Dark Photon Search at Yemilab

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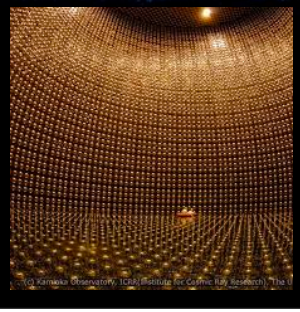

Neutrino Telescope 2021
Venice online

2021.02.26

Dark Photon Search at Yemilab, Korea

arXiv:2009.11155

Under review

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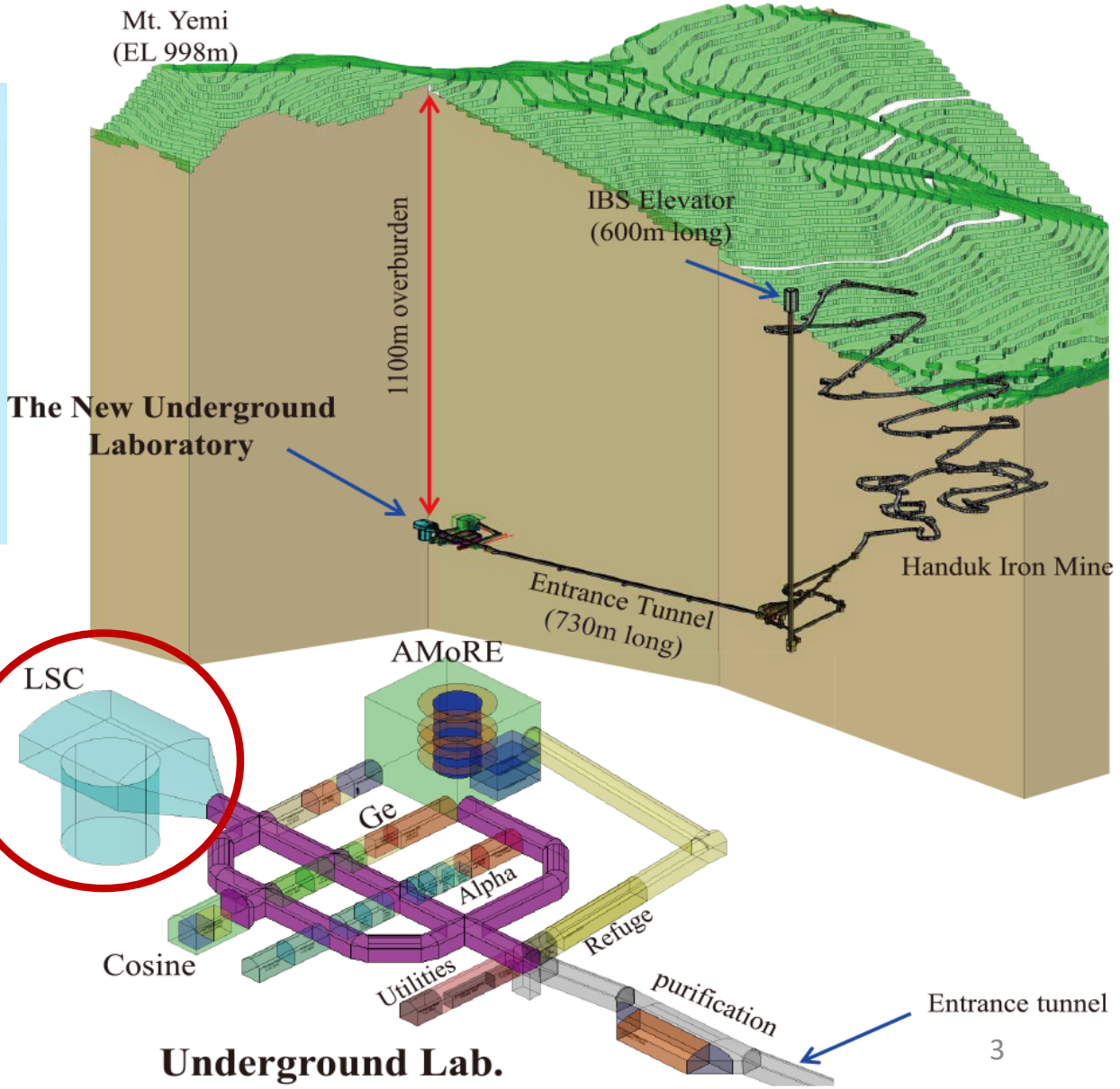
ABSTRACT: Dark photons are well motivated hypothetical dark sector particles that could account for observations that cannot be explained by the standard model of particle physics. A search for dark photons that are produced by an electron beam striking a thick tungsten target and subsequently interact in a 3 kiloton-scale neutrino detector in Yemilab, a new underground lab in Korea, is proposed. Dark photons can be produced by "darkstrahlung" or by oscillations from ordinary photons produced in the target and detected by their visible decays, "absorption" or by their oscillation to ordinary photons. By detecting the absorption process or the oscillation-produced photons, a world's best sensitivity for measurements of the dark-photon kinetic mixing parameter of $\epsilon^2 > 1.5 \times 10^{-13}(4.6 \times 10^{-13})$ at the 95% confidence level (C.L.) could be obtained for dark photon masses between 80 eV and 1 MeV in a year-long exposure to a 100 MeV electron beam with 100 kW (10 kW) beam power. In parallel, the detection of e^+e^- pairs from decays of dark photons with mass between 1 MeV and ~80 MeV would have sensitivities of $\epsilon^2 > \mathcal{O}(10^{-17})$ at the 95% C.L. for the 100 kW beam power, which are comparable to those of the Super-K experiment.

Yemilab: New Underground Lab in Korea

Yang Yang Lab (700 m) → Yemilab (1 km)



~1 km depth

To be completed in 2021

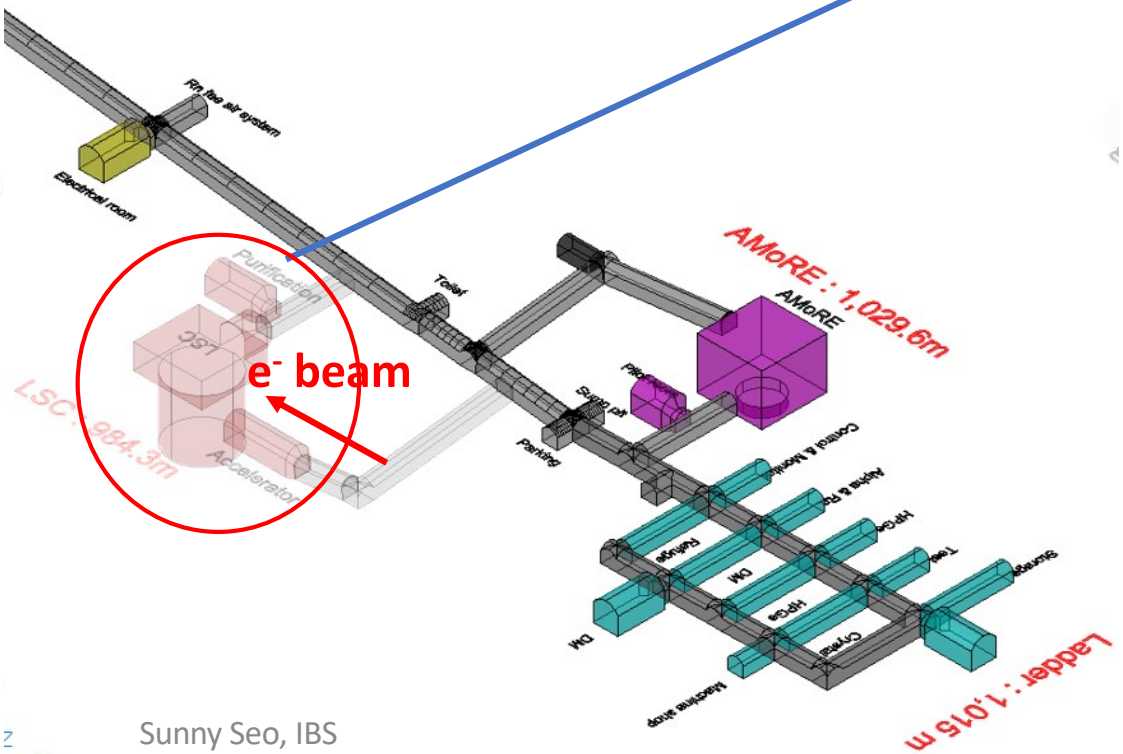
LSC @Yemilab

LSC = Liquid Scintillation Counter

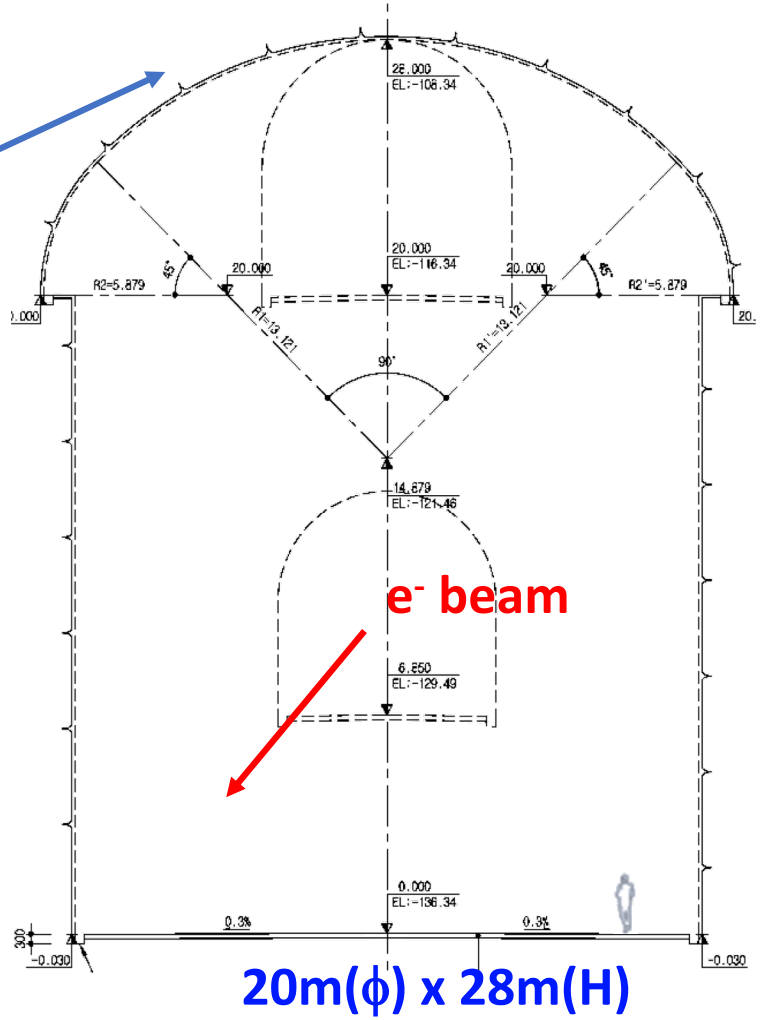
Pit: 20 m (D) x 20 m (H)

→ ν target: ~3 kton

Tunnel entrance

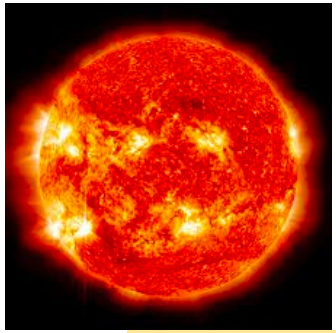


LSC Hall



Broad Physics Program

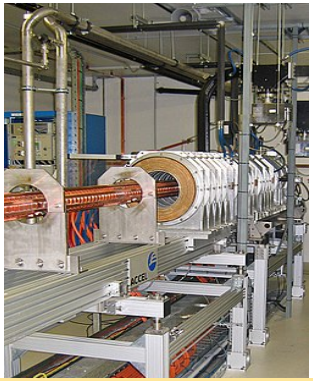
Solar ν



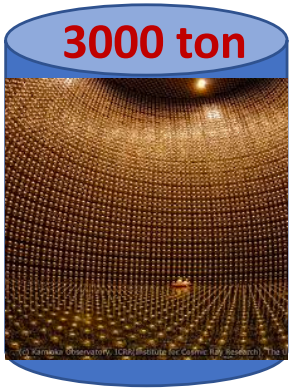
Supernova ν

ν Telescope

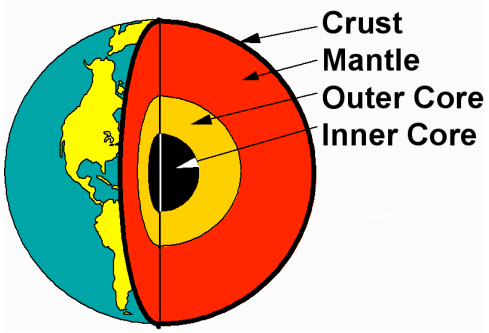
e- beam



Dark Photon

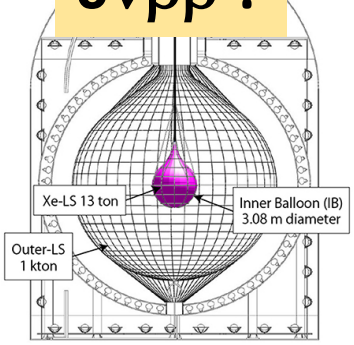


Geo ν

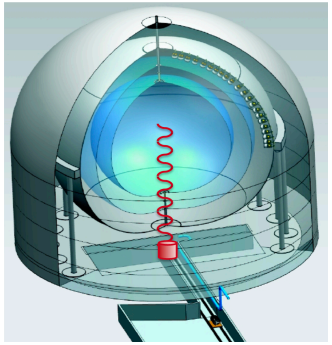


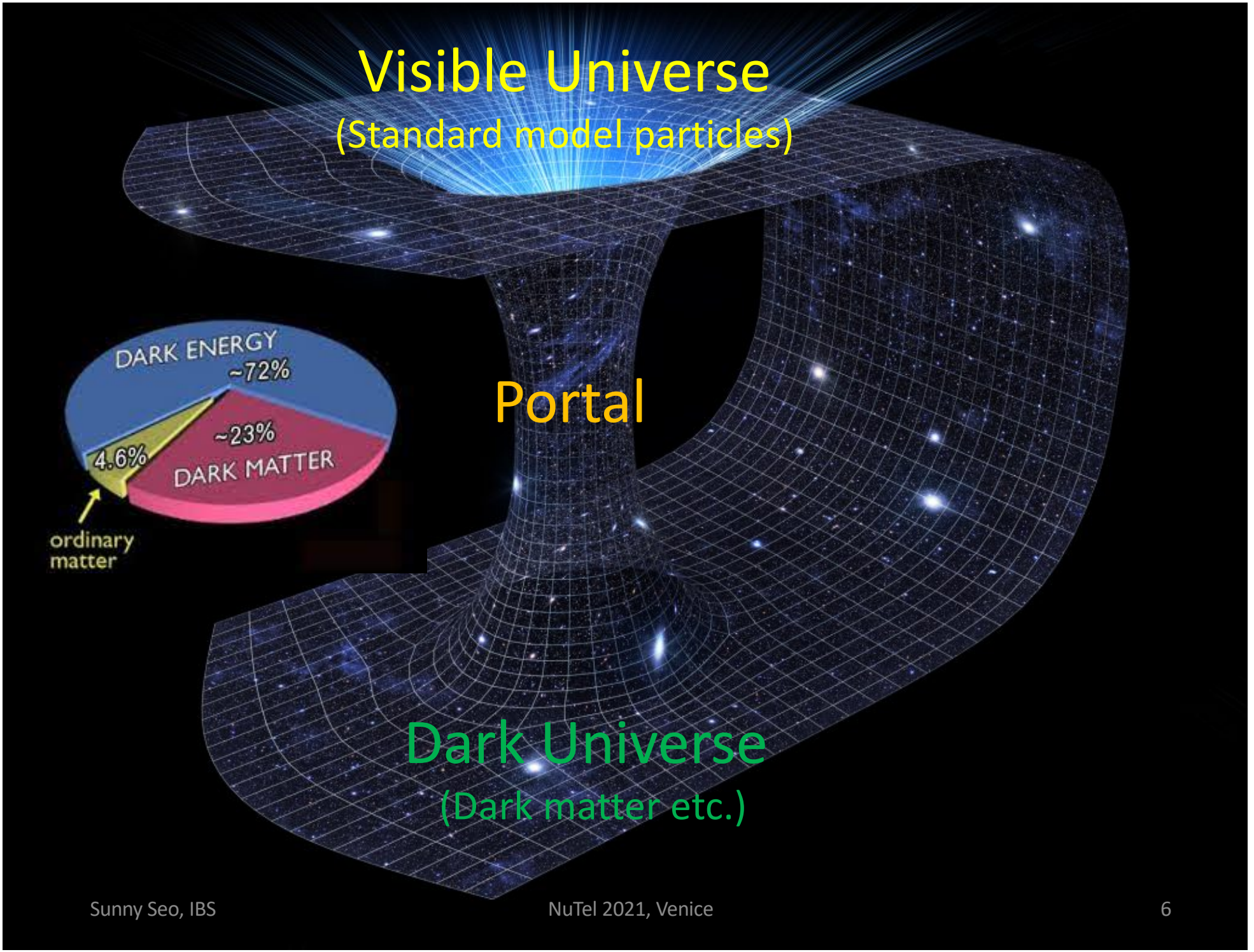
New step to Geo Science

0νββ ?



Sterile ν




Visible Universe
(Standard model particles)
DARK ENERGY
~72%
~23%
DARK MATTER
4.6%
ordinary
matter
Portal
Dark Universe
(Dark matter etc.)

Standard Model symmetries allow only a few important portals.

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

Dark Photon (DP)

- DP can mediate dark matter interaction.
- DP itself can be a candidate of dark matter.

- DP can be searched via vector portal.

$$\mathcal{L} \supset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{m_\phi^2}{2} A'_\mu A'^\mu$$

DP field strength tensor

$U(1)_D$ gauge field

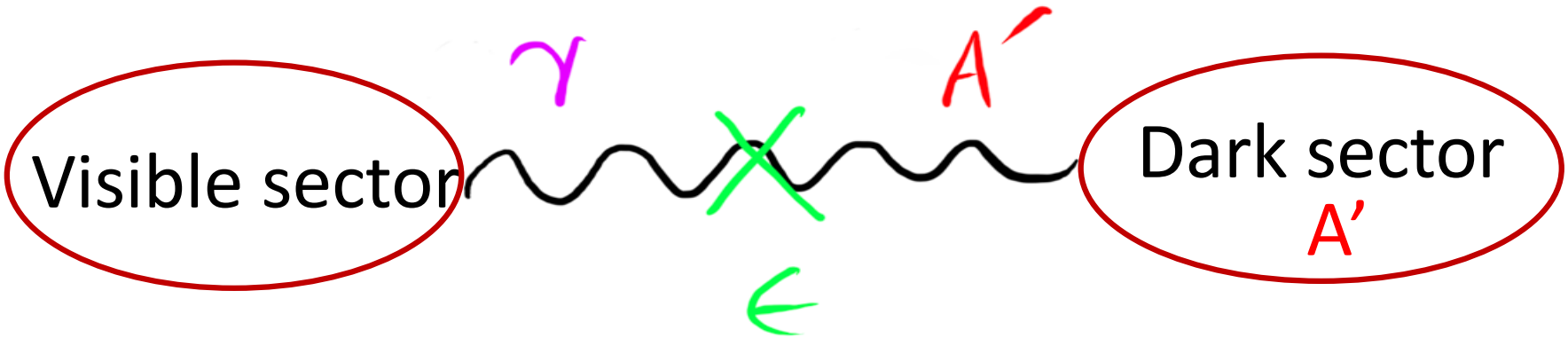
ε: “kinetic mixing” parameter

“Kinetic Mixing”

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

***U*(1) symmetry** **$U(1)_D$ symmetry**

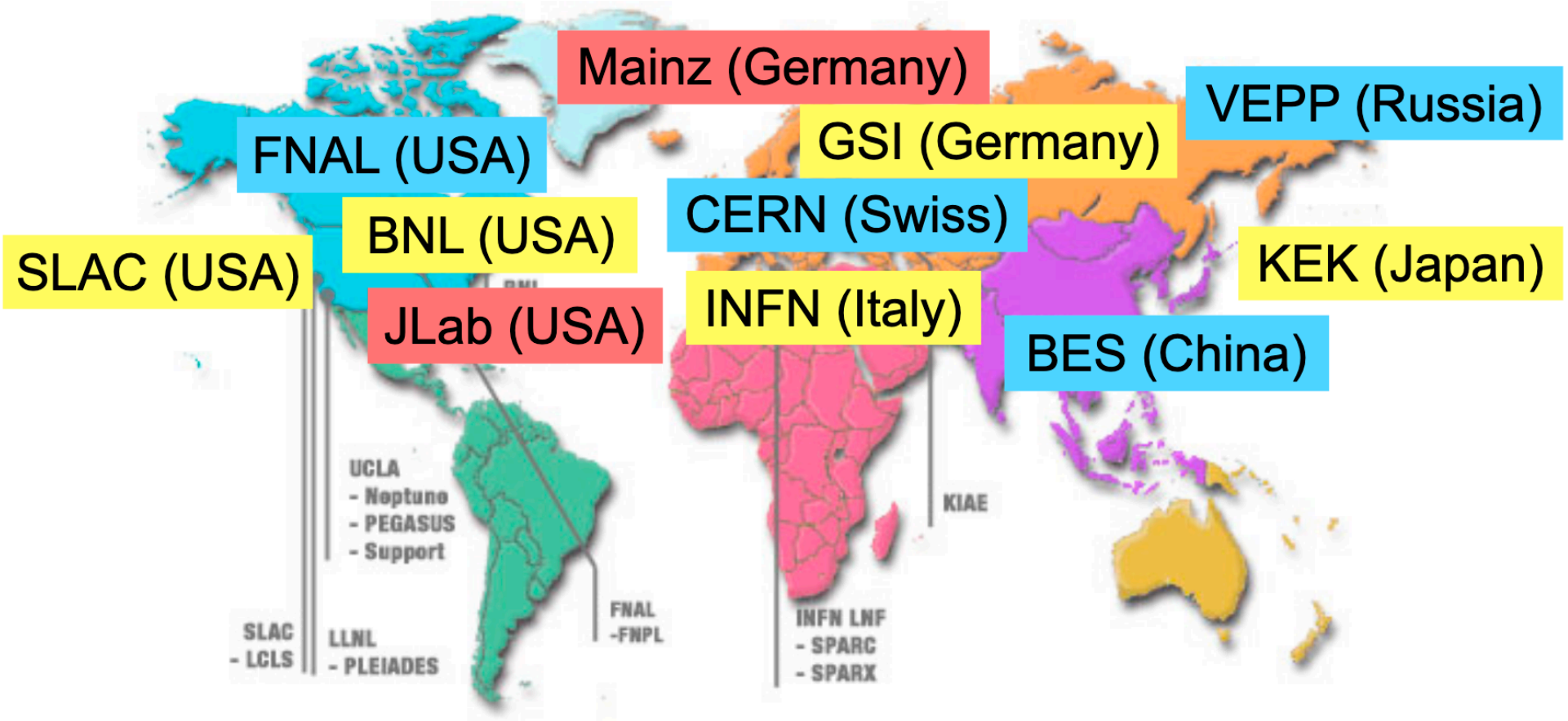
→ Most popular DP model



Other DP models:

- B-L
- Leptophilic gauge boson
- Flavor non-universal coupling
- etc.

Dark Photon Search Labs



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

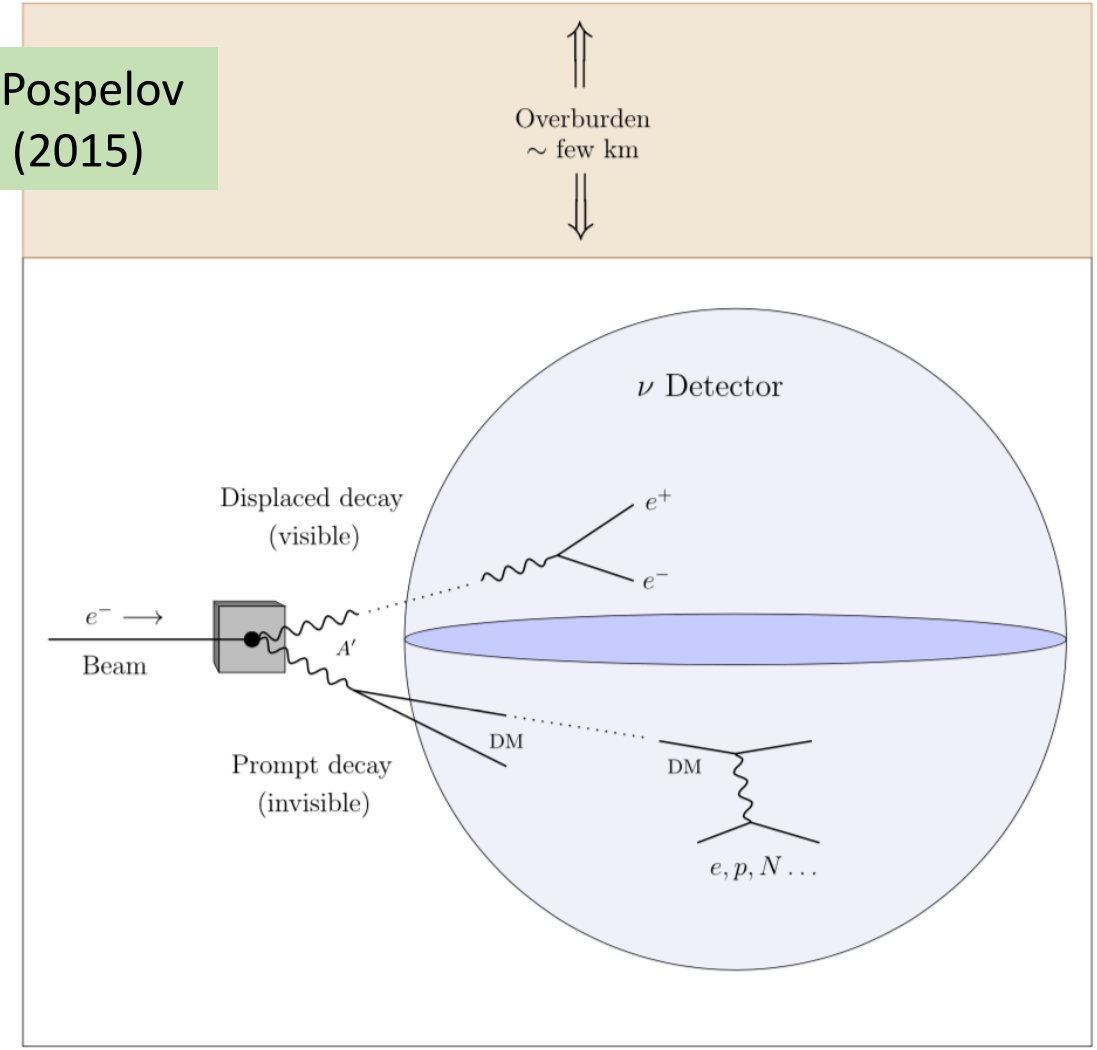
- ❑ Astrophysical Obs.

SN 1987A, Sun etc.

➢ **Increased interest on Dark Photon Search !!**

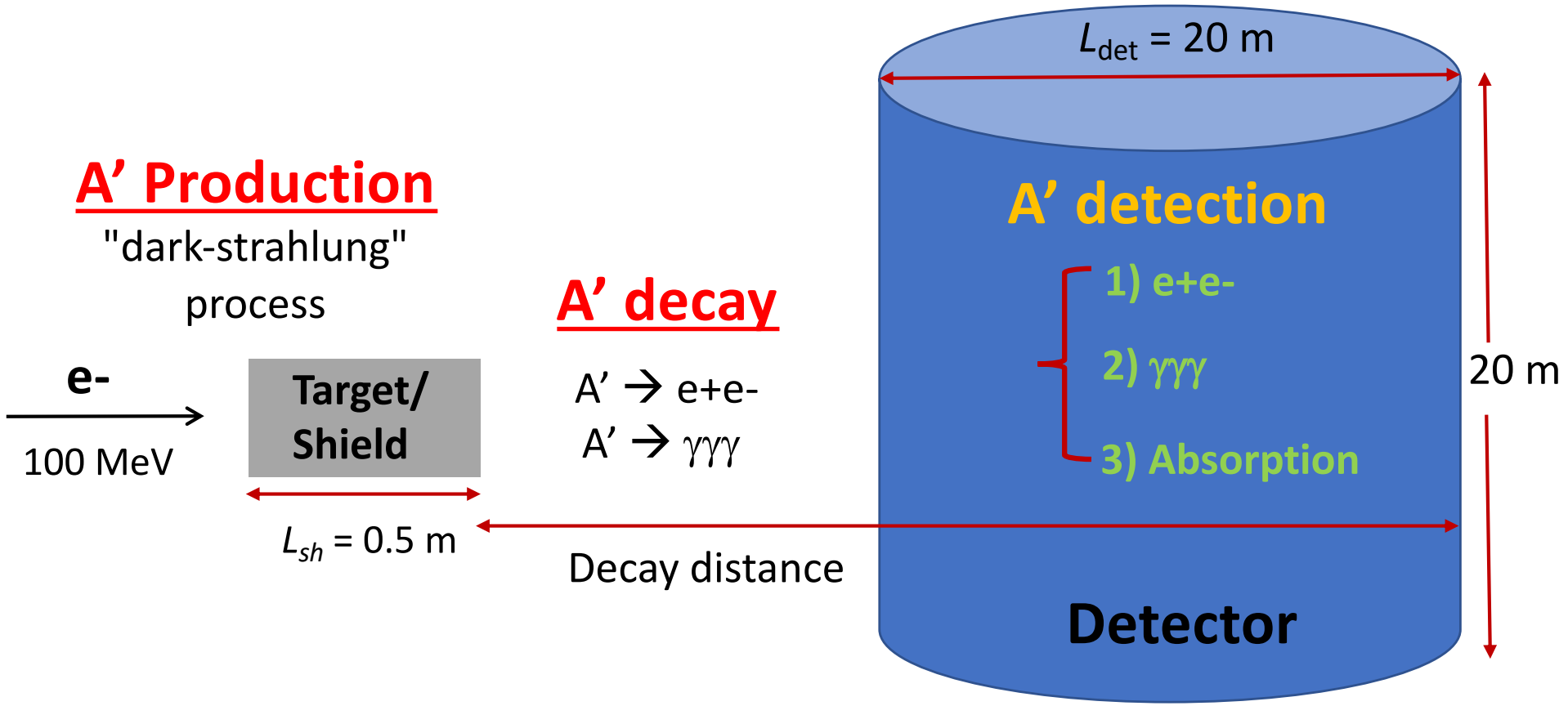
Dark Photon Search at Deep Underground

Izaguirre, Krnjaic, Pospelov
PRD 92, 095014 (2015)



Currently, no DP search experiments underground.

Dark Photon Search Scheme

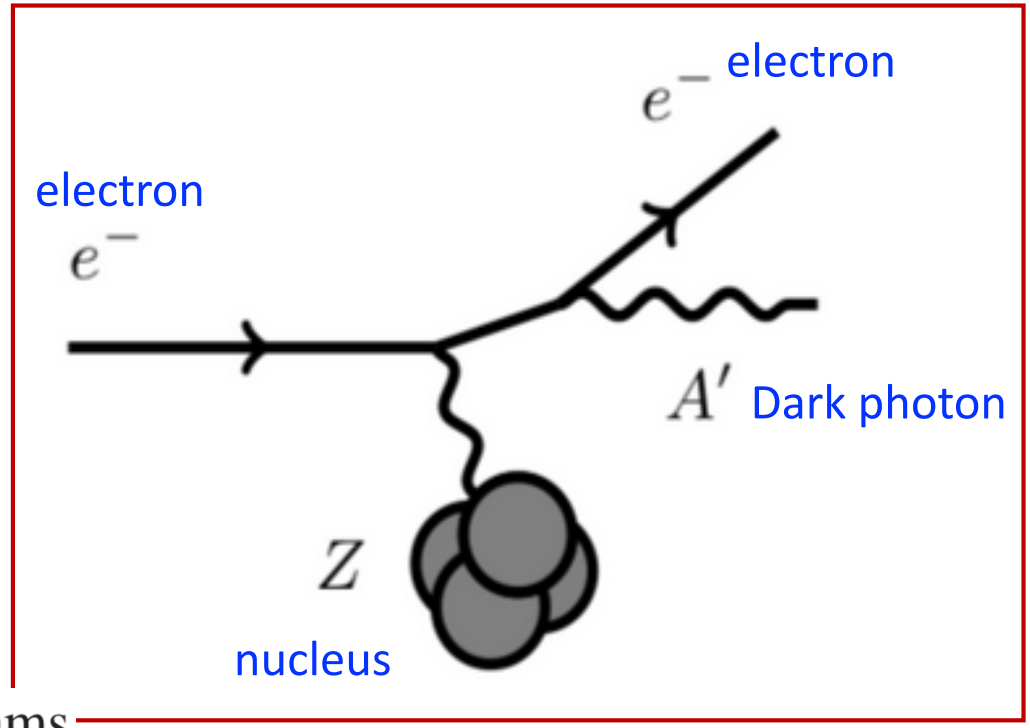


Dark Photon Productions

e⁻ beam

a.k.a.

"Bremsstrahlung-like" process **"dark-strahlung"**



Weizsäcker-Williams

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

Liu & Miller: PRD 96, 016004 (2017)

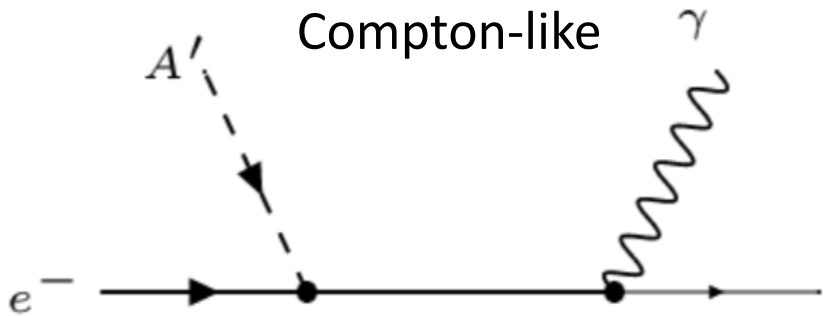
$$\tilde{u}_{\max} = -m_\phi^2\frac{1-x}{x} - m_e^2x.$$

Dark Photon Detections

❑ Visible Decays

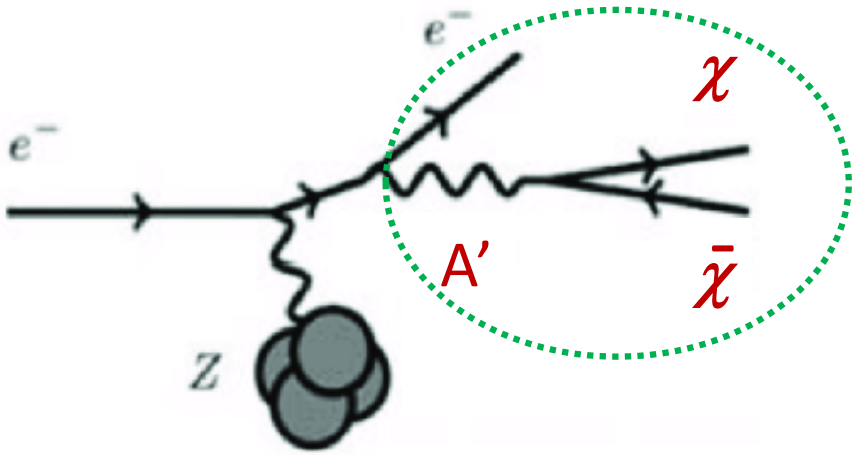
- A’ → e+ e- (> 1 MeV)
- A’ → $\gamma\gamma\gamma$ (< 1 MeV)

❑ Absorption



In our study,
we considered **only <u>visible decay</u> & <u>absorption</u>**.

❑ Invisible Decays



Expected # of Dark Photons

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

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

DP production x-section

only decay signal

Liu & Miller: PRD 96, 016004 (2017)

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

$$x[1 - \exp(-L_{dec}/l_\phi - L_{det}/\lambda_{det})]$$

decay or absorption signal

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

Rough Background Estimation

Signal = Beam (ON – OFF) data ~ 0 events

→ # of background events in beam OFF data can affect our sensitivity

Preliminary

Background types	#. BKG events (/year/1 kton fiducial vol.)	Comments
Solar ν (^{8}B), residual, external BKG	935	Estimated from Borexino arXiv:1709.00756
Atmospheric ν	67	Estimated from Borexino *J.Phys.Conf.Ser.* 675 (2016) 1, 012014
Neutrons from beam	0	Block w/ rocks (few meters) & 5 MeV cut
ν from beam	0	negligible
Total	1002	

Sensitivity w/ Background

Signal = Beam (ON – OFF) data ~ 0 events

$$N_{DP} = N_{ON} - N_{OFF}\left(\frac{T_{ON}}{T_{OFF}}\right) \approx 0.$$

$$\Delta N_{DP} = \sqrt{N_{ON} + \left(\frac{T_{ON}}{T_{OFF}}\right)^2 N_{OFF}} = \sqrt{N_{ON}\left(1 + \frac{T_{ON}}{T_{OFF}}\right)}$$

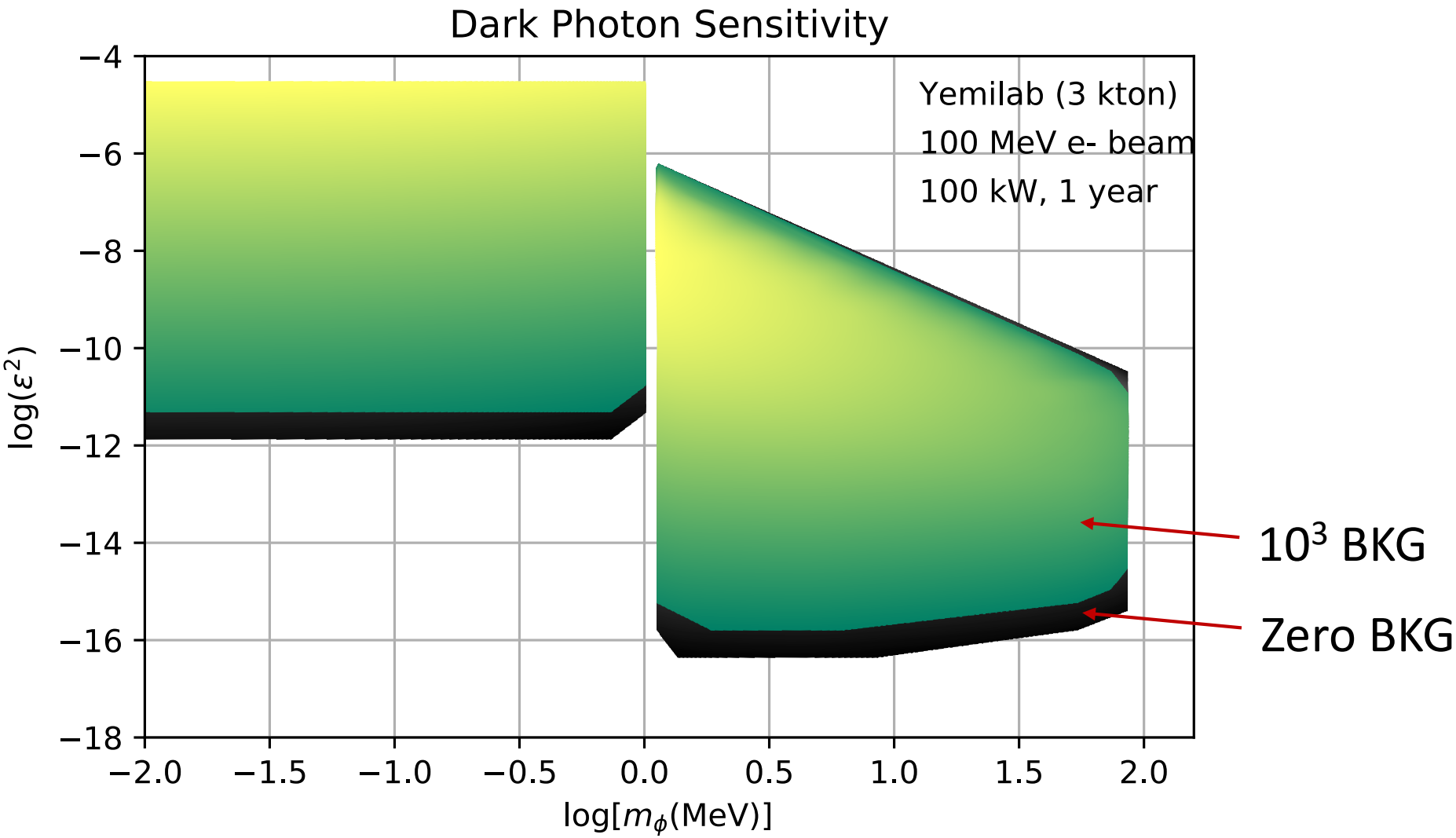
w/ long period of beam OFF data

$$\Delta N_{DP} \approx \sqrt{N_{ON}} \approx 32.$$

1002 BKG events

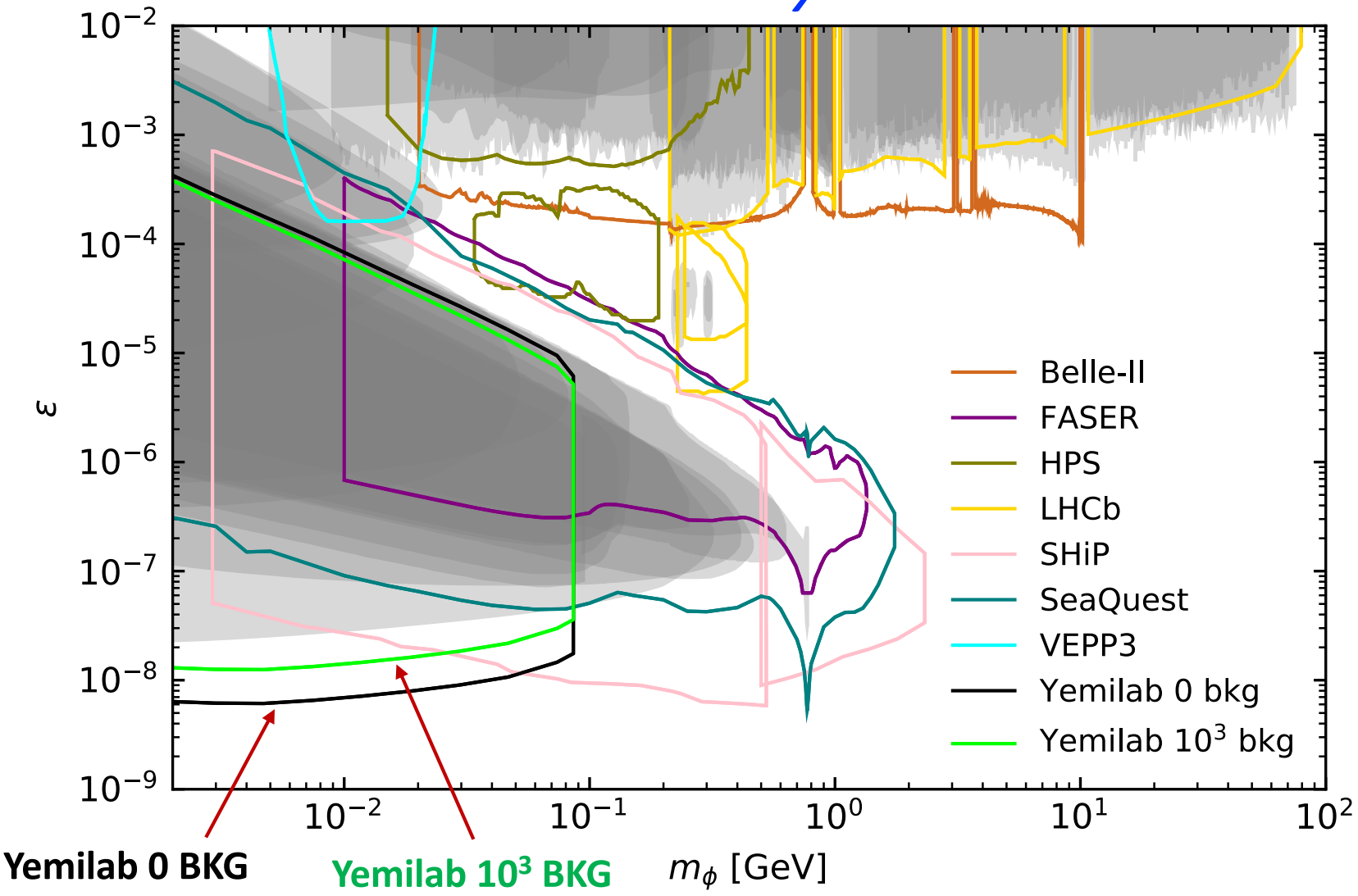
95% CL (one-sided): 1.645 x ΔN_{DP} = 53

Preliminary



Current Limits & Future Projections

Preliminary



https://gitlab.com/philten/darkcast

γ → A' Oscillations

- γ—> A' oscillation @ target (**T**ungsten)

$$P(\gamma \to A') = \epsilon^2 \times \frac{{m_\phi}^4}{(\Delta m^2)^2 + E_\gamma^2 \Gamma^2},$$

1812.02719
1804.10777
1501.07292

- A'—> γ oscillation @ detector (**W**ater)

$$P(A' \to \gamma) = \epsilon^2 \times \frac{{m_\phi}^4}{(\Delta m^2)^2 + E_\gamma^2 \Gamma^2} \times \Gamma L,$$

$$\text{where } \Delta m^2 = \sqrt{(m_\phi^2 - m_\gamma^2)^2 + 2\epsilon^2 m_\phi^2 (m_\phi^2 + m_\gamma^2)} \approx |m_\phi^2 - m_\gamma^2|, \; m_\gamma = \sqrt{4\pi\alpha n_e / m_e}$$

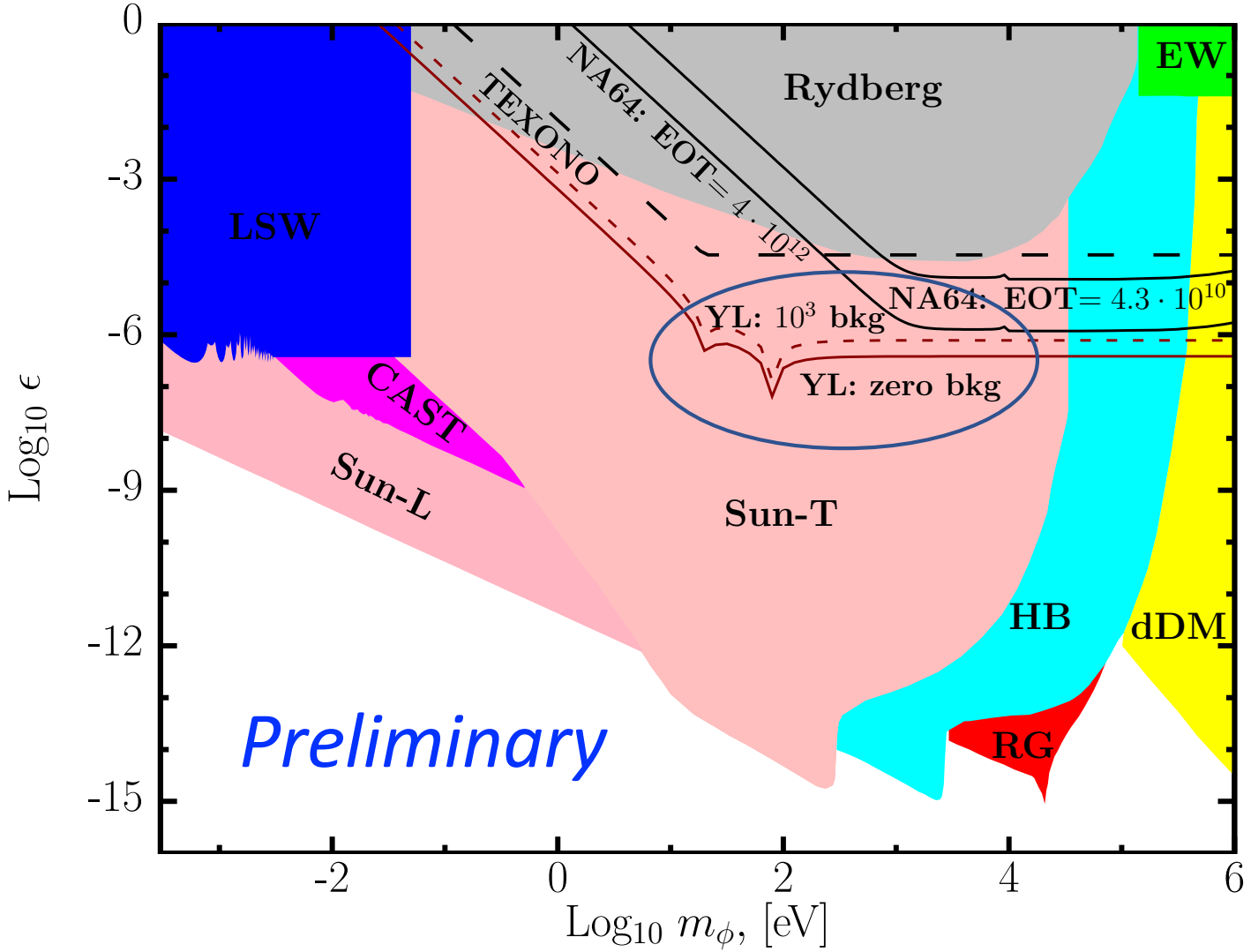
$$P(\gamma \leftrightarrow A') = \epsilon^4 \times \frac{m_\phi^8}{\left((m_\phi^2 - m_\gamma^{\mathrm{T}\,2})^2 + E_\gamma^2 \Gamma_{\mathrm{T}}^2\right) \times \left((m_\phi^2 - m_\gamma^{\mathrm{W}\,2})^2 + E_\gamma^2 \Gamma_{\mathrm{W}}^2\right)} \times \Gamma_{\mathrm{W}} L,$$

$$N_\phi^{\mathrm{osc}} \approx N_{\mathrm{e}} \times \int_{E_\gamma^{\mathrm{min}}}^{E_\gamma^{\mathrm{max}}} dE_\gamma P(\gamma \leftrightarrow A') \int_0^T dt \left(I_\gamma^{(1)}(t, E_\gamma) + I_\gamma^{(2)}(t, E_\gamma) \right)$$

Tsai & Whitis, Phys.Rev. 149 (1966) 1248-1257

Photon flux per electron

γ → A' Oscillation Sensitivity



Best "direct" DP search sensitivity at sub-MeV region

Summary & Conclusion

- In new Yemilab, we'll have a **cavern** for ν det. (~3 kton LS)

Ready by Sept. 2021

→ multi-purpose detector: **dark photon**, **solar ν**, geo ν, sterile ν, etc.

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

- 1 year operation of 100 MeV e^- beam (100 kW):
  best "direct" dark photon search sensitivity
  in O(1 eV) < M_ϕ < 30 MeV (assuming 10^3 background)

- To do: promoting more collaborators, white paper, R&D etc.

You are very welcome to join us !