

# Astroparticle Physics

Maura Pavan



**ECFA**

European Committee for Future Accelerators



# Astroparticle is bridge between SM Physics and Cosmology

**STANDARD MODEL**  
 is probably our deepest  
 insight in Science  
 we have explored 3 out of 4  
 interactions with great  
 success BUT ...

Q U A R K S	<b>UP</b> mass 2,3 MeV/c <sup>2</sup> charge 2/3 spin 1/2 	<b>CHARM</b> 1,275 GeV/c <sup>2</sup> 2/3 1/2 	<b>TOP</b> 173,07 GeV/c <sup>2</sup> 2/3 1/2 	<b>GLUON</b> 0 0 0 1 	<b>HIGGS BOSON</b> 126 GeV/c <sup>2</sup> 0 0 0 
	<b>DOWN</b> 4,8 MeV/c <sup>2</sup> -1/3 1/2 	<b>STRANGE</b> 95 MeV/c <sup>2</sup> -1/3 1/2 	<b>BOTTOM</b> 4,18 GeV/c <sup>2</sup> -1/3 1/2 	<b>PHOTON</b> 0 0 0 1 	G A U G E B O S O N S
	<b>ELECTRON</b> 0,511 MeV/c <sup>2</sup> -1 1/2 	<b>MUON</b> 105,7 MeV/c <sup>2</sup> -1 1/2 	<b>TAU</b> 1,777 GeV/c <sup>2</sup> -1 1/2 	<b>Z BOSON</b> 91,2 GeV/c <sup>2</sup> 0 0 1 	
	<b>ELECTRON NEUTRINO</b> <2,2 eV/c <sup>2</sup> 0 1/2 	<b>MUON NEUTRINO</b> <0,17 MeV/c <sup>2</sup> 0 1/2 	<b>TAU NEUTRINO</b> <15,5 MeV/c <sup>2</sup> 0 1/2 	<b>W BOSON</b> 80,4 GeV/c <sup>2</sup> ±1 1 	

# Astroparticle is bridge between SM Physics and Cosmology

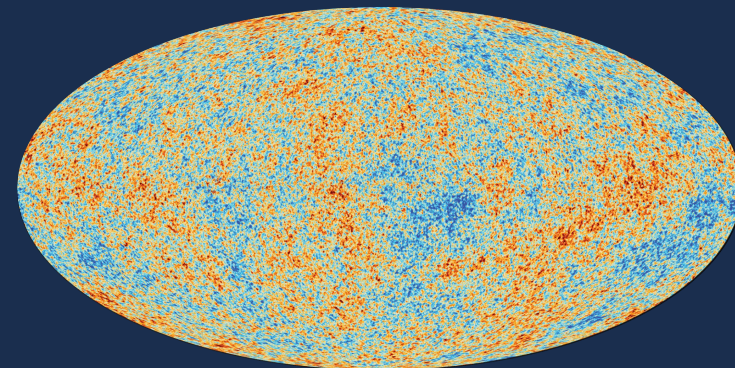
## STANDARD MODEL

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we have explored 3 out of 4 interactions with great success BUT ...

## COSMOLOGY

still a number of “ad hoc” solutions  
inflation & dark energy or the prevalence of matter over antimatter ....

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# Astroparticle is bridge between SM Physics and Cosmology

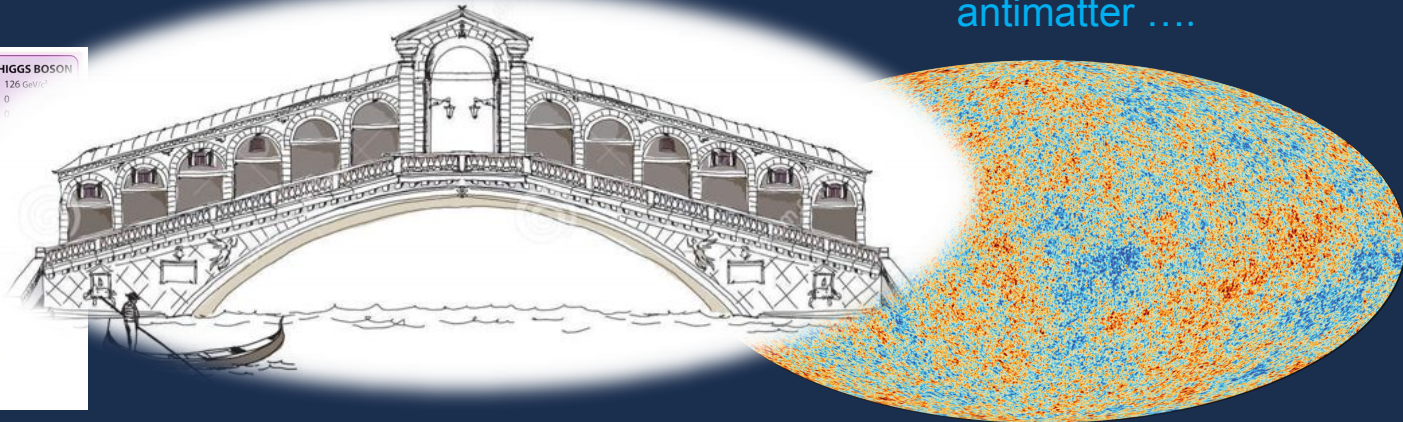
**STANDARD MODEL**  
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 interactions with great  
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ASTROPARTICLE a complementary way  
 to investigate fundamental interactions:

- cosmic rays and waves are messengers from UHE LABS or from the Early Universe
- neutrino experiments shed light on the beyond SM physics
- ...

**COSMOLOGY**  
 still a number of “ad hoc”  
 solutions  
 inflation & dark energy or the  
 prevalence of matter over  
 antimatter ....

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# Astroparticle in CSN2

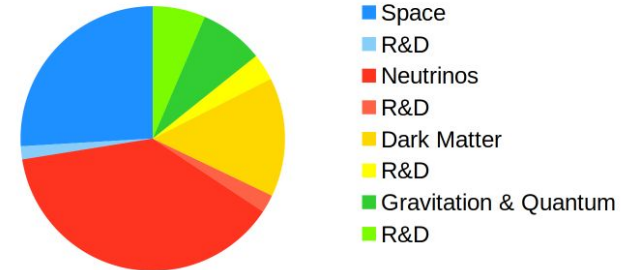
## 4 main research lines

1. Radiation from the Universe
2. Neutrino properties
3. Dark Universe
4. Fundamental Physics: Gravity and Quantum Physics

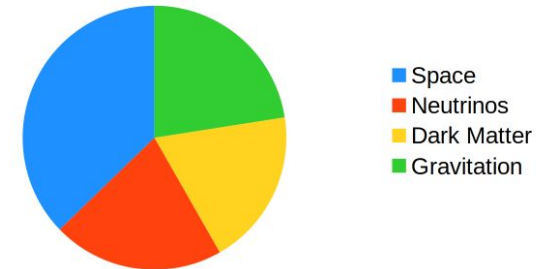
## 2 kind of activities

- high sensitivity expts *"Top few on the international stage"*
- demonstrators and prototypes

2022 BUDGET



FTE



# 1. Radiation from the Universe

A broad field dominated by multi-purpose observatories:

## Objective:

- charged particles
- $\gamma$ 's rays
- X-rays
- microwaves
- HE neutrinos

## Physics case/s:

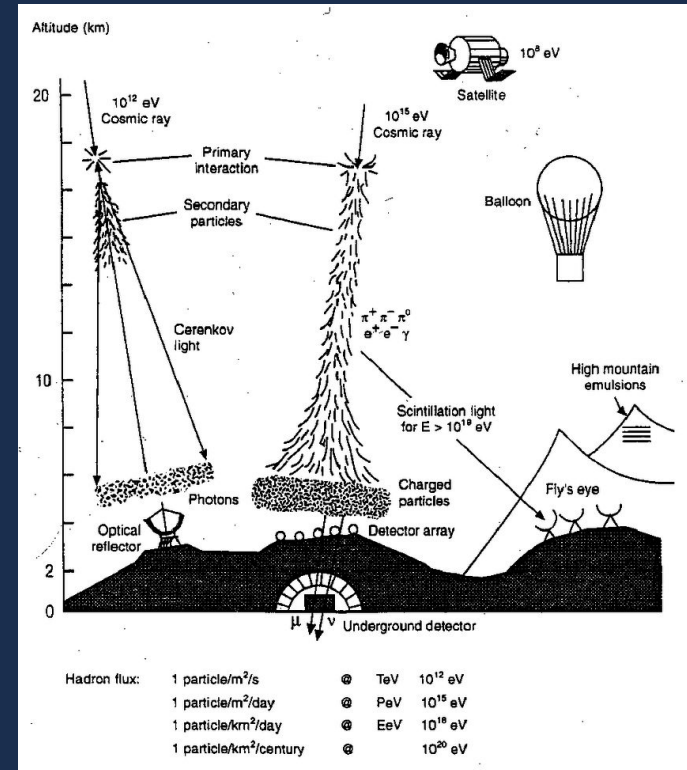
- Cosmic Rays production, acceleration and interaction  $\rightarrow$  a Ultra-High Energy Lab !
- Early Universe through CMB radiation
- Dark Matter through indirect detection
- Astrophysics

# 1. Radiation from the Universe

A broad field dominated by multi-purpose observatories:

## Tools:

- satellites and balloons low E-high  $\Phi$
- ground based observatories high E-low  $\Phi$
- under-water / under-ice detectors
- telescopes



# 1. Radiation from the Universe

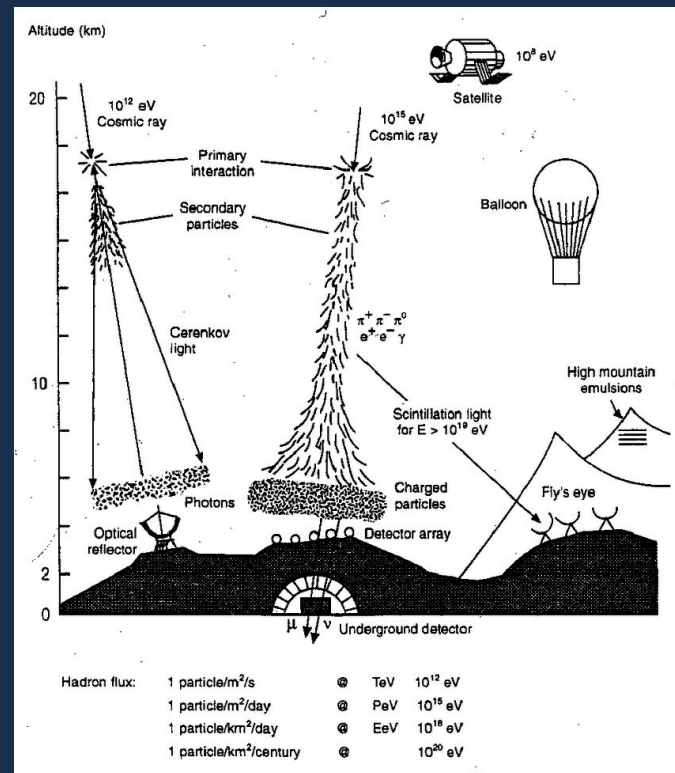
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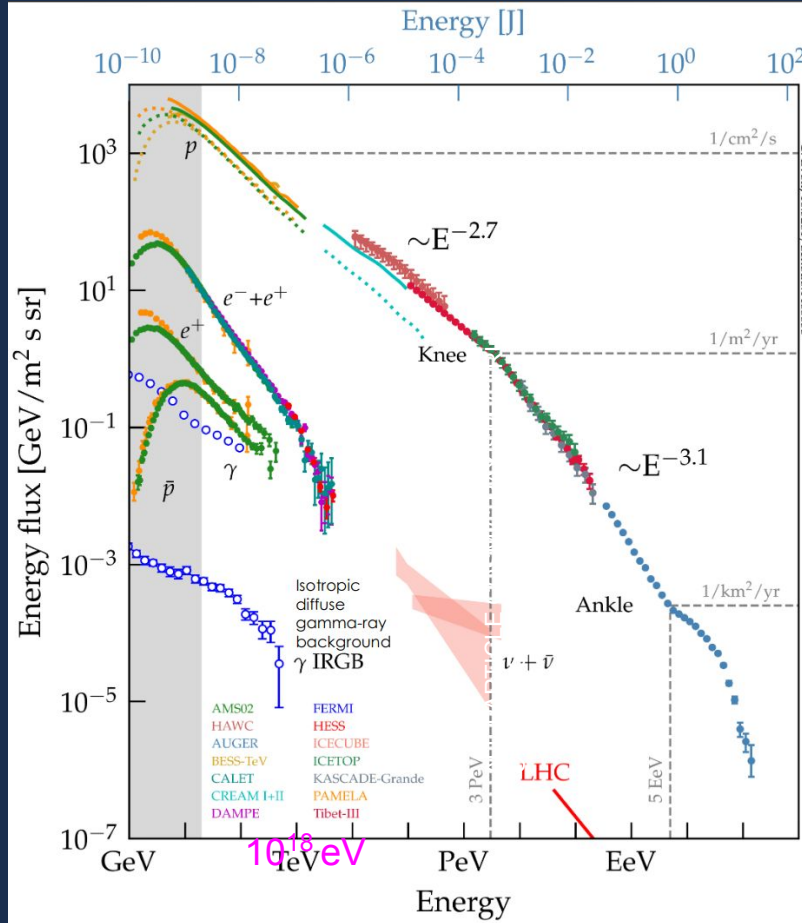
**synergy with Spatial Agencies:** ASI, ESA, NASA, CAS, JAXA ...

**INFN** has a **widely recognized** expertise in technology detector/payloads !!!

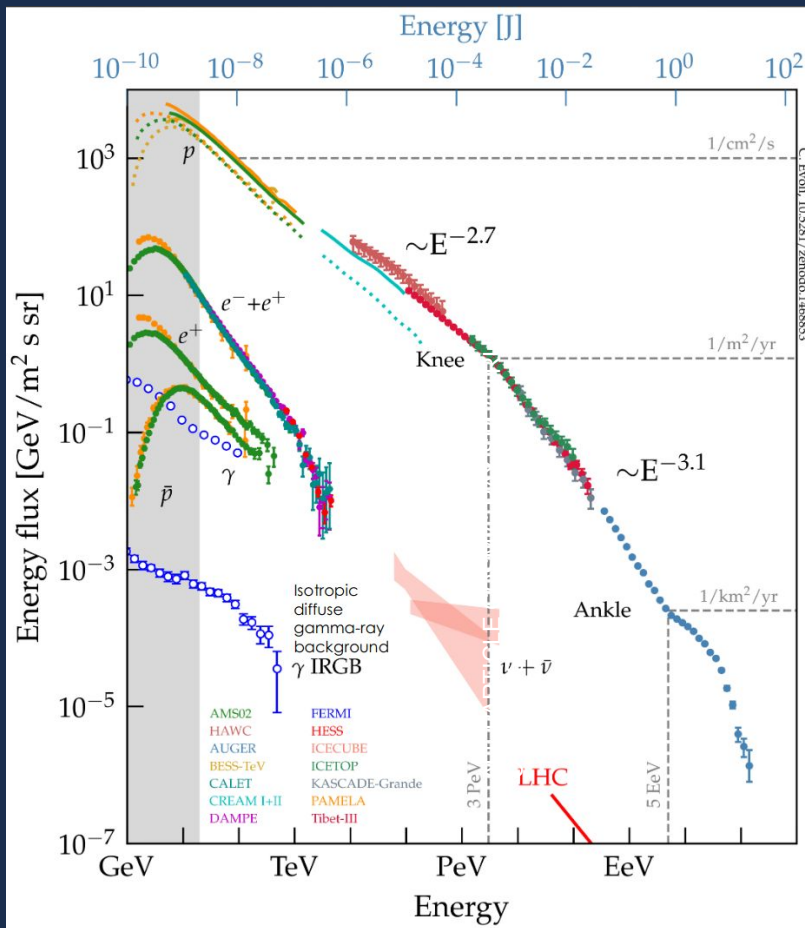




# Cosmic Ray Searches: all particle spectrum



# Cosmic Ray Searches: all particle spectrum



## INFN:

- **PAMELA** satellite
- **AMS02** ISS
- **DAMPE** satellite (γ)
- **FERMI** satellite (γ)
- **AUGER** ground array

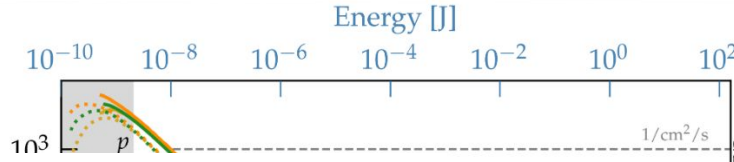
## INFN future:

- **GAPS** balloon - DM search  
anti-p, anti-D, anti-He 100 MeV-10 GeV/n
- **HERD** satellite

	γ	e	p, nuclei
Energy Range	0.5 GeV 100 TeV	10 GeV 100 TeV	30 GeV 3 PeV

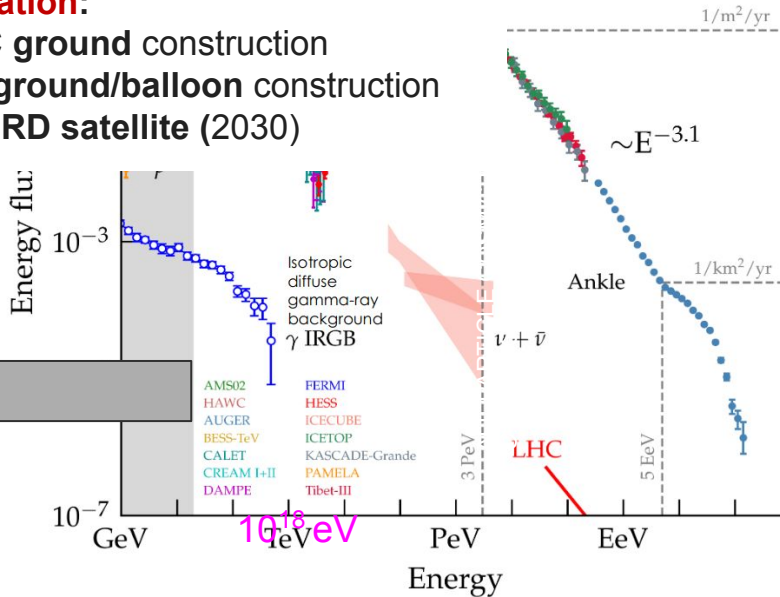
- **CTA** ground array for γ's  
(construction)

# Cosmic Ray Searches: all particle spectrum



## INFN: low E photons

- **X-rays polarization:** IXPE → eXTP (2028)
- **VIS & IR:** EUCLID → Dark Energy (2025)
- **CMB polarization:**
  - QUBIC ground construction
  - LSPE ground/balloon construction
  - LITEBIRD satellite (2030)



## INFN:

- **PAMELA** satellite
- **AMS02** ISS
- **DAMPE** satellite ( $\gamma$ )
- **FERMI** satellite ( $\gamma$ )
- **AUGER** ground array

## INFN future:

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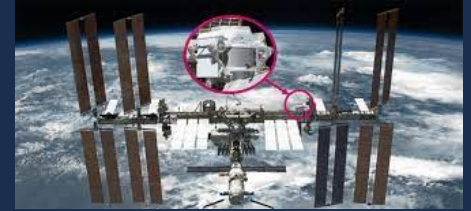
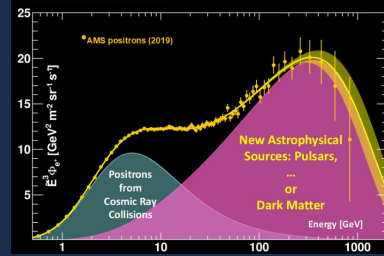
	$\gamma$	e	p, nuclei
Energy Range	0.5 GeV 100 TeV	10 GeV 100 TeV	30 GeV 3 PeV

- **CTA** ground array for  $\gamma$ 's  
(construction)

# Cosmic Rays: selection of running expts

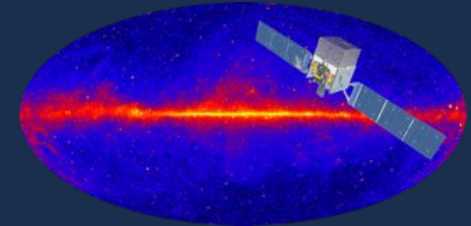
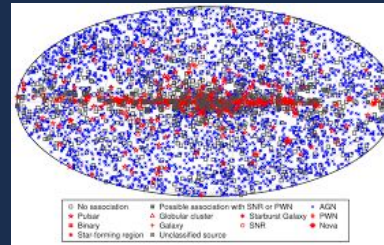
charged cosmic rays **AMS-02** @ ISS  
 anti-particle & DM

- magnetic spectrometer



$\gamma$  rays various sources **FERMI** @ Satellite  
 10 keV-300 MeV  
 (GRB, AGN, Pulsars, DM)

- $\gamma$  ray spectrometer



CR showers in the atmosphere **Auger** @ Argentina  
 10<sup>17</sup>eV - 10<sup>21</sup>eV

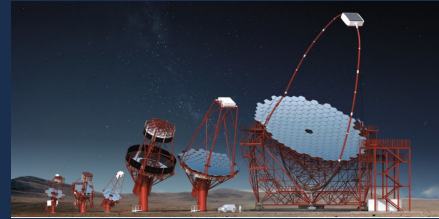
- array of Cerenkov and fluorescence detectors  
 3000 km<sup>2</sup>



# Cosmic Rays: selection of construction expts

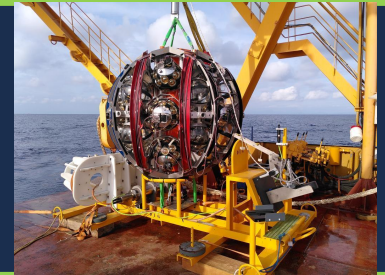
UHE  $\gamma$  ray  
construction

- CTA** @ Canary Islands + Chile
- Cherenkov Telescope Array



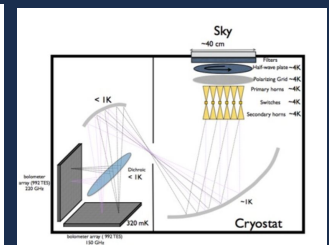
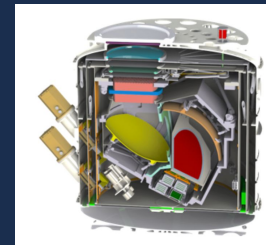
cosmic & atm.  
 $\nu$  observatory  
construction

- KM3NeT** Underwater Cerenkov Telescopes in Mediterrean
- ARCA neutrinos from SN, GRB ...
  - ORCA atmospheric  $\nu$  's used to study  $\nu$  properties



CMB polarization  
B-modes inflation  
construction

- QUIBIC** @ Argentina
- bolometric interferometry



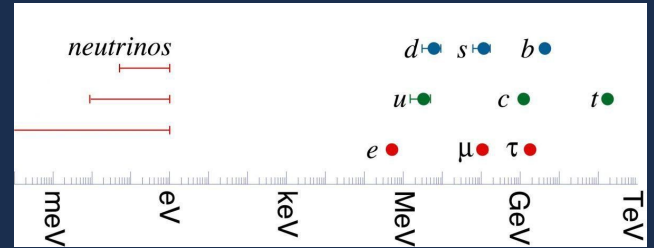
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Tackles the big questions raised after oscillation discovery:

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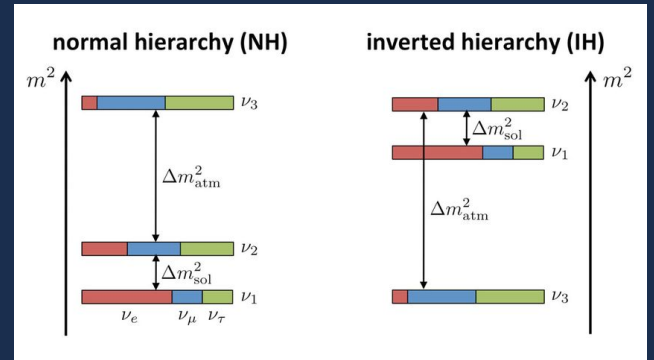
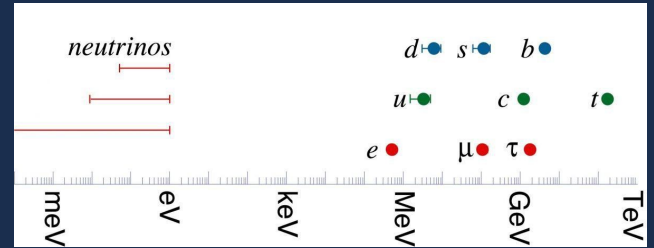
- lightness of  $\nu$  masses



# 2. Neutrino properties

Tackles the big questions raised after oscillation discovery:

- lightness of  $\nu$  masses
- mass hierarchy sign( $\Delta$ )

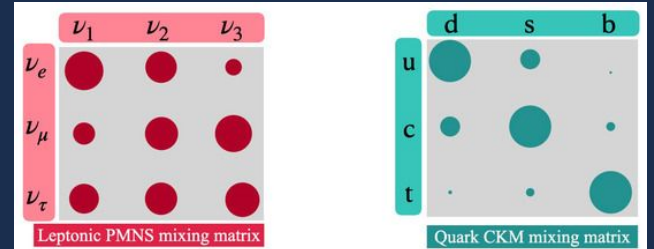
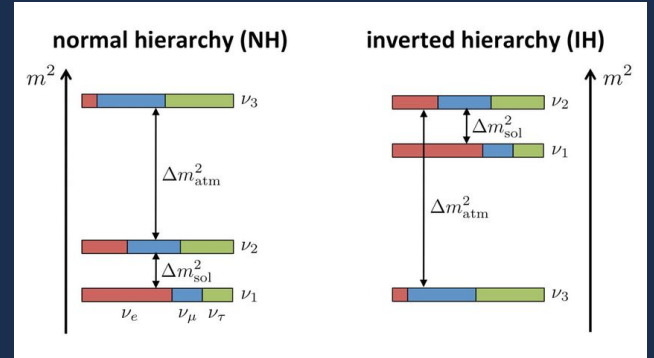
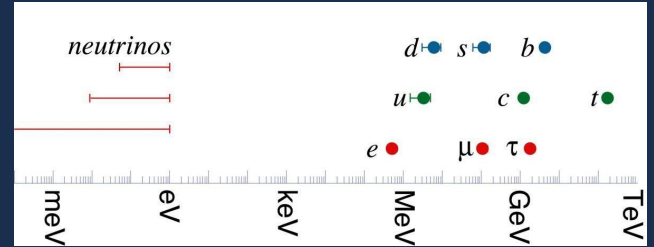




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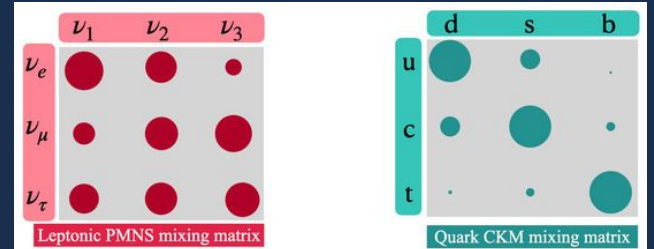
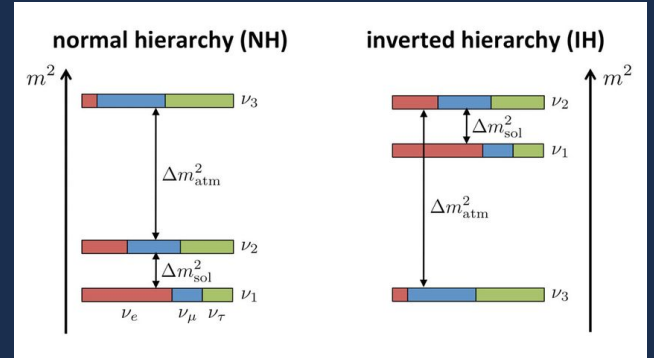
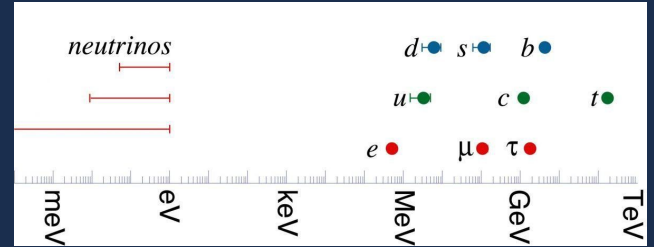
- lightness of  $\nu$  masses
- mass hierarchy sign( $\Delta$ )
- PMNS  $\vartheta_{23}$  (octant problem) &  $\delta_{CP}$



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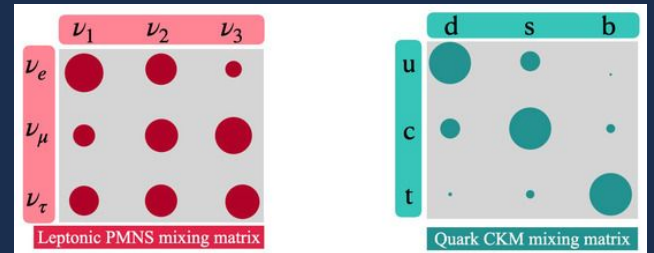
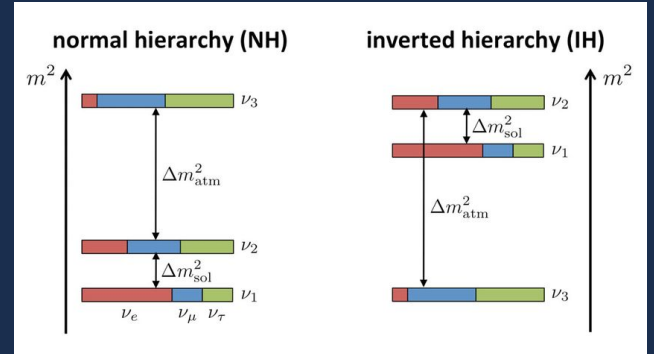
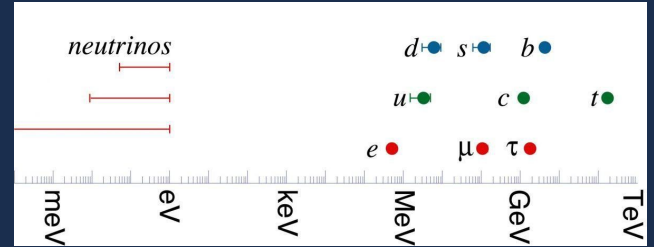
- lightness of  $\nu$  masses
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- sterile  $\nu$



# 2. Neutrino properties

Tackles the big questions raised after oscillation discovery:

- lightness of  $\nu$  masses - sterile  $\nu$
- mass hierarchy sign( $\Delta$ )
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- sterile  $\nu$



## 2. Neutrino properties

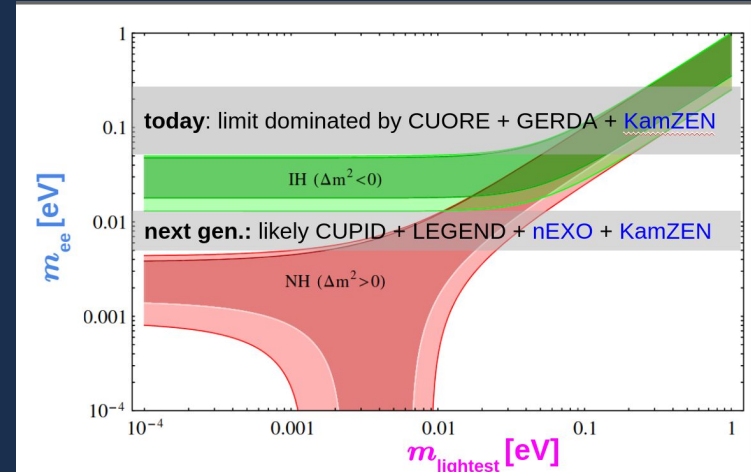
Tackles the big questions raised after oscillation discovery:

- L violation or Majorana  $\nu$  vs Dirac  $\nu$  ?  
explanation of the matter-antimatter asymmetry
- neutrino mass measurement

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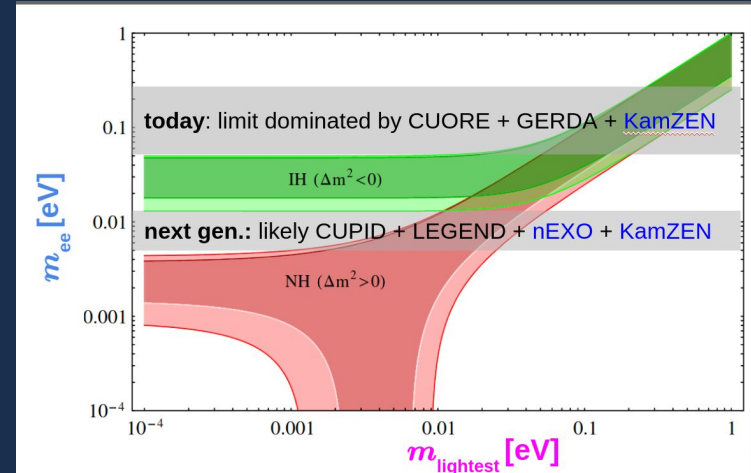
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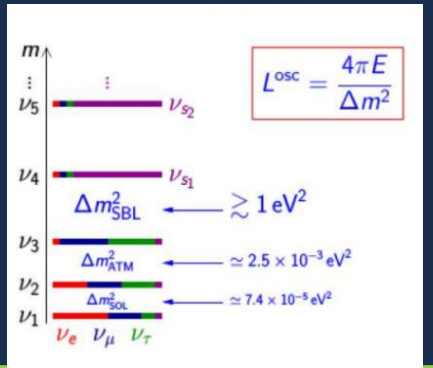
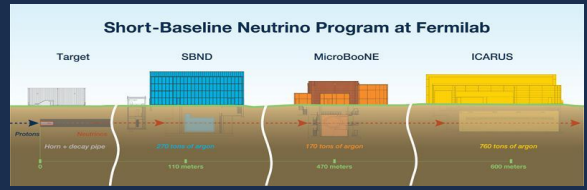
# Oscillations – @ FNAL program

sterile  $\nu$   
running

## ICARUS SBN Program

LAr detector built by INFN

- searches for sterile  $\nu$ 's
- first test will be NEUTRINO4 signal

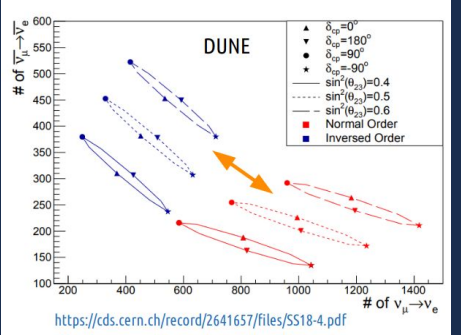
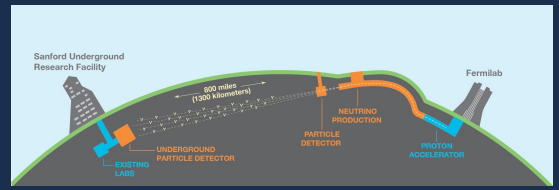


sign( $\Delta$ )

$\delta_{CP}$   
 $\theta_{13}, \theta_{23}$   
project

## DUNE LBN Program > 2026

- one of the near detectors SAND(KLOE)
- LAr far detectors (Photon Detection System)
- 

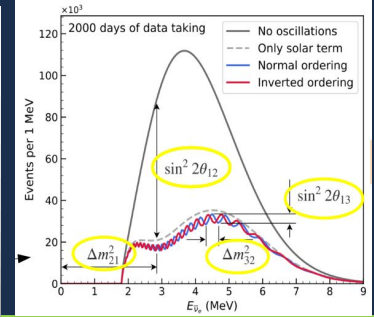
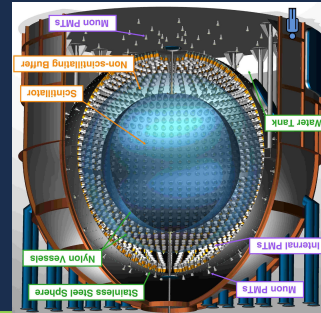


# Oscillations - @China/Japan

## JUNO @ China

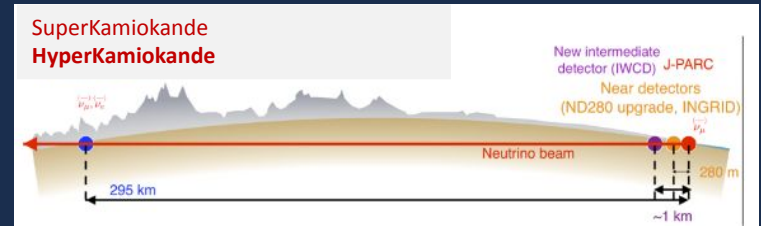
- Borexino experience
- Electronics, Radioactivity
- ...

$\text{sign}(\Delta)$  &  $\theta_{12}$   
 $\Delta m_{12}^2 \Delta m_{32}^2$   
 construction



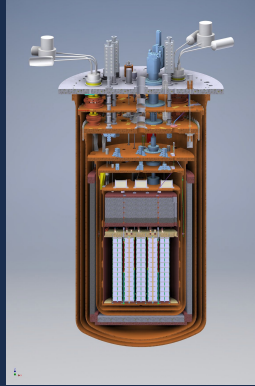
## T2K / HyperK @ Japan

$\text{sign}(\Delta)$  &  $\delta_{CP}$   
 $\theta_{13} \theta_{23}$   
 running / project





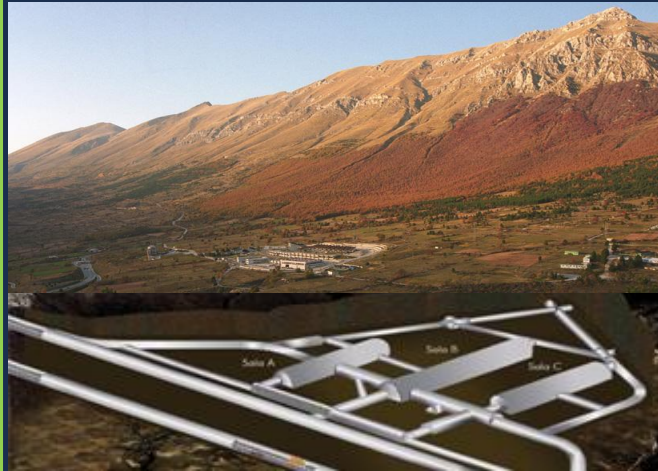
# $0\nu$ Double Beta Decay - LNGS



$^{130}\text{Te}$  running /  $^{100}\text{Mo}$   
project

**CUORE / CUPID**

- $\sim 10^3$  low temperature detectors operated at @ 10 mK
- same cryogenic infrastructure



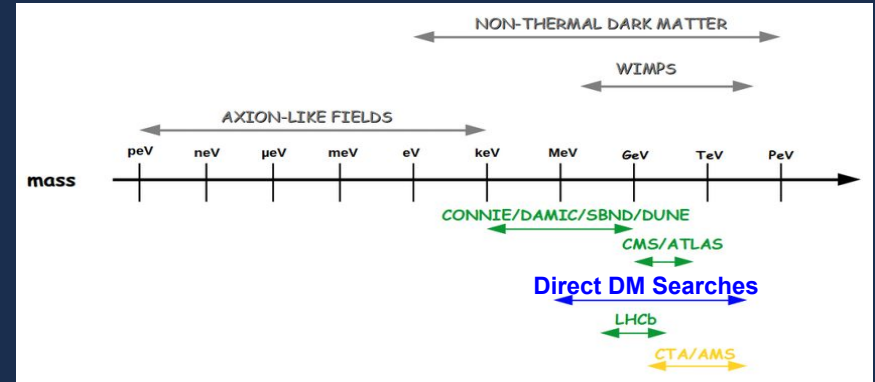
$^{76}\text{Ge}$  running /  $^{76}\text{Ge}$   
project

**GERDA / LEGEND-1000**

- array of Ge diodes in LAr
- for LEGEND-100 new infrastructure (likely LNGS but discussion still open)

# 3. Dark Matter

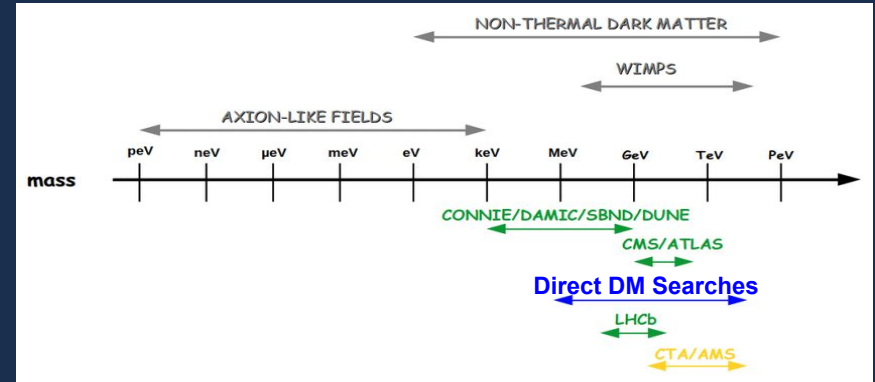
Candidates → accelerators



# 3. Dark Matter

Candidates → accelerators

Indirect Detection → signature from astrophysical sources & cosmology & GW



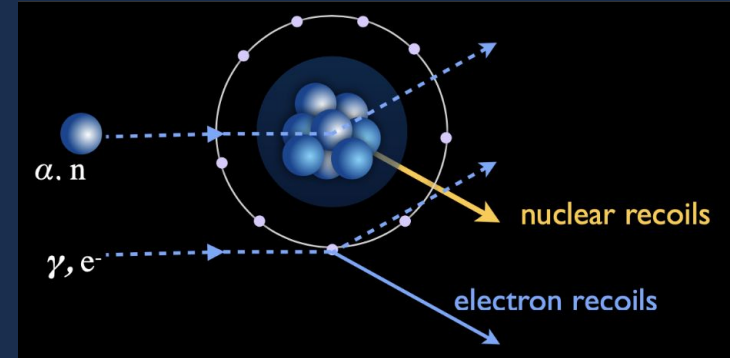
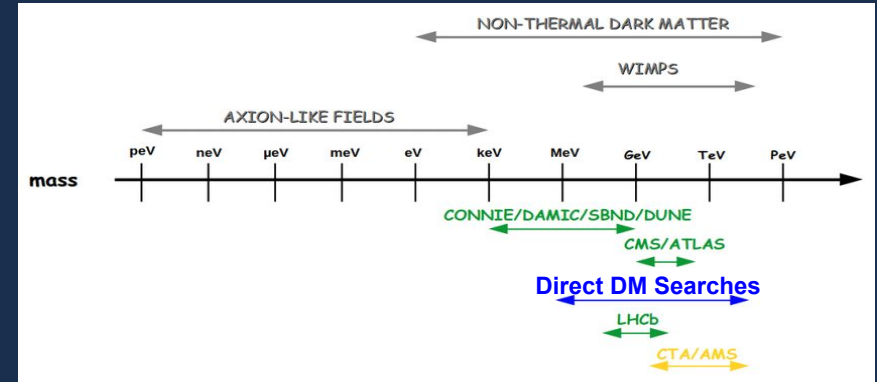
# 3. Dark Matter

Candidates → accelerators

Indirect Detection → signature from astrophysical sources & cosmology & GW

Direct Detection (WIMPS) → big international effort → ton scale exps. in underground labs

- cross section vs. mass
- modulation
- work in progress on directionality

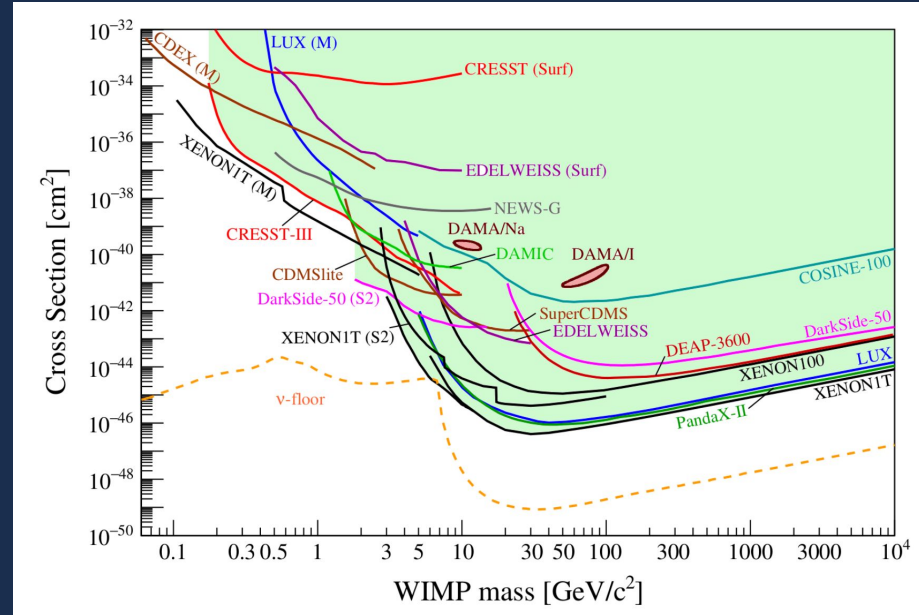


# DM Direct Detection

APPEC Report April 2021

<https://arxiv.org/abs/2104.07634>

Current status of searches for spin-independent elastic WIMP-nucleus scattering

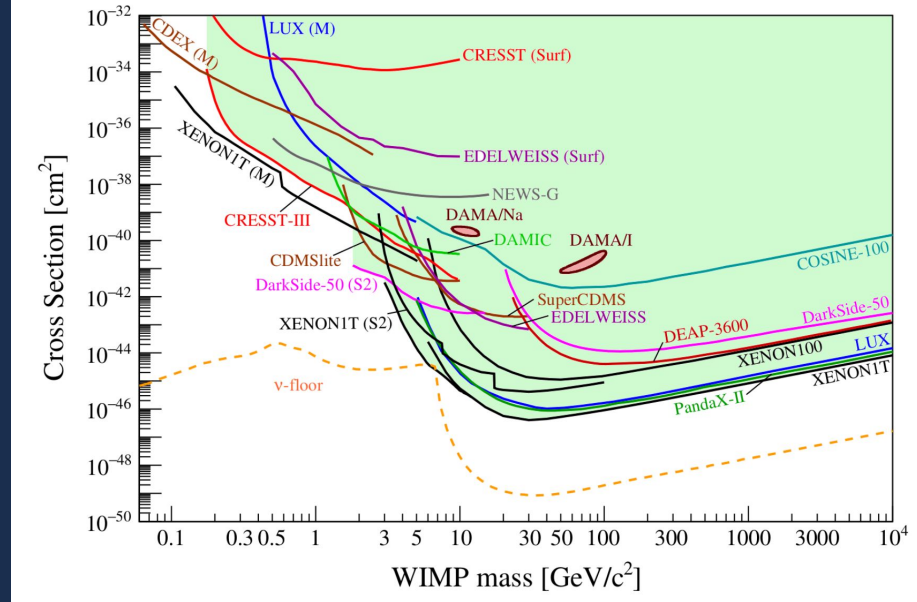


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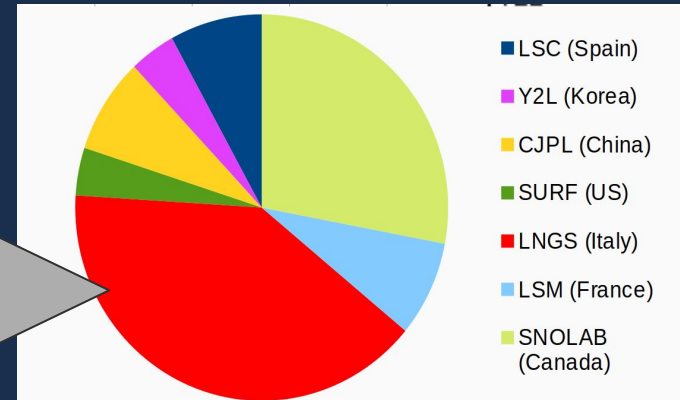


Distribution on DM experiments in underground Labs (APPEC 2021)



**LNGS (INFN)**

- XENON
- CRESST
- DarkSide

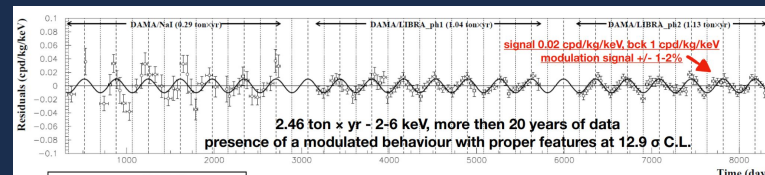


# DM @ LNGS

Nal detectors  
DM  
modulation

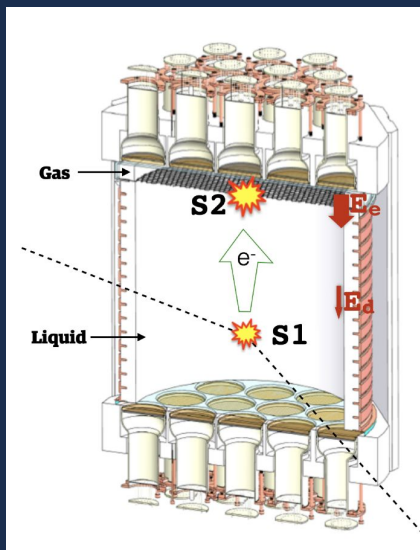
**DAMA/LiBRA** high statistic positive signal - demonstrators for a cross check

- **SABRE** same techniques
- **COSINUS** low temperature detectors



double phase  
Xe/AR TPC

WIMPs

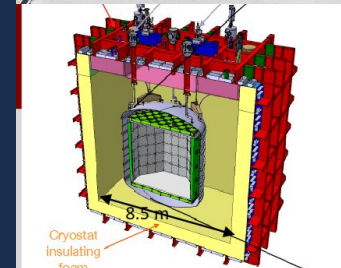
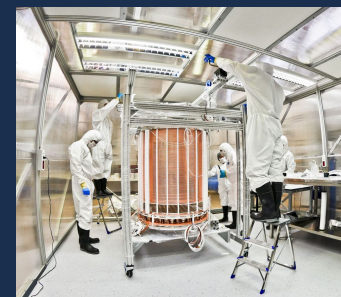


**XENON-nton** running

- phased project, now in n-ton phase

**DarkSide**

- operated a 50 kg demonstrator
- now construction of 20 ton detector
- challenge: use UAr



## 4. Gravity and Quantum Physics

**General Relativity passed a long series of expt. tests:**

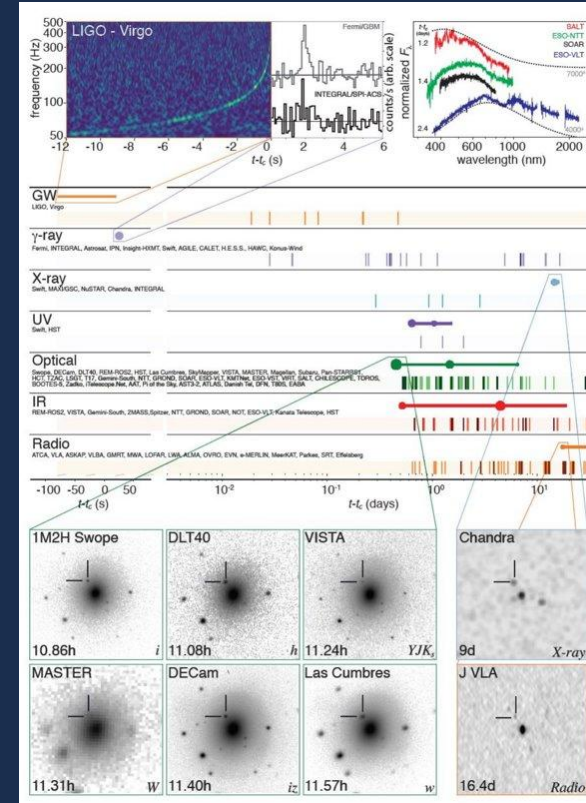
- GW existence & propagation velocity =  $c$  within  $1:10^{15}$
- many alternative models of Gravity ruled out by GW170817



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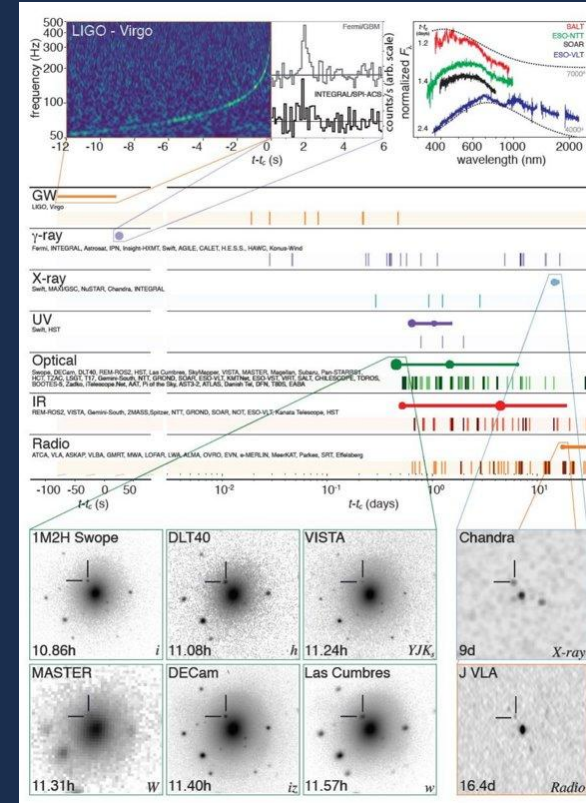
# 4. Gravity and Quantum Physics

## General Relativity passed a long series of expt. tests:

- GW existence & propagation velocity =  $c$  within  $1:10^{15}$
- many alternative models of Gravity ruled out by GW170817

## Open issues e.g.

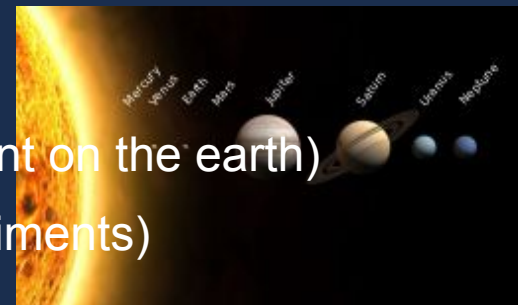
- Non-renormalizability of the theory
- Quantization
- Cosmology: Dark Matter, Dark Energy (cosmological constant), Inflation ...



# Gravitation Tests and GW detection

## Weak Field: Earth & Solar System

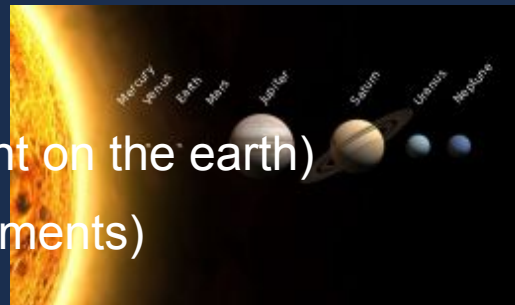
- **GINGER/INO** (Lense-Thirring effect measurement on the earth)
- **MOONLIGHT** + **SATOR-G** (Laser ranging experiments)



# Gravitation Tests and GW detection

## Weak Field: Earth & Solar System

- **GINGER/INO** (Lense-Thirring effect measurement on the earth)
- **MOONLIGHT** + **SATOR-G** (Laser ranging experiments)

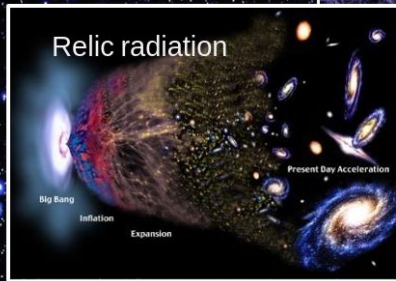


## Strong Field: Black Holes & Neutron Stars Gravitational Waves

- **VIRGO (LIGO)** → **Einstein Telescope**
- LISA Path Finder → **LISA** (satellite)



# GW an open window on Astrophysics



Extreme Mass Ratio  
Inspirals



$10^{-16}$  Hz

$10^{-9}$  Hz

$10^{-4}$  Hz

$10^0$  Hz

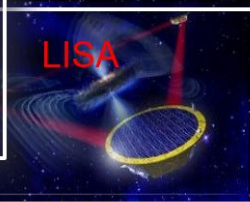
$10^3$  Hz

CMB (polarization)

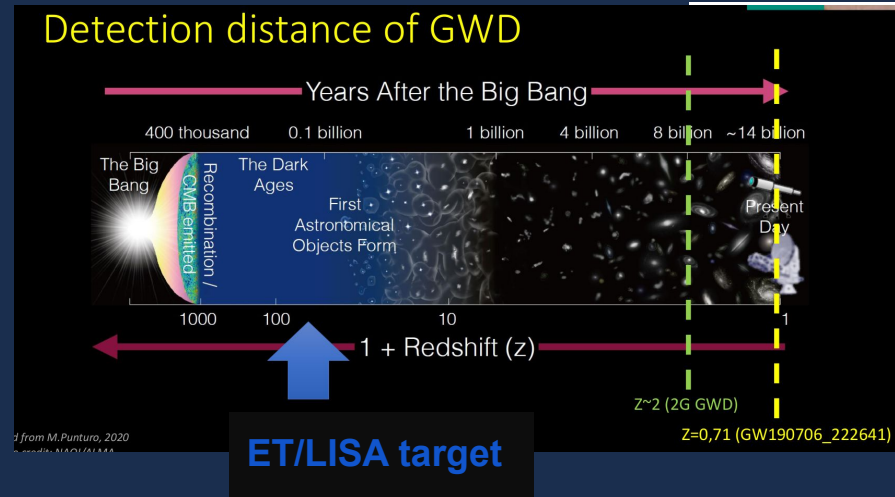
Pulsar Timing (with radiotelescopes)

GW Space detectors

GW ground interferometers

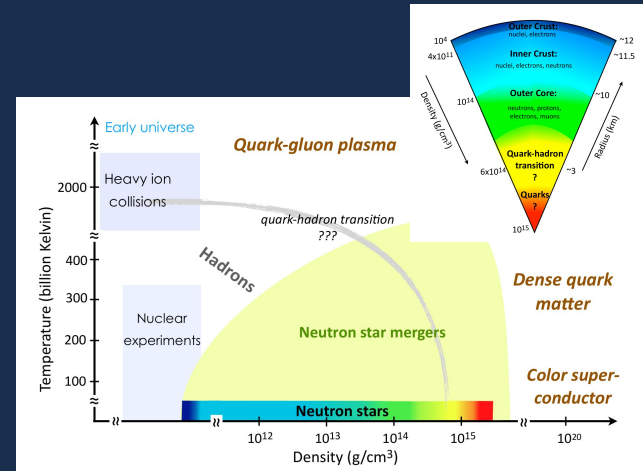
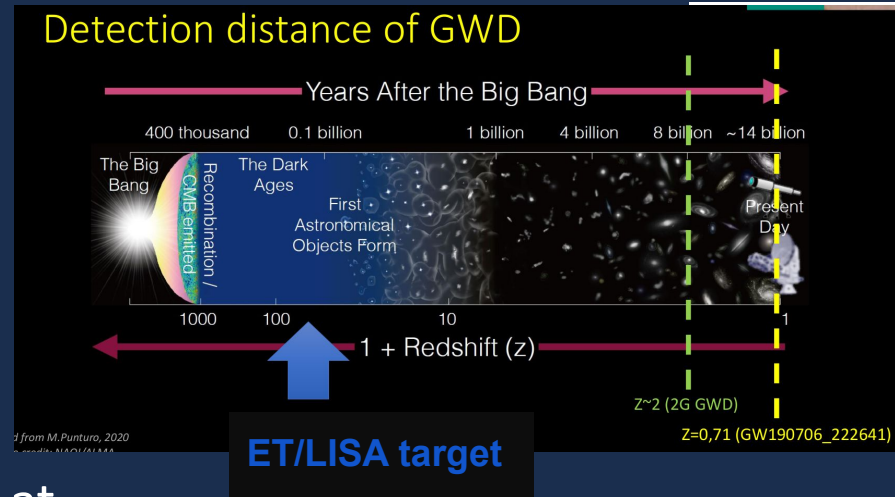


# GW an open window on Fundamental Physics



# GW an open window on Fundamental Physics

- Dark Energy and modification of GT at cosmological scales
- Dark Matter (Primordial BH, Axions ...)
- $H_0$  measurement
- QCD (NS and NS collapse ultra high temperature)



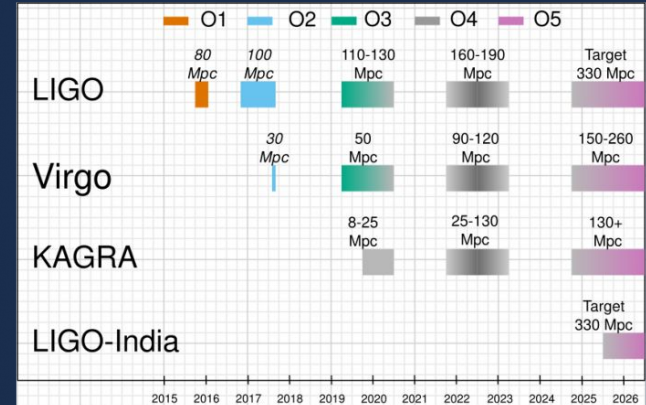
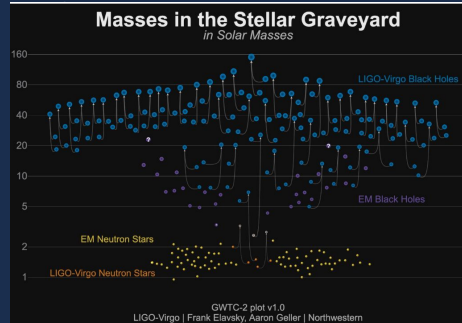
# GW: Experiments

GW  
network LIGO & KAGRA  
+ localization of  
sources in space



## Adv+ VIRGO @ Italy

- LIGO/VIRGO/KAGRA
- discovery of GW
- new population of BH
- Binary Neutron Star and heavy





# GW: Experiments



## GW

- test of GR
- test of QCD
- DarkMatter/Energy
- discovery machine !

## ET @ underground in EU ~ 2035

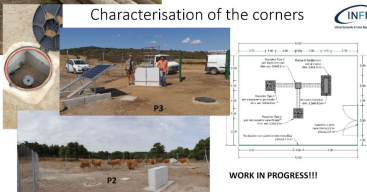
- 41 Institutions, NFN and Nikhef coordinators of the consortium
- site selection/characterization
  - Euregio Meuse-Rhine
  - Sardinia

### Characterisation of the corners



Characterisation of the corners

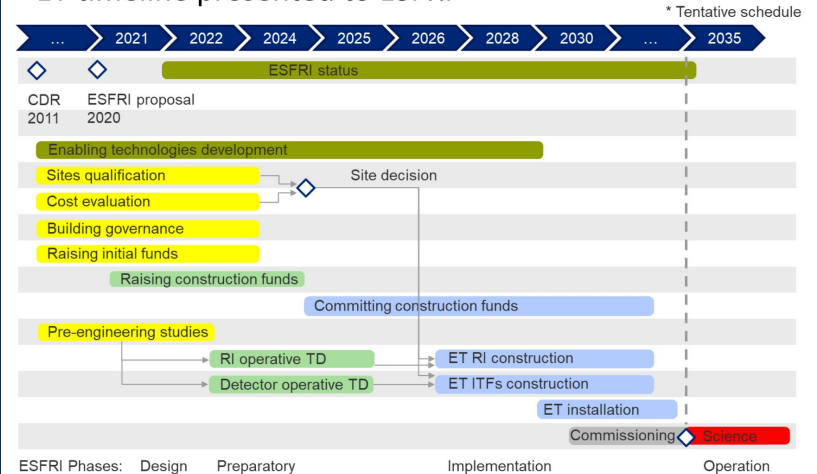
- Active seismic measurements at P2 and P3 with a vibration source (miniwb vehicle) with hundreds of geophones installed in the field (~3km strings and array) and downhole + optical fiber strainmeter in July 2022.
- Data is being processed and analysed.



Characterisation of the corners

WORK IN PROGRESS!!

### ET timeline presented to ESFRI



# Concluding Remarks

Astroparticle offers a complementary approach to Accelerator Particle Physics in the exploration of Fundamental Physics.

In the next ~15 year we will:

- discover the neutrino mass hierarchy
- measure neutrino CP violation
- likely rule-out or discover sterile neutrinos
- hopefully clarify the dark matter puzzle

Finally, multimessenger astronomy or neutrino exp. could discover the unexpected.

# thank you for your attention!

