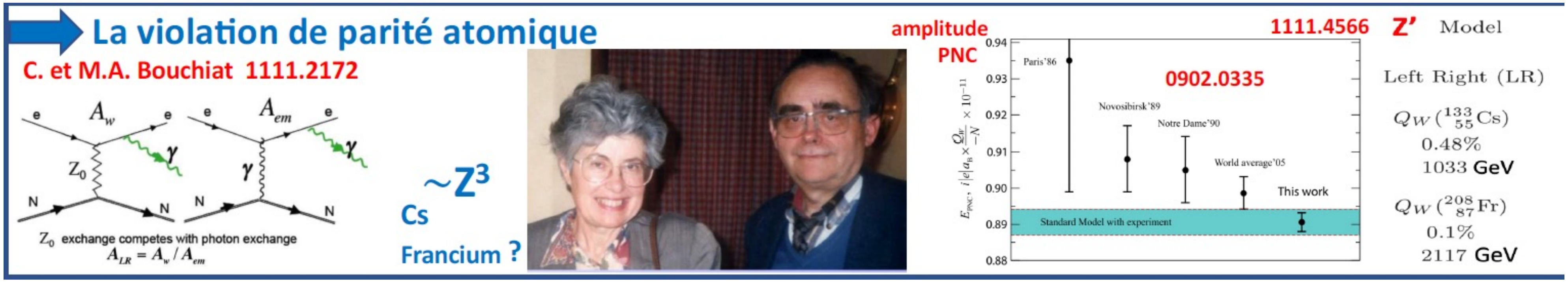
Perspectives in Experimental High Energy Physics

a tribute to C. Bouchiat



It is difficult to make predictions, especially about the future (Mark Twain)

M. Spiro
President IUPAP

Main questions in today's particle physics (a non-exhaustive list ..)

F. Gianotti

Why is the Higgs boson so light (so-called "naturalness" or "hierarchy" problem) ?

What is the origin of the matter-antimatter asymmetry in the Universe ?

Why 3 fermion families ? Do neutral leptons, charged leptons and quarks behave similarly?

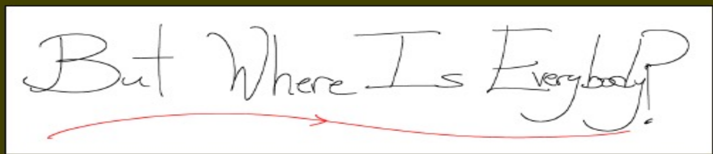
What is the origin of neutrino masses and oscillations ?

What is the composition of dark matter (23% of the Universe) ?

What is the cause of the Universe's accelerated expansion (today: dark energy ? primordial: inflation ?)

Why is Gravity so weak ?

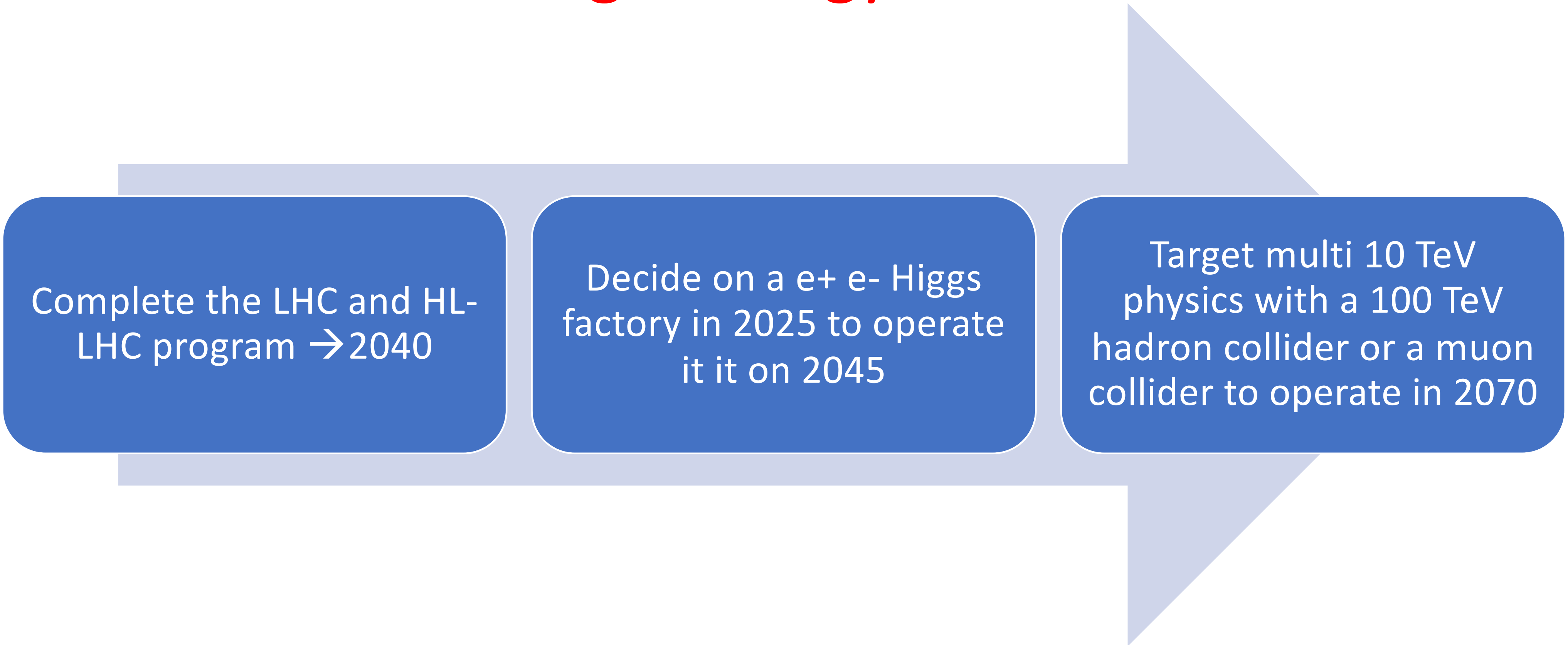
Puzzling: NO evidence of new physics from LHC (yet ...)



N.Arkani-Hamed

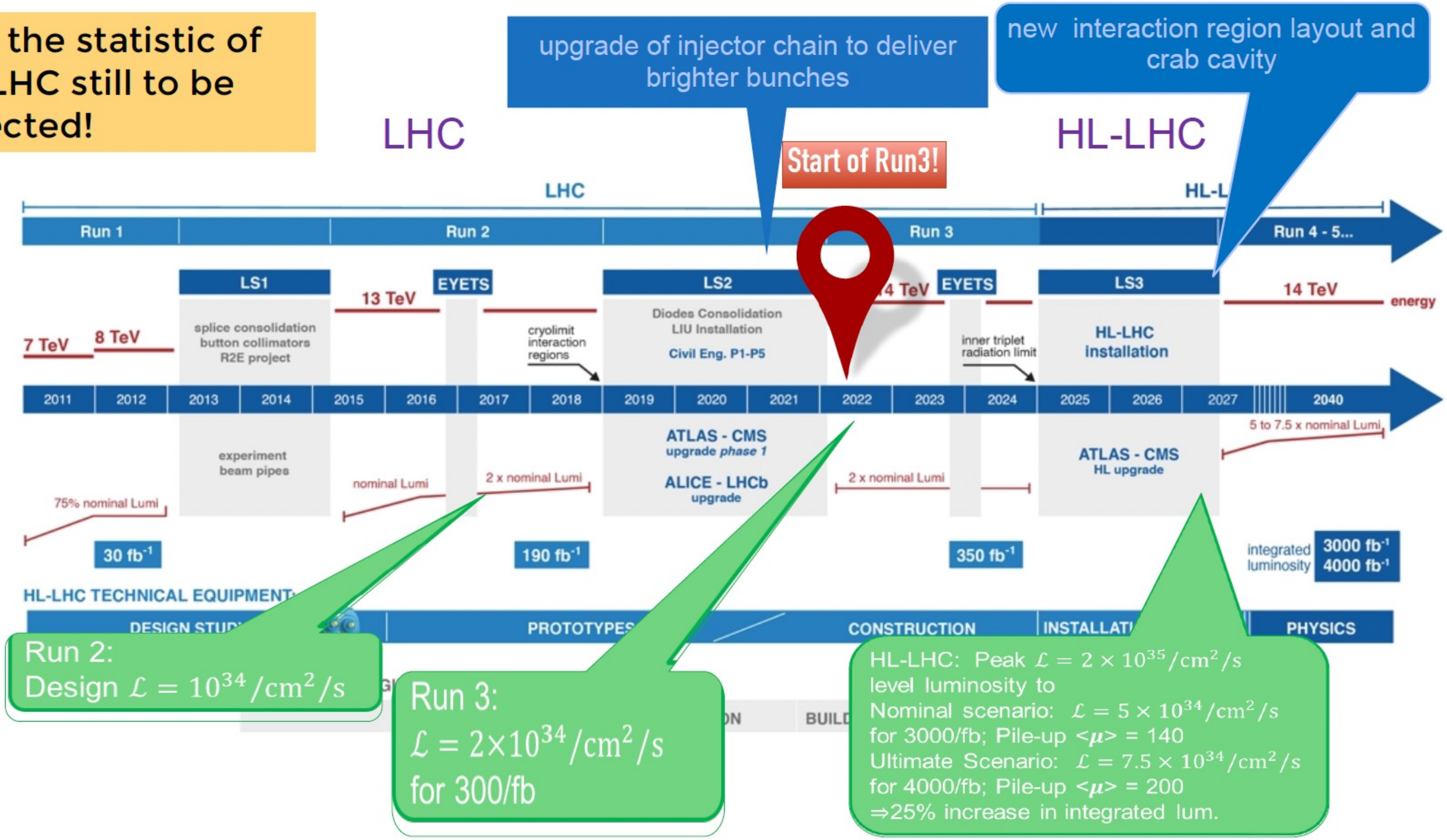
In other words: **at what E scale(s) are the answers to these questions ?**

High energy frontier

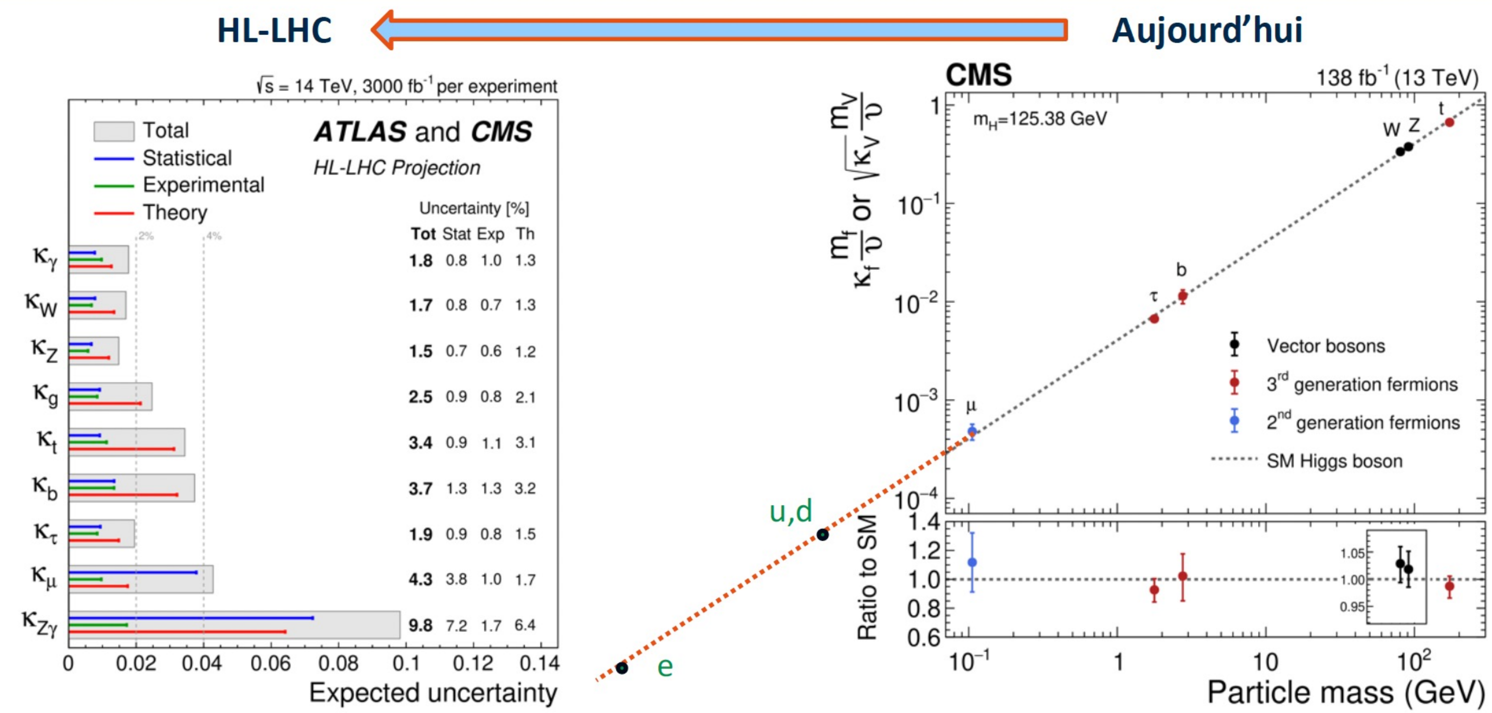


HL-LHC: THE NEAR FUTURE

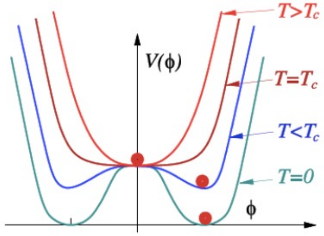
>10x the statistic of the LHC still to be collected!



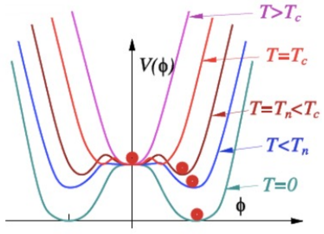
Higgs Boson decay at HL-LHC



Higgs potential at HL-LHC

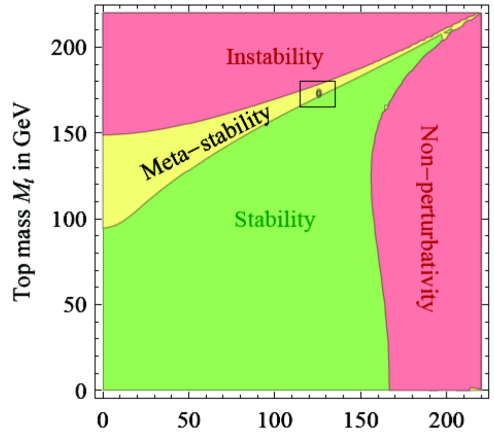


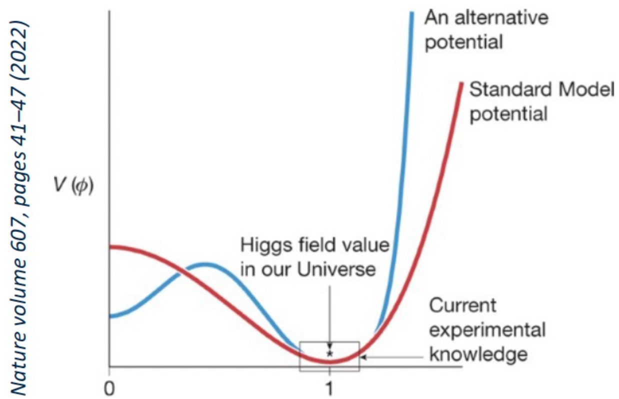
2ème ordre: M_H=125 GeV



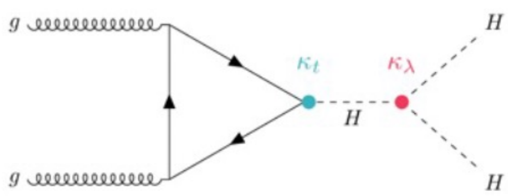
1er ordre: baryogénèse EW

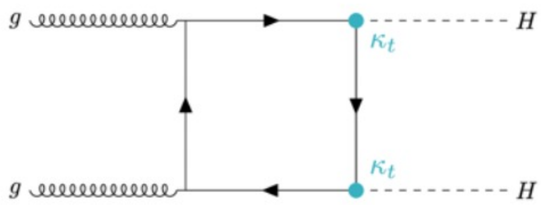
Measurement of λ
and beyond λ
is crucial for HL-LHC and
future colliders





$$V(\phi) = \tfrac{1}{2}m_{\mathrm{H}}^2\phi^2 + \sqrt{\lambda/2}\,m_{\mathrm{H}}\phi^3 + \tfrac{1}{4}\lambda\phi^4$$

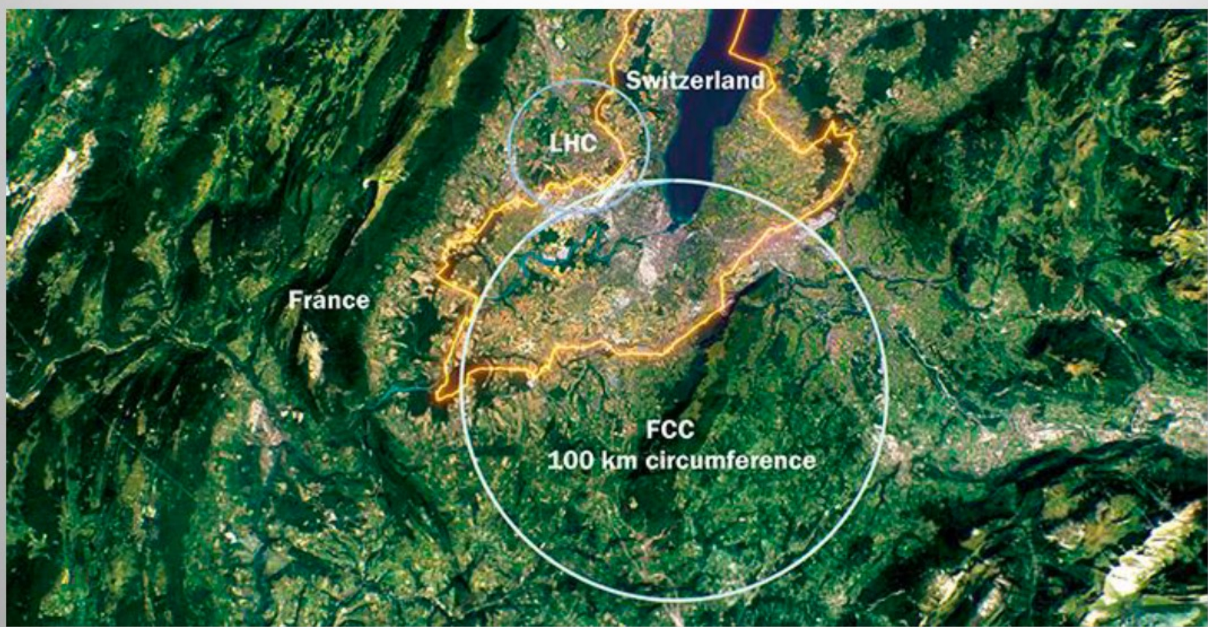




European strategy for particle physics 2020

- ***Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update (2027).***

FCC Feasibility Study (2021-2025)



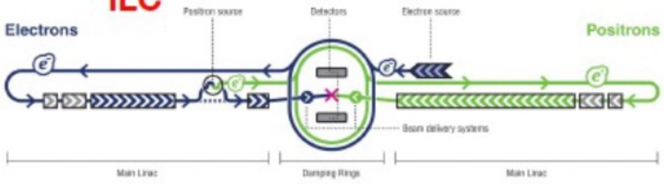
- Tunnel: assess geological, technical, administrative, environmental feasibility → aim is to demonstrate there is no show-stopper for ~ 100 km ring in Geneva region
- Technologies: superconducting high-field magnets and RF accelerating structures; high-efficiency power production; energy savings and other sustainable technologies
- Funding: development of funding model for first-stage machine (FCC-ee and the tunnel, total ~ 10 BCHF) and identification of substantial resources from outside CERN's budget
- "Consensus building": gathering scientific, political, societal support → communication campaign targeting scientists, governmental and other authorities, industry, general public

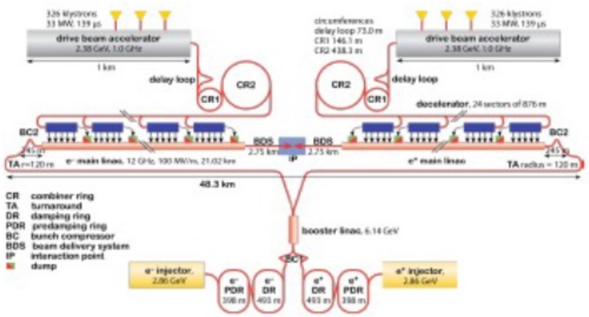
→ Release Feasibility Study Report by end 2025

e^+e^- Higgs Factories

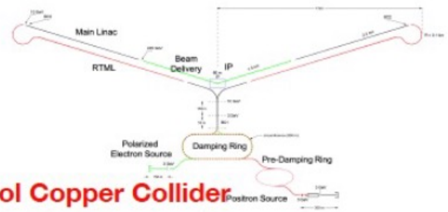
Linear:

ILC





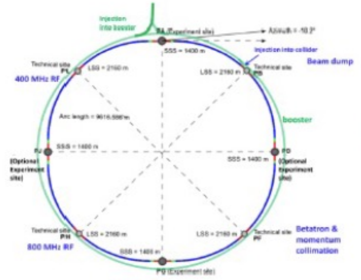
CLIC



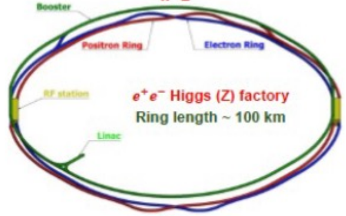
C^3 Cool Copper Collider

- Can go to higher energy – di-Higgs, with limited precision
- Polarization improves some precision measurements significantly

Circular:



FCC-ee



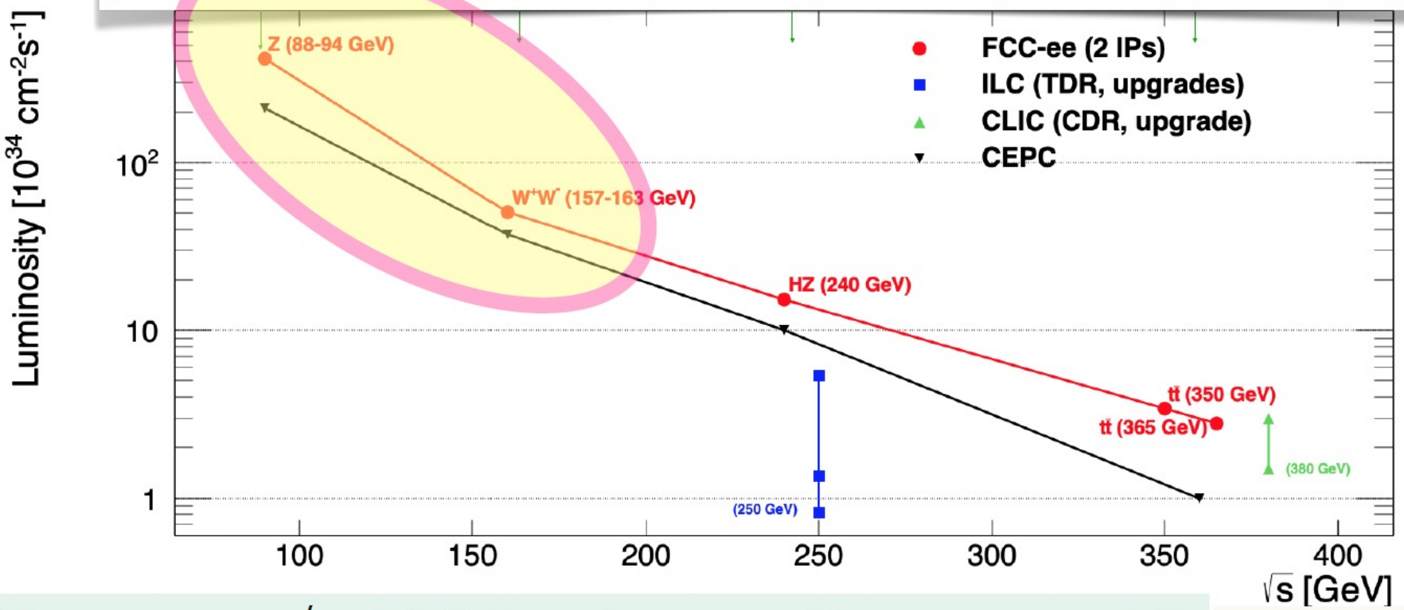
CEPC

- Higher luminosity: can also do Z, WW, top
- Provides ring for future FCC-hh

EWK PRECISION NEEDS LEPTON COLLIDERS

FCC-ee

Can produce all the heaviest particles of the Standard Model



						√s errors
ZH maximum	√s ~ 240 GeV	3 years	10^6	$e^+e^- \to ZH$	Never done	2 MeV
$t\bar{t}$ threshold	√s ~ 350 GeV	5 years	10^6	$e^+e^- \to t\bar{t}$	Never done	5 MeV
Z peak	√s ~ 91 GeV	4 years	5×10^{12}	$e^+e^- \to Z$	LEP x 10^5	< 100 keV
WW threshold+	√s ≥ 161 GeV	2 years	> 10^8	$e^+e^- \to W^+W^-$	LEP x 10^3	< 300 keV
s-channel H	√s = 125 GeV	? Years	~5000	$e^+e^- \to H$	Never done	< 200 keV

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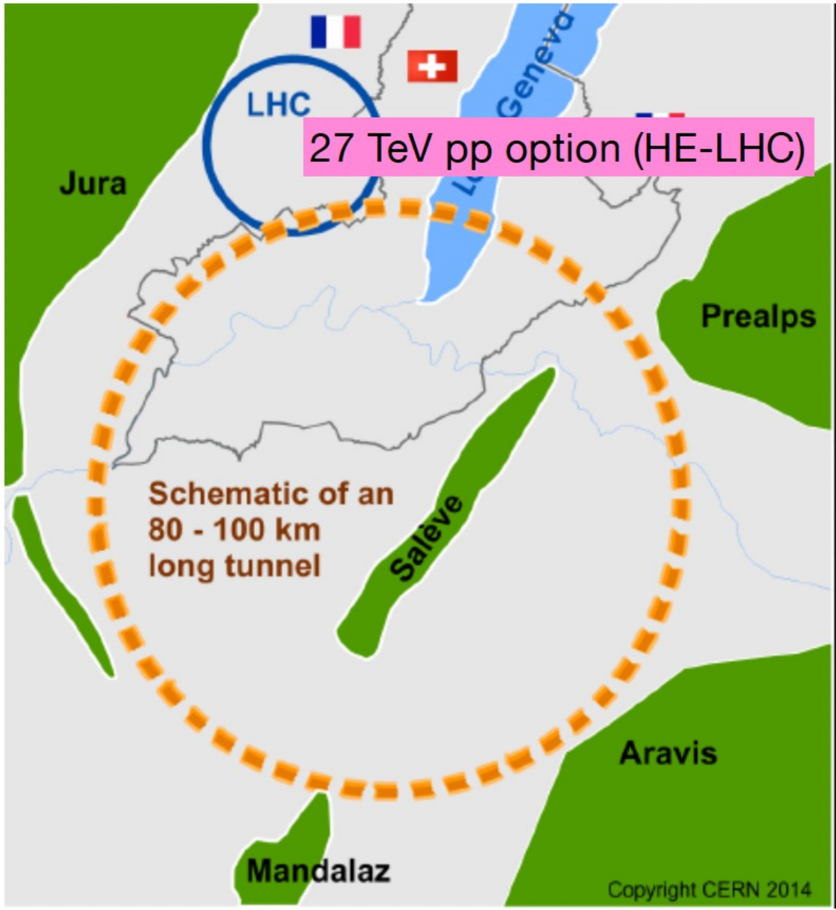
FCC-hh

FUTURE HADRON COLLIDERS



27 TeV pp option (HE-LHC)

CERN - FCC-ee

100 TeV pp option (FCC-hh)

- Approach of reusing a tunnel for more than one machine
  - ex. FCC Integrated Program
- Need time to develop the 16T magnets needed for the high energy
- Possible Heavy-Ion runs with very interesting physics program

CHINA - CEPC

100 TeV pp option (SppC)

NUMEROLOGY FOR FCC-hh, *10ab⁻¹*, √s=100 TeV

Total lumi in studies can be 20ab⁻¹ or 30ab⁻¹

- **10^{10} Higgs bosons** => 10^4x today

➡precision measurements
➡rare decays
➡FCNC probes: H->eμ

- **10^{12} top quarks** => 5 10^4 x today
  - =>10^{12} W bosons from top decays
  - =>10^{12} b hadrons from top decays

➡precision measurements
➡rare decays
➡FCNC probes: t->cV (V=Z,g,γ), t->cH
➡CP violation
➡BSM decays ???

  - =>10^{11} $t \rightarrow W \rightarrow \tau$

➡rare decays τ->3μ, μγ, CPV

  - few $10^{11} t \rightarrow W \rightarrow charm\ hadrons$

➡rare decays D->μ⁺μ⁻,... CPV

Amazing potential, extreme detector and reconstruction challenges

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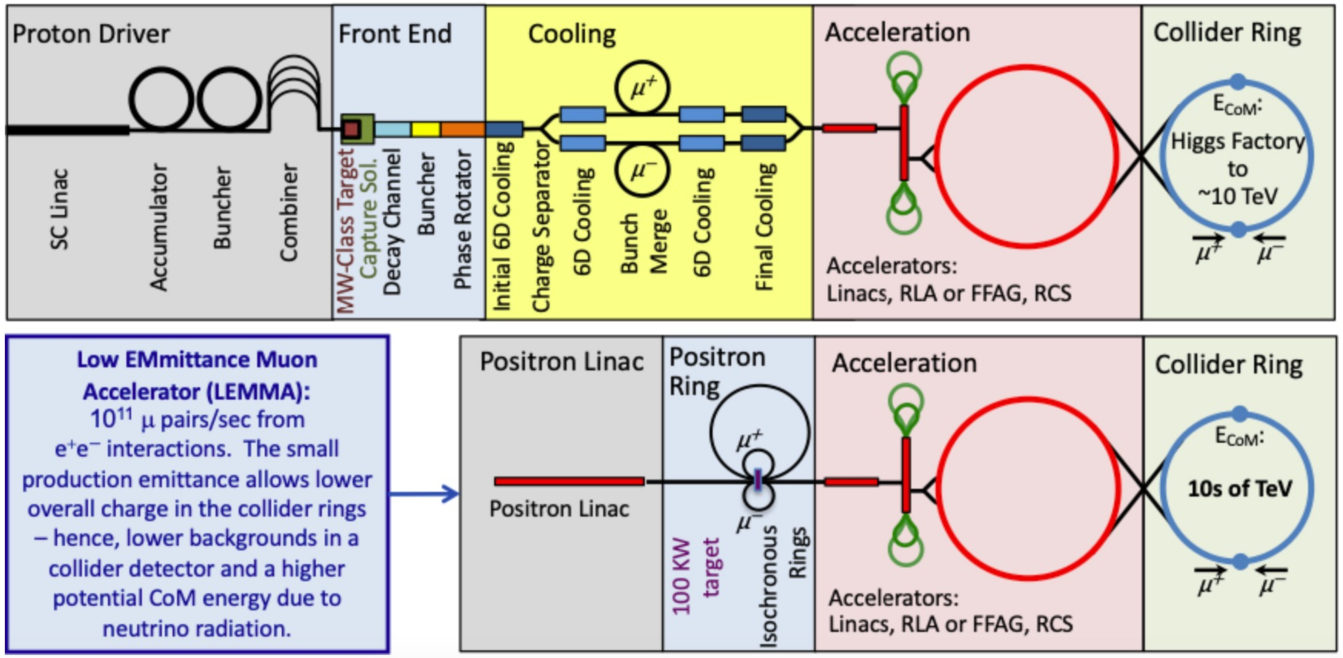
MUON COLLIDER

Schematic layouts of Muon Collider complexes based on the proton driver scheme and on the low emittance positron driver scheme emphasizing syn
sketched below.



Many small or medium size precision experiments to test the Standard model

US: One goal: study **Charged Lepton Flavor Violation** in all three muon modes: $\mu^- N \rightarrow e^- N$; $\mu \rightarrow e\gamma$; and $\mu \rightarrow 3e$

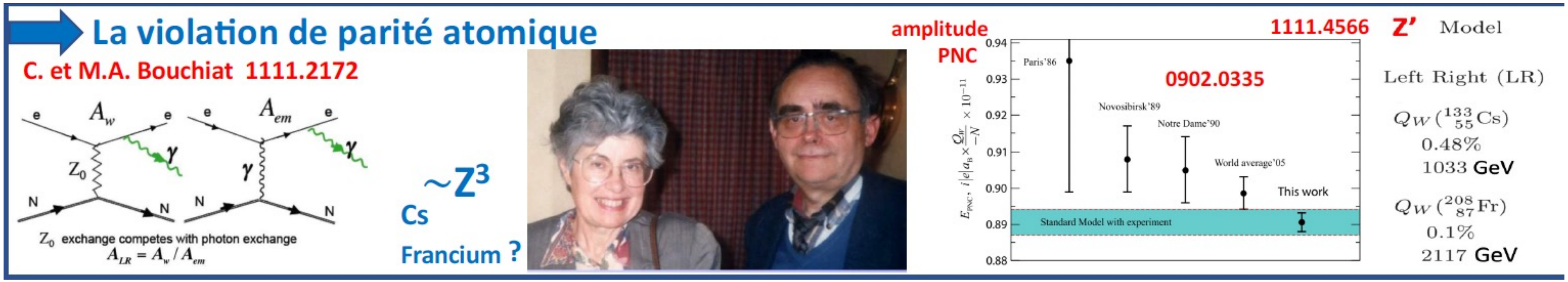
g-2

B decays

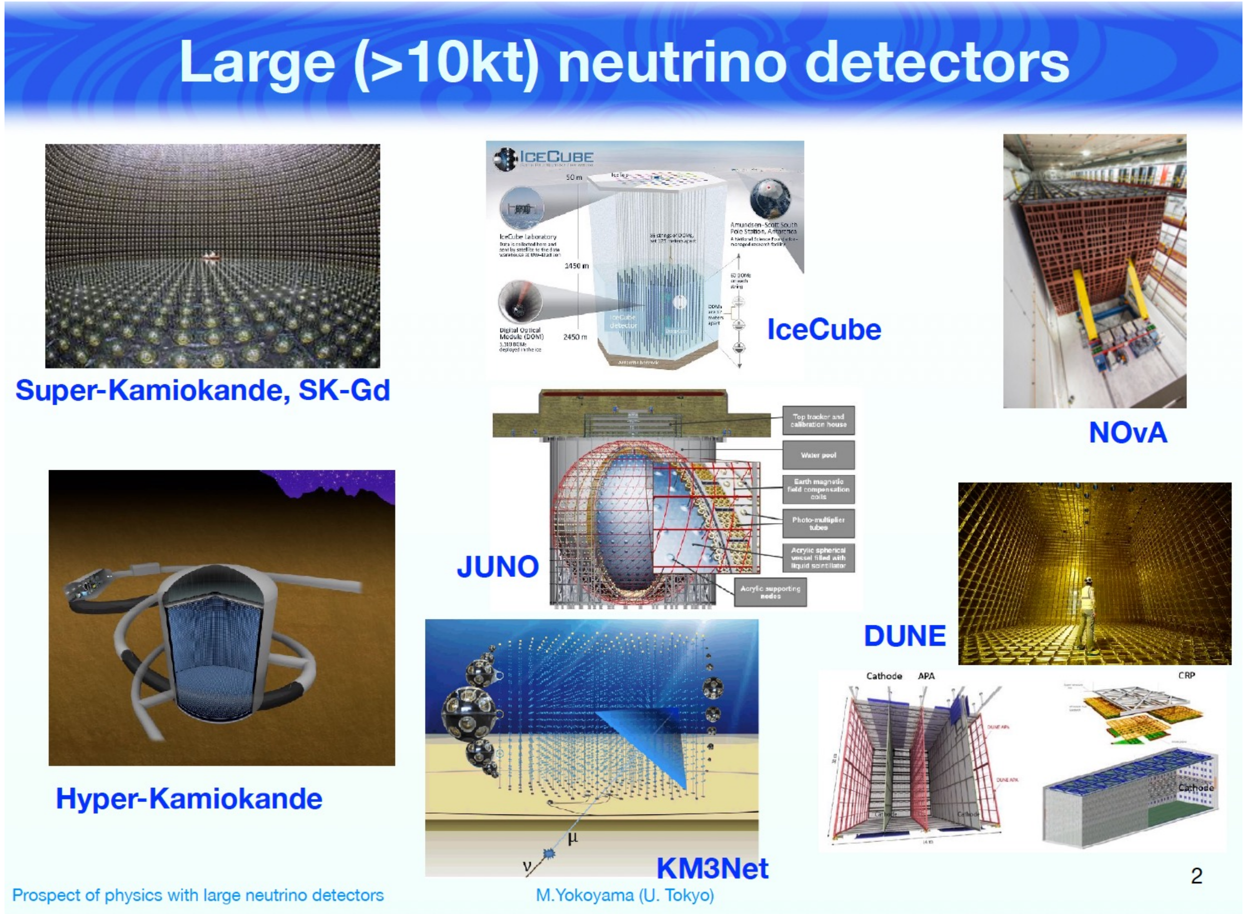
Anti hydrogen atoms

Electric dipole moment, n e

Parity violation and Tests of the SM with ultra cold atoms in the spirit of Bouchiat Bouchiat parity violation experiments.. Beyond the standard model and beyond general relativity evidences might be found first there.



Neutrinos Physics

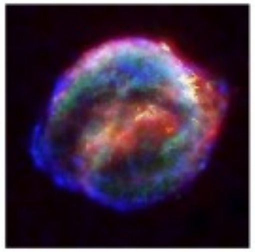


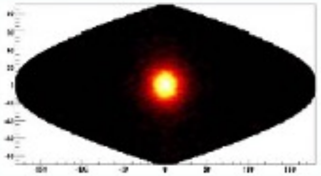
Physics with large neutrino detectors

(MeV)

(>PeV)

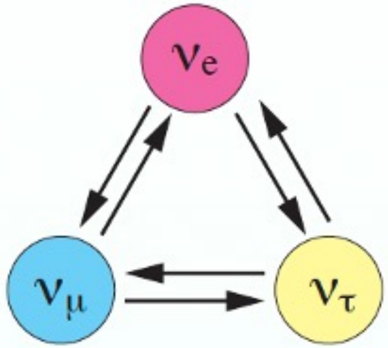
Supernova



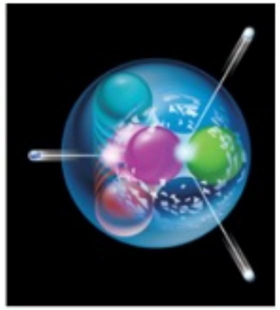


Solar physics

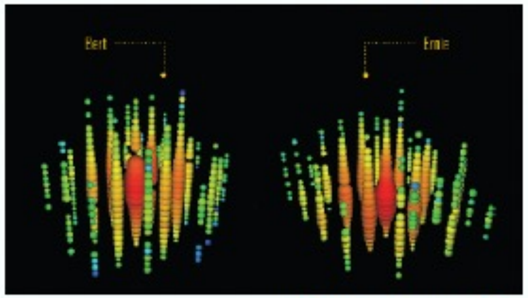
Neutrino oscillations



Nucleon decay

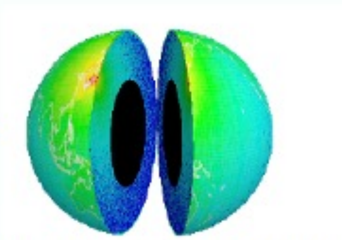


High energy neutrino astrophysics



IceCube collaboration

Geophysics



http://kamland.stanford.edu/GeoNeutrinos/geoNeutrinos.html

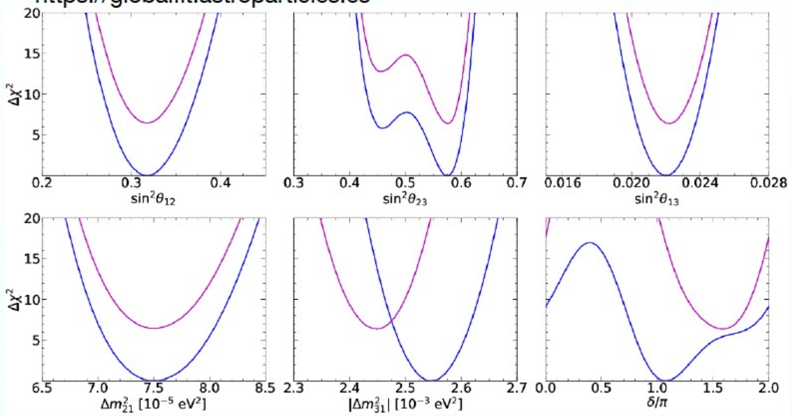
Oscillation measurement status

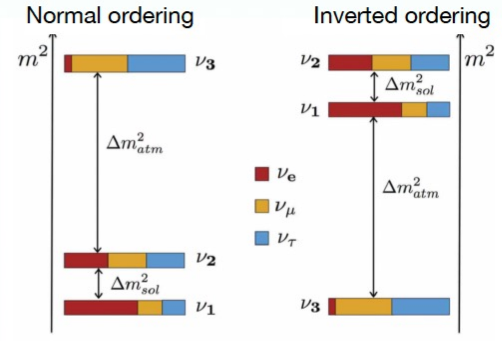
3-flavor mixing matrix

θ_{12}, θ_{23}, θ_{13}, δ_{CP}

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

https://globalfit.astroparticles.es





$|\Delta m^2|$, θ measured to ~3-5%

J_{CP} ~ 0.03 $\sin\delta_{CP}$

(⇔~3×10^{-5} for CKM)

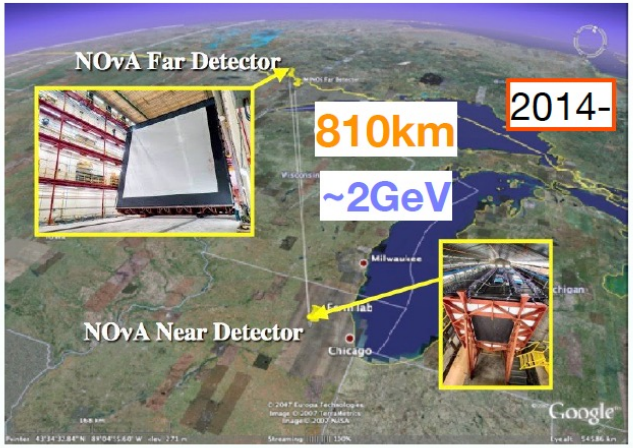
Current major targets

More precision measurements
θ_{23} octant (<=>45°?)
Mass ordering
CP violation
Consistency check of 3ν framework

Long baseline experiments

T2K

NOvA



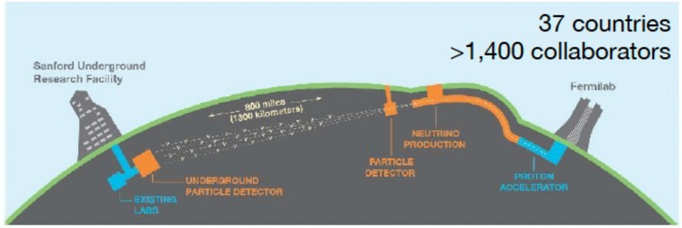
- Different baselines — different effects from matter effect
  (and possibly others not dependent on L/E)
  - T2K has a shorter baseline, purer effect of CPV
  - NOvA has a longer baseline, more matter effect and sensitivity to the mass ordering
- Different detector technology, different systematics

Next generation long baseline experiments

Hyper-Kamiokande in Japan

- 295km baseline
- ~0.6GeV off-axis neutrino beam
  - 1.3MW beam power
- 190kton water Cherenkov detector
- Upgraded/new near detectors

DUNE @LBNF in US



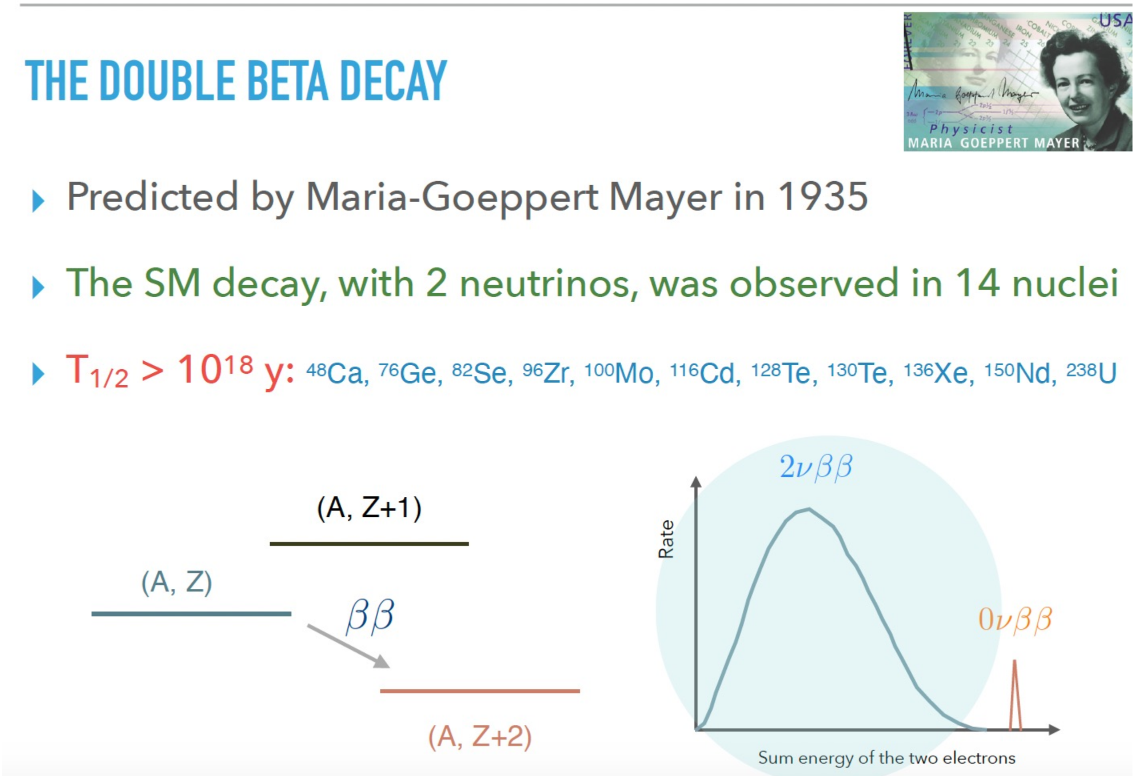
- 1300km baseline
- 0.5-4GeV wide-band beam
  - 1.2MW, upgradable to 2.4MW
- >40kton(4×10) liquid argon TPCs
- Highly capable near detector system
- Expected to start "Phase I" with 2 far detectors, 1.2MW beam, and a limited near detector

arXiv:2203.06100 DUNE Physics Summary (Snowmass white paper)

Different baseline, energy, technology, systematics → complementary

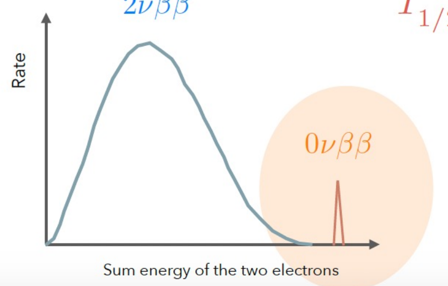
Both have rich non-beam physics programs

0 neutrino double beta decay

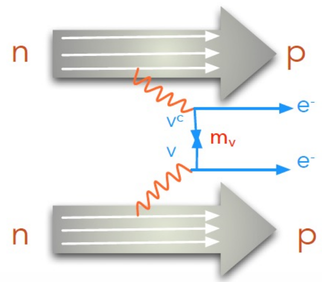


THE NEUTRINOLESS DOUBLE BETA DECAY

- Can only occur if neutrinos have mass and if they are their own anti-particles; $\Delta L = 2$
- Expected signature: sharp peak at the Q-value of the decay



$$T_{1/2}^{0\nu\beta\beta} > 10^{24}\ \mathrm{y}$$



OBSERVABLE DECAY RATE

Leptonic phase space — Axial-vector cc — Nuclear physics NME — Particle physics

$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} \times g_A^4 \times |M^{0\nu}|^2 \times \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Can be calculated: ~ Q^5

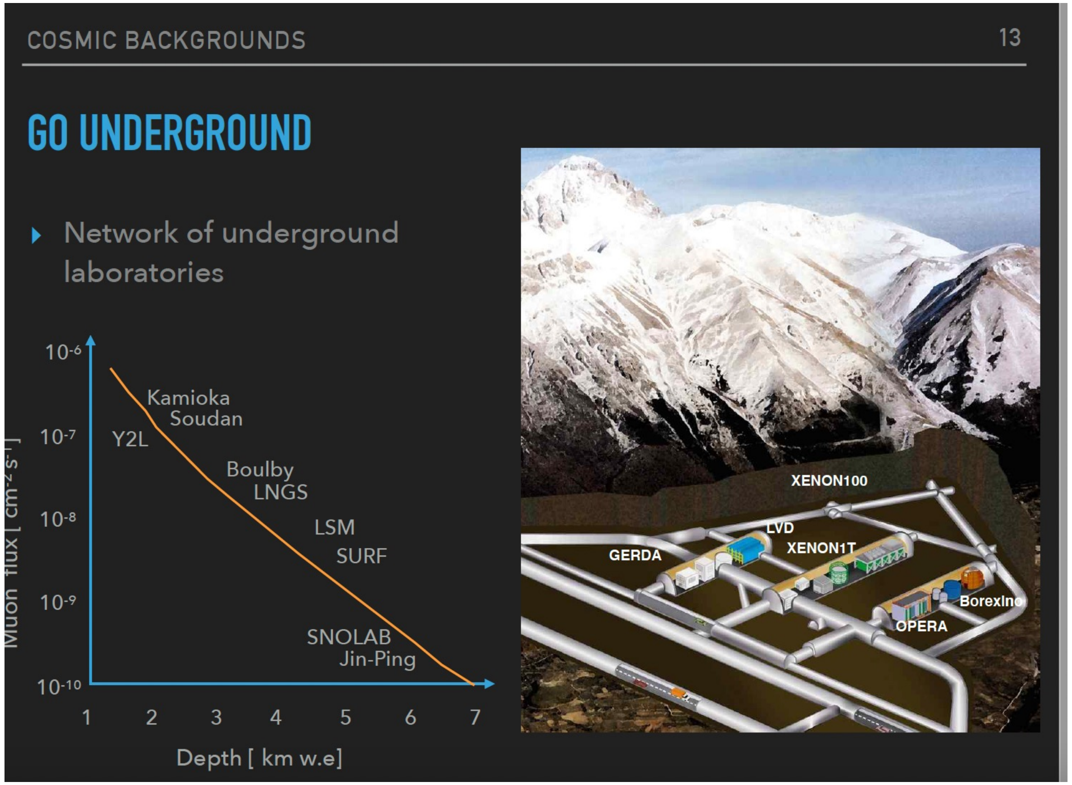
Difficult: factor 2-3

- With the effective Majorana neutrino mass:

$$|\langle m_{\beta\beta}\rangle| = |U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i(\alpha_1-\alpha_2)} + U_{e3}^2 m_3 e^{i(-\alpha_1-2\delta)}|$$

- a coherent sum over mass ES, with potentially CP violating phases
- a mixture of m_1, m_2, m_3, proportional to U^2

High Energy Physics without accelerators



LEADING RESULTS: OVERVIEW

Experiment	Isotope	FWHM [keV]	$T_{1/2}$ [10^{26} y]	$m_{\beta\beta}$ [meV]
CUORE	^{130}Te	7.4	0.15	162-757
CUPID-0	^{82}Se	23	0.024	394-810
EXO-200	^{136}Xe	71	0.18	93-287
KamLAND-Zen	^{136}Xe	270	1.1	76-234
GERDA	^{76}Ge	3.3	0.9	104-228
Majorana	^{76}Ge	2.5	0.27	157-346

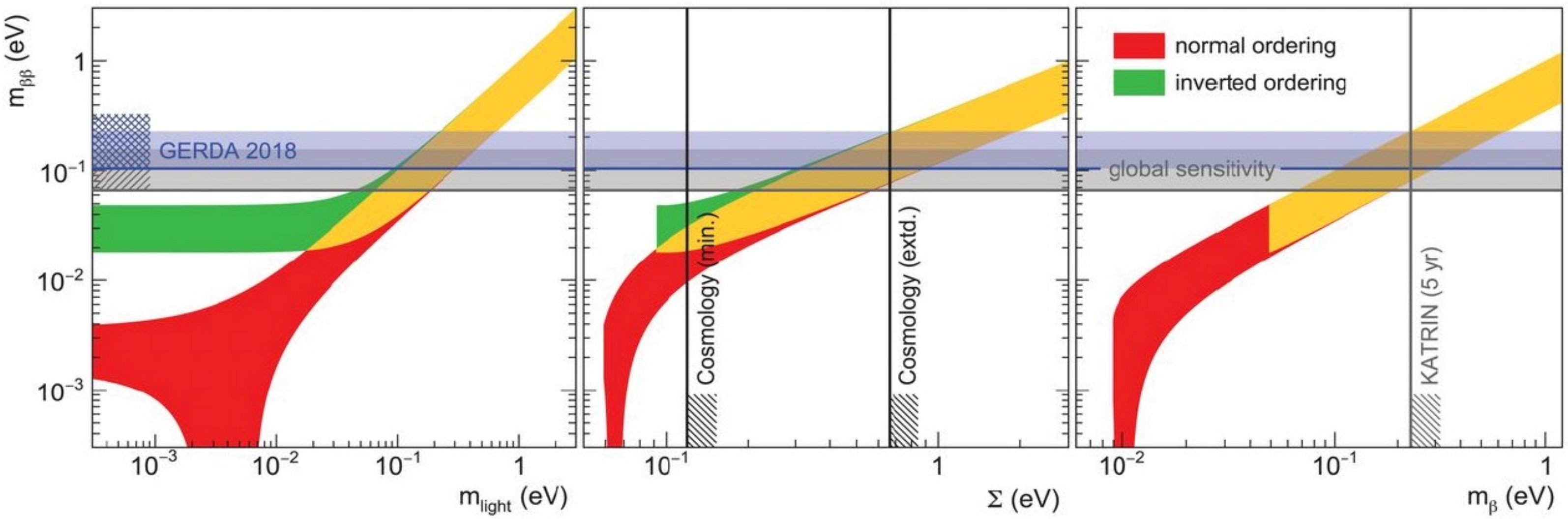
GERDA collaboration, Science 365, Sept 2019

FUTURE PROJECTS: A SELECTION

Experiment	Isotope	Iso mass [kg]	FWHM [keV]	$T_{1/2}$ [10^{27} y]	$m_{\beta\beta}$ [meV]
CUPID	^{130}Te	543	5	2.1	13-31
CUPID	^{82}Se	336	5	2.6	8-38
nEXO	^{136}Xe	4500	59	6	7-21
KamLAND2-Zen	^{136}Xe	1000	141	1.4	14-44
DARWIN	^{136}Xe	1068	20	1.4	14-44
PandaX-III	^{136}Xe	901	24	1.3	14-46
LEGEND-200	^{76}Ge	175	3	1	34-74
LEGEND-1t	^{76}Ge	873	3	6	14-30
SuperNEMO	^{82}Se	100	120	0.1	58-144

MASS OBSERVABLES

- Constraints in the $m_{\beta\beta}$ parameters space in the 3 light ν scenario
- GERDA + leading experiments in the field



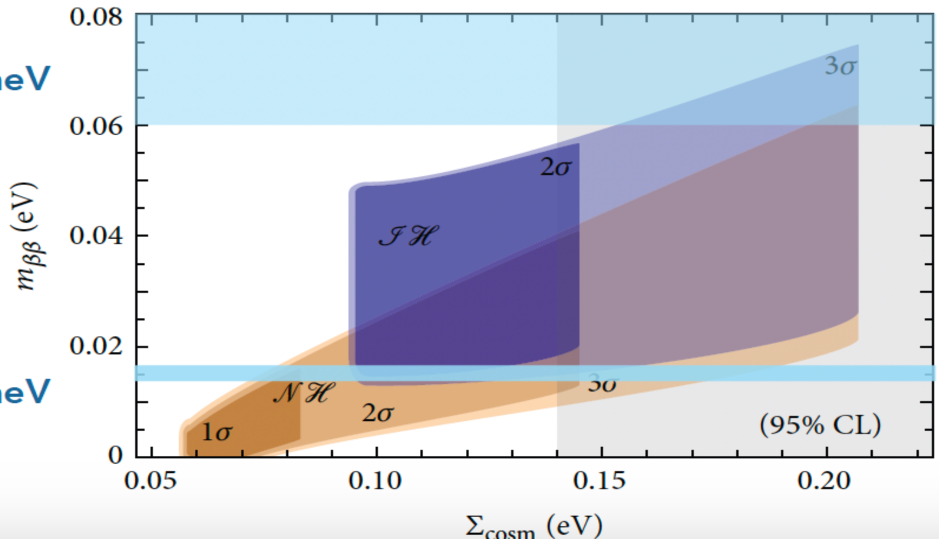
$$m_{\beta\beta} = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right| \qquad \Sigma = \sum_i m_i \qquad m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2}$$

SUMMARY

- Ton-scale experiments are required to probe the IH scenario
- Several technologies move into this direction
- Much larger experiments required to probe the NH scenario

70 meV

10 meV



Current experiments

Future, ton-scale experiments

Dell'Oro, Marcocci, Viel, Vissani, Adv. High Energy Phys. (2016) 2162659

DARK MATTER SEARCH

- Through the high energy frontier (production at high energy accelerators)
- Direct detection of dark matter around us
- Indirect detection of dark matter annihilation in the center of the earth, of the sun, of our galaxy where it should accumulate
- Other various methods (axion, sterile neutrinos…)

Dark Matter Candidates

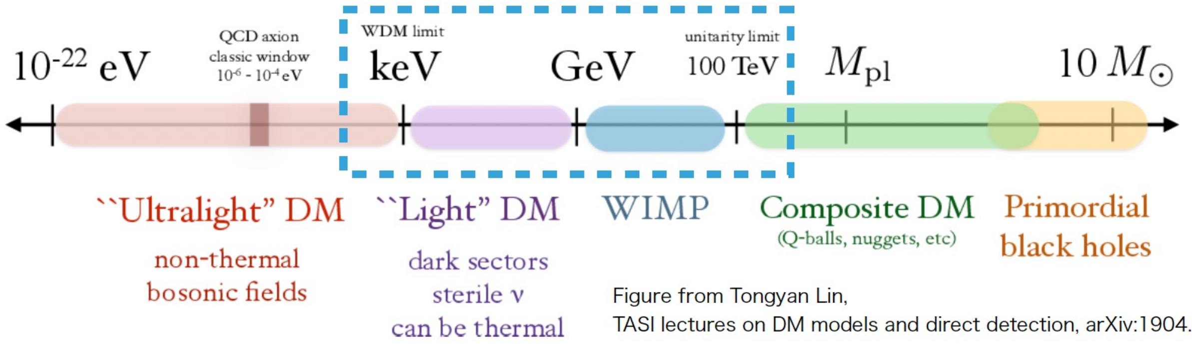
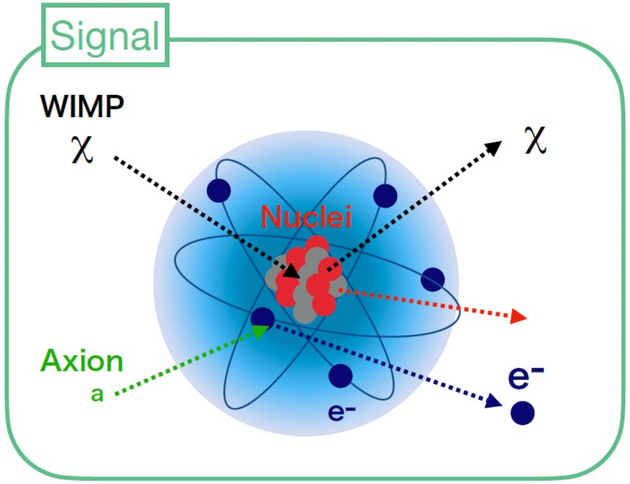
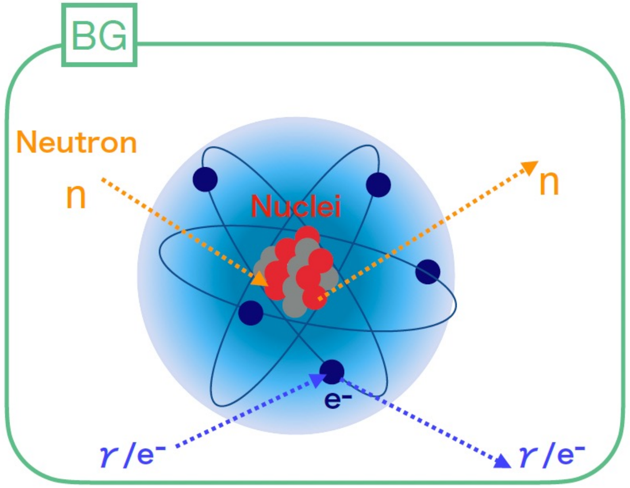


Figure from Tongyan Lin,
TASI lectures on DM models and direct detection, arXiv:1904.07915

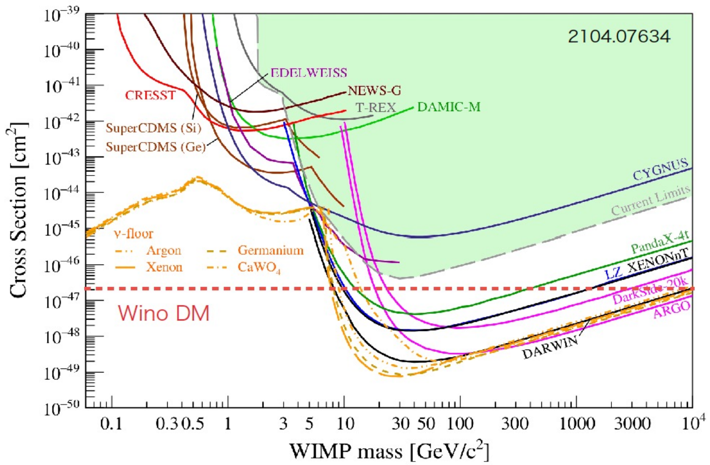




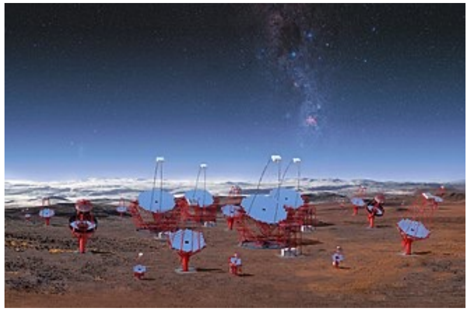
Exciting Future for Direct Detection

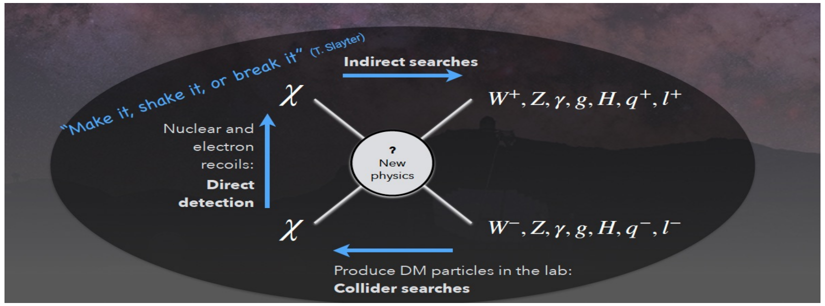
very diverse experimental landscape – many different projects

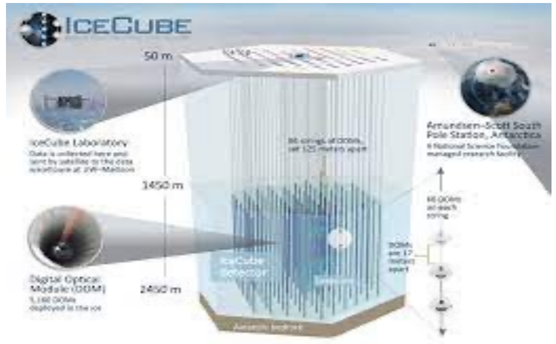
aim at closing most interesting parameter space in the next decade(s)

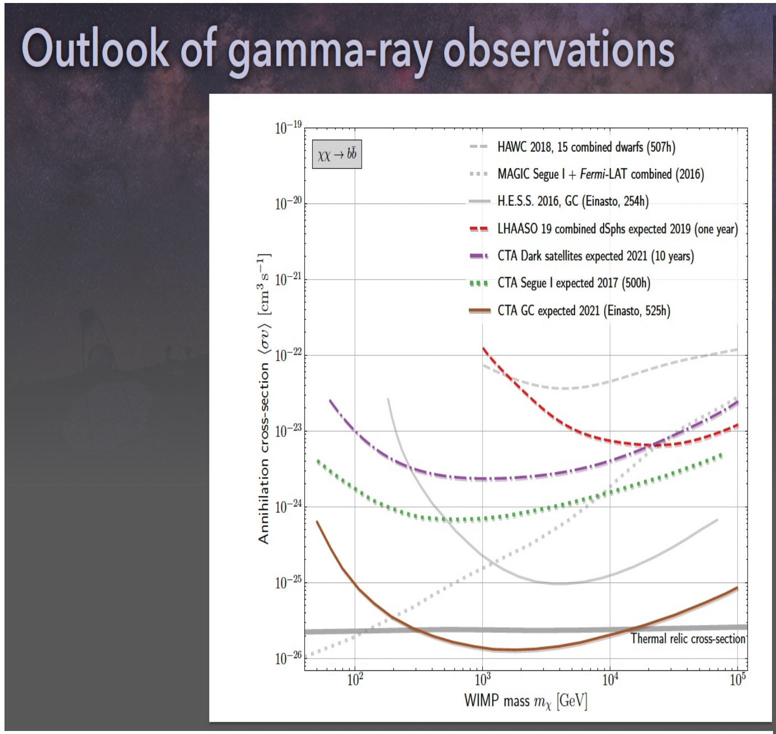


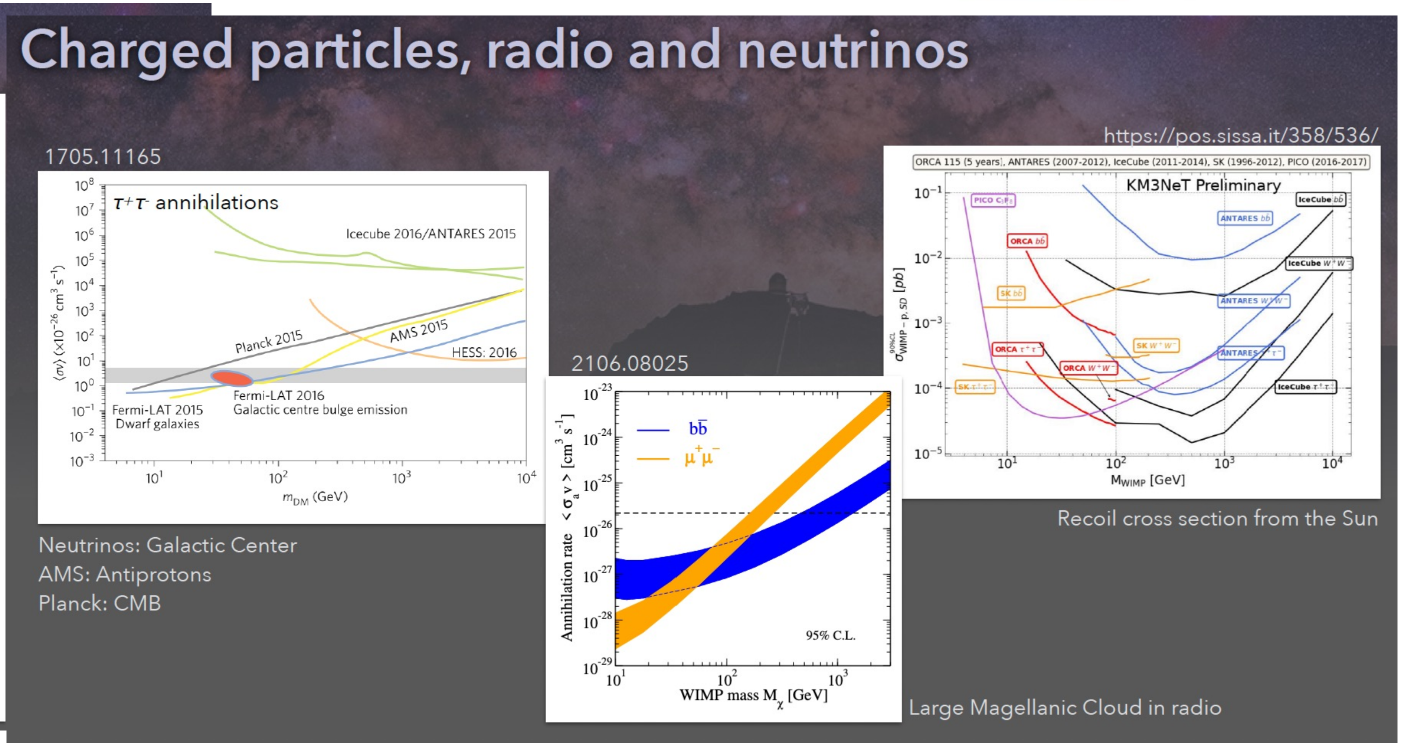
INDIRECT DETECTION: annihilation in the center of the earth or sun











Evidence for Dark Matter or not from positron Cosmic Ray Spectrum in AMS

Samuel Ting vs Sylvie Rosier

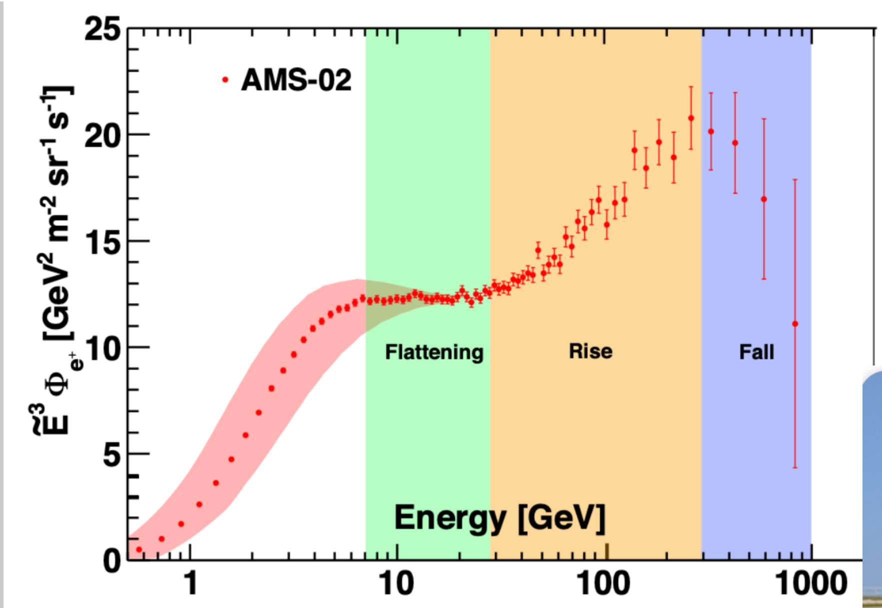
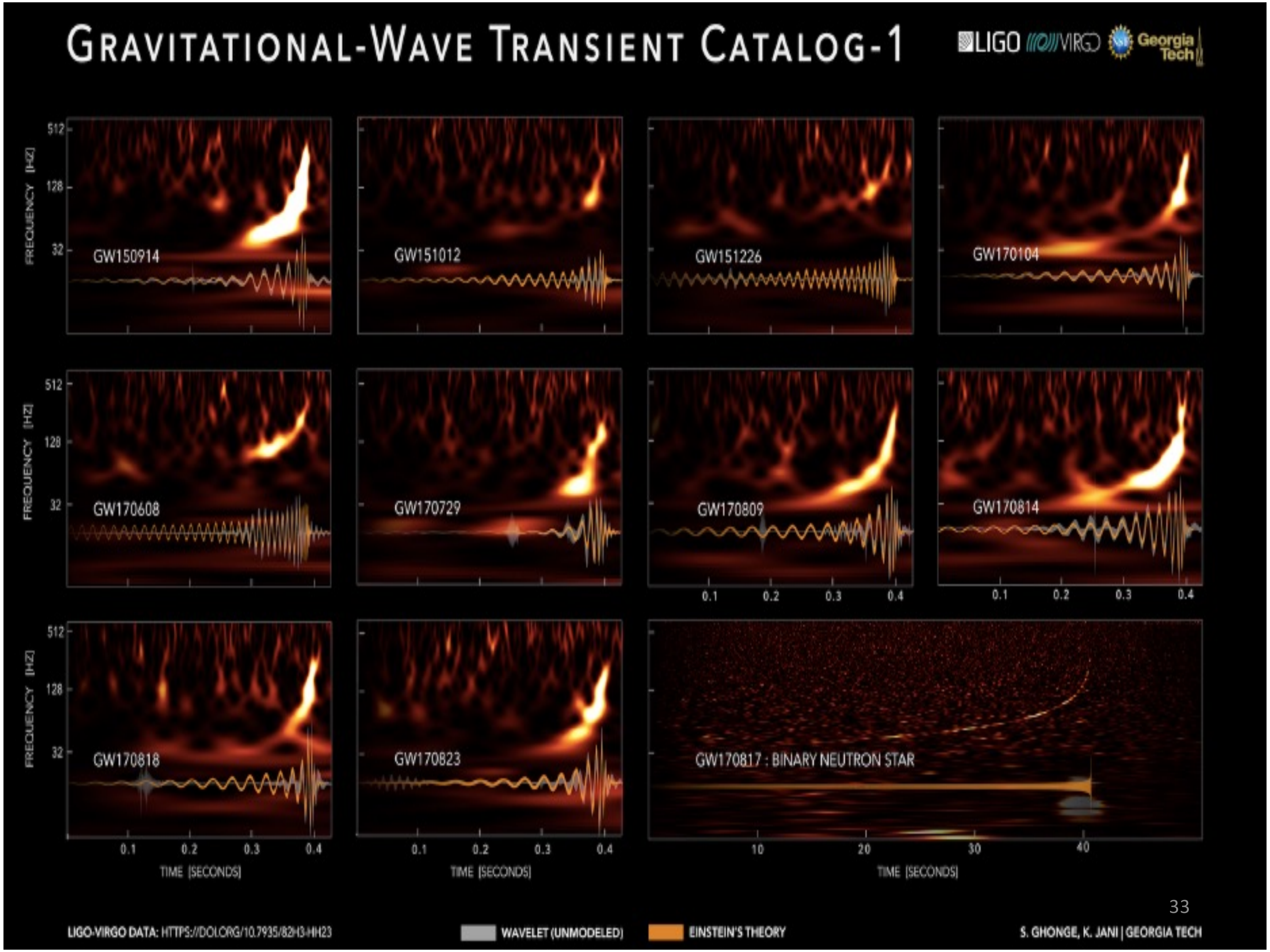


Figure 1. For display purposes, the positron flux, Φ_{e+} is traditionally presented scaled by $\tilde{E}^3$. The resulting AMS positron spectrum, $\tilde{E}^3\,\Phi_{e+}$, (red data points) is shown as a function of energy. $\tilde{E}$ is the spectrally weighted mean energy for a flux proportional to E^{-3}. The time variation of the flux at low energies due to solar modulation is indicated by the red band. To guide the eye, the vertical color bands indicate the energy ranges corresponding to changing behavior of the spectrum: flattening, rising, and falling spectrum.

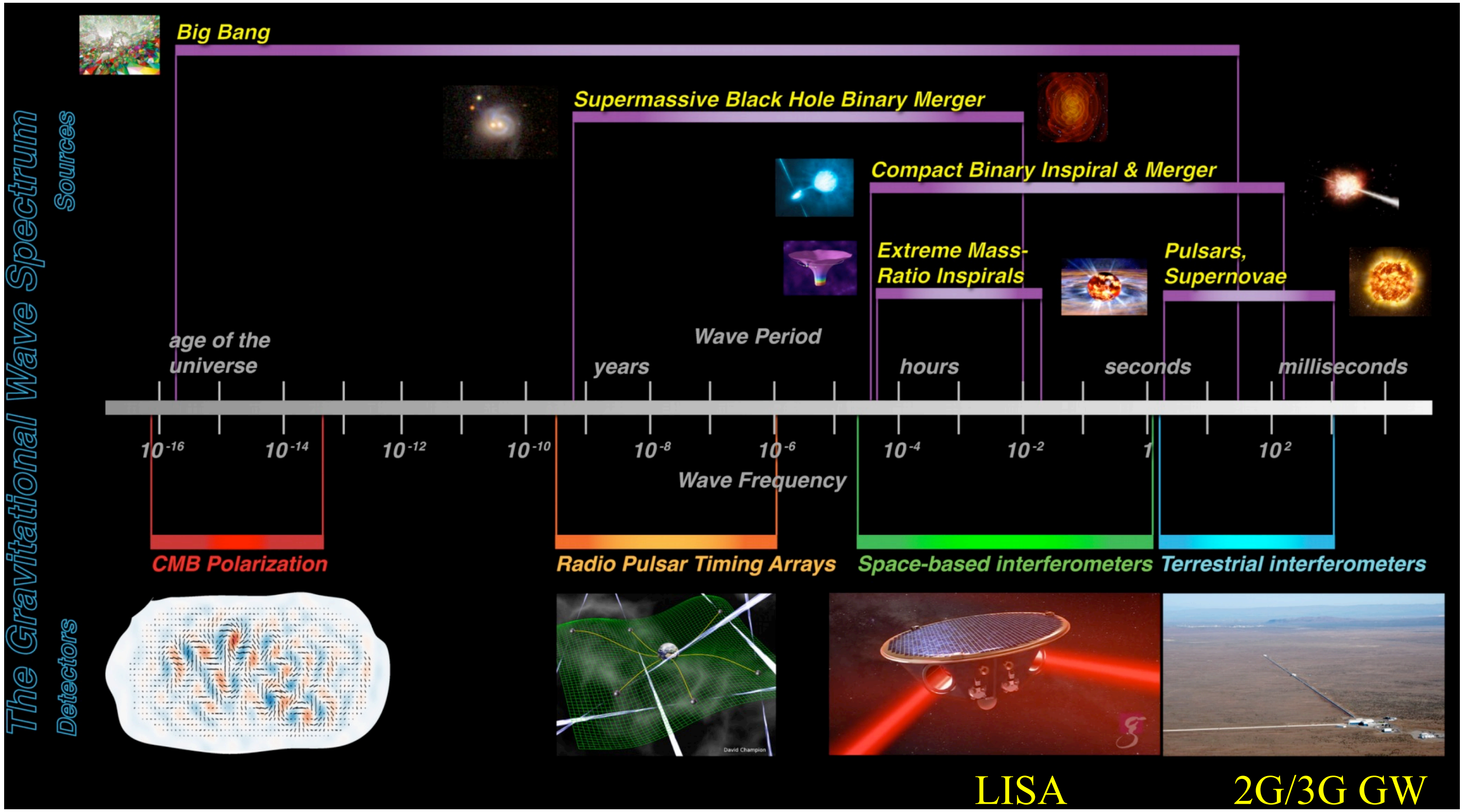
Sylvie Rosier-Lees 1961–2022 – ... Consulter

VIRGO: Project initiated in France by A. Brillet, accepted after the P. Fleury review panel examination (1990)

S. K. Katsanevas EGO Director 2018 - 2022


GRAVITATIONAL-WAVE TRANSIENT CATALOG-1
LIGO VIRGO Georgia Tech
FREQUENCY [HZ]
512
128
32
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
GW170817 : BINARY NEUTRON STAR
0.1 0.2 0.3 0.4
10 20 30 40
TIME [SECONDS]
LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23
WAVELET (UNMODELED)
EINSTEIN'S THEORY
S. GHONGE, K. JANI | GEORGIA TECH

Gravitational Waves « Frequency Domain » Analysis

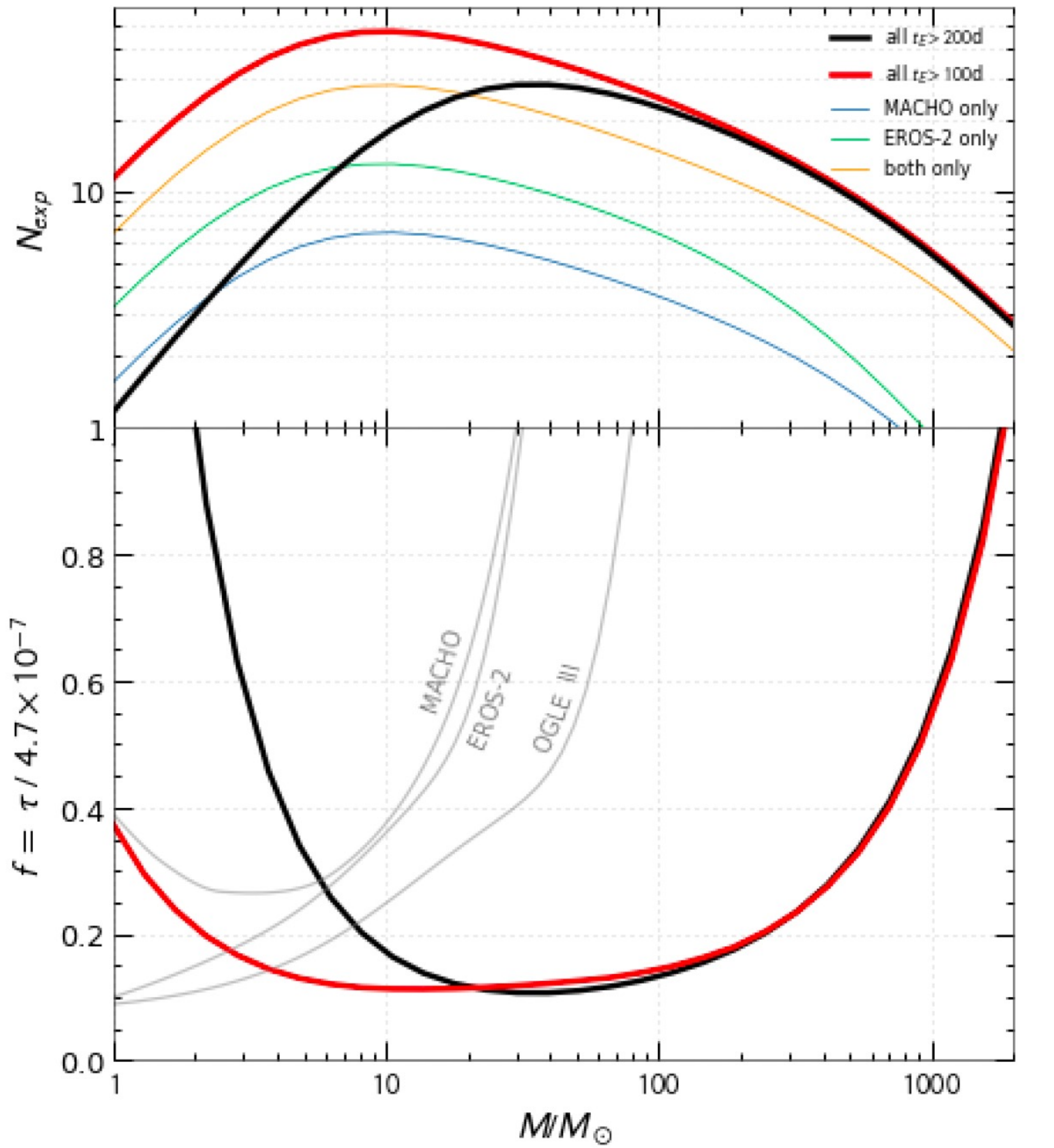


Discovering (direct or indirect) the stochastic GW background from inflation would be a major discovery

Black holes as dark matter?

- Most events seen by LIGO/VIRGO are coalescence of few tens of solar masses black holes (excellent laboratory to test General Relativity)! Could these black holes be the dark matter in the universe?
- Very recently the EROS collaboration, combining its data with MACHO, has shown that the dark matter in the halo of our galaxy cannot be made of compact objects of masses between 10^{-6} and 10^{3} solar masses
- This is based on observations of millions of stars in the LMC, looking (during 10 years) at the occurrence of alignments between us, a dark compact object in the halo of our galaxy and a star in the LMC.
  - Thèse 2021: Tristan Blaineau, directeur de thèse: Marc Moniez

[redacted]



all t_E> 200d
all t_E> 100d
MACHO only
EROS-2 only
both only
N_{exp}
10
1
$f = \tau / 4.7 \times 10^{-7}$
0.0
0.2
0.4
0.6
0.8
1
MACHO
EROS-2
OGLE III
1
10
100
1000
$M/M_\odot$

A multi approach to the future of experimental particle physics

- The high energy frontier
- Precision low energy experiments: the precision frontier
- Neutrino physics: the neutrino frontier
- Dark matter, gravitational waves, high energy astrophysics: the cosmic frontier

- A rich landscape. I very much hope it is affordable.