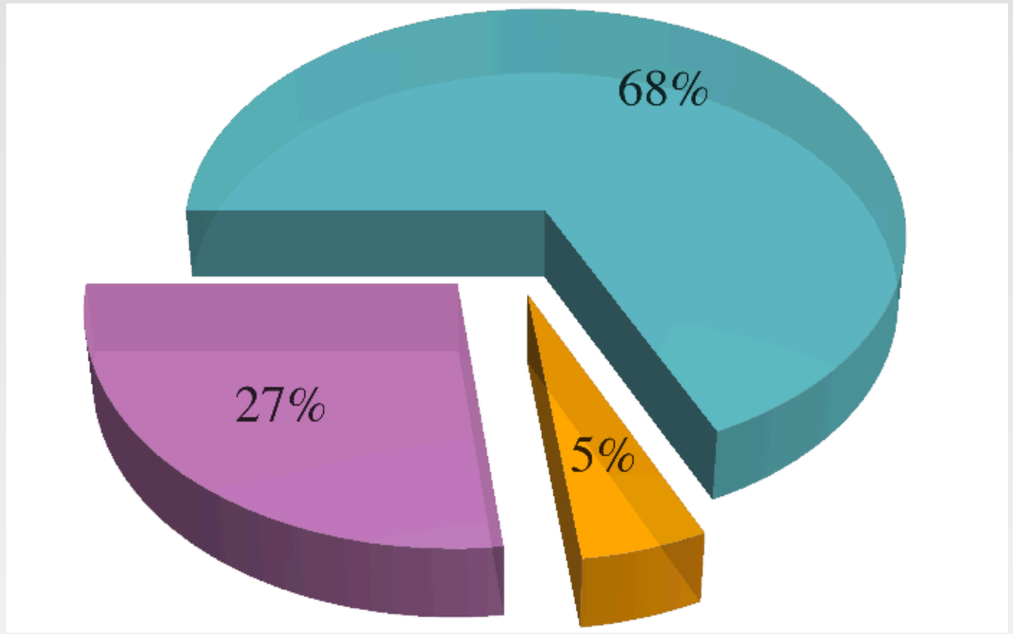
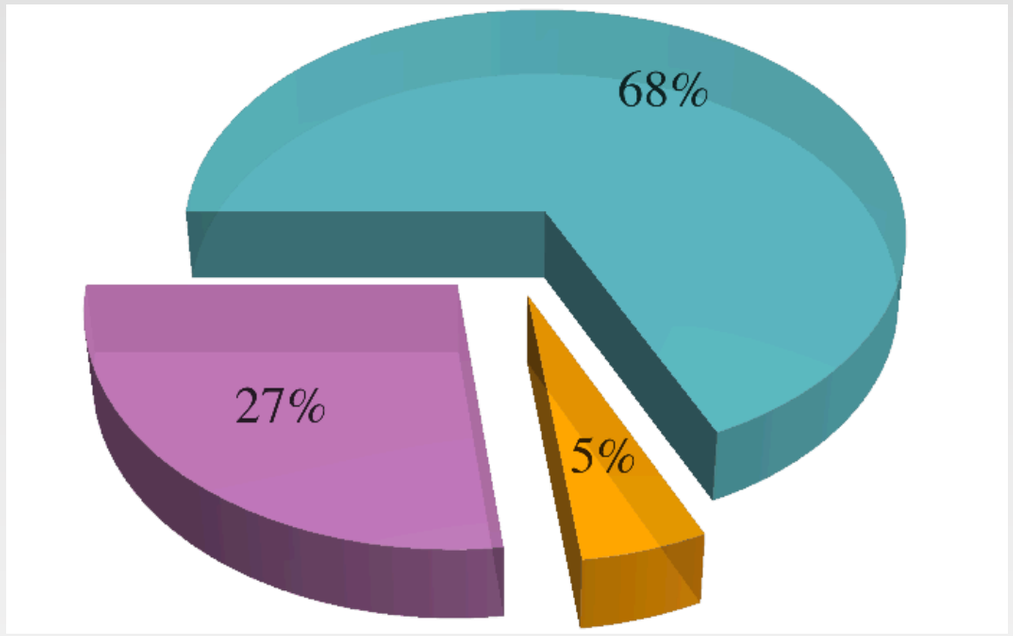
Fixed target Dark sectors Searches



Vera Rubin, ca. 1970

Claudia Frugiuele
INFN, Sezione di Milano

Dark Matter
@ neutrino detectors

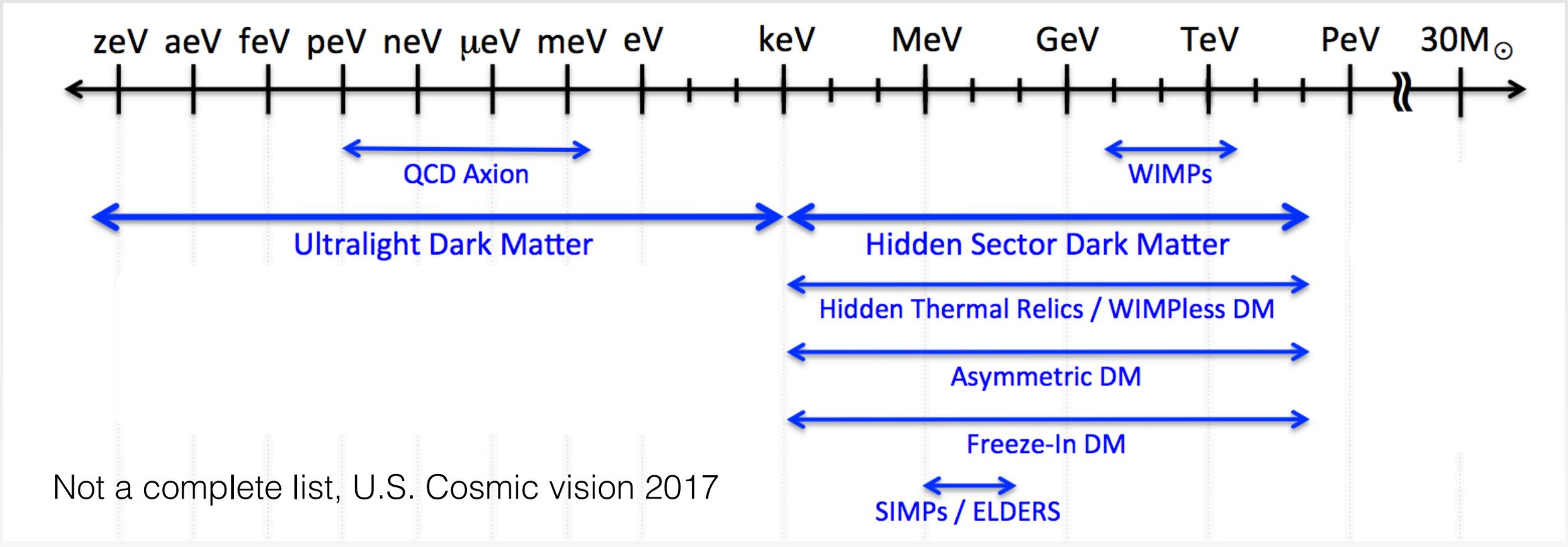


Vera Rubin, ca. 1970

Great opportunity to complement and broaden the current DM search program for WIMPS

DM theoretical landscape is broad

Most of the experimental efforts focus on a small region.

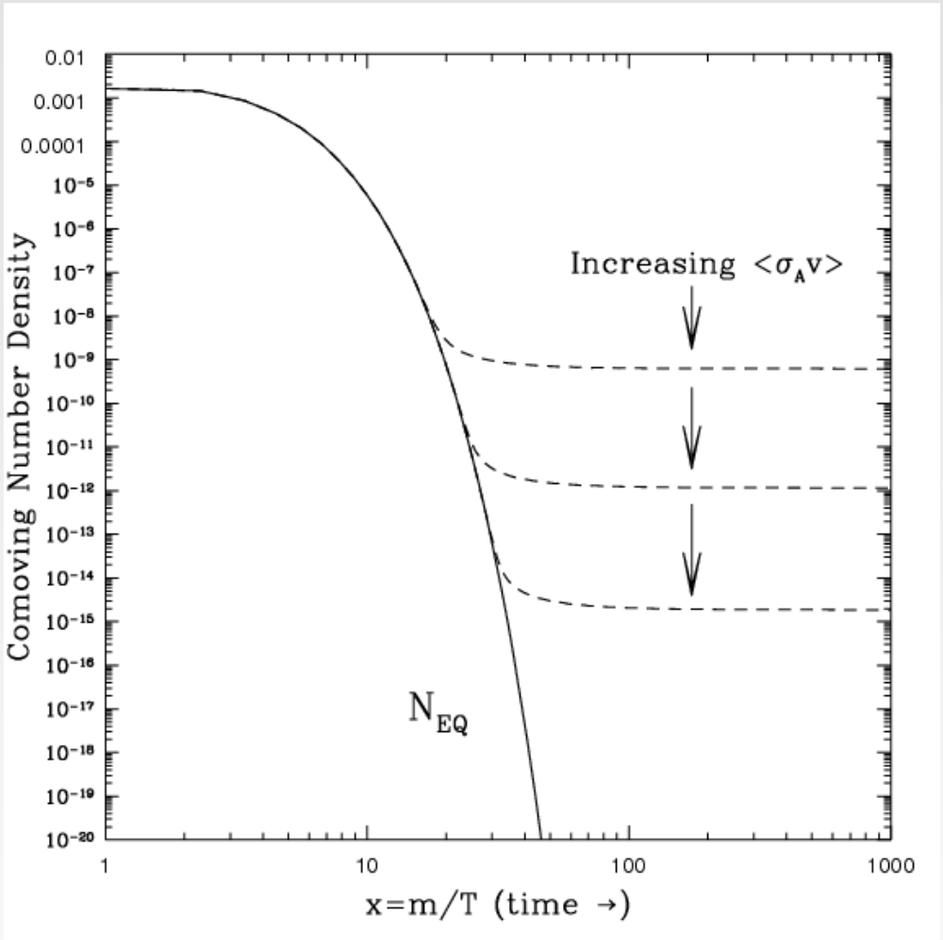


Not a complete list, U.S. Cosmic vision 2017

Many compelling scenarios to guide the experimental searches:
cosmological history of DM ?
Connection to other particle physics long standing questions (e.g. strong CP problem) ?

Thermal DM

Thermal DM acquires its abundance through thermal contact with the Standard Model bath. **DM mass range: 10 keV-100 TeV**



$$n_\chi^{(\mathrm{eq})} = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \propto \begin{cases} T^3 & (T \gg m) \\ e^{-m/T} & (T \ll m) \end{cases}$$

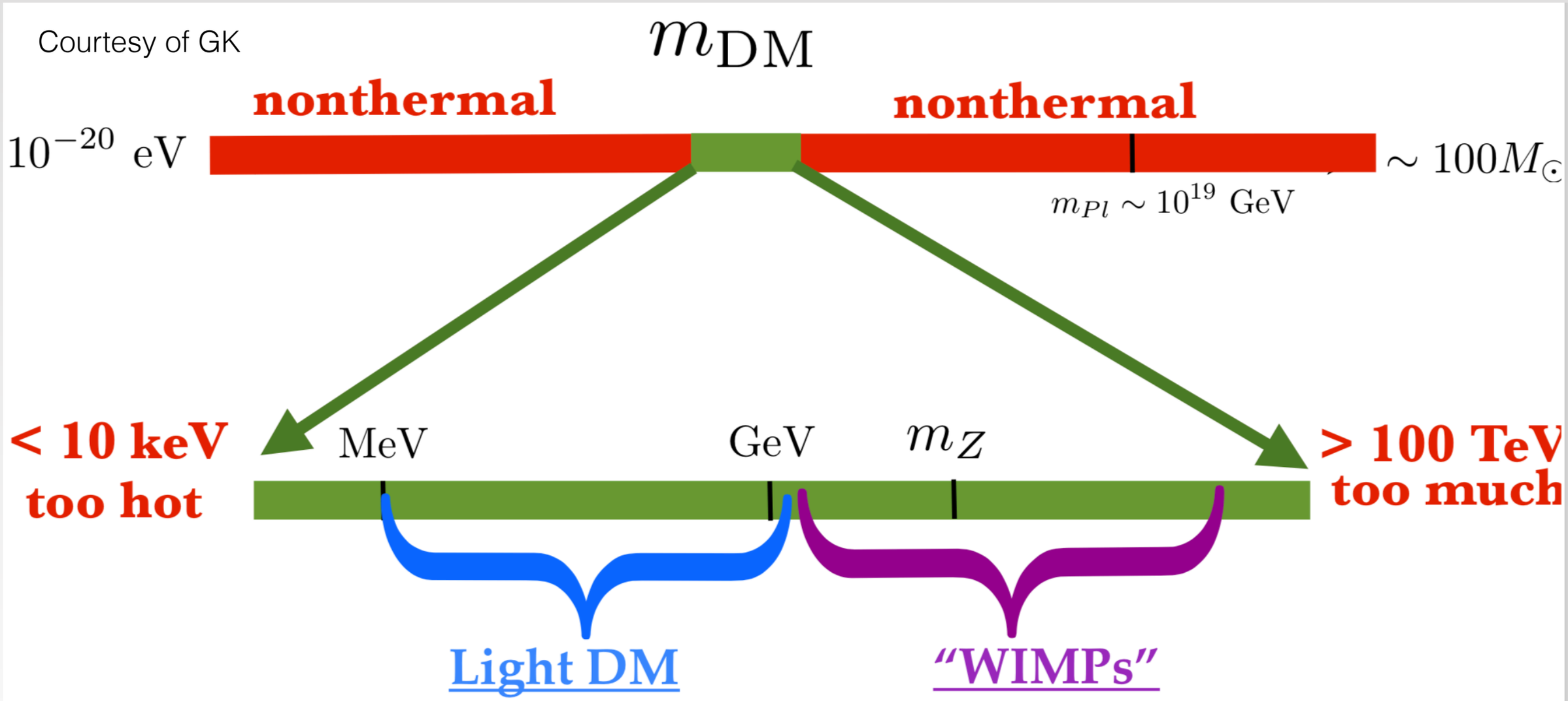
$$\sigma v \sim 2 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

This is one of the reasons why we love WIMPS!

Thermal DM is a is a theoretically attractive and experimentally testable scenario for explaining DM puzzle

Thermal DM

Essential to extend the experimental effort to cover broadly the thermal DM paradigm.



Beam dumps & fixed targets cover MeV-GeV DM complement the current WIMP effort

Thermal DM

Essential to extend the experimental effort to cover broadly the thermal DM paradigm.

Courtesy of GK

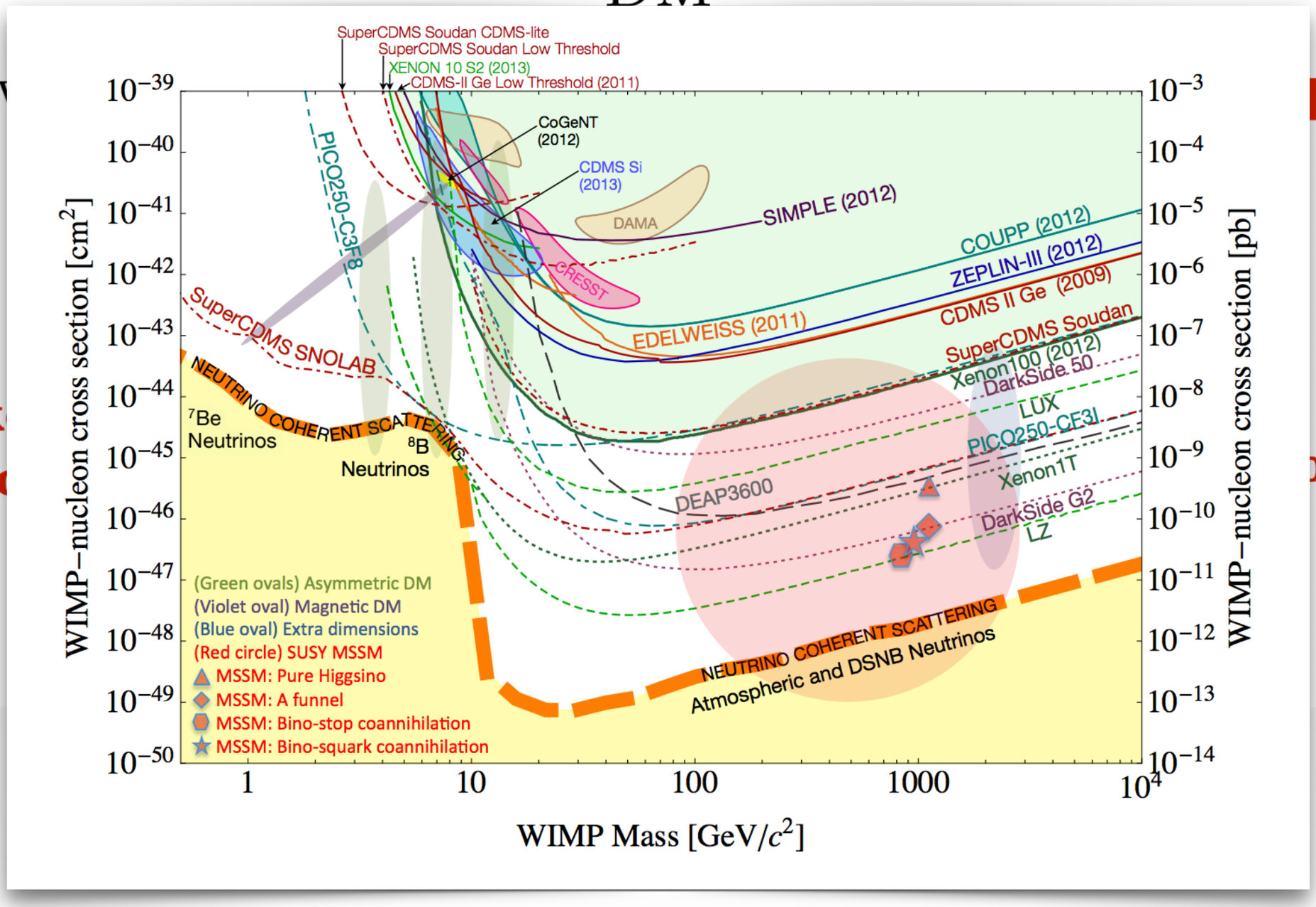
$m_{\rm DM}$

10^{-20} eV

$\sim 100 M_\odot$

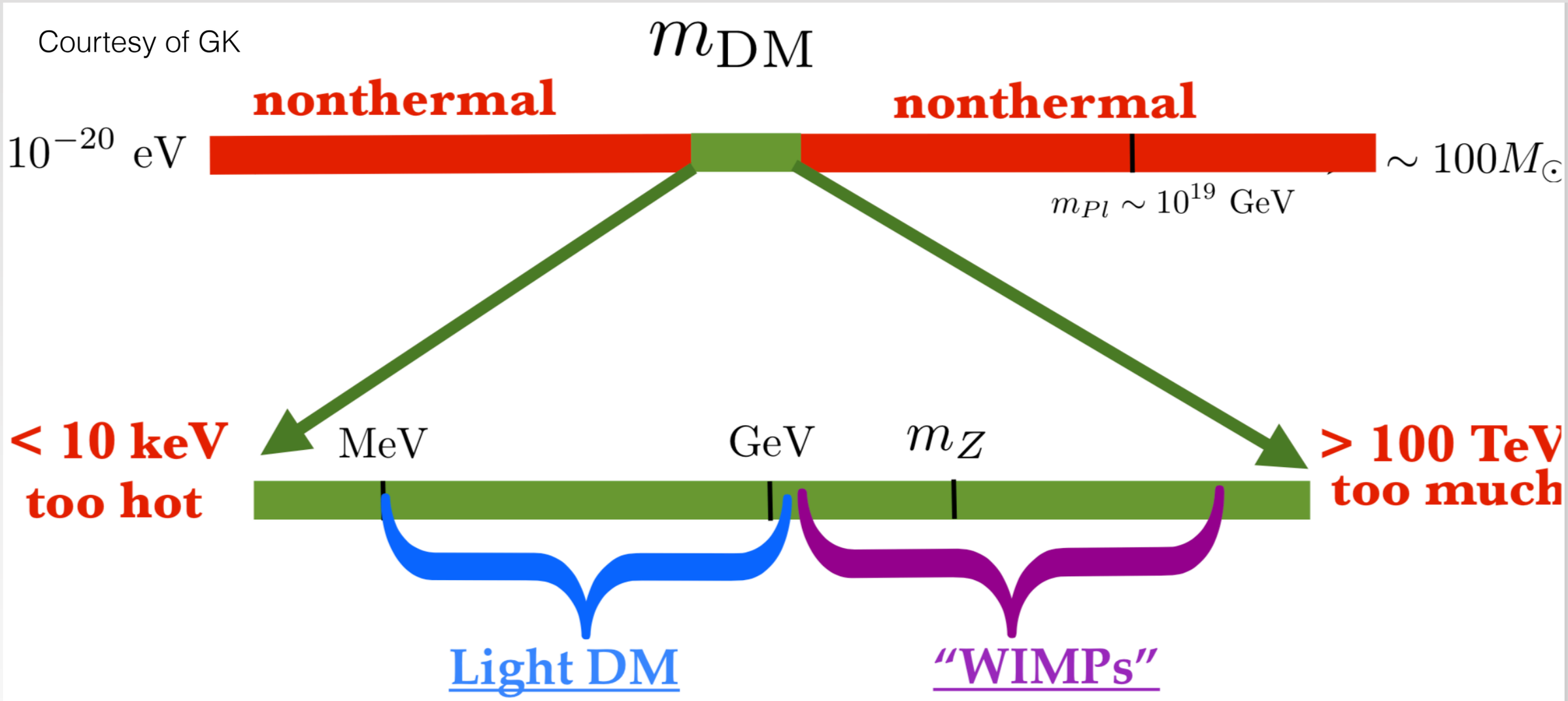
< 10 k… too h…

100 TeV … too much



Thermal DM

Essential to extend the experimental effort to cover broadly the thermal DM paradigm.

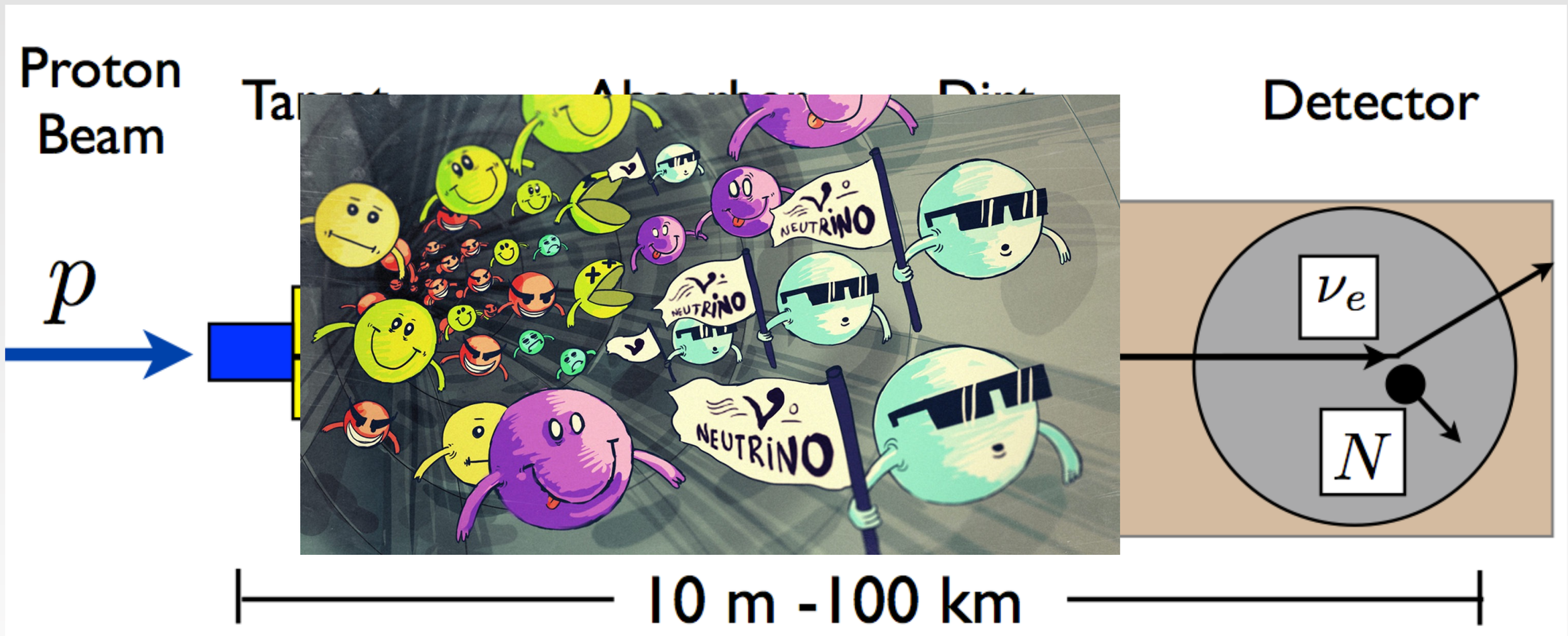


Beam dumps & fixed targets cover MeV-GeV DM complement the current WIMP effort

Neutrino facilities to look for DM

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

[Batell, Pospelov Ritz, 2009]

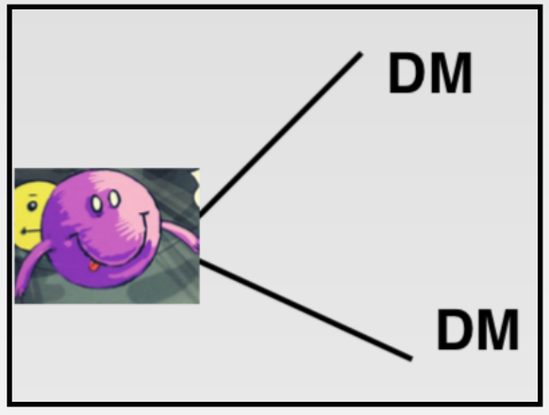


Dark photon portal

[Holdom,Okun]

MeV-GeV gauge boson kinetically mixed with the photon

$$\epsilon F_{\mu\nu} F'^{\mu\nu} \qquad g_{A'}^{\rm SM} = \epsilon e x_{\rm f} \qquad g_{A'}^{\phi} \sim \mathcal{O}(1)$$



A beam of dark photons is produced, these immediately decay into DM particles

Cosmological safe scenarios

DM could be a Scalar or Majorana or Pseudo-Dirac fermions

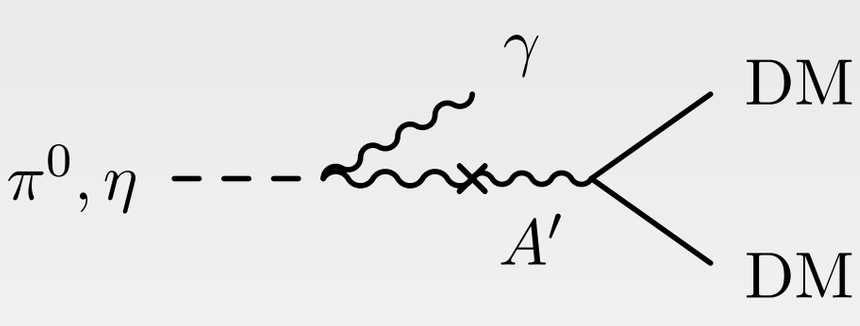
How is the DM beam produced?

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

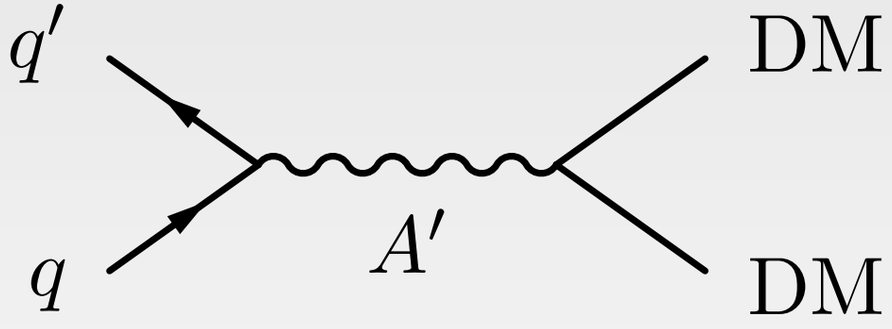
MeV-GeV scalar DM (no tension with cosmology) $g_{A'}^{\phi} \sim \mathcal{O}(1)$

On shell production of the mediators is essential

- Production via meson decay



- Direct Production

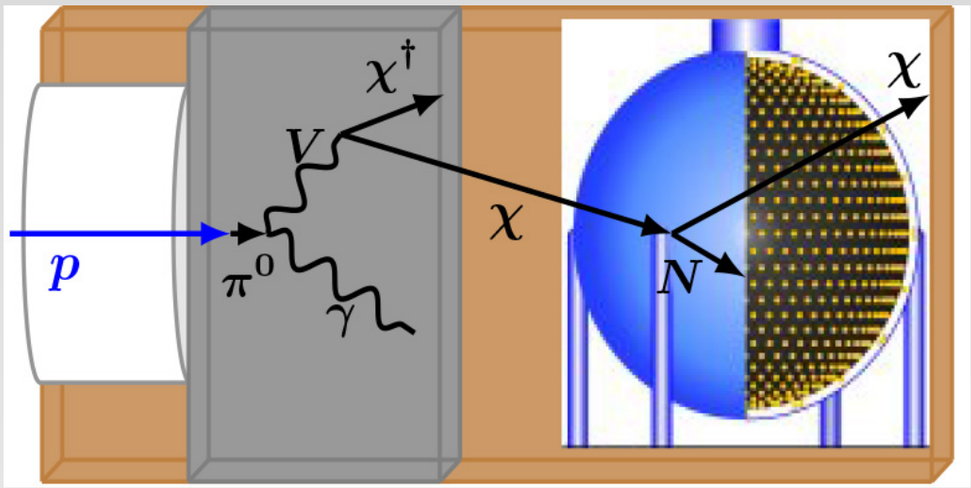


A. Celentano,L. Darme, L. Marsicano, and E. Nardi 2020 for secondary production via electromagnetic shower

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 main observables

- DM-nucleus scattering

- DM-electron scattering

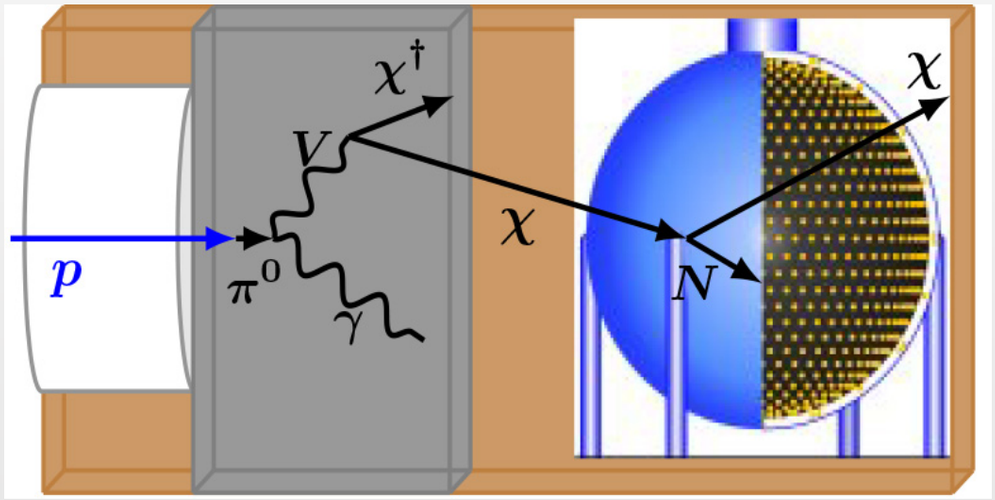
Trident scattering promising signature for compressed region of the parameter space.

De Gouvea et al 2018

Decay of a heavier DM into visible+ lighter DM (Pseudo-Dirac DM) Krnjaic et al. 2017

Main challenge: suppression of neutrino background.

DM-electron scattering

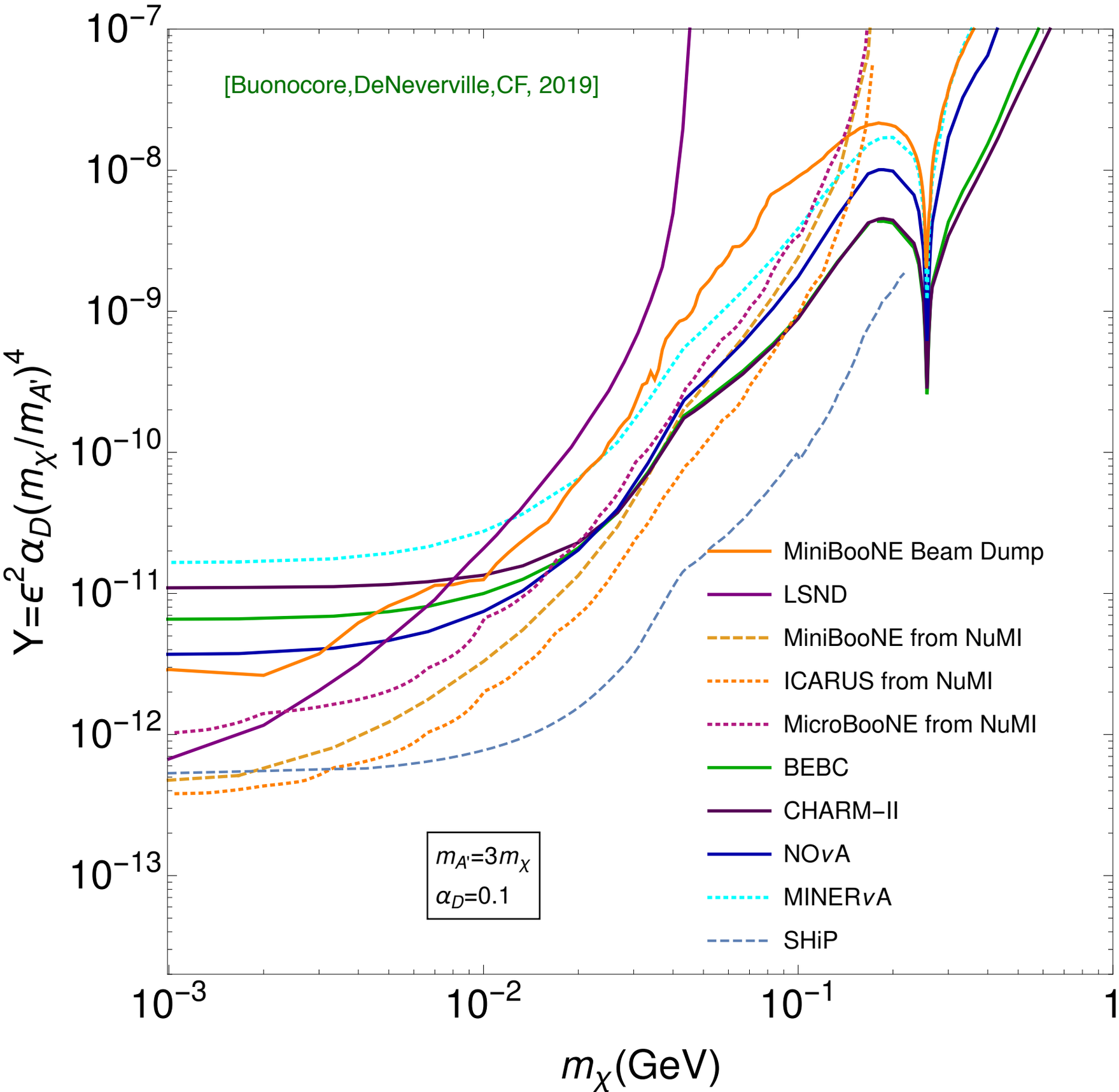


Small neutrino background

Past, present and future

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

Izaguirre, et al 2014



Off-axis sensitivity

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

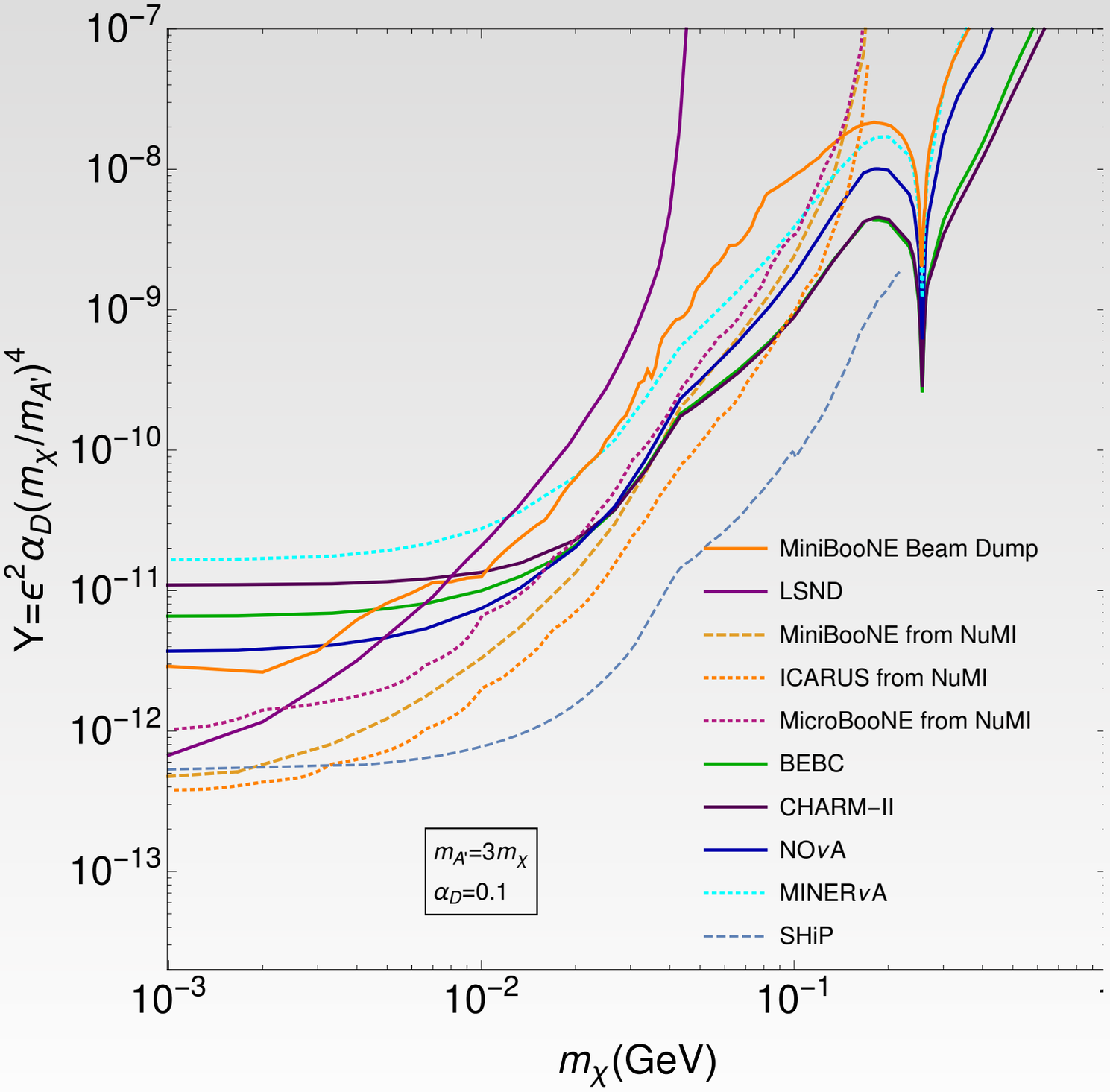
Izaguirre, et al 2014

Same cuts at the MB on axis analysis

$$cos\theta > 0.99$$

$$E_{reco} > 75 \text{ MeV}$$

[Buonocore,DeNeverville,CF, 2019]

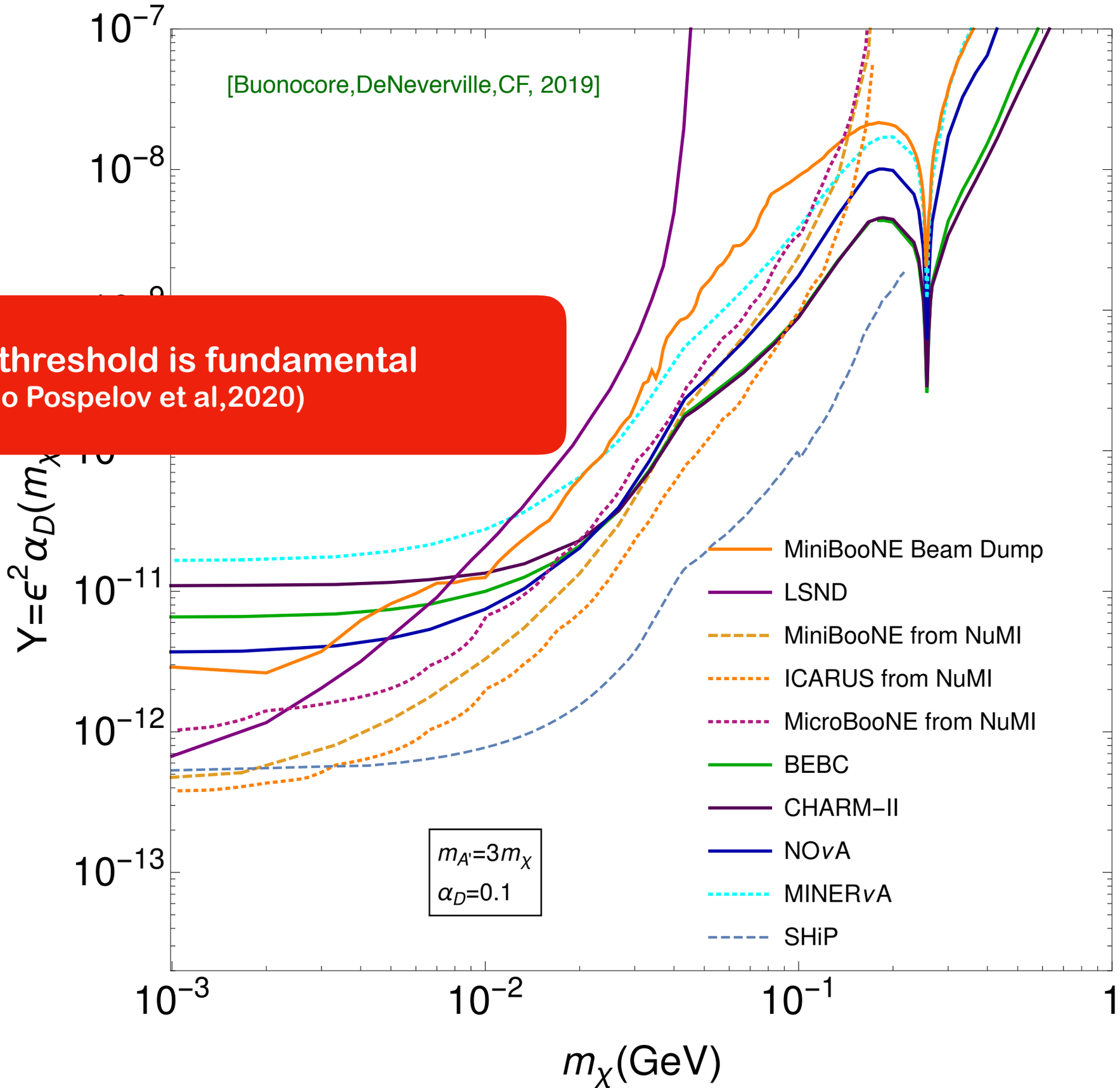


Past, present and future

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

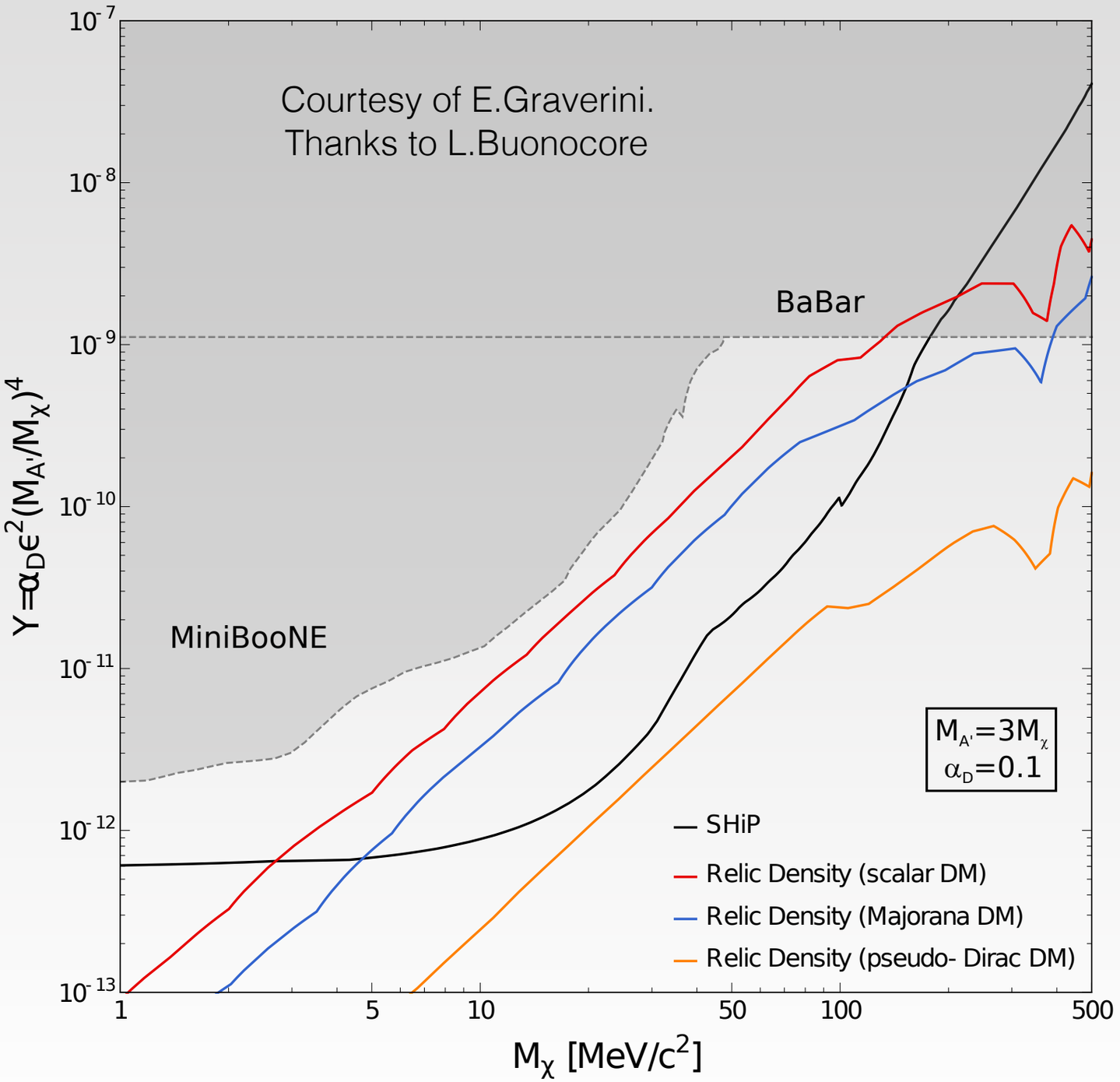
Izaguirre, et al 2014

Low energy threshold is fundamental
(see also Pospelov et al,2020)

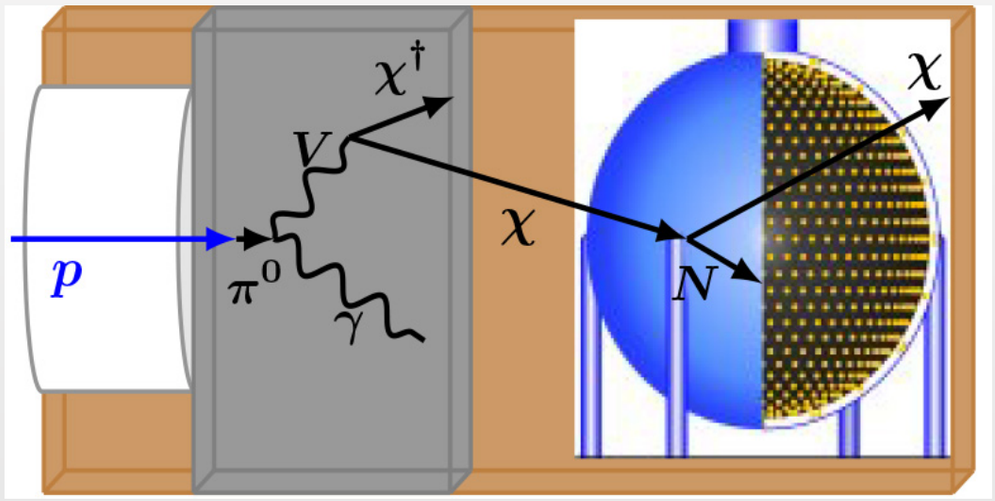


Future experiments:SHiP

SHiP sensitivity (Buonocore, DeLellis, DeCrescenzo,Ferillo, CF, Tramontano in progress)



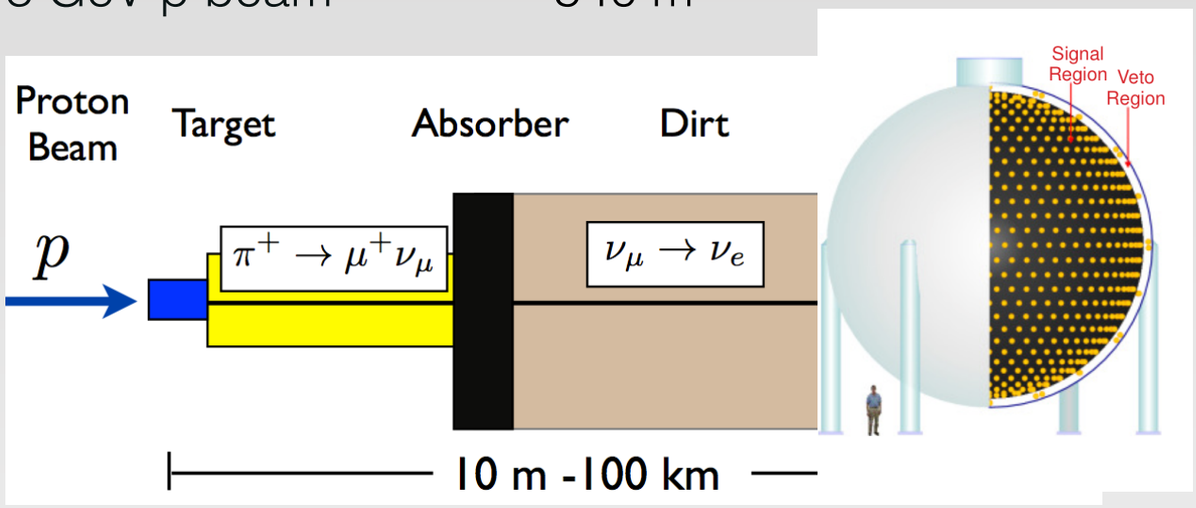
DM-quark scattering



Complementarity with direct detection program for sub-GeV mass range

DM search @ MiniBooNE

8 GeV p beam 540 m

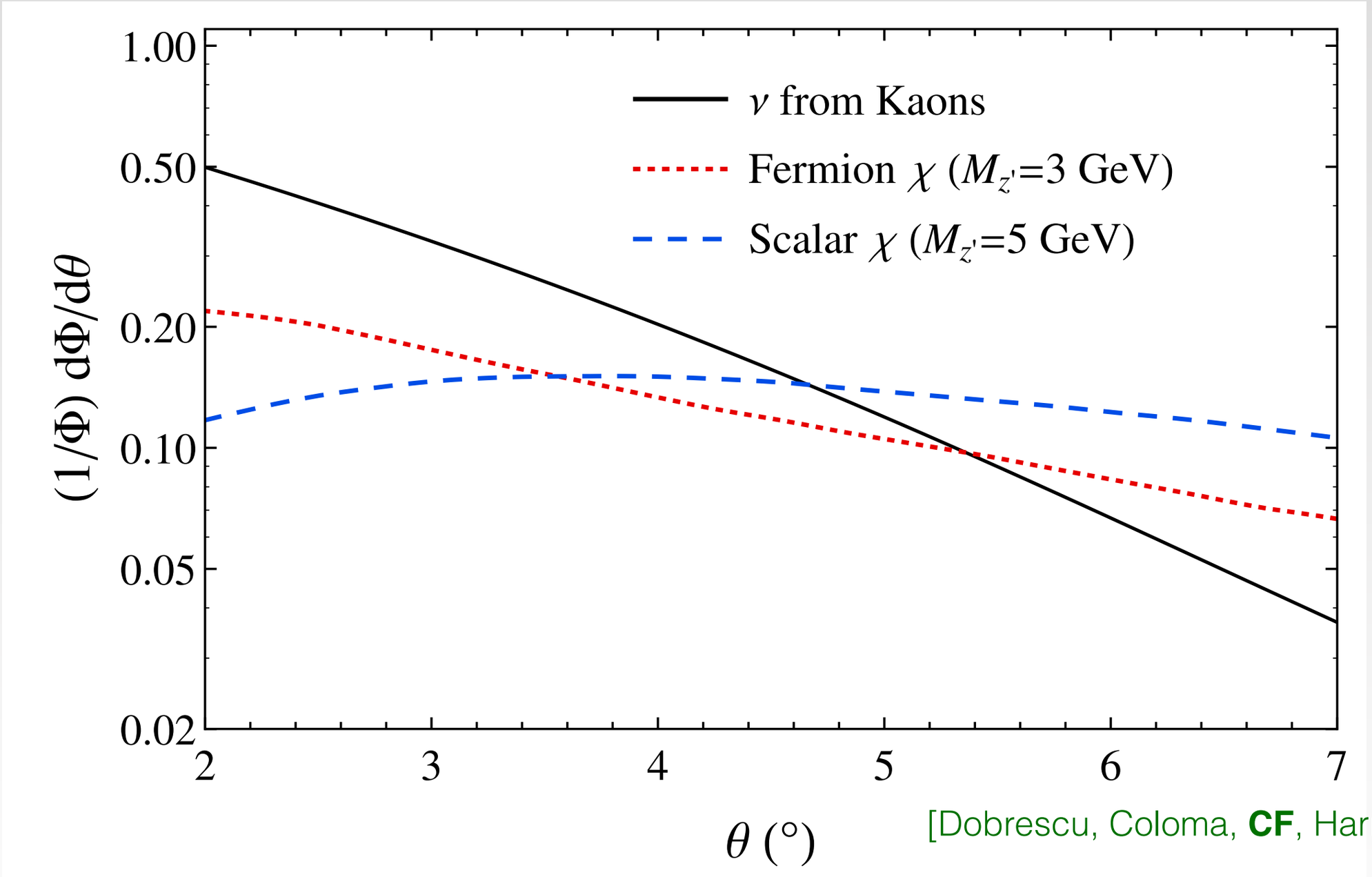


MiniBooNE:800 tons detector

- 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

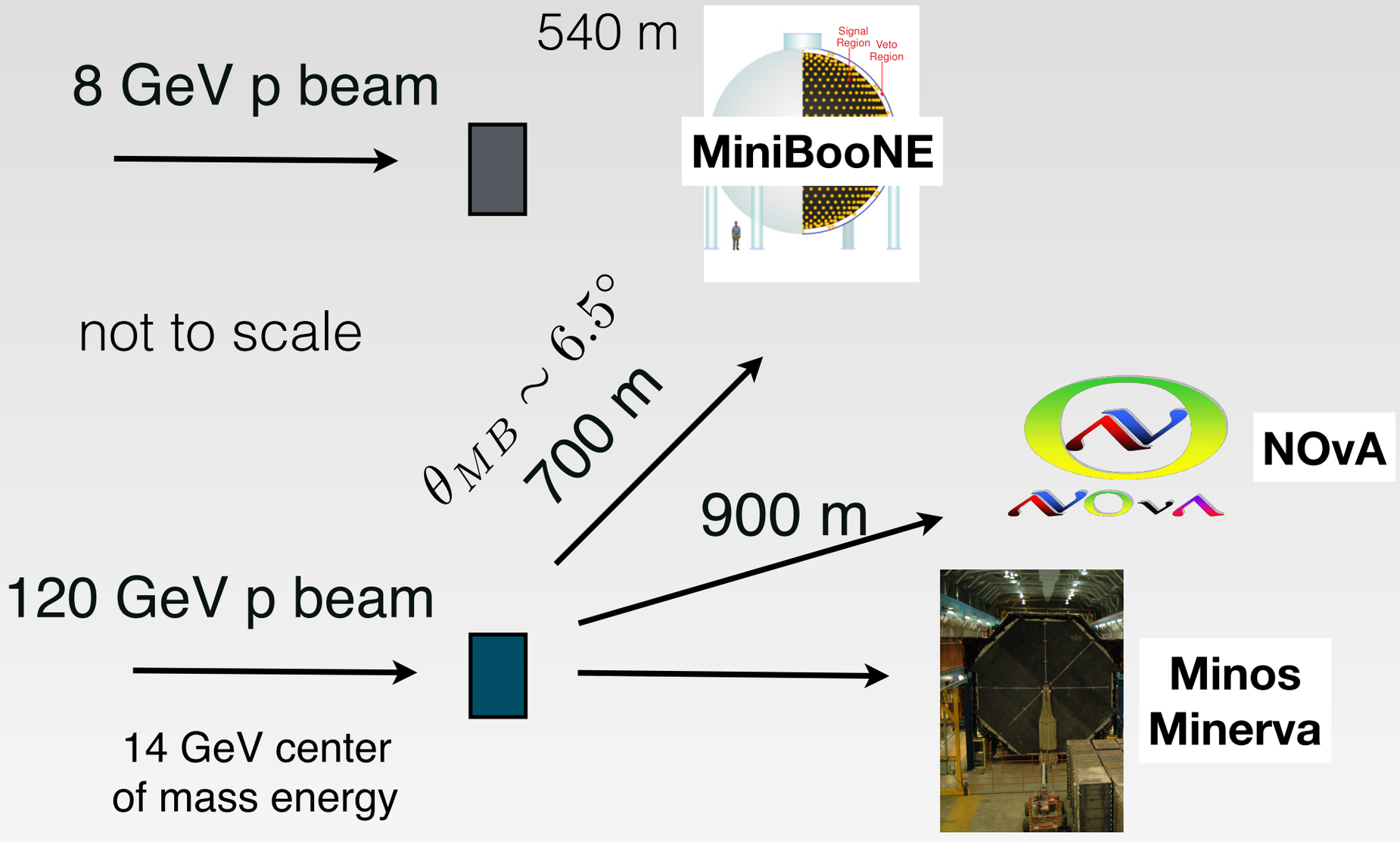
Difference angular distribution of DM and neutrino flux



[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

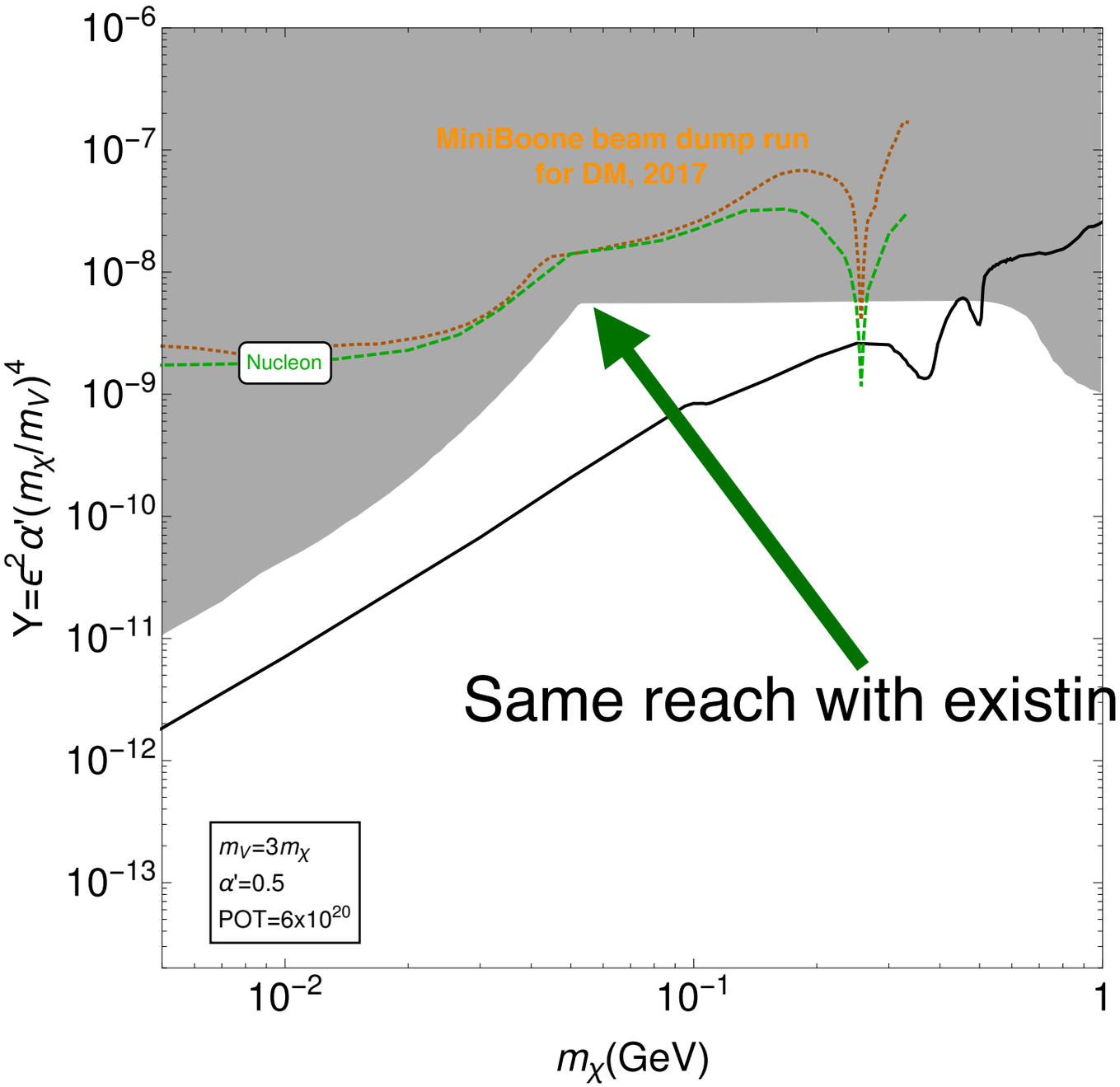
Neutrinos @ Main Injector (NuMI)



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

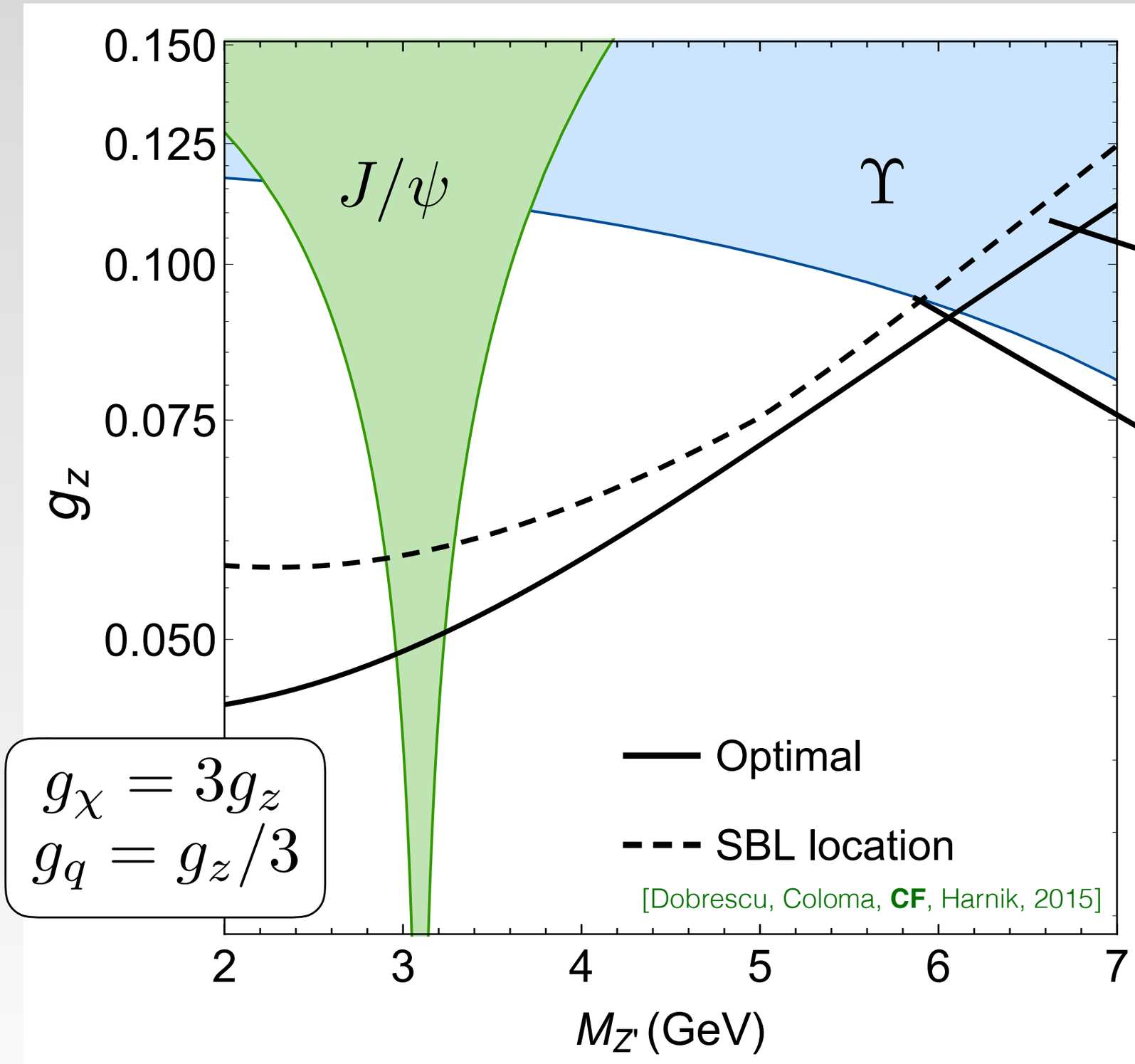
DM-quark scattering in MiniBooNE

Similar location as future detector ICARUS!



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

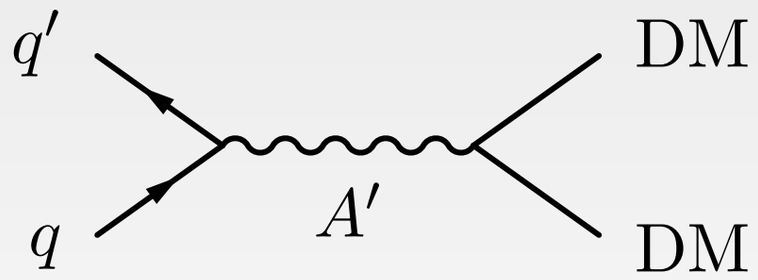
DM-quark scattering in MiniBooNE



Analysis of deep inelastic scattering events

Ideal detector (DUNE/LBNF)

Existing MiniBooNE data



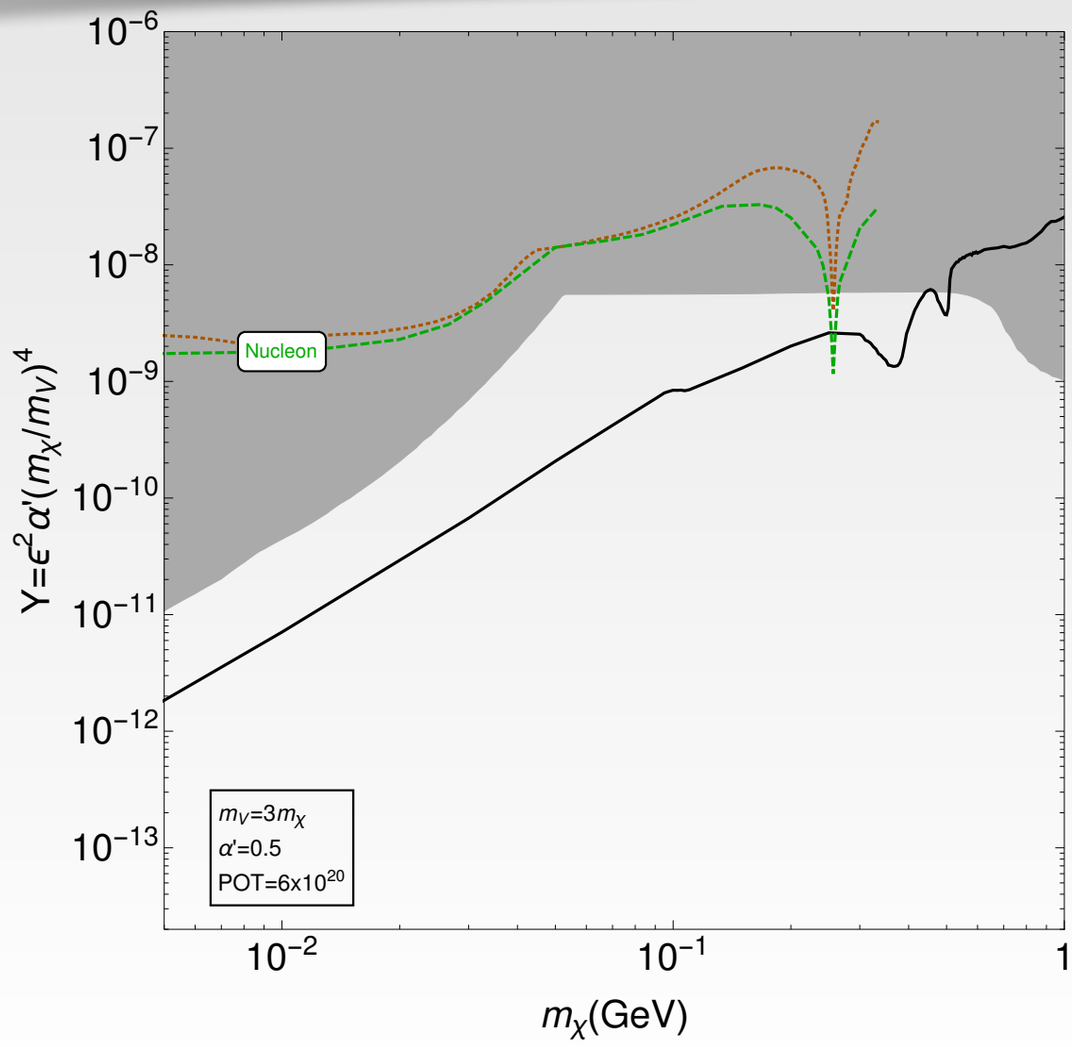
In this mass range
Drell-Yan production

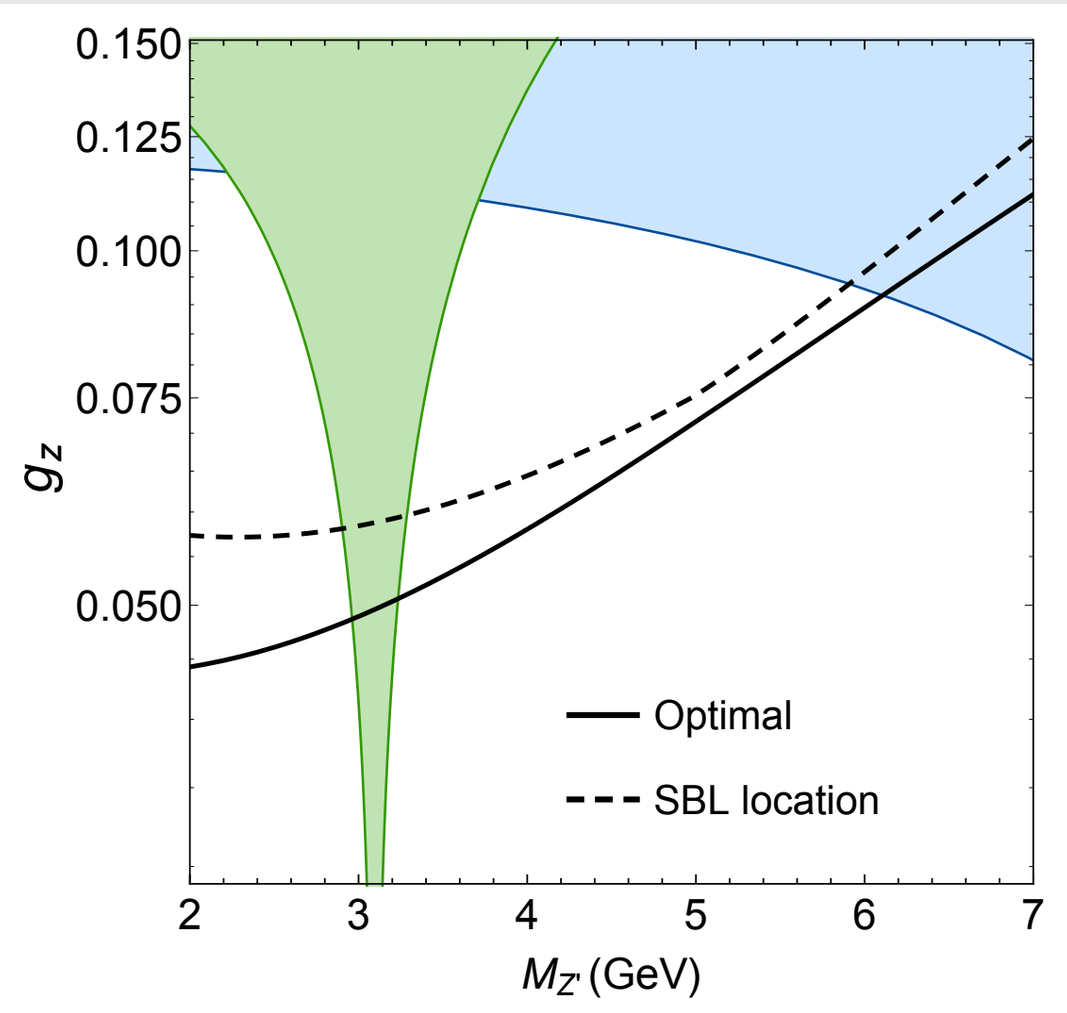
UV dependent constraints from anomalies

[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.
- Off-axis detectors are also promising to look for dark trident signatures (De Gouvea et al 2018)

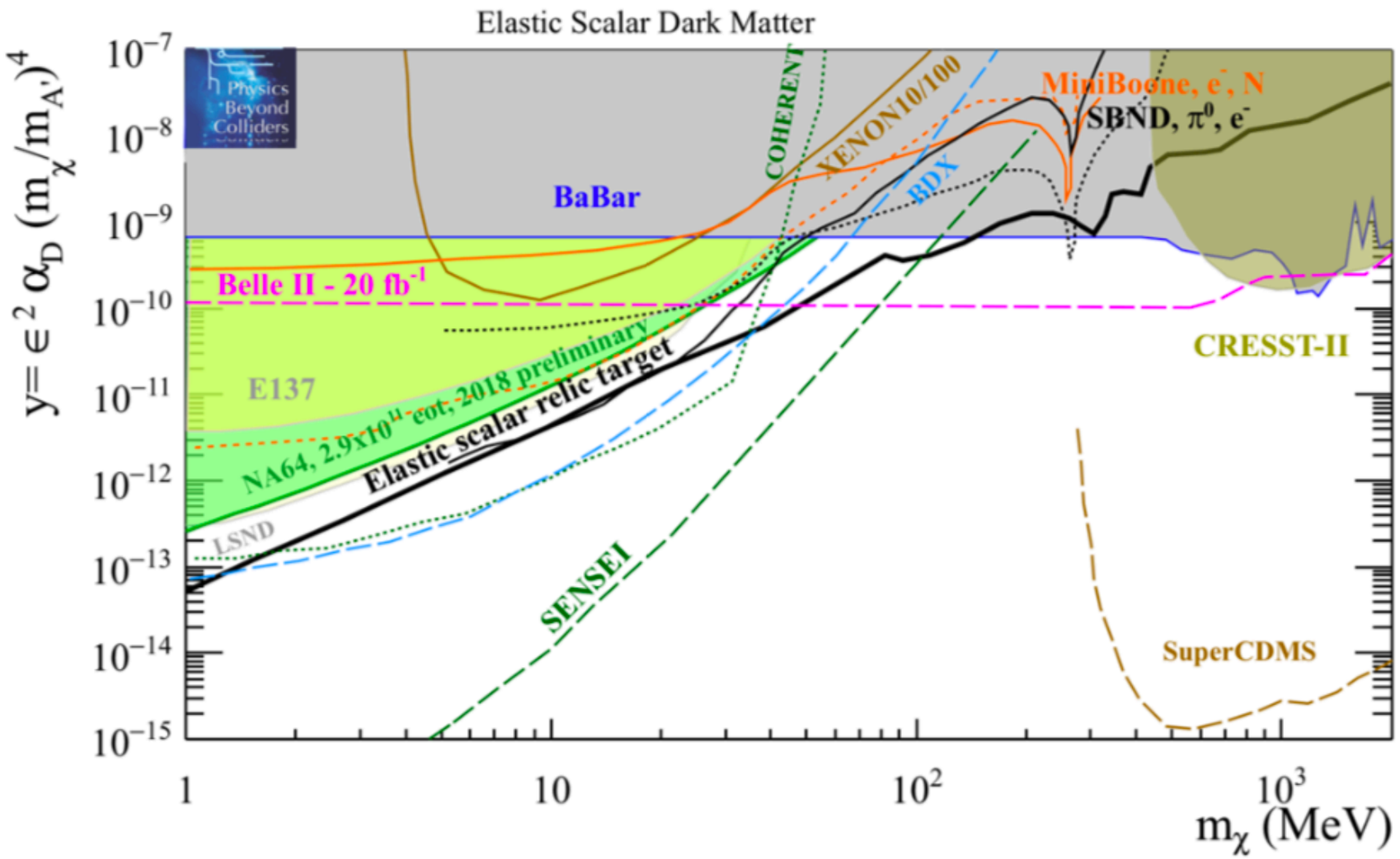




Coherent

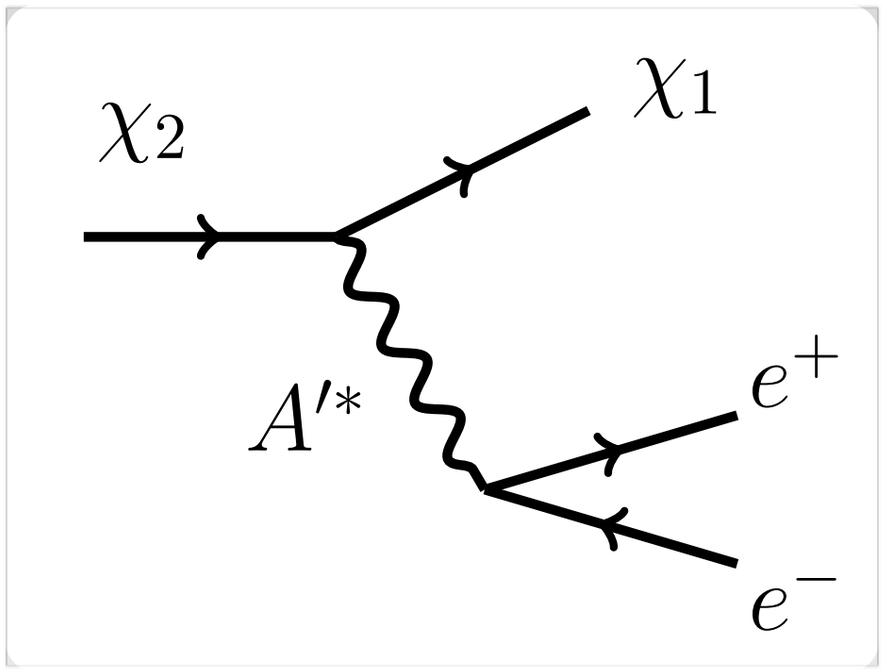
See also Shoemaker et al 2018

Physics Beyond Colliders at CERN- Beyond the Standard Model Working Group Report (2019) **arxiv: 1901.09966**



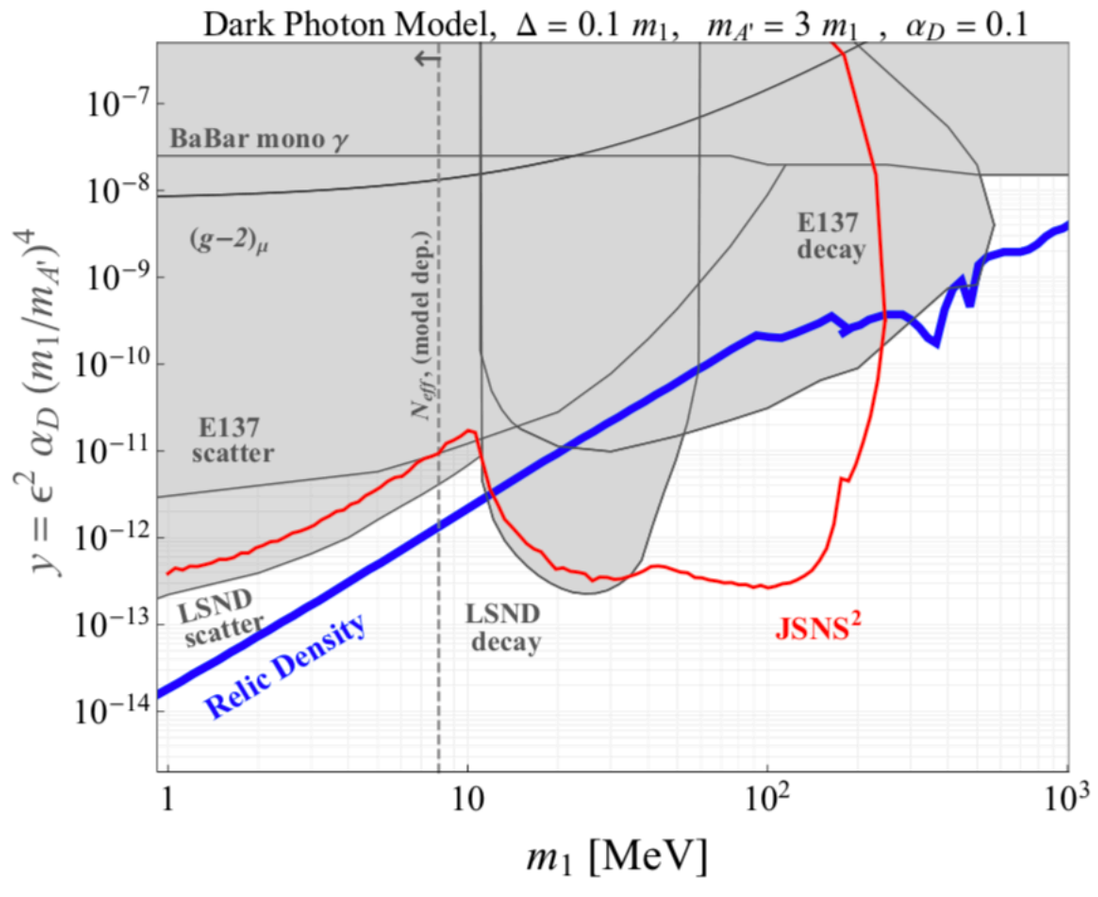
Strong sensitivity below 10 MeV

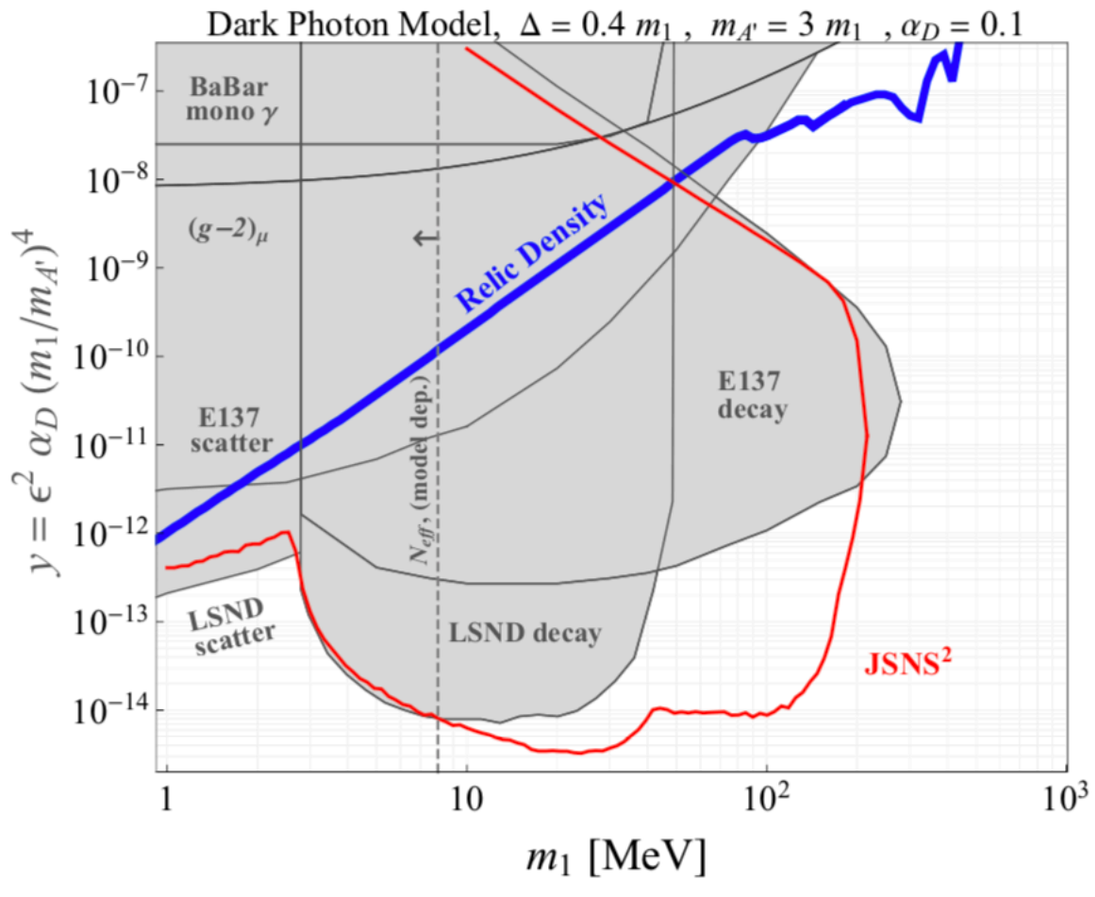
Exotic DM signatures



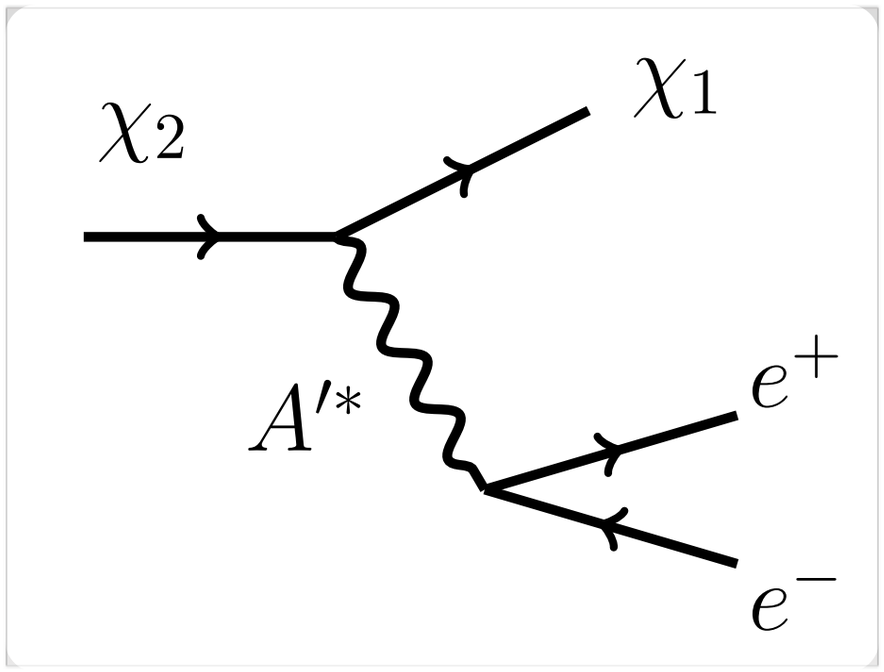
Visible decay of the heavier DM particle

Jordan,Kahn,Krnjaic,Moschella,Spitz,2018





Exotic DM signatures



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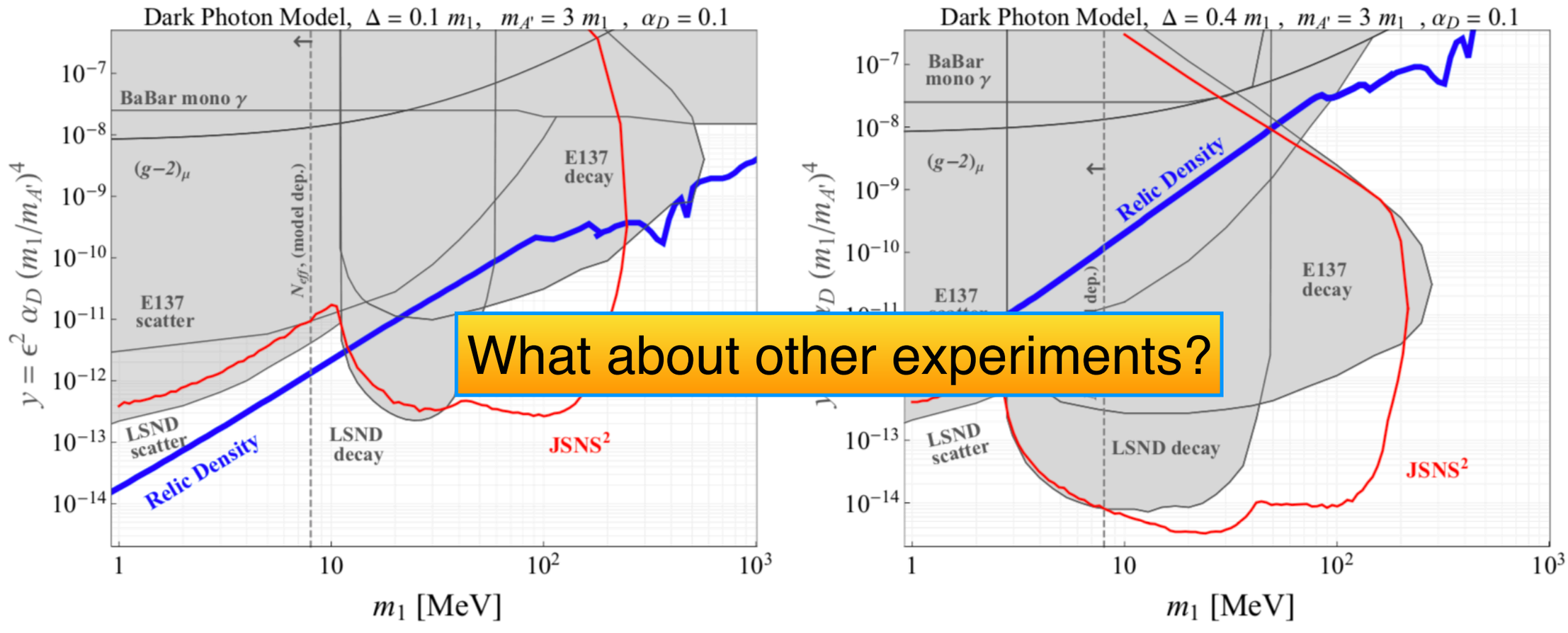

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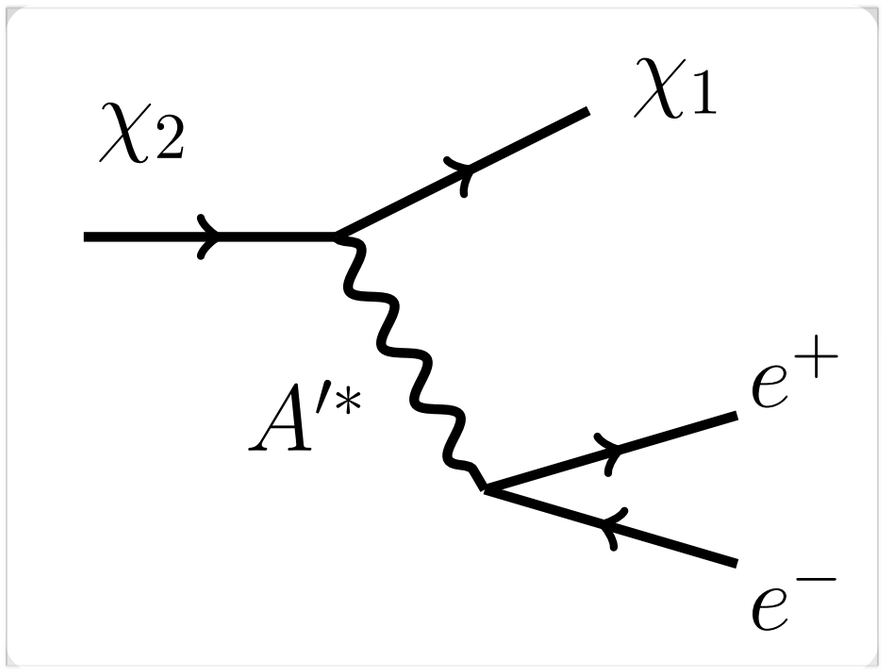

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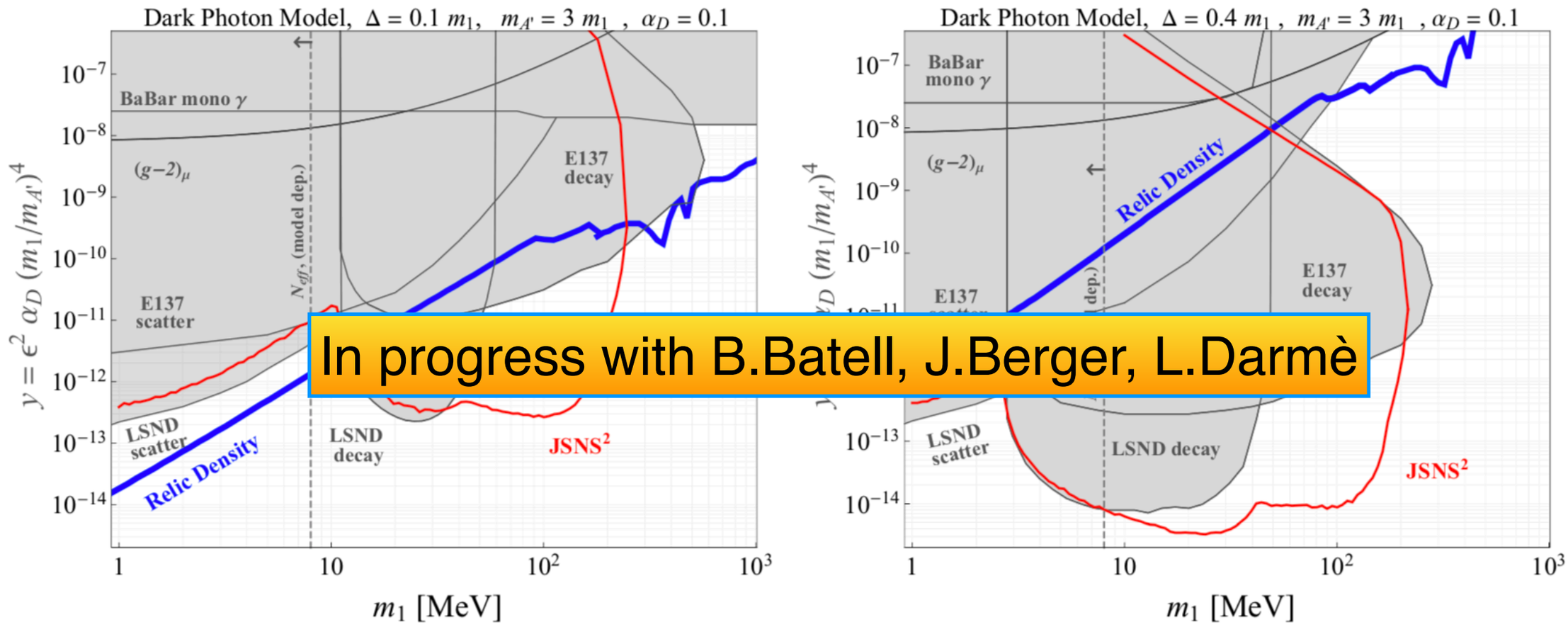
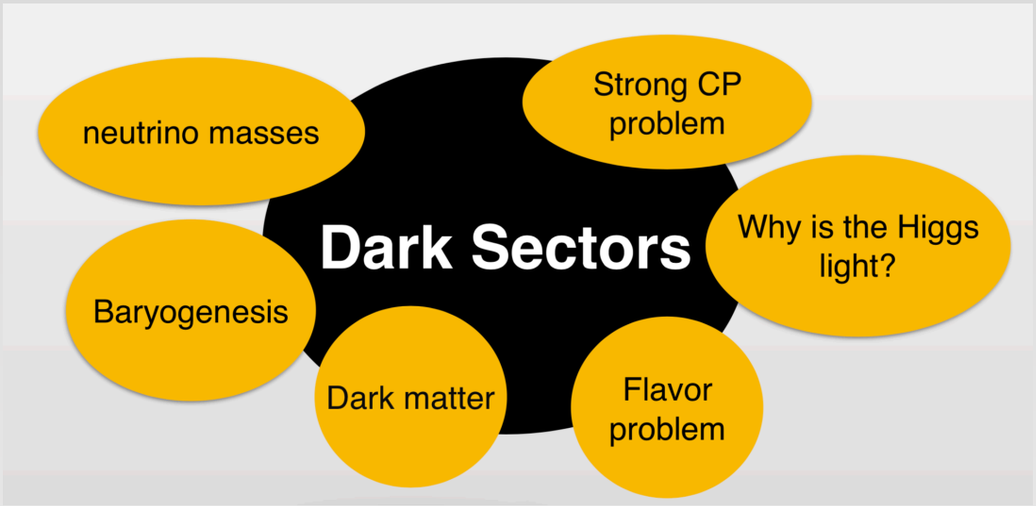
Jordan,Kahn,Krnjaic,Moschella,Spitz,2018

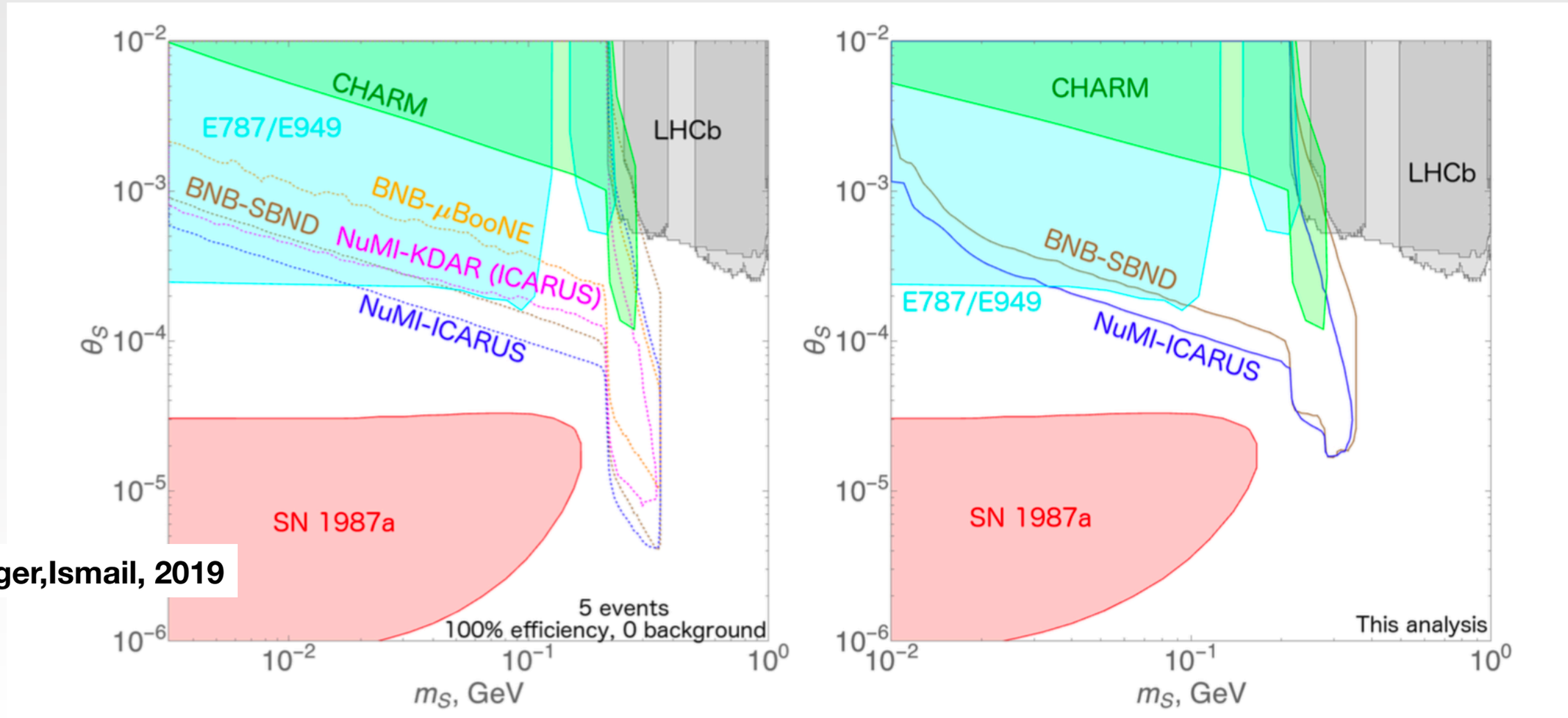


In progress with B.Batell, J.Berger, L.Darmè

A broad physics program

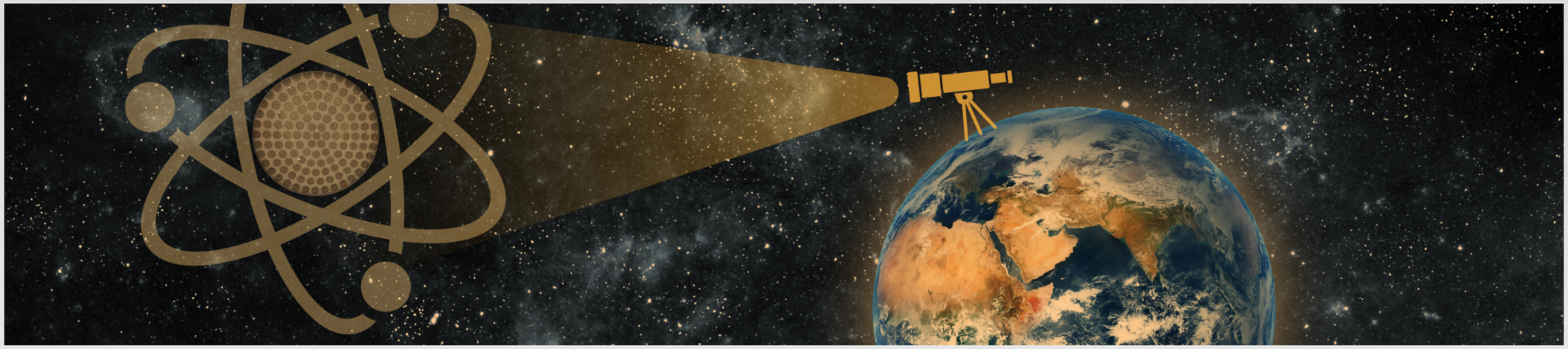


Possible connections to other longstanding open problems of the SM.



E.g. Batell,Berger,Ismail, 2019

Outlook



Neutrino fixed target experiments can play a key role in the quest for sub-GeV thermal DM.

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