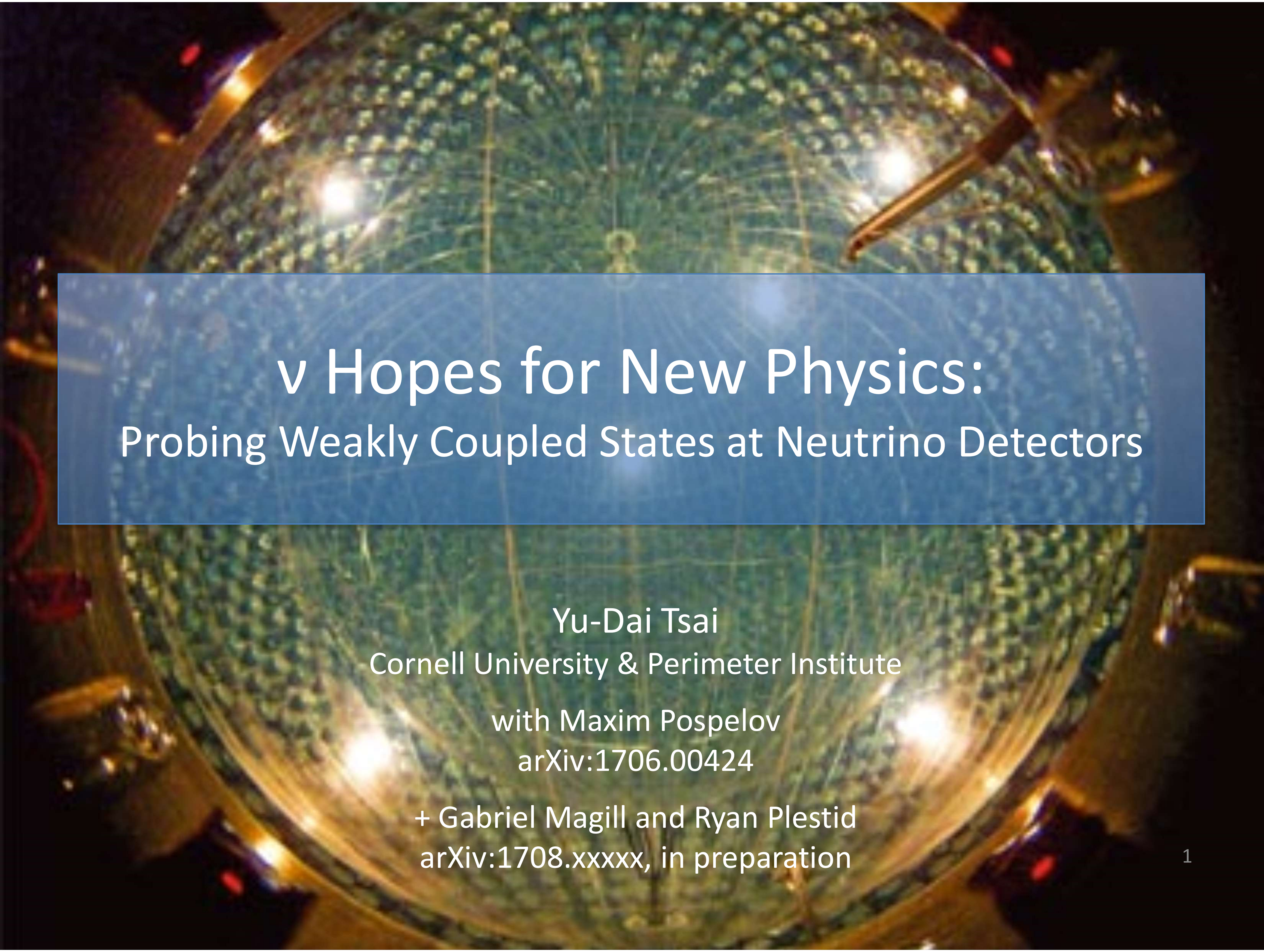


ν Hopes for New Physics:

Probing Weakly Coupled States at Neutrino Detectors

Yu-Dai Tsai
Cornell University & Perimeter Institute

with Maxim Pospelov

arXiv:1706.00424

+ Gabriel Magill and Ryan Plestid

arXiv:1708.xxxxx, in preparation

Ongoing Research

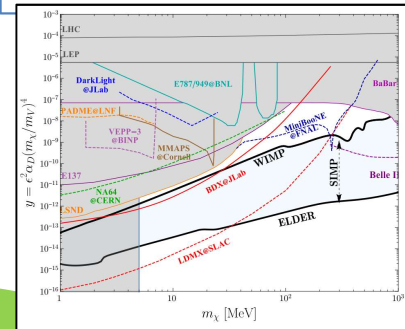
I'm Yu-Dai Tsai,
a rising 5th year PhD
student at Cornell

1 Sub-GeV Thermal DM

- Perelstein + Slatyer
- Kuflik + Xue
- Lorier + Liu

- **ELDER** / ELDER + **NFDM**
- Experimental /Observational Signatures
  - 1512.04545, 1706.05381...

ELastic (Thermal) DEcoupling Relic often with 3 to 2!
Related to Hitoshi's Amazing Talk this Morning.



2 ν Hopes for New Physics

- Maxim Pospelov
- Gabriel Magill
- Ryan Plestid

Constraints and signatures of new physics in **neutrino detectors**, including **BoreXino**, **LSND**, SBND, Mini/MicroBooNE, and SHiP
- arXiv: 1706.00424 ...

3 New Lampposts from Astrophysics

- Joseph Bramante
- Tim Linden

Talk on Tuesday 3:00 PM

"Optical, Gravitational, and Radio Signatures of DM-induced Neutron Star Implosions."
- arXiv: 1706.00001 ...
- Video on PI website

ν Hopes for New Physics:

- Light Bosons at BoreXino (and LSND)

- Heavy Neutral Leptons at SHiP (and MiniBooNE, MicroBooNE, ICARUS, Mu2e, DUNE)

Thanks for all the amazing neutrino/sterile neutrino talks!

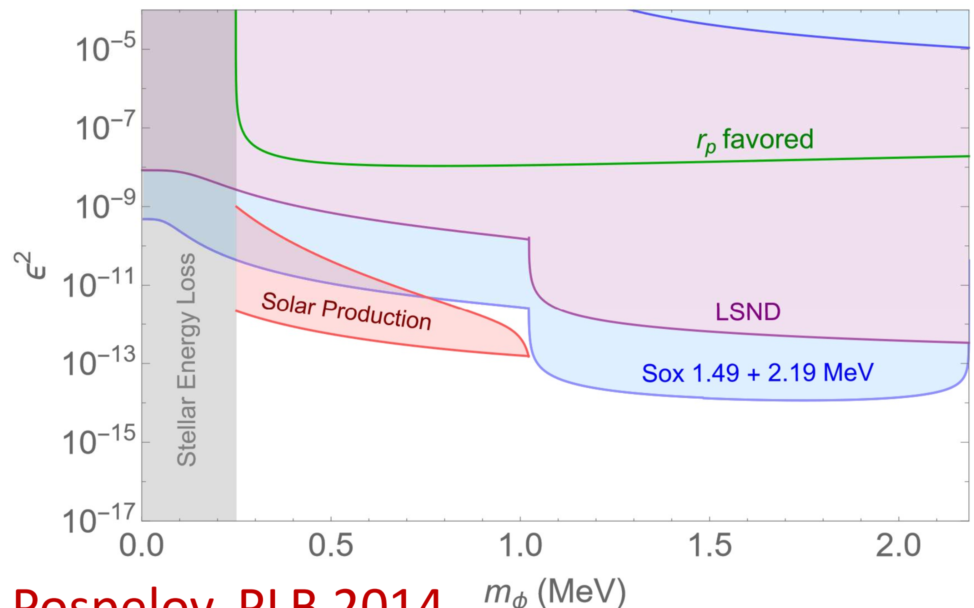
ν Hopes for New Physics:

- Light Bosons at BoreXino (and LSND) ✓

- Heavy Neutral Leptons at SHiP (and MiniBooNE, MicroBooNE, ICARUS, Mu2e, DUNE)

Outline

- Intro to the BoreXino-SOX experiment
- Physical Motivation for the Light Scalar
- Sensitivity Reach and Other Constraints
- Study of Dark Photon
- Conclusion and Outlook



Izaguirre, Krnjaic, and Pospelov, PLB 2014

Maxim Pospelov and Yu-Dai Tsai, [arXiv: 1706.00424]

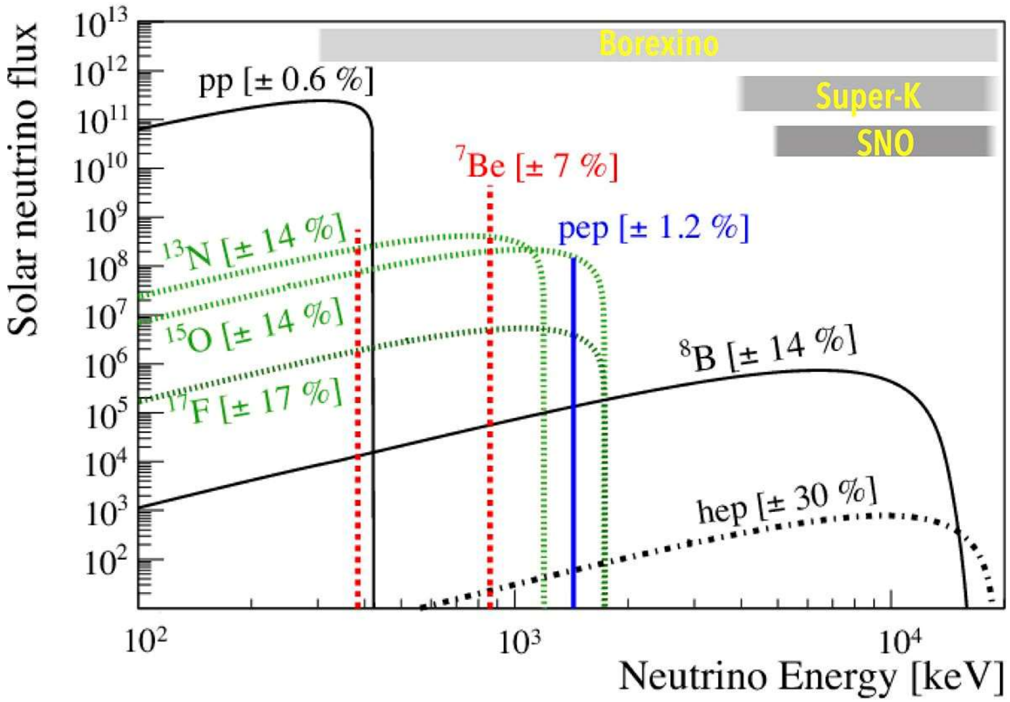
Exploration of Light & Weakly Coupled States

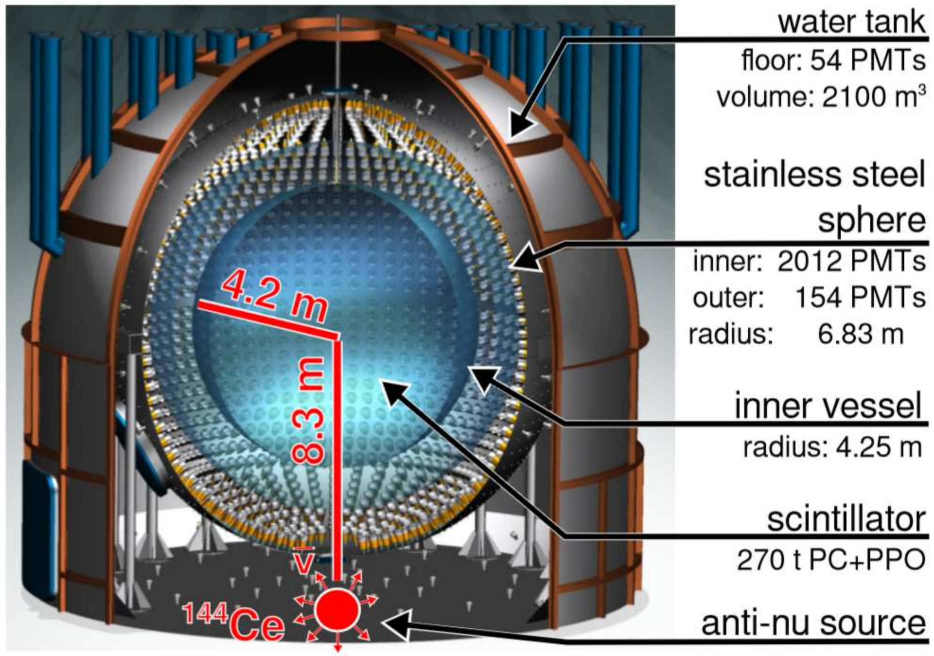
- **Light and very weakly coupled states** are explored by performing experiments in
- **Deep underground laboratories:** the external backgrounds are low
- **Large detectors:** usually built for the purpose of studying solar neutrinos.

- Solar neutrino programs currently **getting the last components of the neutrino flux.** New applications:
- **BoreXino** will expand its program into the **sterile neutrino searches** when powerful external beta-decay sources are placed near the detector in **year 2017** (arXiv:1304.7721.)
- KamLAND and SNO detectors are proposed/used to study ν-less double-beta decays (arXiv:1605.02889 & arXiv:1508.05759.)

BoreXino Detector

- BoreXino is a particle physics detector to study low energy (sub-MeV) solar neutrinos.





Matteo Agostini on behalf of BoreXino (TU Munich & GSSI), 2015

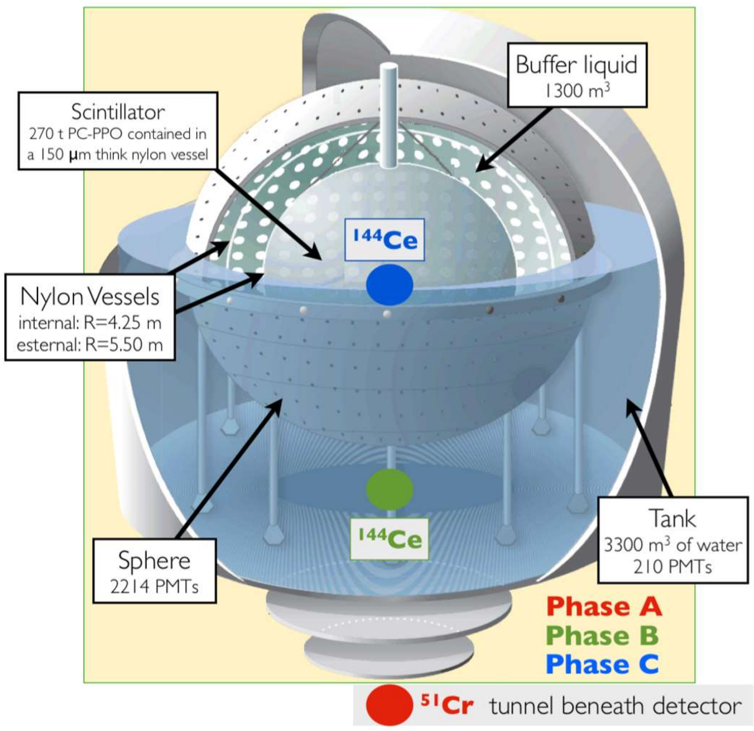
I) ~ 4000 m of water equivalent underground

II) Detect electron/photon events

III) 5% energy resolution – 10 cm spatial resolution (determined at 1MeV)

Short-distance Oscillation in BoreXino (SOX)

- The SOX experiment investigate **short-distance neutrino anomalies**, a set of circumstantial evidences of excess in **electron anti-neutrino / neutrino** at **LSND, MiniBooNE,** and associated anomalies from nuclear reactors and solar neutrino Gallium detectors (GALLEX/GNO and SAGE).
- Powerful external **beta-decay sources (neutrino /anti-neutrino sources)** are placed near the detector
- Observe **disappearance** and **spatial modulations**
- Phase B: external ^{144}Ce (Cerium) placed 8.25 m from BoreXino center
- Borexino Collaboration, arXiv:1304.7721

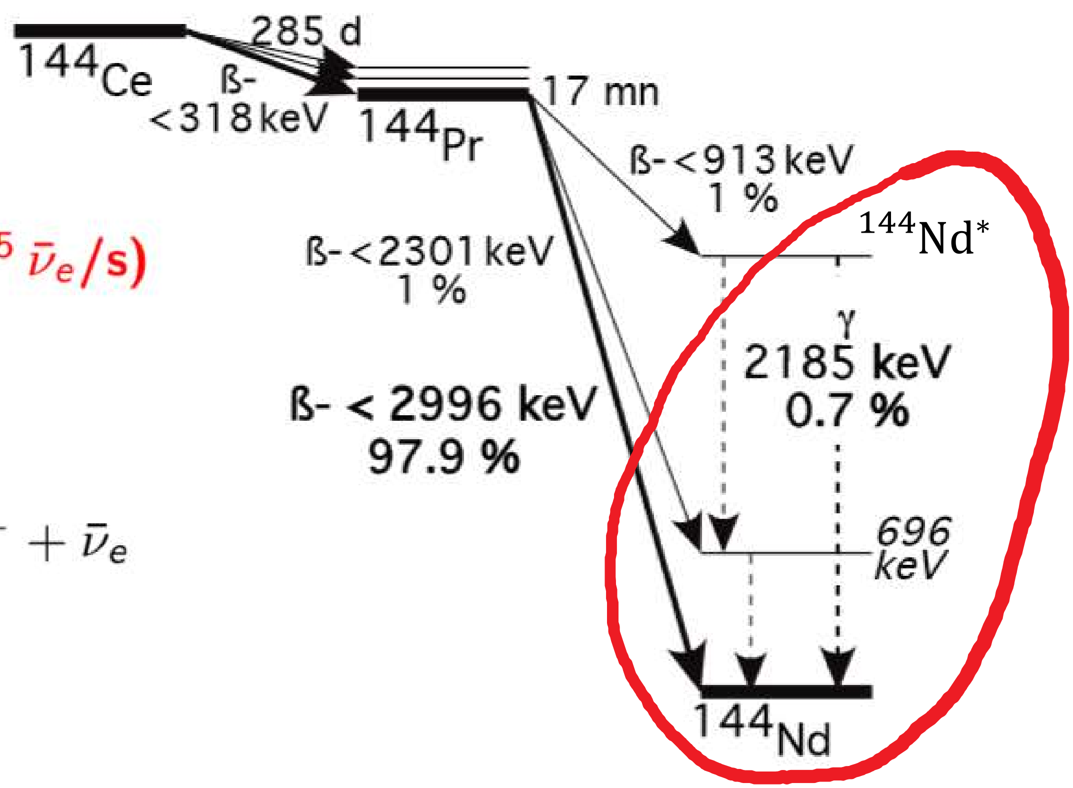


Energy Levels and Beta Decays

$\bar{\nu}/\nu$ source candidates:

Source	Neutrinos	Decay	τ	E [MeV]	Mass [kg/MCi]	Heat [W/kCi]
^{51}Cr	ν	e-capt., 320 keV γ 10%	40 d	0.781 (81%)	0.011	0.19
^{90}Sr-^{90}Y	$\bar{\nu}$	Fission prod. β^-	15160 d	<2.28 (100%)	7.25	6.7
^{144}Ce-^{144}Pr	$\bar{\nu}$	Fission prod. β^-	411 d	<2.9975 (97.9%)	0.314	7.6

- 100–150 kCi activity ($> 10^{15}\ \bar{\nu}_e/\mathrm{s}$)
- β^- decay chain:
  $^{144}\mathrm{Ce} \to {}^{144}\mathrm{Pr} + e^- + \bar{\nu}_e$
  $\searrow$
  $^{144}\mathrm{Nd} + e^- + \bar{\nu}_e$
- $T_{1/2}(^{144}\mathrm{Ce}) = 285\,\mathrm{d}$
- $T_{1/2}(^{144}\mathrm{Pr}) = 17\,\mathrm{m}$

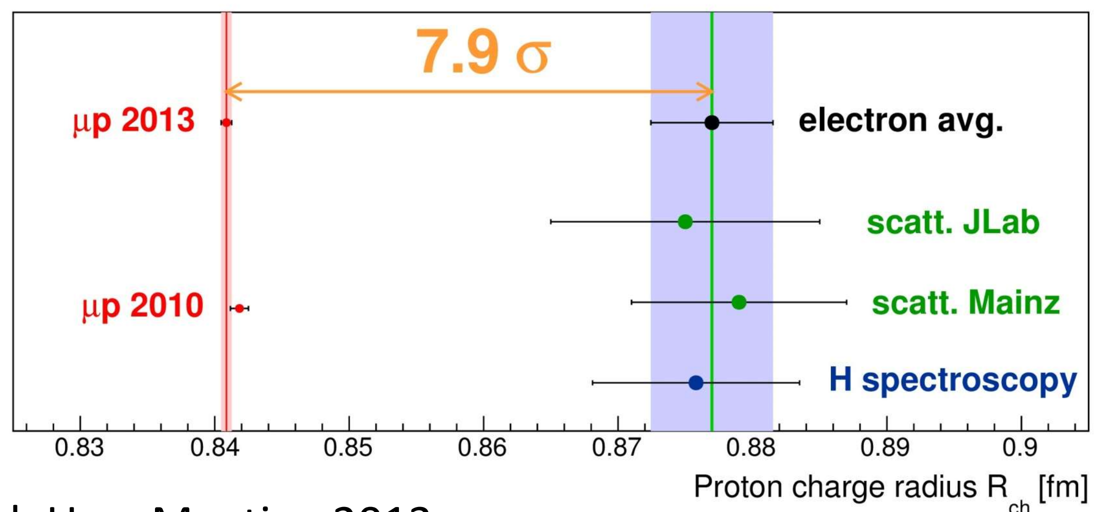


Can emit light scalars

One Motivation: Charge Proton Radius Anomaly

- Use the SOX setup we study a new physics scenario of a ~ **MeV scalar particle, very weakly O(10^{-4}) coupled to nucleons and leptons**.
- This range of masses and couplings is motivated by the persistent **proton charge-radius anomaly:**
- **Proton charge radius r_p** determined from **muonic hydrogen measurement** is 4 % smaller than the values from **elastic electron-proton scattering** and **hydrogen spectroscopy**.
- 7 - 8σ in significance.

	Muon	Electron
Spectroscopy	**0.8409(4)**	**0.8758(77)**
Scattering	**TBD**	**0.8770(60)**



Arrington, Jlab User Meeting 2013

Scalar Solution

$$\mathcal{L}_\phi = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m_\phi^2 \phi^2 + (g_p \bar{p} p + g_e \bar{e} e + g_\mu \bar{\mu} \mu + g_\tau \bar{\tau} \tau)\phi.$$

$$\epsilon^2 \equiv g_e g_p / e^2$$

$$\Delta r_p|_{\mathrm{eH}} = -\frac{6\epsilon^2}{m_\phi^2}, \; \Delta r_p|_{\mu\mathrm{H}} = -\frac{6\epsilon^2 (g_\mu / g_e)}{m_\phi^2} f(a m_\phi)$$

$$\Delta r_p|_{\mathrm{eH}} - \Delta r_p|_{\mu\mathrm{H}} = 0.063 \pm 0.009 \ \mathrm{fm}^2,$$

$f = x^4(1-x)^{-4}$ and $a \equiv (\alpha m_\mu m_p)^{-1}(m_\mu + m_p)$ is the μH Bohr radius.

Scalar Emission

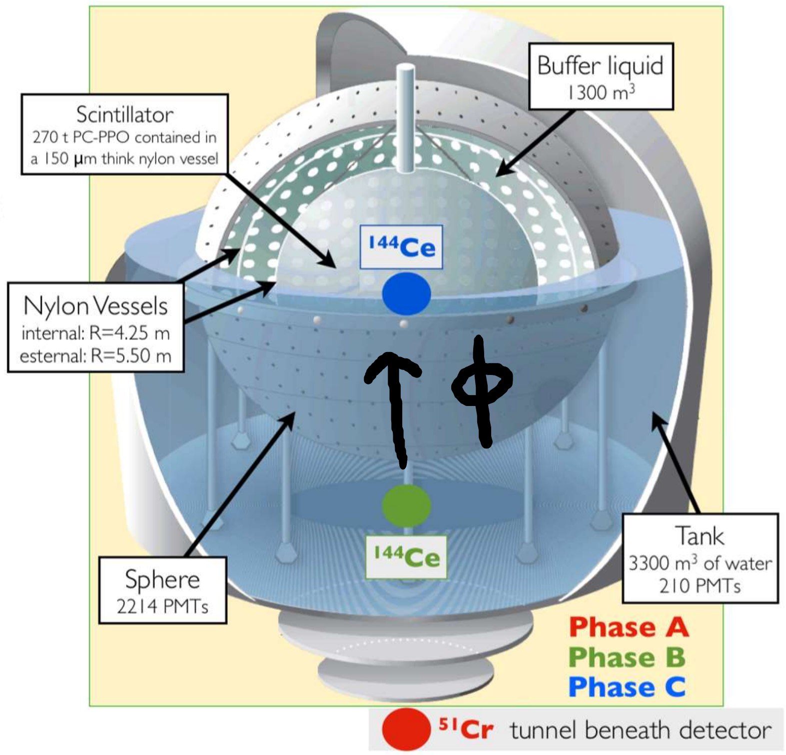
- The scalar emission can be estimated as follows

$$H_{\mathrm{int},\gamma} \simeq e\omega A_0 \sum_p (\vec{\epsilon}\vec{r_p});$$

$$H_{\mathrm{int},\phi} \simeq g_p\sqrt{\omega^2 - m_\phi^2}\,\phi_0 \sum_p (\vec{n}\vec{r_p}),$$

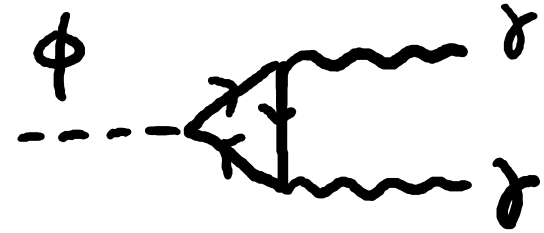
$$\frac{\Gamma_\phi}{\Gamma_{\gamma,\ E1}} = \frac{1}{2}\left(\frac{g_p}{e}\right)^2\left(1-\frac{m_\phi^2}{\omega^2}\right)^{3/2}.$$

Hitoshi's 221B Lecture Notes



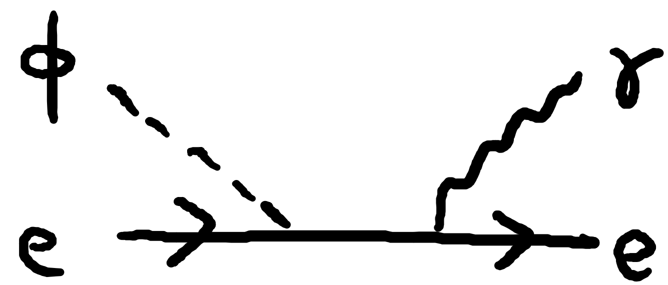
Scalar Signal Rate in Borexino-SOX

$$\dot{N}_{2.185\text{ MeV}}\left[\frac{\text{counts}}{\text{day}}\right] = 1.5\times 10^{18}\times \exp\left(-\frac{t[\text{day}]}{285d}\right)\times\frac{\left(\frac{dN}{dt}\right)_0}{5\text{PBq}}$$
$$\times\left(\frac{g_p}{e}\right)^2\left(1-\left(\frac{m_\phi}{2.185\text{MeV}}\right)^2\right)^{3/2}\times P_{\text{deposit}}$$



diphoton decay

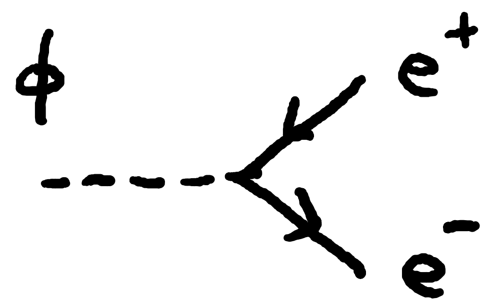
$$\begin{aligned}P_{\text{deposit}} &= \int \frac{d(\theta)}{L_{\text{dec, abs}}}\frac{2\pi}{4\pi}d\cos\theta\\ &= \frac{1}{L_{\text{dec, abs}}}\int_{\sqrt{1-(R/L)^2}}^{1}\sqrt{R^2-L^2(1-\cos^2\theta)}d\cos\theta\\ &= \frac{1}{L_{\text{dec, abs}}}\times\frac{2LR+(L^2-R^2)\log\left(\frac{2L}{L+R}-1\right)}{4L}\end{aligned}$$



e-ϕ scattering

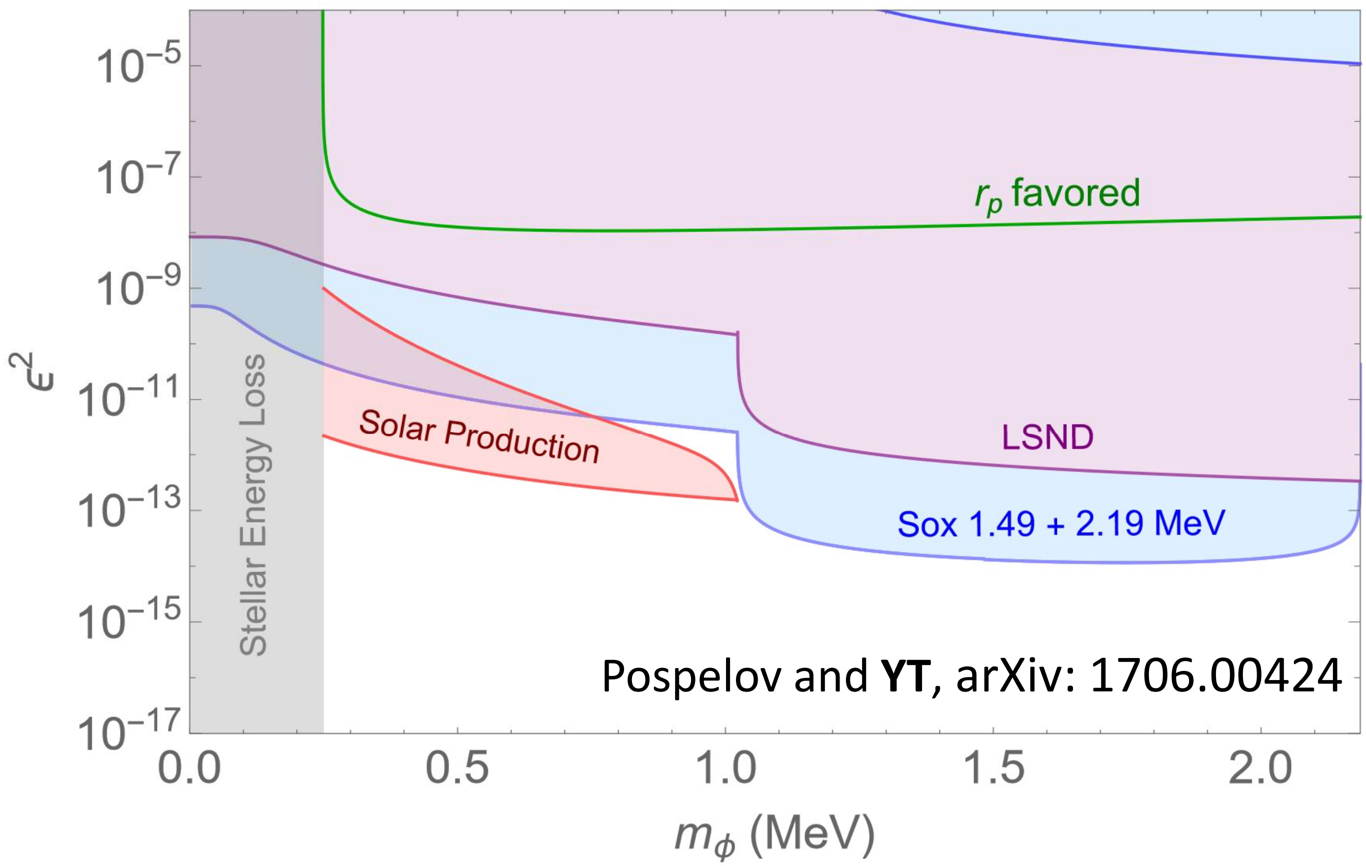
Backgrounds $(p+\bar{\nu}\to n+e^+)$

- Source Background: electron anti-neutrino inverse beta decay: prompt e+/e− annihilation + delayed neutron absorption (more discussions in 1706.00424)
- Source unrelated: studied in BoreXino previous runs (see e.g. 1311.5347)



di-electron decay
($m_\phi > 2m_e$)

Sensitivity Reach and Constraints



$e\phi \to e\gamma$ $\phi \to \gamma\gamma$ $\phi \to e^+e^-$

$$\boxed{\epsilon^2 \equiv g_e g_p / e^2}$$

$$g_e = (m_e/m_\mu) g_\mu,\ g_\tau = (m_\tau/m_\mu) g_\mu,\ g_p = (m_p/m_\mu) g_\mu,$$

LSND Constraint

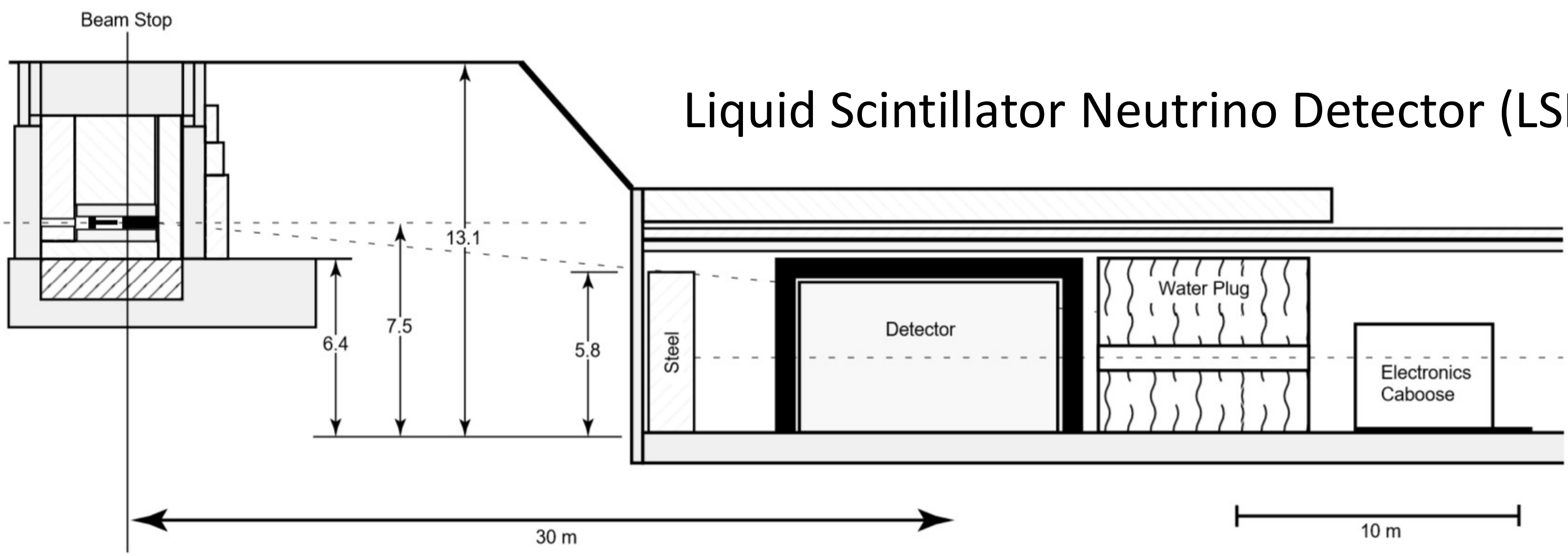
- We **revisit the LSND data** to derive the bound on the light scalar
- The important process for the pion production at LSND is the excitation of Δ resonance in the collisions of incoming protons with nucleons inside the target.

$$N_\phi \sim N_\pi \times \frac{\Gamma_{\Delta\to p\pi\phi}}{\Gamma_{\Delta\to p\pi}} \simeq N_\pi \times 0.04 g_p^2.$$

$$N_{LSND} \sim N_\pi \times 0.04 g_p^2 \times P_{\text{survive + deposit in LSND}}$$

$$\simeq N_\pi \times 0.04 g_p^2 \times \left[\exp\left(-\frac{L_{\rm LSND} - \frac{d_{\rm LSND}}{2}}{L_{\rm dec}}\right) - \exp\left(-\frac{L_{\rm LSND} + \frac{d_{\rm LSND}}{2}}{L_{\rm dec,\ scat}}\right)\right]\left(\frac{A_{\rm LSND}}{4\pi L_{\rm LSND}^2}\right).$$

- From the **LSND papers (hep-ex/0101039 and hep-ex/0104049)** we estimate that there are less than 20 events during the exposure to set the bound.



Liquid Scintillator Neutrino Detector (LSND)

Solar Production

- The light scalar ϕ can be produced in sun through the nuclear interaction

p + D→ 3He + ϕ. This process generates a **5.5 MeV ϕ flux** that was constrained by the search conducted by the BoreXino experiment.

- *P*esc is the probability of the light scalar escaping the sun
- *P*surv is the probability of the scalar particle do not decay before reaching the detector

$$P_{\rm esc} = \exp\left(-\int^{R_\odot} dr\; n_e \sigma_{e\phi\to e\gamma}\right)$$

$$P_{\rm surv} = \exp\left(-\frac{L_\odot}{L_{\rm dec}}\right)$$

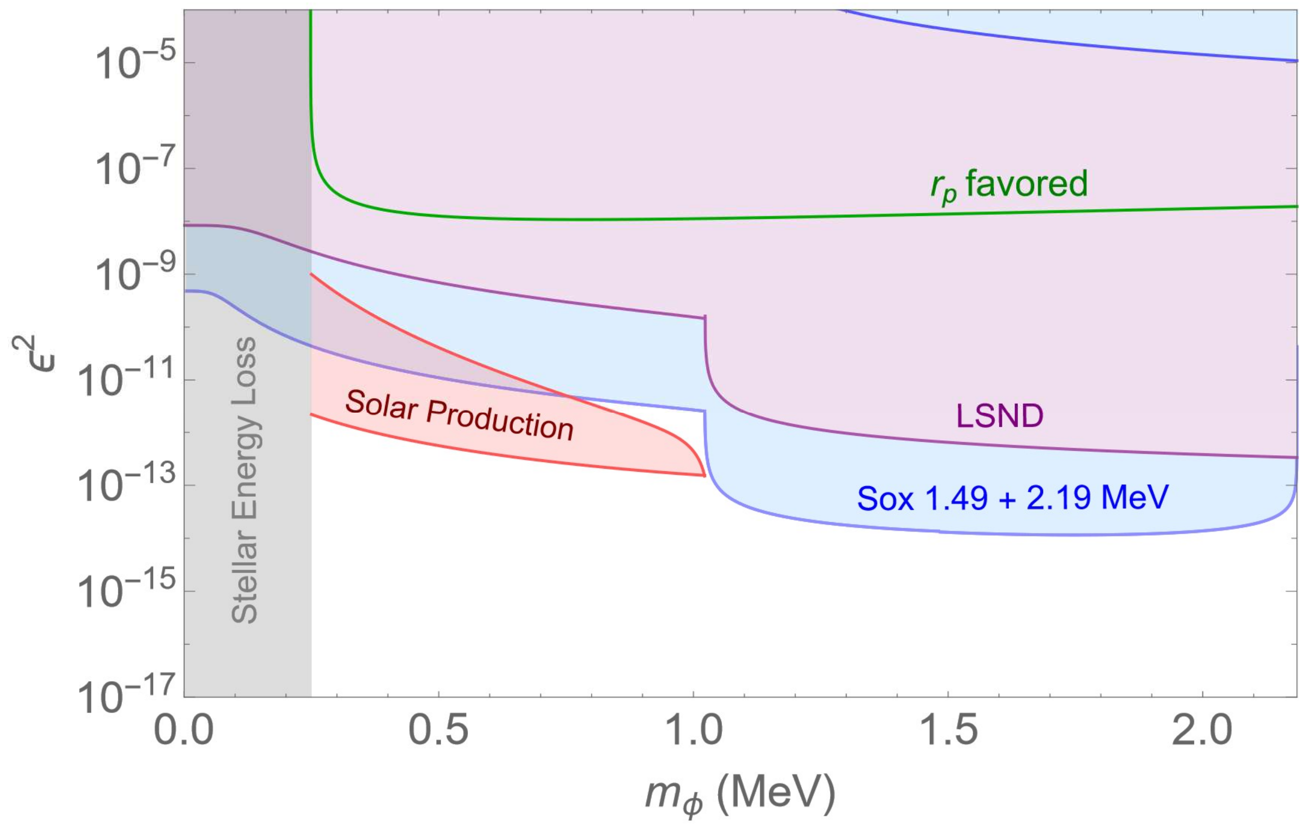
- The flux can be estimated as

$$\Phi_{\phi,\rm solar} \simeq (g_p/e)^2 \Phi_{pp\nu} P_{\rm esc} P_{\rm surv}.$$

$$\Phi_{pp\nu} = 6.0 \times 10^{10}\ {\rm cm}^{-2} s^{-1}$$

- The bound can be place by the data collected in previous BoreXino runs arXiv:1311.5347 [hep-ex].

Stellar Energy Loss

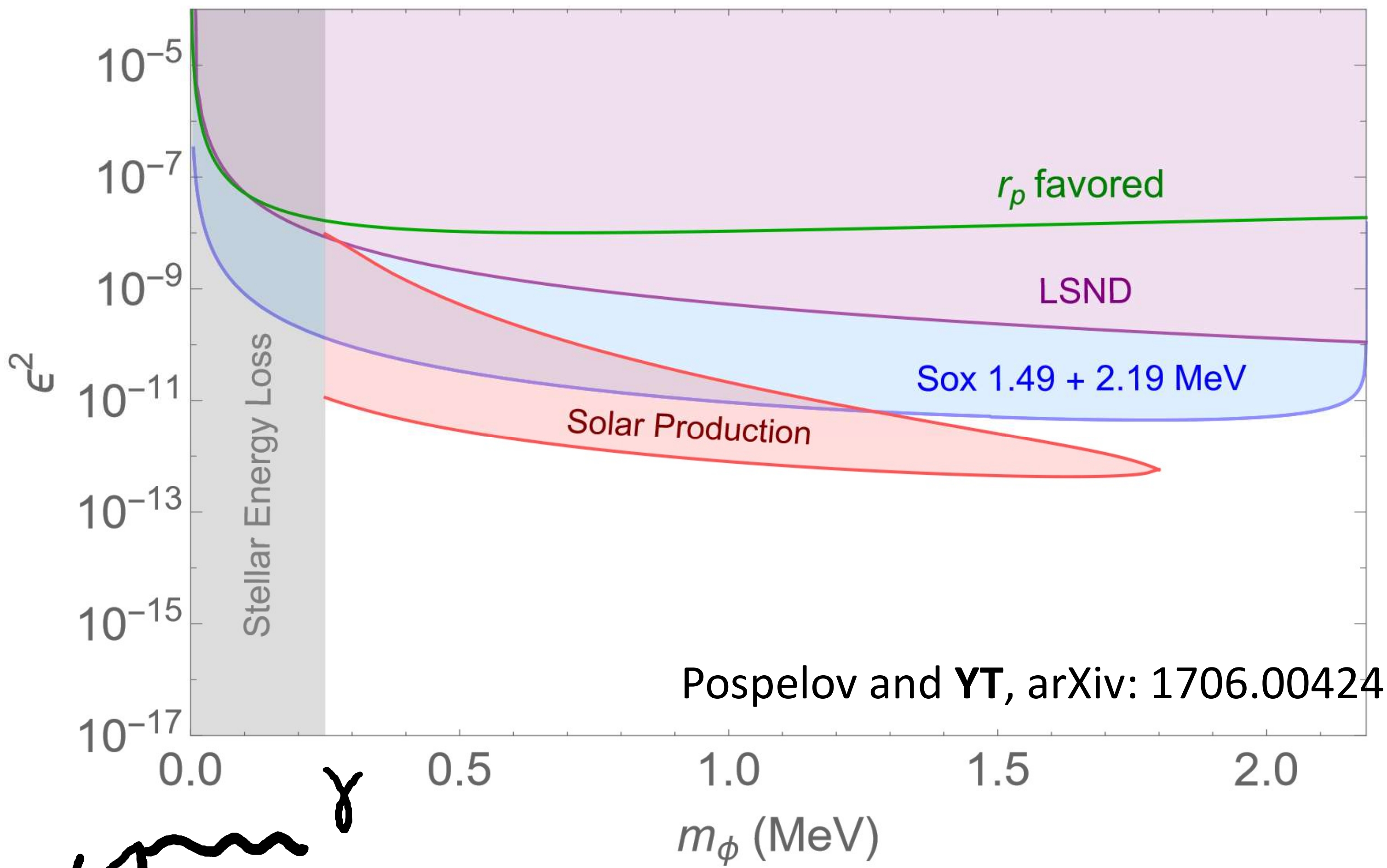


- Thermal production of scalars may lead to **abnormal energy losses** (or **abnormal thermal conductivity**)
- alter the **time evolution of well known stellar populations**
- In the regime of m_ϕ > T, the thermally averaged energy loss is proportional to $g_e^2 \exp(-m_\phi/T_{\rm star})$
- Given the strict stellar constraints (Raffelt & Weiss 1994), one safely exclude $\boldsymbol{m_\phi}$ **< 250 keV** for the whole range of coupling constants considered in the figure.

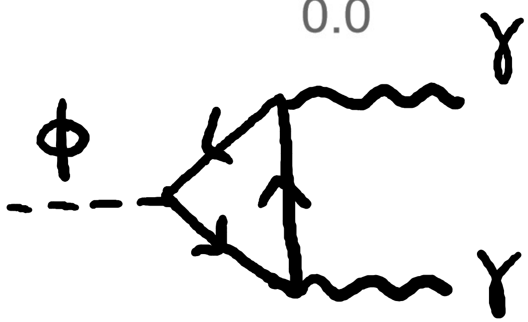
Yu-Dai Tsai, TeVPA 2017

φ – μ and φ - p couplings only

- One can turn off the φ to e and φ to τ couplings and keep the muon and proton couplings only.



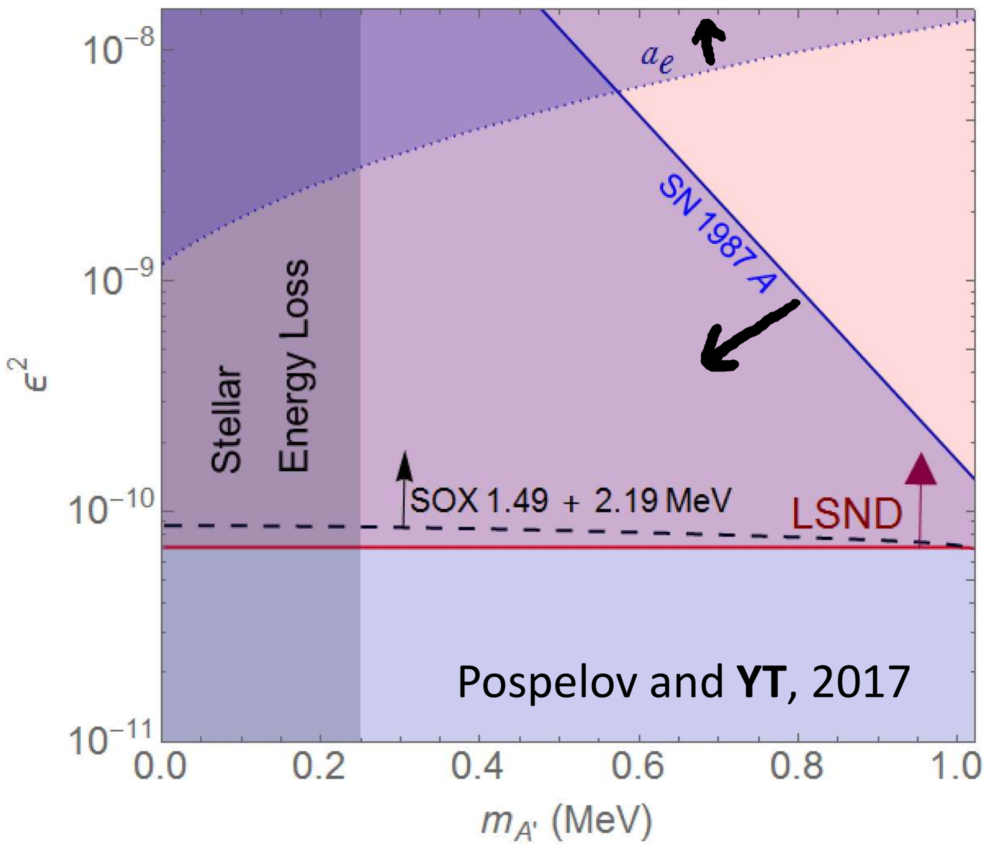
Pospelov and **YT**, arXiv: 1706.00424



ν Constraints on Dark Photon

Bounds on Dark Photon

$$\mathcal{L}_{\rm d.ph.} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2(A'_\mu)^2 + \epsilon A'^\mu J_\mu^{EM}.$$

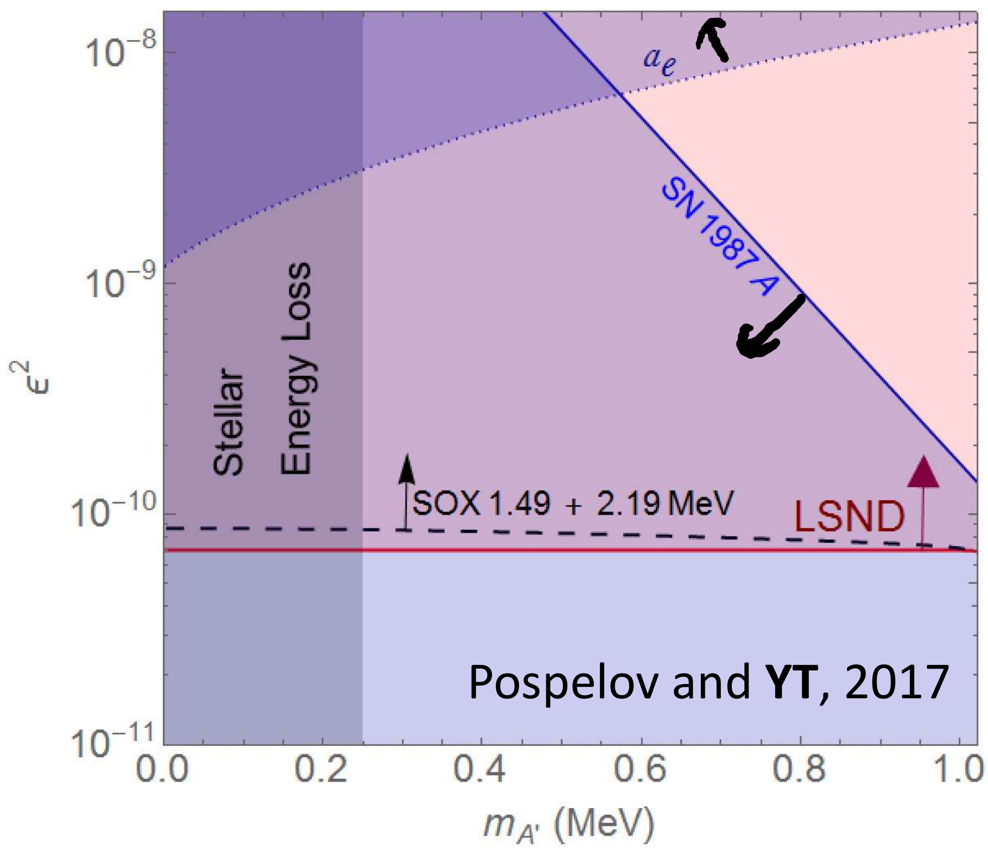


YU-DAI TSAI, TEVPA 2017

- $m_{A'} < 2m_e$, dark photons are cosmologically disfavored ($N_{eff} < 2$) (Nollett and Steigman 13).
- A' to 3 γ decay (Pospelov, Ritz, and Voloshin 08 and McDermott, **Patel**, and Ramani 17)
- A compilation of all the other constraints and the future BoreXino sensitivity projection
- Electron g-2 vs α_{EM} constraint (see e.g. Odom et al, PRL 06, Pospelov 08, Bjorken, Essig, Schuster, Toro 09…)
- The "robust" bound from SN 1987A is taken here (**Chang**, Essig, and McDermott 16, Hardy and Lasenby 16)

Bounds on Dark Photon

$$\mathcal{L}_{\text{d.ph.}} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}(A'_\mu)^2 + \epsilon A'^\mu J^{EM}_\mu.$$



- **The recast of LSND data & BoreXino-SOX projection** excludes the triangle regime that was not excluded by previous considerations

- Major energy depositions:

$$e + A' \to e + \gamma$$

Conclusion and Outlook

- BoreXino-SOX is expected to start this year.

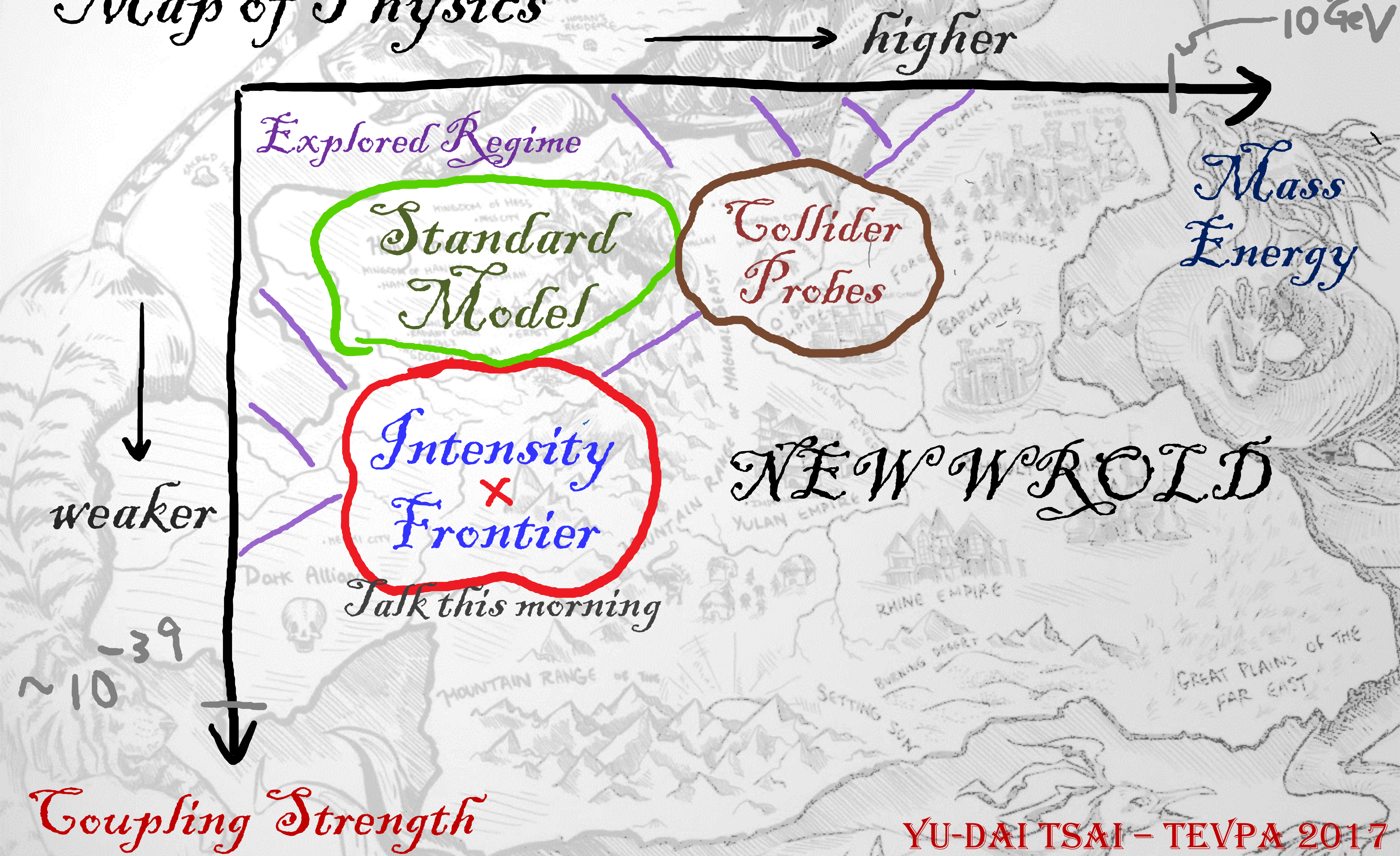
- Within one year and with the proposed setup, coupling strength $\epsilon^2 = g_e g_p/e^2 = 10^{-9} - 10^{-14}$ will be probed for the "dark" scalar

- The scalar-solution to the proton charge-radius anomaly can be definitively tested

- Bounds on dark photon is revisited and $\epsilon_\gamma \geq 10^{-5}$ is excluded by the recast of LSND data

- Look for more traces of new physics at current and future neutrino experiments!

Map of Physics



YU-DAI TSAI – TEVPA 2017

BACKGROUND BY PHUSROCAT

http://forum.wuxiaworld.com/discussion/416/phusrocat-coiling-dragon-map-pen-and-ink

Thanks!

Special thanks go to Maxim, Eder and Gordan.

More on Dark Photon

- **Dark photon production:**

- **Borexino:**

$$\frac{\Gamma_{A'}}{\Gamma_{\gamma,\ E1}} = \frac{v_{A'}(3 - v_{A'}^2)}{2}\epsilon^2,$$

$$v_{A'} = (1 - m_{A'}^2/\omega^2)^{1/2}.$$

- **LSND:**

$$Br_{\pi^0 \to A'\gamma} = 2\epsilon^2.$$

- **Main energy deposition:** $e + A' \to e + \gamma.$

Maxim Pospelov and Yu-Dai Tsai, arXiv: 1706.00424

BoreXino Backgrounds

- In order to compare the counting rate to the background rate, we notice first that the radioactive source creates additional inverse beta decay (IBD) events in Borexino, $p + \bar{\nu} \rightarrow n + e^+$, which is the primary goal of the SOX project.
- Such events have double structure in time (initial energy deposition followed by neutron capture). Also, the initial energy deposition is 0.784 MeV lower than the energy of antineutrino. Why
- This puts the 2.185 MeV energy deposition by scalars above the initial energy deposition of the antineutrino events, and we can assume that the IBD events can be cleanly separated from our suggested signal.