Feebly Interacting Particles (FIPs): Introduction

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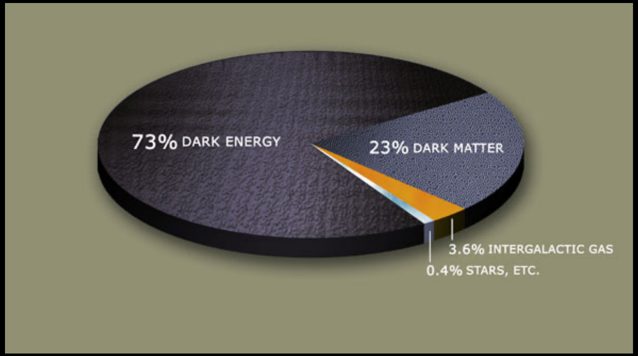
CHIPP Roadmap Workshop – 19 January 2024

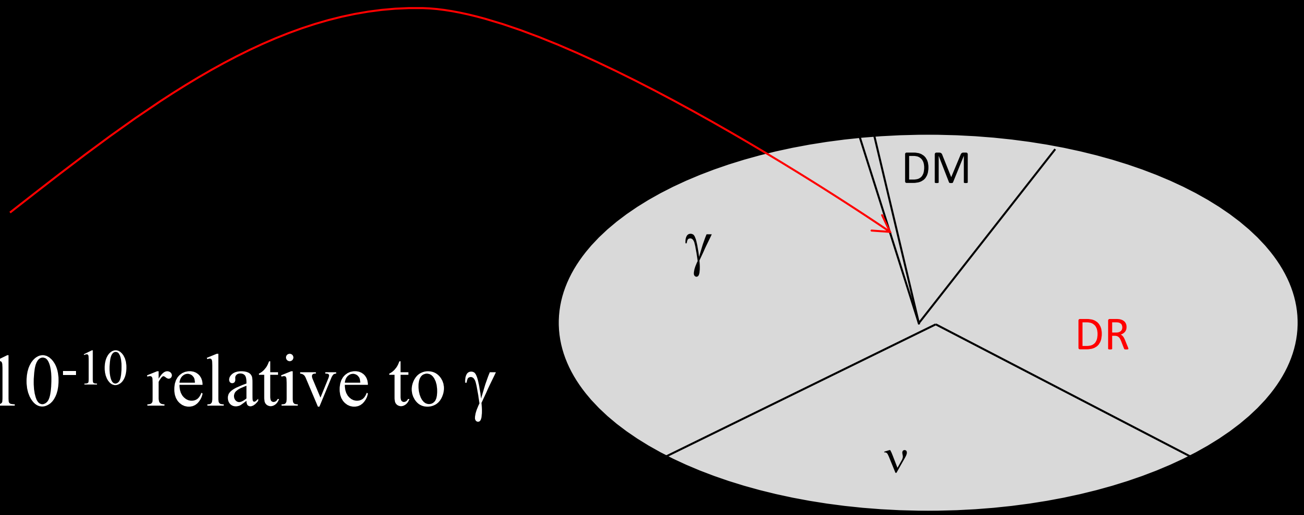
Clues for New Physics: Dark Matter



Atoms

In Energy chart they are 4%.

In number density chart ~ 5 $\times 10^{-10}$ relative to γ



Dark Matter:

In Energy chart it is 23%.

We have no idea about DM number densities. (WIMPs ~ 10^{-8} cm^{-3}; axions ~ 10^{9} cm^{-3}. Dark Radiation, Dark Forces – Who knows!).

Lack of precise knowledge about nature of dark matter leaves a lot of room for existence of dark radiation, and dark forces – dark sector in general.

Clues of New Physics: origin of the neutrino masses and oscillations

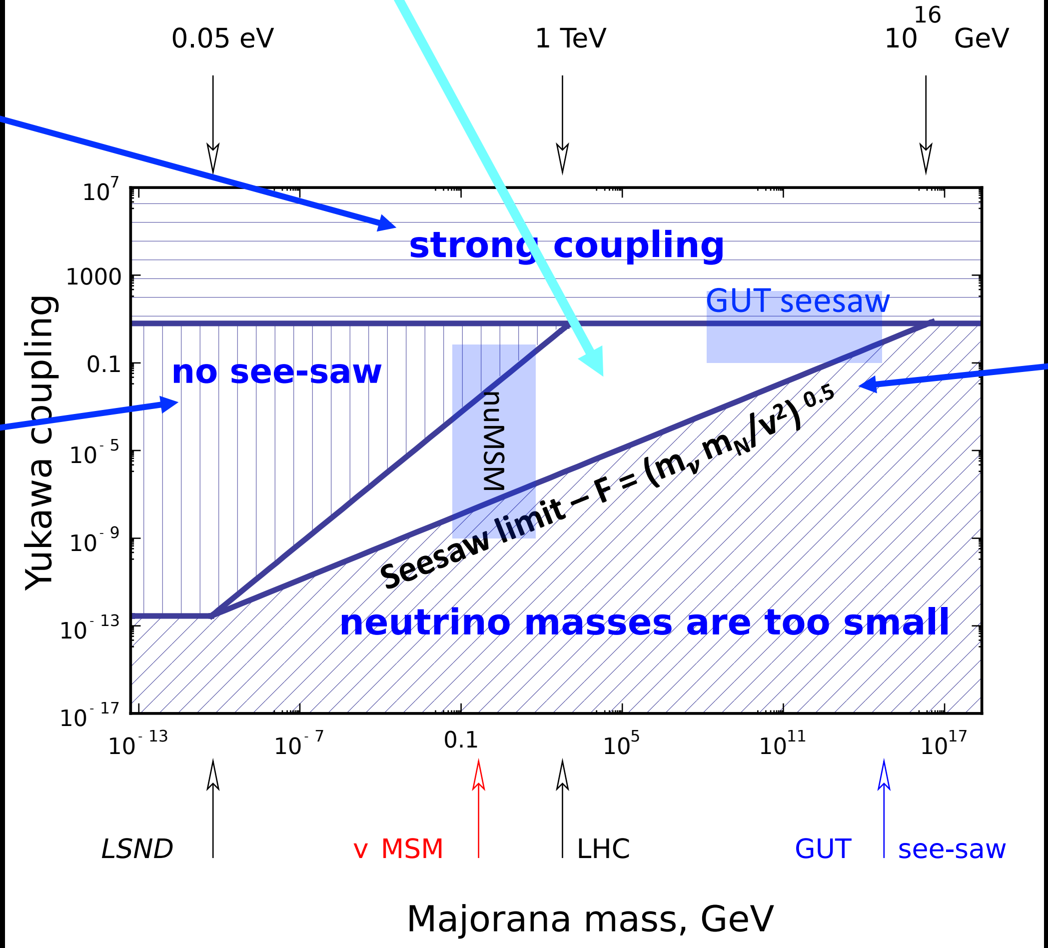
$SU(2)xU(1)_L$ singlet Right Handed Neutrinos responsible of the neutrinos' mass generation can have any coupling/mass in the white area, assuming an approximate $U(1)_L$ global symmetry

One or few of the Yukawas exceed unity.

-> perturbative treatment is not valid.

Dirac neutrino masses exceed the Majorana masses of the HNLs.

(In this domain HNLs interact with the neutrinos too strongly and would lead to visible effects in different neutrino experiments, would modify the invisible width of Z, etc.)



Seesaw line:

Below this line neutrino masses cannot be explained.

Couplings, masses, and number of HNLs are unknown:

N = 2 if m(active lightest) = 0;

N = 3 if m(active lightest)>0

Large spectrum of possible masses & couplings

Clues of New Physics…. *and the Feeble front.*

A (very) limited list of examples

Dark Matter:

candidates \w mass from 10^{-22} eV (light feeble scalars) to 10^{20} GeV (black holes).

⟶ FIPs: if DM is a thermal relic, then mass is restricted o(10) keV – 100 TeV: MeV-GeV DM requires light mediators

Neutrino masses and oscillations

explanation: RH neutrinos with masses from 10^{-2} eV to 10^{15} GeV.

⟶ FIPs: If RHN have generic (feeble) Yukawa's + approximate $U(1)_L$*, masses can be below EW scale.*

Matter-antimatter asymmetry

hard to associate scale, solutions of many orders of magnitudes:

⟶ FIPs: baryogenesis could occur via CPV relaxion-Higgs couplings;

⟶ FIPs: baryogenesis could occur via leptogenesis via neutrino oscillations of RHN with masses below EW scale.

Naturalness problem: why M(Higgs) << M(Planck) ?

Symmetry-based solutions => TeV partners;

⟶ FIPs: relaxion => light feeble Goldstone bosons (ALPs)

Strong CP problem:

⟶ FIPs: axion = light feeble Goldstone boson;

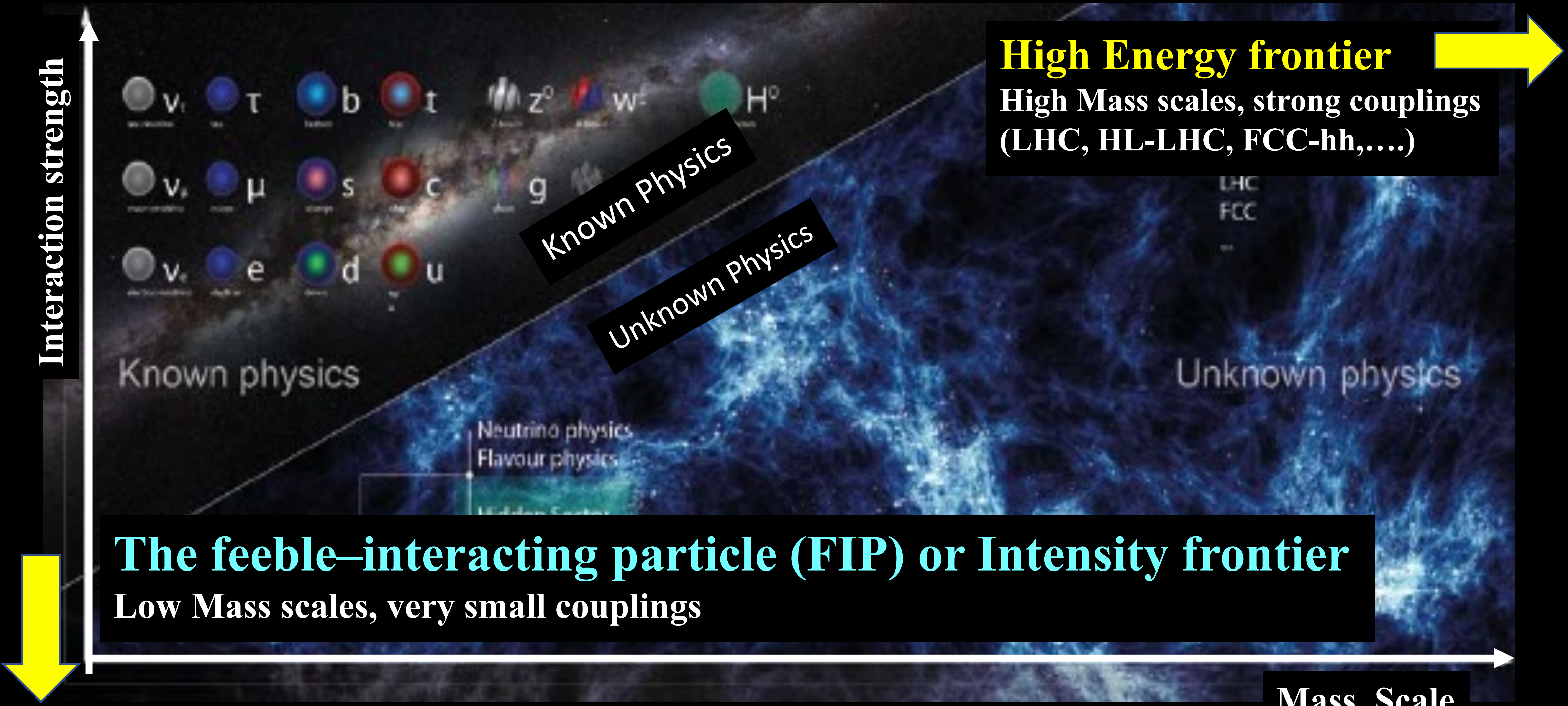
Why *Feebly-Interacting* Particles (FIPs)?

FIPs have (dimensional or dimensionless) effective couplings $<< 1$

[The smallness of the couplings can be generated by an approximate symmetry almost unbroken, and/or a large mass hierarchy between particles (as data seem to suggest)]

Fully complementary to high-energy searches.
Naturally long-lived.

The Quest for New Physics



Interaction strength

High Energy frontier

High Mass scales, strong couplings (LHC, HL-LHC, FCC-hh,….)

Known Physics

Unknown Physics

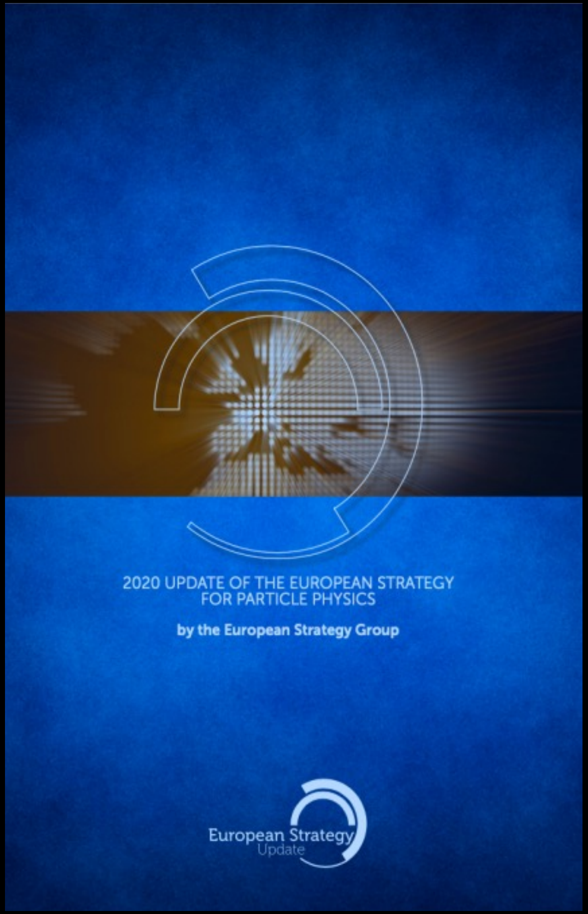
The feeble–interacting particle (FIP) or Intensity frontier

Low Mass scales, very small couplings

Mass Scale

European Strategy for Particle Physics recommendations (2020)

https://cds.cern.ch/record/2721370/files/CERN-ESU-015
2020%20Update%20European%20Strategy.pdf


2020 UPDATE OF THE EUROPEAN STRATEGY
FOR PARTICLE PHYSICS

by the European Strategy Group

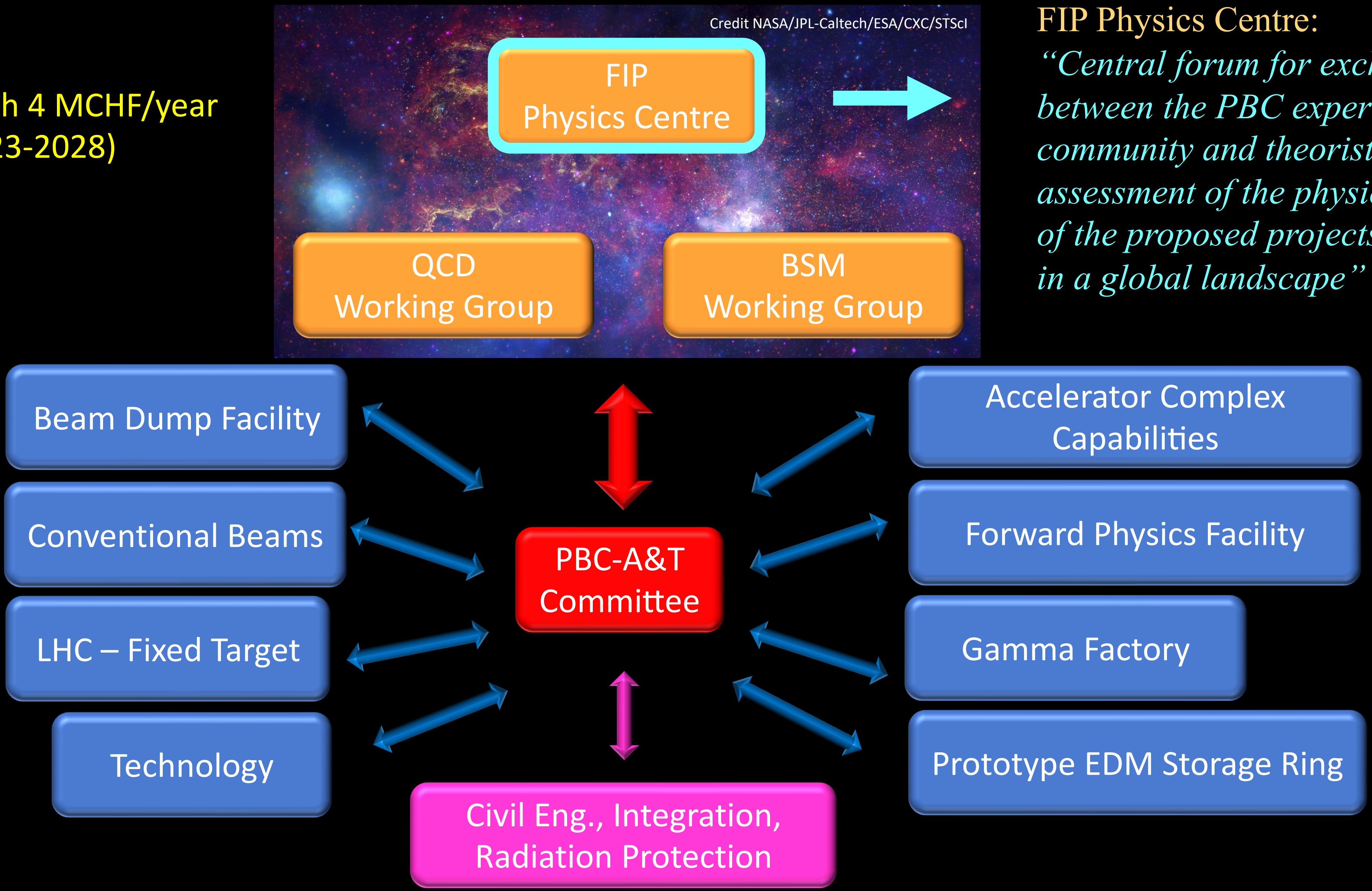
European Strategy
Update

"4. *<u>Other essential scientific activities for particle physics:</u>*

- *a) The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics.*
- *This search can be done in many ways, for example through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions, <u>dark sector candidates and feebly interacting particles</u>.*
- *There are many options to address such physics topics including energy-frontier colliders, accelerator and non-accelerator experiments. <u>A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy</u>.*

The Physics Beyond Colliders initiative at CERN

PBC funded with 4 MCHF/year
(CERN MTP 2023-2028)



Credit NASA/JPL-Caltech/ESA/CXC/STScI

FIP
Physics Centre

QCD
Working Group

BSM
Working Group

Beam Dump Facility

Conventional Beams

LHC – Fixed Target

Technology

PBC-A&T
Committee

Civil Eng., Integration,
Radiation Protection

Accelerator Complex
Capabilities

Forward Physics Facility

Gamma Factory

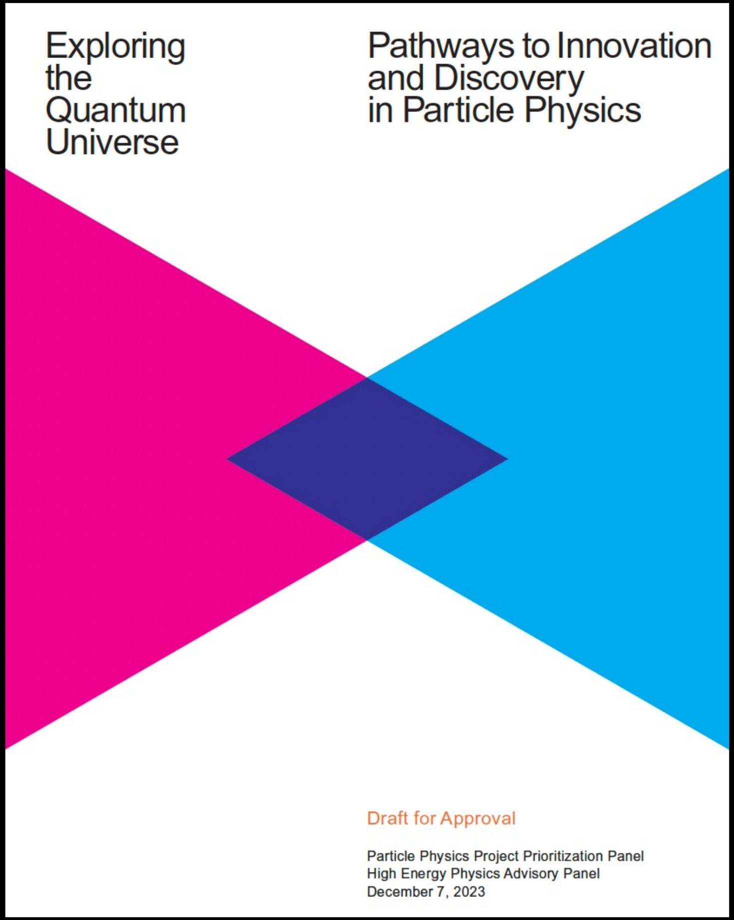
Prototype EDM Storage Ring

FIP Physics Centre:

“Central forum for exchanges between the PBC experimental community and theorists for assessment of the physics reach of the proposed projects in a global landscape”

US P5 Report (December 2023)

https://www.usparticlephysics.org/wp-content/uploads/2023/12/P5Report2023_120723-DRAFT_single-pages.pdf



Exploring
the
Quantum
Universe

Pathways to Innovation
and Discovery
in Particle Physics

Draft for Approval

Particle Physics Project Prioritization Panel
High Energy Physics Advisory Panel
December 7, 2023

Section 2.2, Recommendations:

Recommendation 3:
Create an improved balance between small-, medium-, and large-scale projects to open new scientific opportunities and maximize their results, enhance workforce development, promote creativity, and compete on the world stage.

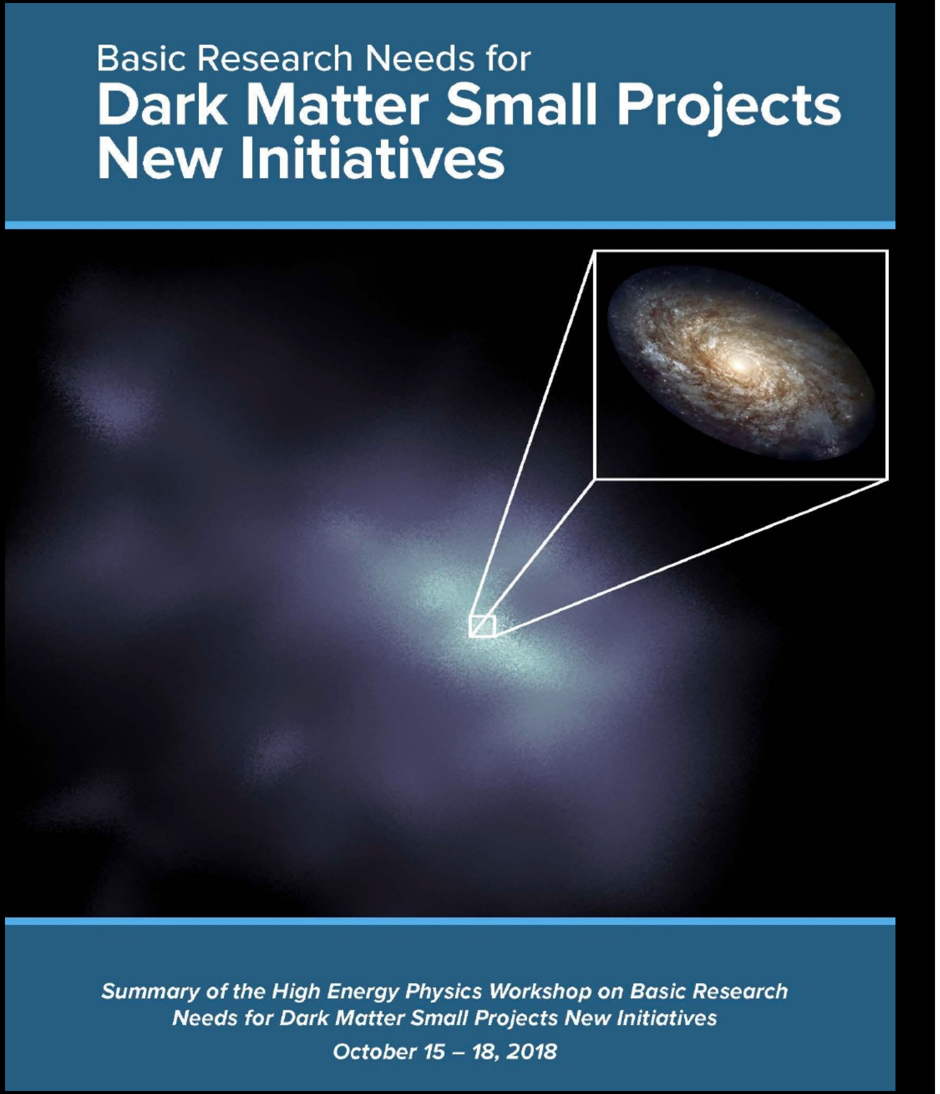
In order to achieve this balance across all project sizes we recommend the following:

a. Implement a new small-project portfolio at DOE, Advancing Science and Technology through Agile Experiments (ASTAE), across science themes in particle physics with a competitive program and recurring funding opportunity announcements. This program should start with the construction of experiments from the Dark Matter New Initiatives (DMNI) by DOE-HEP (section 6.2).

b. Continue Mid-Scale Research Infrastructure (MSRI) and Major Research Instrumentation (MRI) programs as a critical component of the NSF research and project portfolio.

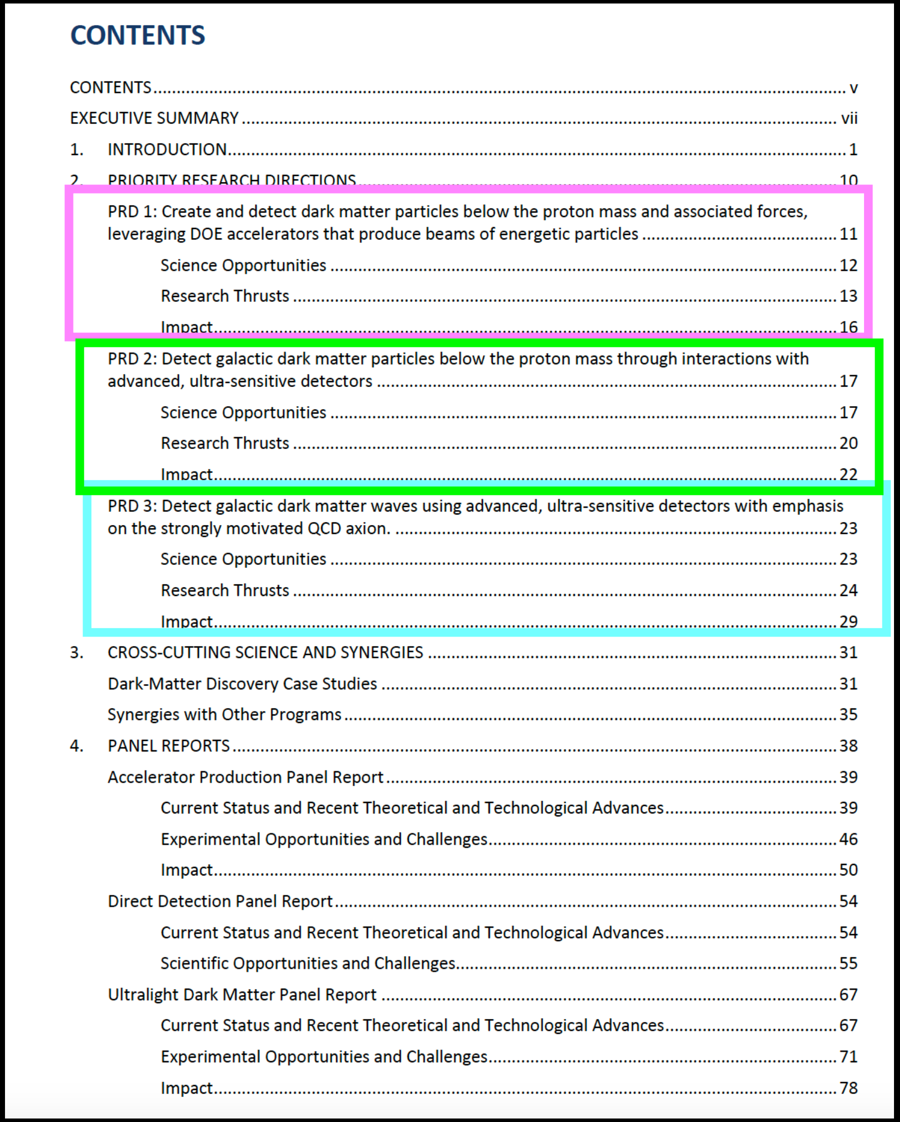
c. Support DESI-II for cosmic evolution, LHCb upgrade II and Belle II upgrade for quantum imprints, and US contributions to the global CTA Observatory for dark matter (sections 4.2, 5.2, and 4.1).

US Dark Matter New Initiatives (DMNI) Projects



Basic Research Needs for
Dark Matter Small Projects New Initiatives

Summary of the High Energy Physics Workshop on Basic Research Needs for Dark Matter Small Projects New Initiatives
October 15 – 18, 2018



CONTENTS

DM particles below the proton mass (accelerators)

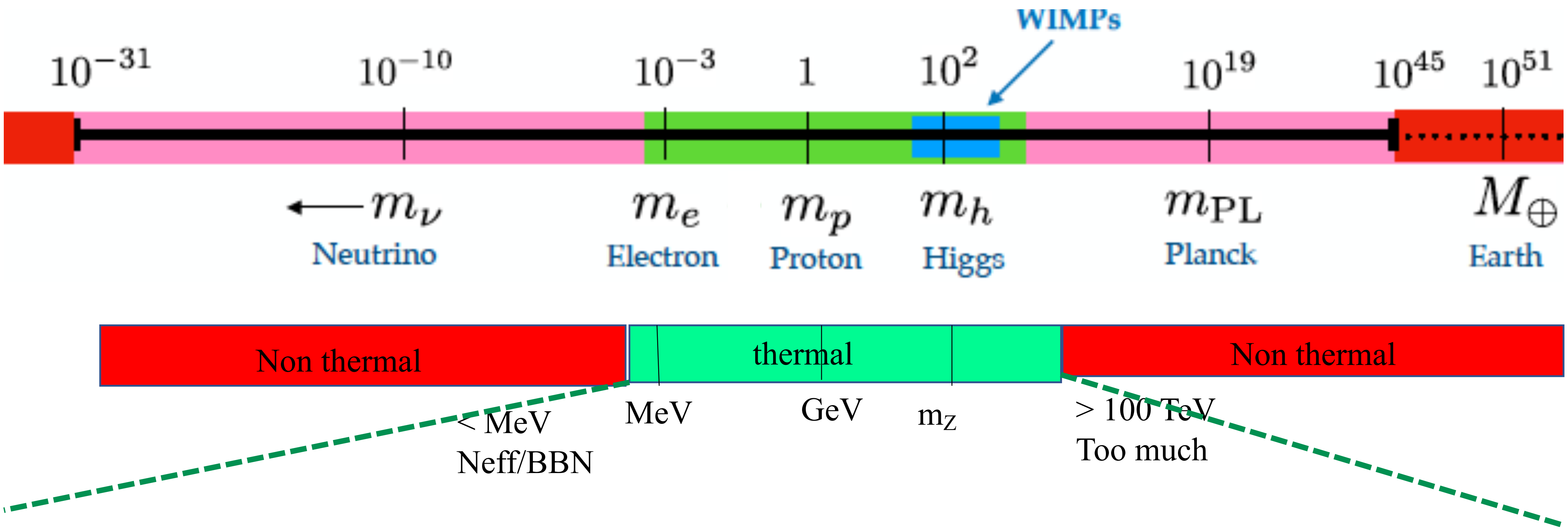
DM particles below the proton mass (direct detection)

DM waves (axions, and the likes)

https://science.osti.gov/-/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf

Dark Matter: a huge range of possible masses

80 orders of magnitude allowed for DM ….



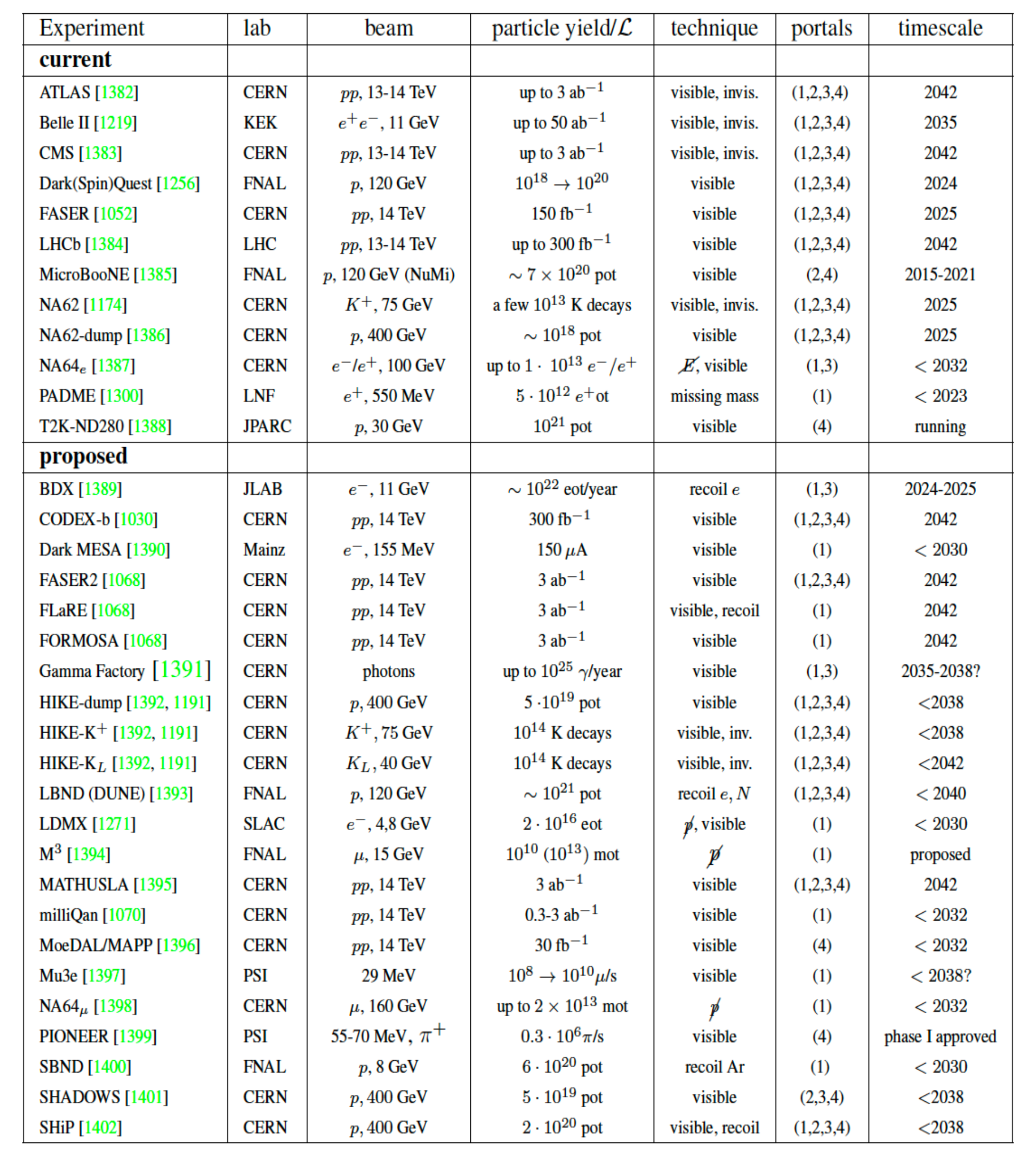
…but only a narrow range for thermal equilibrium with SM bath at some point in the Early Universe:

for m(DM) < m(e):
DM is relativistic at BBN time
and spoils light element yield

for m(DM)>100 TeV :
DM is overproduced unless
unitarity is violated.

Search for light (MeV- GeV) DM at accelerators

Main current, and future accelerator-based experiments sensitive to light DM and related mediators at CERN, FNAL, SLAC, JLAB, KEK, MAINZ, Frascati, JPARC,….



Experiment	lab	beam	particle yield/$\mathcal{L}$	technique	portals	timescale
current						
ATLAS [1382]	CERN	pp, 13-14 TeV	up to 3 ab^{-1}	visible, invis.	(1,2,3,4)	2042
Belle II [1219]	KEK	e^+e^-, 11 GeV	up to 50 ab^{-1}	visible, invis.	(1,2,3,4)	2035
CMS [1383]	CERN	pp, 13-14 TeV	up to 3 ab^{-1}	visible, invis.	(1,2,3,4)	2042
Dark(Spin)Quest [1256]	FNAL	p, 120 GeV	$10^{18} \to 10^{20}$	visible	(1,2,3,4)	2024
FASER [1052]	CERN	pp, 14 TeV	150 fb^{-1}	visible	(1,2,3,4)	2025
LHCb [1384]	LHC	pp, 13-14 TeV	up to 300 fb^{-1}	visible	(1,2,3,4)	2042
MicroBooNE [1385]	FNAL	p, 120 GeV (NuMi)	$\sim 7 \times 10^{20}$ pot	visible	(2,4)	2015-2021
NA62 [1174]	CERN	K^+, 75 GeV	a few 10^{13} K decays	visible, invis.	(1,2,3,4)	2025
NA62-dump [1386]	CERN	p, 400 GeV	$\sim 10^{18}$ pot	visible	(1,2,3,4)	2025
NA64$_e$ [1387]	CERN	e^-/e^+, 100 GeV	up to $1 \cdot 10^{13}$ e^-/e^+	$\not{E}$, visible	(1,3)	< 2032
PADME [1300]	LNF	e^+, 550 MeV	$5 \cdot 10^{12}$ e^+ot	missing mass	(1)	< 2023
T2K-ND280 [1388]	JPARC	p, 30 GeV	10^{21} pot	visible	(4)	running
proposed						
BDX [1389]	JLAB	e^-, 11 GeV	$\sim 10^{22}$ eot/year	recoil e	(1,3)	2024-2025
CODEX-b [1030]	CERN	pp, 14 TeV	300 fb^{-1}	visible	(1,2,3,4)	2042
Dark MESA [1390]	Mainz	e^-, 155 MeV	150 μA	visible	(1)	< 2030
FASER2 [1068]	CERN	pp, 14 TeV	3 ab^{-1}	visible	(1,2,3,4)	2042
FLaRE [1068]	CERN	pp, 14 TeV	3 ab^{-1}	visible, recoil	(1)	2042
FORMOSA [1068]	CERN	pp, 14 TeV	3 ab^{-1}	visible	(1)	2042
Gamma Factory [1391]	CERN	photons	up to 10^{25} γ/year	visible	(1,3)	2035-2038?
HIKE-dump [1392, 1191]	CERN	p, 400 GeV	$5 \cdot 10^{19}$ pot	visible	(1,2,3,4)	<2038
HIKE-K$^+$ [1392, 1191]	CERN	K^+, 75 GeV	10^{14} K decays	visible, inv.	(1,2,3,4)	<2038
HIKE-K$_L$ [1392, 1191]	CERN	K_L, 40 GeV	10^{14} K decays	visible, inv.	(1,2,3,4)	<2042
LBND (DUNE) [1393]	FNAL	p, 120 GeV	$\sim 10^{21}$ pot	recoil e, N	(1,2,3,4)	< 2040
LDMX [1271]	SLAC	e^-, 4,8 GeV	$2 \cdot 10^{16}$ eot	$\not{p}$, visible	(1)	< 2030
M^3 [1394]	FNAL	μ, 15 GeV	10^{10} (10^{13}) mot	$\not{p}$	(1)	proposed
MATHUSLA [1395]	CERN	pp, 14 TeV	3 ab^{-1}	visible	(1,2,3,4)	2042
milliQan [1070]	CERN	pp, 14 TeV	0.3-3 ab^{-1}	visible	(1)	< 2032
MoeDAL/MAPP [1396]	CERN	pp, 14 TeV	30 fb^{-1}	visible	(4)	< 2032
Mu3e [1397]	PSI	29 MeV	$10^8 \to 10^{10}\mu$/s	visible	(1)	< 2038?
NA64$_\mu$ [1398]	CERN	μ, 160 GeV	up to 2×10^{13} mot	$\not{p}$	(1)	< 2032
PIONEER [1399]	PSI	55-70 MeV, π^+	$0.3 \cdot 10^6\pi$/s	visible	(4)	phase I approved
SBND [1400]	FNAL	p, 8 GeV	$6 \cdot 10^{20}$ pot	recoil Ar	(1)	< 2030
SHADOWS [1401]	CERN	p, 400 GeV	$5 \cdot 10^{19}$ pot	visible	(2,3,4)	<2038
SHiP [1402]	CERN	p, 400 GeV	$2 \cdot 10^{20}$ pot	visible, recoil	(1,2,3,4)	<2038

FIPs 2022 Workshop Report arXiv: 2305.01715

Search for light (MeV-GeV) DM with direct detection experiments

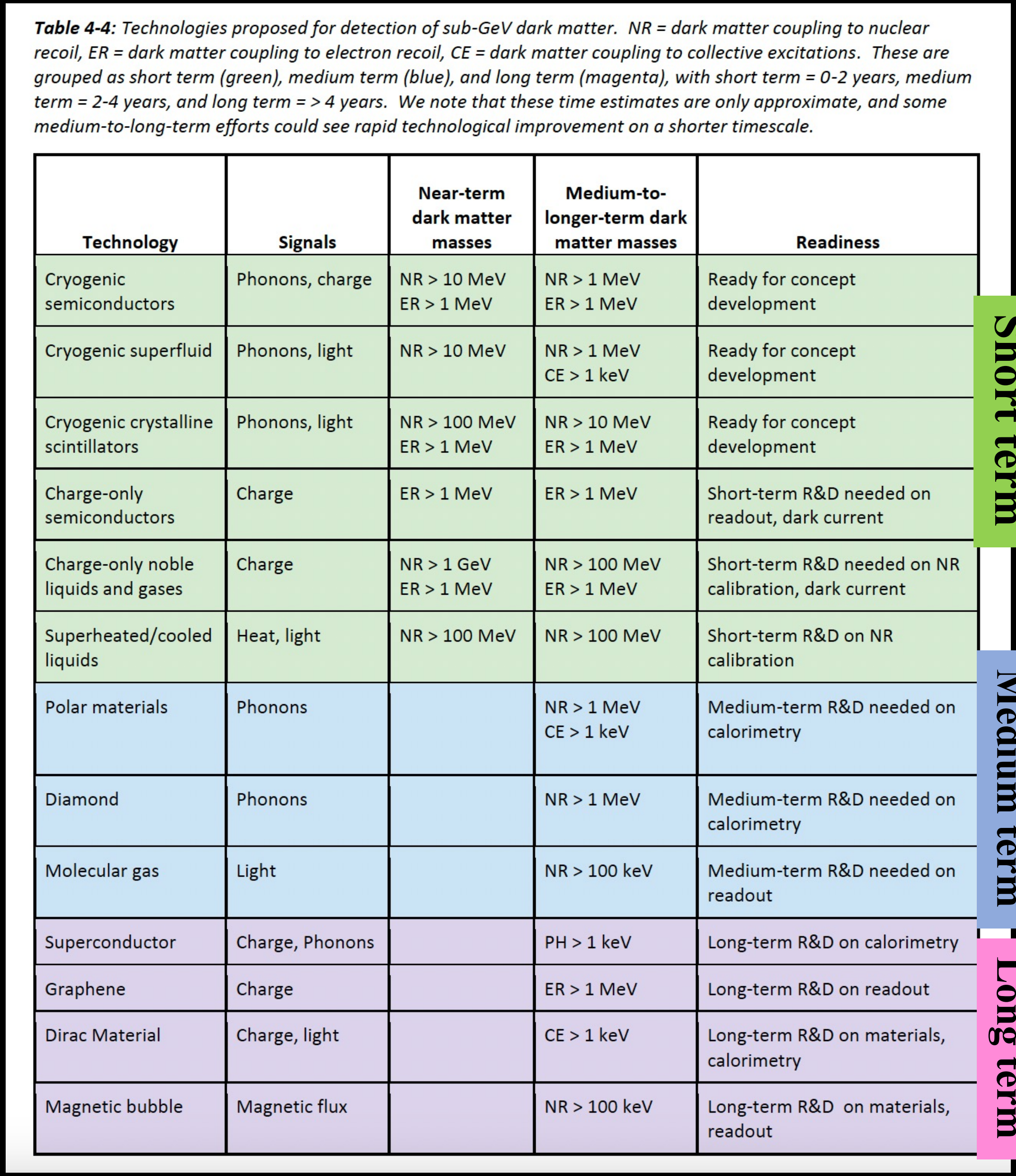


Table 4-4: *Technologies proposed for detection of sub-GeV dark matter. NR = dark matter coupling to nuclear recoil, ER = dark matter coupling to electron recoil, CE = dark matter coupling to collective excitations. These are grouped as short term (green), medium term (blue), and long term (magenta), with short term = 0-2 years, medium term = 2-4 years, and long term = > 4 years. We note that these time estimates are only approximate, and some medium-to-long-term efforts could see rapid technological improvement on a shorter timescale.*

Technology	Signals	Near-term dark matter masses	Medium-to-longer-term dark matter masses	Readiness
Cryogenic semiconductors	Phonons, charge	NR > 10 MeV ER > 1 MeV	NR > 1 MeV ER > 1 MeV	Ready for concept development
Cryogenic superfluid	Phonons, light	NR > 10 MeV	NR > 1 MeV CE > 1 keV	Ready for concept development
Cryogenic crystalline scintillators	Phonons, light	NR > 100 MeV ER > 1 MeV	NR > 10 MeV ER > 1 MeV	Ready for concept development
Charge-only semiconductors	Charge	ER > 1 MeV	ER > 1 MeV	Short-term R&D needed on readout, dark current
Charge-only noble liquids and gases	Charge	NR > 1 GeV ER > 1 MeV	NR > 100 MeV ER > 1 MeV	Short-term R&D needed on NR calibration, dark current
Superheated/cooled liquids	Heat, light	NR > 100 MeV	NR > 100 MeV	Short-term R&D on NR calibration
Polar materials	Phonons		NR > 1 MeV CE > 1 keV	Medium-term R&D needed on calorimetry
Diamond	Phonons		NR > 1 MeV	Medium-term R&D needed on calorimetry
Molecular gas	Light		NR > 100 keV	Medium-term R&D needed on readout
Superconductor	Charge, Phonons		PH > 1 keV	Long-term R&D on calorimetry
Graphene	Charge		ER > 1 MeV	Long-term R&D on readout
Dirac Material	Charge, light		CE > 1 keV	Long-term R&D on materials, calorimetry
Magnetic bubble	Magnetic flux		NR > 100 keV	Long-term R&D on materials, readout

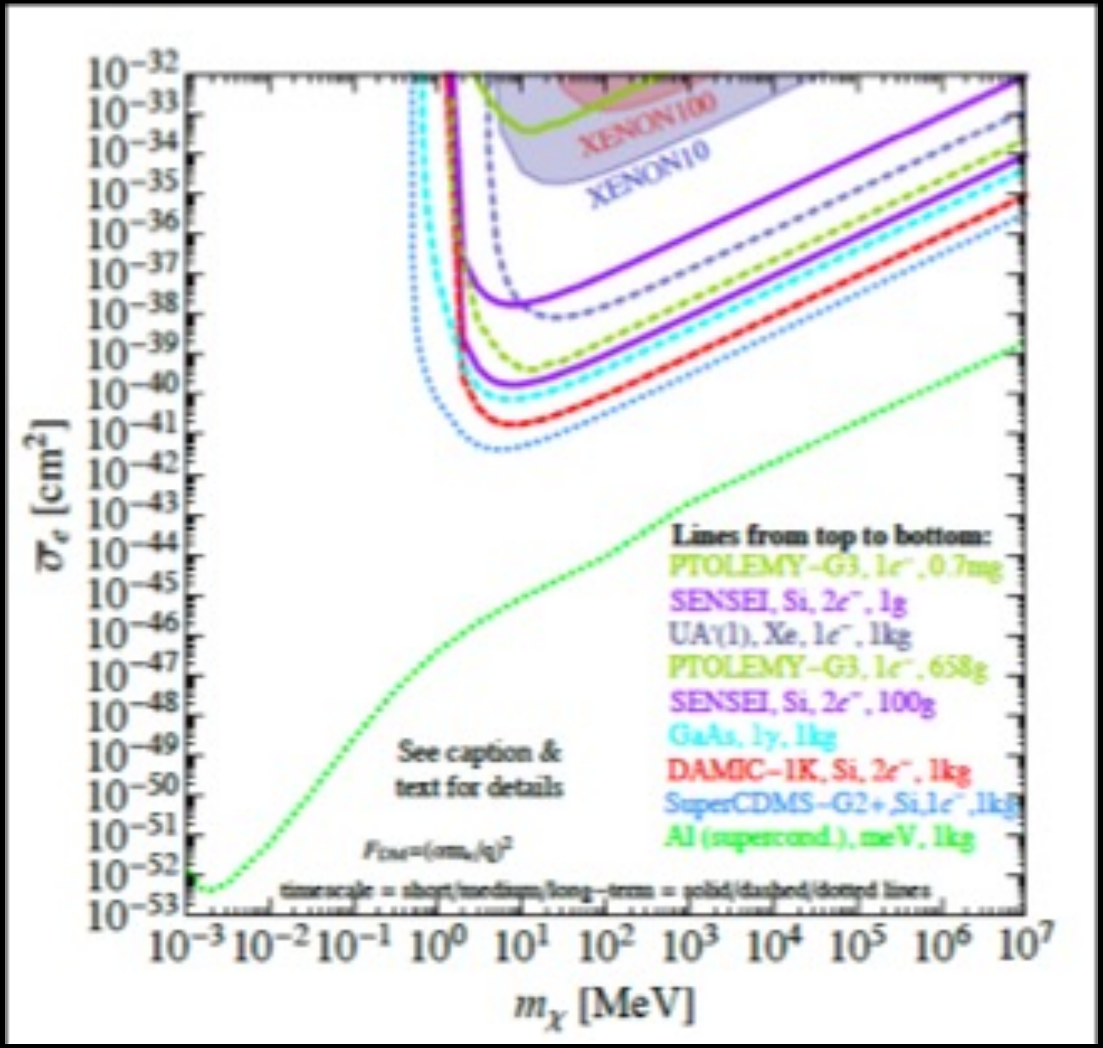
Short term

Medium term

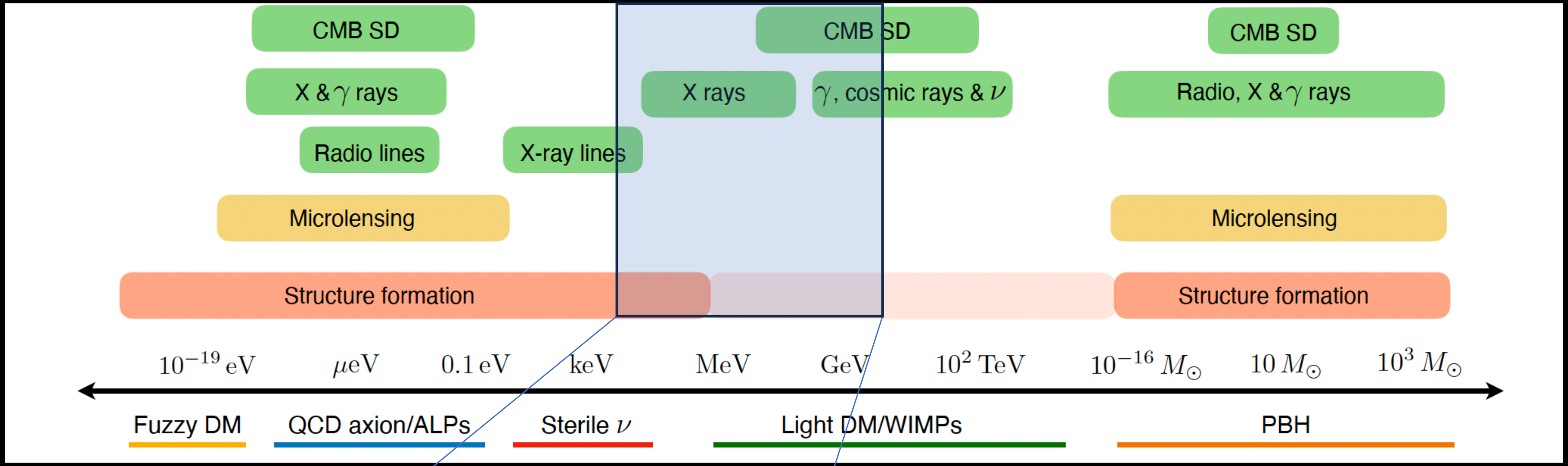
Long term

https://science.osti.gov/-
/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf

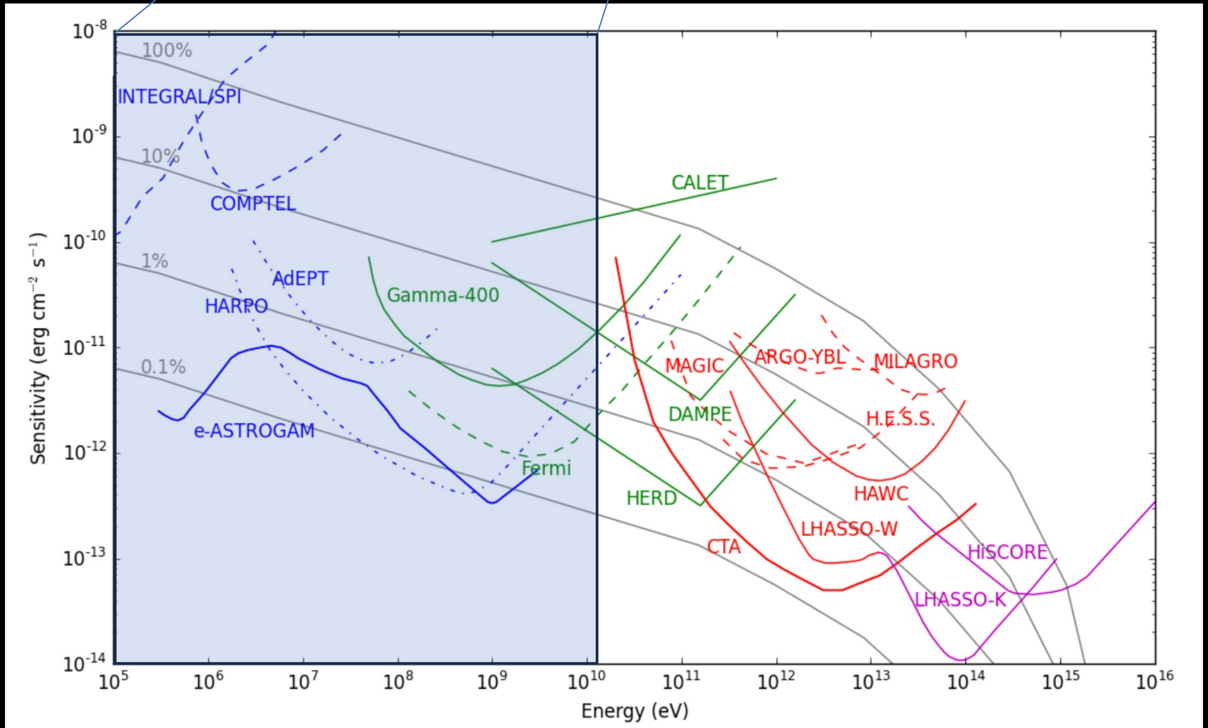
Innovative and cutting edge technologies involved



Search for light (MeV-GeV) DM with indirect detection experiments



Main experimental devices
Sensitive to DM in MeV-GeV range
Via hard x-rays or soft gamma rays signals



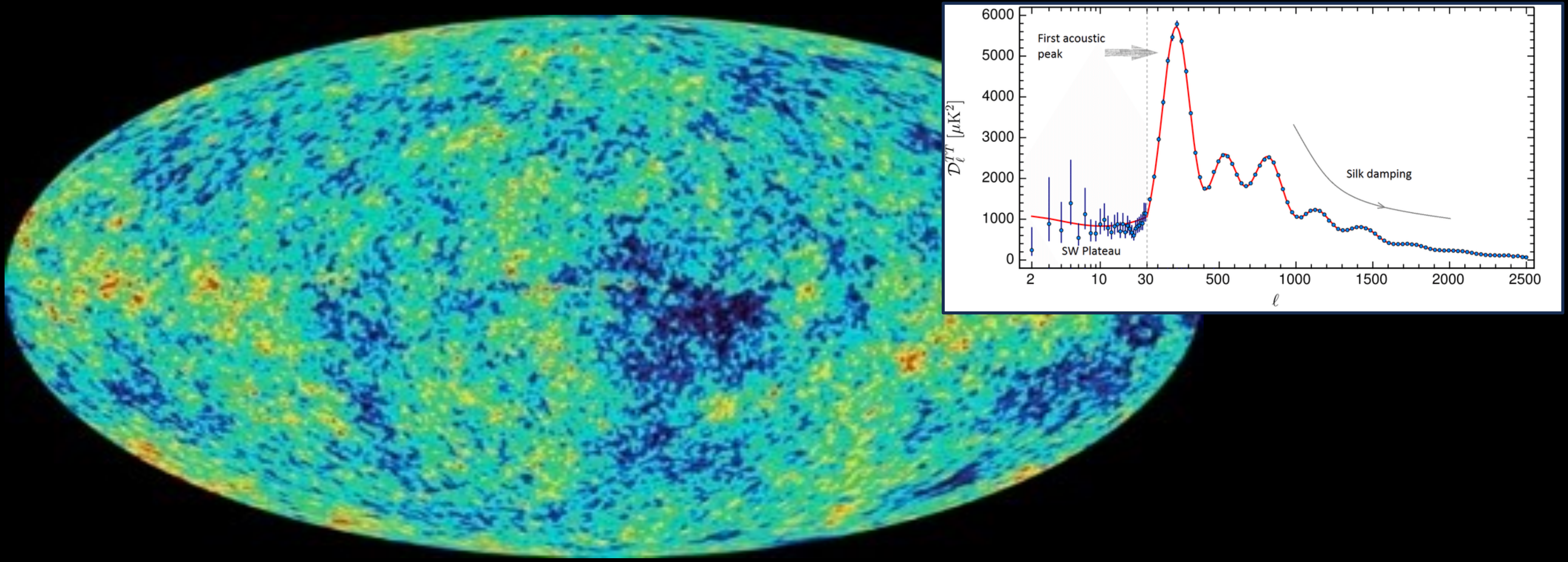
Fermi Large Area Telescope (LAT)
Lifetime: 2008 — present
Energy: 20 MeV - 300 GeV
Large FoV: 2.4 sr
Excellent angular res: 0.1 deg@10 GeV

CGRO Compton Telescope (COMPTEL)
Lifetime: 1991 — 2000
Energy: 0.8 MeV - 30 MeV
Large FoV: 1 sr
Angular res: 1 deg

INTEGRAL Spectrometer (SPI)
Lifetime: 2002 — present
Energy: 20 keV - 8 MeV
Good energy res
Angular res: 2.5 deg

Search for light DM with CMB/BBN

The Cosmic Microwave Background (CMB) from Planck satellite:



If DM annihilates during CMB era (370 000 years after Big Bang), some extra-energy is injected in the photon plasma during recombination. The CMB bounds are based on visible energy injection at T ~eV (4000 K), which re-ionizes the newly recombined hydrogen and thereby modifies the ionized fraction of the early universe.

DM at accelerators, direct detection, and in cosmology

Mediator: scalar or vector

Accelerator-based experiments

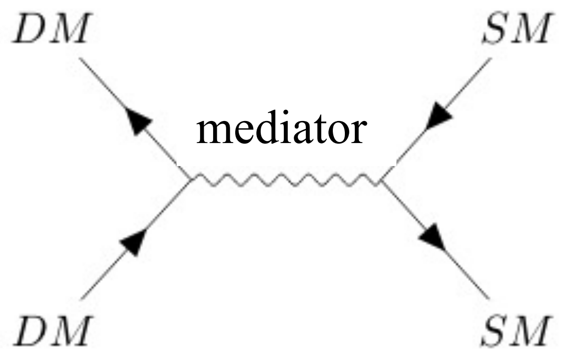
Production of DM at accelerators
(via SM (electron/proton/..) particles)

$$<\sigma\, v> = f(m_{DM}, m_{med}, g_{DM}, g_{SM})$$

DM Direct detection experiments

DM scattering with e/protons

$$\sigma = f\,'(m_{DM}, m_{med}, g_{DM}, g_{SM})$$



Astroparticle, cosmology

Direct DM annihilation
(main process to get the thermal relic abundance)

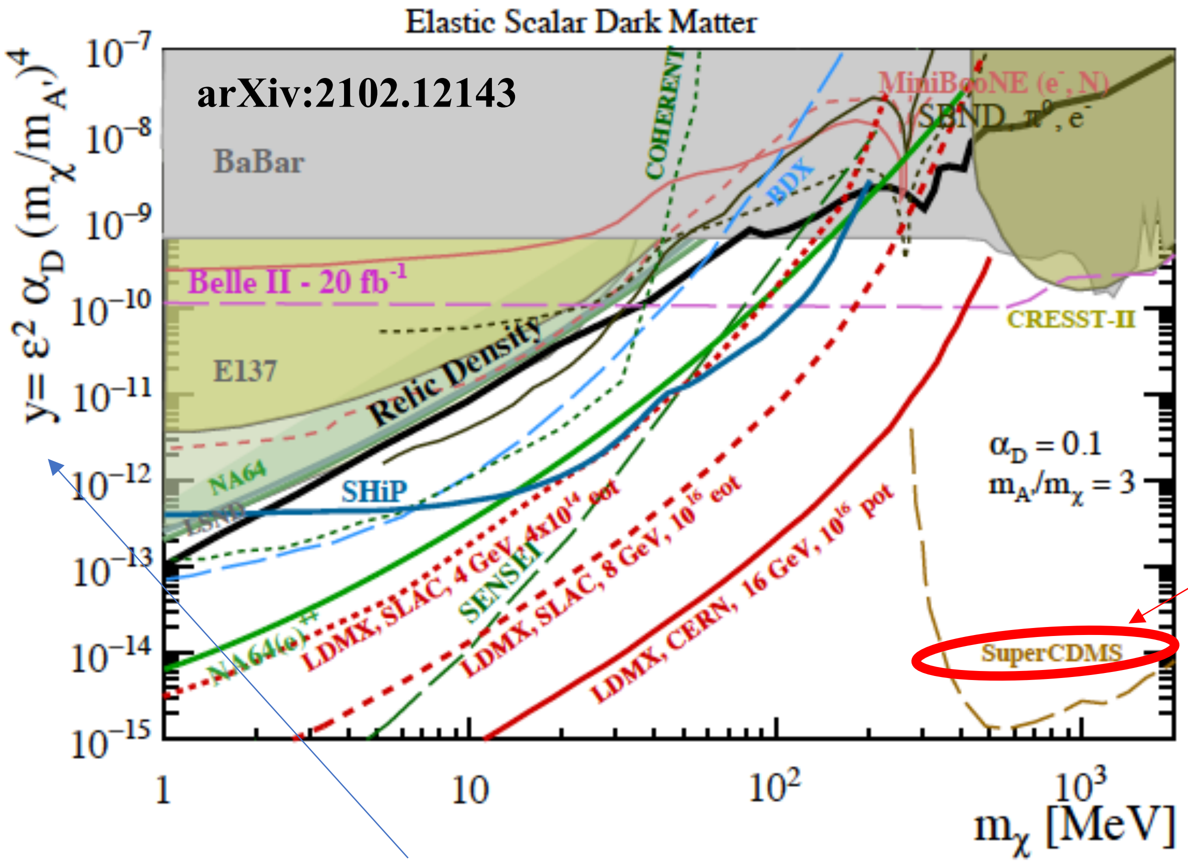
$$\Omega_{DM}h^2 \sim \frac{10^9\ \mathrm{GeV}^{-1}}{M_{pl}} \frac{1}{\langle\sigma v\rangle}$$

A theoretical framework is key to interpret results and compare them across different fields

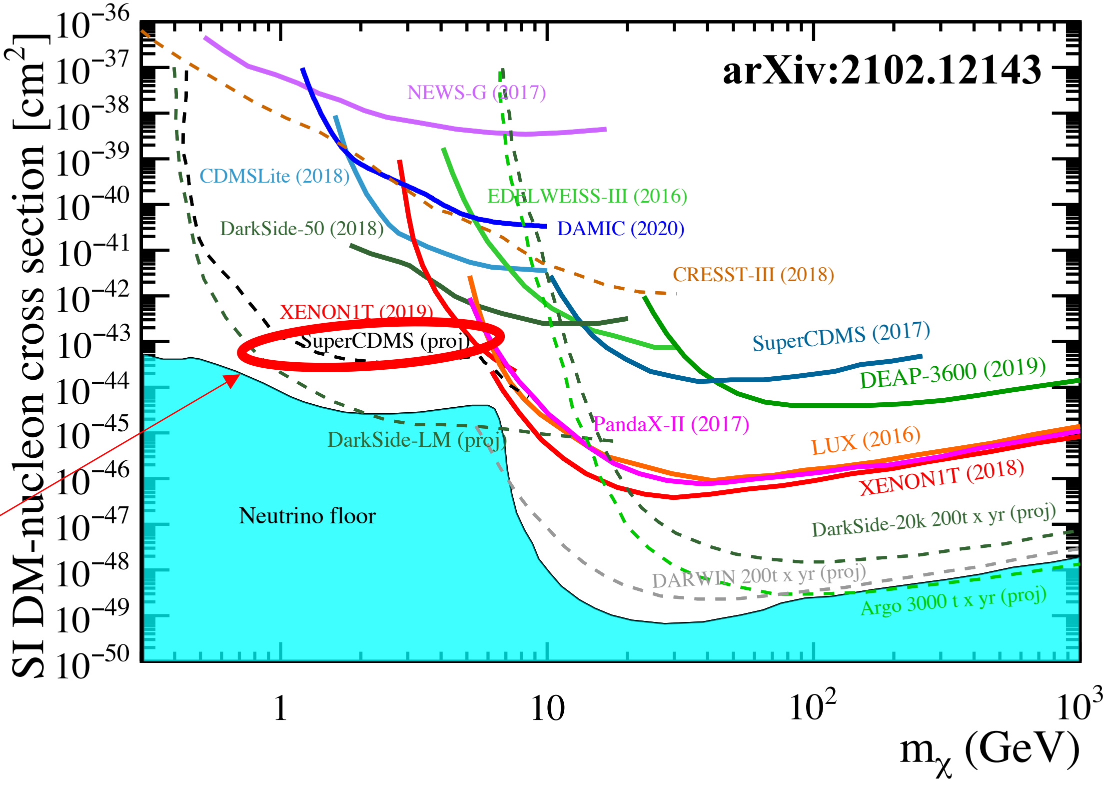
Scalar DM with Vector mediator

(a clear, predictive model to compare DD and accelerator-based experiment results).

Accelerator based:



Direct detection:



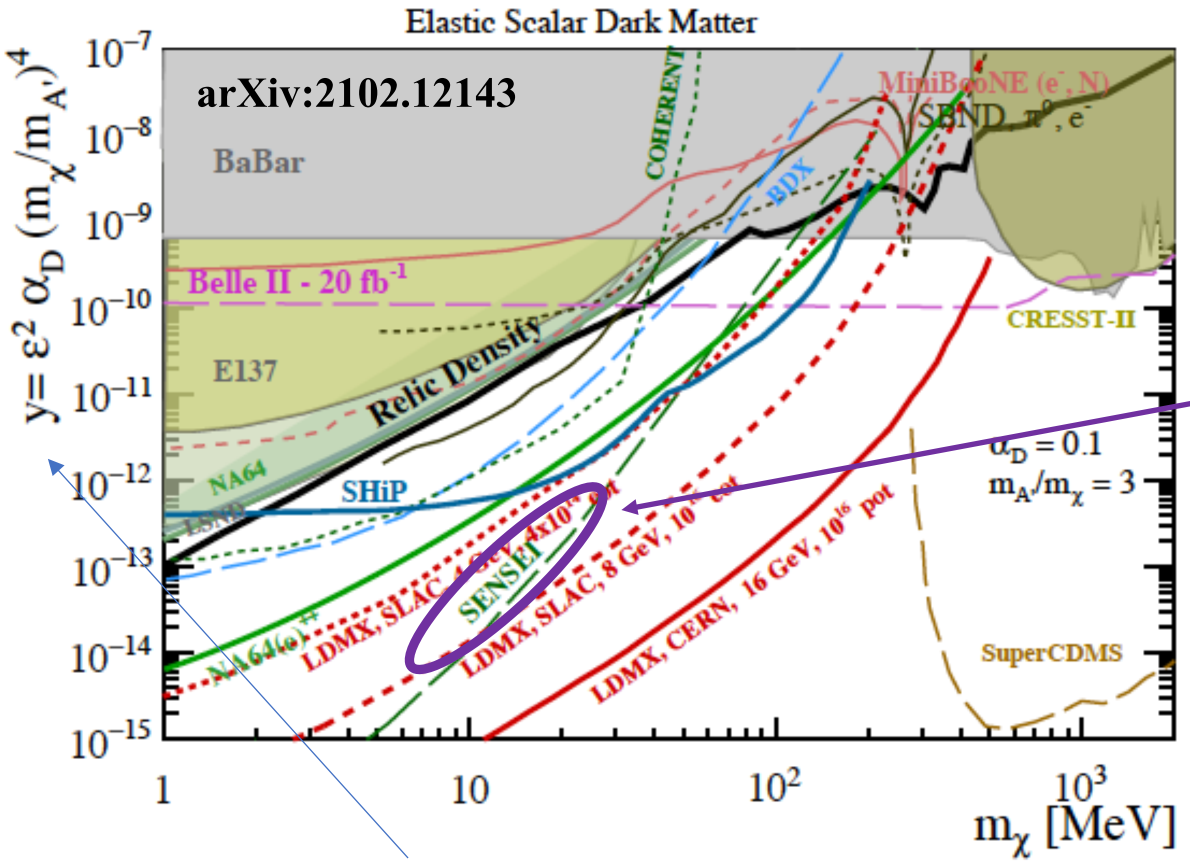
$$< \sigma v > \sim \alpha_D \varepsilon^2 \alpha \times \frac{m_{\rm DM}^2}{m_{A'}^4} \times m_{\rm DM}^2 \times \frac{1}{m_{\rm DM}^2}$$

$$\sigma(\chi f \to \chi f) \simeq \frac{16\pi\, \alpha_{\rm em}\, \epsilon^2\, \alpha_D\, \mu_{\chi f}^2}{(q^2 + m_{A'}^2)^2} \,,$$

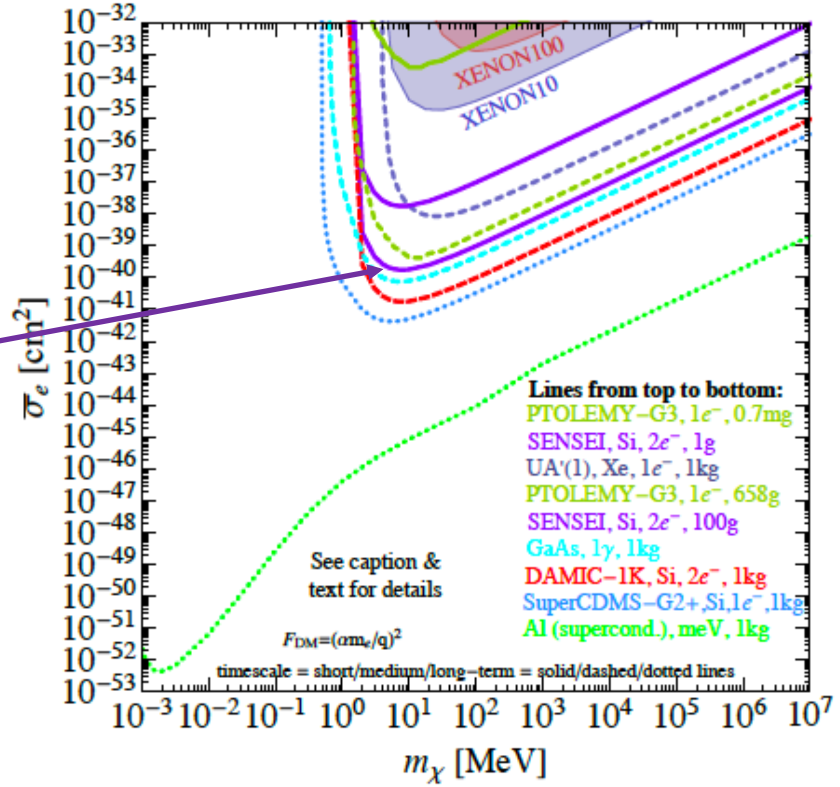
Scalar DM with Vector mediator

(a clear, predictive model to compare DD and accelerator-based experiment results).

Accelerator based:



Direct detection:

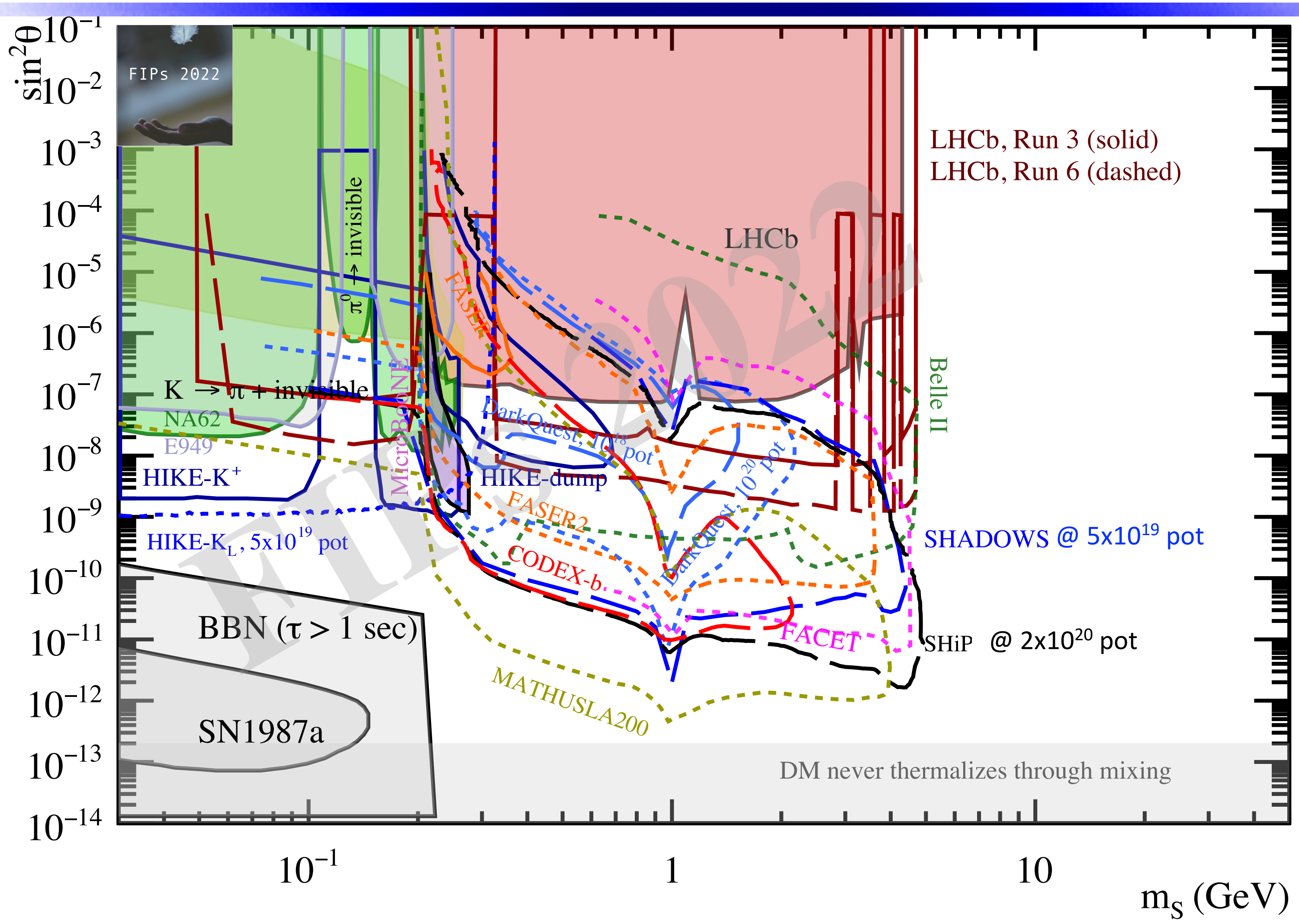


$$< \sigma v > \sim \alpha_D \varepsilon^2 \alpha \times \frac{m_{\rm DM}^2}{m_{A'}^4} \times m_{\rm DM}^2 \times \frac{1}{m_{\rm DM}^2}$$

$$\sigma(\chi f \to \chi f) \simeq \frac{16\pi\, \alpha_{\rm em}\, \epsilon^2\, \alpha_D\, \mu_{\chi f}^2}{(q^2 + m_{A'}^2)^2} \,,$$

Scalar mediator going to visible final states

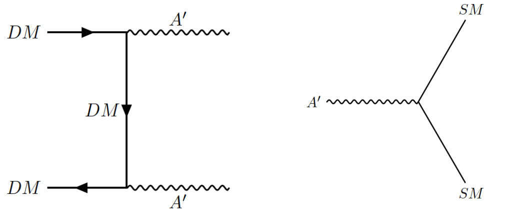
Experimental bounds and projections for accelerator-based experiments:



FIPs 2022 Report, arXiv:2305.01715

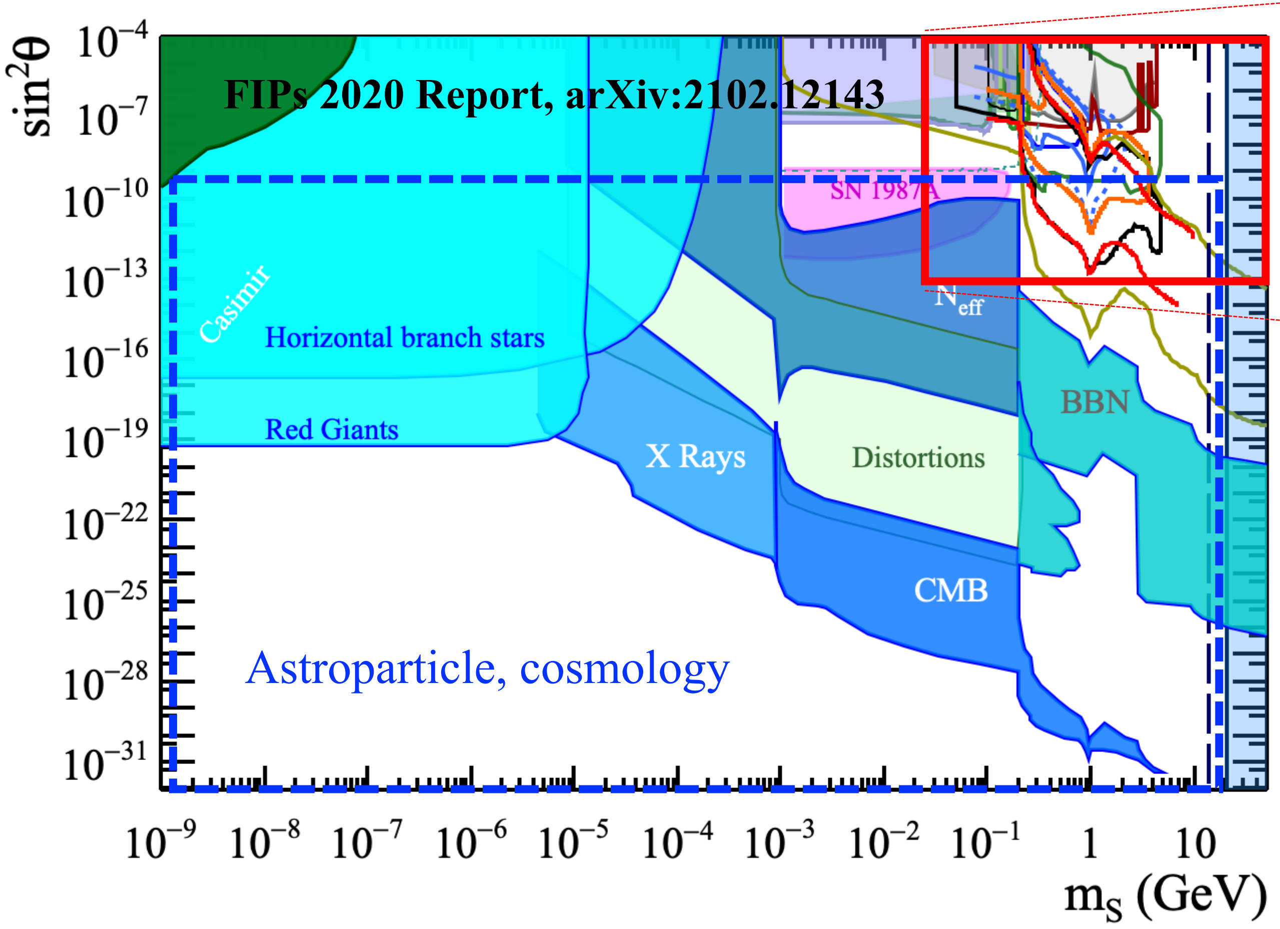
$M_{med} < 2\ m_{DM}$

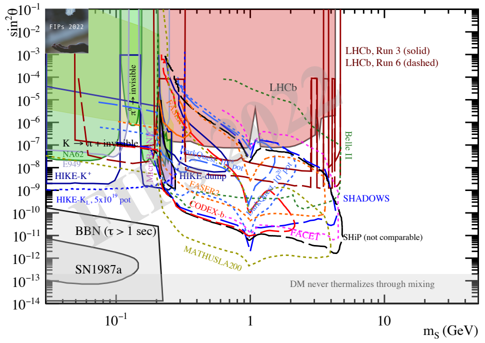
Hidden or secluded annihilation



A light scalar as a non-thermal bosonic DM condensate

a simple but UV complete model, fully compliant with astroparticle & cosmology



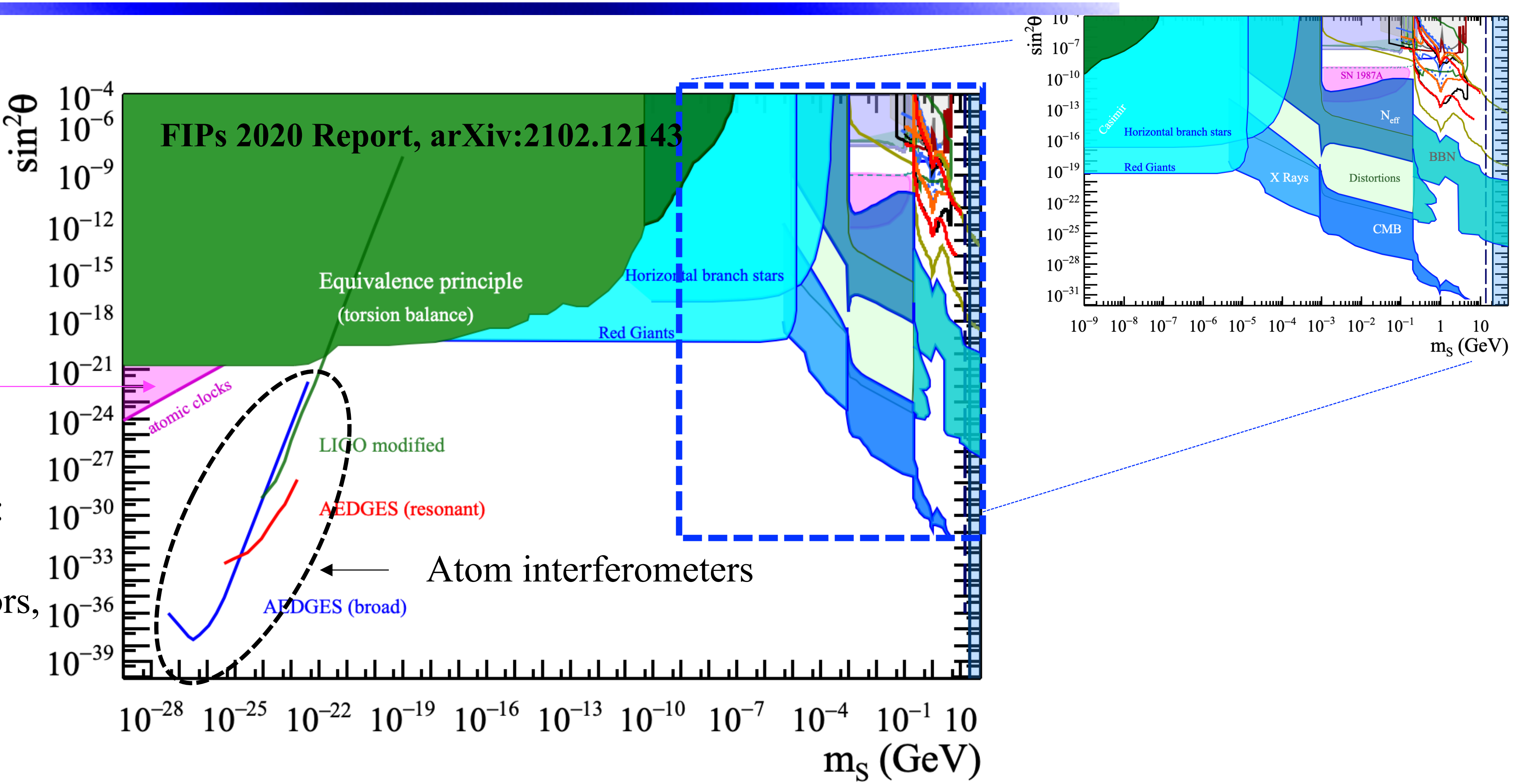


Accelerator-based experiments

Astroparticle, cosmology go deep inside in the “natural” region of parameter space covering 10 orders of magnitude in mass and 20 in coupling.

A light scalar as a non-thermal bosonic DM condensate

a simple but UV complete model, fully compliant with astroparticle & cosmology



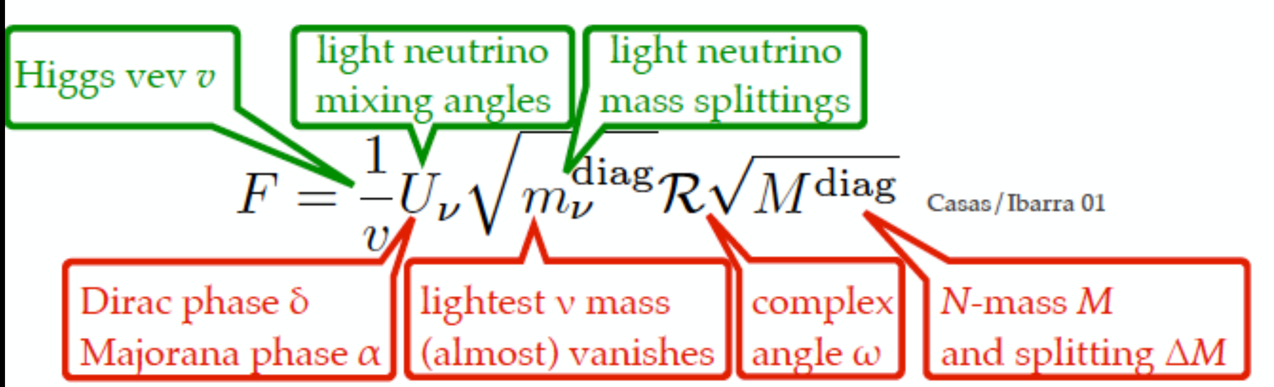
Atomic clocks

Atom interferometers

Ultra-light DM searches with:
atom interferometry,
atomic clocks, quantum sensors,
emerging technologies,…

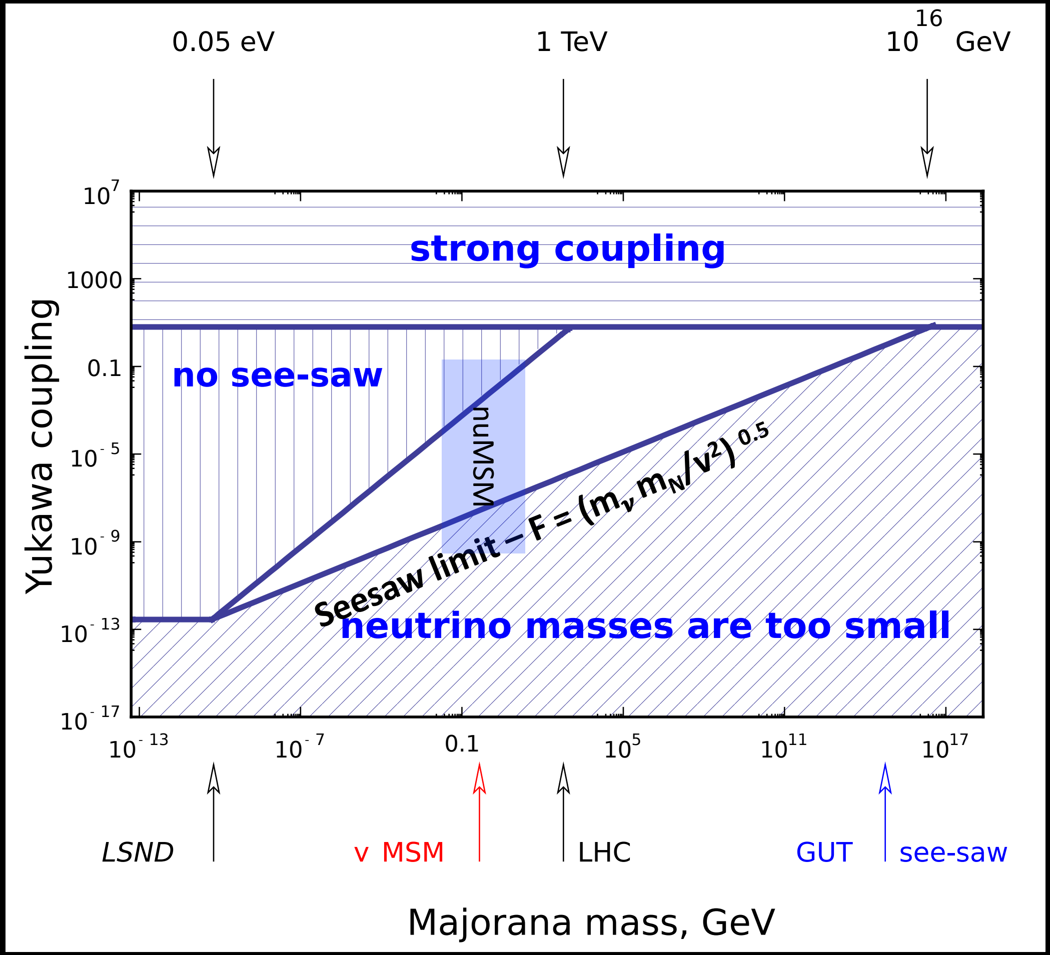
Clues of New Physics: origin of the neutrino masses and oscillations

Close connection with the physics of active neutrinos



$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\mathrm{diag}}} \mathcal{R} \sqrt{M^{\mathrm{diag}}}$$

Casas/Ibarra 01



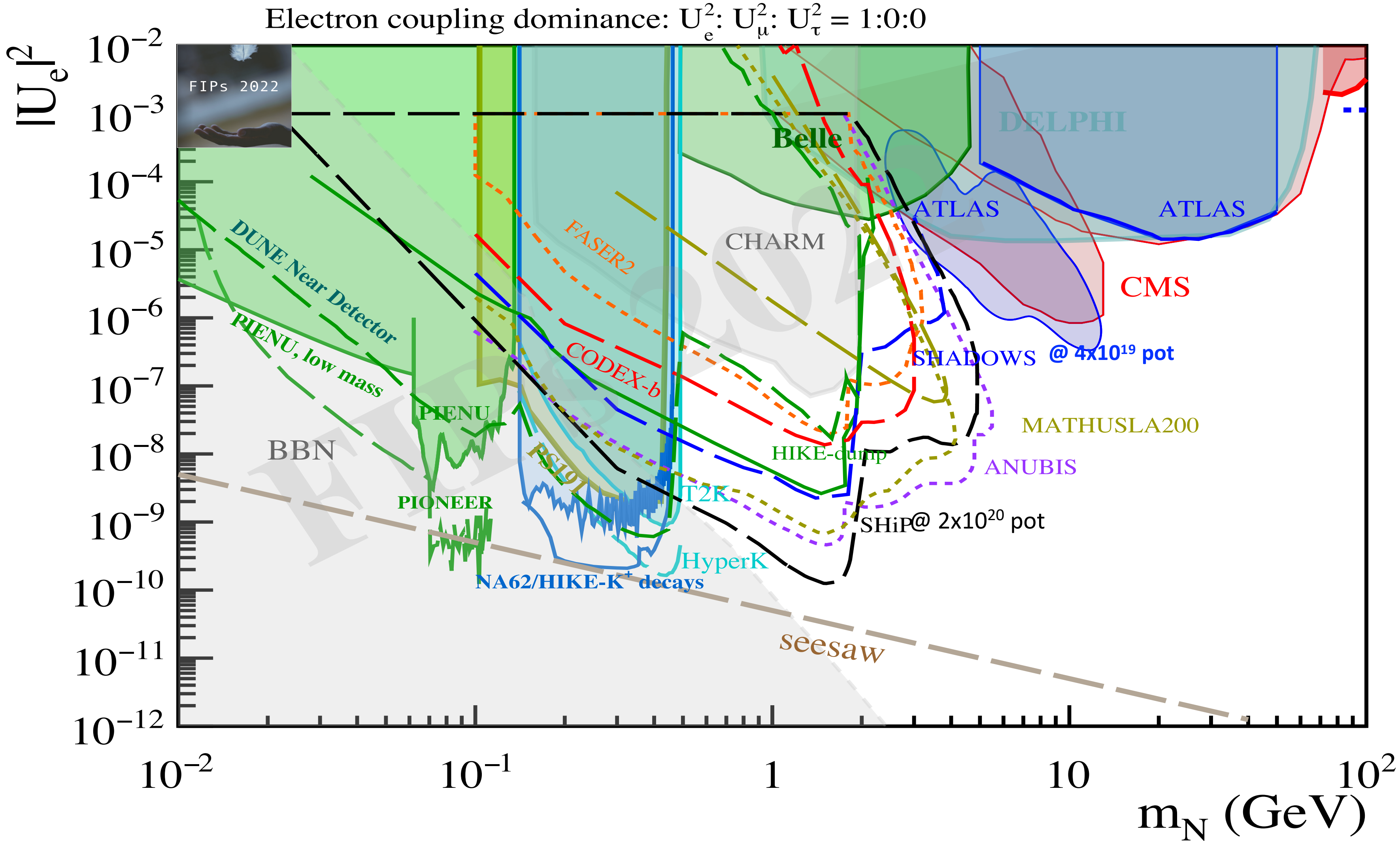
In case of one generation the seesaw formula holds:

$U^2 = v^2F^2/m_N^2$

For m_N= 2 GeV , $U^2 \sim 10^{-8}$

→ Yukawa coupling ~ 10^{-6} (like the electron…)

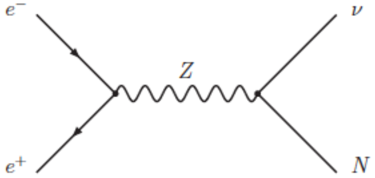
HNL searches: electron coupling



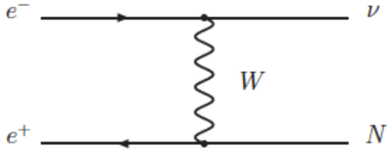
Fermion Portal: Heavy Neutral Leptons below/around EW scale

Prospects for FCC-ee : combination of data at the Z-pole (110 ab^{-1}), 2 m_W (7.5 ab^{-1}) and 240 GeV (5 ab^{-1}).

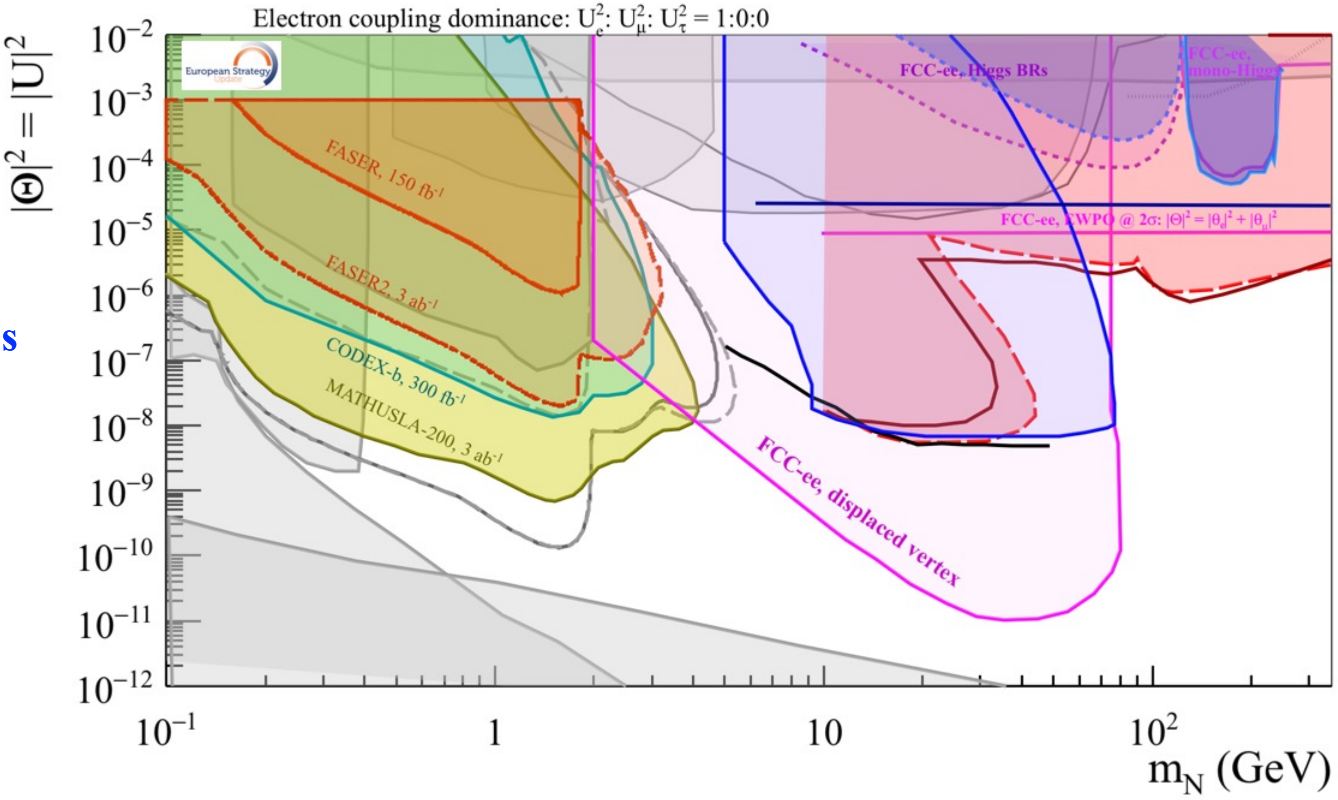
Production mechanisms at $e^+ e^-$ colliders:



production channel: $\mathbf{Z_s}$



production channel: $\mathbf{W_t}$

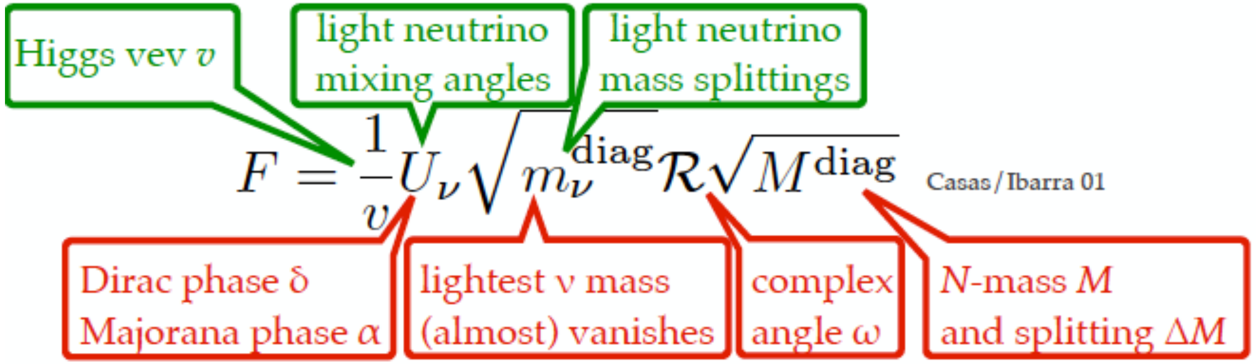


Source:
FCC report,
CERN-ACC-2018-0057
(based on Antusch et al.,
arXiv:1612.02728)

FCC-ee is highly competitive when running at the Z-pole

HNL-active neutrino mixing angles and active neutrino physics

The present status of neutrino oscillation experiments allows to do some quantitative analysis.
One can use the statistical information about the light neutrino parameters gathered
in various neutrino oscillation experiments to obtain a **probability distribution for the U^2_a/U^2**.



$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\mathrm{diag}}}\, \mathcal{R} \sqrt{M^{\mathrm{diag}}}$$

Casas/Ibarra 01

Higgs vev v

light neutrino mixing angles

light neutrino mass splittings

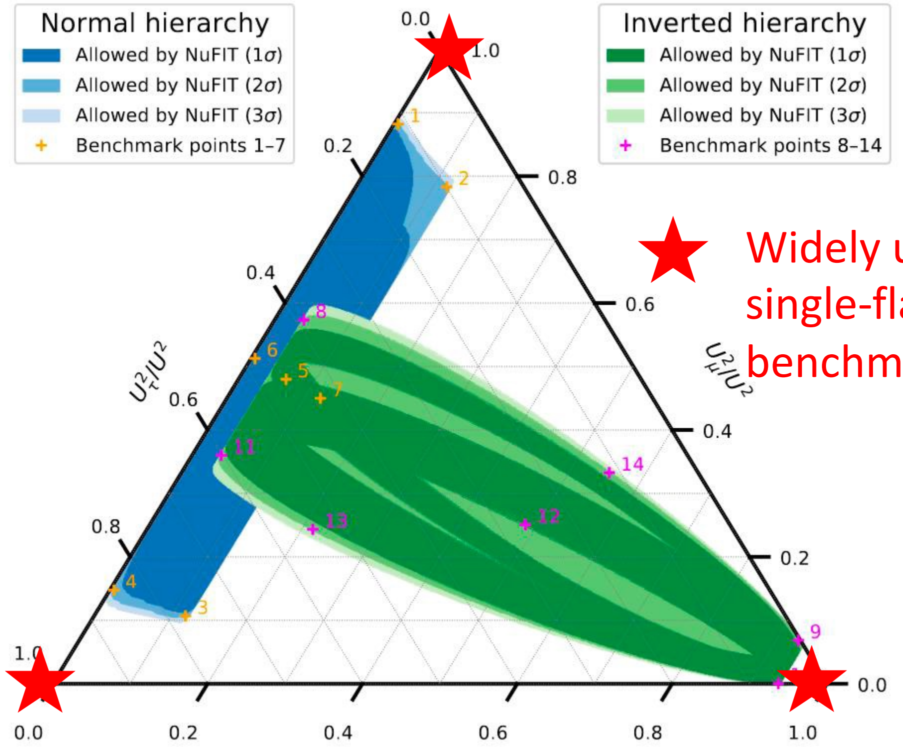
Dirac phase δ
Majorana phase α

lightest ν mass (almost) vanishes

complex angle ω

N-mass M and splitting ΔM

In case of one generation the seesaw formula holds:
$U^2 = v^2 F^2 / m_N^2$



Widely used single-flavor benchmark

2 RHN coupled to active neutrinos

We cannot know absolute values of couplings to the three active neutrino generations
but we can constrain the ratios.

Questions to drive the discussion during the parallel session tomorrow:

- How can we search for feebly interacting particles in colliders, fixed target projects, direct and indirect detection dark-matter experiments, including astroparticle and cosmology?
- Is there a way to think about these areas cohesively ?
- Is there a way we can put results coming from different areas onto the same plots in order to highlight motivated but still uncharted parameter regions and guiding new experimental proposals?
- Which is the status of these searches in the international landscape and which are the prospects in Europe and US (including the recent US P5 recommendations)?