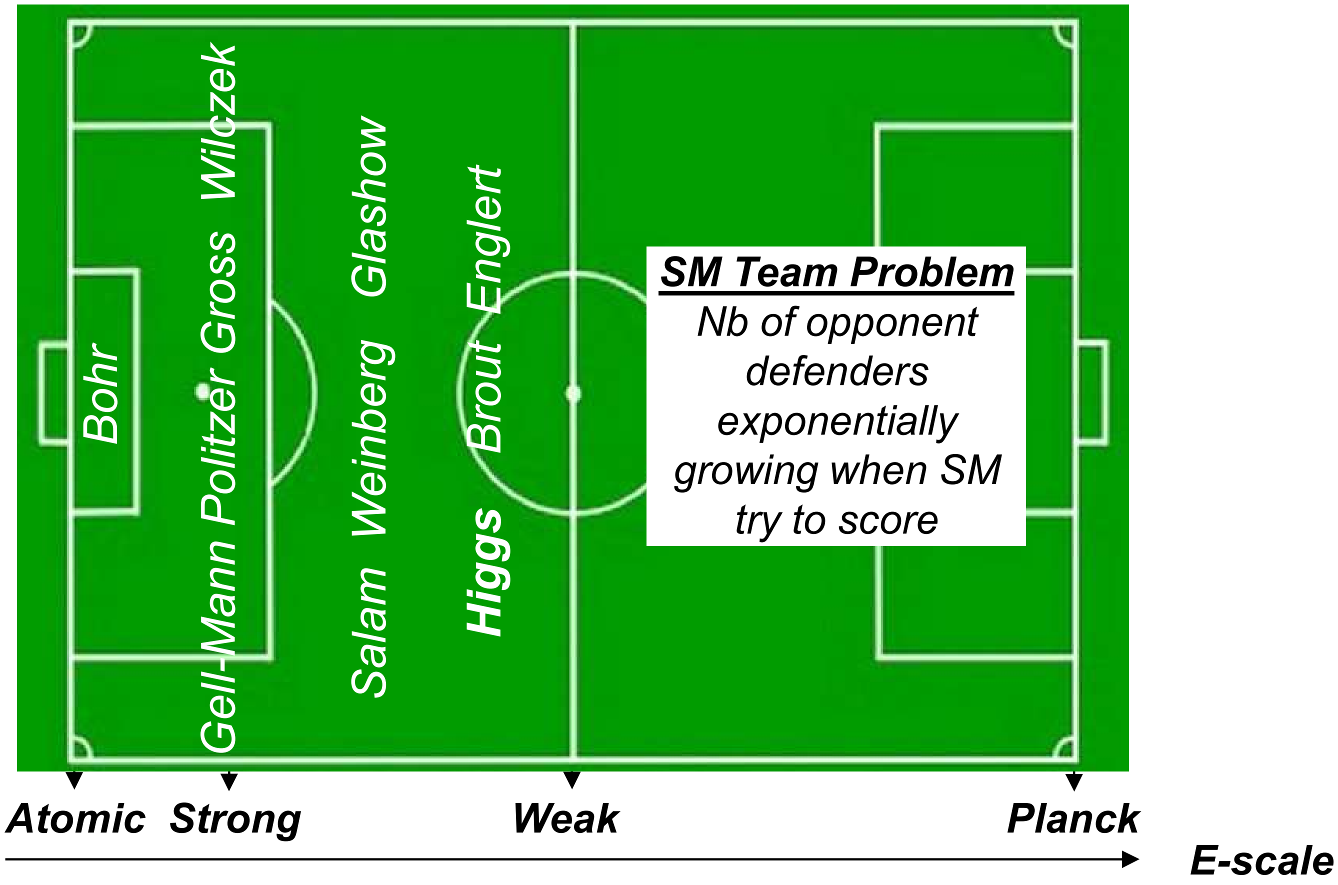




- Higgs discovery in 2012 : SM complete
- Direct searches → no sign of New Physics so far up to TeV scale

Higgs mass fine tuning

Quantum Field

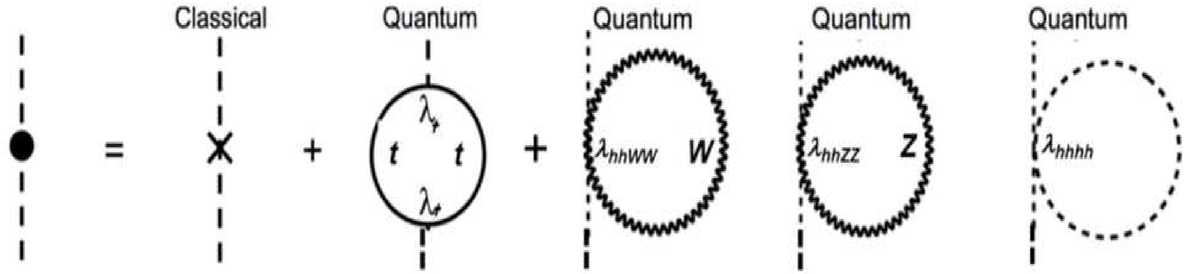


Can SM Team score at the Planck Scale given this problem ?
***SUSY** coach (formed in the Poincare training academy) knows how to annihilate the defenders …*

Higgs mass fine tuning

- **Standard Model is a perturbative theory wrt weak interaction**

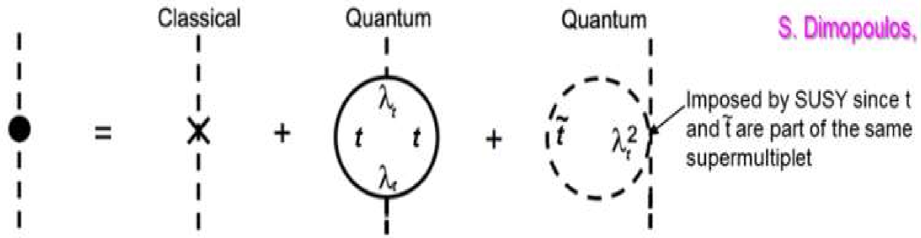
- Standard Model (SM) is an effective field theory valid up to Λ_{NP} M. Veltman, Acta Phys. Polon. B 12, 437 (1981)



$$125)^2 = m_H^2 = (m_H^2)_0 - \frac{3G_F}{4\sqrt{2}\pi^2}(4m_t^2)\Lambda_{NP}^2 + \frac{3G_F}{4\sqrt{2}\pi^2}(2m_W^2 + m_Z^2 + m_H^2)\Lambda_{NP}^2 + O(m^2 \ln[\Lambda_{NP}/\mu^*])$$

- Some SUSY realizations are 'natural' candidate for New Physics (NP) (e.g. for the top loop)

S. Dimopoulos, H. Georgi, Nucl. Phys. B193 (1981) 150

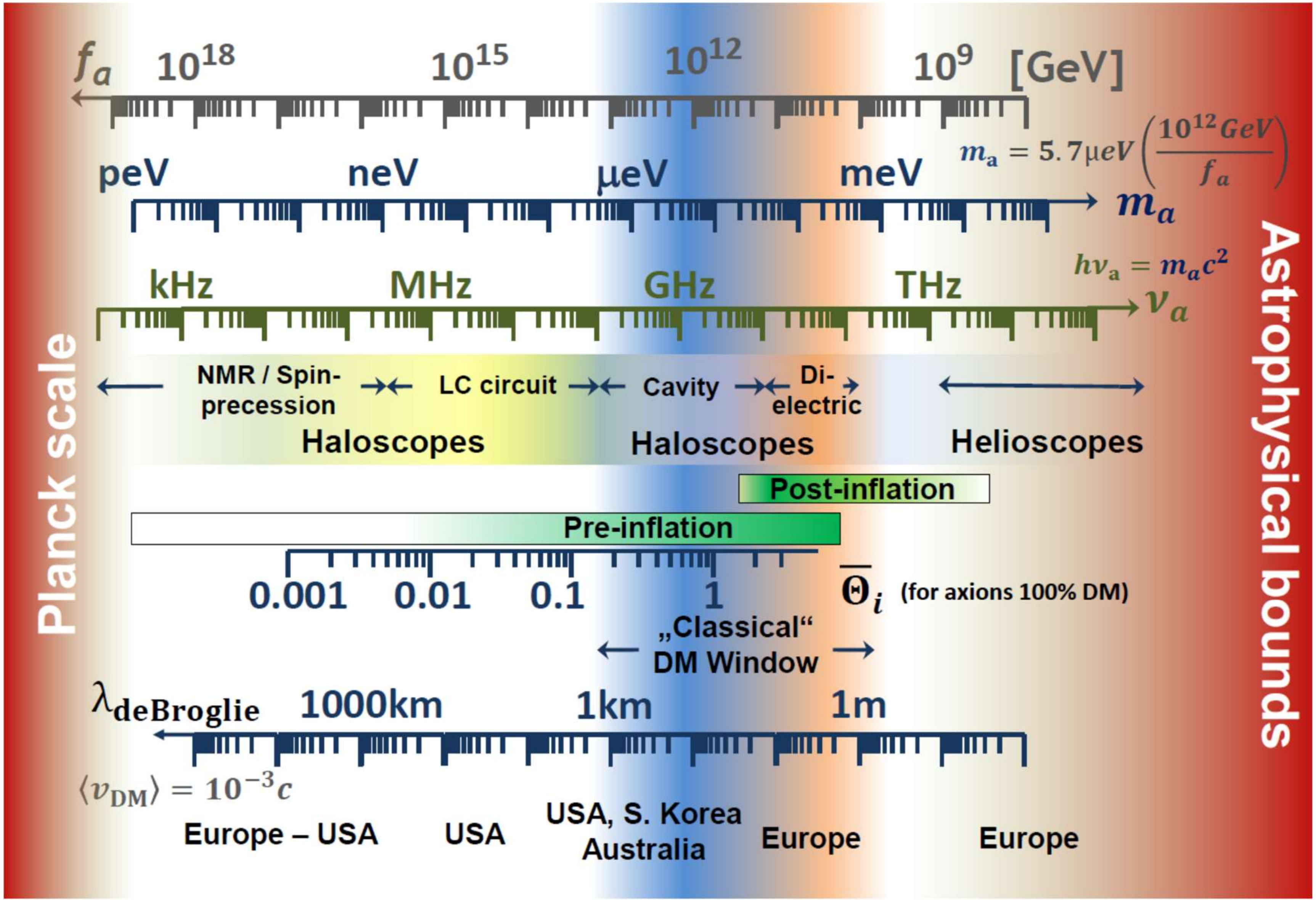


$$m_H^2 = (m_H^2)_0 - \frac{3G_F}{4\sqrt{2}\pi^2}(4m_t^2)\Lambda_{NP}^2 + \frac{3G_F}{4\sqrt{2}\pi^2}(4m_{\tilde{t}}^2)\Lambda_{NP}^2 + O(m^2\ln[\Lambda_{NP}/m_{\tilde{t}}])$$

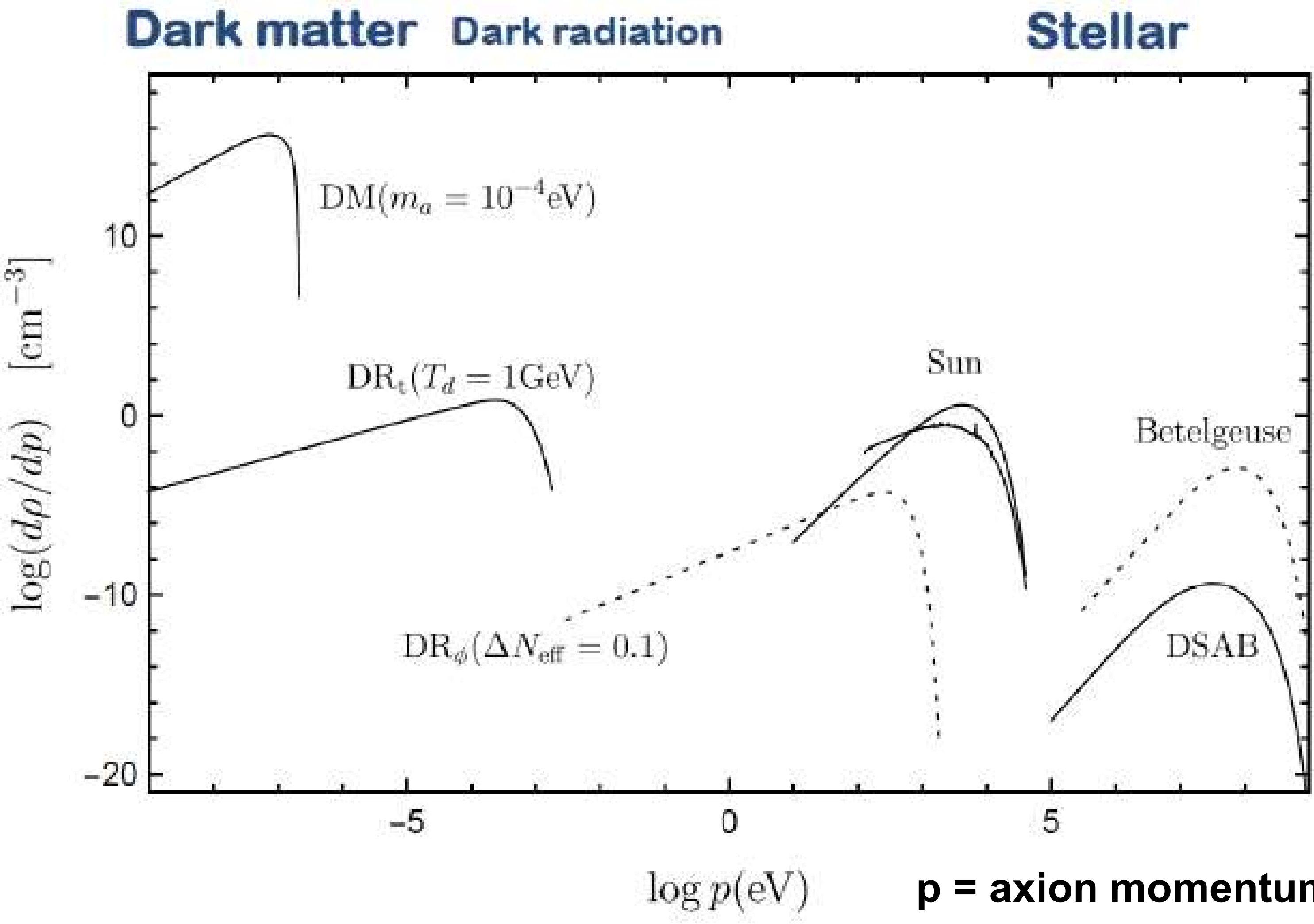
$$+\frac{6G_F}{2\sqrt{2}\pi^2} m_t^2 (m_{\tilde{t}}^2 - m_t^2) \ln(\Lambda_{NP}^2/m_{\tilde{t}}^2)$$

Note: to have 4, two scalars are considered ($\tilde{t}_R$ and $\tilde{t}_L$)

Axion scales



Axion sources



p = axion momentum

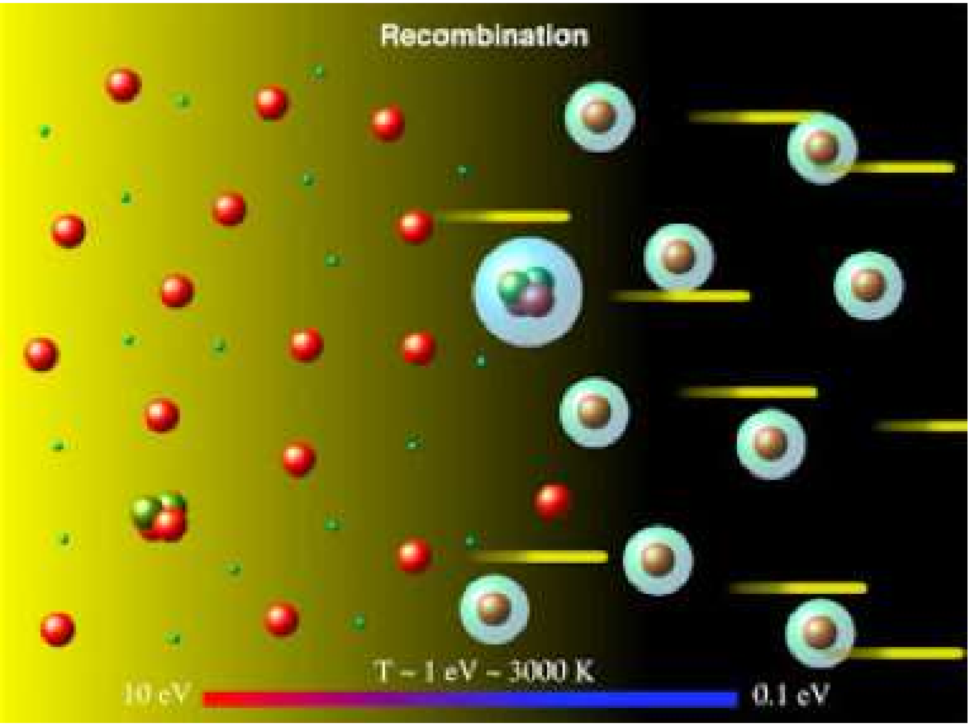
Axion detector types

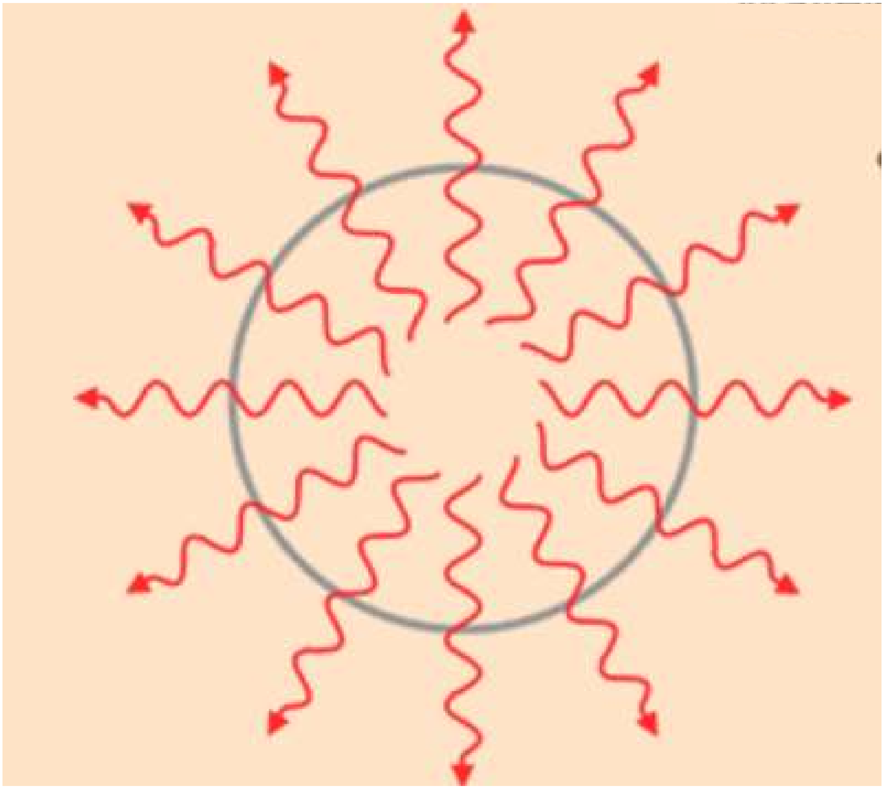
Lab experiments	Helioscopes	Haloscopes
Lab produced → fully controlled setup	Solar axions	Relic DM axions
Low axion flux	Medium axion flux	High axion flux
Model independent	Mildly model dependent	Model dependent
ALP	QCD axion / ALP	QCD axion DM [1-1000 μeV]
e.g. ALPS II	**e.g. (Baby)IAXO**	**e.g. MADMAX**

Complementary experimental approaches

Cosmic microwave background

- **Early Universe: dense plasma of charged particles and photons**
  - Rapidly expanding and cooling during 380 000 years …
  - … until neutral atoms formed (T=3000 K) → Universe transparent to photons …
  - … which create an isotropic relic radiation *(cosmic microwave background)*





Cosmic microwave background

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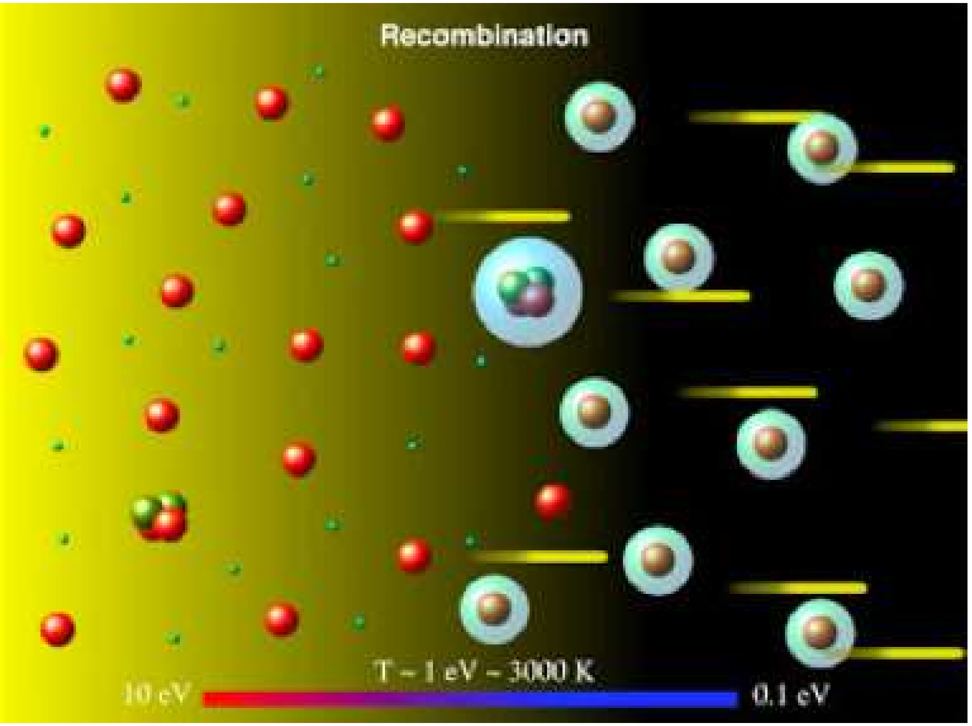
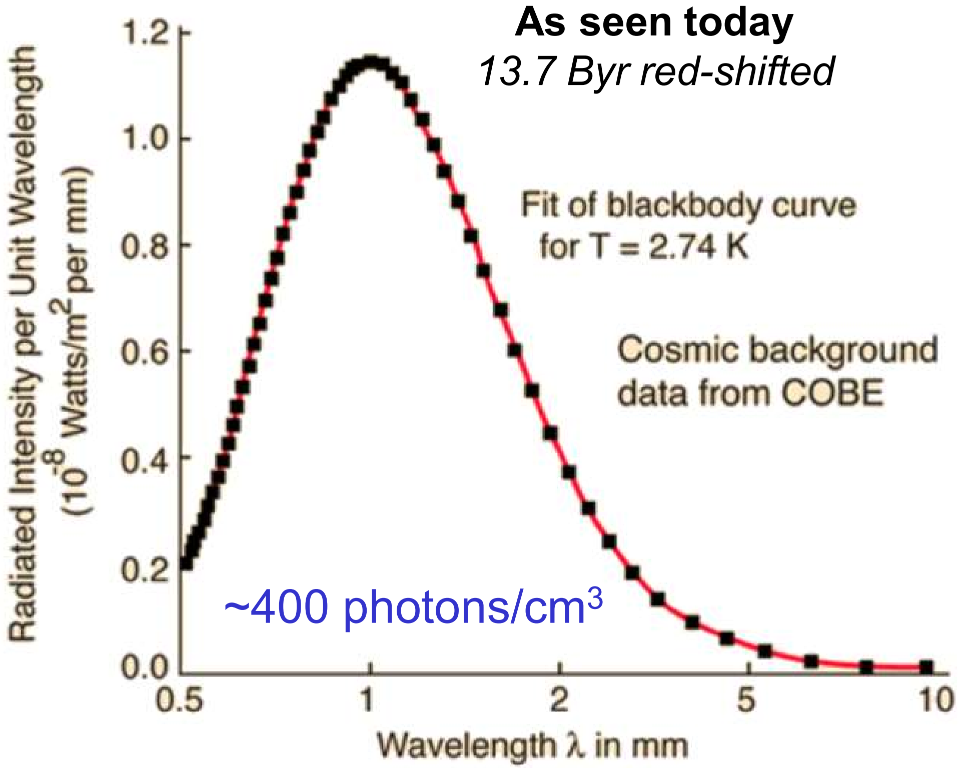




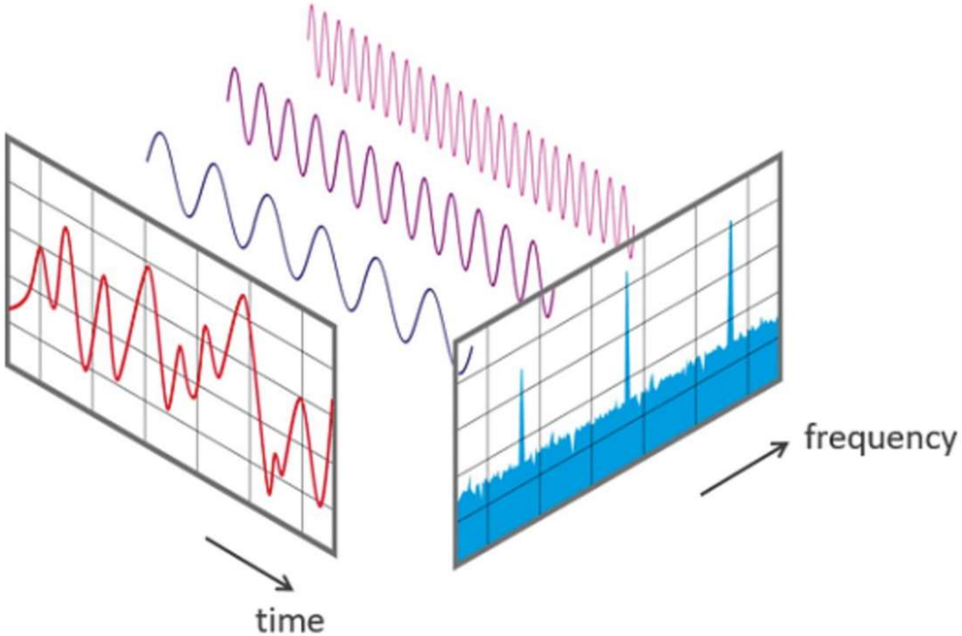
Intermezzo

- **When you listen to a note played by a musical instrument …**
  - … you can directly infer what is the instrument. How it is possible ?

Uniform blow
in a music instrument

Ear
+ brain

➔ **Spectral analysis (Fourier transform):**
Which material produce this sound



Cosmic microwave background

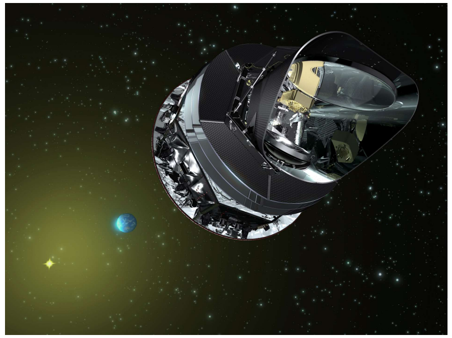
- Use this photon flux to know the composition of the Universe

Uniform blow
in a music instrument

Ear
+ brain

→ **Spectral analysis (Fourier transform):**
Which material produce this sound

Uniform light
in the whole Universe

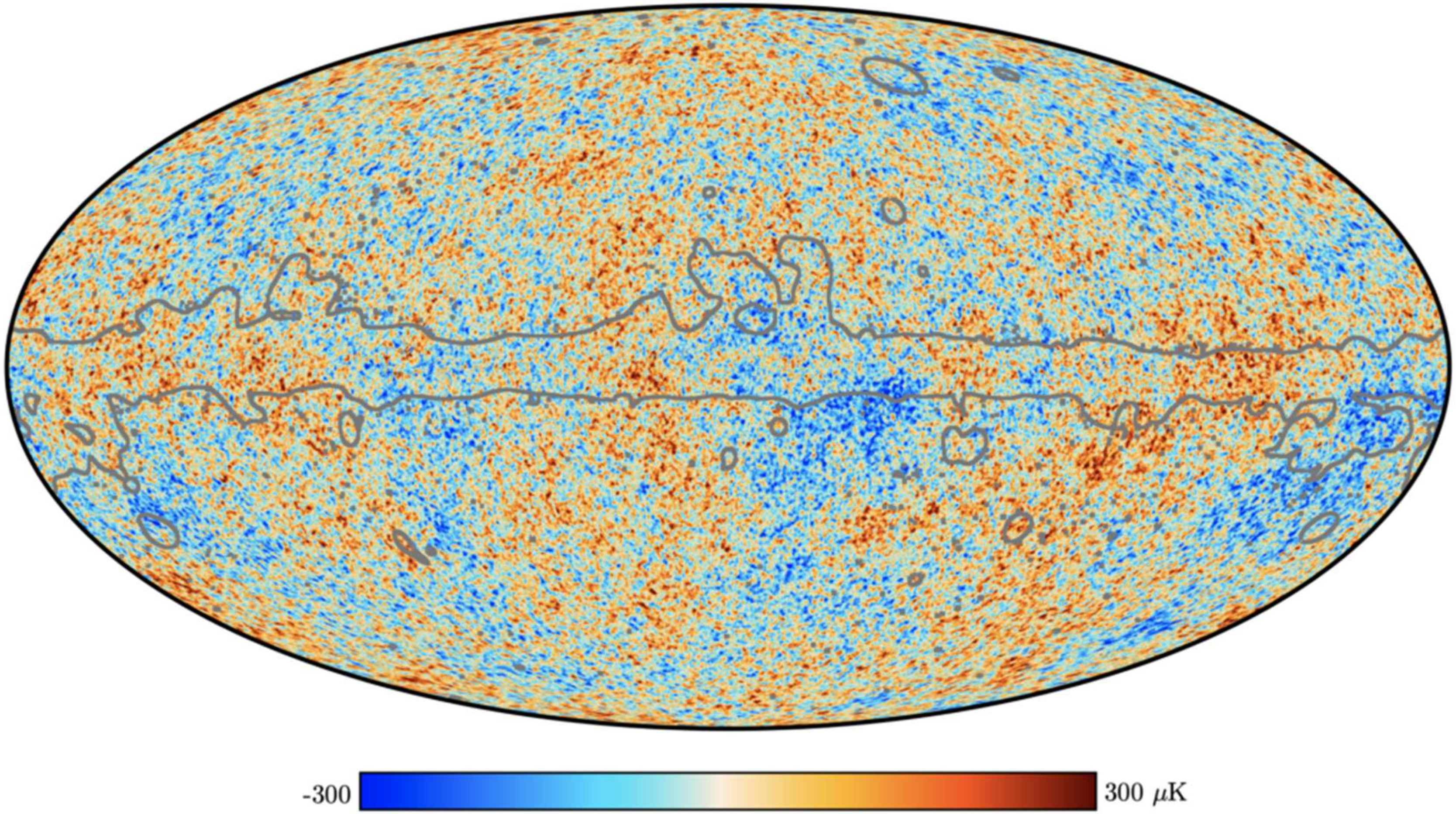


Spatial telescope
+ computer

→ **Angular analysis of thermal fluctuation around 2.74 K:**
What is the Universe composition ?

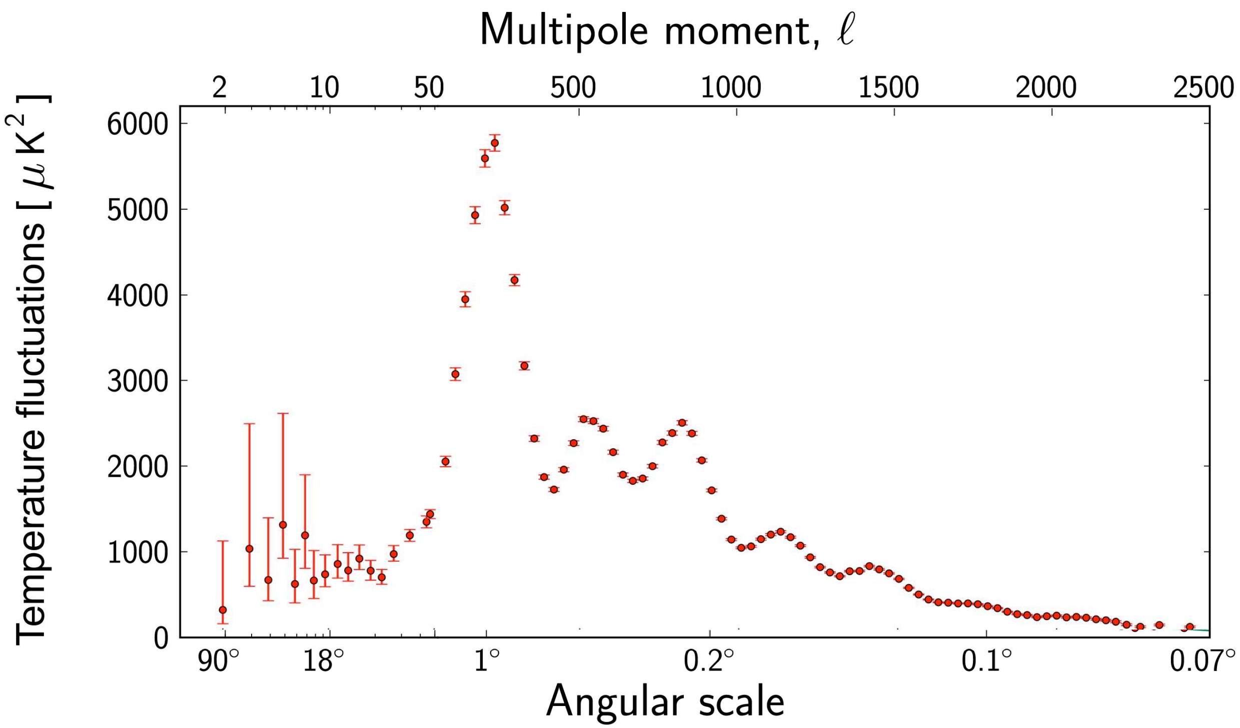
Cosmic microwave background

- **Use this photon flux to know the composition of the Universe**
  - Very small anisotropy (μK) observed – once background subtracted



Cosmic microwave background

- **Use this photon flux to know the composition of the Universe**
  - Decompose data in spherical harmonics
  - Amplitude and position of "acoustic" peaks gives the composition of the Universe



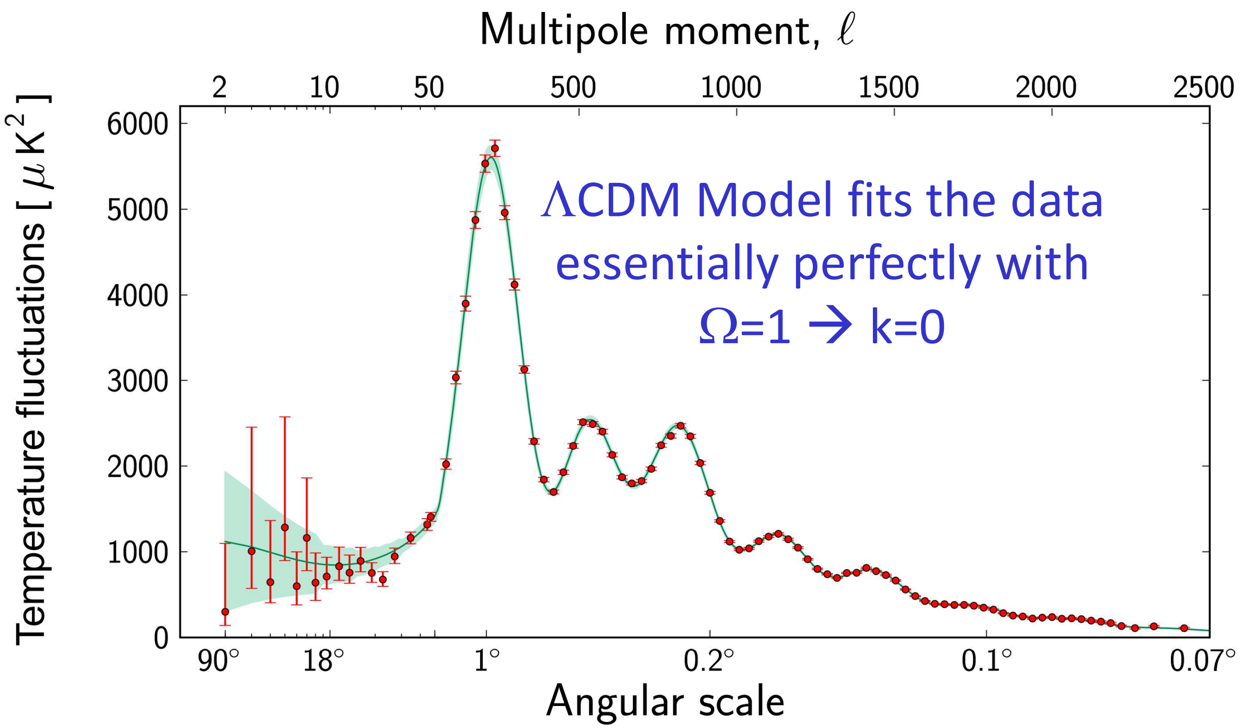
ΛCDM Model
- ✓ Matter particles (p, n, e-)
- ✓ Cold Dark Matter (CDM)
- ✓ Radiation (γ, ν)
- ✓ Dark Energy (Λ)

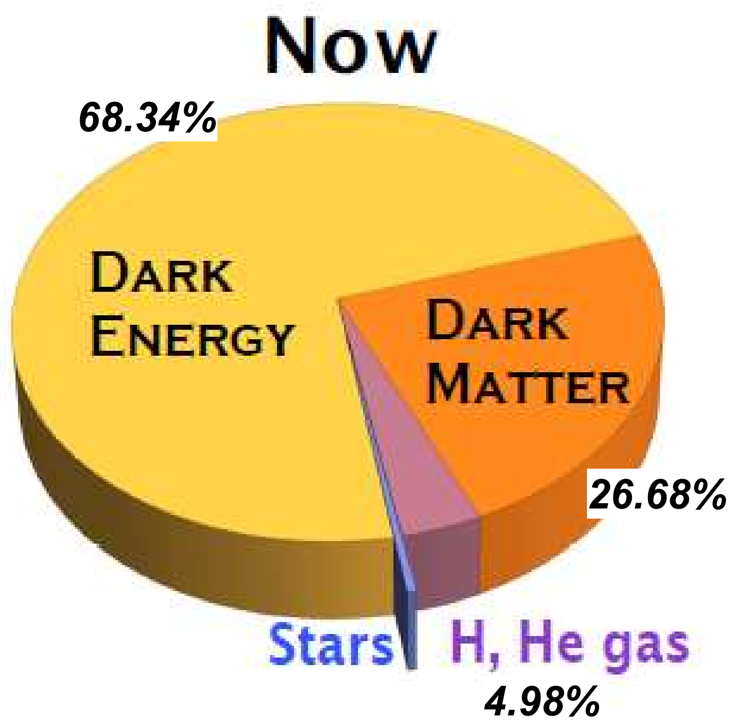
Ready to extract the abundances Ω of the ΛCDM Model ?

Cosmic microwave background

❑ **Use this photon flux to know the composition of the Universe**

- Decompose data in spherical harmonics
- Amplitude and position of “acoustic” peaks gives the composition of the Universe



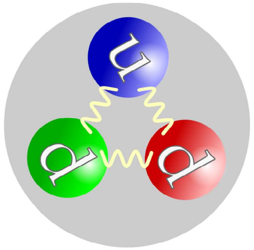


Cosmology is making precision measurements **… and**
we don’t know 95% of the Universe and 85% of the matter !

Axion

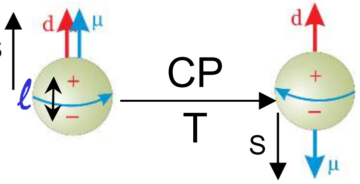
❑ Strong CP problem

- Neutron electric dipole moment: $d_e \approx q.\ell.\Theta = 10^{-16}\,\Theta$ e.cm



$Q_u = (2/3)\,e$
$Q_d = (-1/3)\,e$

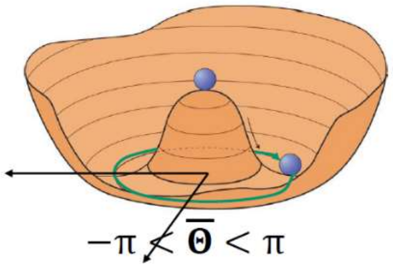
Neutron
(udd, S=1/2)



- Measure $d_e < 10^{-26}$ cm → $|\Theta|$ **< 10^-10, why ??**
- Global $U(1)_{PQ}$ symmetry *(Peccei-Quinn, 1977)* spontaneously broken at scale f_a

U(1) with Peccei-Quinn symmetry breaking

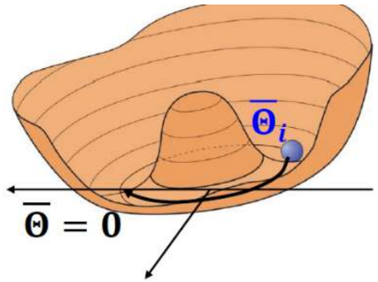
f_a



Axion, a massless and neutral scalar boson, is created, $\overline{\Theta} = \Theta_i$

QCD: explicit symmetry breaking

250 MeV



Axion oscillates around $\overline{\Theta}=0$ → mass $m_a=\nu_a$

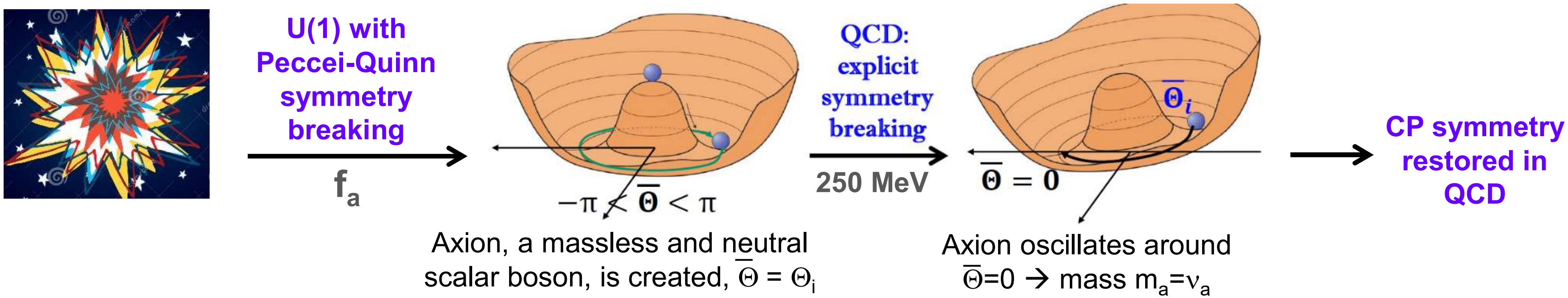
→ CP symmetry restored in QCD

Axion

- ✓ Massive
- ✓ Neutral
- ✓ Stable
- ✓ Weakly interacting
- ✓ Non relativistic

❑ Strong CP problem ($|\Theta| < 10^{-10}$)

- Global $U(1)_{PQ}$ symmetry *(Peccei-Quinn, 1977)* spont. broken at scale f_a



- Consequence: neutral scalar boson created = **axion** *(Weinberg-Wilczek, 1978)*
  - ✓ Properties given by the scale of symmetry breaking f_a [$f_a >> f_{EWSB}$]
  - ✓ Very weakly interacting with SM [f_a suppressed] and stable [f_a enhanced] : $\tau_{axion} > t_{Universe}$
  - ✓ Tiny mass [$m_a \approx m_\pi f_\pi / f_a$ << eV]
  - ✓ Non-relativistic [v_a << c]: time scales >> oscillation period

Axion is a very good dark matter candidate ($10^{-15}<m_a<10^{-12}$ GeV)

$1<m_a<10^3$ μeV

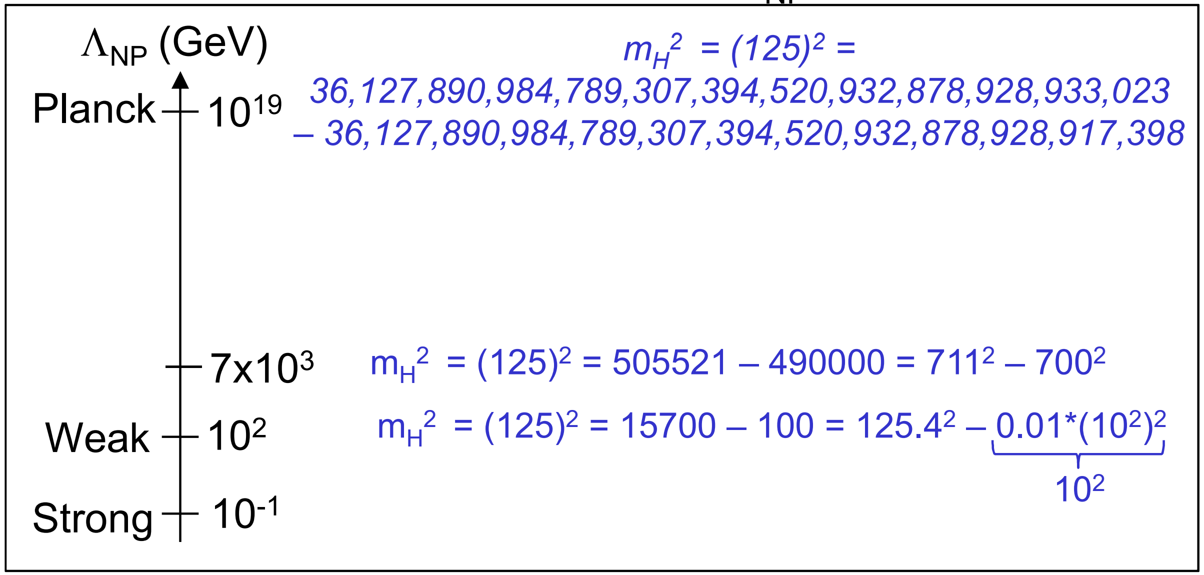
Lightest SUSY Particle

- ✓ Massive
- ✓ Neutral
- ✓ Stable
- ✓ Weakly interacting

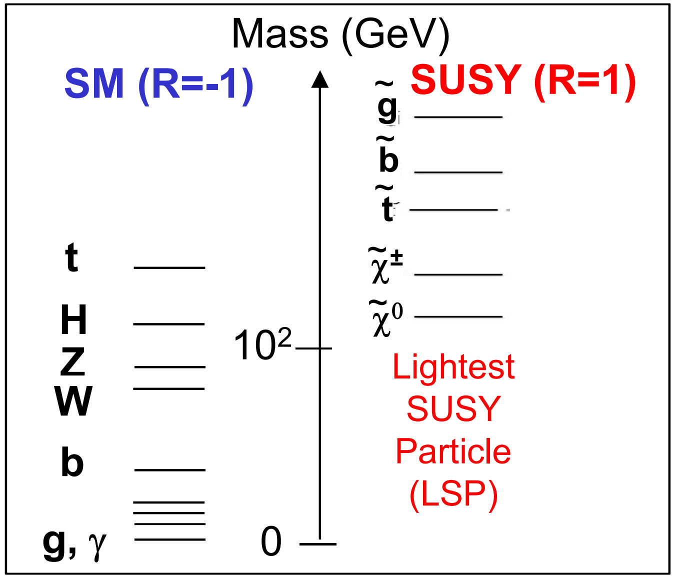
❑ Higgs mass fine tuning (a.k.a. gauge hierarchy problem)

- Corrections to the Higgs mass *(ΔM)* increase with E: $m_H^2 = (m_H^2)_0 - \Delta M^2$
- Add new 'mirror' SUSY particles* to mitigate the problem

$\Delta M^2 \approx 0.01 \Lambda^2_{NP}$



$\Delta M^2 \approx 0.01(m_{SUSY}^2 - m_{SM}^2) \ln(\Lambda_{NP}/m_{SUSY})$



- LSP χ: stable *(protected by a new R symmetry)*, massive, neutral, weakly interacting

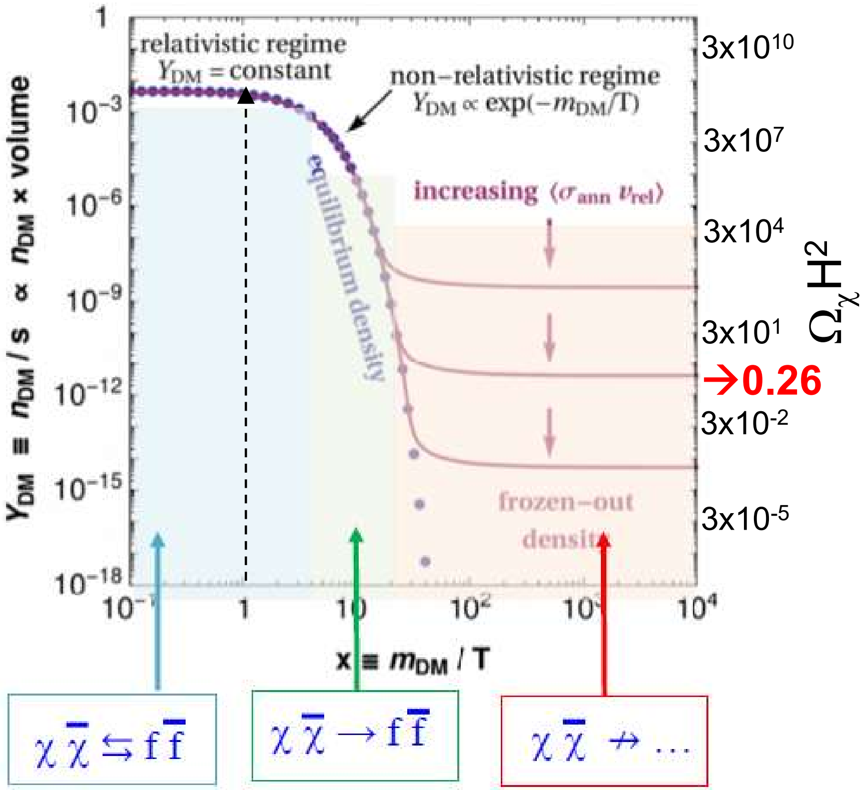
* Same quantum numbers as SM particles but the spin (S-1/2) and the mass (as SUSY us broken).

Lightest SUSY Particle

- ✓ Massive
- ✓ Neutral
- ✓ Stable
- ✓ Weakly interacting
- ✓ Non relativistic

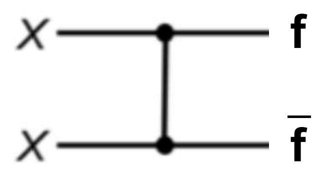
❑ Thermal production in the Early Universe

- When T(K) < m_χ, $\chi\,\chi$ → f f ↗ to maintain thermal equilibrium
- ρ_χ drops so that $\chi\,\chi$ → f f stops: freeze-out with χ non-relativistic



WIMP Miracle

$$\Omega_X \propto \frac{1}{\langle\sigma v\rangle} \sim \frac{m_X^2}{g_X^4}$$



Assuming g_{DM} = weak interaction = 0.6 and $\Omega\chi = \Omega_{DM}$ **= 0.26 → m_χ ~ 200 GeV**

Close to the EWSB scale → Miracle ?

Weakly interacting Massive Particle)

χ is a very good dark matter candidate called WIMP ($10<m_\chi<10^4$ GeV)