Feebly Interacting Particles (FIPs):

Topical Session @ CHIPP Roadmap Workshop

Questions to drive the discussion:

- 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 areasonto 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)?

The 2020 ESPP and 2023 US P5 Recommendations highlight the importance to support a portfolio of small-medium size experiments, to balance the large projects in the search for answers to open questions in particle physics:

- Most of these small/medium size projects are dedicated to FIPs or Dark Sector.

- The community is very lively and a plethora of new initiatives is emerging
  (see for example FIPs 2022 Report, arXiv:2305.01715, EPJC 83 (2023) 1122)

- In the following I will concentrate to the MeV-GeV range, accessible at accelerator & direct/indirect detection experiments. (The sub-eV range would require a stand-alone discussion)

Outline of the items open for discussion

1. Dark Matter in the MeV-GeV range:
    - why in this range
    - current theoretical-phenomenological approach
    - current experimental results
    - future prospects

2. Heavy Neutral Leptons below EW scale
    - why in this range
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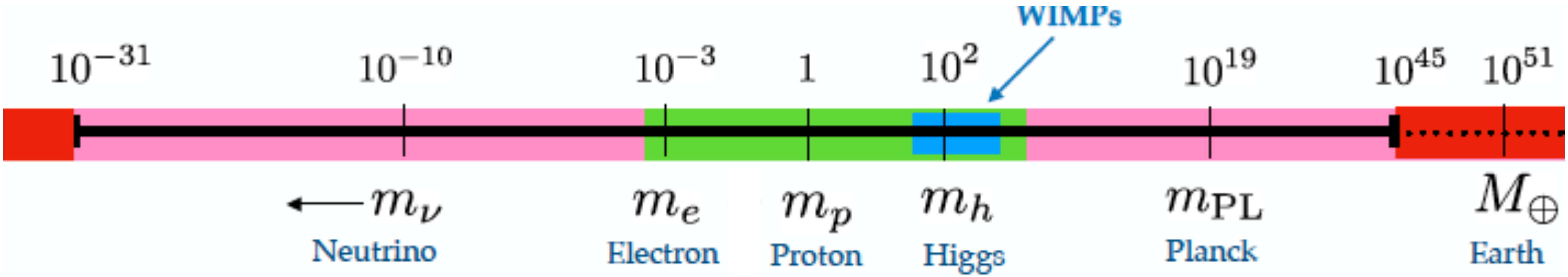
Dark Matter: a huge range of possible masses

80 orders of magnitude allowed for DM ….



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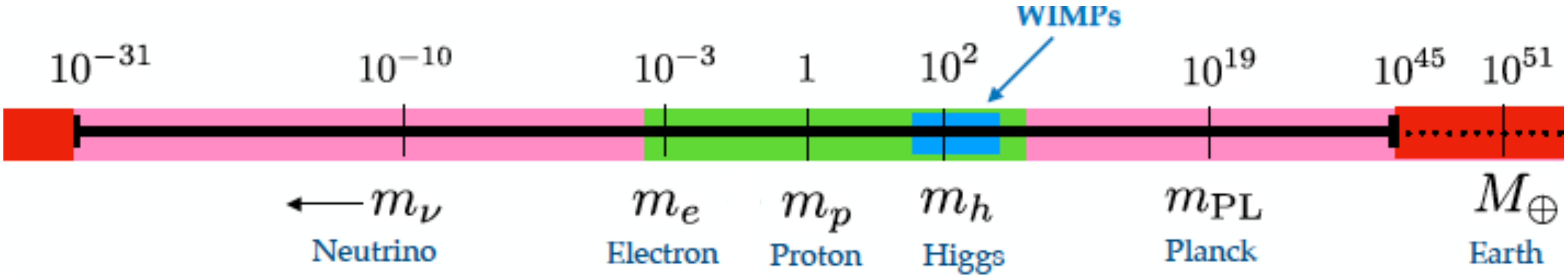
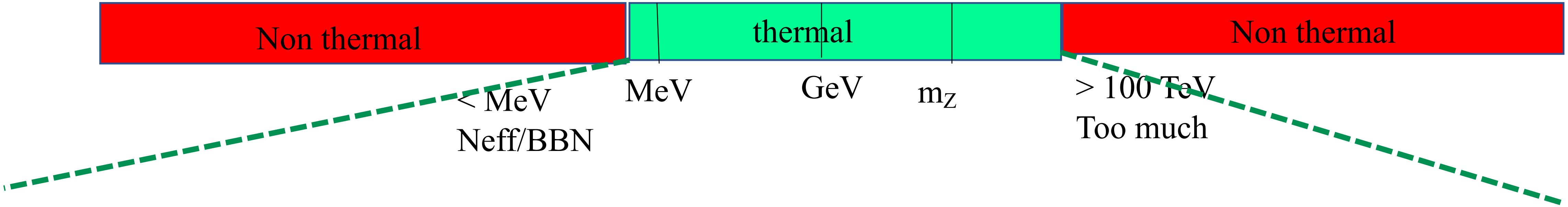




Non thermal

thermal

Non thermal

< MeV
Neff/BBN

MeV

GeV

m_Z

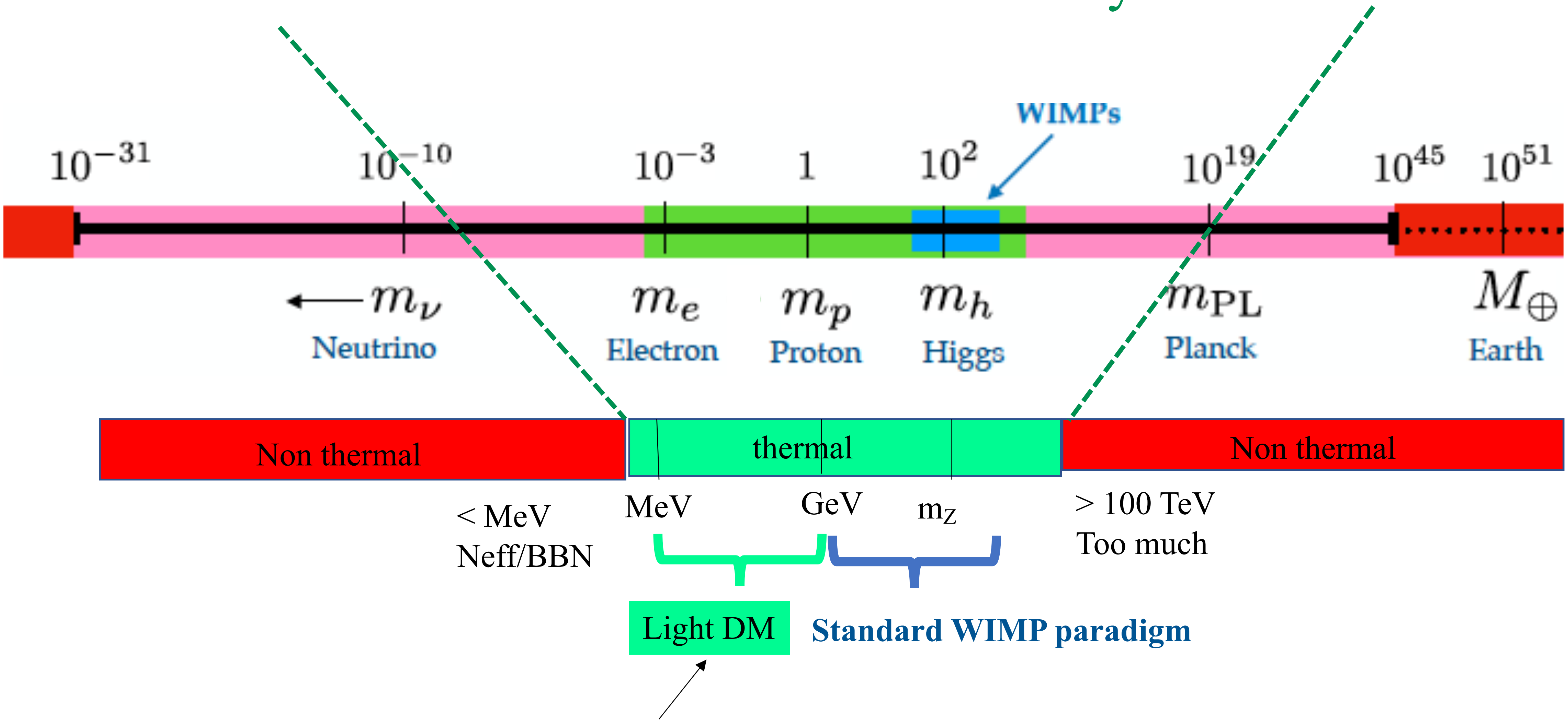
> 100 TeV
Too much

…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.

DM as a thermal relic from the Early Universe



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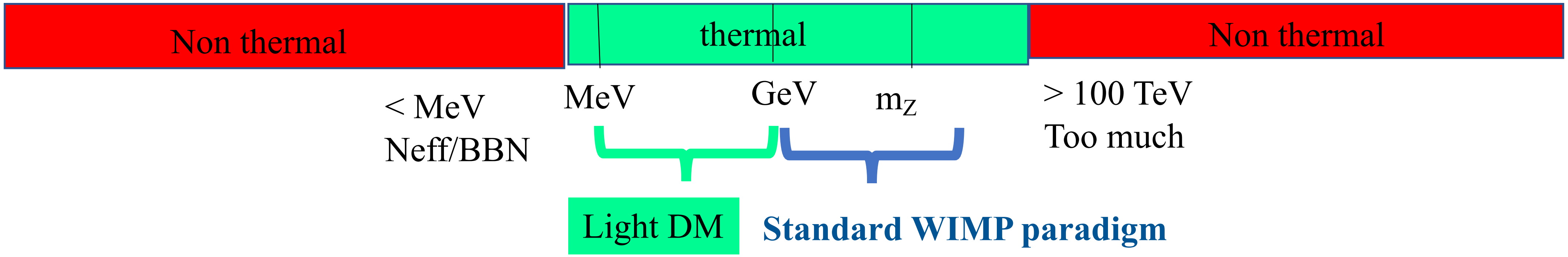
Light DM

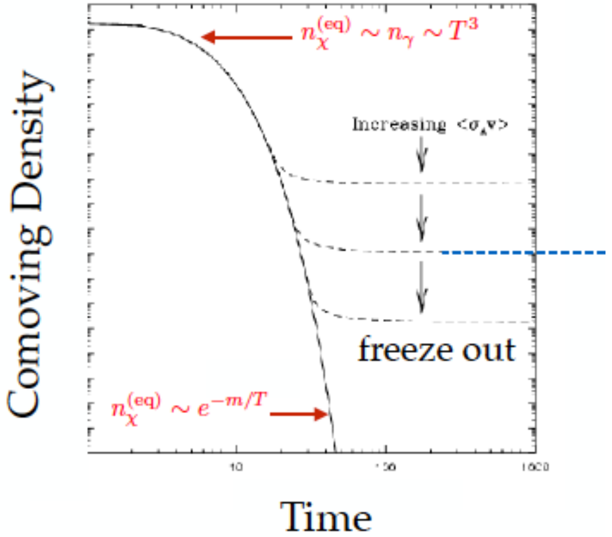
Standard WIMP paradigm

This is the range of familiar matter (electron, proton,….)

The beauty of the equilibrium



1) <u>Initial conditions known</u> (and independent of unknown high energy scales):



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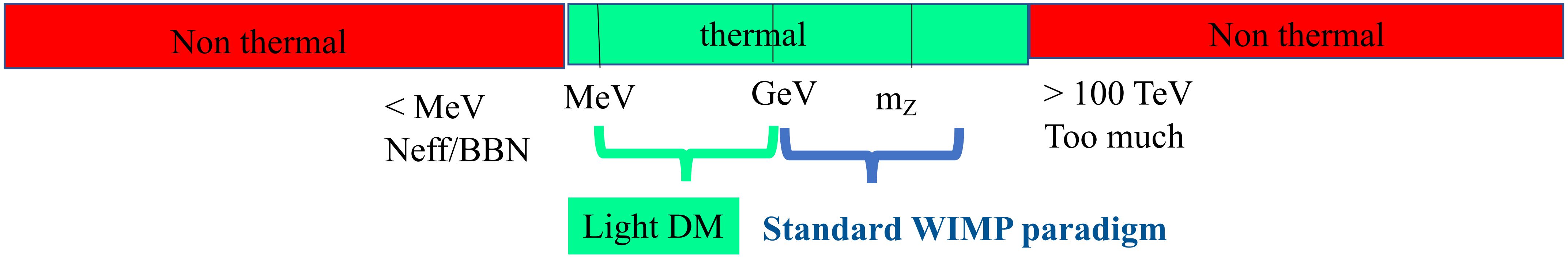

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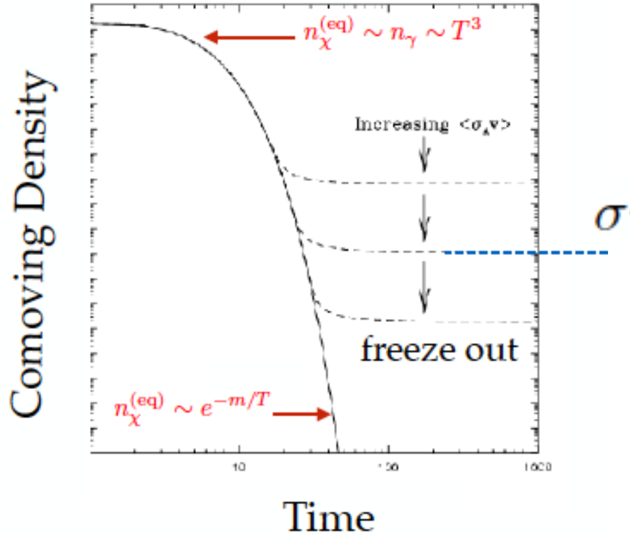
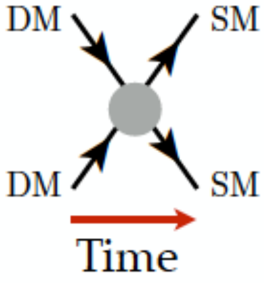
Light DM

Standard WIMP paradigm

2) Clear thermal relic abundance to target: Mass and coupling set the abundance



$$\sigma v \sim 2 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$



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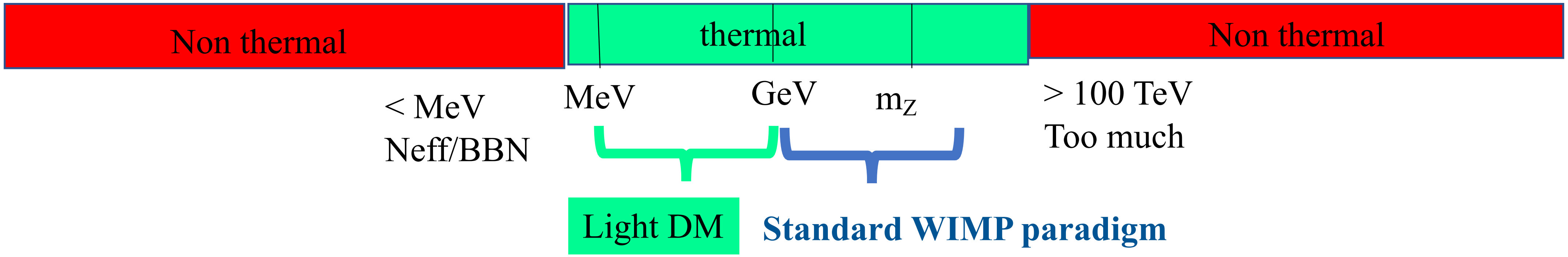

Non thermal | thermal | Non thermal

< MeV
Neff/BBN

MeV

GeV

m_Z

> 100 TeV
Too much

Light DM

Standard WIMP paradigm

3) Equilibrium is generic and easy to achieve:

Assume a 4-fermion effective interactions

$$\mathcal{L}_{\rm eff} = \frac{g^2}{\Lambda^2}(\bar{\chi}\gamma^\mu\chi)(\bar{f}\gamma_\mu f)$$

Compare interaction rate to Hubble expansion

$$H \sim n\sigma v \qquad \Longrightarrow \qquad \frac{T^2}{m_{Pl}} \sim \frac{g^2 T^5}{\Lambda^4}\Big|_{T=m_\chi}$$

Equilibrium is reached if:

$$\boxed{g \gtrsim 10^{-8}\left(\frac{\Lambda}{10\,\mathrm{GeV}}\right)^2\left(\frac{\mathrm{GeV}}{m_\chi}\right)^{3/2}}$$

For Λ, $m_\chi \sim$ GeV
we need very feeble couplings….

Dark Matter as a thermal relic: What do we know?

1) If DM was in equilibrium at some point, where did its density/entropy go?

1. Nowhere

Today we know that:

$\rho_\chi \sim 10^3$ eV cm^{-3}

$n_\gamma \sim 10^2$ cm^{-3}

Equilibrium predicts DM mass

$m_\chi = \rho_\chi / n_\gamma \sim 10$ eV

Too hot for large scale structure

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Too hot for large scale structure

2. Stable dark states

↙ ↘

Heavy

Too much stuff

$\sum \Omega_{\rm dark} > \Omega_{\rm DM}$

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Too much stuff

$N_{\rm eff} > 3$ spoils

CMS/BBN/LSS

Requires non standard cosmology

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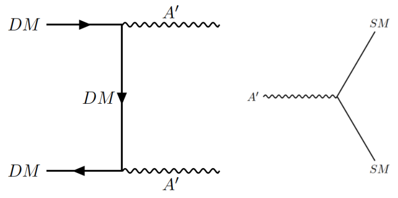
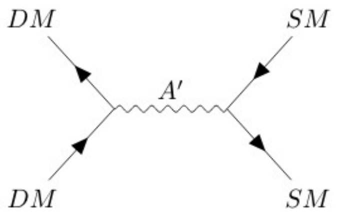
3. Visible matter

Secluded annihilation



Visibly decaying mediator

Direct annihilation



Direct connection with cosmology

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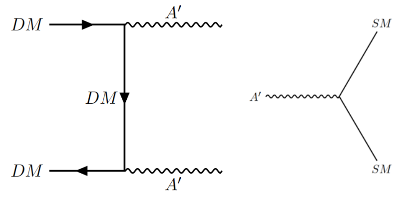

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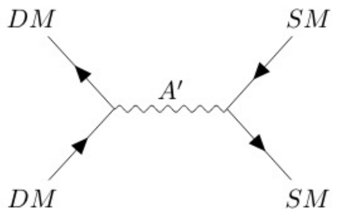


Direct connection with cosmology

Interactions with SM particles are necessary to provide mechanisms able to deplete the DM abundance in the early Universe to the levels known today in agreement with observations in standard cosmology.

→ DM has to interact to SM particles to deplete its initial abundance.

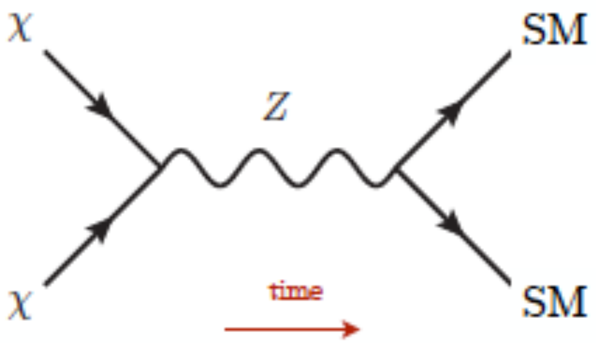
How does DM interact with SM?

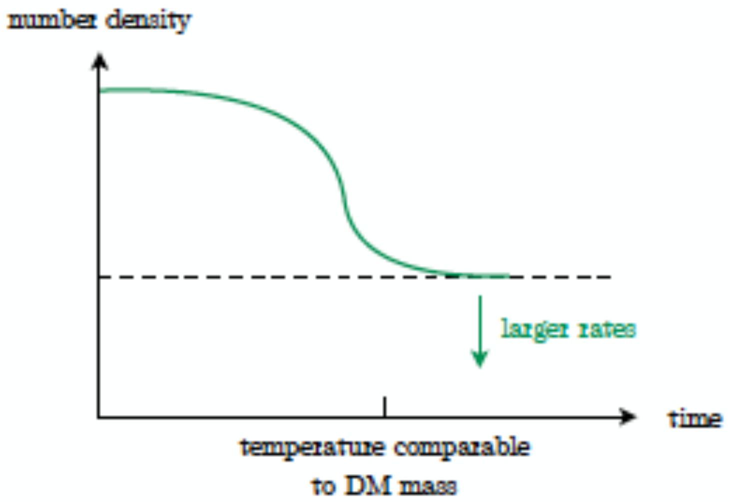
➡ 1. To reproduce DM abundance sub-GeV DM has to interact with SM world via new forces

  - to evade the Lee-Weinberg bound valid if interactions occur via weak force.

What do we know about MeV-GeV DM?

1. To reproduce DM abundance sub-GeV DM has to interact with SM world via new forces.





$$\text{(perturbative)} \qquad \sigma v \lesssim \frac{m_\chi^2}{m_Z^4} \Longrightarrow m_\chi \gtrsim \frac{m_Z^2}{(T_{\rm eq}\, m_{\rm pl})^{1/2}} \sim \text{GeV}$$

thermal WIMP interacting solely through the electroweak force must be heavier than a GeV

Lee-Weinberg bound

sub-GeV thermal DM motivates light mediators

arXiv: hep-ph/0305261
Phys.Rev.Lett. 39 (1977) 165-168

How does DM interact with SM?

1. To reproduce DM abundance sub-GeV DM has to interact with SM world via new forces

   - to evade the Lee-Weinberg bound valid if interactions occur via weak force.

➡ 2. DM & mediators must be SM-neutral

   - if the carry ew quantum numbers they would have been already observed at LEP, Tevatron and LHC

New IR degrees of freedom = light (e.g. sub-GeV) BSM states

Typical BSM model-independent approach is to include all possible BSM operators once very heavy new physics is integrated out:

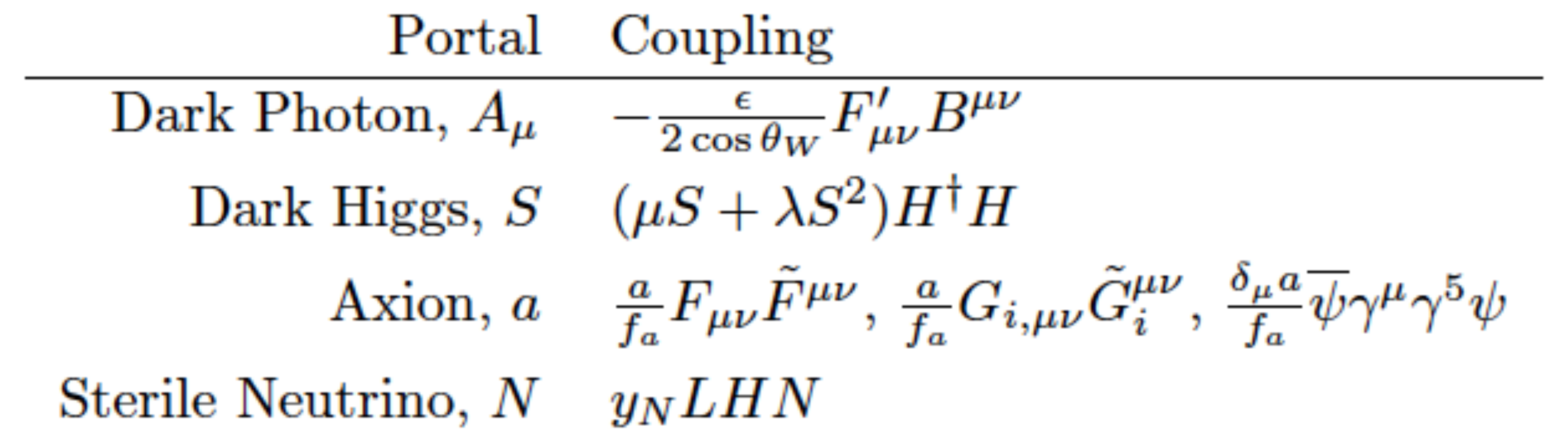
$L_{\mathrm{SM+BSM}} = - m_H^2\, (H^+_{SM} H_{SM})$ + all dim 4 terms (A_{SM}, y_{SM}, H_{SM}) +
(W.coeff. $/\mathrm{L}^2$) × Dim 6 etc (A_{SM}, y_{SM}, H_{SM}) + …
all lowest dimension portals $(A_{SM}, y_{SM}, H, A_{DS}, y_{DS}, H_{DS})$ × portal couplings
\+ dark sector interactions (A_{DS}, y_{DS}, H_{DS})

SM = Standard Model
DS – Dark Sector

Golden rule of any EFT approach: first look at low-dim operators !

The Portal Framework

Expand the SM with the minimal set of operators of lowest dimension gauge-invariant and renormalizable (all but the pseudo-scalar).
This guarantees that the theoretical structure of the SM is preserved and any NP is just a simple (natural?) extension of what we already know..



Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Dark Higgs, S	$(\mu S+\lambda S^2)H^\dagger H$
Axion, a	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\delta_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N LHN$

They are representative of broad classes of models:
Each may predict distinct texture of New Physics interactions.

DM & mediators must be SM-neutral:

sub-GeV relics must not carry electroweak quantum numbers; new electroweak states are essentially ruled out for masses below $m_Z/2$ = 45 GeV by LHC, Tevatron, and LEP measurements. This restricts hugely the number of available operators (only 3 operators at dim-4, relevant at low-energies):

Main portals to investigate for MeV-GeV DM

	Portal	Coupling
dim=4	Vector: Dark Photon, A'	$-\frac{\varepsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
	Scalar: Dark Higgs, S	$(\mu S+\lambda_{\rm HS}S^2)H^\dagger H$
	Fermion: Heavy Neutral Lepton, N	$y_N LHN$
dim=5	Pseudo-scalar: Axion, a	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$

Today we focus on the vector and scalar portals

Couplings too tiny to produce thermal DM

ALP can be SM-DM mediator (but it needs UV completion);

Mediators with spin=3/2 or higher are severely constrained by Lorentz symmetry and basic principles of quantum mechanics. Higher dimensional operators enable a variety of novel couplings but they are expected to be suppressed with respect to the four portals in the range of light (MeV-GeV) DM.

How does DM interact with SM?

1. To reproduce DM abundance sub-GeV DM has to interact with SM world via new forces

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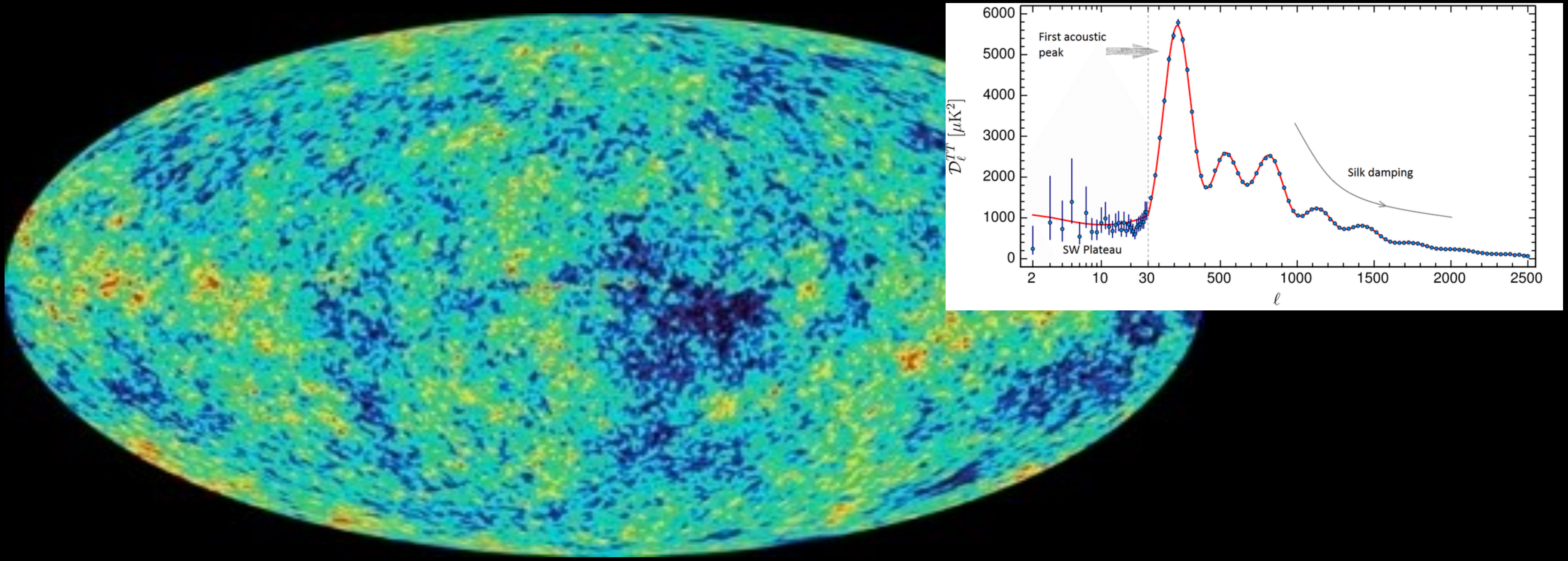
2. DM & mediators must be SM-neutral

   - if the carry ew quantum numbers they would have been already observed at LEP, Tevatron and LHC

3. For s-wave annihilating DM, measurements of the CMB rule out $m_{DM} < o(10)$ GeV

What do we know about MeV-GeV DM ?

The Cosmic Microwave Background (CMB) from Planck satellite:



electromagnetic radiation (microwave, 2.7 K) , a remnant from an early stage of the universe, dating of the epoch of recombination (370 000 years after the Big Bang, T~4000 K ~ eV). In this period the universe is expanded (and cooled down) enough that nuclei & electrons can form atoms. The radiation then can travel freely without interacting with electrical charged particles.

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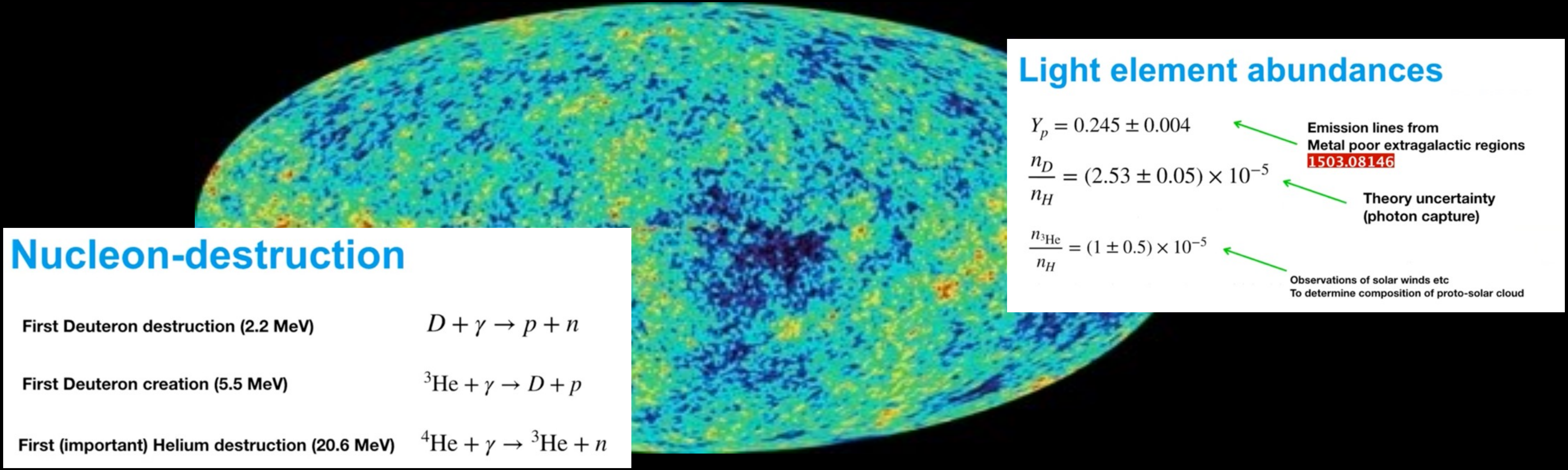


Light element abundances

$Y_p = 0.245 \pm 0.004$ ← Emission lines from Metal poor extragalactic regions 1503.08146

$\frac{n_D}{n_H} = (2.53 \pm 0.05) \times 10^{-5}$ ← Theory uncertainty (photon capture)

$\frac{n_{^3\mathrm{He}}}{n_H} = (1 \pm 0.5) \times 10^{-5}$ ← Observations of solar winds etc To determine composition of proto-solar cloud

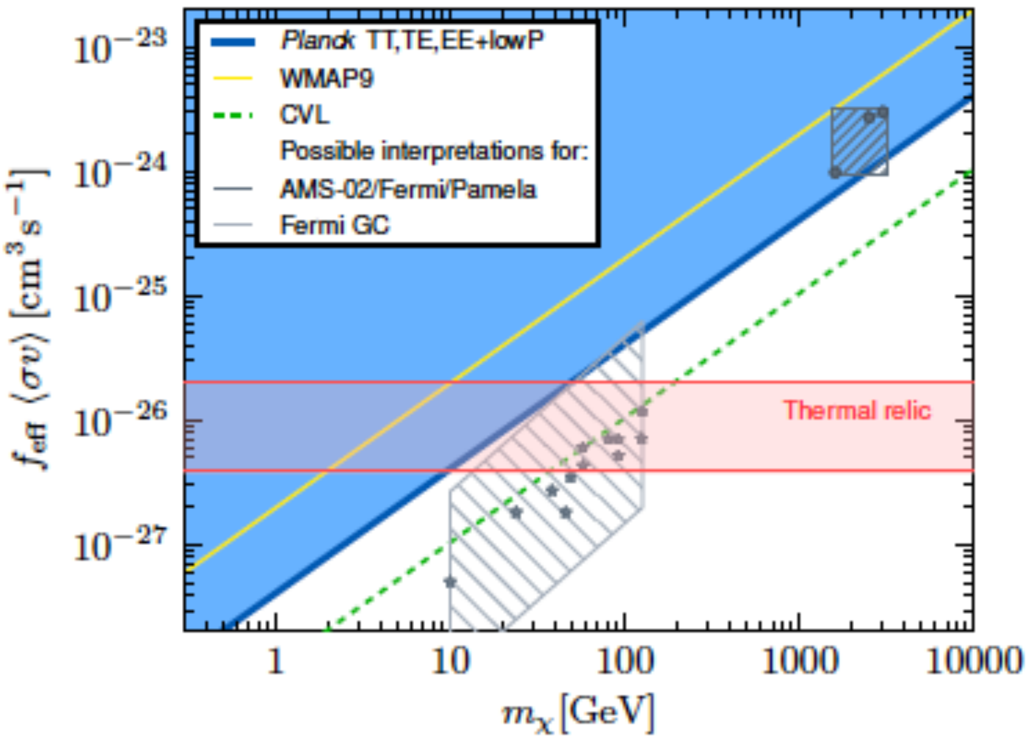
Nucleon-destruction

First Deuteron destruction (2.2 MeV)	$D + \gamma \to p + n$
First Deuteron creation (5.5 MeV)	$^3\mathrm{He} + \gamma \to D + p$
First (important) Helium destruction (20.6 MeV)	$^4\mathrm{He} + \gamma \to {}^3\mathrm{He} + n$

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

What do we know about MeV-GeV DM ?

If DM annihilates during CMB era, strong constraints exist on the energy injected in the photon plasma during recombination. The CMB bounds are based on visible energy injection at T ~eV, which re-ionizes the newly recombined hydrogen and thereby modifies the ionized fraction of the early universe.



DM below 10 GeV annihilating in s-wave is excluded by CMB

What do we know about MeV-GeV DM ?

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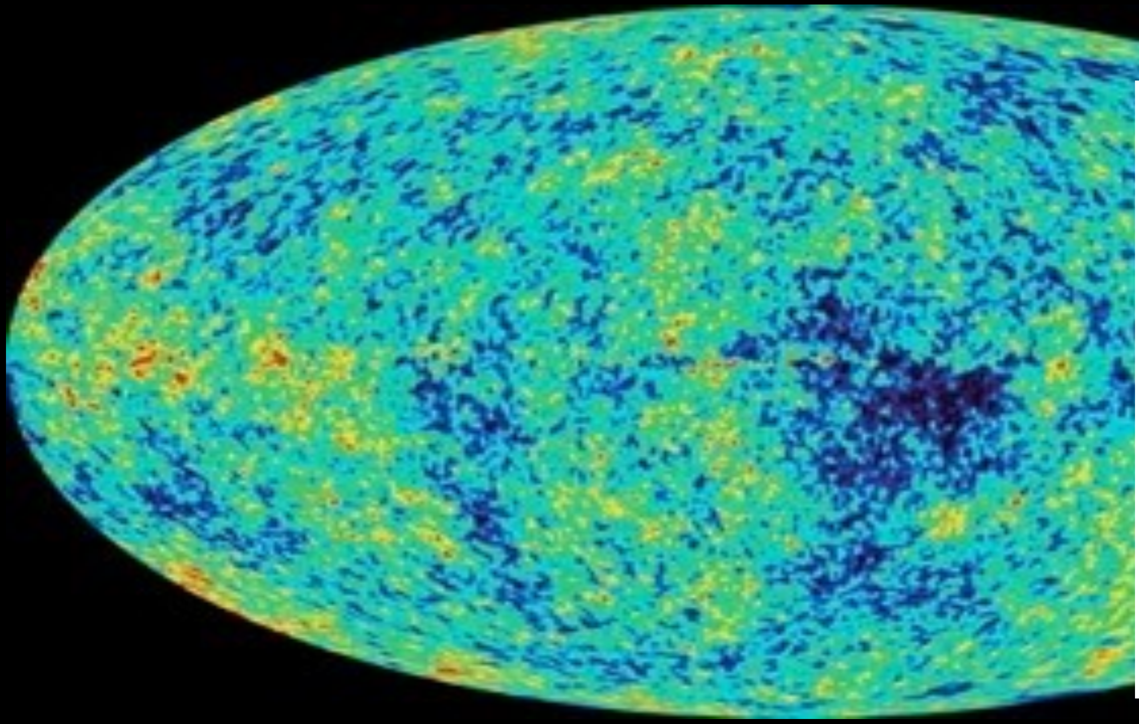
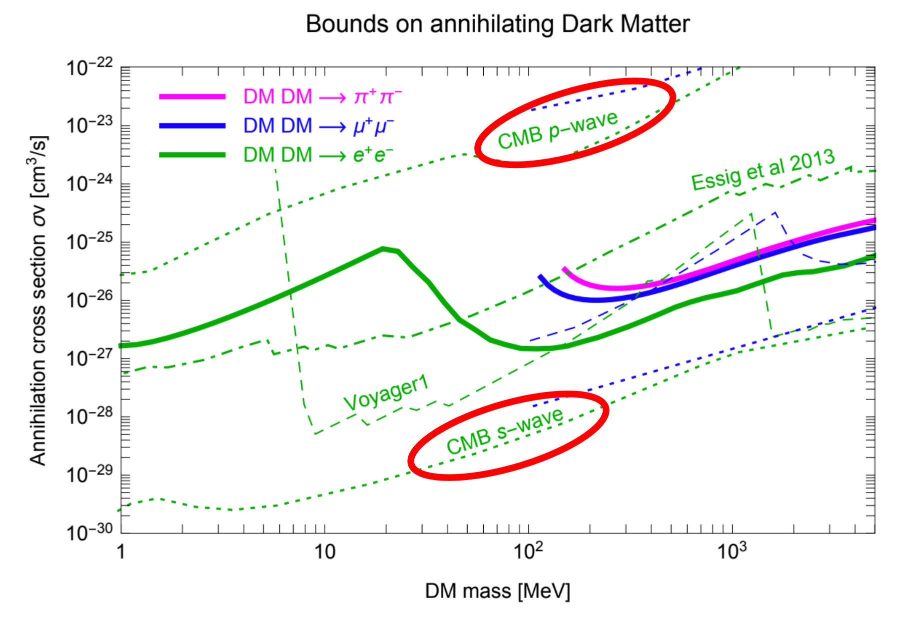




Other viable options:

- DM annihilated in p-wave (hence the **σ**v is v^2 suppressed, hence smaller at low-T (low-v)).
- Presence of a mechanism that cuts off late time annihilation, as eg. mass splitting in the $\chi - \bar{\chi}$ system
- other

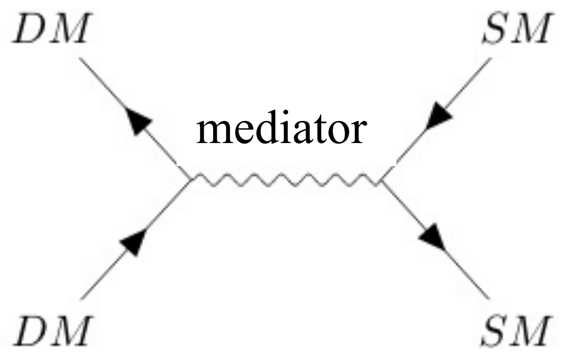
DM at accelerators, direct detection, and in cosmology

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)

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

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

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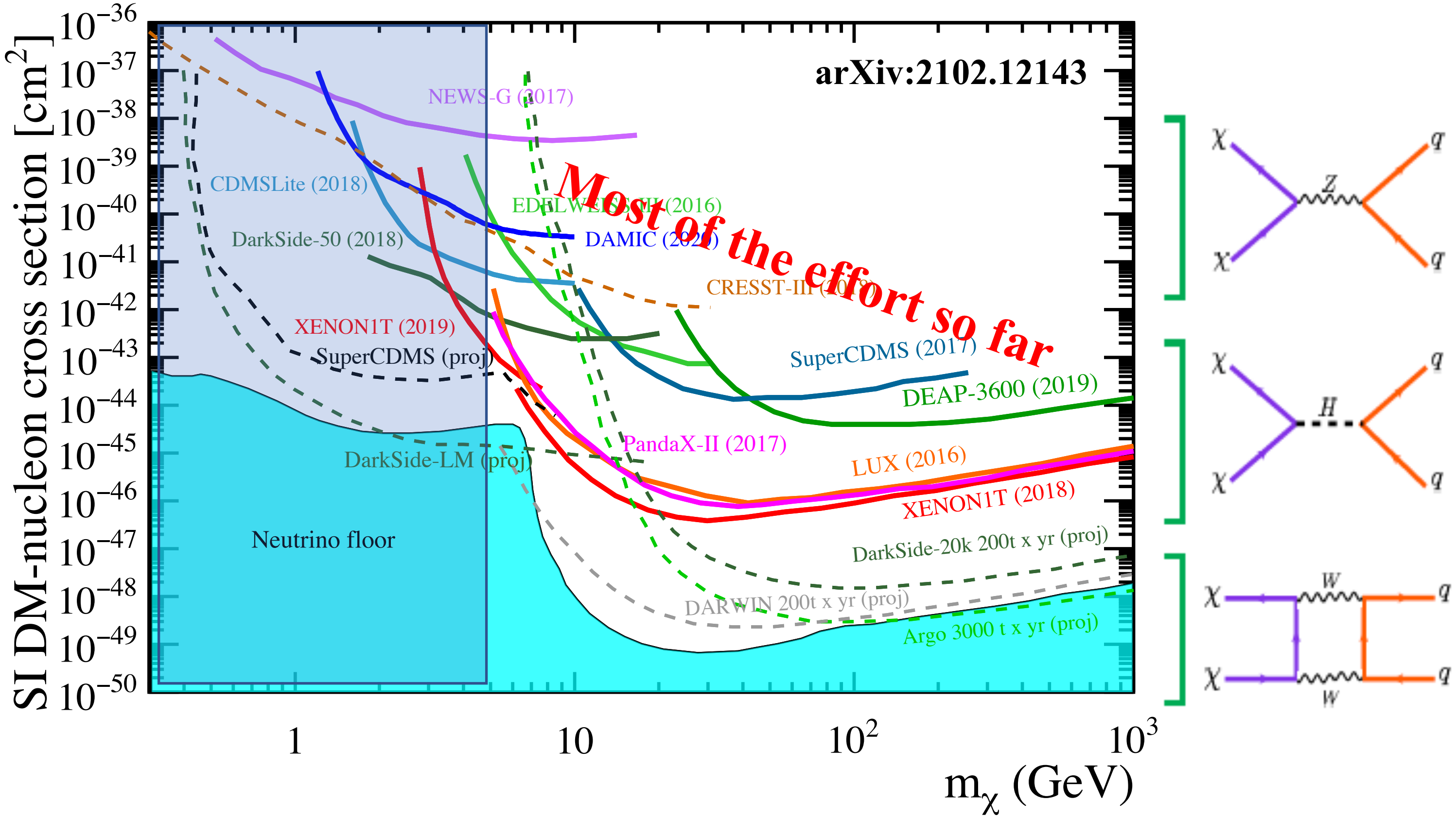
Direct Detection DM searches in the MeV-GeV range: A vibrant field.

DM in the MeV-GeV range: a blooming field

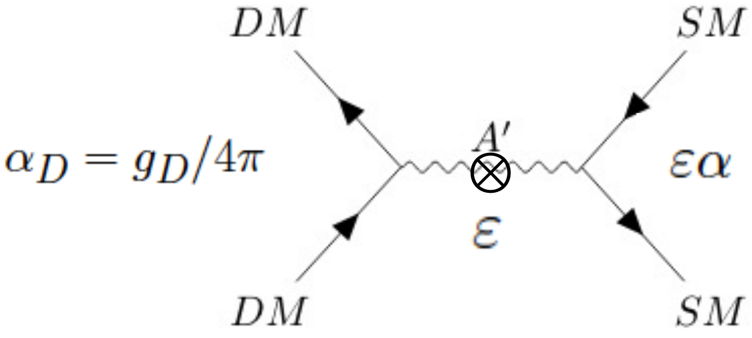


Light DM direct detection experiments are pushing the exploration almost down to the neutrino floor in the MeV-GeV range.

Mediator-DM mass hierarchy also defines how DM annihilates in the early Universe into SM particles:

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

Direct annihilation

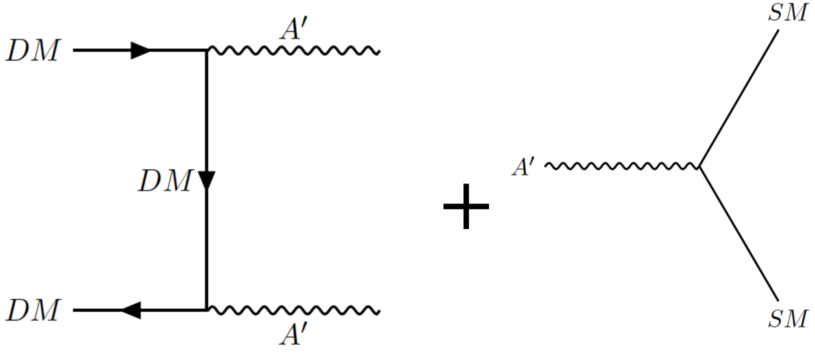


Clear relic target:

$\sigma v \propto \epsilon^2 \alpha_D$

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

Hidden or secluded annihilation



No thermal target, the space is wide open:

$\sigma v \propto \alpha_D^2$

no clear target for ϵ

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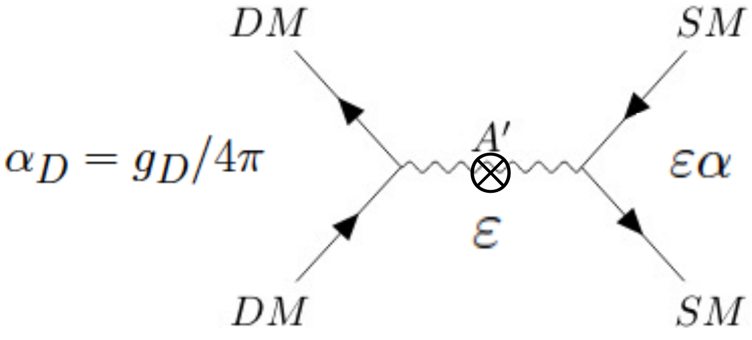

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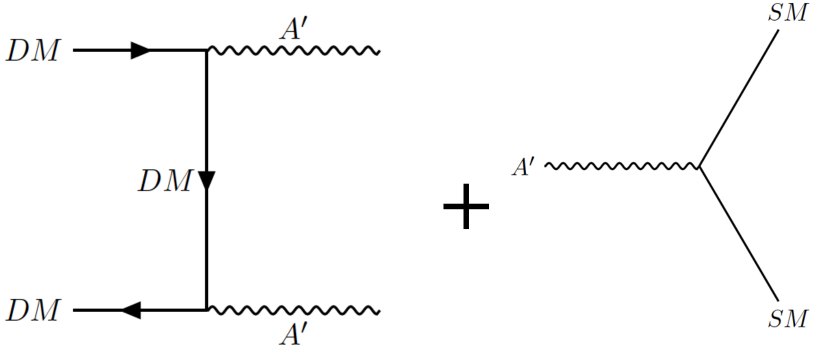

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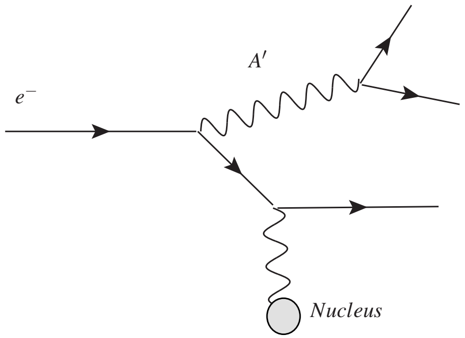
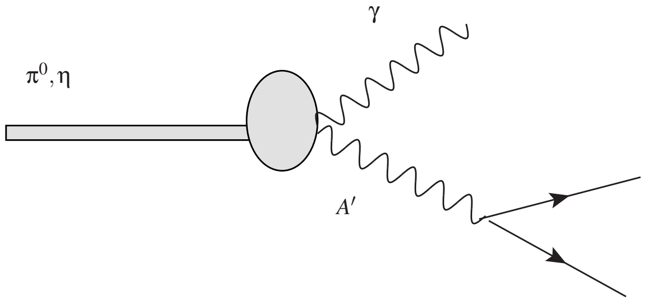
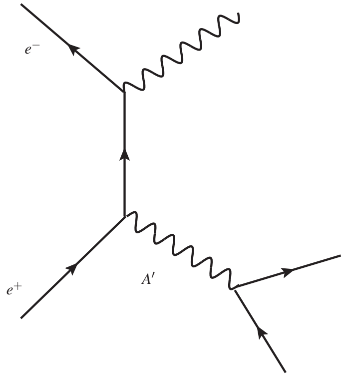
How can we produce vector & scalar mediators at accelerators?

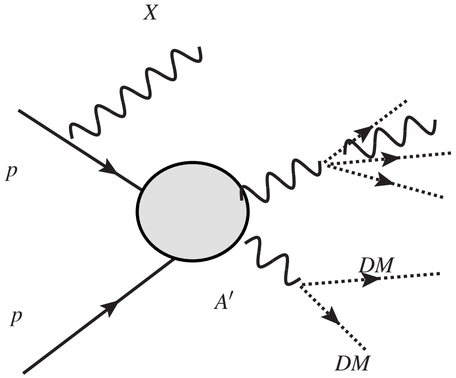
Vector mediator (wherever there is a photon):

- Dark Bremsstrahlung (p and electron beam dump)
- Annihilation ($e^+ \ e^- \rightarrow A' \gamma$) (positron beam dump or e+ e- collider)
- Light meson decays (eg: $\pi^0 \rightarrow A' \gamma$) (proton/e beam dump, e+ e-/pp colliders)



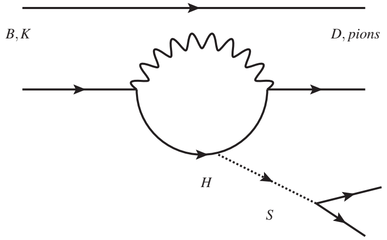






Scalar mediator (wherever there is a Higgs):

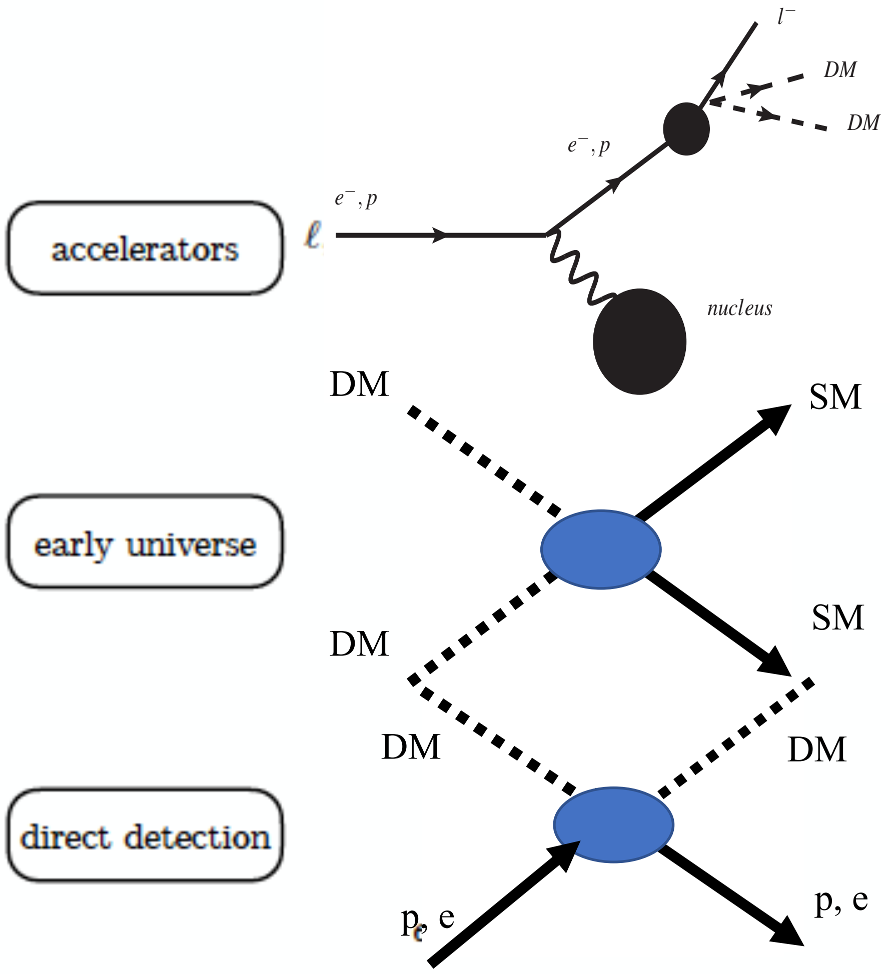
1) K, B decays: b,s → S X (virtual Higgs): p beam dump, K factory, pp collider
2) Higgs → SS (Higgs on shell): LHC



Different signatures expected depending on the mass hierarchy between mediator and DM.

DM at accelerators, direct detection, and in cosmology

The momentum scale is very different between accelerator, early universe, and direct detection….



momentum transfer $\sim q$

$q \gtrsim m_\chi$ (robust)

↑ less sensitive to interaction structure

$q \sim m_\chi$

↓ more sensitive to interaction structure

$q \ll m_\chi$ (suppressions/enhancements)

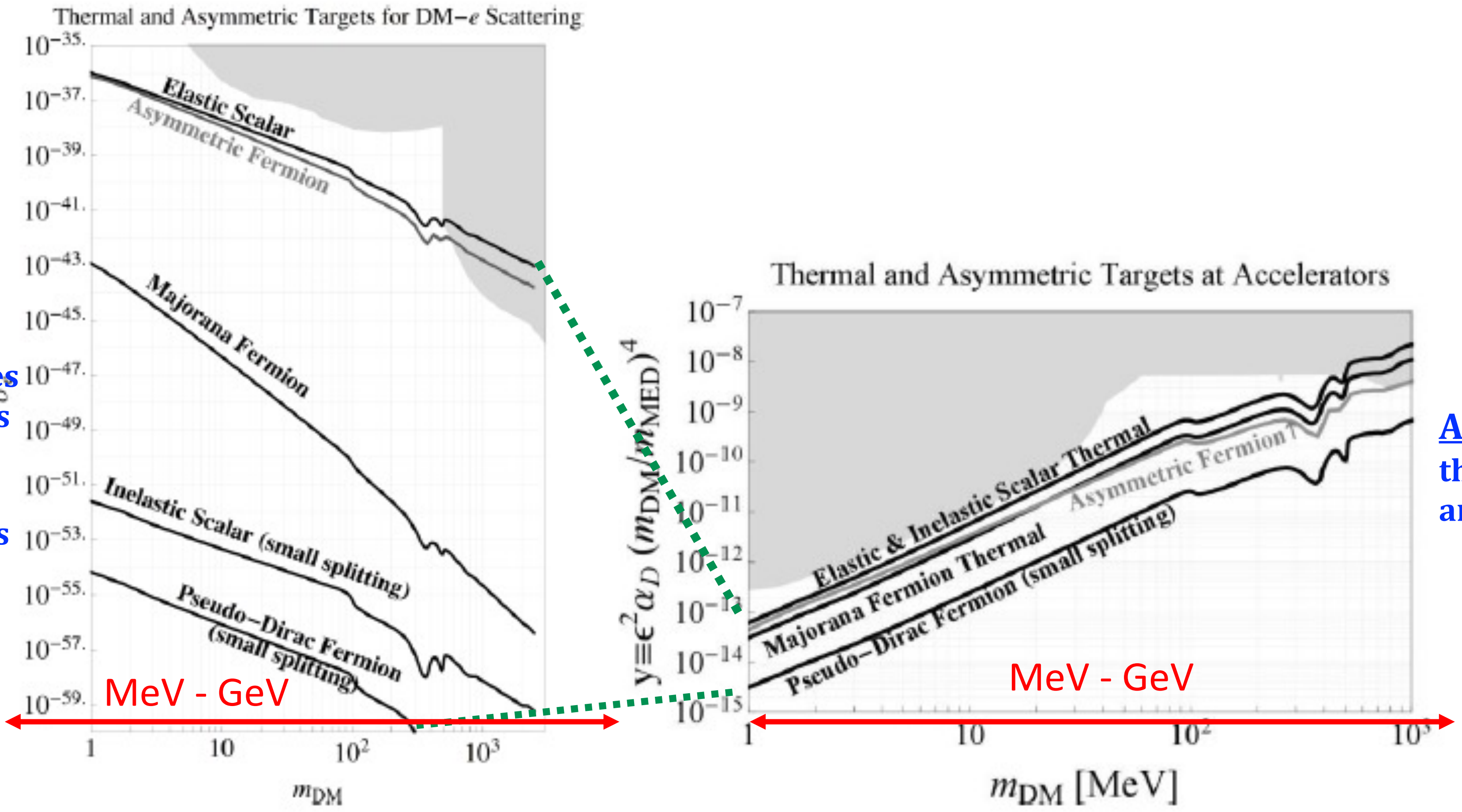
DD experiments are sensitive to the details of the interaction, accelerator-based exps are not

DM at accelerators, direct detection, and in cosmology

.. and this makes a huge difference in terms of thermal relic targets:

DM DD:

thermal relic abundances are spread over 20 orders of magnitude depending on the nature of DM & Mediators



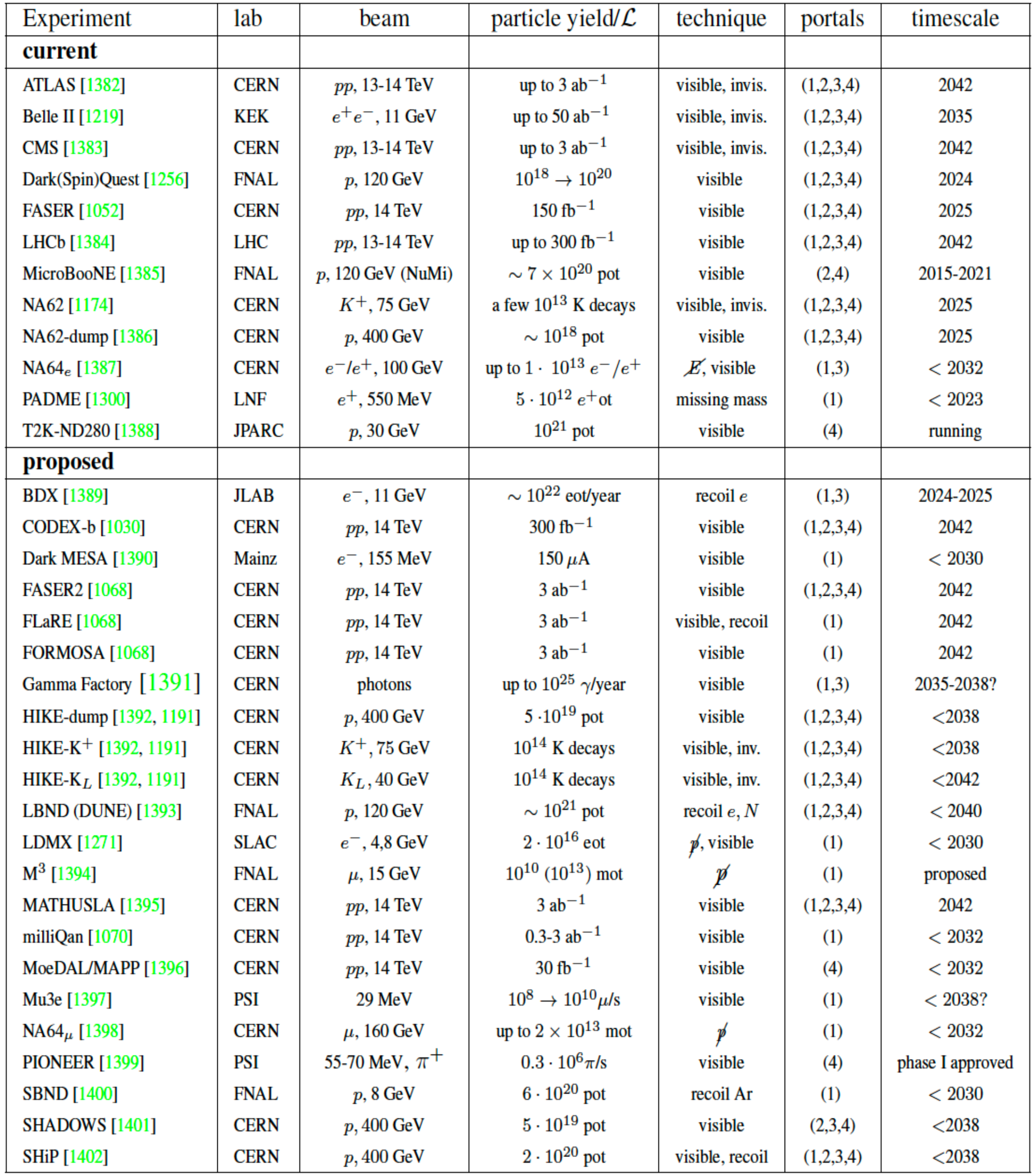
Accelerators:

thermal relic abundances are confined in a narrow band

Cosmic visions, arXiv:1707.04591

The Search for light (MeV- few GeV) DM at accelerators: A worldwide effort

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	$10^{18} \rightarrow 10^{20}$	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	$10^8 \rightarrow 10^{10} \mu$/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 in the worldwide context

Experiments/proposals related to FIPs in PBC

FIPs @ CERN

SPS
(MeV- few GeV)

HIKE (NA62-successor)
FIPs with kaons/proton beam dump

SHiP

NA64-e/mu/h
Light DM with e/mu beams

SHADOWS
FIPs @ proton beam dump

Gamma-factory
(mostly ALPs)

(Baby-)IAXO
solar axions

Axions/Dark Photons
(< meV)

VMB
Vacuum birifrangence

proton-EDM

AION
FIPs with atom interferometer

Gravitational Waves
via atom interferometry
(10^{-20} eV)

CODEX-b
FIPs @ LHCb IP

ANUBIS
(FIPs @ ATLAS shaft)

LHC
(few GeV – TeV)

MATHUSLA
FIPs @ CMS IP

Forward Physics Facility (FASER2, …)

ISOLDE

AD
FIPs @ anti-proton decelerator

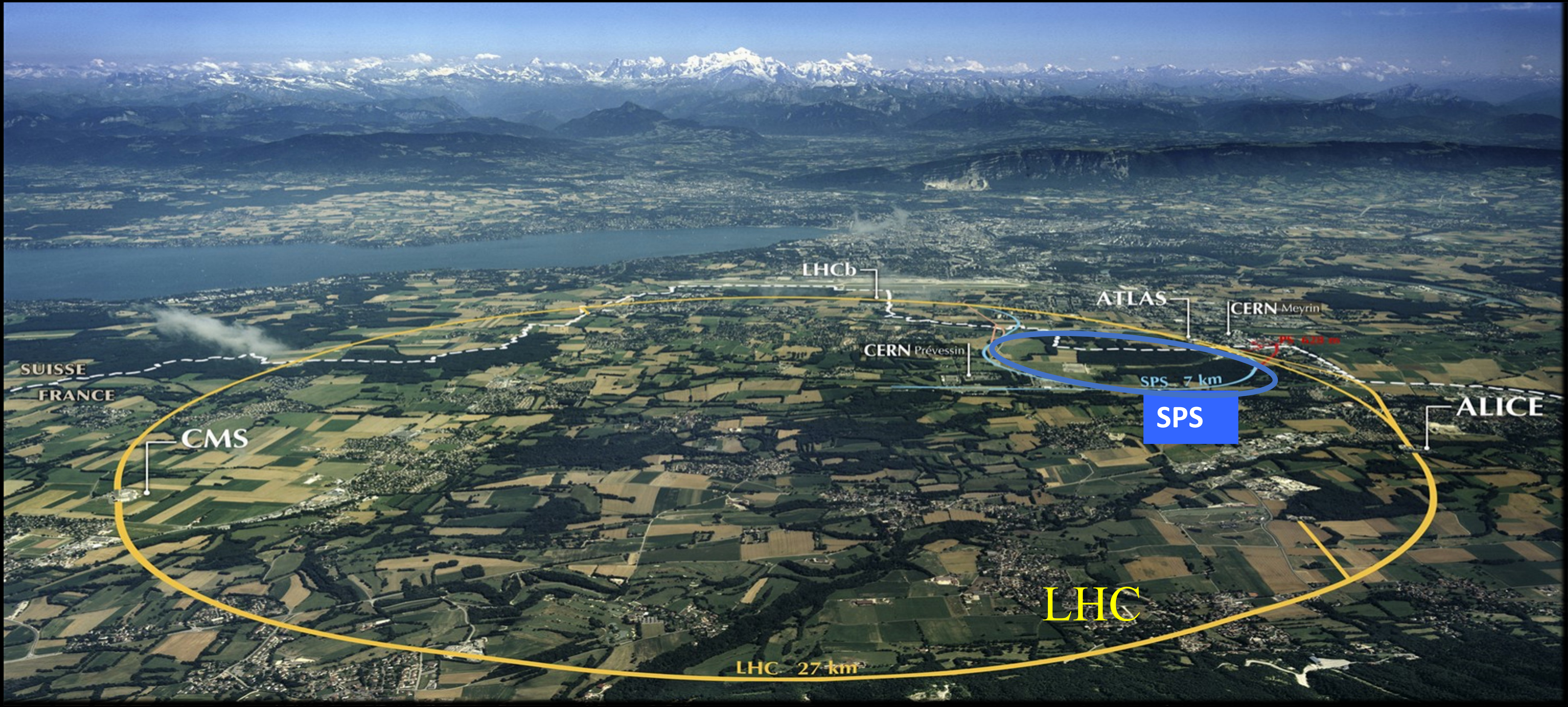
nTOF

Nuclear astrophysics

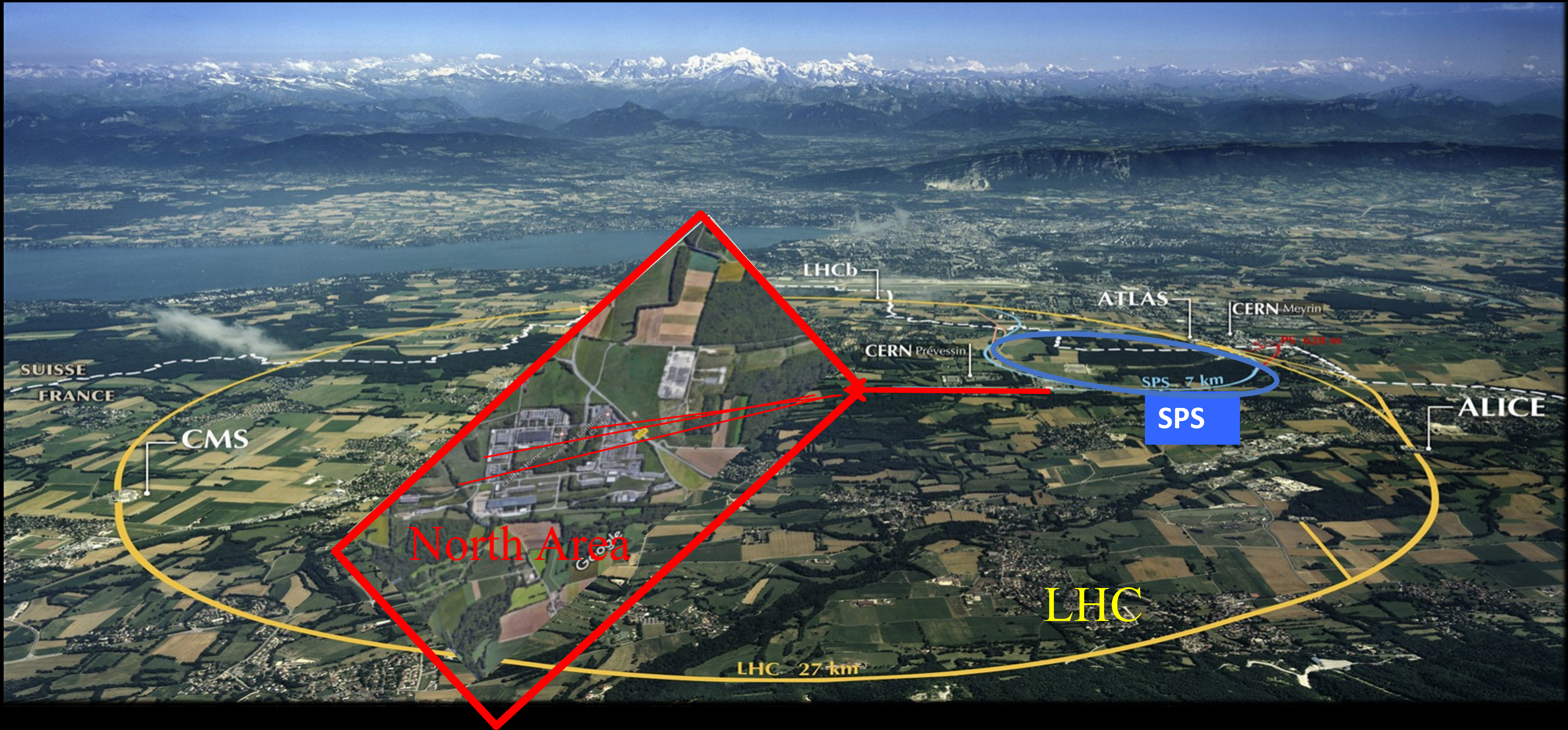
Ultra-light FIPs
(atomic clocks, quantum sensors and the likes)

+ an extremely active community in ATLAS-CMS-LHCb

Search for FIPs @ CERN

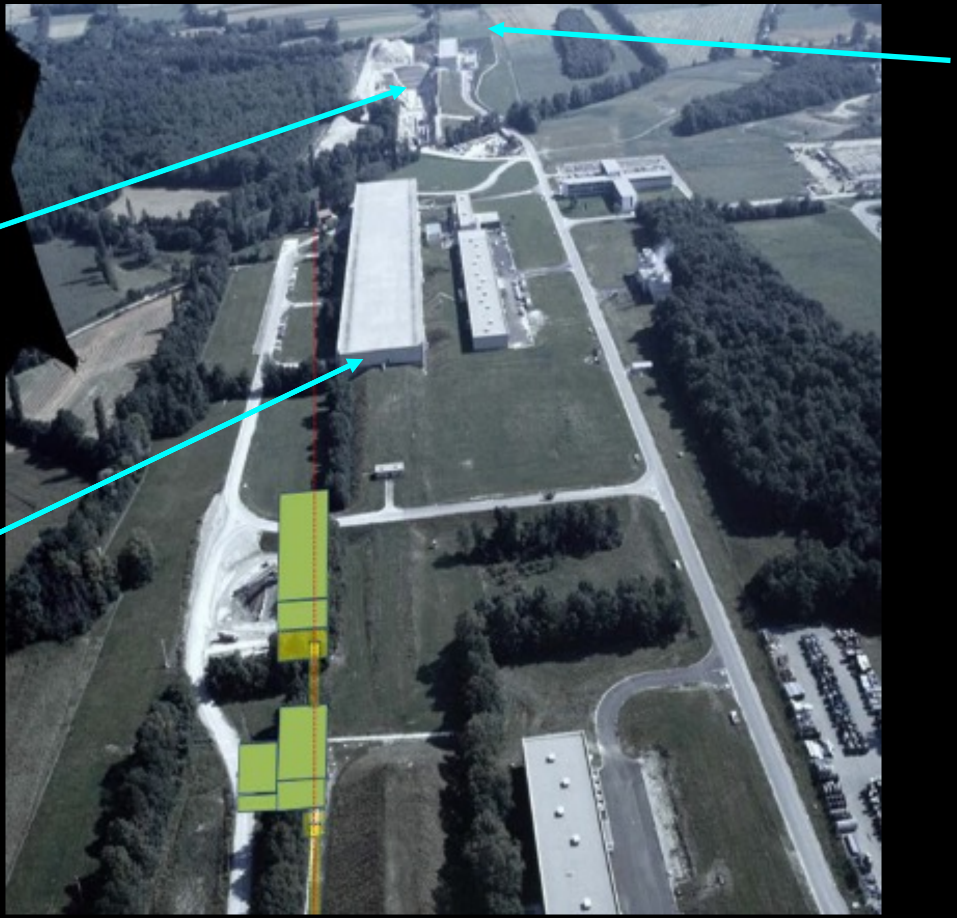


Search for FIPs @ CERN



Highest energy proton, electrons and muon beams in the world.

MeV-GeV DM @ CERN – The North Area: a unique infrastructure…



ECN3:
P42/K12: 400 GeV p beam
up to 3×10^{18} pot/year (now)
→ **NA62**
up to a few 10^{19} pot/year
→ **HIKE, SHiP, SHADOWS**

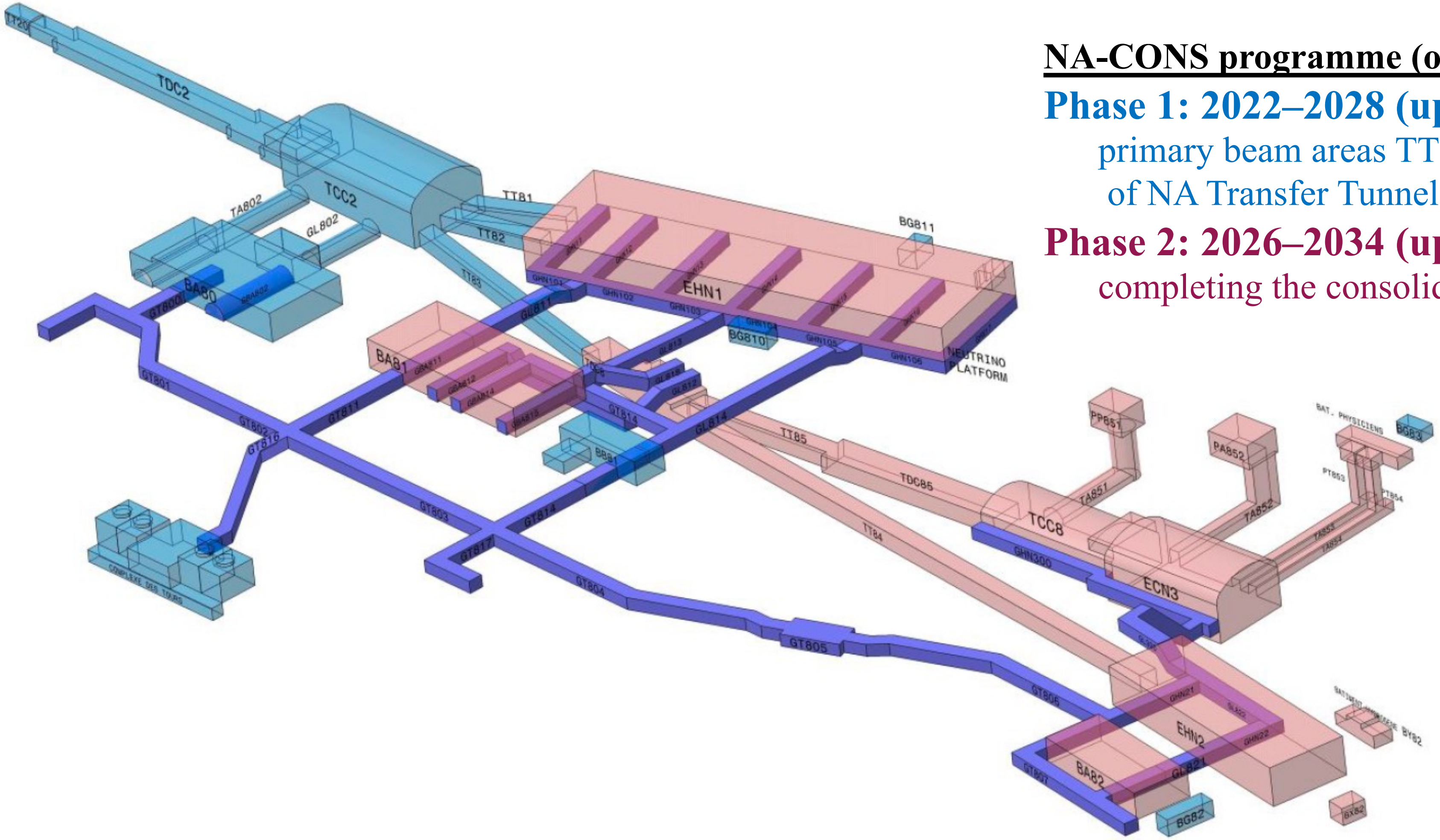
EHN1:
H4: 100 GeV e- beam
up to 5×10^{12} eot/year
→ **NA64^{++} (e), NA64^{++}(hadrons)**

EHN2:
M2: 100-160 GeV, mu beam
up to 10^{13} μ/year
→ **NA64^{++} (mu)**

… to search for light DM and mediators at extracted beam lines….

A big consolidation of the North Area (from the 1970's) is currently planned

The North Area Consolidation (NA-CONS) project



NA-CONS programme (o(100) MCHF)

Phase 1: 2022–2028 (up to end LS3),

primary beam areas TT20, TDC2, TCC2 and initial section of NA Transfer Tunnels.

Phase 2: 2026–2034 (up to end LS4),

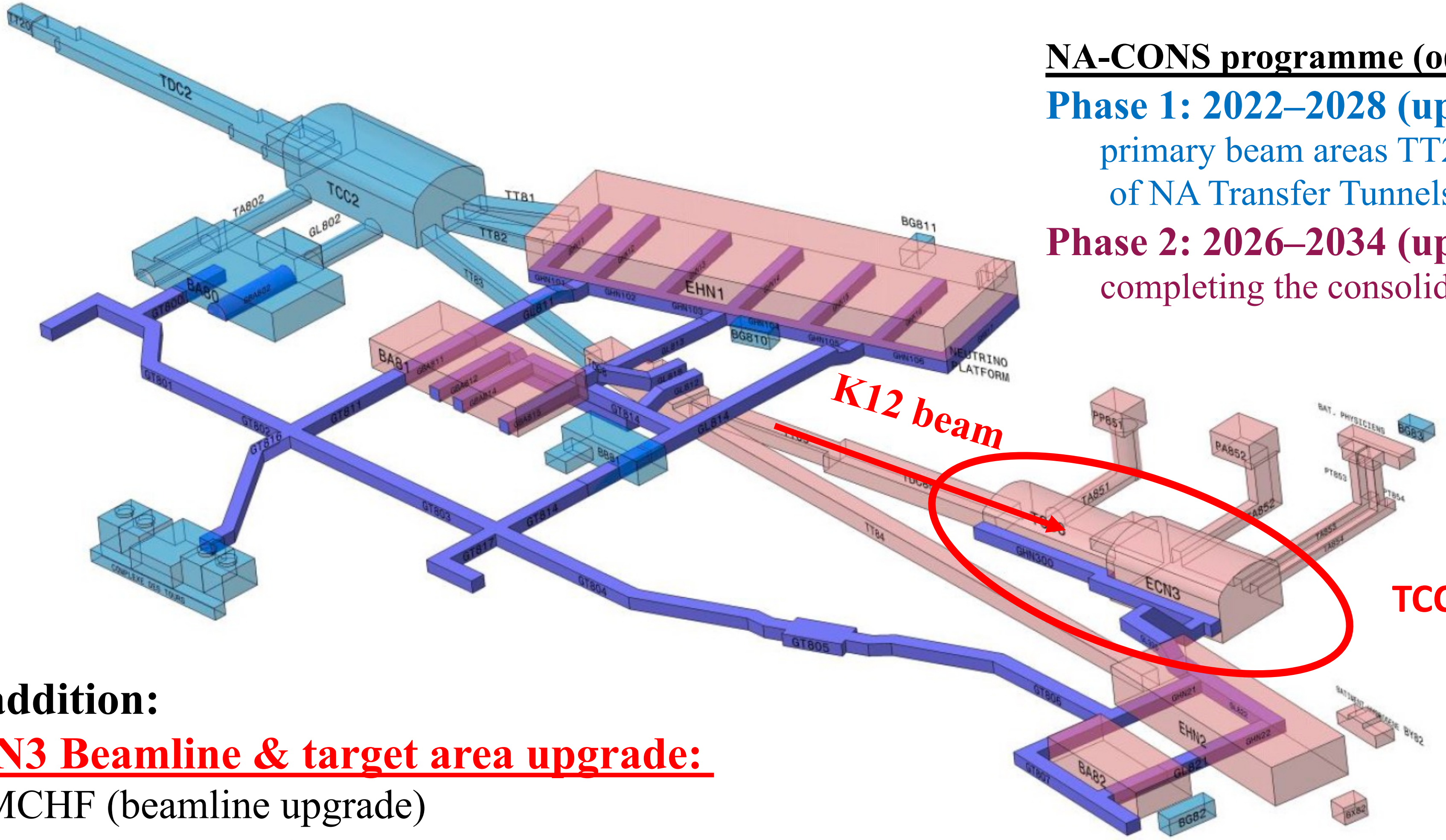
completing the consolidation of the secondary beam areas.

The North Area Consolidation (NA-CONS) project

NA-CONS programme (o(100) MCHF)

Phase 1: 2022–2028 (up to end LS3),
primary beam areas TT20, TDC2, TCC2 and initial section of NA Transfer Tunnels.

Phase 2: 2026–2034 (up to end LS4),
completing the consolidation of the secondary beam areas.



K12 beam

TCC8+ECN3 complex

In addition:

ECN3 Beamline & target area upgrade:

16 MCHF (beamline upgrade)

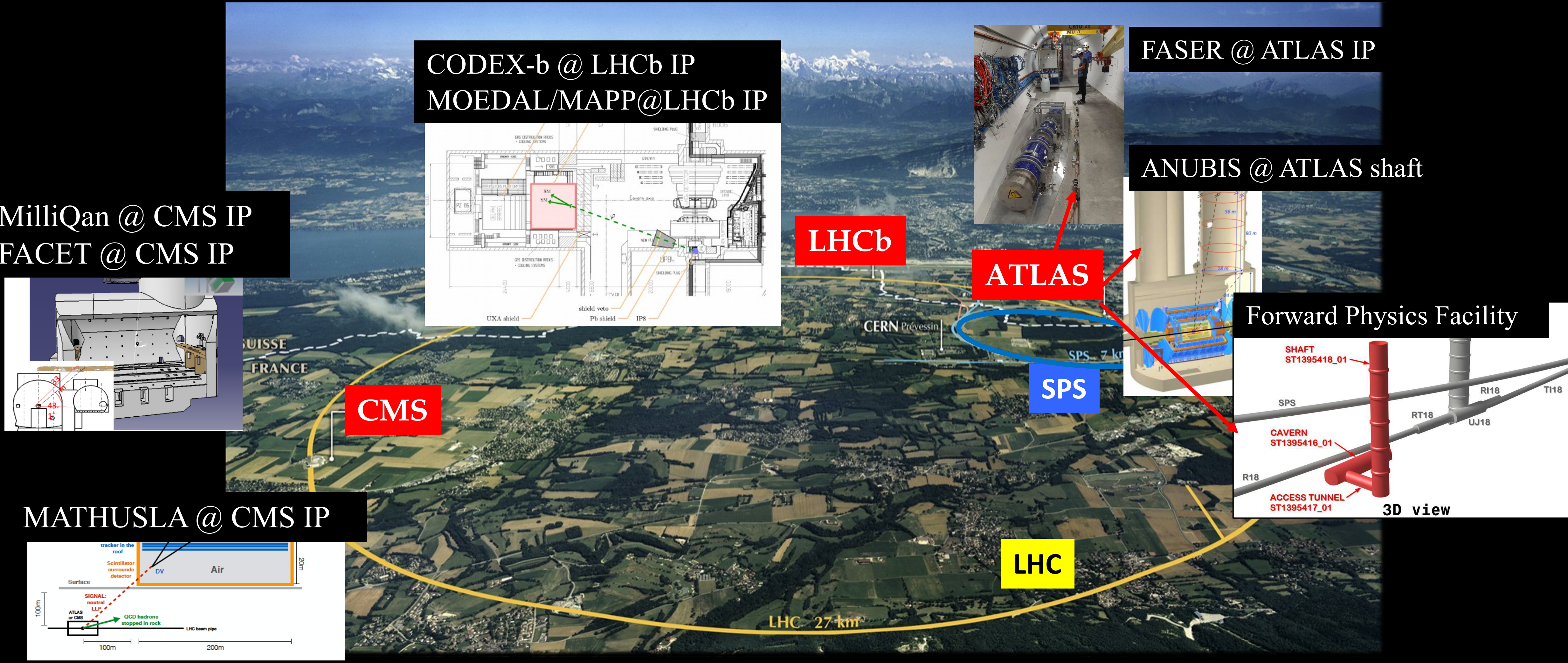
50 MCHF (target area)

Two possible options:

1. SHiP
2. HIKE + SHADOWS

Decision about which project(s) will run in ECN3 in the next 10-20 years will be taken by the CERN Management in March.

FIPs @ CERN –The Long-Lived Particle detectors at the LHC IPs



CODEX-b @ LHCb IP
MOEDAL/MAPP@LHCb IP

FASER @ ATLAS IP

ANUBIS @ ATLAS shaft

MilliQan @ CMS IP
FACET @ CMS IP

Forward Physics Facility

MATHUSLA @ CMS IP

+ an active LLP community inside ATLAS, CMS, and LHCb collaborations

US P5 process recommendations as a function of the budget level

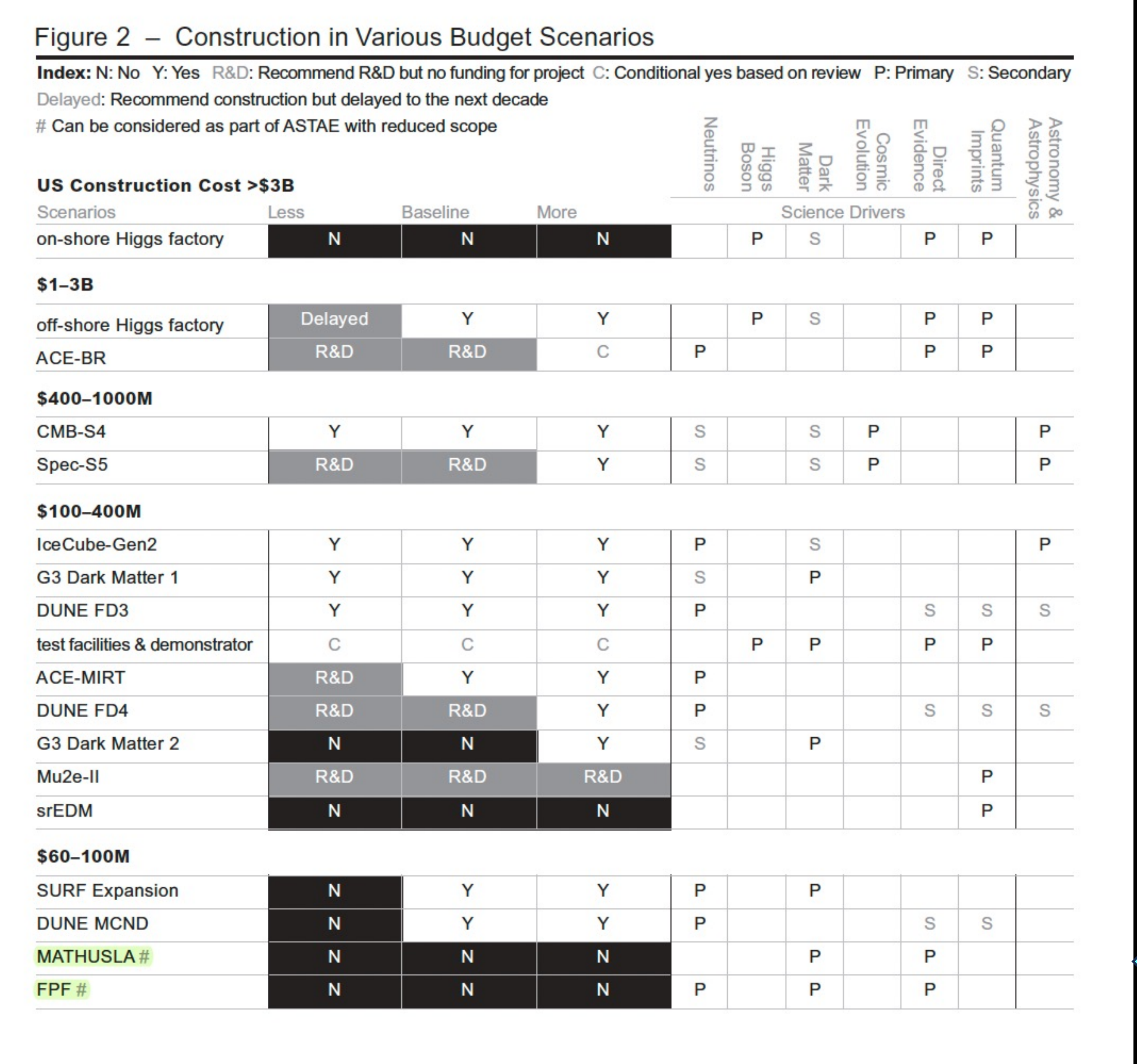


Figure 2 – Construction in Various Budget Scenarios

Index: N: No Y: Yes R&D: Recommend R&D but no funding for project C: Conditional yes based on review P: Primary S: Secondary

Delayed: Recommend construction but delayed to the next decade

Can be considered as part of ASTAE with reduced scope

Scenarios	Less	Baseline	More	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
US Construction Cost >$3B										
on-shore Higgs factory	N	N	N		P	S		P	P	
$1–3B										
off-shore Higgs factory	Delayed	Y	Y		P	S		P	P	
ACE-BR	R&D	R&D	C	P				P	P	
$400–1000M										
CMB-S4	Y	Y	Y	S		S	P			P
Spec-S5	R&D	R&D	Y	S		S	P			P
$100–400M										
IceCube-Gen2	Y	Y	Y	P		S				P
G3 Dark Matter 1	Y	Y	Y	S		P				
DUNE FD3	Y	Y	Y	P				S	S	S
test facilities & demonstrator	C	C	C		P	P		P	P	
ACE-MIRT	R&D	Y	Y	P						
DUNE FD4	R&D	R&D	Y	P				S	S	S
G3 Dark Matter 2	N	N	Y	S		P				
Mu2e-II	R&D	R&D	R&D						P	
srEDM	N	N	N						P	
$60–100M										
SURF Expansion	N	Y	Y	P		P				
DUNE MCND	N	Y	Y	P				S	S	
MATHUSLA #	N	N	N			P		P		
FPF #	N	N	N	P		P		P		

both MATHUSLA & FPF were not recommended unless heavily downscoped.

US P5 process recommendations as a function of the LAB

Spallation neutron source at Oak Ridge Laboratory

Los Alamos

Fermilab - Booster

JLAB

SLAC

Fermilab, Muon campus

Fermilab, Main Injector

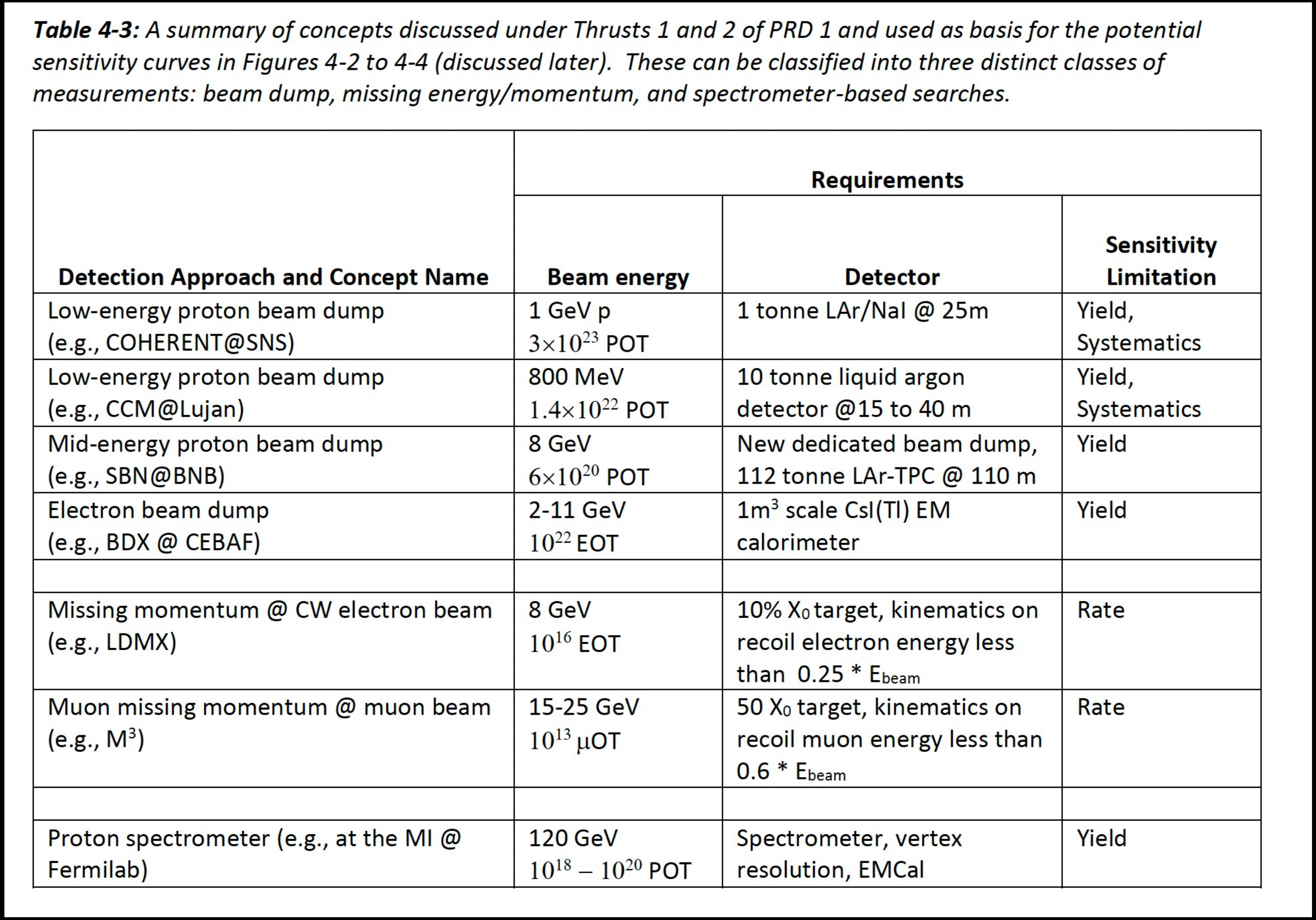


Table 4-3: *A summary of concepts discussed under Thrusts 1 and 2 of PRD 1 and used as basis for the potential sensitivity curves in Figures 4-2 to 4-4 (discussed later). These can be classified into three distinct classes of measurements: beam dump, missing energy/momentum, and spectrometer-based searches.*

	Requirements		
Detection Approach and Concept Name	**Beam energy**	**Detector**	**Sensitivity Limitation**
Low-energy proton beam dump (e.g., COHERENT@SNS)	1 GeV p 3×10^{23} POT	1 tonne LAr/NaI @ 25m	Yield, Systematics
Low-energy proton beam dump (e.g., CCM@Lujan)	800 MeV 1.4×10^{22} POT	10 tonne liquid argon detector @15 to 40 m	Yield, Systematics
Mid-energy proton beam dump (e.g., SBN@BNB)	8 GeV 6×10^{20} POT	New dedicated beam dump, 112 tonne LAr-TPC @ 110 m	Yield
Electron beam dump (e.g., BDX @ CEBAF)	2-11 GeV 10^{22} EOT	1m^3 scale CsI(Tl) EM calorimeter	Yield
Missing momentum @ CW electron beam (e.g., LDMX)	8 GeV 10^{16} EOT	10% X_0 target, kinematics on recoil electron energy less than 0.25 * E_{beam}	Rate
Muon missing momentum @ muon beam (e.g., M^3)	15-25 GeV 10^{13} μOT	50 X_0 target, kinematics on recoil muon energy less than 0.6 * E_{beam}	Rate
Proton spectrometer (e.g., at the MI @ Fermilab)	120 GeV $10^{18} - 10^{20}$ POT	Spectrometer, vertex resolution, EMCal	Yield

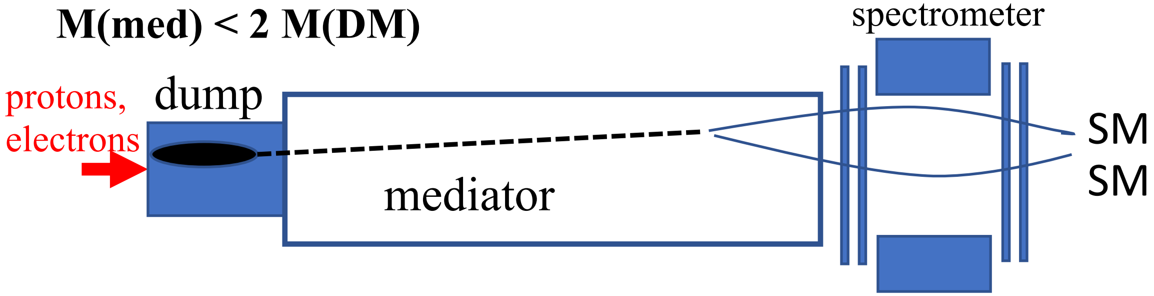
https://science.osti.gov/-/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf

All the main US labs involved: priority to on-site projects

How can we “see” DM & mediators at accelerators ?

Experiments at extracted beam lines:

M(med) < 2 M(DM)



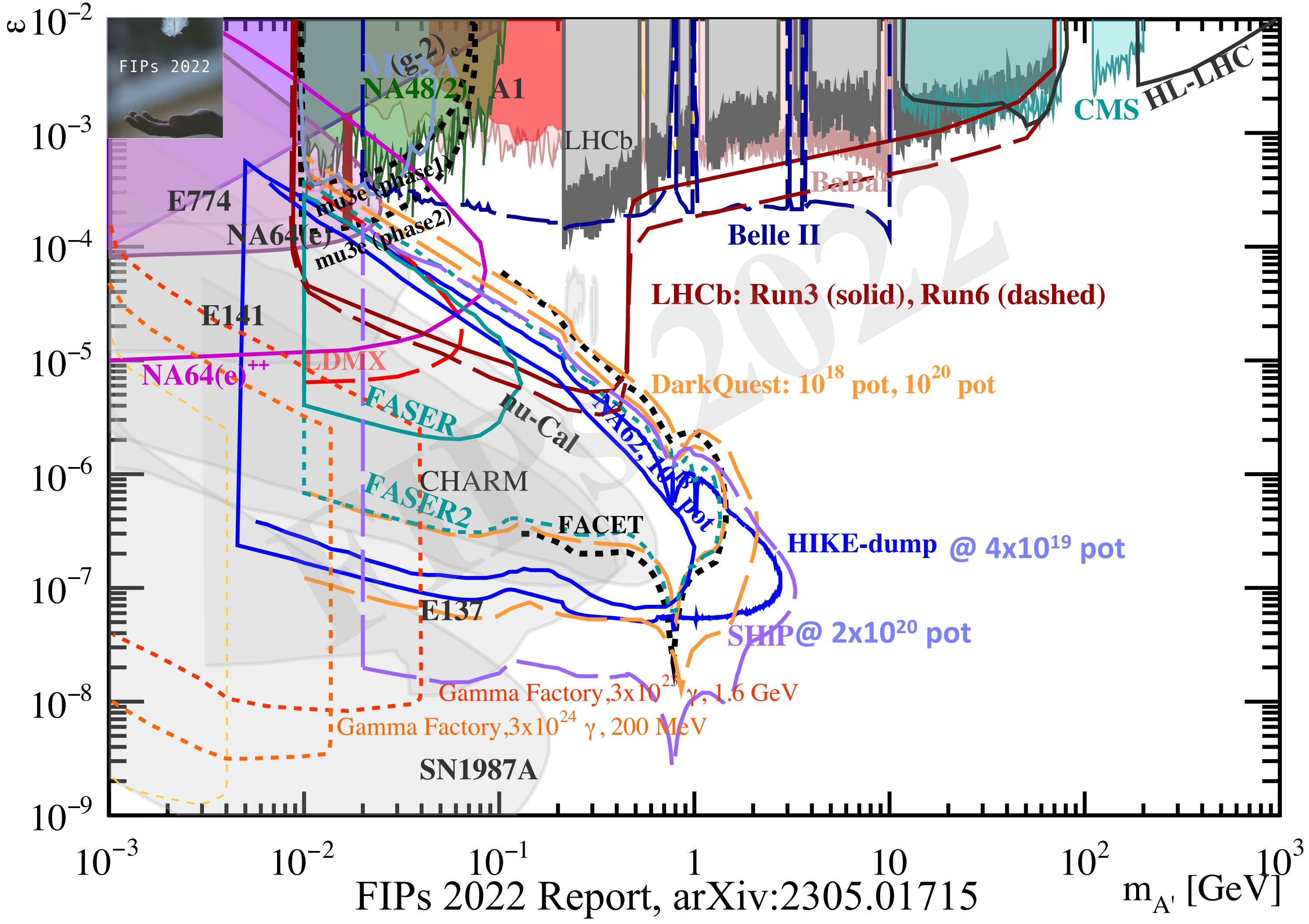
1. Mediators to visible final states:

Technique: bump searches:

- **NA62@CERN**, p@400 GeV, $N_{pot} = 10^{18}$-few 10^{19}
- **SHADOWS (proposal)**, p@400 GeV, N_{pot} = few 10^{19} pot
- **NA64@CERN**, e@100 GeV, N_{eot}: 10^{12}-10^{13} eot
- **SHiP@CERN (proposal),** p@400 GeV
- **HPS, APEX, DarkLight @ JLAB** e@1-10 GeV
- **Sea(Dark)QUEST @ FNAL**, p@120 GeV, $10^{18} – 10^{20}$ pot
- **Short-baseline neutrino exps**
- **Near detectors of long baseline neutrino exps.**

Vector mediator going to visible final states

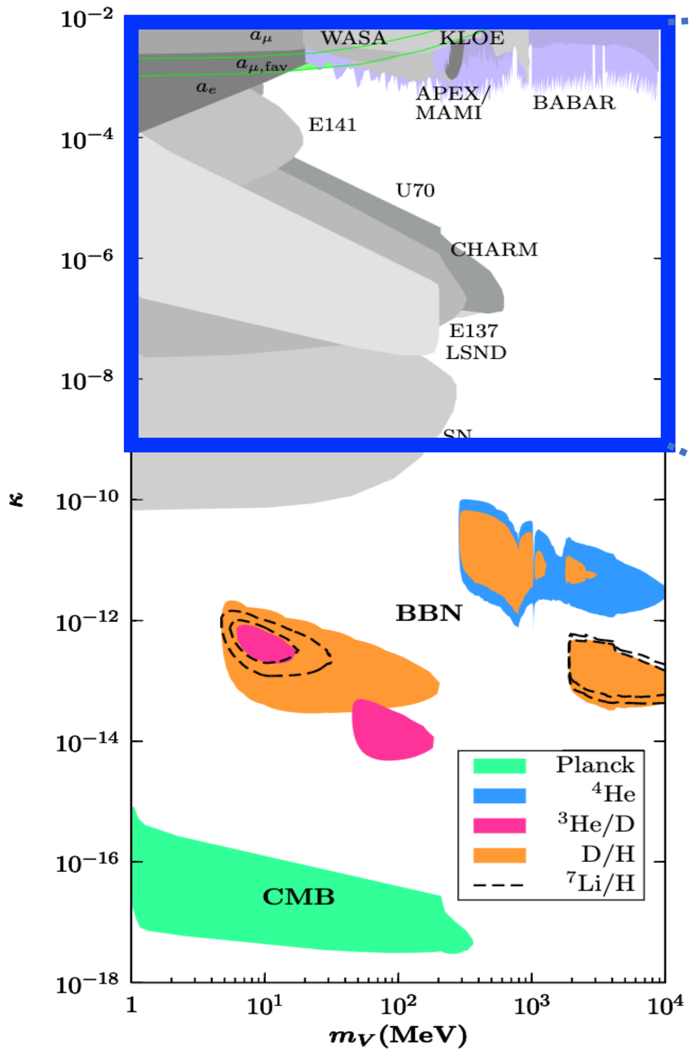
Experimental bounds and projections for accelerator-based experiments:

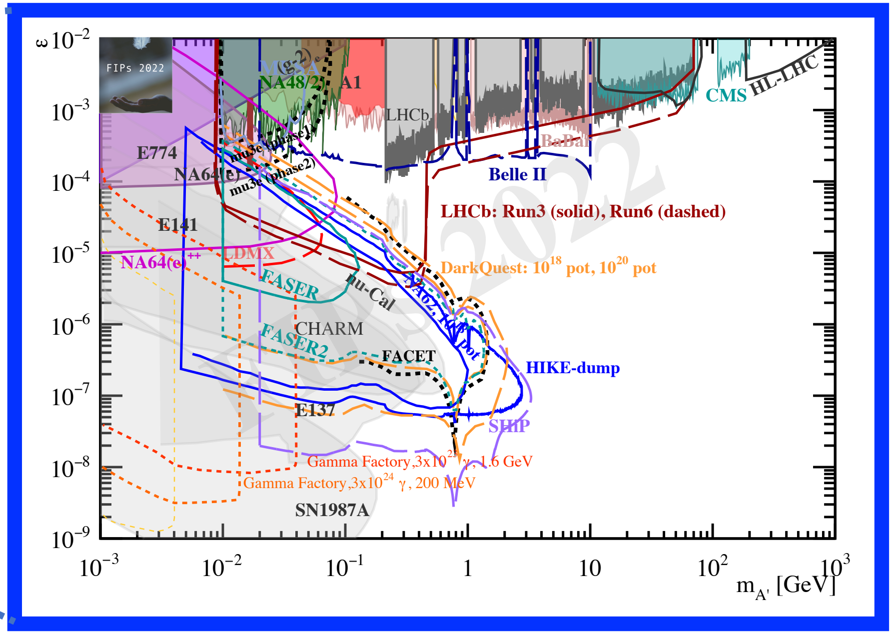


FIPs 2022 Report, arXiv:2305.01715

Vector mediator going to visible final states

Experimental bounds and projections for accelerator-based experiments:



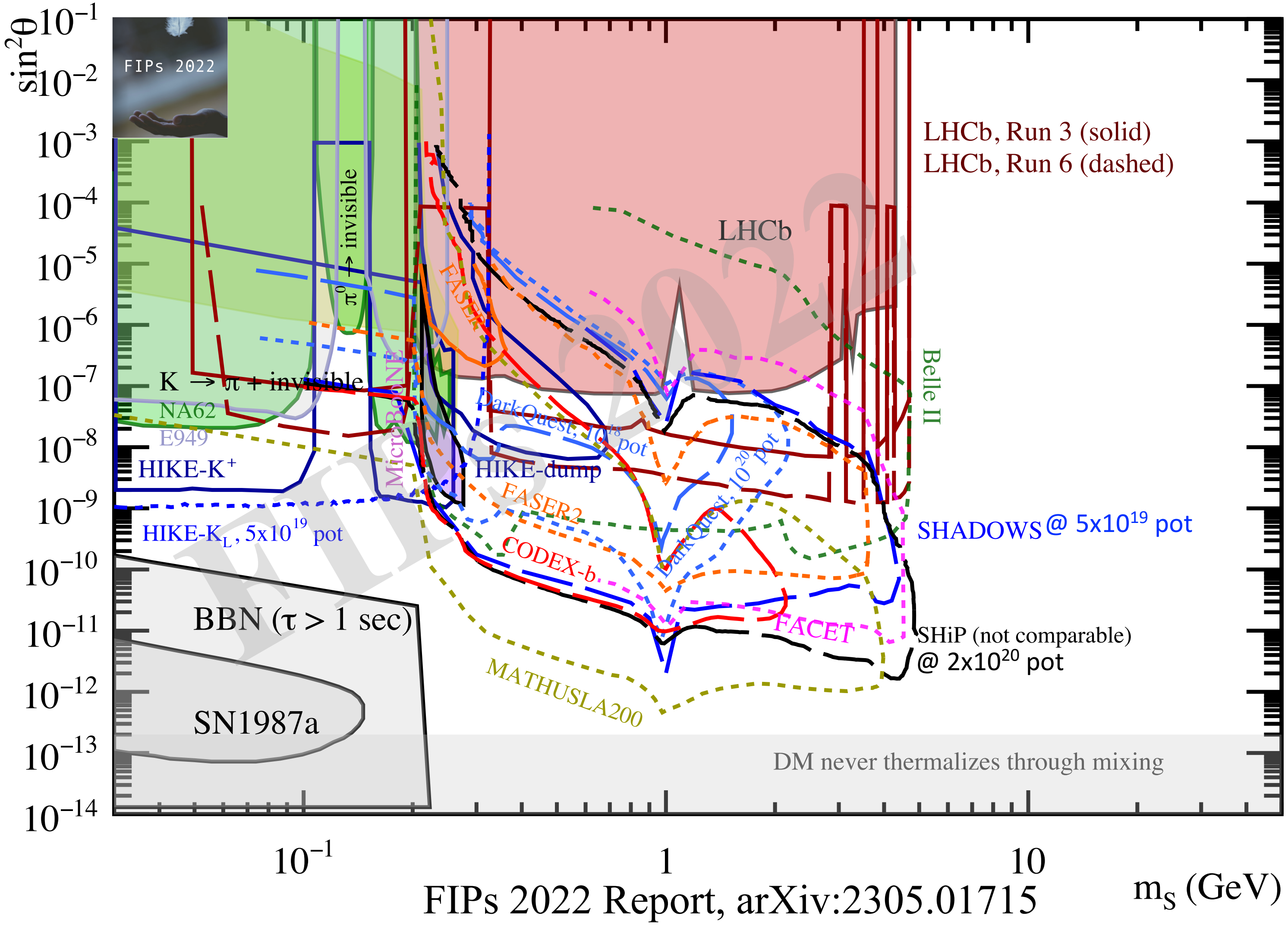


Astroparticle and cosmology inputs populate very low couplings

M. Pospelov et al, arXiv:1407.0993

Scalar mediator going to visible final states

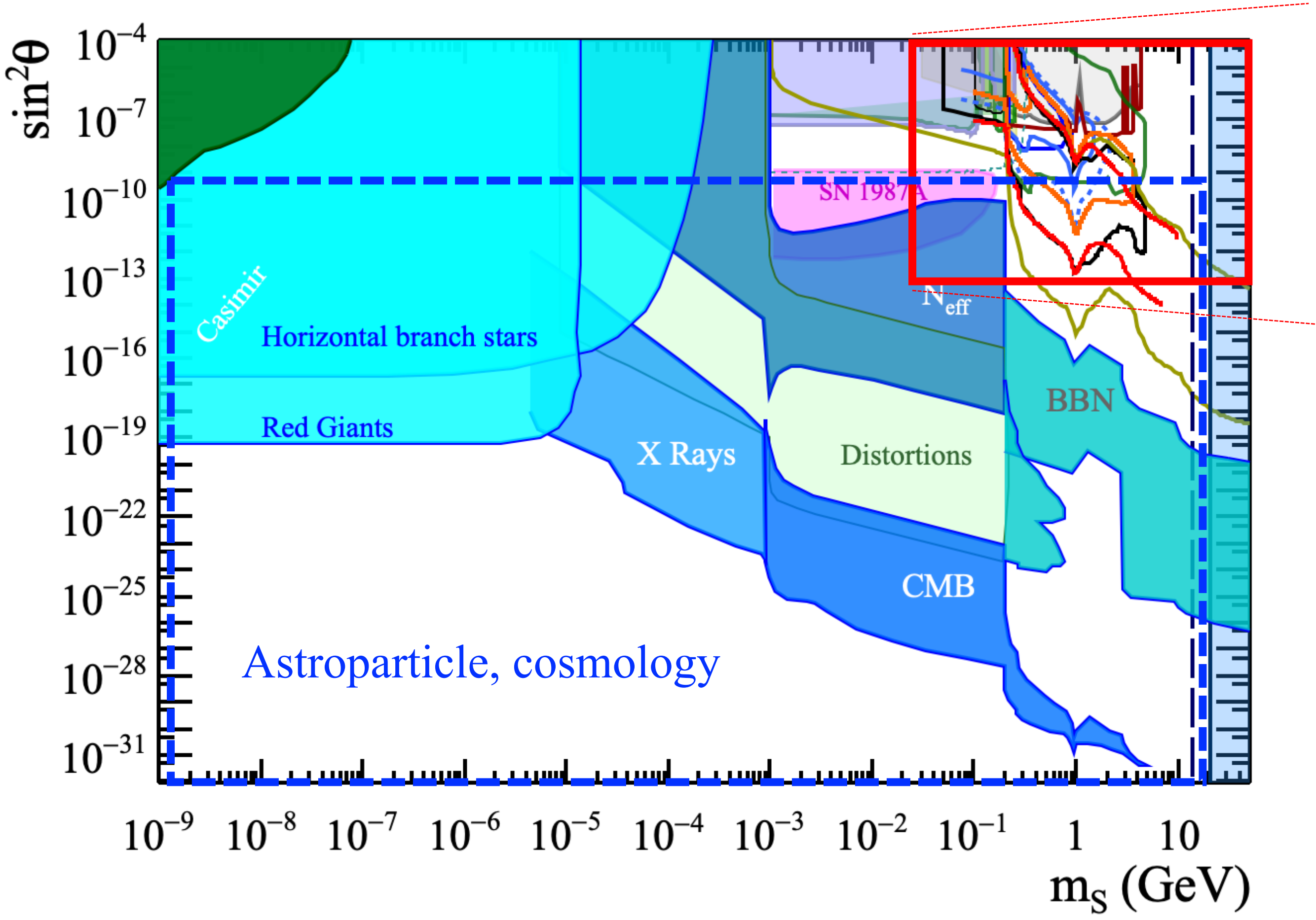
Experimental bounds and projections for accelerator-based experiments:

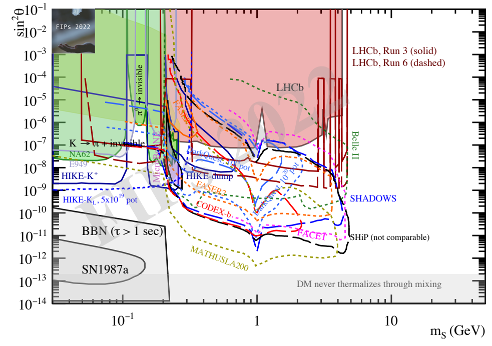


FIPs 2022 Report, arXiv:2305.01715

A light scalar as a non-thermal bosonic DM condensate

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



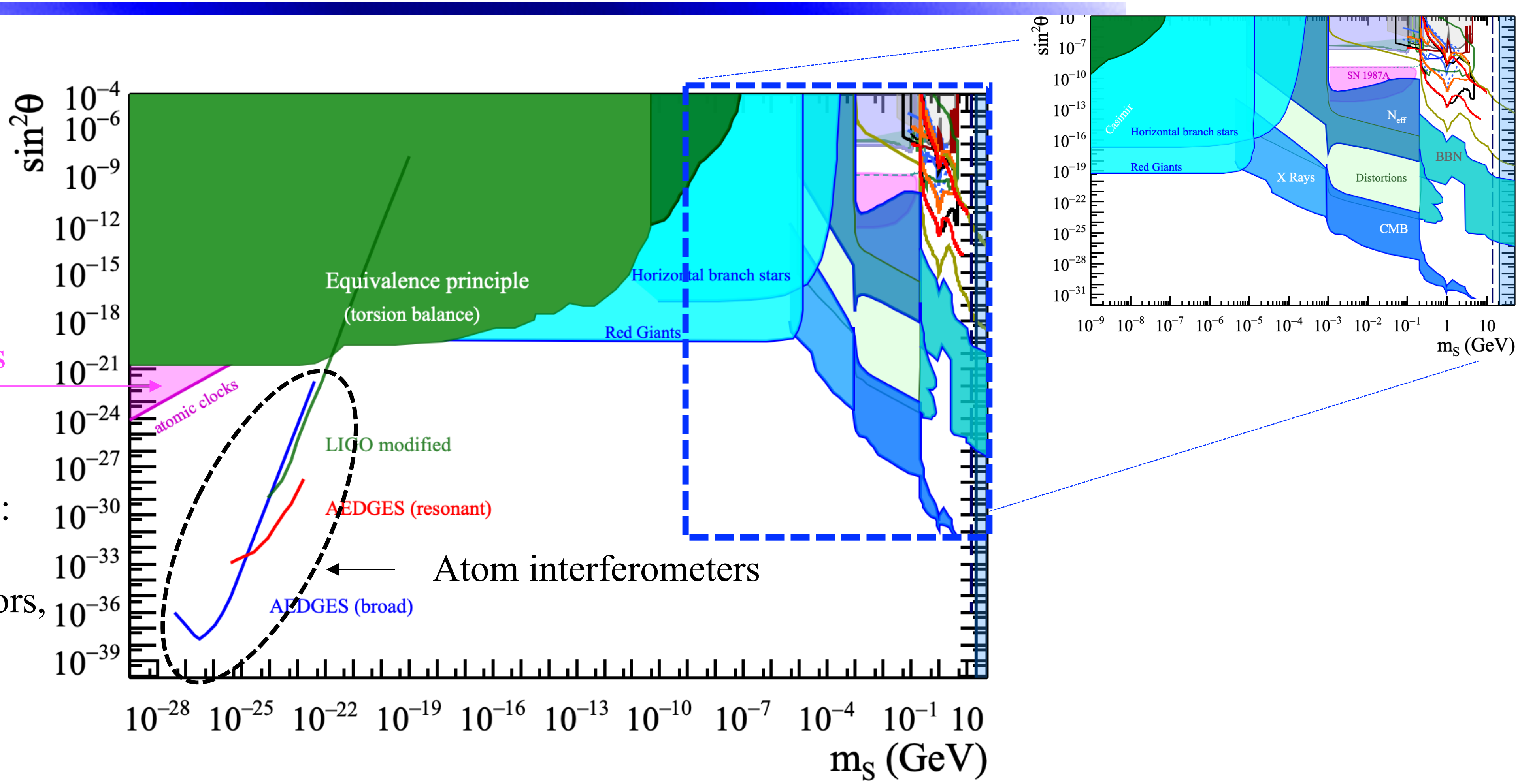


Accelerator-based experiments

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 (CMB)



Atomic clocks

Atom interferometers

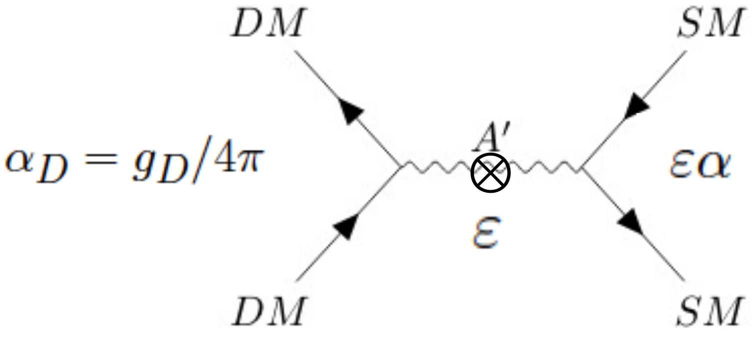
Ultra-light DM searches with:
atom interferometry,
atomic clocks, quantum sensors,
emerging technologies,…

In the same mass range we can search for axions/ALPs……

Mediator-DM mass hierarchy also defines how DM annihilates in the early Universe into SM particles:

$\mathbf{M_{med} > 2\ m_{DM}}$

Direct annihilation

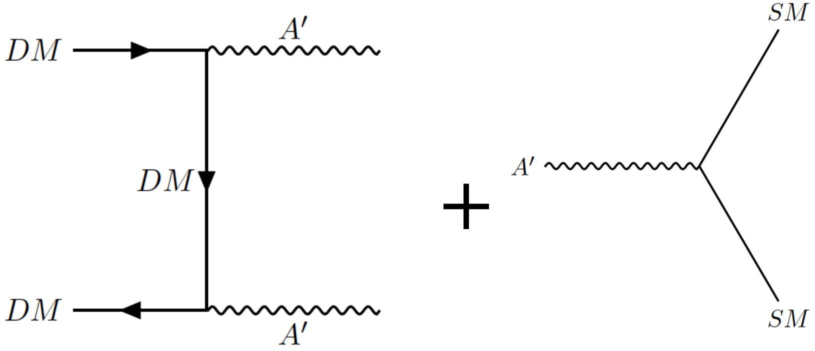


Clear relic target:

$\sigma v \propto \epsilon^2 \alpha_D$

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

Hidden or secluded annihilation



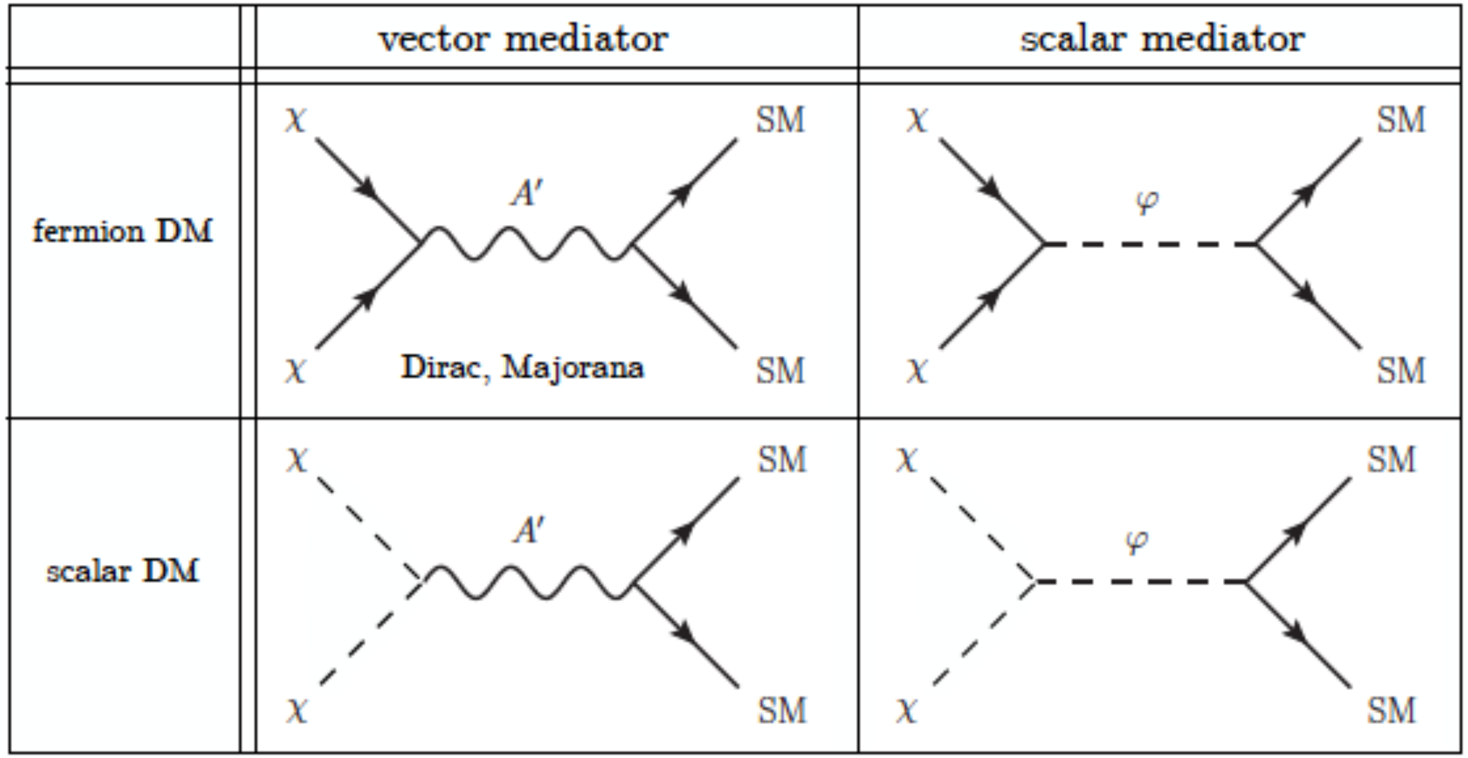
No thermal target, the space is wide open:

$\sigma v \propto \alpha_D^2$

no clear target for ϵ

Direct annihilation: Vector & Scalar mediators DM-SM:

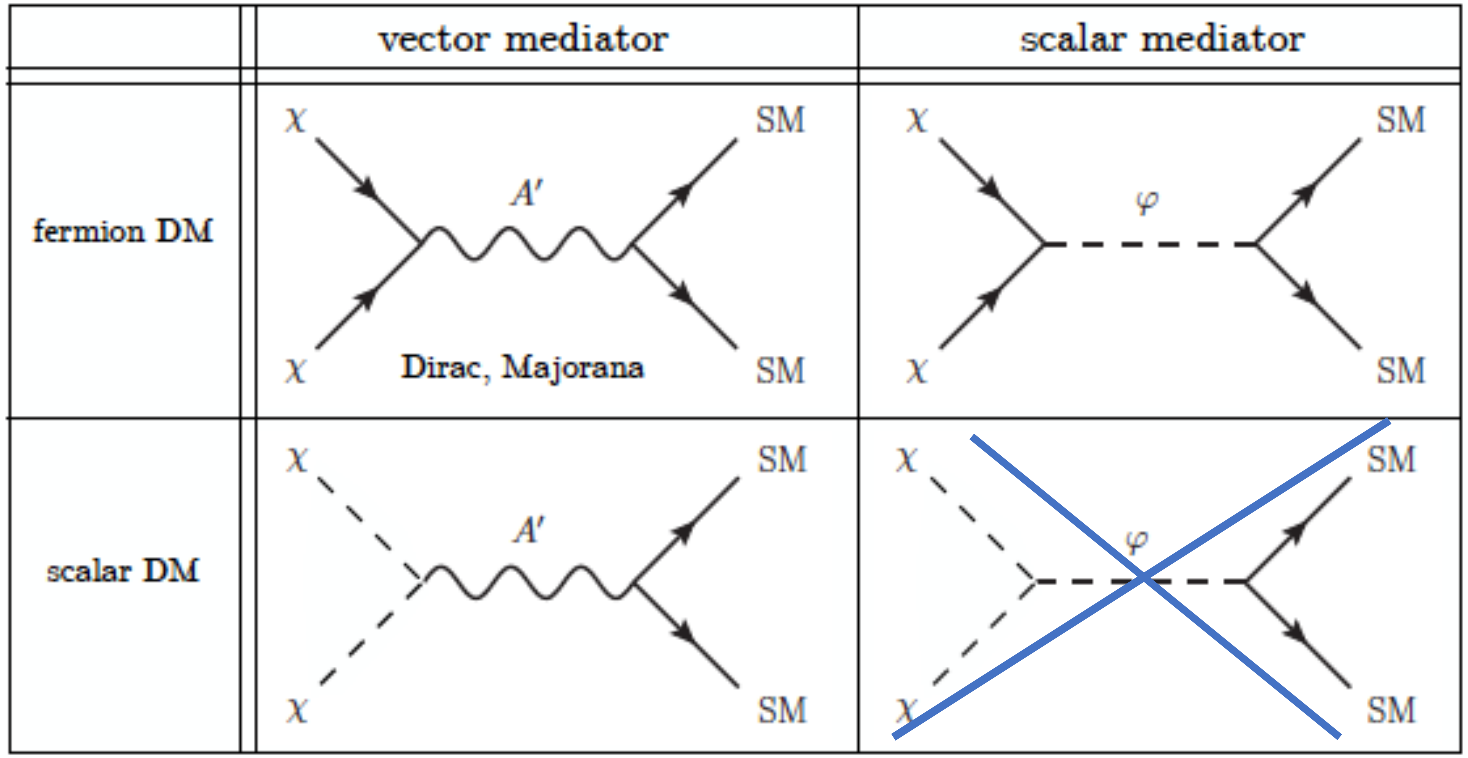
different combinations are allowed in p- and s-wave.



Different phenomenology depending on the spin of DM and mediator

Direct annihilation: Vector & Scalar mediators DM-SM:

different combinations are allowed in p- and s-wave.



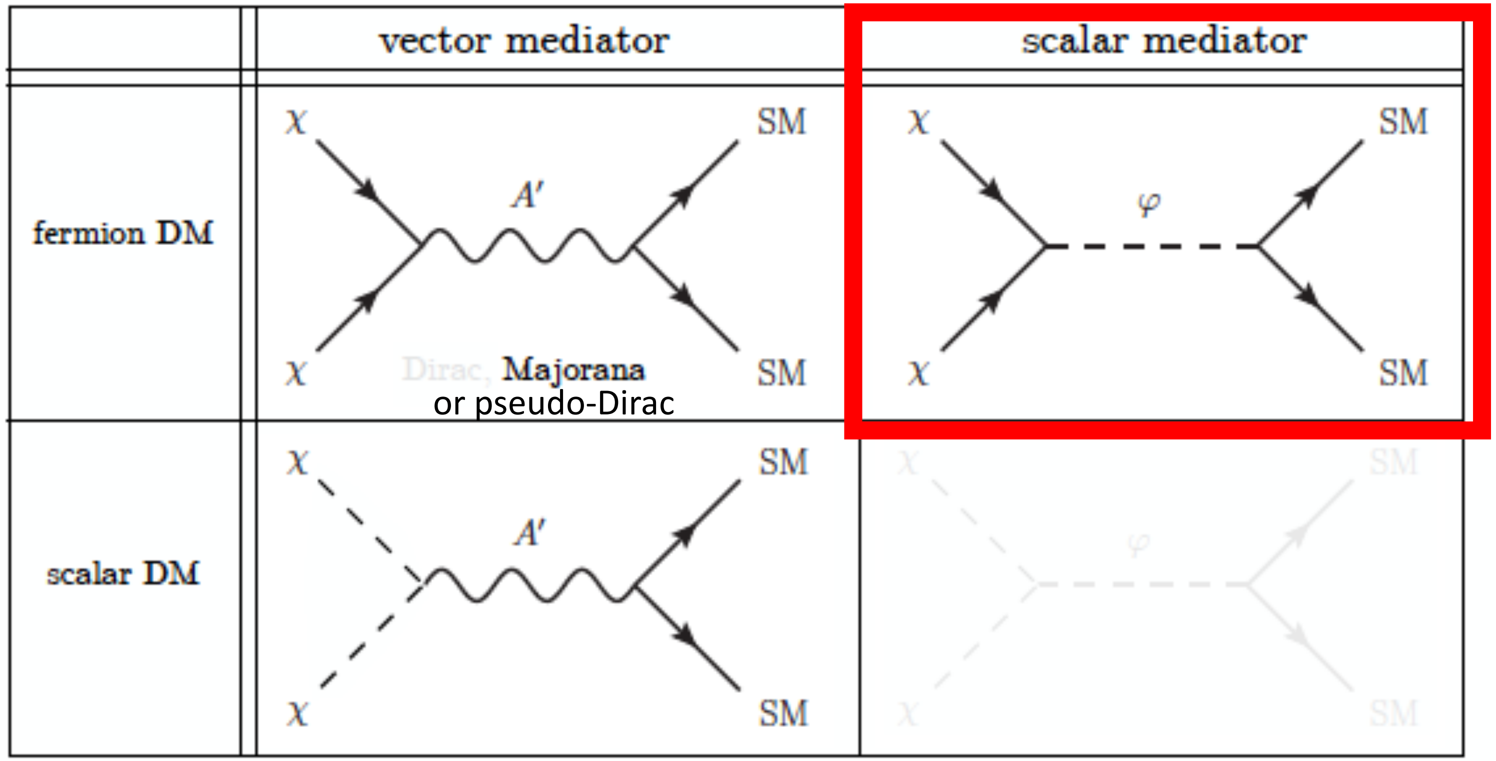
	vector mediator	scalar mediator
fermion DM	Dirac, Majorana	
scalar DM		

DM below 10 GeV annihilating in s-wave is excluded by CMB

Direct annihilation: Vector & Scalar mediators DM-SM:

different combinations are allowed in p- and ~~s-wave.~~

p-wave: $\sigma v \propto v^2$



Fermionic DM with a Scalar mediator

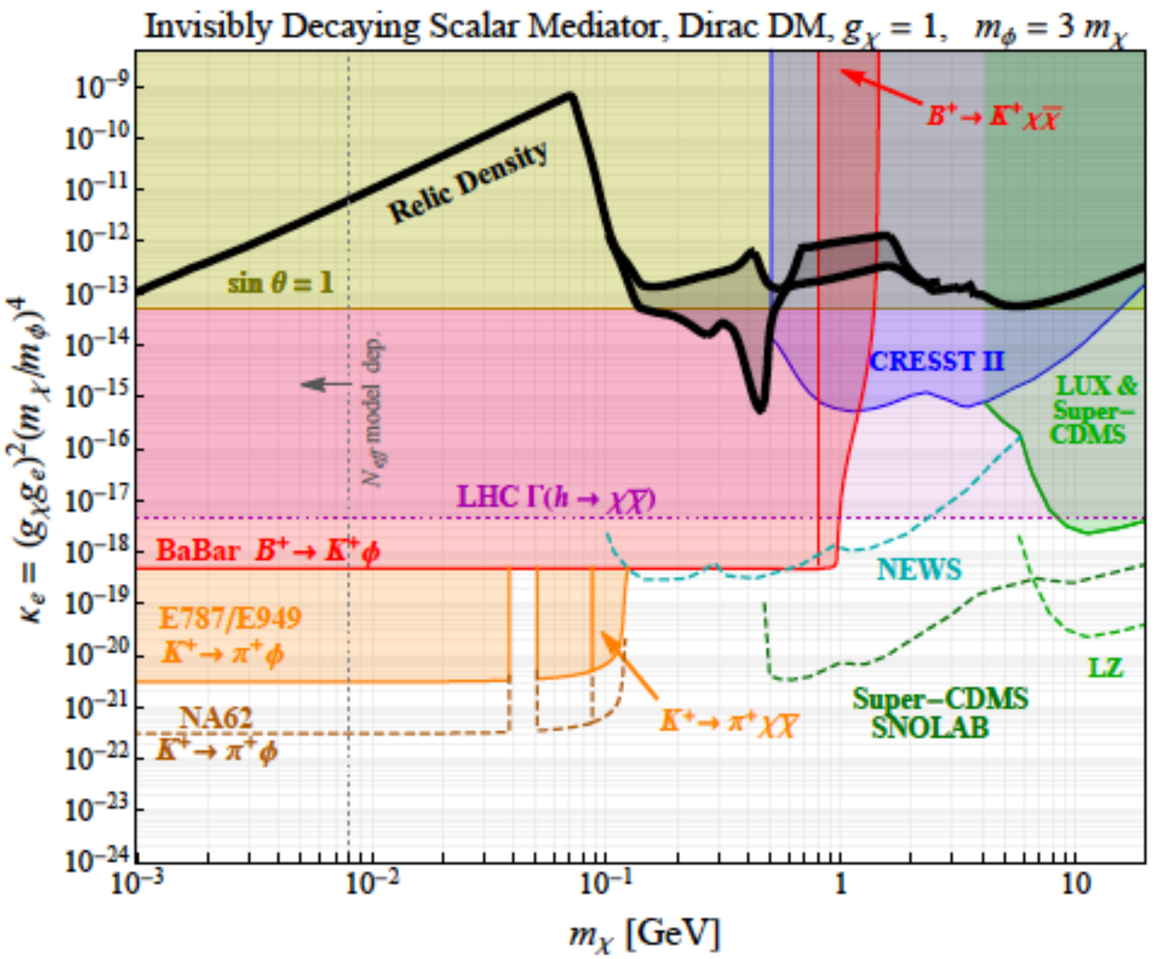
Berlin, FIPs 2020

(non-relativistic) annihilation cross-section

$$\sigma v_{\mathrm{rel.}}(\chi\chi \to f\bar{f}) = \frac{g_\chi^2 g_f^2 m_\chi^2 v_{\mathrm{rel.}}^2}{8\pi(m_\phi^2 - 4m_\chi^2)^2} \propto g_\chi^2 g_f^2 \left(\frac{m_\chi}{m_\phi}\right)^4 \frac{1}{m_\chi^2}$$

Light Fermionic DM and scalar mediator:

experimental bounds and projections



G. Krnajic arXiv: 1512.04119

In case of scalar mediator and Dirac DM, for s-channel, p-wave annihilation,
the DM thermal relic bound is saturated by low-energy and DD experiments below 10 GeV

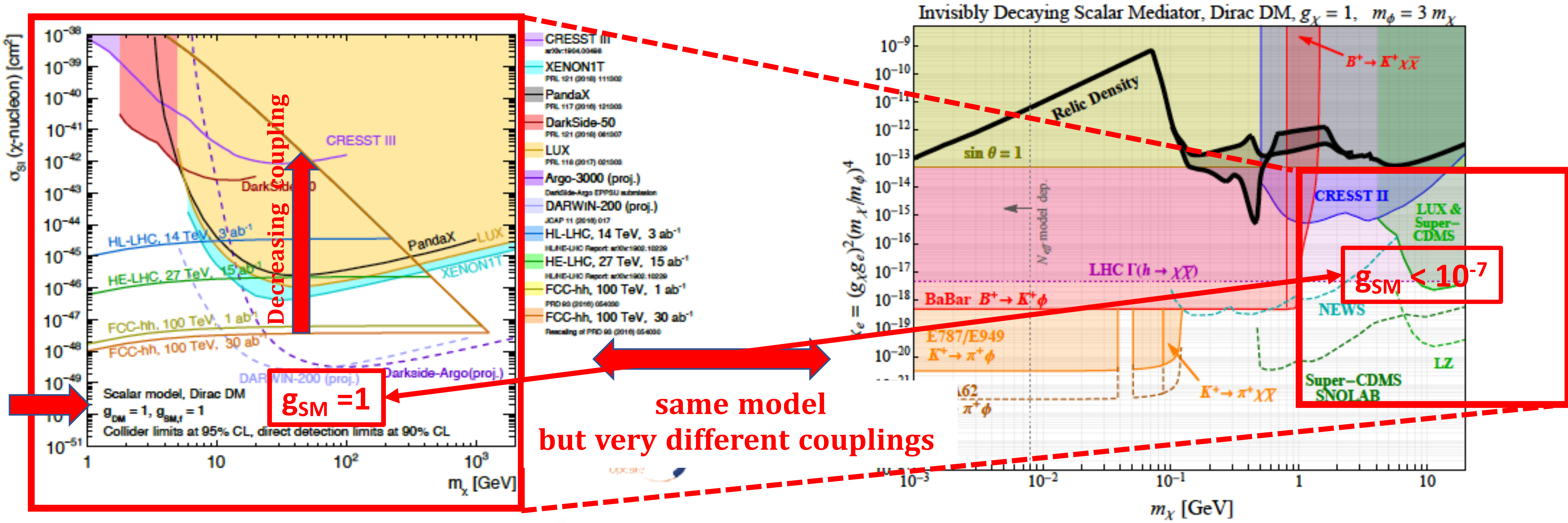
Light Fermionic Dark Matter with scalar mediator

DM Direct Detection vs Colliders vs Extracted beams

Specific model: SM SM ⟶ Dark Scalar ⟶ DM DM

Physics Briefing Book, 1910.11775, Fig.9.4, p.150

Phys.Rev. D94 (2016) no.7, 073009 arXiv: 1512.04119

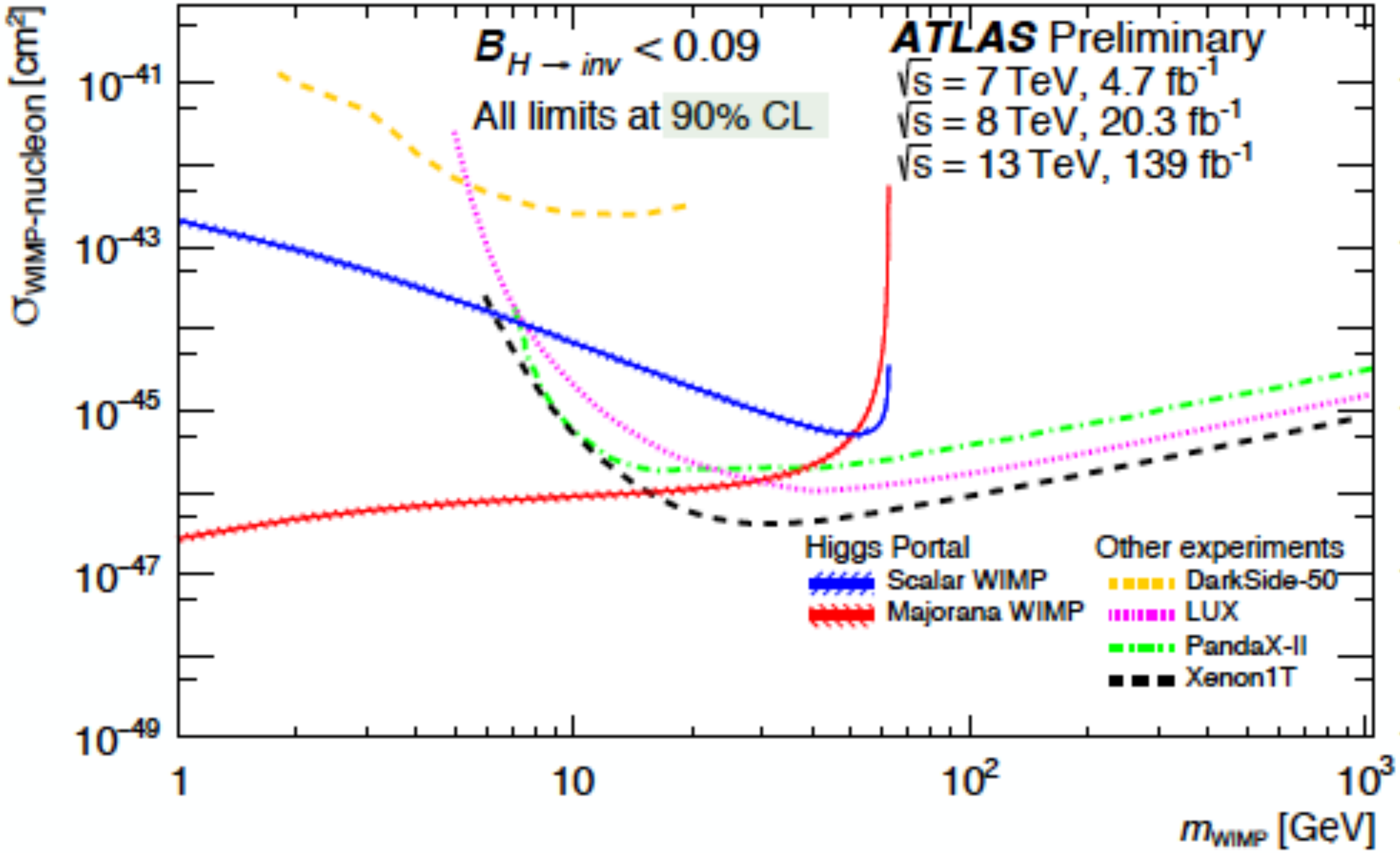


same model
but very different couplings

$$\sigma_{SI} \simeq 6.9 \times 10^{-43}\ \mathrm{cm}^2 \cdot \left(\frac{g_q g_{DM}}{1}\right)^2 \left(\frac{125\ \mathrm{GeV}}{M_{med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$$

It would be important to test LHC sensitivity to much smaller couplings for mass ranges below 10 GeV

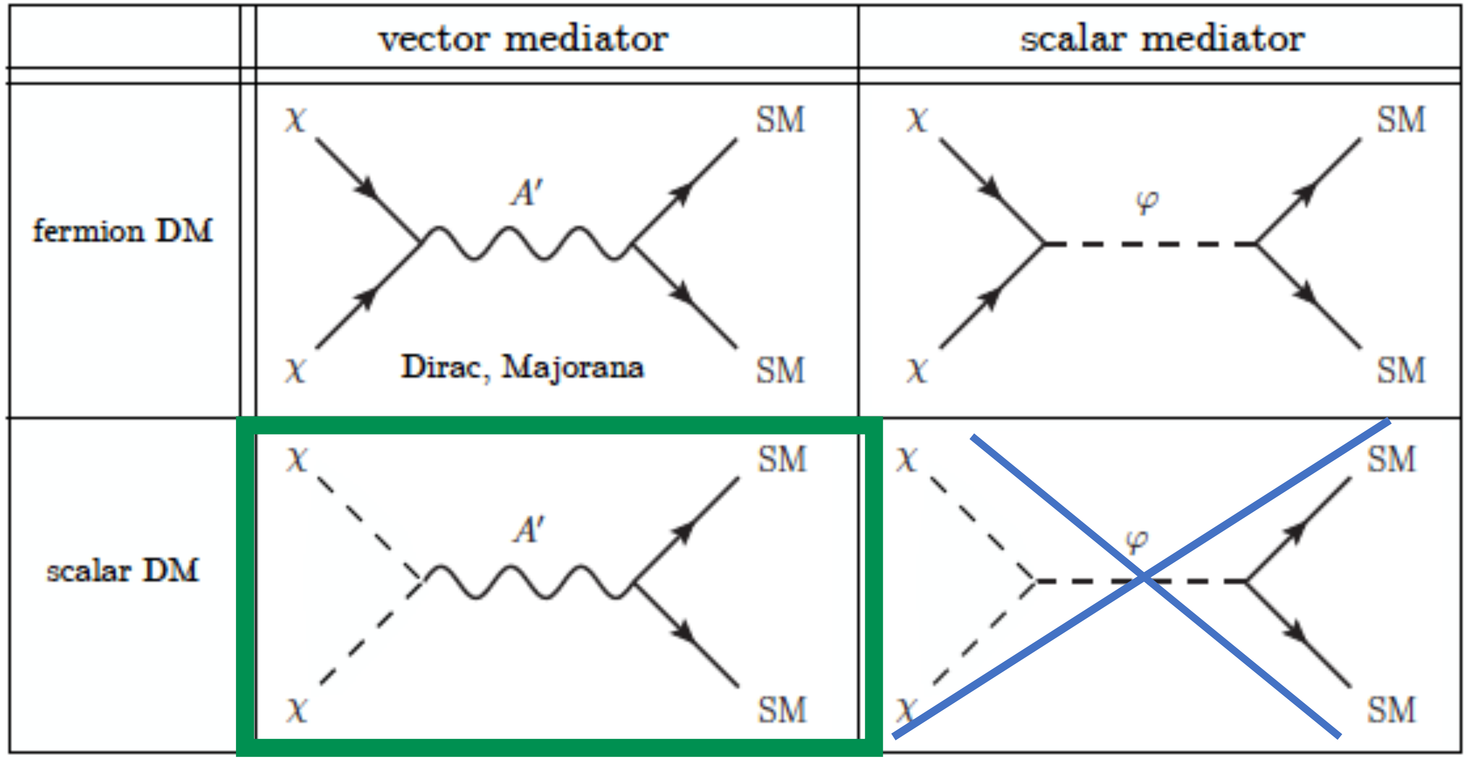
Search for Dark Matter through the invisible Higgs width



Very powerful method used at the LHC. Of course this is valid only if DM is Higgs-mediated.

Direct annihilation: Vector & Scalar mediators DM-SM:

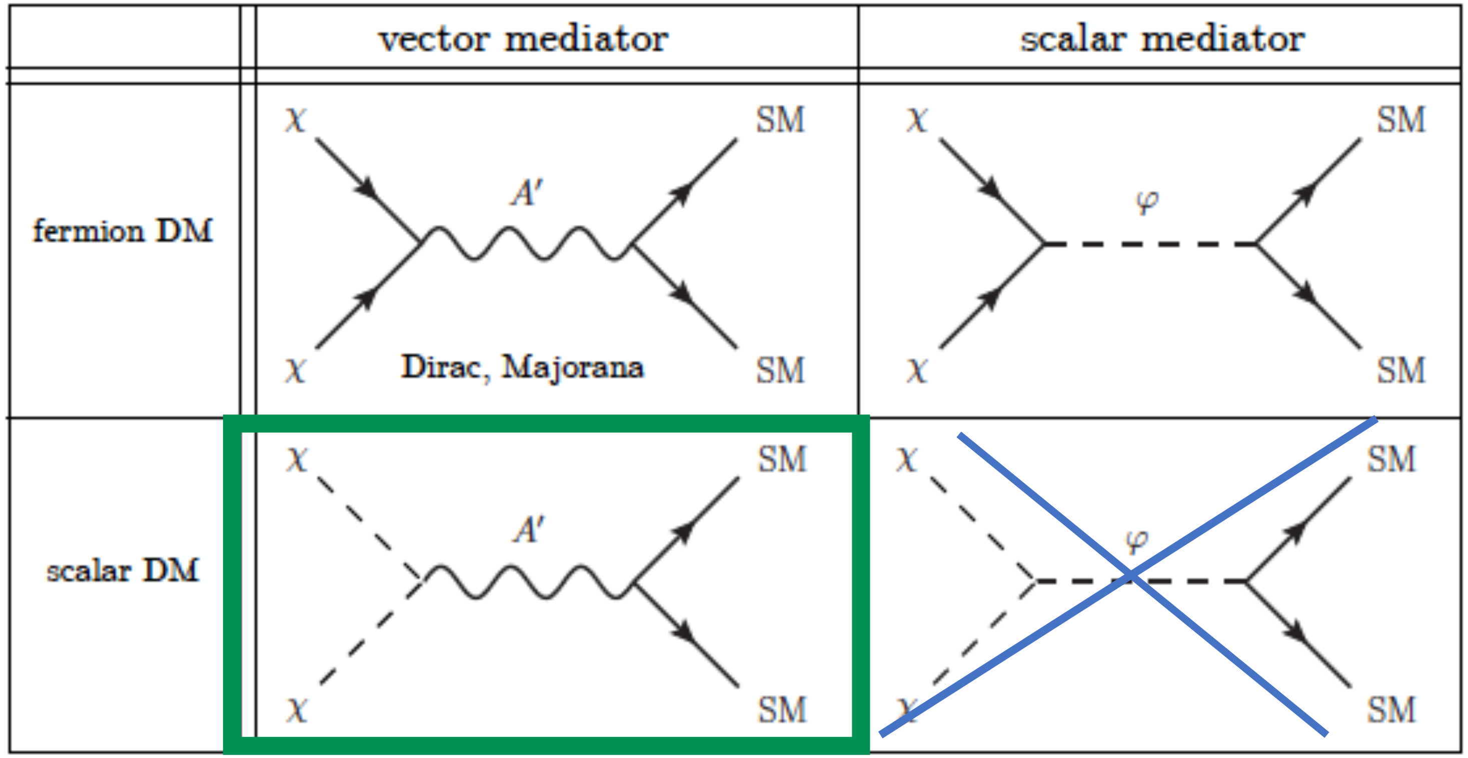
different combinations are allowed in p- and s-wave.



	vector mediator	scalar mediator
fermion DM	Dirac, Majorana	
scalar DM		

But p-wave ($\sigma v \sim v^2$) is compatible with cosmology (the annihilation rate is smaller at low T as the velocity redshifts with Hubble expansion).

Direct annihilation: Vector & Scalar mediators DM-SM:
different combinations are allowed in p- and s-wave.



But p-wave ($\sigma v \sim v^2$) is compatible with cosmology (the annihilation rate is smaller at low T as the velocity redshifts with Hubble expansion). However this could be a problem for DD:

MeV scale DM: Kin. Energy = m v^2/2 ~ (10-3)^2 MeV ~ eV (below the ionization threshold! For Xe is 13 eV…)

Direct annihilation: Vector mediator DM-SM:

Accelerator-based experiments

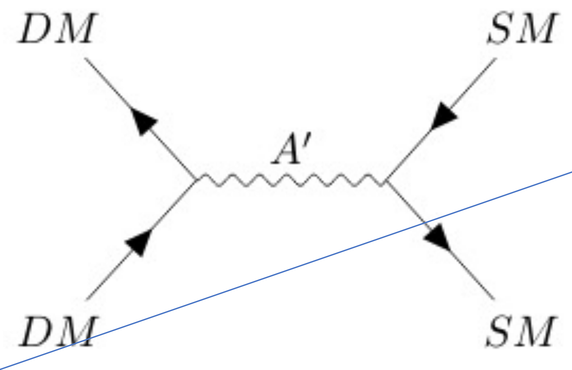
Production of DM at accelerators
(via SM (electron/proton/..) particles)

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

y variable

DM Direct detection experiments

DM scattering with e/protons



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

Astroparticle, cosmology

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

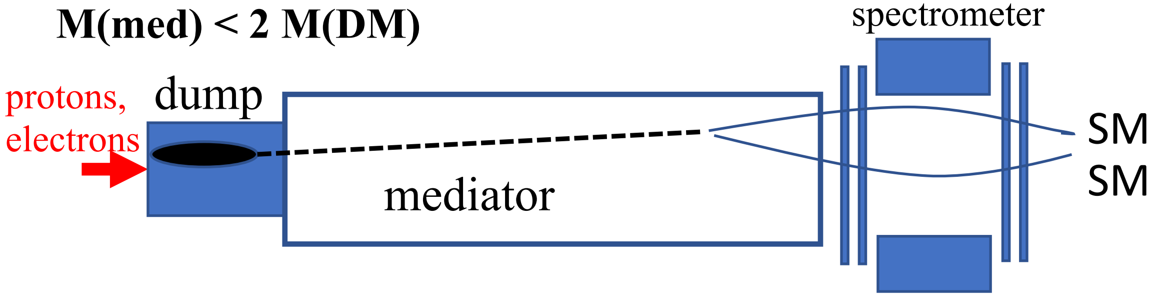
$$\boxed{\Omega_{\mathrm{DM}} h^2 \sim \frac{10^9\ \mathrm{GeV}^{-1}}{M_{\mathrm{pl}}} \frac{1}{\langle \sigma v \rangle}}$$

Within this framework we can interpret results from different fields.

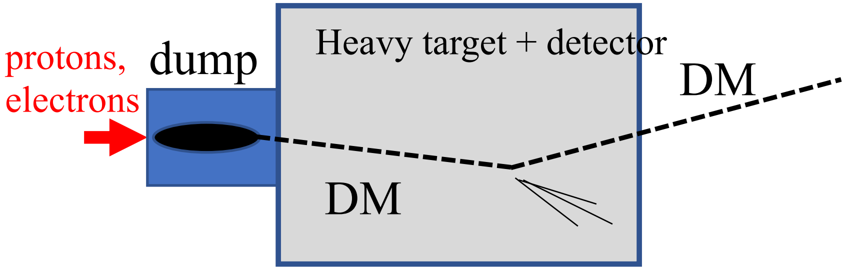
How can we “see” DM & mediators at accelerators ?

Experiments at extracted beam lines:

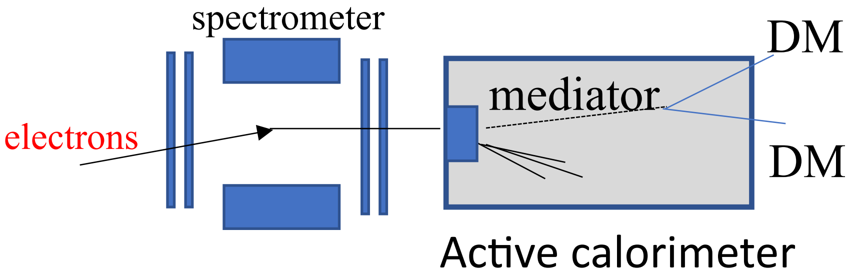
M(med) < 2 M(DM)



M(med) > 2 M(DM)



M(med) > 2 M(DM)



1. Mediators to visible final states:

Technique: bump searches:

- **NA62@CERN**, p@400 GeV, $N_{pot} = 10^{18}$-few 10^{19}
- **SHADOWS (proposal)**, p@400 GeV, N_{pot} = few 10^{19} pot
- **NA64@CERN**, e@100 GeV, N_{eot}: 10^{12}-10^{13} eot
- **SHiP@CERN (proposal),** p@400 GeV, $N_{pot} = 2\ 10^{20}$ pot
- **HPS, APEX, DarkLight @ JLAB** e@1-10 GeV
- **Sea(Dark)QUEST @ FNAL**, p@120 GeV, $10^{18} – 10^{20}$
- **Short-baseline neutrino exps**
- **Near detectors of long baseline neutrino exps.**

2. Mediators to invisible (light DM) final states:

Technique: DM scattering with the detector medium:

- **BDX @ JLAB** (e @ 11 GeV, 10^{22} eot)
- **MiniBooNE@FNAL** (p@8 GeV, 10^{20} pot)
- **SHiP@CERN (proposal),** p@400 GeV, $2\text{x}10^{20}$ pot

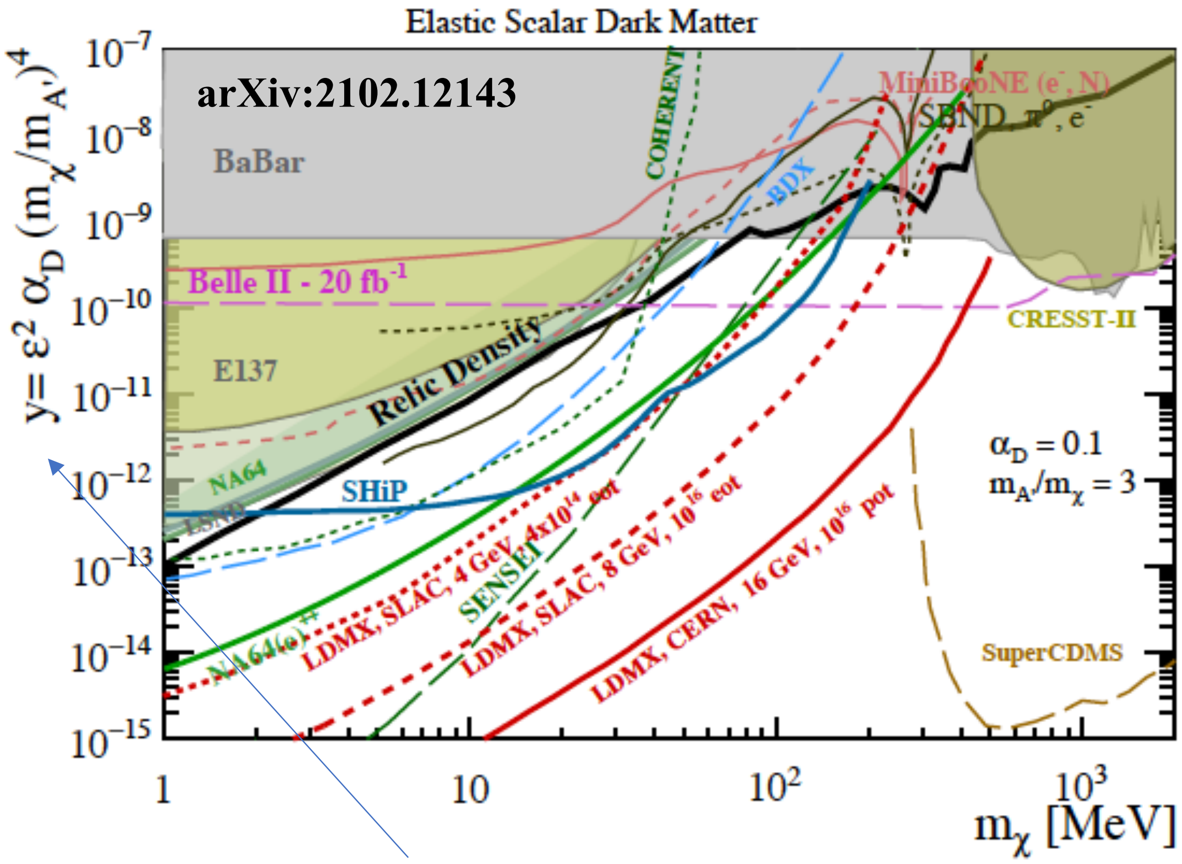
Technique: missing mass/energy/momentum

- **NA64(e)@CERN:** e@100 GeV, 10^{12}-10^{13} eot
- **NA62@CERN:** 10^{13} K decays
- **NA64(μ)@CERN (proposal):** μ@160GeV, 10^{13} mot
- **LDMX @ SLAC (proposal) :** e@4-8 GeV, **PADME @ LNF:** e@ 500 MeV

Scalar DM with Vector mediator

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

Accelerator based:

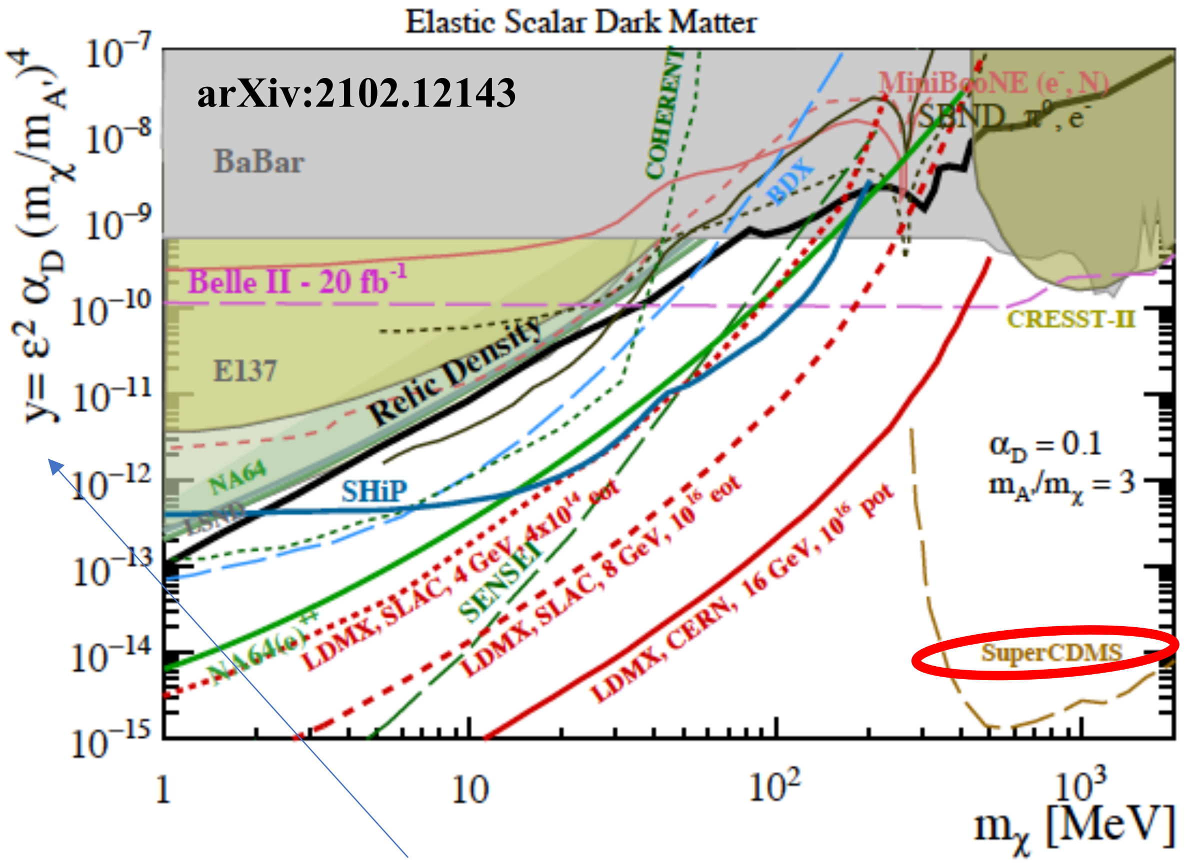


$$< \sigma v > \sim \alpha_D \varepsilon^2 \alpha \times \frac{m_{\rm DM}^2}{m_{A'}^4} \times m_{\rm DM}^2 \times \frac{1}{m_{\rm DM}^2}$$

Scalar DM with Vector mediator

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

Accelerator based:



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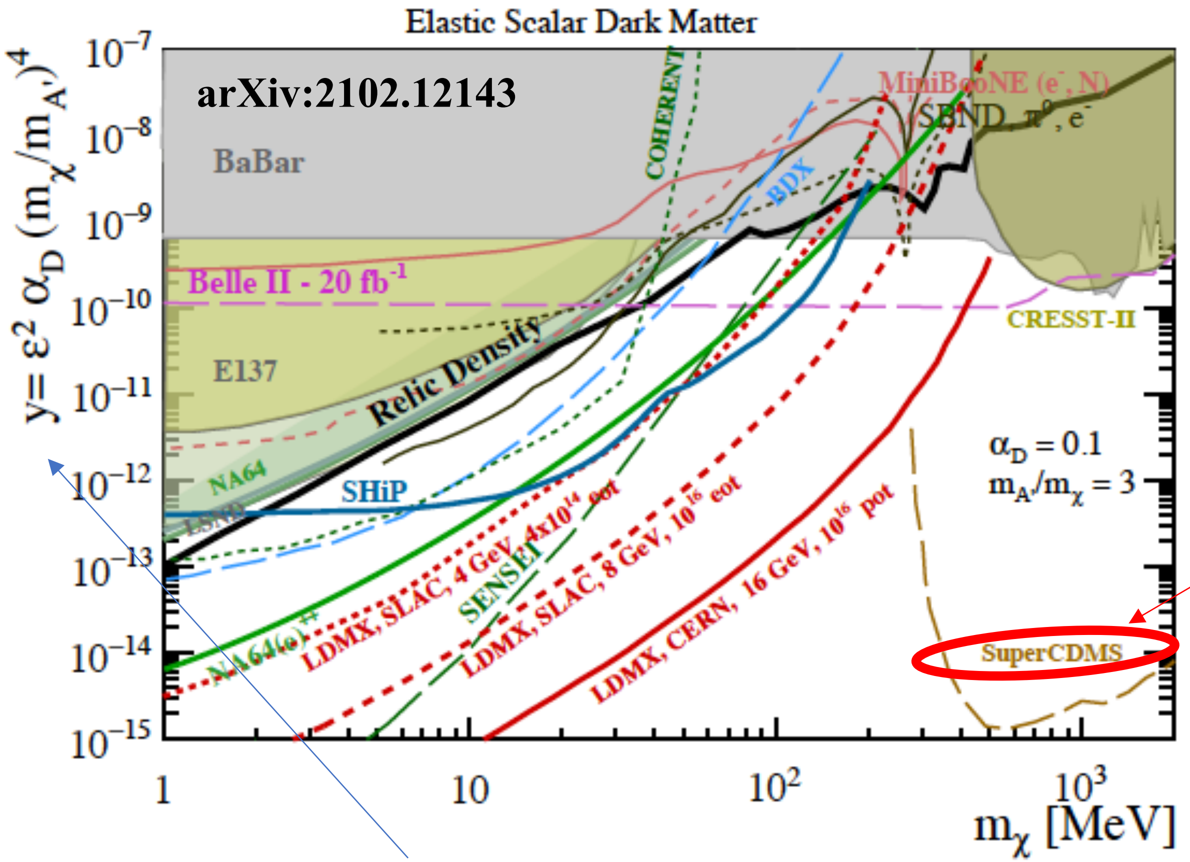
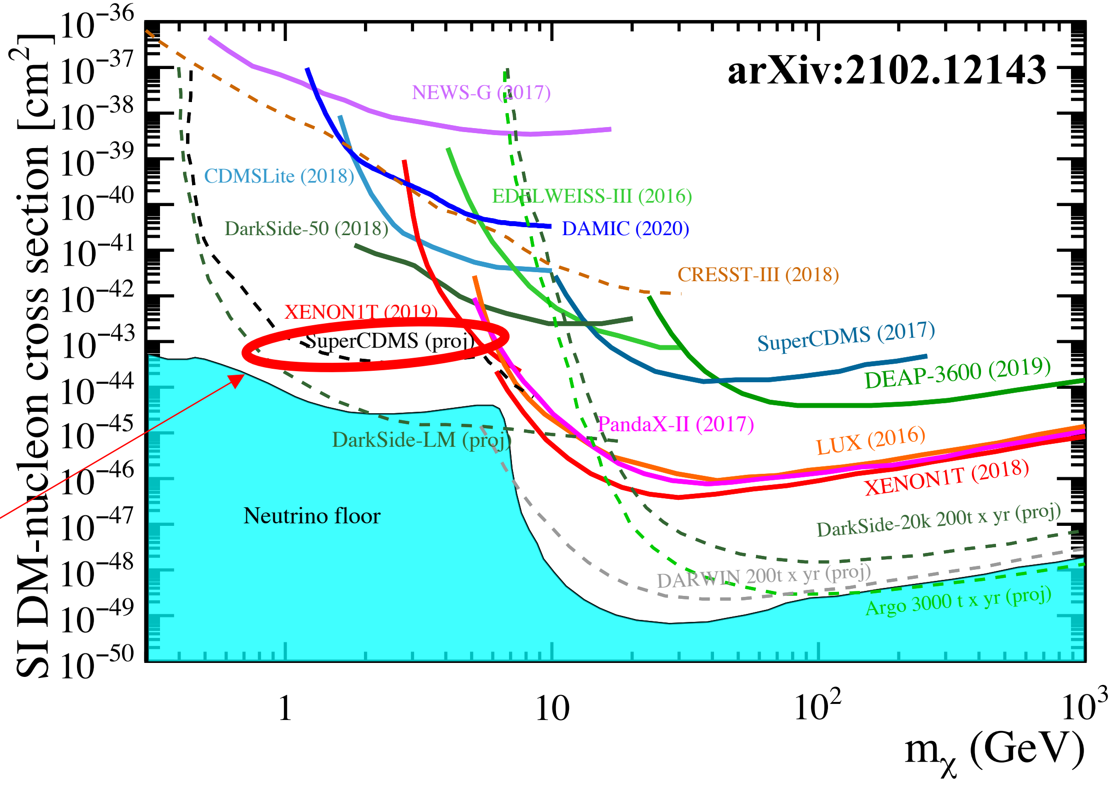


Direct detection:



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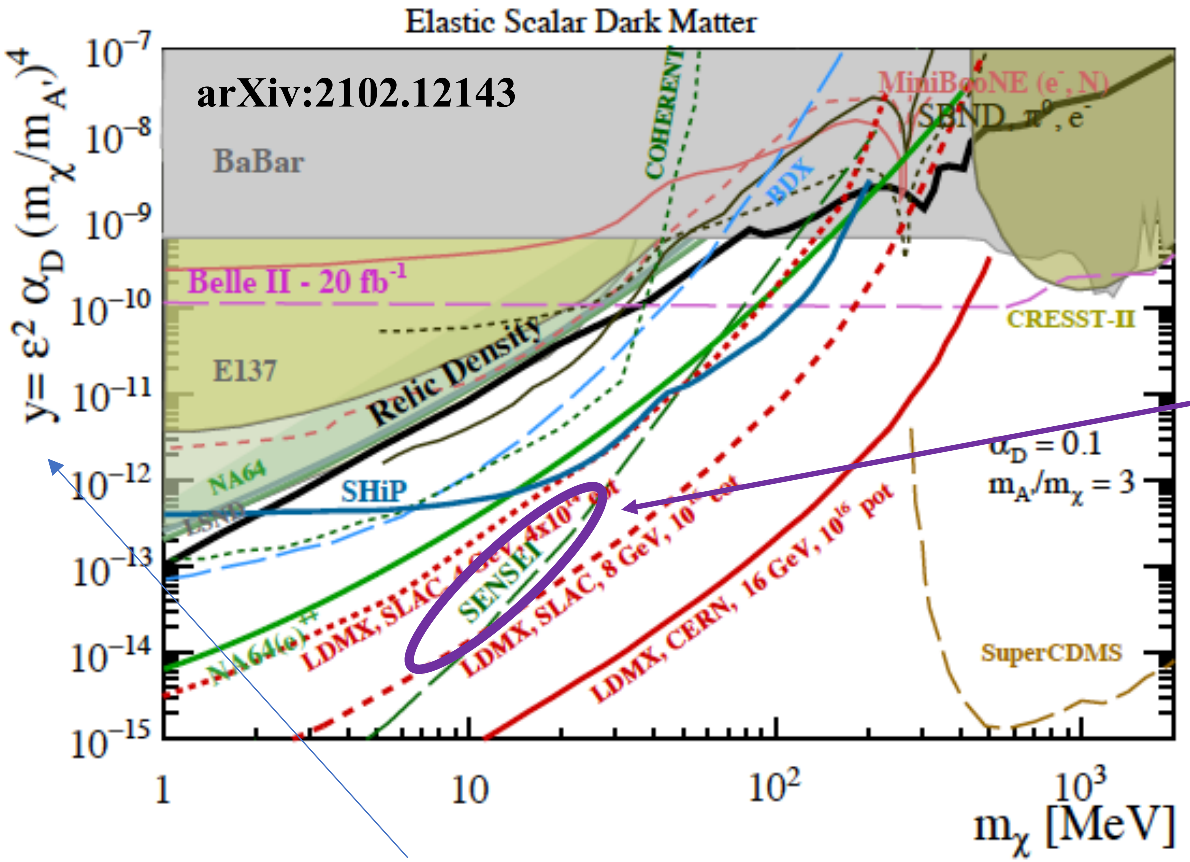
$$\sigma(\chi f \to \chi f) \simeq \frac{16\pi\, \alpha_{\rm em}\, \epsilon^2\, \alpha_D\, \mu_{\chi f}^2}{(q^2 + m_{A'}^2)^2},$$

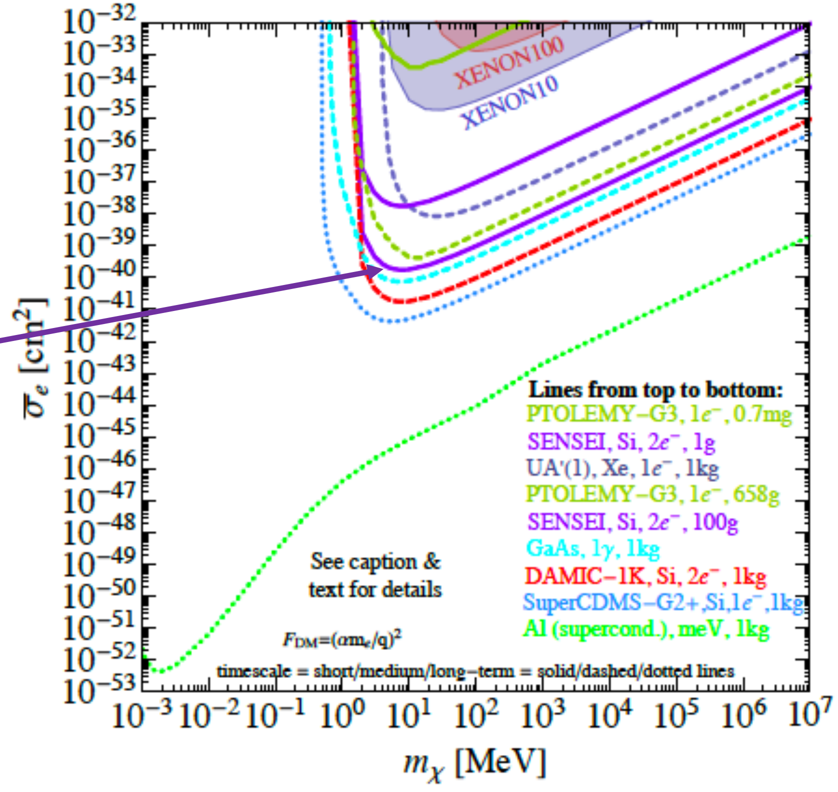
Scalar DM with Vector mediator

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

Accelerator based:



Direct detection:

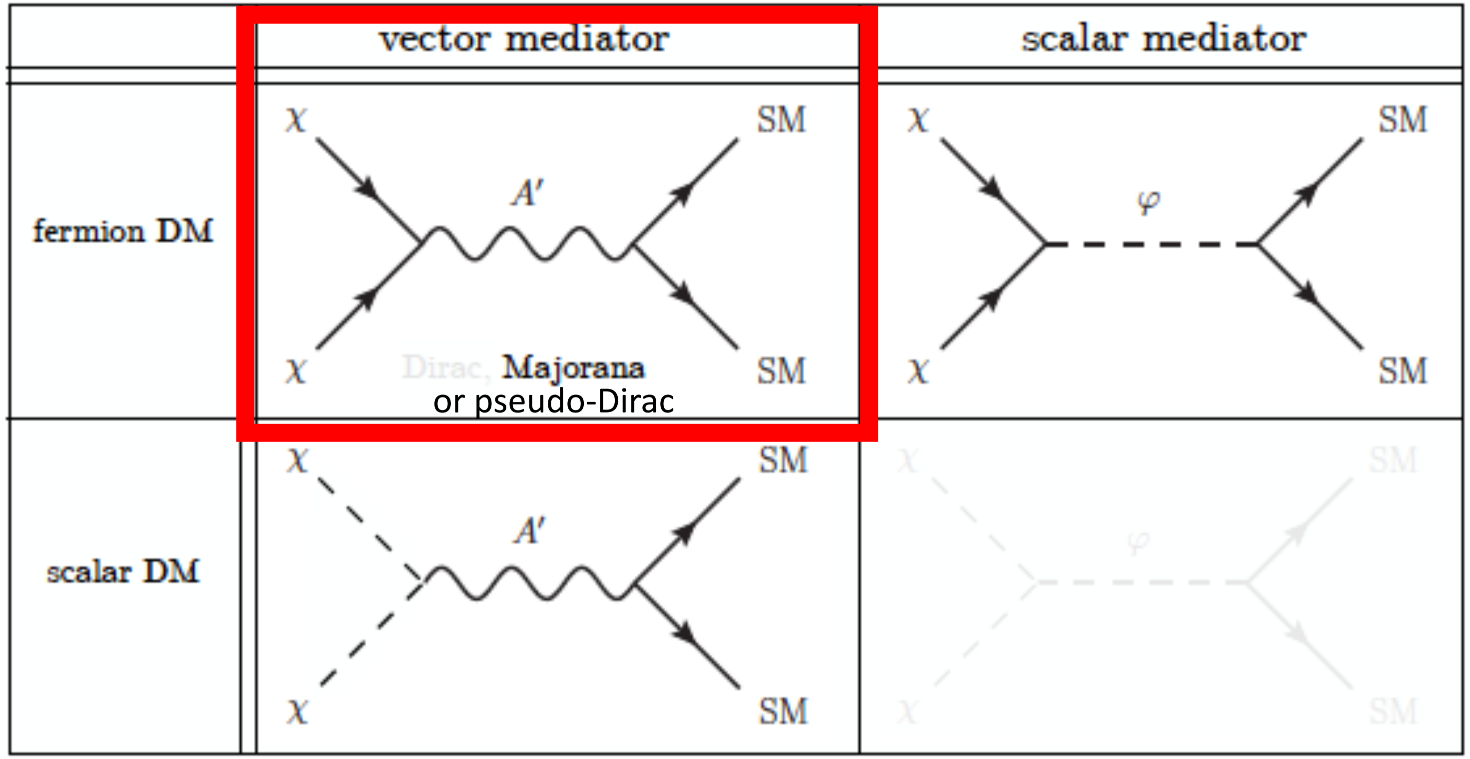


$$< \sigma v > \sim \alpha_D \varepsilon^2 \alpha \times \frac{m_{\rm DM}^2}{m_{A'}^4} \times m_{\rm DM}^2 \times \frac{1}{m_{\rm DM}^2}$$

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

Direct annihilation: Vector & Scalar mediators DM-SM:

<u>p-wave</u>: $\sigma v \propto v^2$



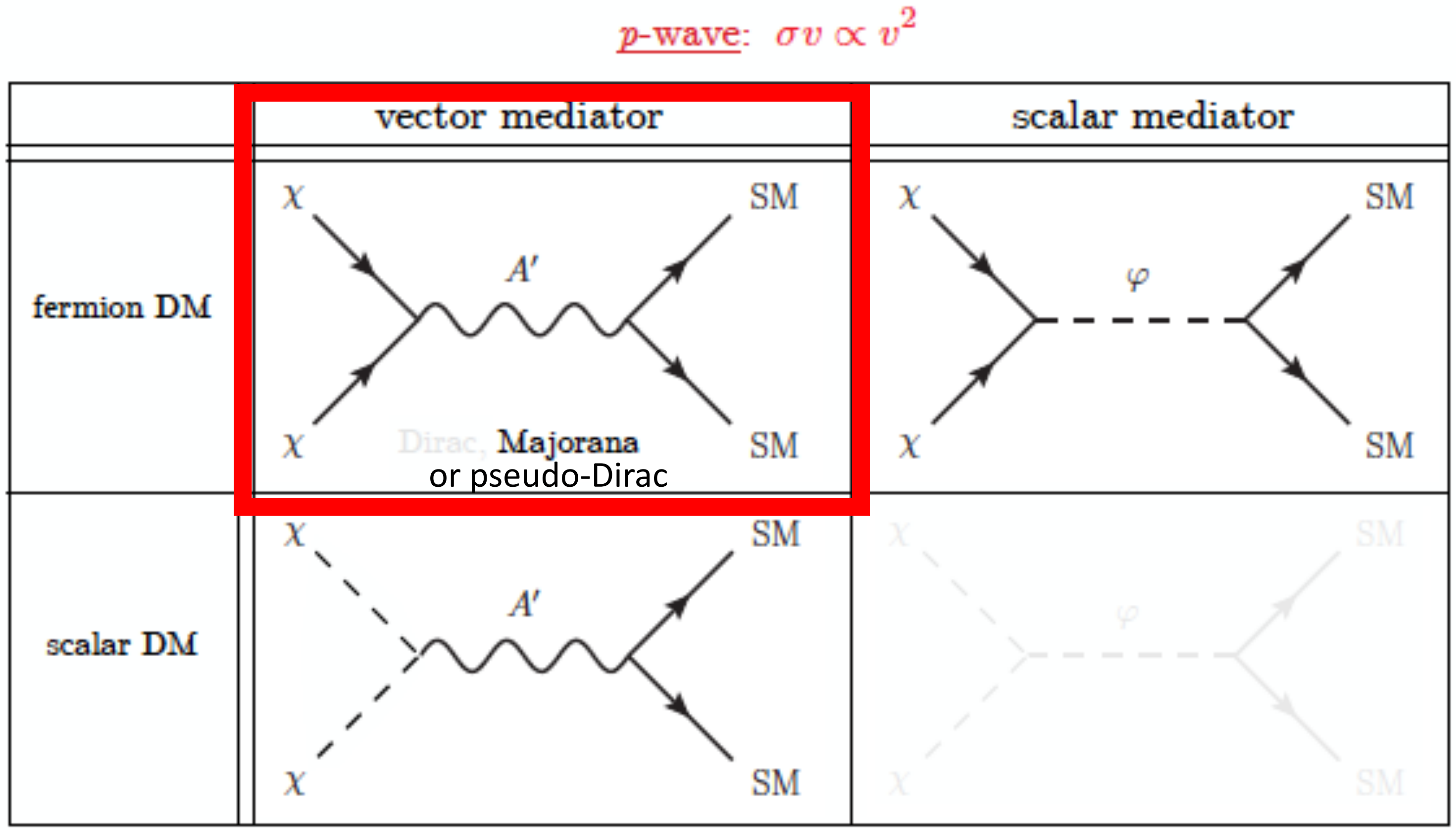
Berlin, FIPs 2020

Scattering off of SM fermions (χ_1 f → χ_2 f) is kinematically suppressed for DM mass-splitting larger than $\Delta/m_1 > O(10^{-6})$.

In this case DD sees nothing, accelerator-based exps could see it.

Direct annihilation: Vector & Scalar mediators DM-SM:

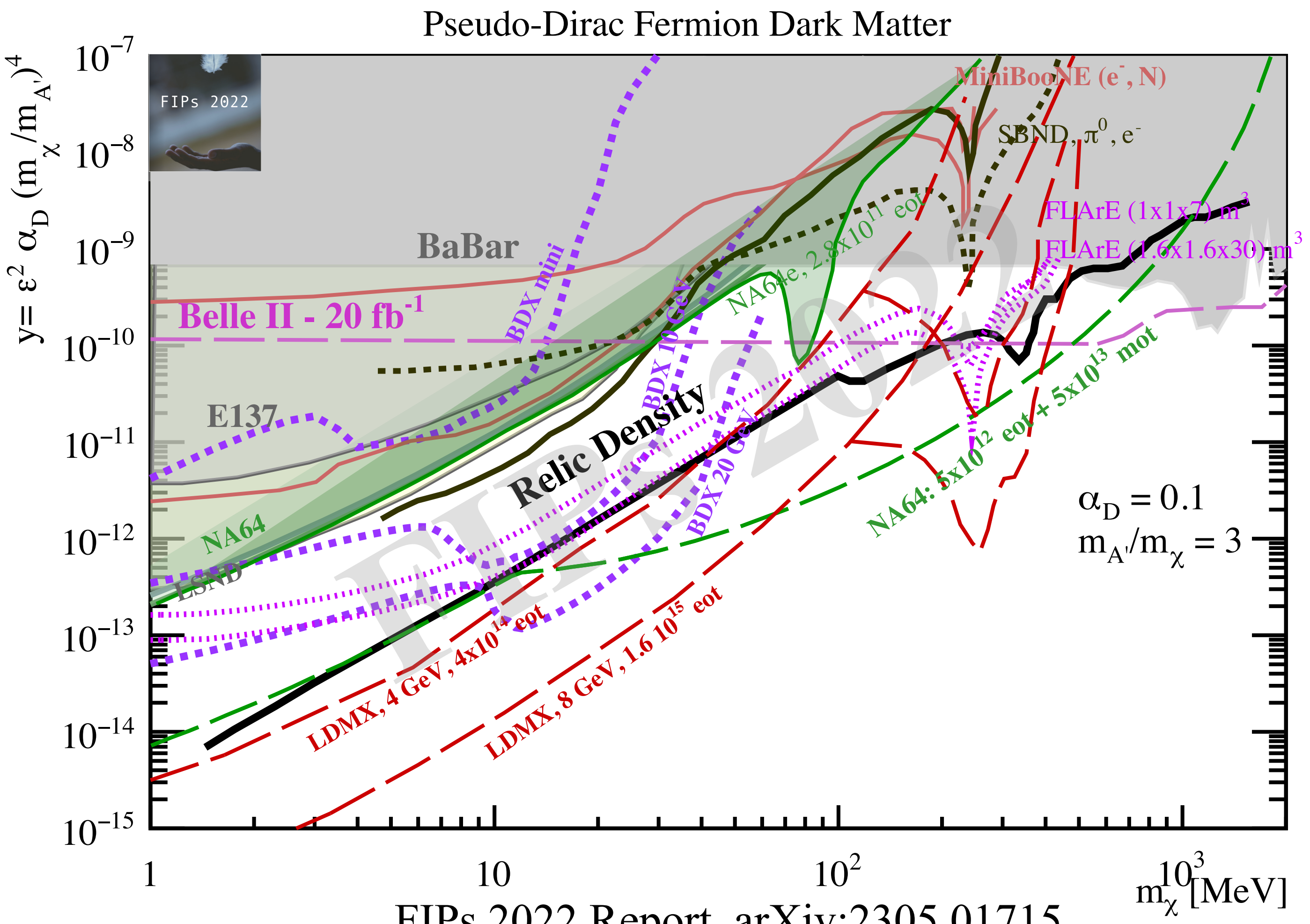
Berlin, FIPs 2020



Assume a pseudo-Dirac fermion with two components and Delta M = 10^{-3} M, M ~ MeV

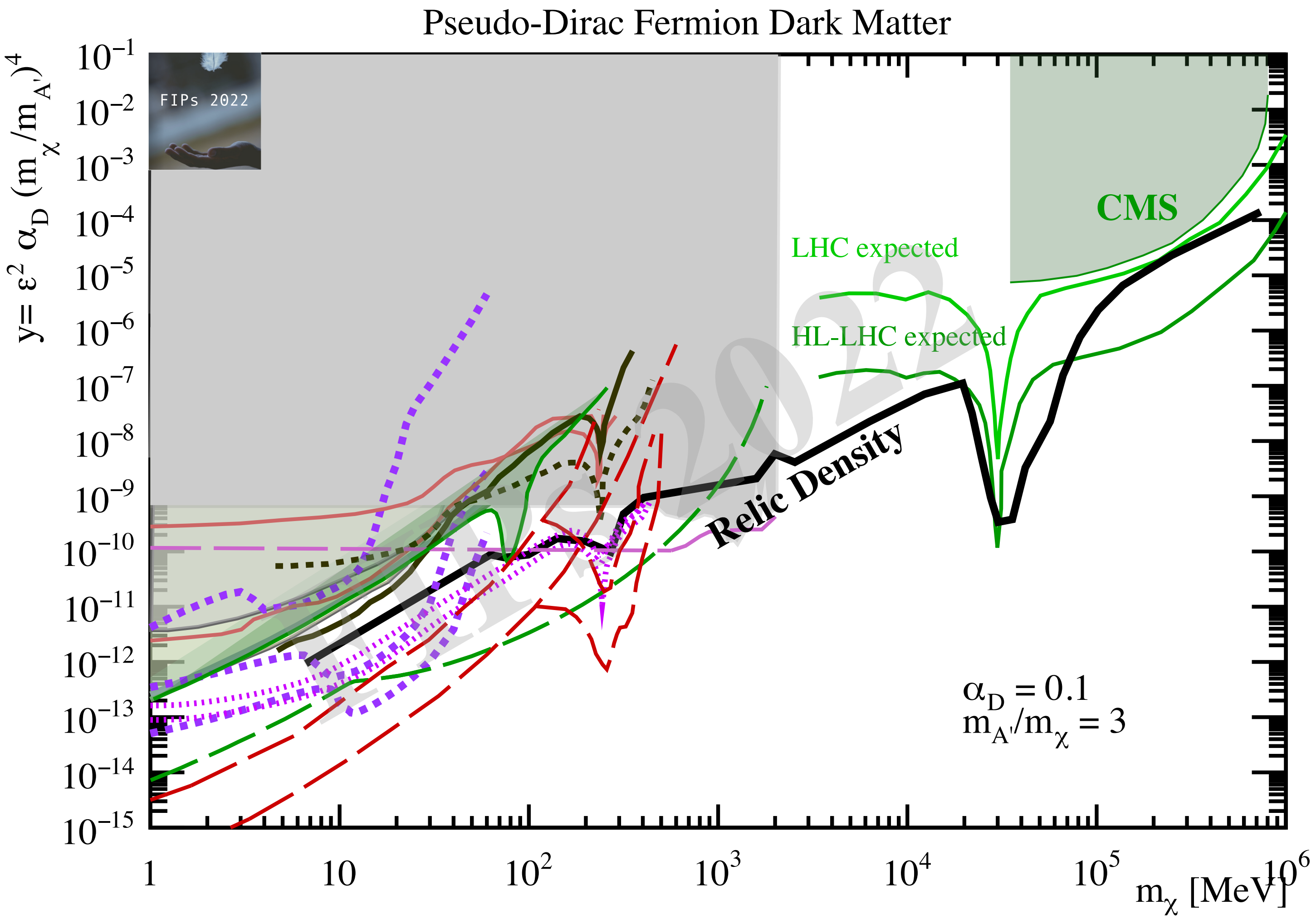
During annihilation, for T = 0.1 m(chi) this Delta M does not play any role, but in the t-channel, for direct detection, the lightest particle can scatter into the heavier only if the kinetic energy transfer is larger than Delta M (keV) → hence the scattering can be quenched down.

Pseudo-Dirac DM with a Vector mediator


Pseudo-Dirac Fermion Dark Matter

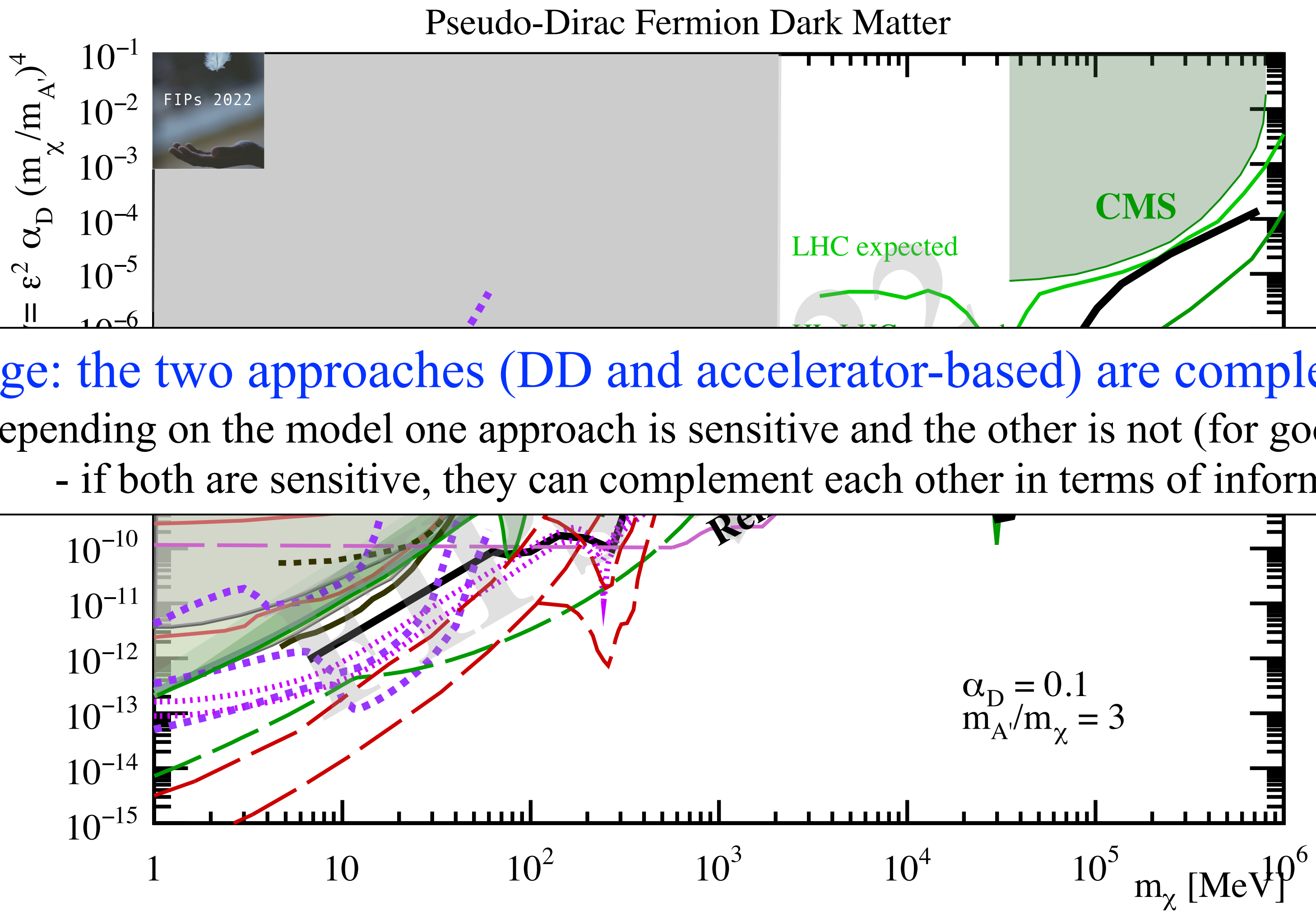
FIPs 2022 Report, arXiv:2305.01715

Pseudo-Dirac DM with a Vector mediator


Pseudo-Dirac Fermion Dark Matter

Extension of sensitivity in the high mass region – LHC physics reach

Pseudo-Dirac DM with a Vector mediator



Take home message: the two approaches (DD and accelerator-based) are complementary and synergistic:

- depending on the model one approach is sensitive and the other is not (for good reasons).
- if both are sensitive, they can complement each other in terms of information.

Extension of sensitivity in the high mass region – LHC physics reach

Outline of the items open for discussion

1. Dark Matter in the MeV-GeV range:
    - why in this range
    - current theoretical-phenomenological approach
    - current experimental results
    - future prospects

➡ 2. Heavy Neutral Leptons below EW scale
    - why in this range
    - current theoretical-phenomenological approach
    - current experimental results
    - future prospects

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

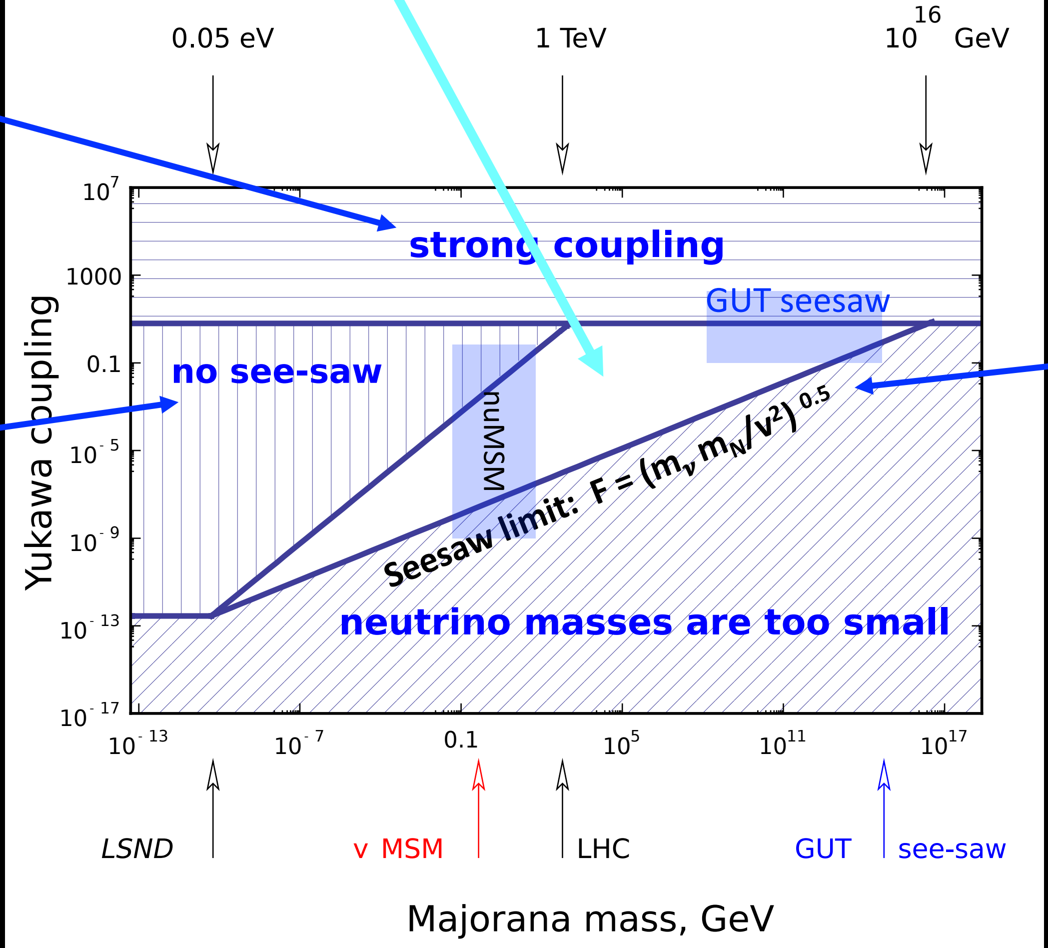
$SU(2)xU(1)_L$ singlet Right Handed Neutrinos responsible of the neutrinos' mass generation can have any coupling/mass in the white area, assuming an approximate $U(1)_L$ global symmetry

<u>One or few of the Yukawas exceed unity</u>.

-> perturbative treatment is not valid.

<u>Dirac neutrino masses exceed the Majorana masses of the HNLs.</u>

(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.)



<u>Seesaw line:</u>

Below this line neutrino masses cannot be explained.

Couplings, masses, and number of HNLs are unknown:

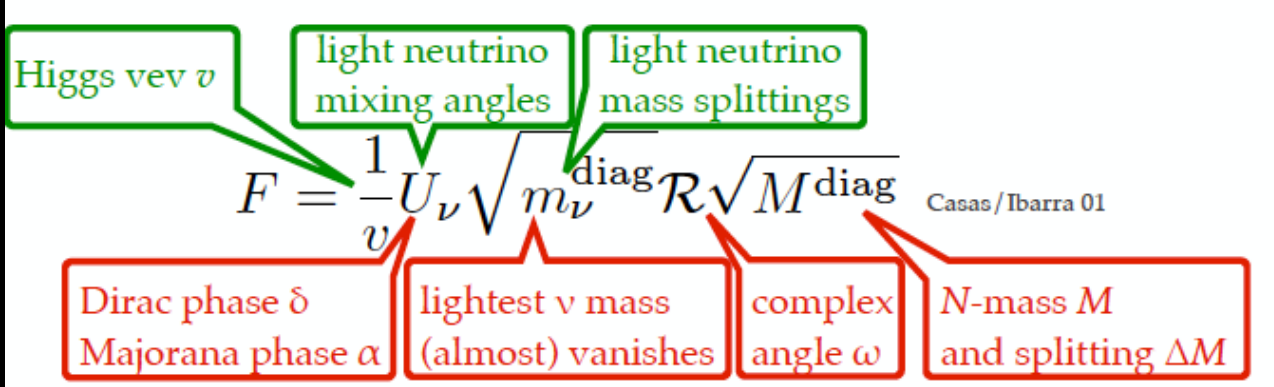
N = 2 if m(active lightest) = 0;

N = 3 if m(active lightest)>0

Large spectrum of possible masses & couplings

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

Close connection with the physics of active neutrinos



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

Casas/Ibarra 01

Higgs vev v

light neutrino mixing angles

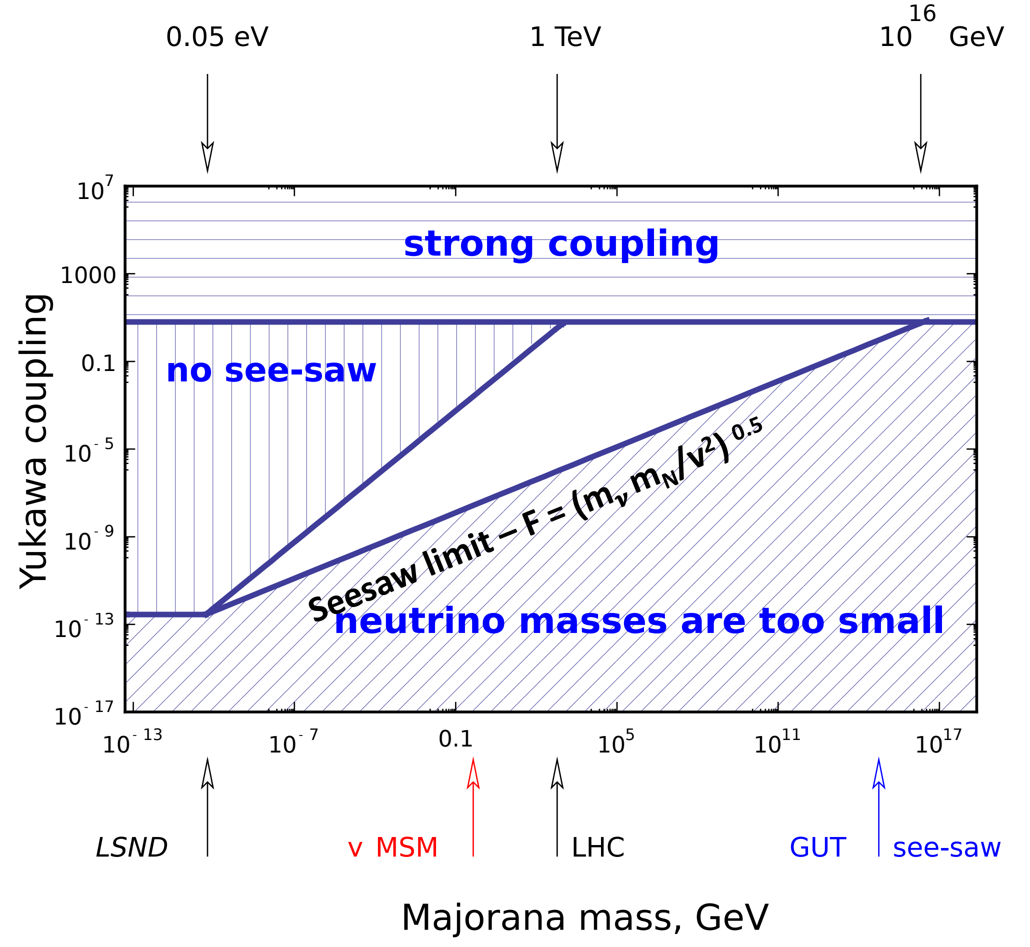
light neutrino mass splittings

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:

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

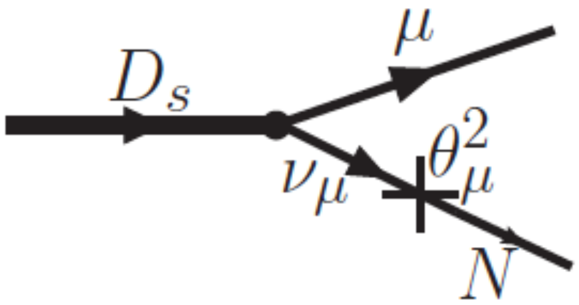
For m_N= 2 GeV , $U^2 \sim 10^{-8}$

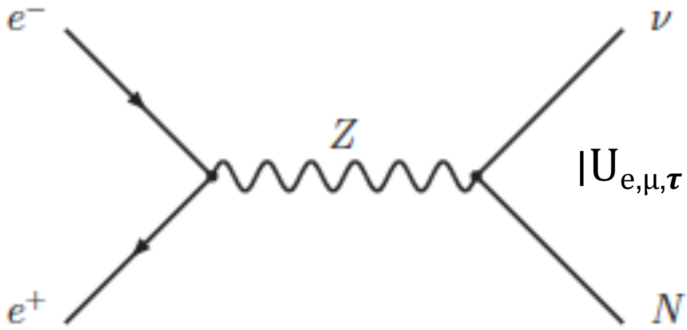
→ Yukawa coupling ~ 10^{-6} (like the electron…)

HNL below EW scale: production modes
(and corresponding experimental facilities)

If the HNLs exist, they would be produced in every process containing active neutrinos with a branching fraction proportional to the mixing parameters $|U_{e,\mu,\tau}|^2$.

K decays ⟶ kaon and neutrino experiments;
D,B decays ⟶ B-factories, LHCb and beam-dump
W decays ⟶ LHC and future pp, ep colliders
Z decay ⟶ LEP and future e+ e- colliders

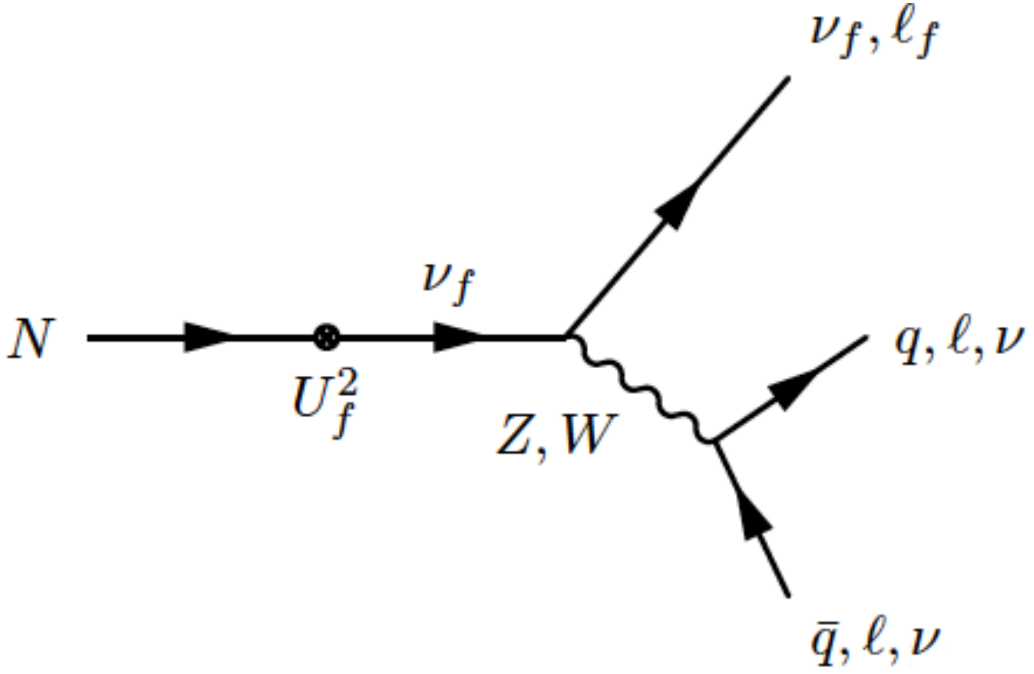




$|U_{e,\mu,\tau}|^2$

HNL decay modes

Once produced, they can then decay again to SM particles through mixing (U^2) with a SM neutrino. This (now massive) neutrino can decay to a large amount of final states through emission of a Z^0 or W boson (NC or CC currents):



Decay channels

$N \to H^0\nu$, with $H^0 = \pi^0, \rho^0, \eta, \eta'$

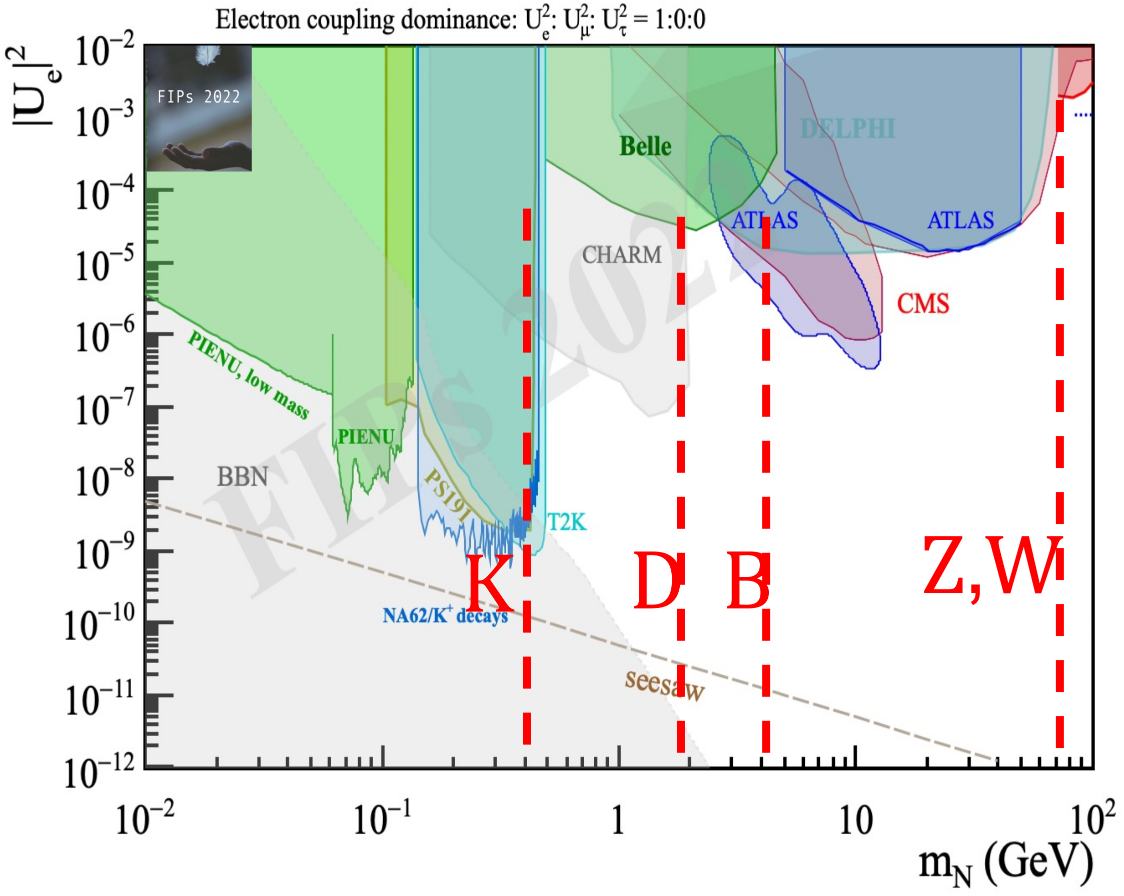
$N \to H^\pm\ell^\mp$, with $H = \pi, \rho$

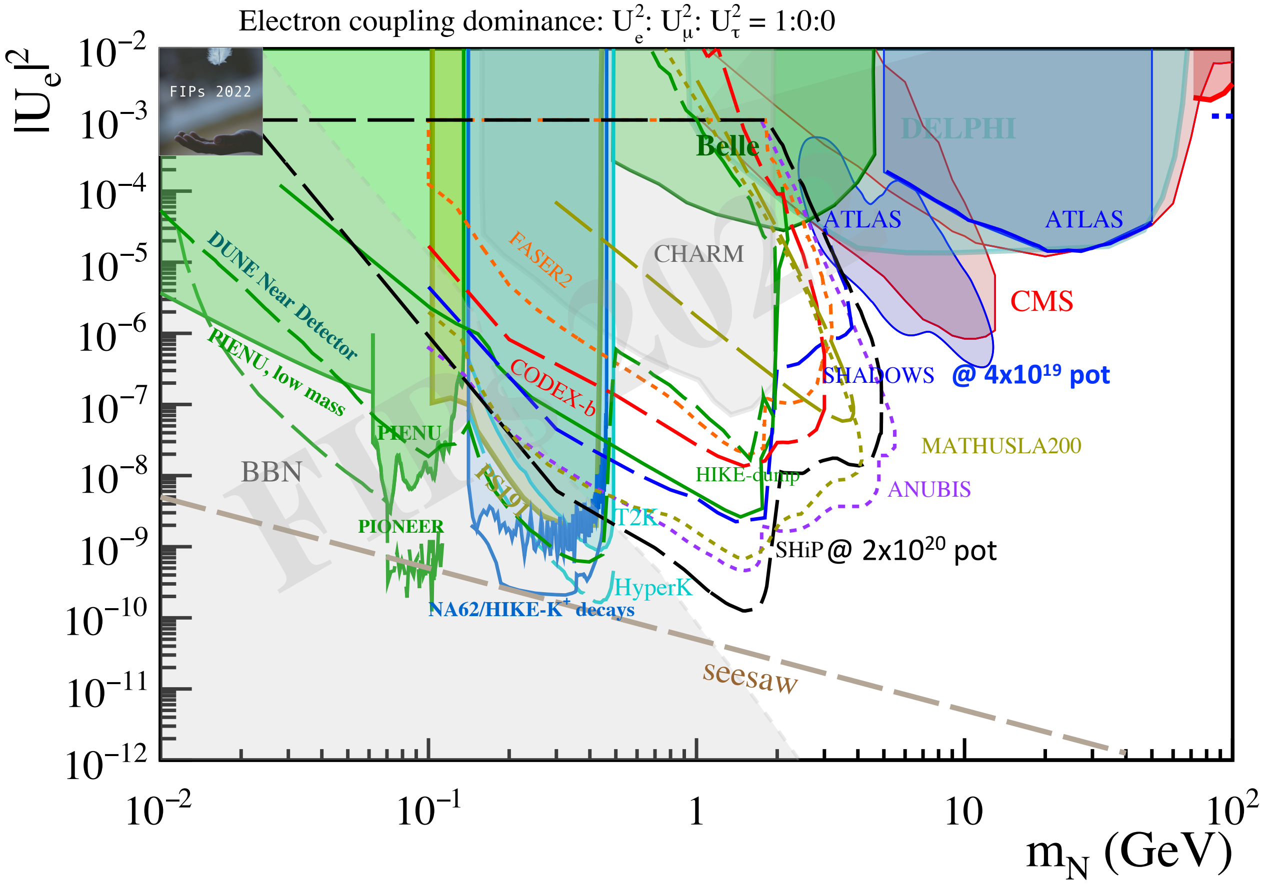
$N \to 3\nu$

$N \to \ell_i^\pm \ell_j^\mp \nu_j$

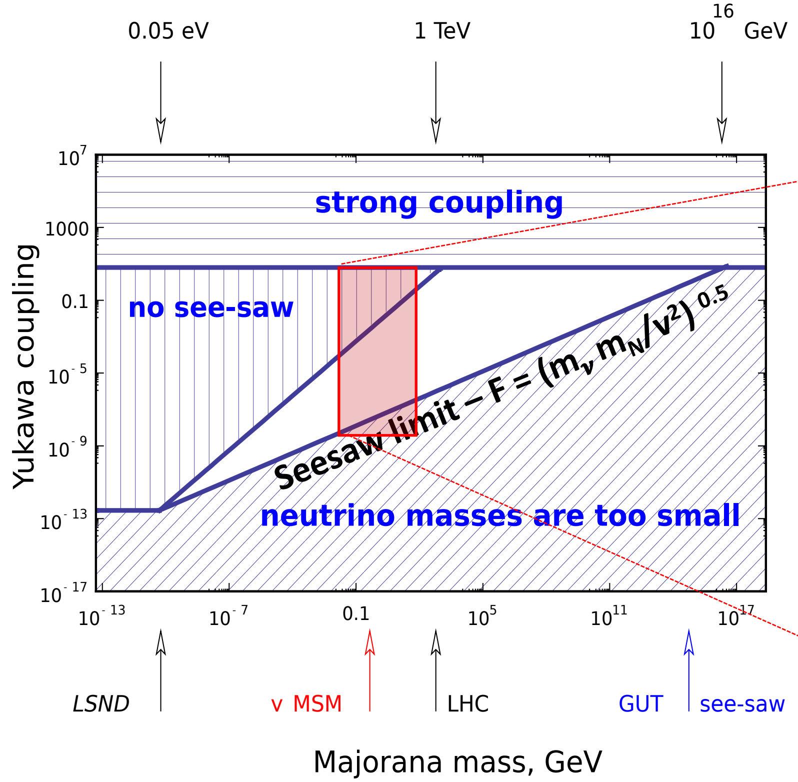
$N \to \nu_i \ell_j^\pm \ell_j^\mp$

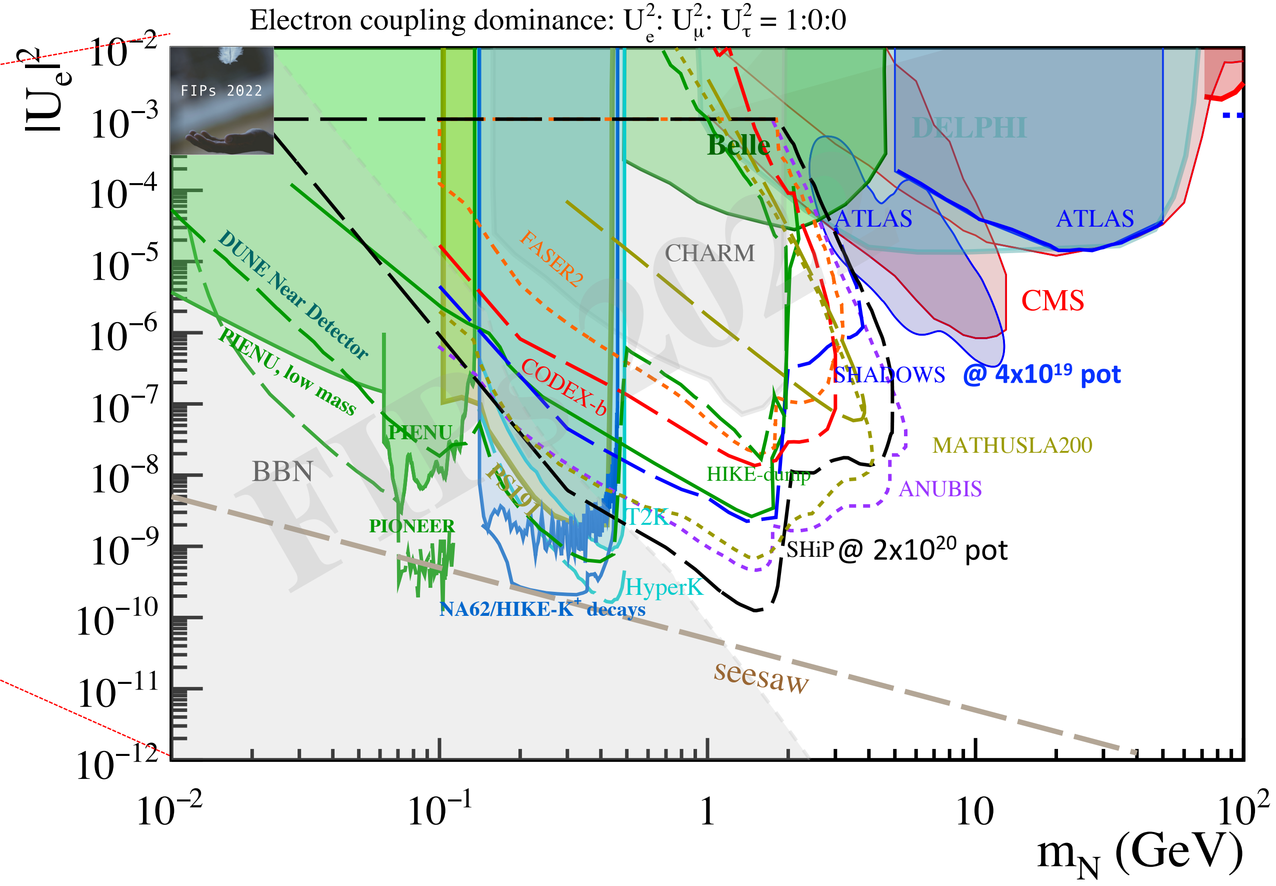
HNL searches: electron coupling





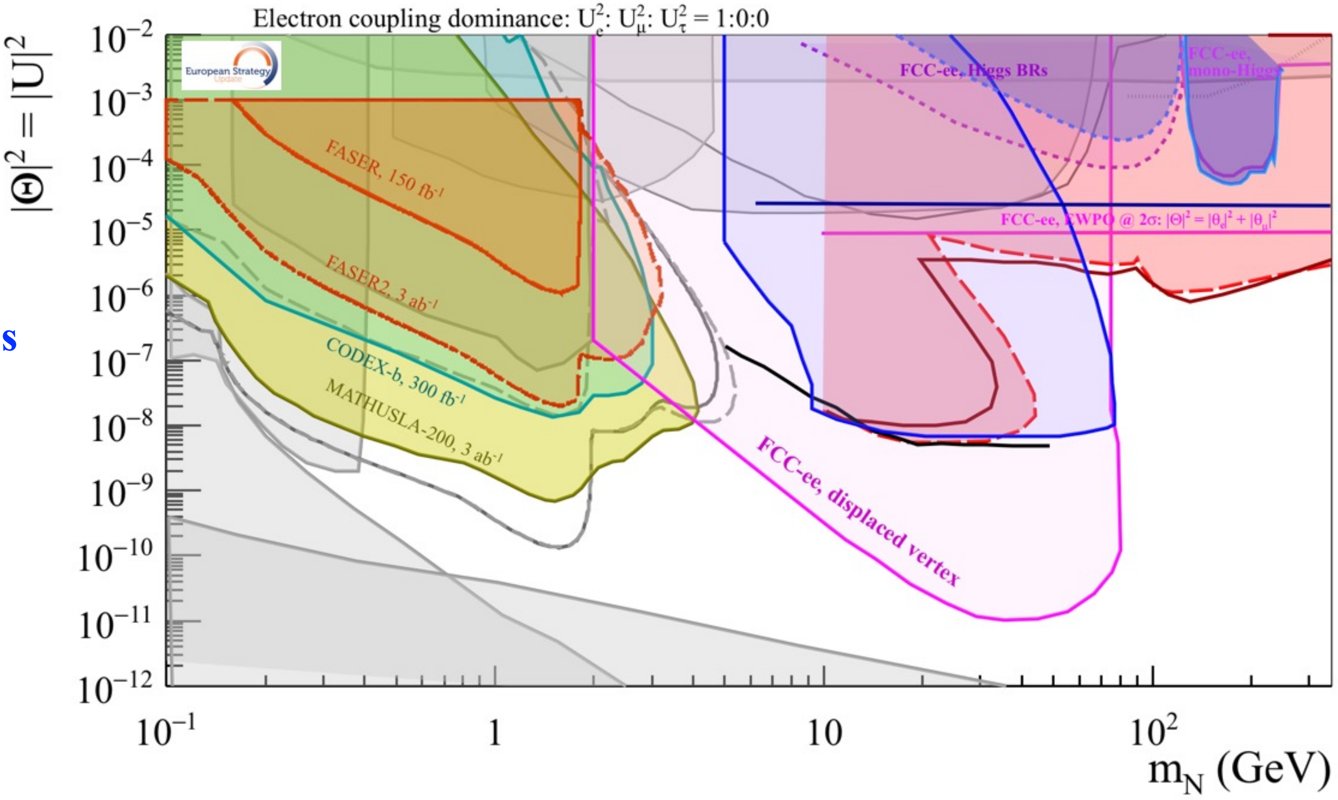
HNL searches: electron coupling





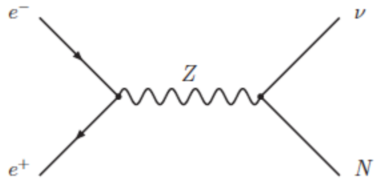
Fermion Portal: Heavy Neutral Leptons below/around EW scale

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}).

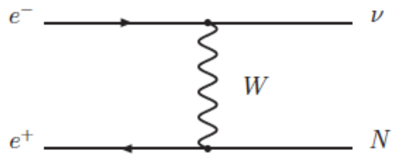


Source:
FCC report,
CERN-ACC-2018-0057
(based on Antusch et al.,
arXiv:1612.02728)

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



production channel: $\mathbf{Z_s}$

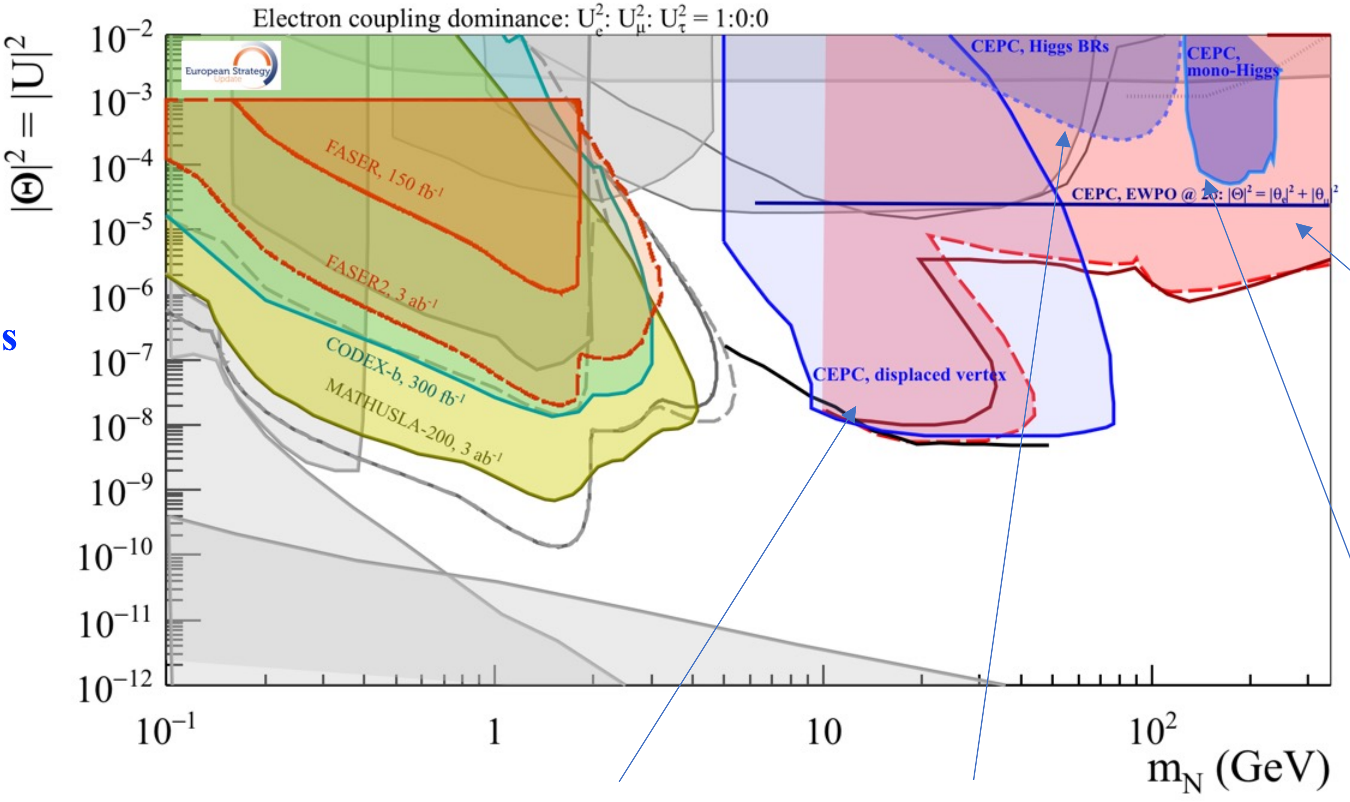


production channel: $\mathbf{W_t}$

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

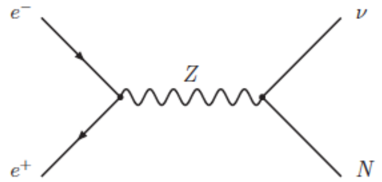
Fermion Portal: Heavy Neutral Leptons below/around EW scale

Prospects for CEPC: 10 ab^{-1} at the Z-pole and 5 ab^{-1} at 240 GeV.

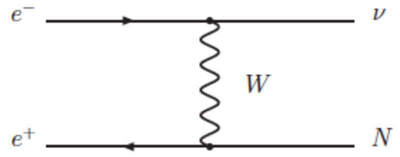


Source:
CEPC report, arXiv: 1811.10545
Based on arXiv:1612.02728

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



production channel: Z_s



production channel: W_t

EWPO:
The PMNS matrix in presence of HNLs is not unitary. Modification of the theory prediction of precision observables. Present constraints include: EWPO, lepton universality, charged LFV, CKM unitarity

Mono-Higgs:
if m_N is above the Higgs mass,
$N \longrightarrow \nu\ H$, $H \longrightarrow$ hadronically (dijet).

Displaced vertex searches:
Several decay modes accessible

Higgs BR:
presence of HNL modifies the Higgs width and BRs. The more sensitive is the $H \longrightarrow WW$ which constrains $H \longrightarrow \nu N$ (and Θ^2)

What do we know about HNL couplings to active neutrinos?

Very little: in fact with 3 HNLs we introduce 18 new parameters that can easily accommodate any PMNS pattern.
But, in presence of additional terms, the PMNS matrix could become not unitary:

Leptonic mixing matrix for 3 active neutrinos and 2 RHN in the limit of exact symmetry
(3 active neutrinos massless and 2 heavy neutrinos with degenerate mass values)

PMNS matrix

$$U = \begin{pmatrix} \boxed{\begin{matrix} \mathcal{N}_{e1} & \mathcal{N}_{e2} & \mathcal{N}_{e3} \\ \mathcal{N}_{\mu1} & \mathcal{N}_{\mu2} & \mathcal{N}_{\mu3} \\ \mathcal{N}_{\tau1} & \mathcal{N}_{\tau2} & \mathcal{N}_{\tau3} \end{matrix}} & \begin{matrix} -\frac{\mathrm{i}}{\sqrt{2}}\theta_e \\ -\frac{\mathrm{i}}{\sqrt{2}}\theta_\mu \\ -\frac{\mathrm{i}}{\sqrt{2}}\theta_\tau \end{matrix} & \begin{matrix} \frac{1}{\sqrt{2}}\theta_e \\ \frac{1}{\sqrt{2}}\theta_\mu \\ \frac{1}{\sqrt{2}}\theta_\tau \end{matrix} \\ \begin{matrix} 0 & 0 & 0 \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* \end{matrix} & \begin{matrix} \frac{\mathrm{i}}{\sqrt{2}} \\ \frac{-\mathrm{i}}{\sqrt{2}}(1-\frac{1}{2}\theta^2) \end{matrix} & \begin{matrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}}(1-\frac{1}{2}\theta^2) \end{matrix} \end{pmatrix}$$

The leptonic mixing matrix U is unitary up to second order in theta:
→ The PMNS matrix becomes the non-unitary 3x3 submatrix N

The mixing of the active and sterile neutrinos can be quantified by the mixing angles:

$$\theta_\alpha = \frac{y^*_{\nu_\alpha}}{\sqrt{2}}\frac{v_{\mathrm{EW}}}{M}\,, \qquad |\theta|^2 := \sum_\alpha |\theta_\alpha|^2$$

HNL-active neutrino mixing angles and PMNS non unitarity

Current knowledge of the active neutrino mixing angles is still very poor with respect to e.g. CKM elements:

CKM

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

$$J = (3.18 \pm 0.15) \times 10^{-5}$$

PMNS

3σ

NuFIT 3.2 (2018)

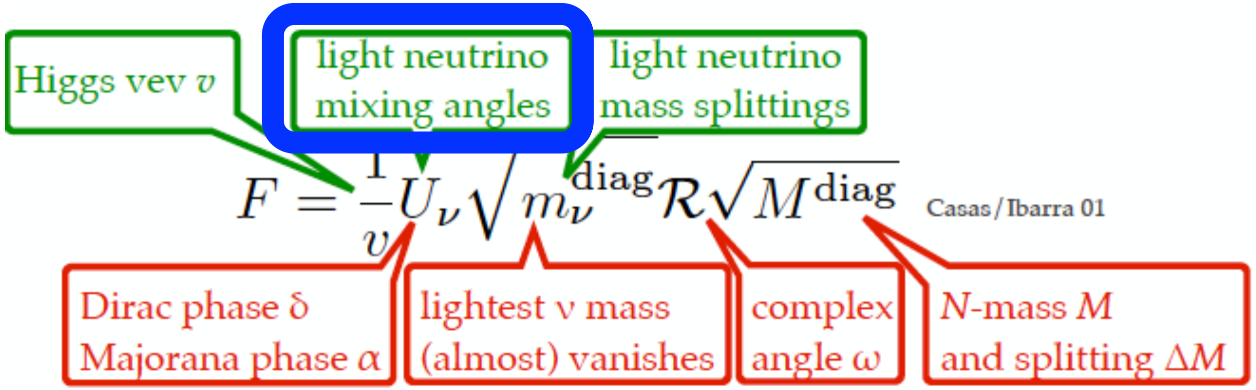
$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.141 \to 0.156 \\ 0.242 \to 0.494 & 0.467 \to 0.678 & 0.639 \to 0.774 \\ 0.284 \to 0.521 & 0.490 \to 0.695 & 0.615 \to 0.754 \end{pmatrix}$$

$$J \simeq 0.033 \sin\delta$$

Precision might be key not only to to discriminate different models and identify a clear pattern but also to shed light on the possible PMNS non-unitarity effects.

HNL-active neutrino mixing angles and PMNS non unitarity

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

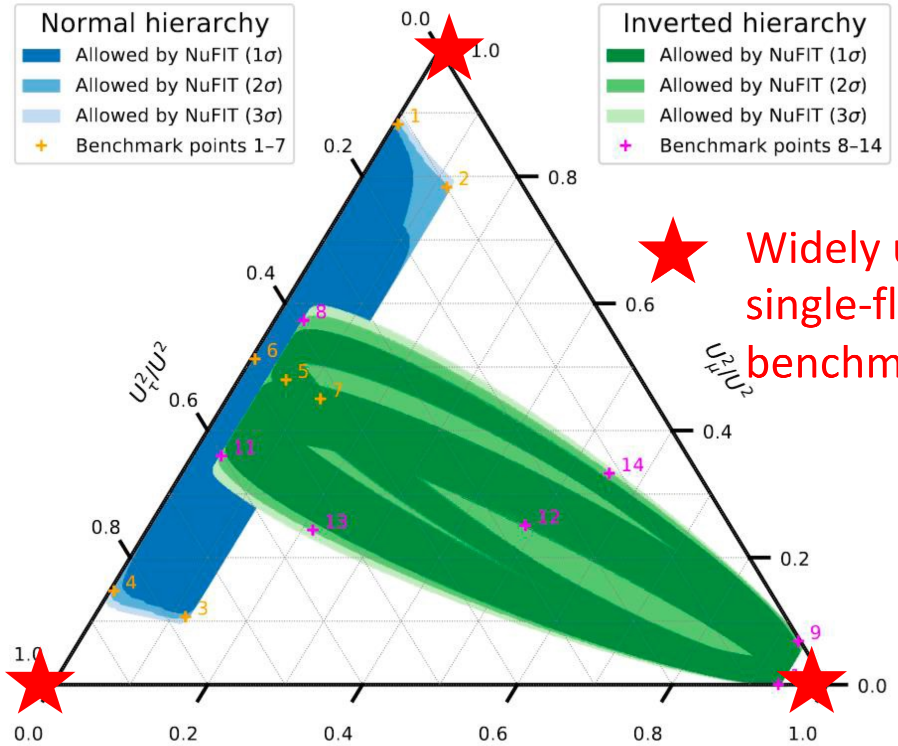
Dirac phase δ
Majorana phase α

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.

HNL-active neutrino mixing angles and PMNS non unitarity

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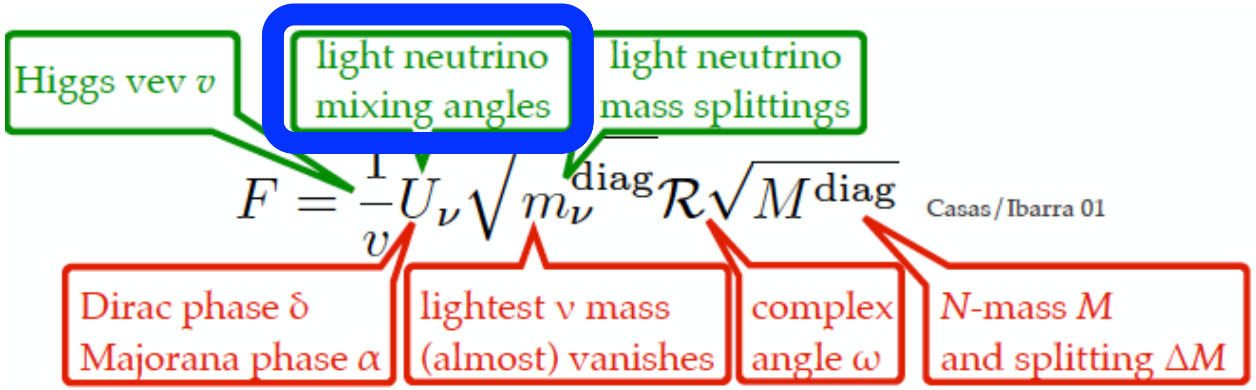
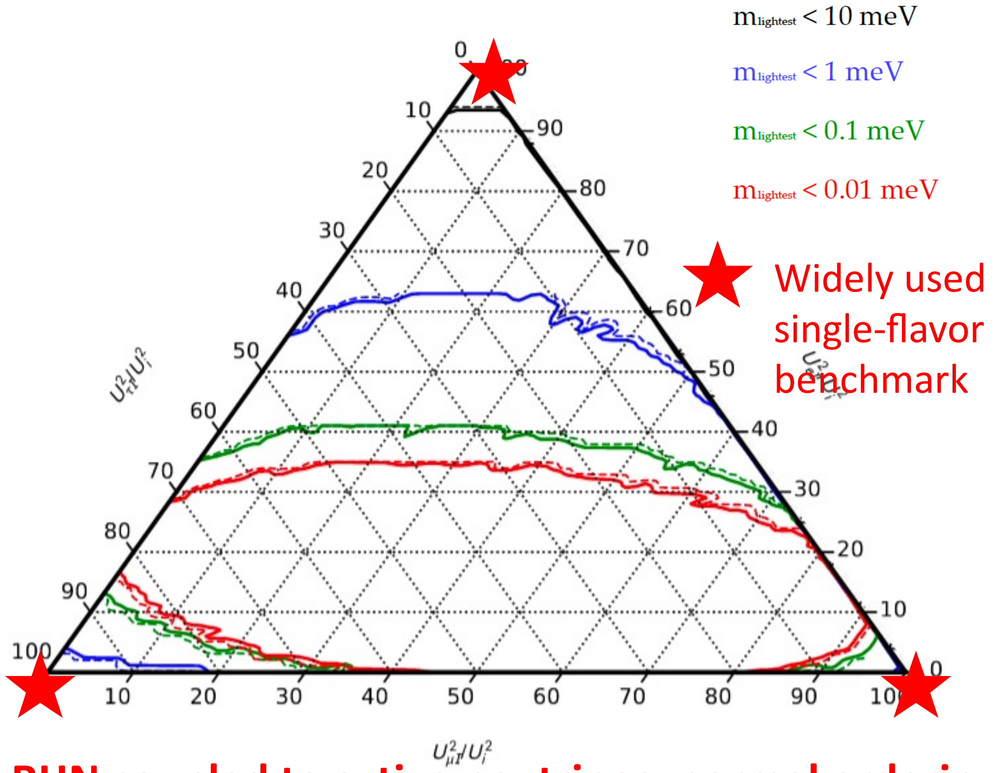


$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\mathrm{diag}}} \mathcal{R} \sqrt{M^{\mathrm{diag}}}$$

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



Widely used single-flavor benchmark

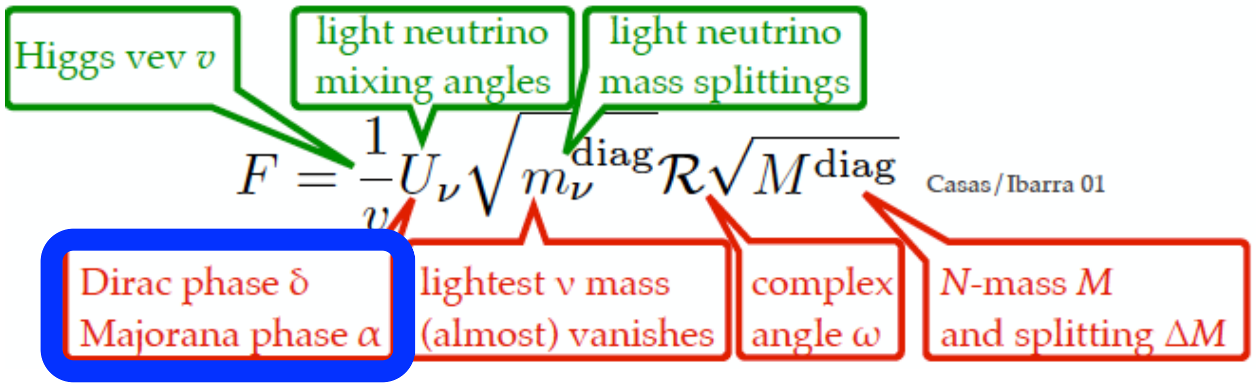
3 RHN coupled to active neutrinos, normal ordering

Chrzaszczet al 1908.02302

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

HNL-active neutrino mixing angles and δ_{CP}

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**.



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Casas / Ibarra 01

In case of one generation you have the seesaw formula:
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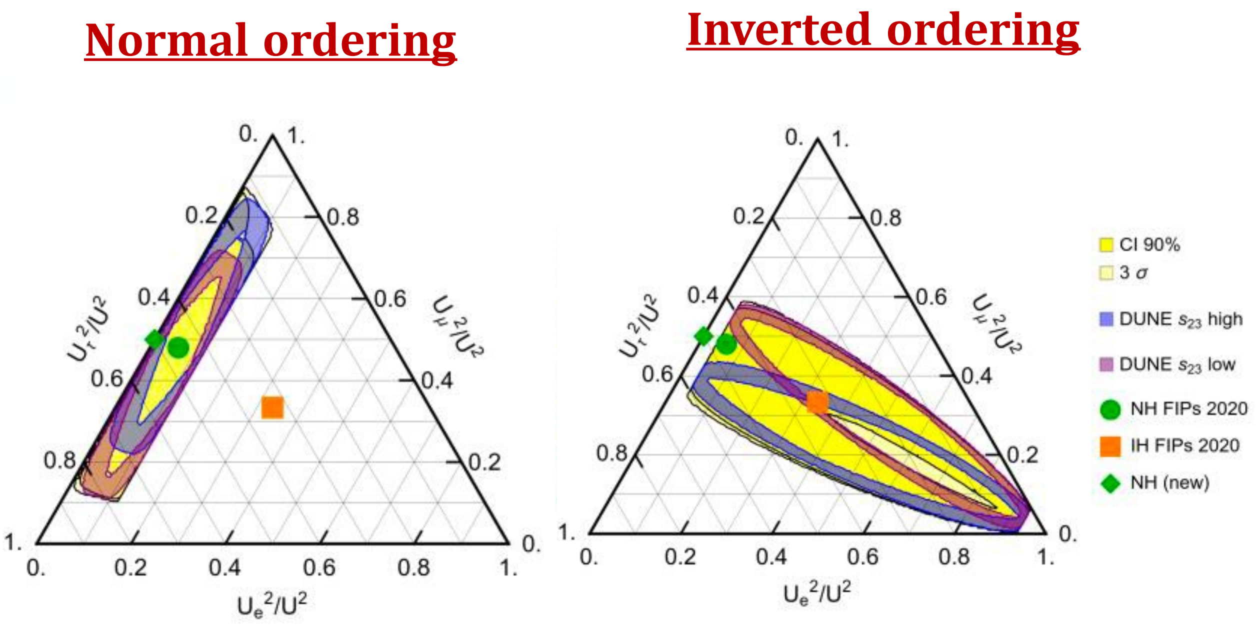

Normal ordering

Inverted ordering

M. Drewes et al., 1801.04207

Inclusion of knowledge of δ_{CP} and two values of s_{23}

HNL-active neutrino mixing angles and 0νββ decay

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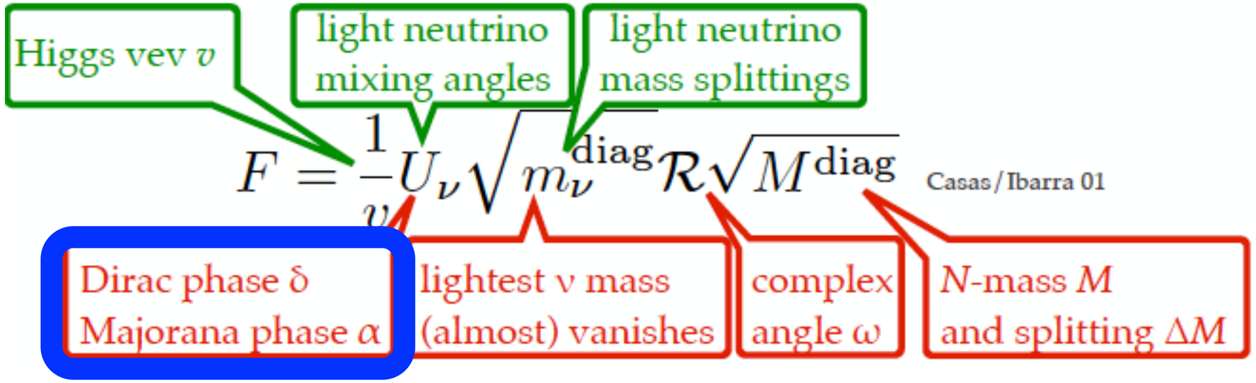


Higgs vev v

light neutrino mixing angles

light neutrino mass splittings

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

Casas / Ibarra 01

Dirac phase δ
Majorana phase α

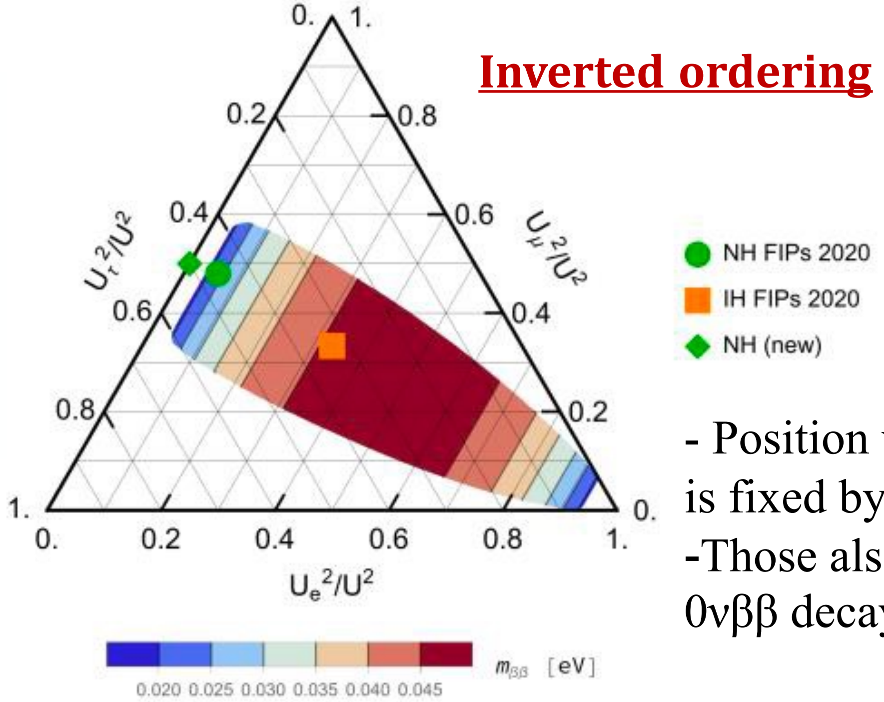
lightest ν mass (almost) vanishes

complex angle ω

N-mass M and splitting ΔM

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

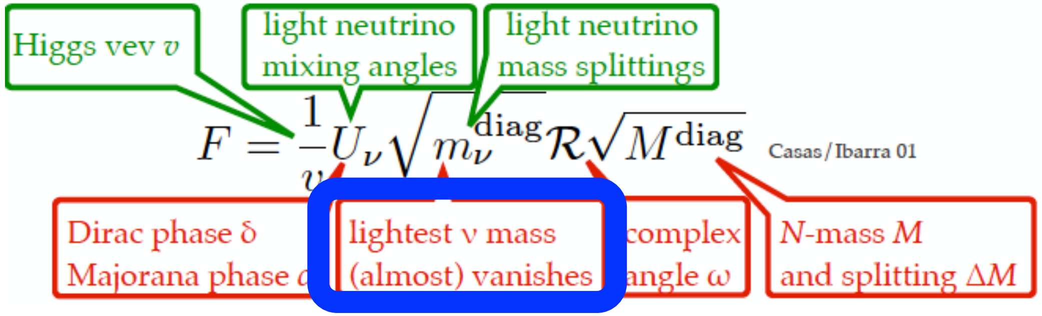
Inverted ordering



- Position within the triangle is fixed by PMNS phases
-Those also fix the rate of 0νββ decay

Value of $m_{\beta\beta}$ within the current 3σ regions

HNLs mixing parameters: lower limit from lightest active neutrino



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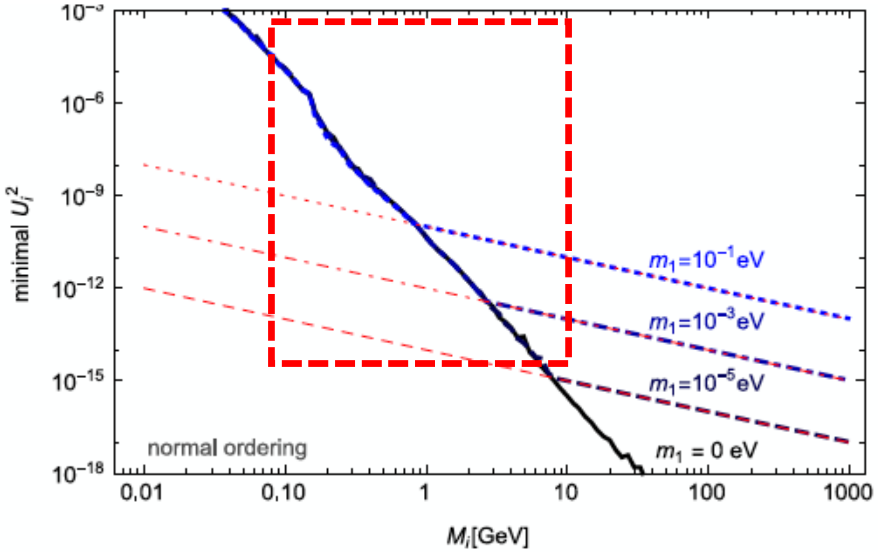
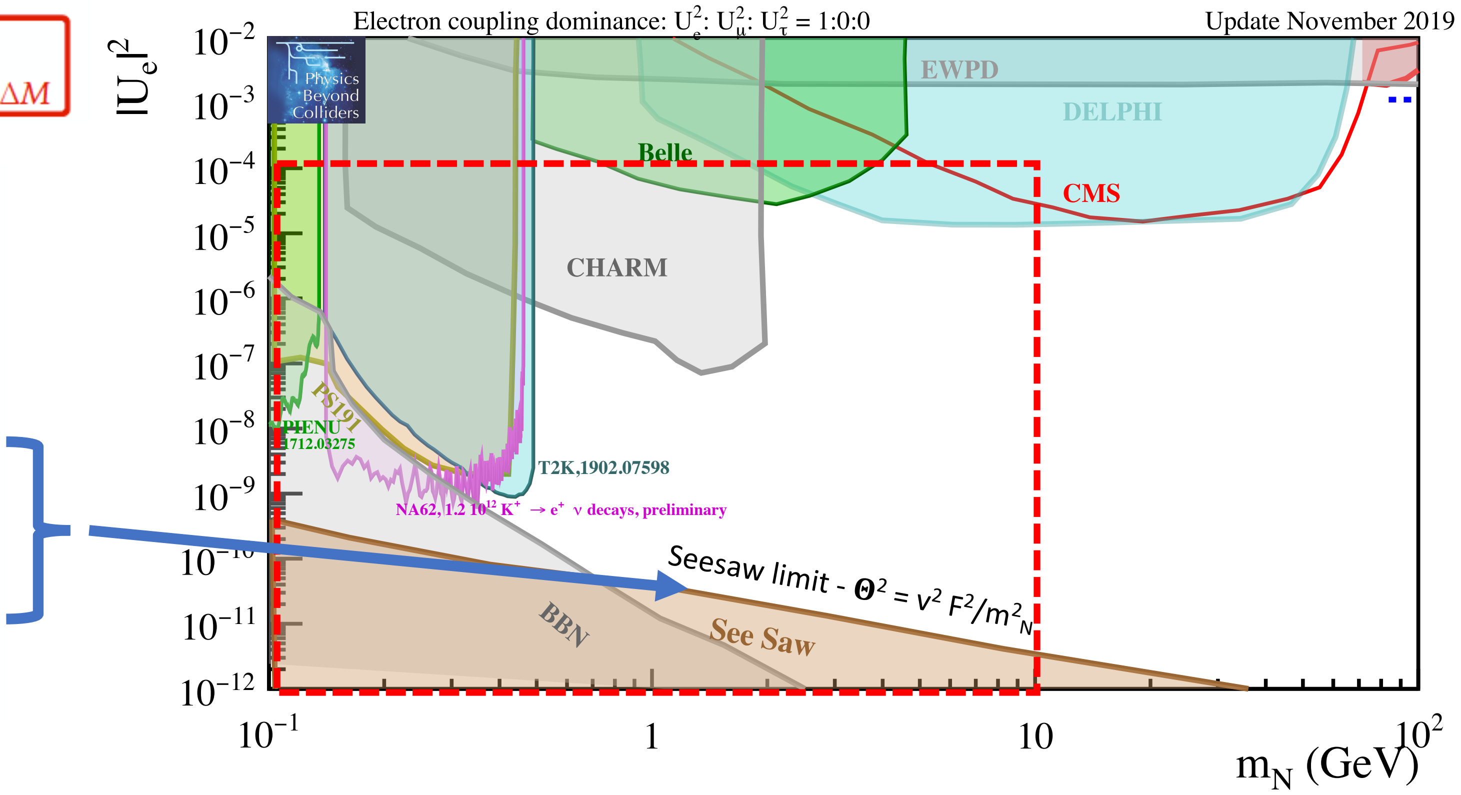
N-mass *M*
and splitting Δ*M*



M. Drewes et al., 1904.11959

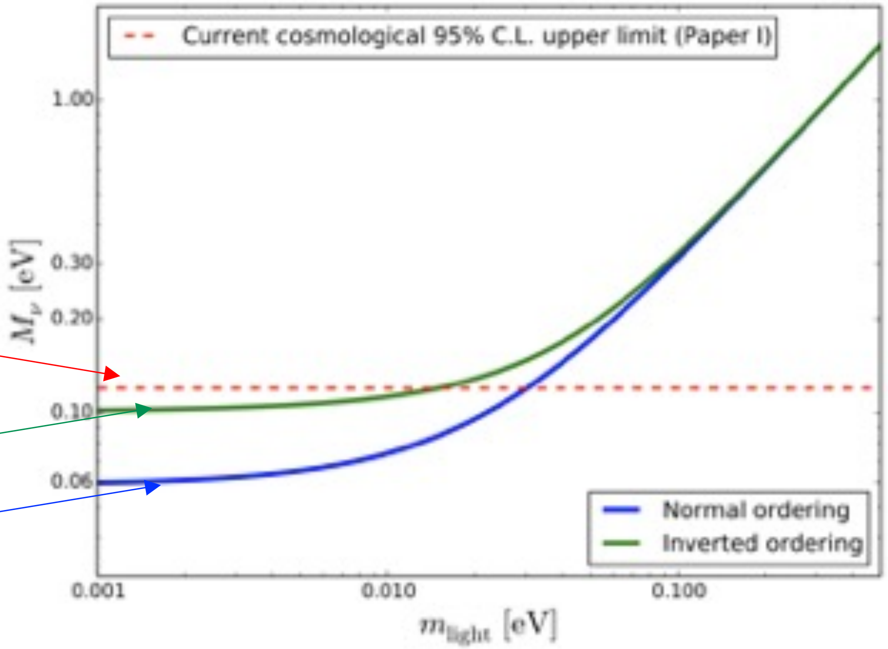


Lower boundary depends on the mass of the lightest active neutrino

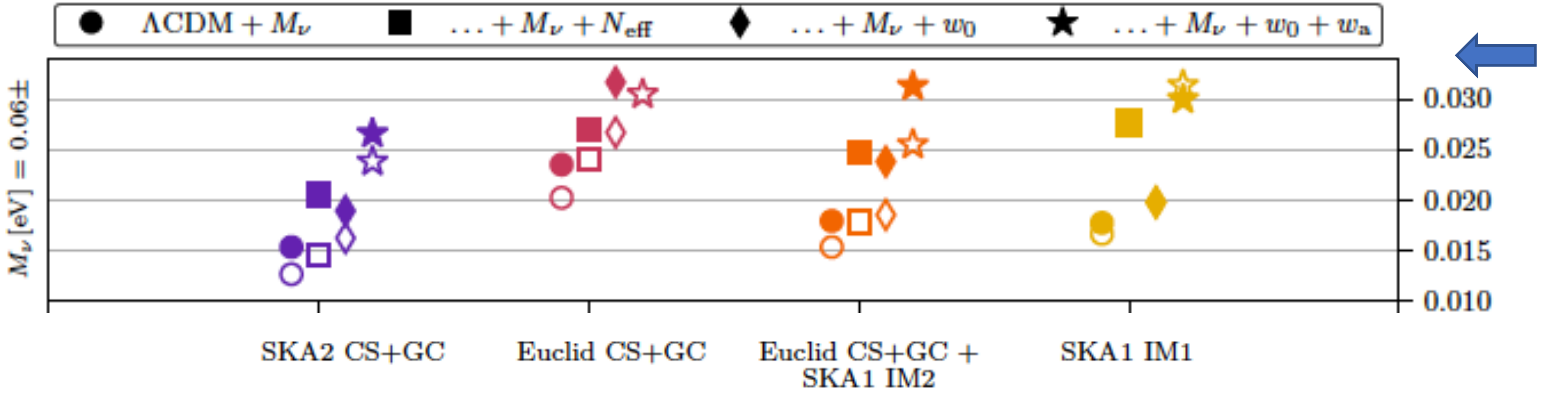
Current knowledge on the absolute active neutrino masses

Current cosmological limits on the sum of neutrino masses is between 0.12 - 0.14 eV, (depending on what dataset you use).

From oscillations we know that
$\sum m_\nu$ >= 0.10 eV for Inverted Ordering
$\sum m_\nu$ >= 0.06 eV for Normal Ordering.



Sprenger et al., 1801.08331

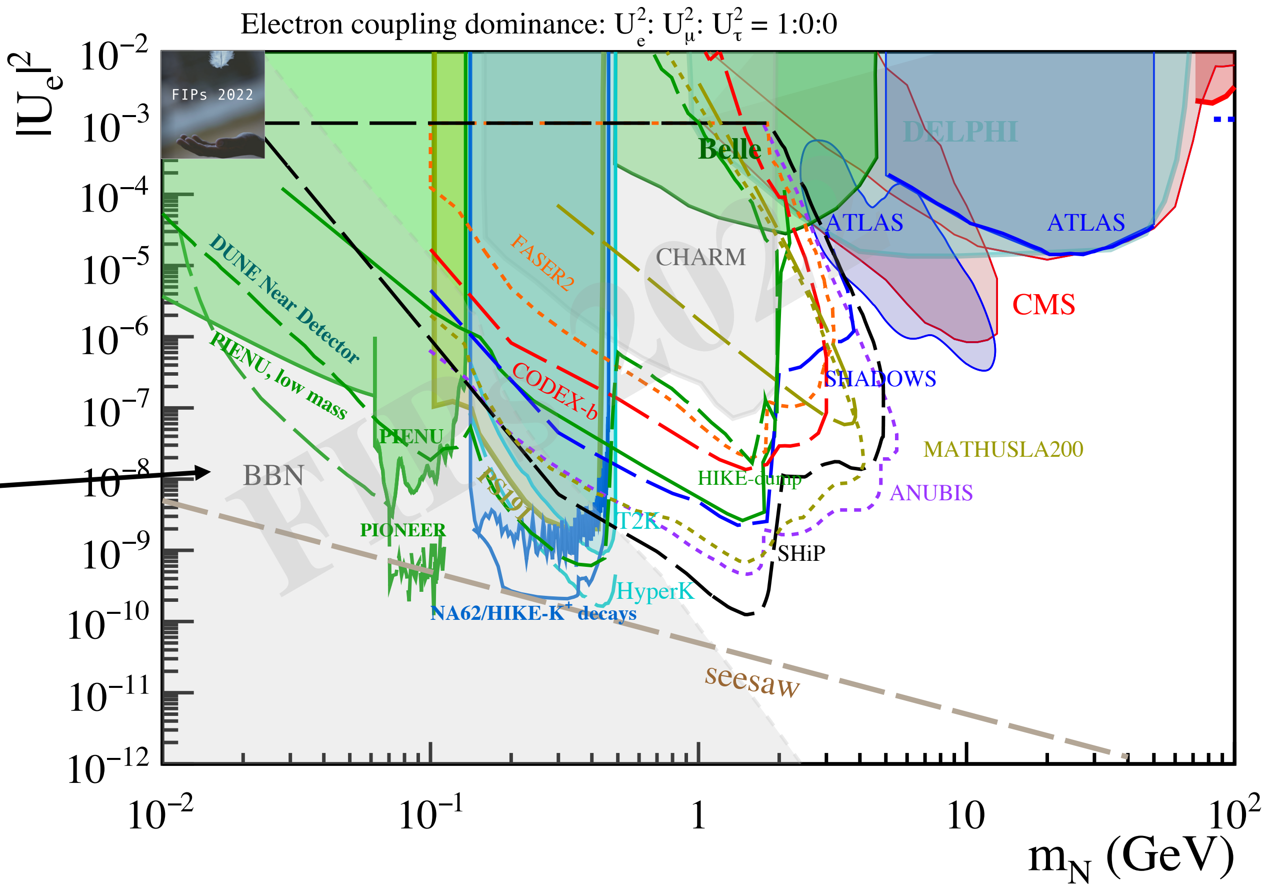


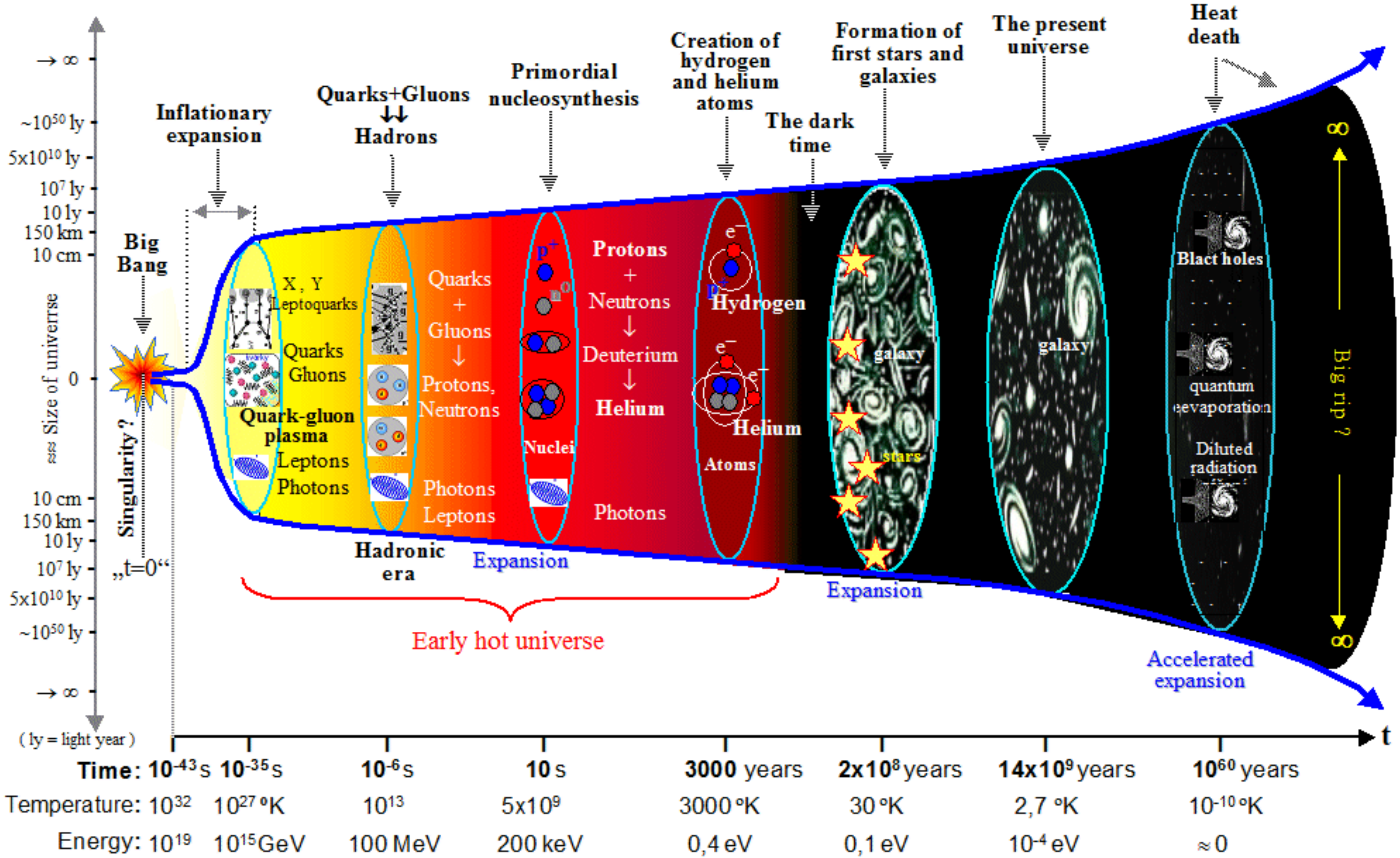
New data from Euclid and Square Km Array (SKA) will be able to bring the cosmological limit down to $\sum m_\nu$ <= 0.06 ± 0.02 eV and shed light on the value of the mass of the lightest neutrino
(and the seesaw limit of HNLs…)

HNLs and Big Bang Nucleo-synthesis

<u>**Big Bang Nucleosynthesis (BBN):**</u>
to avoid tension with the observed abundance of light elements in the intergalactic medium, HNLs should be enough short-lived that their decays do not disturb the primordial nucleosynthesis and the measured density of light elements (eg. ^{4}He).

NB:
any feebly-interacting particle should decay before 0.1 sec (< BBN) or after 300,000 years (eg. Dark Matter) in order to not perturb BBN and CMB expectations
- see Hufnagel et al, arXiv:1808.09324.




→ ∞
~10^50 ly
5x10^10 ly
10^7 ly
10 ly
150 km
10 cm
0
10 cm
150 km
10 ly
10^7 ly
5x10^10 ly
~10^50 ly
→ ∞
≈ Size of universe
(ly = light year)
Big Bang
Singularity ?
„t=0“
Inflationary expansion
Quarks+Gluons ↓↓ Hadrons
Primordial nucleosynthesis
Creation of hydrogen and helium atoms
The dark time
Formation of first stars and galaxies
The present universe
Heat death
X , Y Leptoquarks
Quarks Gluons
Quark-gluon plasma
Leptons
Photons
Quarks + Gluons ↓ Protons, Neutrons
Photons Leptons
Hadronic era
p+
n0
Nuclei
Protons + Neutrons ↓ Deuterium ↓ Helium
Photons
Expansion
e−
p+
Hydrogen
e−
e−
Helium
Atoms
galaxy
stars
Expansion
galaxy
Blact holes
quantum eevaporation
Diluted radiation
Accelerated expansion
∞
Big rip ?
∞
Early hot universe
t
Time: 10^-43 s 10^-35 s 10^-6 s 10 s 3000 years 2x10^8 years 14x10^9 years 10^60 years
Temperature: 10^32 10^27 °K 10^13 5x10^9 3000 °K 30 °K 2,7 °K 10^-10 °K
Energy: 10^19 10^15 GeV 100 MeV 200 keV 0,4 eV 0,1 eV 10^-4 eV ≈ 0