BSM @ fixed target experiments

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

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Beyond Standard Model: Where do we go from here?

BSM at the intensity frontier

- **Thermal light dark matter** LDM (MeV-GeV): next to minimal particle content: DM and a mediator. Ex dark photons, B-L Z',dark Higgs…

$$\epsilon F_{\mu\nu} F^{\mu\nu}_{\rm dark} \quad J^{\mu}_{\rm SM} Z'_{\mu}$$

- **Axion like particles**

$$F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- **Relaxion**: Light particle associated to a new solution of the hierarchy problem of the electroweak scale

$$h^{\dagger} h S \qquad F_{\mu\nu} \tilde{F}^{\mu\nu}$$

[Graham, Kaplan,Rajendran, 2016]

Fixed target experiments

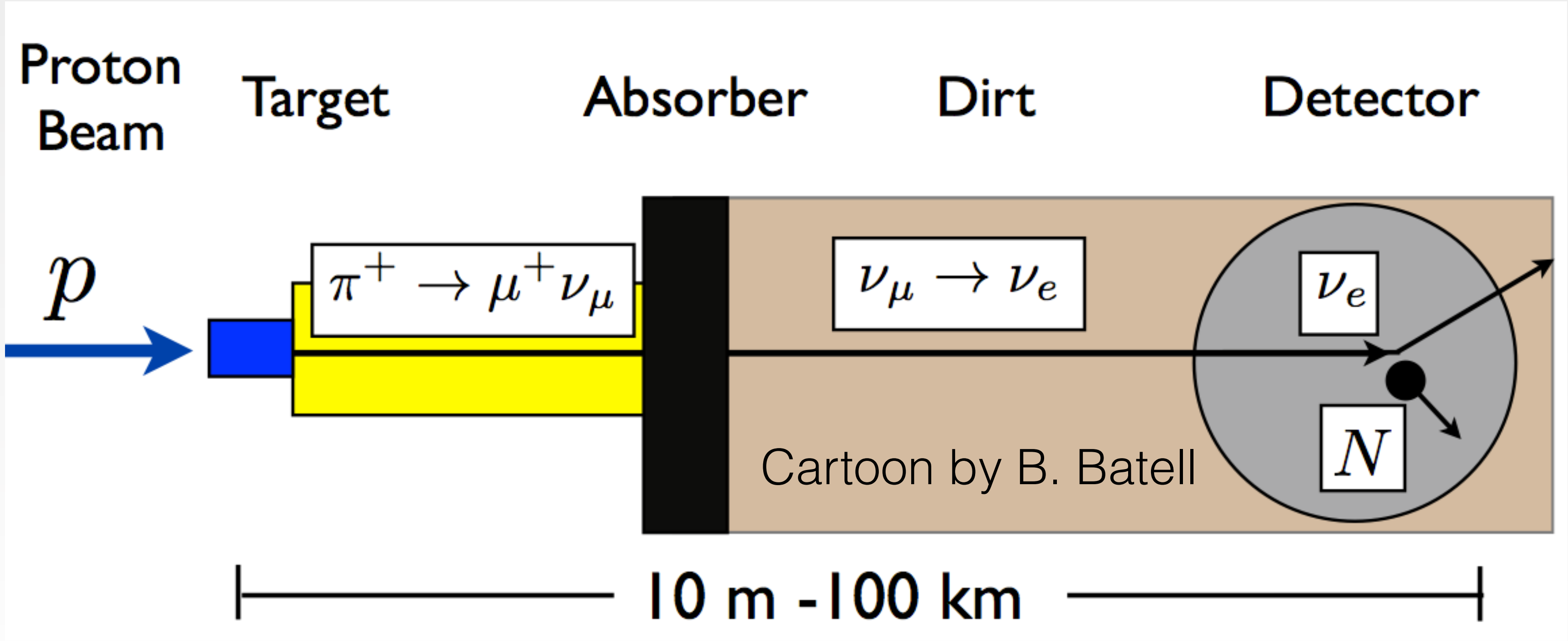
Proton beam

NA62, MiniBooNE, NOVA, MINOS..
Future: LBNF/DUNE, SHIP (?)

Electron beam

NA64,APEX,MAMI
Future:BDMX,HPS..

Example: Proton fixed target experiment for neutrino physics



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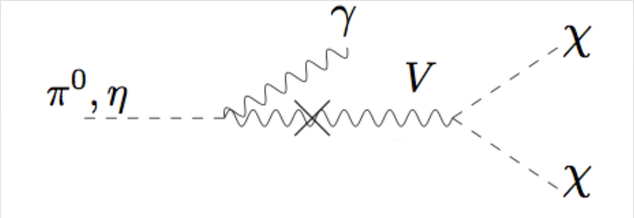
Future:BDMX,HPS..

Example: Proton fixed target experiment for neutrino physics

Production

It depends on their mass and their interaction with the visible sector



(1) Dark sector-quark interaction:

Rare meson decay, proton bremstrahlung, Drell Yan production

(proton fixed target)

(2) Dark sector-electron interaction:

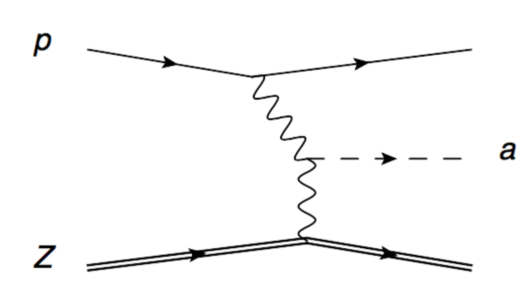
Bremsstrahlung, annihilation (positron beam)

(electron fixed target)

(3) Dark sector-photon interaction:

Primakoff production

(axion production)



Detection

Visible decay

The dark particle travel a long distance and eventually decay inside the detector. Sensitivity depends on its size and location

Invisible decay

Dark particles might scatter off electrons or nucleons inside the detector. At electron fixed target machine measure missing energy/momentum

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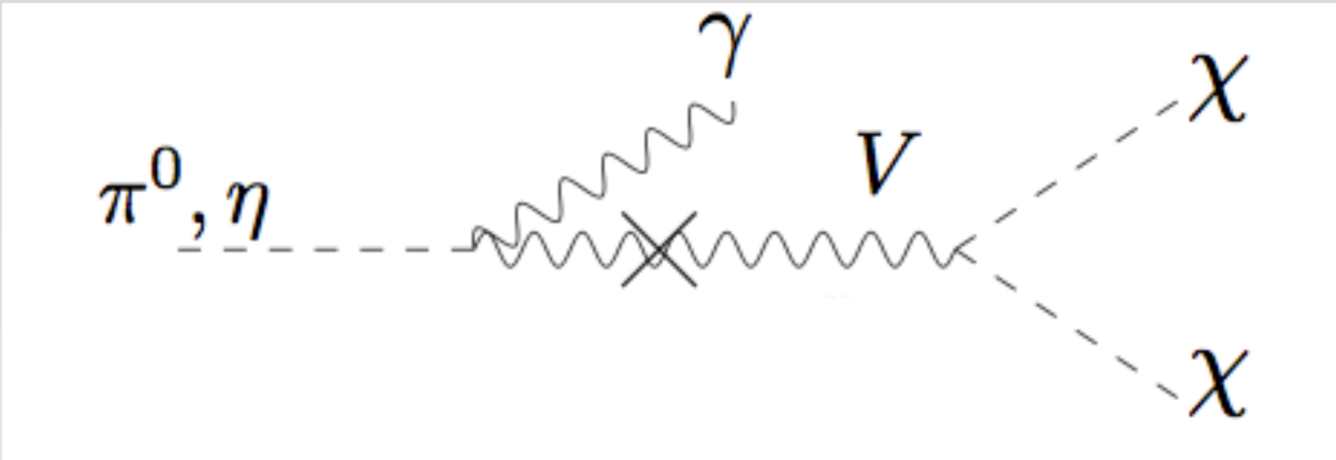
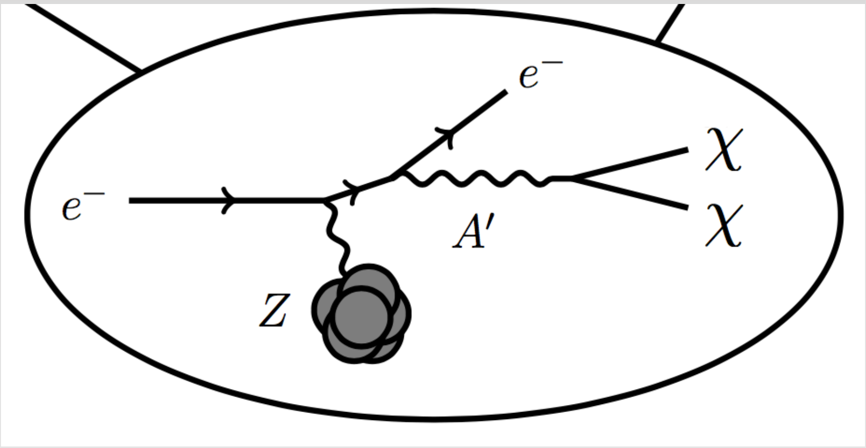
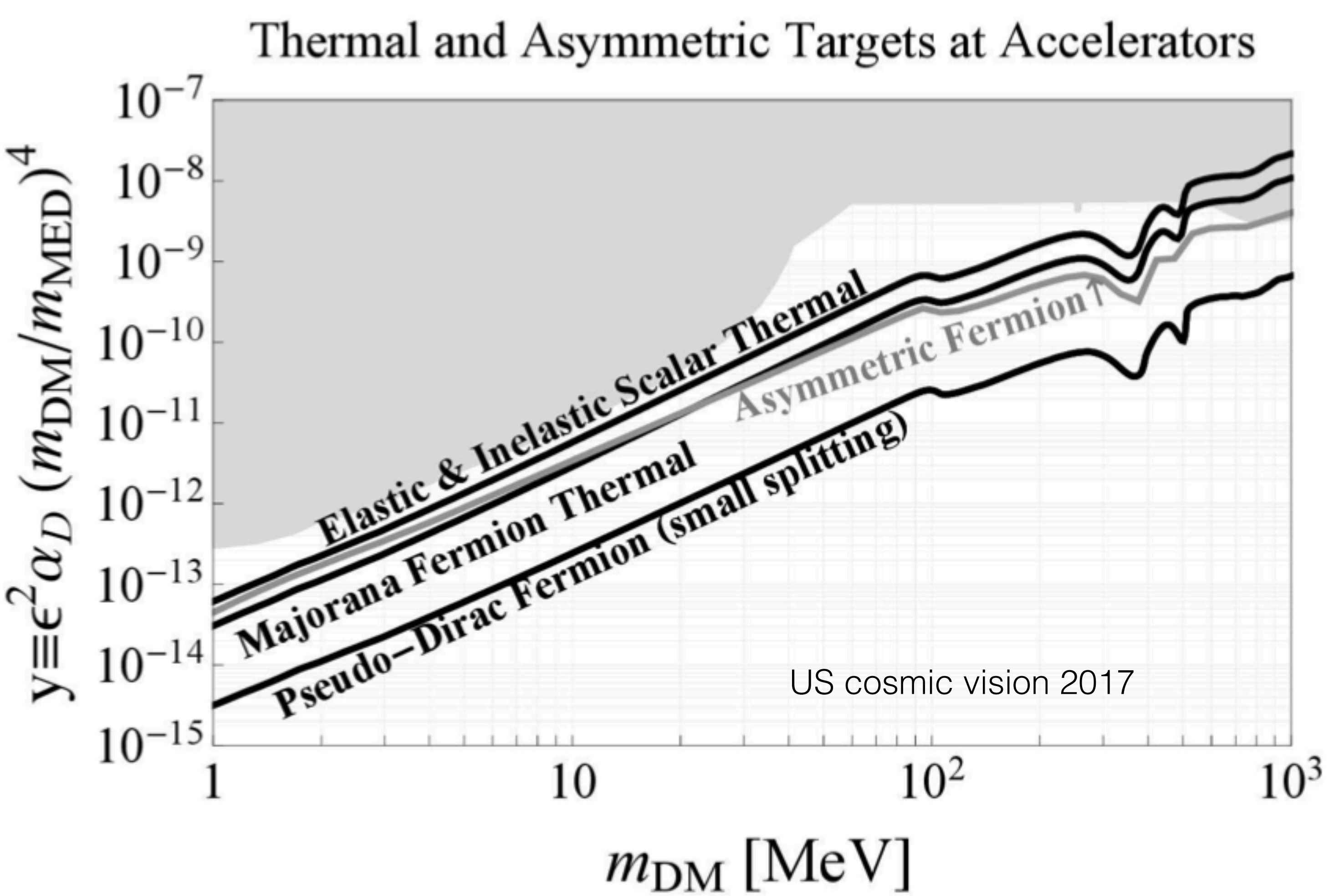
Invisible signature





If stable, It can account for the right amount of dark matter



Target for existing and future experiments

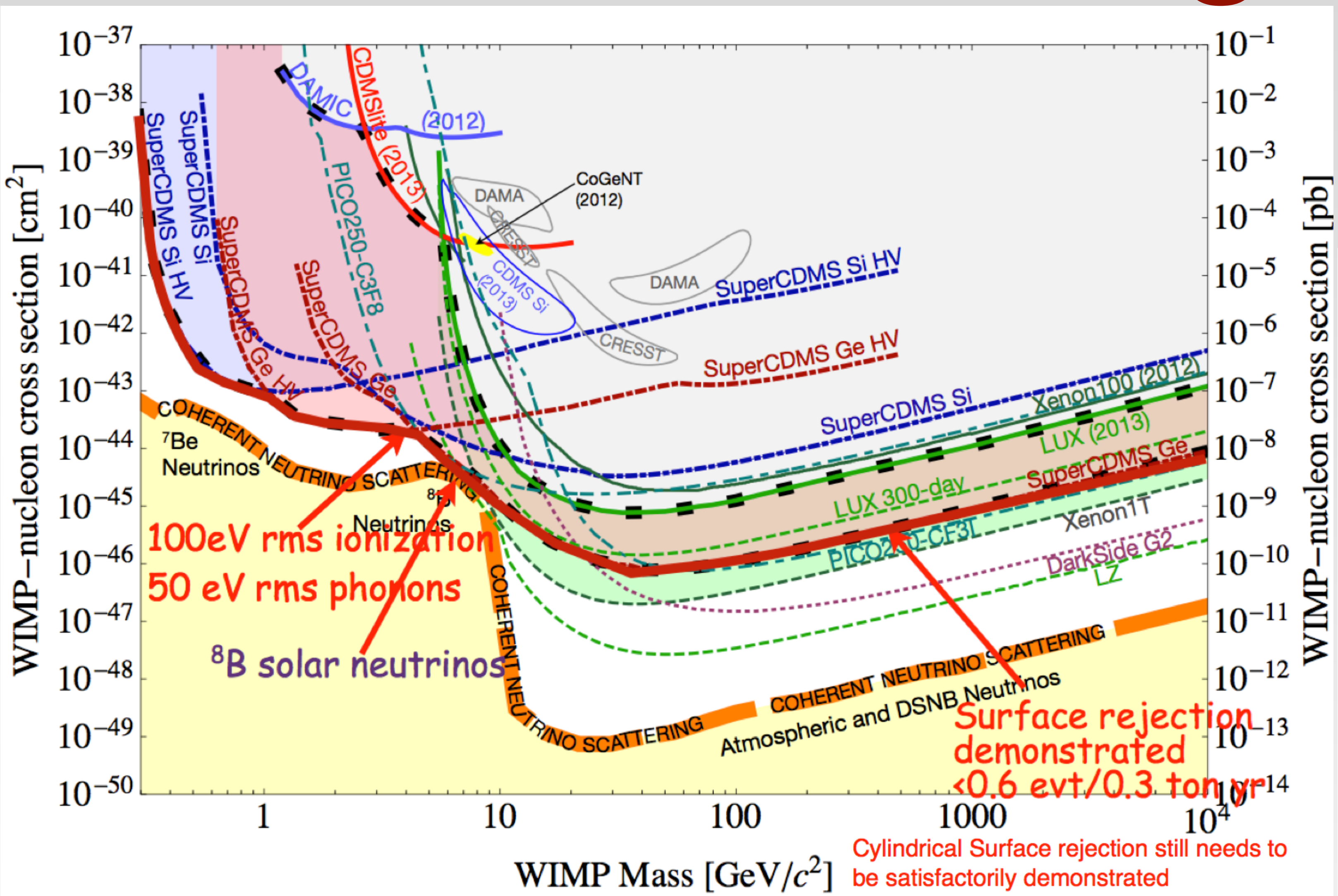
$$< \sigma v > \sim \alpha_D \epsilon^2 \frac{m_\chi^2}{m_A^2} \sim \frac{Y}{m_\chi^2}$$

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

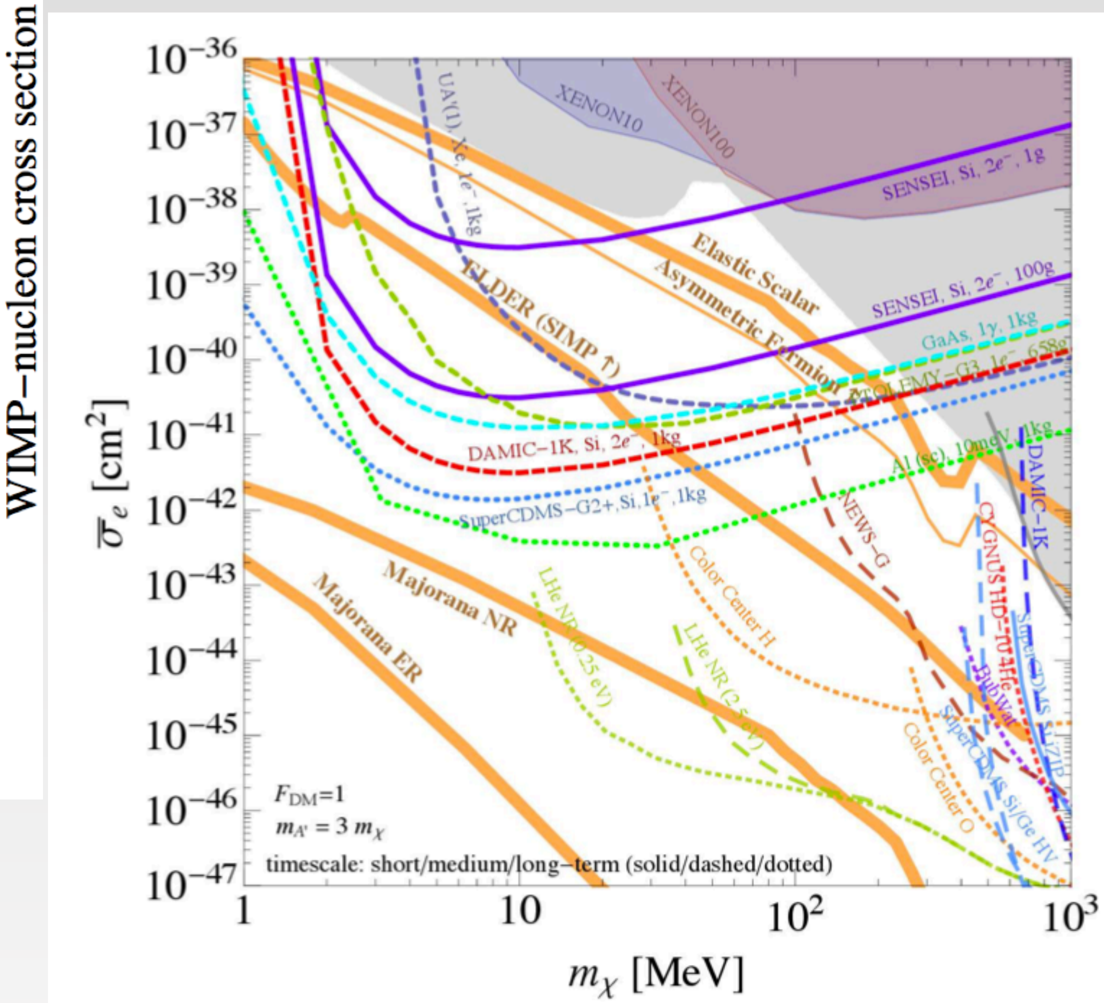
$$\alpha_D = 0.5 \ , \ m_{A'} = 3 m_\chi$$

Izaguirre, Krnjaic, Schuster, Toro,2014

Invisible signature



US cosmic vision 2017

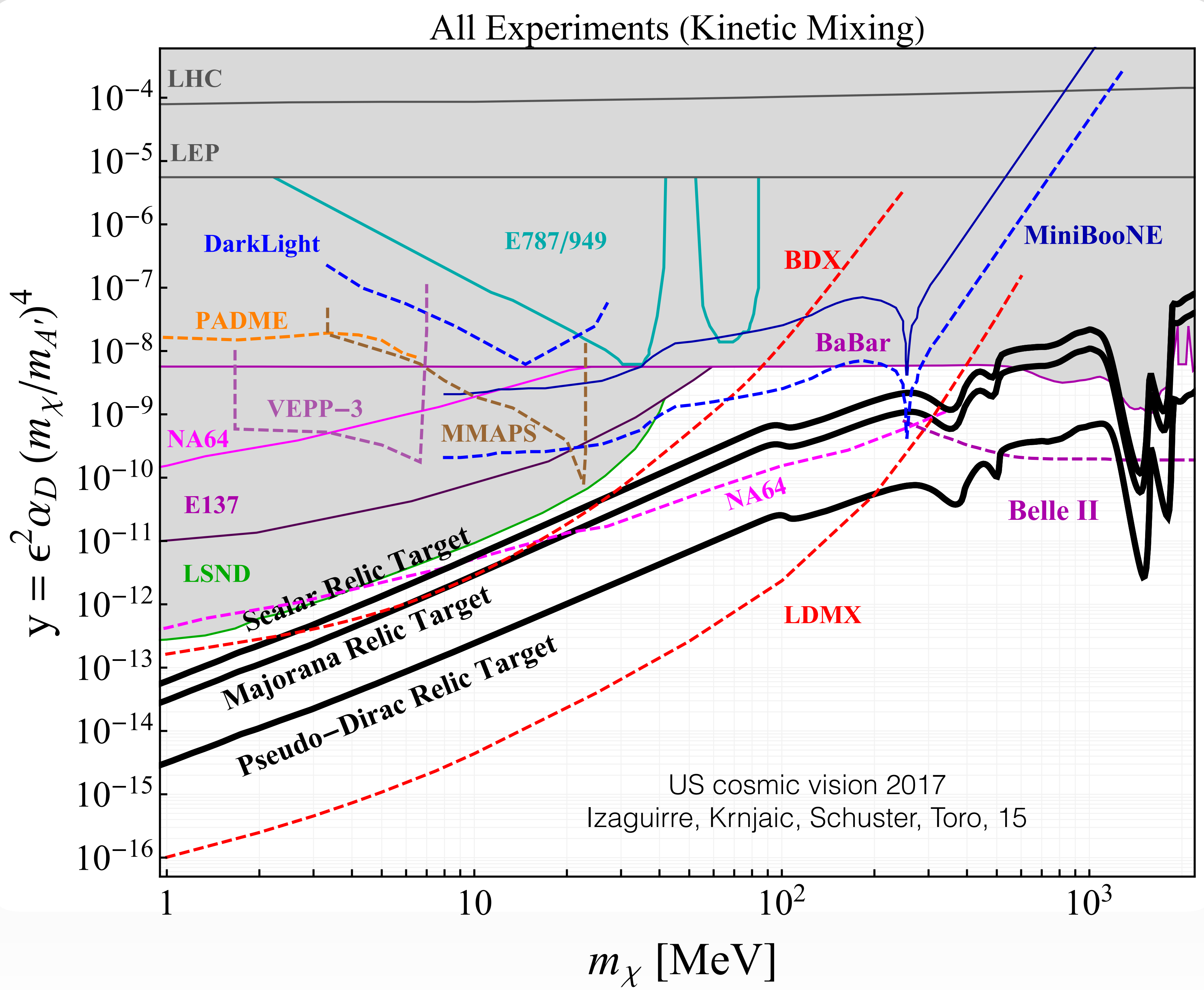


Complementarity with direct detection

See Volanski's and Kurek's talk

Accelerator based searches

Important role played by fixed target experiments



Dark photon benchmark model

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

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Dark photon invisible decay

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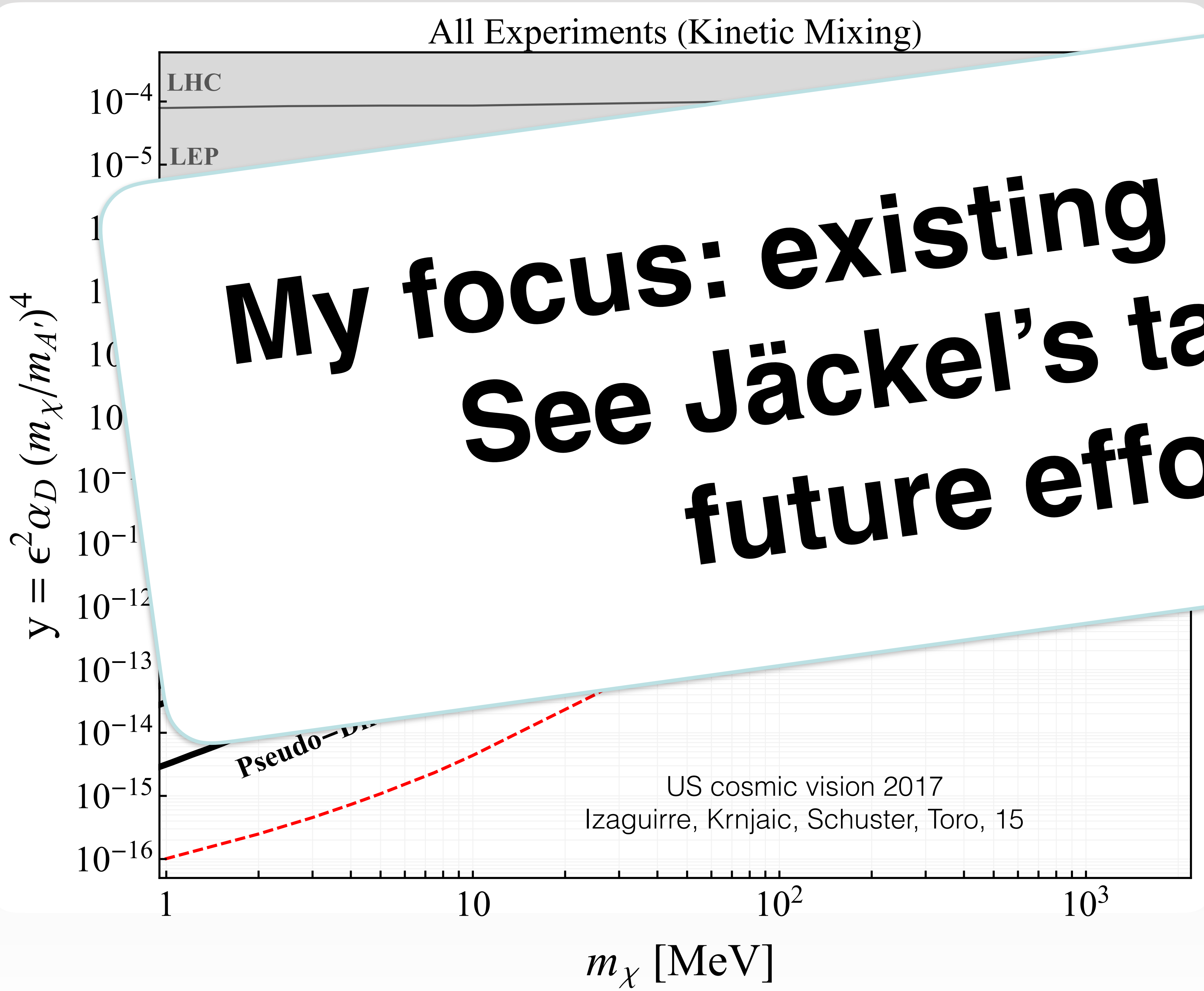
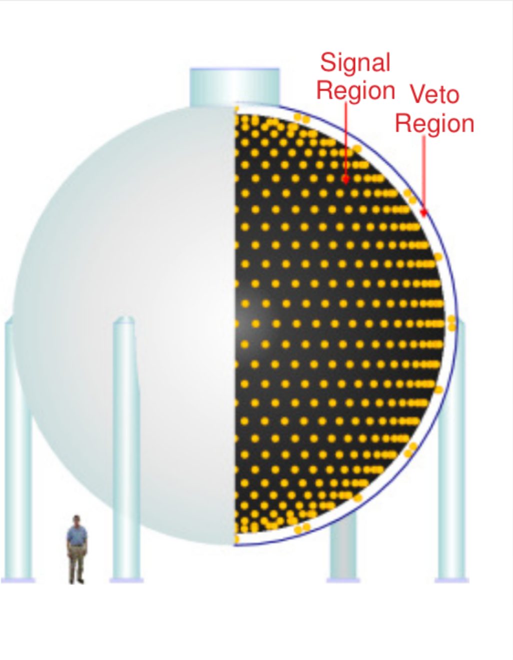


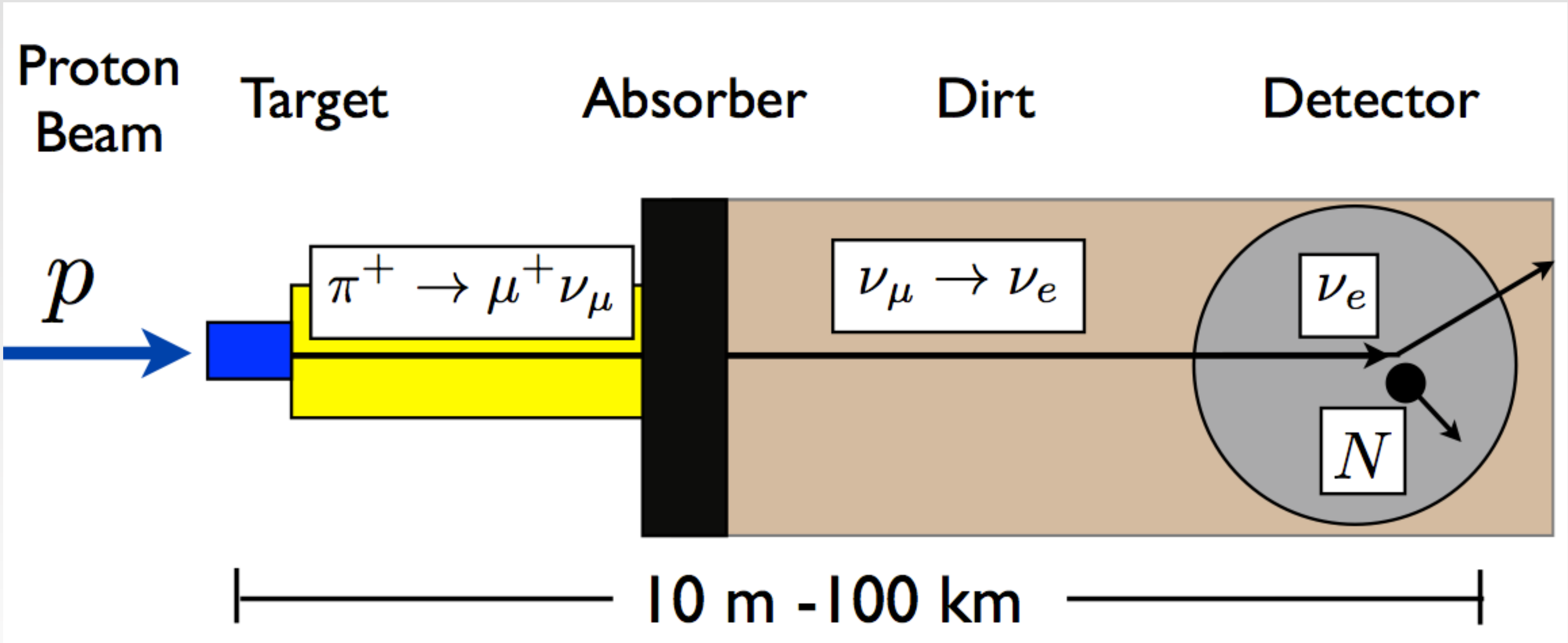
My focus: existing facilities.
See Jäckel's talk for future effort

LDM @proton fixed target experiments



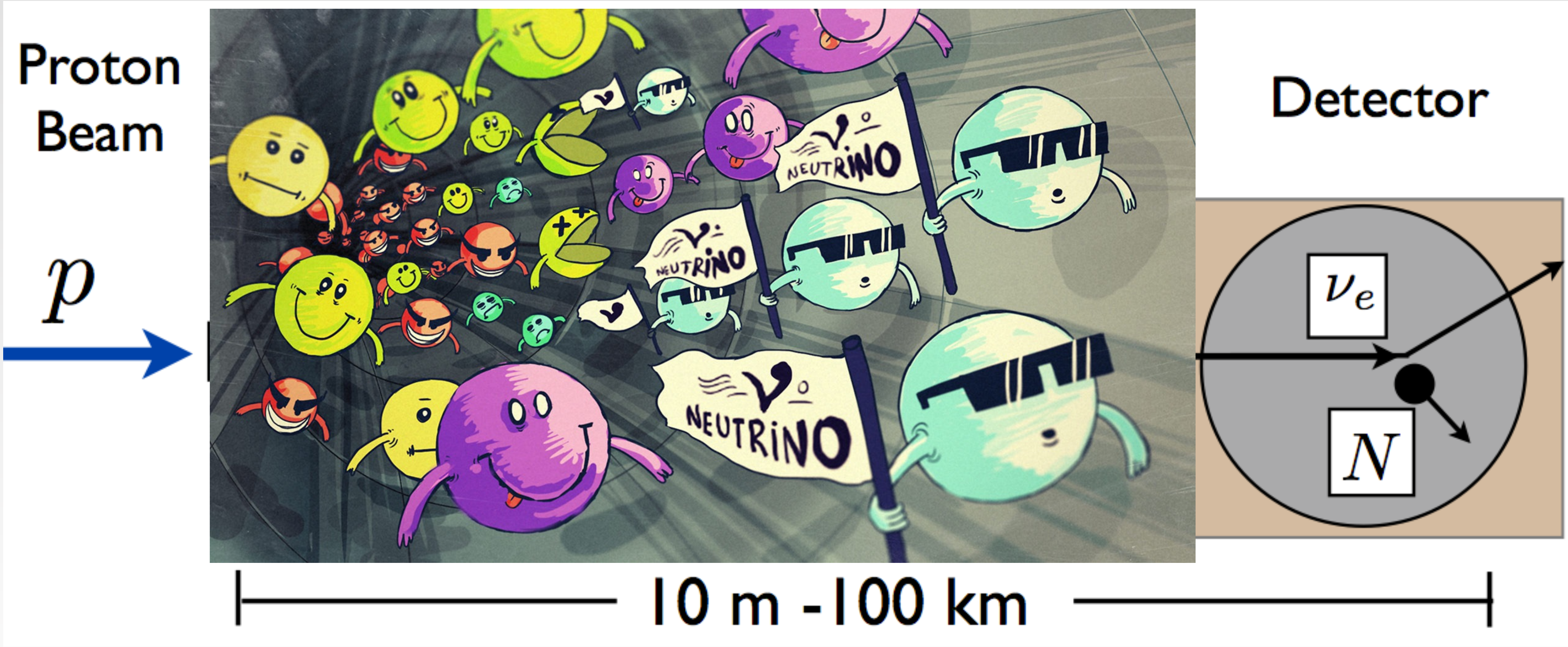
Original goal

measuring neutrino masses and mixings

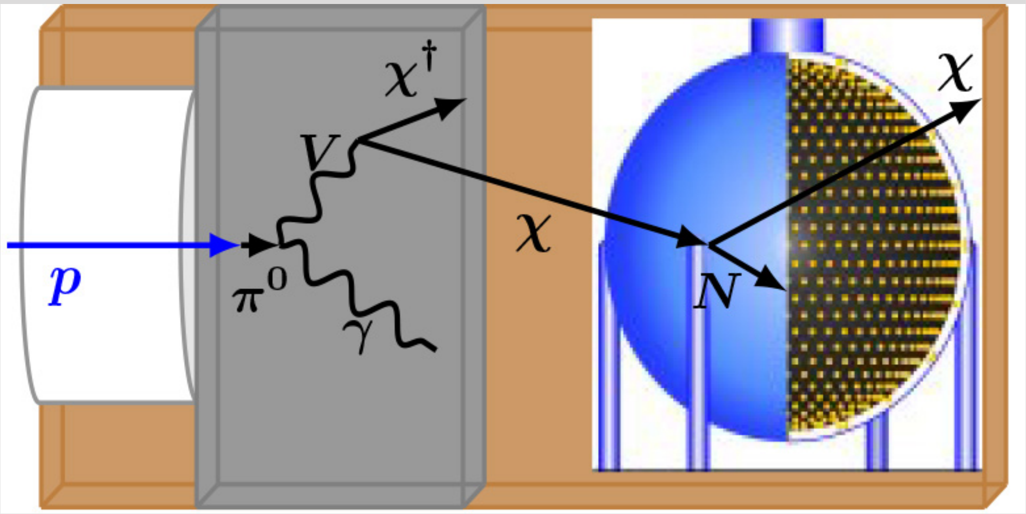


New complementarity goal

Dark matter discovery [Batell, Pospelov Ritz, 2009]



How do we detect DM ?



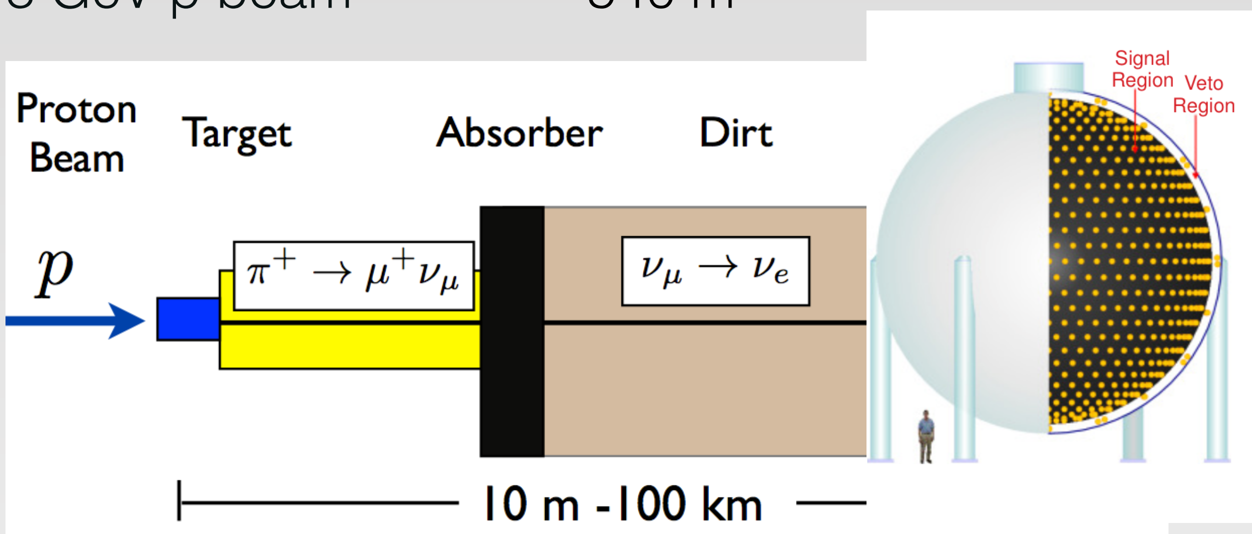
Two observables

- DM-nucleus scattering
- DM-electron scattering

Main challenge: suppression of neutrino background.

DM search @ MiniBooNE

8 GeV p beam 540 m



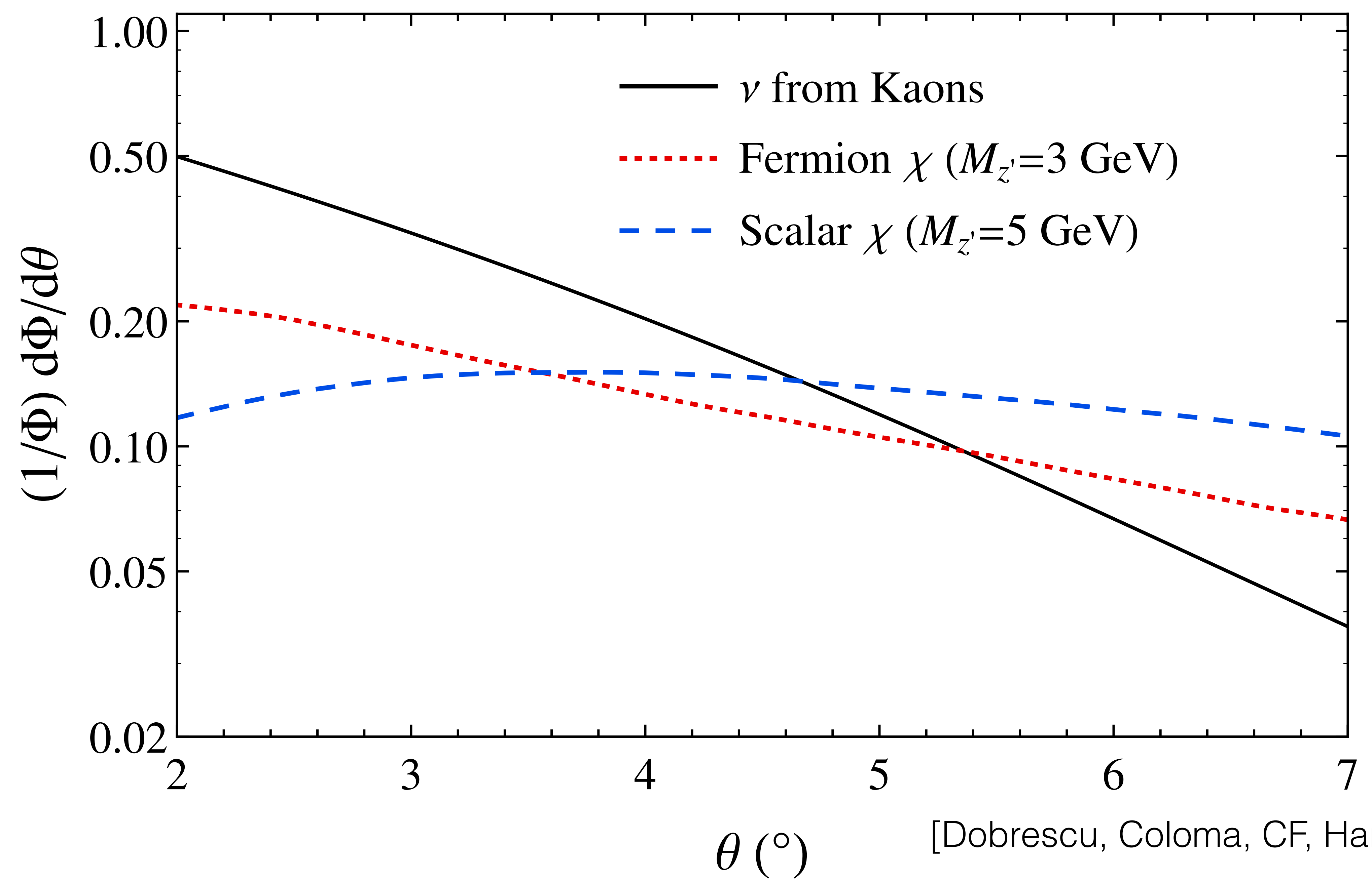
MiniBooNE: 800 tons detector

- LDM analysis in beam dump mode [A.A. Aguilar-Arevalo et al. 2017 & 2018]
- Constraints for sub-GeV vector mediator (not reaching the thermal line)

LDM program calls for a dedicated run to suppress the neutrino background ? Can we improve MiniBooNE reach using existing facilities?

Off-axis detectors for DM

Difference angular distribution of DM and neutrino flux

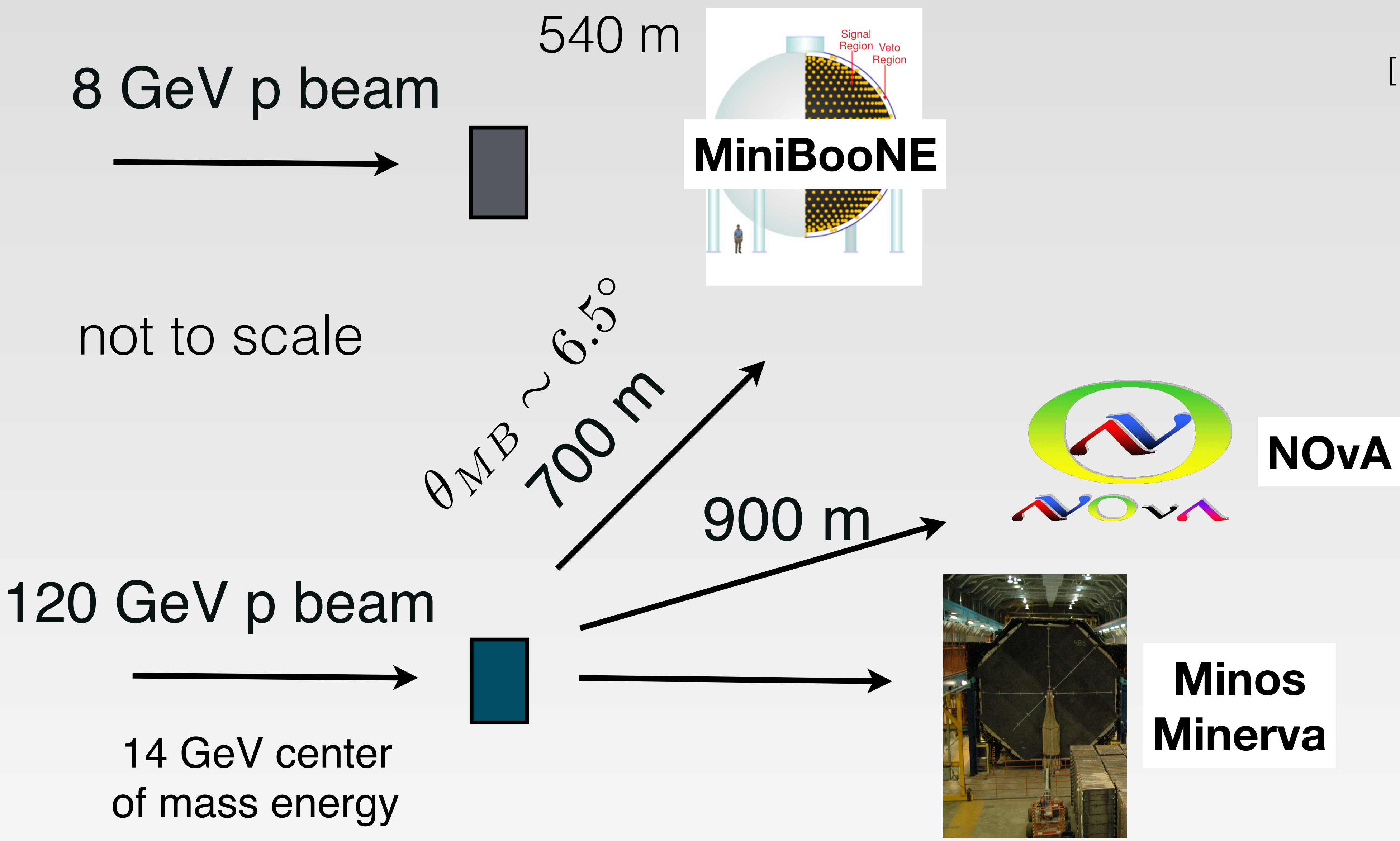


[Dobrescu, Coloma, CF, Harnik 2015]

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)

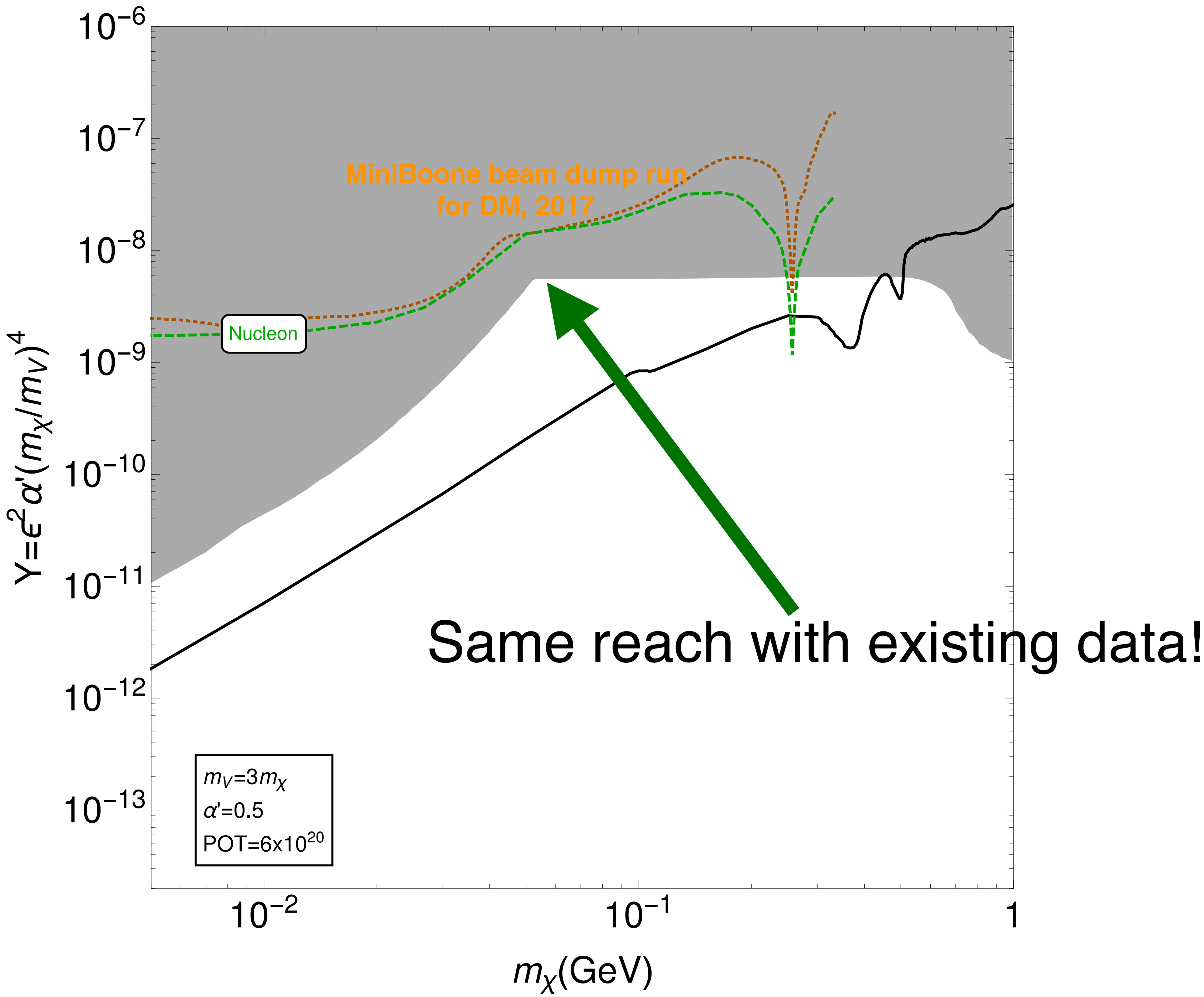
[Dobrescu, CF, 2014]
[Dobrescu, Coloma, CF, Harnik, 2015]
[CF , 2017]
[DeNeverville,CF, 2018]



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

DM-quark scattering in MiniBooNE

Larger neutrino bkg: going very off axis helps

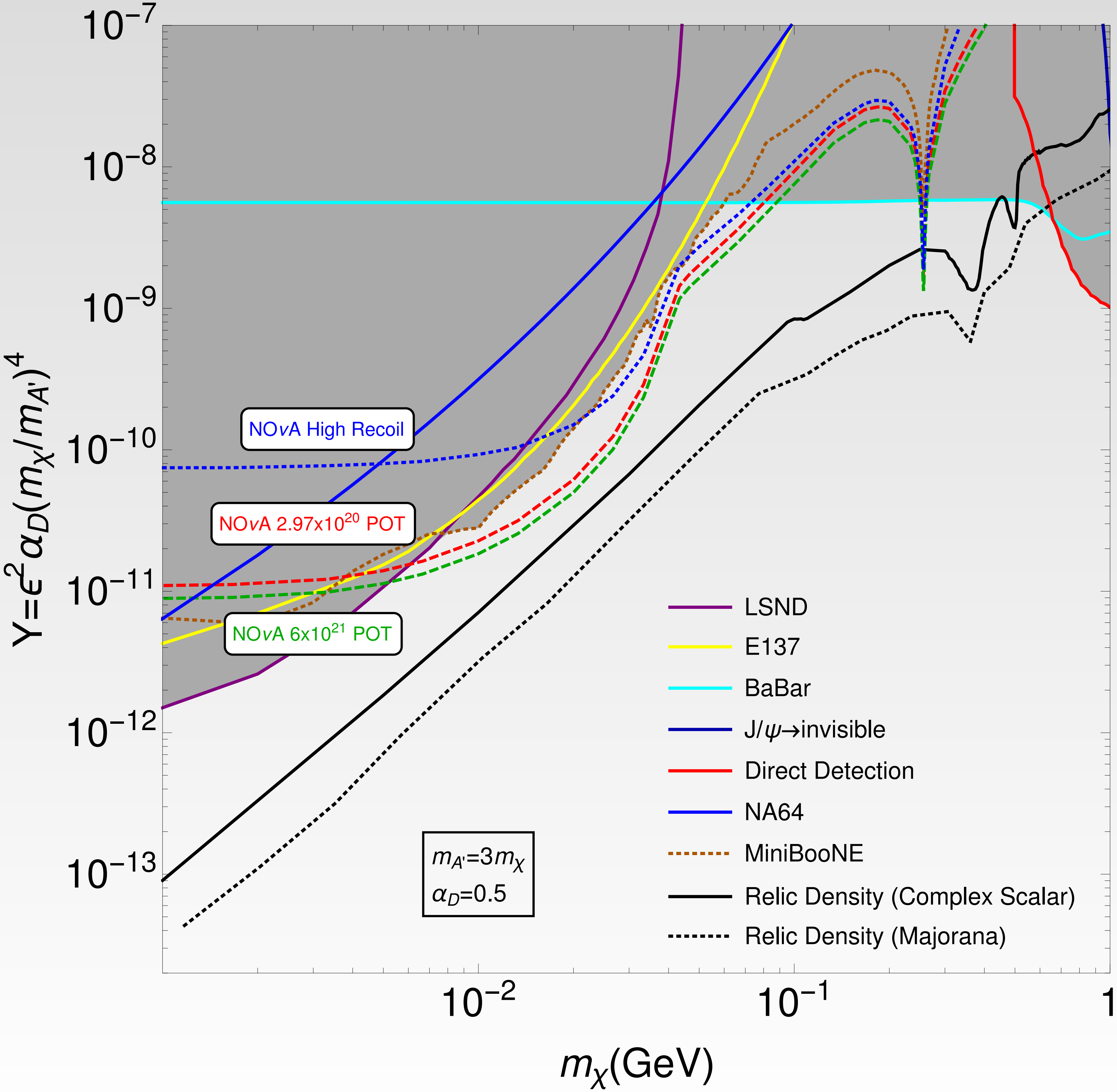


[DeNeverville,CF, in progress] [CF,2017]

NOvA as a DM detector

[DeNeverville,CF, 2018]

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



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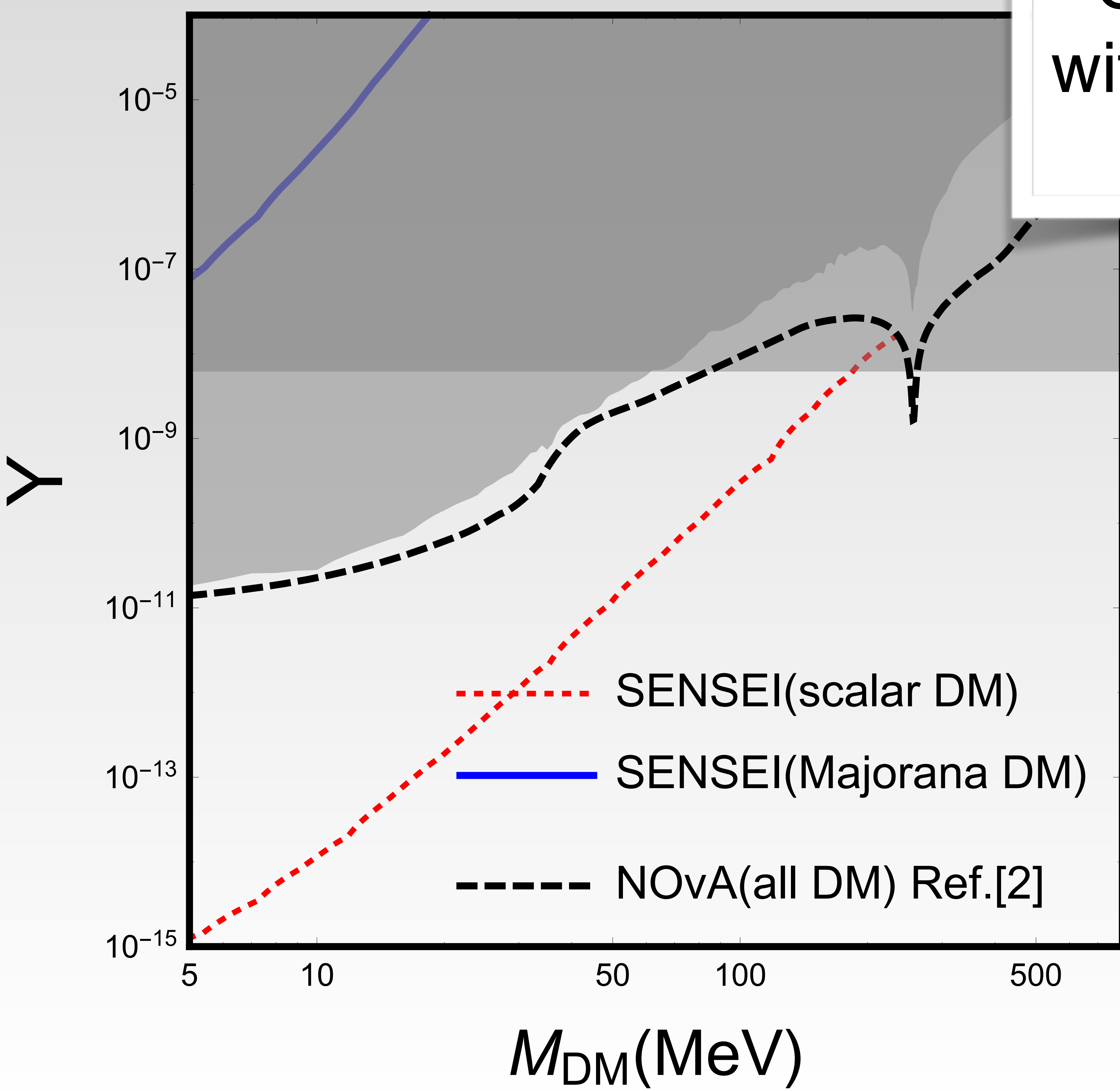
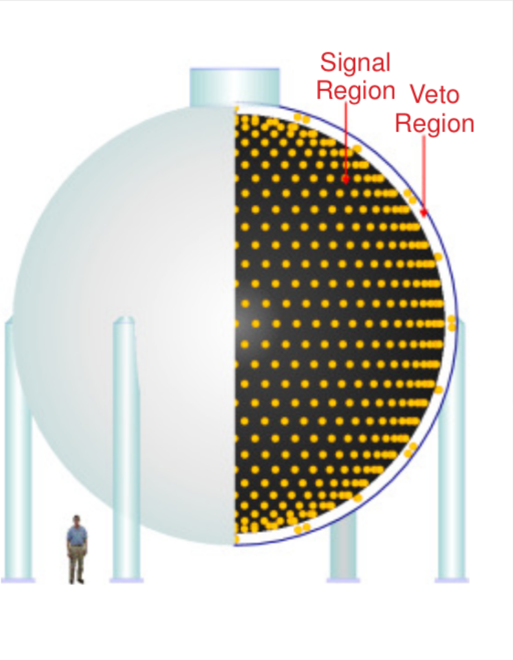


Complementarity with direct detection

LDM @ electron fixed target experiments



Invisible signature: electron FT

Advantage over proton machine: it can look not only for (electron) DM scattering events inside the detector (THICK TARGET),

but also perform a missing energy/momentum analysis (THIN TARGET)

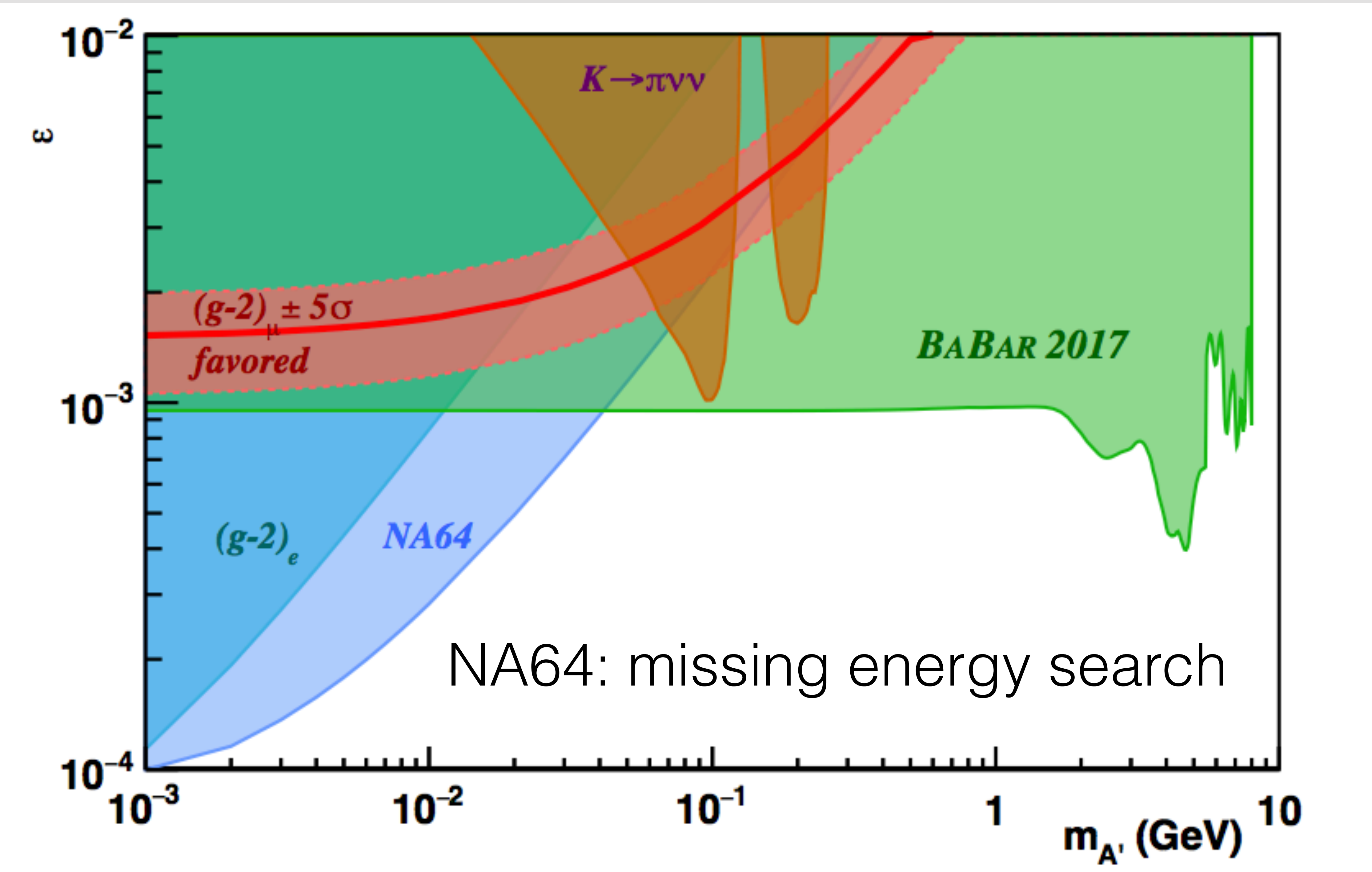
Missing momentum experiment (thin target): $N \propto \epsilon^2$

Beam dump experiment (thick target): $N \propto \epsilon^4$

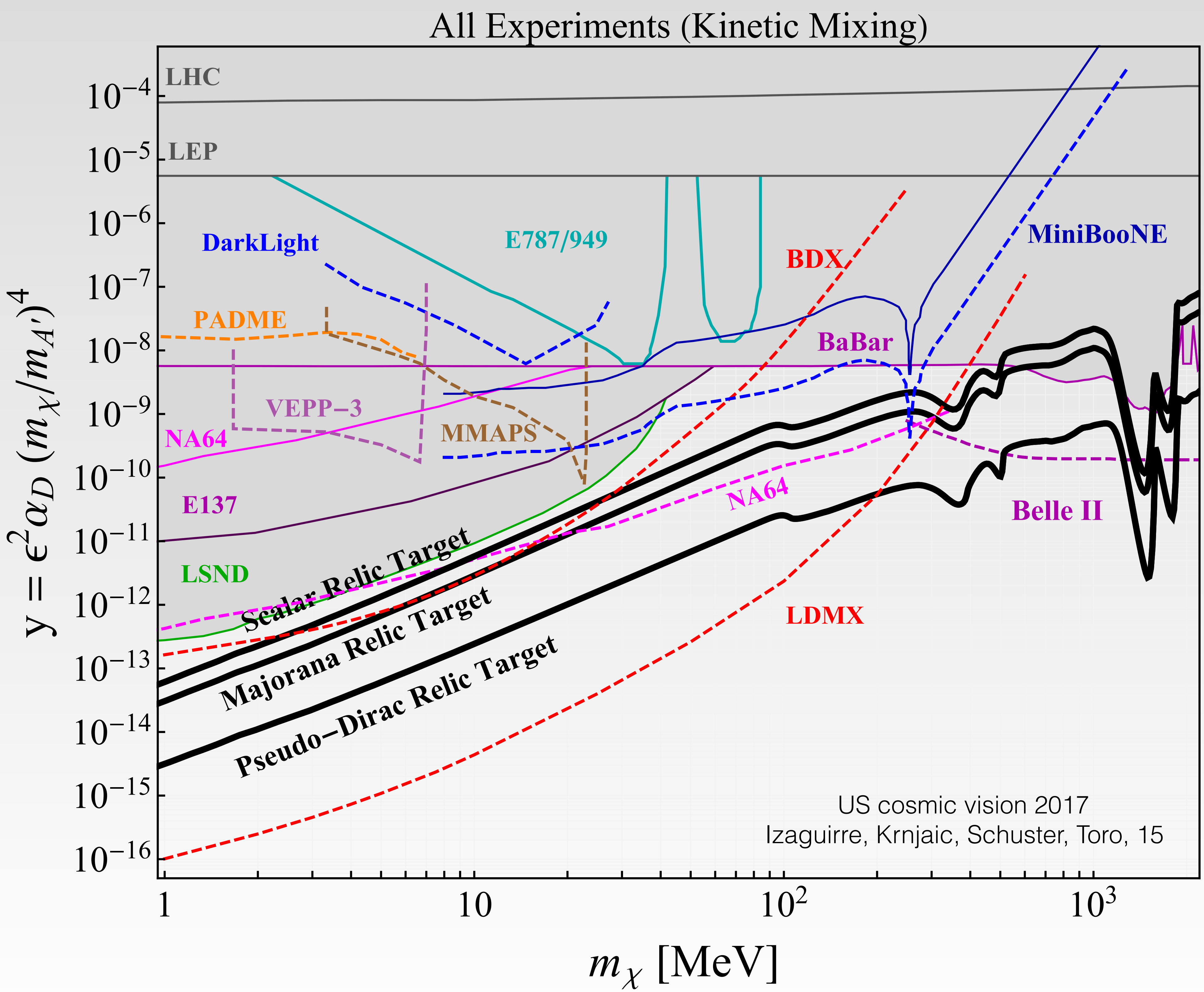
Invisible signature: electron FT

NA64: missing energy search @ CERN

fully hermetic detector



Missing Momentum Technique



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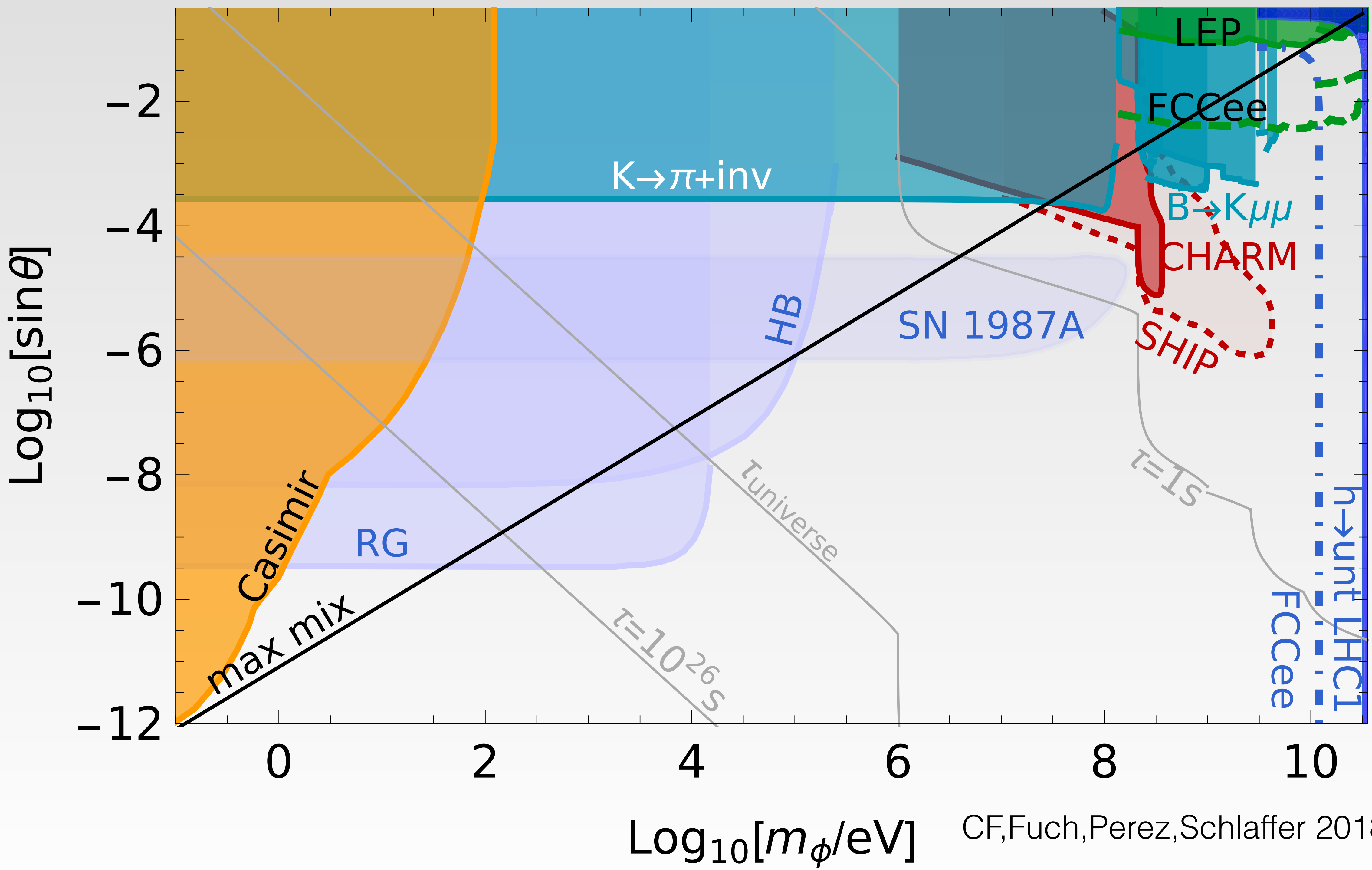
[Graham, Kaplan,Rajendran, 2016]

MeV-GeV relaxion

Relaxion-Higgs mixing a generic feature

[Flacke,CF, Fuchs,Gupta,Perez 2016} [Choi,Im,2016}

Higgs portal probes



CF,Fuch,Perez,Schlaffer 2018

[Graham, Kaplan,Rajendran, 2016]

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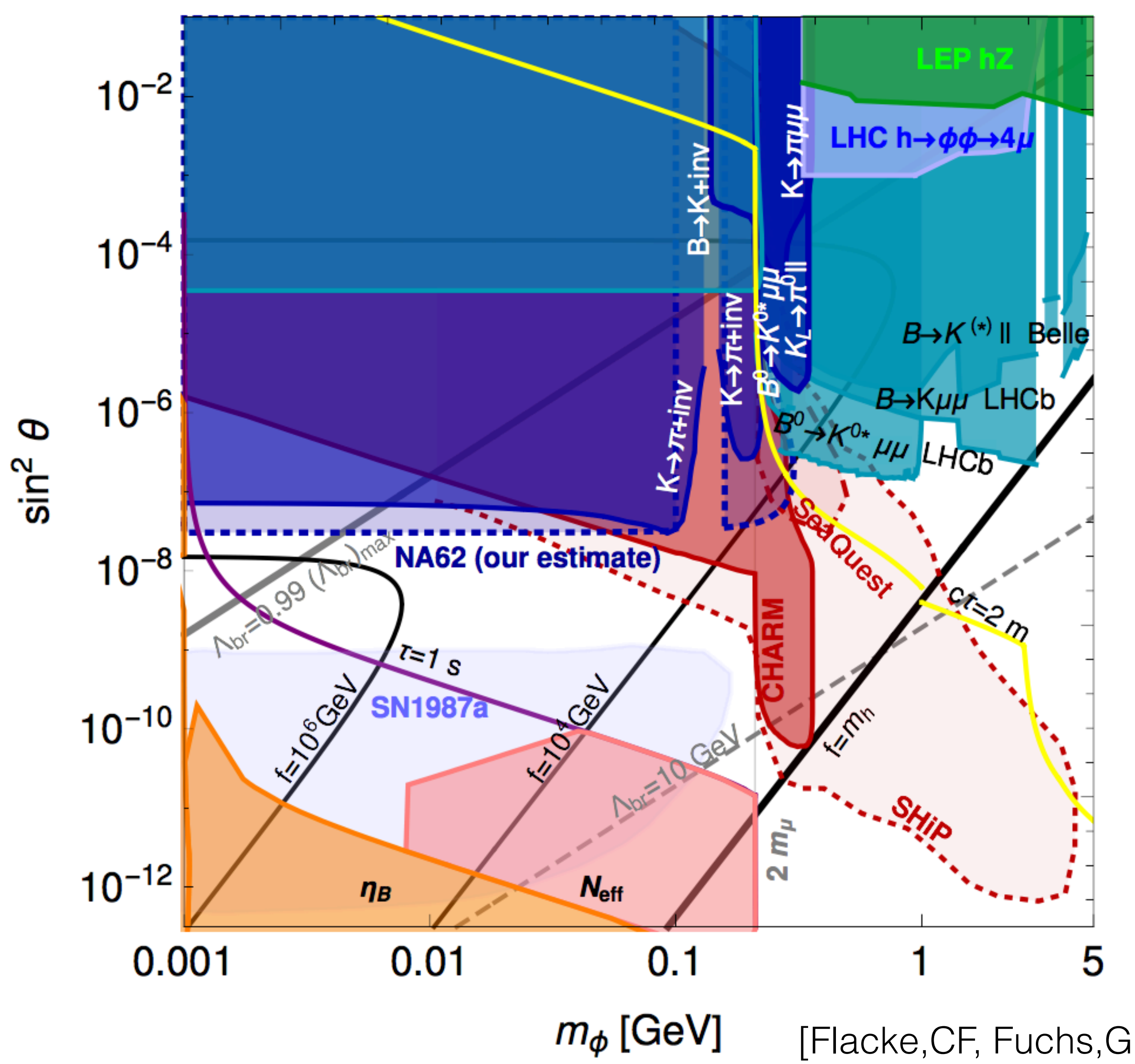

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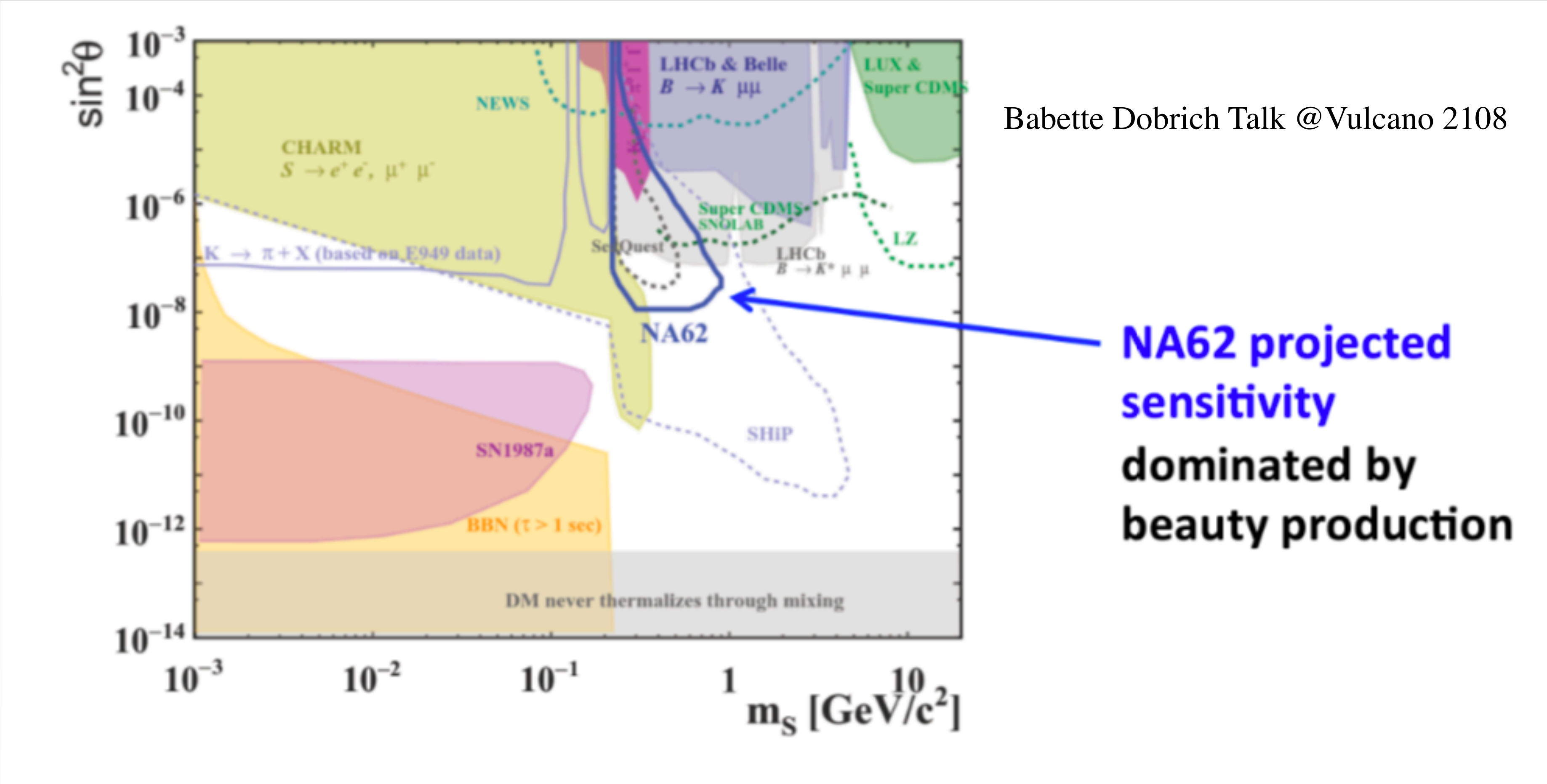
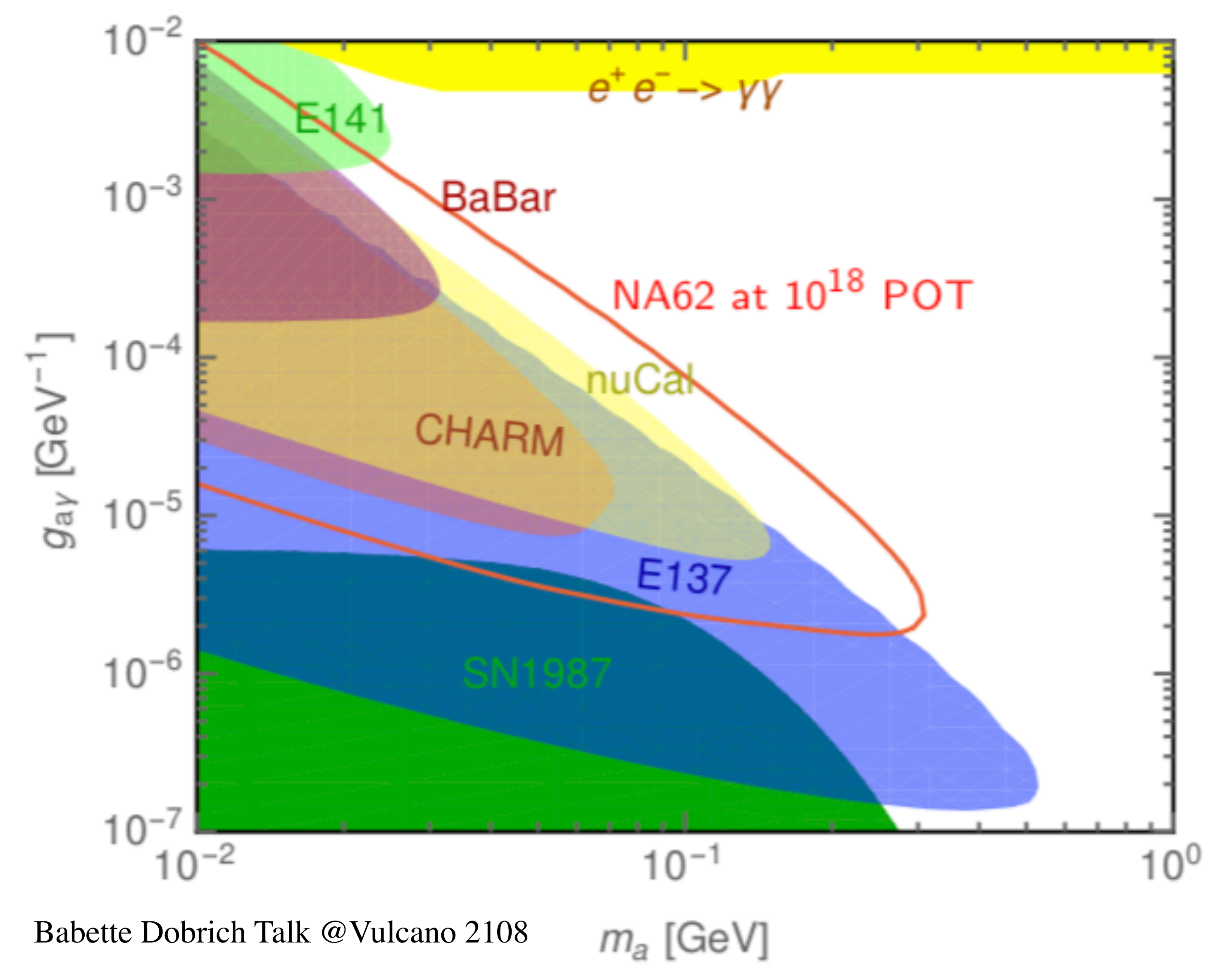


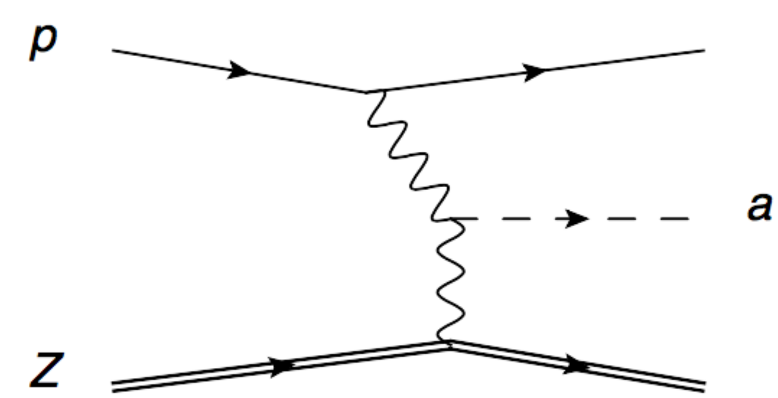
Among present facilities SeaQuest @ Fermilab and NA62 @ CERN can already explore interesting “ relaxion” regions

Diphotons @fixed target



Babette Dobrich Talk @Vulcano 2108

Axion like particles

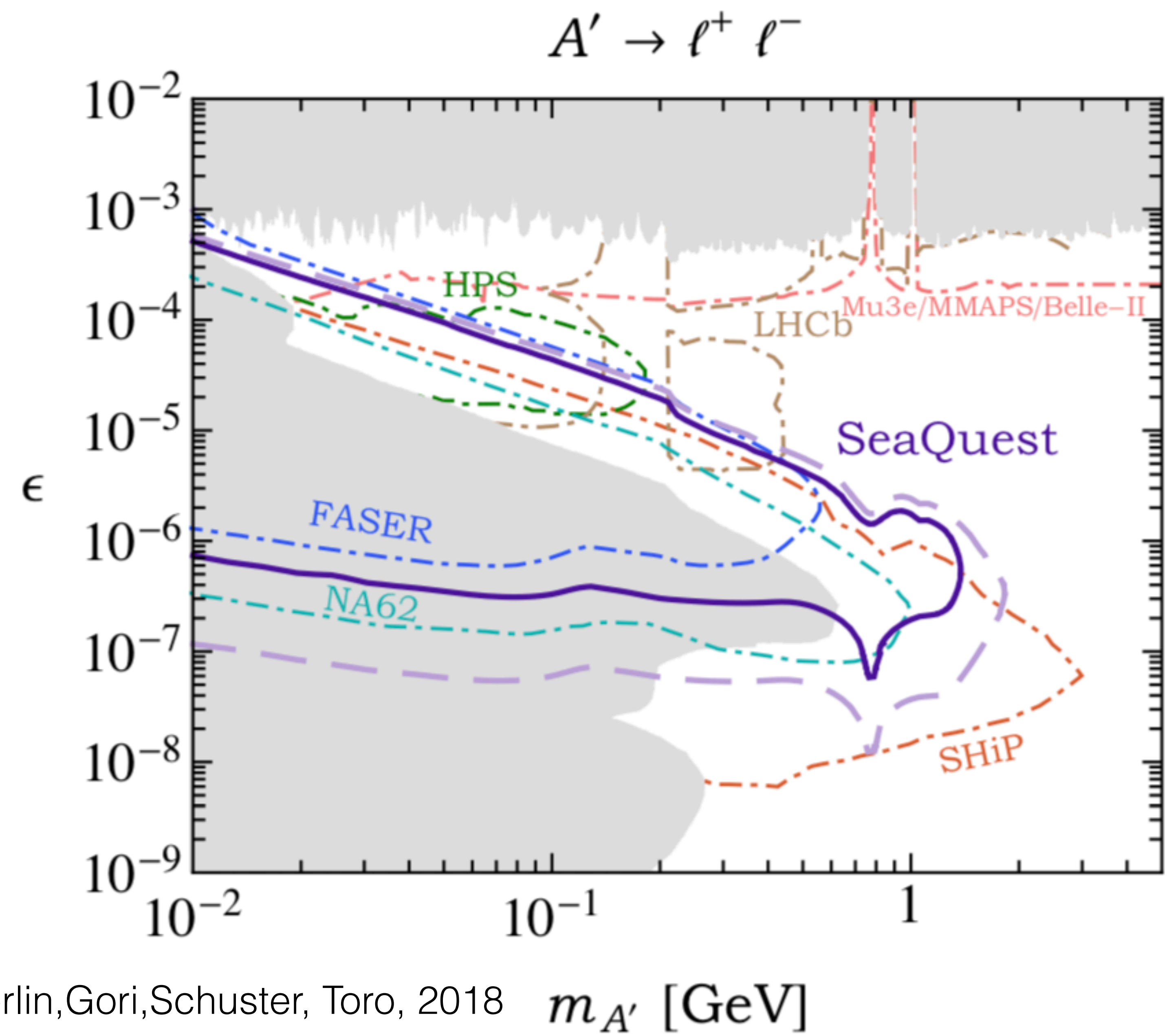


projection based on Primakov production and 0 background

Displaced decay inside the detector

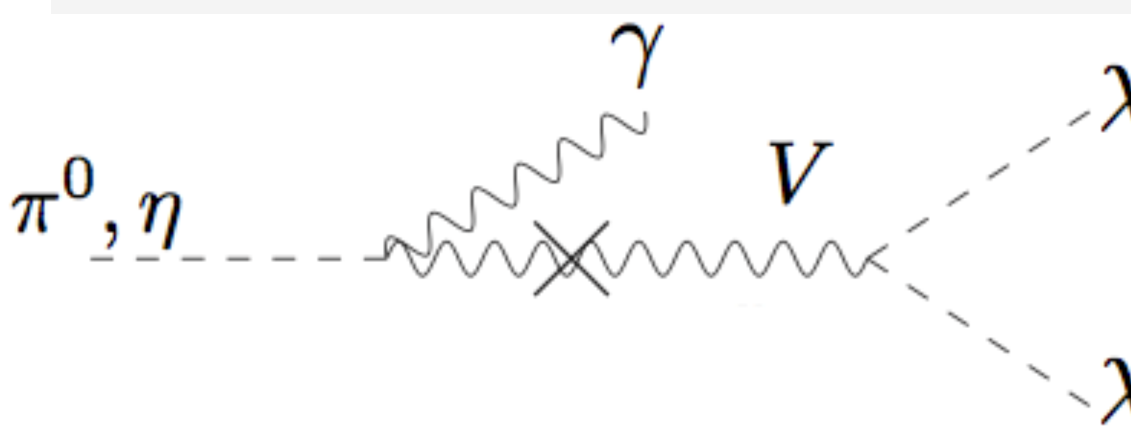
$$a \to \gamma\gamma$$

Visible decays



Berlin,Gori,Schuster, Toro, 2018

$$\epsilon F_{\mu\nu} F^{\mu\nu}_{\text{dark}}$$



SeaQuest could play a major role!
Beam energy here not so relevant

Dark photon visible signatures present and future effort

TABLE I: Summary of dark photon experiments.

Experiment	*Lab*	*Production*	*Detection*	*Vertex*	*Mass(MeV)*	*Mass Res. (MeV)*	*Beam*	*Ebeam (GeV)*	*Ibeam or Lumi*	*Machine*	*1st Run*	*Next Run*
APEX	JLab	e-brem	$\ell^+\ell^-$	no	$65 - 600$	0.5%	e^-	1.1–4.5	150 μA	CEBAF(A)	2010	2018
A1	Mainz	e-brem	e^+e^-	no	$40 - 300$	?	e^-	0.2–0.9	140 μA	MAMI	2011	–
HPS	JLab	e-brem	e^+e^-	yes	$20 - 200$	1–2	e^-	1–6	50–500 nA	CEBAF(B)	2015	2018
DarkLight	JLab	e-brem	e^+e^-	no	< 80	?	e^-	0.1	10 mA	LERF	2016	2018
MAGIX	Mainz	e-brem	e^+e^-	no	$10 - 60$	?	e^-	0.155	1 mA	MESA	2020	–
NA64	CERN	e-brem	e^+e^-	no	$1 - 50$	?	e^-	100	2×10^{11} EOT/yr	SPS	2017	2022
Super-HPS	SLAC	e-brem	vis	yes	< 500	?	e^-	$4 - 8$	1 μA	DASEL	?	?
(TBD)	Cornell	e-brem	e^+e^-	?	< 100	?	e^-	0.1-0.3	100 mA	CBETA	?	?
VEPP3	Budker	annih	invis	no	$5 - 22$	1	e^+	0.500	$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	VEPP3	2019	?
PADME	Frascati	annih	invis	no	$1 - 24$	$2 - 5$	e^+	0.550	$\leq 10^{14}\, e^+$OT/y	Linac	2018	?
MMAPS	Cornell	annih	invis	no	$20 - 78$	$1 - 6$	e^+	6.0	$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	Synchr	?	?
KLOE 2	Frascati	several	vis/invis	no	$< 1.1\,\mathrm{GeV}$	1.5	e^+e^-	0.51	$2 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	DAϕNE	2014	-
Belle II	KEK	several	vis/invis	no	$\lesssim 10\,\mathrm{GeV}$	$1 - 5$	e^+e^-	4×7	$1 \sim 10\ \mathrm{ab}^{-1}$/y	Super-KEKB	2018	-
SeaQuest	FNAL	several	$\mu^+\mu^-$	yes	$\lesssim 10\,\mathrm{GeV}$	$3 - 6\%$	p	120	10^{18} POT/y	MI	2017	2020
SHIP	CERN	several	vis	yes	$\lesssim 10\,\mathrm{GeV}$	$1 - 2$	p	400	2×10^{20} POT/5y	SPS	2026	-
LHCb	CERN	several	$\ell^+\ell^-$	yes	$\lesssim 40\,\mathrm{GeV}$	~ 4	pp	6500	$\sim 10\ \mathrm{fb}^{-1}$/y	LHC	2010	2015

US cosmic vision 2017

Conclusions

New physics can be light and weakly coupled to SM.
High energy colliders have limited sensitivity to such scenario, while fixed target experiments can probe compelling regions of the parameter space.

Many experiments are currently running and several new have been proposed

Important to make the experimental program inclusive

Conclusions

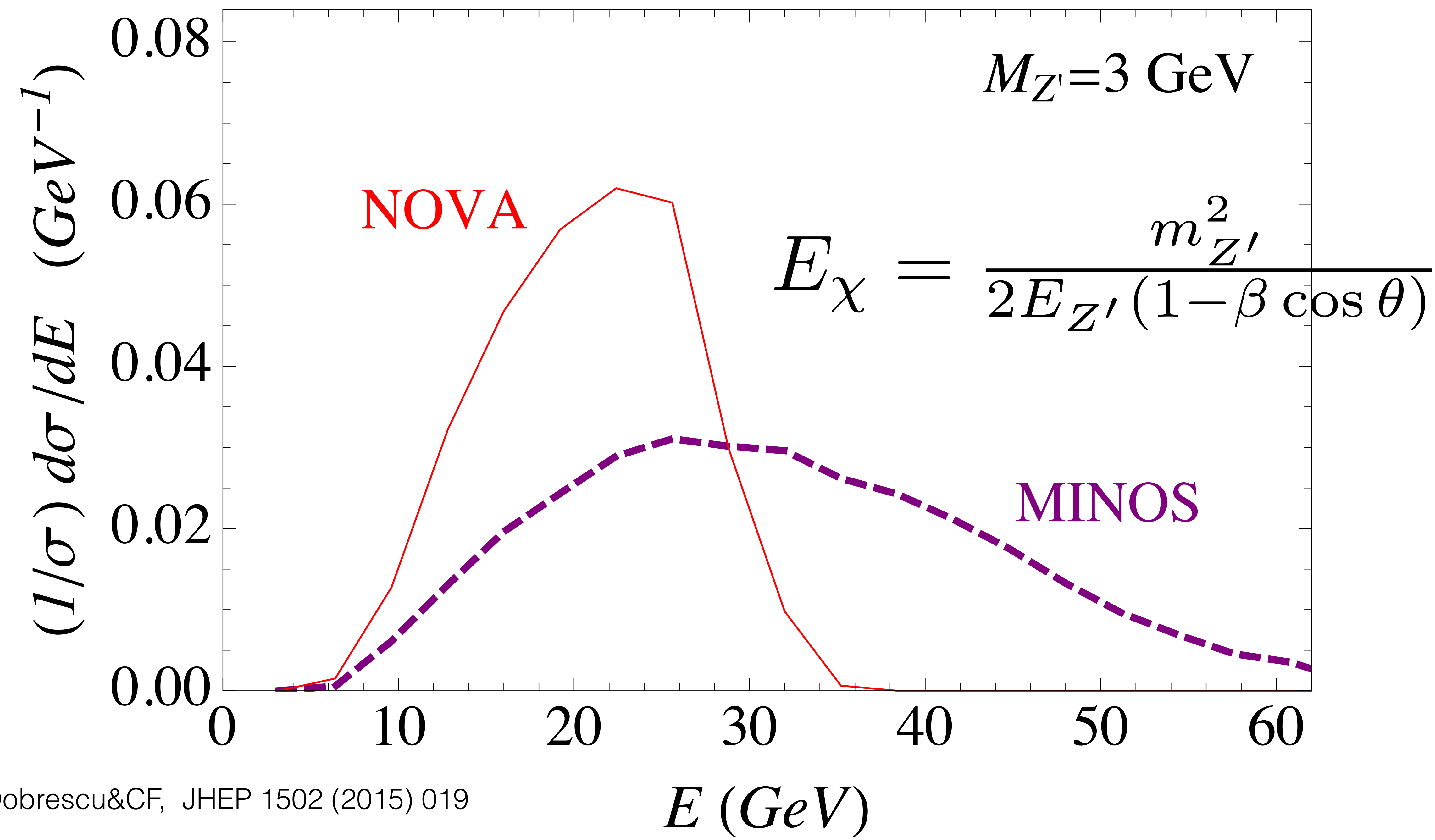
New physics can be light and weakly coupled to SM.
High energy colliders have limited sensitivity to such scenario, while fixed target experiments can probe compelling regions of the parameter space.

Release of a MadGraph plugin (MadDump) to facilitate these analysis. Ongoing studies for SHiP and LBNF.
We will also include visible decay, inelastic DM signatures…
(L.Buonocore, **CF**, F.Maltoni, O.Mattelaer, F.Tramontano, in progress)

Backup

Experiment Class	**Production Modes**	**Detection**
B-factory	$e^+e^- \to \gamma A'$	missing mass
Electron fixed-target	$e^-Z \to e^-ZA'$	DM scatter or missing energy/mass
Hadron collider	$pp \to$ (jet/γ)A$'$	missing energy
Positron fixed-target	$e^+e^- \to \gamma A'$	missing mass
Proton fixed-target	$\pi^0/\eta/\eta' \to \gamma A'$, $q\bar{q} \to A'$, $pZ \to pZA'$	DM scatter downstream

DM energy spectrum

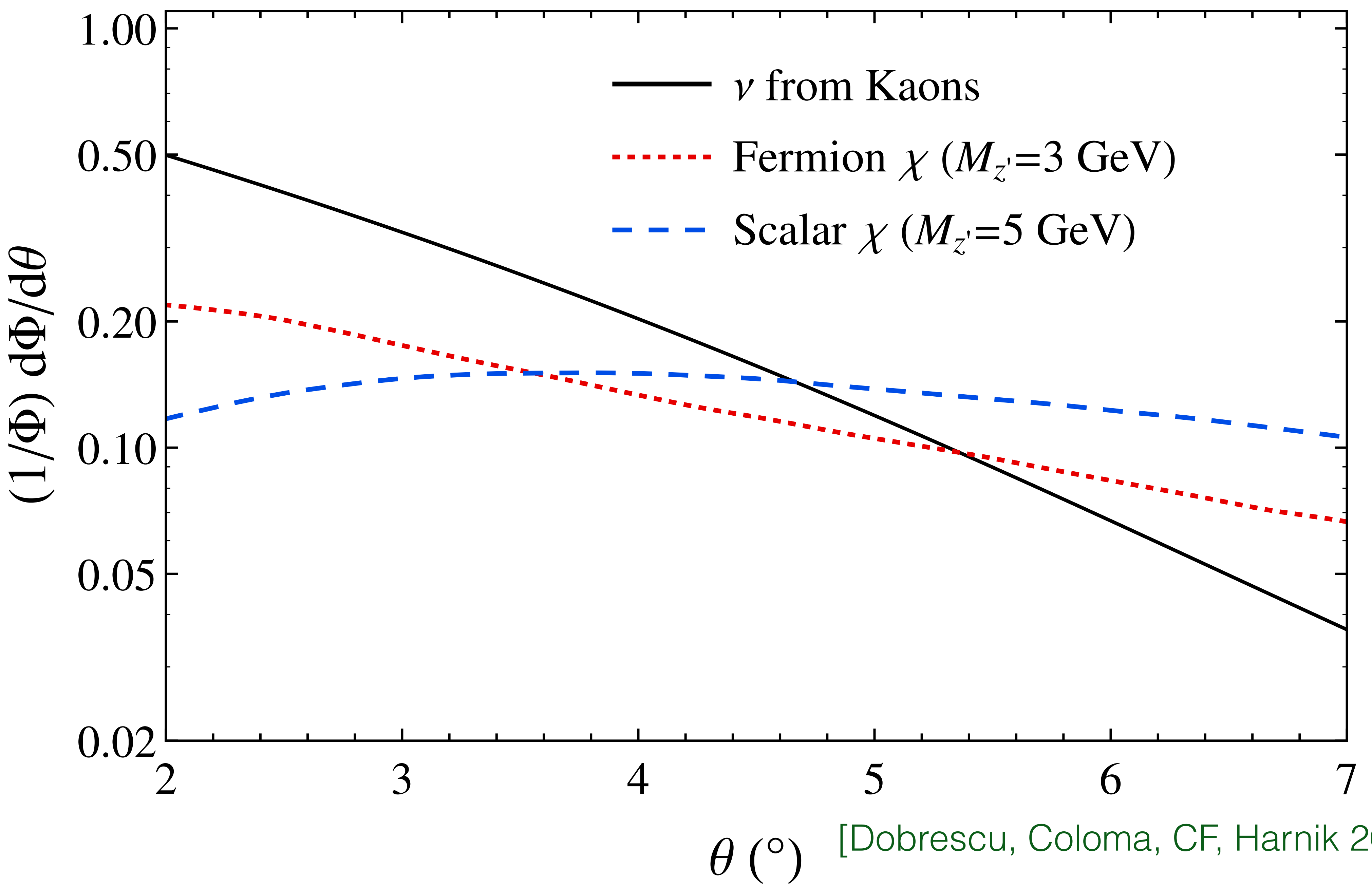


Dobrescu&CF, JHEP 1502 (2015) 019

DM energy peak is significantly higher than neutrino peak

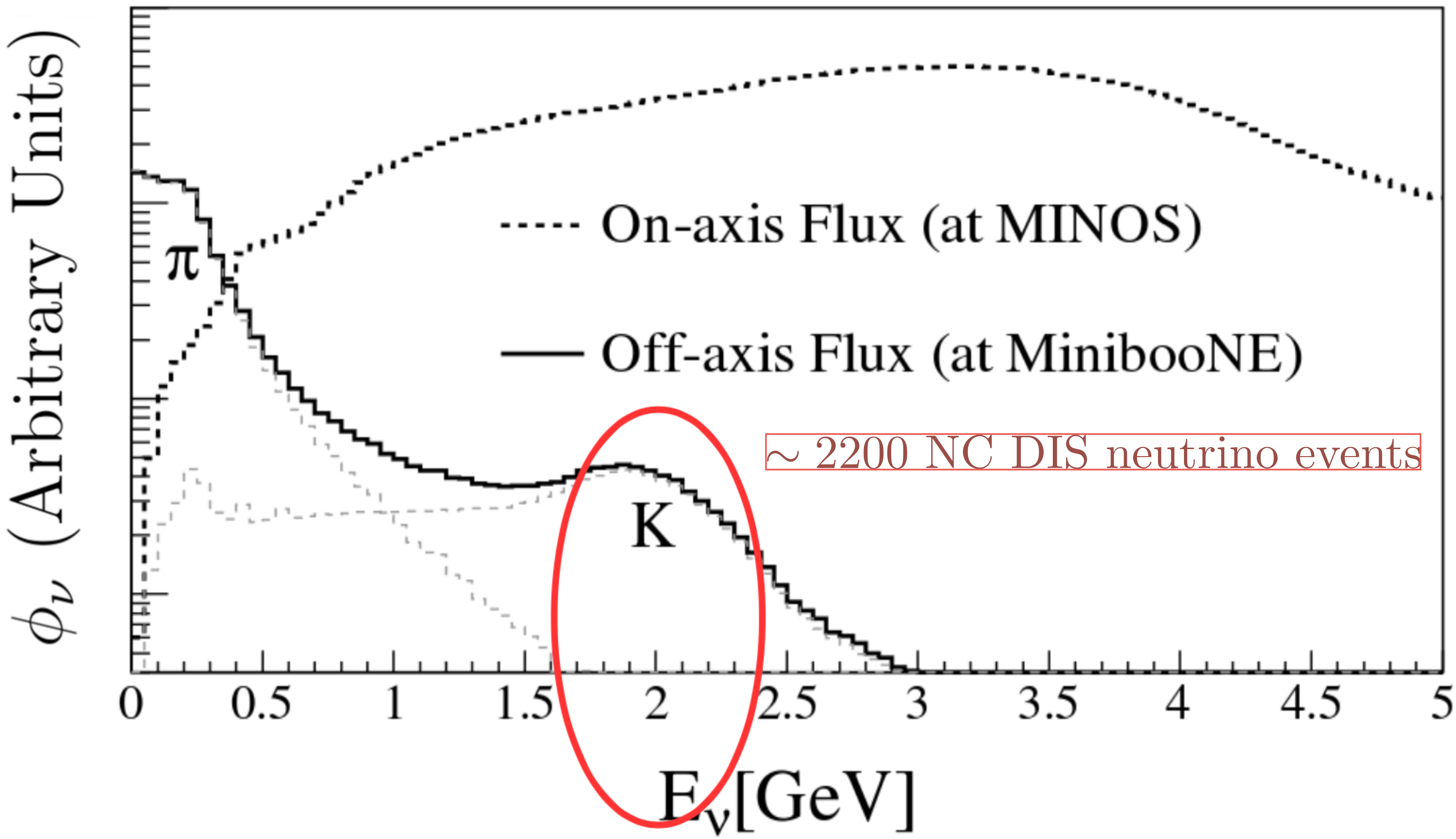
Off-axis detectors for DM

MiniBoonNE's location with respect to the Main injector beam is ideal



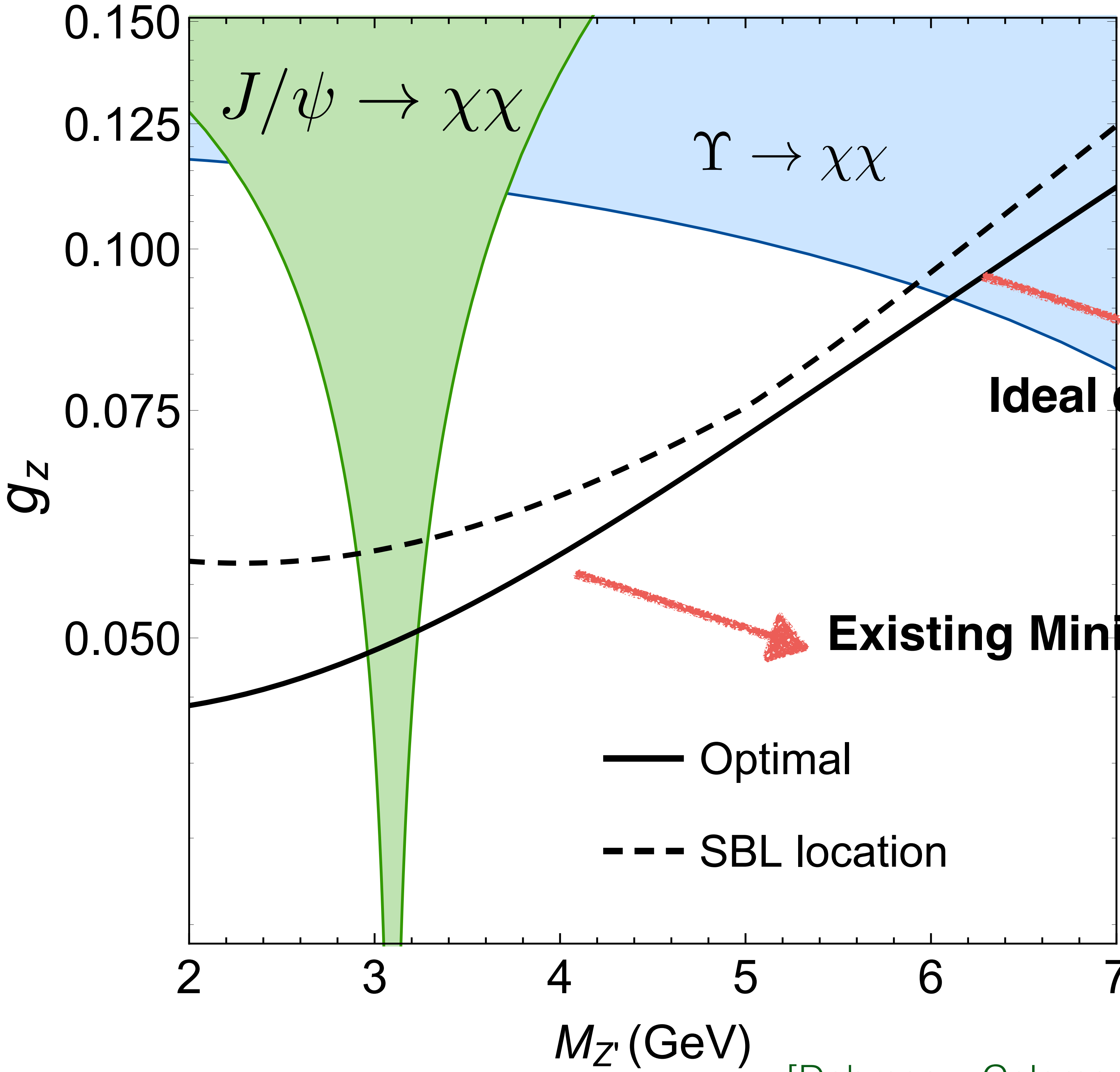
[Dobrescu, Coloma, CF, Harnik 2015]

Off-axis neutrino background



The energy of neutrinos is too small to give rise to numerous deep inelastic scattering events

Projected sensitivity



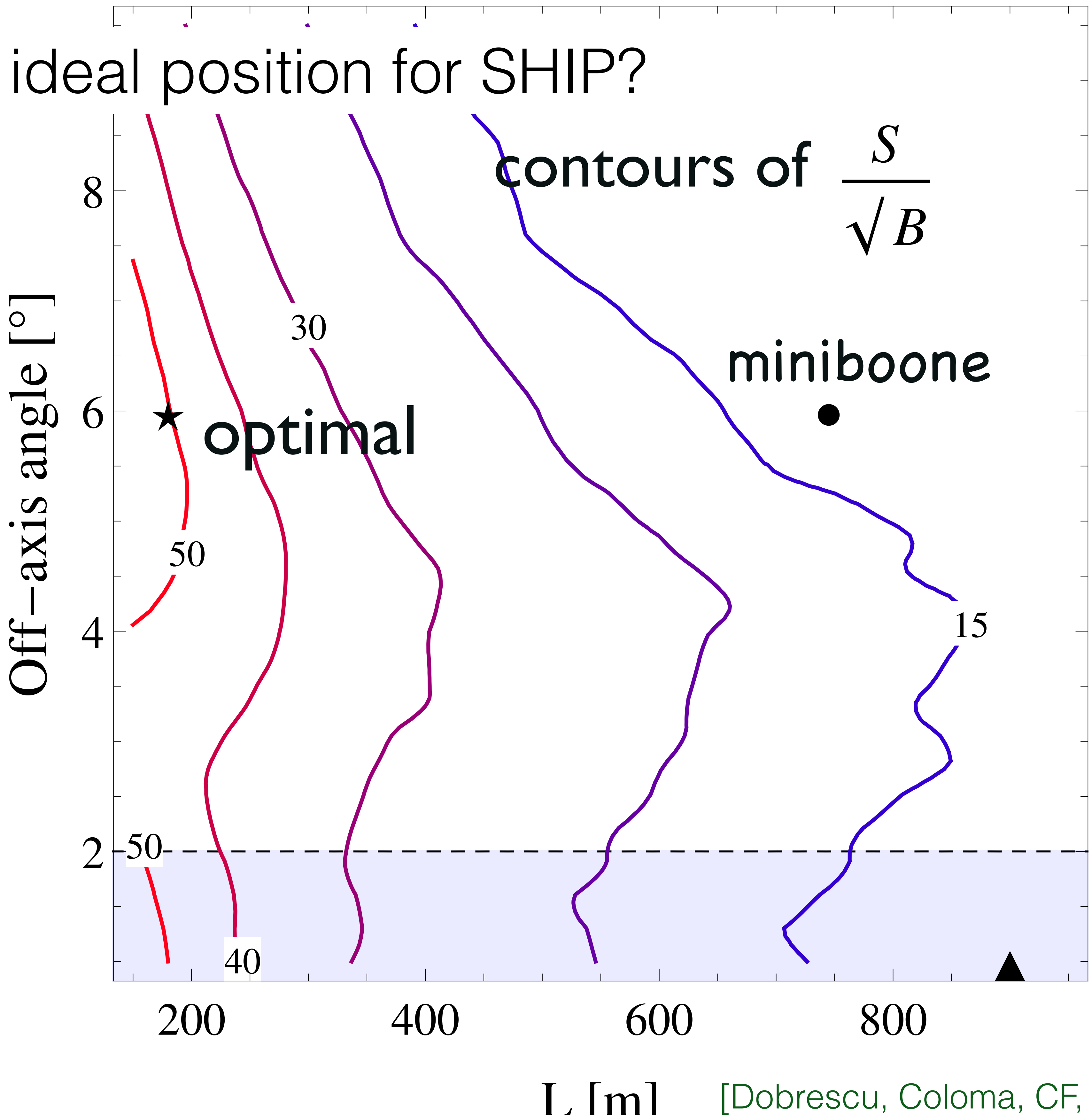
Ideal detector for DUNE

Existing MiniBooNE data!!

[Dobrescu, Coloma, CF, Harnik 2015]

Ideal position for a future LBNF detector

What is the ideal position for SHIP?



$g_z = 0.1$

[Dobrescu, Coloma, CF, Harnik 2015]