Cosmological Implications of Kalb-Ramond-Like Particles

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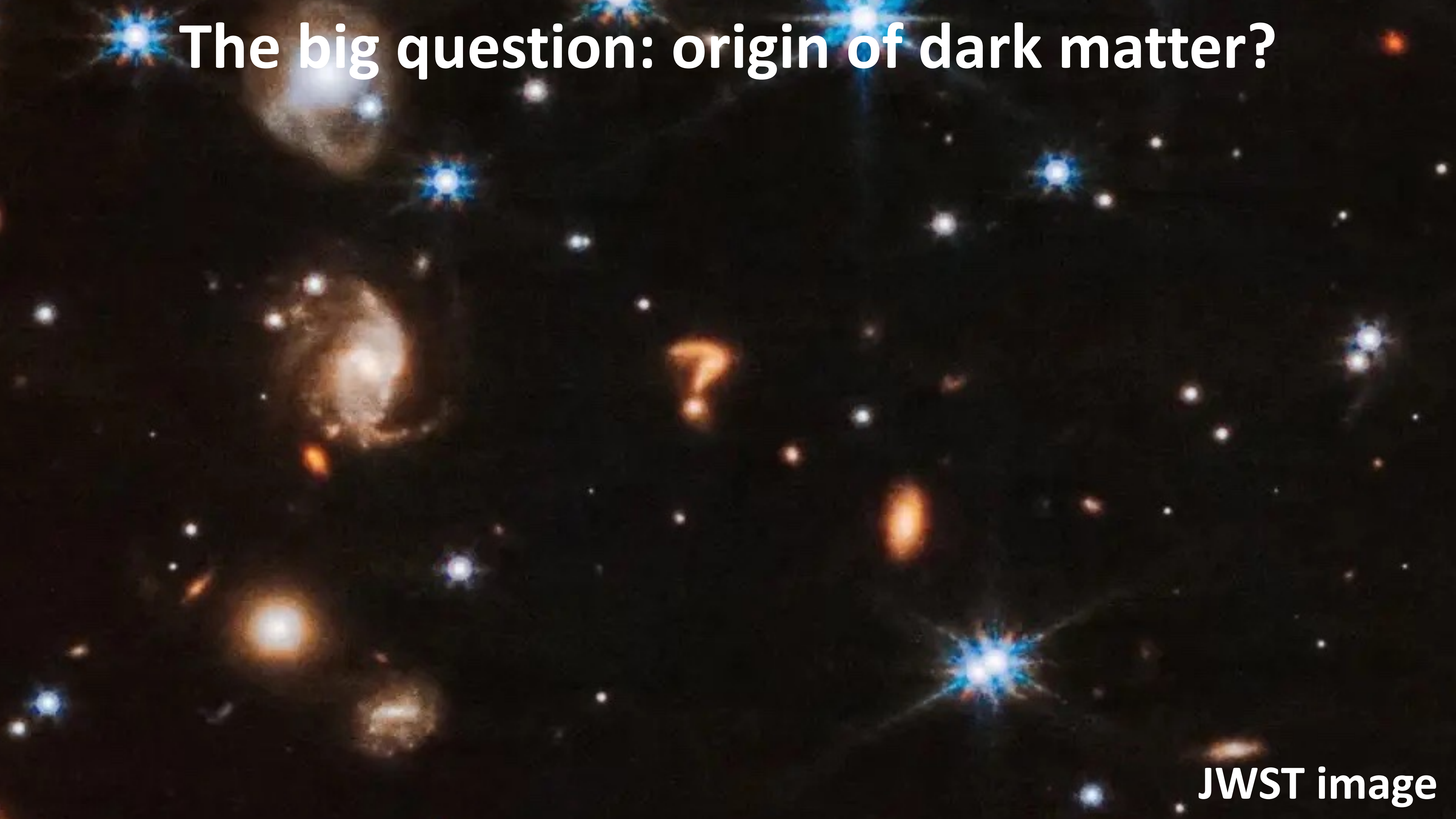
Rocky Kolb Kavli Institute for Cosmological Physics The University of Chicago

The big question: origin of dark matter?



JWST image

Inner Space/Outer Space Interface

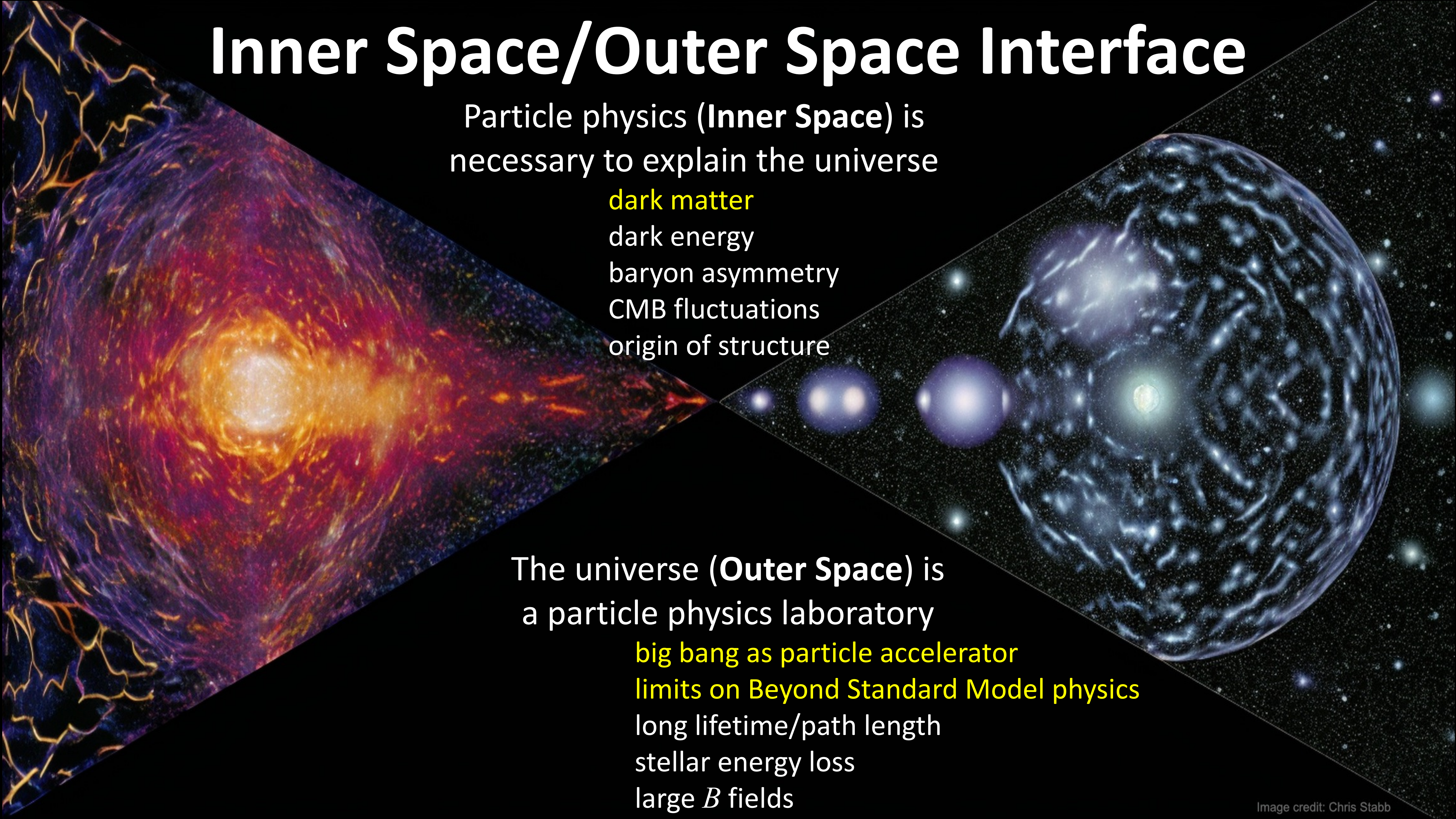


Image credit: Chris Stabb

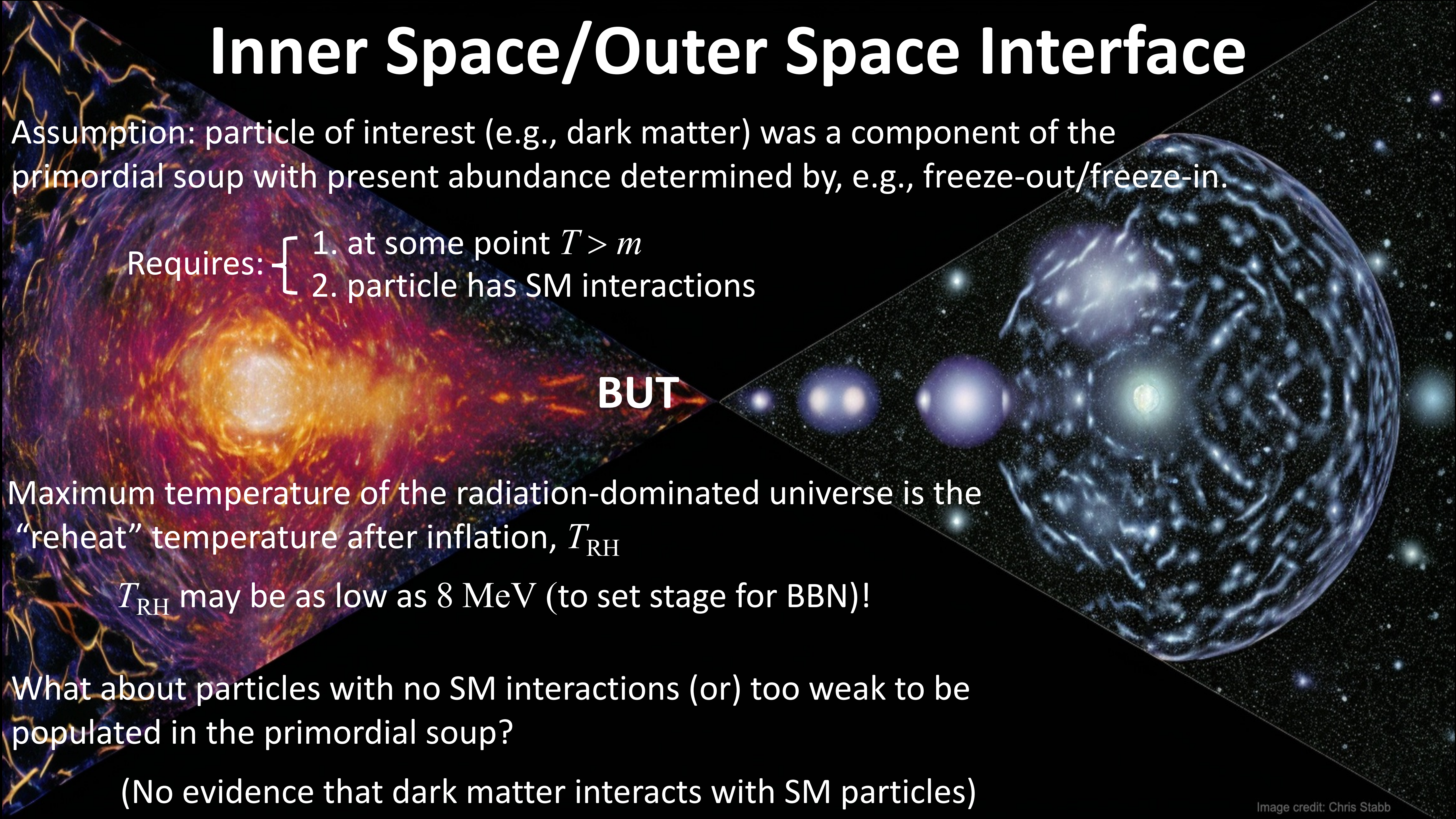
Particle physics (**Inner Space**) is necessary to explain the universe

- dark matter
- dark energy
- baryon asymmetry
- CMB fluctuations
- origin of structure

The universe (**Outer Space**) is a particle physics laboratory

- big bang as particle accelerator
- limits on Beyond Standard Model physics
- long lifetime/path length
- stellar energy loss
- large B fields

Inner Space/Outer Space Interface



Assumption: particle of interest (e.g., dark matter) was a component of the primordial soup with present abundance determined by, e.g., freeze-out/freeze-in.

Requires: $\begin{cases} \text{1. at some point } T > m \\ \text{2. particle has SM interactions} \end{cases}$

BUT

Maximum temperature of the radiation-dominated universe is the "reheat" temperature after inflation, $T_{\rm RH}$

$T_{\rm RH}$ may be as low as $8\ {\rm MeV}$ (to set stage for BBN)!

What about particles with no SM interactions (or) too weak to be populated in the primordial soup?

(No evidence that dark matter interacts with SM particles)

Image credit: Chris Stabb

Representation	Particle	1-point function Dark Matter	2-point function CMB Isocurvature	3-point function CMB Nongaussian
(0,0)	Conformally Coupled Scalar $\xi = 1/6$ (use as template)	Kuzmin & Tkachev (99)	Expected to be very small (blue)	Chung & Yoo (13)
(0,0)	Minimally Coupled Scalar $\xi = 0$ (e.g., inflaton)	Kuzmin & Tkachev (99)	Chung, EWK, Riotto, & Senatore (05)	
$(1/2,0) \oplus (0,1/2)$	"Dirac" Fermion	Chung, EWK, & Riotto (98)	Expected to be very small (blue)	
(1/2,1/2)	de Broglie-Proca Vector	Graham & Mardon (16); Ahmed, Grzadkowski,& Socha (20); EWK & Long (21)		
$(1,0) \oplus (0,1)$	2-Form (Pseudo) Vector (e.g., Kalb-Ramond)	Capanelli, Jenks, EWK, & McDonough (23)		
$(1/2,1) \oplus (1,1/2)$	Rarita-Schwinger Fermion (e.g., gravitino)	EWK, Long, & McDonough (21)		
(1,1)	Fierz-Pauli (massive graviton)	EWK, Liang, Long, Rosen (23)		
Higher-spin bosons		Jenks, Koutrolikos, McDonough, Alexander, Gates (23)		

For 40 Years, Leading DM Candidate: "Weak"-Scale Cold Thermal Relic

- Mass: GeV – TeV
- "Weak-scale" interaction strength with SM (WIMP miracle)
- No self-interactions
- Produced by "freeze-out" from primordial plasma. COLD dark matter. CDM.
- "Detectable" by direct detection, indirect detection, decay products, production at colliders
- Just BSM, e.g., low-energy SUSY!

But WIMPs have stubbornly evaded detection!

Perhaps DM interacts with SM only gravitationally or much weaker than weakly to be established in LTE?

Perhaps dark matter comes from a "Dark Sector"

Example #1 of Dark Sector Particle: Dark Photons

1. Suppose there is another $\mathrm{U}(1)$ field A'^{μ}

2. Give it a mass $m_{A'}$ via the trick of
   Baron Ernst Carl Gerlach Stueckelberg von Breidenbach zu Breidenstein und Melsbach
   (Abelian Higgs mechanism) → de Broglie-Proca field

3. Kinetically couple de Broglie-Proca field to $\mathrm{U}(1)_{\mathrm{EM}}$

$$\mathcal{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + eA^{\mu}J^{\mathrm{EM}}_{\mu} \boxed{- \epsilon\frac{1}{4}F^{\mu\nu}F'_{\mu\nu}}$$

3. After diagonalizing kinetic term $\mathcal{L} \supset \epsilon A'^{\mu}J^{\mathrm{EM}}_{\mu}$

4. If ϵ sufficiently small, de Broglie-Proca field "dark" and never in LTE in early universe

5. Produce dark photons via "freeze-in" mechanism $f + \bar{f} \to \gamma + \gamma'$ or $f + \gamma \to f + \gamma'$
   and if $m_B > 2m_f$ also $f + \bar{f} \to B$

Example #2 of Dark Sector: Axion Like Particles (ALPs)

1. Original Weinberg-Wilczek axion is a pseudo-Nambu-Goldstone boson resulting from breaking of Peccei-Quinn symmetry. Introduced to solve strong CP-problem.

   two scales: 1. SSB , scale $= f_a$, leading to NG boson. Original proposal, $f_a =$ EWK
   2. Explicit symmetry breaking scale f_π resulting in mass for pNGB axion:

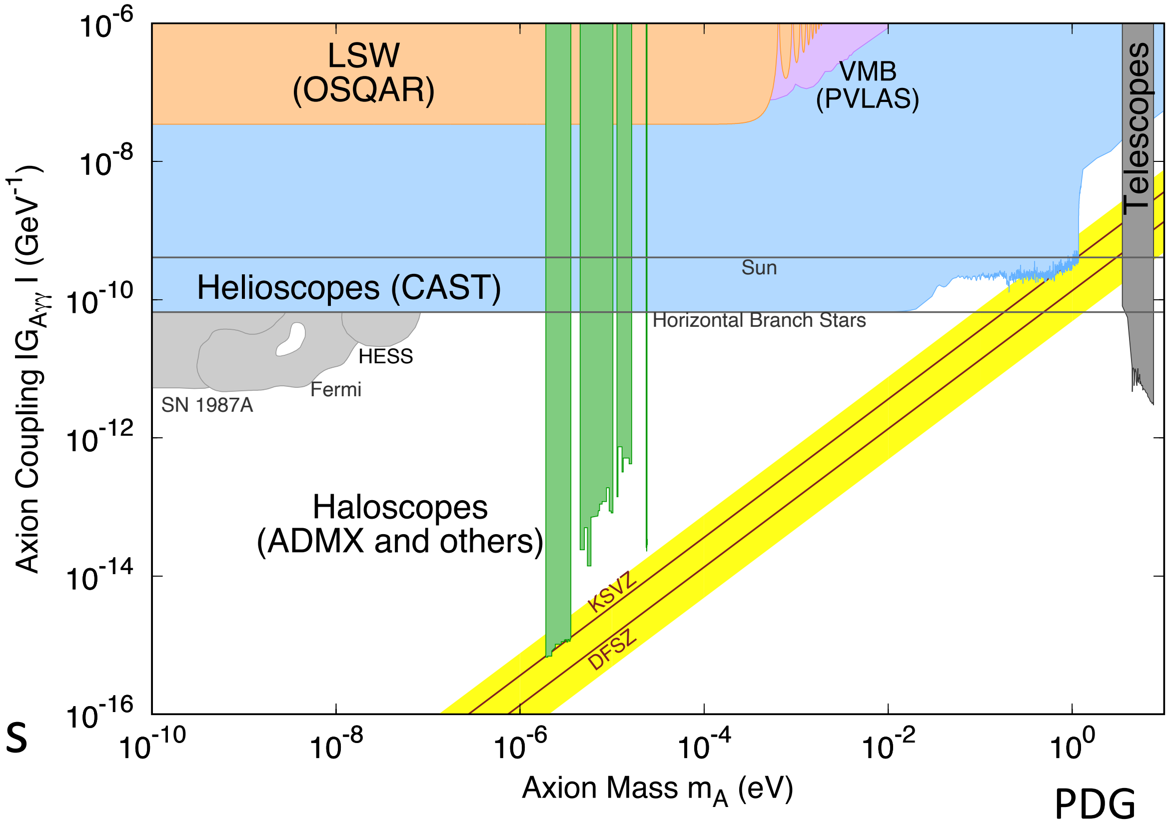
   $m_a f_a = m_\pi f_\pi$

   couplings to SM proportional to f_a^{-1}

   combination of experimental/astrophysical constraints ruled out original model

2. Invisible axion (introduced by Kim) f_a could be much larger → m_a much smaller

3. Axion DM: several possible cosmological origins for axions: misalignment, strings, freeze-in, …
   → many experimental searches for cosmic axions



PDG

4. QCD axion generalized to ALPs: ALP is a pseudoscalar, derivatively coupled, but $m_a f_a \neq m_\pi f_\pi$

In the spirit of Axion Like Particles (ALPs)

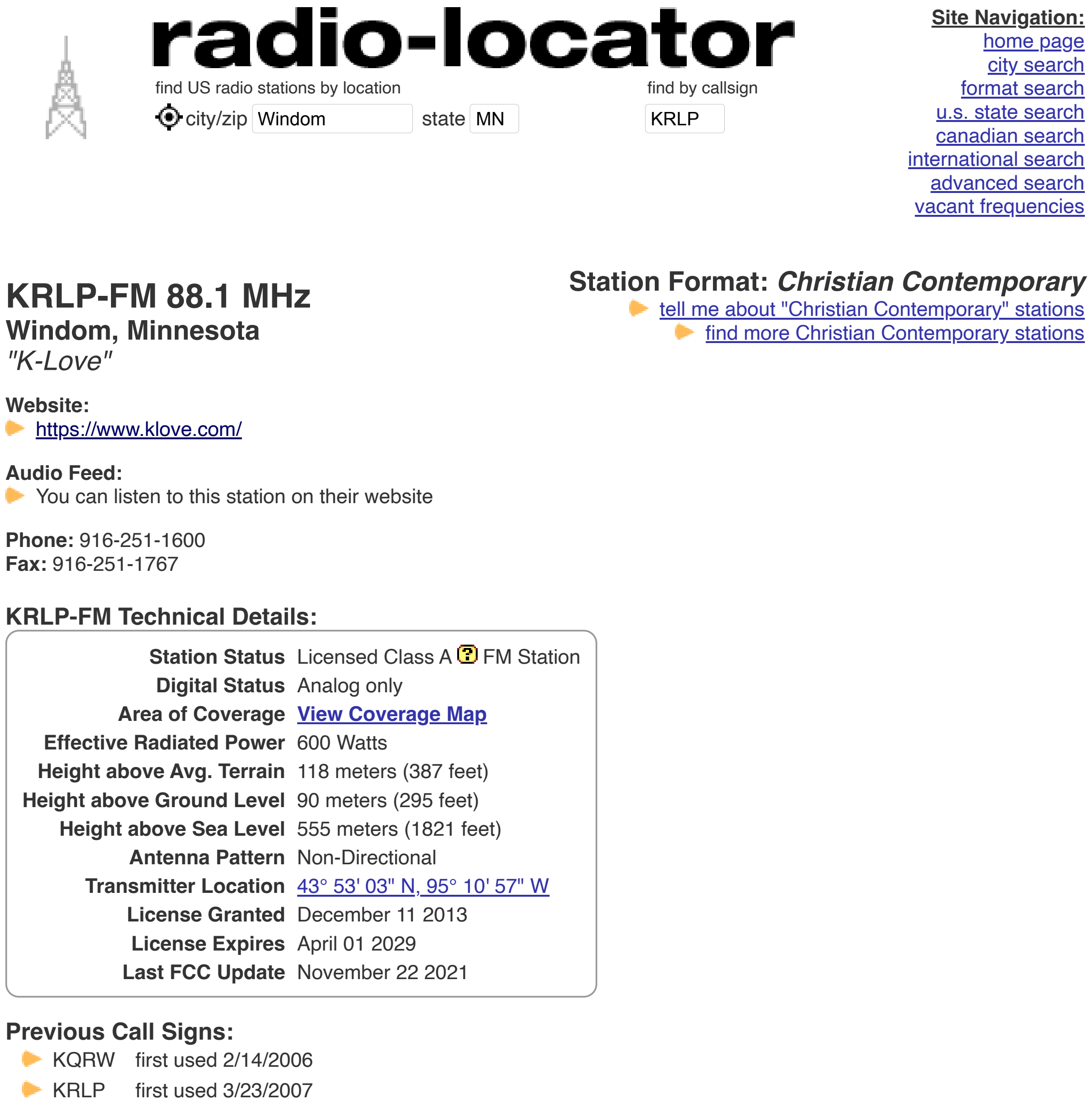
Kalb Ramond Like Particles (KRLPs)

Why a Kalb Ramond Field?	Why Kalb Ramond “Like” Field?
Fundamental in construction of string theory	Consider in the spirit of EFT
Proposed in strings in 1974 by Kalb & Ramond	Agnostic whether descends from string theory
2-form antisymmetric (pseudo) vector field	2-form antisymmetric (pseudo) vector field
$(1,0) \oplus (0,1)$ representation of Lorentz group	$(1,0) \oplus (0,1)$ representation of Lorentz group

$$B^{\mu\nu}$$

Note: $B^{\mu\nu}$ is the field, not the field strength

Kalb-Ramond Like Particles (KRLPs) will share properties with Dark Photons and ALPs (also see Hell 2109.05030)



city/zip Windom state MN

find by callsign KRLP

KRLP-FM 88.1 MHz

Windom, Minnesota

"K-Love"

Station Format: ***Christian Contemporary***

- tell me about "Christian Contemporary" stations
- find more Christian Contemporary stations

Website:

- https://www.klove.com/

Audio Feed:

- You can listen to this station on their website

Phone: 916-251-1600
Fax: 916-251-1767

KRLP-FM Technical Details:

Station Status	Licensed Class A ? FM Station
Digital Status	Analog only
Area of Coverage	**View Coverage Map**
Effective Radiated Power	600 Watts
Height above Avg. Terrain	118 meters (387 feet)
Height above Ground Level	90 meters (295 feet)
Height above Sea Level	555 meters (1821 feet)
Antenna Pattern	Non-Directional
Transmitter Location	43° 53' 03" N, 95° 10' 57" W
License Granted	December 11 2013
License Expires	April 01 2029
Last FCC Update	November 22 2021

Previous Call Signs:

KQRW	first used 2/14/2006
KRLP	first used 3/23/2007

Top Down: String Theory Origin

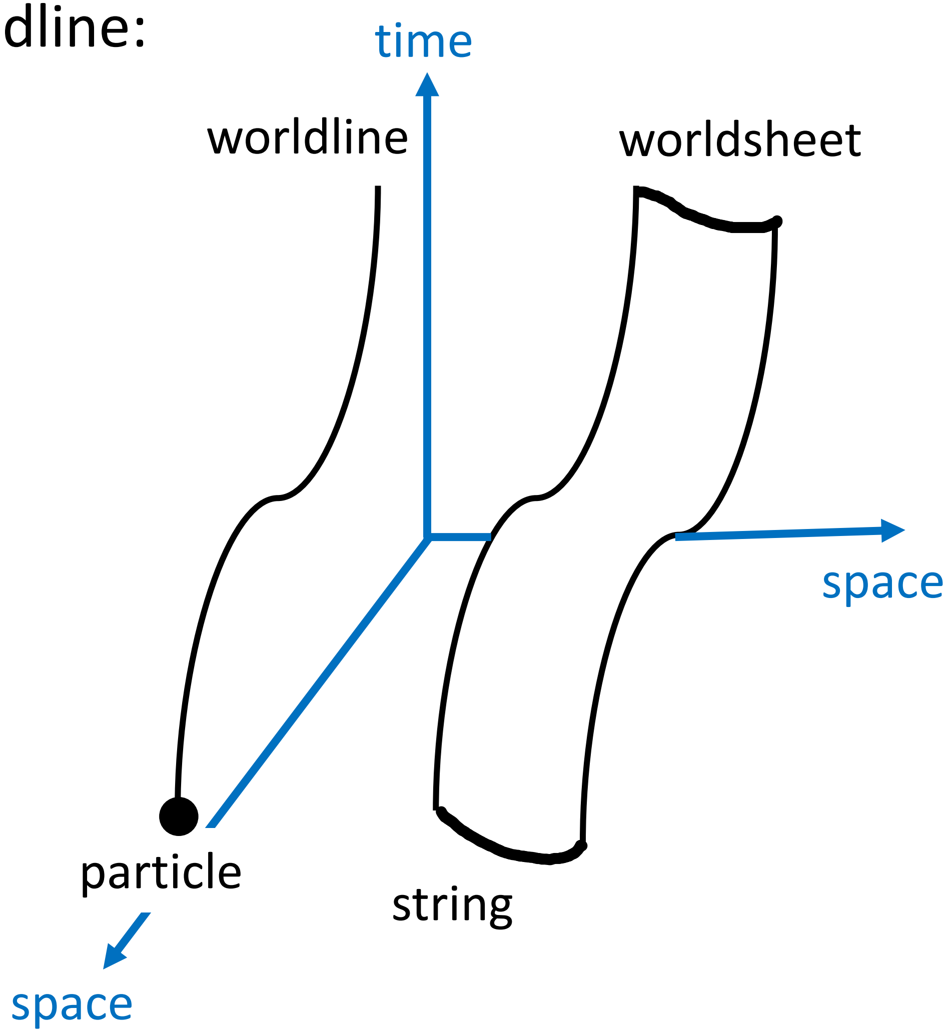
Kalb & Ramond 1974

One of the contributions to the action for usual electromagnetic potential is found by integrating A^μ over the <u>one-dimensional</u> worldline:

$$q\int dx^\mu A_\mu$$

For a string, must integrate over the <u>two-dimensional</u> worldsheet:

$$q\int dx^\mu dx^\nu B_{\mu\nu}$$



Insert Here Your Favorite String Jargon and Equations Using $\wedge$ and $\star$

- Neveu-Schwartz sector
- Type IIB
- Supergravity
- Ramond-Ramond sector
- Chern-Simons
- D-branes
- Dirac-Born-Infeld
- Brane tension
- Dimensional reduction
- B_2 axions, C_2 axions
- Kahler potential
- F_3 flux
- Large Volume Scenario
- Flux-induced superpotential
- KKLT
- Moduli stabilization
- ….

KRLPs exist in string theories

Possibly many KLRPs

They are presumably massive

Presumably have string-scale masses

Presumably unstable

They have interactions with SM fields

String theory friends should investigate if they can be light and stable

Bottom Up: EFT

1. KRLPs not part of SM.
2. But they are legitimate subjects of study as an EFT as (1,0) $\oplus$ (0,1) tensor repn. of Lorentz group.
3. They can be gauged by Baron Stueckelberg’s trick.
4. They are BSM, so they must interact very weakly with SM or have very large mass.

Free KRLPs

Action: $S_{\mathrm{KR}} = \frac{1}{12}\int d^4x\left(H_{\mu\nu\rho}H^{\mu\nu\rho} - 3m^2 B_{\mu\nu}B^{\mu\nu}\right)$

$B^{\mu\nu}$ is the antisymmetric KRLP field

m is the mass

$H_{\mu\nu\rho}$ is the KRLP field strength: $H_{\mu\nu\rho} = \partial_\mu B_{\nu\rho} + \partial_\nu B_{\rho\mu} + \partial_\rho B_{\mu\nu}$

Unlike familiar vector field, $B^{\mu\nu}$ is <u>even</u> under parity → $H_{\mu\nu\rho}$ parity <u>odd</u>

In <u>massless</u> limit local gauge invariance: $B_{\mu\nu} \to B_{\mu\nu} + F_{\mu\nu}$ where $F_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$

In <u>massless</u> limit Kalb-Ramond pseudoscalar axion θ is defined by $\partial_\mu\theta = \epsilon_{\mu\nu\sigma\rho}H^{\nu\sigma\rho}$

EOM for <u>massive</u> KRLP: $\partial_\mu H^{\mu\nu\rho} = m^2 B^{\nu\rho}$ → constraint equation $m^2\partial_\mu B^{\mu\nu} = 0$
removies three degrees of freedom

Dualities

Free <u>massless</u> KRLP dual to massless axion (Sverk & Witten 2006).

Massive axion is not dual to Kalb-Ramond, but dual to a massive three-form gauge field (Dvali 2005; Sakhelashvili 2022).

Free, <u>massive</u> KRLP resembles massive de Broglie-Proca field (Hell 2022), except that it is a pseudo-vector (axial vector) and not a vector.

Massless limit of Stueckelberged Proca is standard U(1) gauge theory plus decoupled scalar field.

Massless limit of Stueckelberged KRLP vector decouples.

Massive KRLP is a distinct physical object!

Furthermore, interacting KRLPs will have SM interactions different from Proca because it is parity even.

KRLP Interactions

Based on symmetry properties:

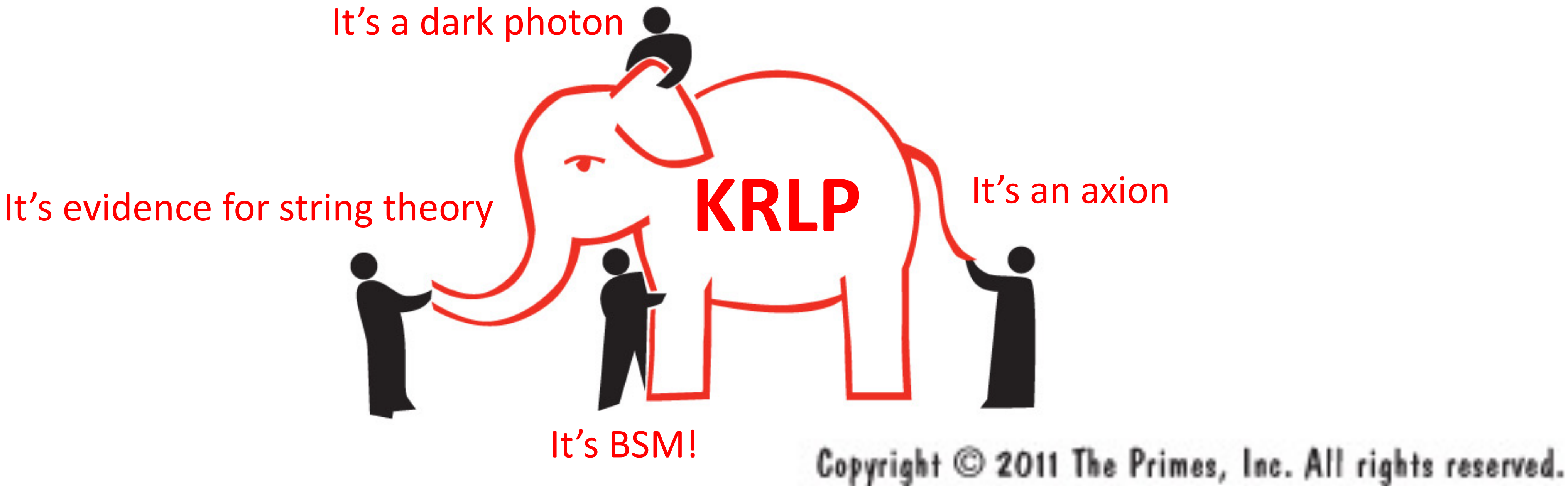
1. The KRLP is an antisymmetric matrix
2. $B^{\mu\nu}$ is parity even, a pseudovector
3. $H_{\mu\nu\rho}$ is parity odd
4. Dual field strength is parity even

Two portals to SM:

1. Dark photon-like portal couples to fermions by dim-4 operator $\mathcal{L} = -igB_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$
2. Axion-like portal with dim-5 operator $\mathcal{L} = \tilde{g}\tilde{H}_{\mu}\bar{\psi}\gamma^{\mu}\gamma^{5}\psi,$ with $\tilde{H} \equiv \star H$

KRLP Interactions

KRLP has aspects of dark photon and aspects of axion, but it’s a different beast!



It’s a dark photon

It’s evidence for string theory

It’s an axion

It’s BSM!

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E.g., KRLP vs. Dark Photon:

both feature direct coupling of the gauge field to a fermion current

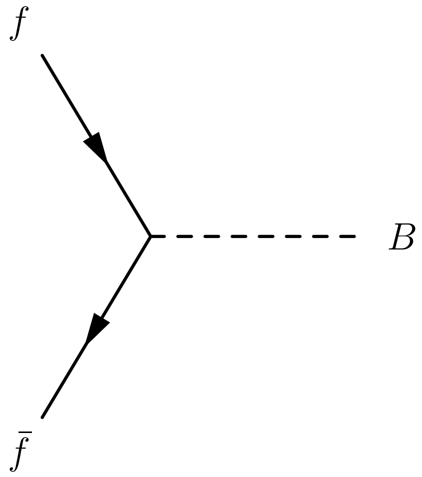
for dark photons mass mixing leads to photon—dark photon oscillations, absent for KRLPs

photon—dark photon conversion leads to resonance and dark photon coupling is temperature dependent leading to resonance as T falls below DP mass. Absent for KRLPs.

Many Threads to Follow—First Consider Freeze-in Production

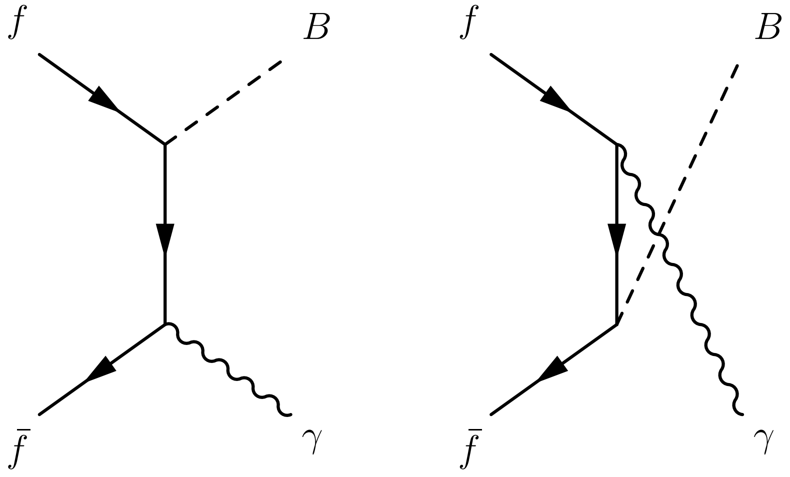
Coalescence
(inverse decay)

$f + \bar{f} \rightarrow B$



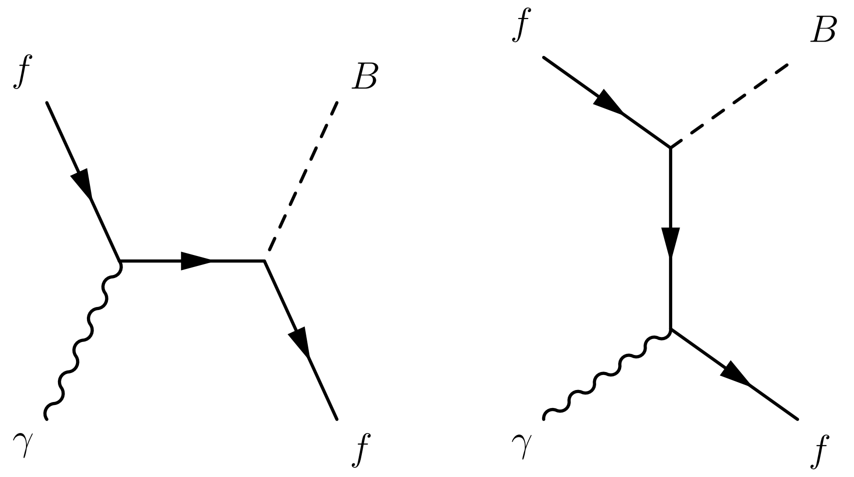
Annihilation

$f + \bar{f} \rightarrow B + \gamma$



Compton

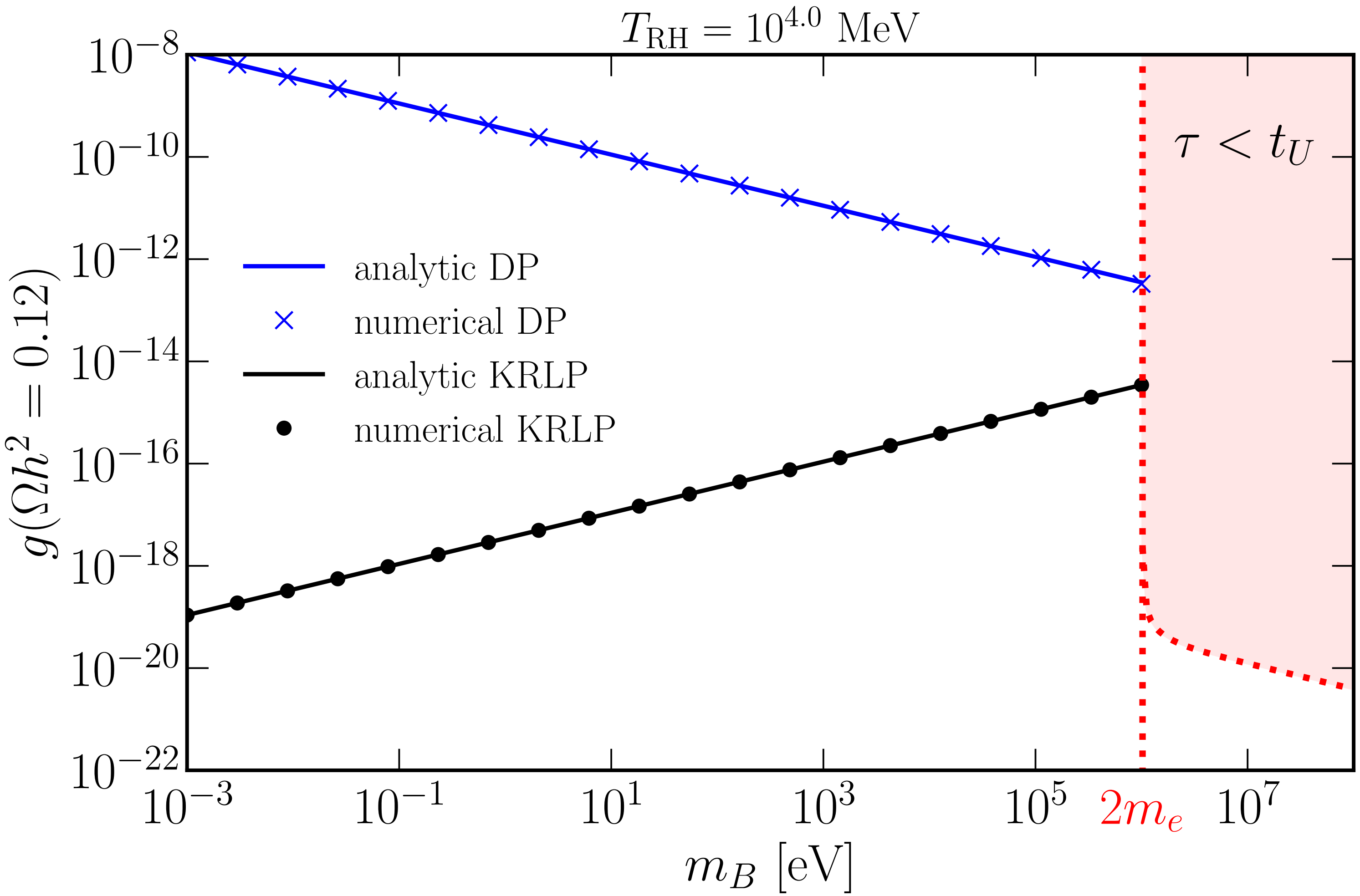
$f + \gamma \rightarrow B + f$



- Freeze-in assumes that species was never in LTE: $n_B < \bar{n}_B$ always ($\bar{n}_B$ is equilibrium value)
- Boltzmann equation for freeze-in: $\dot{n}_B + 3Hn_B \simeq \bar{n}_1 \bar{n}_2 \langle \sigma v \rangle_{12 \rightarrow 3B}$
- $\langle \sigma v \rangle_{12 \rightarrow 3B}$ is thermal average of cross section × Møller flux

$$\langle \sigma v \rangle_{12 \rightarrow 3B} = \frac{\int ds\, \sigma_{12 \rightarrow 3B}(s)\, K_1(\sqrt{s}/T)\, \sqrt{s} \left[s - 2(m_1^2 + m_2^2) + \frac{(m_1^2 - m_2^2)^2}{s} \right]}{8T\, m_1^2 K_2(m_1/T)\, m_2^2 K_2(m_2/T)}$$

Freeze-in B Production via Dark Photon-Like Portal



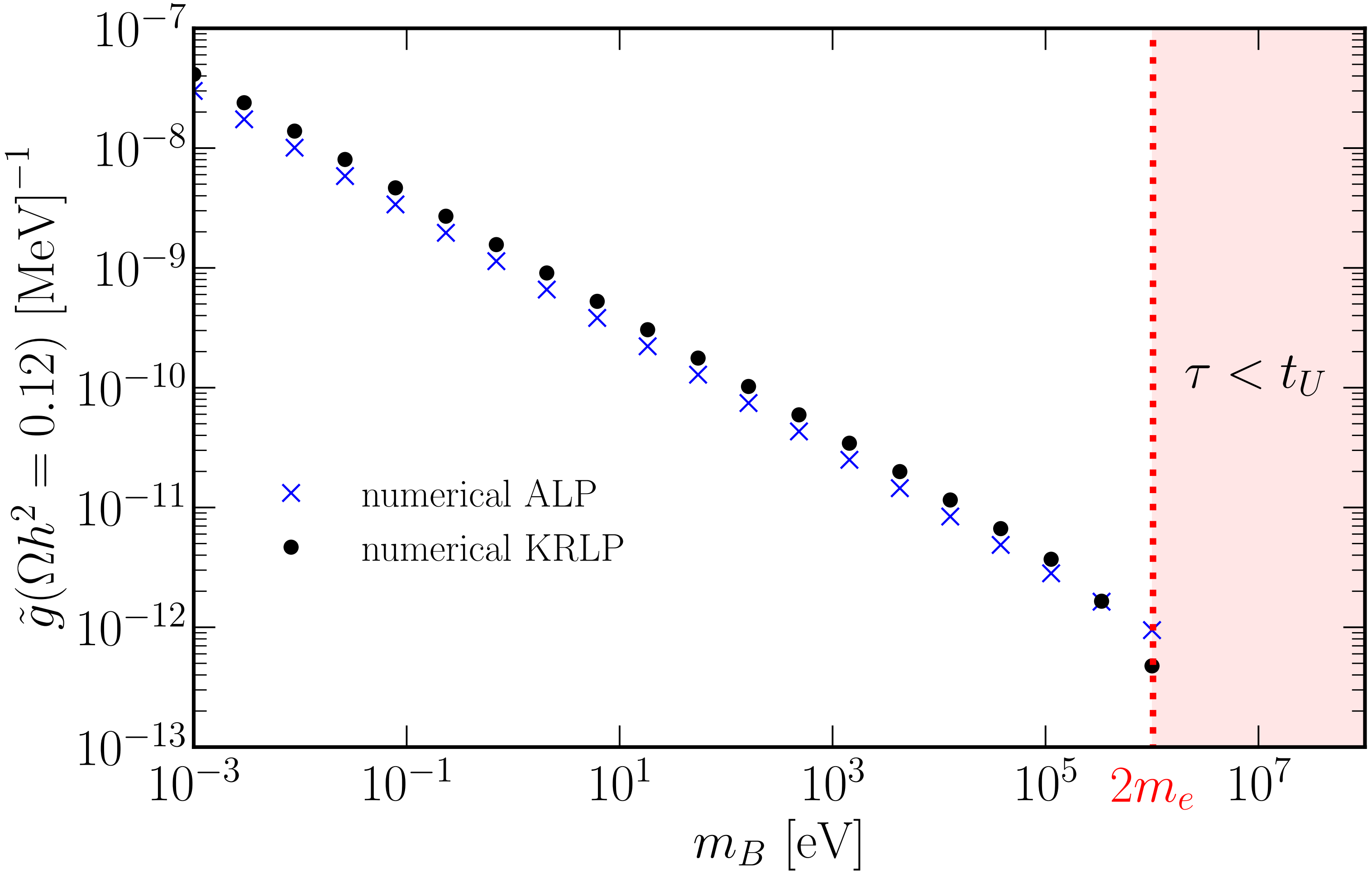
Dark Photon: $\mathcal{L} = gA'_\mu \bar{\psi}\gamma^\mu\psi$

KRLP: $\mathcal{L} = -igB_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$

Analytic DP: $g = 3.5 \times 10^{-10}(\mathrm{eV}/m_B)^{1/2}(m_f/m_e)^{1/2}$

Analytic KRLP: $g = 3.5 \times 10^{-16}(m_B/\mathrm{eV})^{1/2}(\mathrm{MeV}/T_{\rm RH})^{1/2}$

Freeze-in B Production via Axion-Like Portal



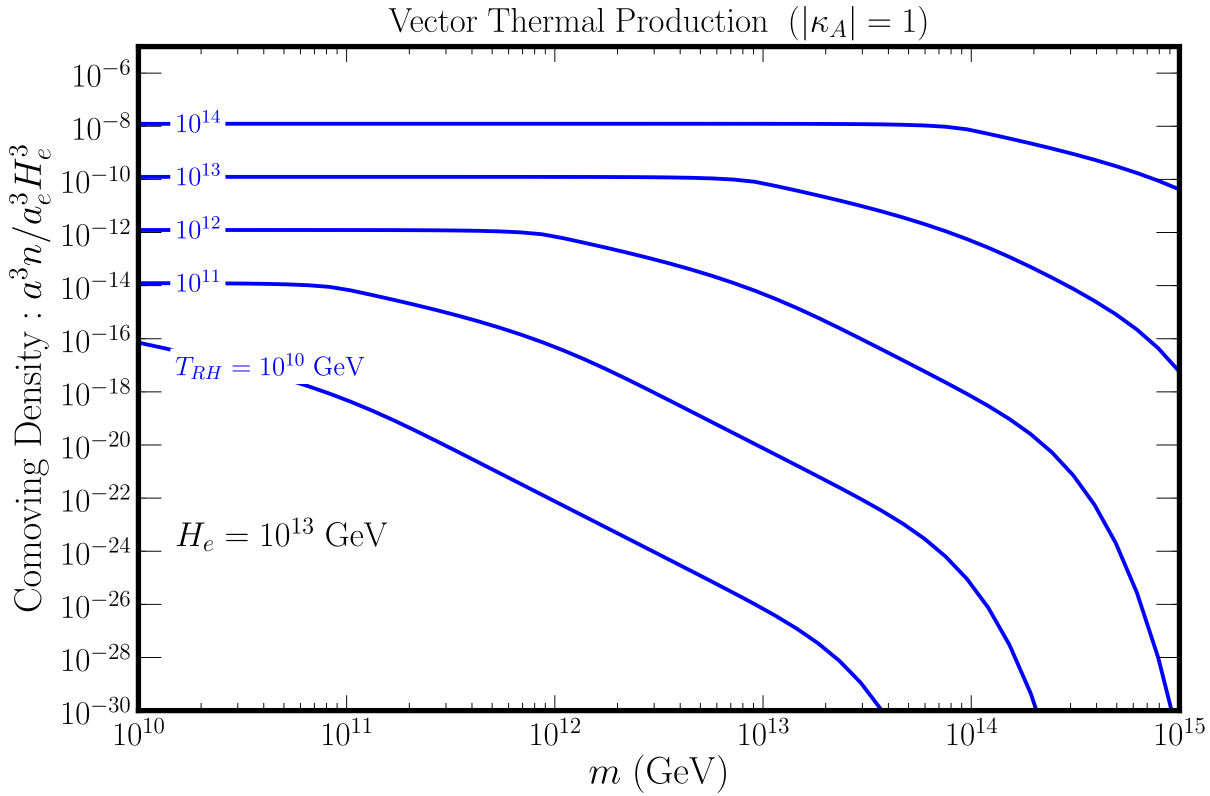
Analytic ALP and KRLP: $\tilde{g} = 1.3 \times 10^{-9} (\mathrm{eV}/m_B)^{1/2} (m_f/m_e)^{1/2}\ \mathrm{MeV}^{-1}$

Freeze-In via Higgs Portal

$$\mathcal{L} \supset \kappa \, \frac{m^2}{M_{\rm Pl}^2} B_{\mu\nu} B^{\mu\nu} \Phi^\dagger \Phi$$

Contributes to effective mass for *B*
Identical to spin-1 (EWK & Long 1708.04293)

$$\frac{\Omega h^2}{0.12} = \left(\frac{H_e}{10^{13}\mathrm{GeV}}\right) \left(\frac{T_{RH}}{10^{13}\mathrm{GeV}}\right) \left(\frac{m}{10^{13}\mathrm{GeV}}\right) \frac{1}{10^{11}} \frac{a^3 n}{a_e^3 H_e^3}$$



Easily can saturate dark matter density for e.g.,
$H_e = T_{RH} = m = 10^{13}$ GeV

Cosmological Gravitational Particle Production

Nonminimal couplings for Proca →

$$S \supset \int d^4x\sqrt{-g}\left[-\frac{1}{2}\xi_1 R g^{\mu\nu}A_\mu A_\nu - \frac{1}{2}\xi_2 R^{\mu\nu}A_\nu A_\nu\right]$$

In FRW background effective masses for transverse/longitudinal modes depend on

$$m^2_{\mathrm{eff},t} = m^2 - \xi_1 R - \frac{1}{2}\xi_2 R - 3\xi_2 H^2$$

$$m^2_{\mathrm{eff},x} = m^2 - \xi_1 R - \frac{1}{6}\xi_2 R + \xi_2 H^2$$

Nonminimal couplings for KRLP →

$$S \supset \frac{1}{12}\int d^4x\sqrt{-g}\Big[-\xi_3 R B^{\mu\nu}B_{\mu\nu} - \xi_4 R^{\mu\nu\rho\sigma}B_{\mu\nu}B_{\rho\sigma}\Big]$$

$B^{\mu\nu}$ antisymmetric, so can't couple to $R^{\mu\nu}$, but can couple to Riemann tensor

In FRW background effective masses for transverse/longitudinal modes depend on

$$m^2_{\mathrm{eff},t} = m^2_B - \frac{2}{3}\xi_3 R - \frac{2}{9}\xi_4 R - \frac{4}{3}\xi_4 H^2$$

$$m^2_{\mathrm{eff},x} = m^2_B - \frac{2}{3}\xi_3 R - \frac{2}{27}\xi_4 R + \frac{4}{3}\xi_4 H^2$$

Cosmological Gravitational Particle Production

With redefinition of coupling parameters $\begin{array}{l} \xi_3 \to \frac{3}{2}\xi_1 \\ \xi_4 \to \frac{9}{4}\xi_2 \end{array}$ effective masses for KRLPs same as Proca

Even including nonminimal couplings to gravity same results as for Proca

For minimal coupling can be DM for wide range of DM masses $\mu\mathrm{eV}$ to $10^{14}\ \mathrm{GeV}$
[Graham, Mardon, Rajendran (2016); Ahmed, Grzadkowski, Socha (2020); EWK & Long (2021)]

For some choices of nonminimal parameters can propagate ghosts in longitudinal mode if

$$m^2_{\mathrm{eff},t} = m_B^2 - \frac{2}{3}\xi_3 R - \frac{2}{9}\xi_4 R - \frac{4}{3}\xi_4 H^2 < 0$$

Perfectly consistent in Minkowski but ghostly in FRW.   WTF (why this feature)?

Conclusions #1/3

Two-form (pseudo-)vector field (KRLP) appears in string theory and can also be studied as an EFT

KRLPs share features of ALPs and Proca fields, but is neither, and is worthy of further study

KRLPs are a DM candidate. (Does the world need another DM candidate?)

Lot of experimental effort to discover **dark photon**. Discover **KRLPs** instead?

Dark photon has vector coupling to fermions
KRLPs have magnetic dipole coupling to fermions

Dark photon/photon oscillations absent for KRLPs
Dark photons can have a much larger coupling

KRLPs can simultaneously produce coincident dark photon and axion signals

Conclusions #2/3

Two-form (pseudo-)vector field (KRLP) appears in string theory and can also be studied as an EFT.

KRLPs share features of ALPs and Proca fields, but is neither and is worthy of further study

They are a DM candidate. (Does the world need another DM candidate?)

Lots of experimental effort to discover **axions**. Discover **KRLP**s instead?

- Away from massless limit KRLP is not dual to an axion
- For KRLP the Hodge dual of the field strength couples to axial current
- For axion, derivative of field couples to axial current
- Can experiment distinguish scalar from pseudo-vector?
- KRLP does not couple to electromagnetic $F_{\mu\nu}\tilde{F}^{\mu\nu}$, implies e.g., ADMX won't see KRLPs
- Axion helioscopes will be sensitive to KRLPs as well as ALPs

Conclusions #3/3

Two-form (pseudo)vector field (KRLP) is (well?) motivated as a subject of study.

Many avenues for future studies:

- Coupling to cosmic strings
- Decay of strings/walls produce gravitational waves
- Inflation-produced nongaussanities in CMB
- Muon g–2 anomaly
- Collider production
- Ghosts?

Please, string theory friends, investigate whether light KRLPs can exist and be stable.

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