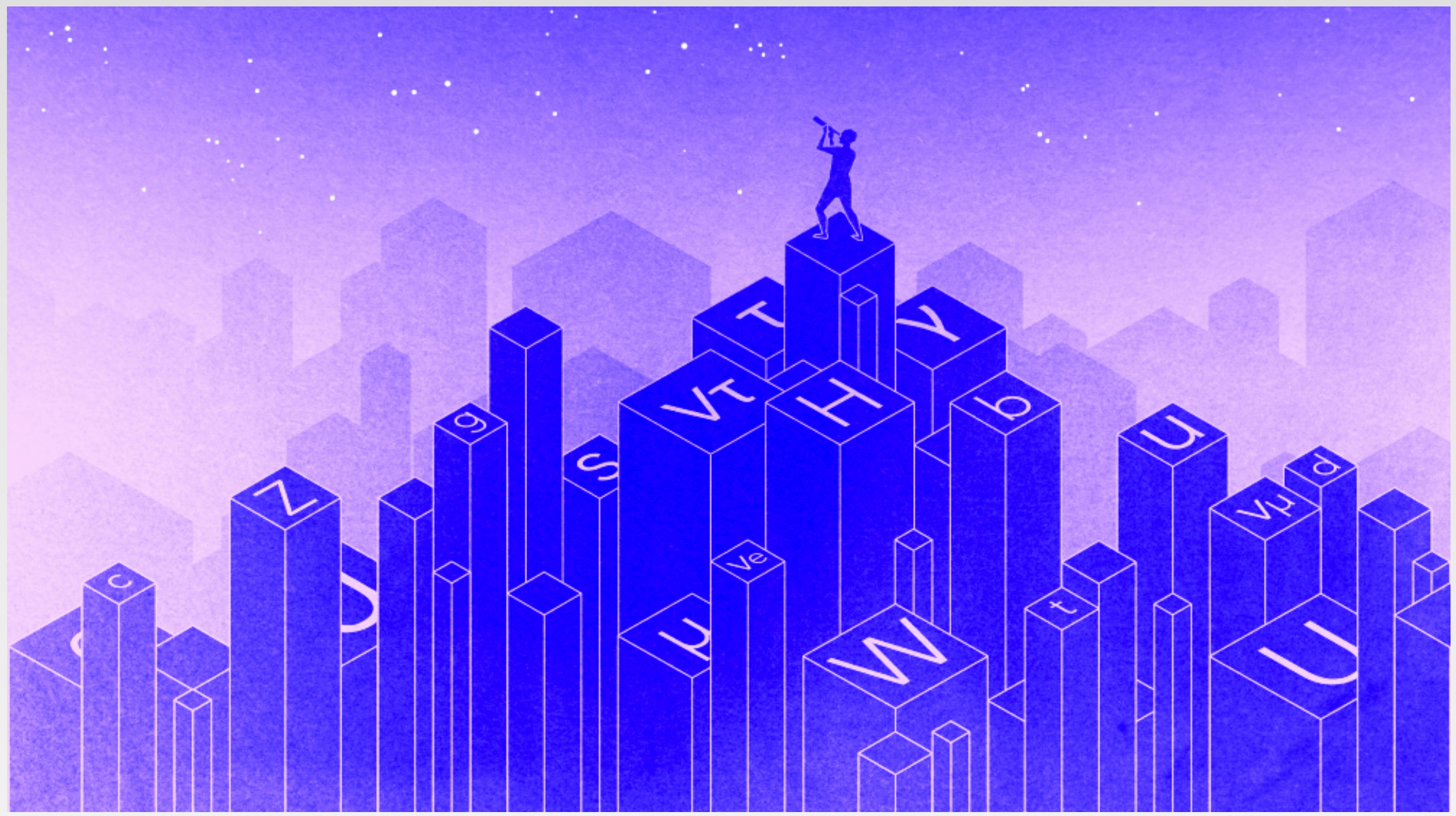
A new quest for physics beyond the Standard Model



Claudia Frugiuele

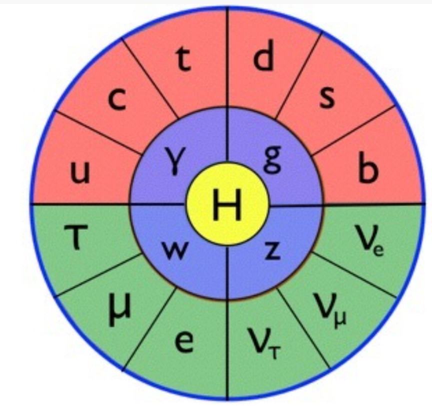
מכון ויצמן למדע

WEIZMANN INSTITUTE OF SCIENCE

The Standard Model is now complete!

What's next?

Still many open questions



Neutrino Masses

Strong CP problem

Baryogenesis

Physics beyond the Standard model

Flavor problem

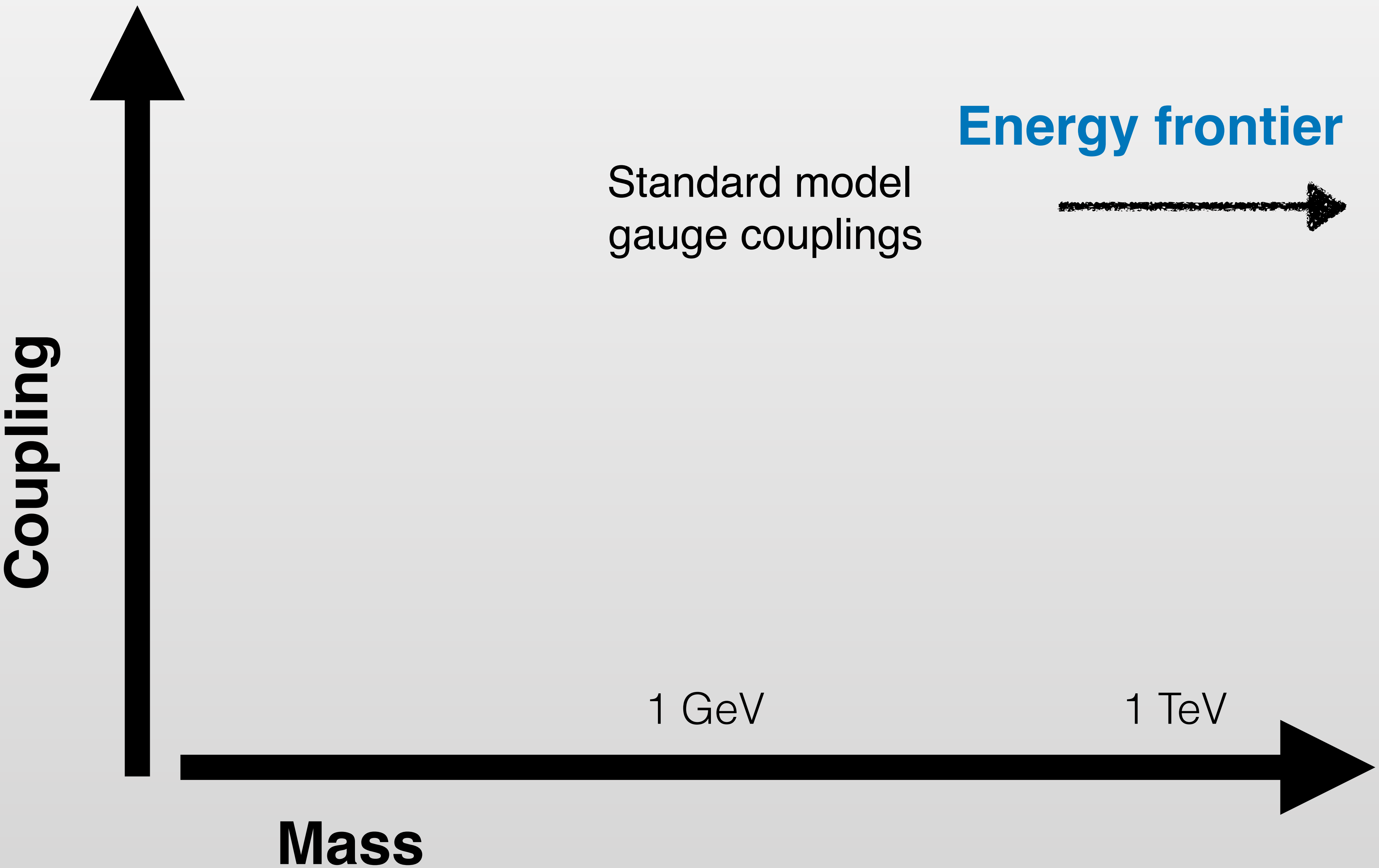
Dark matter

Why is the Higgs light?

The quest for BSM physics

What is dark matter ?

Why is the Higgs light?



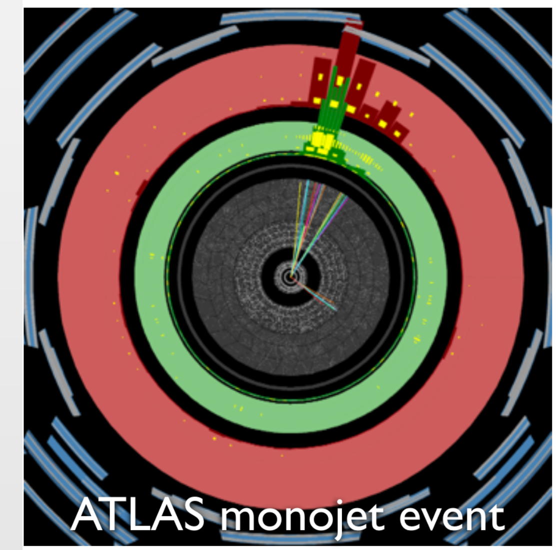
The quest for BSM physics

What is dark matter ?

Why is the Higgs light?

Energy frontier

Standard model
gauge couplings



What about light (sub GeV) particles very weakly coupled to the SM?

Coupling

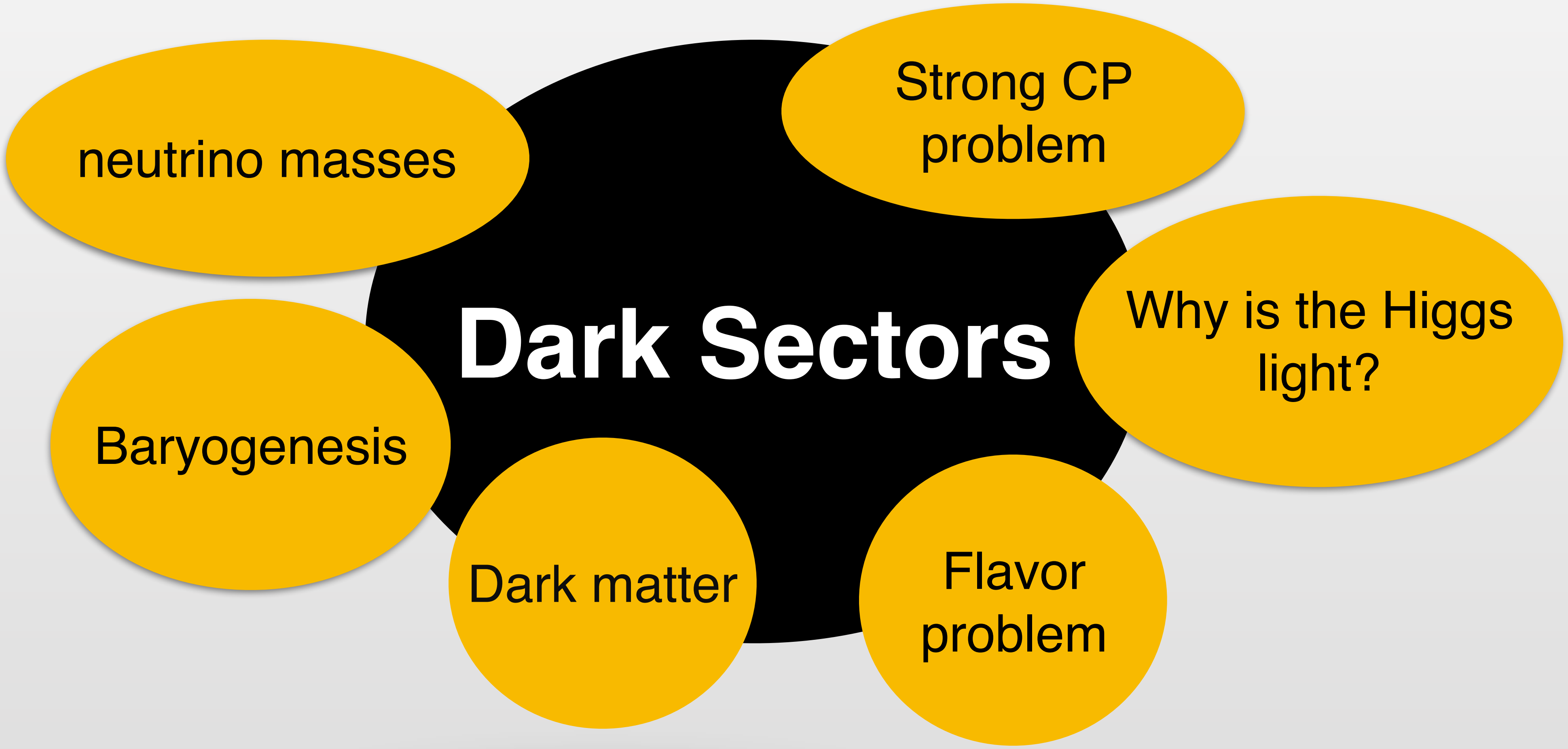
1 GeV

1 TeV

Mass

Dark sectors

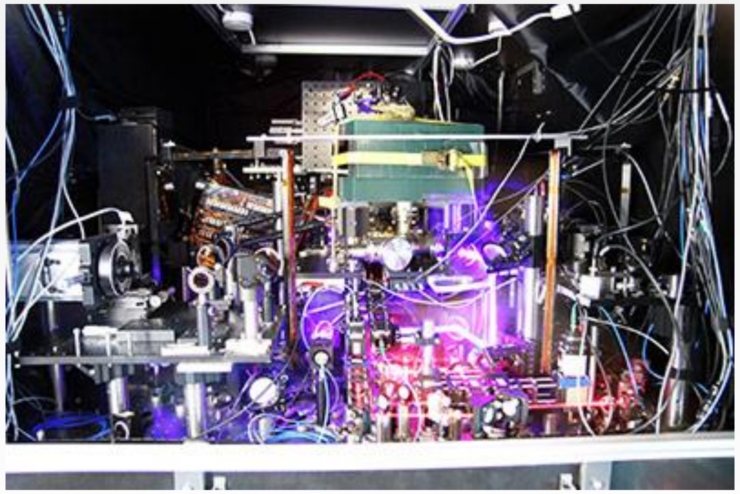
Sectors containing new particles which interact with the visible sector, beyond gravitation, via unknown forces



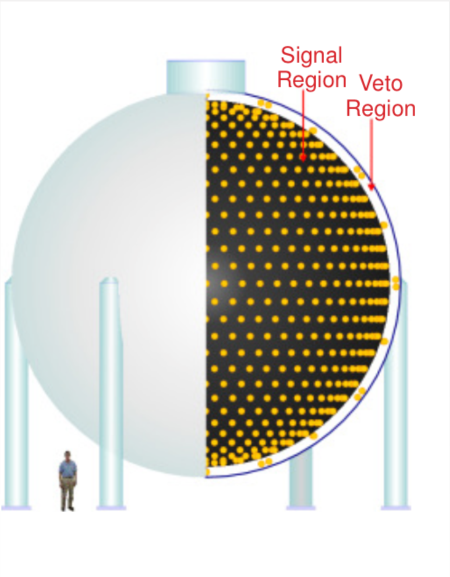
Overlap with many crucial long standing questions of particle physics

A new quest for physics beyond the Standard Model

- **Direct probe**: searching for MeV-GeV invisible particles @ neutrino facilities
- **Indirect probe**: searching for new dark forces via atomic spectroscopy



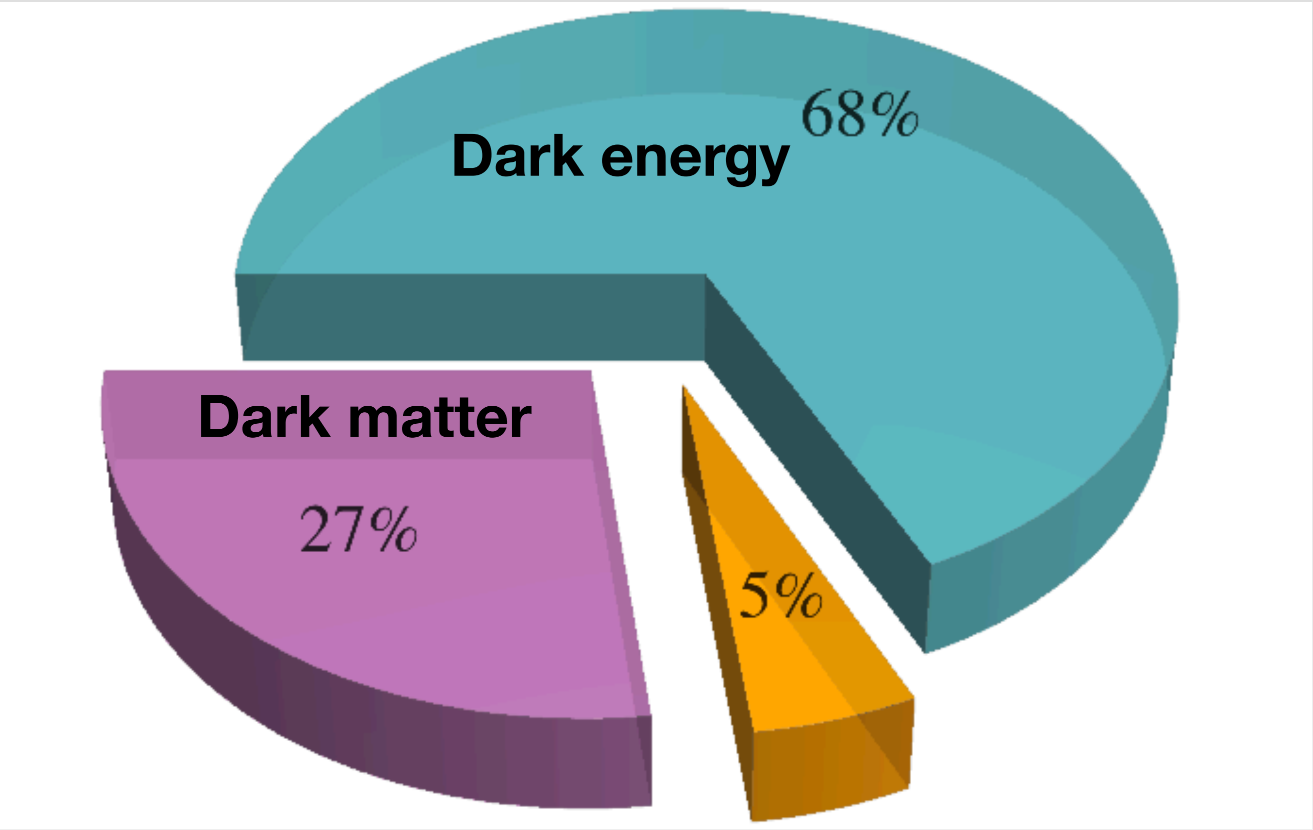
Strontium atomic clock



MiniBooNE neutrino detector

The universe is dark

Vera Rubin, ca. 1970



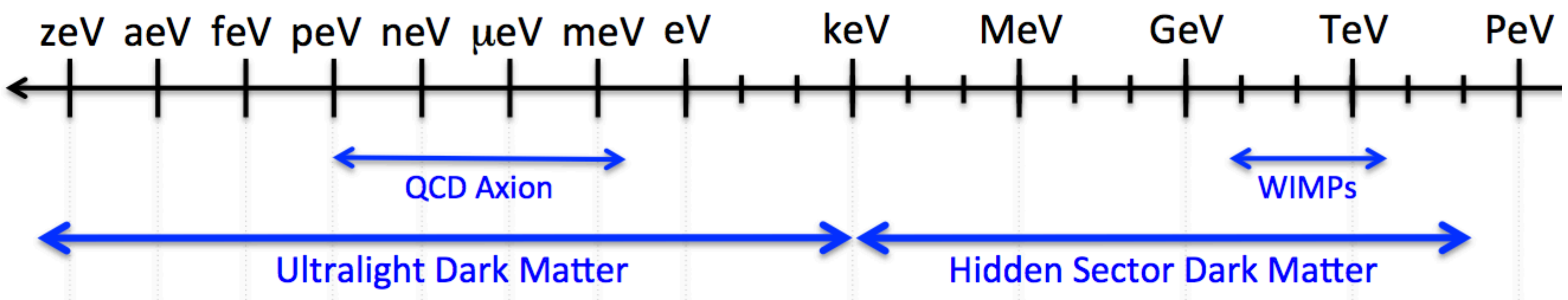
What is Dark Matter (DM) made of?

Requires at least one new particle to exist today

DM model landscape is broad

Theoretical guidance is crucial

Not a complete list, U.S. Cosmic vision 2017

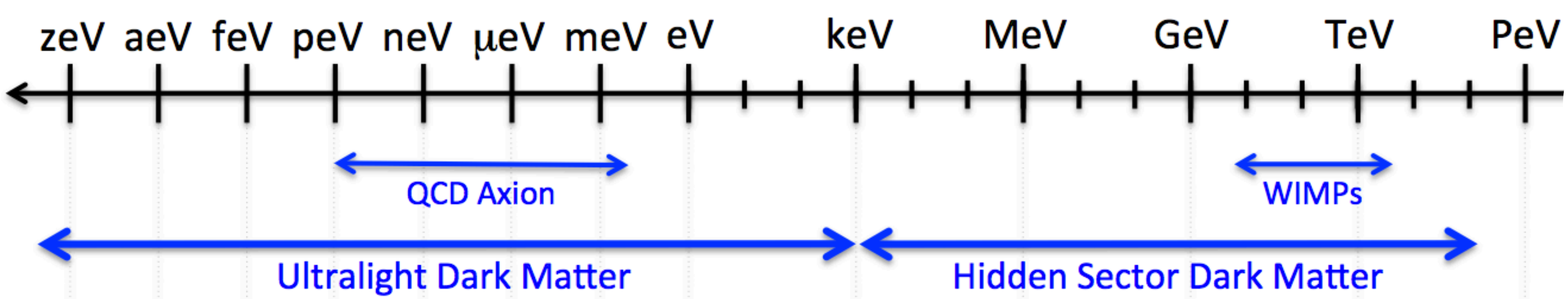


Cosmological history of DM ?
Connection to other particle physics long standing questions
(e.g. strong CP problem and hierarchy problem) ?

DM model landscape is broad

Theoretical guidance is crucial

Not a complete list, U.S. Cosmic vision 2017

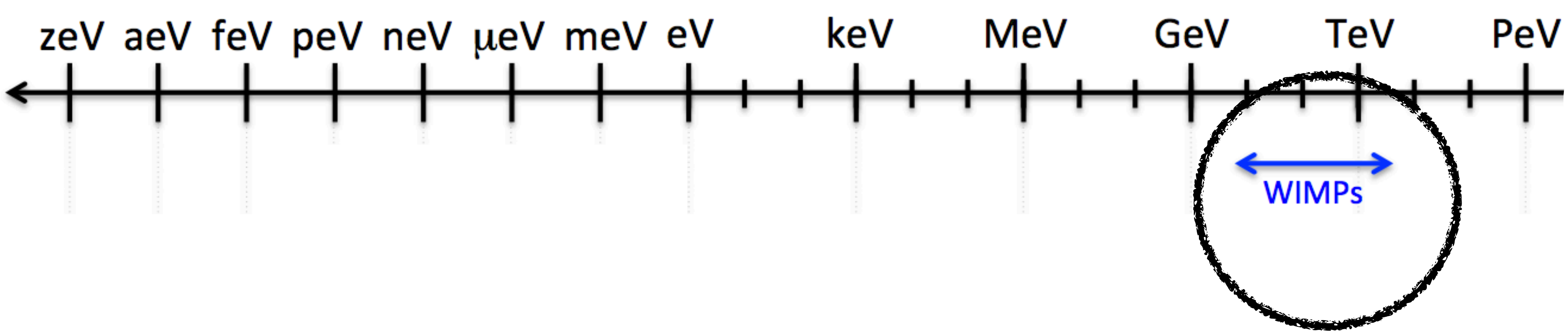


Cosmological history of DM ?
Connection to other particle physics long standing questions
(e.g. strong CP problem and hierarchy problem) ?

DM production mechanism is a powerful guidance to select well motivated DM candidates

Thermal DM acquires its abundance through thermal contact with the Standard Model bath. **DM mass range: 1 keV-100 TeV**

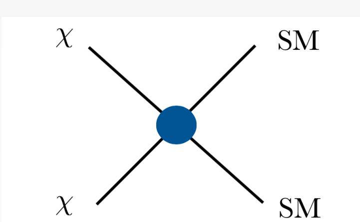
Most of the experimental efforts focus on a small region

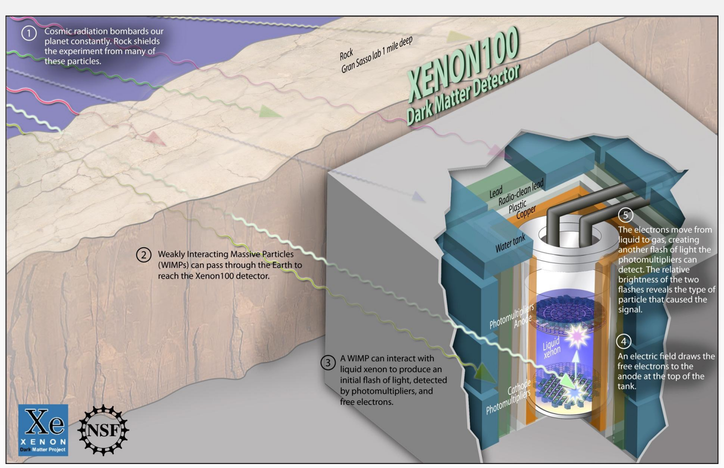


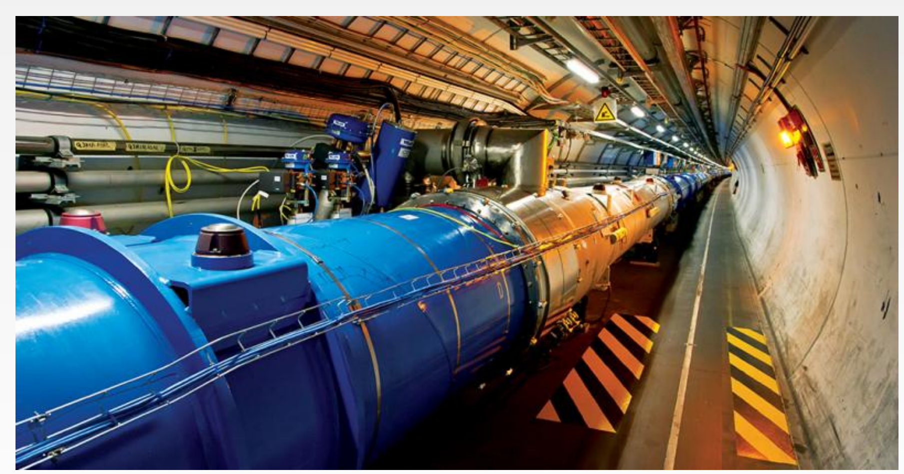
Weakly Interacting Massive Particles

What if DM interact with us via the weak force (W and Z) ?

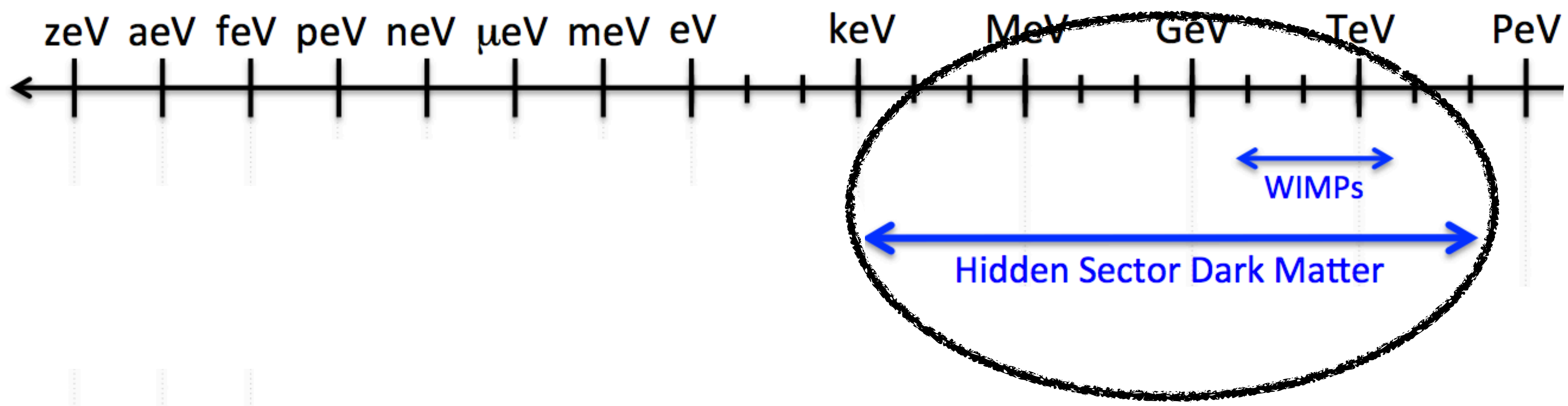
Ubiquitous in SM extensions aimed to solve the hierarchy problem







Going beyond WIMPS?



Interesting mass range for thermal DM: 1 keV-100 TeV

Focus on the sub-GeV window

Direct detection experiments lose sensitivity& LHC has a limited reach.
New experimental strategy required

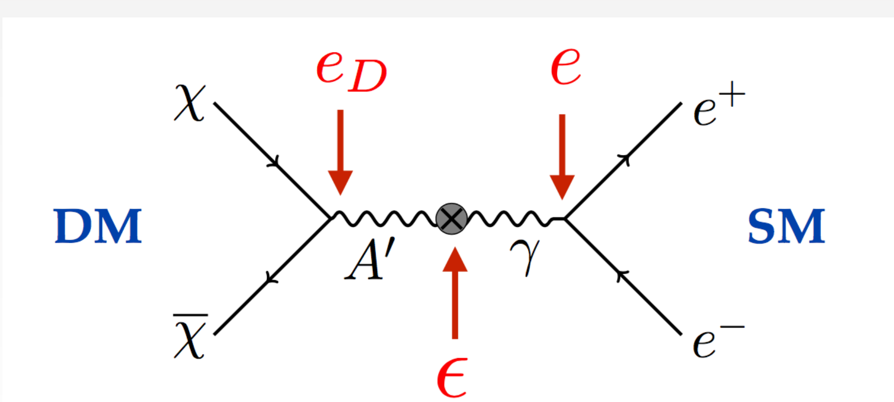
MeV-GeV thermal DM

An MeV-GeV particle interacting with the visible sector via new MeV-GeV forces could account for the observed DM abundance in the universe

$$\epsilon F_{\mu\nu} F'^{\mu\nu}$$

$$g_{A'}^{\mathrm{SM}} = \epsilon e x_{\mathrm{f}}$$

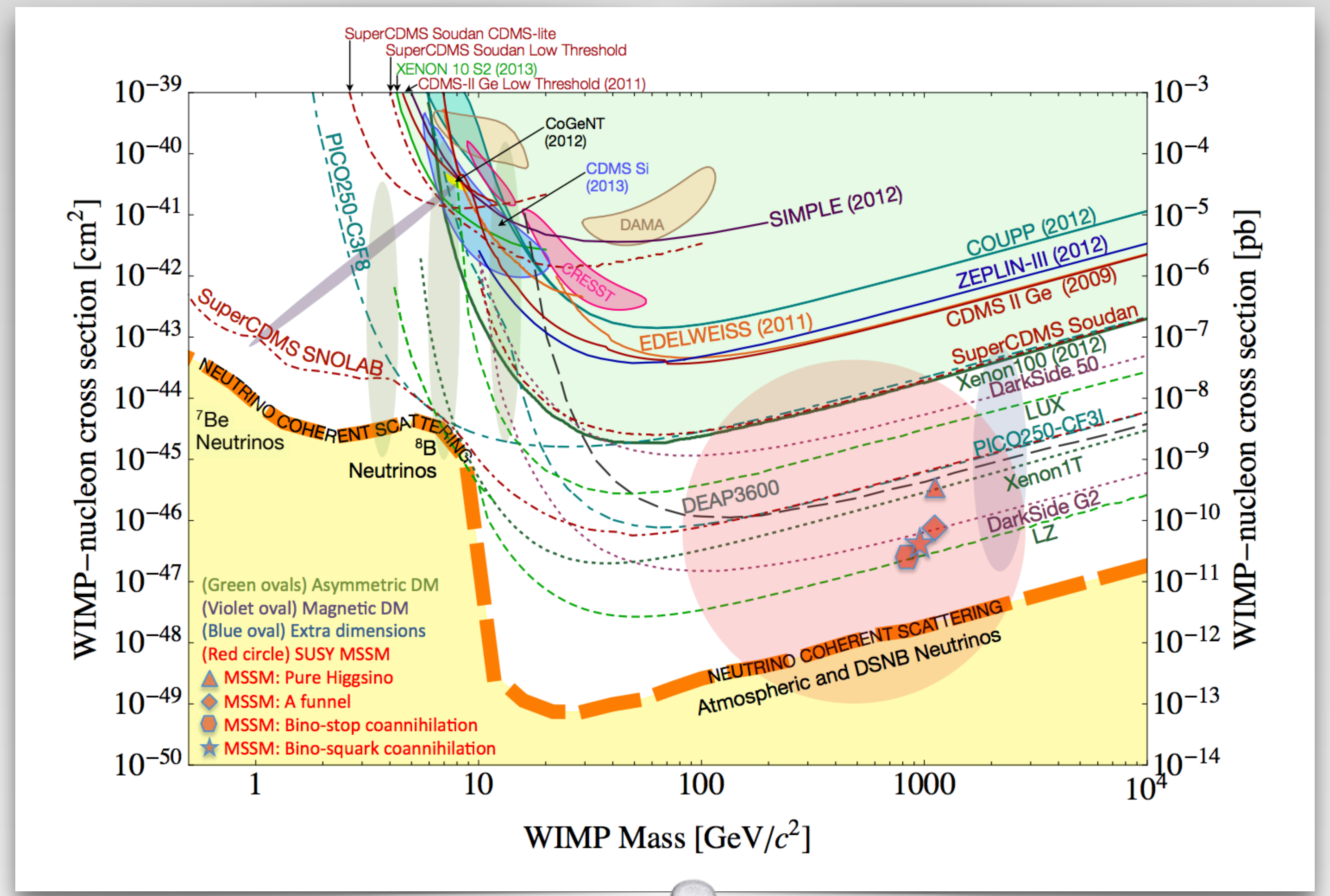
$$g_{A'}^{\phi} \sim \mathcal{O}(1)$$



Dark Photon portal:
MeV-GeV gauge boson
kinetically mixed with the photon

[Holdom 1985]

Experimental probes



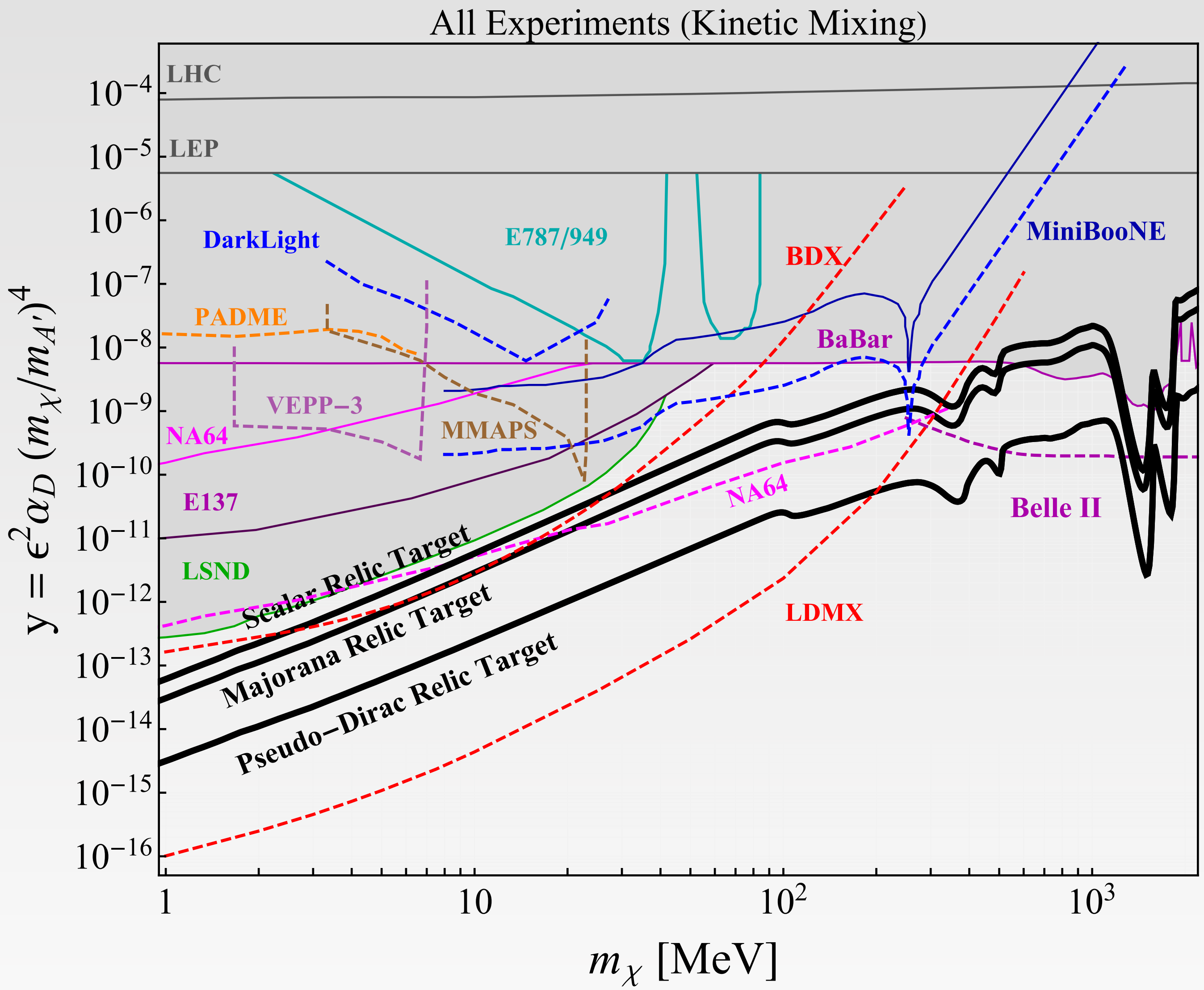
1. DM-electron direct detection experiments (e.g. Essig et al. 2012)

2. Low energy/ high intensity experiment

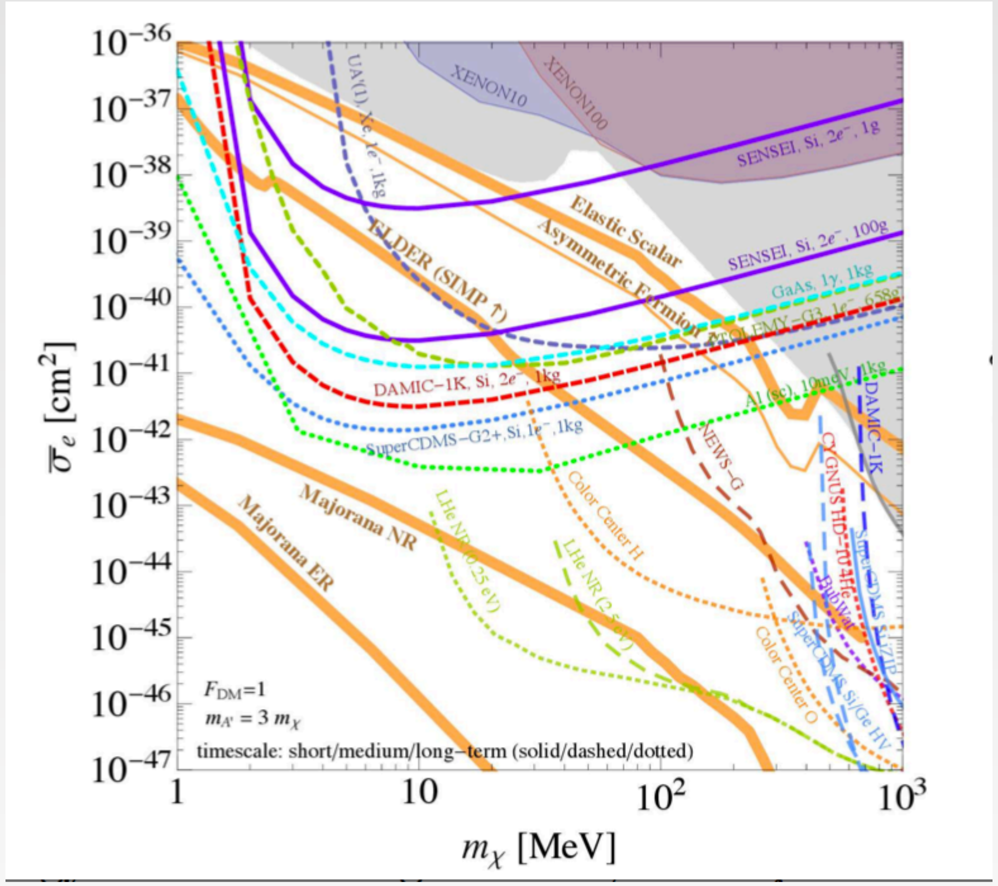
New experimental program is needed

An impressive future effort

Intensity frontier: fixed targets and low energy colliders



Dark photon invisible decay

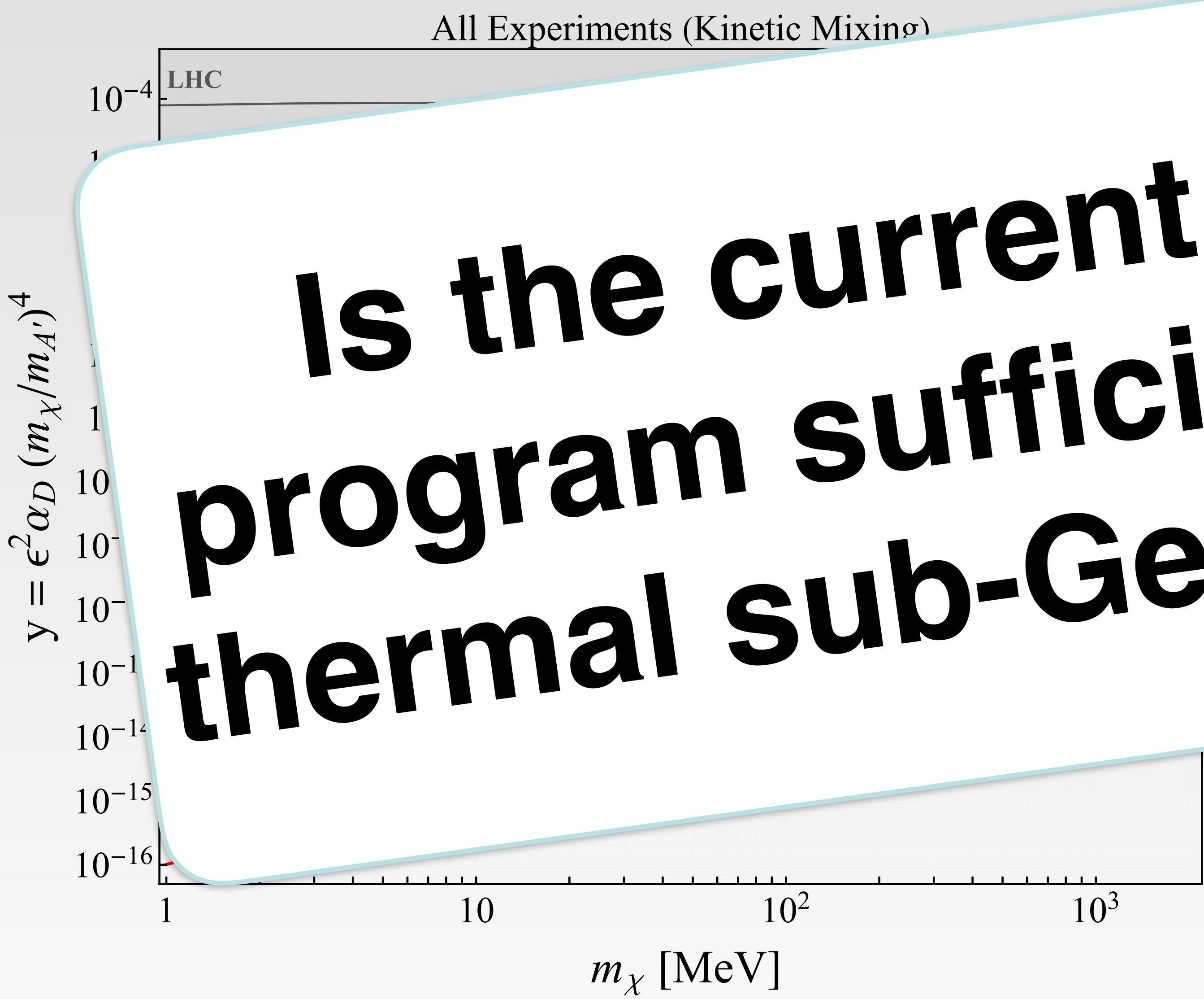


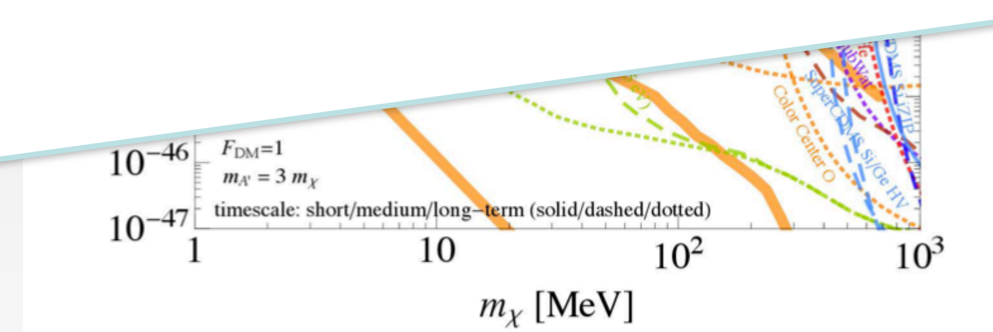
Next generation direct detections experiments

U.S. Cosmic vision 2017

An impressive future effort

Intensity frontier: fixed targets and low energy colliders





Is the current experimental program sufficient to probe the thermal sub-GeV DM paradigm?

Dark photon invisible decay

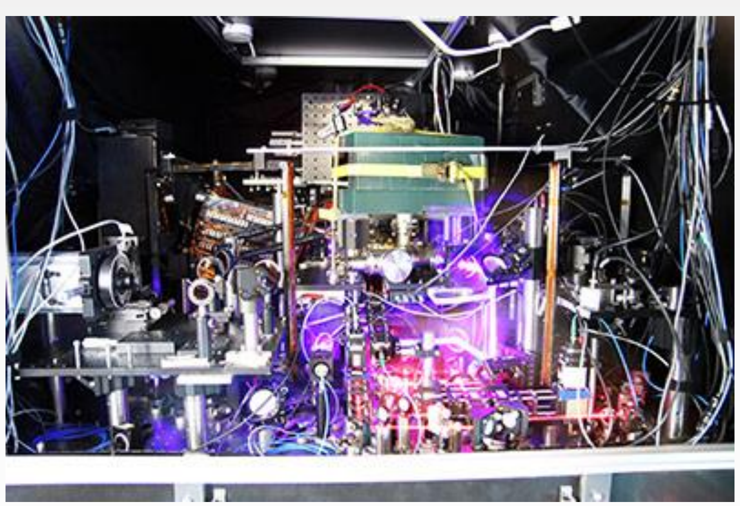
Next generation direct detections experiments

U.S. Cosmic vision 2017

A new quest for physics beyond the Standard Model

- **Direct probe:** searching for MeV-GeV dark matter @ neutrino facilities

- **Indirect probe:** searching for dark forces via atomic spectroscopy



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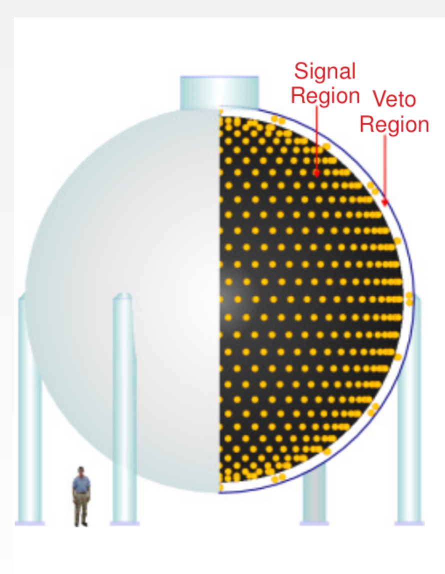
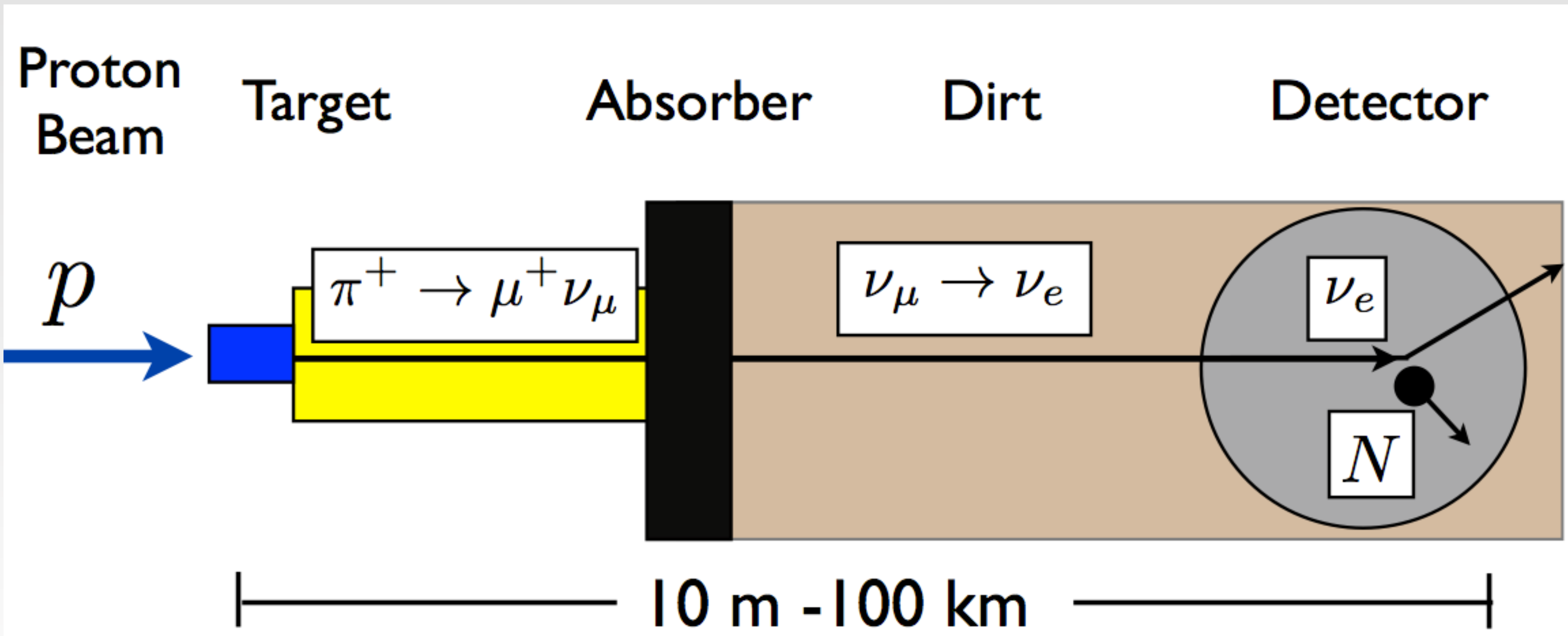


MiniBooNE neutrino detector

Neutrino facilities

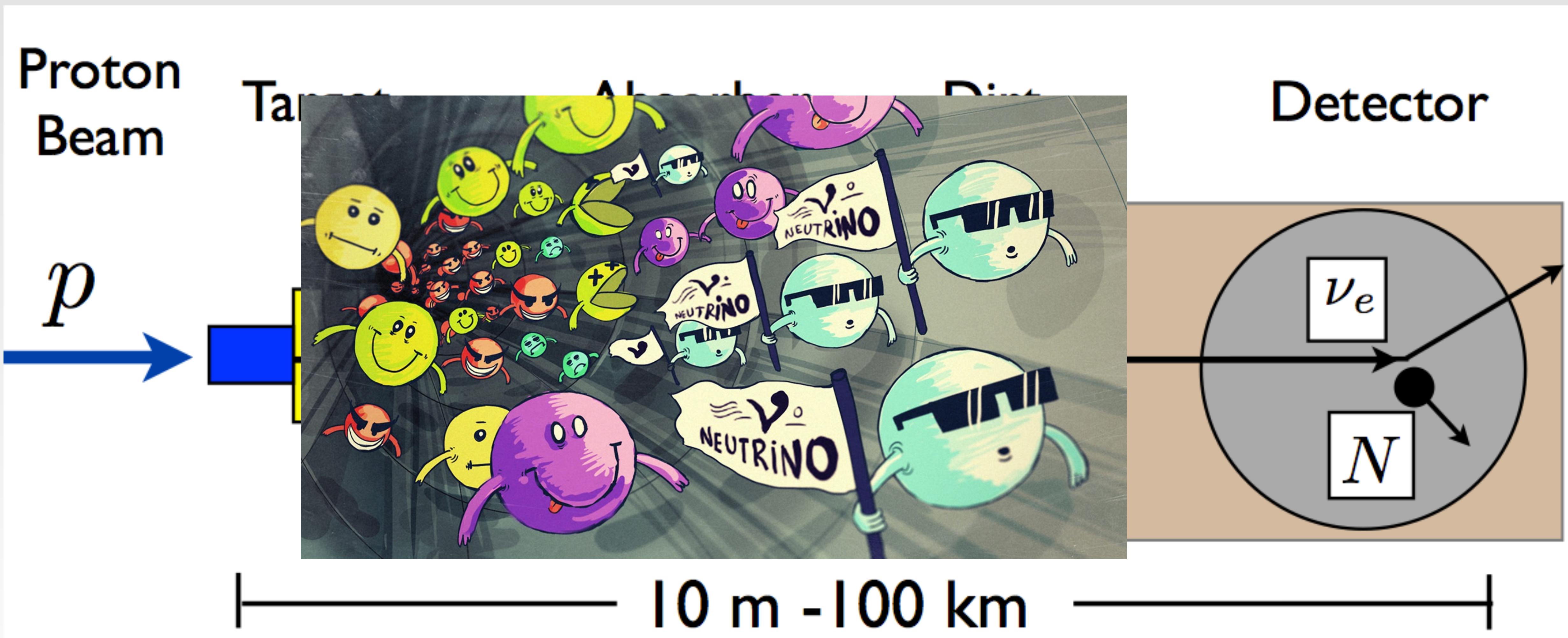
Original goal: measuring neutrino masses and mixings



Neutrino facilities

New proposal goal: use neutrino facilities to search for DM

[Batell, Pospelov Ritz, 2009]



A relativistic DM beam is produced along the neutrino one.
DM particles also enter the detector and scatter off electrons and nuclei

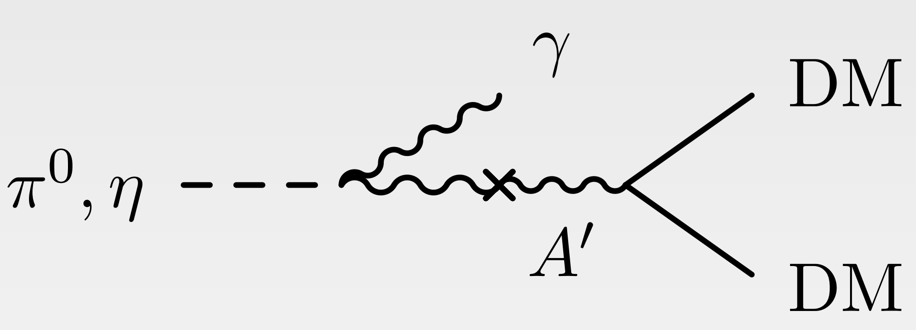
How is the DM beam produced?

MeV-GeV gauge boson kinetically mixed with the photon $g_{A'}^{\rm SM} = \epsilon e x_{\rm f}$

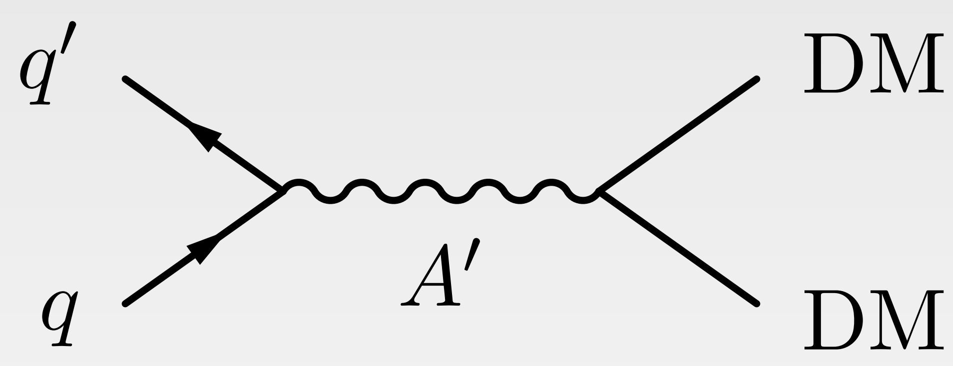
MeV-GeV scalar DM (no tension with cosmology) $g_{A'}^{\phi} \sim \mathcal{O}(1)$

On shell production of the mediators is essential

- Production via meson decay



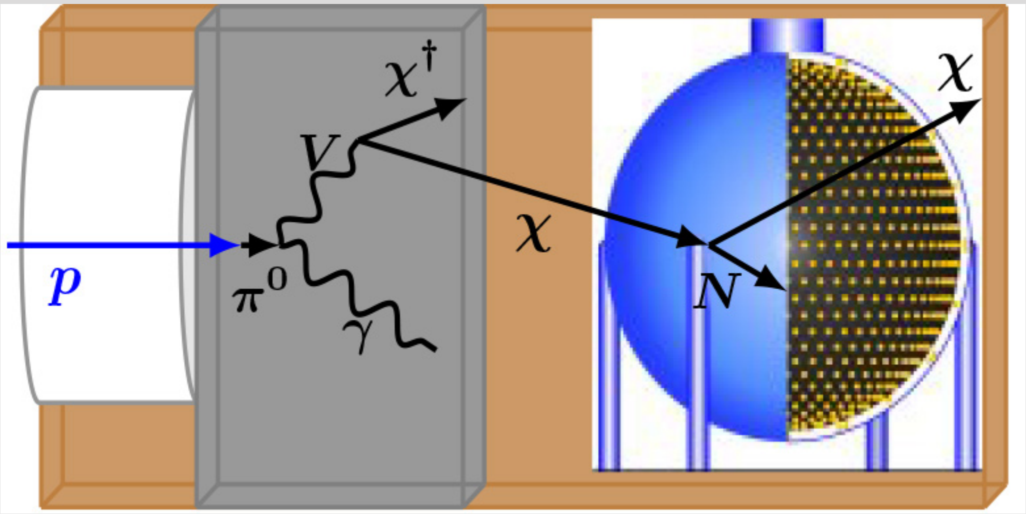
- Direct Production



Type of signature: MeV-GeV mediator decaying into DM

High intensity experiments:
order 10^{20} protons on target per year!

How do we detect DM ?



Two observables

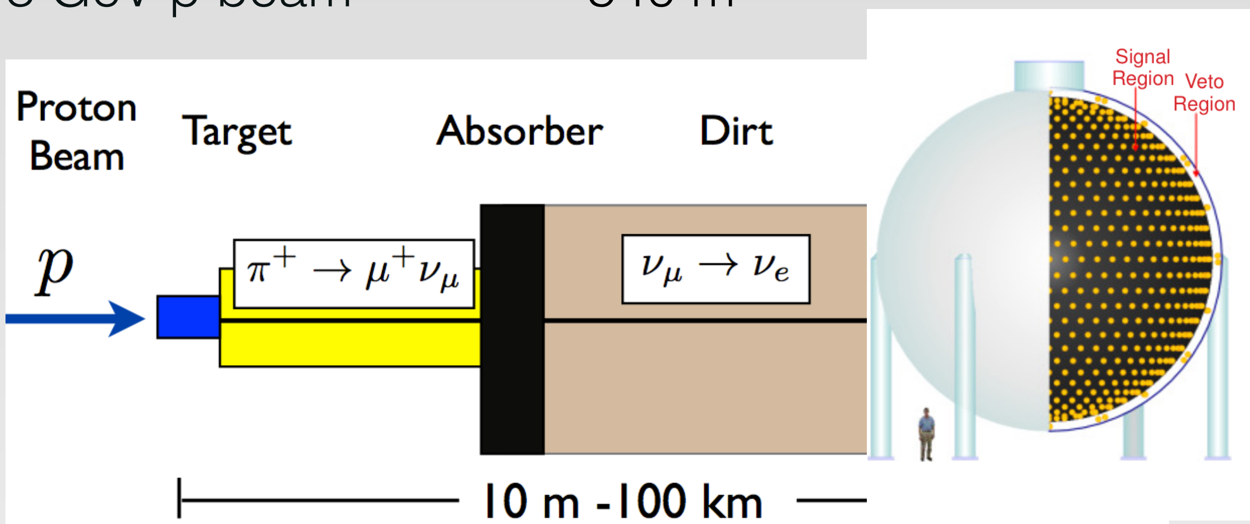
- DM-nucleus scattering
- DM-electron scattering

Main challenge: suppression of neutrino background.

Currently only one experimental collaboration (MiniBooNE) is performing DM searches

DM search @ MiniBooNE

8 GeV p beam 540 m



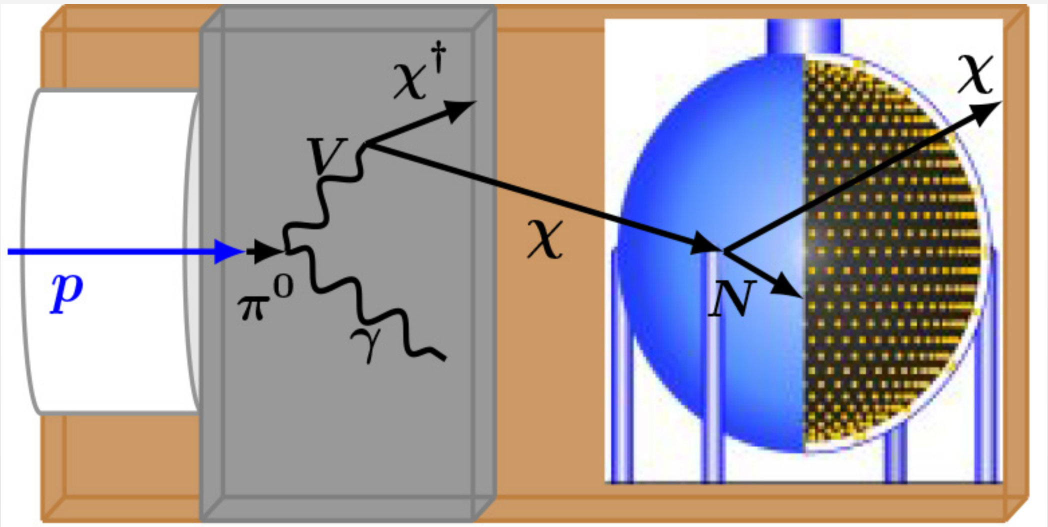
MiniBooNE:800 tons detector

- Light DM analysis in beam dump mode [A.A. Aguilar-Arevalo et al. 2017]
- Constraints for sub-GeV vector mediator
- Light DM program calls for a dedicated run to suppress the neutrino background ?

Building a DM program@ accelator neutrino facilities

- Rich and diverse experimental program
- We are sitting on many datas which might be used to search for DM **symbiotically** to the neutrino program
- Massive **future experimental effort** (SBND,ICARUS, HyperK, DUNE)
- **Complementarity** to future direct detection experiments (nucleon-DM)
- **Broad class of signals** to explore (extend the effort to visible decays, other light dark matter scenarios)

DM-electron scattering



[DeNeverville, **CF**, 2018]
[DeNeverville, **CF**, Shoemaker, 2019 in progress]

Small neutrino background

Neutrinos @ Main Injector (NuMI)

[Dobrescu, **CF**, 2014]
[Dobrescu, Coloma, **CF**, Harnik, 2015]
[**CF** , 2017]
[DeNeverville,**CF**, 2018]

8 GeV p beam

540 m

MiniBooNE

not to scale

$\theta_{MB} \sim 6.5^{\circ}$

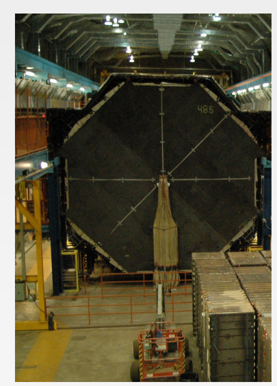
700 m

900 m

NOvA

120 GeV p beam

14 GeV center of mass energy



Minos Minerva

Many possibilities (and existing data) to explore DM parameter space

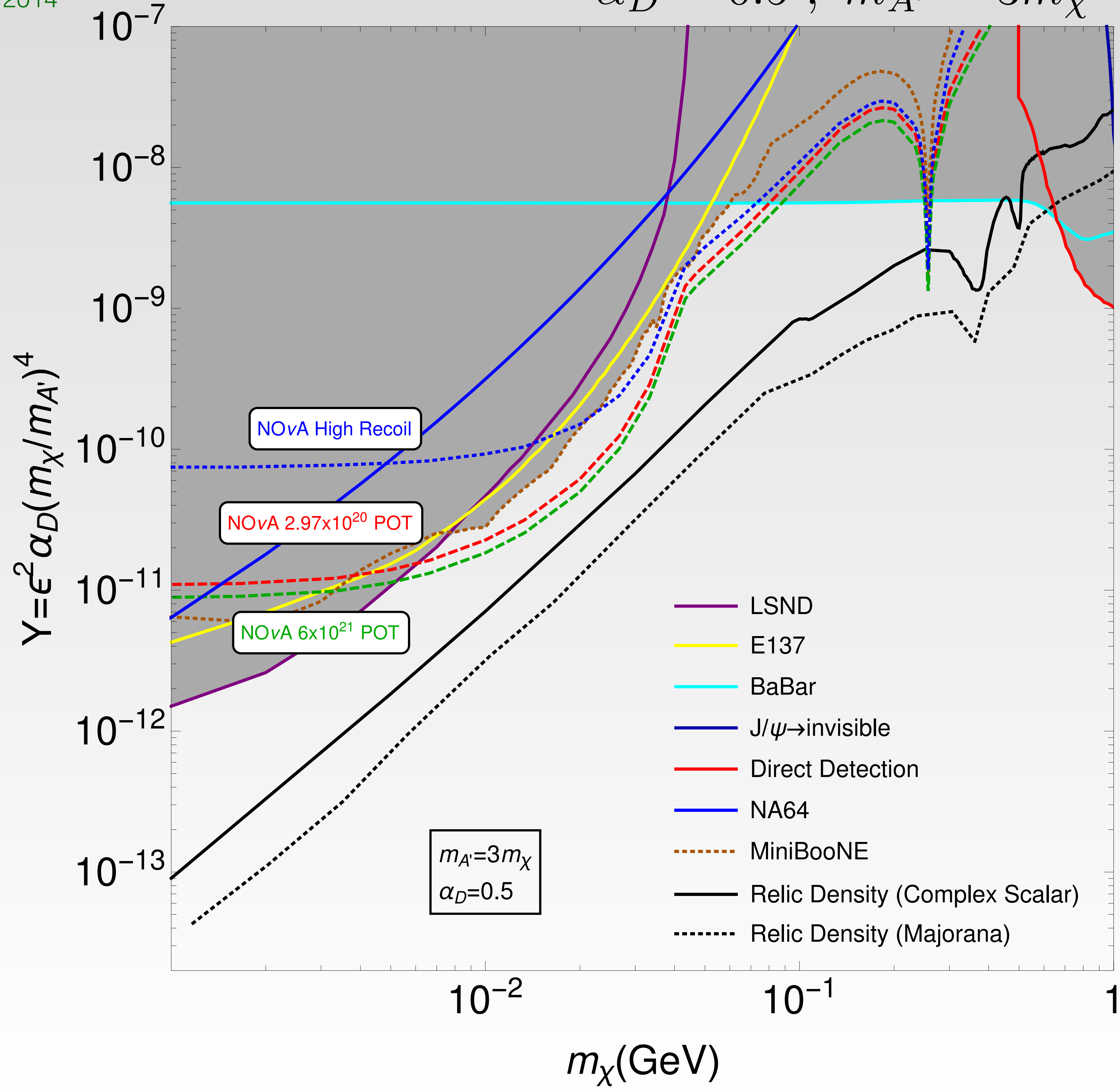
NOvA as a DM detector

$< \sigma v > \propto \frac{Y}{m_\chi^2}$

Izaguirre, et al 2014

[DeNeverville,**CF**, 2018]

$\alpha_D = 0.5\ ,\ m_{A'} = 3m_\chi$



NOvA as a DM detector

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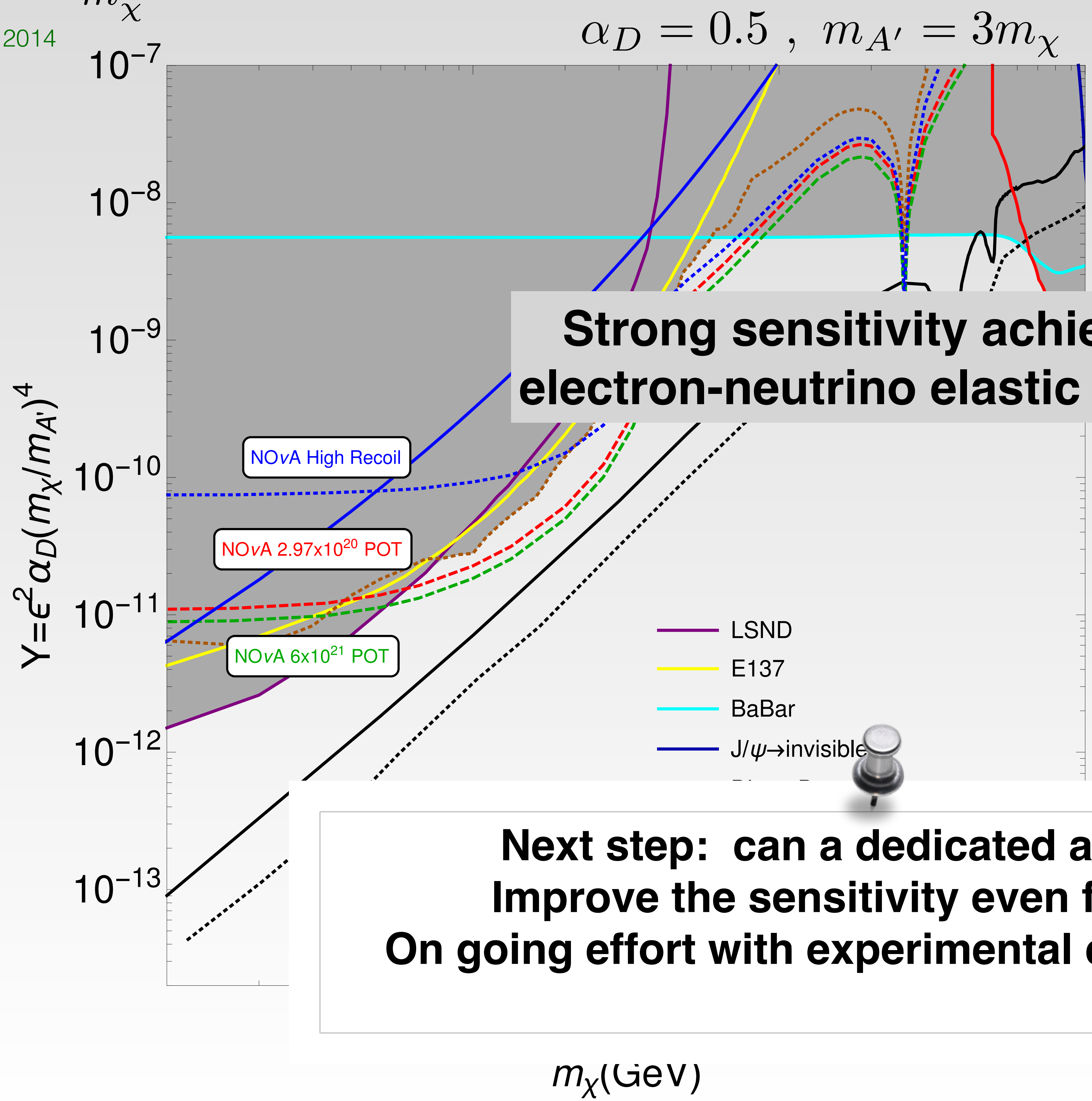
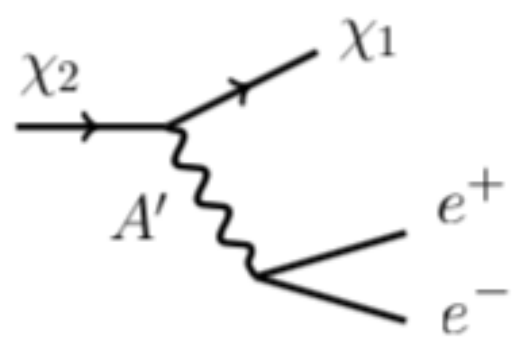


Strong sensitivity achieved by recasting electron-neutrino elastic scattering analysis

Next step: can a dedicated analysis Improve the sensitivity even further?
On going effort with experimental collaboration

Symbiotic neutrino/DM programs

- NOvA dedicated analysis to light dark matter
- Study of potential sensitivity of liquid argon detectors such as SBND and ICARUS 8 GeV FNAL Booster beam line
- Prospects to probe DM at DUNE? Study for a dedicated detector
- Study of the sensitivity to non-minimal dark sectors both @ FNAL facilities and @ CERN (i.e. NA62)



Signature for Pseudo-Dirac thermal dark matter @SBND
CF,Palamara,Szelc, in progress

Symbiotic neutrino/DM programs

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- Study of the sensitivity to
  faciliti

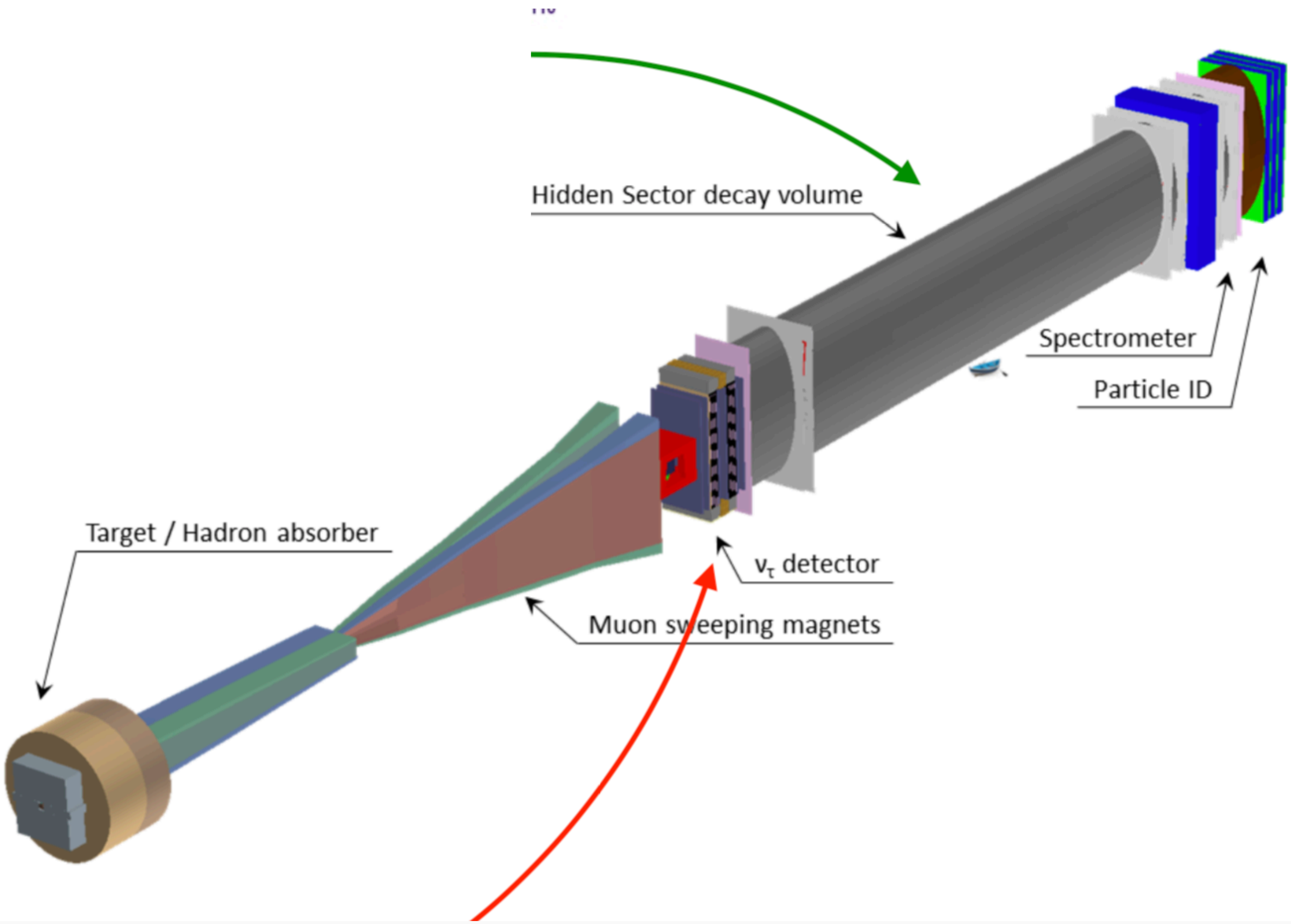
atter @SBND
a,Szelc, in progress

Release of a MadGraph plugin (MadDump) to facilitate these efforts

(L.Buonocore, **CF**, F.Maltoni,O.Mattelaer,F.Tramontano,2018)

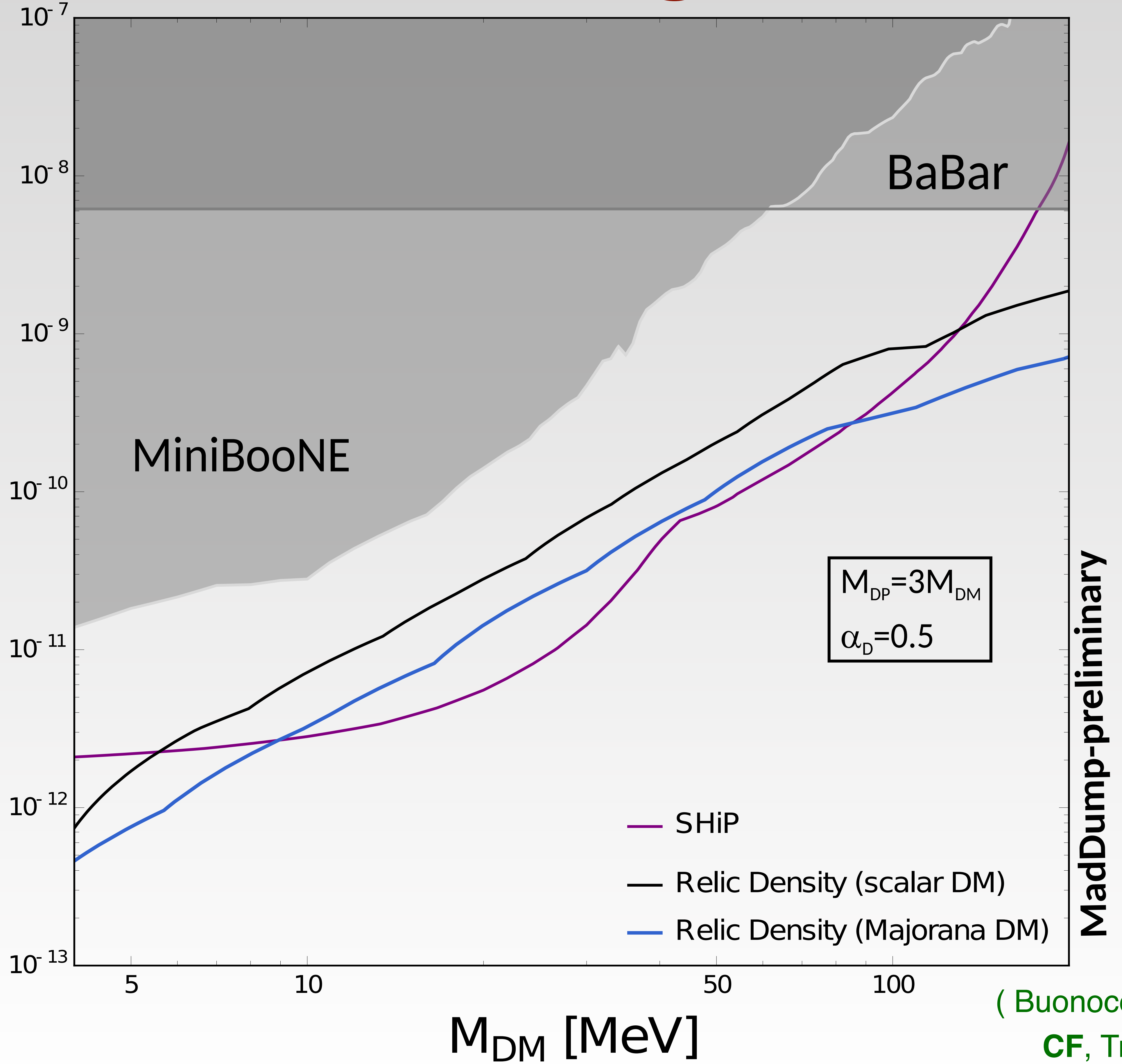
SHiP

Search for long lived particles



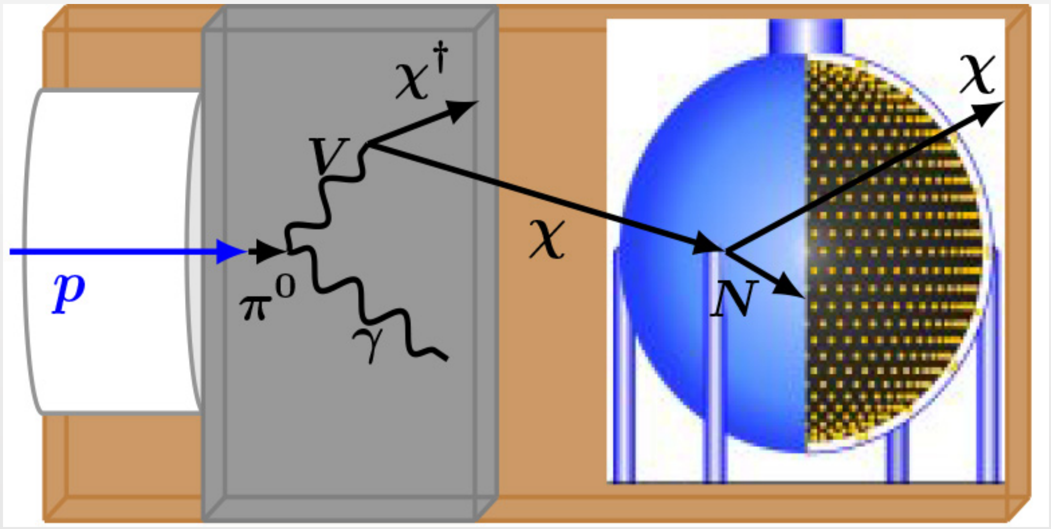
Neutrino detector: looking for invisible signatures

SHiP



(Buonocore, DeLellis,DeCrescenzo, **CF**, Tramontano in progress)

DM-quark scattering

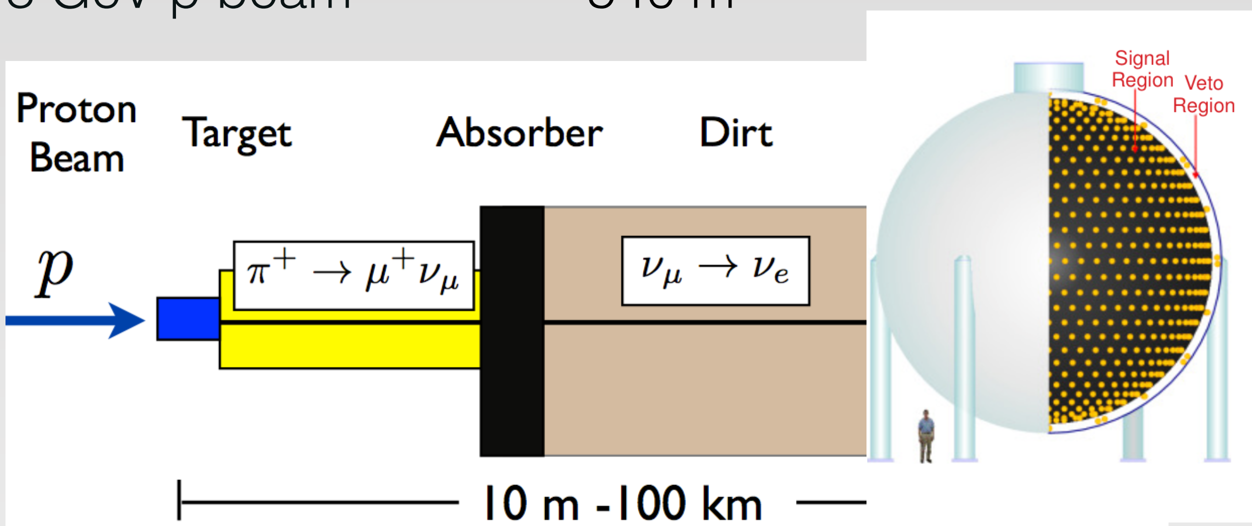


[Dobrescu, **CF** 2014]
[Dobrescu, Coloma, **CF**, Harnik 2015]
[**CF** 2017]

Complementarity with direct detection program for sub-GeV mass range

DM search @ MiniBooNE

8 GeV p beam   540 m

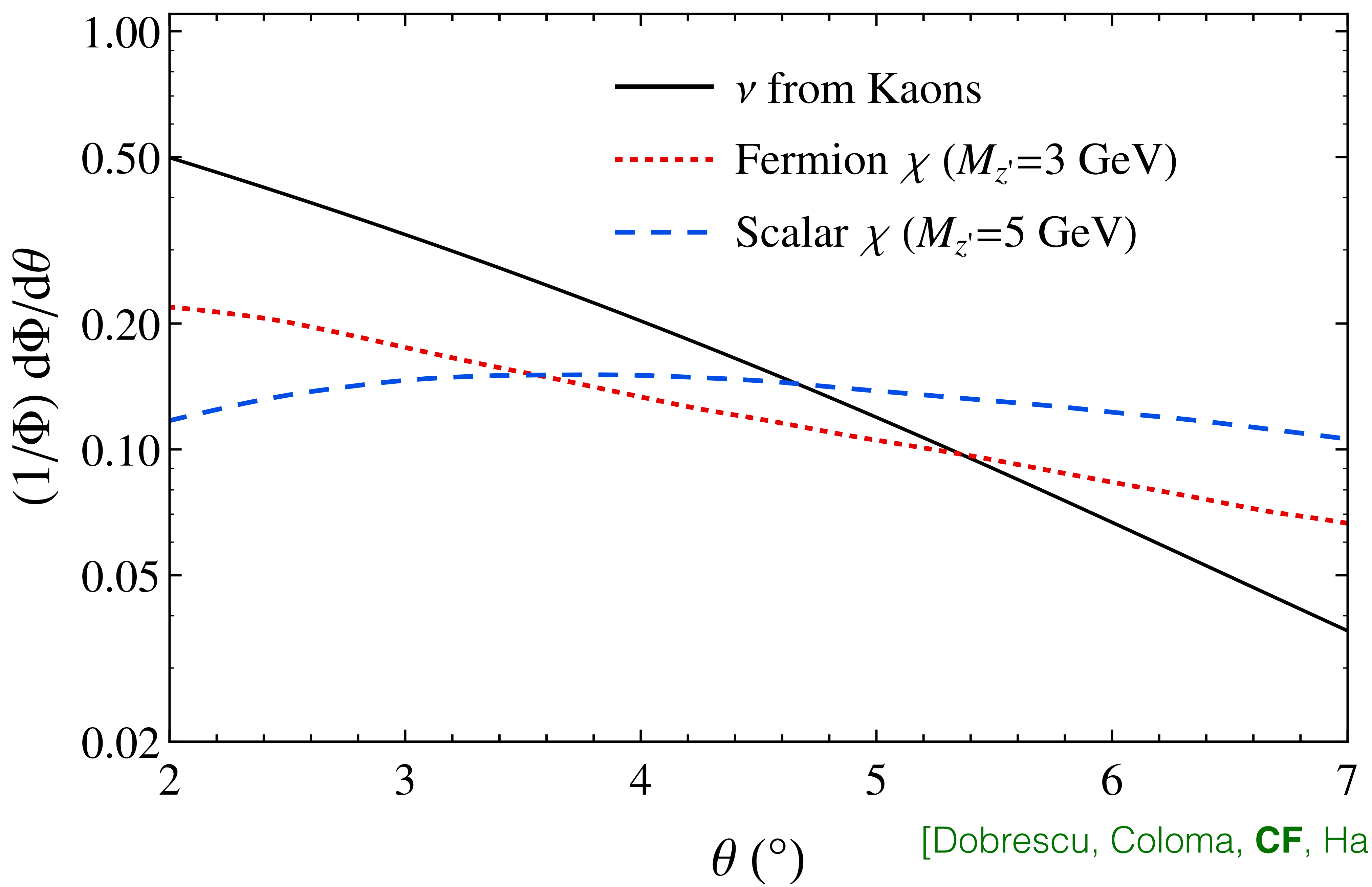


MiniBooNE:800 tons detector

- Light DM analysis in beam dump mode [A.A. Aguilar-Arevalo et al. 2017]
- Constraints for sub-GeV vector mediator
- Light DM program calls for a dedicated run to suppress the neutrino background ?

Off-axis detectors for DM

Difference angular distribution of DM and neutrino flux

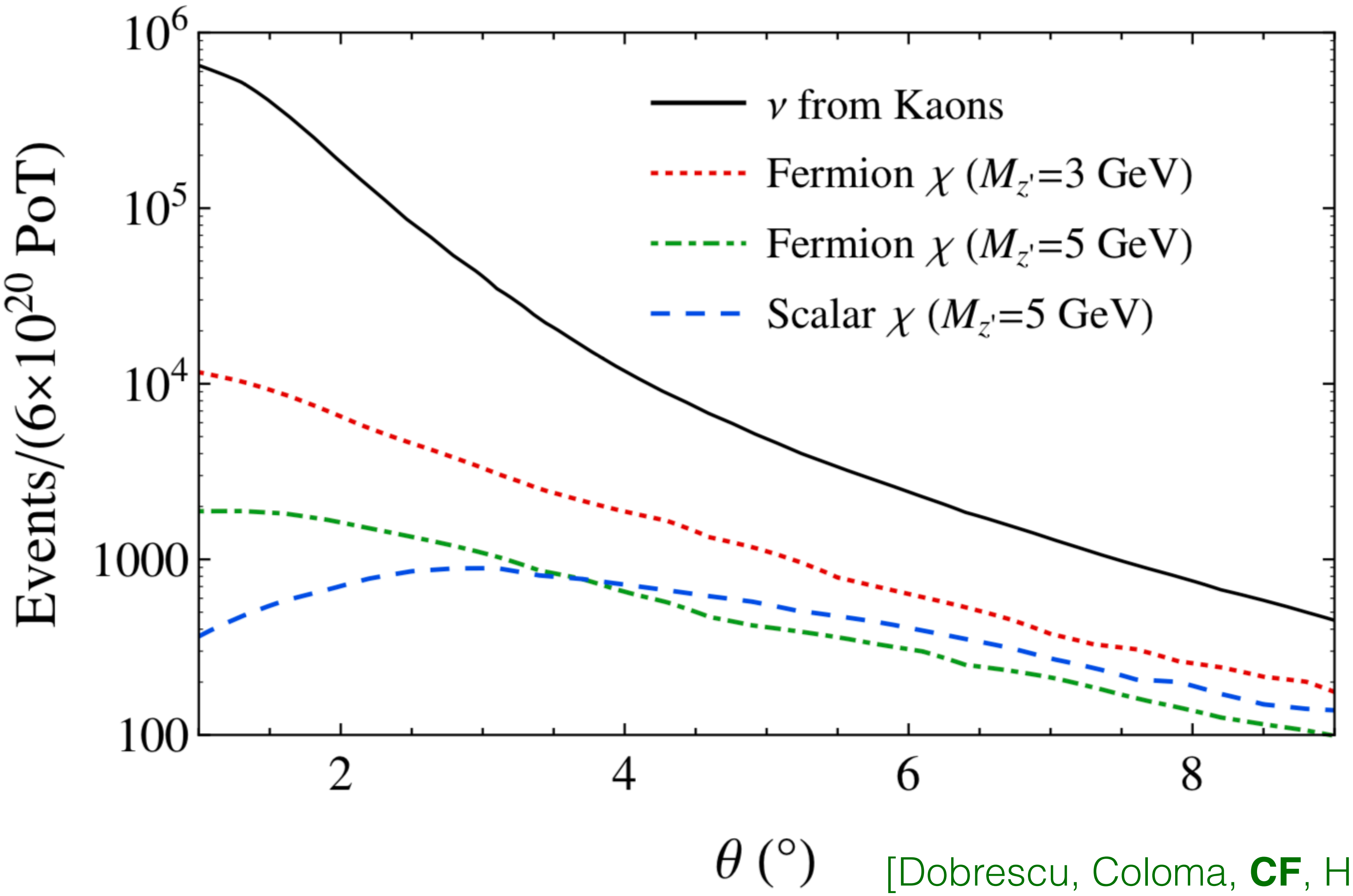


[Dobrescu, Coloma, **CF**, Harnik 2015]

Is it possible to build a DM program symbiotic to the neutrino one?
YES- a crucial role is played by off-axis detectors

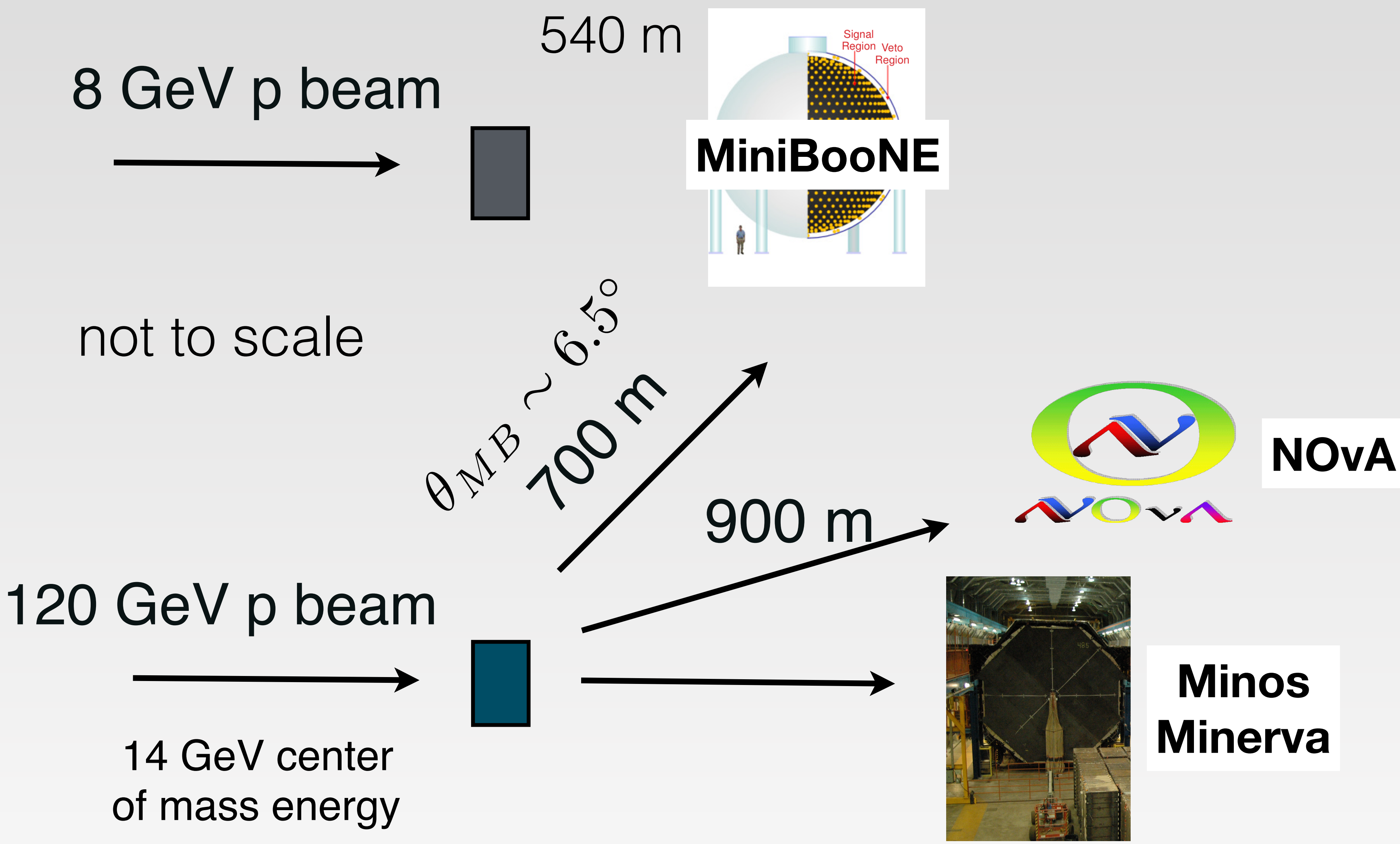
Off-axis detectors for DM

Deep inelastic scattering events



[Dobrescu, Coloma, **CF**, Harnik 2015]

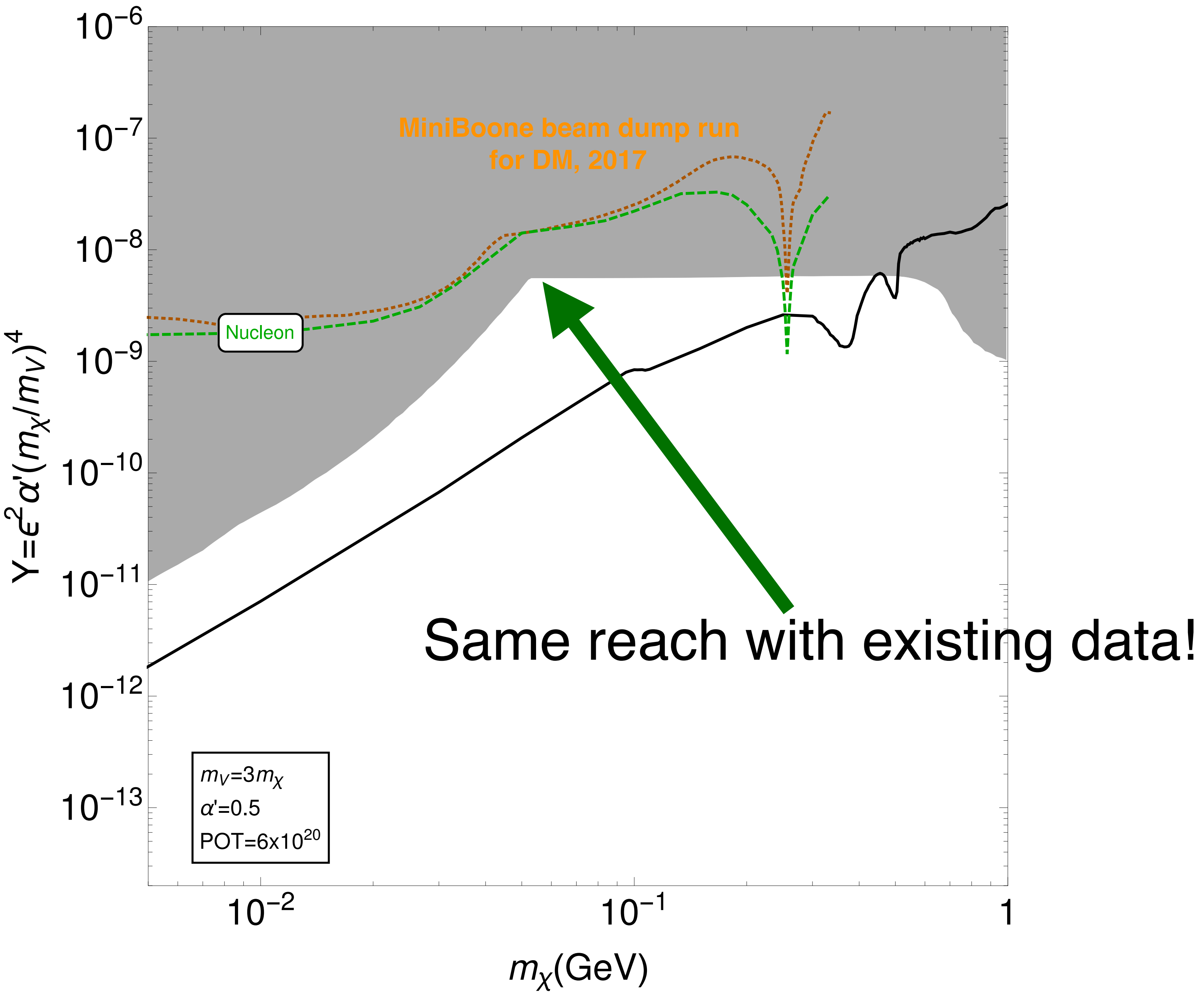
Neutrinos @ Main Injector (NuMI)



Many possibilities (and existing data) to explore DM parameter space

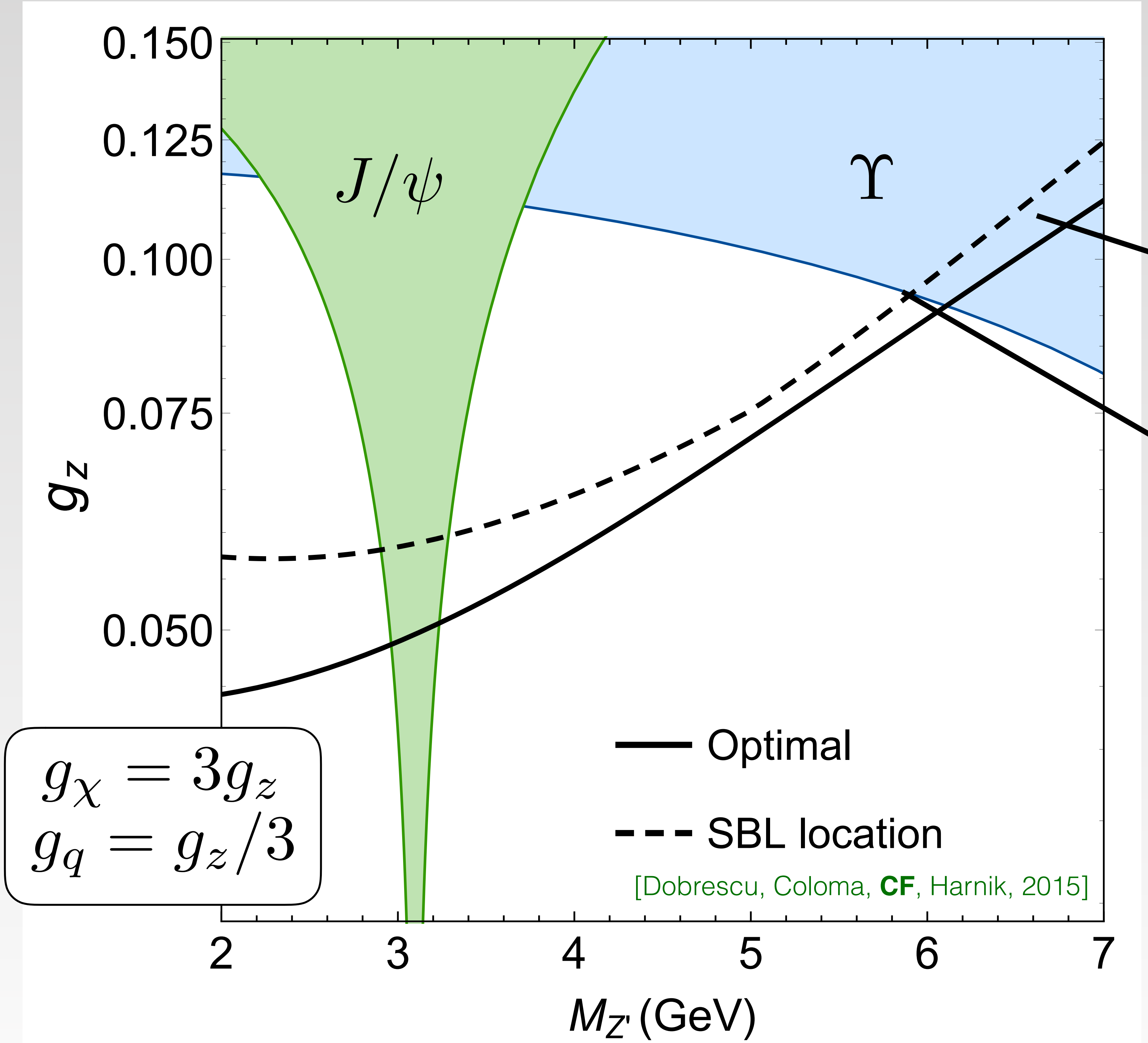
DM-quark scattering in MiniBooNE

Similar location as future detector ICARUS!



[DeNeverville,**CF**,Shoemaker, in progress] [CF,2017]

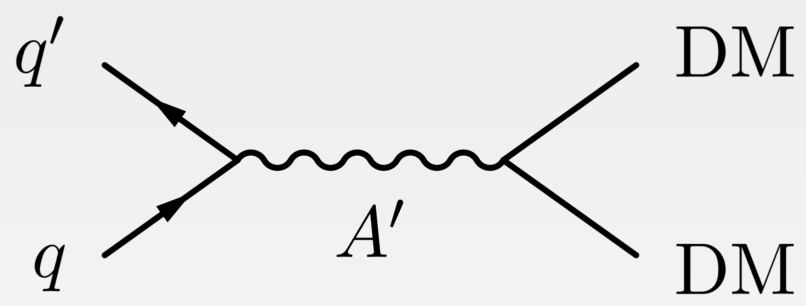
DM-quark scattering in MiniBooNE



Analysis of deep inelastic scattering events

Ideal detector (DUNE/LBNF)

Existing MiniBooNE data



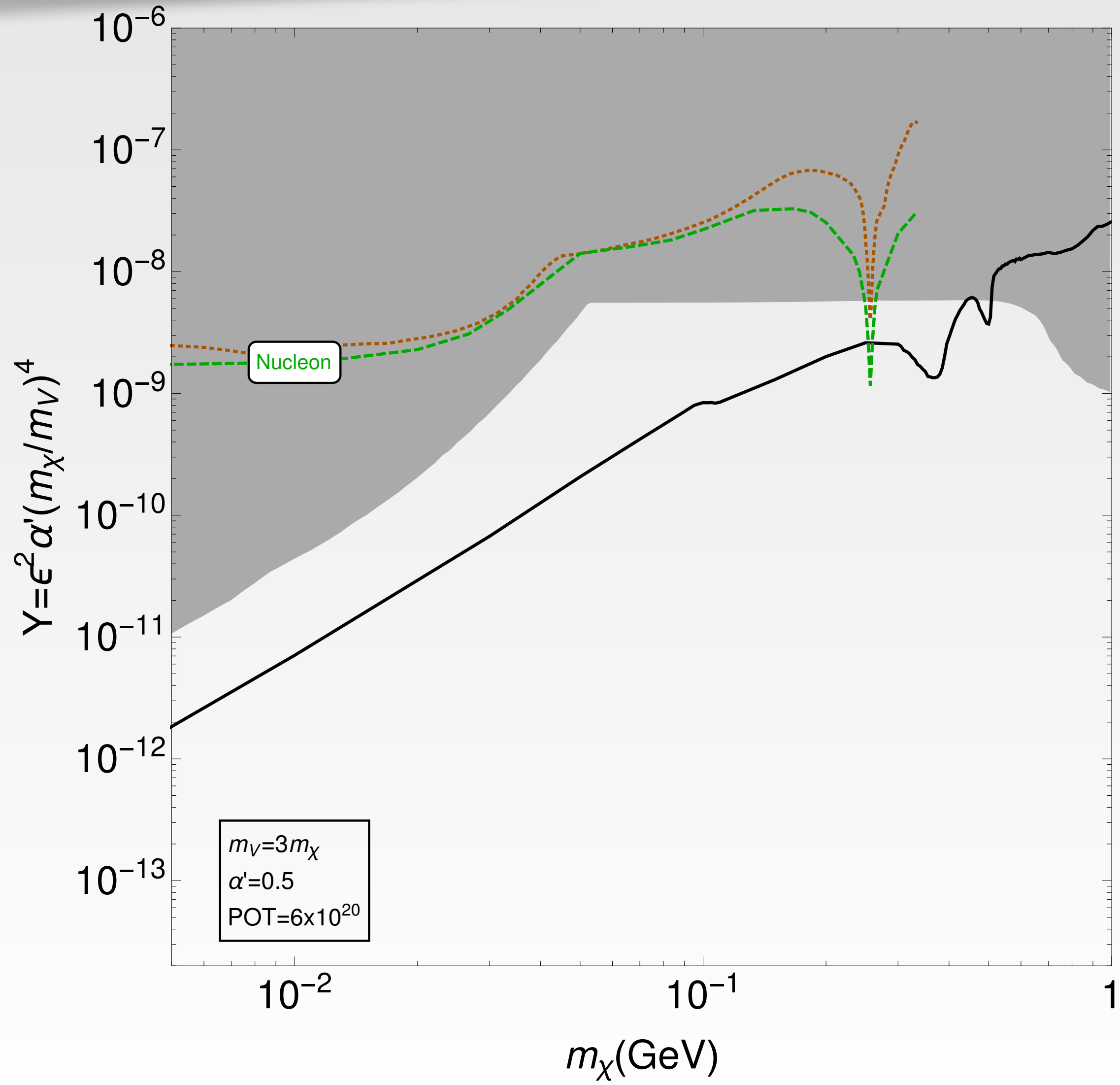
In this mass range Drell-Yan production

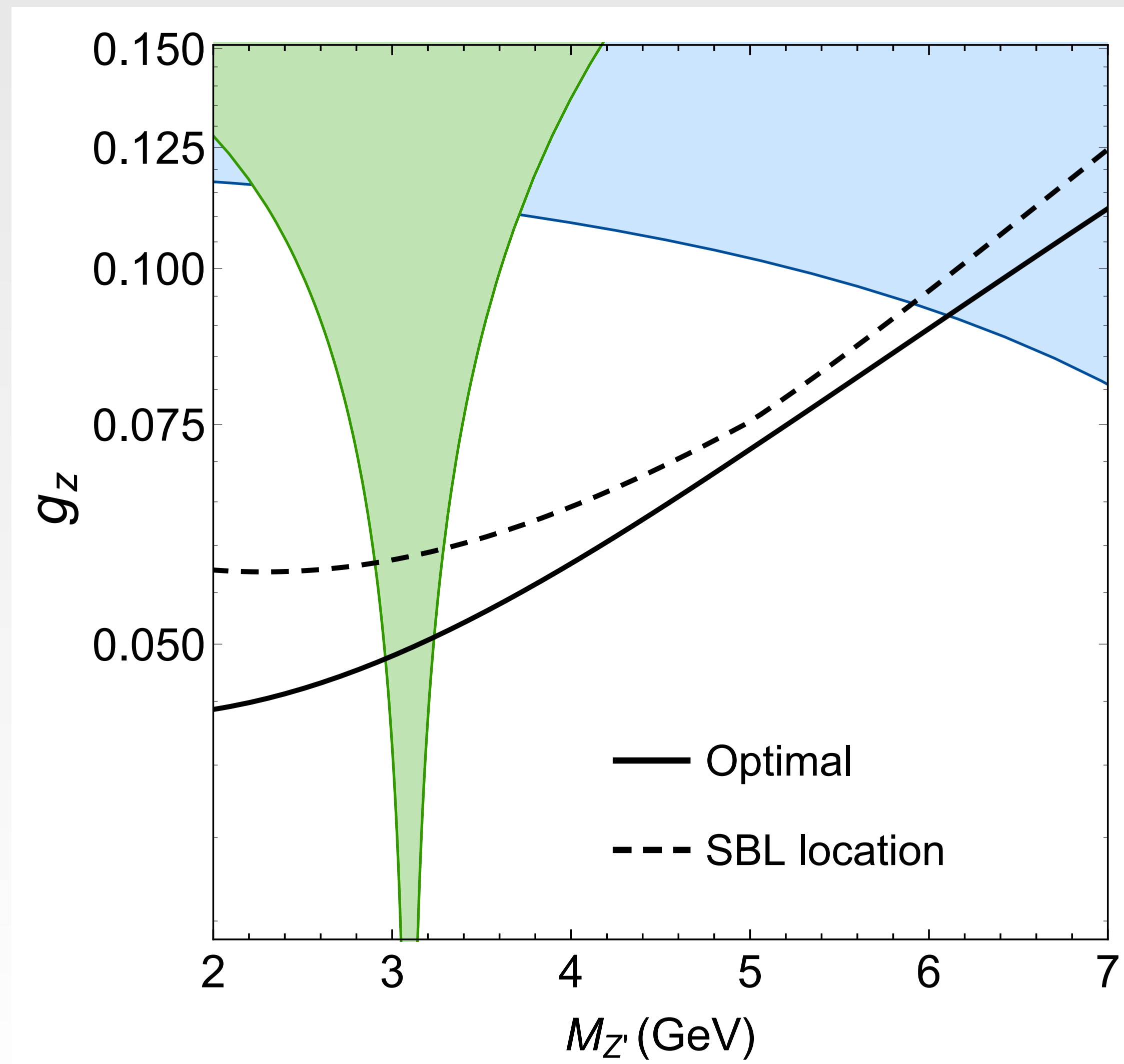
UV dependent constraints from anomalies

[Dobrescu,**CF**, 2014] [Dror et.al ,2017]

Symbiotic neutrino/DM programs

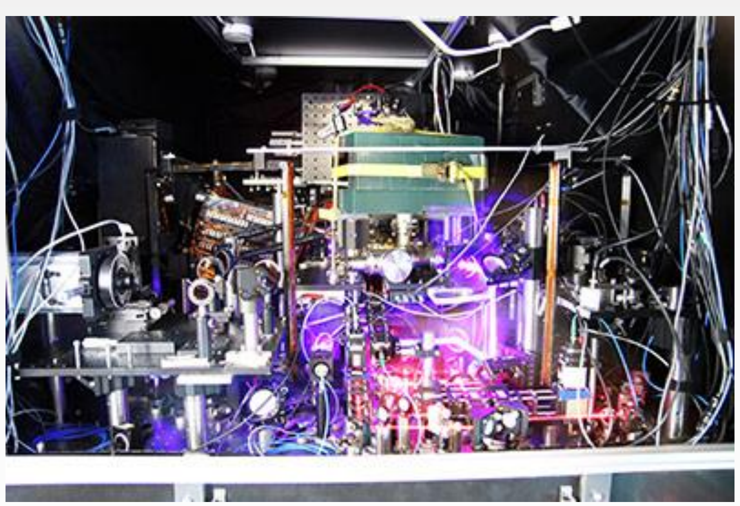
- **MiniBooNE** dedicated analysis to light dark matter
- **ICARUS**: similar location as MiniBooNE: plan to set up the dedicated analysis, possible triggers.



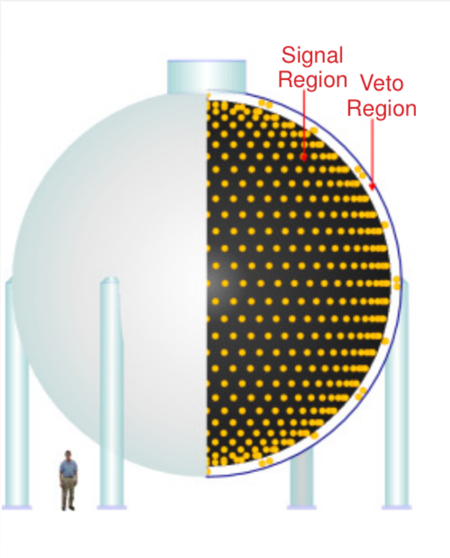


Laboratory probes

- **Direct probe**: searching for MeV-GeV DM@ neutrino facilities
- **Indirect probe**: searching for long/medium range dark forces via atomic spectroscopy



Strontium atomic clock



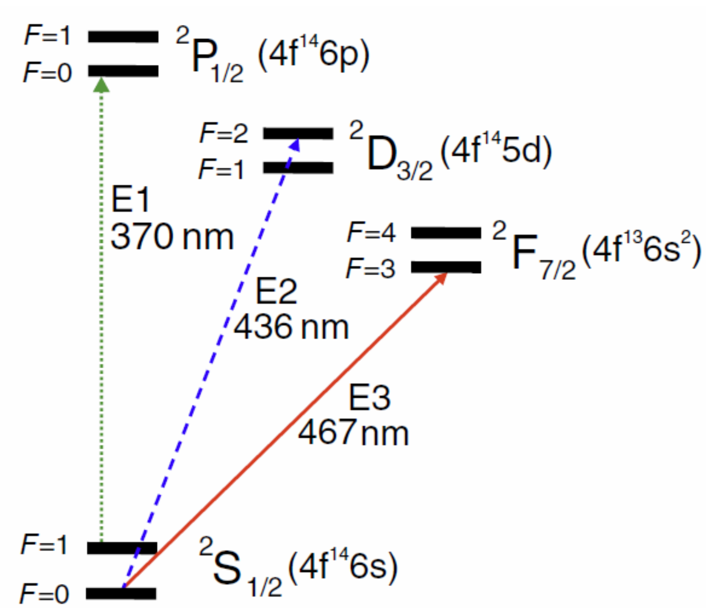
MiniBooNE neutrino detector

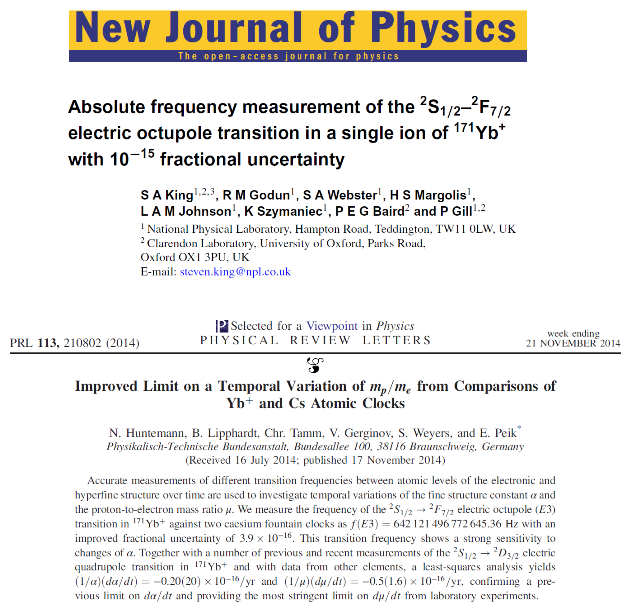
Atomic probes of new physics

Atomic spectroscopy measurements reached an extraordinary precision (relative error 10^{-16} - 10^{-18})

Yb^+ ion-clock

Two working experiments:
PTB Germany, NPL UK




New Journal of Physics
The open-access journal for physics

Absolute frequency measurement of the $^2S_{1/2}$–$^2F_{7/2}$ electric octupole transition in a single ion of $^{171}Yb^+$ with 10^{-15} fractional uncertainty

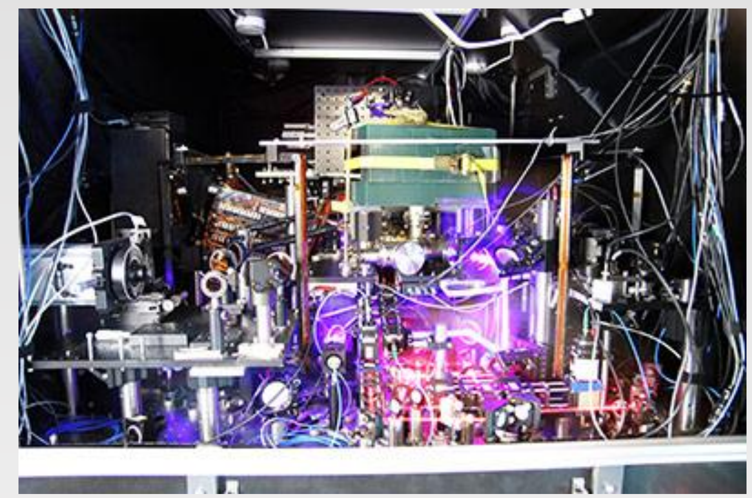
S A King[1,2,3], R M Godun[1], S A Webster[1], H S Margolis[1], L A M Johnson[1], K Szymaniec[1], P E G Baird[2] and P Gill[1,2]
[1] National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, UK
[2] Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK
E-mail: steven.king@npl.co.uk

Selected for a Viewpoint in *Physics*
PRL **113,** 210802 (2014) PHYSICAL REVIEW LETTERS week ending 21 NOVEMBER 2014

Improved Limit on a Temporal Variation of m_p/m_e from Comparisons of Yb^+ and Cs Atomic Clocks

N. Huntemann, B. Lipphardt, Chr. Tamm, V. Gerginov, S. Weyers, and E. Peik*
Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
(Received 16 July 2014; published 17 November 2014)

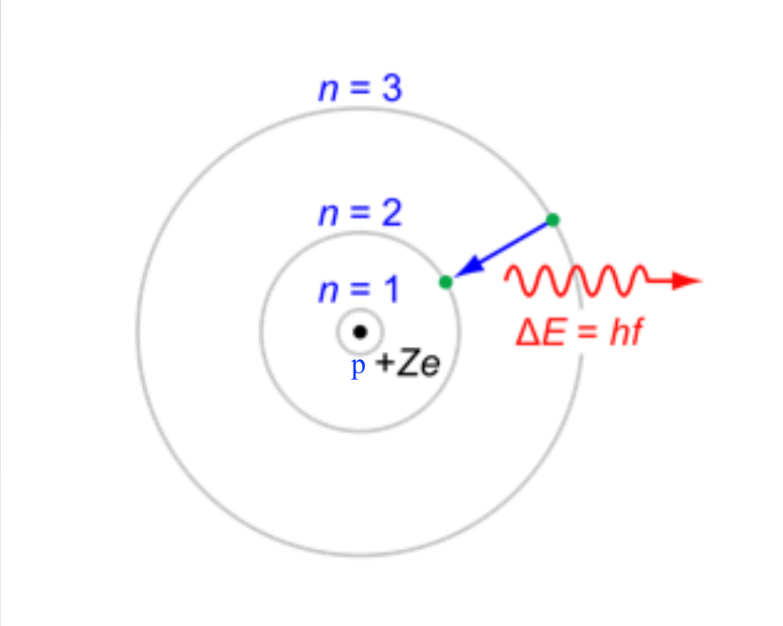
Accurate measurements of different transition frequencies between atomic levels of the electronic and hyperfine structure over time are used to investigate temporal variations of the fine structure constant α and the proton-to-electron mass ratio μ. We measure the frequency of the $^2S_{1/2} \rightarrow {}^2F_{7/2}$ electric octupole ($E3$) transition in $^{171}Yb^+$ against two caesium fountain clocks as $f(E3) = 642\,121\,496\,772\,645.36$ Hz with an improved fractional uncertainty of 3.9×10^{-16}. This transition frequency shows a strong sensitivity to changes of α. Together with a number of previous and recent measurements of the $^2S_{1/2} \rightarrow {}^2D_{3/2}$ electric quadrupole transition in $^{171}Yb^+$ and with data from other elements, a least-squares analysis yields $(1/\alpha)(d\alpha/dt) = -0.20(20) \times 10^{-16}$/yr and $(1/\mu)(d\mu/dt) = -0.5(1.6) \times 10^{-16}$/yr, confirming a previous limit on $d\alpha/dt$ and providing the most stringent limit on $d\mu/dt$ from laboratory experiments.



Strontium atomic clock

How can we exploit such a precision to probe fundamental physics ?

Spin independent dark forces



mediator spin
s=0,1,2

mediator mass

$$V_\phi(r) = \frac{(-1)^{s+1}}{4\pi} y_e y_N \frac{e^{-m_\phi r}}{r}$$

e-coupling

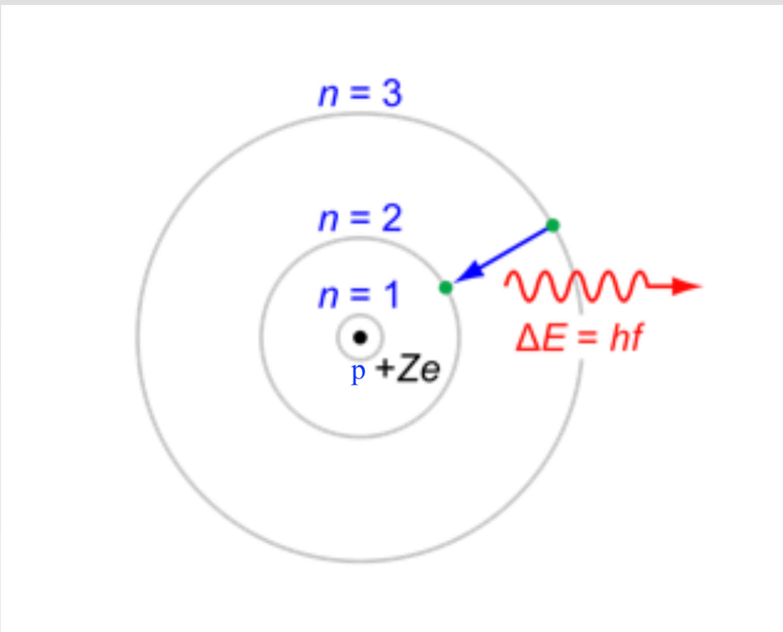
nucleus-coupling

$$y_N = y_p Z + y_n (A - Z)$$

This gives rise to an additional contribution to the frequency shift.

$$\delta\nu_i = y_e y_N X_i \qquad X_i \simeq \int d^3r \, \frac{e^{-m_\phi r}}{r} \left[|\psi_b(r)|^2 - |\psi_a(r)|^2 \right]$$

How do we probe this new contribution?



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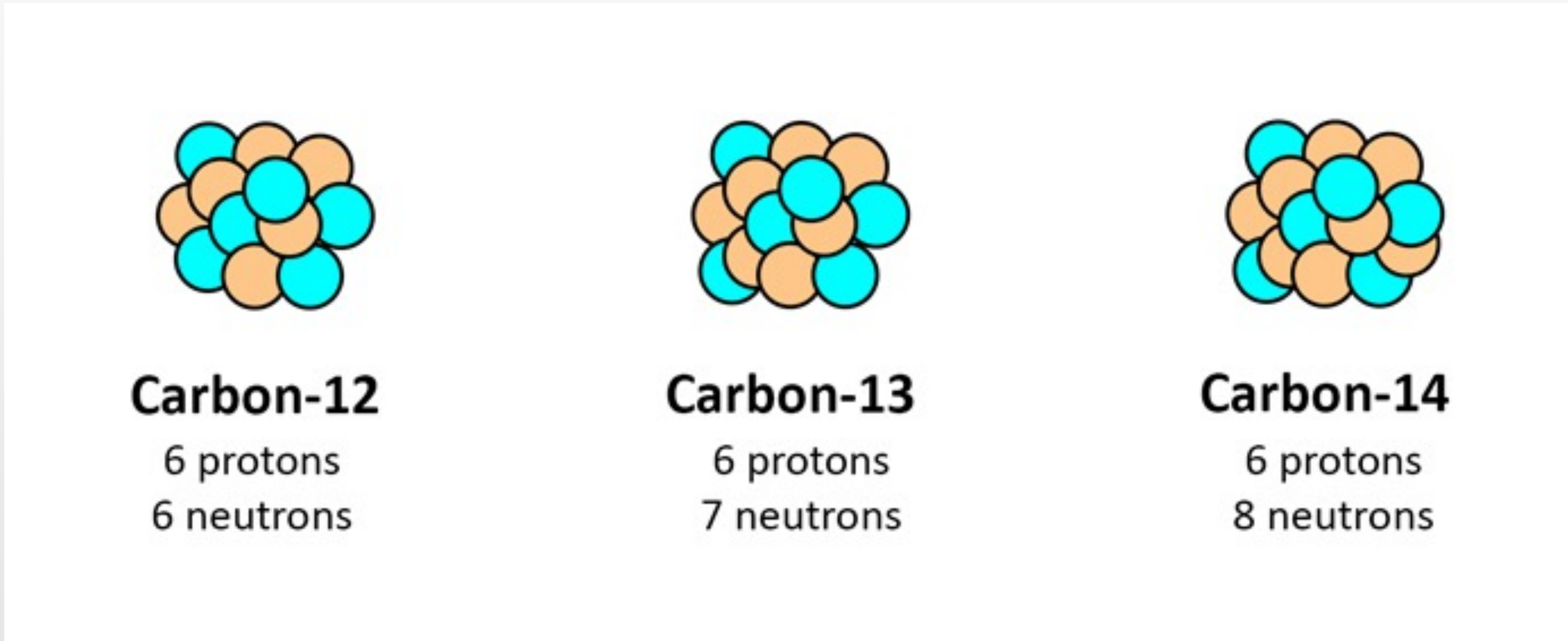
A) Precise theoretical prediction versus experimental measurement (few electrons atoms)

B) A new observable to distinguish new physics signal from “QED background” (also many electrons atoms)

Probing new physics with Isotope shift

atoms with the same number of protons but different number of neutrons

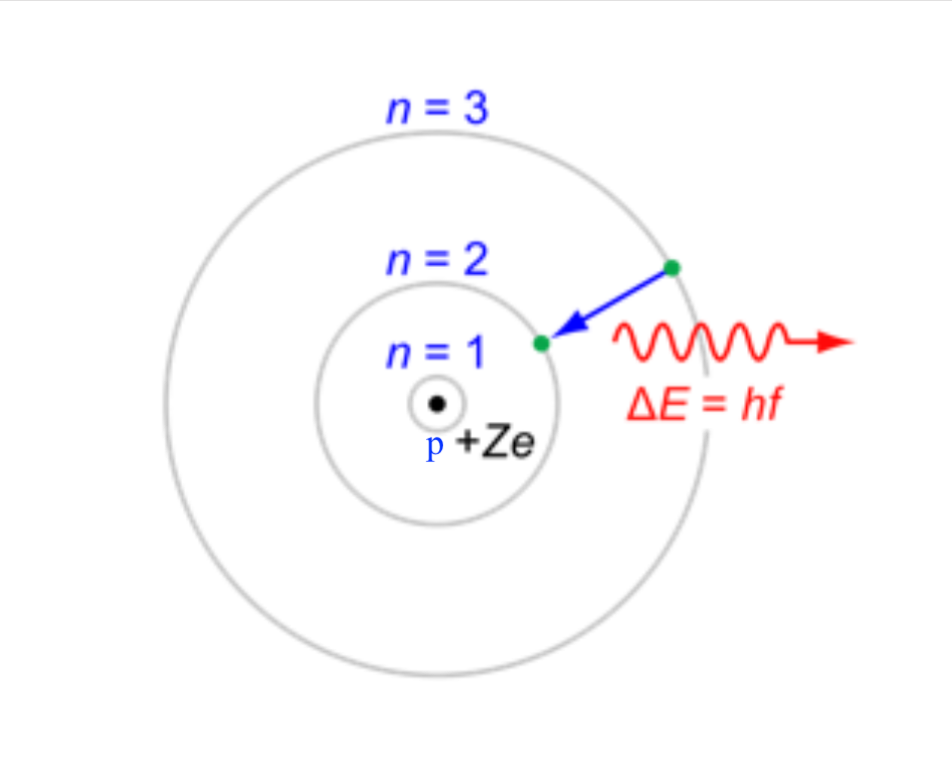


Focus on **spin-less** isotopes of a given element A and A'

[Berengut, Budker, Delaunay, Flambaum, **CF,** Fuchs, Grojean, Harnik, Ozeri, Perez, Soreq, 2017].
[Delauney,**CF**,Fuchs,Soreq, 2017]

Isotope Shifts Spectroscopy

Consider an **atomic optical transition**
and consider two **spin-less** isotopes of a given element A and A'



$$\nu_i^A \quad \nu_i^{A'}$$

Is the frequency different? How?

$$\nu_i^{AA'} = \nu_i^A - \nu_i^{A'}$$

→ QED effects cancel. Uncertainty greatly reduced

Isotope Shifts Spectroscopy

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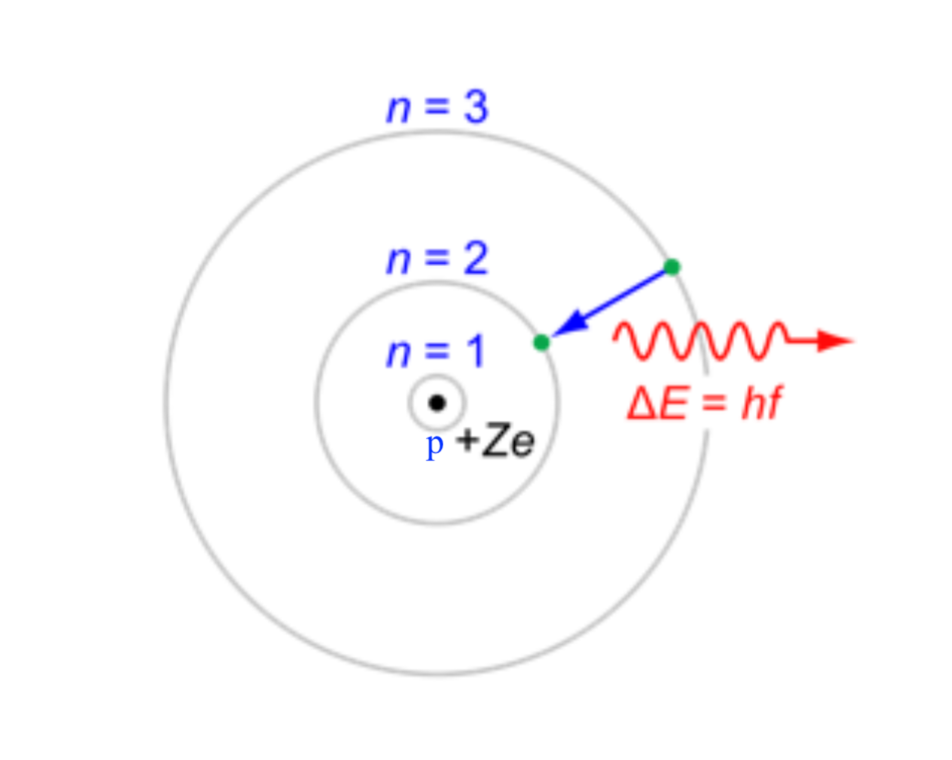


$$\nu_i^A \quad \nu_i^{A'}$$

Is the frequency different? How?

$$\nu_i^{AA'} = \nu_i^A - \nu_i^{A'}$$

New Physics contribution only slightly reduced (A-A')/A
(at most one order of magnitude suppression for heavy atoms)

$$(\Delta\nu_i^{AA'})_{\rm NP} = y_e y_N (A - A') X_i$$

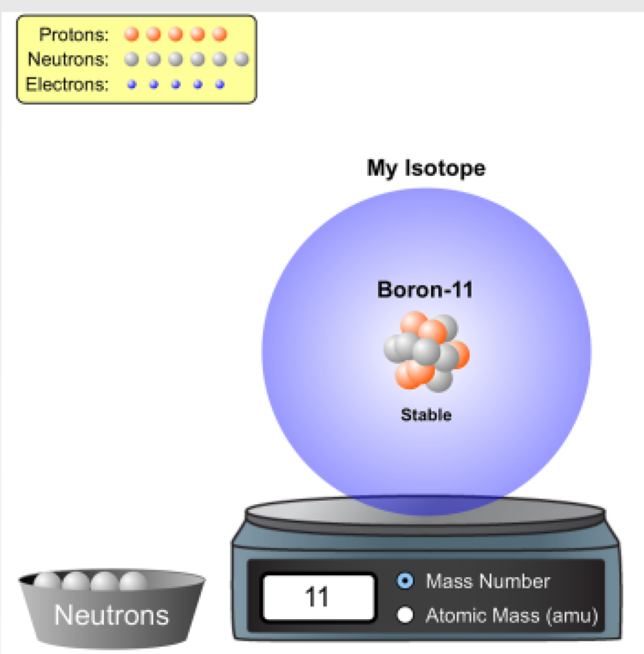
Isotope Shifts Spectroscopy

QED effects cancel up to:

electronic factors

Optical transition i

$$\nu_i^{AA'} \approx K_i \mu_{AA'} + F_i \lambda_{AA'}$$



mass shift

$$\mu_{AA'} \equiv m_A^{-1} - m_{A'}^{-1}$$

field shift

$$\lambda_{AA'} = \delta\langle r^2 \rangle + \text{higher moments}$$

Key point: electronic and nuclear dependence is **factorised**

King's linearity

Given 2 transitions for the same isotopes A and A'

$$\nu_i^{AA'} \approx K_i \mu_{AA'} + F_i \lambda_{AA'}$$

$$m\nu_i^{AA'} \equiv \nu_i^{AA'} / \mu_{AA'}$$

Factorisation

$$m\nu_2 = F_{21} m\nu_1 + K_{21}$$

Linear relation

$F_{21} \equiv F_2/F_1 \quad i = 1, 2$ Slope $\quad K_{21} \equiv K_2/K_1 - F_{21}K_1$ Offset

At what level does this relation hold?

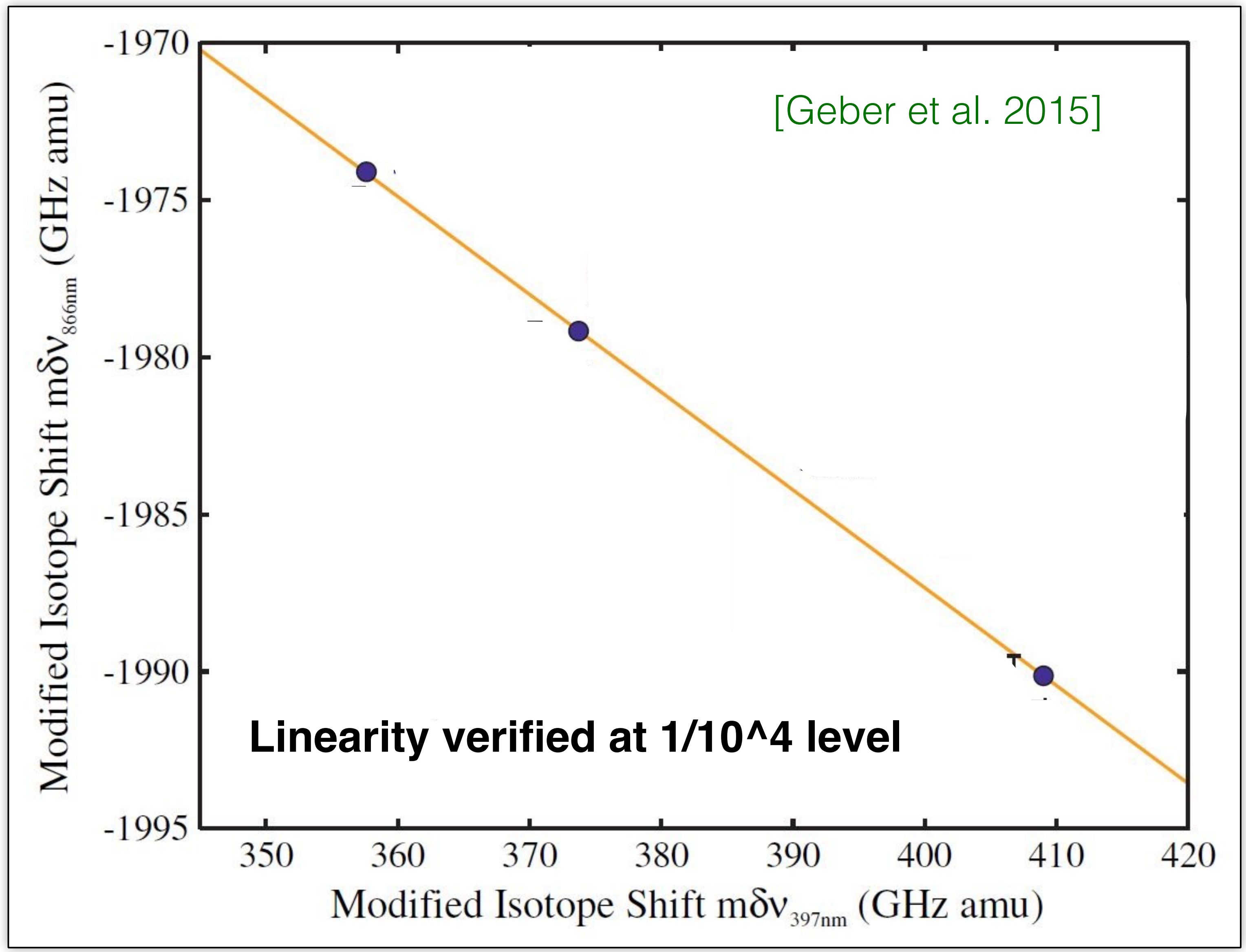
[Flaumbam et al 2017 for theory estimates]

King’s Plot

Considering then 3 pairs of isotopes

$$m\nu_2 = F_{21} m\nu_1 + K_{21}$$

Calcium Z=20
Precision 0.1 MHZ



King's linearity

Adding the contribution of a new spin independent dark force

[**CF** et al , 2017]

Neutron coupling

$$m\nu_2 = F_{21} m\nu_1 + K_{21} + y_e y_n A A' X_{21}$$

NP electronic factors Xi: the only theoretical inputs (depend on mediator mass) calculated using many-body perturbation theory [Berengut et al. 2005]

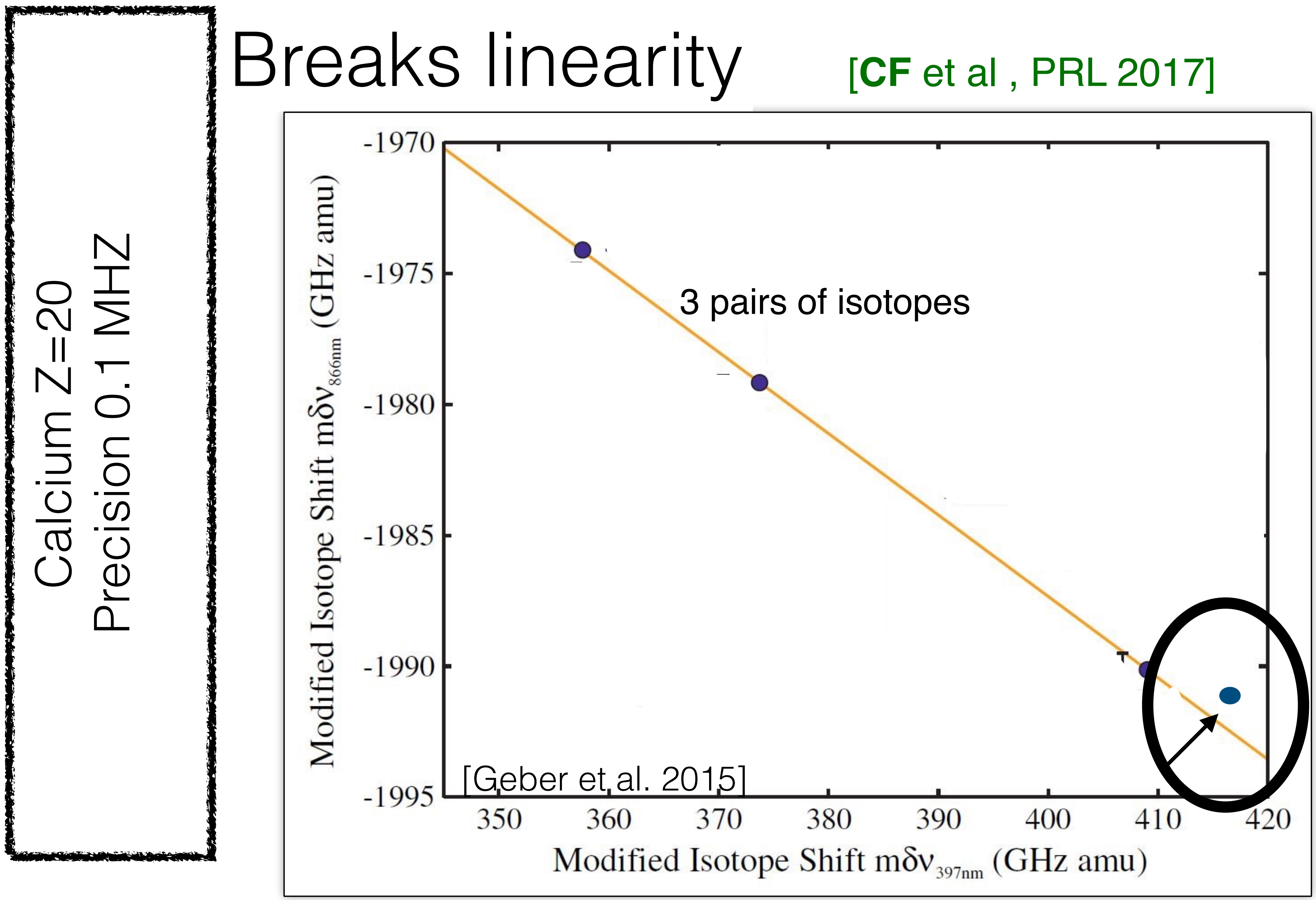
$$X_{21} = X_2 - F_{21} X_1$$

Non linearity from BSM unless: $X_i \propto F_i$ **Short range interactions**

King's Plot

Adding the contribution of a new spin independent dark force

$$m\nu_2 = F_{21} m\nu_1 + K_{21} + y_e y_n A A' X_{21}$$

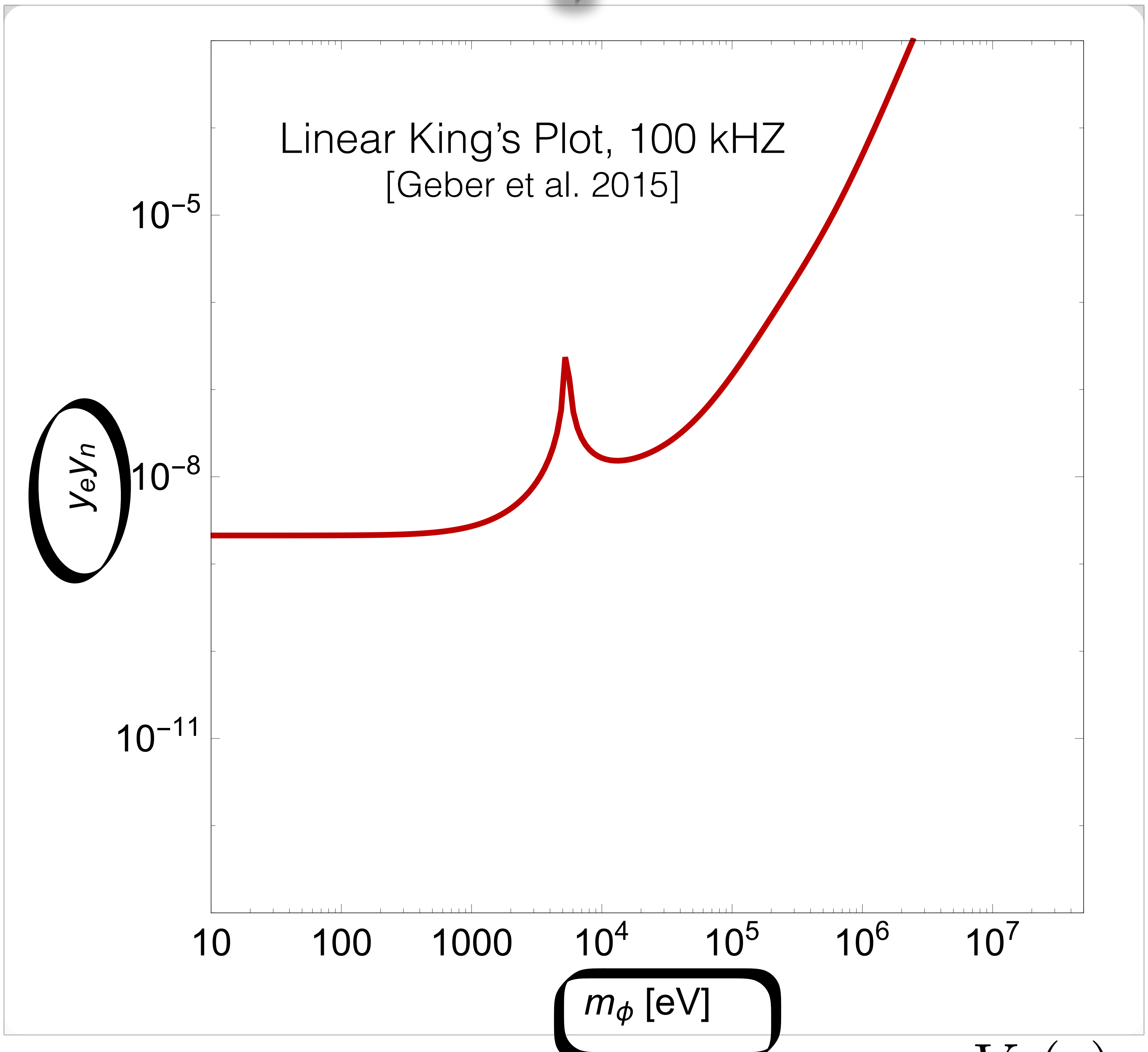


If data gives a linear King's plot:

[**CF** et al,2017]

Constraints on new physics!

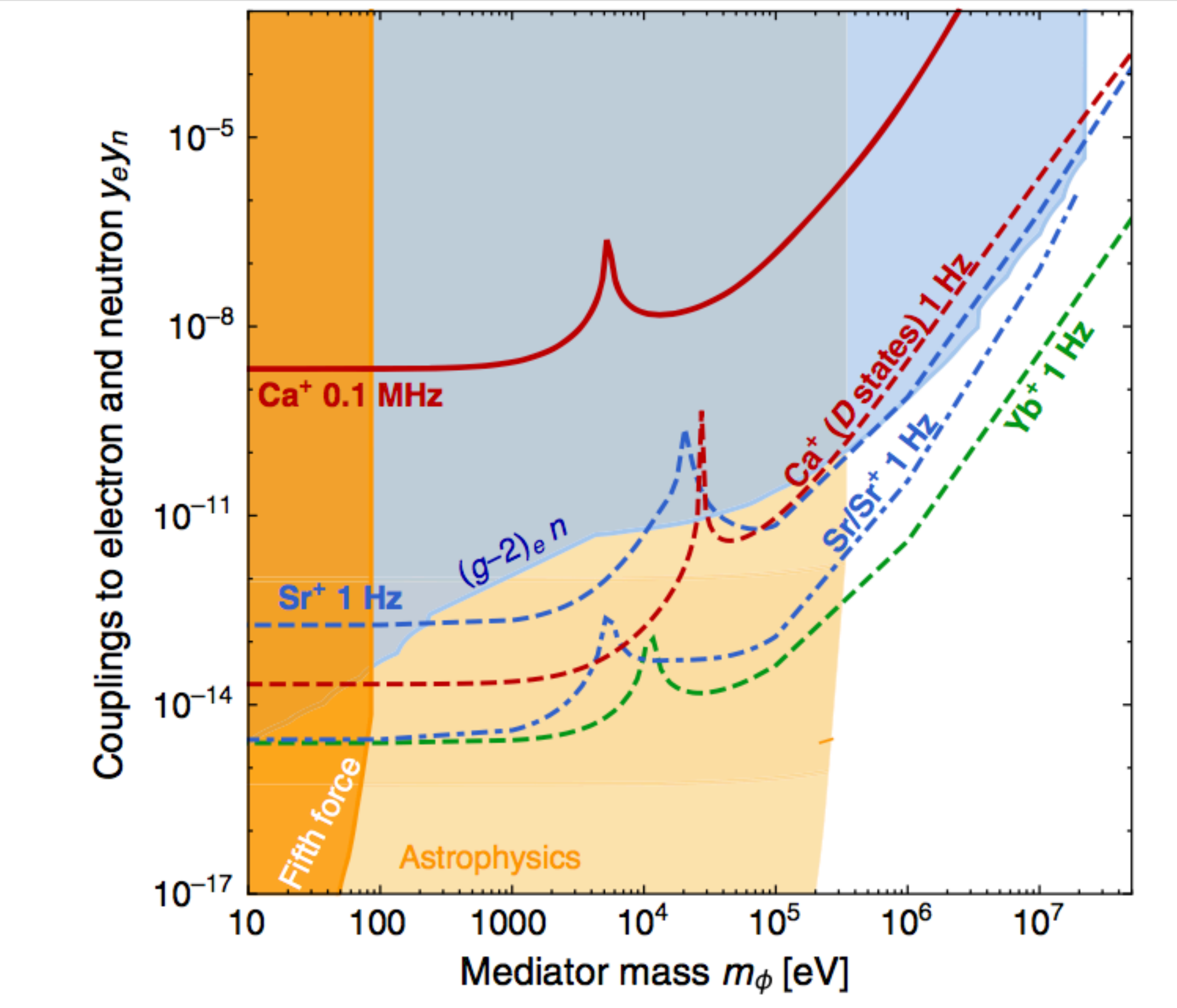
[**CF** et al ,2017]



$$V_\phi(r) = \frac{(-1)^{s+1}}{4\pi} y_e y_N \frac{e^{-m_\phi r}}{r}$$

Projections for clock transitions

[**CF** et al ,2017]



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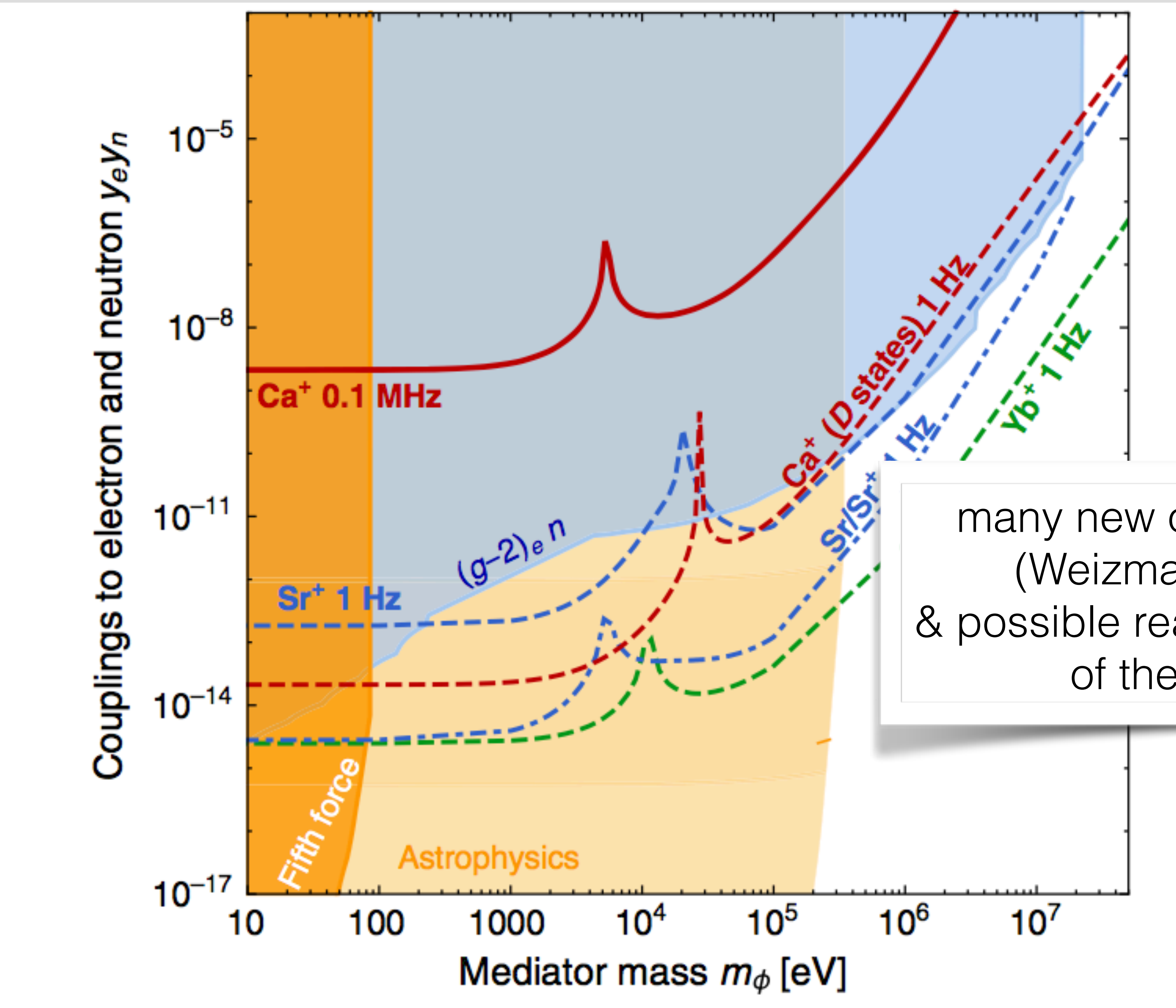


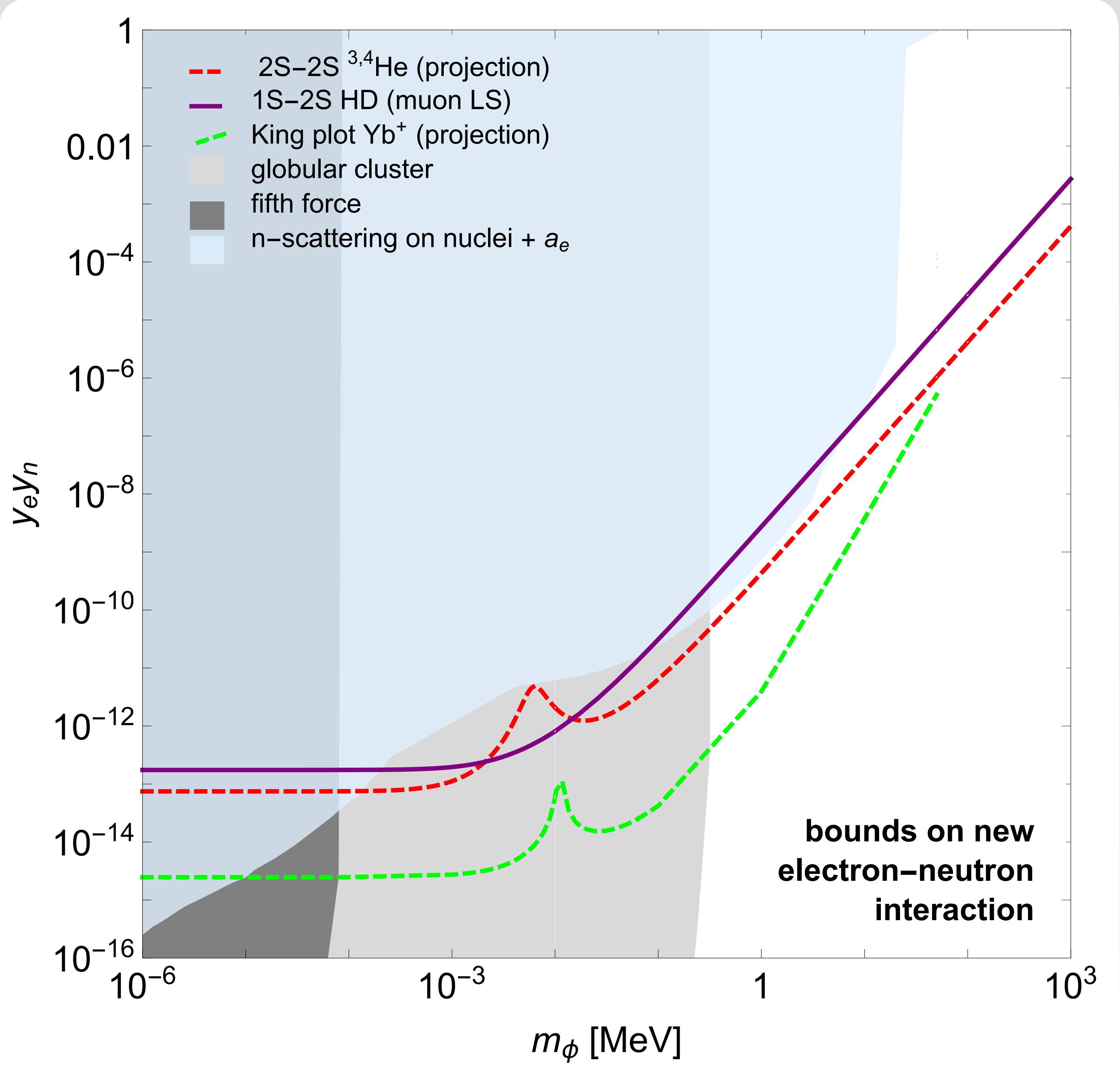
many new ongoing measurements
(Weizmann, PTB,Mainz, MIT..)
& possible reach to unexplored regions
of the parameter space

What about few electron atoms?

Exploiting precision of theoretical predictions and comparing it with experiments

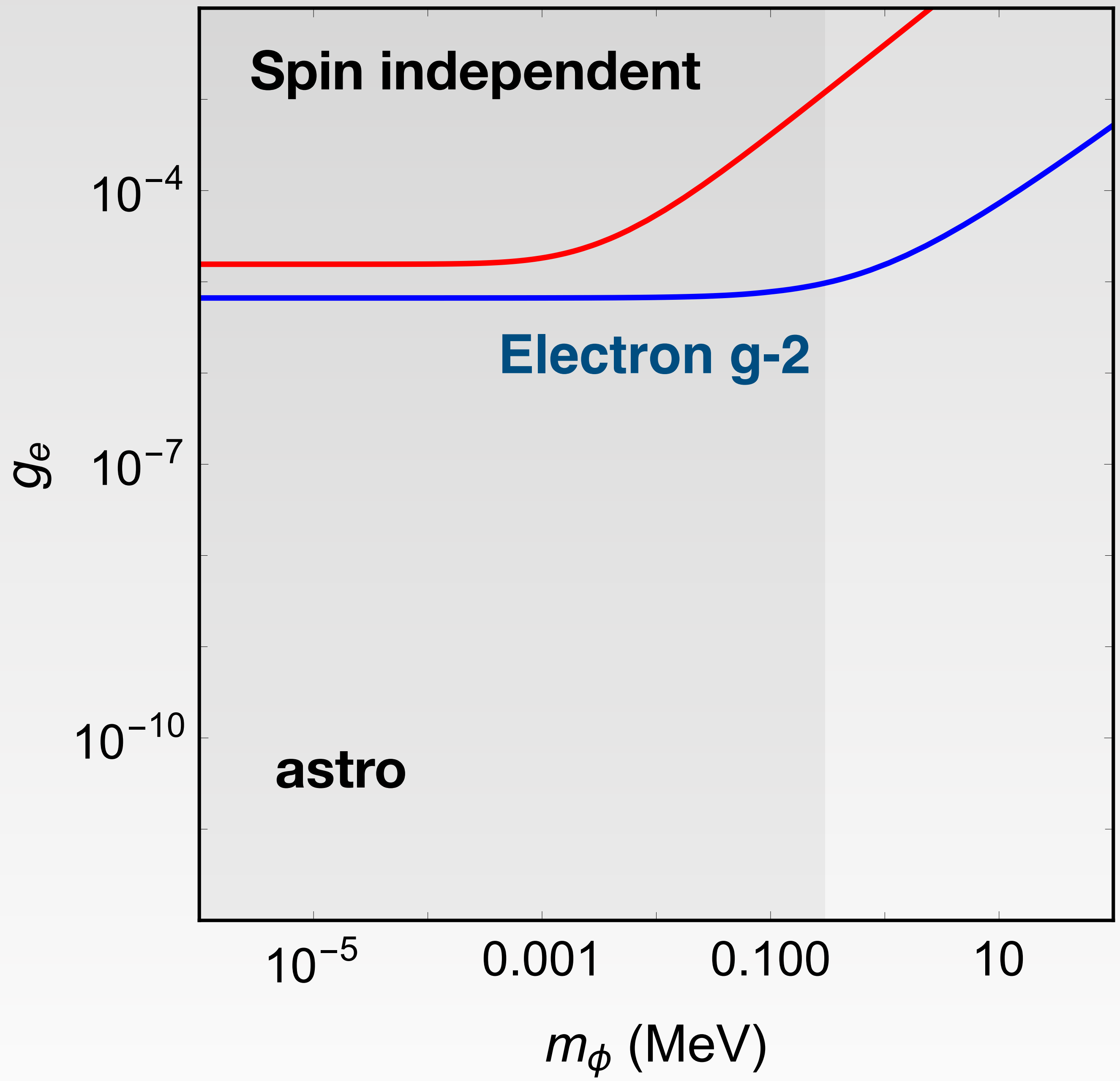
[Delauney,**CF**,Fuchs,Soreq 2017]

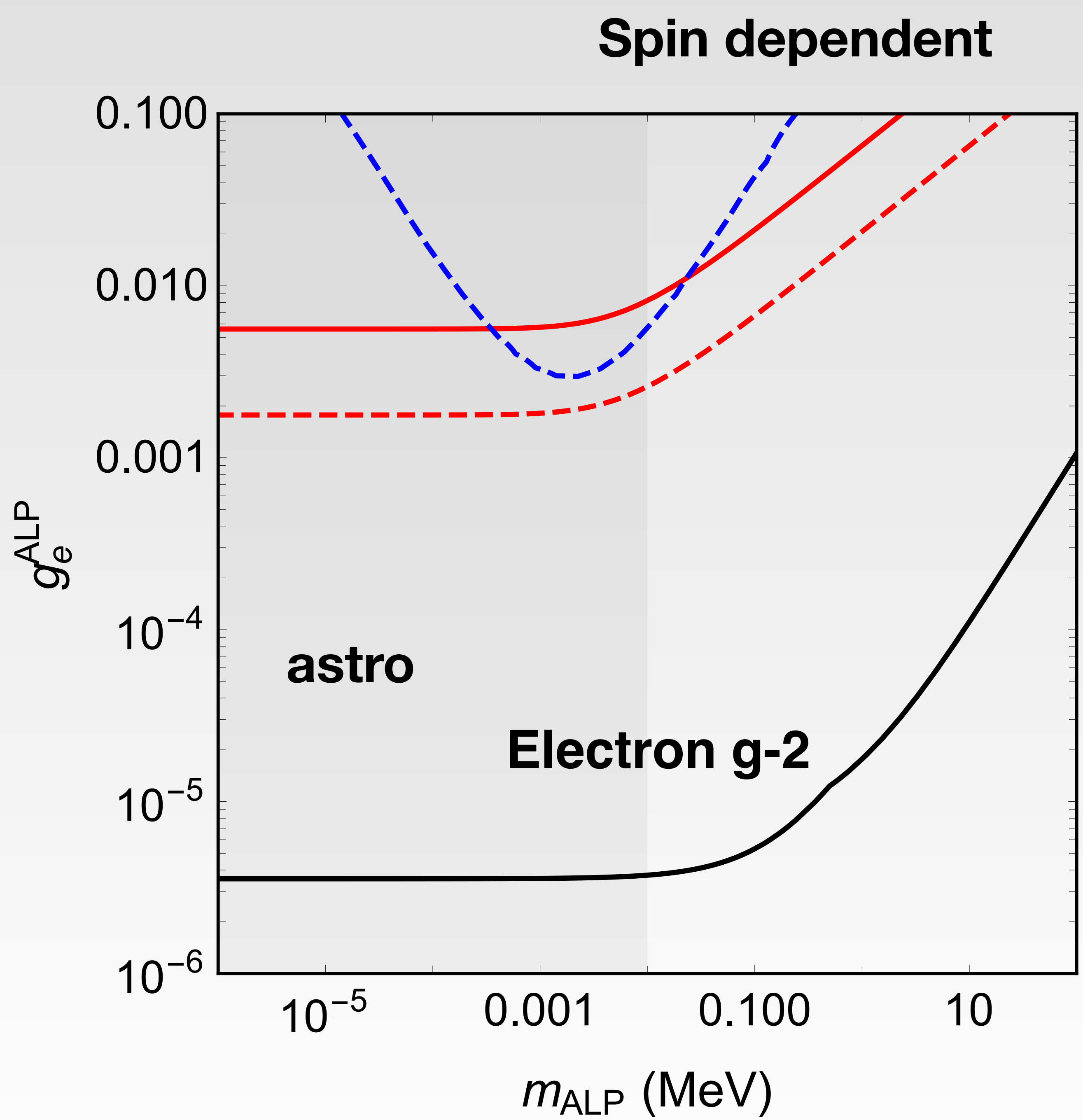
Helium 3,4
and H/D IS measurements



Perspectives with positronium

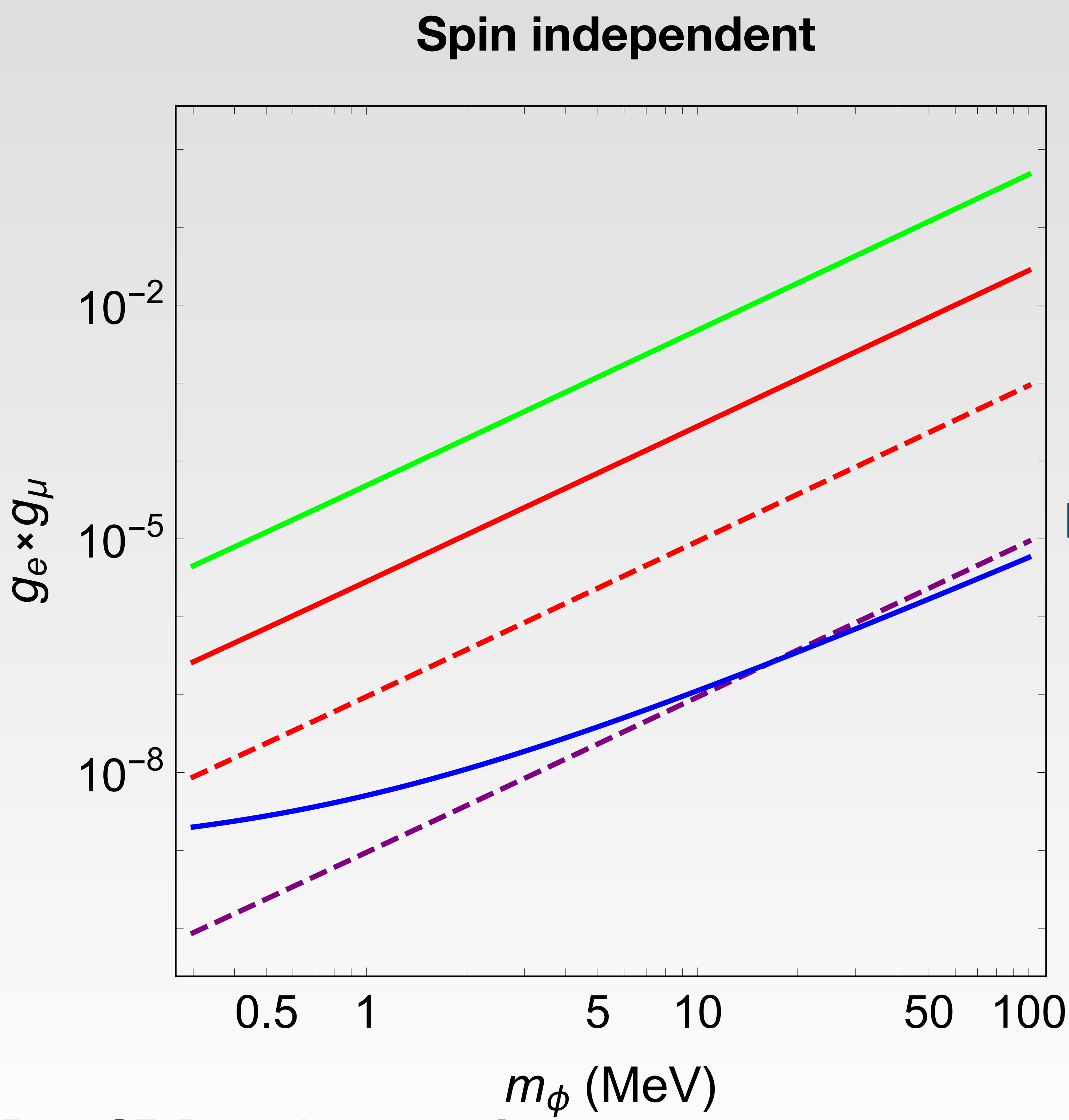
In order to overcome existing bounds from astro and g-2 a precision several orders beyond state of the art would be needed





[Perez-Rıos ,CF, Peset, in progress]

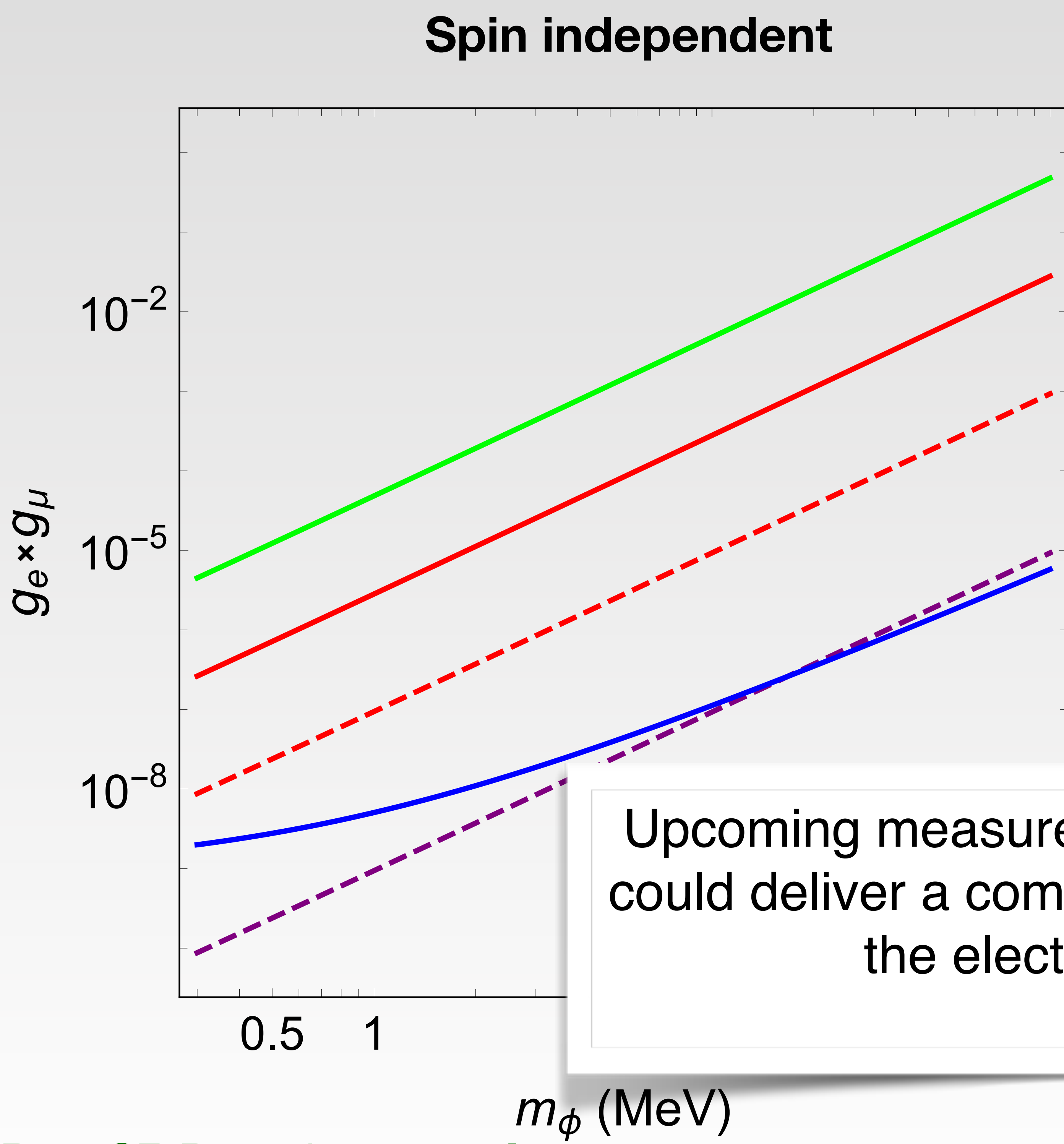
Perspectives with muonium



Electron g-2 and muon g-2

[Perez-Rıos ,CF, Peset, in progress]

Perspectives with muonium

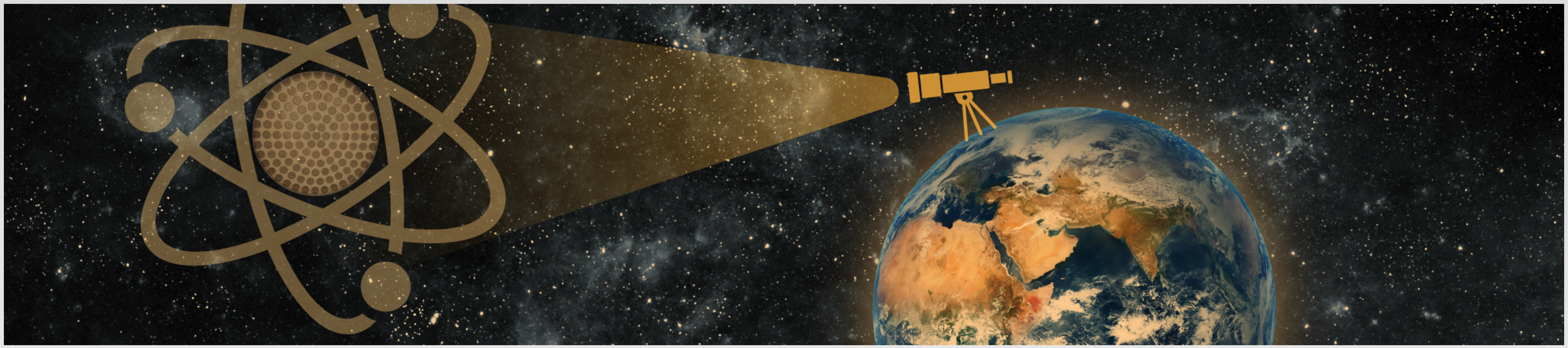


Electron g-2 and muon g-2

Upcoming measurements at JPARC and PSI could deliver a competitive sensitivity to g-2 of the electrons and muons

[Perez-Rıos ,CF, Peset, in progress]

More to explore

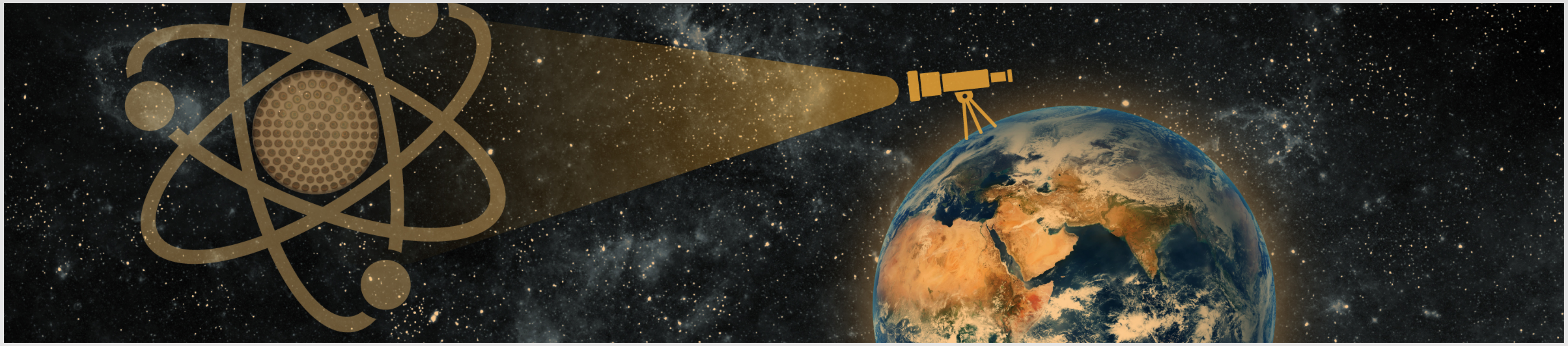


Are there similar observables sensitive to spin-dependent forces?

Study the sensitivity of exotic atoms (e.g. muonic atoms) both to spin-independent and spin-dependent forces. [**CF**,C.Peset,in progress]

Perspectives for future measurements (FAMU,CREMA..) and theory improvements

Outlook

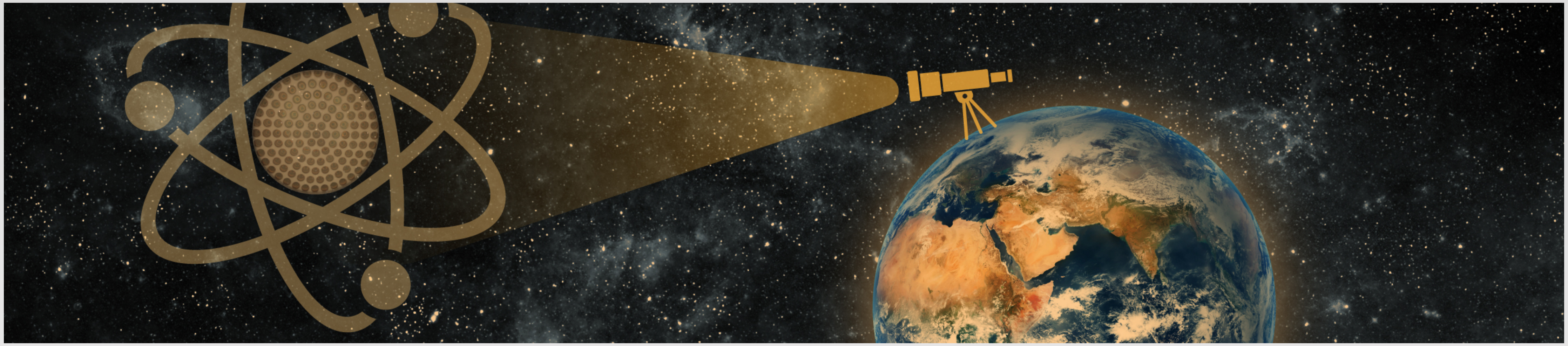


The quest for dark sectors is in full swing

Highly multidisciplinary effort between different branches of physics from particle to nuclear and atomic physics

A discovery could be around the corner: new data and measurements in the next few years will probe interesting regions of the parameter space.

Outlook



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Thank you!

Backup

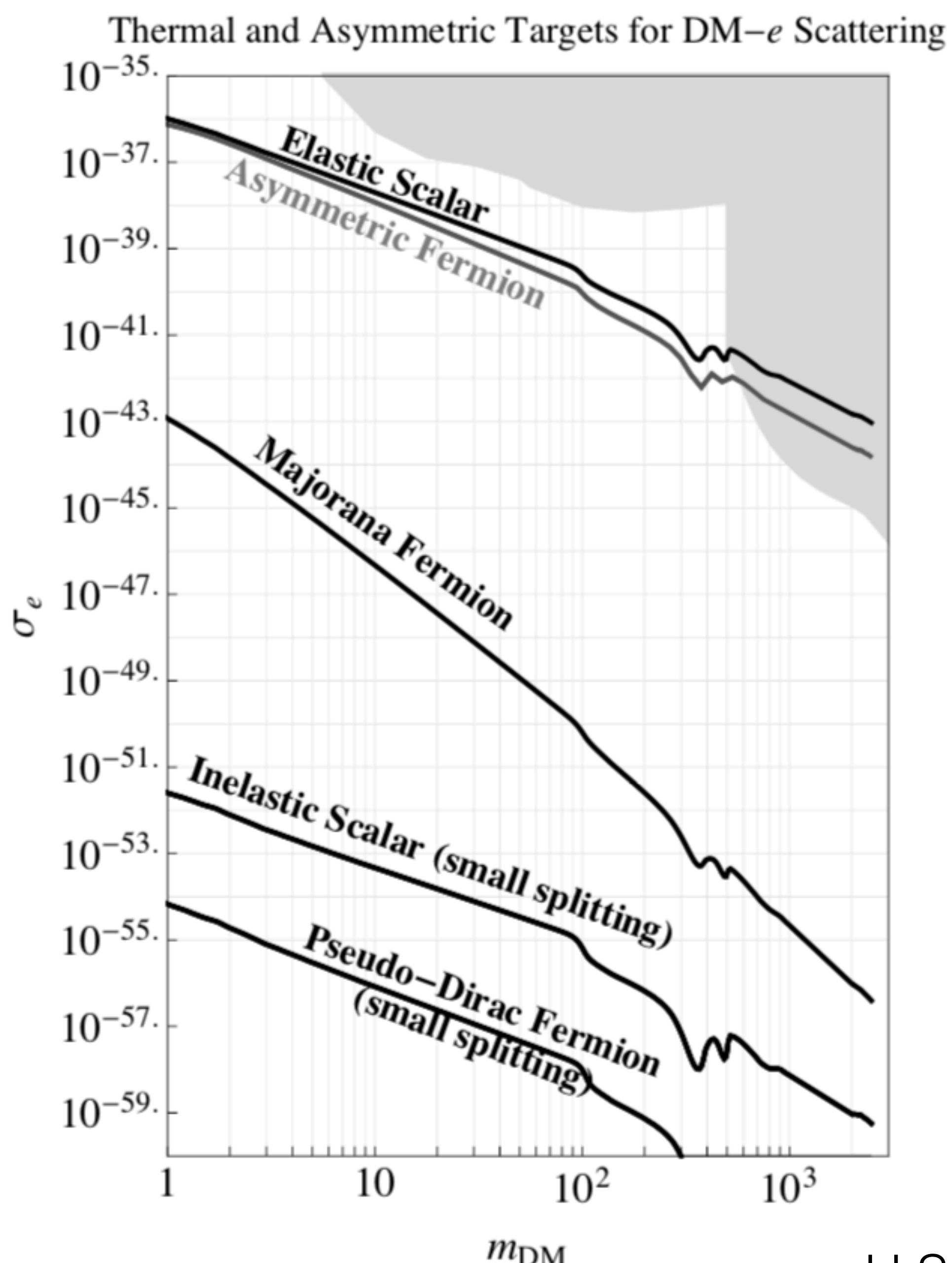
Vector Portal: dark photon

$$\epsilon F_{\mu\nu} F'^{\mu\nu}$$

$$g_{A'}^{\rm SM} = \epsilon e x_{\rm f}$$

$$g_{A'}^{\phi} \sim \mathcal{O}(1)$$

CMB safe: scalar, Majorana or Pseudo-Dirac DM.

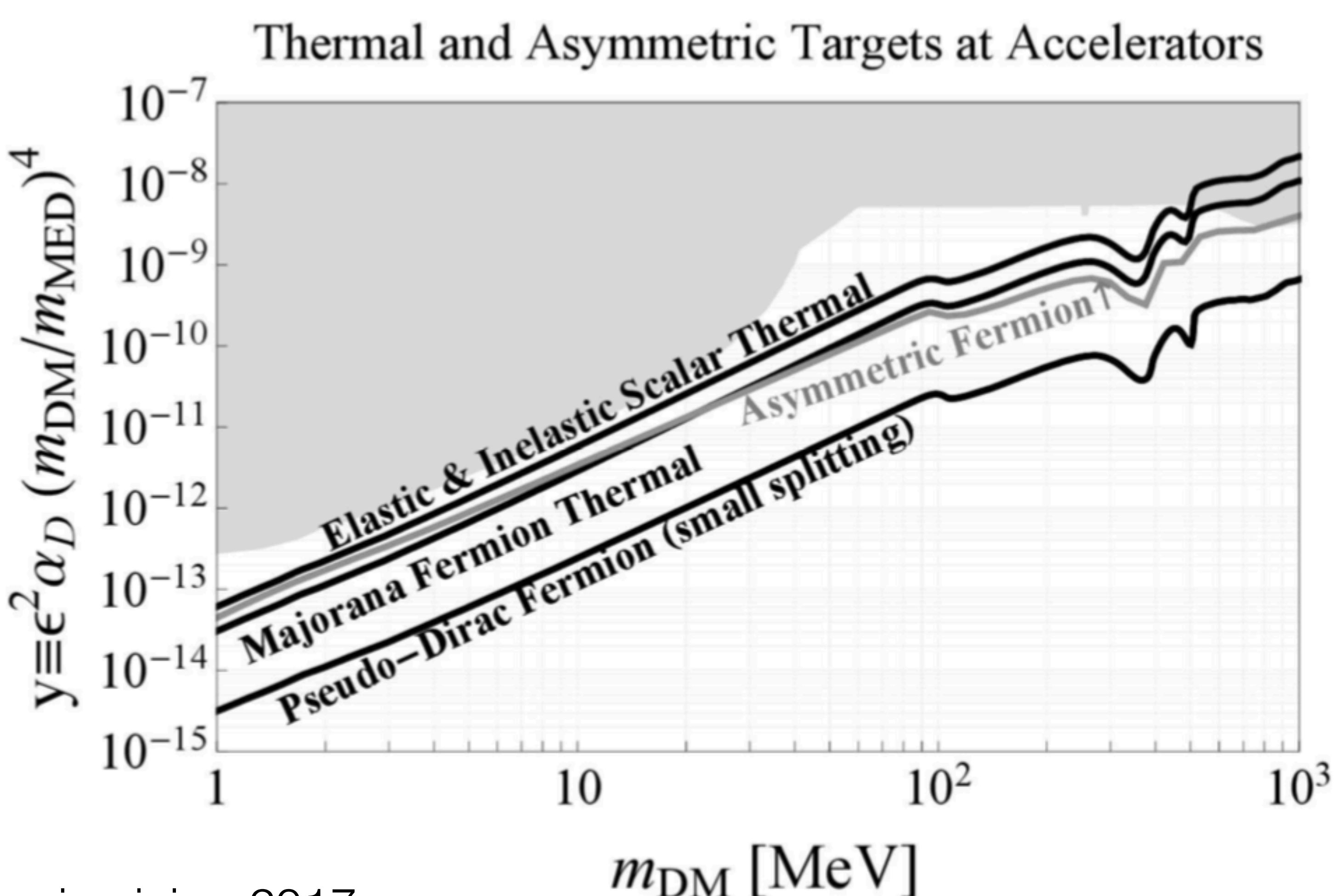


Thermal targets

Izaguirre, Krnjaic, Schuster, Toro,2014

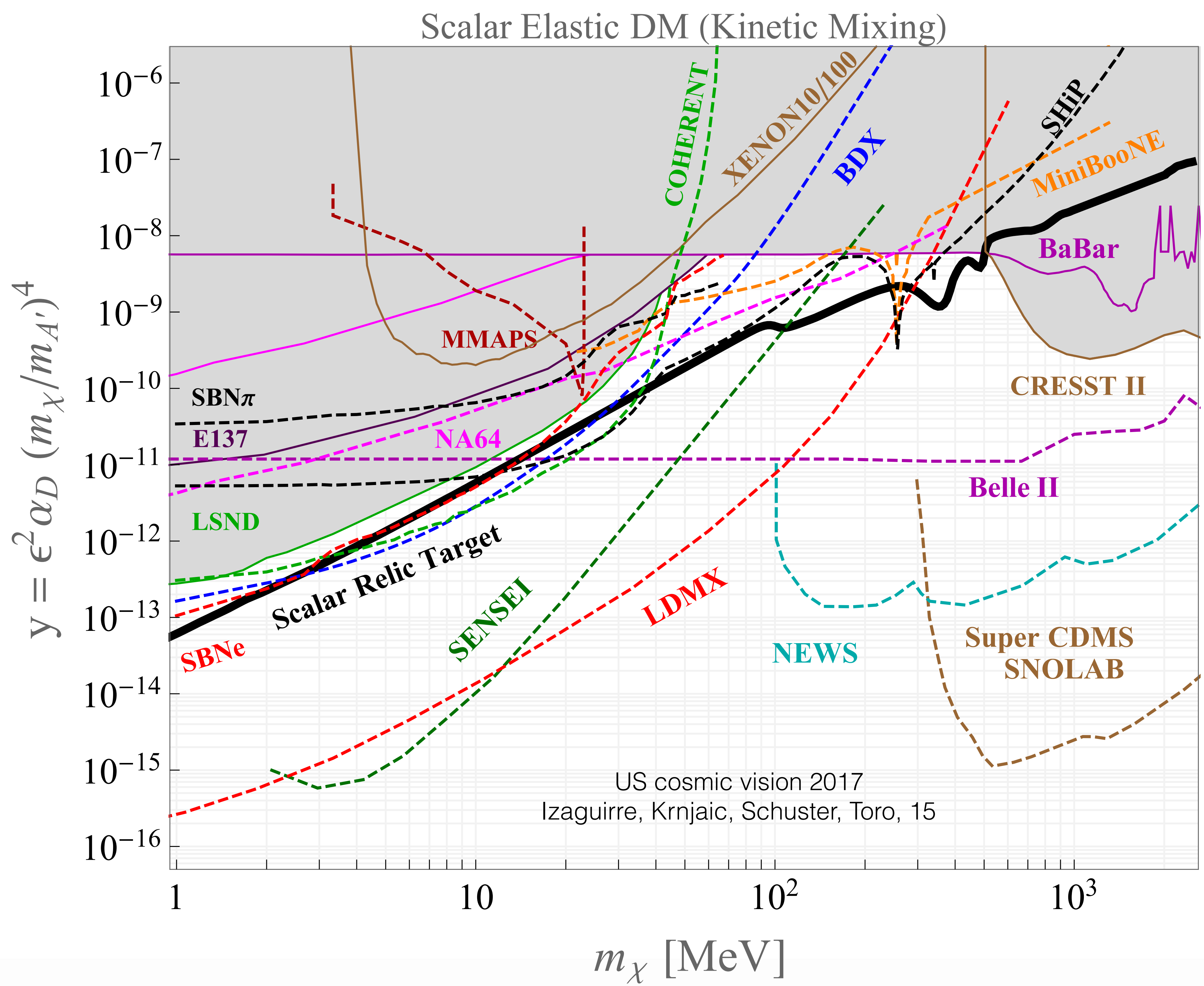
$$< \sigma v > \propto \frac{Y}{m_\chi^2}$$

$$\alpha_D = 0.5 \ , \ m_{A'} = 3 m_\chi$$



U.S. Cosmic vision 2017

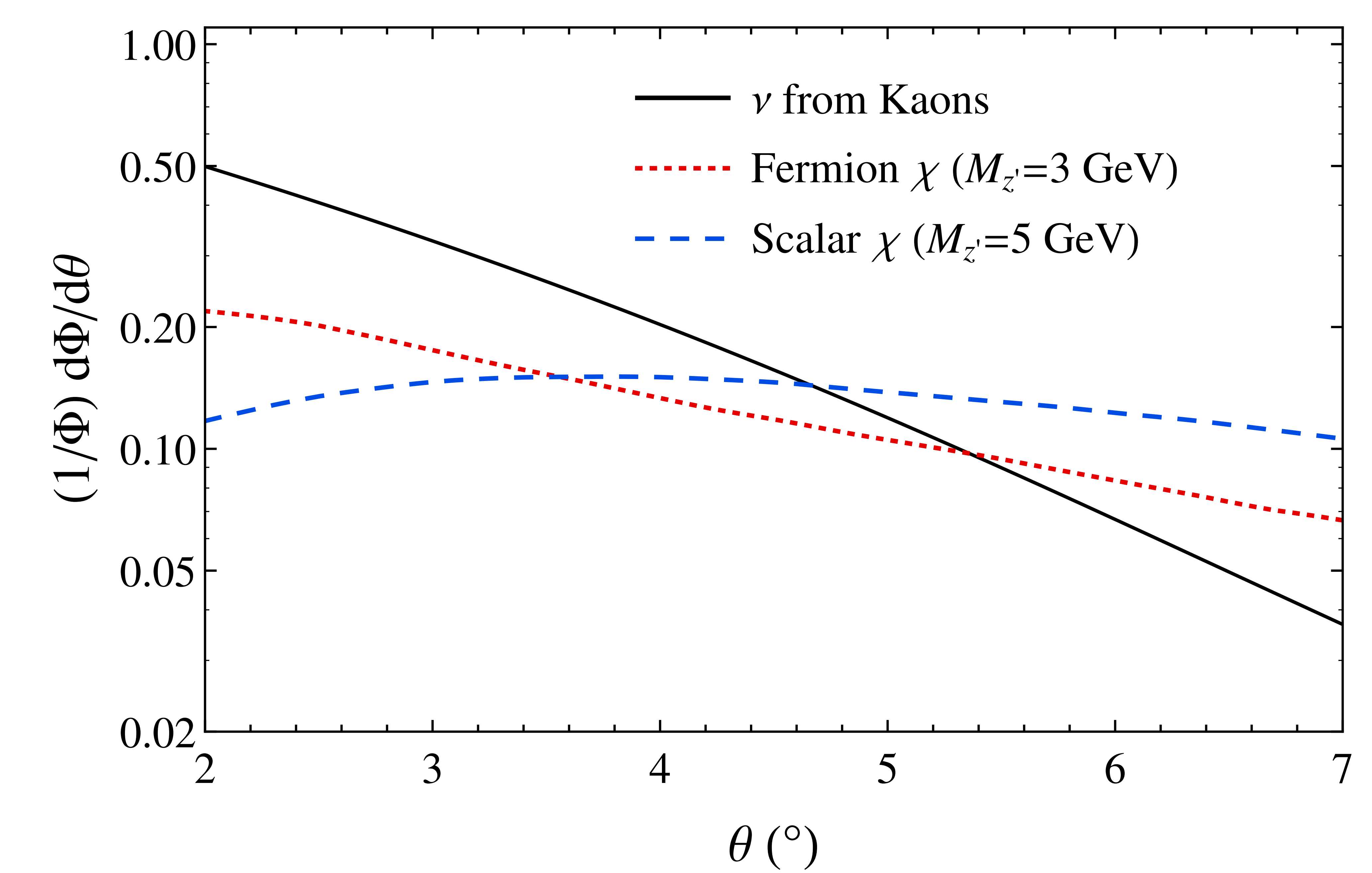
Direct detection for scalar DM



Off axis detectors

Neutrino background "dies" faster than signal going off axis

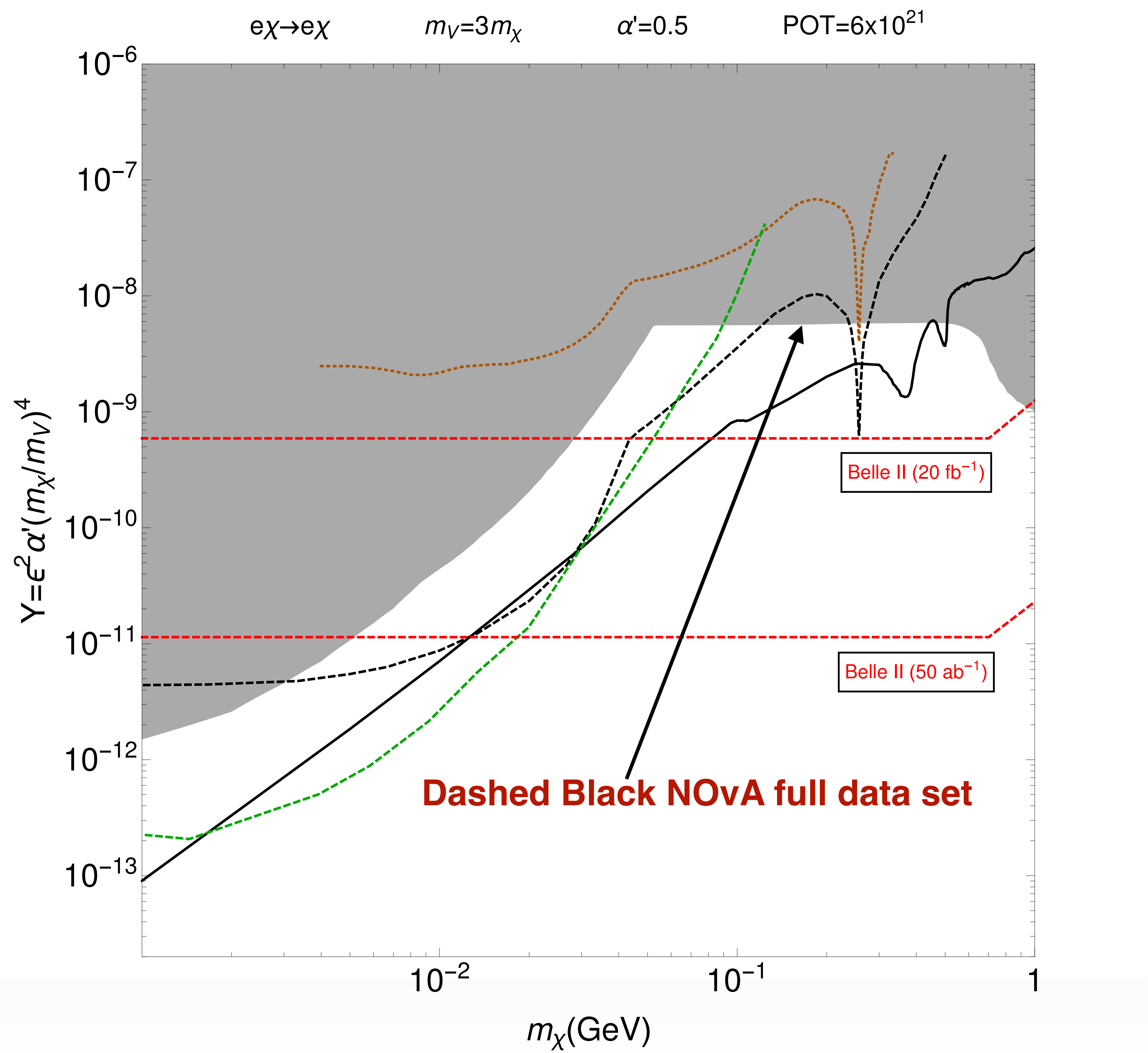
[Dobrescu, Coloma, **CF**, Harnik,JHEP 2015]



NOvA as a DM detector

$$< \sigma v > \sim \alpha_D \epsilon^2 \frac{m_\chi^2}{m_A^2} \sim \frac{Y}{m_\chi^2}$$

$$Y \equiv \epsilon^2 \alpha_D \frac{m_\chi^4}{m_A^4}$$



Dashed Green BDX
proposed electron fixed target experiment

Solid Black Relic density (scalar)

[DeNeverville,**CF**,2018, in progress]

Detector location off-axis location

Location for
an ideal detector