Roni Harnik, Fermilab

 $A_\alpha(p_1)$ $A_{\beta}(p_2)$ (b)

Quantum Devices for Model Builders f(p1) loops that go across the extra dimension and connect the scalar fields on one brane with $\mathbf{t} = \mathbf{t}$ breaking vertex brane. This means, the other brane. This means, the anti- \blacksquare loop tan tan tan t arbitrary flavor structure was allowed. The important point is the important point in the extra that the extra dimensions involve the gaugino fields, which couple universally (as determined by the gauge

Time Capsule: HEP @ Berkeley in the Early 2000's

- LEP concluding. LHC construction beginning.
- Tevatron was on, but already in late years.
- Flavor physics had data w/ Babar+Belle
- Neutrino masses recently established
- DM direct detection was CDMS vs DAMA and that's it.

A lot of theorists, are actively model building.

Grad students joined the fun!

}

Exploring a lot on our own …

Emotional roller coaster. Model alive, model dead, alive, dead …

Model Building Themes

- Hierarchy problem
- SUSY mediation mechanisms
- Problems with SUSY mediation mechanisms
- Flavor in SUSY models
- Extra dimensions of various kinds
- Little Higgs & Little Hierarchy Problem

A bag of tricks! super potentials, symmetries, soft symmetry breaking, collective symmetry breaking, compositness, warped dimensions, branes, brane localized terms, NDA, Seiberg duality,

Phenomenology was confined to "we predict particles within LHC's reach.

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How the hell can Hitoshi be so productive ???

 \bigcup

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Take Hitoshi. Add a Z₂ symmetry. **Twin Hitoshi Theory Abstract:** We present a model that naturally explains how Hitoshi can get so much done by invoking a (softly broken) Z_2 symmetry.

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Twin Hitoshi Theory

- How they get so much done.
- How he calculated overnight and looked refreshed in the morning.
- Other rare phenomena:

Teaching at Berkeley while being in Japan on Kamland shift¹.

Our model explains:

Having enough frequent flyer mile for two people2

On few occasions I told Hitoshi something, and the next day he did not remember…3

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3 However, after interacting with Lawrence, I concluded that this effect was not statistically significant.

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Model Building Themes

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Cosmology sometimes played a more minor role…

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In 2001 Lawrence gave a talk about this paper: $R = 2$ in COOT Cawrence gave a raik abour rhis paper:

A Constrained Standard Model from a Compact Extra Dimension

Riccardo Barbieri^a, Lawrence J. Hall^{b,c}, Yasunori Nomura^{b,c}

 $A SU(3) \times SU(2) \times U(1)$ supersymmetric theory is constructed with a TeV sized extra dimension compactified on the orbifold $S^1/(Z_2 \times Z'_2)$. The compactification breaks supersymmetry leaving a set of zero modes which correspond precisely to the states of the 1 Higgs doublet standard model.... symmetry leaving a set of σ set of σ and σ and states of the states of the σ the σ $\mathcal{H}(\mathcal{O}(\Theta) \wedge \mathcal{O}(\mathcal{L}) \wedge \mathcal{O}(\mathbf{1})$ supersymmetric theory is constructed writt a Tev sized extractions are localized at $\mathcal{H}(\mathcal{L}(\mathcal{L}) \cap \mathcal{L}(\mathcal{L}) \cap \mathcal{L}(\mathcal{L}))$ $\sum_{i=1}^{\infty}$ fixed fixed points. The top $\sum_{i=1}^{\infty}$ and $\sum_{i=1}^{\infty}$ the top $\sum_{i=1}^{\infty}$ symmetry $\sum_{i=1}^{\infty}$ fixed $\sum_{i=1}^{\infty}$ fixed $\sum_{i=1}^{\infty}$ breaking, yielding which is finite and insensitive to physics potential which is finite and exponentially insensitive to physics and exponentially instruments of the set of the s above the compactification scale. This potential depends on only a single free parameter,

symmetry leaving a set of zero modes which correspond to the states of the states of the states of the 1990 and 19

leads to the parameter having to the parameter θ and unknown physics in the unknown physics in the ultraviolet.

of the all superpartners, and the all superport of the Kaluza-Klein excitations are also predicted. The lightest predicted in the lightest product of the lightest product of the light excitations are also producted. The li

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iggs mas \ldots yielding a Higgs mass prediction of 127 ± 8 GeV. The masses

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hep-ph 0011311

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Our bag of tricks

In recent years I'm working quite a bit at the interface of HEP and QIS.

QIS folks are playing with a lot of our tricks!

But: • Calling them by different names.

- Different goals.
- They are not only building models. They are building stuff!

…

compositness, EFT THE SM FERMIONS WILL BE SEEN AT THE SM FERMION SEEN AT THE BEGINNING OF THE BEGINNING OF THE BEGINNING OF compact dimensions branes branes brane localized terms NDA neutrino oscillations Matter effects $T_{\rm eff}$ important σ most important σ magnitude of the masses of the scalar partners of the scalar p where \mathbf{C} is the susy flavor problem. Qualitatively we can also features: since its features: si we have assumed that the SM matter fields are on the visible brane, they will not directly couplet dividualized sector. loops that go across the extra dimension and connect the scalar fields on one brane with θ arbitrary flavor structure was allowed. The important point is that the extra the extra that the extra dimensions involved the gauge the gaugino fields, which couple universally (as determined by the gauge α coupling to the MSS matter in the MSS matter fields. models (which we have not discussed here since those are not relying on extra dimensions) $t \in \mathbb{R}$ the soft scalar masses will be flavor universal, and thus this setup has a se Even though we basically already roughly know the answer for what the size of the this show the metal user that involve loops in the bulk in the bulk. Before we have a set of the bulk. Before The reason is the reason is the size of the loops in a usual F diagram shrinks to zero. However here the size of the extra dimension provides a UV cutoff,

fields have to propagate from one brane to the other.)

Quantum Devices

Ion traps

SC qubits

Atom interferometers

Quantum algorithms

(But in model builder's language)

At the heart of QFT is a mode expansion. We get to pick the modes. Something like -

Quantum Field Theory

$$
[a_k, a_k'^t] = \delta_{kk'}
$$

This is sometimes referred to as "second quantization". For us its first!

-
-

$$
\phi(x_{\mu}) = \int \frac{d^3k}{(2\pi)^3} \frac{1}{\sqrt{2\omega}} \left(a_{\vec{k}} u_{\vec{k}}(\vec{x}) e^{i\omega t} + a_{\vec{k}}^{\dagger} u_{\vec{k}}^{\dagger}(\vec{x}) e^{-i\omega t} \right)
$$

Quantize: a, a^t are operators.

 $Satisfy:$

In this big Universe, fields sometimes get localized to a finite regions. Either "naturally" or in a lab.

$$
\phi(x_{\mu}) = \int \frac{d^3k}{(2\pi)^3} \frac{1}{\sqrt{2\omega}} \left(a_{\vec{k}} u_{\vec{k}} (\vec{x}) \right)
$$

Quantum Fields in Small Devices **S** *Quantum Fields in 3* **GUANTUM FIEIDS IN SMAIL DEVICES** signal pump

 $\vec{x})e^{i\omega t}+a\frac{\partial f}{\partial x}$ \vec{k} *k* $u_{\vec{k}}$ *k* $*(\vec{x})(e^{-i\omega t})$ \setminus

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$$

Quantum Fields in Small Devices **S** *Quantum Fields in 3* **GUANTUM FIEIDS IN SMAIL DEVICES** signal pump

Only a discretum satisfies boundary conditions.

 $\vec{x})e^{i\omega t}+a\frac{\partial f}{\partial x}$ \vec{k} *k* $u_{\vec{k}}$ *k* $*(\vec{x})(e^{-i\omega t})$ \setminus

 $\begin{array}{c} + \end{array}$ $\sqrt{ }$ *j* 1 $\sqrt{2\omega}$ $\sqrt{2}$ $a_ju_j(\vec{x})e^{i\omega t} + a^\dagger_j$ $\int\limits_j^{\text{+}}u_j\text{ }^*(\vec{x})(e^{-i\omega t}%)\left(e^{-i\omega t}\right) \cdot e^{-i\omega t}$ \setminus

In these EFTs, modes separate from the continuum, Quantum Mechanics shines:

Device EFT

 \square Consider the low energy EFT of the discretum. Often in terms of a, at

Optical

waveguide Superconducting circuits

Electromagnetic Cavities

Atoms

$$
\phi_j(x_\mu) = \frac{1}{\sqrt{2\omega}} \left(a_j u_j(\vec{x}) e^{i\omega t} + a_j^\dagger u_j^*(\vec{x}) (e^{-i\omega t}) \right)
$$

Defects

Atoms Defects Artificial Atoms (particle in trap) $(\rho$ ar

200

Examples

Optical Devices (e.g. "photonics")

Superconducting qubits and cavities

Estrada, RH, Senger, Rodriguez *PRX Quantum* **2 (2021) 3, 030340**

Blinov, Gao, RH, Janish, Sinclair [2401.17260](https://arxiv.org/abs/2401.17260)

RH In preparation

Optics

Laser

[Chapter 6 of Jackson]

The EFT of light traveling through a medium, made of atoms: N_{atoms} ~ 10²³!!
B^{SB} & ⁸ & 8 & 8 & 8 & 8 & 8 & **O** The EFT of light traveling through a medium, made of atoms: N_{atoms}
se as Natoms ~ 1023 !! 300 \$ 88 Δ SSS HOR 480 3 E 888 \rightarrow 88 SSS **REER** Lyo SSS 88 \$ 球 888 \$ \$ **REP** $\omega_{atoms} \sim \alpha^2 m_e$ $\delta x_{atoms} \sim a_{Bohr} \sim (\alpha m_e)^{-1}$

The EFT of light traveling through a medium, made of atoms
B & & & & & & The EFT of light traveling through a medium, made of atoms: N_{atoms} ~ 10²³!!
B^{SB} & ⁸ & 8 & 8 & 8 & 8 & 8 & **O** The EFT of light traveling through a medium, made of atoms: N_{atoms}
se as The EFT of light traveling through a medium, made of atoms: Natoms ~ 1023 !! 30 3 \$ **REP** HOS 480 \$ 爱 **RED** \$ **REP REER** Lyu 3 3 \$ \$ 绿 \$ \$ $\omega_{atoms} \sim \alpha^2 m_e$ $\delta x_{atoms} \sim a_{Bohr} \sim (\alpha m_e)^{-1}$ $\delta x_{atoms} \ll \lambda_{light} \rightarrow$ atoms react collectively! $2E - \frac{1}{n^2}$ $\partial_t^2 E - \partial_x^2 E = 0 \longrightarrow \partial_t^2 E - \frac{1}{n^2} \partial_x^2 E = 0$ ∂_t^2 *n*2

At the renormalizable level:

[Chapter 6 of Jackson]

Consider a small 1D optical device in large dimensions. Lets think of it as a fat brane.

Optical Device

- On the brane we can write a brane localized kinetic term
	- $*$ On the brane the field obeys: $k = u$ ω * The field can be brane-localized. * Index of refraction n can depend on other UV effects

 ∂_t^2 $2E - \frac{1}{n^2}$ *n*2 ∂_x^2 $\frac{2}{x}E$ $\partial_t^2 E - \partial_x^2 E$

- On the brane we can write a brane localized kinetic term □ On the brane we can write a brane localized kinetic
term
* The field can be brane-localized.
* ∩ H L L L C H L L L L L d
- On the brane we can write a brane localiz
term
* The field can be brane-localized.
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 ∂_t^2 $2E - \frac{1}{n^2}$ *n*2 ∂_x^2 $\frac{2}{x}E$ $\partial_t^2 E - \partial_x^2 E$ $\overline{\partial_t^2 E \overline{\partial_t^2 E - \partial_x^2 E}$ mui de mui de mui de $\frac{\partial^2 E}{\partial t^2} - \frac{\partial^2 E}{\partial t^2}$

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Optical Device

Consider a small 1D optical device in large dimensions. Lets think of it as a fat brane. $\frac{1}{2}$ r a
uk $\frac{1}{2}$ evice or

^s Pump photon

- On the brane we can write a brane localized kinetic term d
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$\frac{1}{2}$ $\frac{1}{2}$

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"Integrated photonics" "Integrated photonics"

Optical Device

Consider a small 1D optical device in large dimensions. Lets think of it as a fat brane. r a
uk evice or

^s Pump photon

The dispersion relation determines kinematic properties! Would be nice to control it.

> But we have no interactions between flavors… Linear Optics: $H = E^2 + B^2 = \sum \hbar \omega (a^{\dagger} a + \frac{1}{2})$

Degree of Freedom in Optical Devices

- Fields on the fat brane live in a compact dimension. The field can be expanded in KK modes
- If the material is anisotropic, n can depend on polarization.

"Flavor!!"

jkl in the nonlinear optics crystal. We note that Equation (3) violates both charge conjugation (Furry's theorem in particle parlance) and with 3 and the third order susceptibility. As opposed the third order susceptibility. As opposed to (2) , four-wave mixing mixi

² there is a UV cutoff.
For example, in optics

$$
\int d^3\vec{x} \left(\chi_{jkl}^{(2)} E_j E_k E_l\right)
$$
crystal

$$
\int d^3\vec{r} \left(\chi^{(3)} E_i E_l E_l E_l\right)
$$

 $d^3\vec{x}$ $\chi^{(3)}_{\textit{\textbf{i}}\textit{\textbf{k}}\textit{l}}$ $\frac{(9)}{jkl}E_{j}E_{k}E_{l}E_{m}$

 \setminus

crystal

Nonlinear Devices

\n
$$
\Box
$$
 Like any EFT, in a quantum device there is a UV cutoff.

\n
$$
\Box
$$
 We can add higher dim operators. For example, in optics

\n
$$
Dim-6:
$$

\n
$$
U_{\text{SPDC}} = \int_{\text{crystal}} d^3 \vec{x} \left(\chi_{jkl}^{(2)} E_j E_k E_l \right)
$$

\n
$$
Dim-8:
$$

\n
$$
U_{\text{4-wave}} = \int_{\text{crystal}} d^3 \vec{x} \left(\chi_{jkl}^{(3)} E_j E_k E_l \right)
$$

\n
$$
\frac{W_{\text{e can estimate}} \chi'_{\text{S in naive dimensional analysis:}}}{W_{\text{hen the field is set to that in an atom, we set (Dim-4 ~ Dim-6 ~ Dim-8):}
$$

\n
$$
E_{\text{atom} \sim e/4 \pi a_0^2} \qquad \frac{\sqrt{4\pi}}{a^{5/2} m_e^2} \qquad \text{(by comparison, in vacuum)}
$$

\n
$$
\chi^{(2)} = \frac{2a^2}{45 m_e^4}
$$

SPDC , (9)

Now we can have "flavor" changing decays: Photon -> two other photons $Pump \longrightarrow Signal + Idler$

…. can we use this to search for BSM?

Phase Matching in dSPDC

D Two obser

Figure 2: *Left:* The allowed phase space for SPDC (black), dSPDC with *m* = 0 (red), and dSPDC with *m* = 0*.*1*Ê^p* \mathbf{b} rather by sending it has \mathbf{b} and \mathbf{b} and \mathbf{b} with the formation is k linemation ticularly apparent if A is an extremely weekly coupling if A is an extremely weekly coupling if A are $O(1)$ different! coupling *'* to photons. The rate of information flow ϵ CPDC and dSPDC In this work we propose to use quantum imag- \cdot) or \cdot free search \cdot Kinematically, SPDC and dSPDC are O(1) different!

 θ_s

$$
\mathrm{dSPDC} \qquad \qquad \underbrace{\hspace{1cm}|\textbf{\textit{k}}_s|=n_s\omega_s\qquad \qquad |\textbf{\textit{k}}_\varphi|=\omega_\varphi}{|\textbf{\textit{k}}_p|=n_p\omega_p}
$$

sin *◊ⁱ* = *ks* process of \mathcal{L} \int an obeca neakal fore and new be

sin *◊^s* Of course, not any combination of *n^p* and *n^s* will Can phase match for any ns > np. $Lan Phase match for any $h_s > h_\rho$.$

$$
\omega_s = \omega_p - \frac{\left(n_s - n_p\right)n_s\omega_p \pm \sqrt{\left(n_s - n_p\right)^2\omega_p^2 - \left(n_s^2 - n_p\right)^2\omega_p^2 - \omega_p^2}}{n_s^2 - 1}
$$

^s 1) *m*²

(d)SPDC Interaction and Rates

(d)SPSC Interactions:

SPDC and dSPDC can be described using an effective interaction:

• SPDC (& nonlinear optics):

• Dark photons (linear extension)

 $H \supset H_{\text{options}} + \varepsilon \vec{\epsilon} \cdot \vec{\epsilon}' + \vec{B} \cdot \vec{B}'$

• Axion-like particles (nonlinear)

ℋSPDC ⊃ *χ* Ep Es Ei + …

 H a $\frac{1}{f}$ E⋅B

<u>Note</u>: axions and dark photons have index or refraction 1! (Rather k_p² = ${\omega_\phi}^2$ +m_p²) ⁻

(d)SPSC Interactions: We dispese interactions: We have written this work. We have written the two dispersions of the two dispersions Equation (32) for axions and Equation (35) to a form which is very similar to that of the SPDC is very similar to the SPDC is very similar to that of the SPDC is very similar to the SPDC is very similar to the SPDC is ver

I Expanding the fields as in quantum optics SPDC & dSPDC can be treated similarly. SPDC rates, e.g. [17] and [19], to estimate the rates of dSPDC. For ease of use later we can thus

Define *φ* as an idler photon, axion, or dark photon -

Expanding the fields as in quantum optics, SPDC & dSPDC can be treated similarly:

 $\sqrt{\omega_p \omega_s \omega_{\varphi i}}$ $8n_p^2n_s^2n_{\varphi i}^2$ $\mathcal{I}_j e^{i\Delta \omega t}$ $a_{k_p}a_{k}^{\intercal}$ *k^s* $\mathcal{H}_{\text{(d)SPDC}} = \sum_{\alpha} \sum_{\alpha} \chi_{\text{eff}} \sqrt{\frac{\omega_p \omega_s \omega_{\varphi_l}}{8n_s^2 n_s^2 n_{\varphi}^2}} \mathcal{I}_j e^{i \Delta \omega t} a_{k_p} a_{k_s}^\dagger b_{k_{\varphi i}}^\dagger + \text{h.c.}$

 $\pi T(p) T(r(s) * T(r(i)) * p(i)$ $i \Delta kz$ $dz\,d^2r\,U^{(p)}U^{(s)\,*}U^{(\varphi i)}_i$ *j* ⇤ $(z) e^{i\Delta kz}$

[in preparation (RH)]

(d)SPSC Interactions: We dispese interactions: We have written this work. We have written the two dispersions of the two dispersions Equation (32) for axions and Equation (35) to a form which is very similar to that of the SPDC is very similar to the SPDC is very similar to that of the SPDC is very similar to the SPDC is very similar to the SPDC is ver

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Define *φ* as an idler photon, axion, or dark photon -

 $\pi T(p) T(r(s) * T(r(i)) * p(i)$ $i \Delta kz$ $\varphi i \hspace{1.5cm} \chi_{\rm eff} \hspace{1.5cm} n_{\varphi i}$ $\frac{d}{dk}$ $\frac{p}{j}\varepsilon^s_k\varepsilon^i_l$ n_i $\frac{d^2 a \gamma}{d a a} (n_s - n_p) \sin \phi_{\rm pol} \qquad 1$ $\frac{m_{A'_L}}{\omega_{A'}}$ *L* ω_A *L* $\chi^{(2)}_{i k z}$ $\frac{(2)}{jkz}\varepsilon$ *p* $\frac{p}{j}\varepsilon^{\scriptscriptstyle S}_{k}$ $\frac{s}{k}$ 1 $dz\,d^2r\,U^{(p)}U^{(s)\,*}U^{(\varphi i)}_i$ *j* ⇤ $(z) e^{i\Delta kz}$ (3) $\chi_{jkl} \varepsilon_j \varepsilon_k \varepsilon_l$

avion a

avion a
 $\frac{g_{a\gamma}}{n}$ $\int_{-\infty}^{\infty} \frac{\chi_{jkl} \varepsilon_j \varepsilon_k \varepsilon_l}{n}$ *p* $\chi^{(2)}_{ikz}$ $\int\limits_{\gamma}$ \mathcal{E}^{p}_{i} $\sum_{i}^{0} \varepsilon_k^s$ 1 axion *a ^ga* !*^a* (*n^s np*) sin pol 1 $\sqrt{\omega_p \omega_s \omega_{\varphi i}}$ $8n_p^2n_s^2n_{\varphi i}^2$ $\mathcal{I}_j e^{i\Delta \omega t}$ $a_{k_p}a_{k}^{\intercal}$ *k^s* $\mathcal{H}_{\text{(d)SPDC}} = \sum_{\alpha} \sum_{\alpha} \chi_{\text{eff}} \sqrt{\frac{\omega_p \omega_s \omega_{\varphi_l}}{8n_s^2 n_s^2 n_{\varphi}^2}} \mathcal{I}_j e^{i \Delta \omega t} a_{k_p} a_{k_s}^\dagger b_{k_{\varphi i}}^\dagger + \text{h.c.}$ \int with $\mathcal{I}_i \equiv \int dz \, d^2 r \, U^{(p)} U^{(s)} \, U_i^{(\varphi)} \, (z) \, e^{i \Delta \kappa z}$ is a proportion of the emission of the extension of the $\frac{1}{\sqrt{2}}$ ϵ Phase matching!

Expanding the fields as in quantum optics, SPDC & dSPDC can be treated similarly:

[in preparation (RH)]

ous and dark photous are not confined! t_{0} around by since the interaction of the inte nian jieuw vontri c. But axions and dark photons are not confined! Does rate grow with L?

due to interference along full length of the system.

due to interference along full length of the system.

But axions and dark photons are not confined! Does rate grow with L?

Yes. Due to incoherent sum.

second are achievable in KTP crystals [15, 39], and are achievable in KTP crystals [15, 39], and and and and a
In KTP crystals [15, 39], and a condition in KTP crystals [15, 39], and a condition in KTP crystals [15, 39],

Improving the limits from solar cooling, for which **PRX Quantum 2 (2021)** *Ê*axion*npnsA*e *PRX Quantum* **2 (2021) 3, 030340**

Unusual requirements

Axion:

- A long medium. Enhance effective (length) x(power) with resonators?
- Highly bi-refringent.
- As linear as possible.
- Low dark count (e.g Skipper few pixels of Skipper CCD).

Dark Photon:

- A long medium. Ditto.
- Nonlinear coupling to longitudinal mode!
- Bi-refriengence helps to phase match.

Photonic systems, and other quantum devices are a new tool to search for new physics.

Dark SPDC searches for missing energy/momentum

Also Dark matter searches

To Summarize

$\mathbf{1}$ schematic sketch of the SPDC prosess (top) and the data SPDC prosess (both data SPDC process (bottom). The a new tool to signal photon in different standard case due to the standard case of the standard case of the

Also give us an opportunity to model build! (and build). particle physicists who are accustomed to working in the vacuum, the conversion (or decay) of a

Thank you Lawrence and Hitoshi for the impact!

DM searches on a photonics chip $\mathsf{ind}\ \mathsf{build}).\qquad \qquad \mathsf{Blinov},$ Gao, RH, Janish, Sinclair (2024)

 \blacksquare

Deleted Scenes

Optics

The hierarchy of scales, $\delta x_{atoms} \ll \lambda_{light}$, has several implications:

Collective (coherent) back reaction:

- Amplitude for forward scattering of:
- Amplitude for forward scattering of:
- \square The effect of the medium can be described as mean field(s) in a derivative expansion:

If an atom may be small,
$$
O(\alpha)
$$
.
If of the medium can be $O(1)$.
ribed as mean field(s) in a derivation

Polarization and magnetization densities \vec{P} and \vec{M} . ⃗

Optics

The hierarchy of scales, $\delta x_{atoms} \ll \lambda_{light}$, has several implications:

Collective (coherent) back reaction:

-
- Amplitude for formation the mast of the media in sight be \mathcal{B}

umd ynd

.
155

 $\overline{\mathcal{L}}$

medium

expansion: Polarization and magnetization densities P Iden Particle θ_i θ_i **SPDC** pump dipoles in meding manapoleon & sig as d'usguetizat $\frac{1}{\sqrt{2}}$ un neact $pump'$ signal signal pump $pump'$ dipoles in medium react

incoming light \prod_{i} induces

Mode Expansions: which source brightness is enhanced, and bulk crystal setups. We will follow \mathbb{R} for a calculation \mathbb{R} *E* $\bar{\bar{E}}$ and *a*[~] *B* ϕ_a

in a forthcoming ω_j, κ *H*axion $u \cdot$ u

SIONS.
$$
\phi_a(x_\mu) = \sum_j \sum_{\vec{k}_a} \frac{1}{\sqrt{2\omega_a}} \left(b_{j,\vec{k}} u^a_{j,\vec{k}}(\vec{x}) e^{i\omega_a t} + b_{j,\vec{k}}^\dagger u^a_{j,\vec{k}}{}^* (\vec{x}) (e^{-i\omega_a t}) \right)
$$

$$
\vec{E}(\vec{x},t) = \sum_{\vec{k},\sigma} \sqrt{\frac{\omega_k}{2n^2}} \vec{\varepsilon}_{\vec{k},\sigma} \left[a_{\vec{k},\sigma} u_{\vec{k}}(\vec{x}) e^{-i\omega t} - a_{\vec{k},\sigma}^{\dagger} u_{\vec{k}}^* (\vec{x}) e^{+i\omega t} \right]
$$
\n
$$
\vec{B}(\vec{x},t) = \sum_{\text{minph}(\text{bin})} \sqrt{\frac{\text{Maxpl}}{\text{maxpl}} \vec{v}_{\vec{k}}^{\text{max}}} \sqrt{\frac{\text{maxpl}}{\text{maxpl}} \vec{v}_{\vec{k}}^{\text{max}} \sqrt{\frac{\text{maxpl}}{\text{maxpl}} \vec{v}_{\vec{k}}^{\text{max}}}} \sqrt{\frac{\text{maxpl}}{\text{maxpl}} \vec{v}_{\vec{k}}^{\text{max}} \sqrt{\frac{\text{maxpl}}{\text{maxpl}} \vec{
$$

n where the index of refraction *n* is implicitly also dependent on frequency and polarization. Here we ignore corrections to the dispersion relation due to the confinement of photons in a waceguide or a fiber, but those can be added trivially. The transverse polarization vectors satisfy ~"[~] Colinear case: are normalized to one. The mode functions *u*[~] *^k* satisfy the equation of motion (r² ⁺ *ⁿ*²!²)*u*[~] In practice this means that the axion hamiltonian couples, say, a horizontally polarized pump photon to a vertically polarized signal photon. The axion field can also be expanded in modes *a*(*xµ*) = ^X X 1 ^p2! dark SPDC dark photon ⇣ *b*~ *x*)*eⁱ*!*^t* + *b n, k* ~ Idler particle Idler particle Idler particle Pump photon ^s Signal photon Material medium Pump photon ^s Material medium Pump photon ^s Signal photon pump signal axion or form similar to Equation (16), we will parametrize the mode functions as *u*(*a*) *j, k* = *U*(*a*) *j,k^a* (~ *r, z*)*eika^z* (31) where, as opposed to Equation (12) for the waveguided case, here the mode function *U*(*a*)

$$
\text{Useful to define:} \qquad u_{j,k}(\vec{x}) = U_{j,k}(\vec{r},z)e^{ikz}
$$

 \overline{a}

with *z*, though it will vary slowly on the scale of *k*¹

^a . The axion Hamiltonian can be written as

Two options in general (with gaussian examples): and the convenience in the following for convenience \mathbf{r} *r*
r ⇡*W*² *^e ^r*² eral (with gaussian exar \square Two options in general (with gaussian examples): some cases a sum over a complete basis *uj, ^k* will be needed, as we shall see later. Since we focus some cases a sum over a complete basis *uj,* ~ *^k* will be needed, as we shall see later. Since we focus \square Two options in general (with gaussian examples):

 Γ_{α} resemble the galaxy resemble the gaussian bulk mode described below, will also describe Γ_{α} some results and the results and the shapes would will be shaped as in the shape similar results. The same similar results. The same similar results are such as $\frac{1}{2}$ on colinear (d)SPDC in this paper, we will consider light traveling in the *z* direction and name *<u>r v</u> signals* Inlavequide mode

Figure 2: A sketch of a waveguide mode, *[|]u*(waveguide)*[|]* confined to a transverse region of size *^W*,

$$
u_{\vec{k}}^{\text{(bulk)}} = \sqrt{\frac{2}{\pi}} \frac{W}{q(z)} e^{-\frac{r^2}{q(z)} + ikz}
$$

 \mathcal{L} abulk mode can have a significant overlap with a waveguide mode living in the waveguide mode living in the significant overlap with a waveguide mode living in the waveguide mode living in the waveguide mode livin $\cos^2\theta = \cos^2\theta$ and $\sin^2\theta = W^2k$ $\gamma = \sqrt{\pi W^2}$ is not a contrast of the gaussian is not a constant in $\frac{2v}{\pi W^2}$ from the *z* α β and β β is the Rayleigh range. $\frac{r}{W^2}$ where $q(z) = W^2 + 2iz/k$ \mathbf{r} is not a contrast of the gaussian is not a constant in \mathbf{r} $\text{Conrocal length } b = W^2k$ from that point by ^p² at the *^z* ⁼ *[±]zR*, where *^z^R* ⁼ *^W*²*k/*² is the Rayleigh range. Of course, *^W*² *.* (13) $\sqrt{W^2}$ $\big(\text{confocal length } b = W^2 k\big)$ $I_{\rm conv11GHz}$

Modes: Bulk vs Waveguide k Wodes: Bulk vs Wavequide ~ *k* = 0 and are normalized to one. The mode functions *u*[~] \blacksquare *k,·* —
— *k* = 0 and are normalized to one. The mode functions *u*[~] satisfy the equation of motion (r² ⁺ *ⁿ*²!²)*u*[~] *^k* = 0. Here we took a single mode function *u*[~]

Bulk mode (disperses)

In SPDC there is a big difference in mode overlap (and hence rate) b/w waveguide

Wavegũide mode

Rate: Bulk vs Waveguide *DUIK* ⇡*W*² *^e ^r*² *^W*² *.* (13)

and bulk: T the concerning resemble the gaussian bulk mode description bulk mode description \mathbb{R}^n some results and all the results and mode over α

Does dSPDC behave like waveguide or bulk? $m = 1$ functions can be written in the form *k* ⇡ *q*(*z*) can nap *^q*(*z*) ⁺*ikz* (14) where *q*(*z*) = *W*² + 2*iz/k*. The gaussian beam is structurally similar to our choice of waveguide

: *I I* Mode overlap and rate Gaussian beam with waist size *W* takes up a confocal length *b* = *W*²*k* in the longitudinal direction. do not grow with L Figure 2: A sketch of a waveguide mode, *[|]u*(waveguide)*[|]* confined to a transverse region of size *^W*, Mode overlap and rate

> Though dSPDC can happen in a waveguide, the dark particle is not confined. *Waveguide, the dati*s farriore is not confined. \mathbf{m} requide or bulk!

within a volume of order *W*²*b*. $\{91\}$ modes: We now the bulk modes, which propagate in a homogeneous and infinite in a homogeneous and infinite infinite in a homogeneous and infinite in a homogeneous and infinite in a homogeneous and infinite in a ho Ω data opposed to modes in a waveguide, electromagnetic waveguide, electromagnetic waves disperse in the set Rate grows with L Mode overlap grows with L (diff. rate with L2)

Rate: Bulk vs Waveguide

- dSPDC can still occur along the whole crystal:
- Proof in two ways: \Box
	- An "almost orthonormal" anzatz. Good for intuition.

• An exact calculation w/ full Laguerre-Gauss basis confirms growth of the rate $\frac{a}{\sigma}$ with L. [Following Bennink 2010]

dSPDC Rate does grow with L!

[in preparation (RH)]

2π w / λ