Summary of the Dark Sector Workshop @ SLAC: Focus on dark photon/dark Higgs decays to visible channels

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SHiP collaboration meeting, Imperial College, 13-15 June

Focus on Dark Matter: thermal origin (recap)

As universe cools below DM mass, density decreases as exp{-m/T}

- DM interacts with SM to stay in equilibrium
- eventually DM particles can't find each other to annihilate
- and a (minimal) DM abundance is left over the present day.

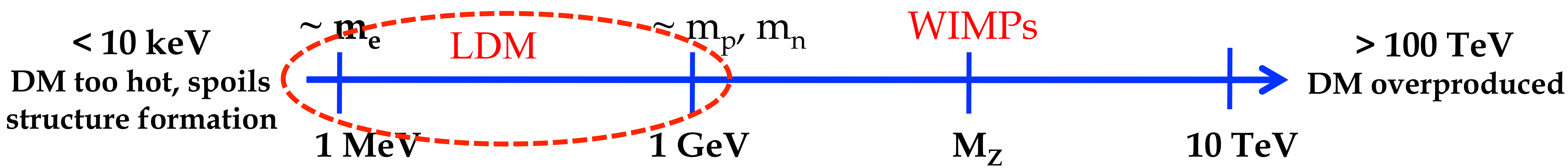
Equilibrium reached easily with a tiny DM-SM coupling.

DM annihilation cross-section necessary to obtain the relic density:

σ v (relic) = 3x10^{-26} cm^3/s

This equilibrium can be reached:

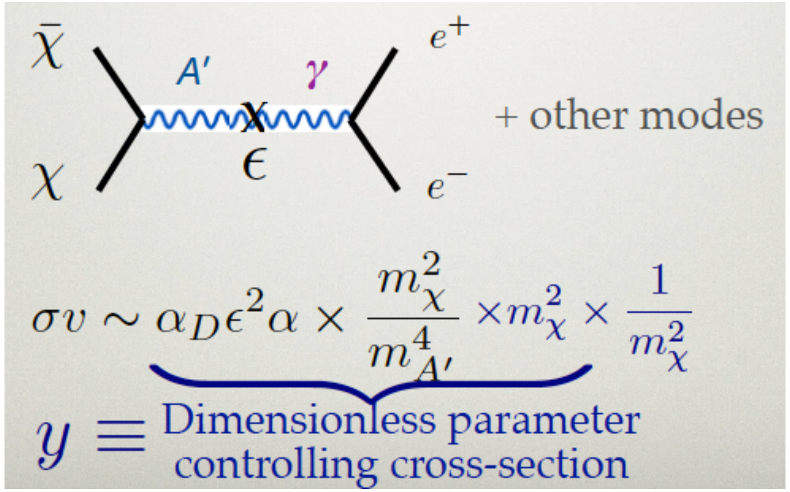
- either with traditional WIMP at TeV scale with Z mediator (excluded by current limits)
- or with light DM with light mediator (hence new forces).

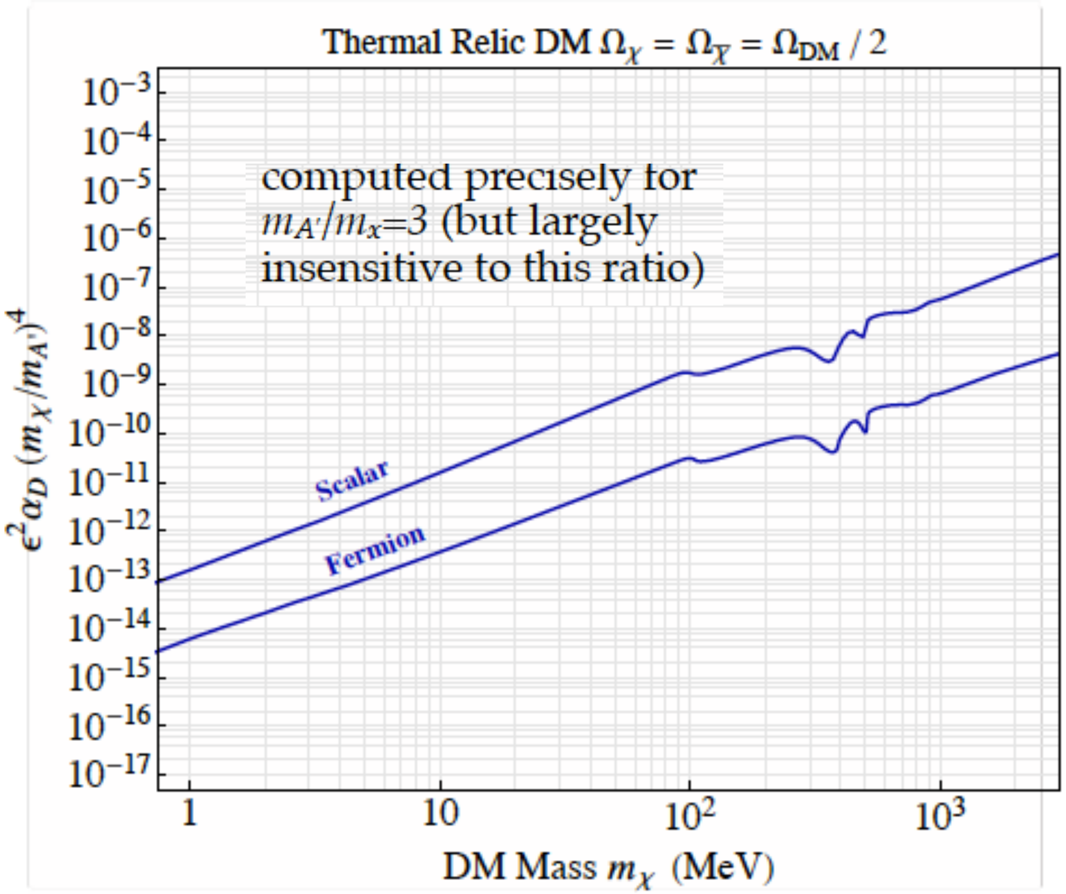


Light mediator must be SM singlet, options limited by SM gauge invariance:

1) Vector Portal; 2) Scalar Portal; 3) Neutrino Portal

1) Vector Portal





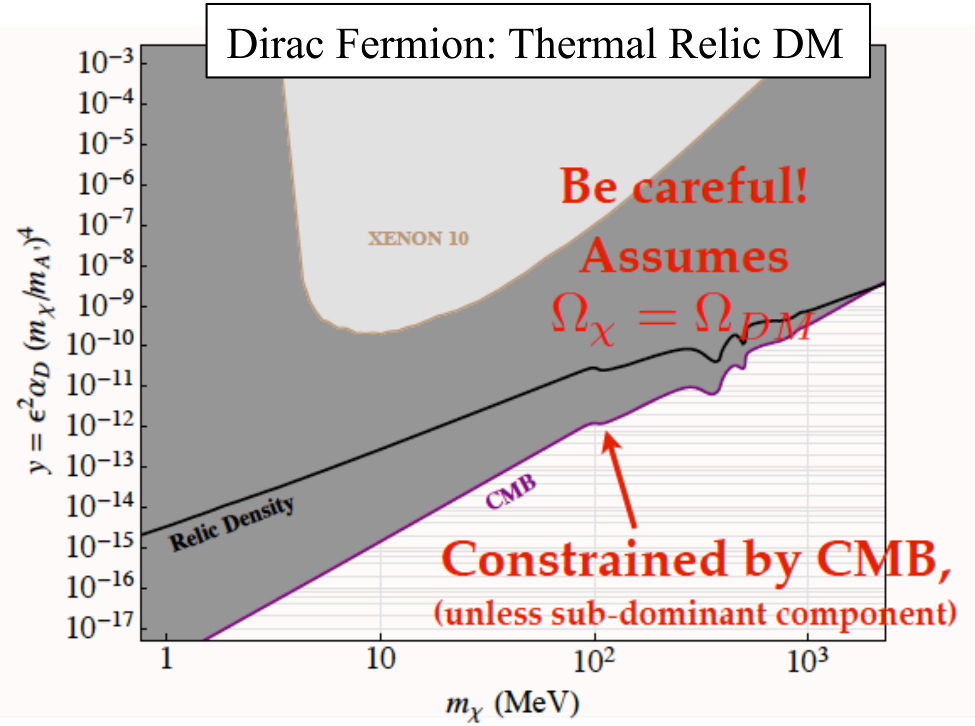
Four minimal LDM scenarios:

1) Dirac fermion;
2) (elastic) complex scalar
3) Majorana (inelastic) fermion
4) (Inelastic) complex scalar

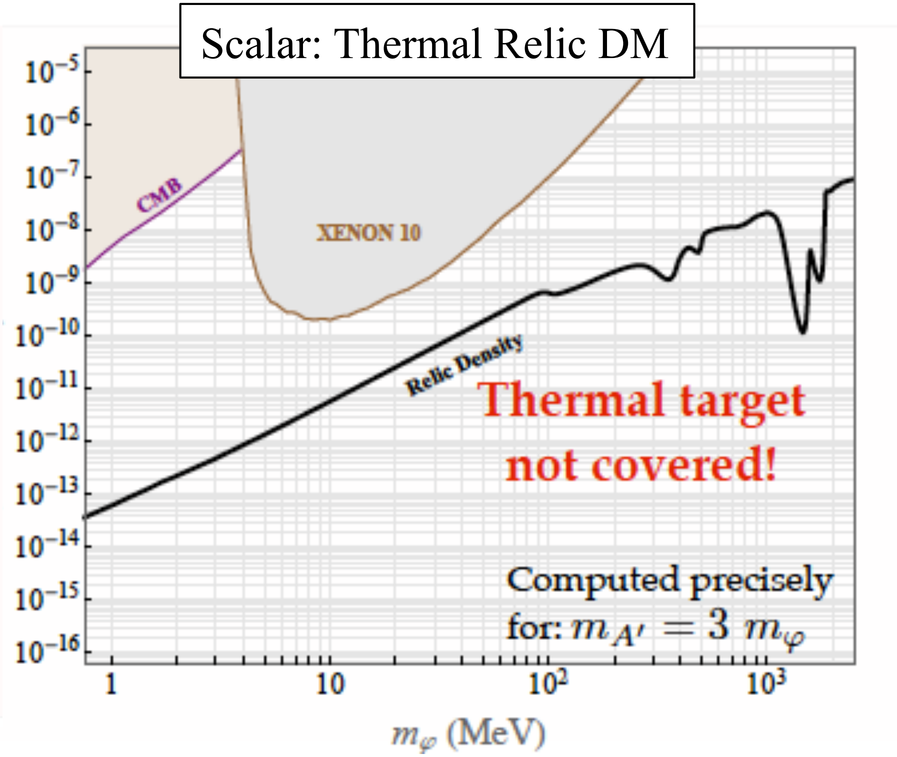
First case: m(A') > m(chi)
(mediator decays predominantly in DM)

Elastic Interactions: constraints from CMB and DM Direct Detection

CMB: late time annihilation of DM into charged particles increases ionization of IGM near recombination. CMB power spectrum constrains ionization and hence DM annihilation.



CMB constrains Dirac Fermion Relic LDM

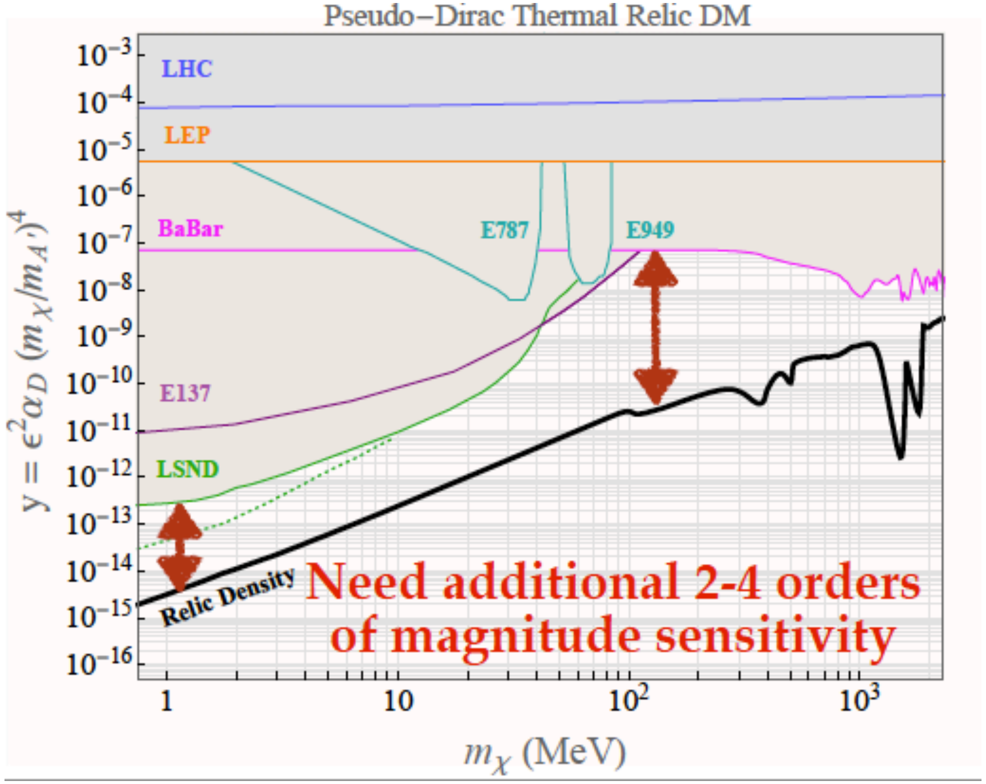


Complex scalar has p-wave annihilation in early universe hence is wide open

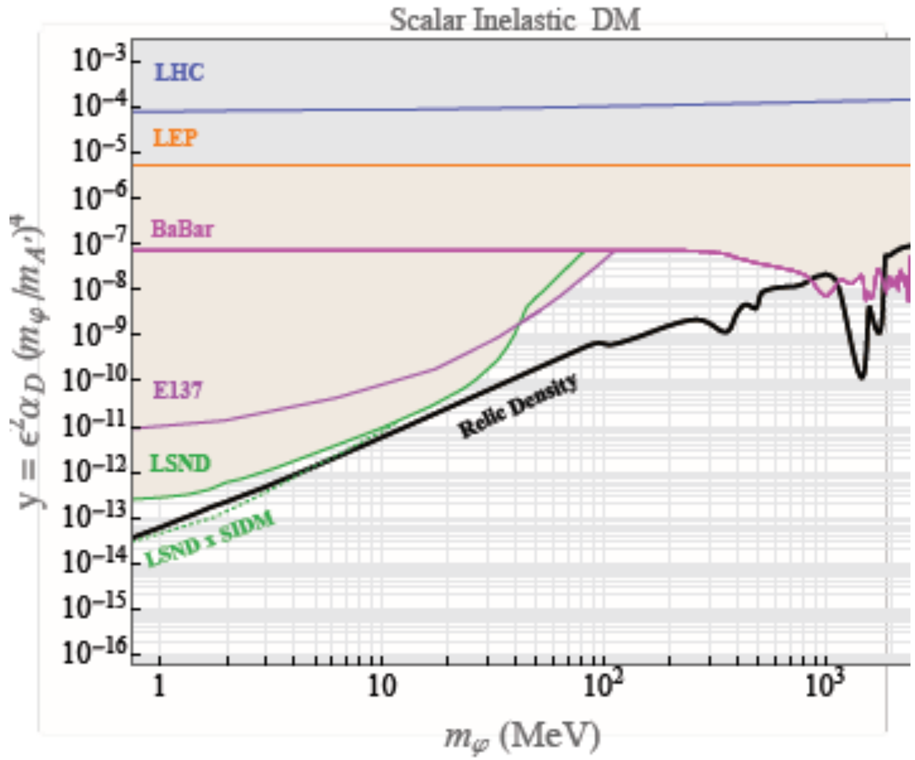
First case: m(A′) > m(chi)
(mediator decays predominantly in DM)

Inelastic interactions: constraints from accelerators and beam dumps

LDM: Majorana fermion



LDM: complex scalar



Second case: m(A') < 2 m(chi) (mediator decays predominantly in SM final states)

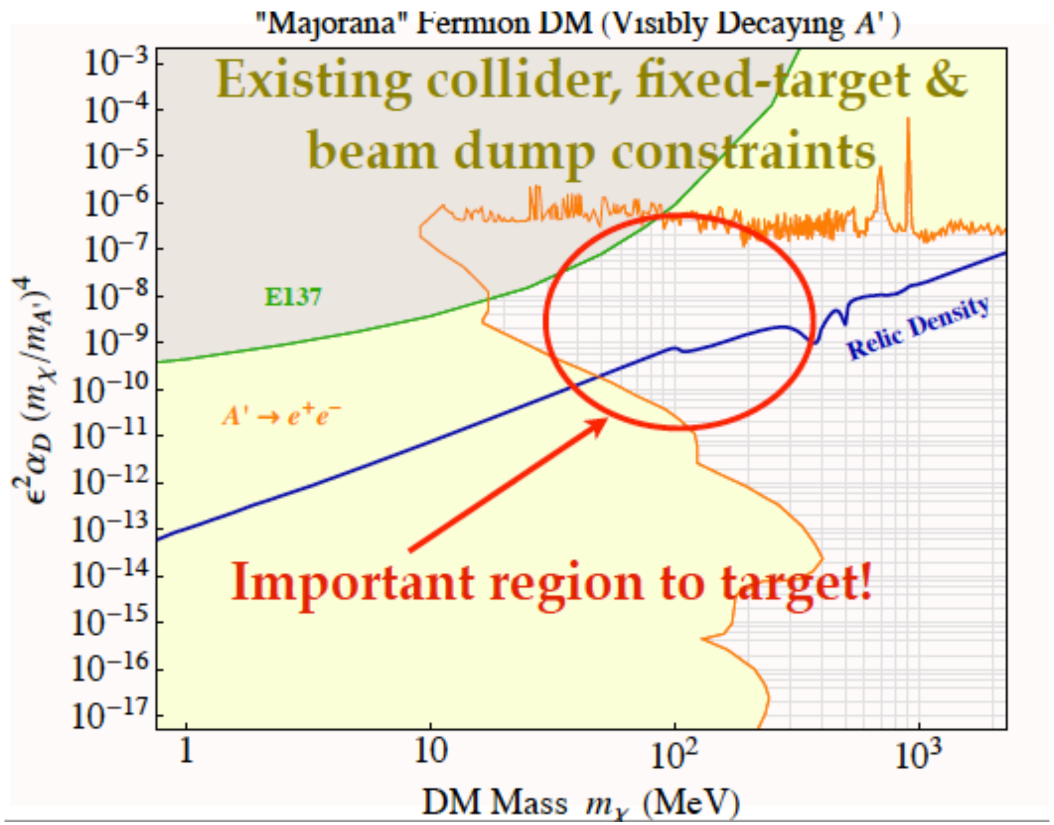
1) m(A')< m(χ):

→ Thermal annihilation, dominates: χχ→A' A'

→ CMB largely constrains thermal scalar and fermion cases.

2) m(χ)< m(A') < 2 m (χ):

Once produced the mediator decays to visible SM states directly:



m(A') = 1.1 m(χ)

Relic abundance is achieved through s-channel annihilation, with A' decays visibly: χχ → A' →SM;

[Is the region below the relic density line still viable?]

DM in MeV-GeV region via the Vector Portal: a vibrant field

Vector portal: visible searches

Name	Where	Source	Intensity	Production mode	Detection mode	Status
Belle-II	Super KEK-B	$e^+e^- \to \Upsilon(3S)$	> 100 fb^{-1} @ $\Upsilon(3S)$	$\Upsilon(3S) \to \gamma A'$	$A' \to e^+e^-, \mu^+\mu^-$	Commis. 2018
Apex	JLAB	e^-, 2 GeV	10^9 EOT (W)	A'-strahlung	$A' \to e^+e^-$	Commis. 2018
HPS	CEBAF12 @ JLAB	e^-,1-2 GeV	10^{14} EOT (W)	A'-strahlung	$A' \to e^+e^-$	Running 2016-20
MAGIX	MESA @ Mainz	e^-, 155 MeV	10^{16} EOT (Xe gas)	A'-strahlung	$A' \to e^+e^-$	Commis. 2020
Mu3e	πE5 line @ PSI	μ^-, 28 MeV	10^{15-16} μ^-	$\mu \to \nu\nu A'$	$A' \to e^+e^-$	Commis. 2017
ATLAS/CMS	LHC @CERN	pp 8, 13 TeV	few fb^{-1}	$H \to 4l$ + MET	$A' \to \mu^+\mu^-$	Running
LHCb	LHC @CERN	pp,13 TeV	15 fb^{-1}	$D^* \to DA'$	$A' \to e^+e^-, \mu^+\mu^-$	Running
NA62	SPS @CERN	p, 400 GeV	2 10^{18} POT	Meson, A'-strahlung	$A' \to e^+e^-, \mu^+\mu^-$	Running -2018
SeaQuest	Main Inj. @ FNAL	p, 120 TeV	1.5	Meson, A'-strahlung	$A' \to \mu^+\mu^-$	Proposed 2017-19
SHiP	SPS @CERN	p, 400 GeV	2 10^{20} POT	Meson, A'-strahlung	$A' \to e^+e^-, \mu^+\mu^-$	Proposed 2026

Vector portal: invisible searches

Babar	PEP-II @ SLAC	$e^+e^- \to \Upsilon(3S)$	57 fb^{-1}	$\Upsilon(3S) \to \gamma A'$	Single-γ trigger	ICHEP 2016
VEPP-3	VEPP-3 @ Budker Inst.	e^+, 500 MeV	1.5 MHz $\gamma\gamma$	$e^+e^- \to A'\gamma$	detect $\gamma + M_{miss}$	Proposed
PADME	BTF @ Frascati INFN	e^+, 550 MeV	15 Hz $\gamma\gamma$	$e^+e^- \to A'\gamma$	detect $\gamma + M_{miss}$	Approved, 2017-19
MMAPS	CESR @ Cornell	e^+, 5.3 GeV	2.2 MHz $\gamma\gamma$	$e^+e^- \to A'\gamma$	detect $\gamma + M_{miss}$	Not funded
NA64	SPS @ CERN	e^-, 100 GeV	$e^-N \to e^-NA'$	10^9-10^{12} EOT	detect $e^- + E_{miss}$	Running, 2016-17
LDMX	LCLS-II @ SLAC	e^-, 4 GeV	$e^-N \to e^-NA'$	10^{15}-10^{16} EOT	detect $e^- + E_{miss}$	Proposed, 2020

Vector portal: direct DM searches

SBND	FNAL	p, 9 GeV	2 10^{20} POT	Meson, A'-strahlung $A' \to \varphi\varphi$	detect ϕ @ 110 m	Under study
T2K	Tokai-Kamioka	p, 30 GeV	10^{21} POT	Meson, A'-strahlung $A' \to \varphi\varphi$	detect ϕ @ 280 m	Running
COHERENT	SNS @ Oak Ridge	p, 1 GeV	10^{23} POT	Meson, A'-strahlung $A' \to \varphi\varphi$	detect ϕ @ 20 m 2°-OA	Proposed
SHiP	SPS @CERN	p, 400 GeV	2 10^{20} POT	Meson, A'-strahlung $A' \to \varphi\varphi$	detect ϕ @ 100 m	Proposed 2026
LBNF	DUNE @FNAL	p, 120 GeV	3 10^{21} POT	Meson, A'-strahlung $A' \to \varphi\varphi$	detect ϕ @ 500 m	Under study 2020

DM in MeV-GeV region via the Vector Portal: a vibrant field

Vector portal: visible searches

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Vector portal: invisible searches

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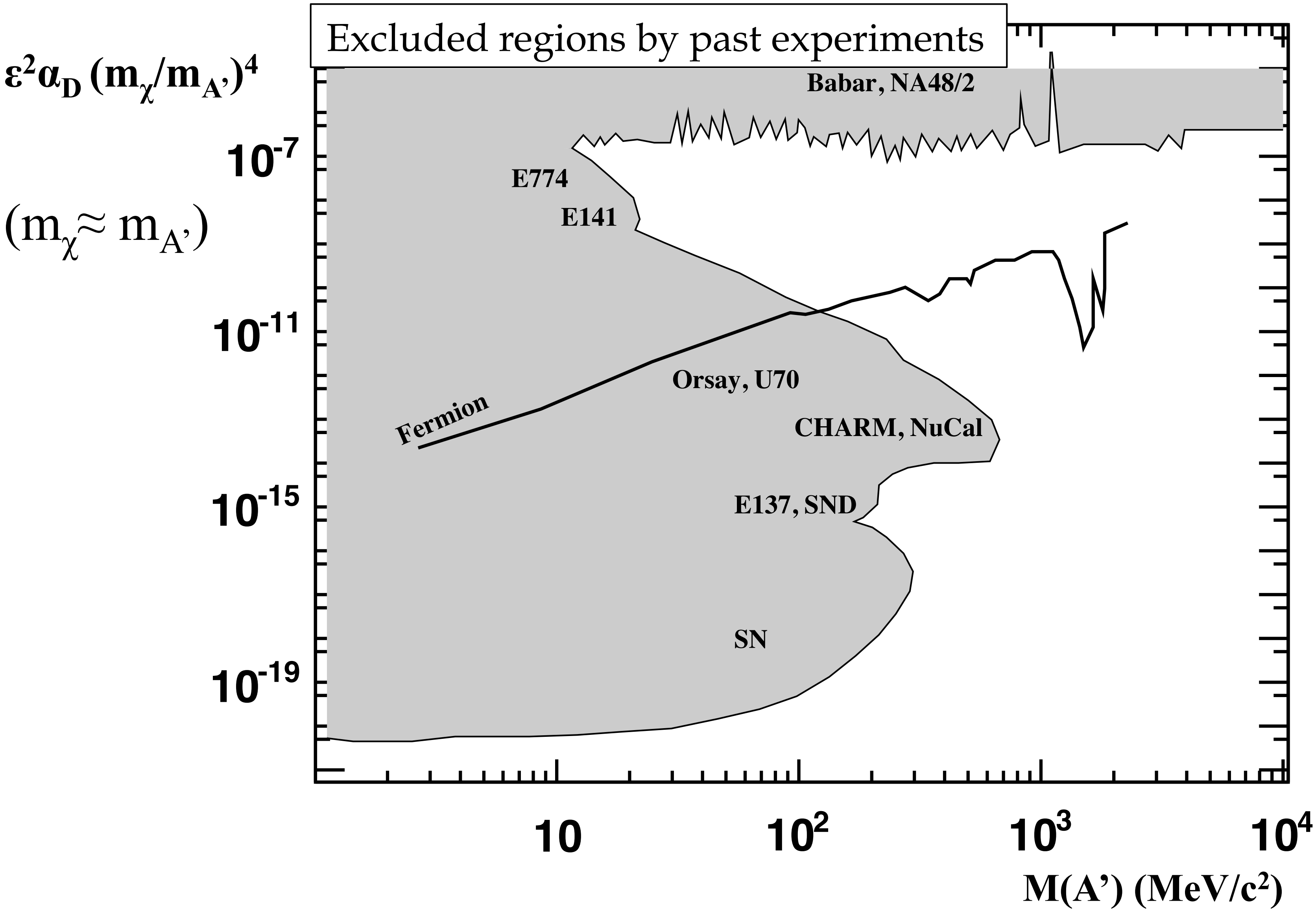
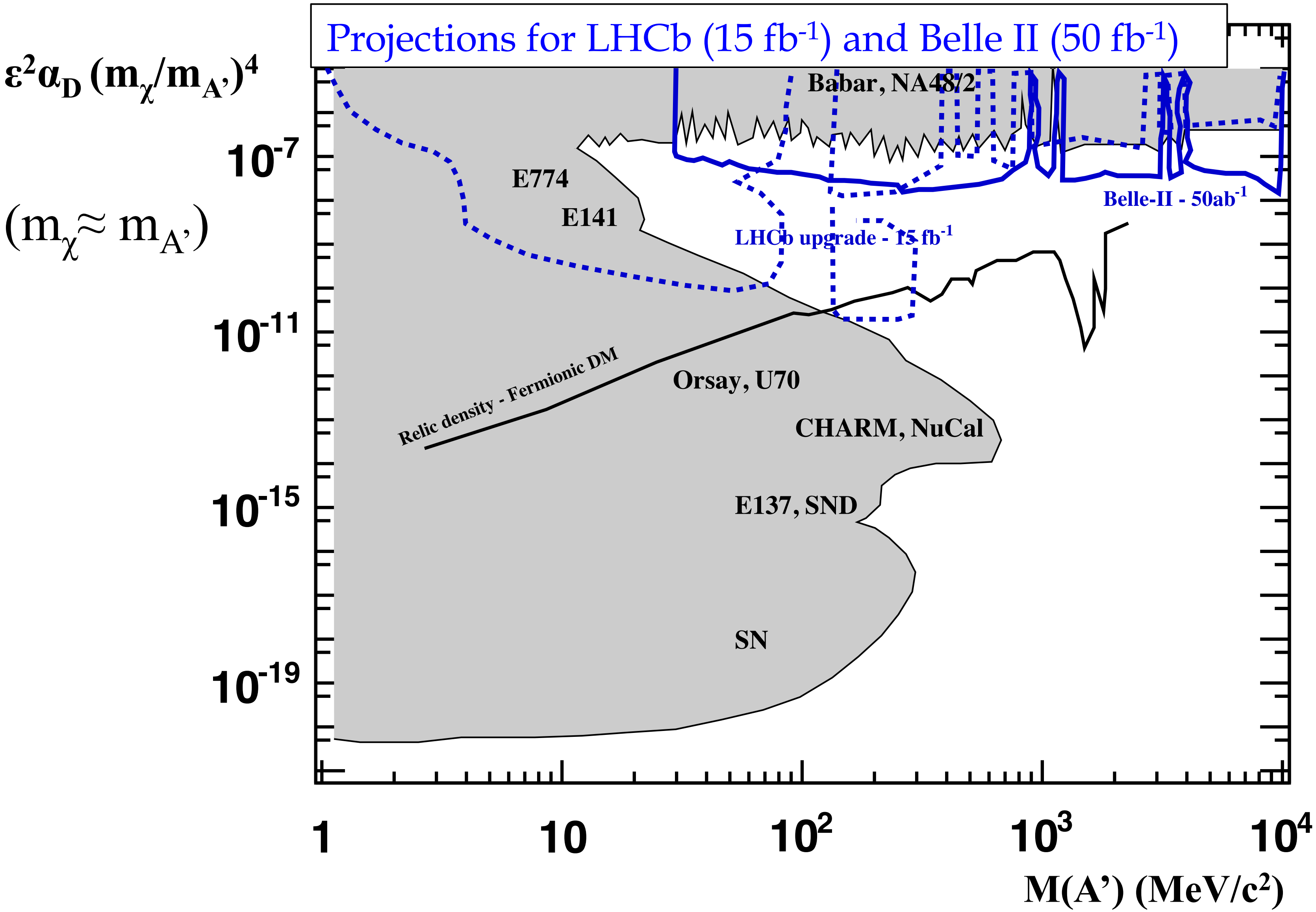
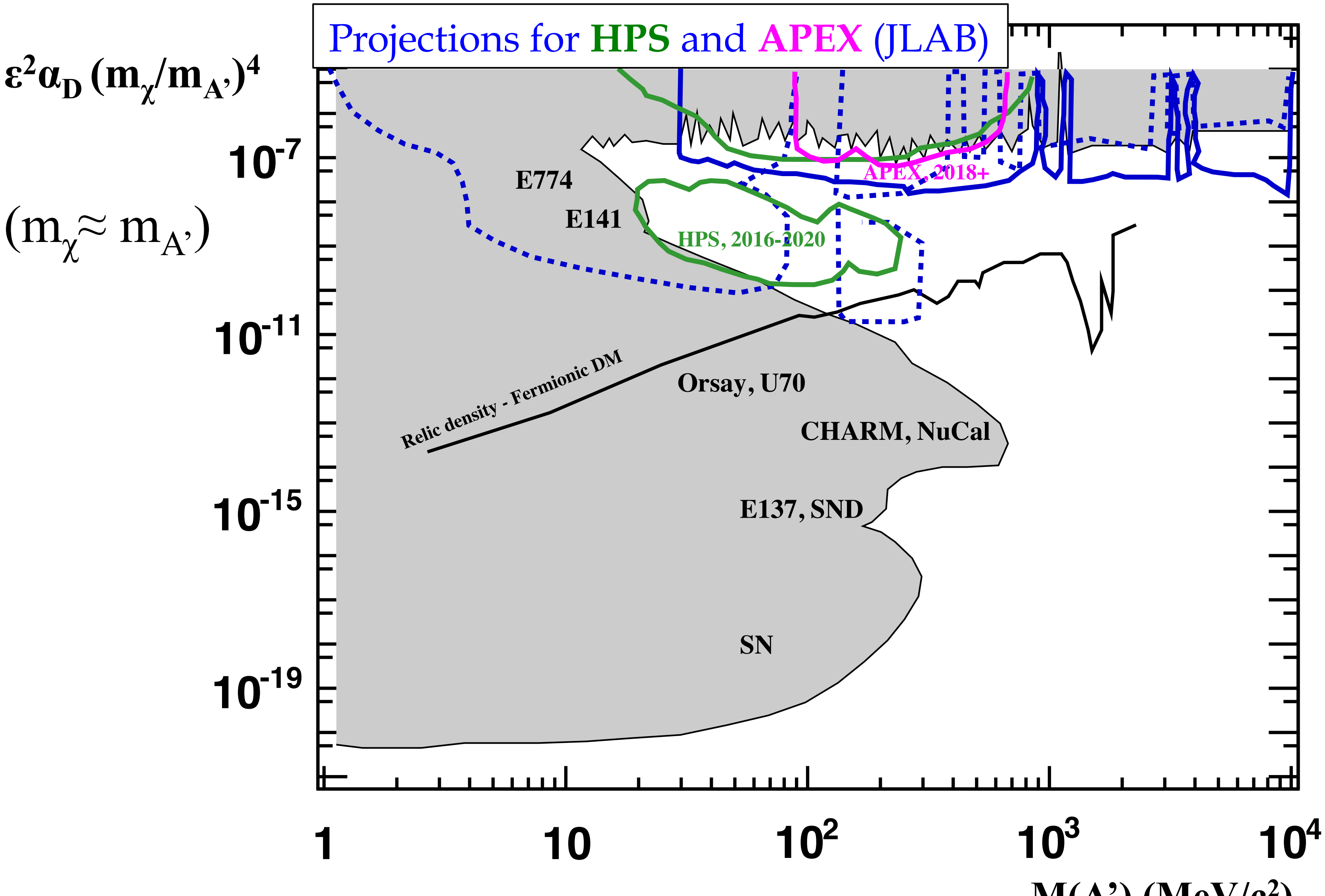
Vector portal: visible searches



Vector portal: visible searches



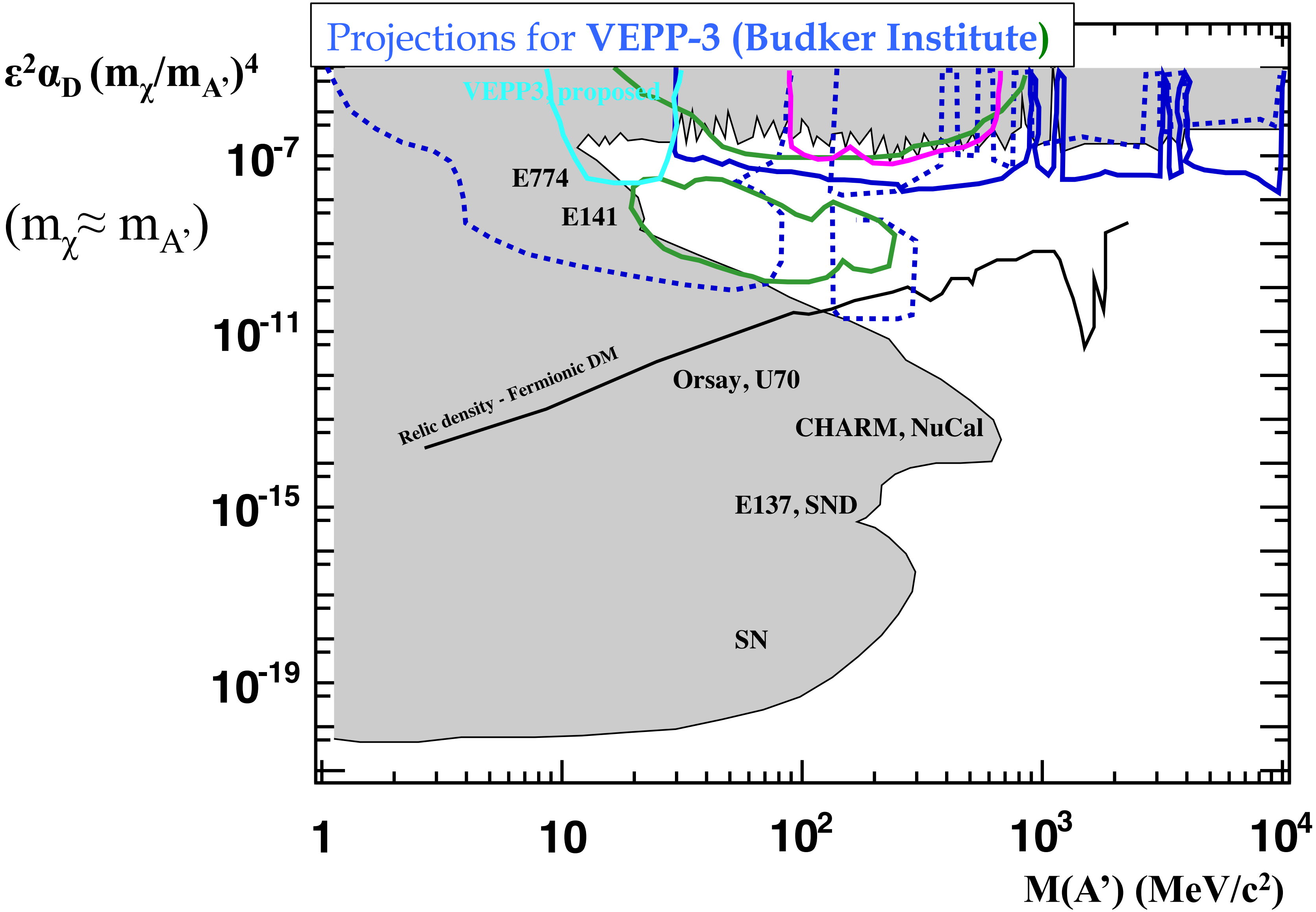
Vector portal: visible searches



HPS: JLAB, 1-2 GeV e-, 10^{14} eot, A'-strahlung, A' $\rightarrow e^+ e^-$, running (2016-2020)

APEX: JLAB, ~2 GeV e-, 10^{9} eot, A'-strahlung, A' $\rightarrow e^+ e^-$, commissioning 2018.

Vector portal: visible searches



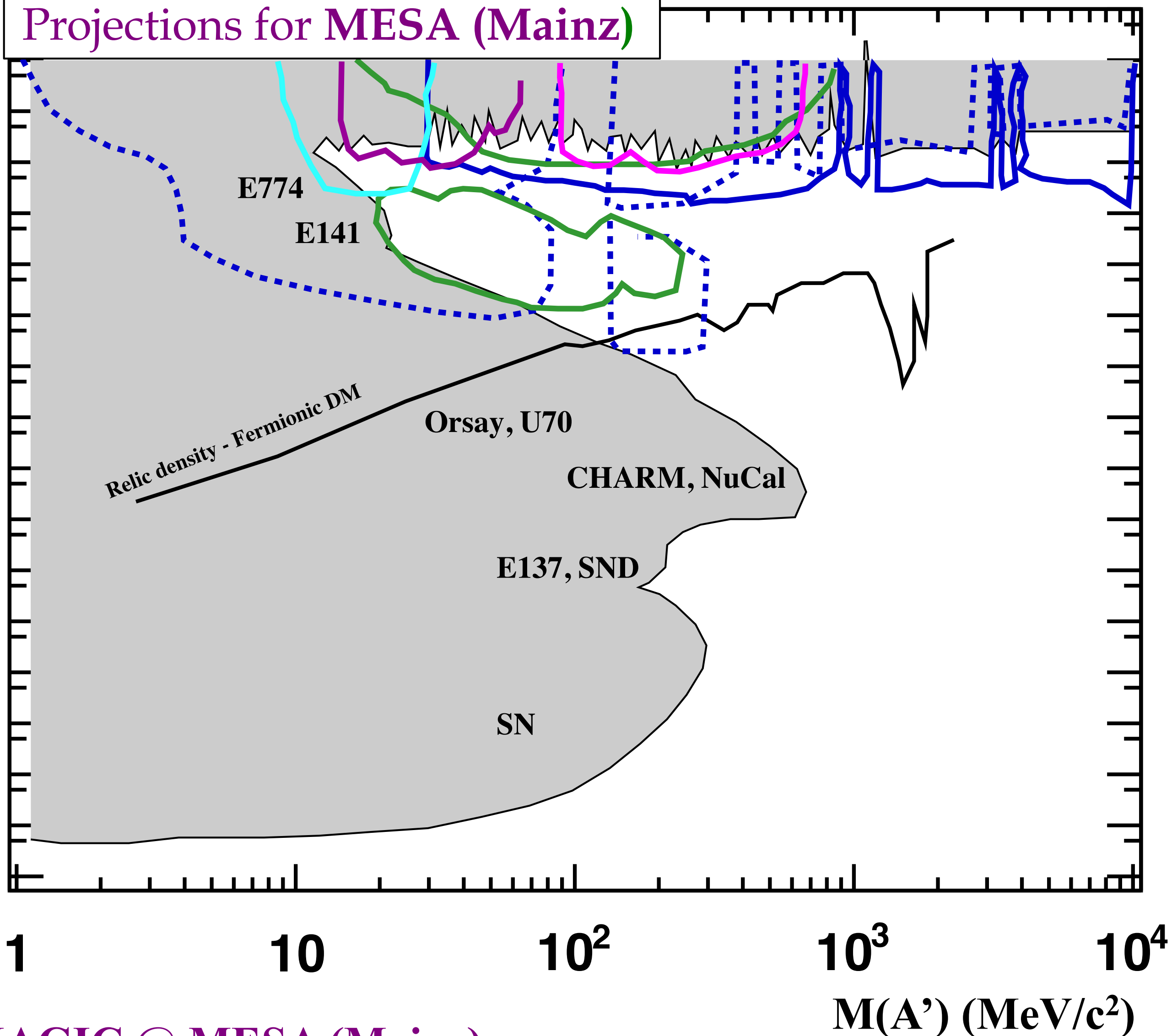
VEPP-3 @ Budker Inst., 500 MeV e^-, 1.5 MHz $\gamma\gamma$, $e^+e^- \rightarrow A'\gamma$, $A \rightarrow e^+ e^-$, Proposed

Vector portal: visible searches

Projections for **MESA (Mainz)**

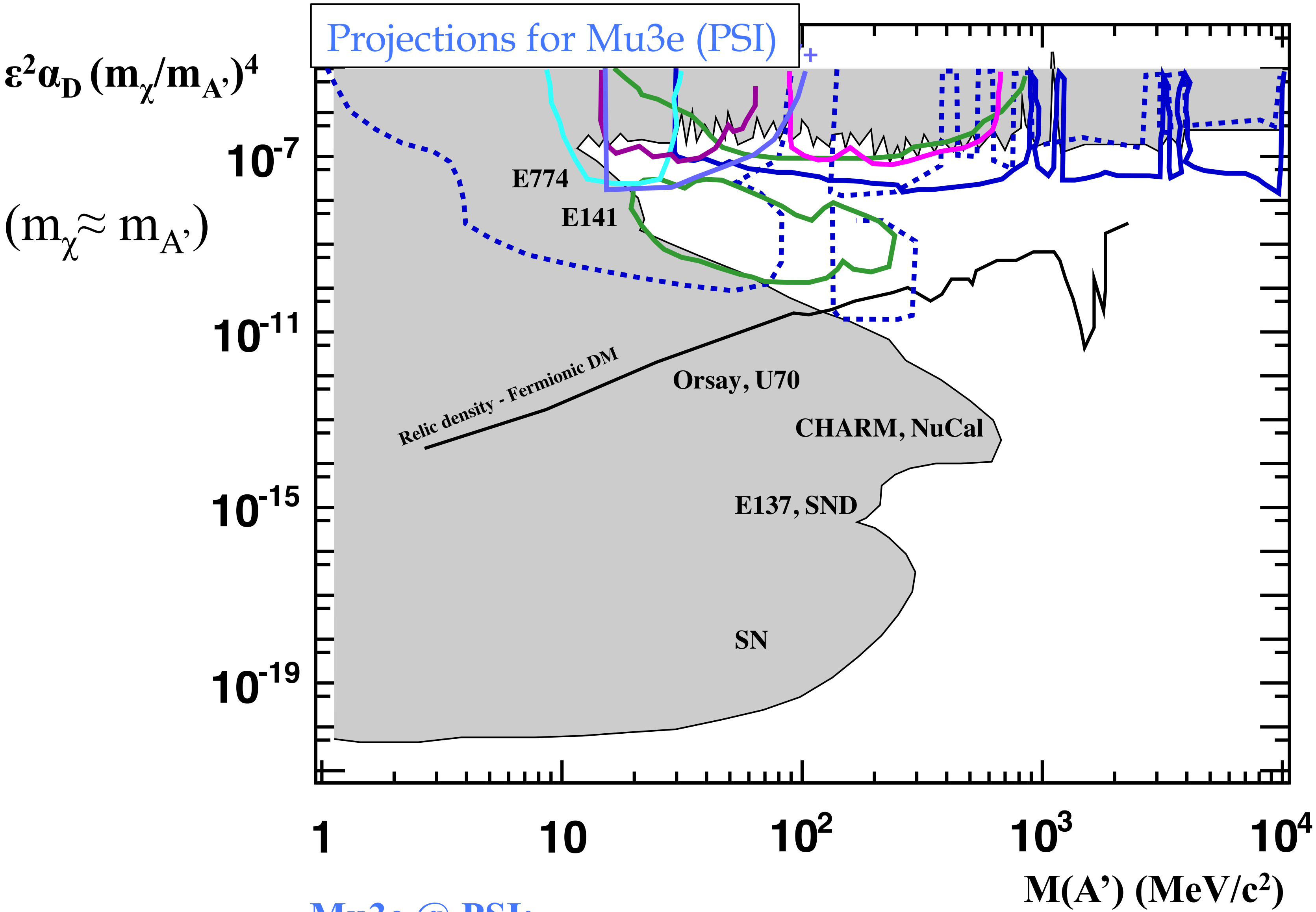
$\varepsilon^2 \alpha_D (m_\chi/m_{A'})^4$

$(m_\chi \approx m_{A'})$



MAGIC @ MESA (Mainz):
155 MeV e^-, 10^{16} eot (Xe gas), A'-strahlung, $A' \to e^+ e^-$, comm:2020

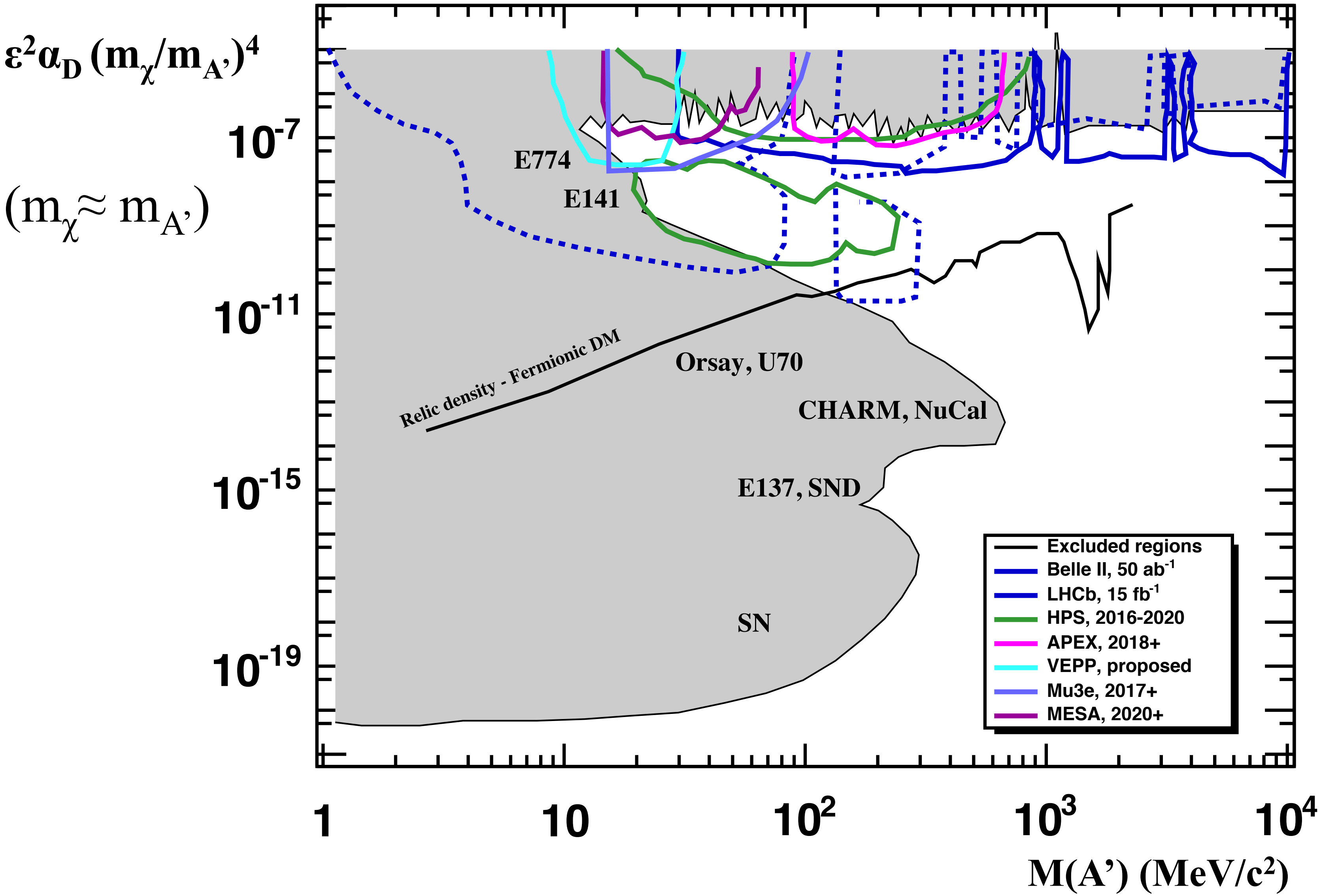
Vector portal: visible searches



Mu3e @ PSI:

28 MeV μ^-, 10^{15}-10^{16} μ-, $\mu\rightarrow\nu\nu A'$, $A' \rightarrow e^+ e^-$, 2017+

Vector portal: visible searches

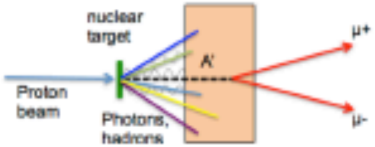


FermiLab - US

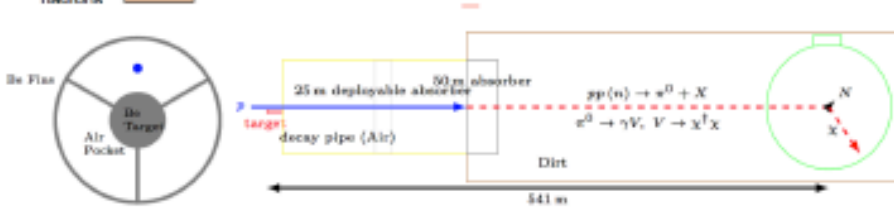
Dark Matter searches at FNAL:

beam dump → dark matter beams → detection by scattering in detector
In neutrino detector, DM signature ~ neutral current event

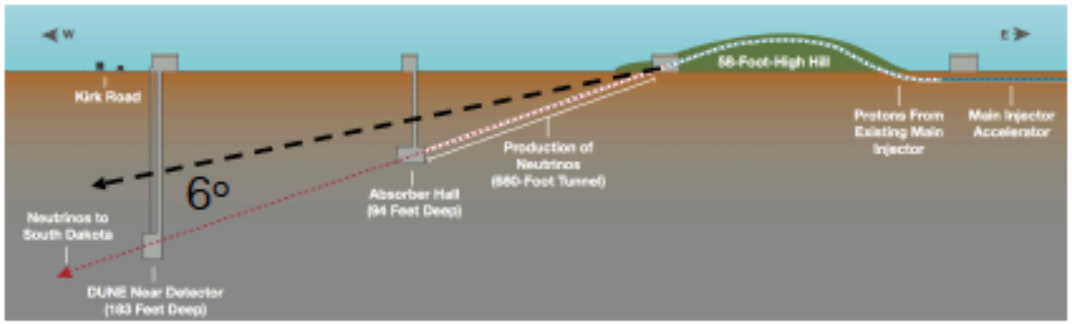
1. SeaQuest arXiv: 1509.00050
(discussed in this workshop)



2. MiniBoone arXiv: 1411.4311
longterm, ~no-cost,
well-understood detector



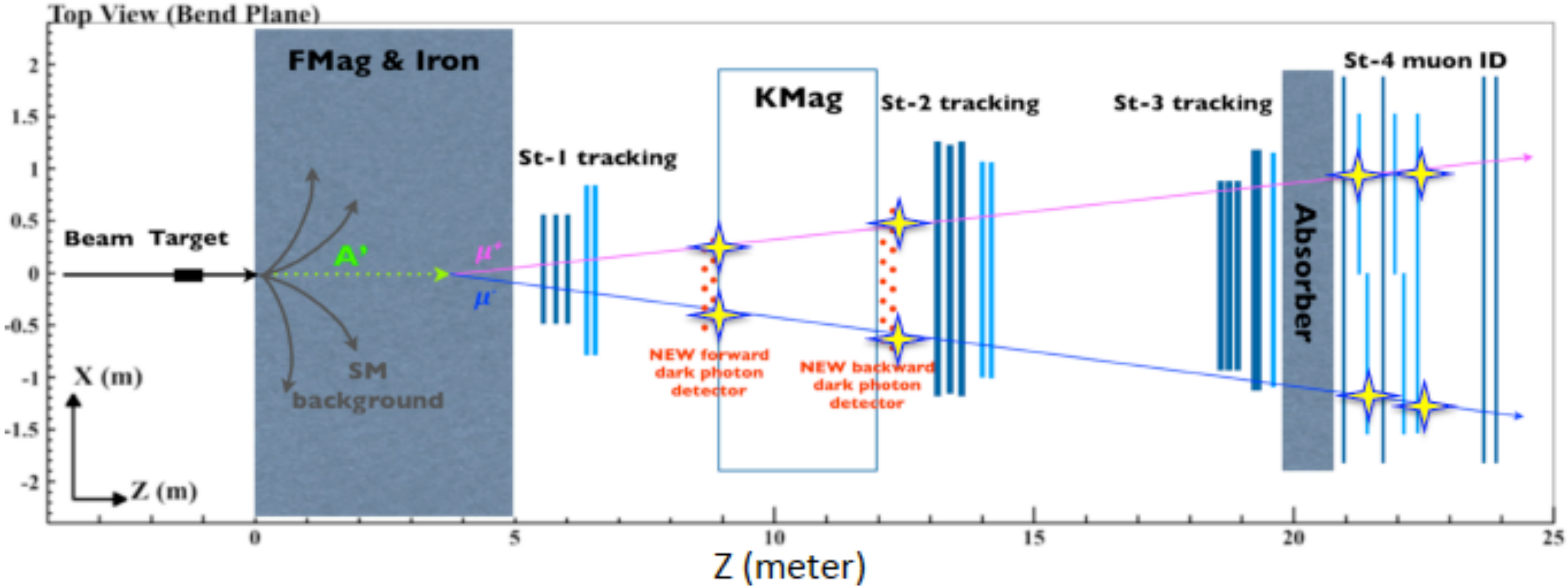
3. "6° of Separation" arXiv: 1512.0385
new ideas for NuMI beam and LBNF: sit 6° away to minimize neutrino flux,
look for dark matter beam.
MiniBoone ~ 6° from NuMi line (but a little close)
LBNF possibilities (see below)



SeaQuest@FNAL: search for Dark Photon and Dark Higgs

120 GeV protons, 2x10^{12} ppp (5% of MI) 4 sec spill, 200 days, 2x10^{18} pot

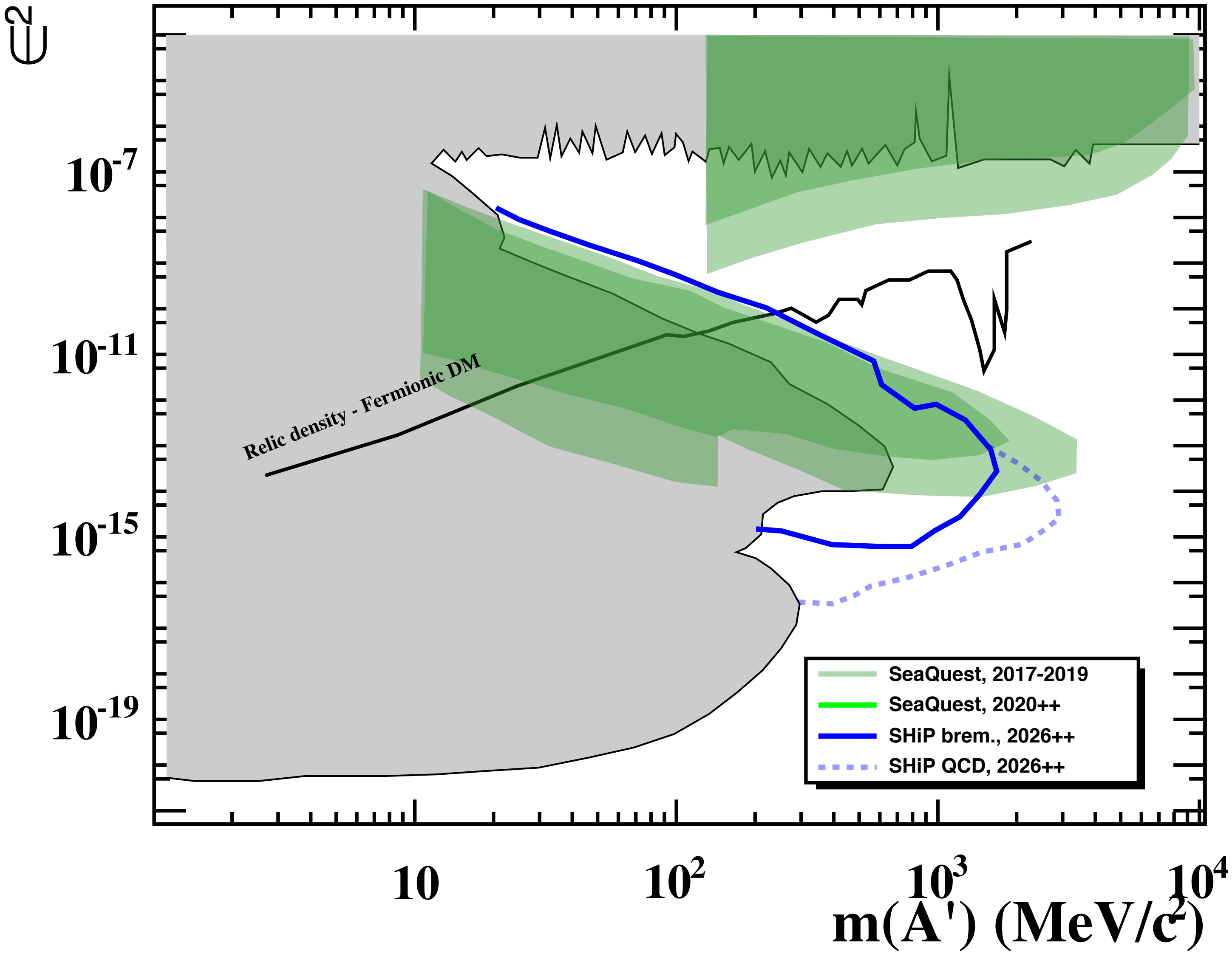
- **now:** Use E906 (currently running) setup (nucleon, nuclear structure physics with DY)
- **2017-2019**: parasitic run with x10 TDAQ rate (10 kHz), new tracker
- **2020++:** dedicated run, e/π PID capability, x100 TDAQ rate (100 kHz)



Interesting experiment: we have to keep an eye on it….

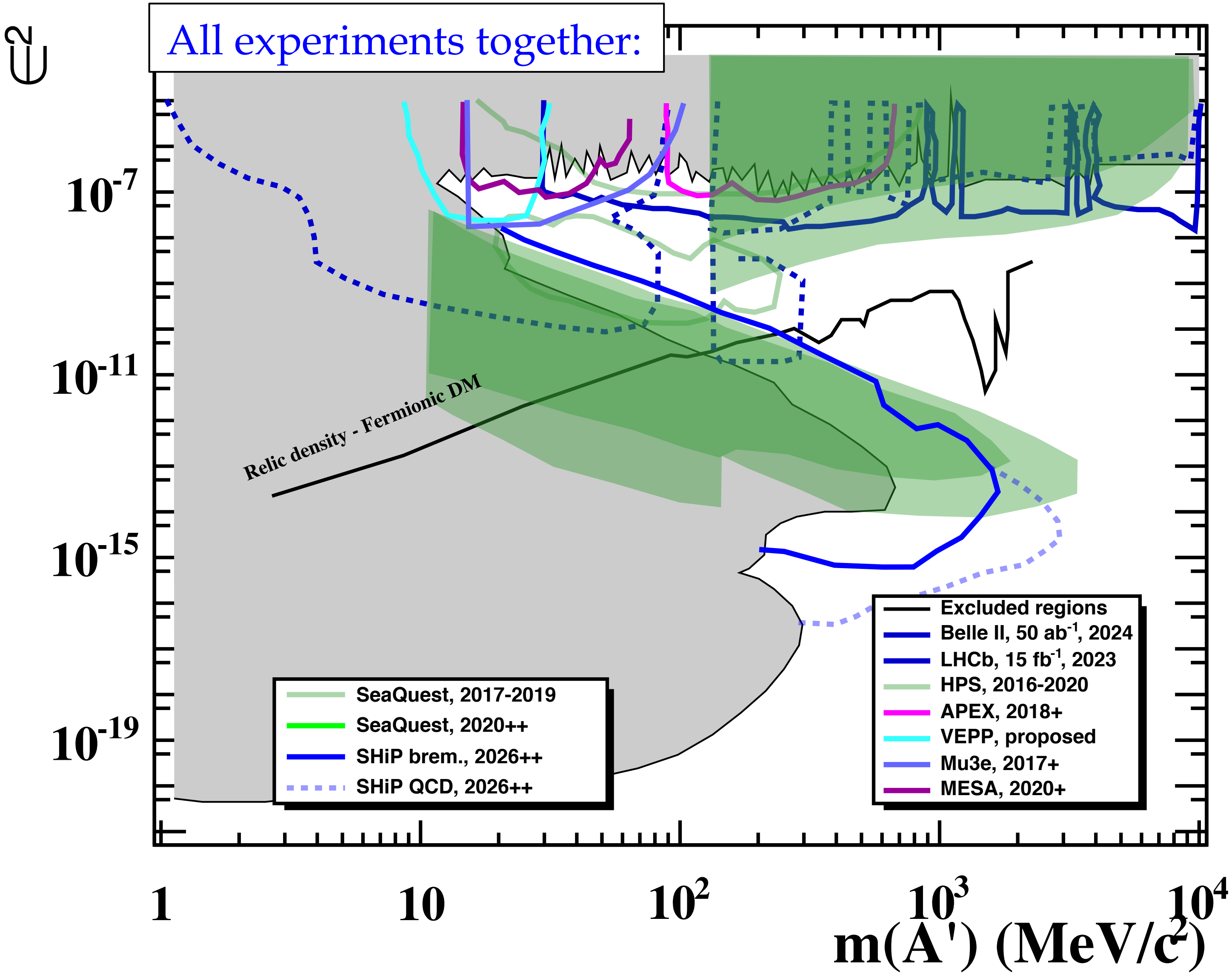
Vector portal: visible searches

SeaQuest compared to SHiP



Vector portal: visible searches

All experiments together:



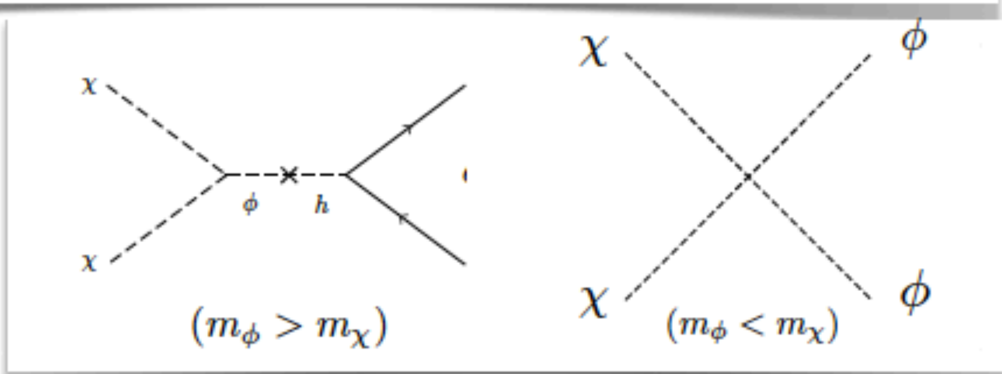
Scalar Mediator

How to survive CMB for scalar mediator?

Choose LDM candidate & coupling

Scalar DM

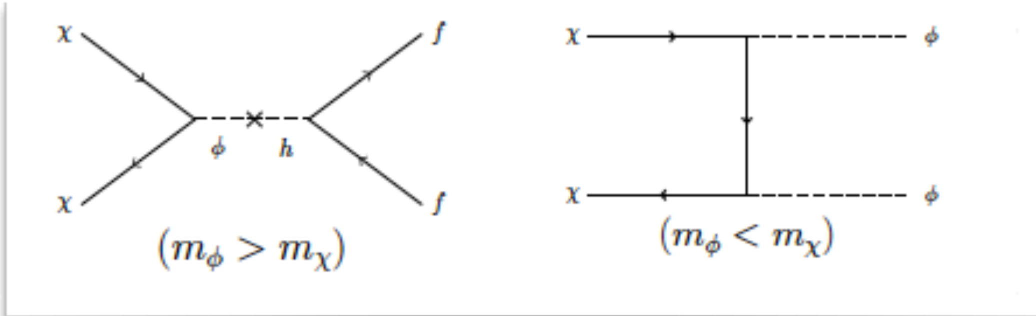
both s-wave!



Need particle asymmetry or inelasticity for CMB safety

Fermion DM

$g_\chi \phi \bar{\chi} \chi$

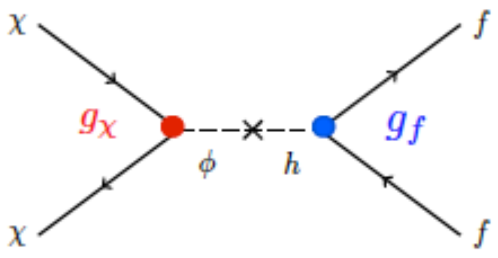


Can also include $\phi \bar{\chi} \gamma^5 \chi$
must be tiny (adds s-wave piece)

Both CMB ok!

$\sigma v \propto v^2$

Thermal Target: Direct Annihilation to SM



$(m_\phi > m_\chi)$

$$g_f = g_e \left(\frac{m_f}{m_e}\right)$$

Coupling scales with SM fermion mass

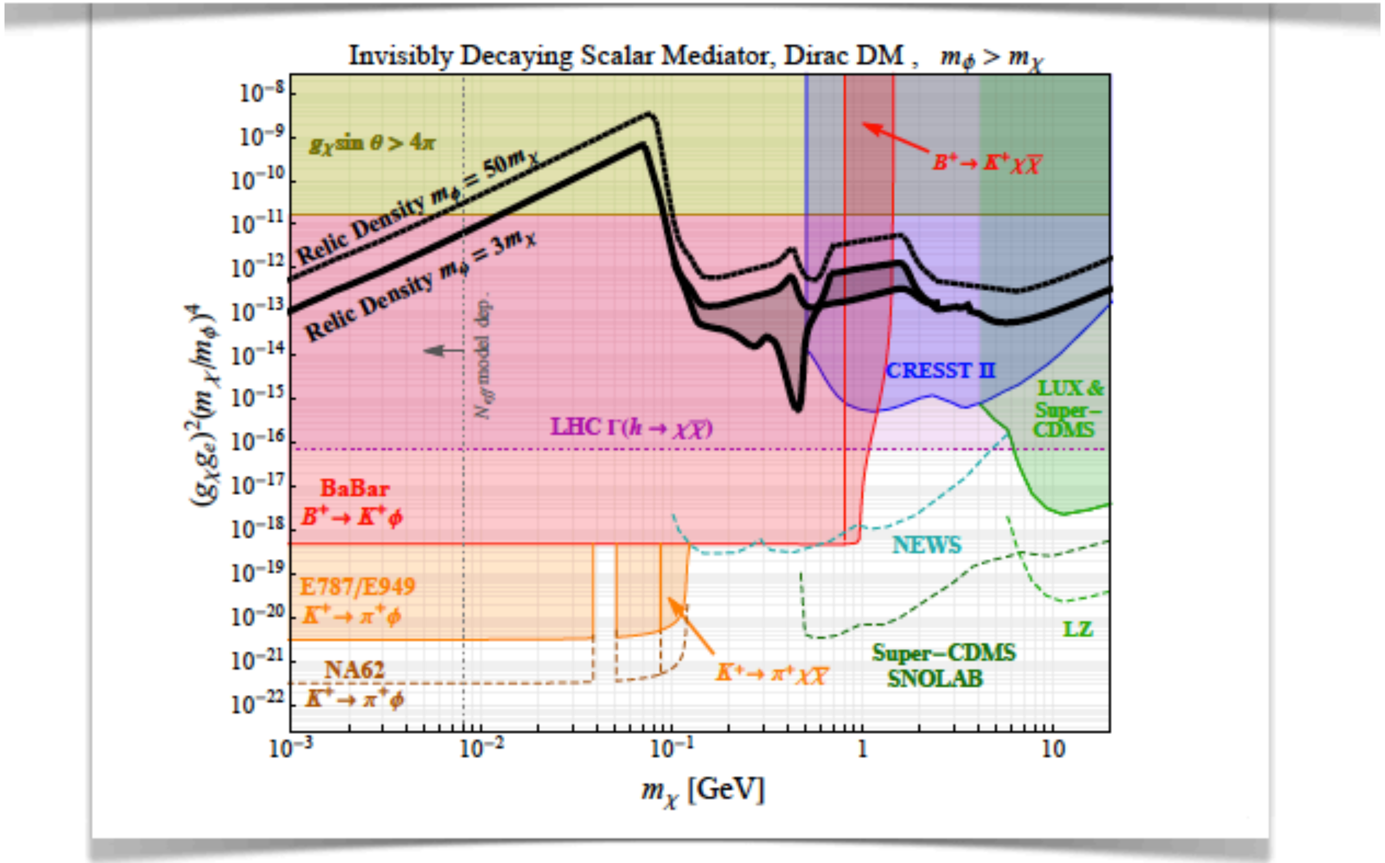
$$\sigma v = \sum_f (\sigma v)_f \propto g_\chi^2 g_e^2 \left(\frac{m_\chi}{m_\phi}\right)^4 \frac{1}{m_\chi^2}$$

In analogy with dark photon target

$$y \equiv g_\chi^2 g_e^2 \left(\frac{m_\chi}{m_\phi}\right)^4$$

Normalized to electron coupling because it's relevant for every mass point

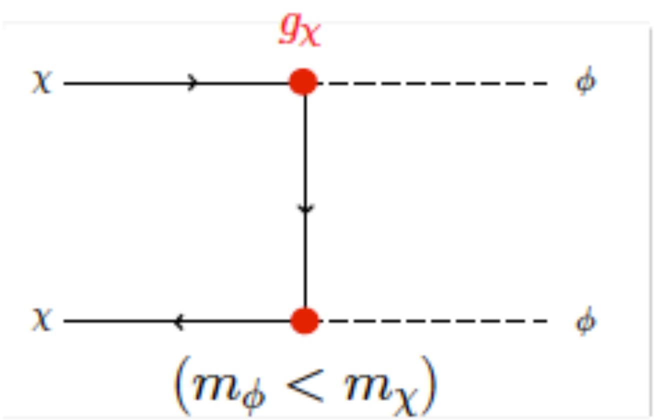
Direct Annihilation: Ruled Out



Collider and meson constraints use conservative $m_\phi = 3m_\chi$ $g_\chi = 1$

Constrained by B→K invisible decays, Higgs invisible width and low mass direct searches

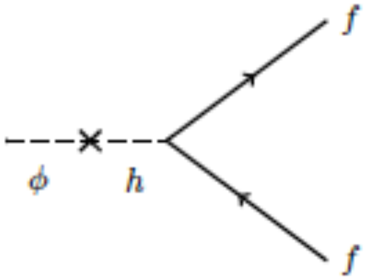
Annihilation to Mediators: Thermal Target?



Annihilation rate independent of SM

$$\sigma v(\chi\chi \to \phi\phi) = \frac{3 g_\chi^4 v^2}{128\pi m_\chi^2}$$

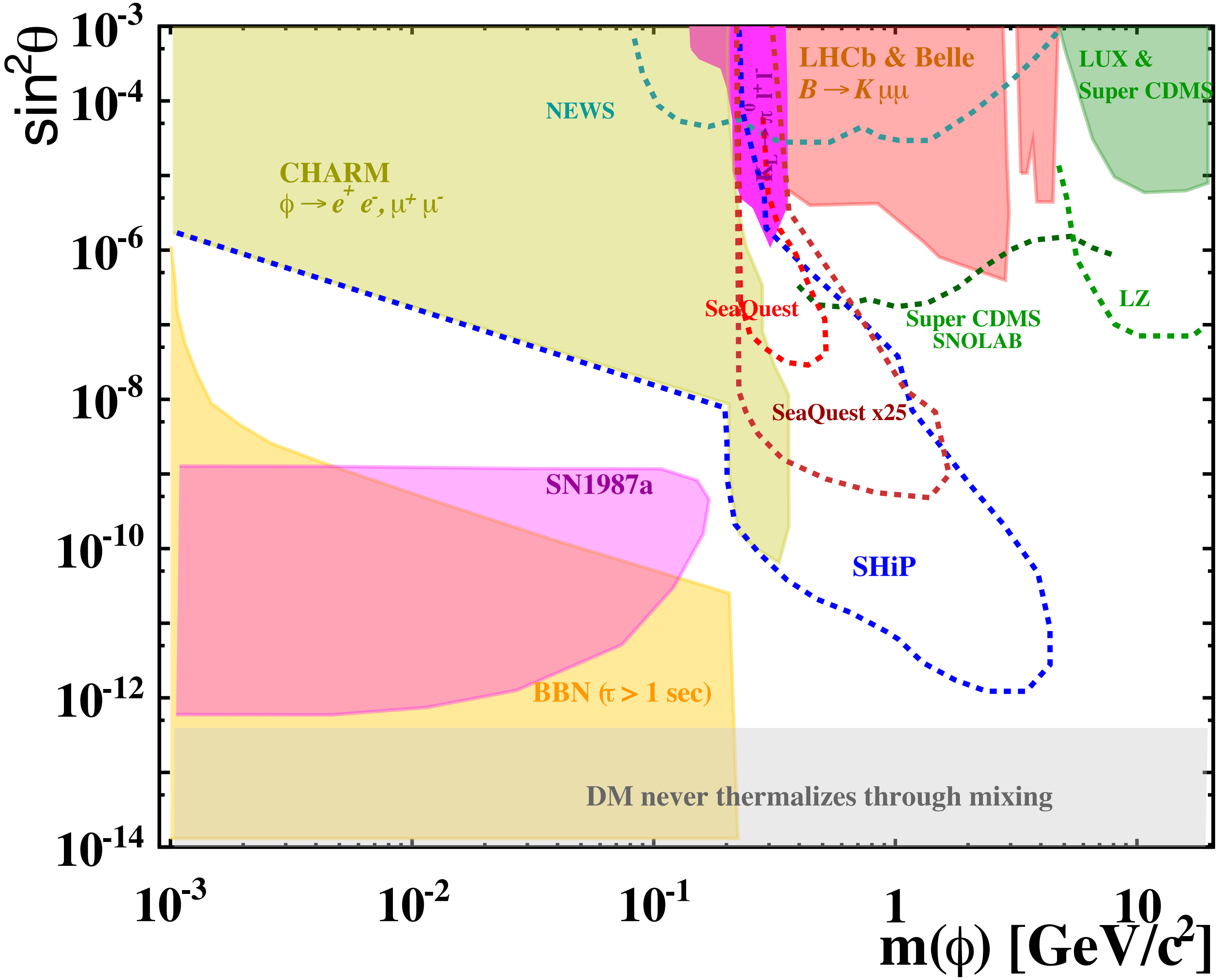
Mediator decays visibly to SM final states



Can still produce/observe mediator, but no direct target

So long as annihilation is p-wave
DM doesn't matter for bounds

Scalar Portal: current and future limits



Conclusions

Focus on light DM with thermal origin:

-light DM requires light mediators to reach equilibrium.

Focus on Vector and Scalar mediators decaying to visible SM final states:

- Very lively community planning several experiment in the near and far future.
- SHiP has a unique sensitivity uncovered by current or future experiments.
- Keep an eye to SeaQuest@FNAL and NA62 @ CERN (see talk later on)

for sensitivities and backgrounds.