Dark Photon Search at Yemilab

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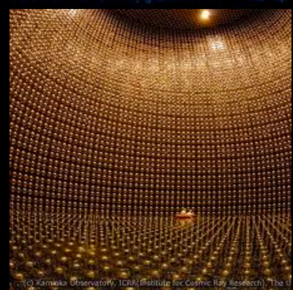


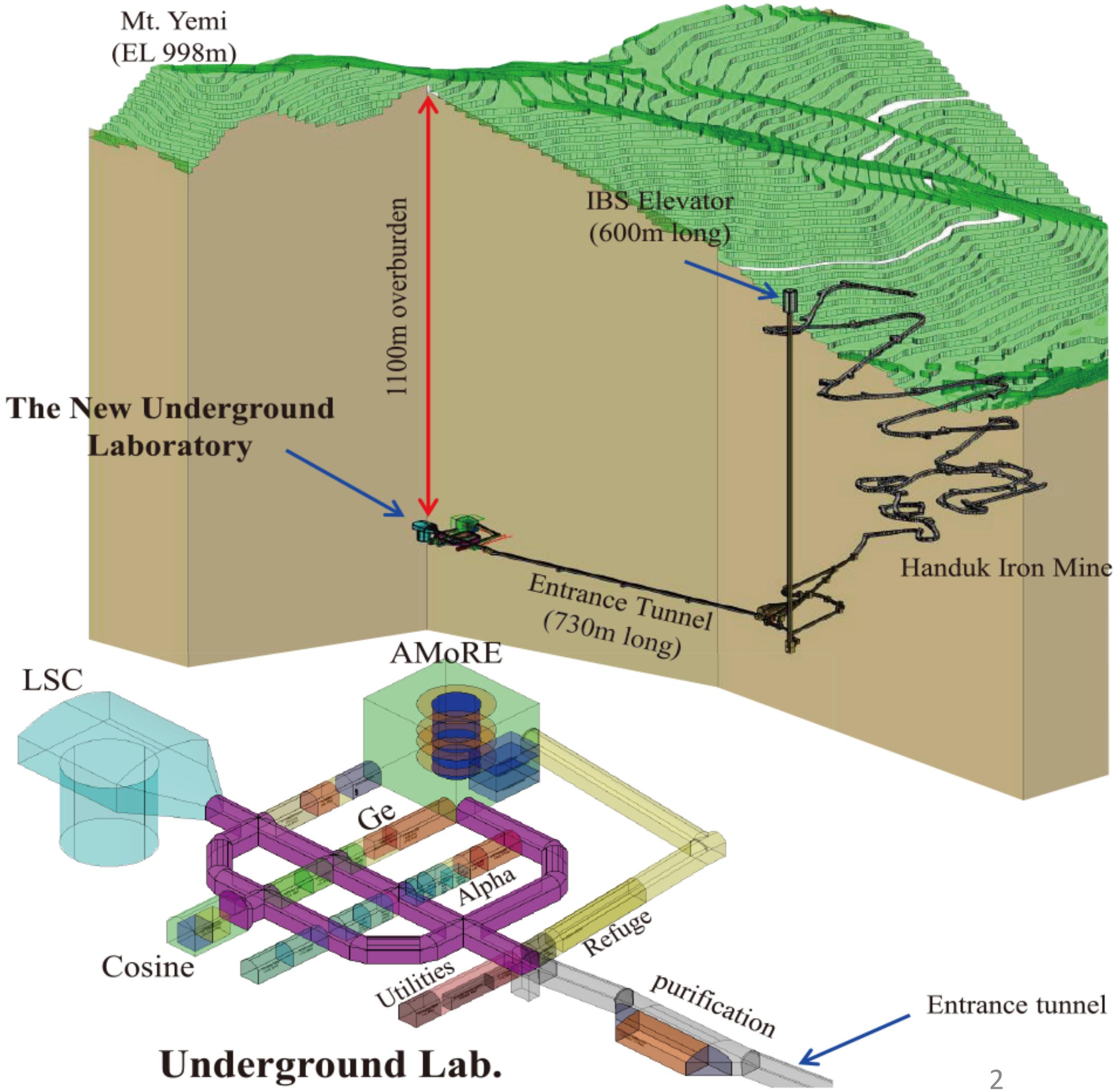
4th TAU Meeting

2020.06.09

Yemilab @Handuk iron mine

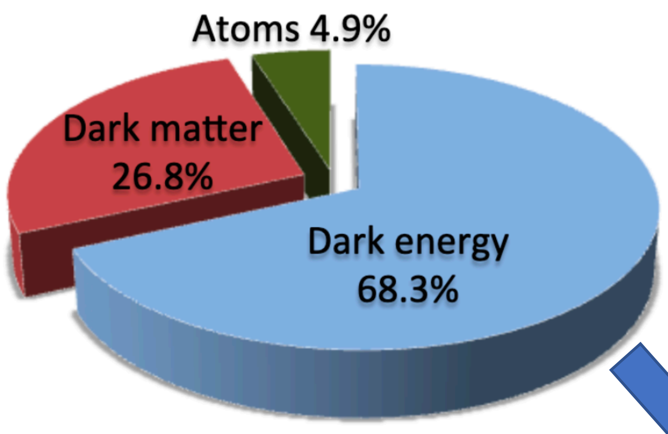
~1 km depth

To be completed in 2021



Standard Model has been very successful

But…



$\bar{p}$ excess
in cosmic rays
(AMS)

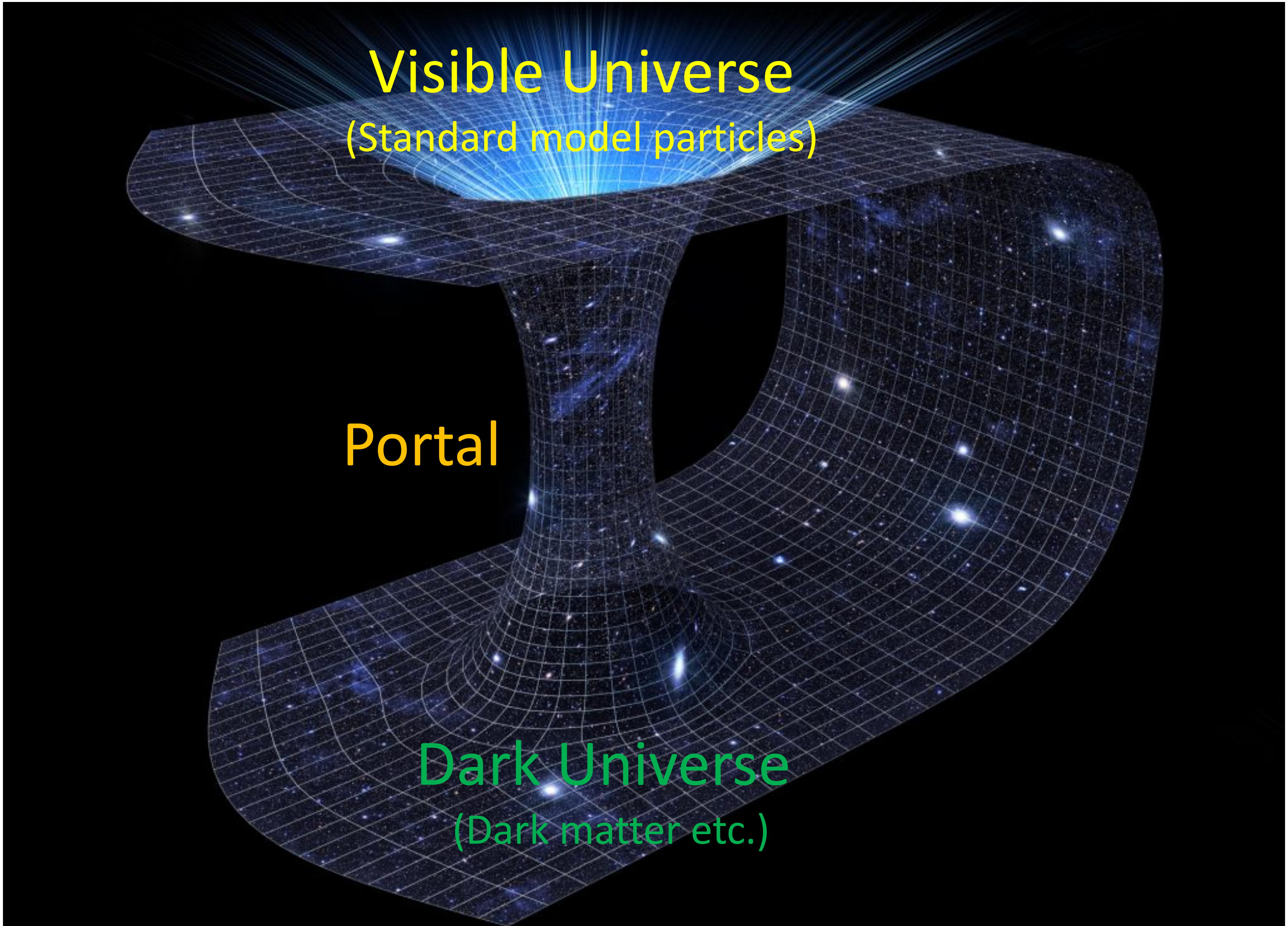
e^+ excess
in cosmic rays
(PAMELA, FERMI, AMS)

Dark sector ?

Excess of events of
unknown origin
(DAMA/LIBRA, CoGENT)

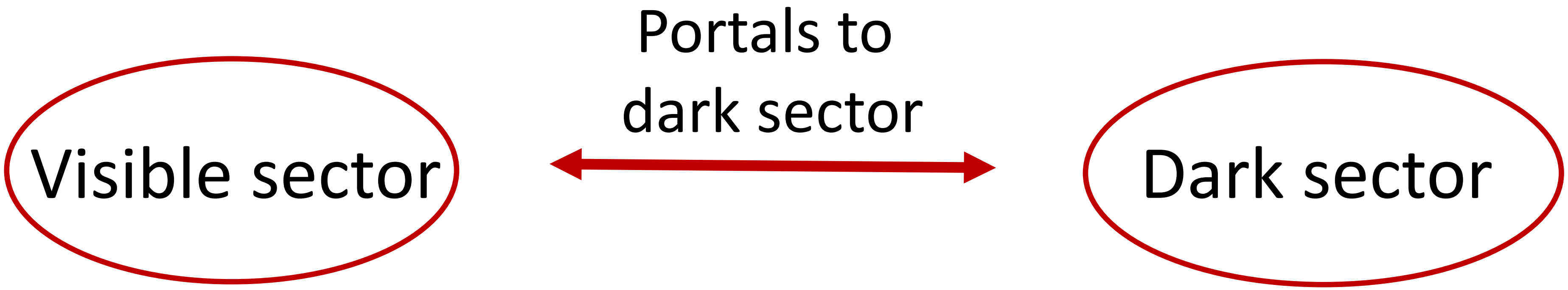
proton radius:
7 σ discrepancy

Anomalous magnetic
moment of muon:
$a_\mu = (g_\mu-2)/2$


Visible Universe
(Standard model particles)
Portal
Dark Universe
(Dark matter etc.)

Portals (mediators) to Dark Sector

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Mediator} + \mathcal{L}_{DS}$$



Standard Model symmetries allow
only a few important interactions.

"Vector", "Higgs", "Neutrino", and "Axion" portals

Visible sector | Portals to dark sector | Dark sector

vector	$\frac{1}{2}\epsilon F^{Y}_{\mu\nu}F'^{\mu\nu}$	dark photon
Higgs	$\epsilon_h \lvert h\rvert^2 \lvert\phi\rvert^2$	dark Higgs
neutrino	$\epsilon_\nu (hL)\psi$	sterile neutrino
axion	$\frac{1}{f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu}$	ALPs

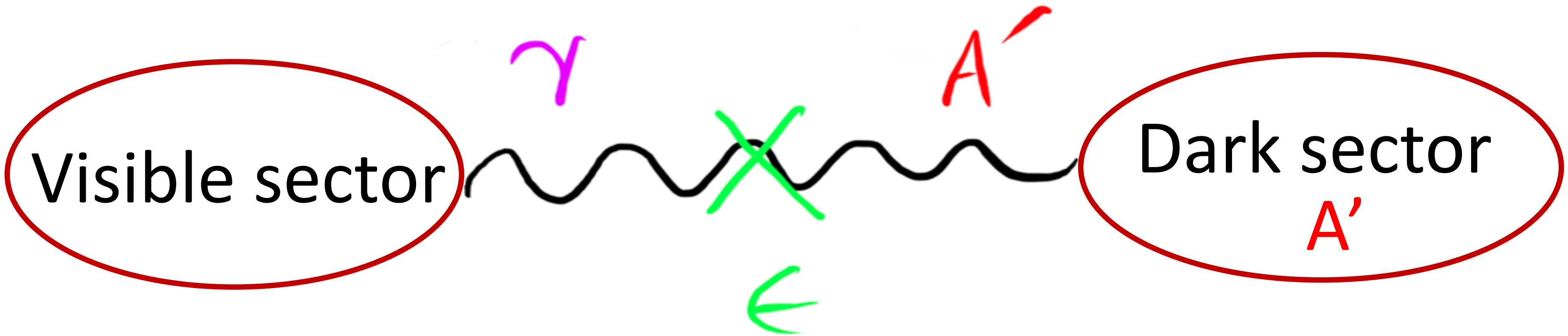
$\mathcal{L}_{\text{mediator}}$

"Kinetic Mixing"

Photon (γ) and Dark Photon (A') can mix.

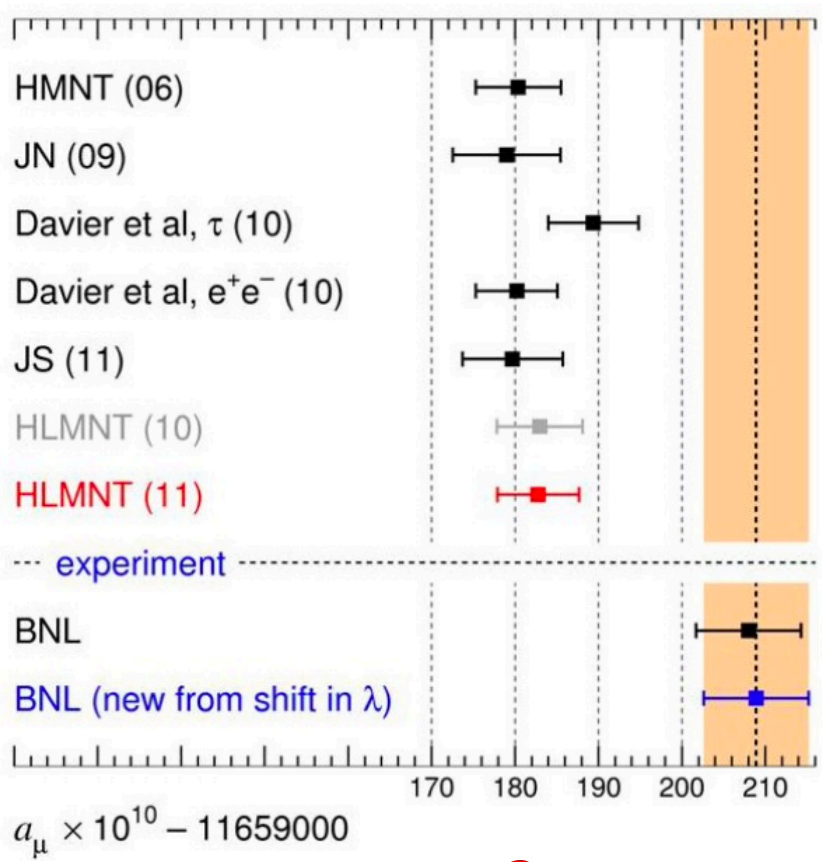
→ one of the best motivated DP models

Need new $U(1)_D$

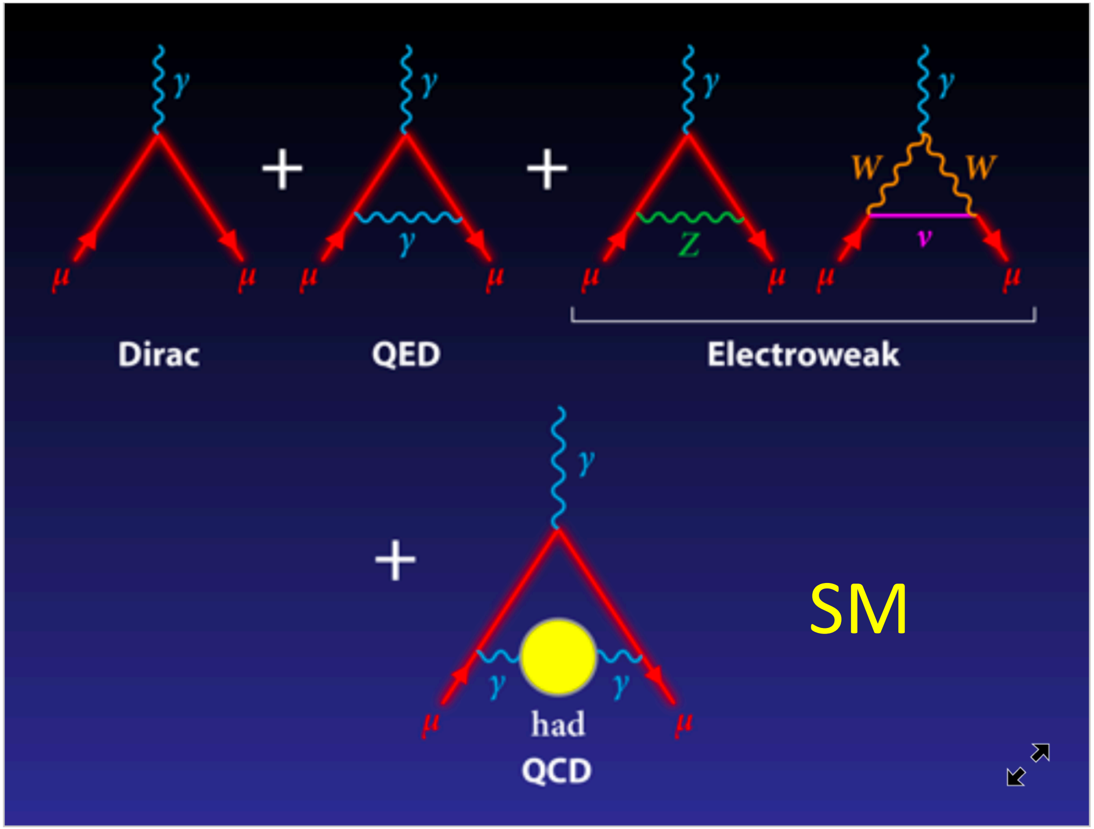


Minimal Dark Sector could consist of A' only.

Anomalous muon g_μ-2

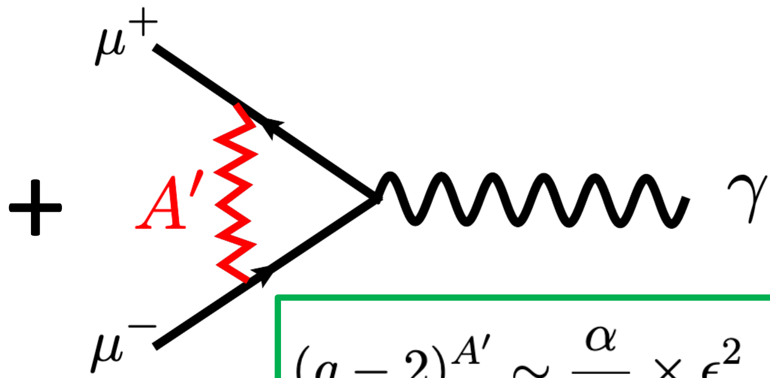


~3 σ



APS/Alan Stonebraker

Anomalous muon g_μ-2 could be explained by Dark photon ?



$$(g-2)_\mu^{A'} \sim \frac{\alpha}{2\pi} \times \epsilon^2, \quad m_{A'} < m_\mu$$

Dark Photon Search World Map

Y2015 Status: publishing, approved, proposal

Dark Photon Search Experiments

- ❑ Beam dump (thick target)
- ❑ Fixed target (thin target)

e^- beam: E137, KEK, Orsay, E141, E774, NA64, BDX, LDMX, HPS

e^+ beam: MMAPS, VEPP-3, PADME

γ beam: GlueX, LEPS2, LEPS, and FOREST

p beam: SHiP, NA62, FASER, REDTOP, SeaQuest

- ❑ Collider Exp.

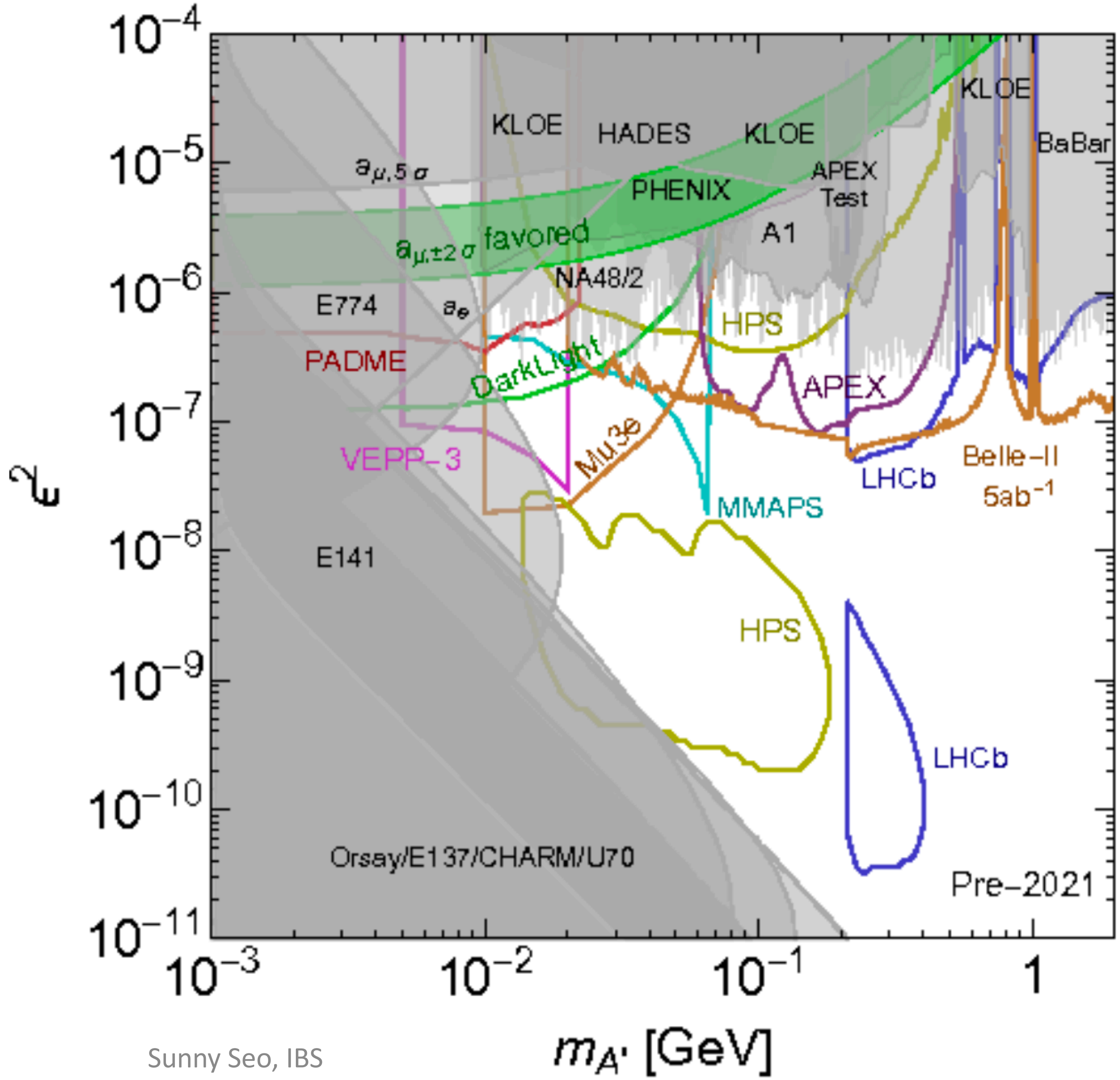
e^+e^-: Belle II, KLOE-2

pp: LHCb

- ❑ Astrophysical Obs.

SN 1987A, Sun etc.

Sub-GeV A' Search Status & Prospects

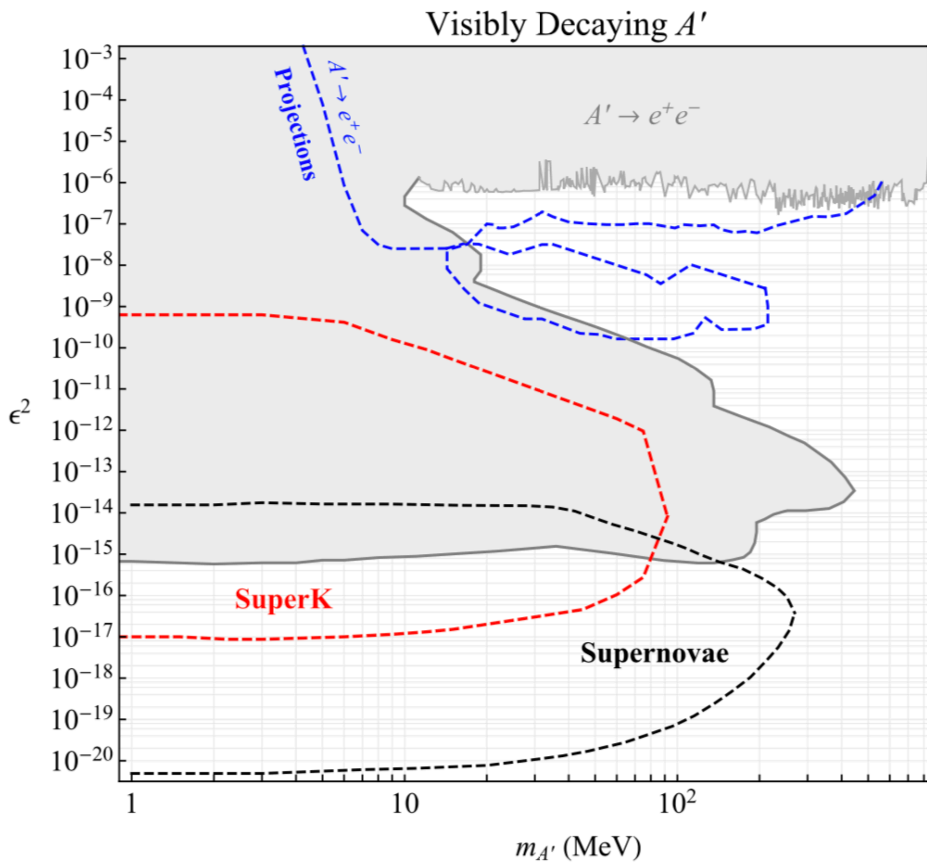


→ DP parameter space favored by anomalous muon g_μ-2 seems to be excluded by most exp.

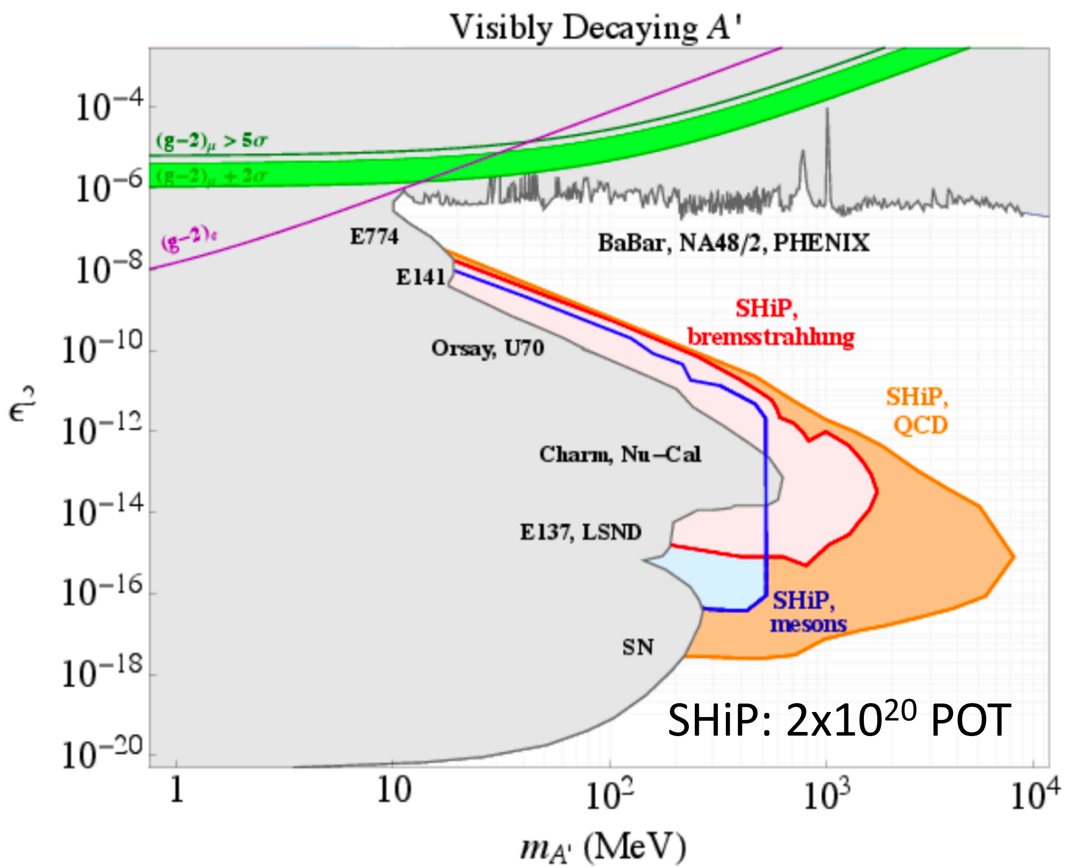
→ In the near future, higher energy and smaller ε region can be explored.

"Dark Sectors 2016 Workshop: Community Report"

Sub-GeV A' Search

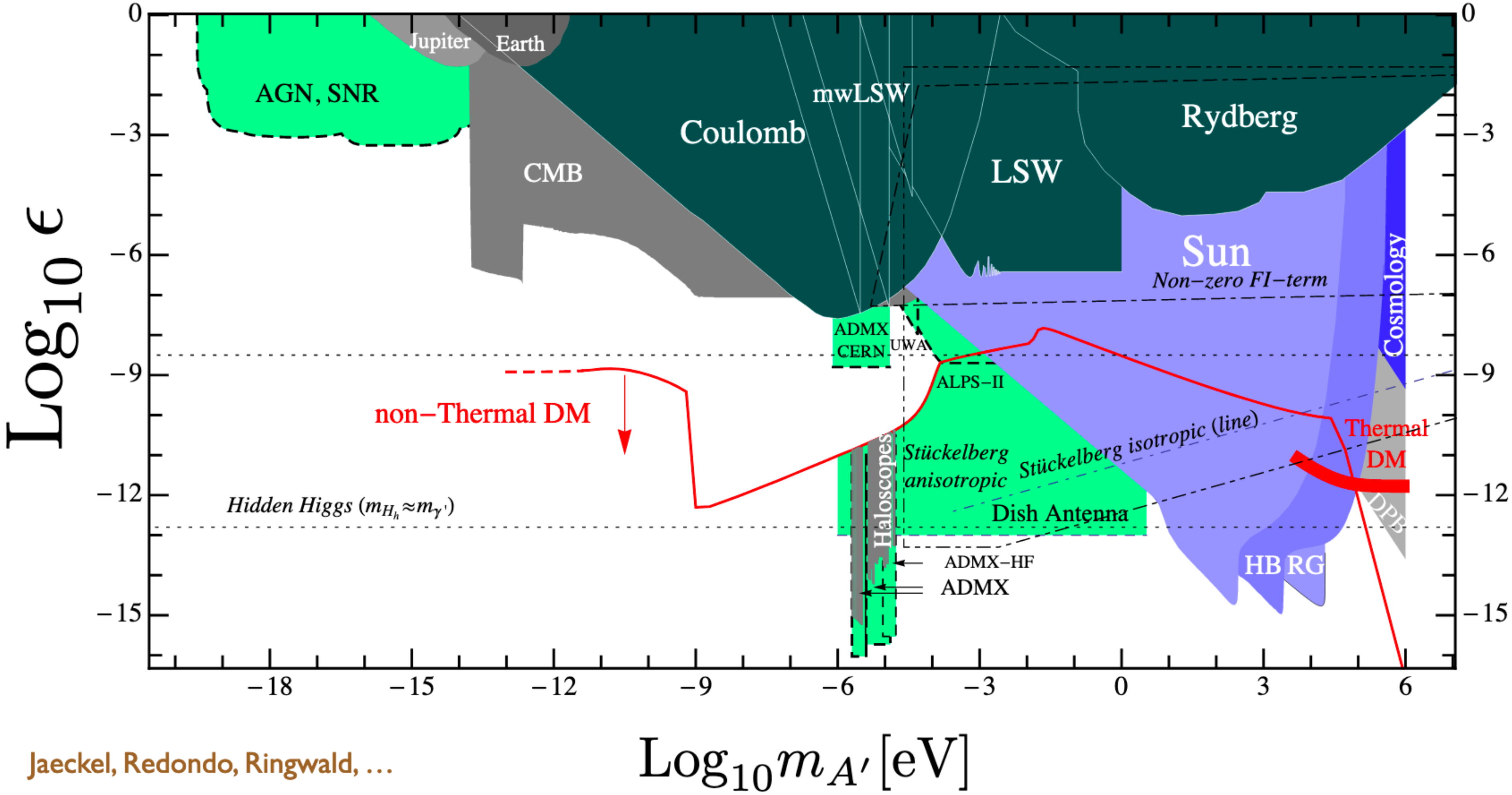


> GeV A' Search



SHiP can explore ~10 GeV region at $\varepsilon \sim 10^{-7} - 10^{-8}$.

Sub-MeV A’ Search Status



Jaeckel, Redondo, Ringwald, …

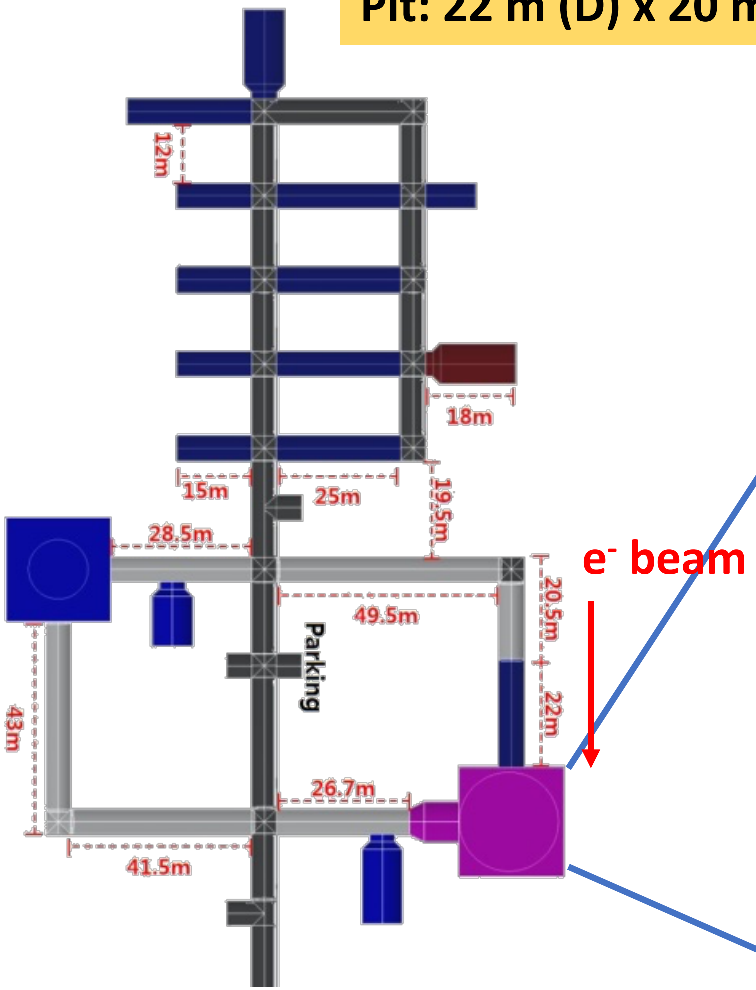
Similar to Axion/ALP search techniques,
but magnet is not required for A’ <-> γ conversion.

LSC @Yemilab

LSC = Liquid Scintillator Counter

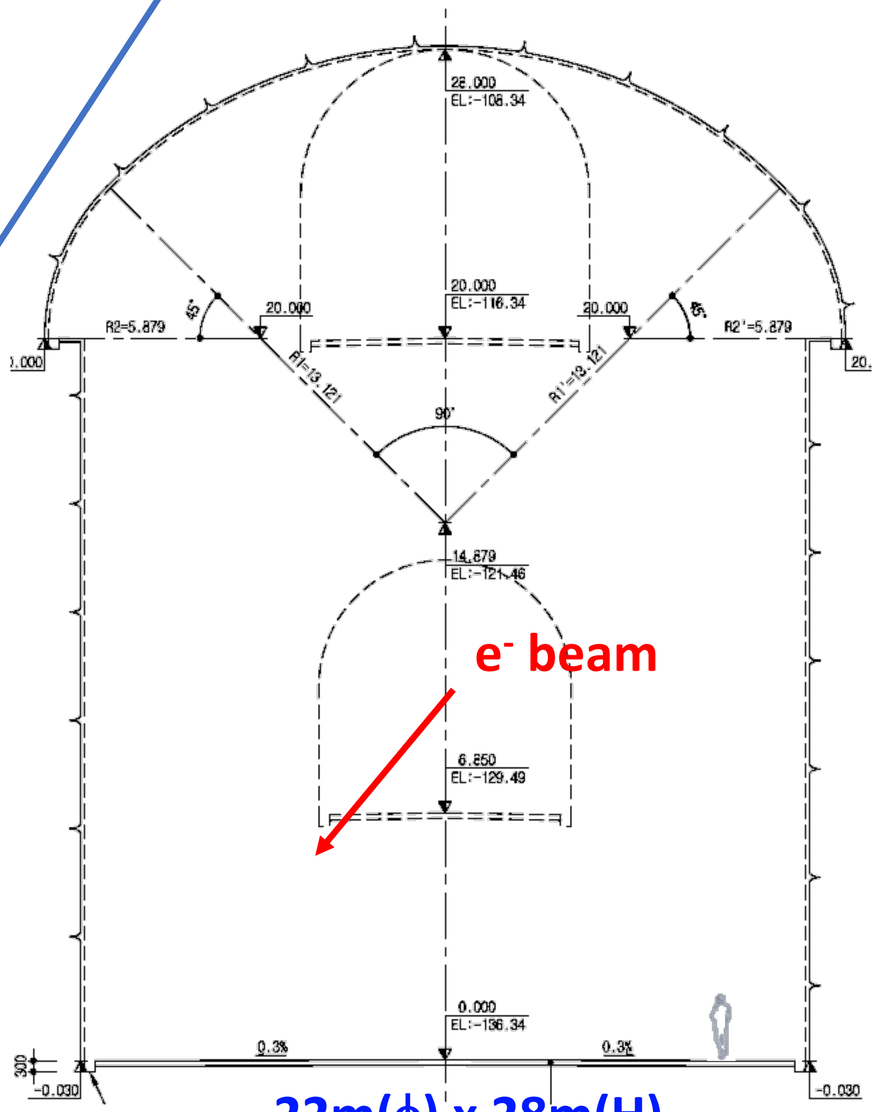
~3 kton

Pit: 22 m (D) x 20 m (H)



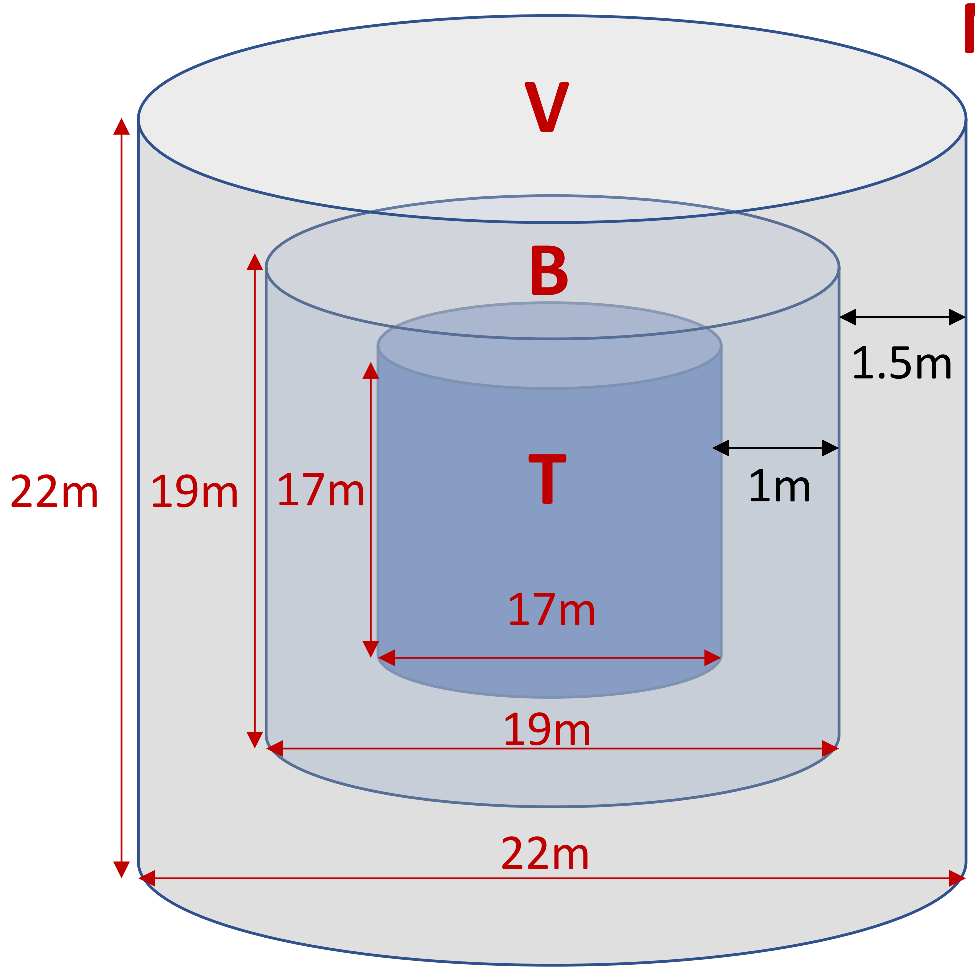
Sunny Seo, IBS

LSC Hall



22m(ϕ) x 28m(H)

Candidate Detector Design



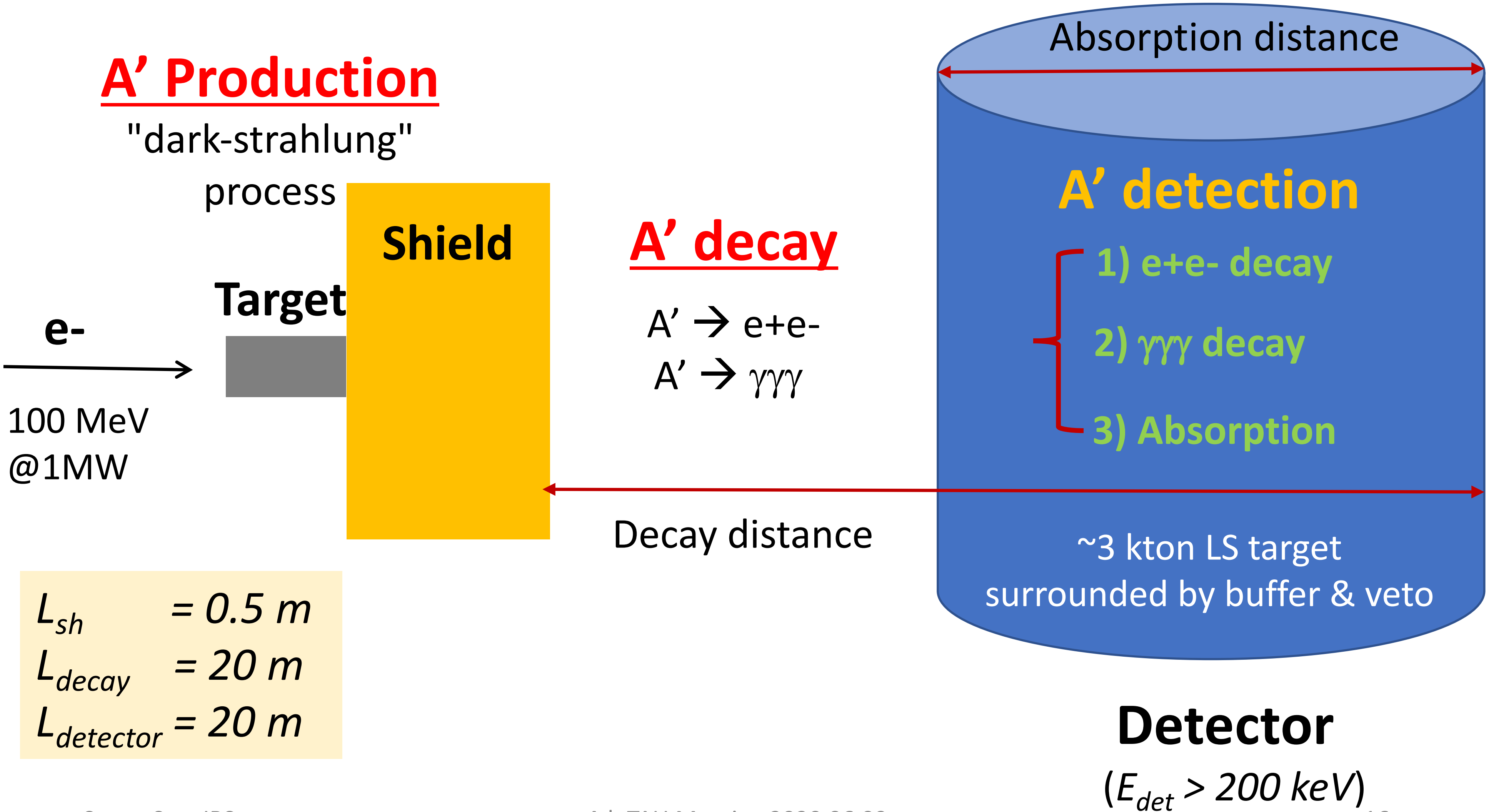
Neutrino Telescope @Yemilab

Target: 3.29 kton
Buffer: 1.44 kton
Veto: 2.96 kton

2000(3000,4000) x 20 inch PMTs = 20% (30, 40)% coverage

Dark Photon Search Scheme

LSC @Yemilab

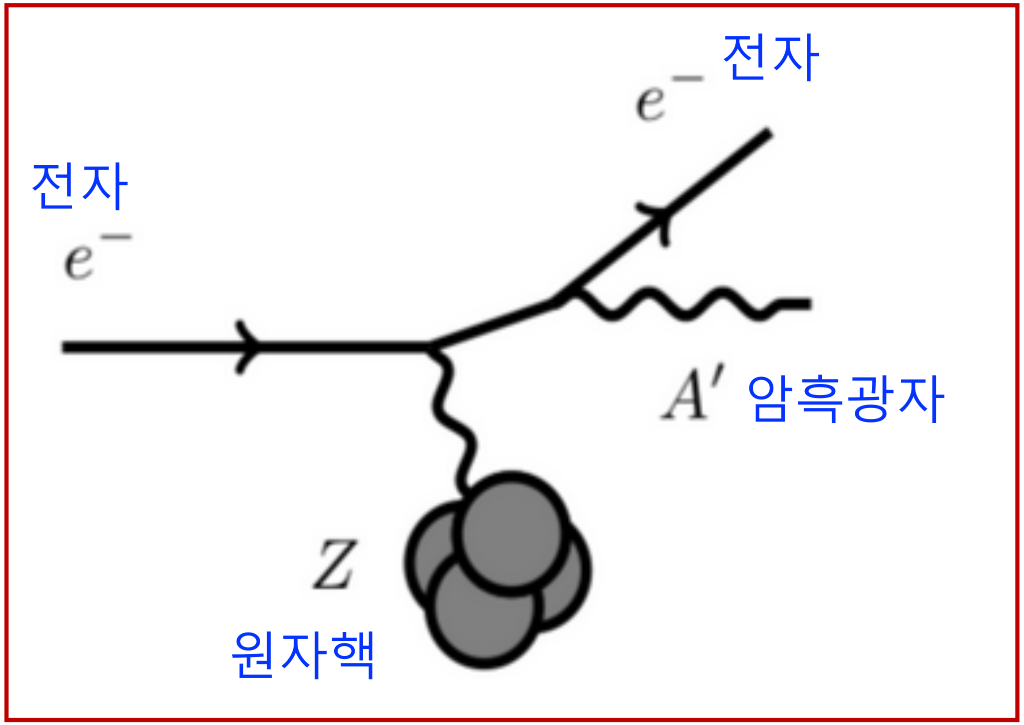


e⁻ beam

Dark Photon Productions

"Bremsstrahlung-like" process

a.k.a. "dark-strahlung"



E137, KEK, Orsay, E141, E774, NA64, BDX, LDMX, HPS

“Dark-strahlung” Production

Liu & Miller: PRD 96, 016004 (2017)

x-section comparison of no approximation, WW, and IWW approximation

Weizsäcker-Williams

- The **WW** approximation relies on the incoming electron energy being much greater than m_ϕ and m_e, such that the final state electron and the new boson are highly collinear.

- The **IWW** reduces the computational time but does not improve accuracy.

"Dark-strahlung" Production

Liu & Miller: PRD 96, 016004 (2017)

$$\frac{d\sigma}{dx} = \epsilon^2 \frac{\alpha^3}{8M^2} \frac{|\mathbf{k}|E}{|\mathbf{p}|} \int_0^{\theta_{\max}} d\cos\theta \frac{1}{V} \times \int_{t_{\min}}^{t_{\max}} dt \frac{F(t)^2}{t^2} \int_0^{2\pi} \frac{d\phi_q}{2\pi} \mathcal{A}^{23},$$

No Approximation

$$\left(\frac{d\sigma}{dx}\right)_{WW} = 2\epsilon^2\alpha^3|\mathbf{k}|E(1-x)\int_0^{\theta_{\max}} d\cos\theta \frac{\mathcal{A}^{22}_{t=t_{\min}}}{\tilde{u}^2}\chi,$$

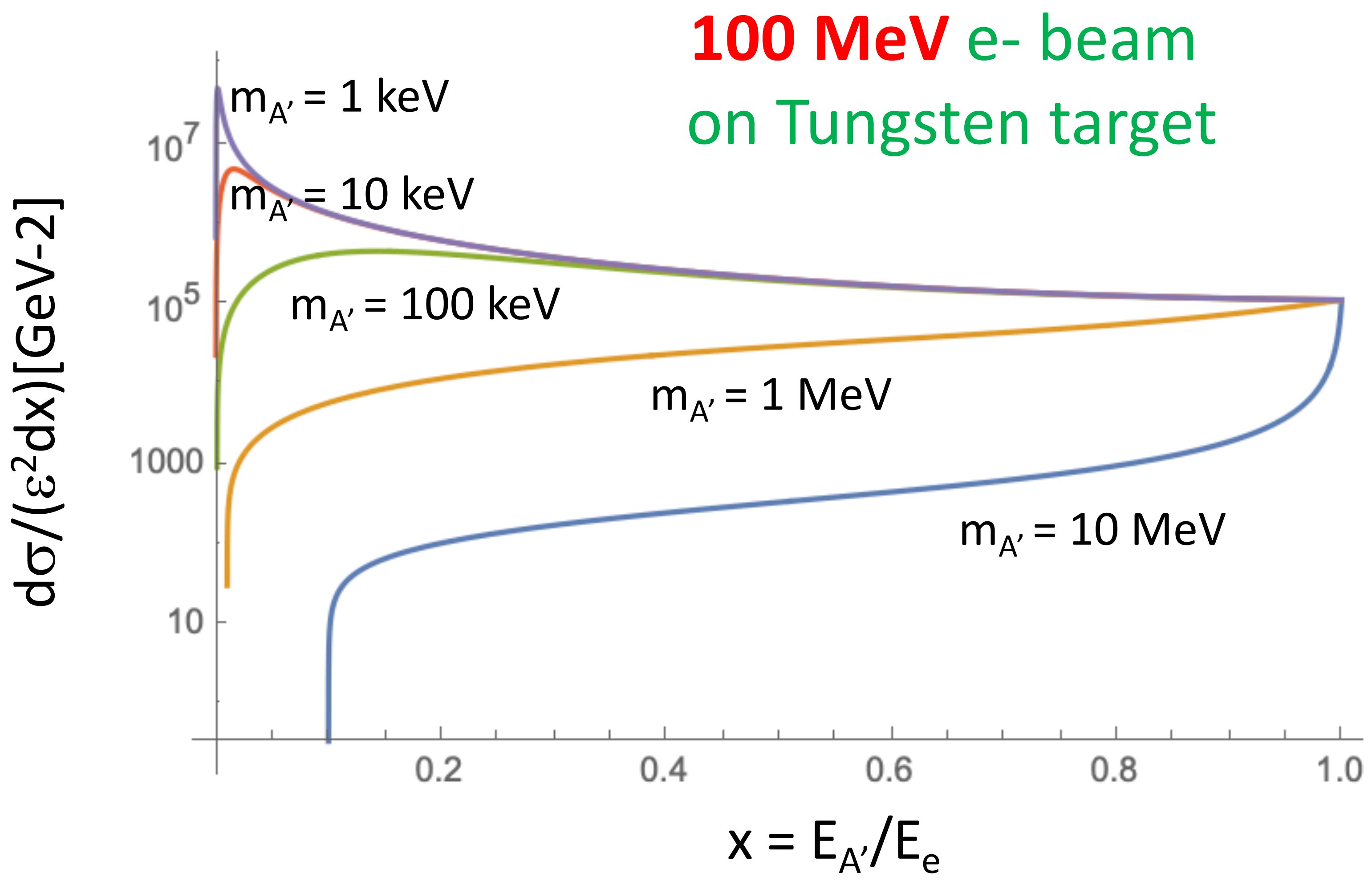
$$\left(\frac{d\sigma_V}{dx}\right)_{IWW} = 2\epsilon_V^2\alpha^3\chi\frac{|\mathbf{k}|}{E}\frac{m_e^2x(-2+2x+x^2)-2(3-3x+x^2)\tilde{u}_{\max}}{3x\tilde{u}_{\max}^2}$$

$$\tilde{u}_{\max} = -m_\phi^2\frac{1-x}{x} - m_e^2 x.$$

IWW approximation works reasonably when $m_{A'} < 100$ MeV.

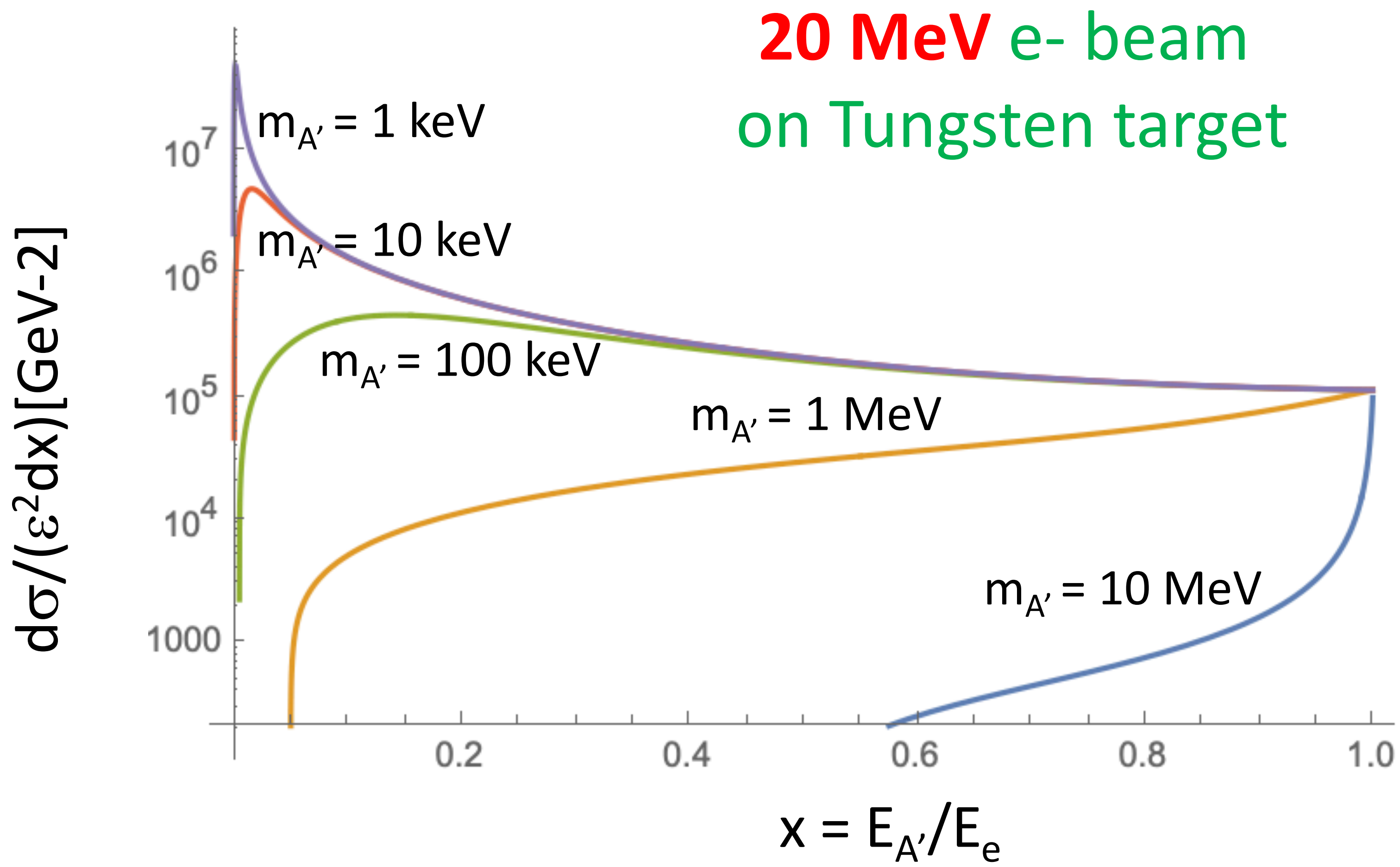
Dark Photon Production by "dark-strahlung"

IWW approximation



Dark Photon Production by "dark-strahlung"

IWW approximation

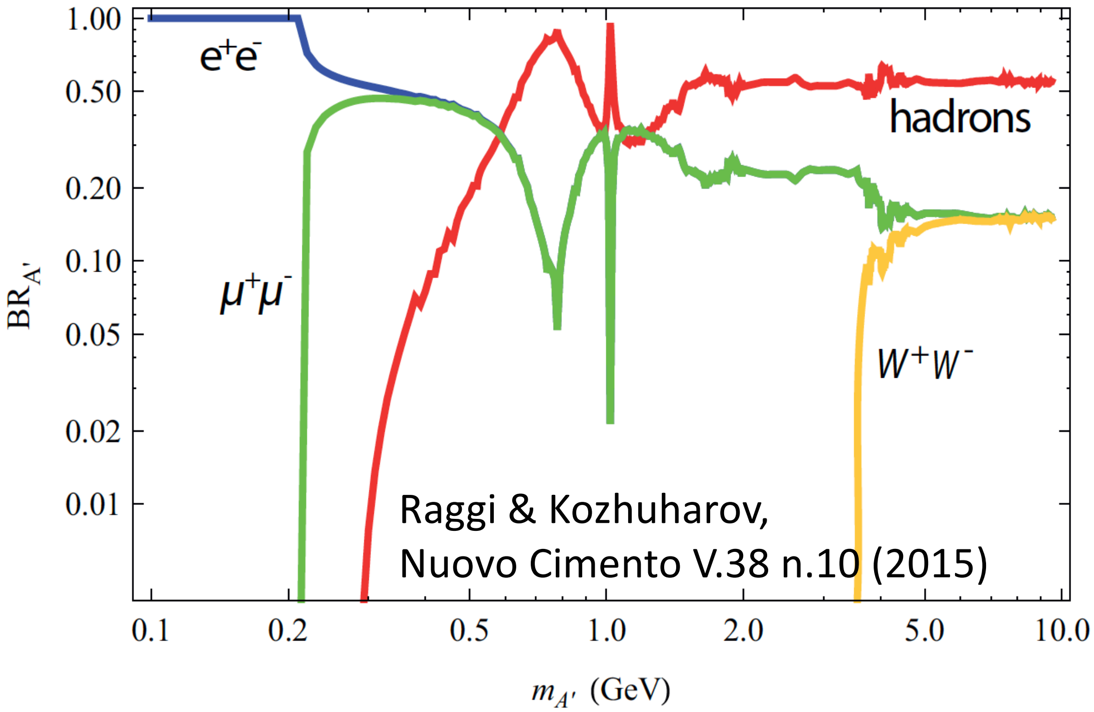


Dark Photon Detections

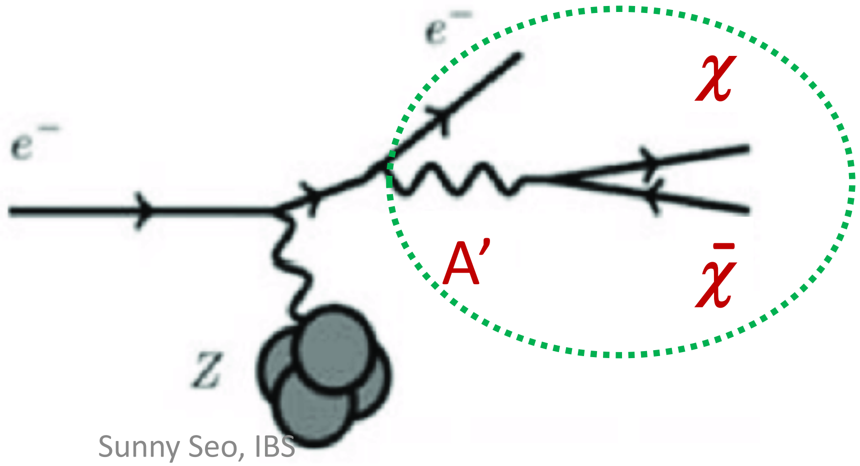
- Visible Decays

A' → e+ e- (> 1 MeV)

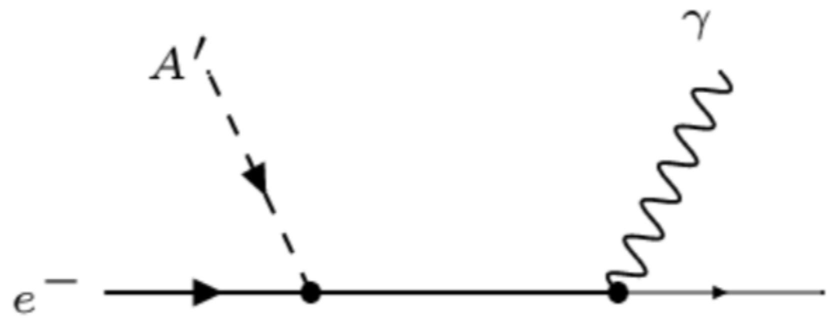
A' → γγγ (< 1 MeV)



- Invisible Decays



- Absorption



Expected Dark Photon Event

- **Production: "dark-strahlung"**
- **Detection : *A' → e+e- or 3γ***

DP production x-section

$$N_\phi \approx \frac{N_e X}{M} \int_{E_{\min}}^{E_0} dE \int_{x_{\min}}^{x_{\max}} \times dx \int_0^T dt I_e(E_0, E, t) \frac{d\sigma}{dx} e^{-L_{\rm sh}\left(\frac{1}{l_\phi}+\frac{1}{\lambda}\right)} \left(1 - e^{-L_{\rm dec}/l_\phi}\right)$$

Liu & Miller: PRD 96, 016004 (2017)

where,

- N_e: # of incident electrons
- X: one radiation length
- M: target mass

- L_{sh}: shield distance
- L_{dec}: decay distance
- l_ϕ: DP decay length
- λ: DP absorption length in shield
- I_e: e- spectrum in beam target

(Continued…)

$$N_\phi \approx \frac{N_e X}{M} \int_{E_{\min}}^{E_0} dE \int_{x_{\min}}^{x_{\max}} \times dx \int_0^T dt I_e(E_0, E, t) \frac{d\sigma}{dx} e^{-L_{\mathrm{sh}}\left(\frac{1}{l_\phi}+\frac{1}{\lambda}\right)} \left(1 - e^{-L_{\mathrm{dec}}/l_\phi}\right)$$

DP decay length (l_ϕ)

$$\boxed{l_\phi = \frac{E_k}{m_\phi} \frac{1}{\Gamma_\phi}}$$

where,
E_k: DP energy
$E_k = xE_e$

$$\Gamma_V(\phi \to e^+e^-) = \epsilon_V^2 \frac{\alpha}{3} m_\phi \left(1 + \frac{2m_e^2}{m_\phi^2}\right)\left(1 - \frac{4m_e^2}{m_\phi^2}\right)^{1/2}$$

(m_ϕ > 1 MeV)

$$\Gamma_V(\phi \to 3\gamma) = \epsilon_V^2 \frac{\alpha^4}{2^7 3^6 5^2 \pi^3} \frac{m_\phi^9}{m_e^8} \times \left[\frac{17}{5} + \frac{67}{42}\frac{m_\phi^2}{m_e^2} + \frac{128941}{246960}\frac{m_\phi^4}{m_e^4} + \mathcal{O}\left(\frac{m_\phi^6}{m_e^6}\right)\right]$$

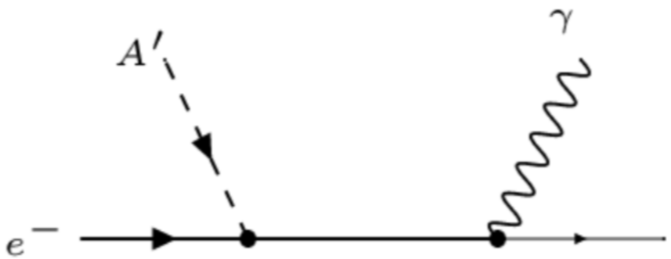
(m_ϕ < 1 MeV)

(Continued…)

$$N_\phi \approx \frac{N_e X}{M}\int_{E_{\min}}^{E_0} dE \int_{x_{\min}}^{x_{\max}} \times dx \int_0^T dt I_e(E_0, E, t)\frac{d\sigma}{dx} e^{-L_{\mathrm{sh}}\left(\frac{1}{l_\phi}+\frac{1}{\lambda}\right)}\left(1 - e^{-L_{\mathrm{dec}}/l_\phi}\right)$$

DP absorption length (λ)

$$\lambda = \frac{1}{n_e \sigma_{\mathrm{abs}}}$$



n_e: electron number density of the shield

σ_{abs}: DP absorption x-section

$$\sigma_{\mathrm{abs}} = \epsilon^2 \frac{c\pi\alpha^2}{2m_e|\mathbf{k}|}\int_{-1}^{1} d\cos\theta_\gamma \frac{|\mathbf{q}|\mathcal{A}^{22}}{E_k + m_e - |\mathbf{k}|\cos\theta_\gamma}$$

where, **|k|:** DP 3 momentum
|q|: γ 3 momentum = E_γ

Yemilab case

- ❑ **Production: "dark-strahlung"**
- ❑ **Detection : *A' → e+e- or 3γ, or A' absorption***

DP production x-section

$$N_\phi \approx \frac{N_e X}{M} \int_{E_{\min}}^{E_0} dE \int_{x_{\min}}^{x_{\max}} \times dx \int_0^T dt I_e(E_0, E, t) \frac{d\sigma}{dx} e^{-L_{\mathrm{sh}}\left(\frac{1}{l_\phi}+\frac{1}{\lambda}\right)} \underbrace{\left(1 - e^{-L_{\mathrm{dec}}/l_\phi}\right)}_{\text{only decay signal}}$$

Liu & Miller: PRD 96, 016004 (2017)

We should add an additional term of DP absorption signal to decay signal.

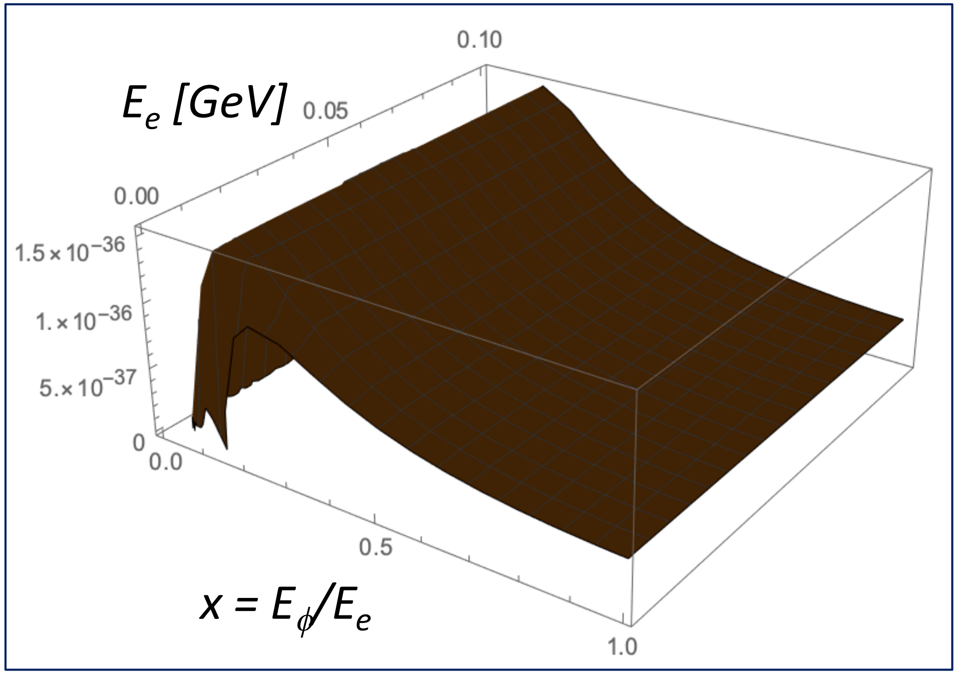
$$\underbrace{\boxed{x[1 - \exp(- L_{dec}/l_\phi - L_{det}/\lambda_{det})]}}_{\text{decay or absorption signal}}$$

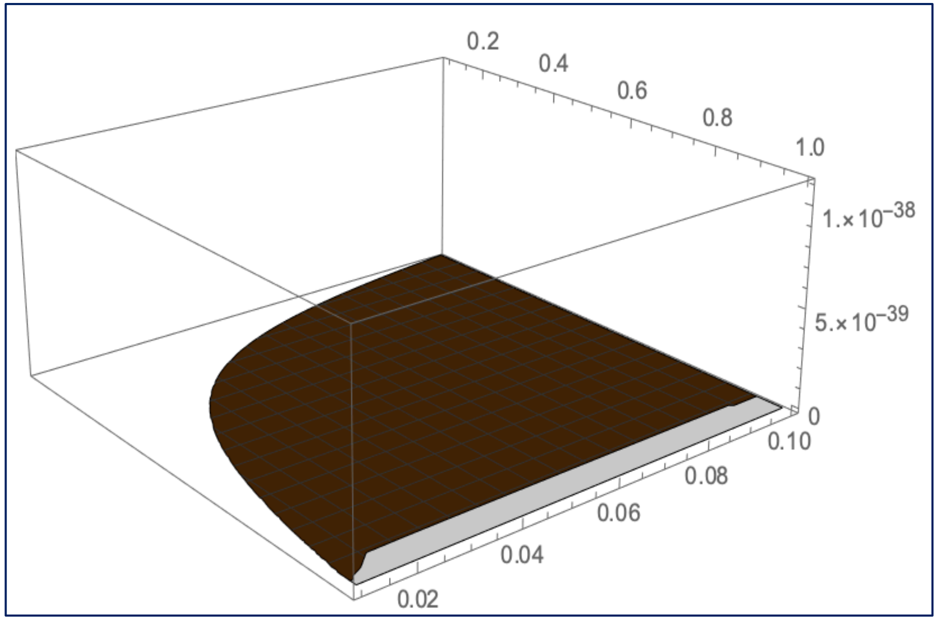
where,
L_{det}: detector length
λ_{det}: DP abs. length in detector

DP Production x-setion (dσ/dx)

dσ/dx ~10^{-36} m^2

dσ/dx ~10^{-39} m^2





m_ϕ = 0.1 MeV
ε = 10^-5

m_ϕ = 10 MeV
ε = 10^-5

ε	DP mass (m_ϕ)	Decay length (l_ϕ)	Absorption length (λ_{sh}) In shield	Absorption length (λ_{det}) In detector
10^-5	0.1 MeV	~10^{22} m (3γ)	~10^{9} m	~10^{10} m
10^-5	10 MeV	< 1 m (e+e-)	~10^{9} m	~10^{10} m
10^-3	0.1 MeV	~10^{18} m (3γ)	~10^{5} m	~10^{6} m
10^-3	10 MeV	~10^-5 m (e^+e^-)	~10^{5} m	~10^{6} m
10^-8	0.1 MeV	~10^{28} m (3γ)	~10^{15} m	~10^{16} m
10^-8	10 MeV	~10^{5} m (e+e-)	~10^{15} m	~10^{16} m

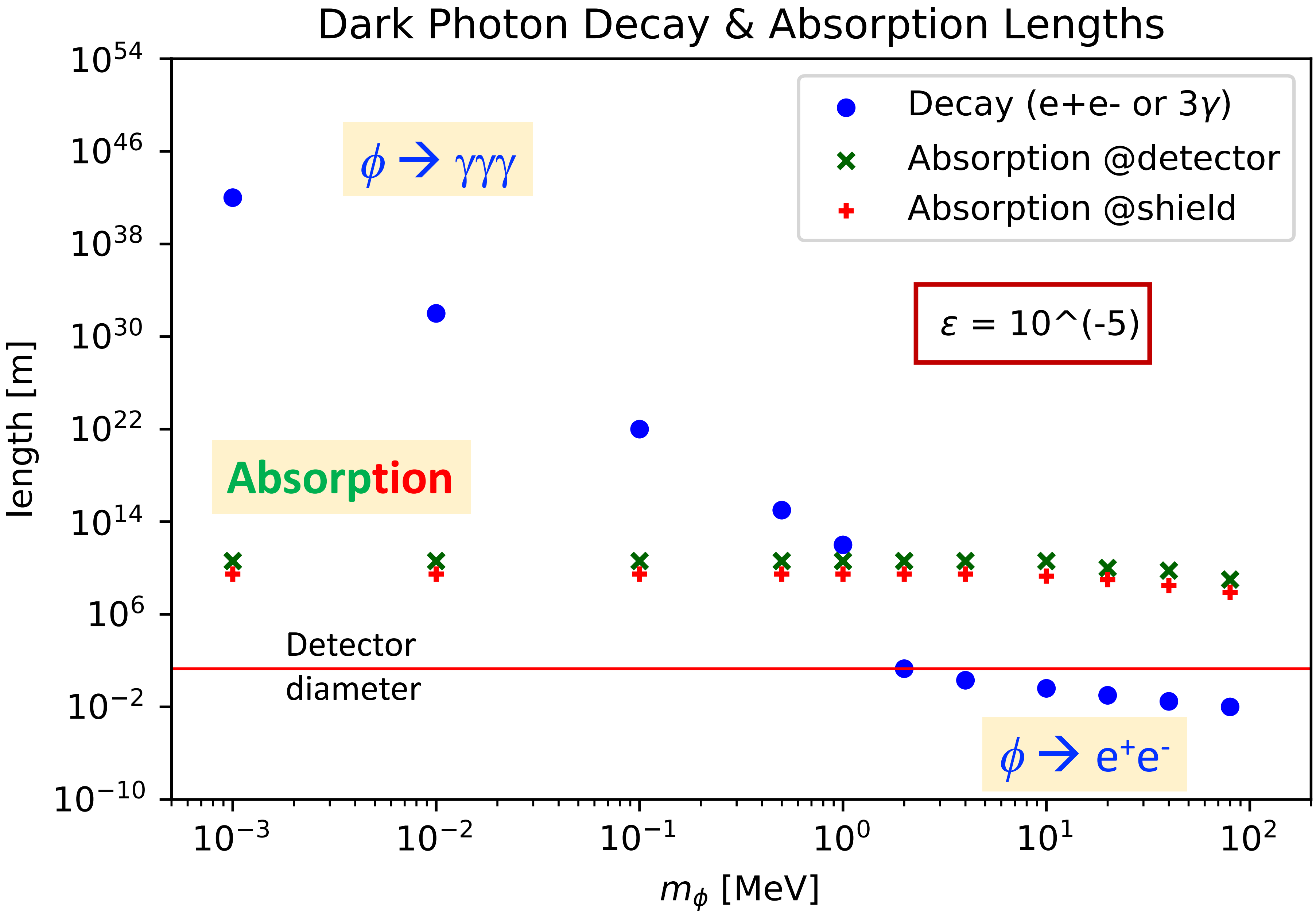
→ **DP absorption** is a dominant DP interaction mode **for light DP**.
< 1 MeV

→ **DP decay** is a dominant DP interaction mode **for heavier DP**.
(Significant fraction of DP loss is possible at shield.) > 1 MeV

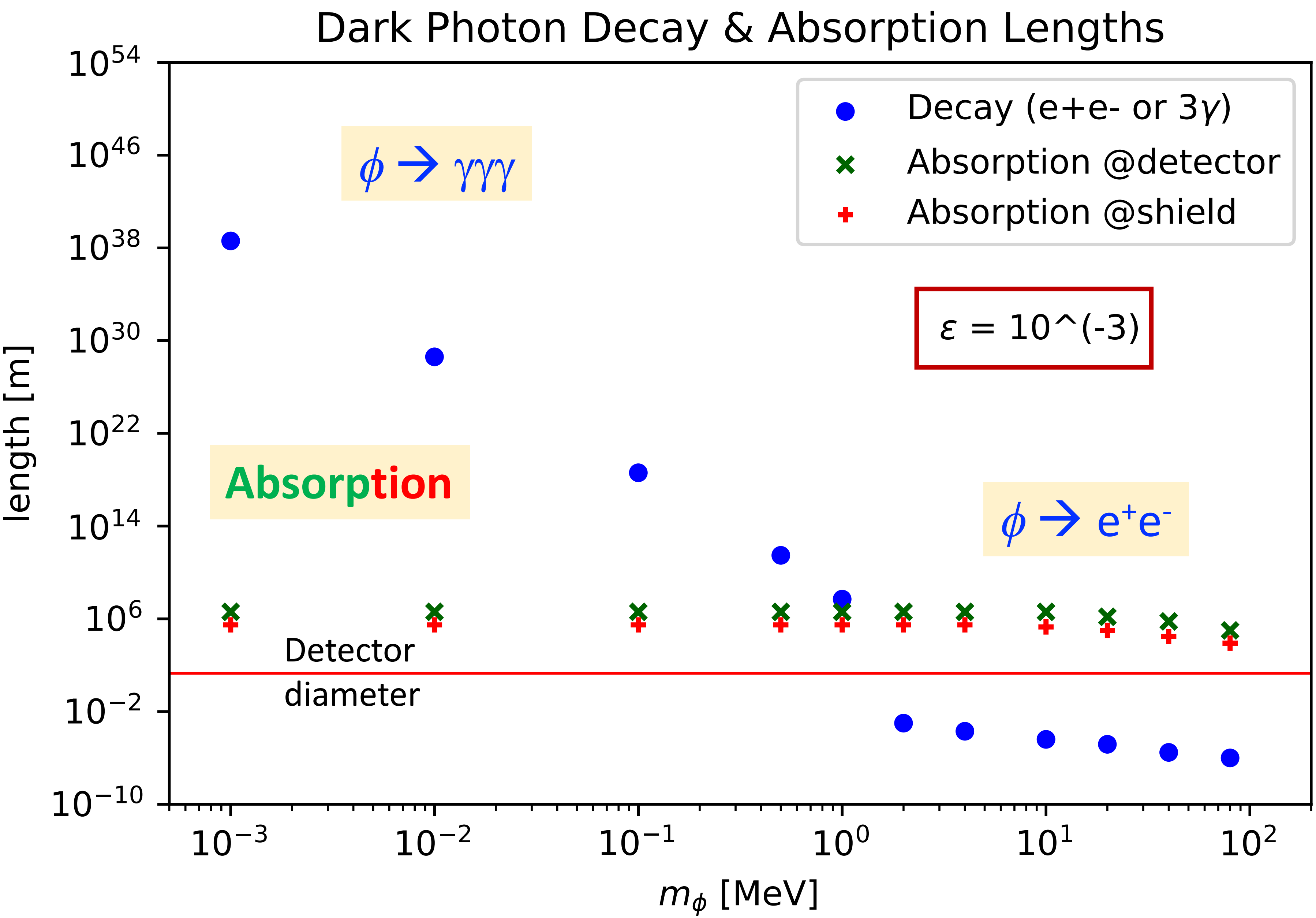
100 MeV *e-* beam
Tungsten target (0.5 m), Water detector

$L_{sh} = 0.5\ m,\ L_{decay} = 20\ m,\ L_{detector} = 20\ m$

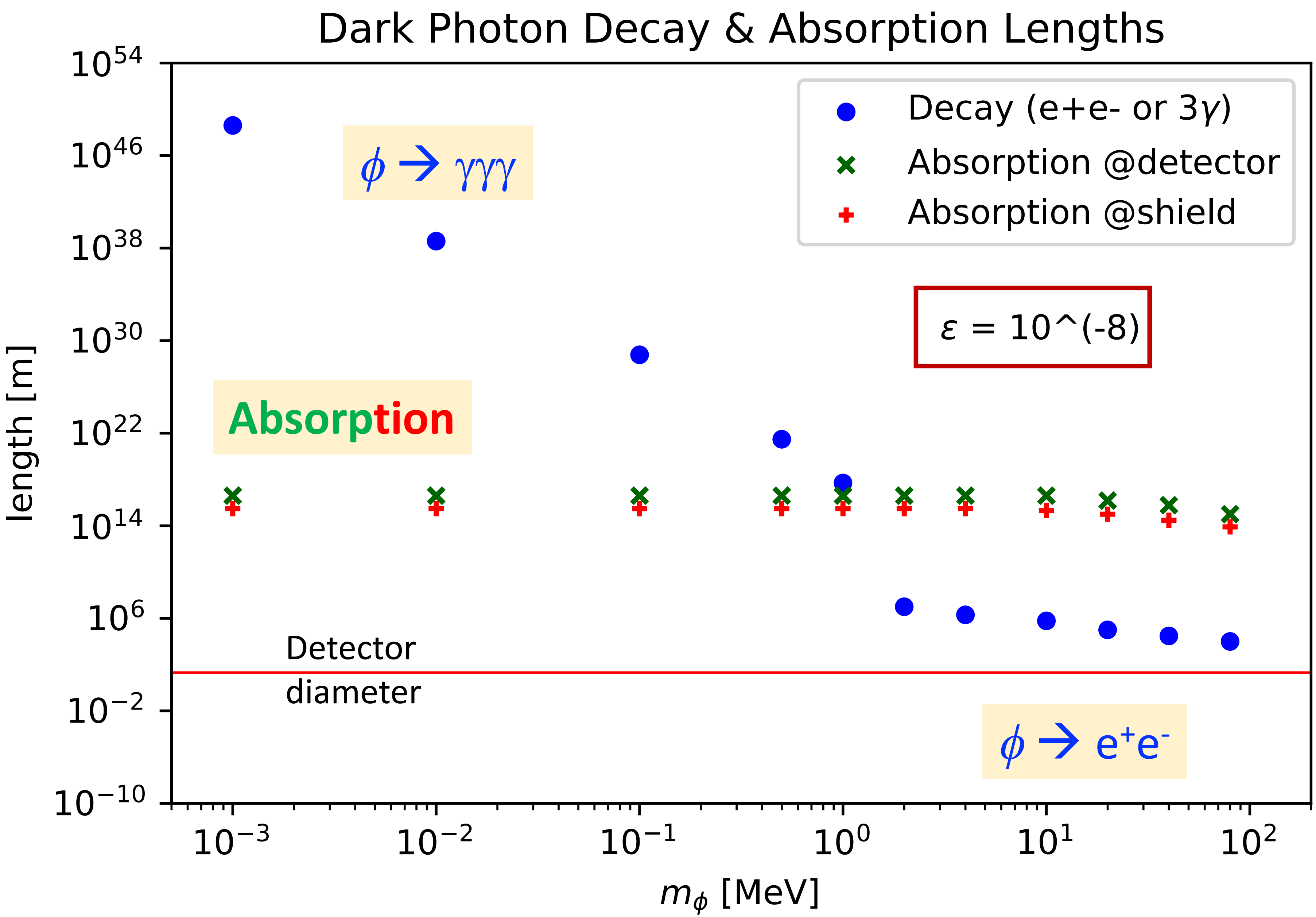
Preliminary



Preliminary



Preliminary



DP Decay or Absorption signal Probability

(A)

m_ϕ = 0.1 MeV
ε = 10^-5

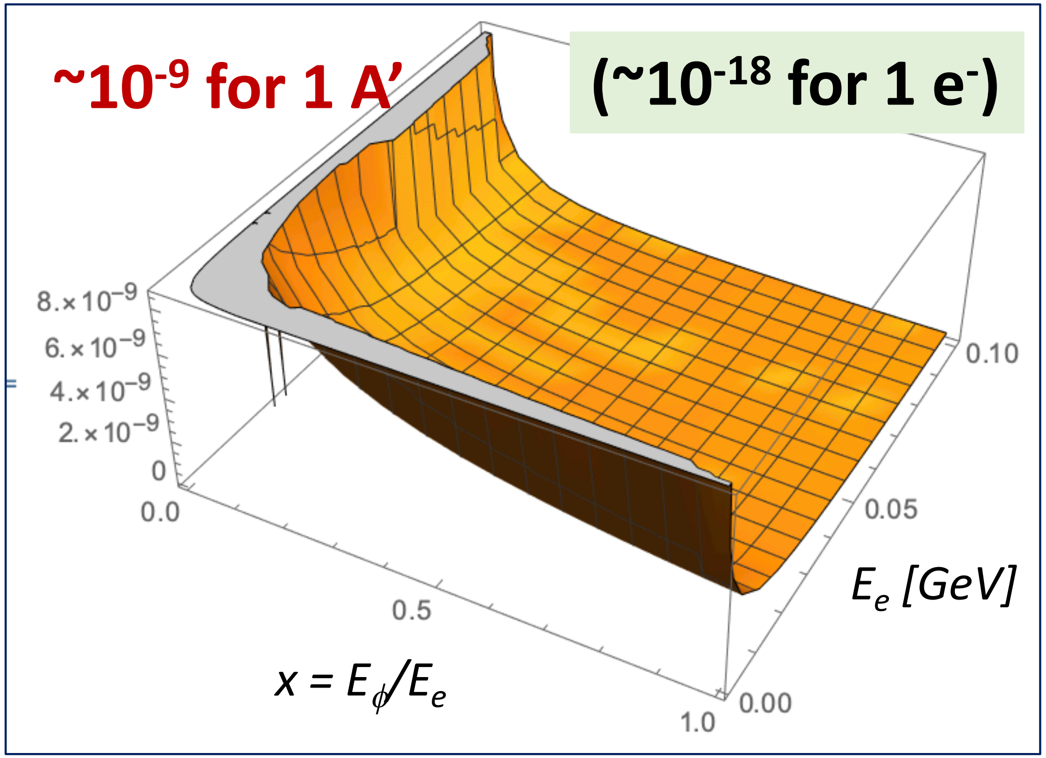
L_{decay} = 20 m
$L_{detector}$ = 20 m

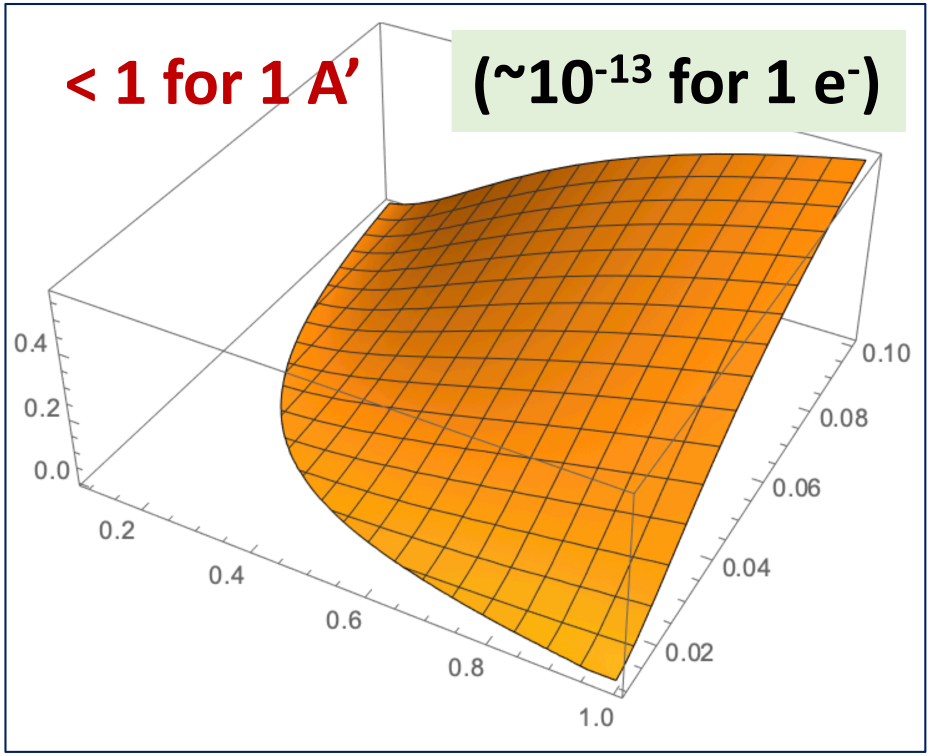
(B)

m_ϕ = 10 MeV
ε = 10^-5

Absorption only

Decay dominant





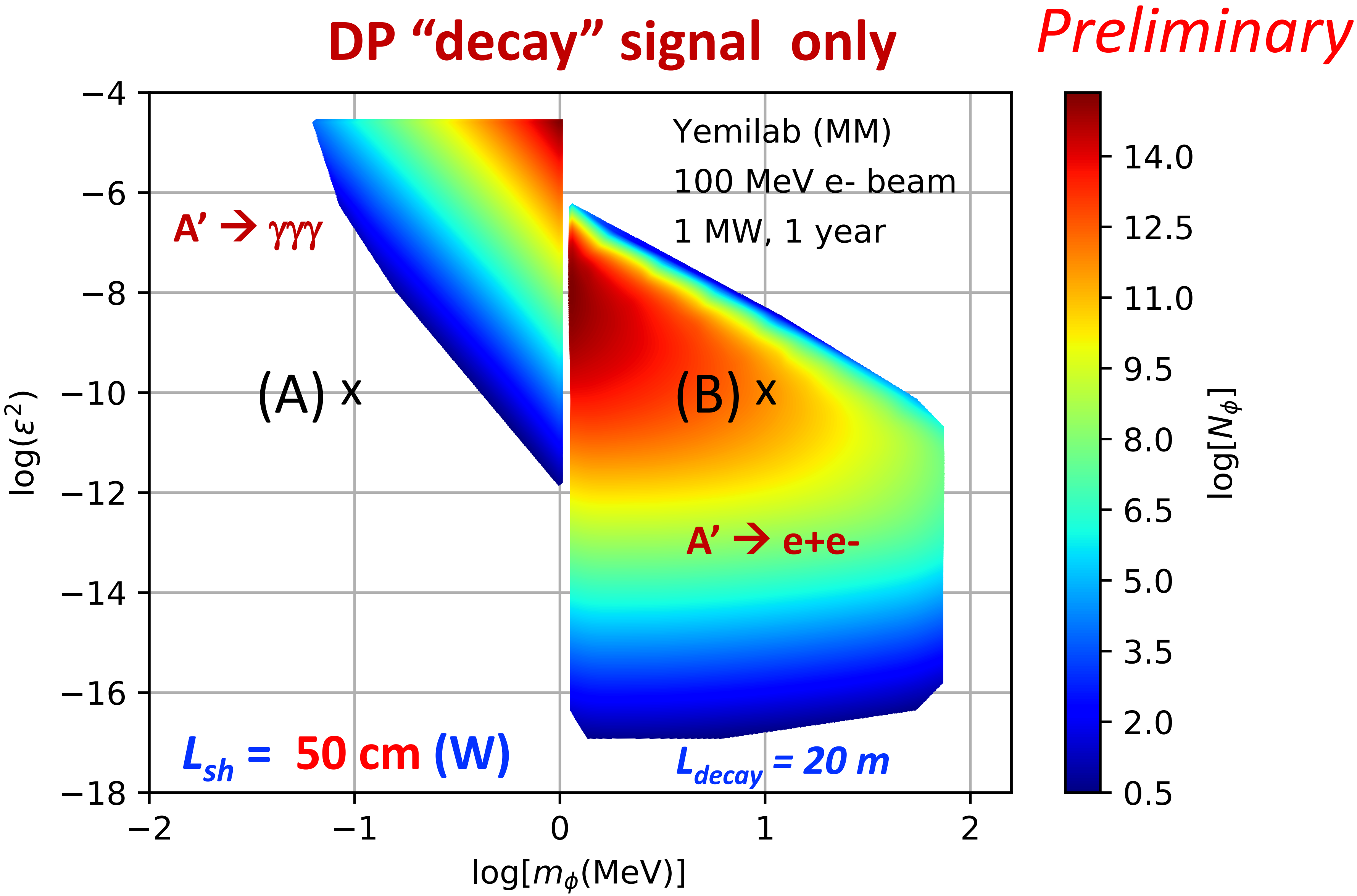
m_ϕ = 0.1 MeV
ε = 10^-8

(~10^{-15} for 1 A'
~ 10^{-30} for 1 e^-)

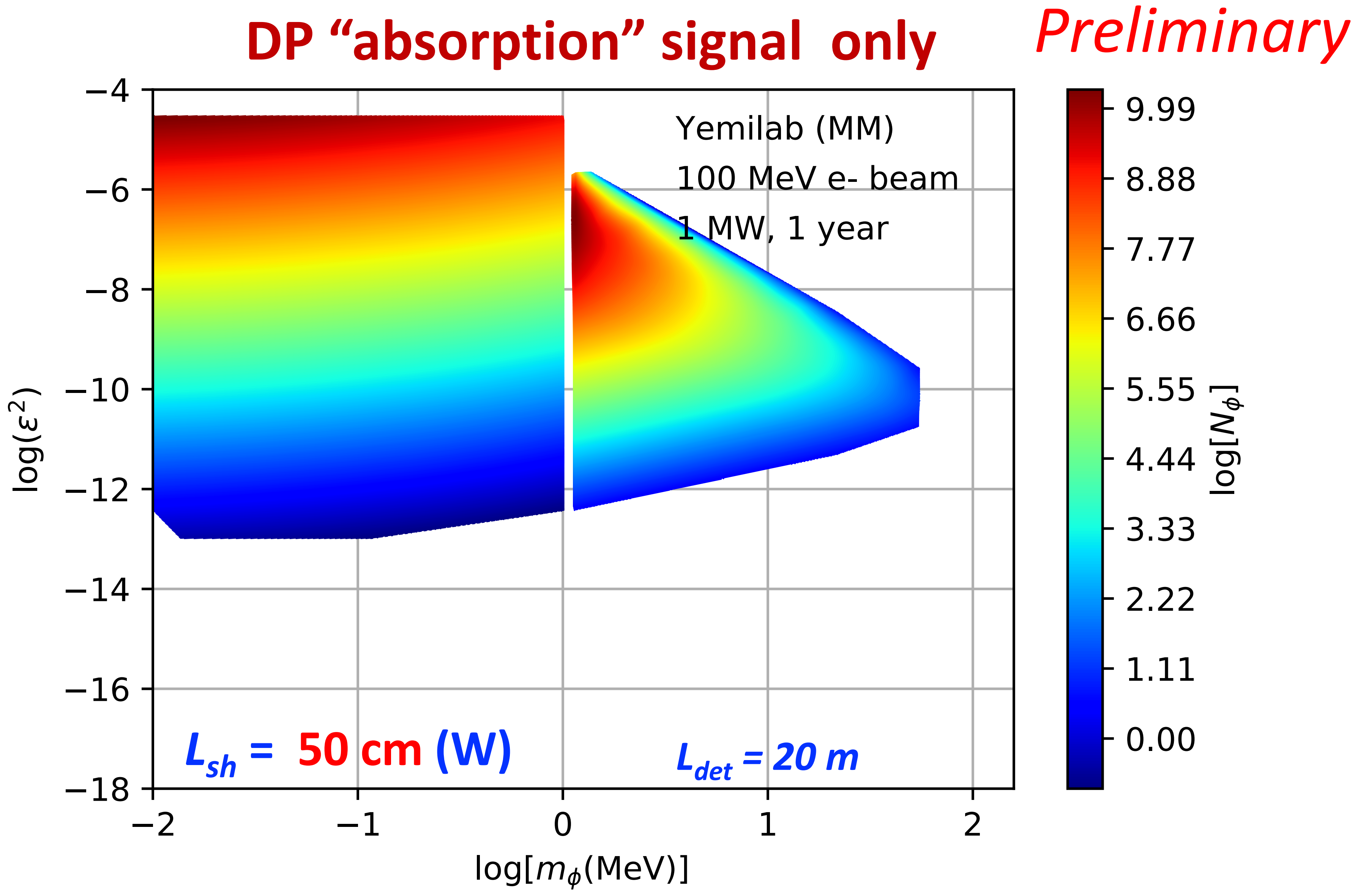
m_ϕ = 10 MeV
ε = 10^-8

(10^{-4} ~10^{-5} for 1 A'
~ 10^{-23} for 1 e^-)

DP Sensitivity @ YemiLab



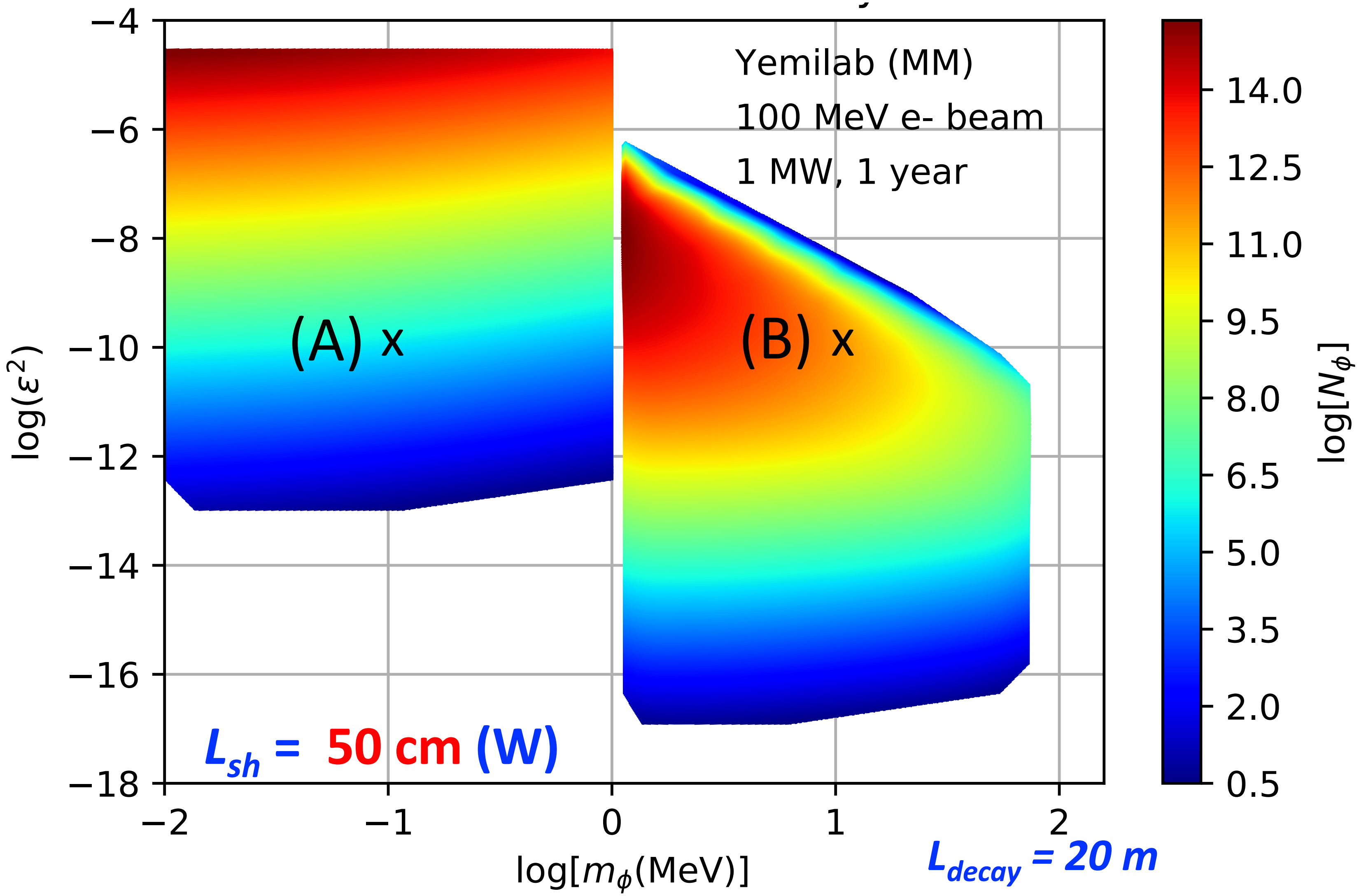
DP Sensitivity @ YemiLab



DP Sensitivity @ YemiLab

DP "decay" + "absorption"

Preliminary



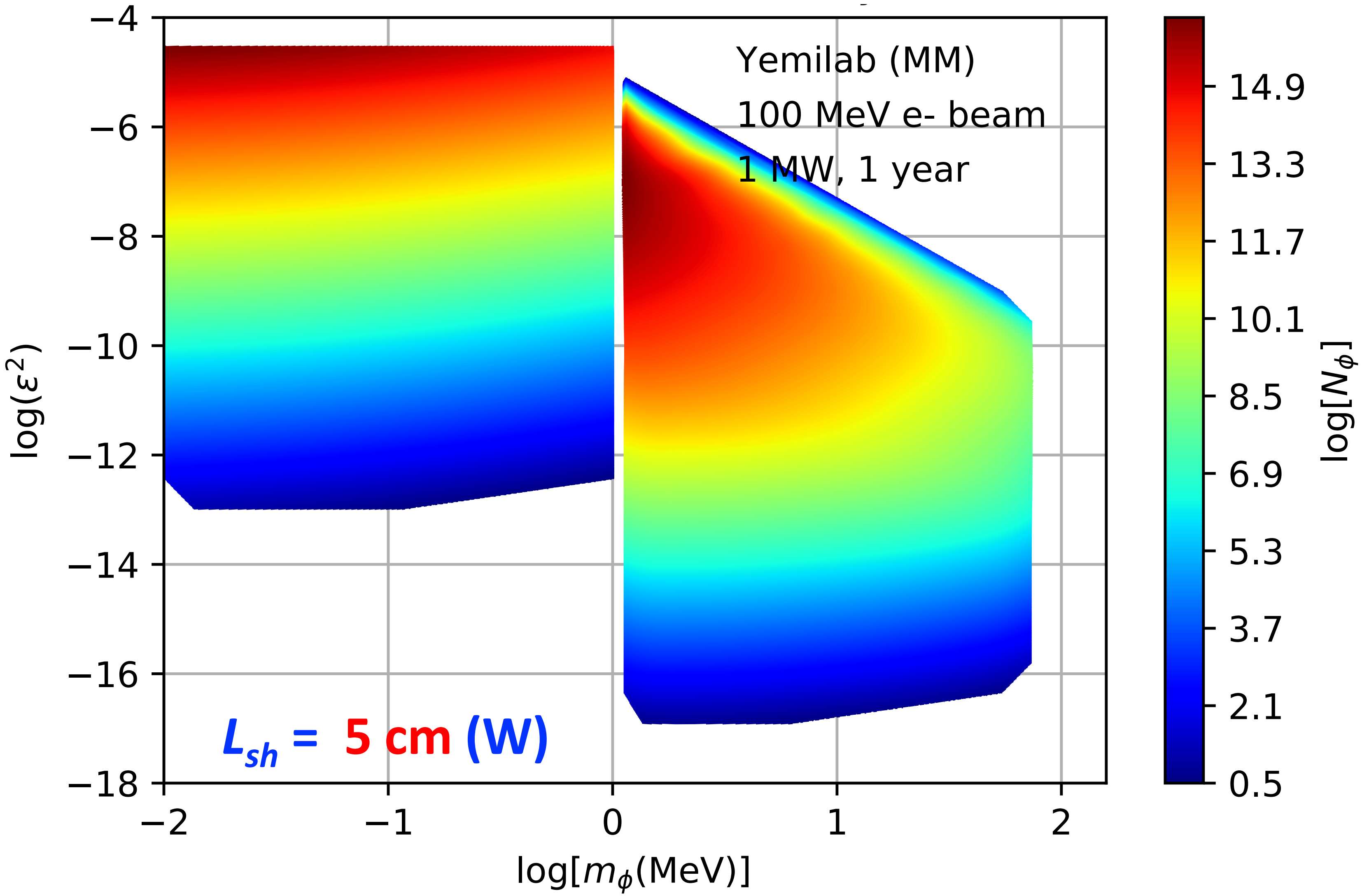
L_{decay} = 20 m

L_{det} = 20 m

DP Sensitivity @ YemiLab

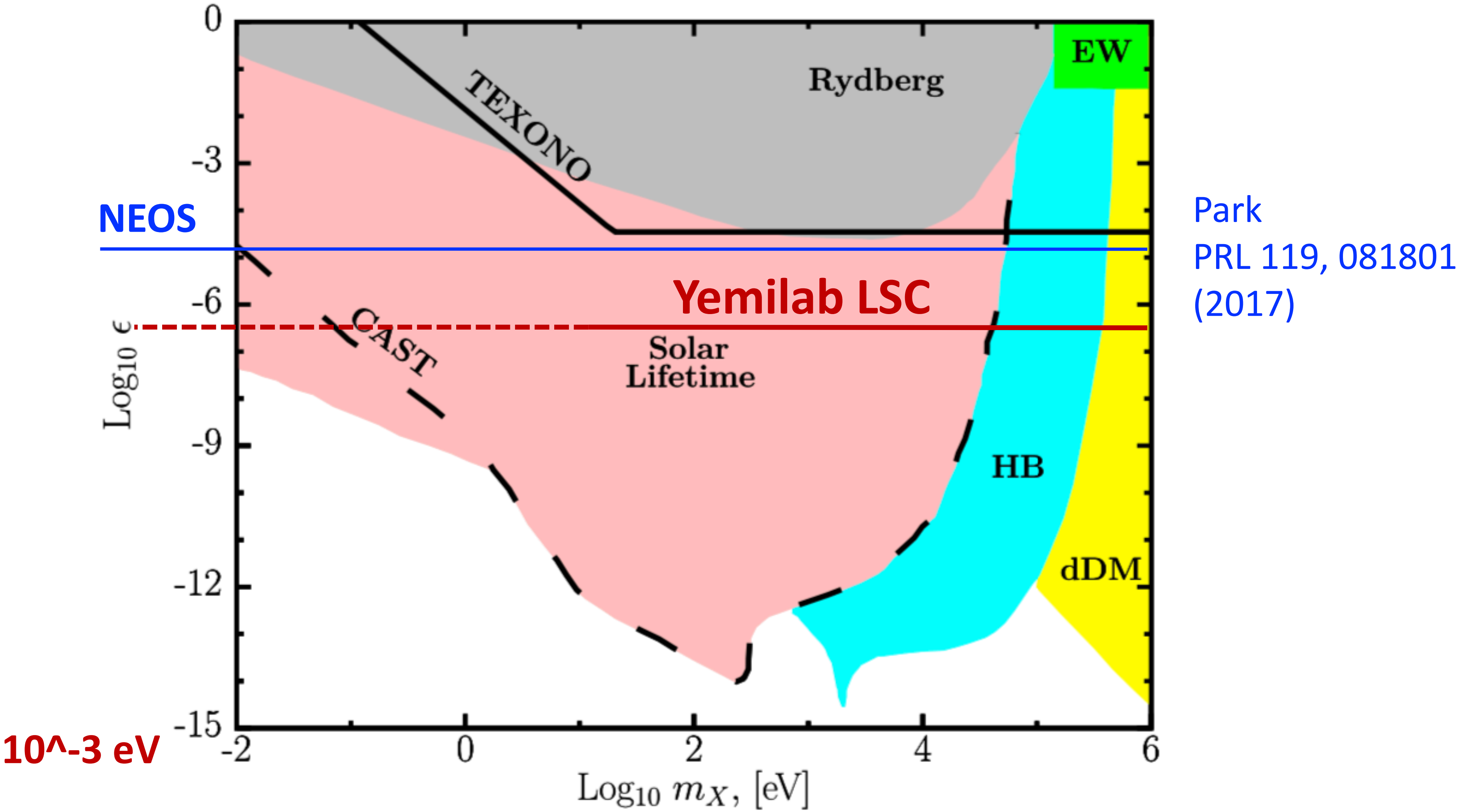
DP decay + absorption

Preliminary



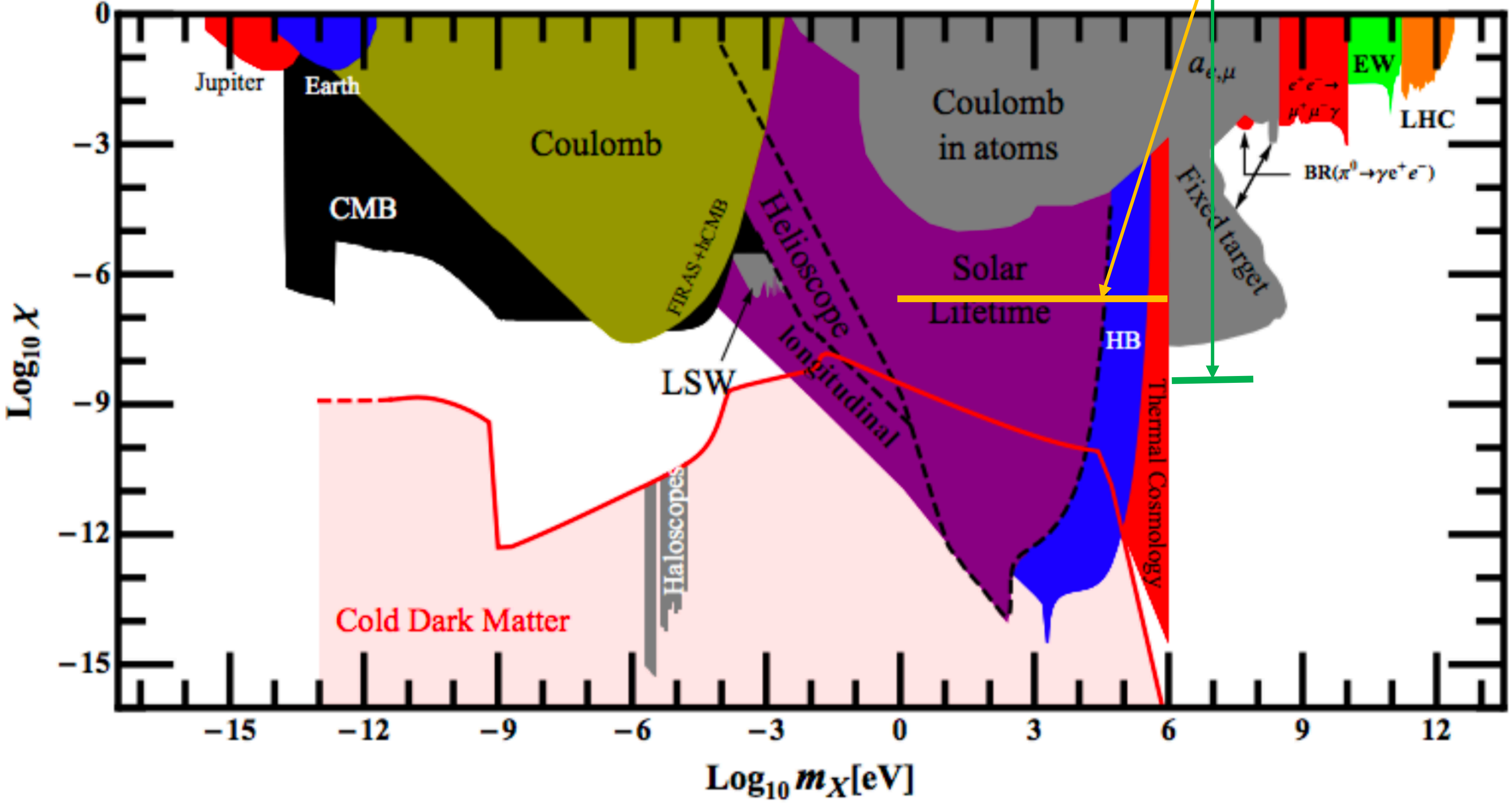
Sub-MeV A' Search

Danilov, Demidov, Gorbunov
PRL 122, 041801 (2019)



Full spectrum of A' search

Yemilab LSC



→ **Best direct DP search sensitivity in O(1 eV) < M_ϕ < 80 MeV**

Summary & Conclusion

- In Yemilab, we can host a ν detector (~3 kton LS).

→ multi-purpose detector: **dark photon**, solar ν, reactor ν, geo ν,…

- There has been increased interest in DP searches and various experimental techniques/models exist.

→ Some interesting results are expected in the near future.

- Using the ν detector (~3 kton LS) in Yemilab, w/ 1 year operation of 100 MeV e^- beam (1 MW), DP kinetic mixing coupling (ε) sensitivities are obtained:

  $\boldsymbol{\varepsilon^2 \sim 10^{-13}}$ (< 1MeV), $\boldsymbol{\varepsilon^2 \sim 10^{-17}}$ (> 1MeV) *preliminary*

→ **Best direct DP search sensitivity in O(1 eV) < M_ϕ < 80 MeV**