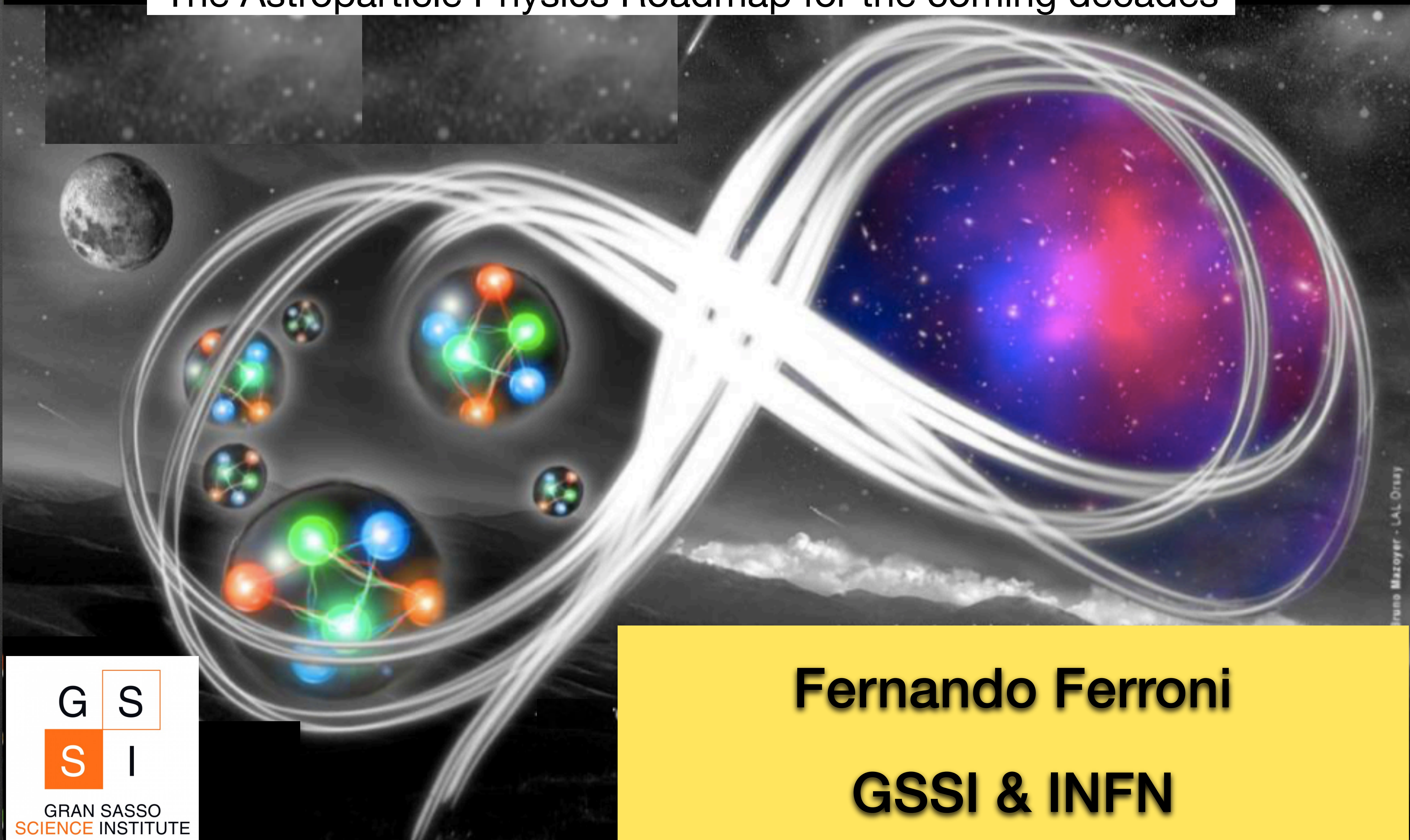
The physics of two infinities

"The Astroparticle Physics Roadmap for the coming decades"



Fernando Ferroni

GSSI & INFN

GRAN SASSO SCIENCE INSTITUTE

Cuando tenìamos las respuestas,
nos cambiaron las preguntas

Victims of too much success

- By the end of the 20th century …
  we have a comprehensive, fundamental theory of all observed forces of nature which has been tested and might be valid from the Planck length scale [10^{-33} cm.] to the edge of the universe [10^{+28} cm.]

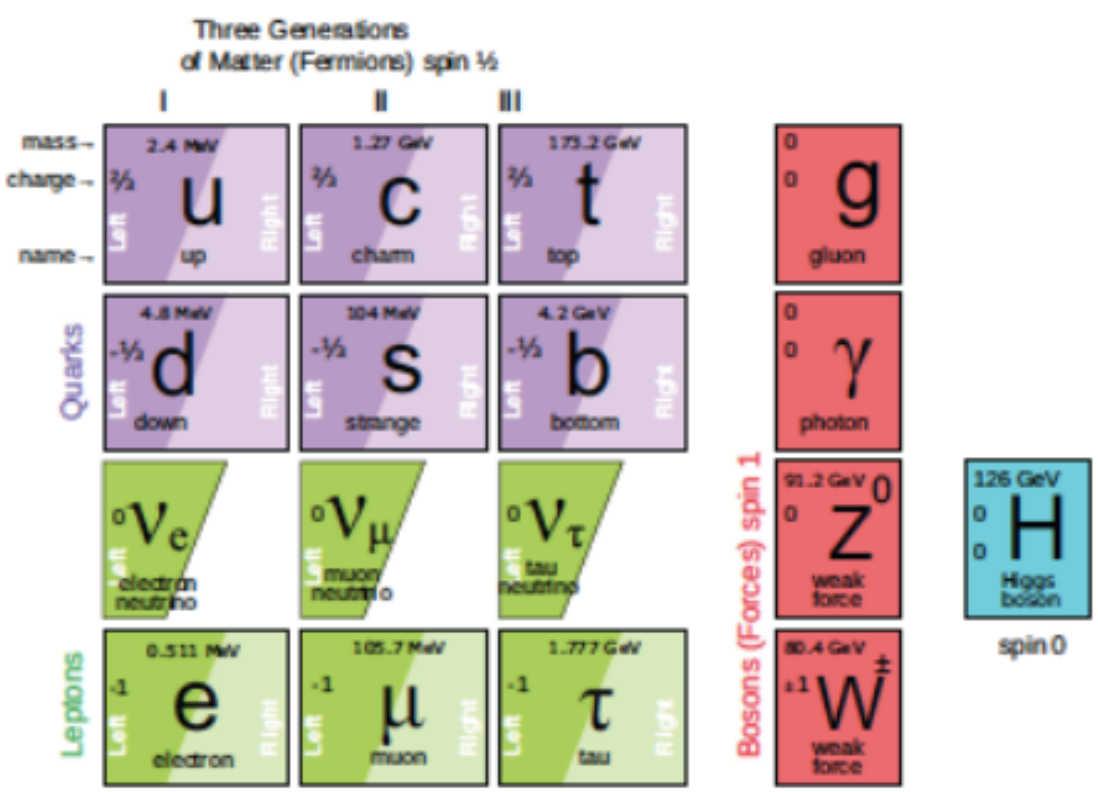
  D. Gross 2007

The time of Glory

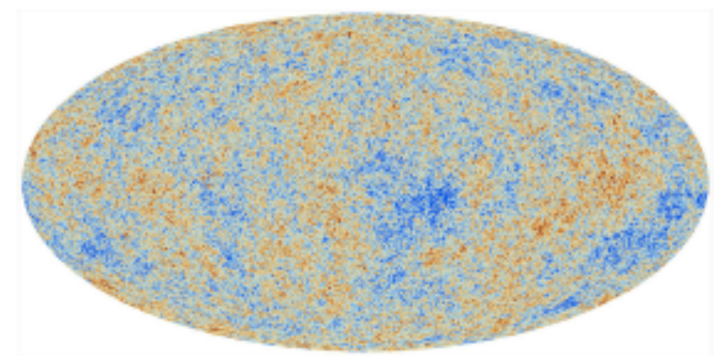
2013 – 2016 : the triumph of the

STANDARD

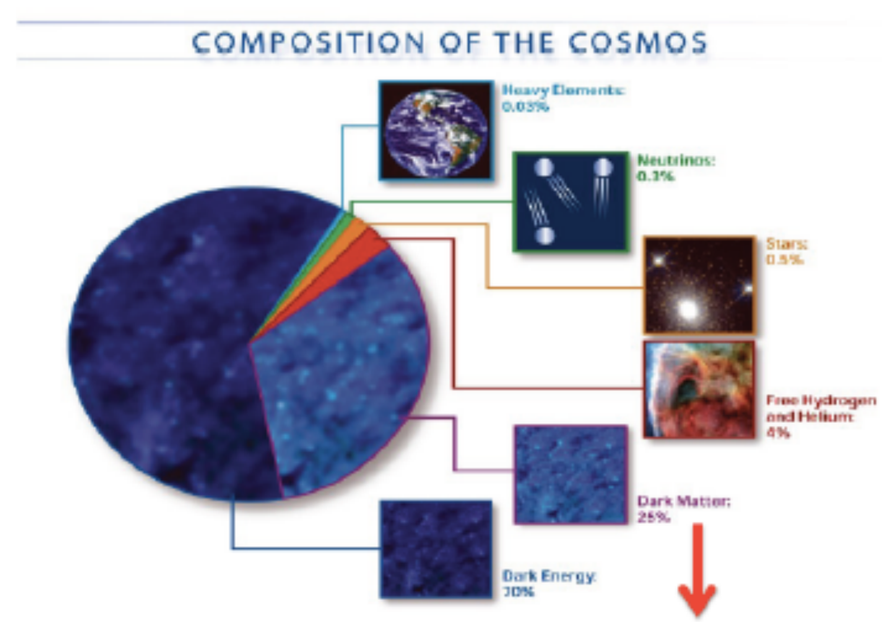
- **PARTICLE STANDARD MODEL**



- **COSMOLOGY STANDARD MODEL**



ΛCDM + “SIMPLE” INFLATION



The Standard Models

Are the SMs really STANDARD?

G-W-S SM

- **All the experimental results** of both **high-energy particle physics** and **high-intensity flavor physics** are surprisingly (and embarrassingly) in **very good agreement** with the predictions of the GSW SM

ΛCDM SM

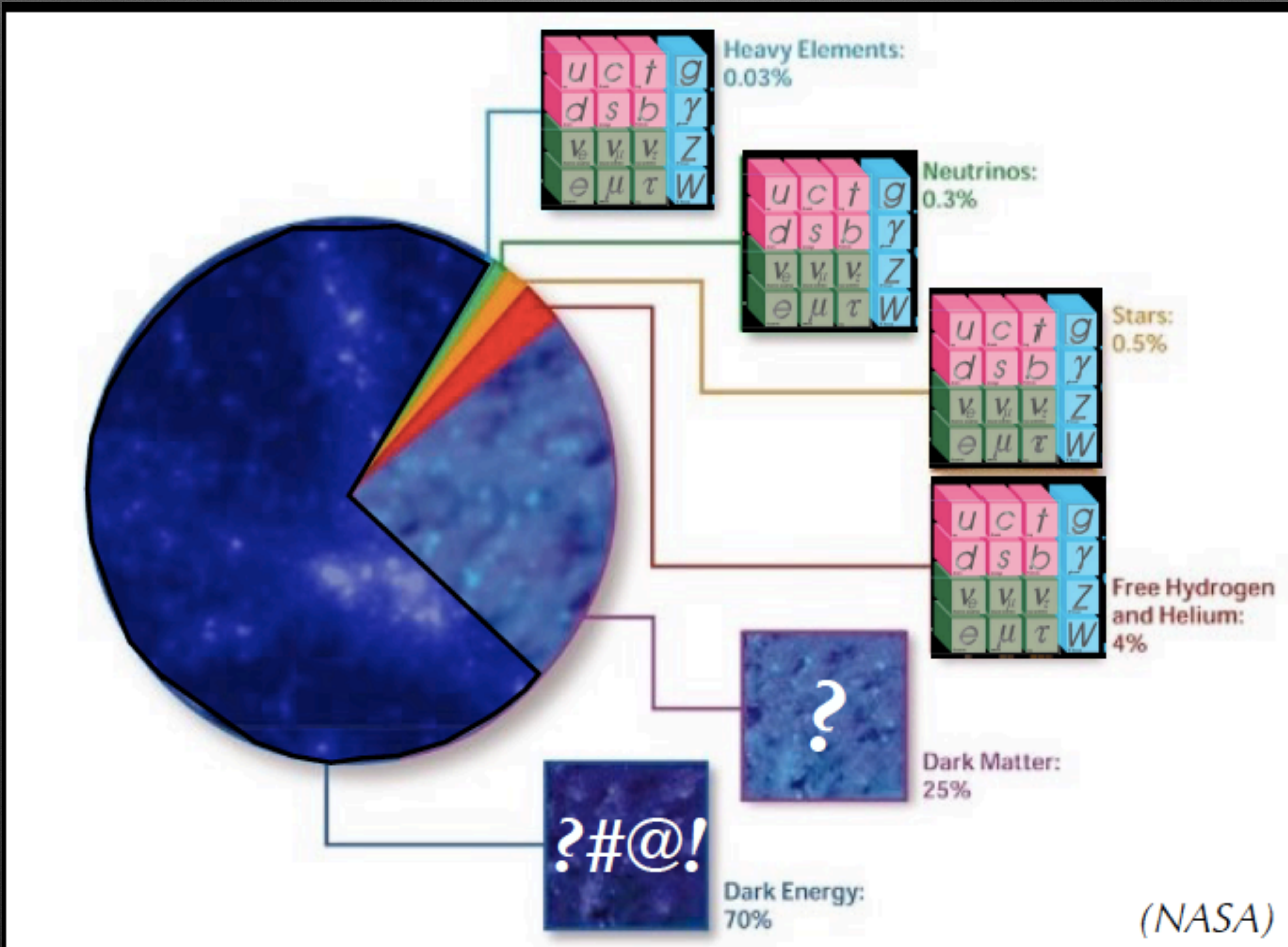
- **All the cosmic observations are in agreement** with the ~25% CDM, ~70% cosmological constant **Λ ,** ~5% ordinary matter of the **ΛCDM SM**

This extraordinary rosy picture that somebody would quote as ‘the end of the physics’ presents in reality quite a few problems. On both sides.

The G-W_S model does not account properly for neutrinos and cannot give reason for the Higgs mass.

The ΛCDM model has yet to incorporate inflation, find what DM is, give a reason for accelerated expansion and reconcile the different values of H_0

Time of Questions



Micro and Macro

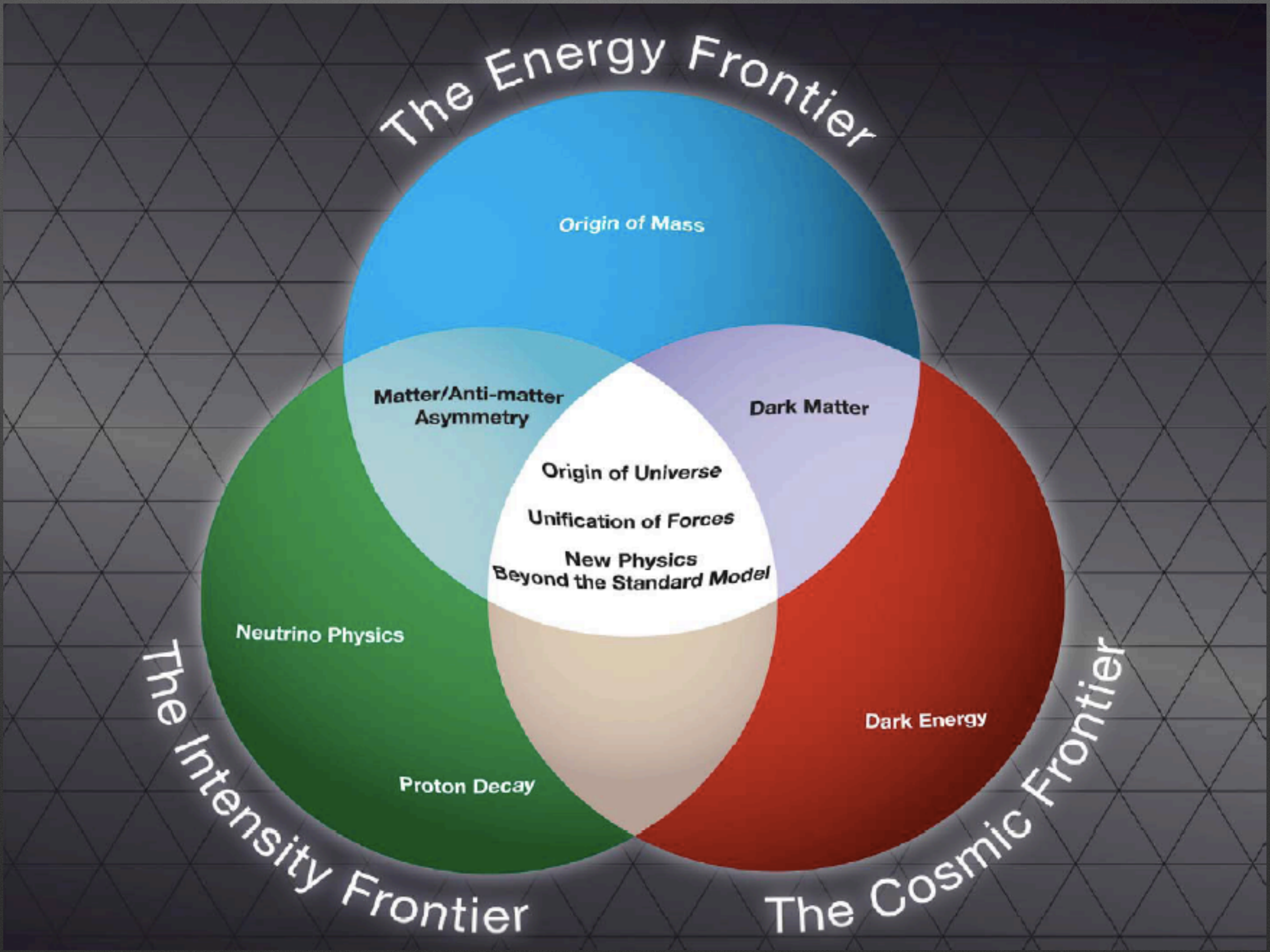
share common technology
and
common themes of research

- Most of the technology in Cosmic Rays (Space, Earth, Underwater) is of HEP origin

- Neutrinos, Dark Matter are of common interest

- Gravitational Waves is something different (although…)

Interlaced and Globalized



The ghost appearing every night to any sensible theoretician

New Physics
or
Beyond Standard Model

The two main arguments

- Neutrino mass does not fit in the simplicity of GWS SM
- Dark Matter is not made by quarks and leptons

and two mysteries

- Antimatter, how did you disappear ?
- Dark Energy, are you real ?

talking of neutrinos

- GWS SM made them massless (why so ? L conservation, a symmetry that looks accidental rather than fundamental)
- Neutrinos are massive
- A Dirac term can give a mass to neutrinos, like the other leptons, but now you say that L is conserved (and why so ?)
- Majorana term is however allowed and nobody knows why should not exist
- The hybrid Dirac-Majorana term is what opens the door of See-Saw mechanism
- Neutrinoless double beta decay is the only realistic option to test the hypothesis

Beware

“you may use any degrees of freedom you like to describe a physical system, but if you use the wrong ones, you will be sorry."

Weinberg’s Laws of Progress in Theoretical Physics
From: “Asymptotic Realms of Physics” (ed. by Guth, Huang, Jaffe, MIT Press, 1983)

First Law:

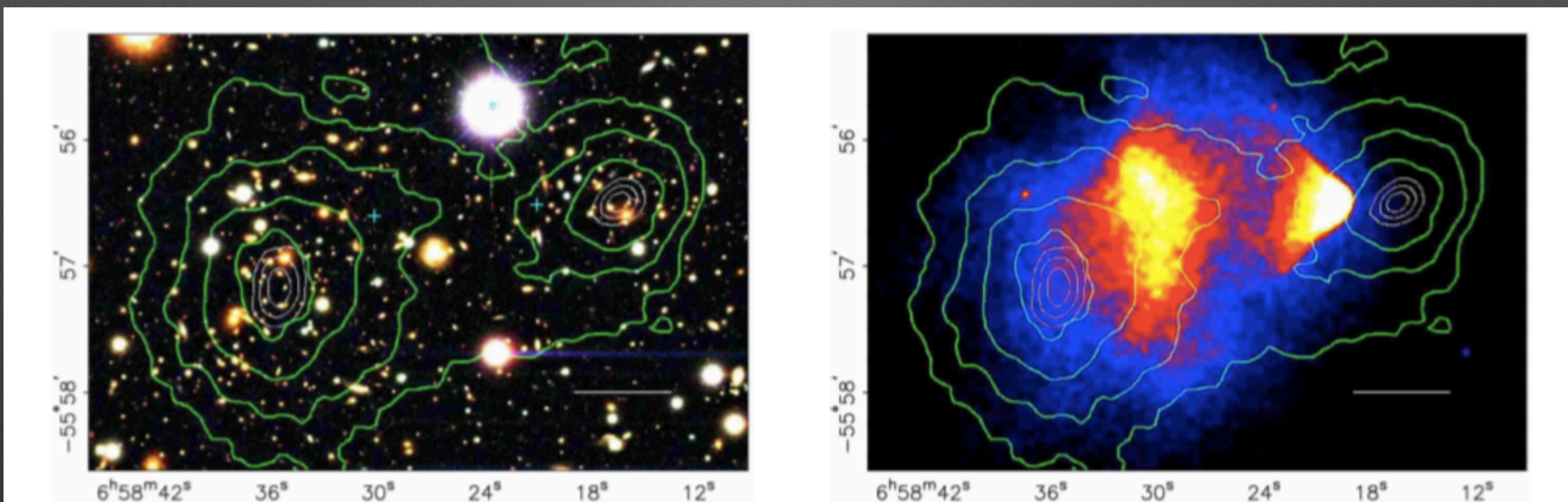
“The conservation of Information” (You will get nowhere by churning equations)
... garbage in, garbage out...

Second Law:
“Do not trust arguments based on the lowest order of perturbation theory”

Third Law:

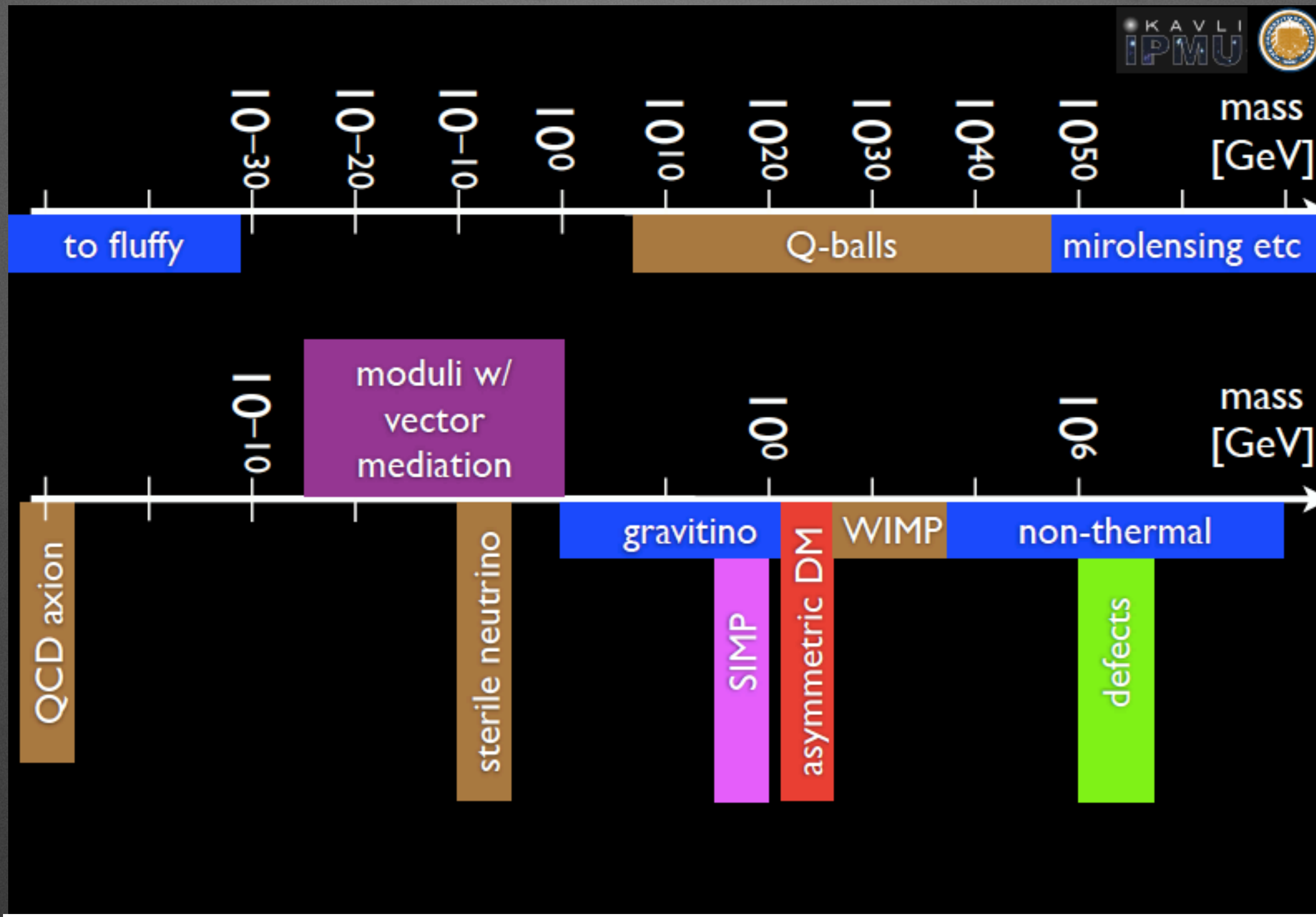
“You may use any degrees of freedom you like to describe
a physical system, but if you use the wrong ones, you’ll be sorry!”

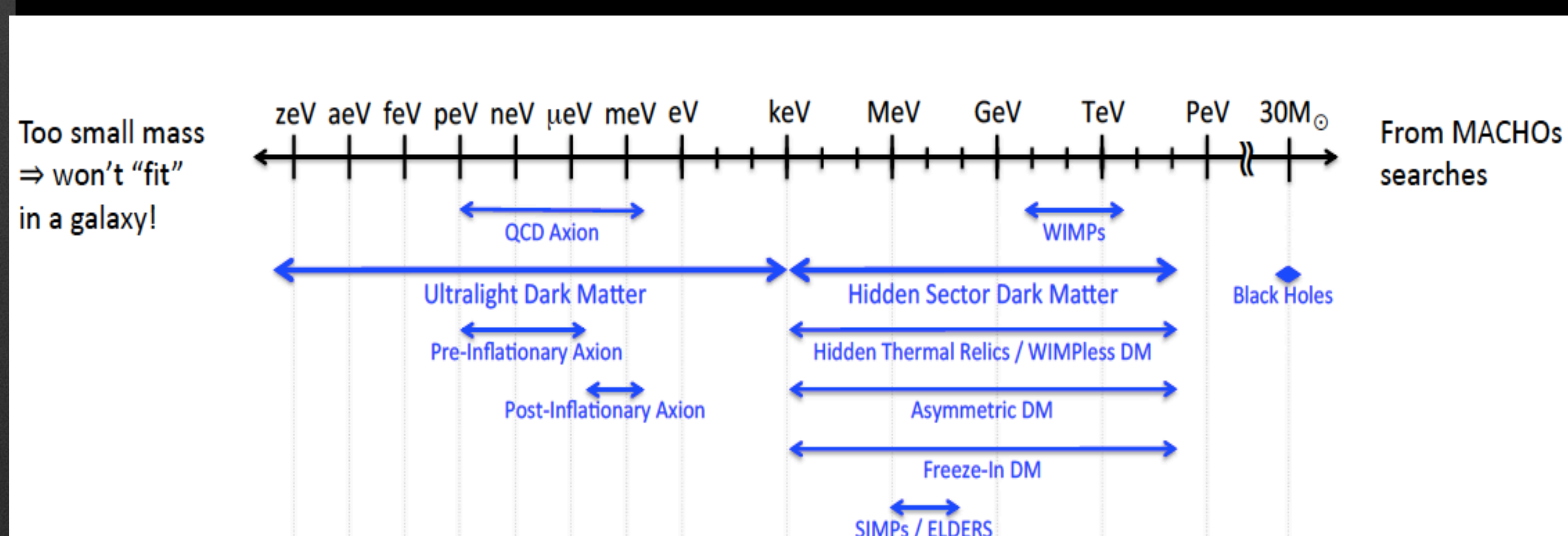
Rotation of galaxies, Einstein's ring and more….



Dark Matter is likely there !

but its nature is object of wild speculations





Rise and (possible) fall of a dream

The WIMP miracle

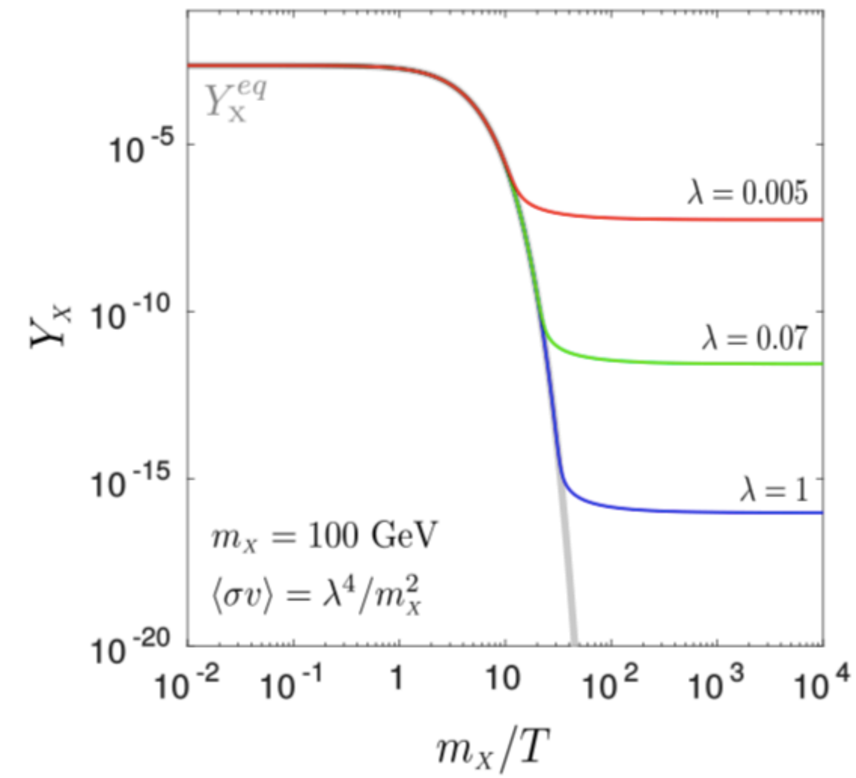
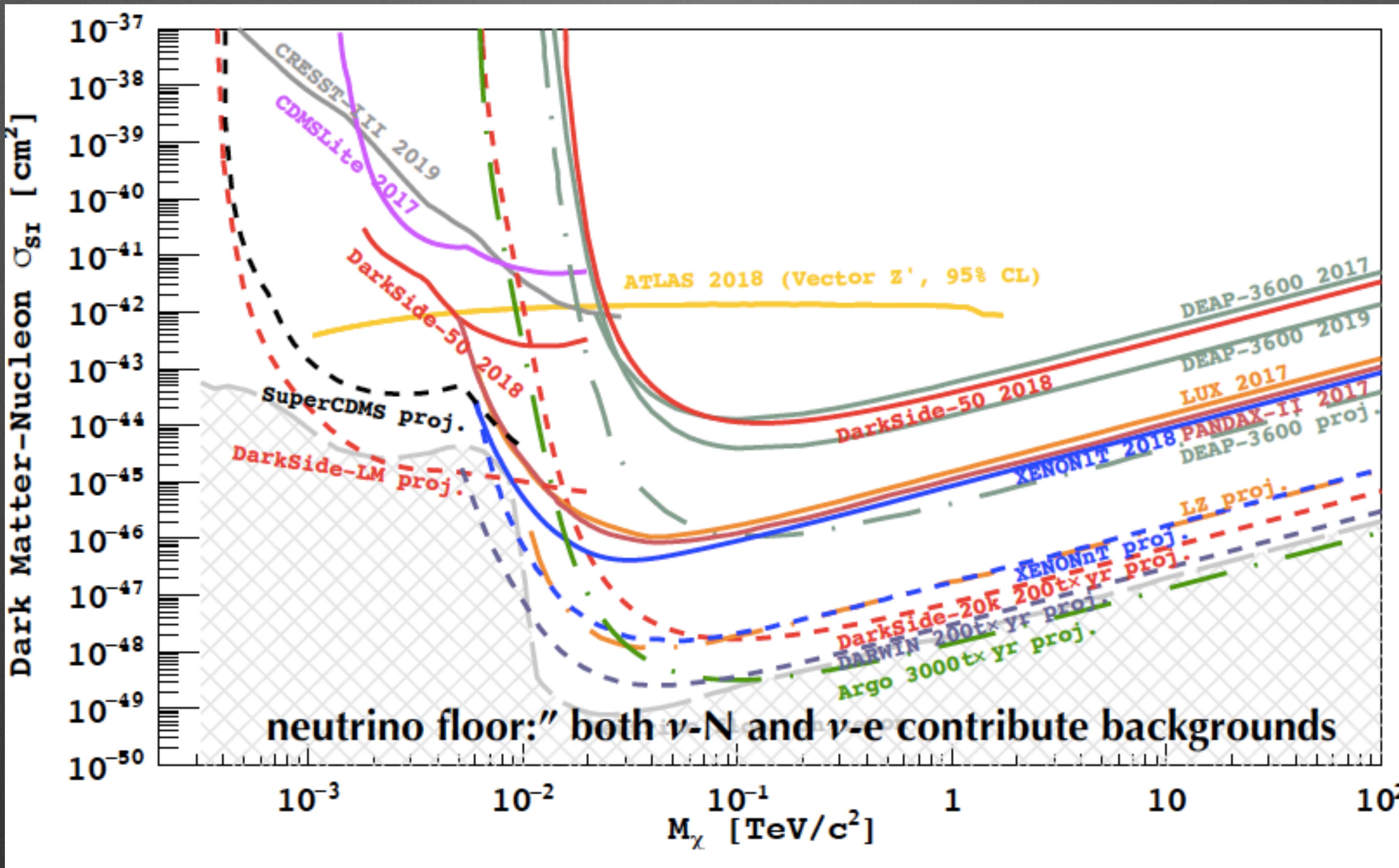


FIGURE 3.1 – *Exact solutions for the yield of a WIMP with mass m_X = 100GeV for three values of its coupling to SM: λ = 0.005 (blue curve), λ = 0.07 (green curve) and λ = 1 (red curve). Equilibrium curve is shown in gray. Notice that the stronger the interactions, the smaller the remaining WIMP relic.*

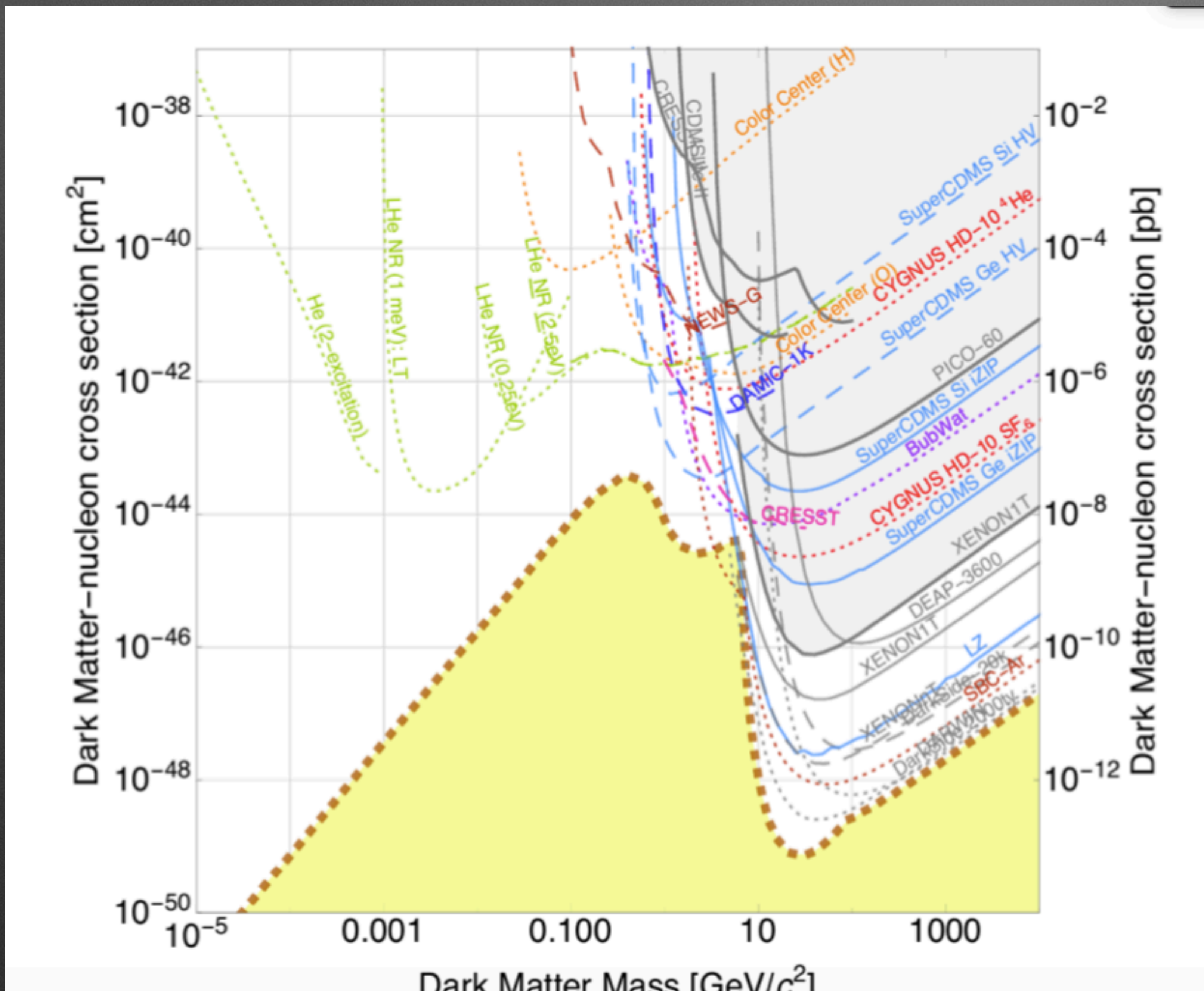
‘Therefore, if the scales of masses and couplings of WIMPs are close to the SM ones, the right amount of dark matter relic density is easily achieved. Moreover, WIMP candidates are a common byproduct of models in which new physics at weak scales solves problems of the SM. This coincidence is the so-called "WIMP miracle". The possibility of probing this scenario at colliders, underground detectors, telescopes and satellites had driven the efforts in the search for dark matter particles in the last decades.’

Point of views

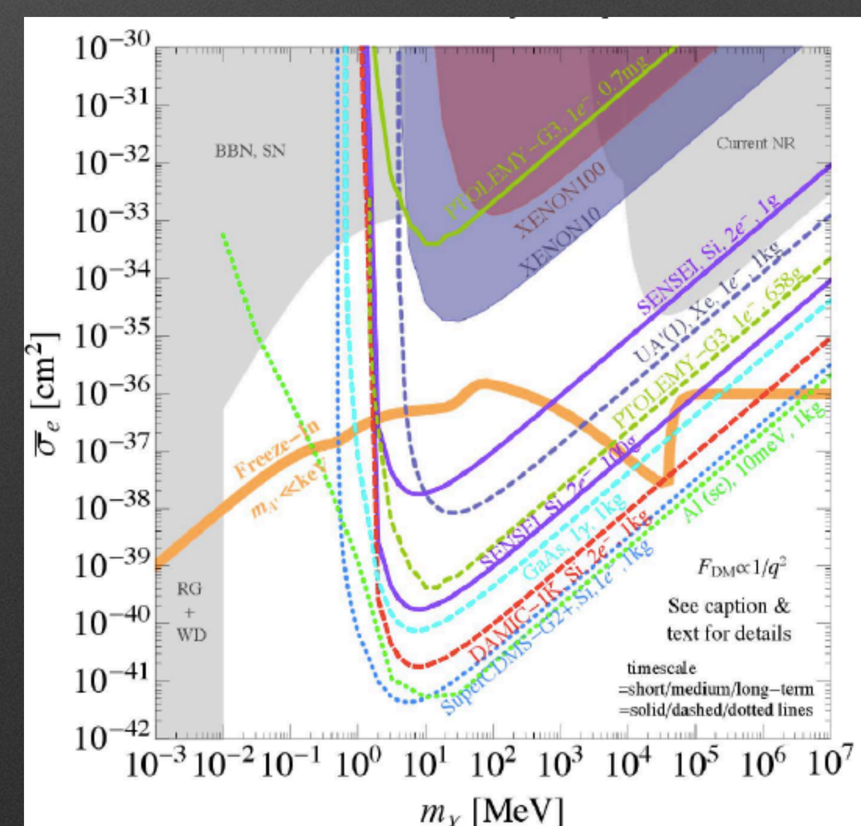


You could say that you are close to moment of truth

if you look with an other eye



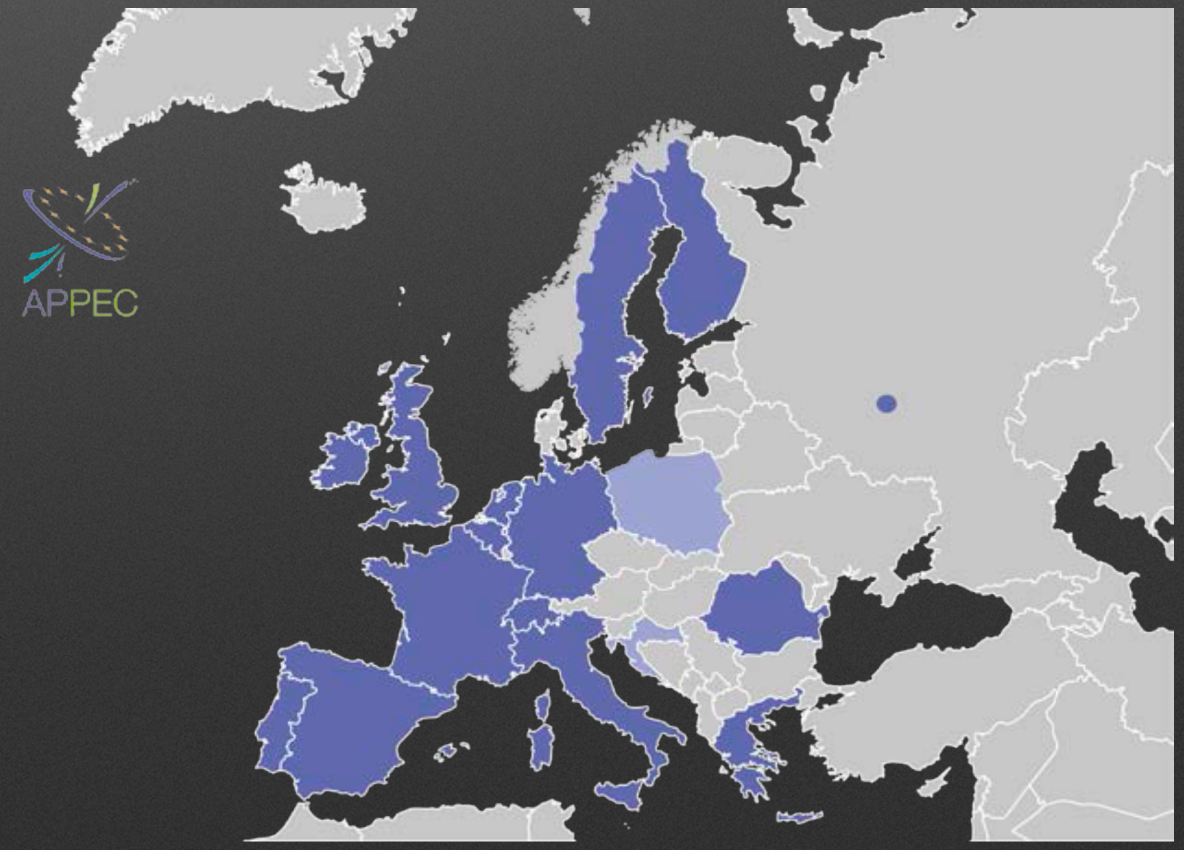
There is space for many



APPEC Roadmap

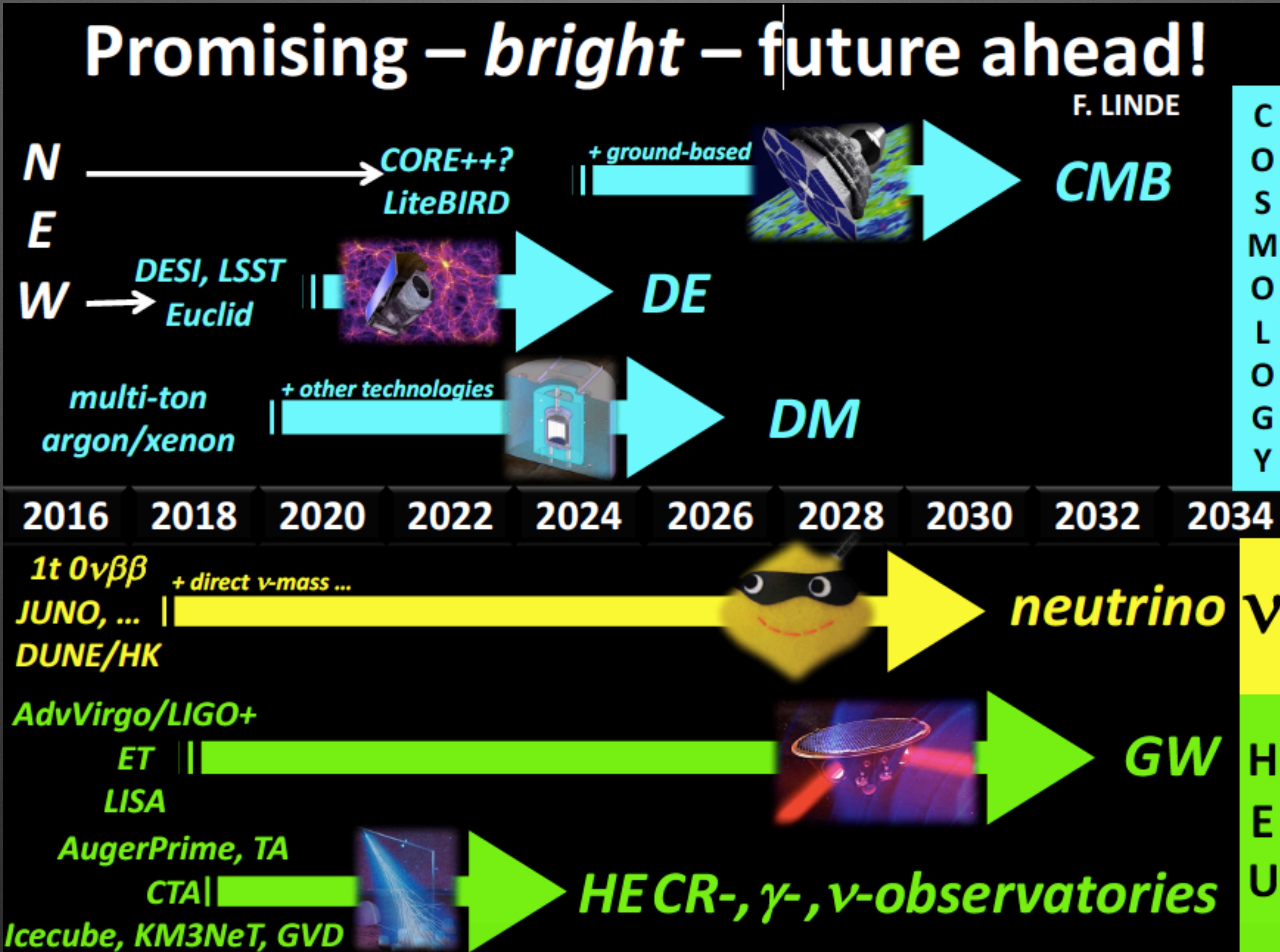
so what should we do
(You dear promising young researchers !)

In 2001, European scientific agencies founded APPEC (the Astroparticle Physics European Consortium).
Since 2012, APPEC became a consortium operated on the basis of a Memorandum of Understanding with the overarching aim of strengthening European astroparticle physics and the community engaged in this field.



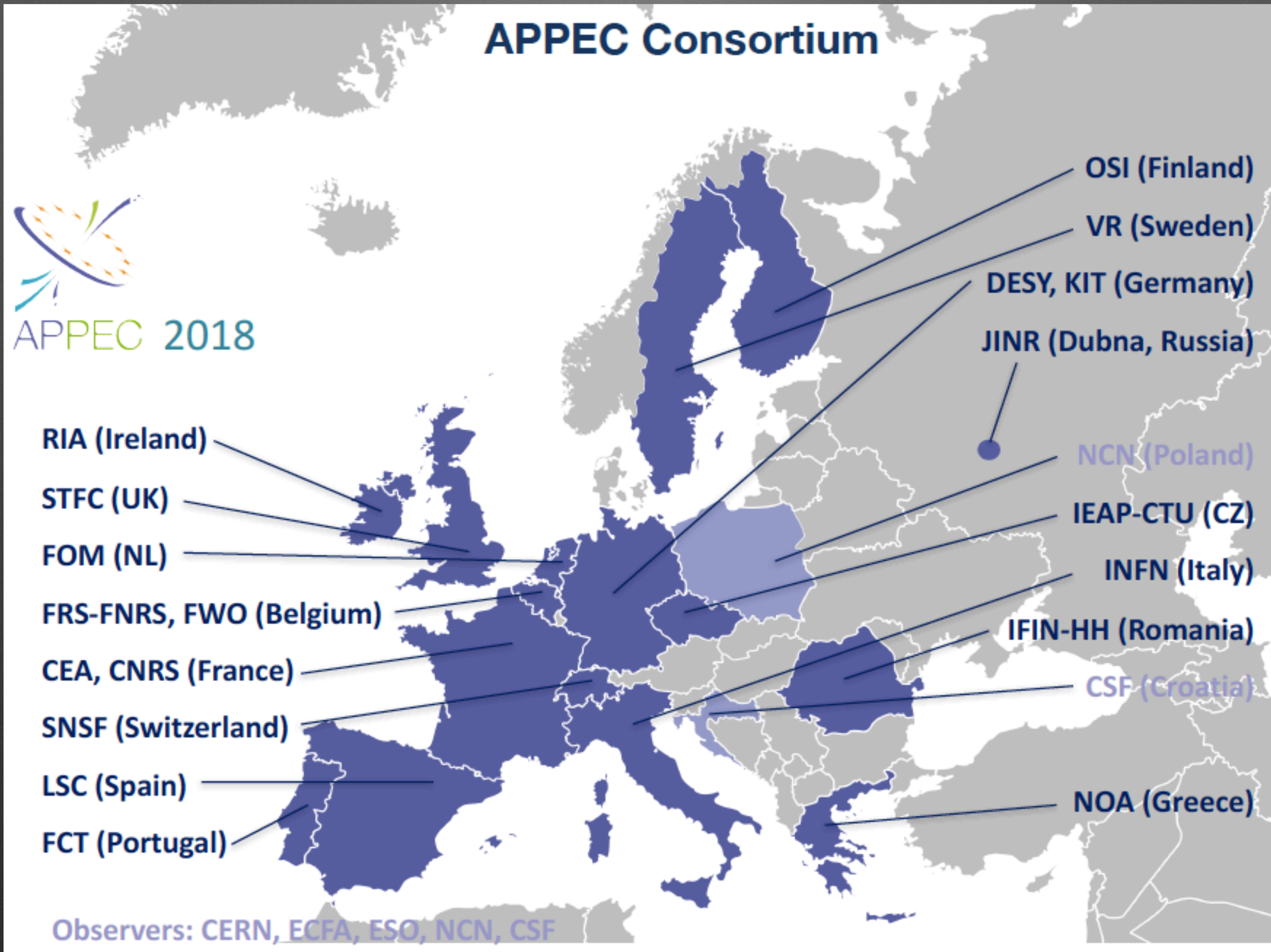
The wide field of investigation

- High Energy Gamma Rays
- High Energy Neutrinos
- High Energy Cosmic Rays
- Gravitational Waves
- Dark Matter
- Neutrino Mass and Nature
- Neutrino Mixing and Mass Hierarchy
- Cosmic Microwave Background
- Dark Energy


Promising – bright – future ahead!
F. LINDE
COSMOLOGY
N
E
W
CORE++?
LiteBIRD
+ ground-based
CMB
DESI, LSST
Euclid
DE
multi-ton
argon/xenon
+ other technologies
DM
2016
2018
2020
2022
2024
2026
2028
2030
2032
2034
1t 0νββ
JUNO, ...
DUNE/HK
+ direct ν-mass ...
neutrino
ν
AdvVirgo/LIGO+
ET
LISA
GW
AugerPrime, TA
CTA
Icecube, KM3NeT, GVD
HE CR-, γ-, ν-observatories
HEU

Crucial ingredients

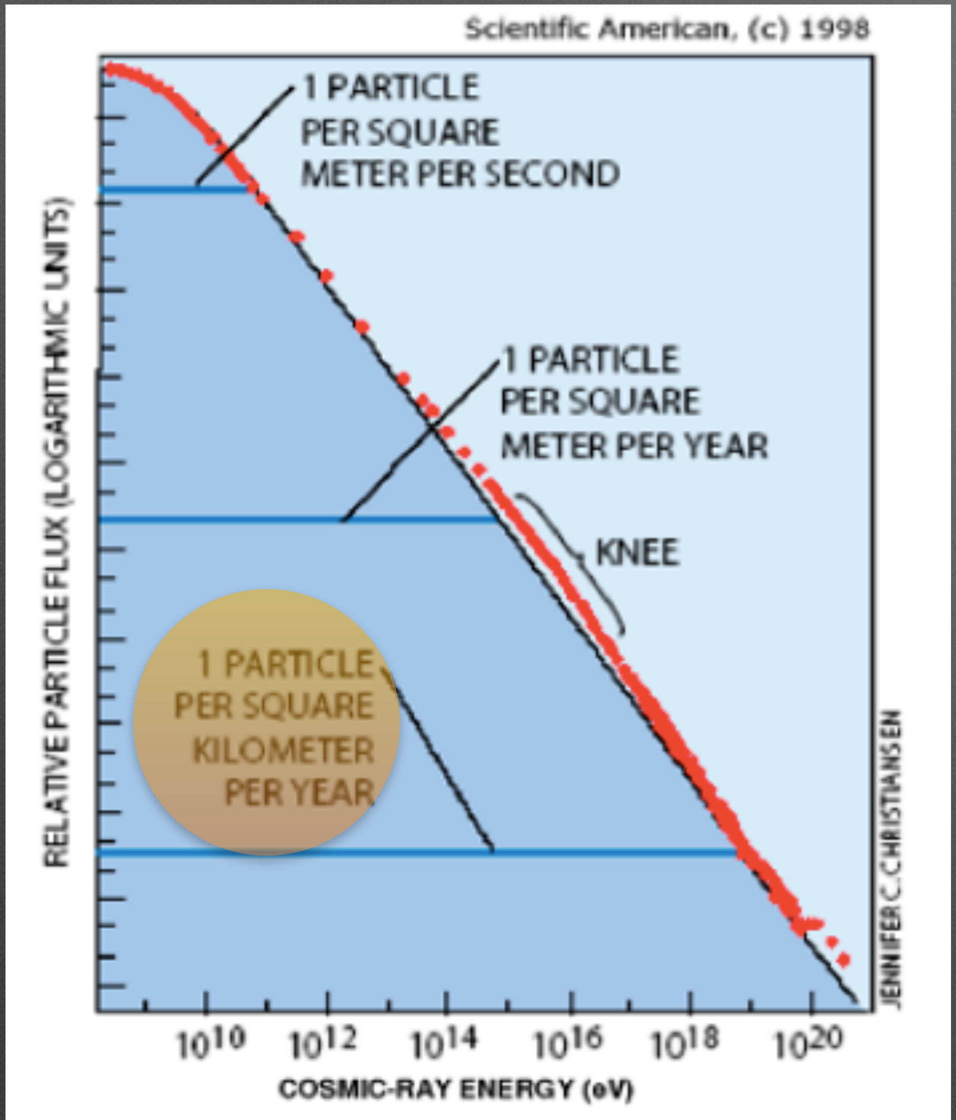
Getting Europe together



The wonderful world of Particles falling from the Sky

where the glory is in finding the sources

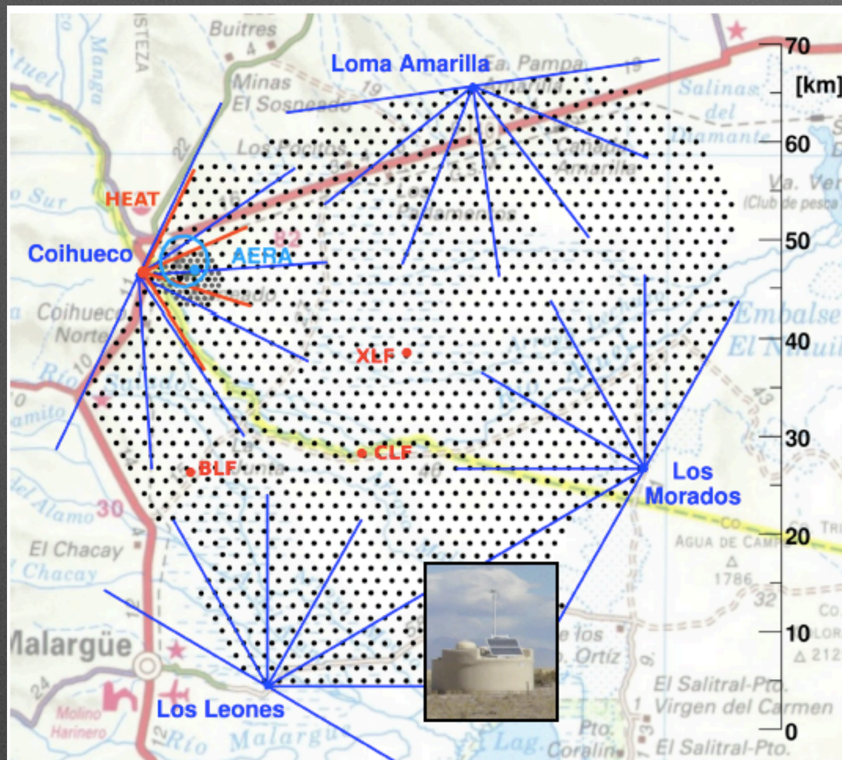
Charged Cosmic Rays

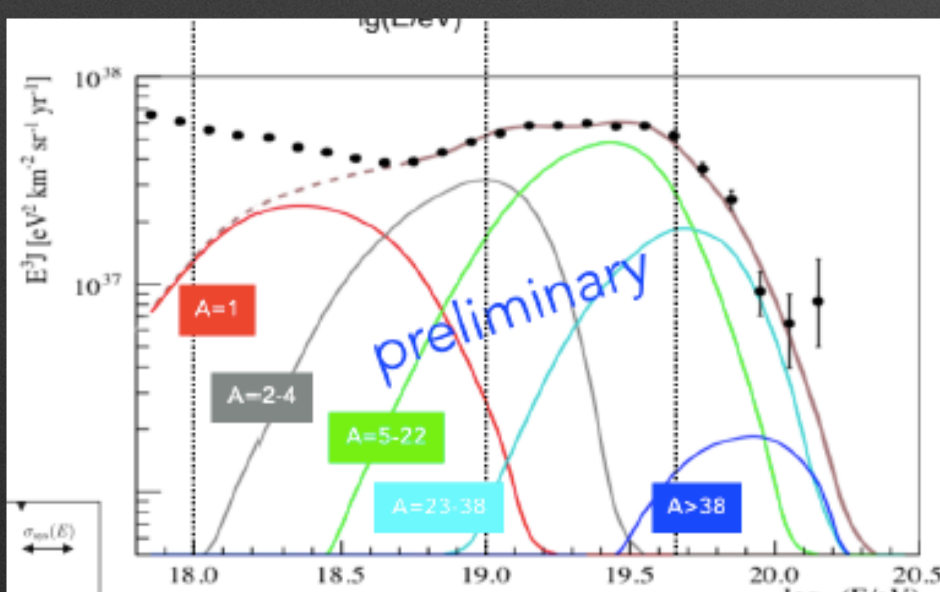


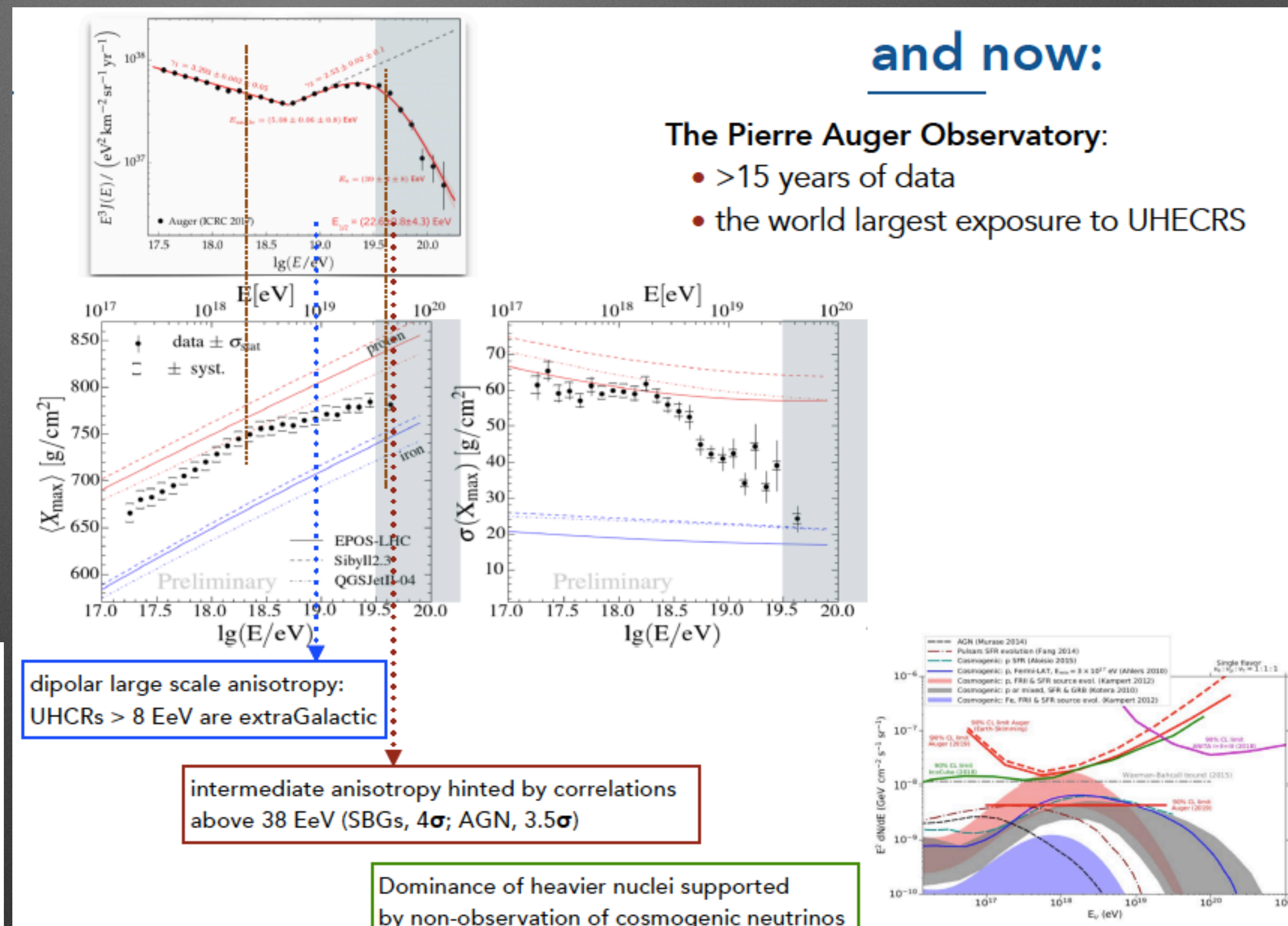
Schematic rendering of the Pierre Auger Observatory (Credit: Pierre Auger Observatory)

AUGER to AUGER Prime

Pierre Auger results







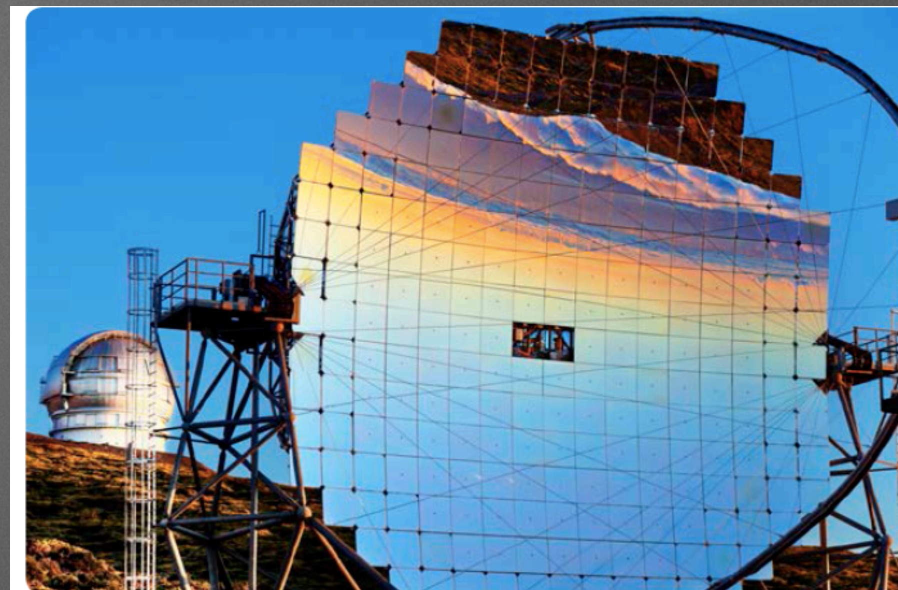
Auger Prime

- Chemical composition
- Nearby sources
- Neutrino showers
- Another piece of multi messenger astronomy

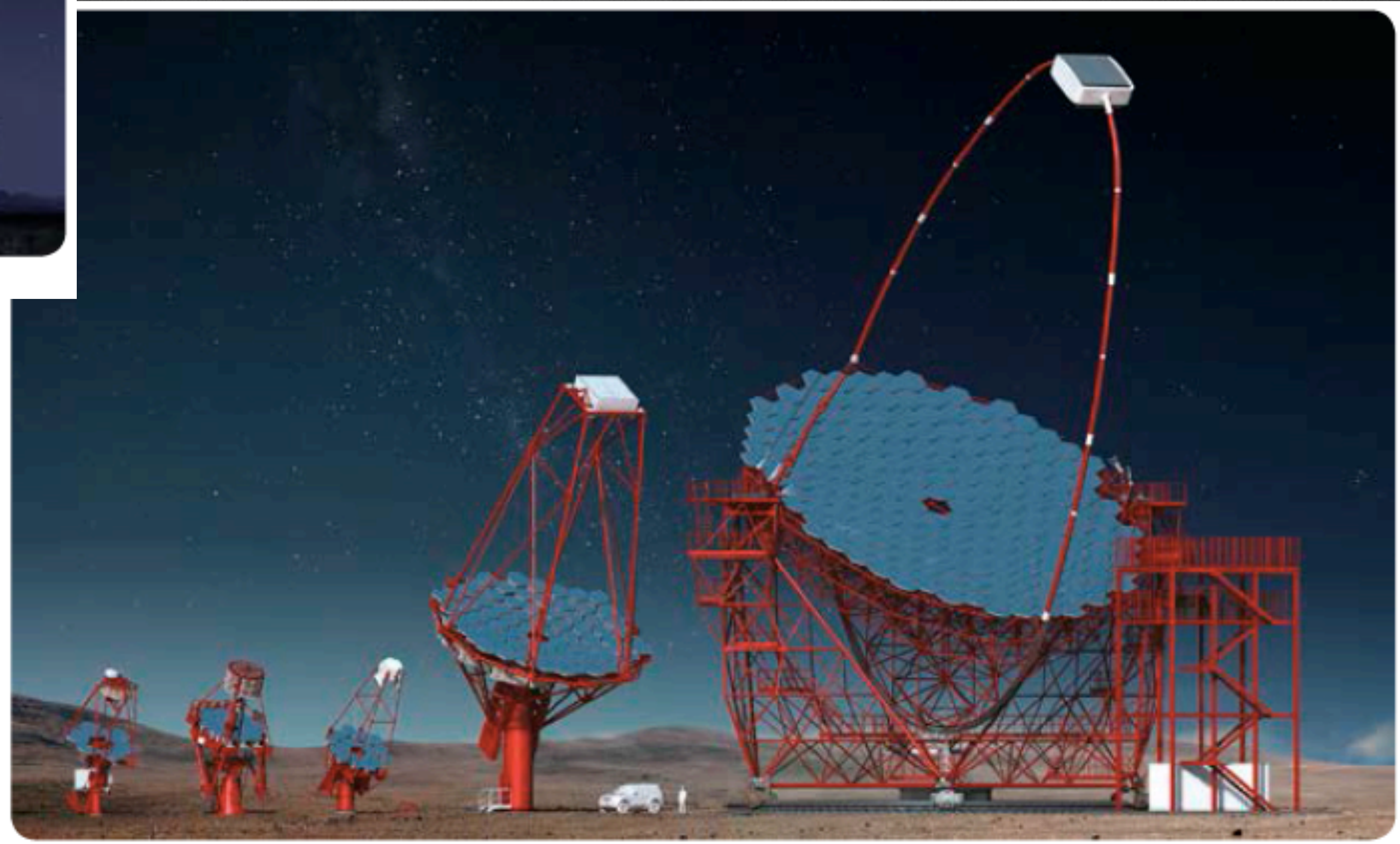
H. E. Gamma Rays


The Imaging Atmospheric Cherenkov Telescope principle

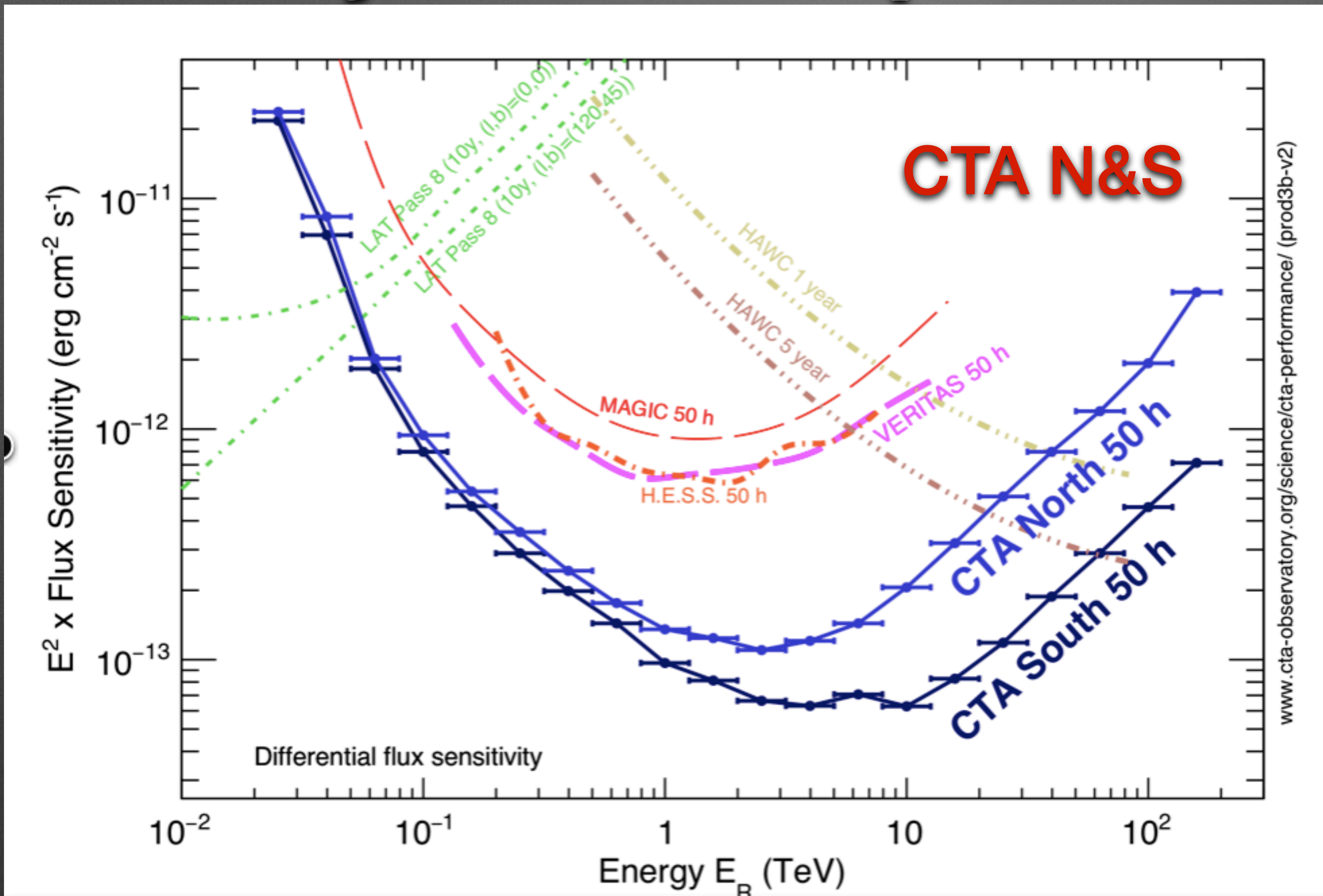
from MAGIC & HESS


MAGIC telescope, La Palma (Credit: CTA)

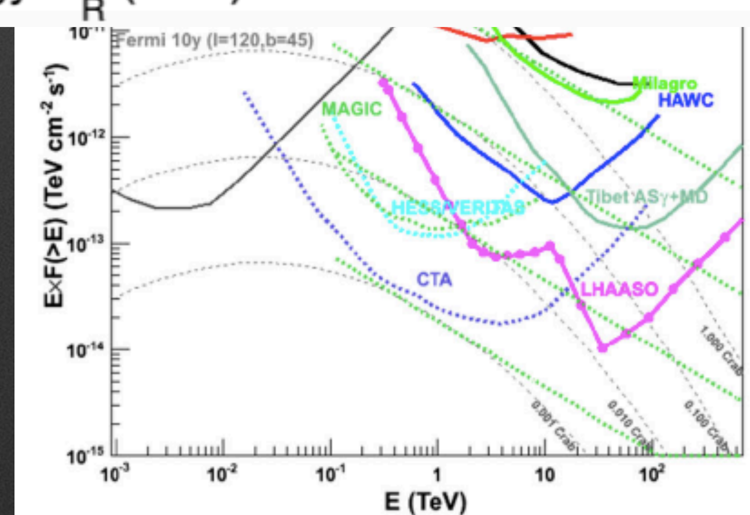
to CTA

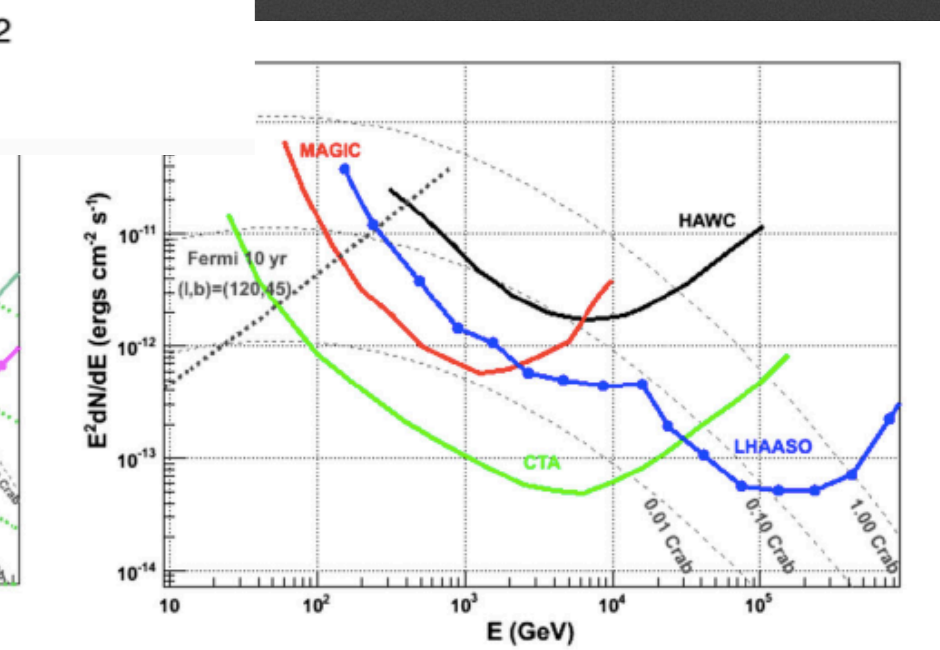


Projection of performances

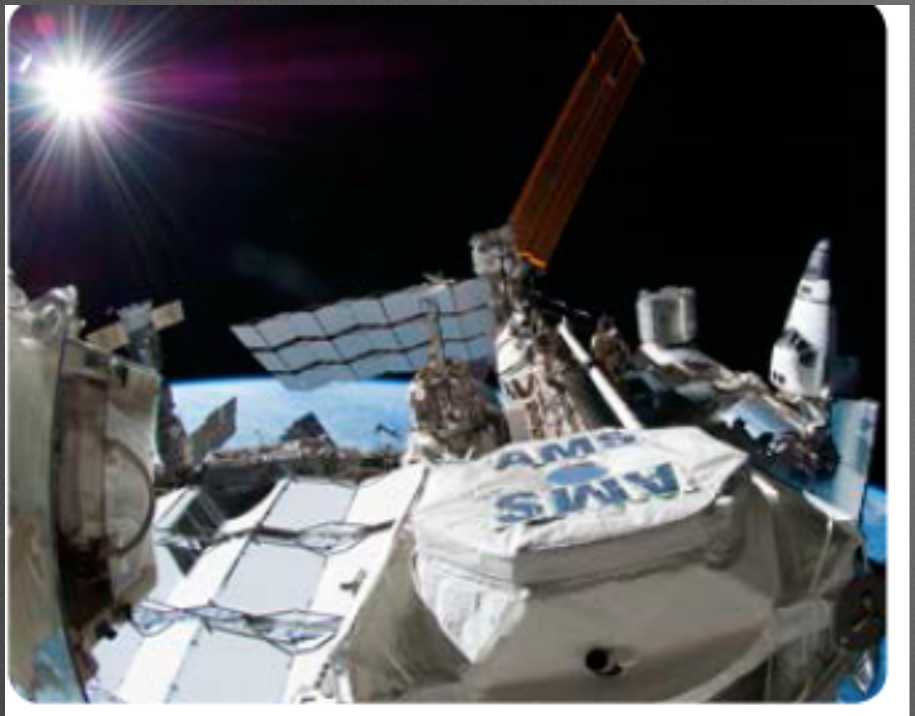


LHASSO
in Sichuan



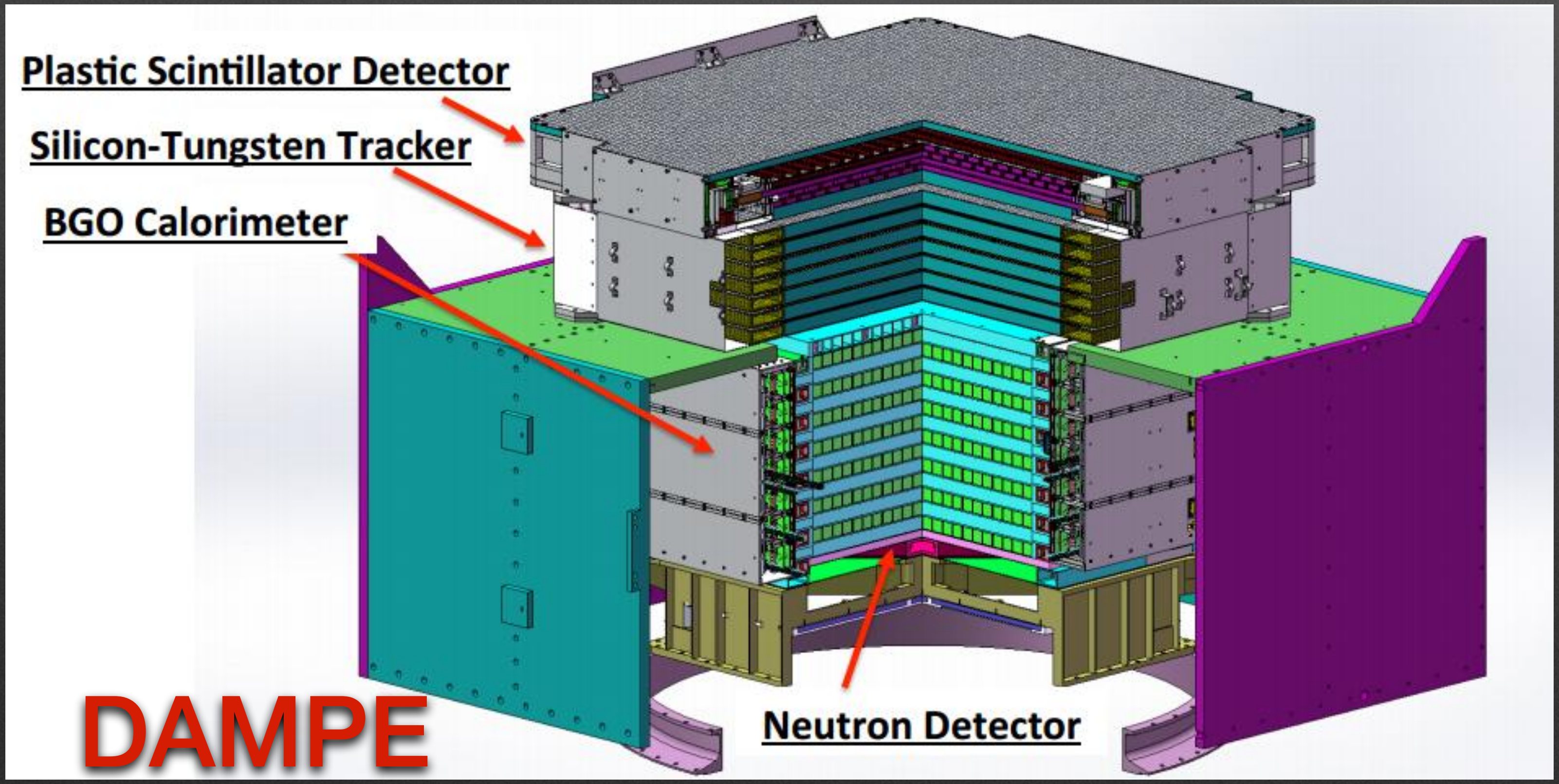


CR in space



The Alpha Magnetic Spectrometer experiment – AMS

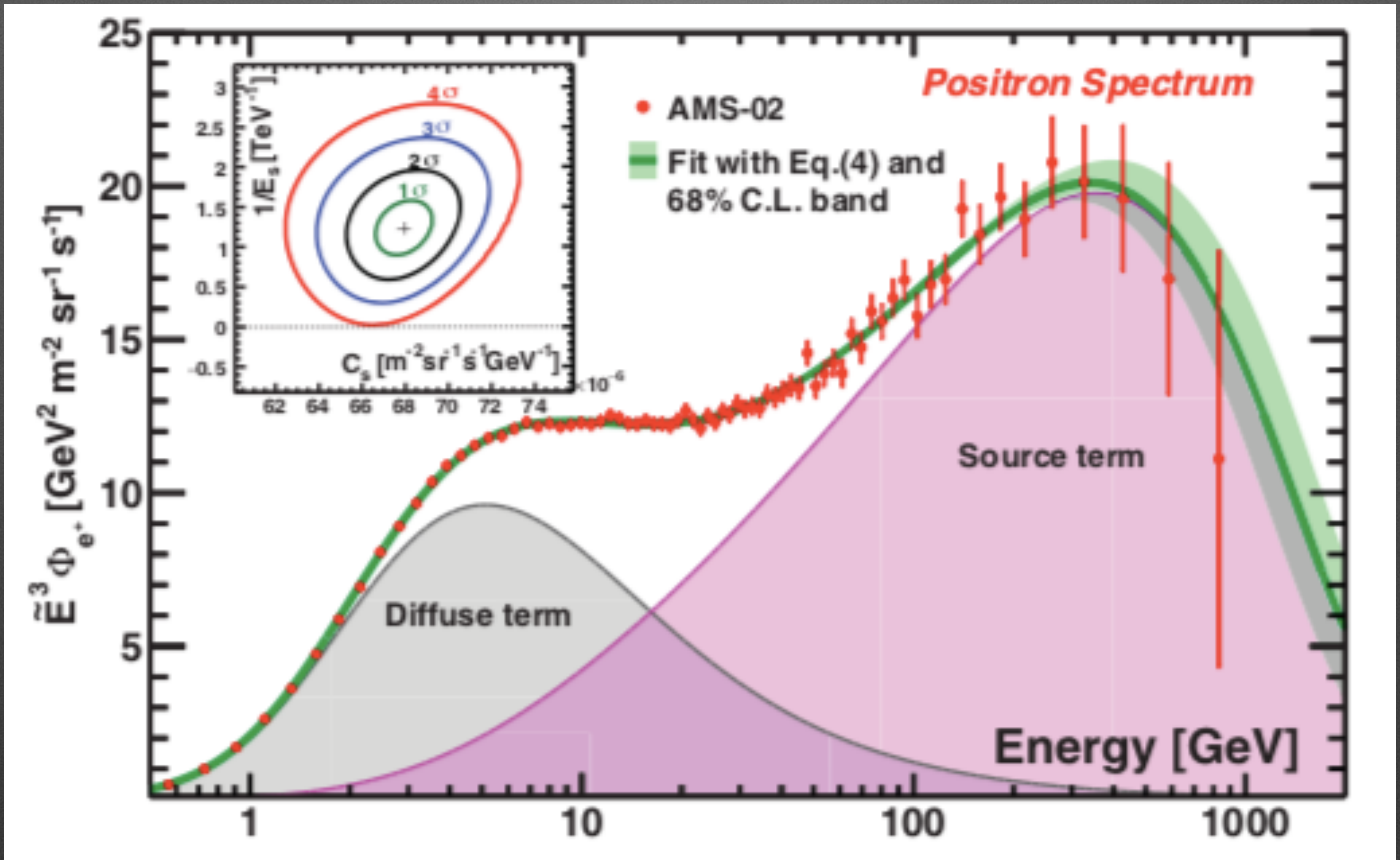
Antimatter & Dark Matter



Gamma Ray bursts

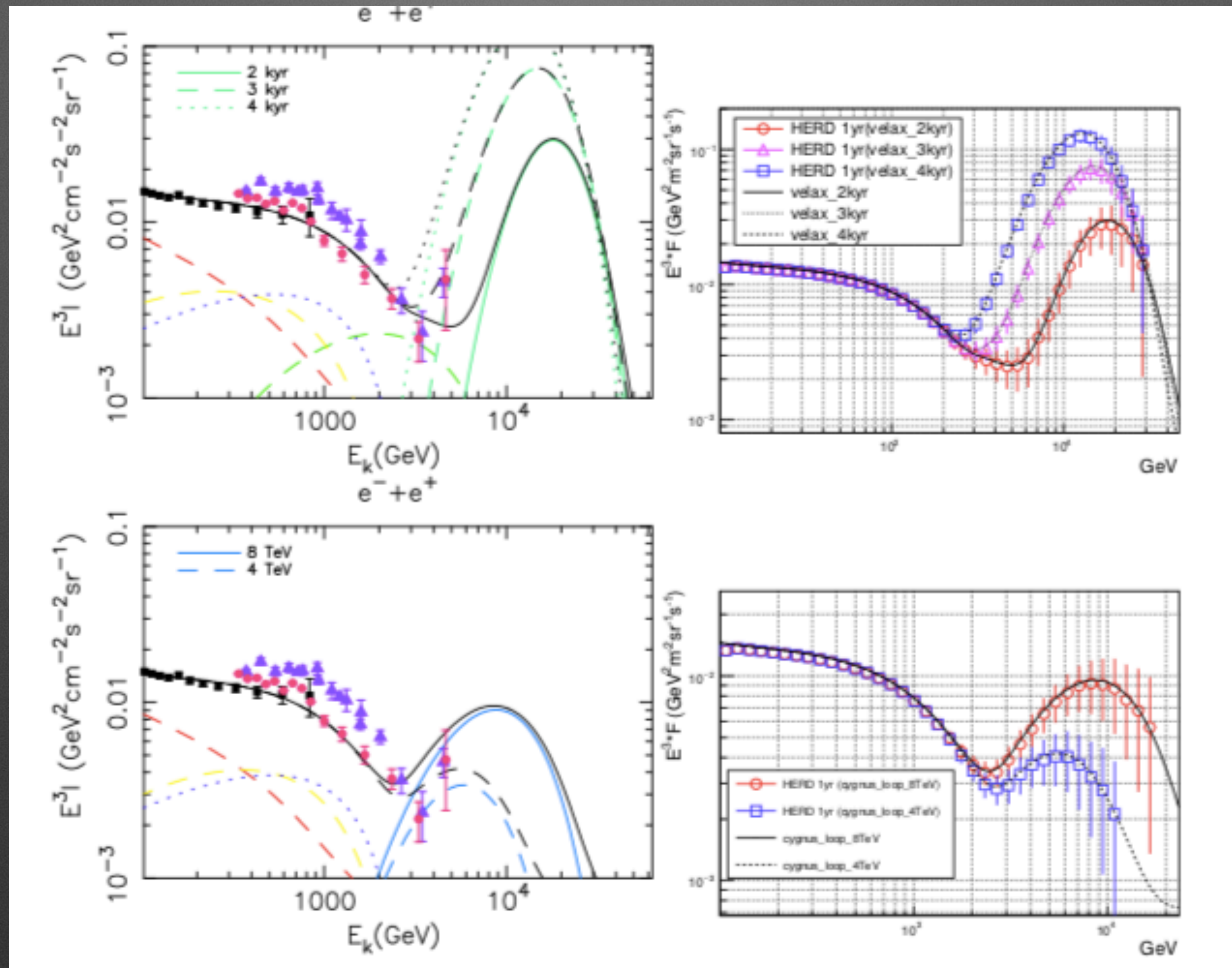
Particle spectra

The AMS puzzle



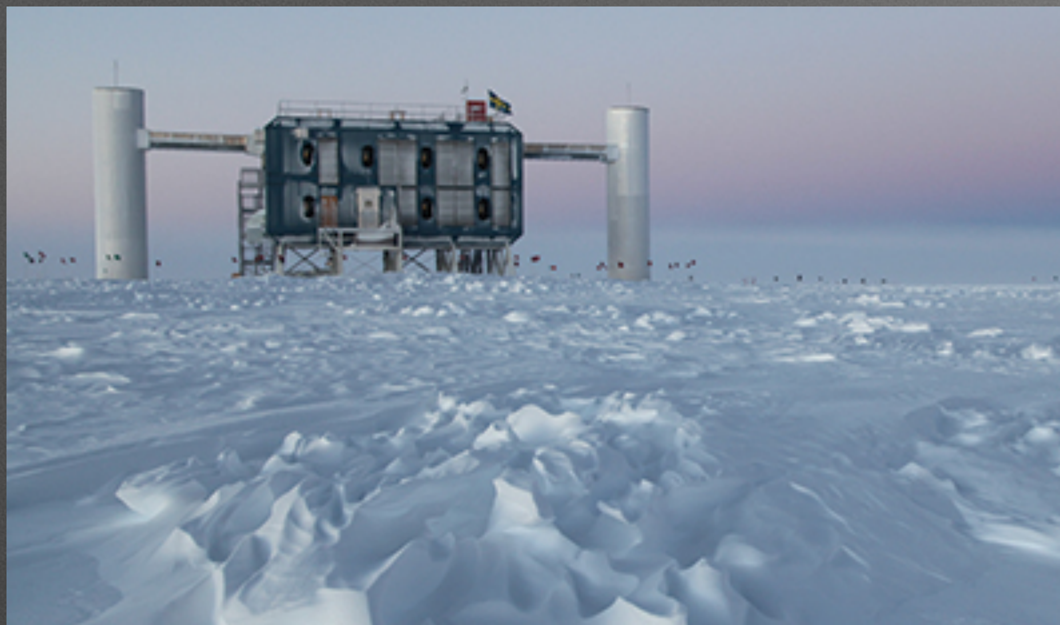
Dark Matter or Astrophysical sources ?

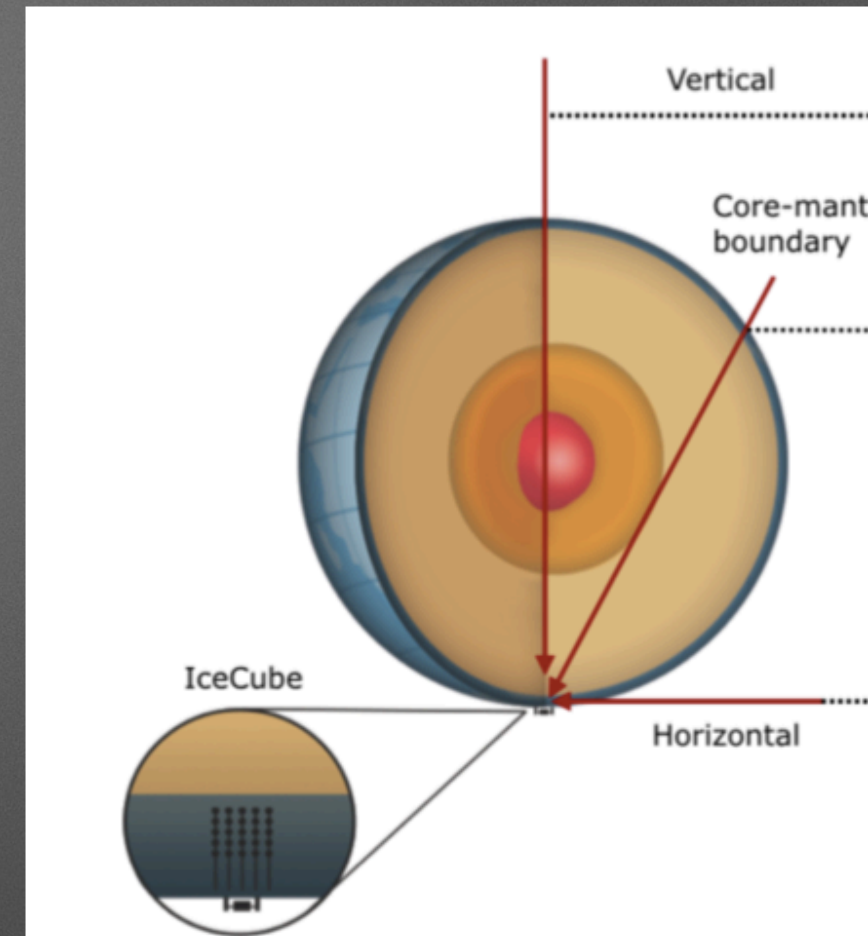
Future is HERD

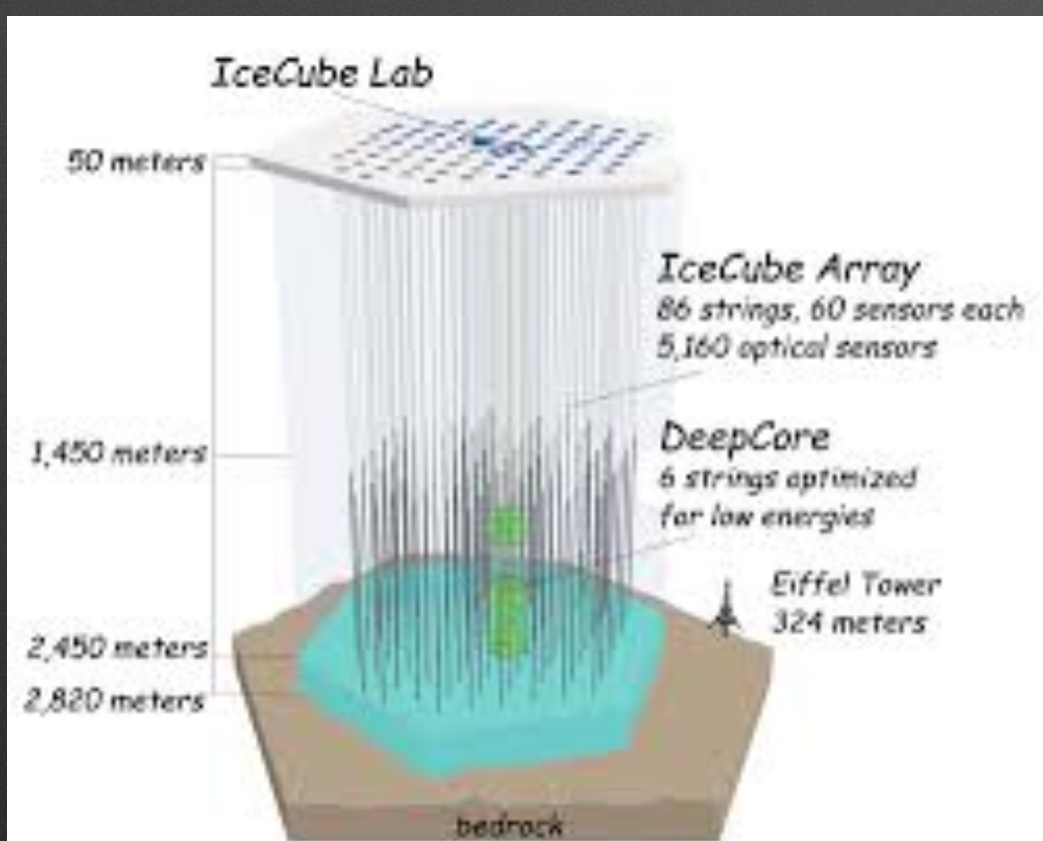


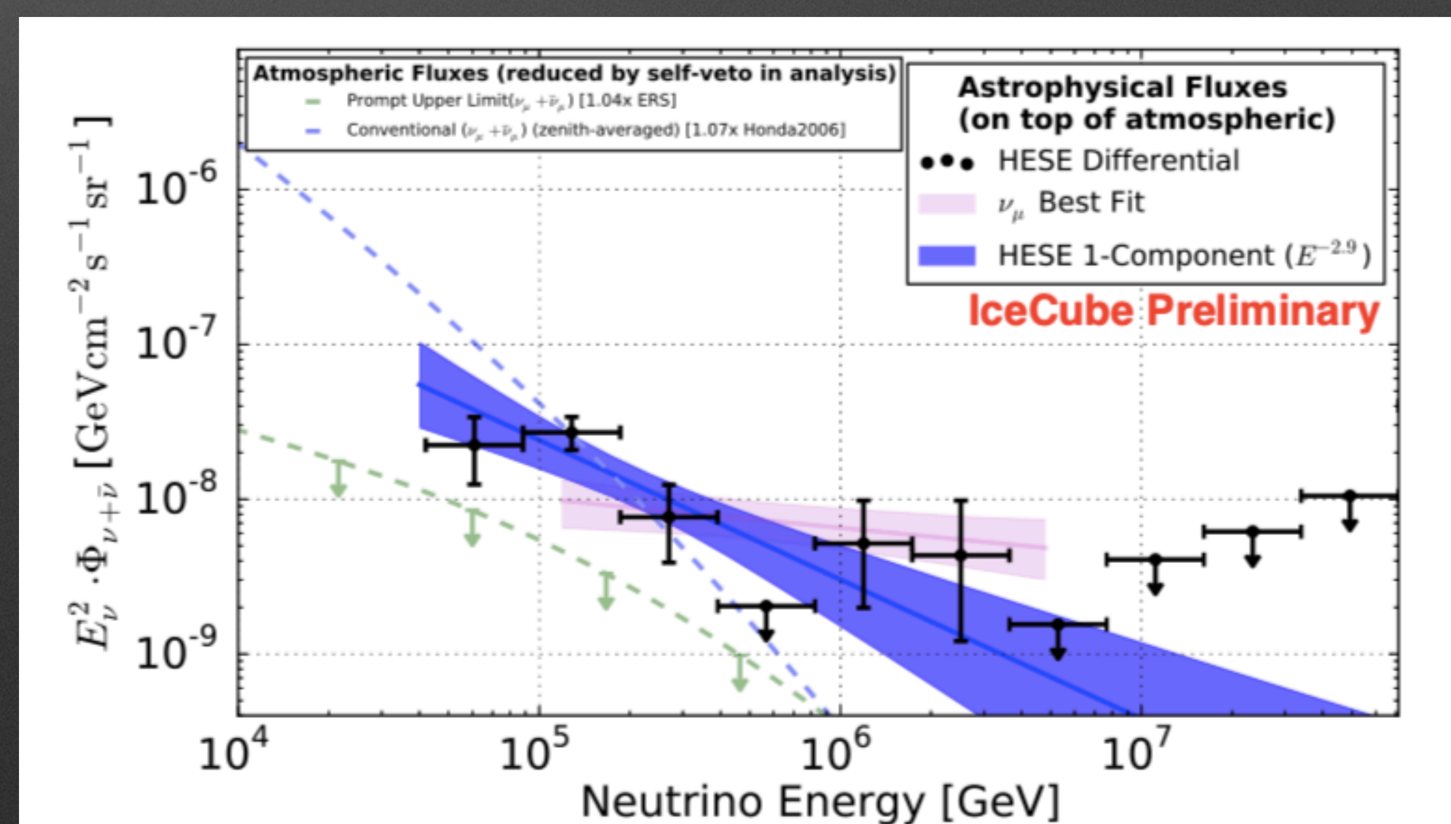
Understand the H.E. emission from nearby sources

IceCube

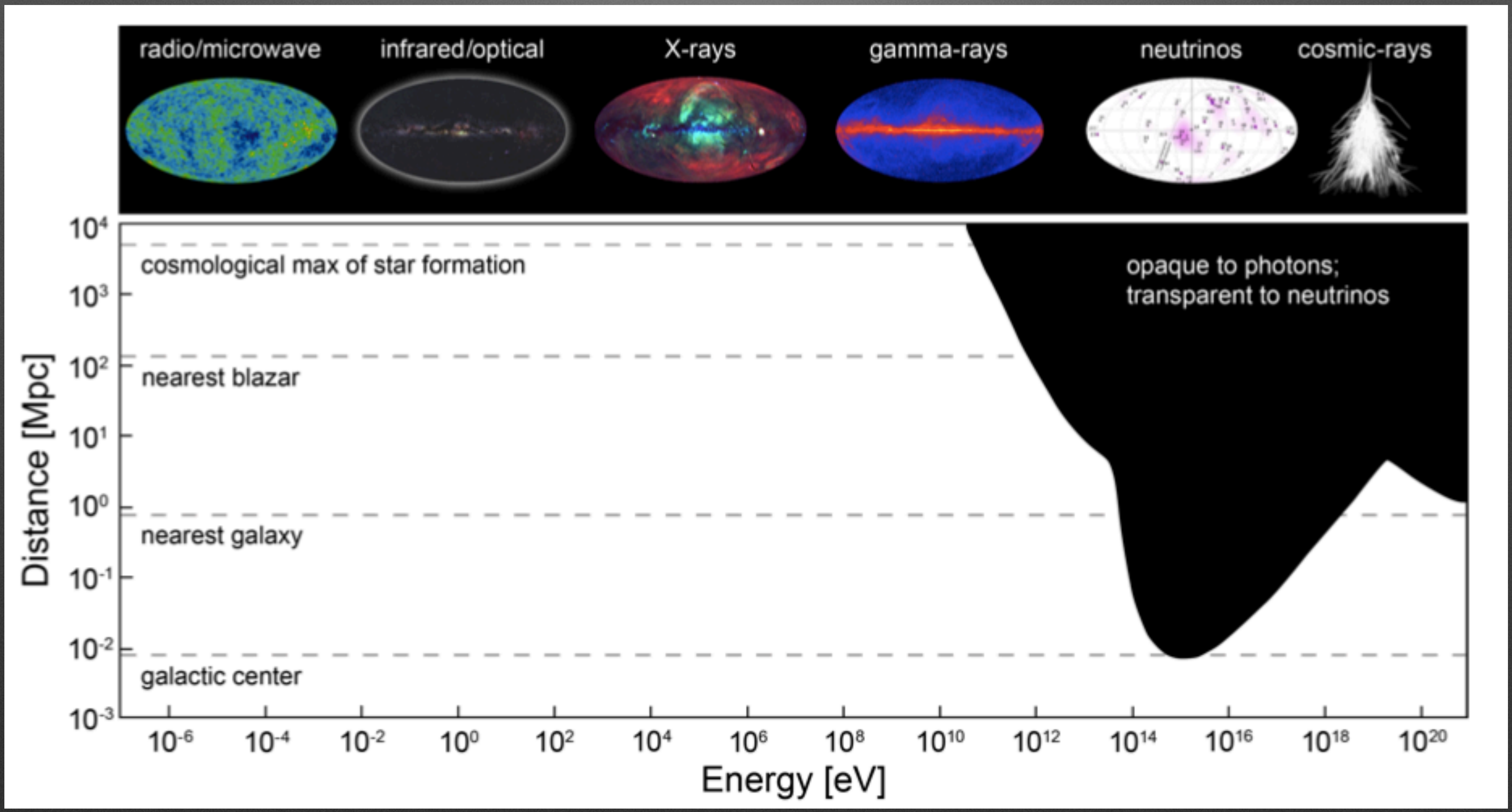



Vertical
Core-mantle
boundary
IceCube
Horizontal

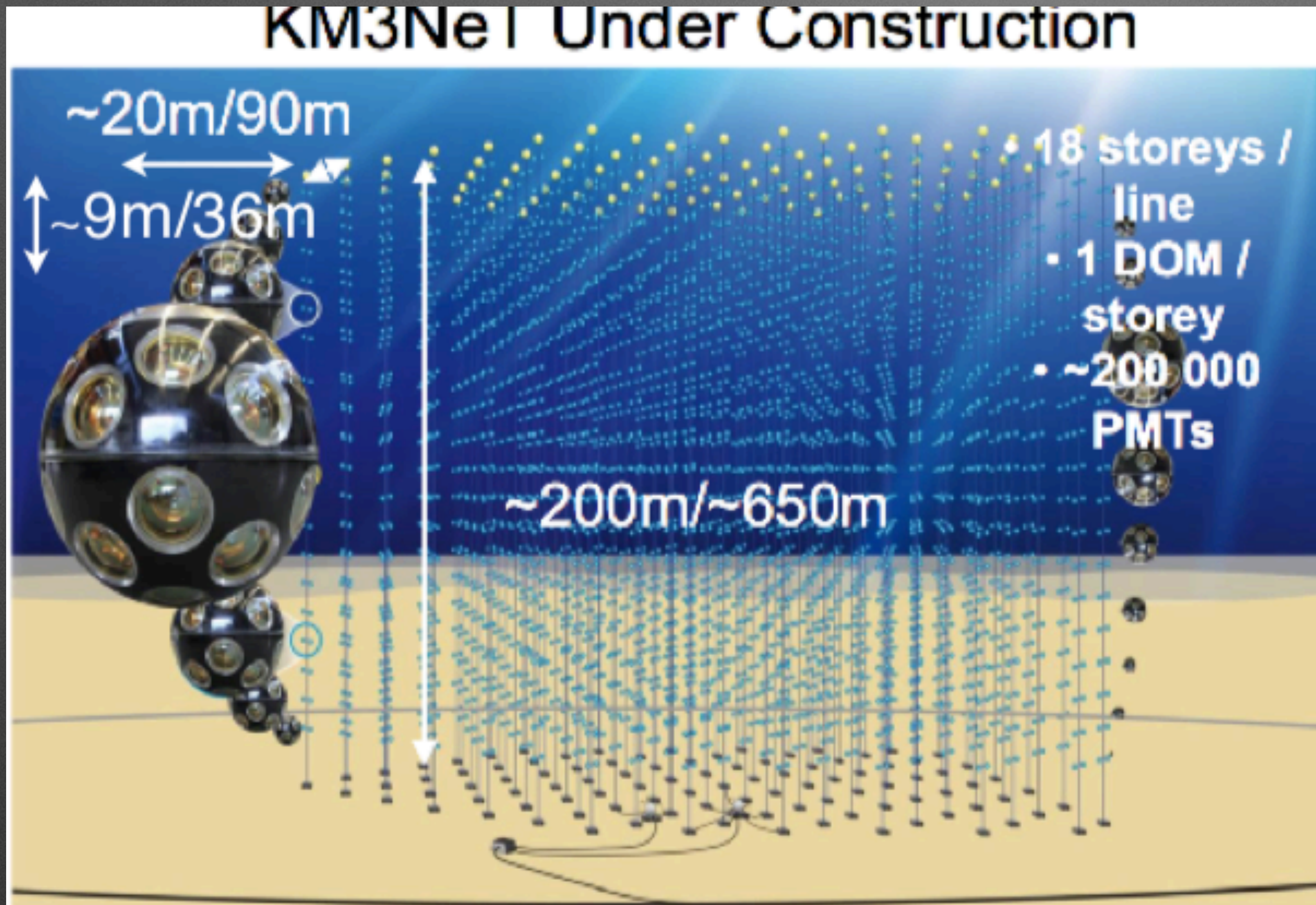

IceCube Lab
50 meters
IceCube Array
86 strings, 60 sensors each
5,160 optical sensors
DeepCore
6 strings optimized
for low energies
1,450 meters
Eiffel Tower
324 meters
2,450 meters
2,820 meters
bedrock

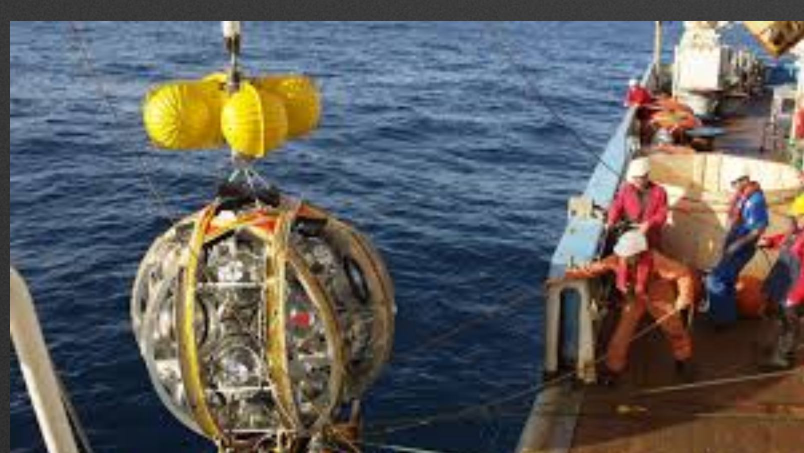

Atmospheric Fluxes (reduced by self-veto in analysis)
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.04x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.07x Honda2006]
Astrophysical Fluxes
(on top of atmospheric)
HESE Differential
ν_μ Best Fit
HESE 1-Component ($E^{-2.9}$)
IceCube Preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^4
10^5
10^6
10^7
Neutrino Energy [GeV]

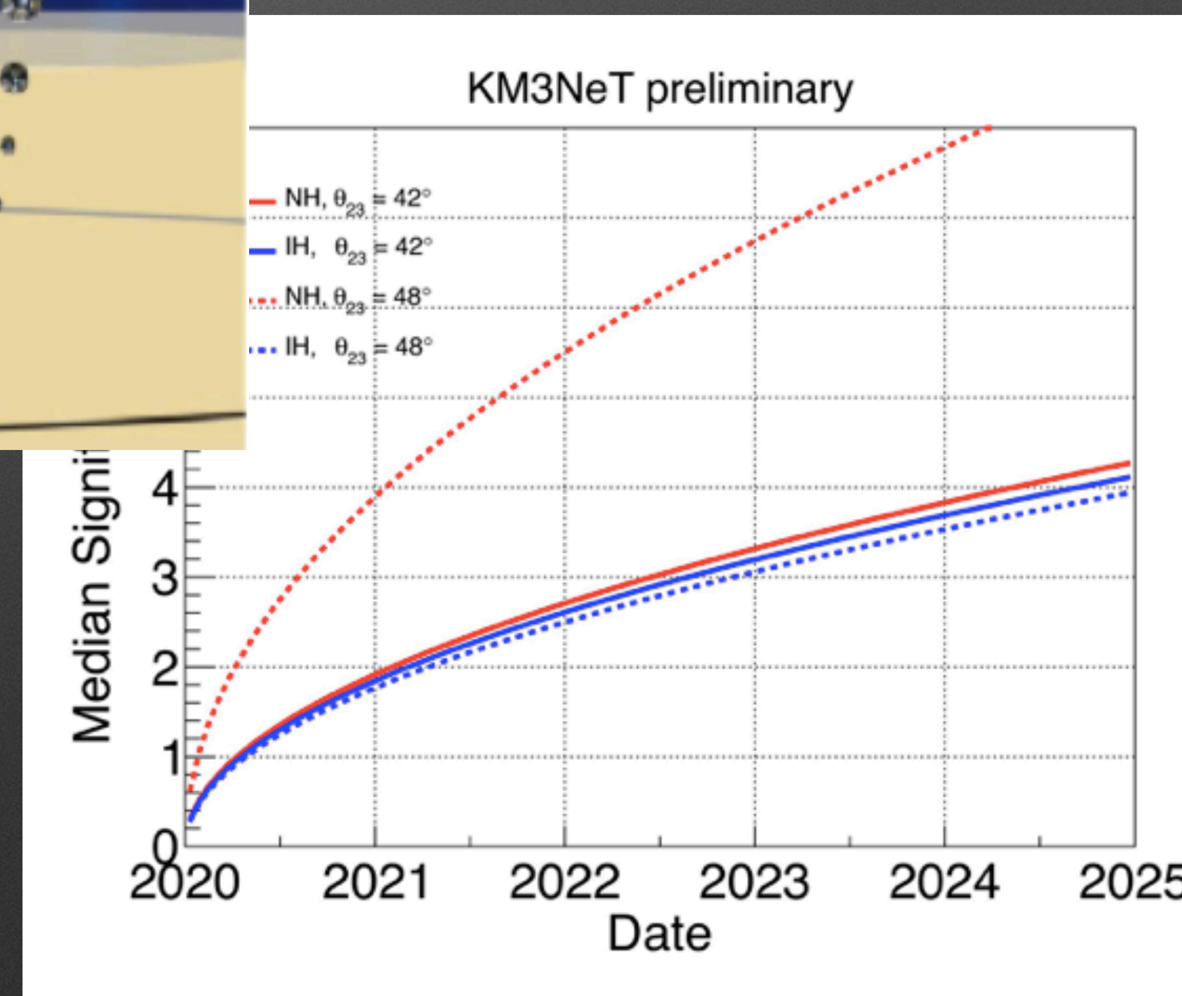
H.E. Neutrinos



an alternative: KM3Net







The mysterious world of Neutrinos

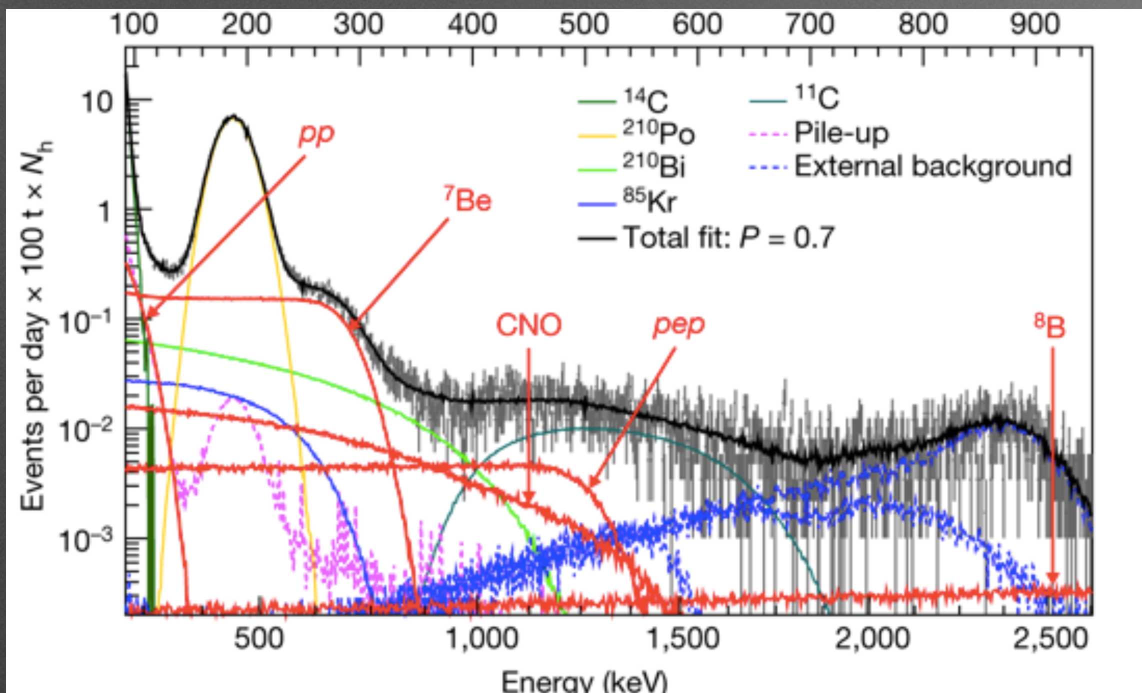
The mysterious neutrino

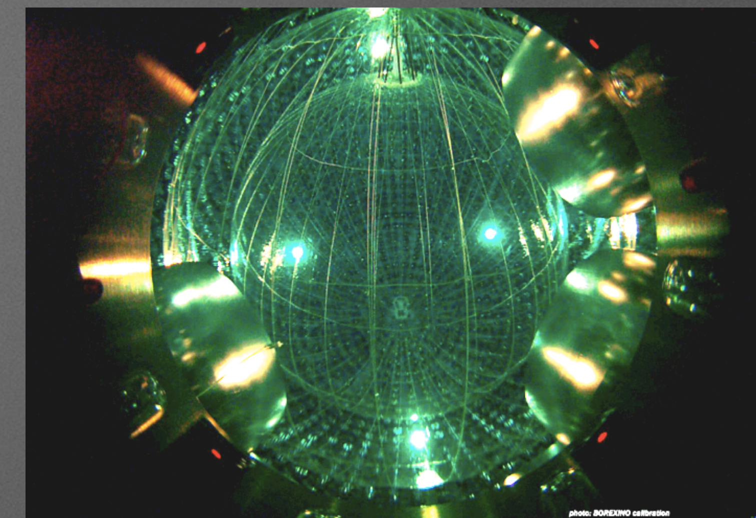
- Neutrinos might hold the key to both the mystery of the antimatter disappearance and the New Physics

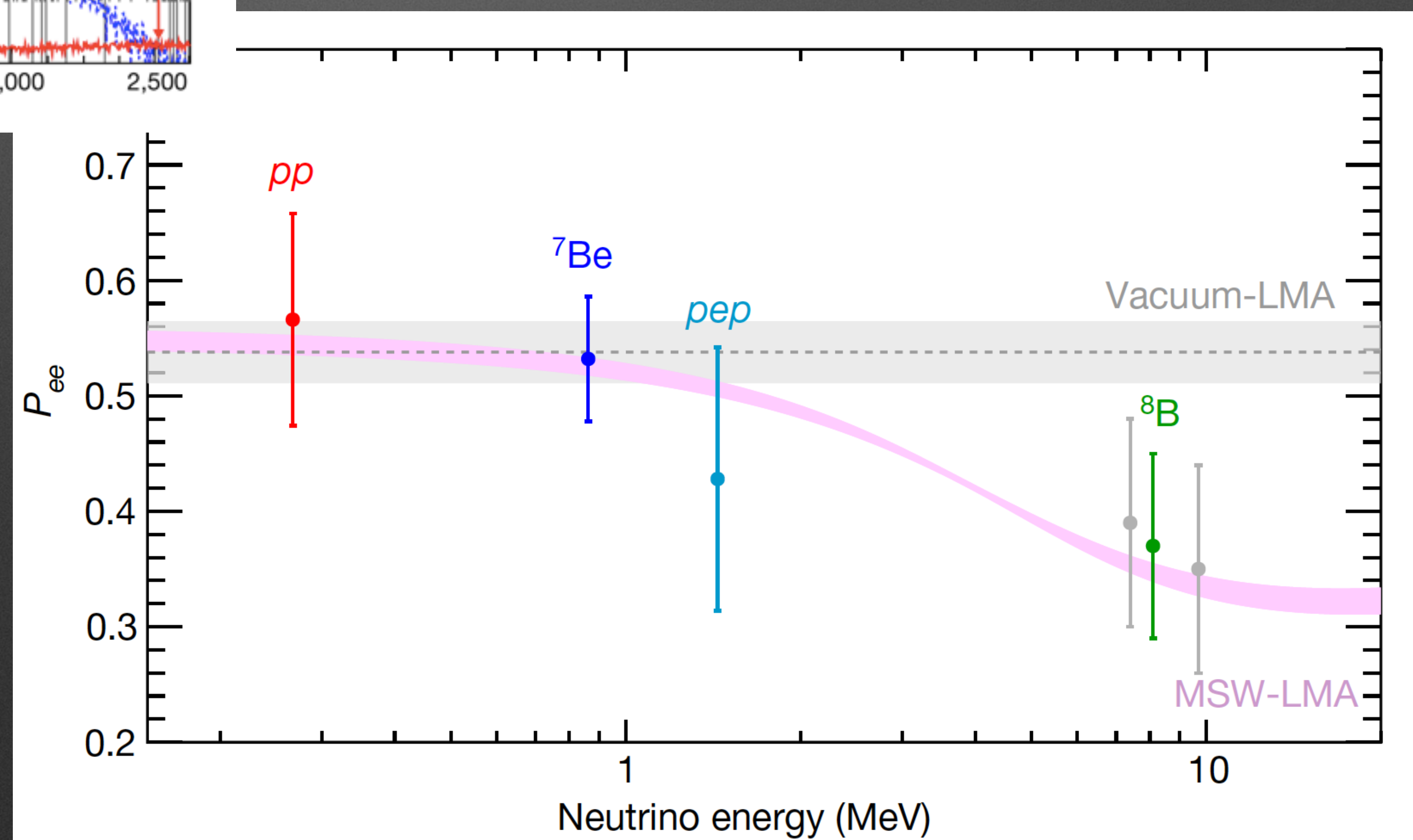
Leptogenesis

Majorana mass

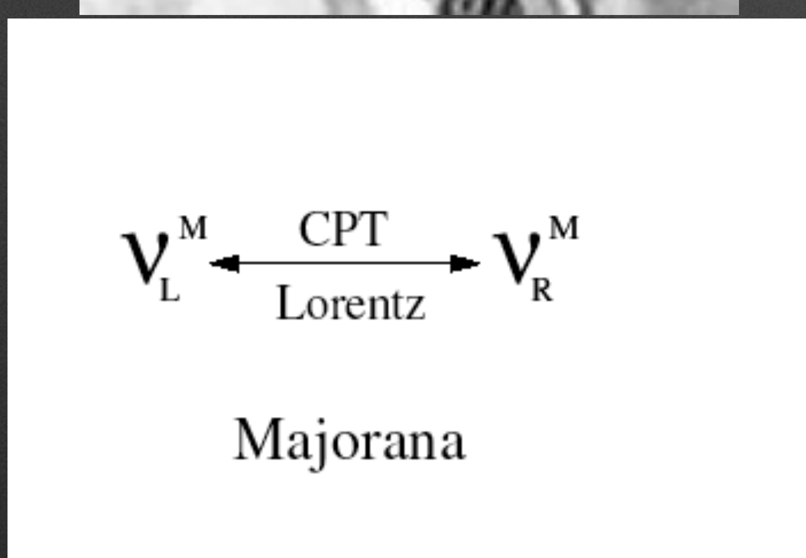
Borexino@LNGS

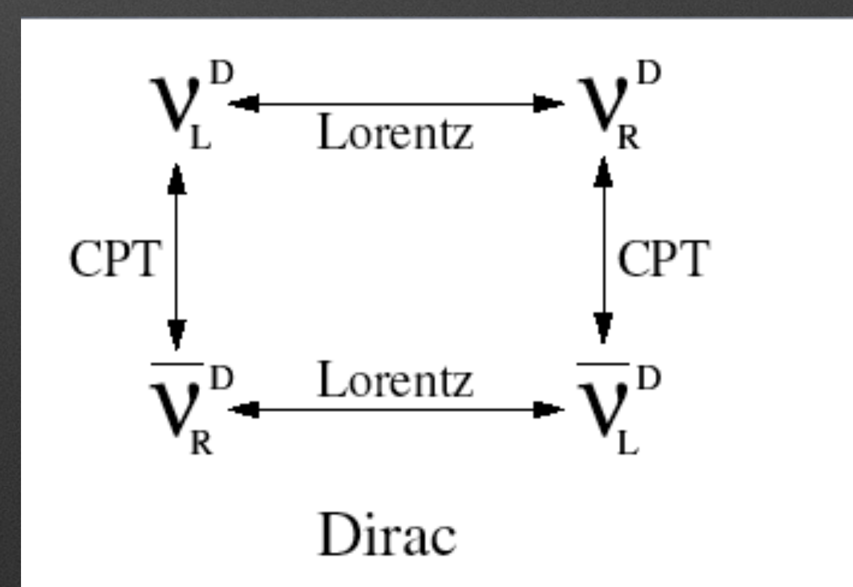






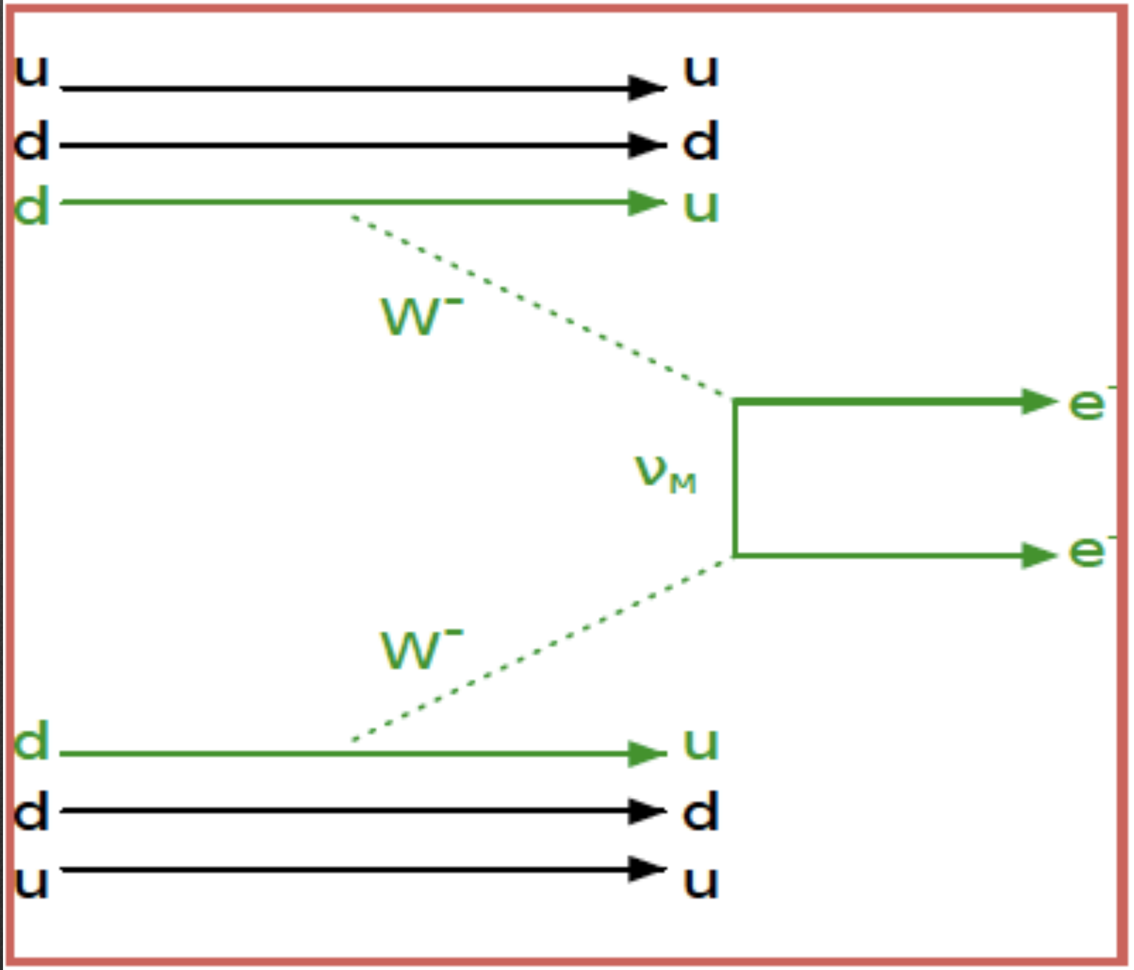
Quest for Majorana particles

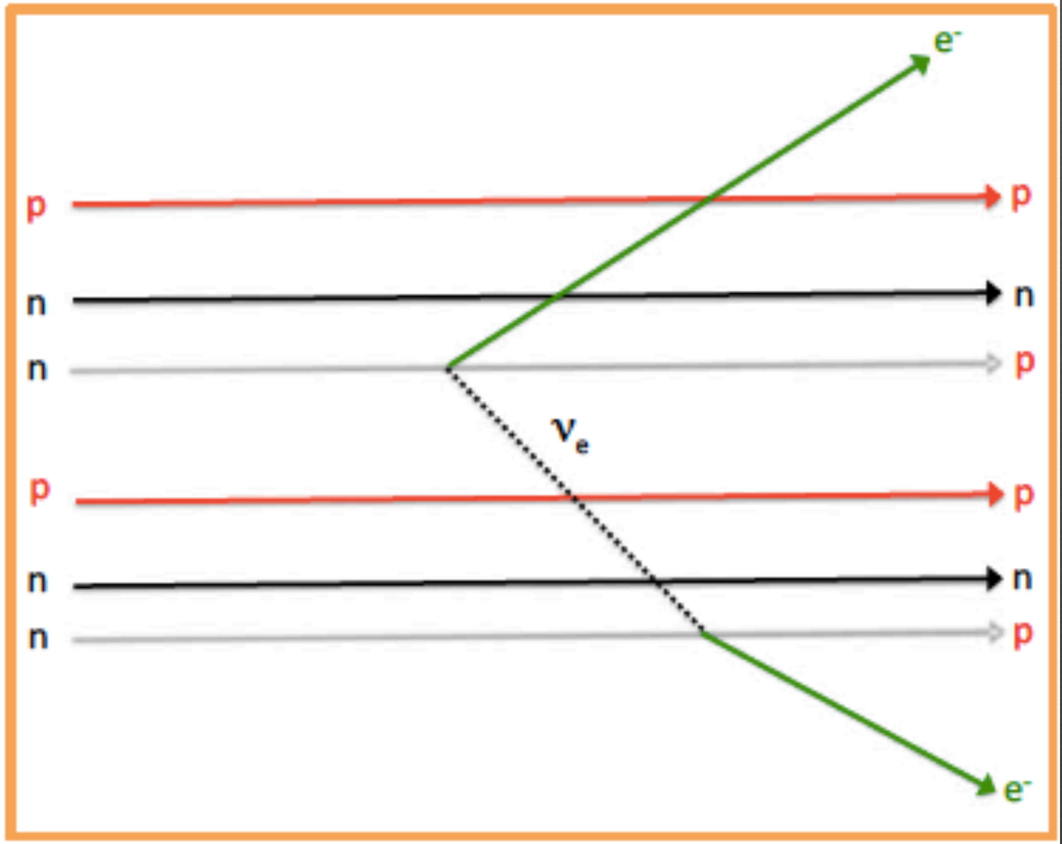


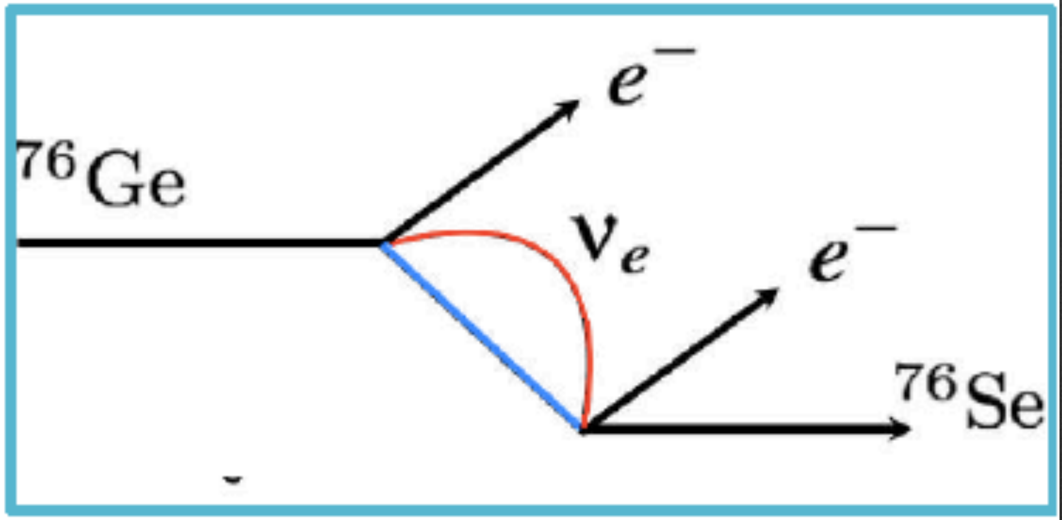


The process

Majorana neutrinos and 0ν2β







Sensitivity

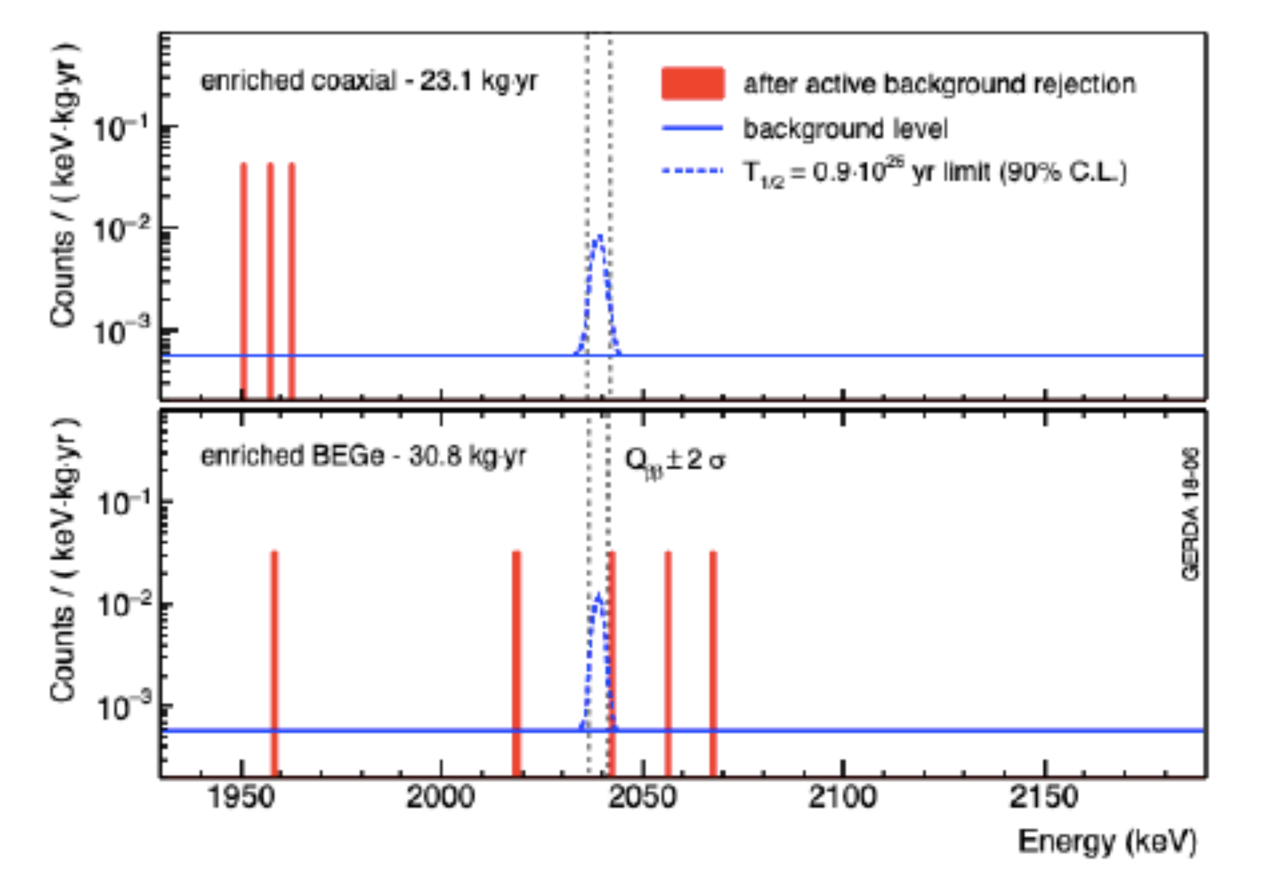
$$\text{Sensitivity} \propto K\sqrt{\frac{M \cdot t}{B \cdot \Delta E}} \quad (\text{i.a.} \bullet \varepsilon)$$

$$m_{\beta\beta} \propto \sqrt{(1/\tau)}$$

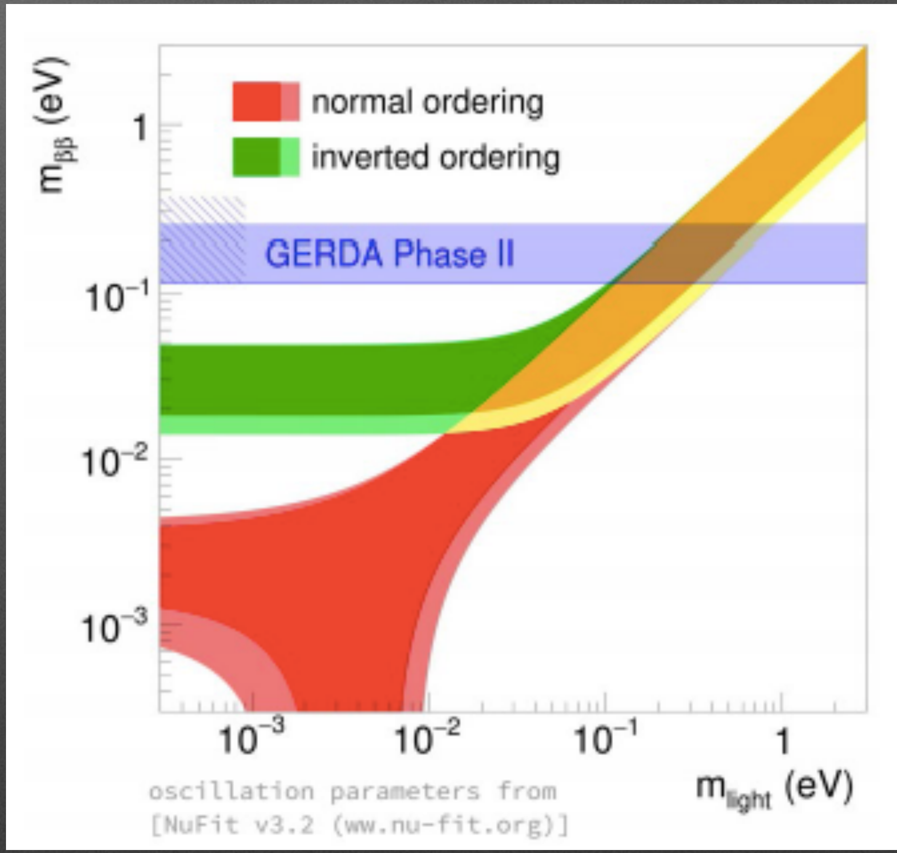
What really counts

- amount of Mass of the right isotopic composition
- Background Index (counts per unit of energy per unit time)
- the best Energy Resolution achievable
- a very good Efficiency

GERDA@LNGS



$T^{0\nu}_{1/2} > 0.9 \cdot 10^{26}$ yr (90% C.L.)

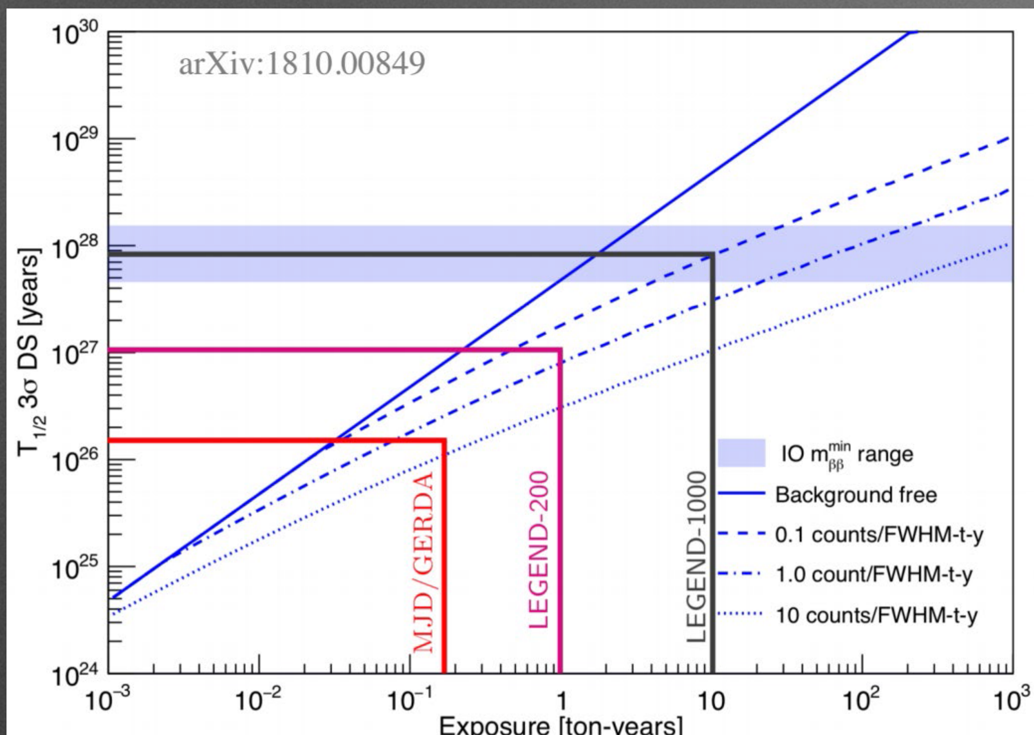


Lowest background per ROI ever achieved in $0\nu\beta\beta$ experiments. Background Index:

- for coaxial detectors: $5.7 \cdot 10^{-4}$ cts/(kg·keV·yr)
- for BEGe detectors $5.6 \cdot 10^{-4}$ cts/(kg·keV·yr)

So, for the given FWHM and the background index you expect to be able to run 2 years 'square root free'

turning to LEGEND@LNGS



BI x FWHM/ε

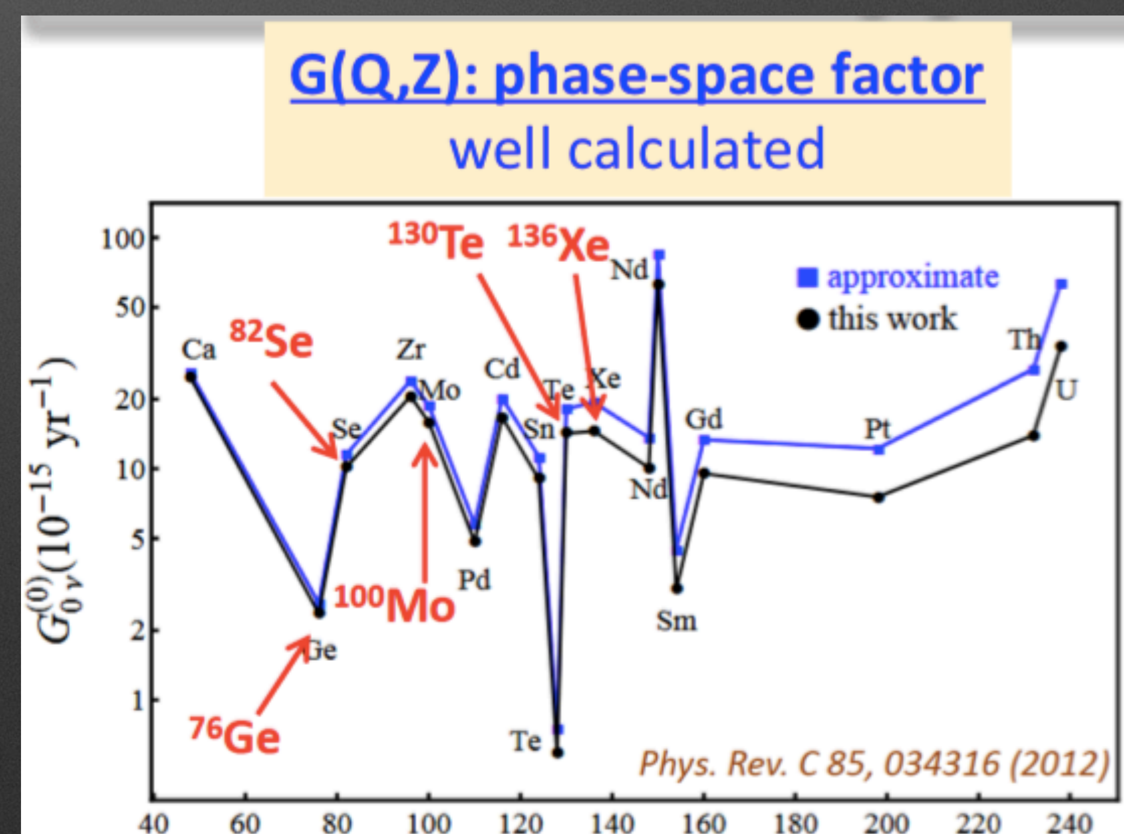
based on BI~6_x10^{-4}
and FWHM~ 3keV

The reach can be 10^{27}

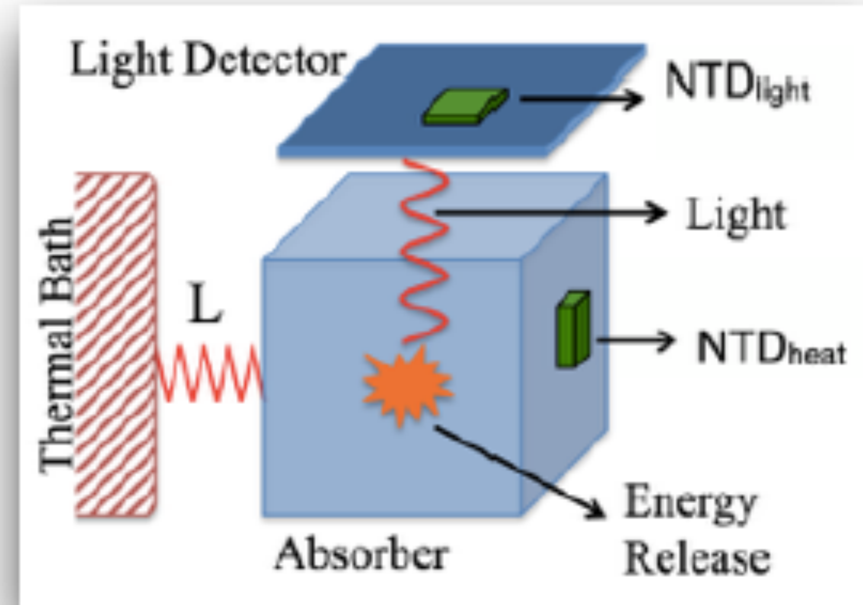
but

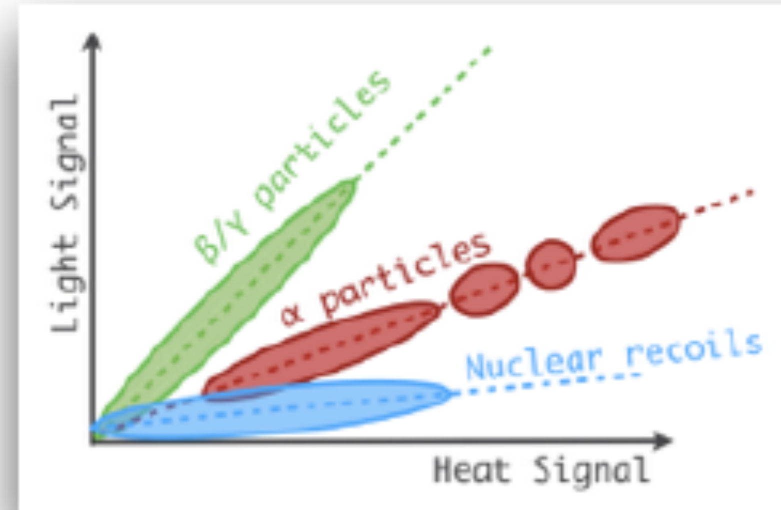
$$\left(T_{1/2}^{0\nu}\right)^{-1} \propto G^{0\nu}(\mathrm{Q},\mathrm{Z})\cdot\left|M^{0\nu}\right|^{2}\left\langle m_{\beta\beta}\right\rangle^{2}$$

heavy price to pay to phase space

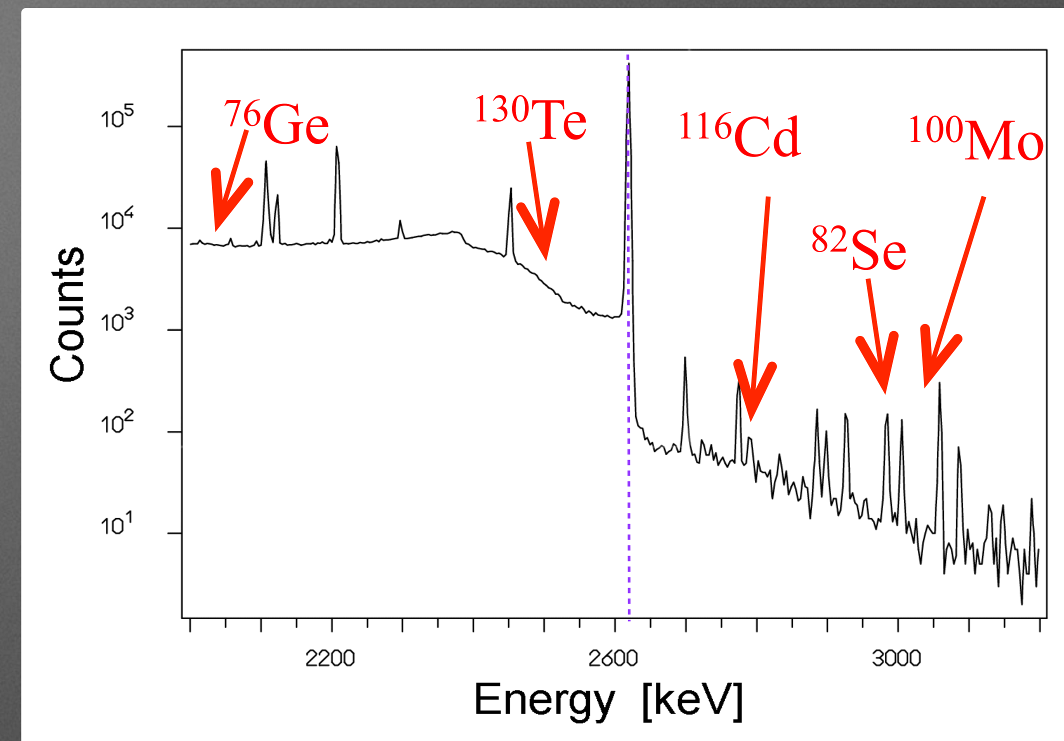


The principles of the alternative





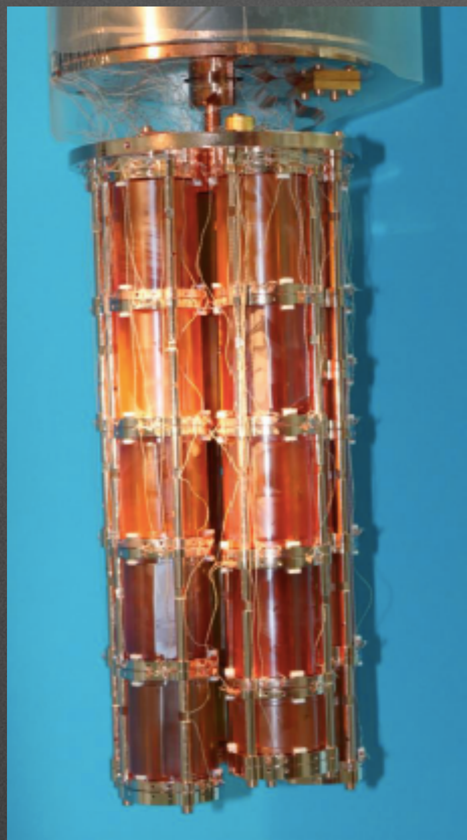
The simultaneous read-out of **HEAT** and **LIGHT** allows particle identification

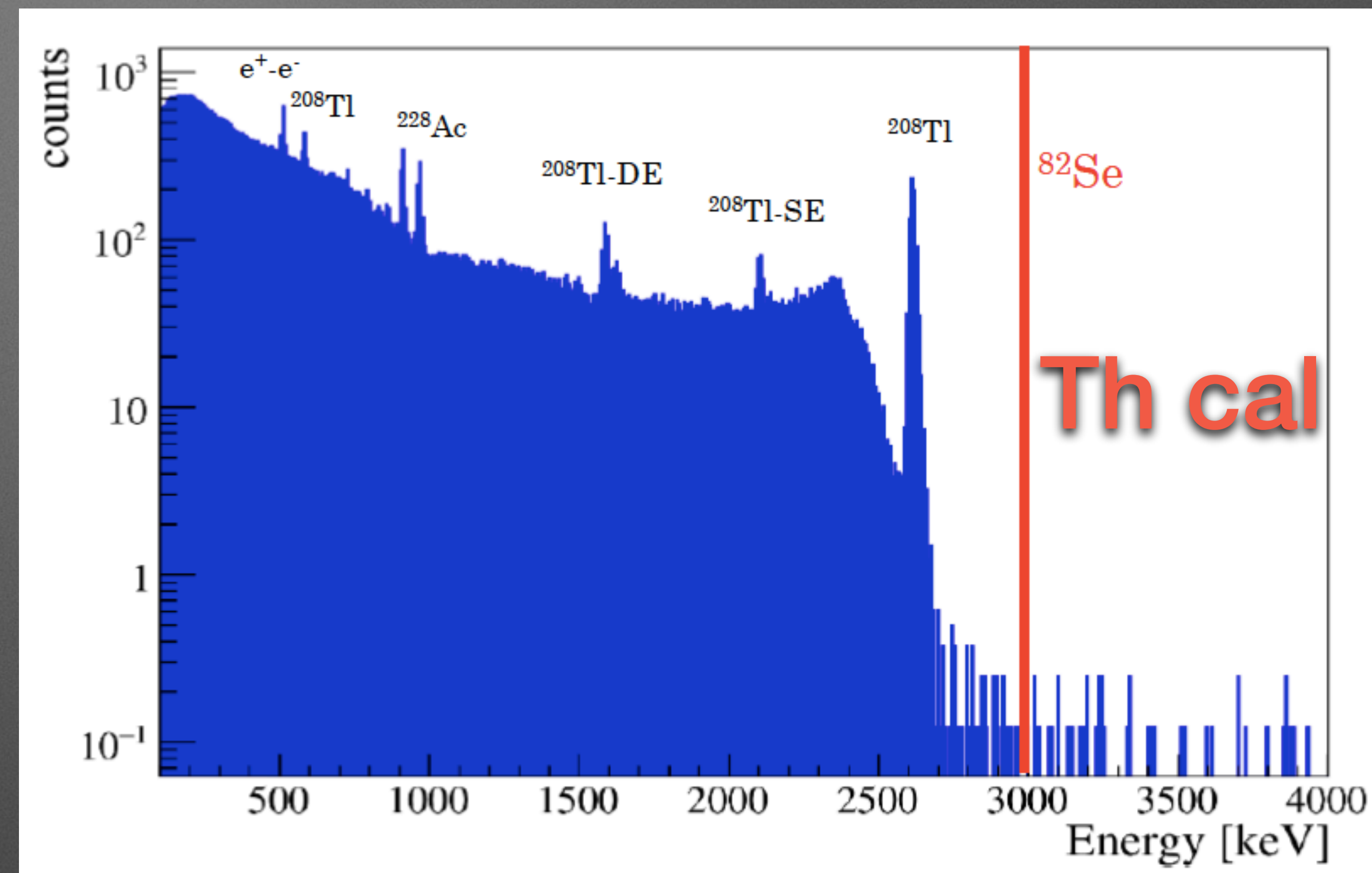


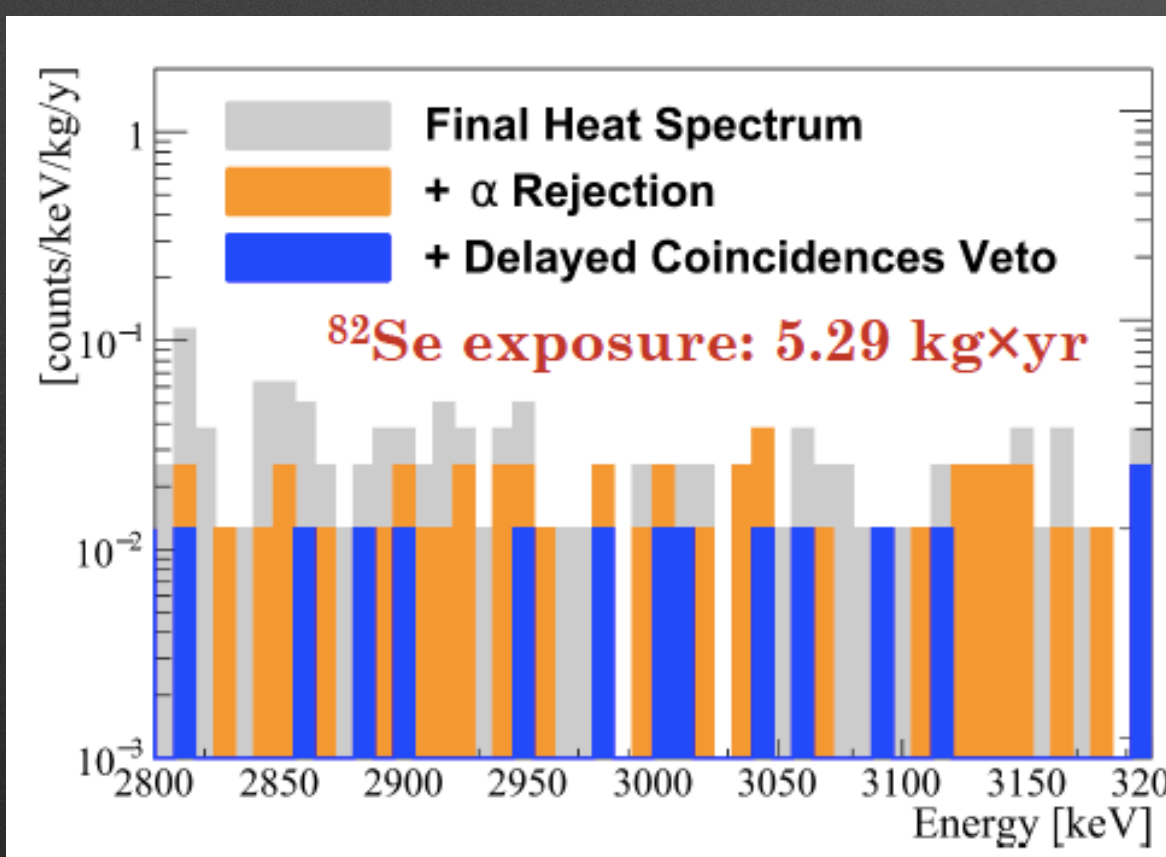
A **background-free experiment** is possible:
α-background: identification and rejection
β-background: ββ isotope with large Q-value

The application: CUPID-0

(former LUCIFER)







Background index in the range [2.8 – 3.2] MeV:

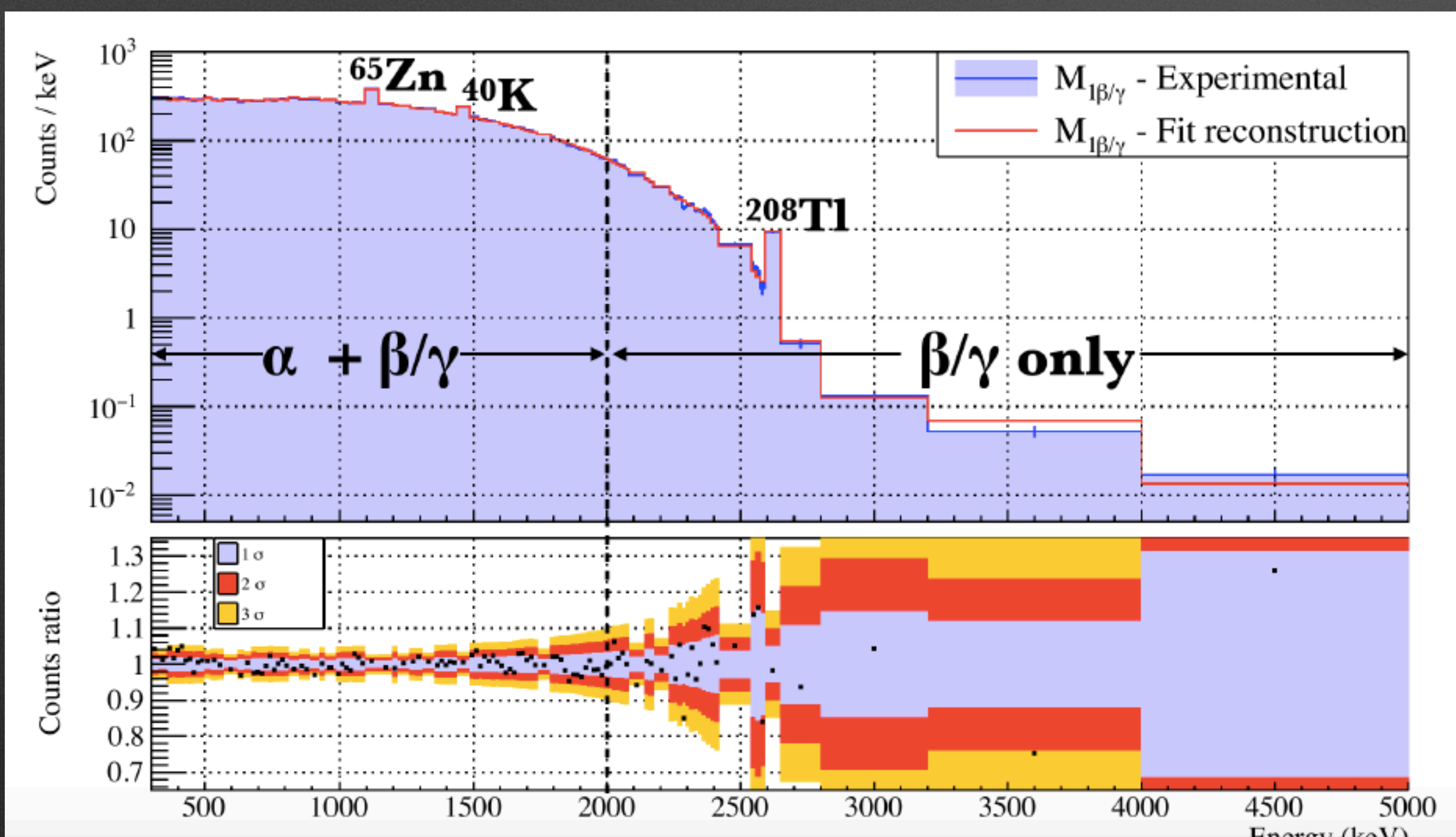
$$\left(3.5^{+1.0}_{-0.9}\right) \cdot 10^{-3} \text{ cnts/(keV·kg·yr)}$$

Lowest background achieved with bolometric experiments.

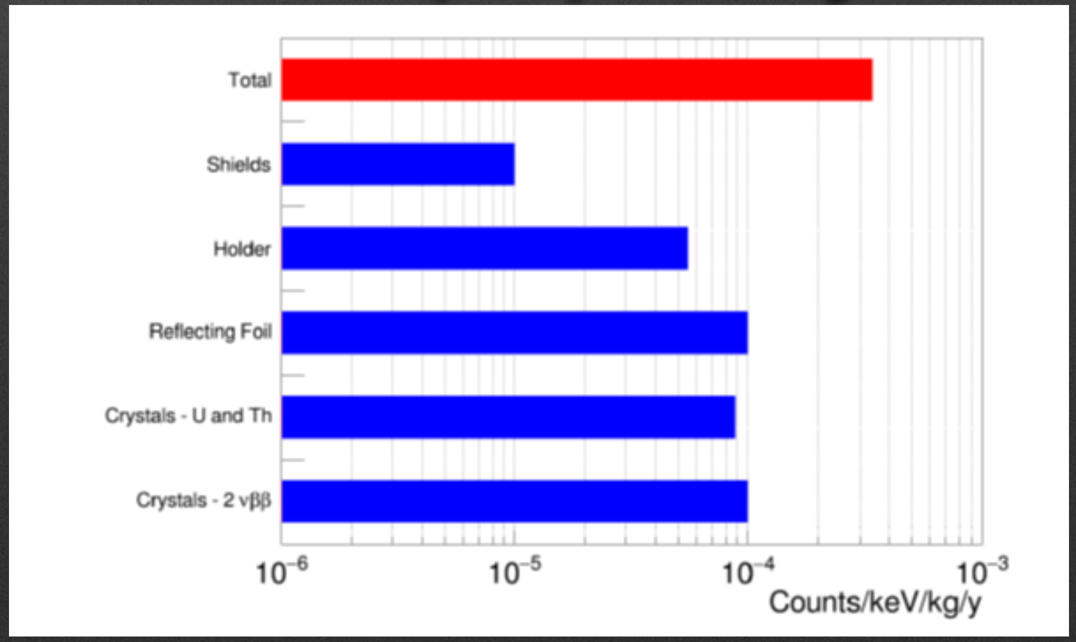
the reason for this choice

- Mo based crystals much easier to produce
- Energy resolution 3-4 times better

Experiment	Iso	M_{iso}	σ	ROI	ϵ_{sig}	$\mathcal{E}$	$\mathcal{B}_{\mathrm{ROI}}$	3σ disc. sens.	
								$T_{1/2}$	$m_{\beta\beta}$
		[kg]	[keV]	[σ]	[%]	$\left[\frac{\mathrm{kg}_{iso}\mathrm{yr}}{\mathrm{yr}}\right]$	$\left[\frac{\mathrm{cts}}{\mathrm{kg}_{iso}\mathrm{yr}}\right]$	[yr]	[meV]
CUPID	^{100}Mo	247	2.1	$-2.0, +2.0$	68	168	$2 \cdot 10^{-3}$	$1.1 \cdot 10^{27}$	12–20



MC simulation from CUPID (Se) analysis



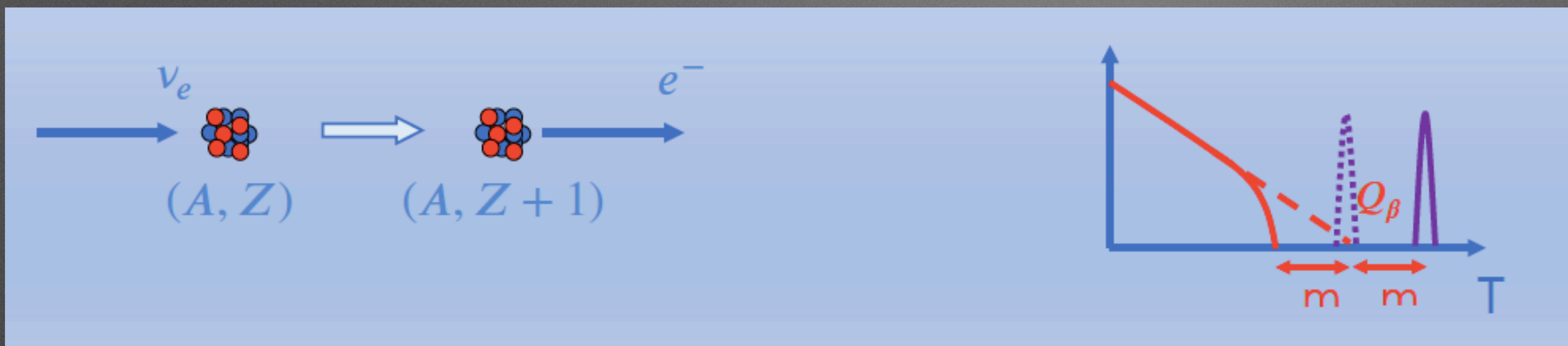
However

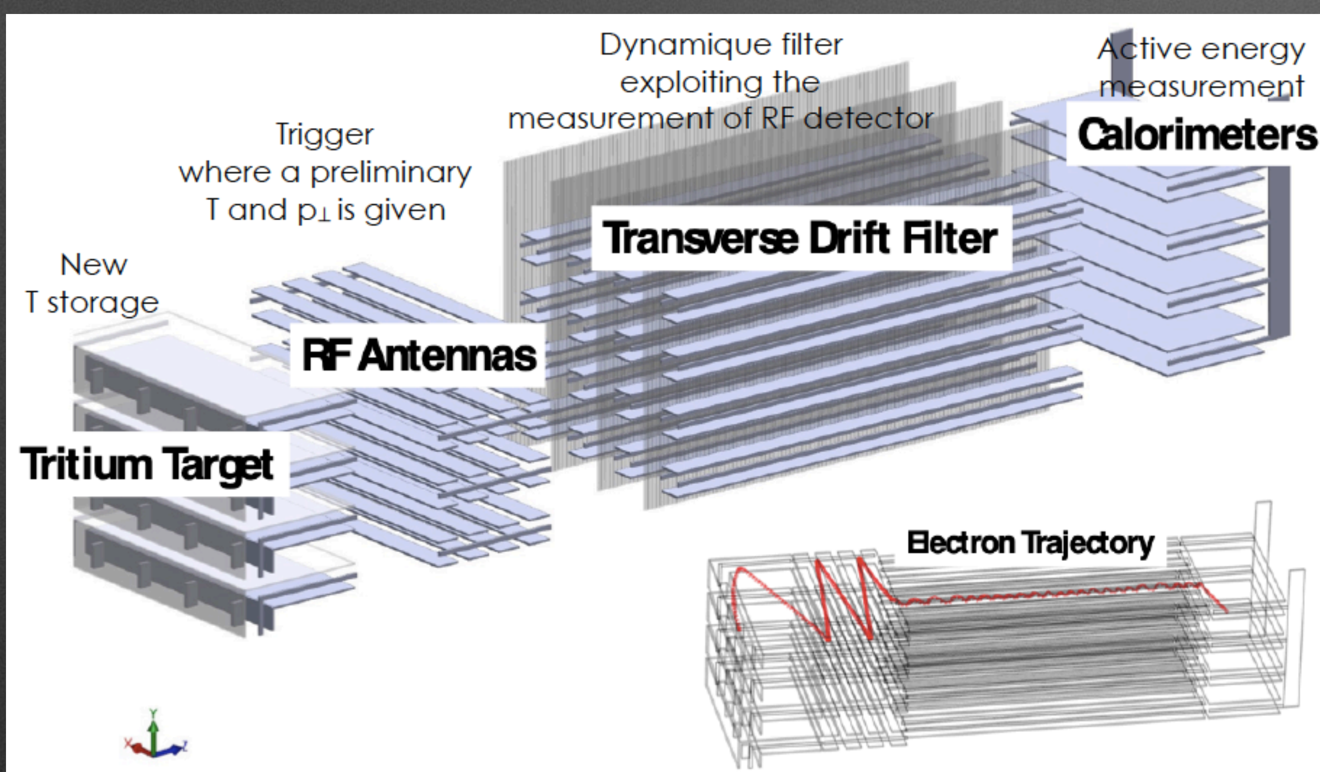
- 10^{26} years reached (Gerda, Kamland-ZEN)
- 10^{27} reachable (LEGEND, CUPID, nEXO)
- 10^{28} ? (background shall be really 10^{-5} or better for a huge mass of isotope)
- 10^{29} direct hierarchy ….here the problem is the detector mass (!!!)

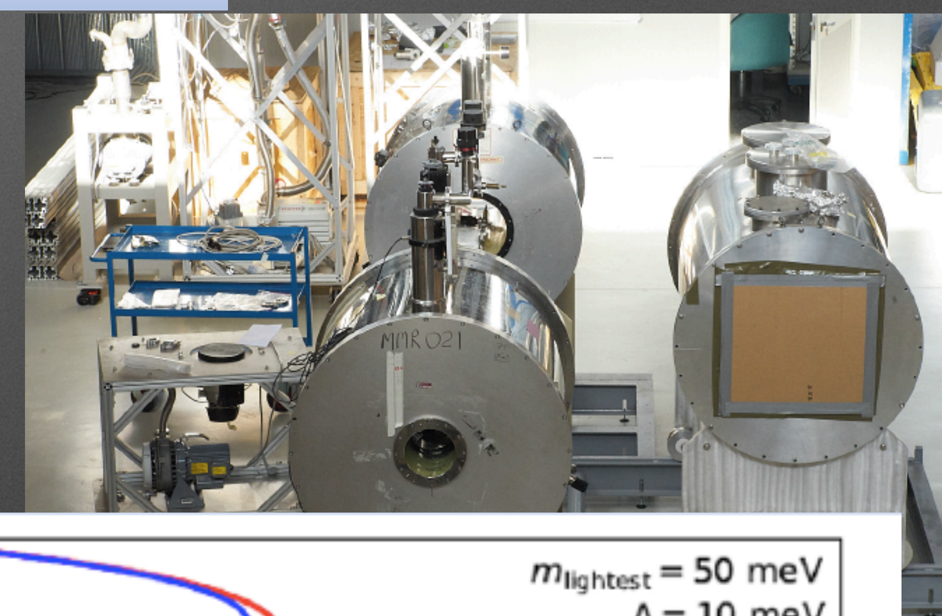
look carefully please

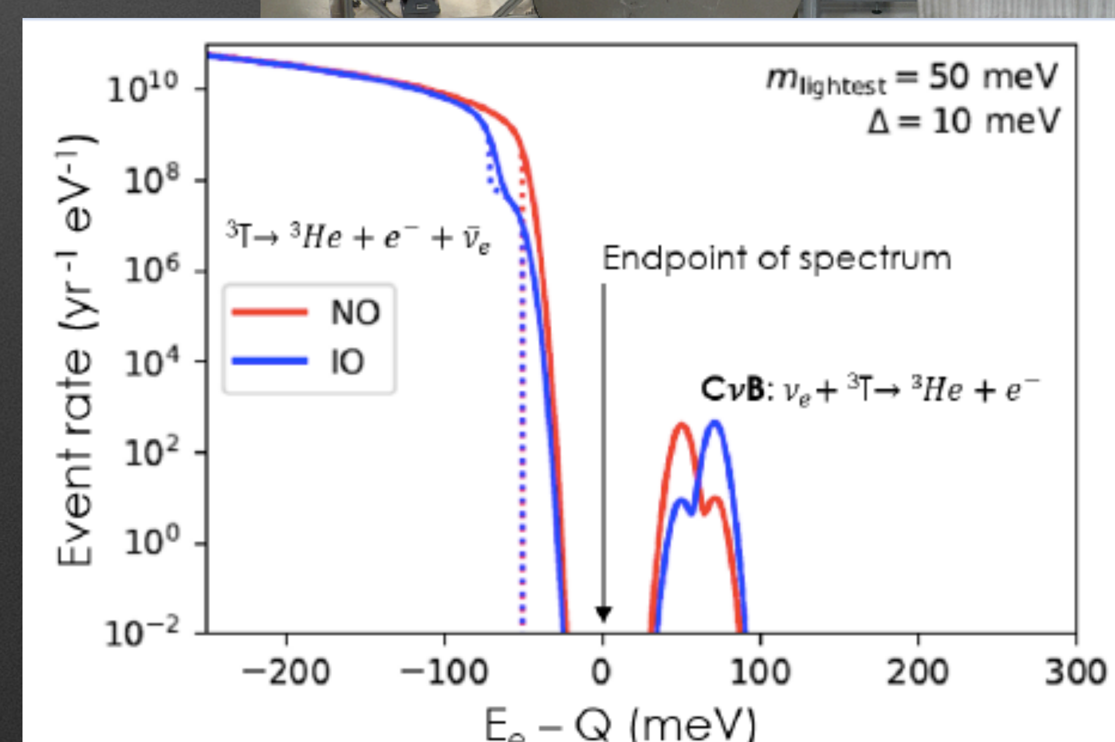
Isotope	Q (MeV)	percent natural abund.	element cost [5] ($/kg)	$G^{0\nu}$ (10^{-14}/yr) [6]	$M^{0\nu}$ (avg) [7]	$T^{0\nu}_{1/2}$ for 2.5meV (10^{29}yrs)	tons of isotope for 1 ev/yr	equivalent natural tons	annual world production [5] (tons/yr)	natural elem. cost ($M)	enriched at $20/g ($M)	$0\nu/2\nu$ rate [2][8] (10^{-8})
^{48}Ca	4.27	0.19	0.16	6.06	1.6	2.70	31.1	16380	2.4×10^8	2.6	622	0.016
^{76}Ge	2.04	7.8	1650	0.57	4.8	3.18	58.2	746	118	1221	1164	0.55
^{82}Se	3.00	9.2	174	2.48	4.0	1.05	20.8	225	2000	39	416	0.092
^{96}Zr	3.35	2.8	36	5.02	3.0	0.93	21.4	763	1.4×10^6	27	427	0.025
^{100}Mo	3.04	9.6	35	3.89	4.6	0.51	12.2	127	2.5×10^5	4.4	244	0.014
^{110}Pd	2.00	11.8	23000	1.18	6.0	0.98	26.0	221	207	5078	521	0.16
^{116}Cd	2.81	7.6	2.8	4.08	3.6	0.79	22.1	290	2.2×10^4	0.81	441	0.035
^{124}Sn	2.29	5.6	30	2.21	3.7	1.38	41.2	736	2.5×10^5	22	825	0.072
^{130}Te	2.53	34.5	360	3.47	4.0	0.75	23.6	68	$\sim$150	24	471	0.92
^{136}Xe	2.46	8.9	1000	3.56	2.9	1.40	45.7	513	50	513	914	1.51
^{150}Nd	3.37	5.6	42	15.4	2.7	0.37	13.4	240	$\sim 10^4$	11	269	0.024

looking for a far future





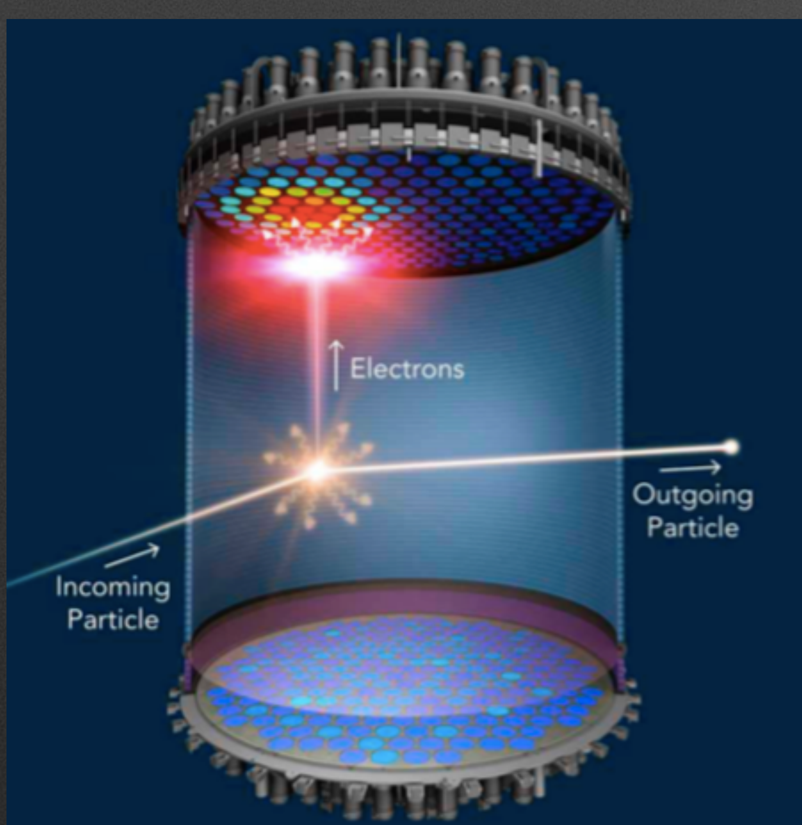


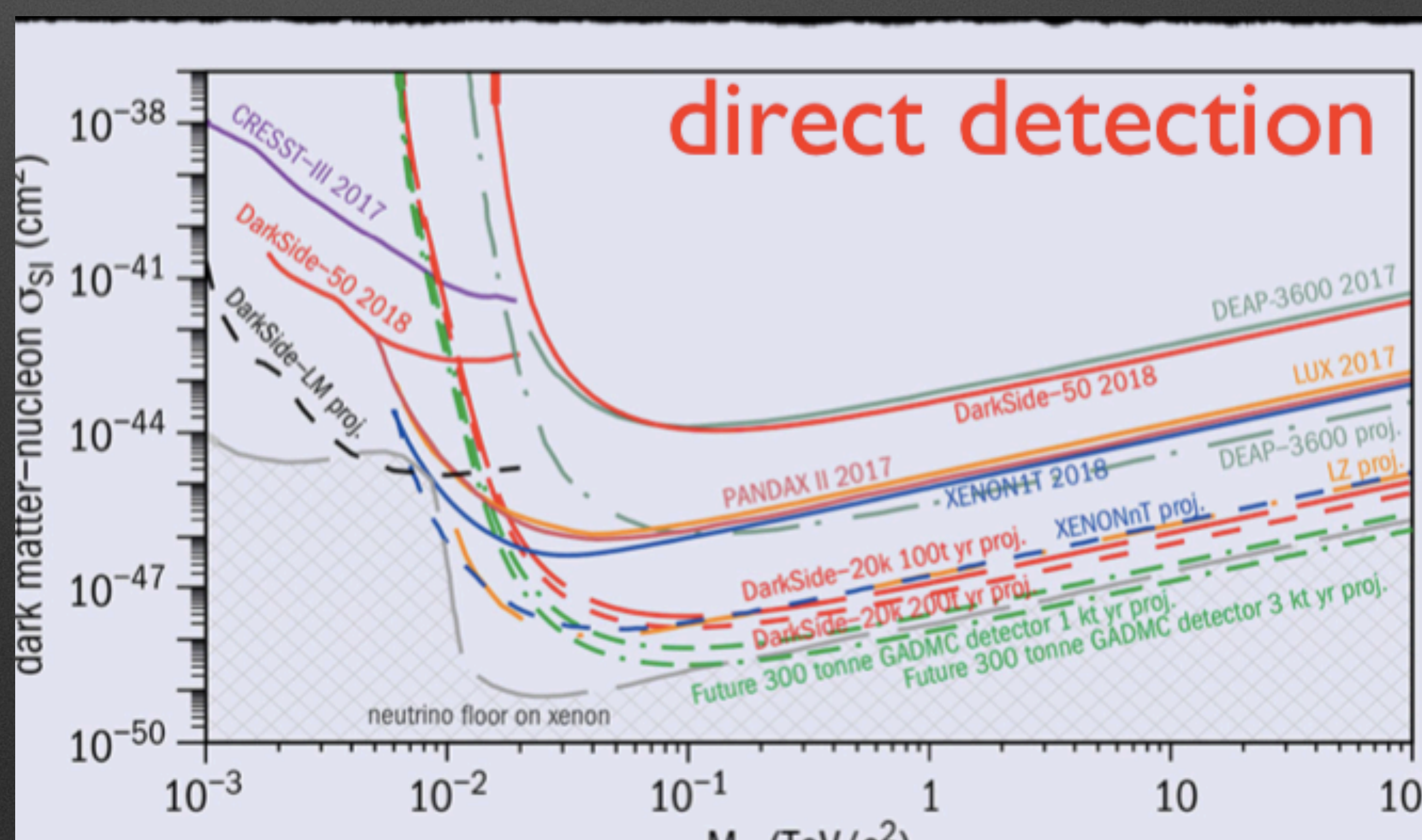


How obscure is Dark Matter

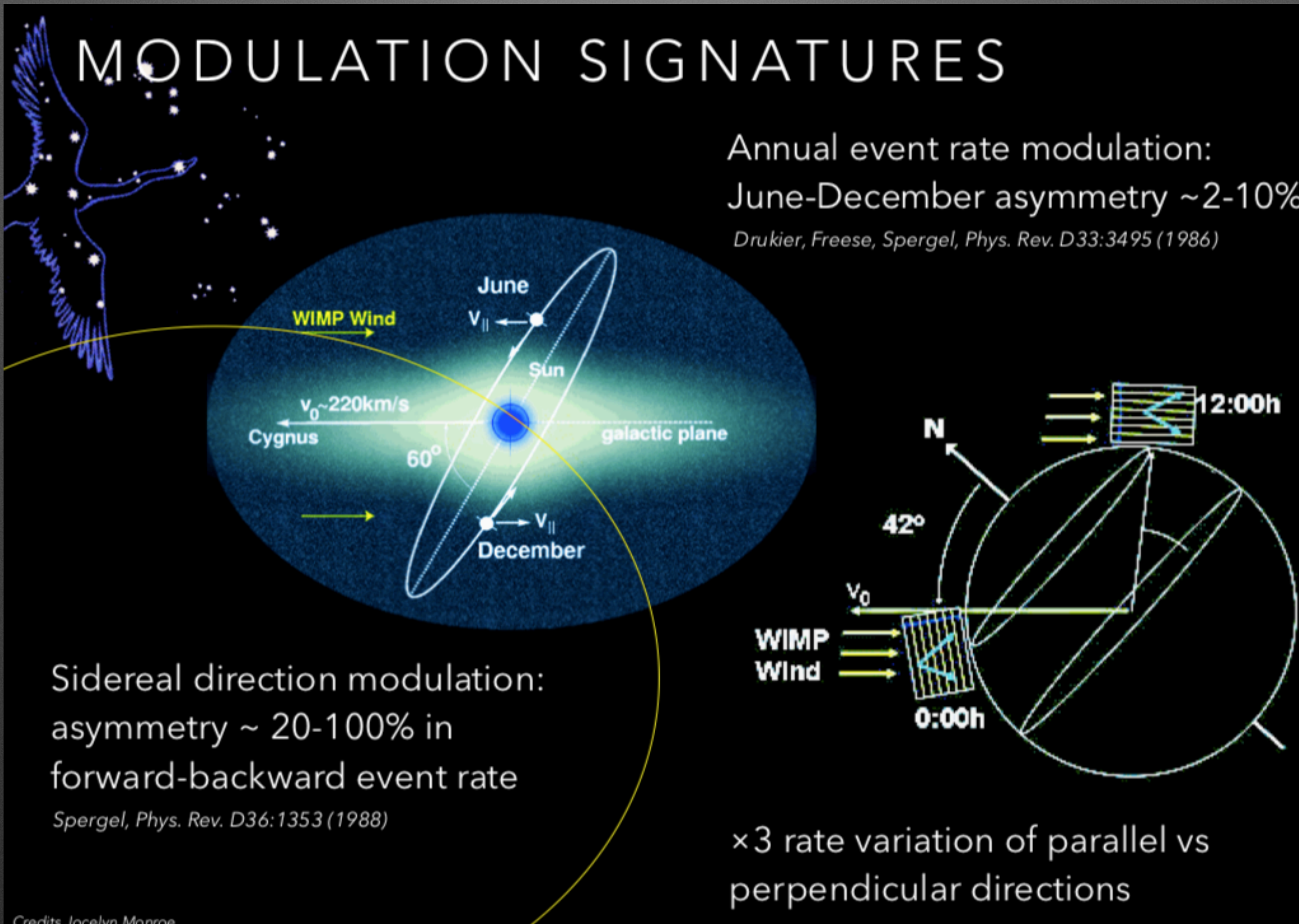
Dark Matter as a substantial slice of the Universe pie

- A duty of bringing the existing lines of research at LNGS to their limit (get to the neutrino floor)
- Xenon nT
- Dark Side 20k (moving eventually to ARGO 300k)





The most intriguing result



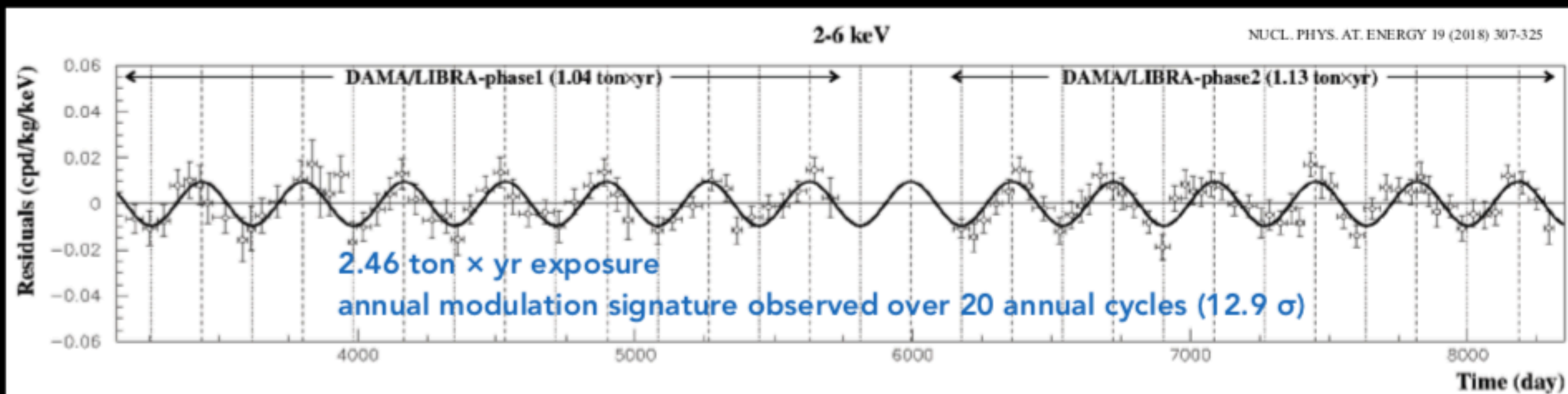
DAMA/LIBRA

MODULATION RECENT RESULTS

Standard Halo Model predicted modulation A~0.02-0.1, t_0=152.5 days

DAMA/NaI + DAMA/LIBRA-phase1 + phase2:

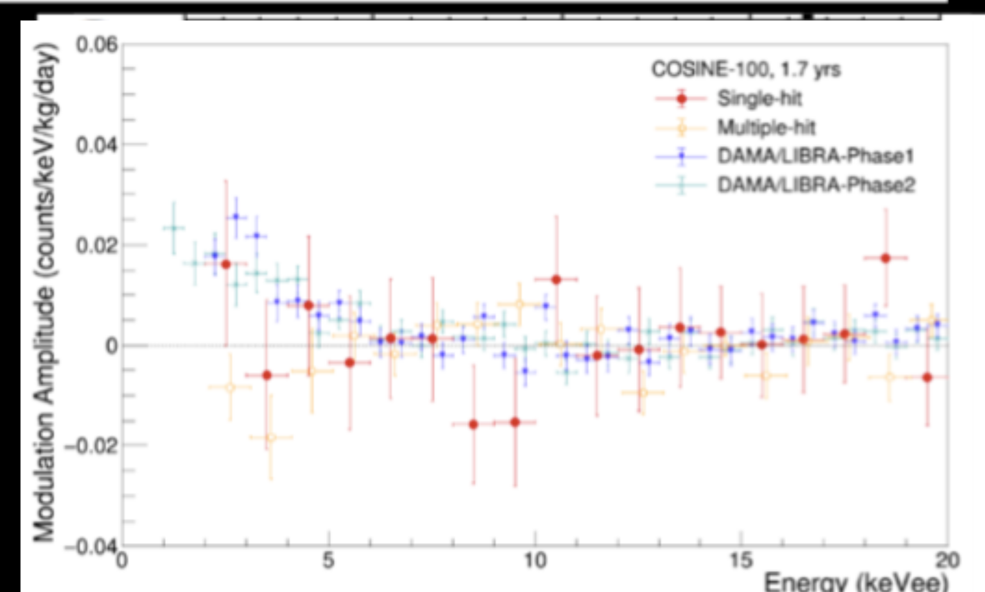
A= (0.0103 ± 0.0008) cpd/kg/keV, t_0 = (145±5) d in 2.46 t-yr (2 - 6 keV)



many other searches, on Ge, CsI, Xe, etc.
observe no evidence of modulation

In the same underground laboratory:
XENON100: Xe, 5.7σ exclusion of DAMA,
dark matter electron interactions via axial vector coupling *PRL118,101101 (2017)*

Using the same target (NaI):
ANAIS (LSC), **COSINE-100** (Y2L)
~consistent at 1σ, project 3σ test in 5 years

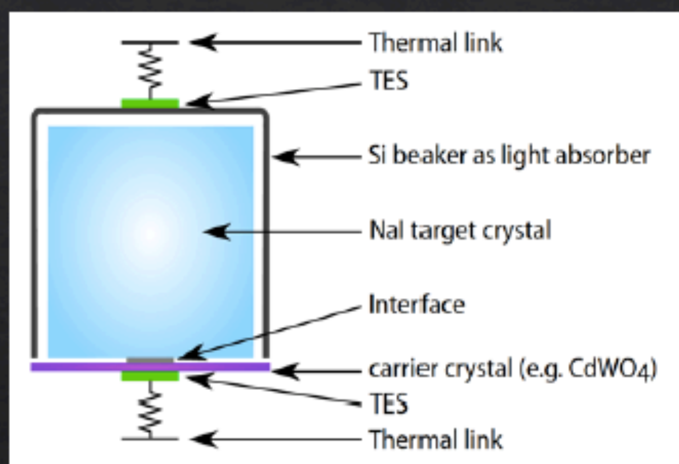


COSINE-100, arXiv:1903.10098

changing the temperature
COSINUS

Method

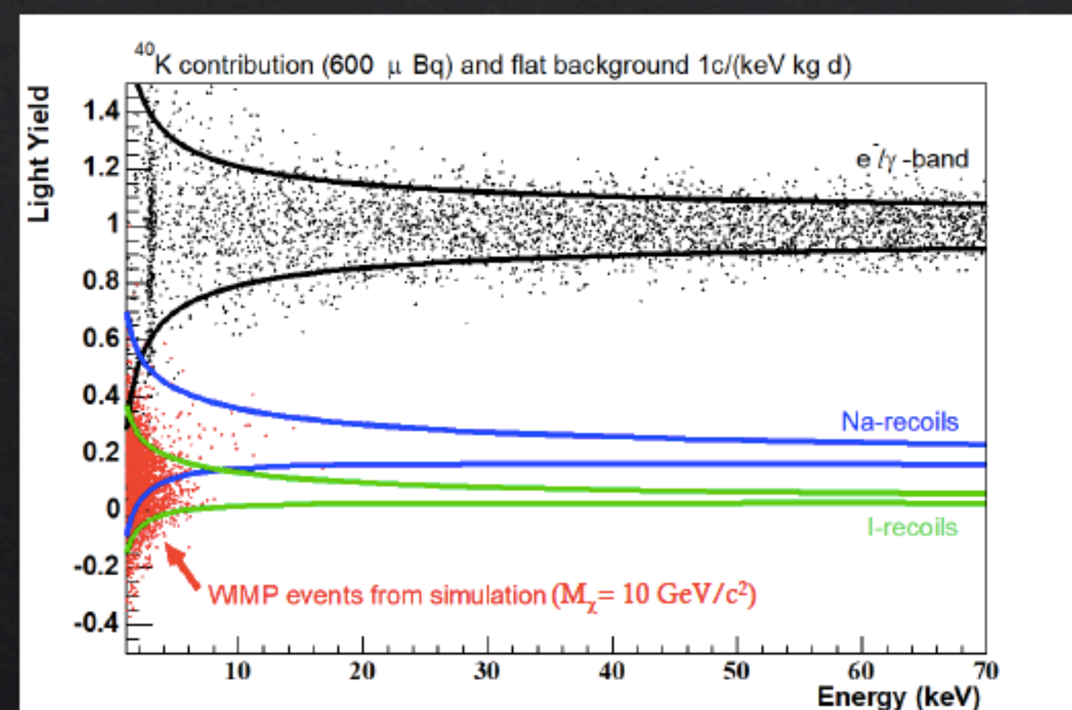
Eur. Phys. J. C (2016) 76:441

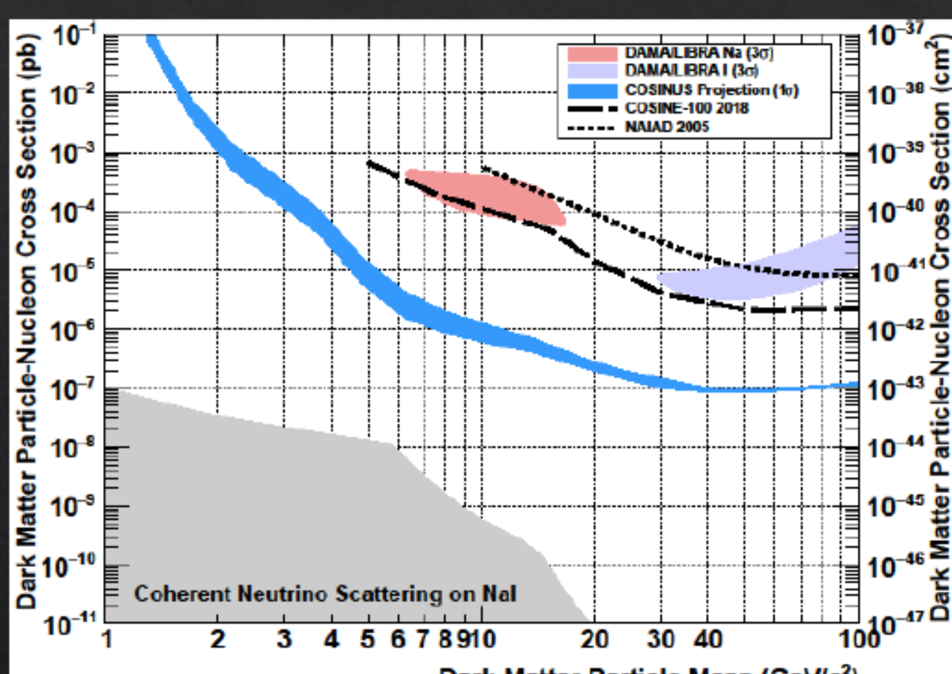


$$\text{LIGHT YIELD} = \frac{\text{LIGHT SIGNAL}}{\text{HEAT SIGNAL}}$$

Performance goal

- $E_{th} = 1$ keV ($5\,\sigma_{Phonon}$)
- $\sigma_{Phonon} = 0.2$ keV
- $\sigma_{Light} = 0.11\ keV_{ee}$
- 4% of deposited energy measured as light

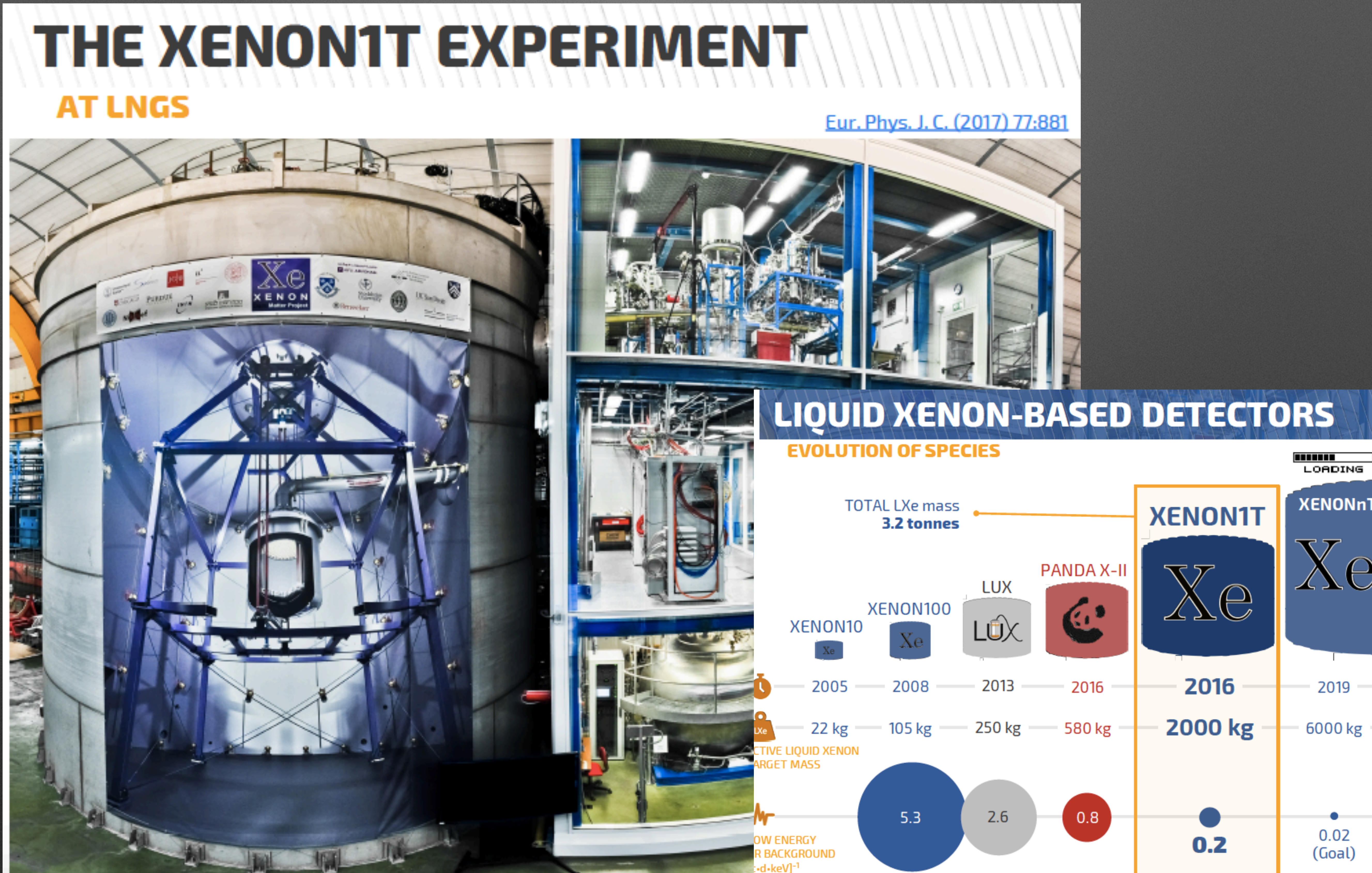




COSINUS should be able to exclude the DAMA region by about two orders of magnitude in cross section with an exposure of 100 kg days

10 crystals, 50 gr each → 1 year of data taking

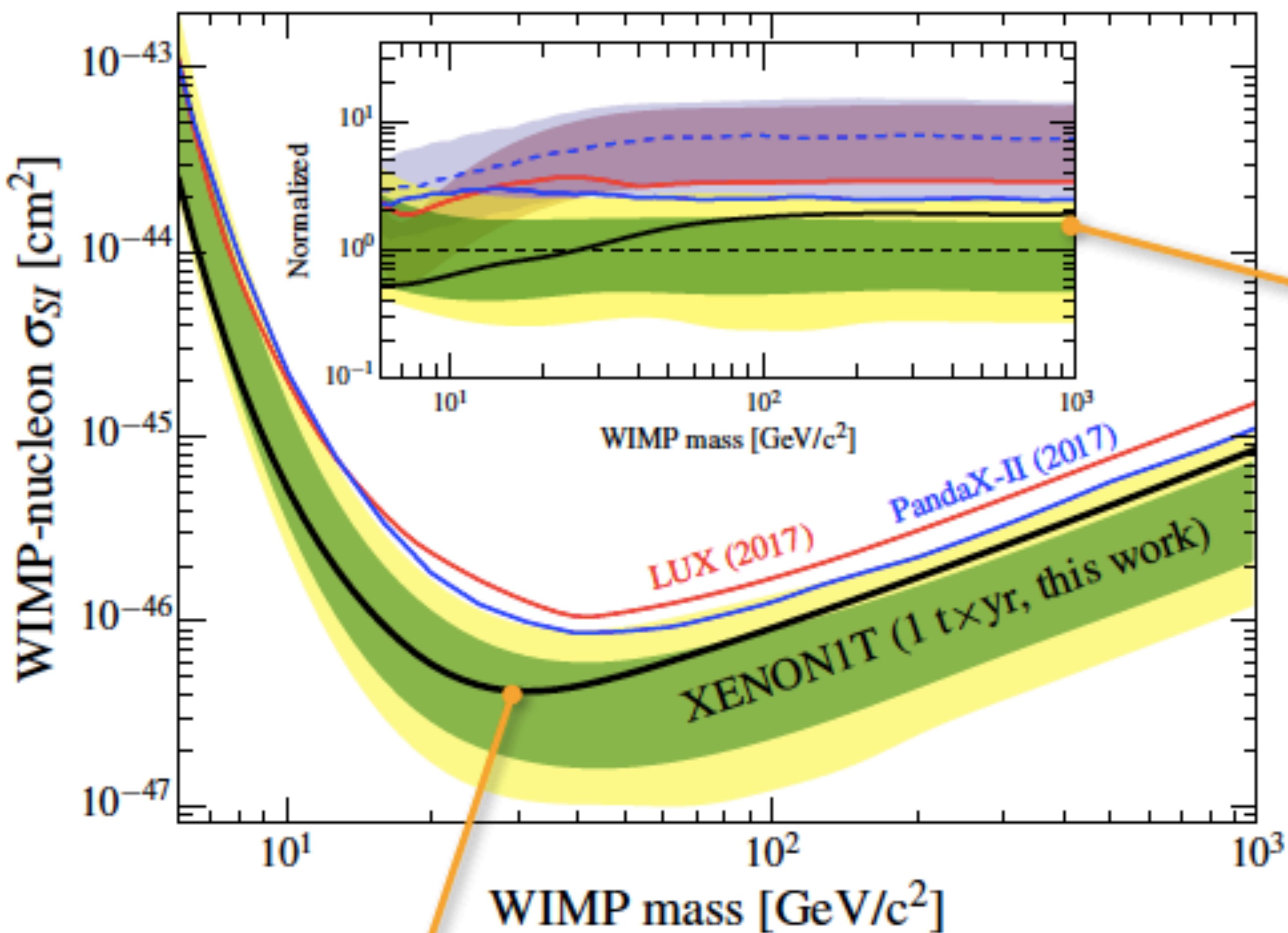
Xenon1(n)Ton


THE XENON1T EXPERIMENT
AT LNGS
Eur. Phys. J. C. (2017) 77:881
XENON
LIQUID XENON-BASED DETECTORS
EVOLUTION OF SPECIES
LOADING
TOTAL LXe mass
3.2 tonnes
XENON10
XENON100
LUX
PANDA X-II
XENON1T
XENONnT
2005
2008
2013
2016
2016
2019
22 kg
105 kg
250 kg
580 kg
2000 kg
6000 kg
CTIVE LIQUID XENON
ARGET MASS
5.3
2.6
0.8
0.2
0.02
(Goal)
OW ENERGY
R BACKGROUND

SPIN-INDEPENDENT WIMP INTERACTION

Phys. Rev. Lett. 121,111302

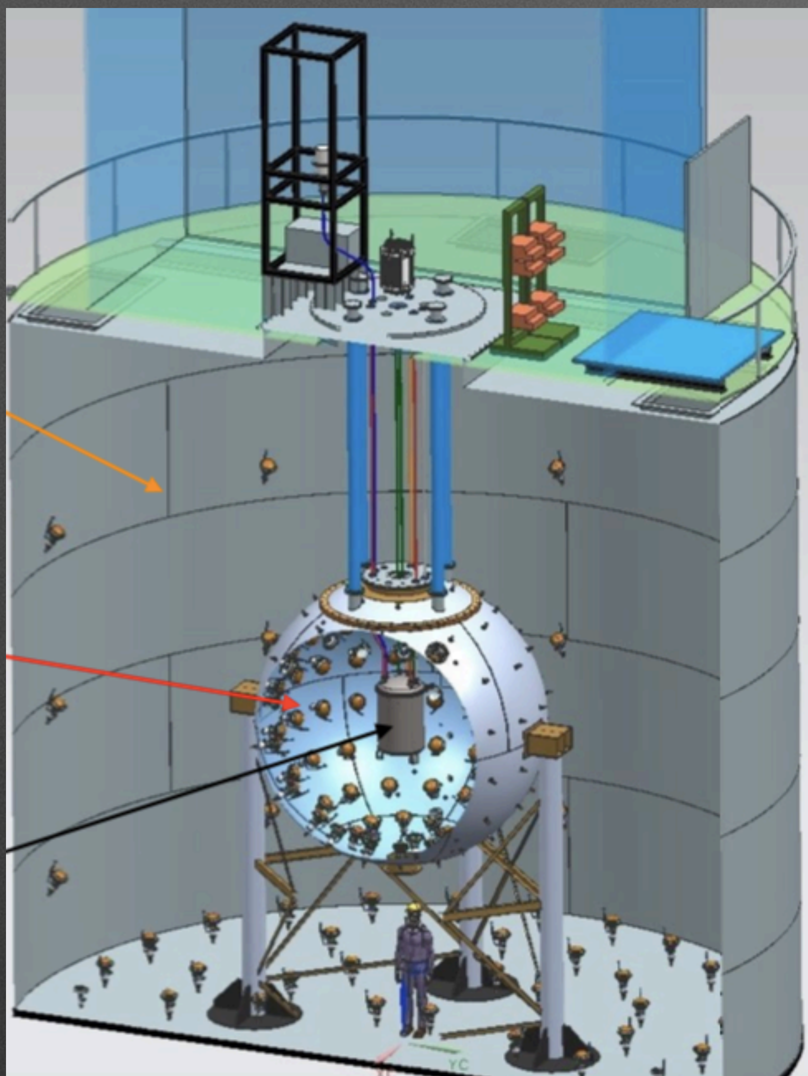
WORLD BEST CONSTRAINT ON WIMP DARK MATTER
Most stringent exclusion limits (at 90% CL) for WIMPs > 6 GeV/c^2

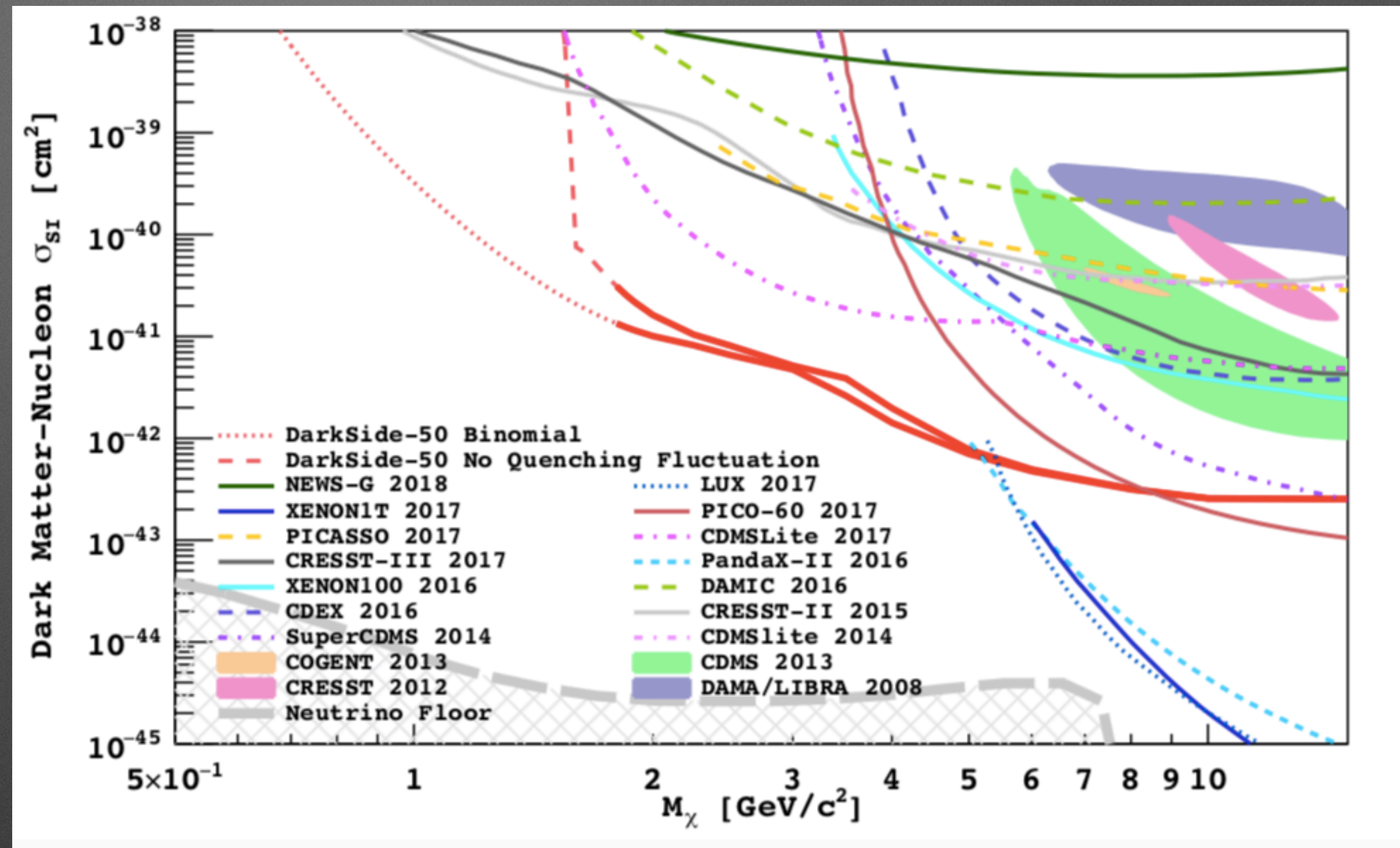


x7 IMPROVED SENSITIVITY with respect to previous experiments (LUX, PANDAX-II)

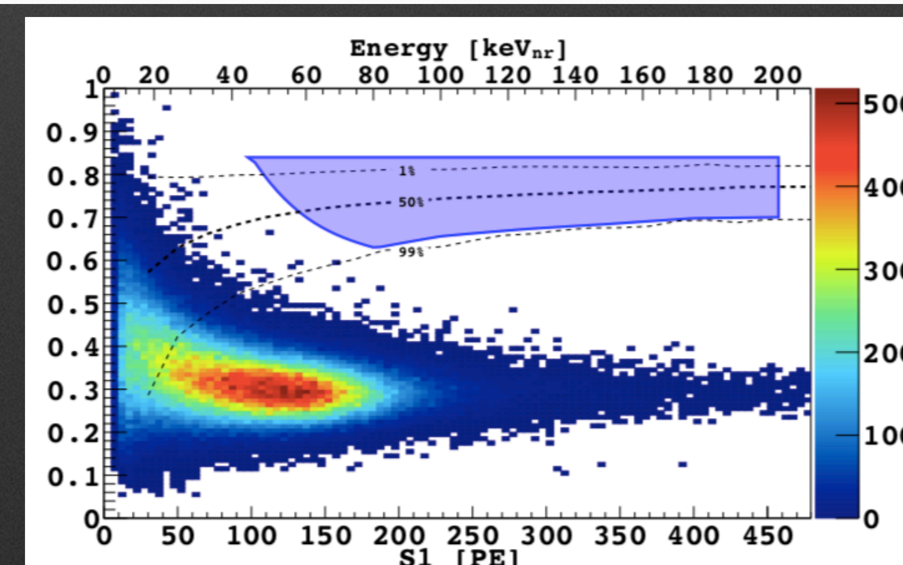
σ_{SI} < 4.1·10^{-47} cm^2 at 30 GeV/c^2

Dark Side 50: low mass DM



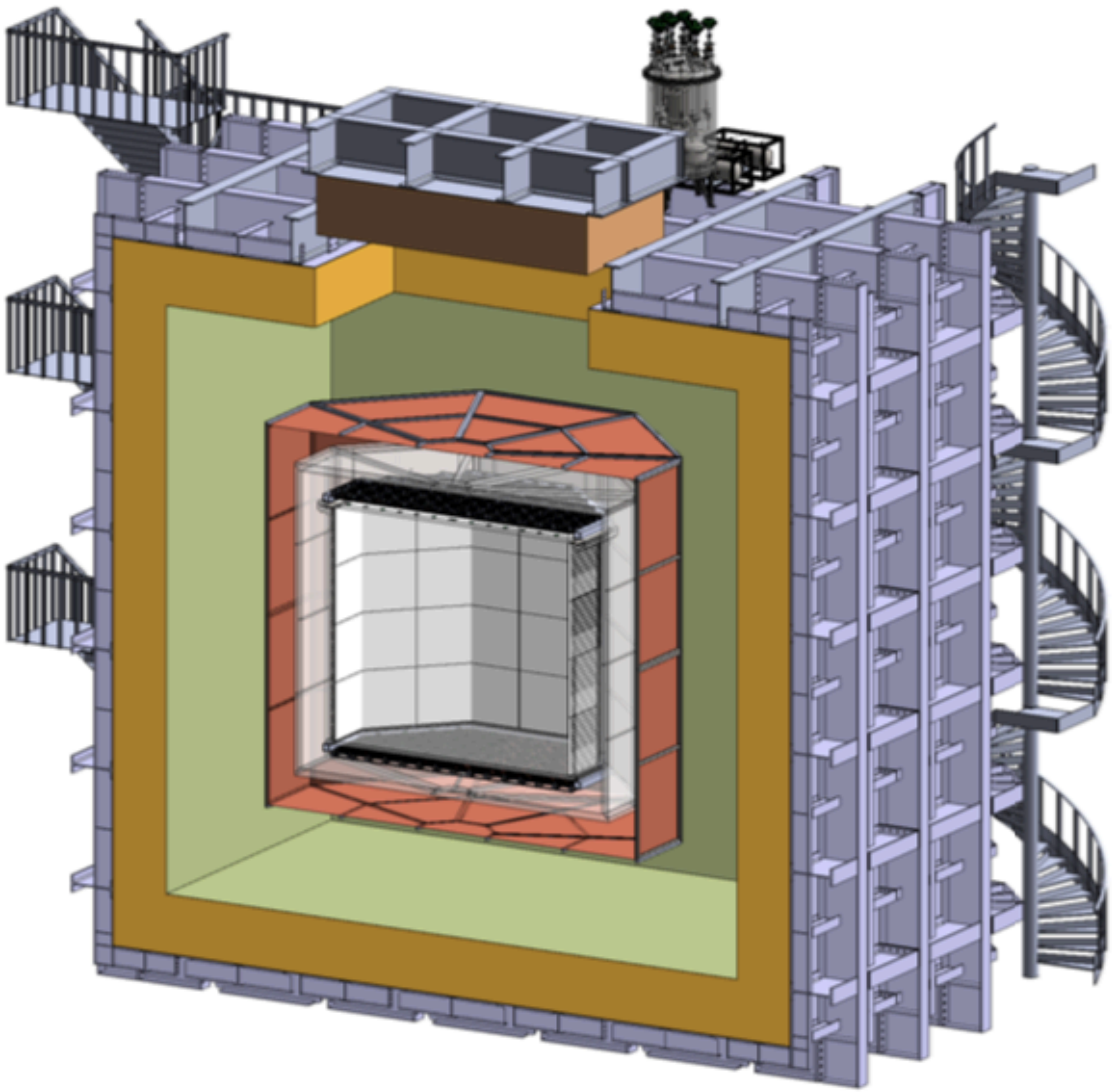


concept for a 0 background 20 ton Dark Side experiment



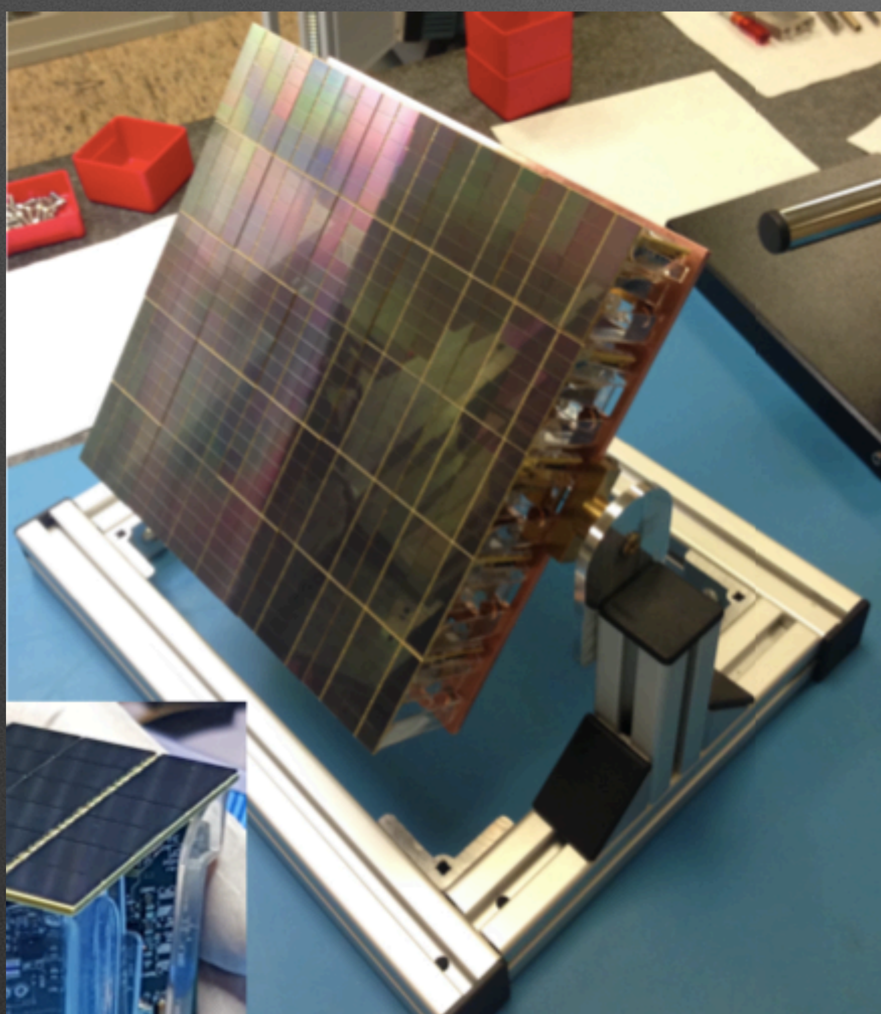
Dark Side 20k @LNGS

- DarkSide-20k @ LNGS
- Sealed acrylic TPC containing 50 tonnes of UAr in a ProtoDUNE-like cryostat filled with ~700 tonnes of AAr
- 30 m^2 SiPMs as photosensors (8280 channels for TPC and ~3000 channels for Veto)
- Gd-doped acrylic panels as neutron veto



main steps forward

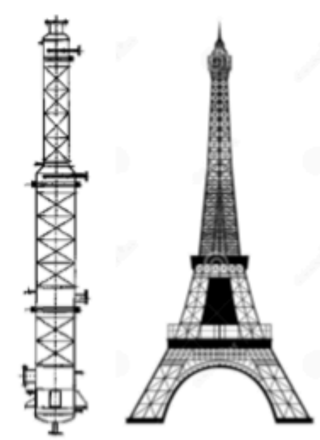
SiPMs to replace PMTs



Low-radioactive argon procurement and purification

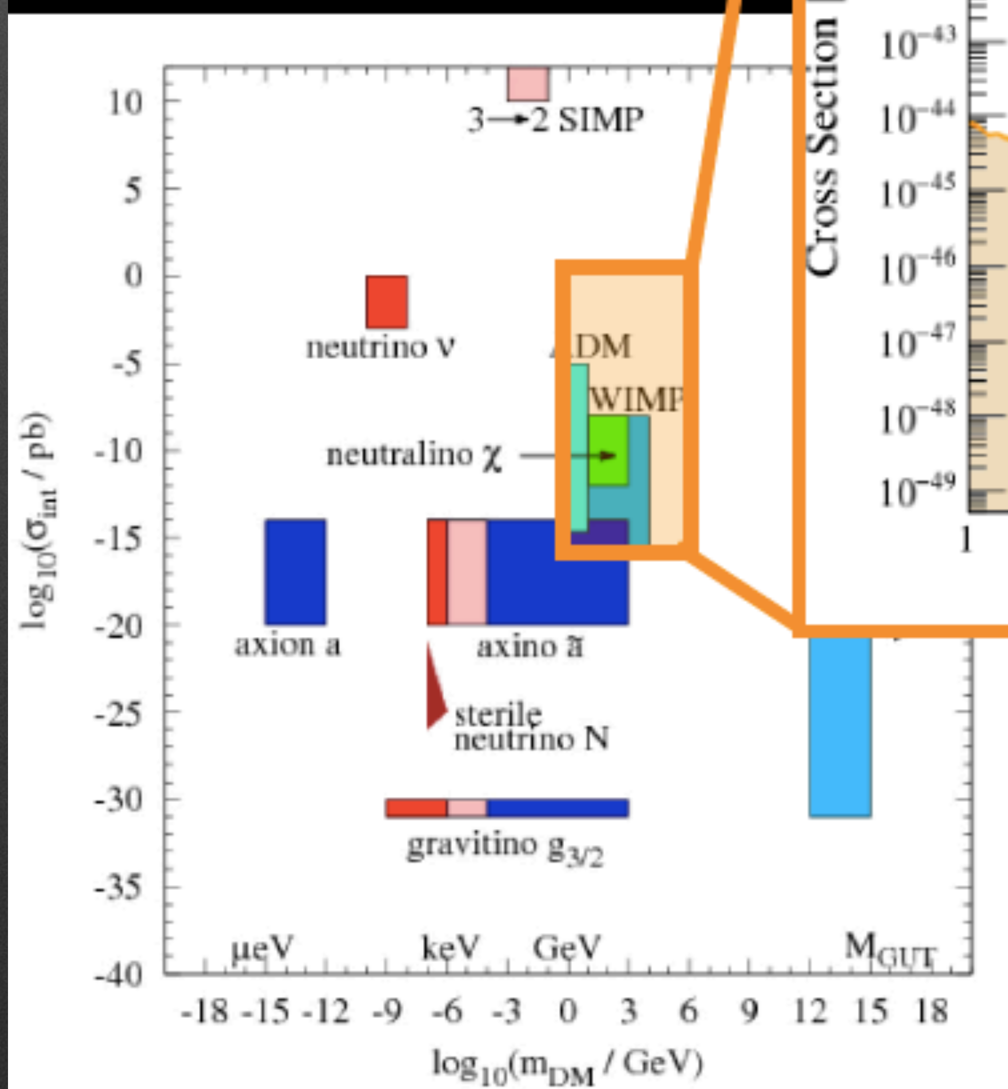
- **Urania:** procurement of at least 60 tonnes of UAr from Colorado, USA (same as DS50) withe extraction rate of 250 kg/day, with 99.9% purity
- **Aria:** UAr transported to Sardinia, Italy for final chemical purification via a 350m tall cryogenic distillation column in Seruci, Sardinia, Italy
  - Process ~1 tonne/day with 1000 reduction of all chemical impurities and isotopically separate ^{39}Ar from ^{40}Ar

Seruci-0 - prototype

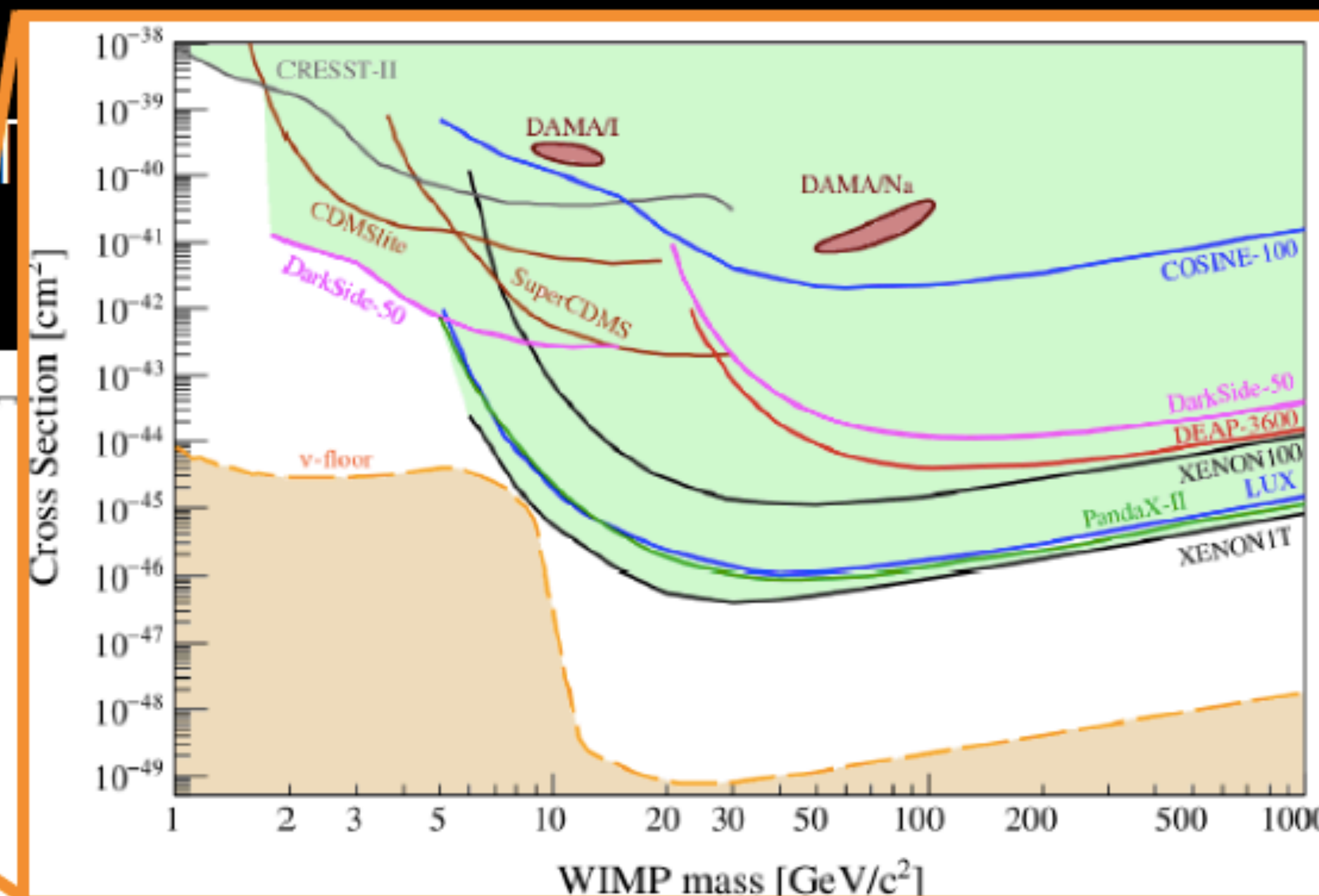


Seruci-I and II

great results and perspectives however........



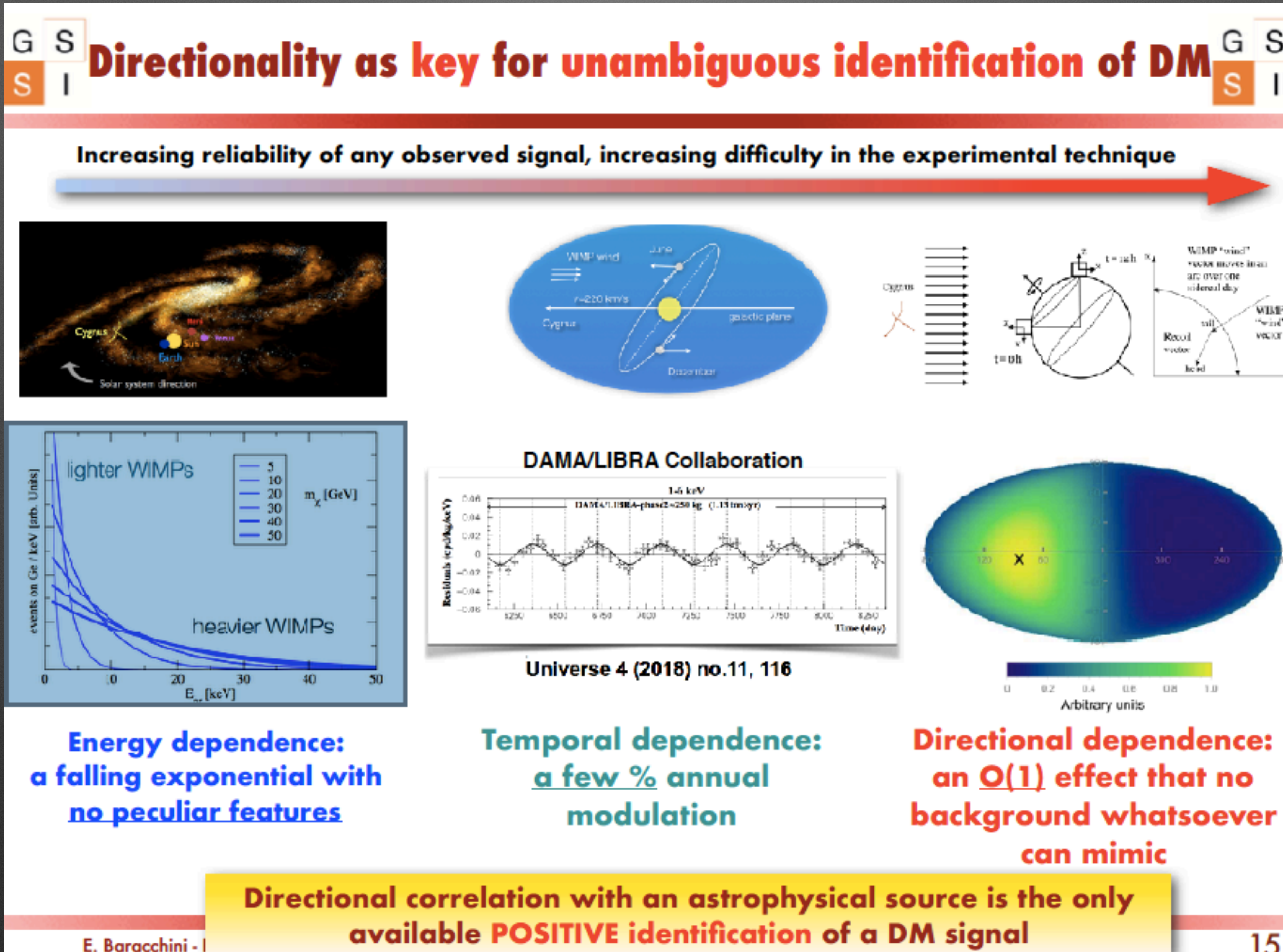
Baer et al., arXiv:1407.0017



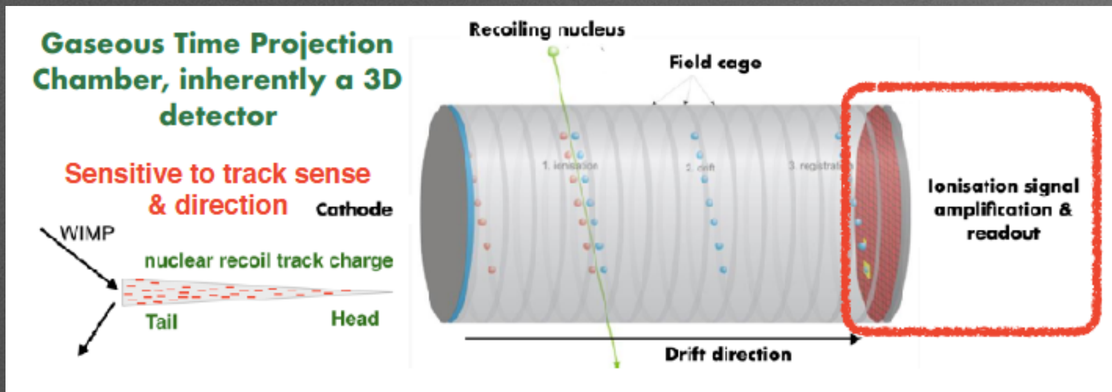
Schumann, arXiv:1903.03026

Direct searches generally optimised for WIMP sensitivity...

after you hit the neutrino floor



Long and winding road

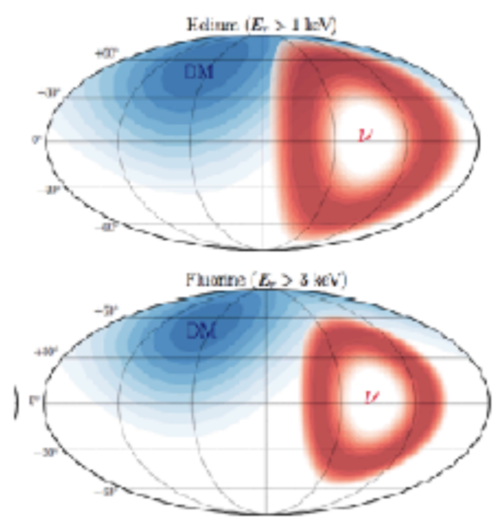


What you will find in the Whitepaper

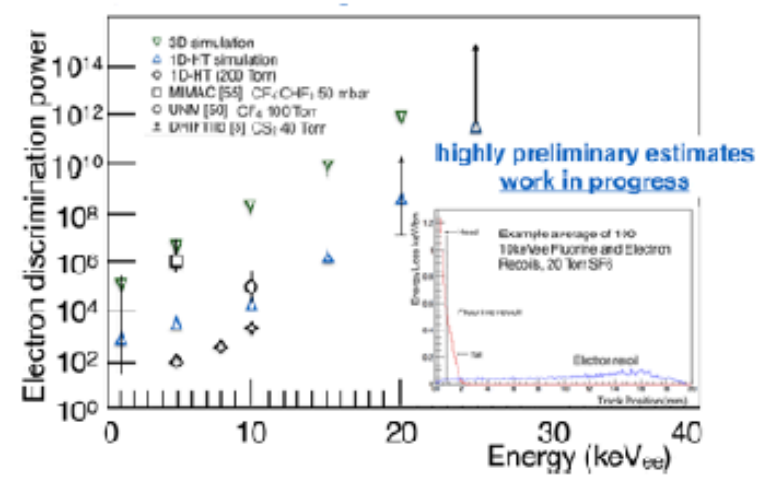
G S
S I

CYGNUS: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos

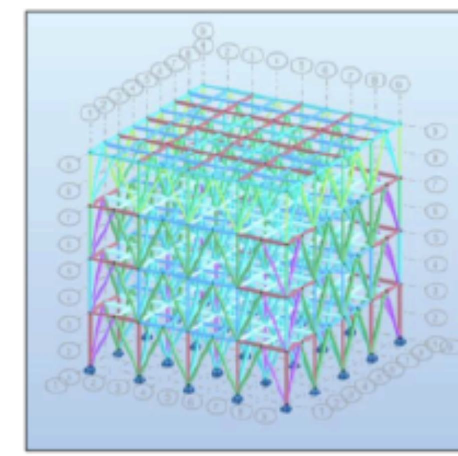
The physics case for DM and neutrinos measurements



Background discrimination @ 10^5 (for 3D readout) down to 1 keV, with simulation and supported by measurements

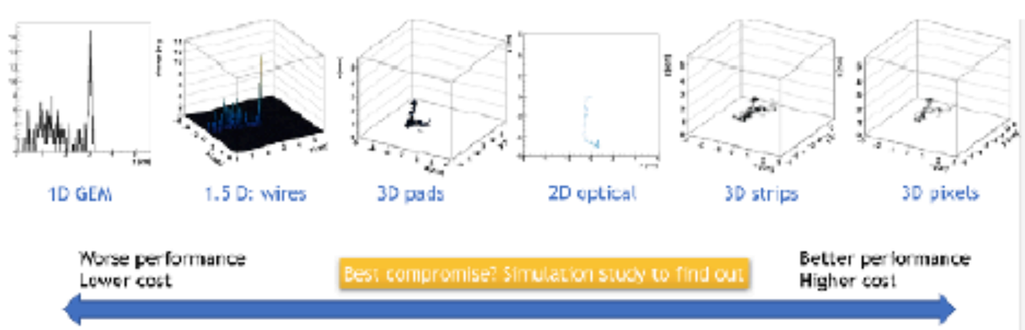


Engineering studies for 1000 m³ detector



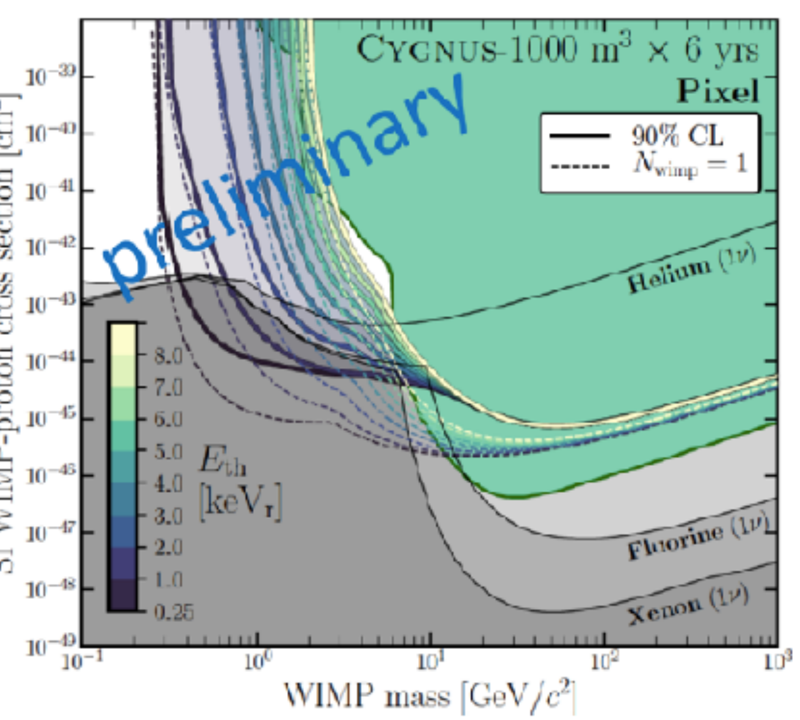
PRELIMINARY

Detailed simulation of six readout options, with both negative ion and electron drift, with a cost/benefit FOM



A detailed simulation & studies of all the internal and external backgrounds

Readout	Material	Thickness (mm)	Total mass (tons)
THGEM	Acrylic	1.0	2.36
THGEM	Copper	0.1	3.6
μ-PIC	Polyimide	1.0	2.84
CEM	Kapton	(0.05)	0.0142
Wires	Steel	0.05	1.94×10^{-3}
Wires (frame)	Acrylic	10	0.236
Pixel Chip	Silicon	0.400	1.86
Pixel Chip	Copper	3.9×10^{-3}	0.07
Pixel Chip	Aluminium	4.5×10^{3}	0.024

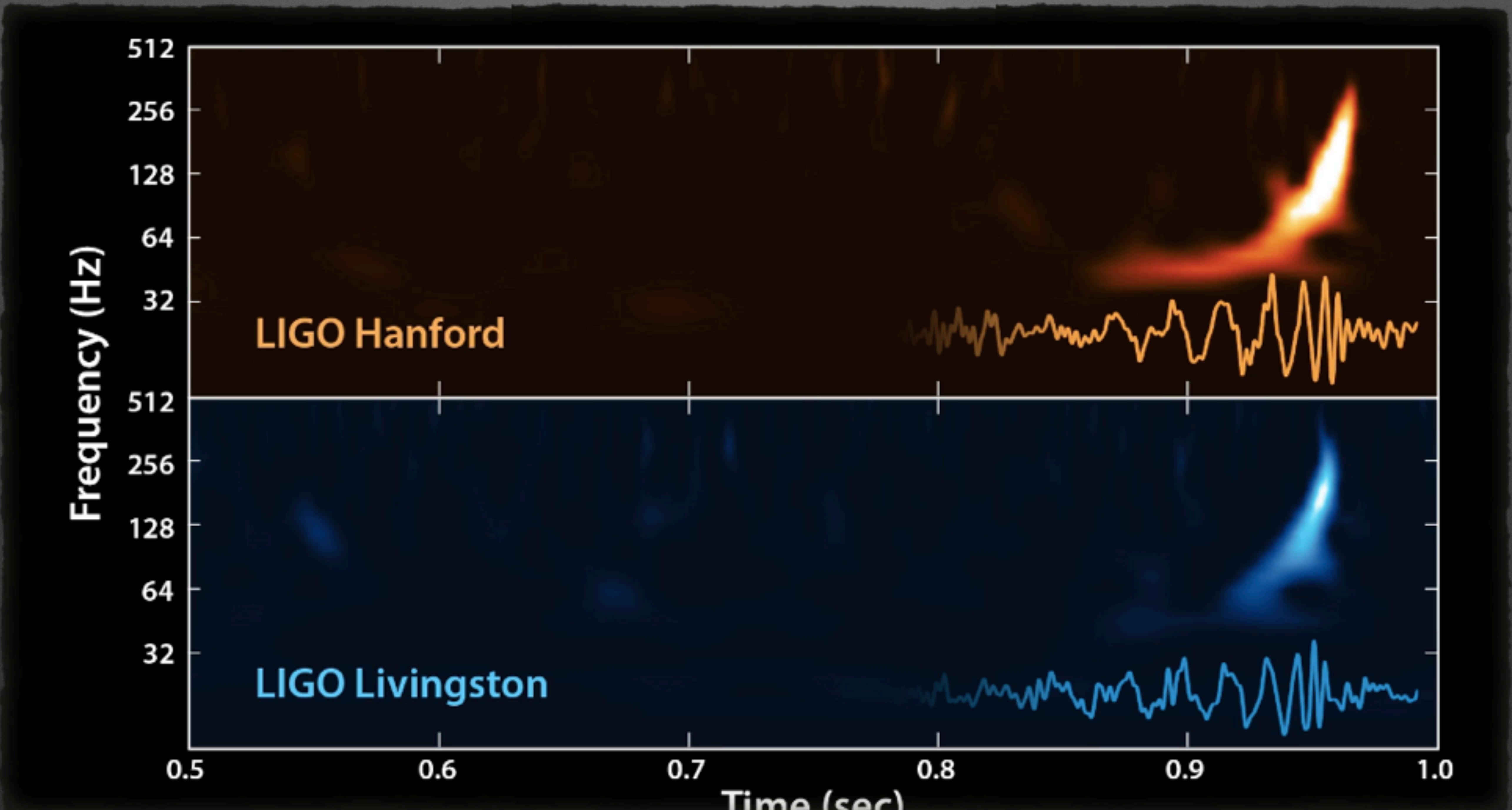


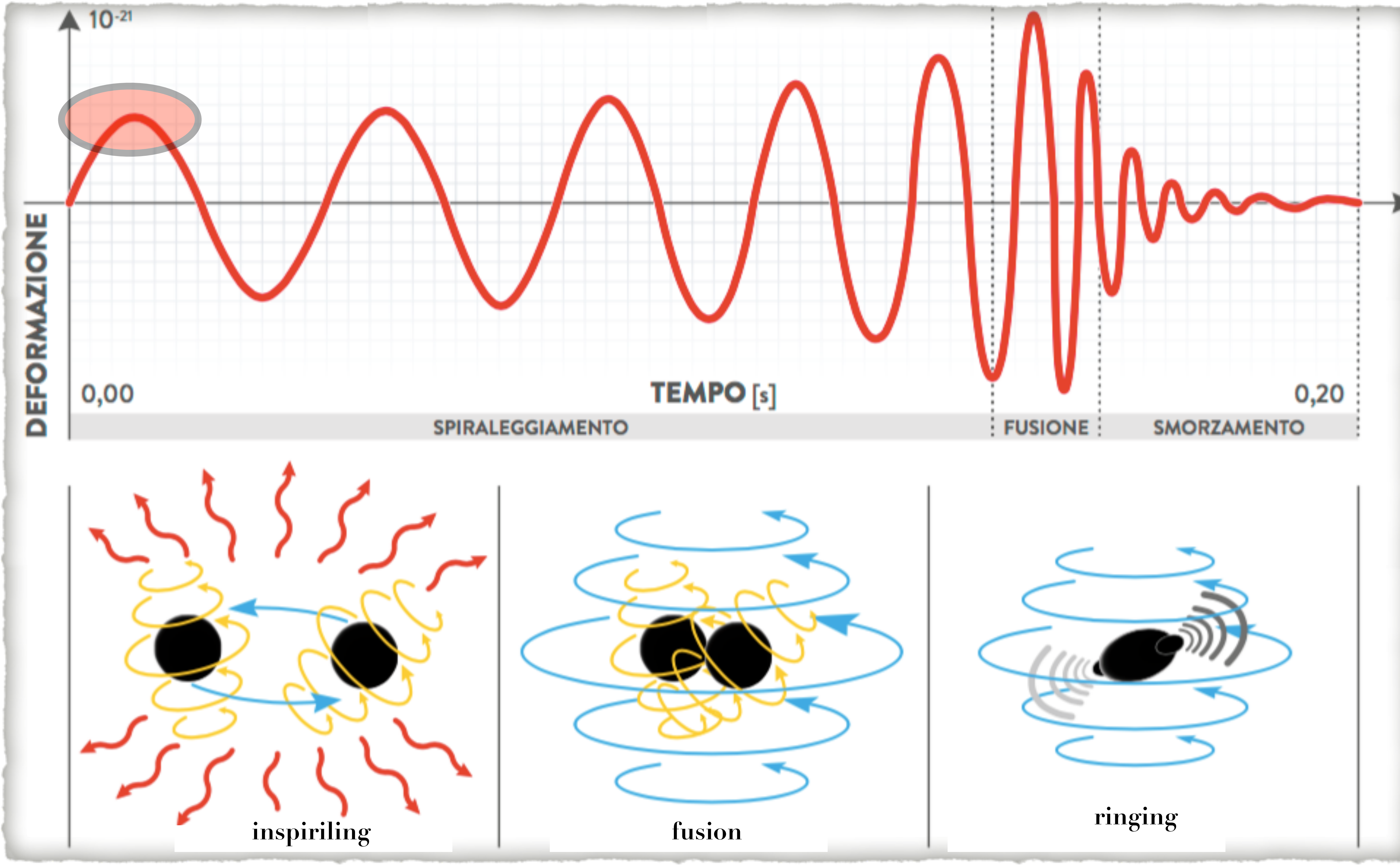
Significant improvement in SI in the low WIMP mass region, expect 10-50 IDENTIFIED neutrino nuclear recoil events

Gravitational Waves

a magic window on Gravity, Astronomy, Cosmology and Nuclear Physics

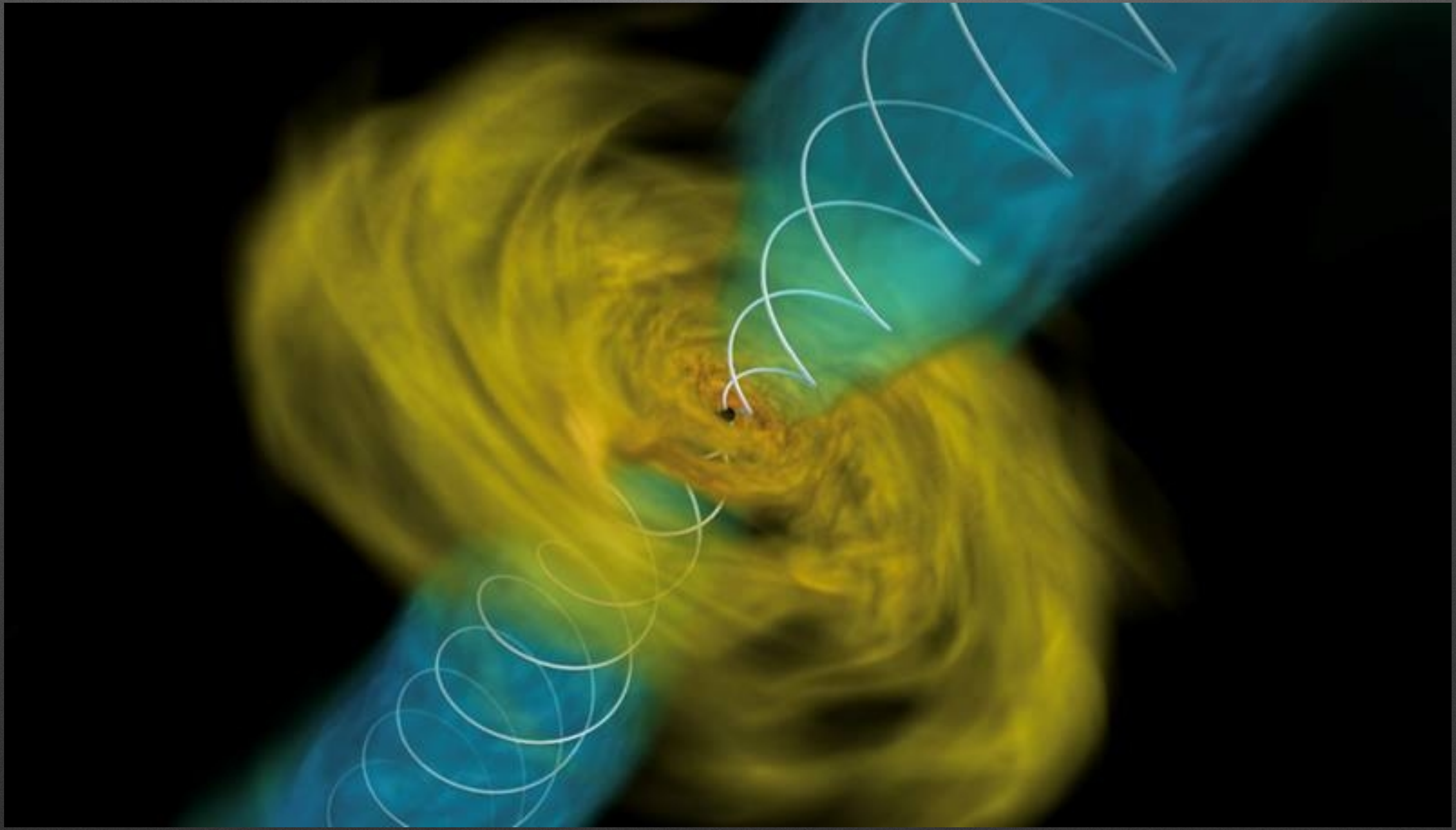
1.3 billion year ago in a far away galaxy



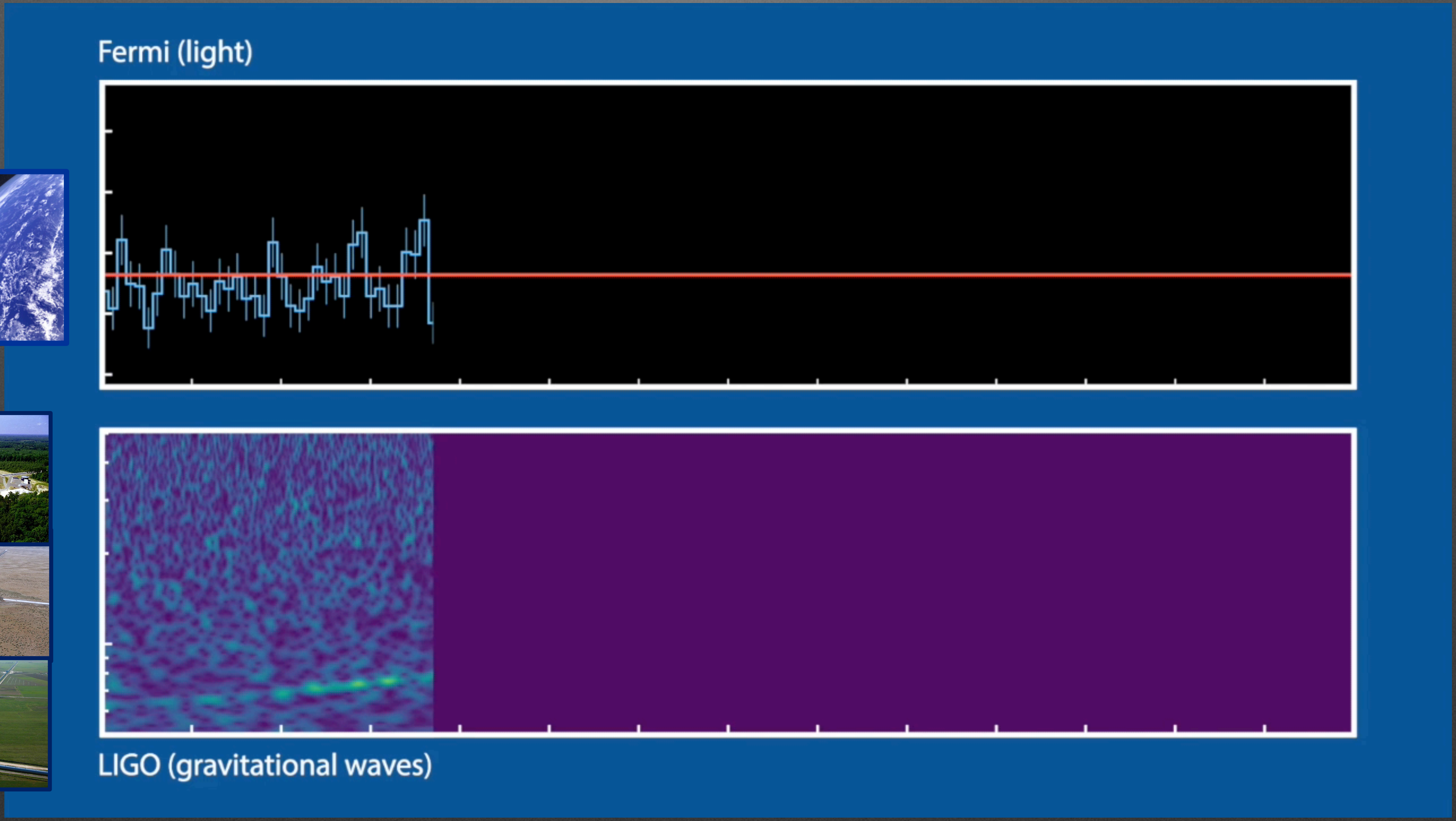


10^{-21}
DEFORMAZIONE
0,00
TEMPO [s]
0,20
SPIRALEGGIAMENTO
FUSIONE
SMORZAMENTO
inspiriling
fusion
ringing

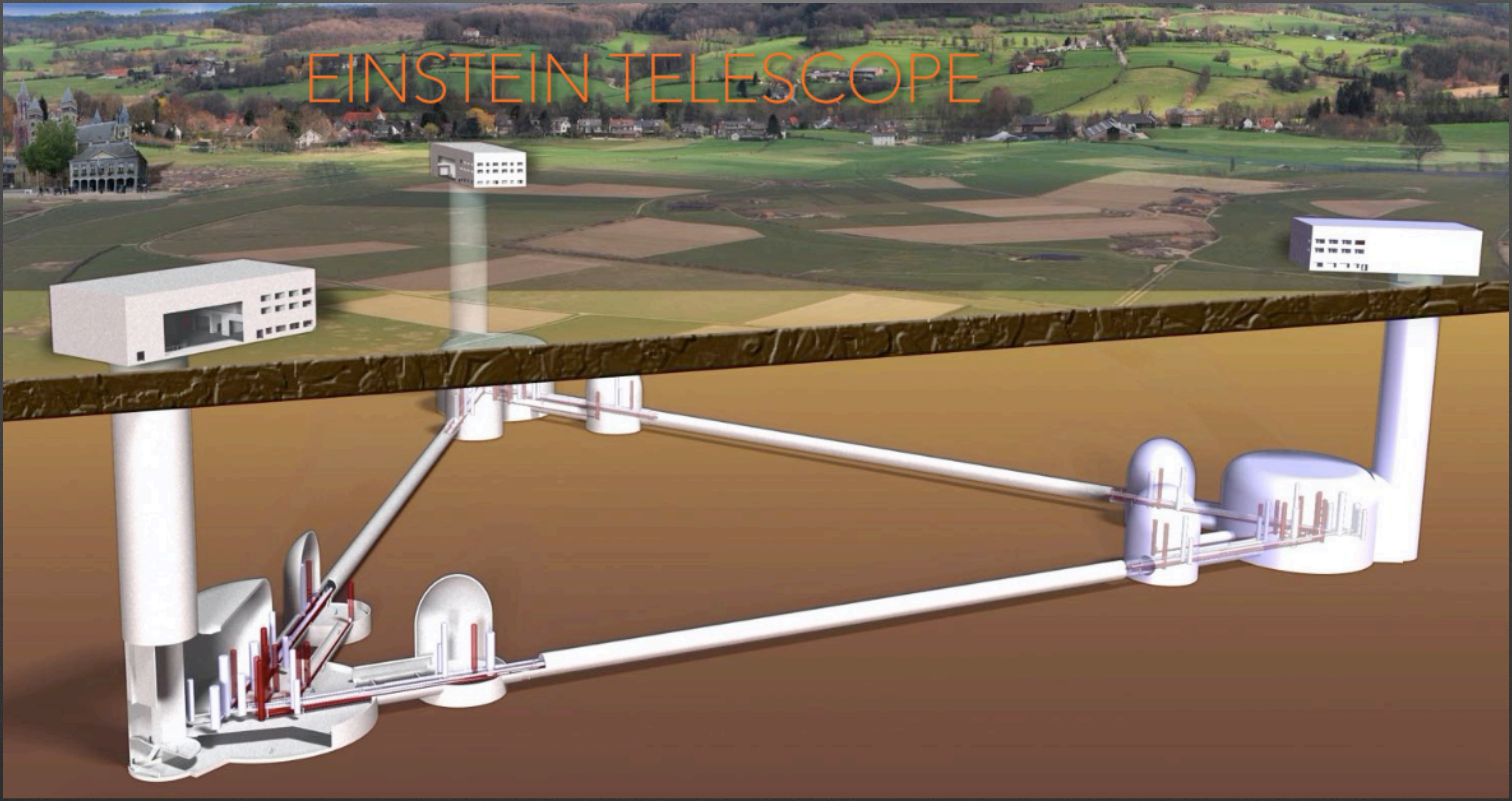
much closer but even more important



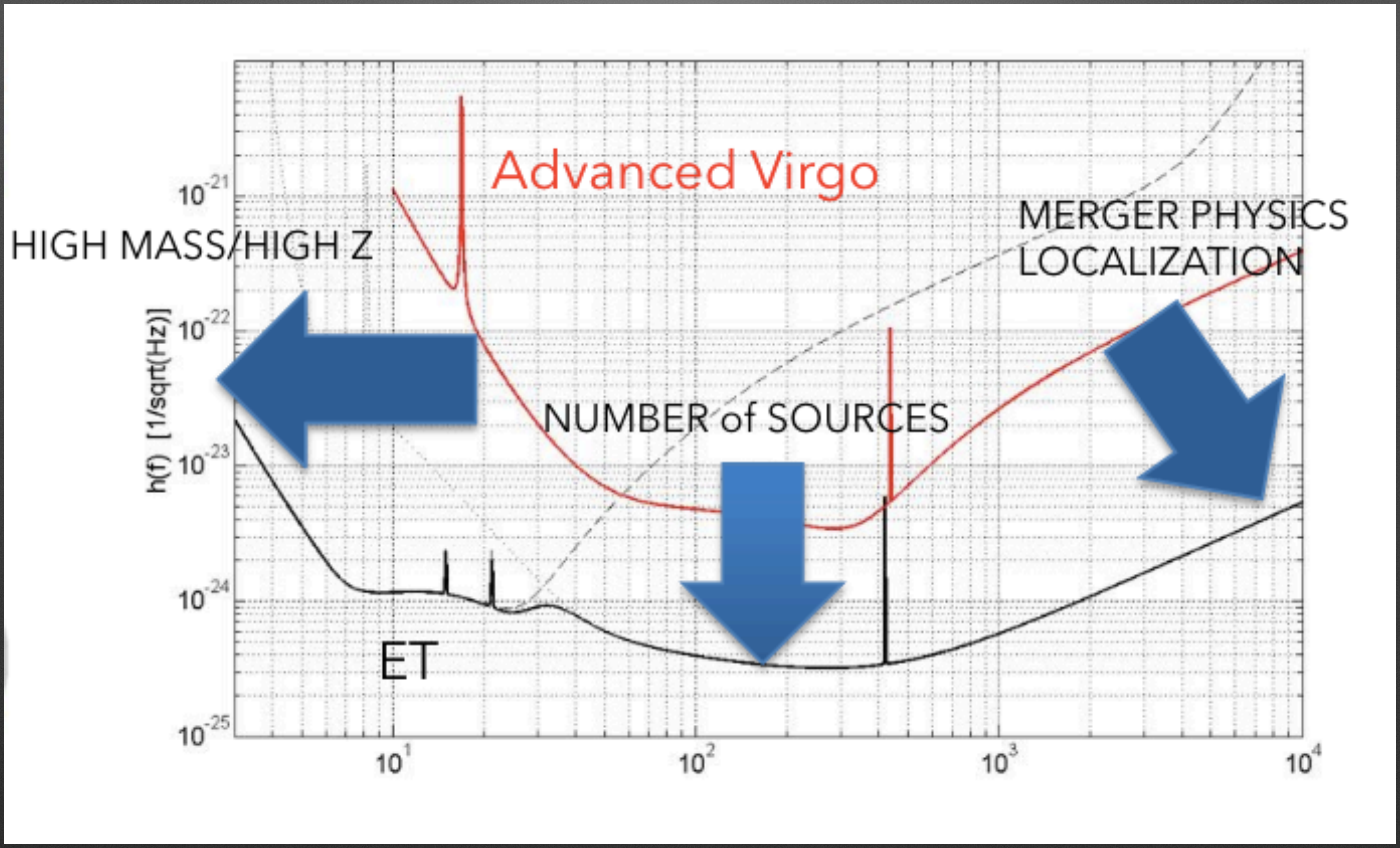
A revolution !



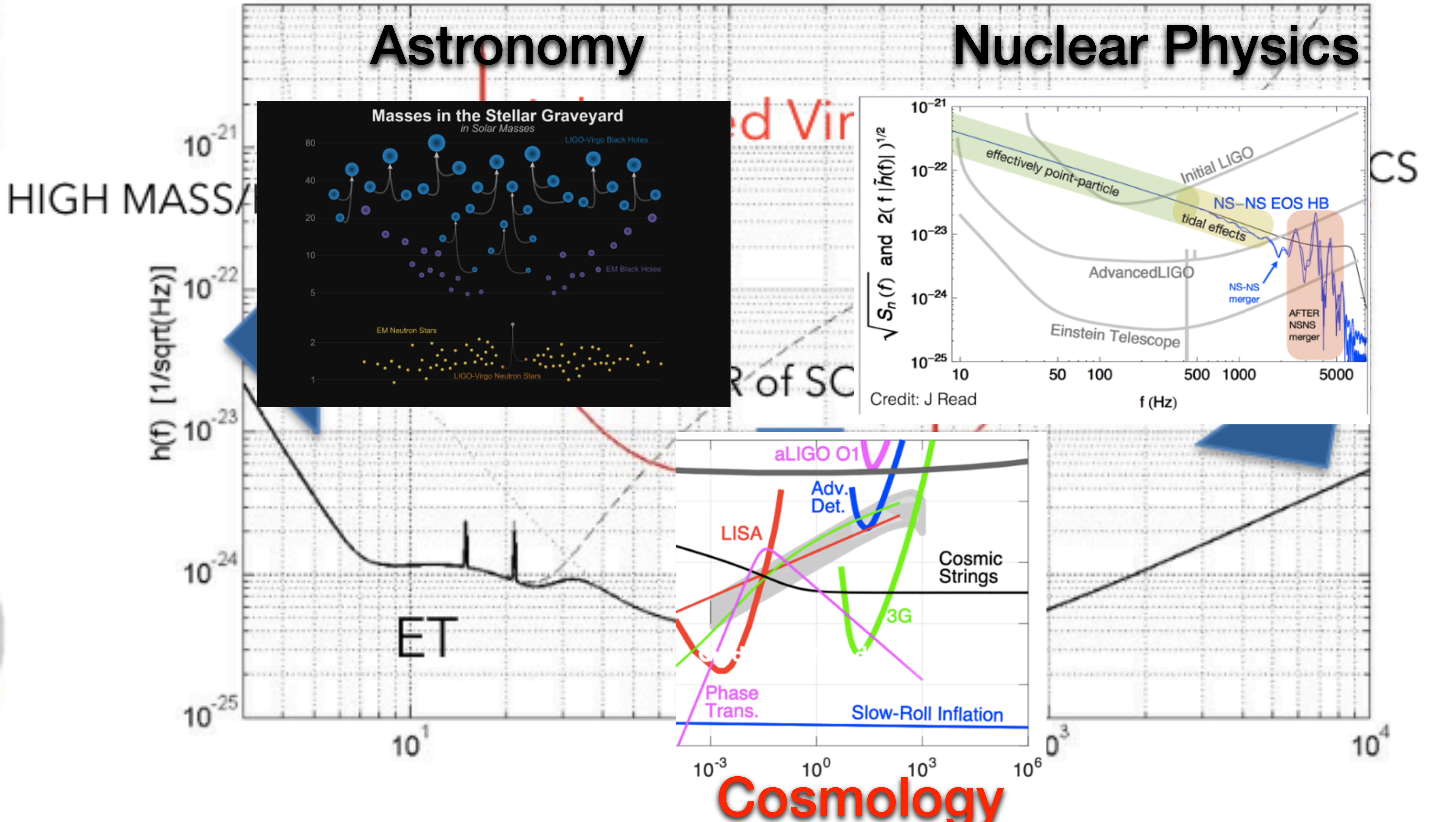
and now ET



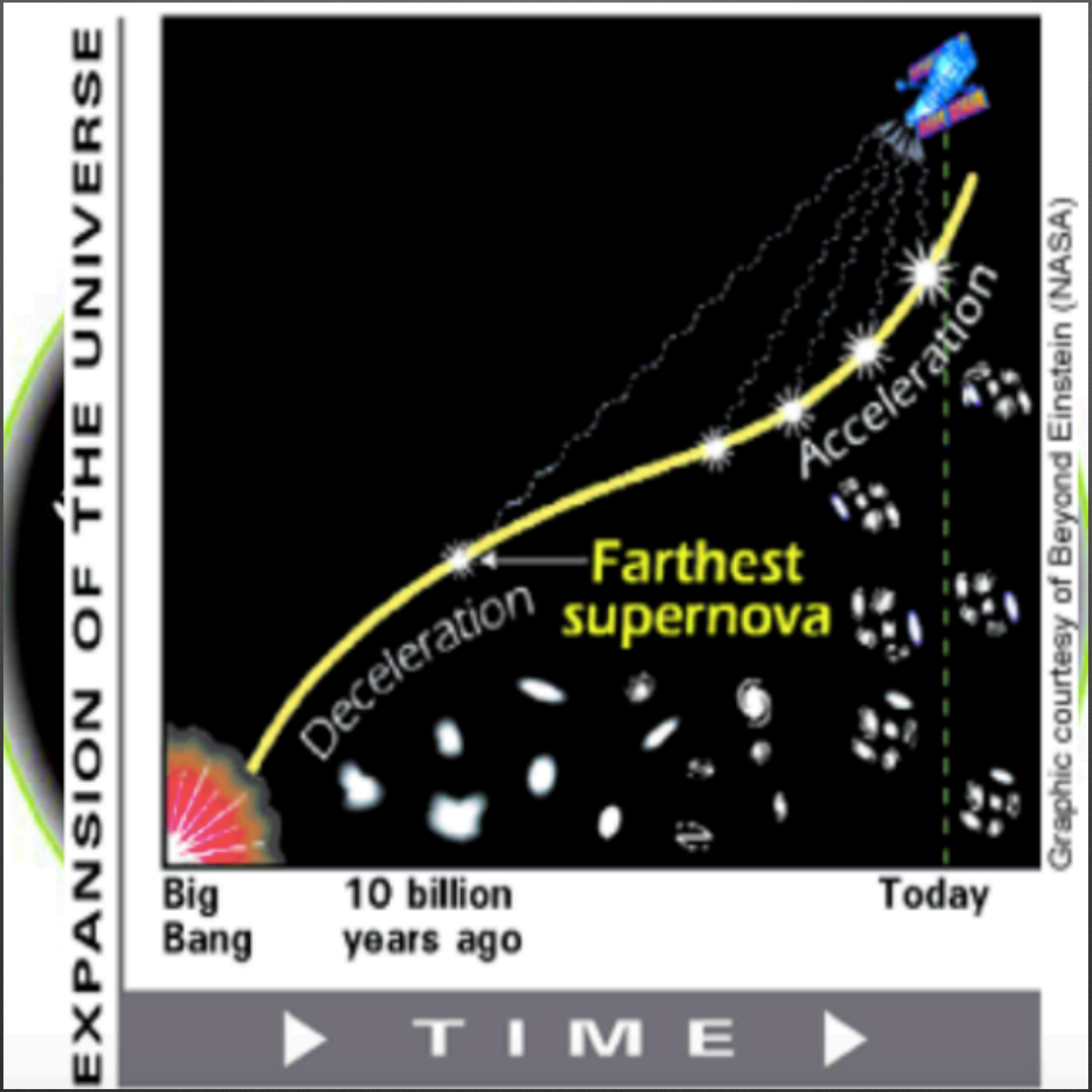
what an improvement !



a brutal way of seeing things

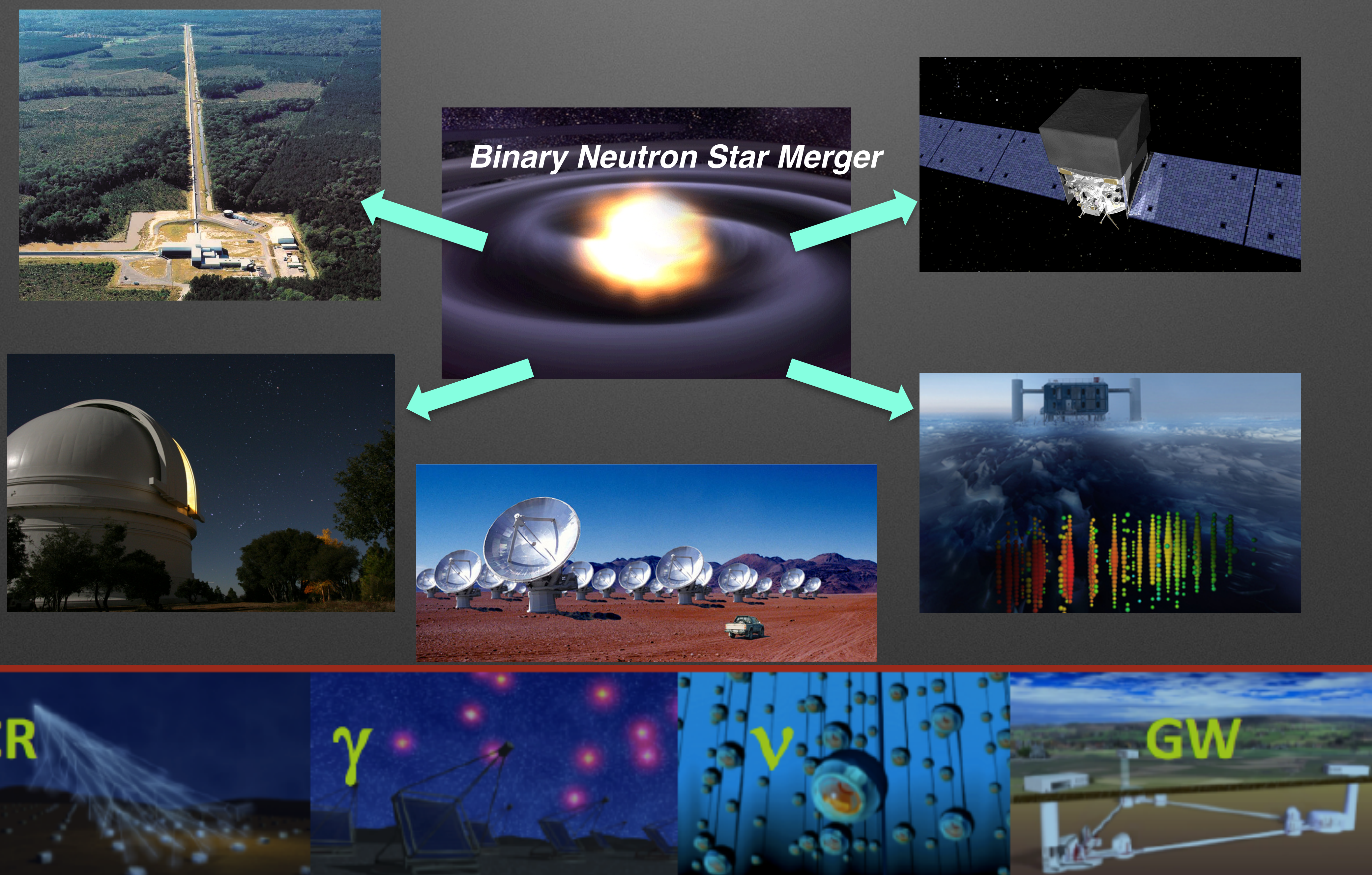


sorry, not for me !

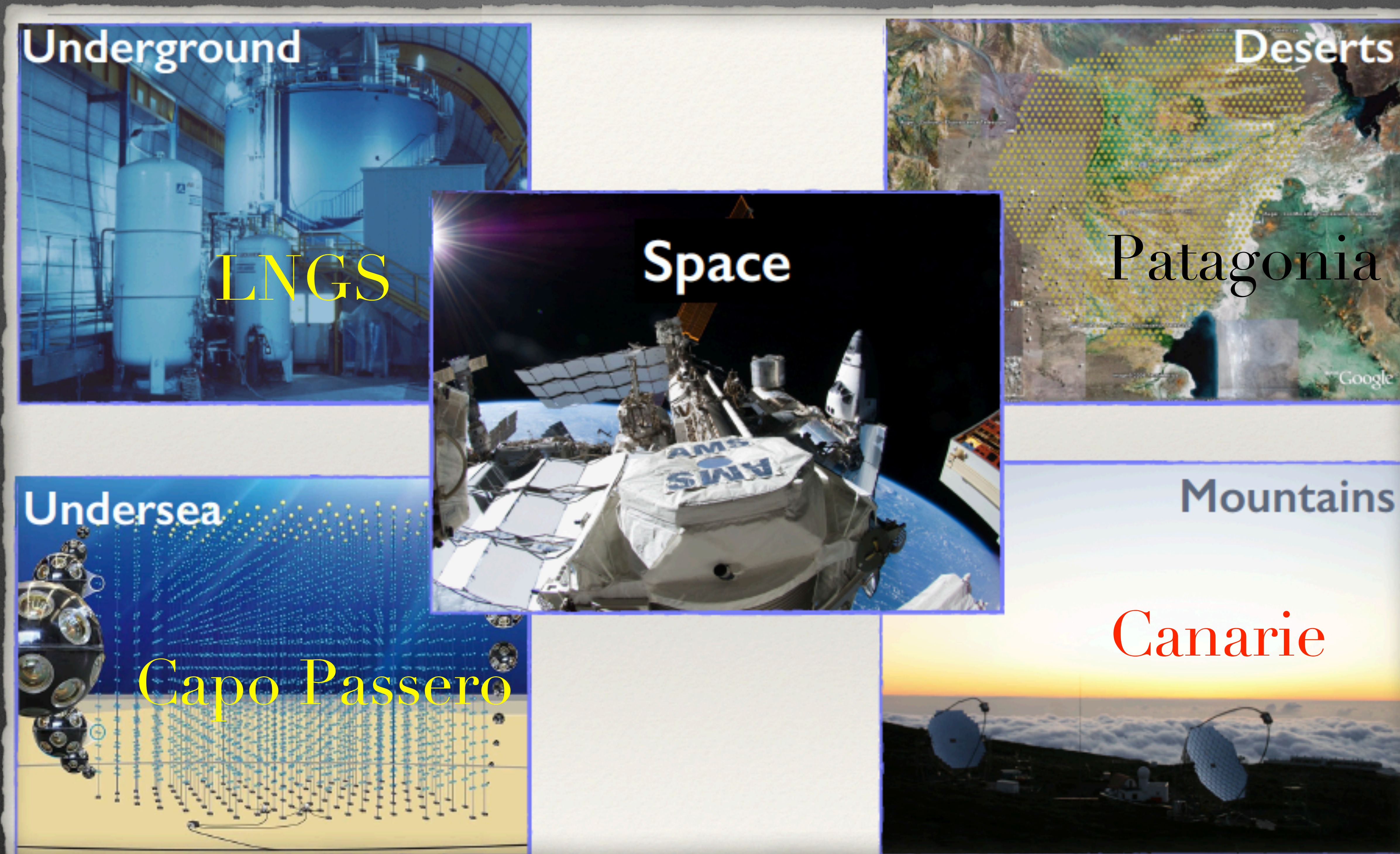


EXPANSION OF THE UNIVERSE
Farthest supernova
Deceleration
Acceleration
Big Bang
10 billion years ago
Today
TIME
Graphic courtesy of Beyond Einstein (NASA)

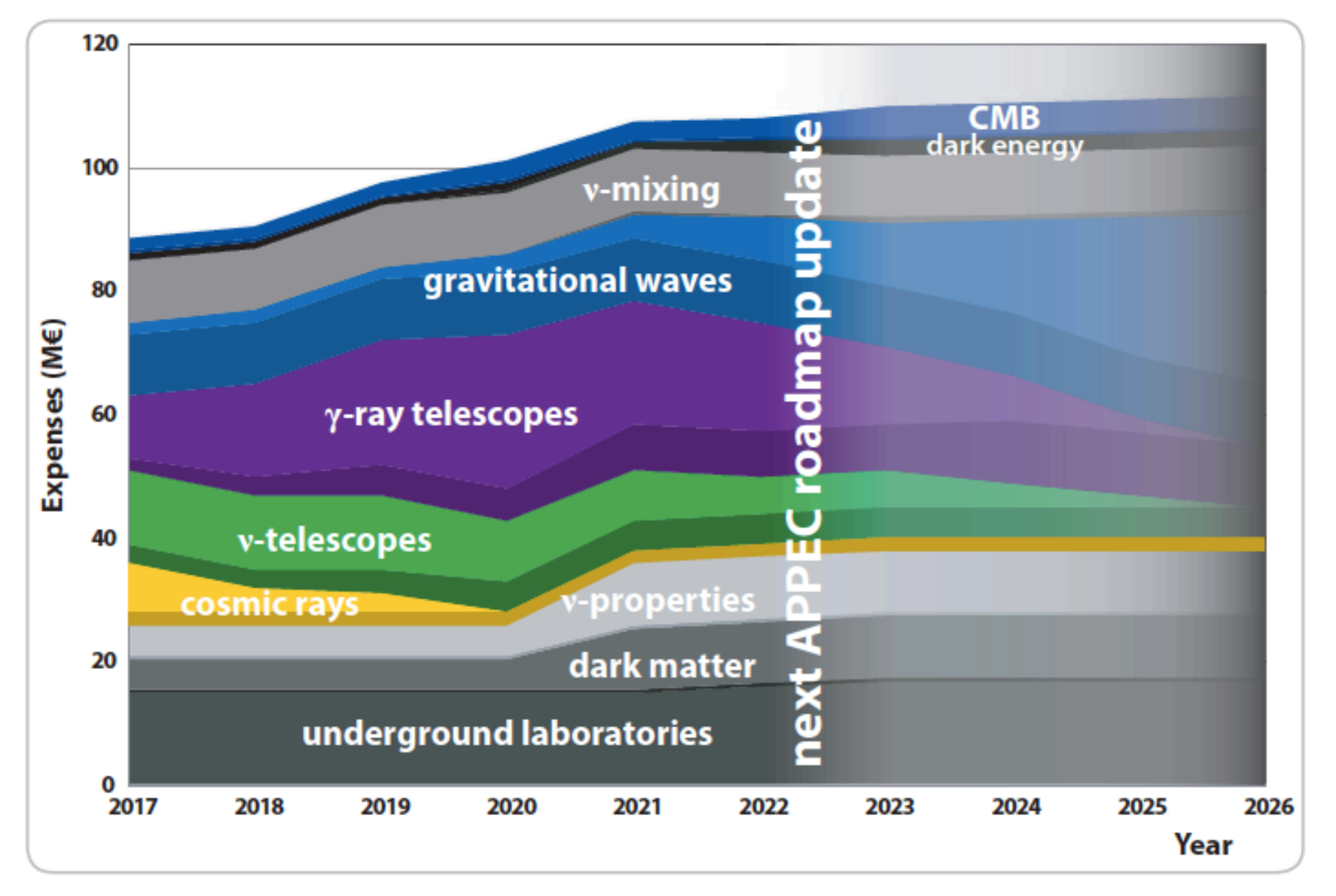
Multi messenger is finally born



Astroparticle everywhere !



is money in issue ?



It is a matter of reflection.
100 MEuro/year from Europe for such a wide field
is little money.

Conclusions

- AstroParticle Physics is a booming field
- Looking to unravel the wonderfulness of cosmo
- Going to understand the fundamental law of Nature
- Plenty of opportunity for young scientists