ν Hopes for New Physics:

Probing Weakly Coupled States at Neutrino Detectors

Yu-Dai Tsai (PhD student)
Cornell University & Perimeter Institute

with Maxim Pospelov
arXiv:1706.00424, coming out now!

+ Gabriel Magill and Ryan Plestid
arXiv:170x.xxxxx, in preparation

Ongoing Research

I'm Yu-Dai Tsai, a 4th year PhD student at Cornell / Perimeter Institute

1 Sub-GeV Dark Matter

- Maxim Perelstein
- Eric Kuflik
- Nicolas Rey-Le Lorier

- ELDER model building
- Observational / experimental signatures

2 ν Hopes for New Physics

- Maxim Pospelov
- Gabriel Magill
- Ryan Plestid

Constraints and possible signatures of new physics in neutrino detectors, including **BoreXino**, **LSND**, MiniBooNE, and SHiP

3 G-Wave/Optical Probes for New Physics

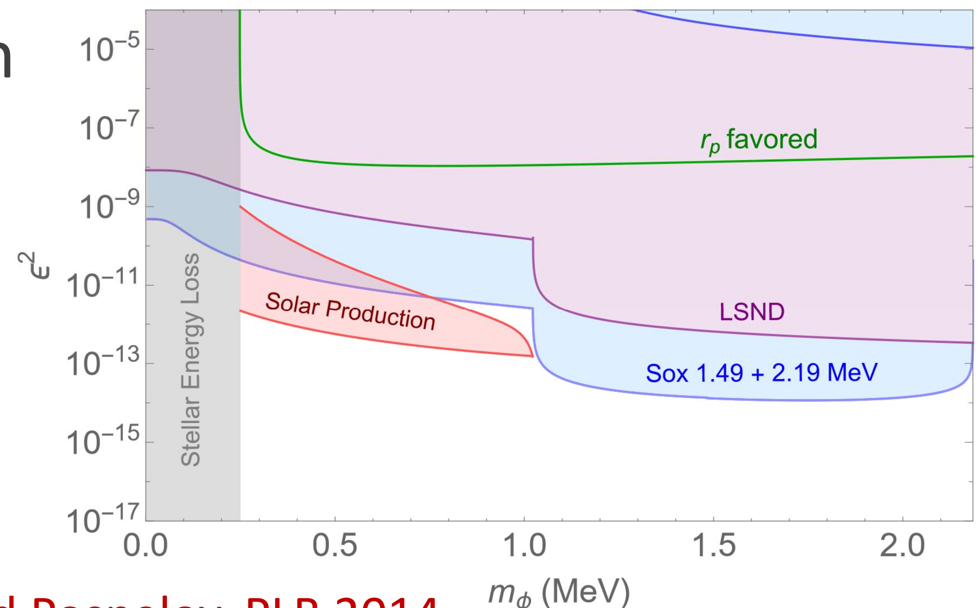
- Joseph Bramante
- Tim Linden

New constraints on PBH and ADM through astrophysical observations

Probing Light Bosons at the BoreXino Detector

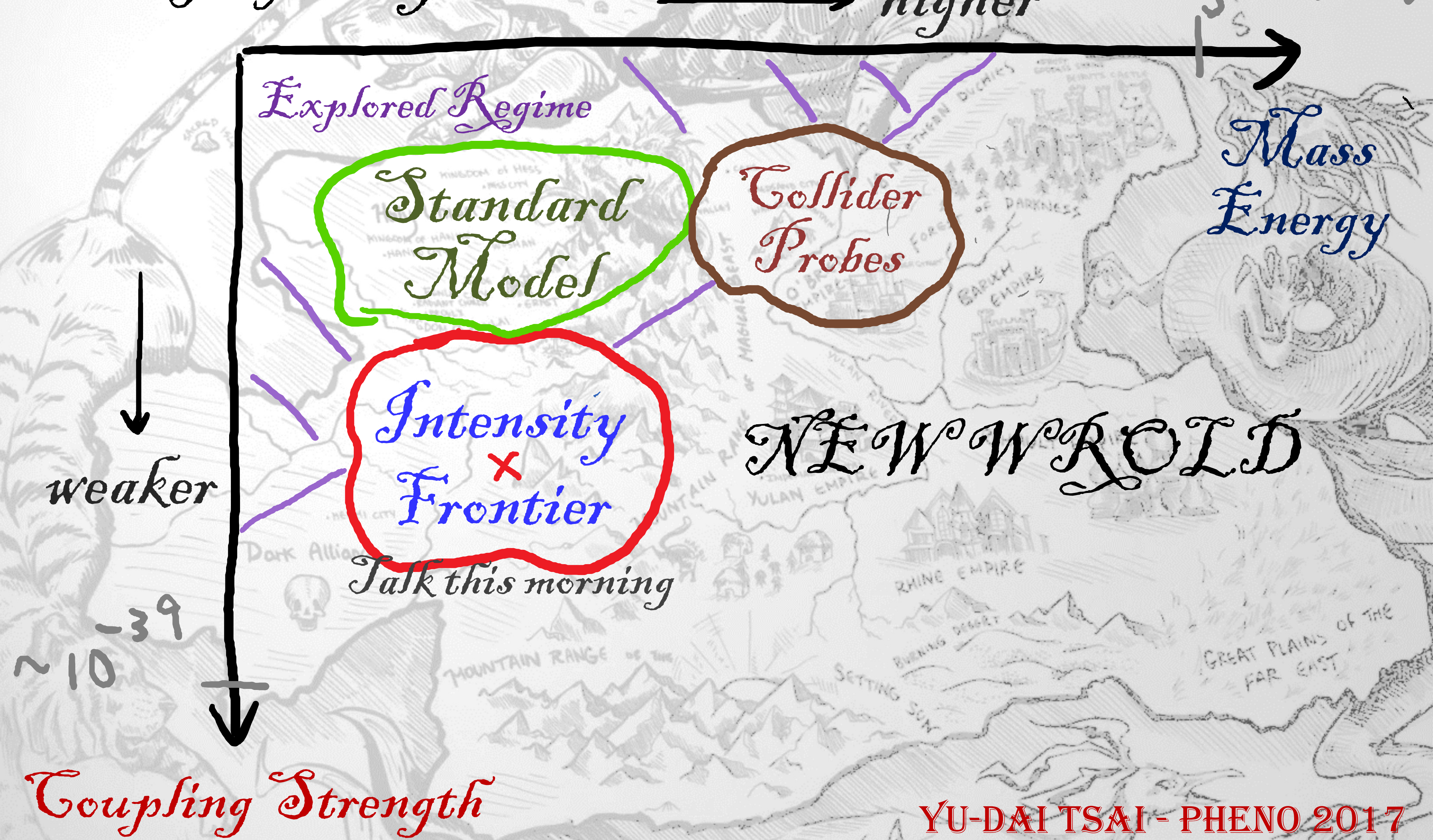
Outline

- Intro to the BoreXino-SOX experiment
- Probing light/weakly coupled scalars at the BoreXino detector: physical motivation
- Sensitivity Reach and Other Constraints
- Constraints on Dark Photon
- Conclusion and Outlook



Izaguirre, Krnjaic, and Pospelov, PLB 2014
Maxim Pospelov and Yu-Dai Tsai, [arXiv: 1706.00424]

Map of Physics



YU-DAI TSAI - PHENO 2017

BACKGROUND BY PHUSROCAT

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

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:
- KamLAND and SNO detectors are proposed or used to study Neutrinoless double-beta decays of Xenon and Tellurium isotopes (arXiv:1605.02889 & arXiv:1508.05759.)
- **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.)

BoreXino Detector

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

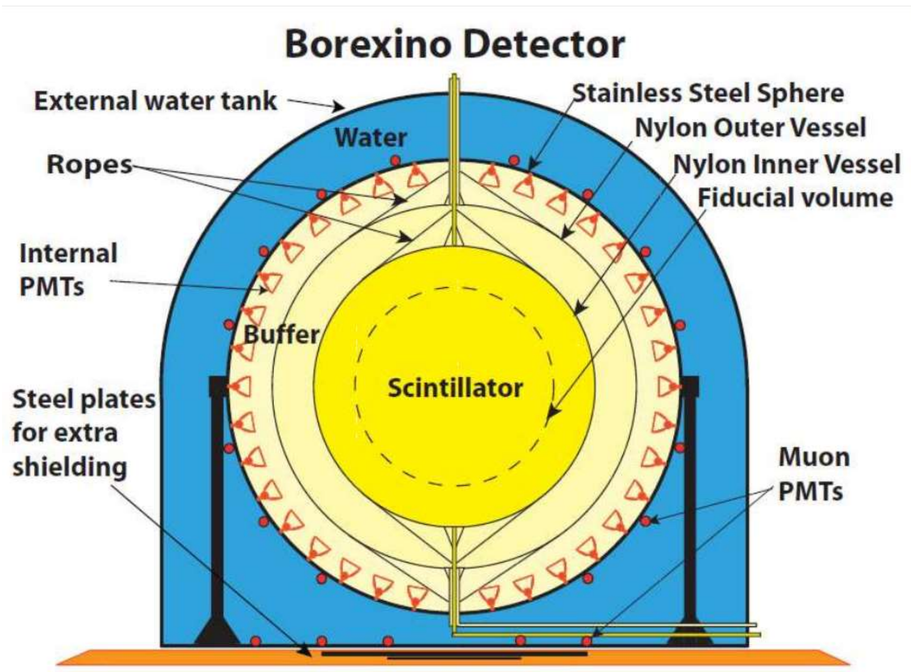
I) Water tank (2100 m^3):
- Absorption of environmental γ's and neutrons
- μ Cherenkov detector (208 PMTs)

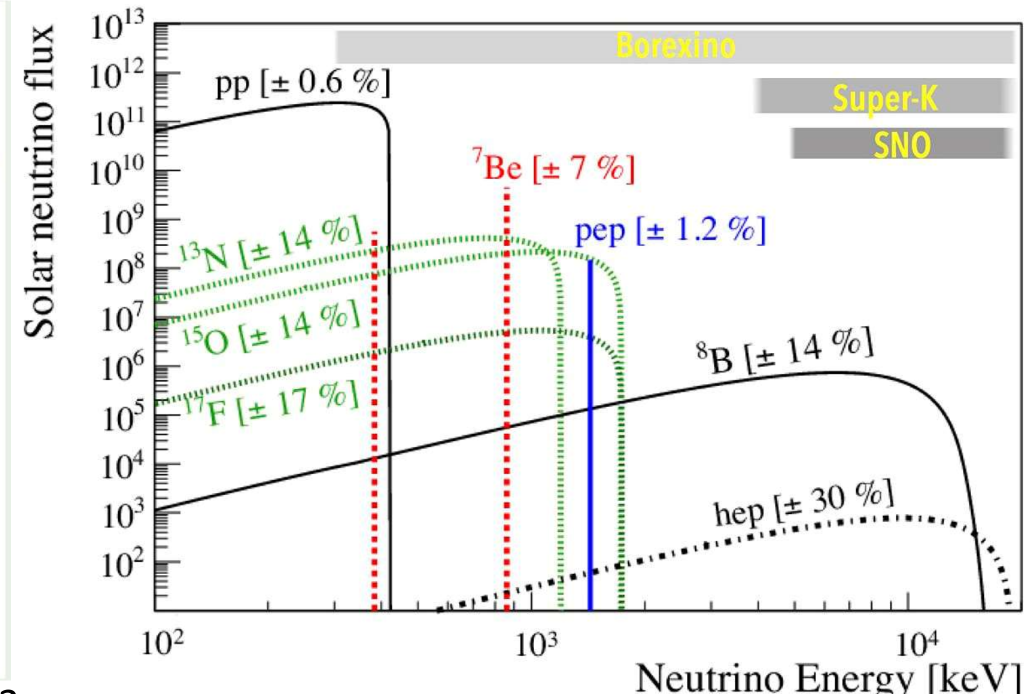
II) Stainless Steel Sphere:
- 2212 PMTs, 1350 m^3 , R=6.85 m

III) Two buffer layers:
- Outer R2=5.50 m, Inner R1=4.25 m.
- Shielding from external γ's.

IV) Scintillator: 270 tons of liquid scintillator

V) 3800 m of water equivalent underground

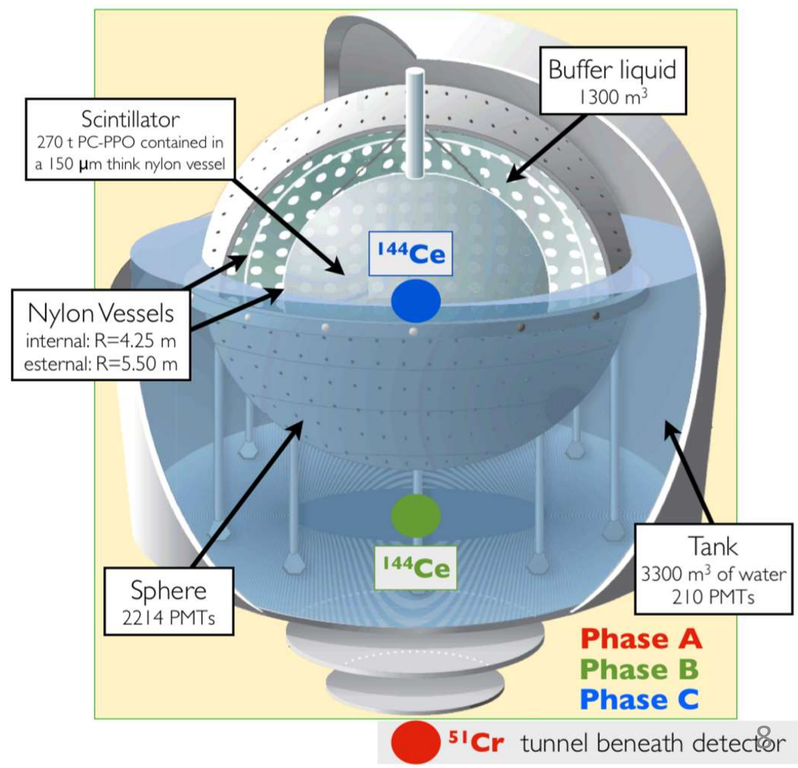




arXiv: 1308.0443

Short-distance **O**scillation in Bore**X**ino (SOX)

- As **Dr. Anne Schukraft** introduced to us this morning
- The SOX experiment investigate **neutrino anomalies, a set of circumstantial evidences of electron neutrino disappearance observed** at **LSND, MiniBooNE**, and with nuclear reactors and with 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

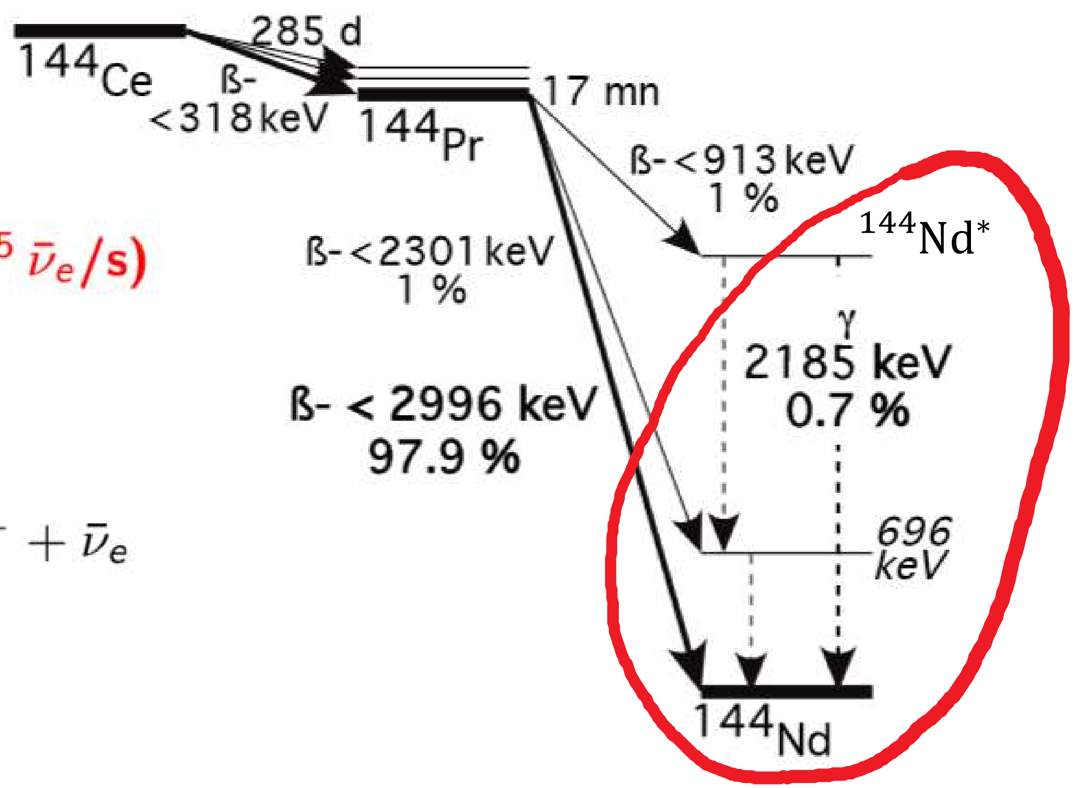


Energy levels and Beta Decays

$\bar{\nu}/\nu$ 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:
  $$^{144}\mathrm{Ce} \rightarrow {}^{144}\mathrm{Pr} + e^- + \bar{\nu}_e$$
  $$\searrow\ {}^{144}\mathrm{Nd} + e^- + \bar{\nu}_e$$
- $T_{1/2}(^{144}\mathrm{Ce}) = 285\,\mathrm{d}$
- $T_{1/2}(^{144}\mathrm{Pr}) = 17\,\mathrm{m}$

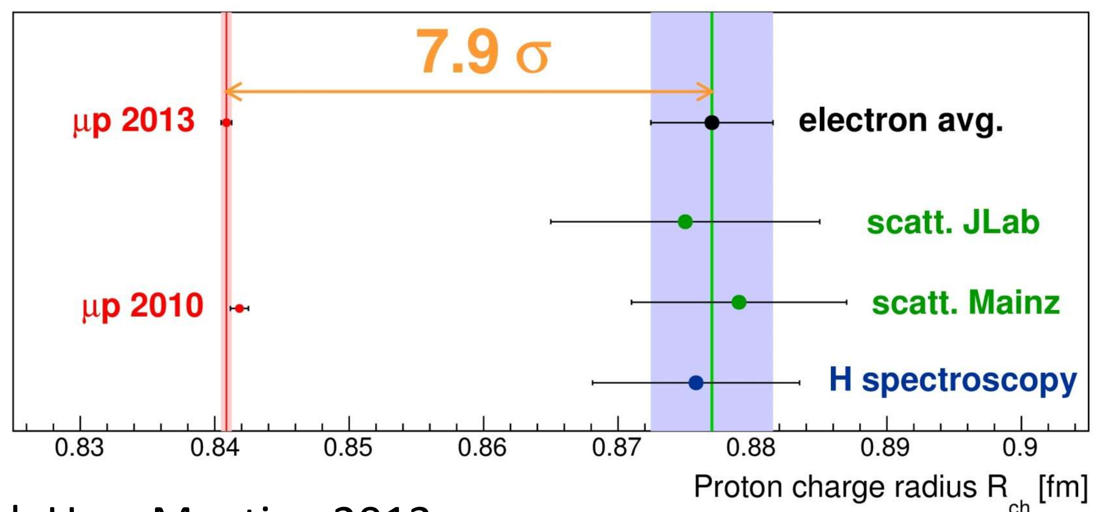


Can emit light scalars

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 μp 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

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

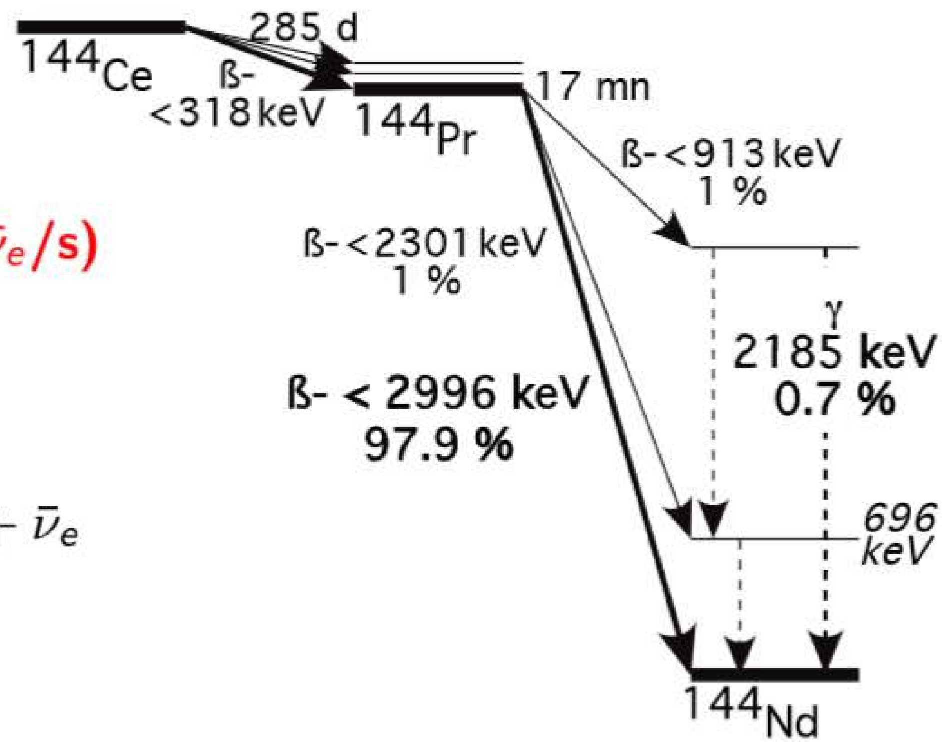
$$\epsilon^2 \ \equiv \ g_e g_p / e^2$$

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

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

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

Scalar Emission



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

- The scalar emission can be estimated as follows

$$H_{\mathrm{int},\gamma} \simeq e\omega A_0 \sum_p (\vec{\epsilon}\vec{r}_p); \quad H_{\mathrm{int},\phi} \simeq g_p \sqrt{\omega^2 - m_\phi^2}\,\phi_0 \sum_p (\vec{n}\vec{r}_p),$$

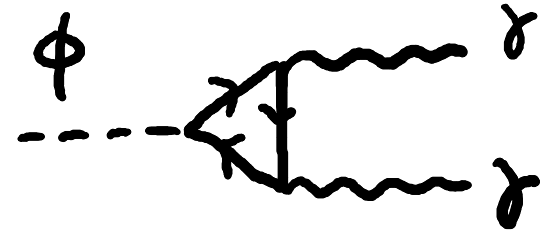
$$\frac{\Gamma_\phi}{\Gamma_{\gamma,\ E1}} = \frac{1}{2}\left(\frac{g_p}{e}\right)^2 \left(1 - \frac{m_\phi^2}{\omega^2}\right)^{3/2}.$$

Scalar Signal Rate in Borexino-SOX

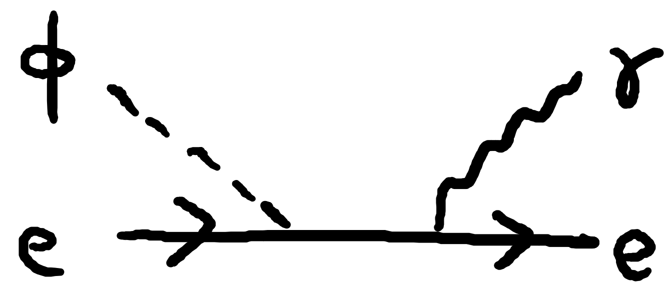
$$P_{\text{deposit}} = \int \frac{d(\theta)}{L_{\text{dec, abs}}} \frac{2\pi}{4\pi} d\cos\theta$$
$$= \frac{1}{L_{\text{dec, abs}}} \int_{\sqrt{1-(R/L)^2}}^{1} \sqrt{R^2 - L^2(1-\cos^2\theta)}\, d\cos\theta$$
$$= \frac{1}{L_{\text{dec, abs}}} \times \frac{2LR + (L^2 - R^2)\log\left(\frac{2L}{L+R} - 1\right)}{4L}$$

$$\dot{N}_{2.185\text{ MeV}}\left[\frac{\text{counts}}{\text{day}}\right] = 1.5\times10^{18} \times \exp\left(-\frac{t[\text{day}]}{285d}\right) \times \frac{\left(\frac{dN}{dt}\right)_0}{5\text{PBq}}$$
$$\times \left(\frac{g_p}{e}\right)^2 \left(1 - \left(\frac{m_\phi}{2.185\text{MeV}}\right)^2\right)^{3/2} \times P_{\text{deposit}}$$

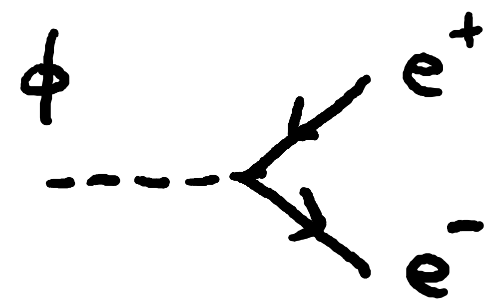
- The background is experimentally determined by the data from the previous BoreXino runs arXiv:1311.5347 [hep-ex]



diphoton decay

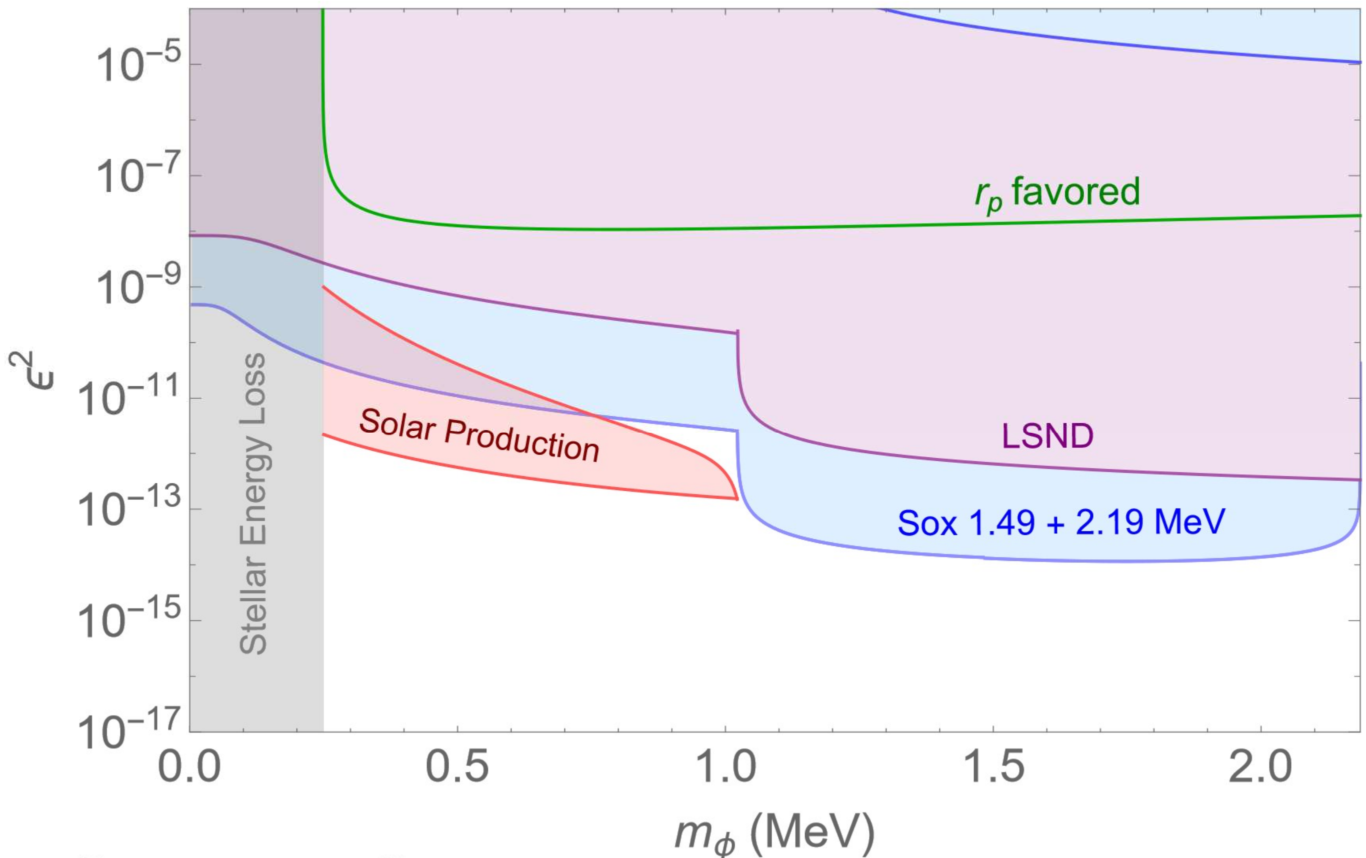


e-ϕ scattering



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

Sensitivity Reach and Constraints



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

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

Yu-Dai Tsai, Pheno 2017

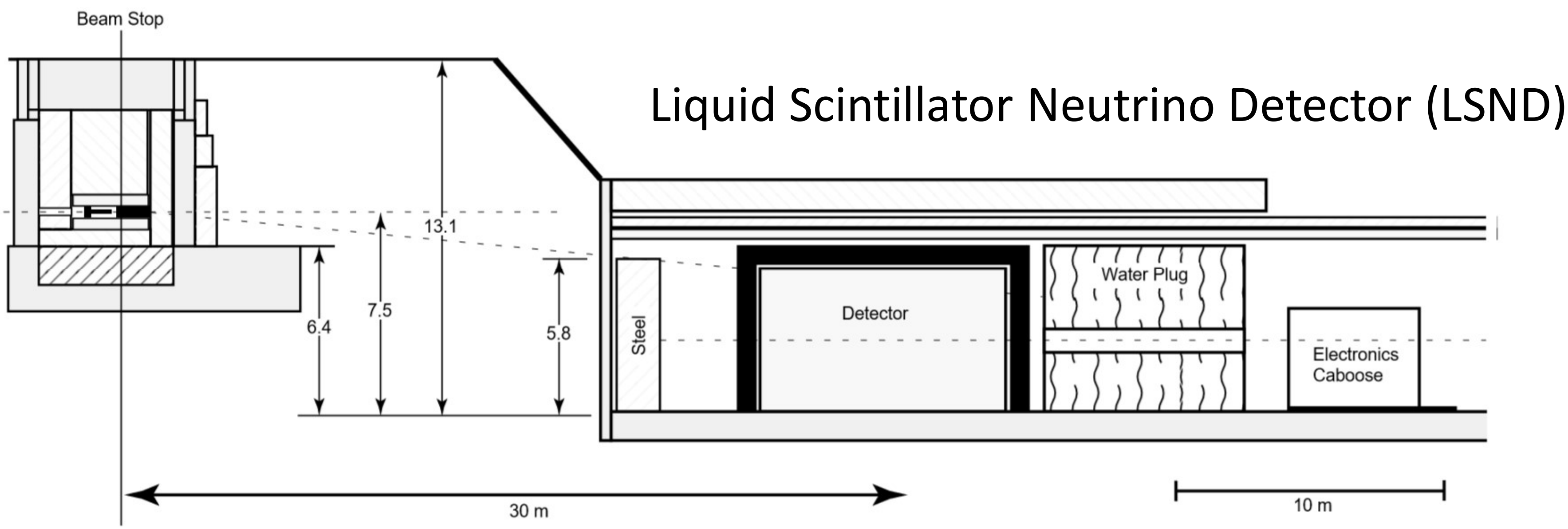
LSND Constraint

- 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.

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

$$\begin{aligned} N_{LSND} \sim & N_\pi \times 0.04 g_p^2 \times P_{\text{survive + deposit in LSND}} \\ \simeq & N_\pi \times 0.04 g_p^2 \times \left[\exp\left(-\frac{L_{\text{LSND}} - \frac{d_{\text{LSND}}}{2}}{L_{\text{dec}}}\right) - \exp\left(-\frac{L_{\text{LSND}} + \frac{d_{\text{LSND}}}{2}}{L_{\text{dec, scat}}}\right)\right]\left(\frac{A_{\text{LSND}}}{4\pi L^2_{\text{LSND}}}\right). \end{aligned}$$

- 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.



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

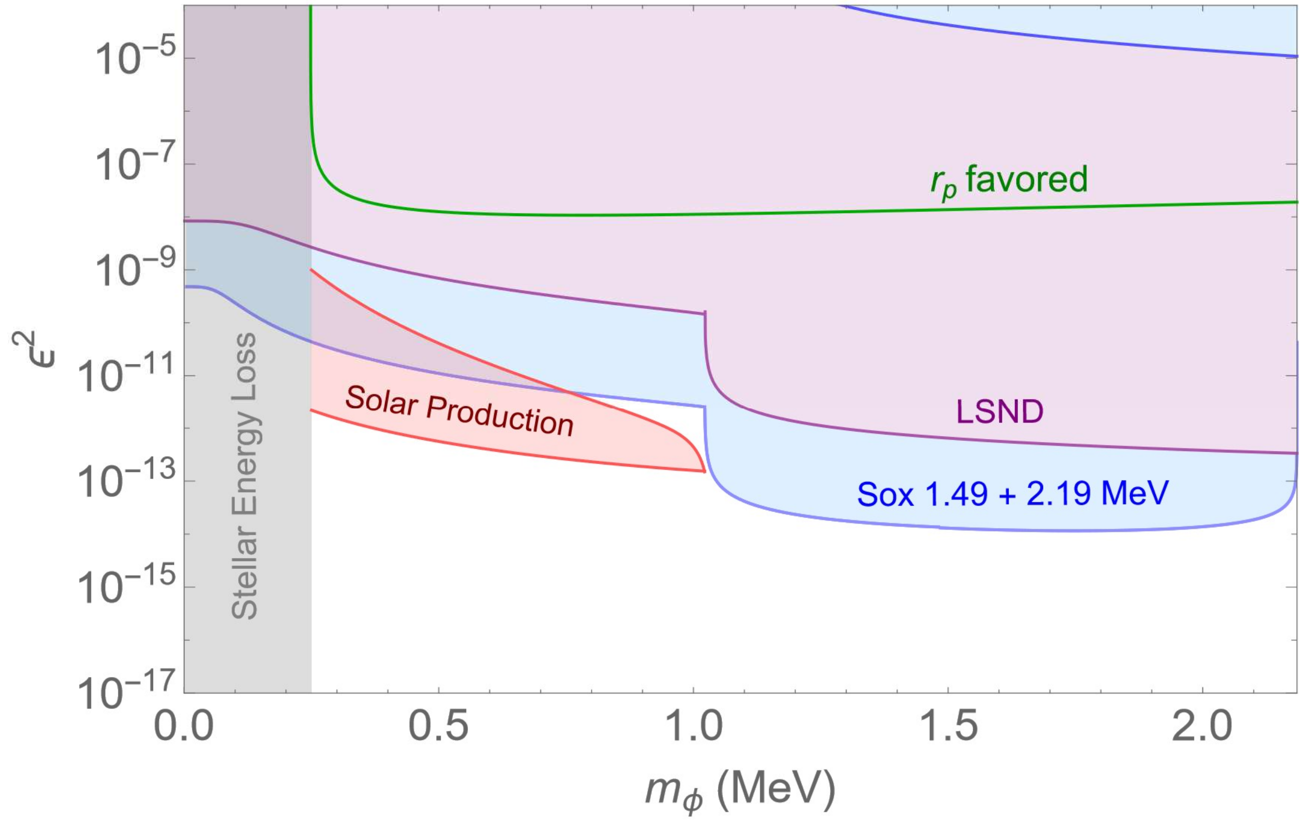
$$\Phi_{\phi,{\rm solar}} \simeq (g_p/e)^2 \Phi_{pp\nu} P_{\rm esc} P_{\rm surv}.$$

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

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

Yu-Dai Tsai, Pheno 2017

Stellar Energy Loss

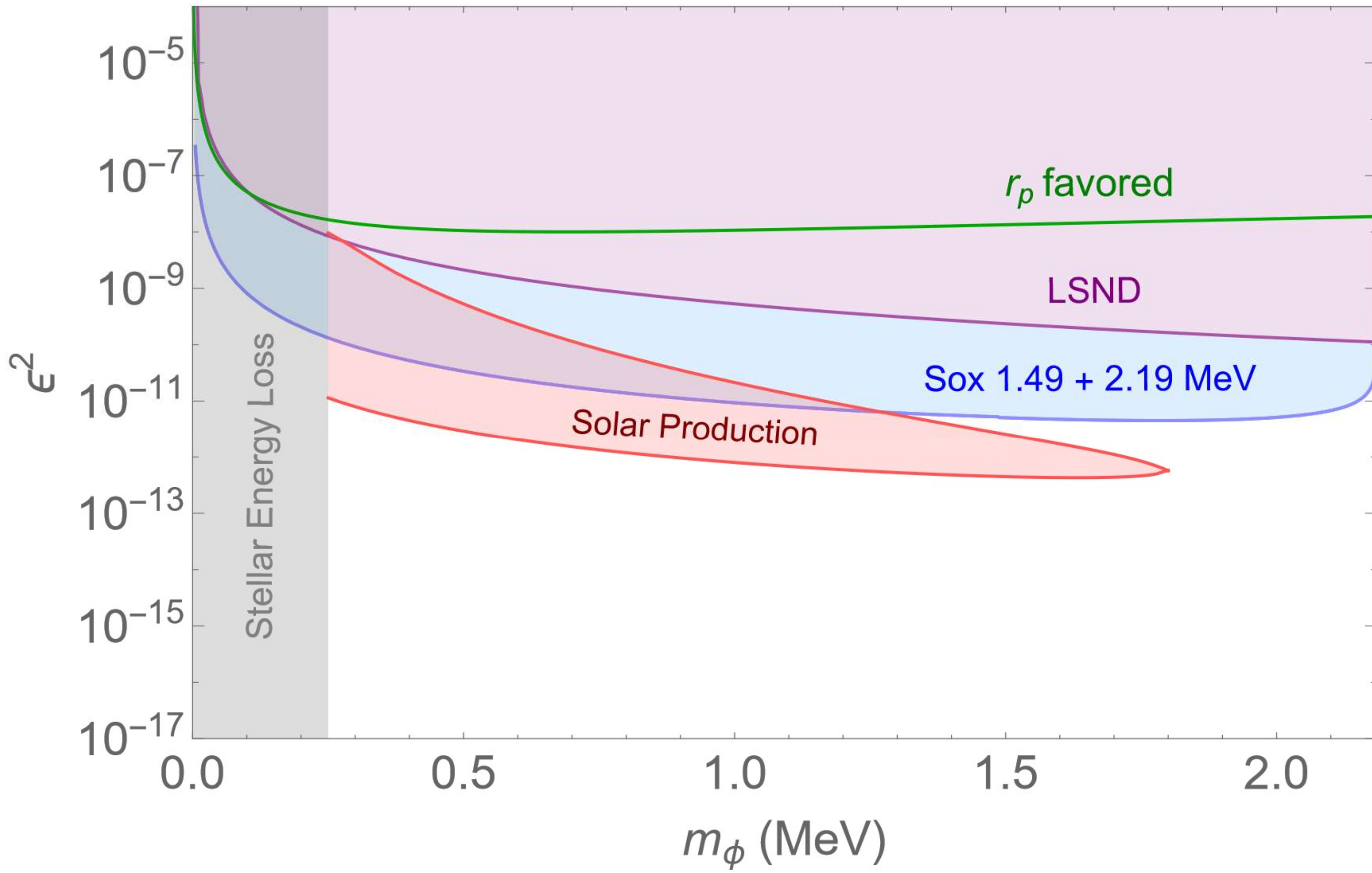


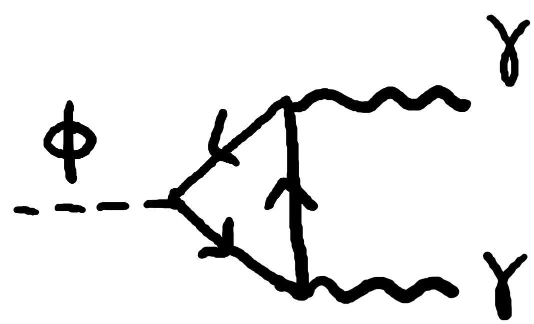
- Thermal production of scalars may lead to **abnormal energy losses** (or **abnormal thermal conductivity**)
- alter the **time evolution of well known stellar populations**
- In the regime of m_ϕ > T, the thermally averaged energy loss is proportional to $g_e^2 \exp(-m_\phi/T_{\rm star})$
- Given the 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, Pheno 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.

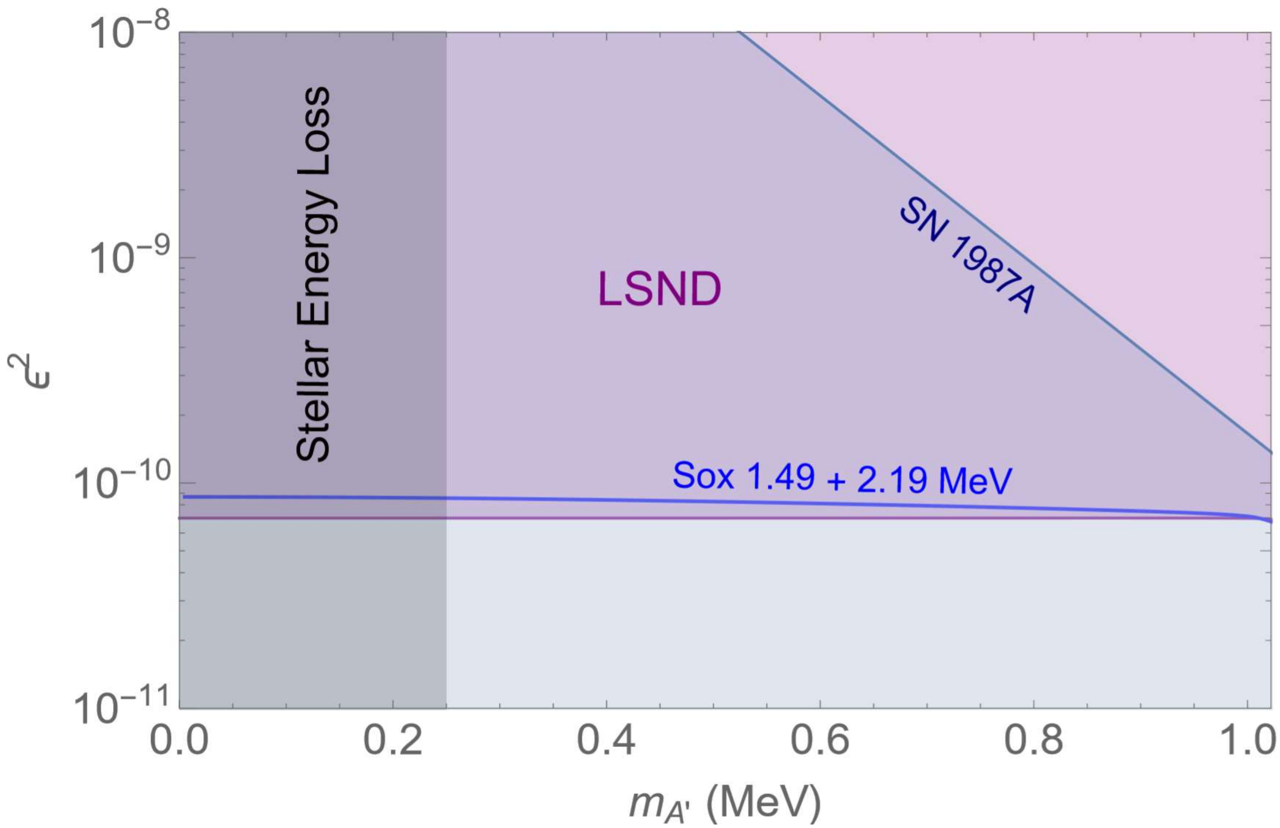




Maxim Pospelov and Yu-Dai Tsai, Pheno 2017

Bounds on Dark Photon

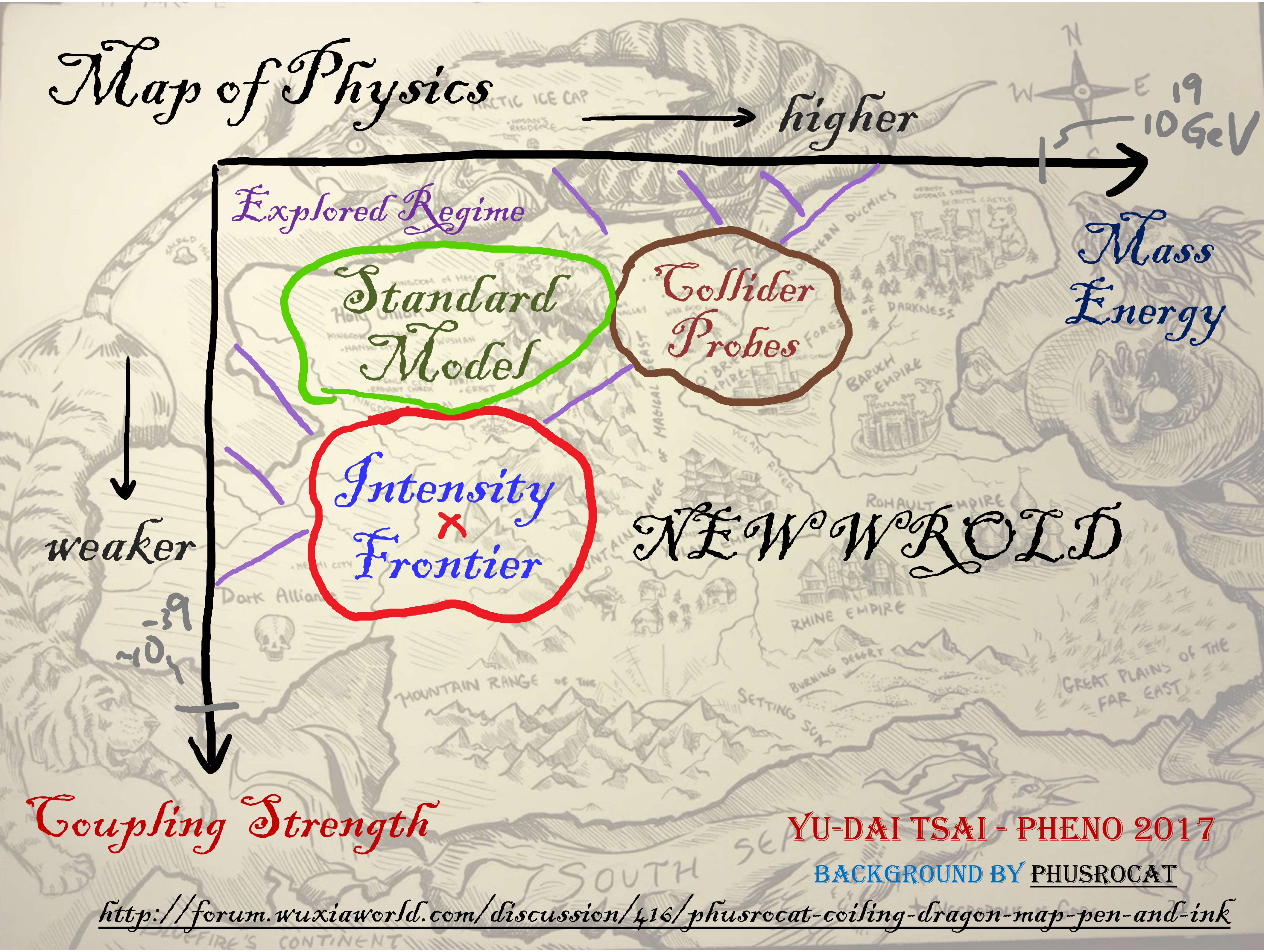
- A compilation of all the constraints and the future BoreXino sensitivity projection
- Dark photons in this parameter space is Cosmologically disfavored
- We found the recast of LSND data excludes the triangle regime that was not excluded by previous considerations



arXiv: 1706.00424

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
higher
10^{19} GeV
Mass
Energy
Explored Regime
Standard Model
Collider Probes
Intensity Frontier
NEW WROLD
weaker
10^{-39}
Coupling Strength
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BACKGROUND BY PHUSROCAT
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Thanks!

Special thanks go to Maxim, Eder and Gordan.