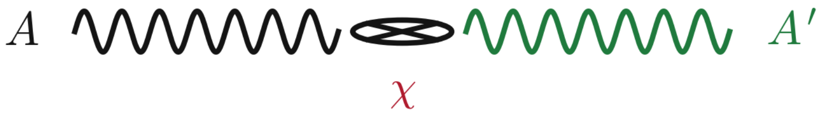
Searching for Dark Matter with Two-Stage Atomic Transitions

ANDREW BUCHANAN

Dark Photon Searches

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}{F'}_{\mu\nu}{F'}^{\mu\nu} + m^2 {A'}_{\mu}{A'}^{\mu} - (A_\mu + \chi {A'}_{\mu})J^{\mu}_{EM}$$



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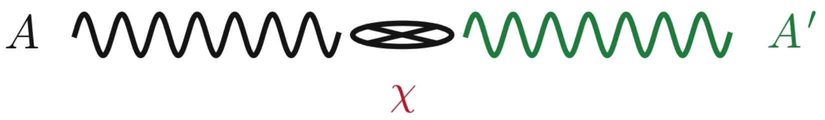
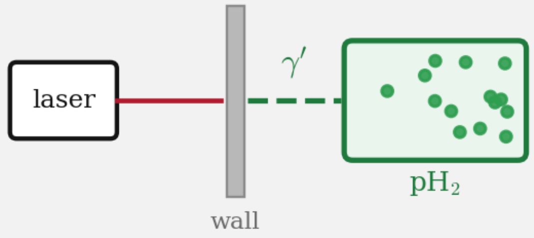


New detection method



dark photon triggers the cell directly

Shining Through a Wall

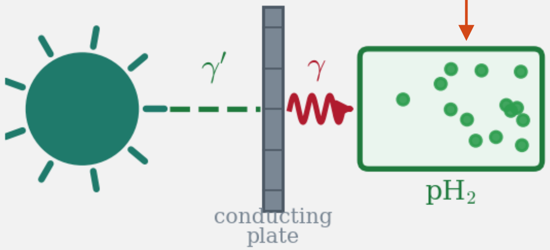
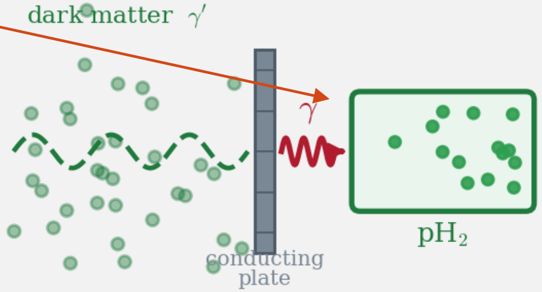


plate reconverts $\gamma' \to \gamma$, emitted normal to it

From the Sun



halo field drives the plate; γ leaves normal to it

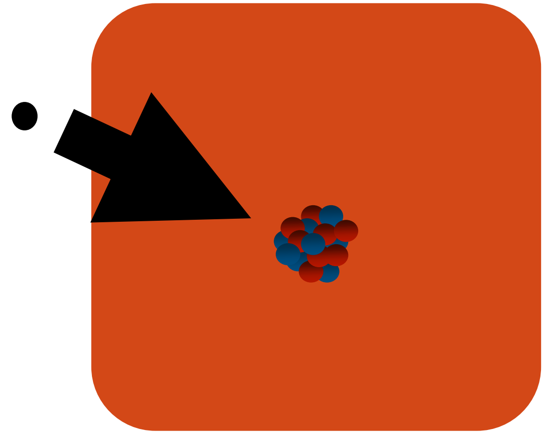
From the Halo

Quantum Detection

$$\text{Signal} = \mathrm{N}\Gamma t$$

$\Gamma \approx n_x v_x A^4 \sigma_{nx}$ $\qquad$ $N = \#\text{Argon, Xenon}$

- Can we get better scaling with N?



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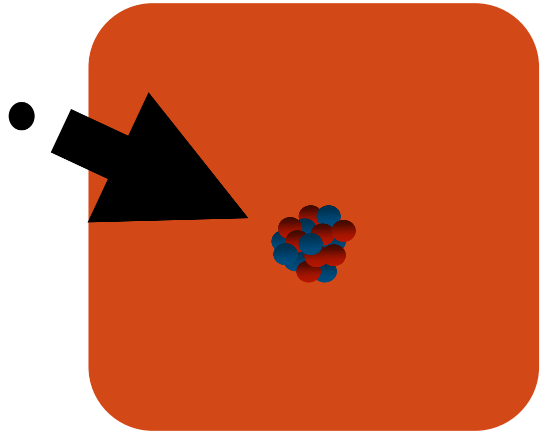
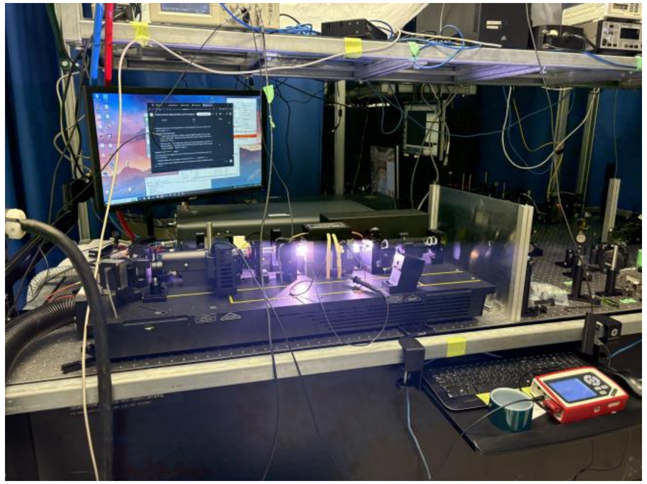


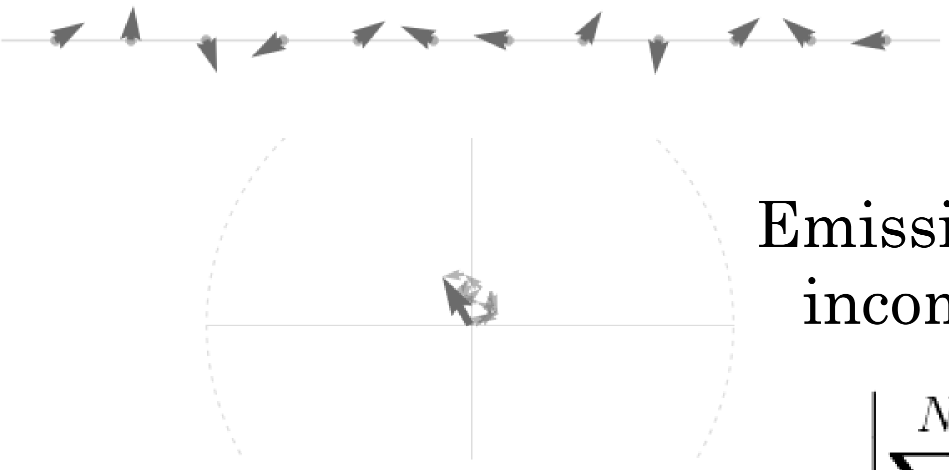
- Quantum effects can make signal $\sim N^2$.
- CATCHY (Coherent Atomic Transition from Counter-pulsed Hydrogen)

Detects dark photons with a quantum detector



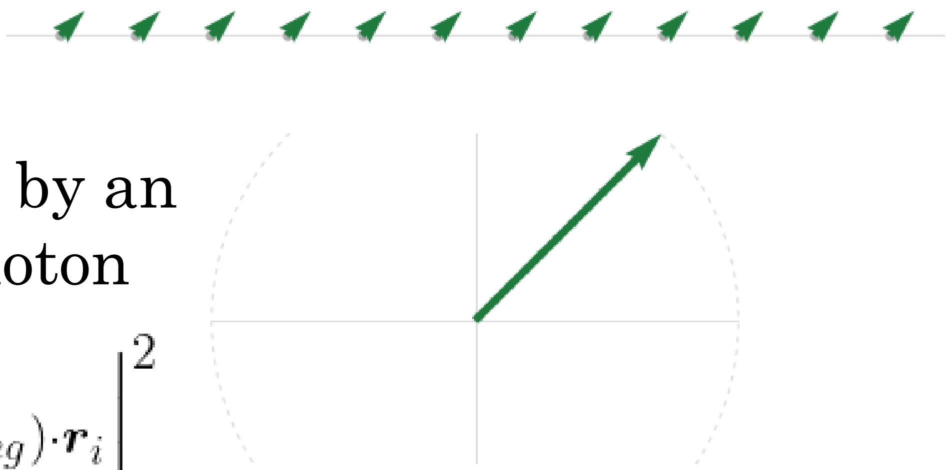
Coherent Atomic Emission

RANDOM PHASES



$$\Gamma \propto N$$

LOCKED PHASES

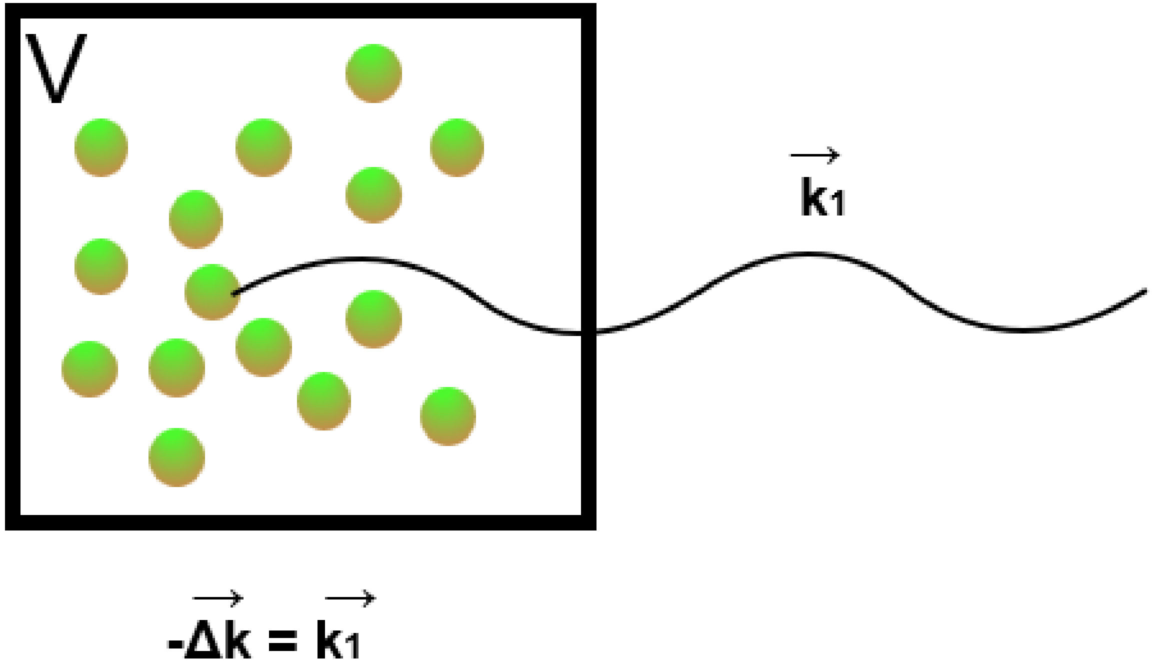


$$\Gamma \propto N^2$$

Emission triggered by an incoming dark photon

$$\Gamma \propto \left| \sum_{i=1}^{N} \mathcal{M} e^{-i(\boldsymbol{k}-\boldsymbol{k}_{eg})\cdot \boldsymbol{r}_i} \right|^2$$

One-Photon Emission

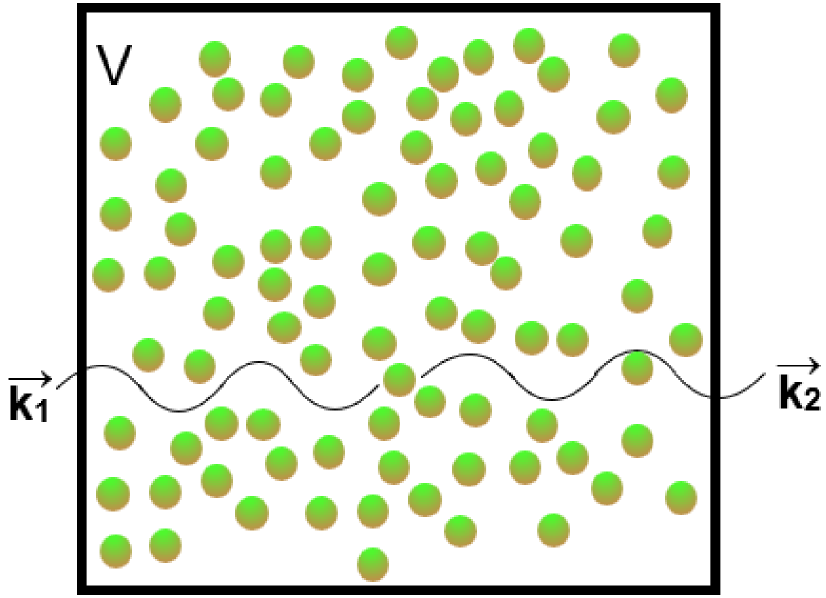


$$\Delta k \Delta x \sim 1$$

$$V \sim \frac{1}{k_1^3}$$

Number of atoms is limited by wavelength of emitted light.

Two-Photon Emission



$$V_{mac} \sim \frac{1}{|\vec{k}_1 + \vec{k}_2|^3}$$

Number of atoms is not limited by wavelength.

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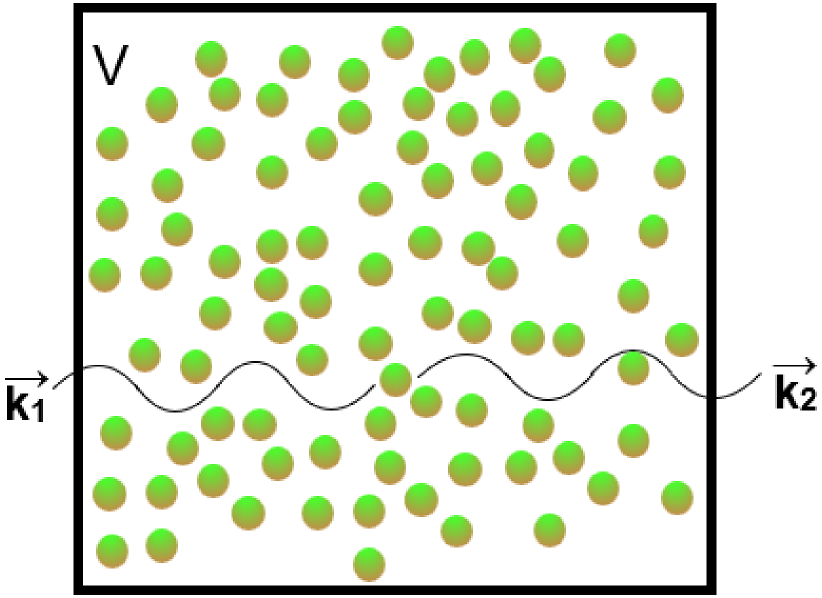


$$V_{mac} \sim \frac{1}{|\vec{k}_1 + \vec{k}_2|^3}$$

Number of atoms is not limited by wavelength.

$$t_{dc} = \frac{1}{n_H \sigma_H \sqrt{2T/m_H}} \approx 10\,\mathrm{ns}$$

$$L \ll c t_{dc} = 3\,\mathrm{m}$$

Response is instead limited by collisional desyncing

Density (cm^{-3})	Temperature (K)	Decoherence Time (ns)
$10^{19} - 10^{20}$	80-500	~ 10
5.6×10^{19}	78	~ 8 (est)
$10^{19} - 5 \times 10^{20}$	78	~ 10 (est)
2.6×10^{22}	4.2	$\gtrsim 140$

CATCHY = 30 cm

Two-Stage Transitions

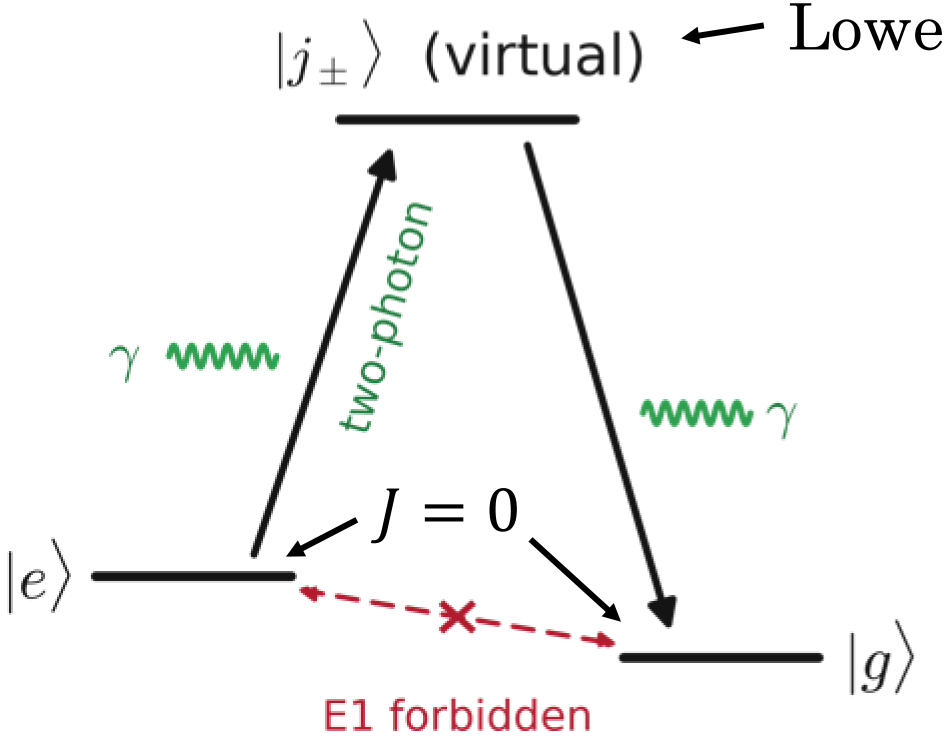
At leading order:

$$H_I = -\mathbf{d} \cdot (\tilde{E}_1 + \tilde{E}_2 + \chi \tilde{E}')$$

Wigner-Eckhart
+ parity

$$|J_f - J_i| = 1$$

E1 transition



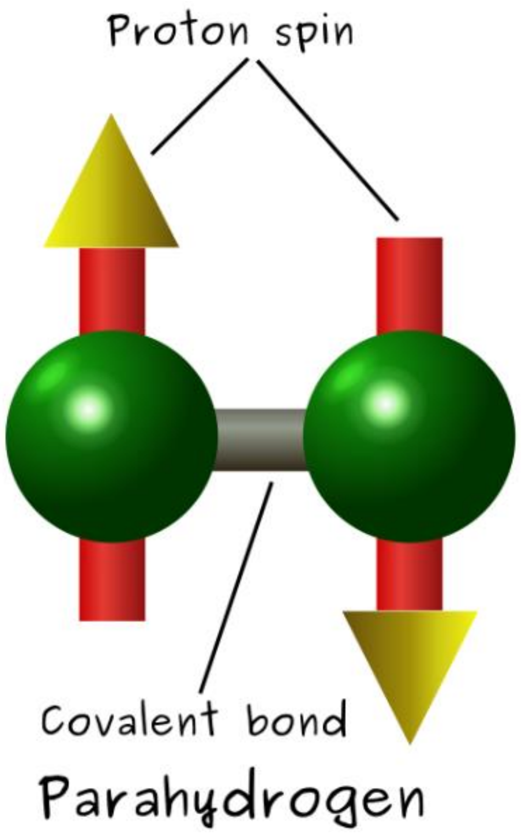
Lowest $J = 1$ energy level

$\omega_{eg} \ll \omega_{jg}, \omega_{je}$

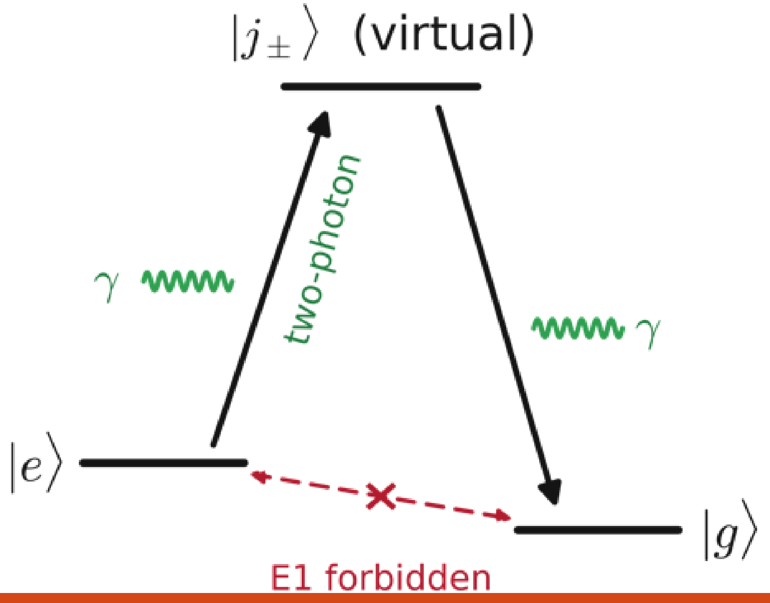
Transitions to
$J = 1$ are virtual

Every deexcitation
releases two photons!

A Candidate: Parahydrogen



- H_2 molecule with opposite proton spins
- Must have orbital angular momentum J even due to fermion asymmetry
- Lowest $J = 1$ level is excited state of *electrons*

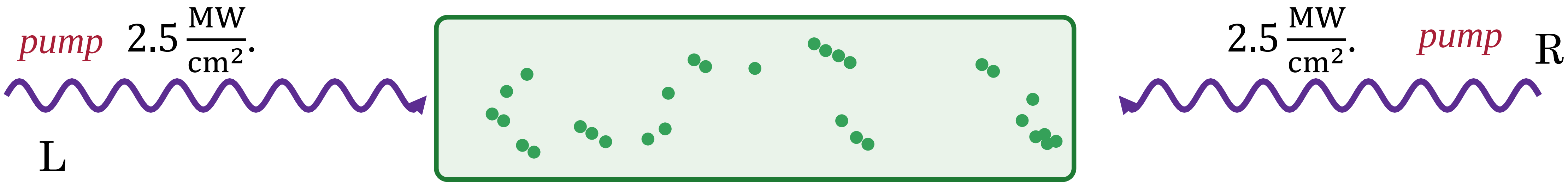


$\omega_{jg} \approx 10$ eV

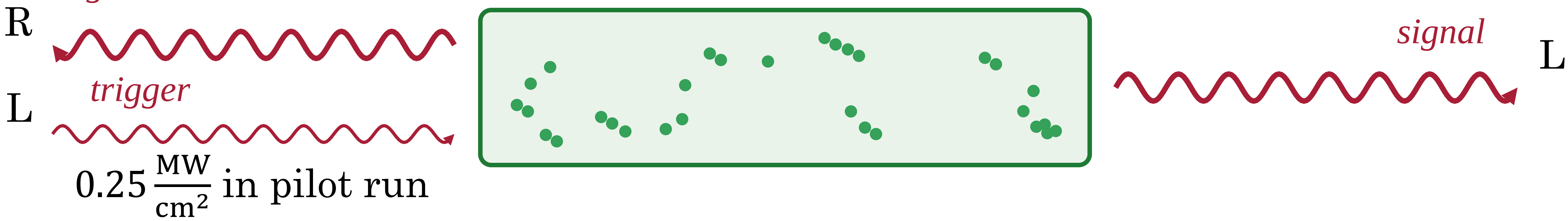
$\omega_{eg} \approx 0.5$ eV

The Protocol

(a) Pump Phase — two counter-propagating lasers phase-lock the sample

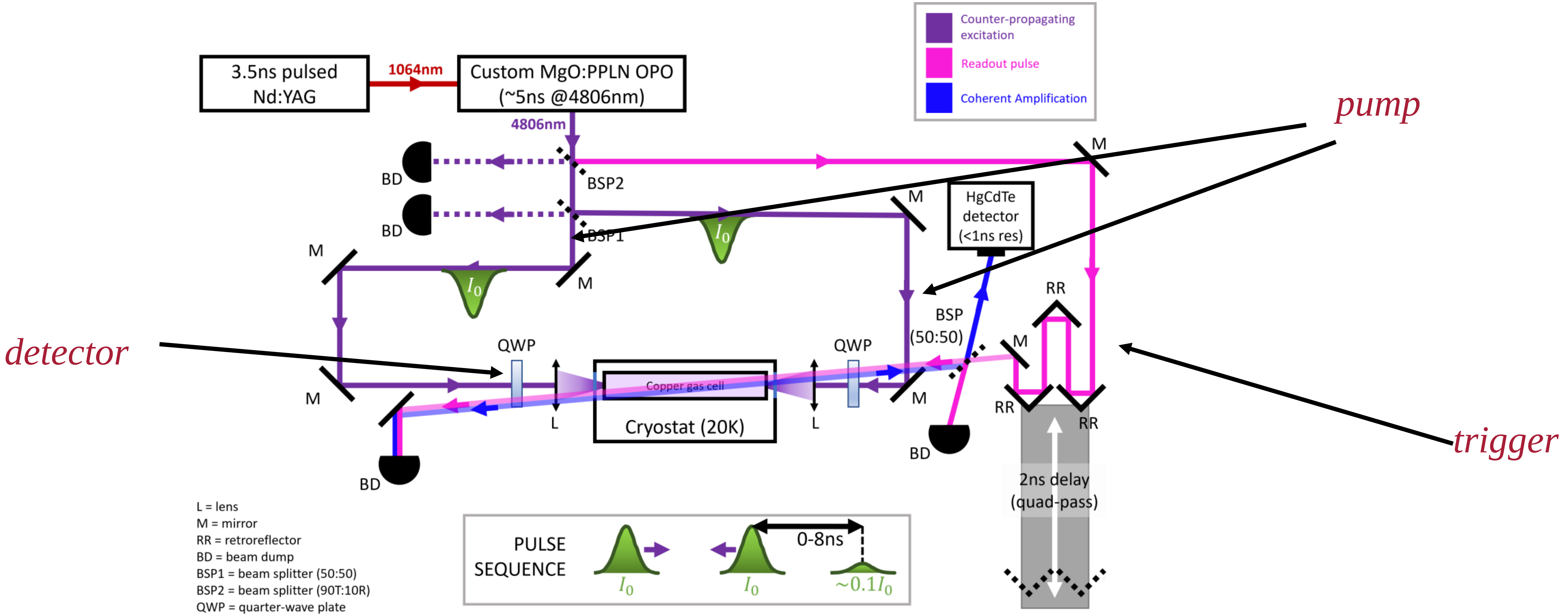


(b) Trigger Phase — a trigger laser deexcites the sample



All light is circularly polarized has $\omega = \frac{E_e - E_g}{2\hbar} = 0.26$ eV and $4.8\ \mu$m.

Experimental Setup



Maxwell-Bloch Equations

ATOMS

- 2×2 density matrix $\hat{\rho}(\vec{x})$
- Parameterized with Bloch Sphere
- Schrodinger evolved by coupling to local E-field

$$
\begin{aligned}
r_1 &= \rho_{ge} + \rho_{eg} \, , \\
r_2 &= i(\rho_{eg} - \rho_{ge}) \, , \\
r_3 &= \rho_{ee} - \rho_{gg} \, .
\end{aligned}
$$

$$
\begin{aligned}
\partial_t r_1 &= \left[-\frac{a_{gg} - a_{ee}}{4} (|\bar{E}_1'|^2 + |\bar{E}_2'|^2) + \delta \right] r_2 + a_{eg} \operatorname{Im}(\bar{E}_1' \bar{E}_2') r_3 - \frac{r_1}{T_2} \, , \\
\partial_t r_2 &= \left[\frac{a_{gg} - a_{ee}}{4} (|E_1'|^2 + |E_2'|^2) - \delta \right] r_1 + a_{eg} \operatorname{Re}(\bar{E}_1' \bar{E}_2') r_3 - \frac{r_2}{T_2} \, , \\
\partial_t r_3 &= -a_{eg} [\operatorname{Im}(\bar{E}_1' \bar{E}_2') r_1 + \operatorname{Re}(\bar{E}_1' \bar{E}_2') r_2] - \frac{1 + r_3}{T_1} \, ,
\end{aligned}
$$

FIELDS

- Atoms induce a polarization
- Acts as a source for E-fields

$$
\begin{aligned}
(\partial_t - \partial_z) E_1 &= \frac{i \omega n}{2} \left[\left(\frac{a_{ee} + a_{gg}}{2} + \frac{a_{ee} - a_{gg}}{2} r_3 \right) E_1 + a_{eg} (r_1 - i r_2)(E_2^* + \chi \eta E'^*) \right] \, , \\
(\partial_t + \partial_z) E_2 &= \frac{i \omega n}{2} \left[\left(\frac{a_{ee} + a_{gg}}{2} + \frac{a_{ee} - a_{gg}}{2} r_3 \right) (E_2 + \chi \eta E') + a_{eg} (r_1 - i r_2) E_1^* \right] \, , \\
(\partial_t + \partial_z) E' &= \frac{i \omega n}{2} \left[\left(\frac{a_{ee} + a_{gg}}{2} + \frac{a_{ee} - a_{gg}}{2} r_3 \right) (2 \chi^2 \eta E' + \chi E_2) + a_{eg} (r_1 - i r_2) \chi \eta E_1^* \right]
\end{aligned}
$$

Photon Avalanche

$$(\partial_t - \partial_z)E_1 = \frac{i\omega n}{2}[(\cdots)E_1 + a_{eg}(r_1 - ir_2)(E_2^* + \chi\eta E'^*)]$$

$$(\partial_t + \partial_z)E_2 = \frac{i\omega n}{2}[(\cdots)(E_2 + \chi\eta E') + a_{eg}(r_1 - ir_2)E_1^*]$$

$$(\partial_t + \partial_z)E' = \frac{i\omega n}{2}[(\cdots)(2\chi^2\eta E' + \chi E_2) + a_{eg}(r_1 - ir_2)\chi\eta E_1^*]$$

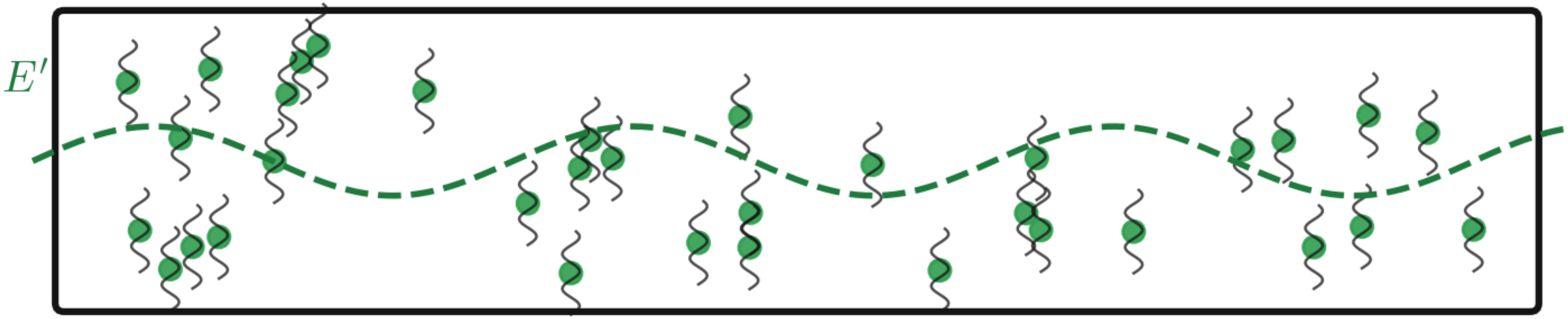
condense field equations,
drop z, r_2, fix r_1

$$(\partial_t^2 - \partial_z^2)E_1 - n^2\Omega_r^2 E_1 = 0$$

$$E_1 \propto e^{n\Omega_r t}$$

$$\Omega_r \propto \omega\, a_{eg}\, r_1$$

r_1 is effective dipole size



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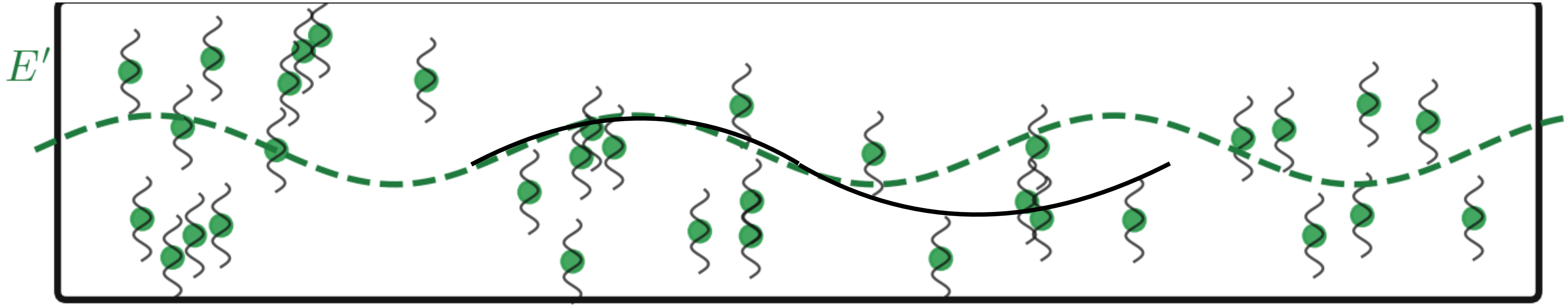

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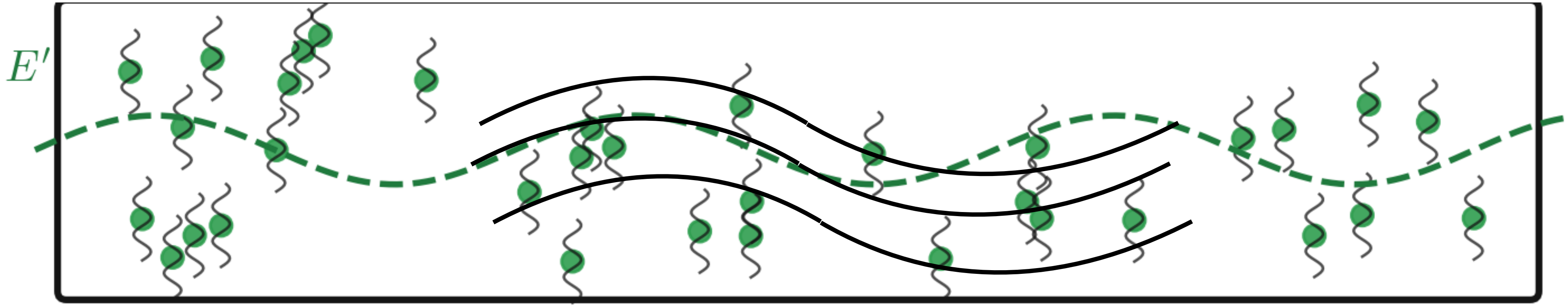

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condense field equations, drop z, r_2, fix r_1 $\Rightarrow$

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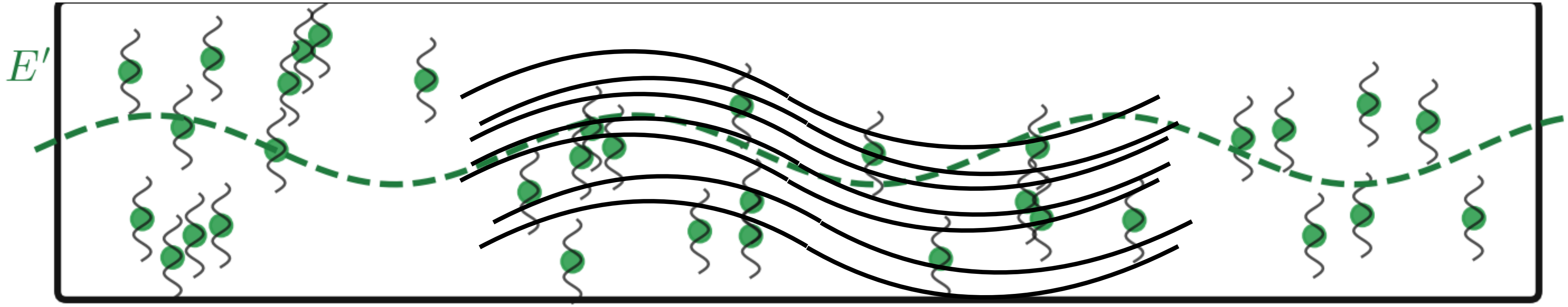
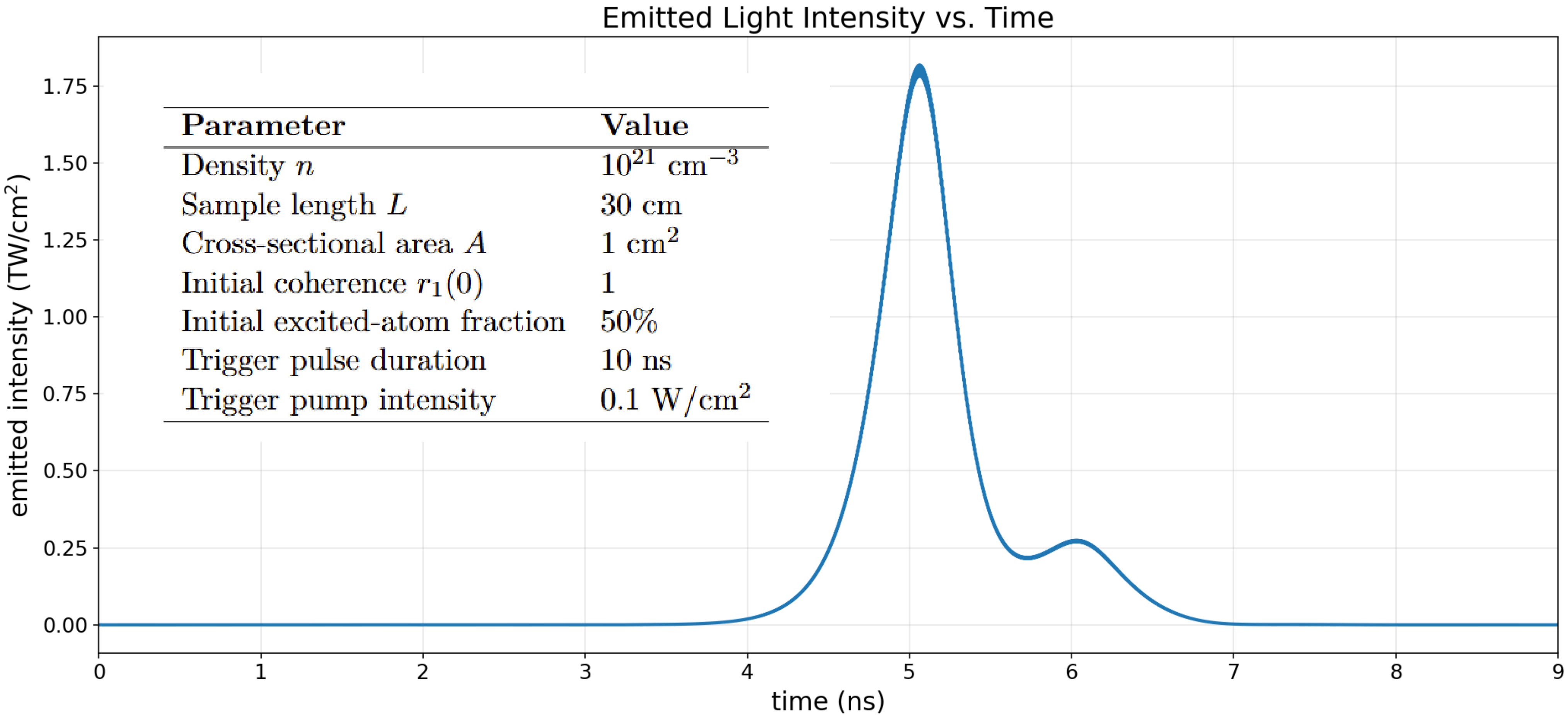
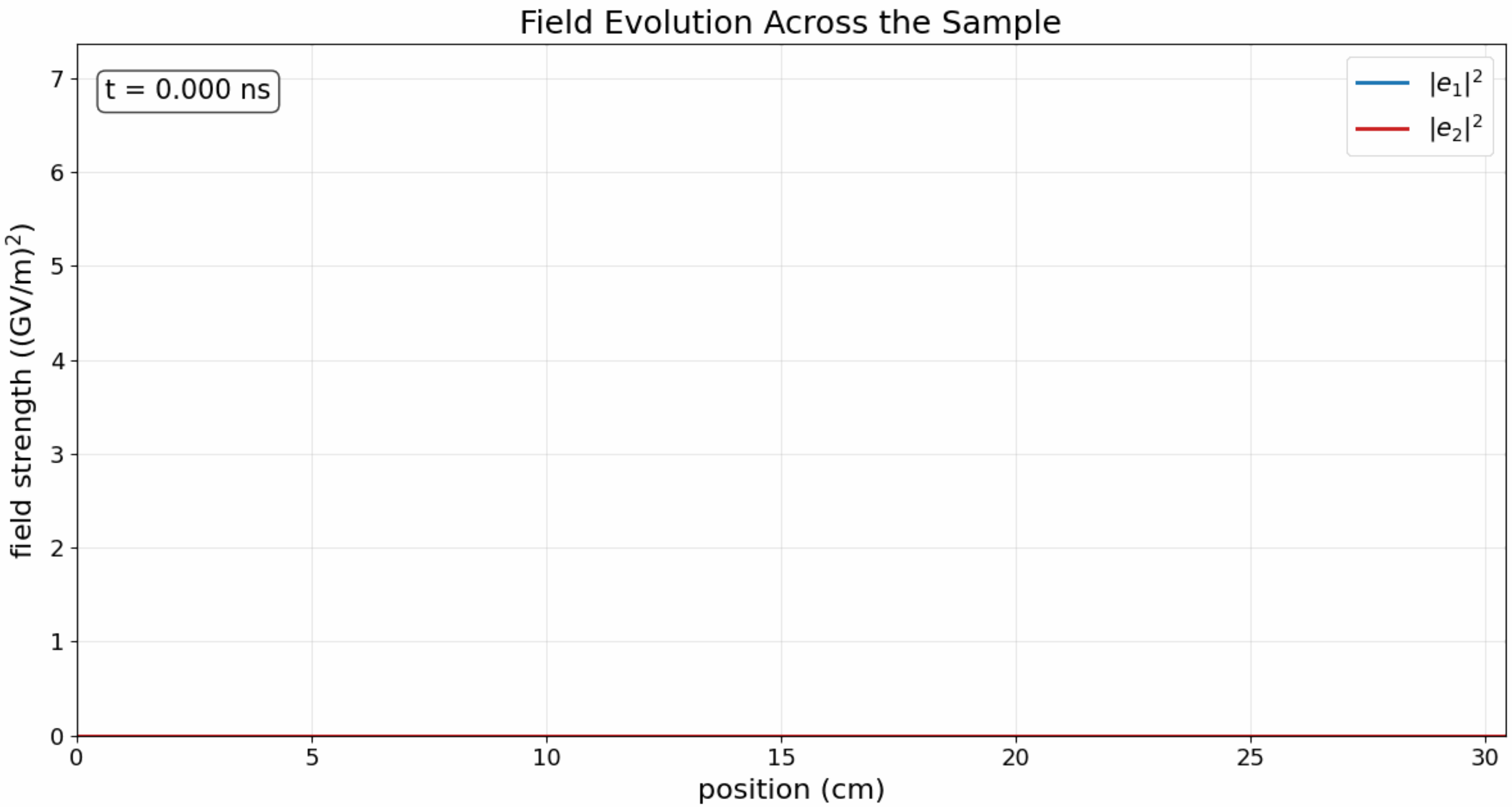


The Intensity Spike

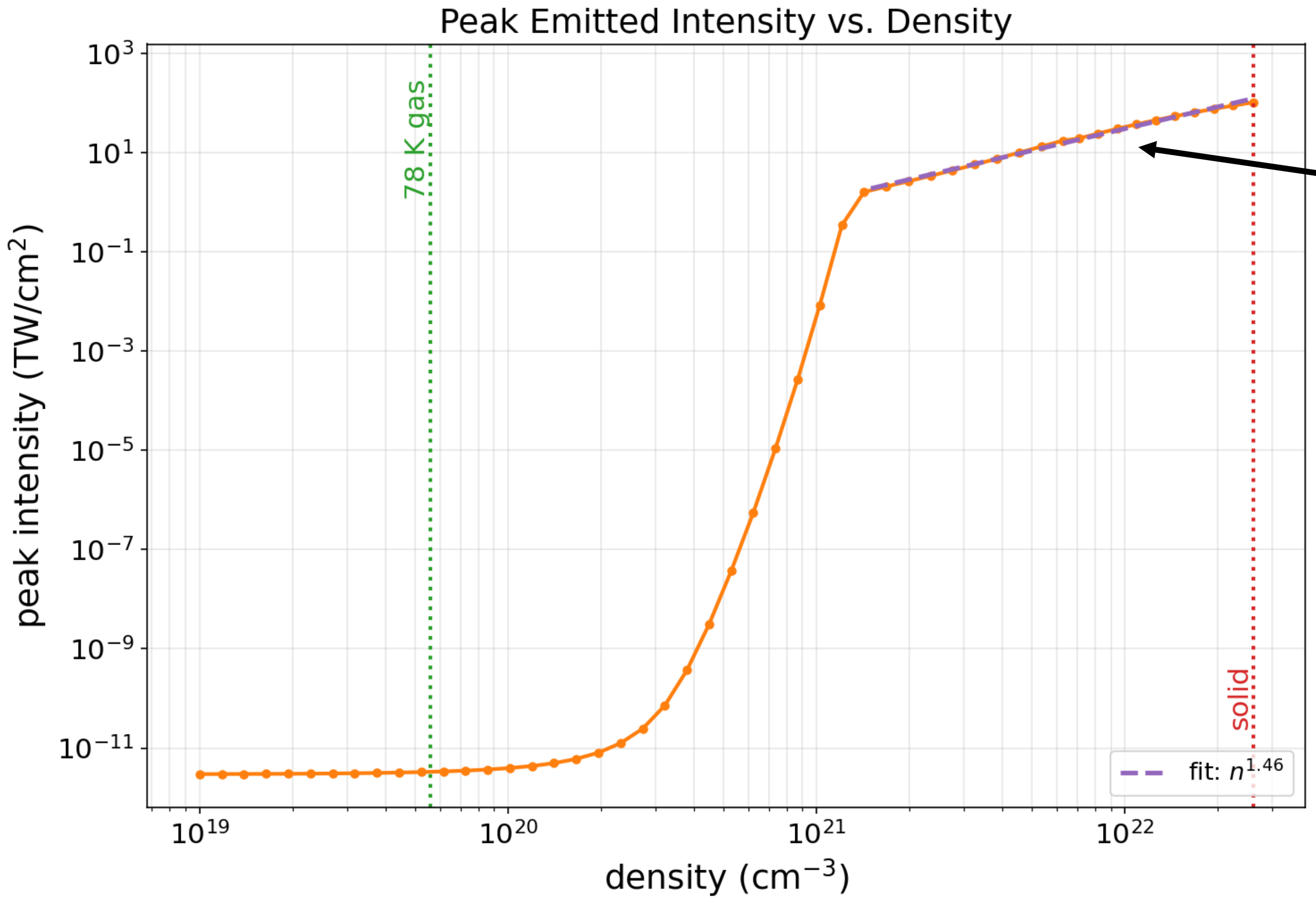


Parameter	**Value**
Density n	10^{21} cm^{-3}
Sample length L	30 cm
Cross-sectional area A	1 cm^2
Initial coherence $r_1(0)$	1
Initial excited-atom fraction	50%
Trigger pulse duration	10 ns
Trigger pump intensity	0.1 W/cm^2

Evolution of the Electric Field

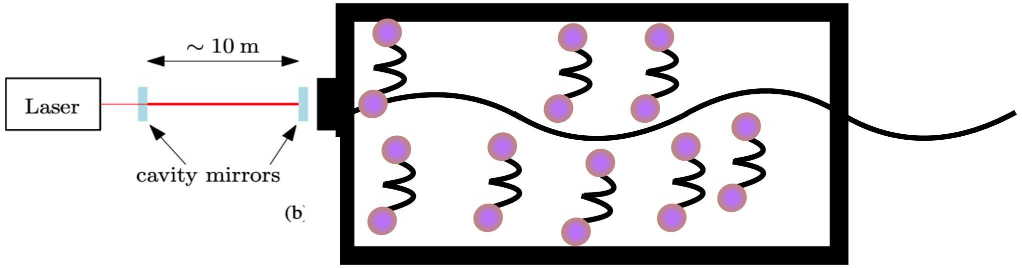


Is the Sensitivity N^2?



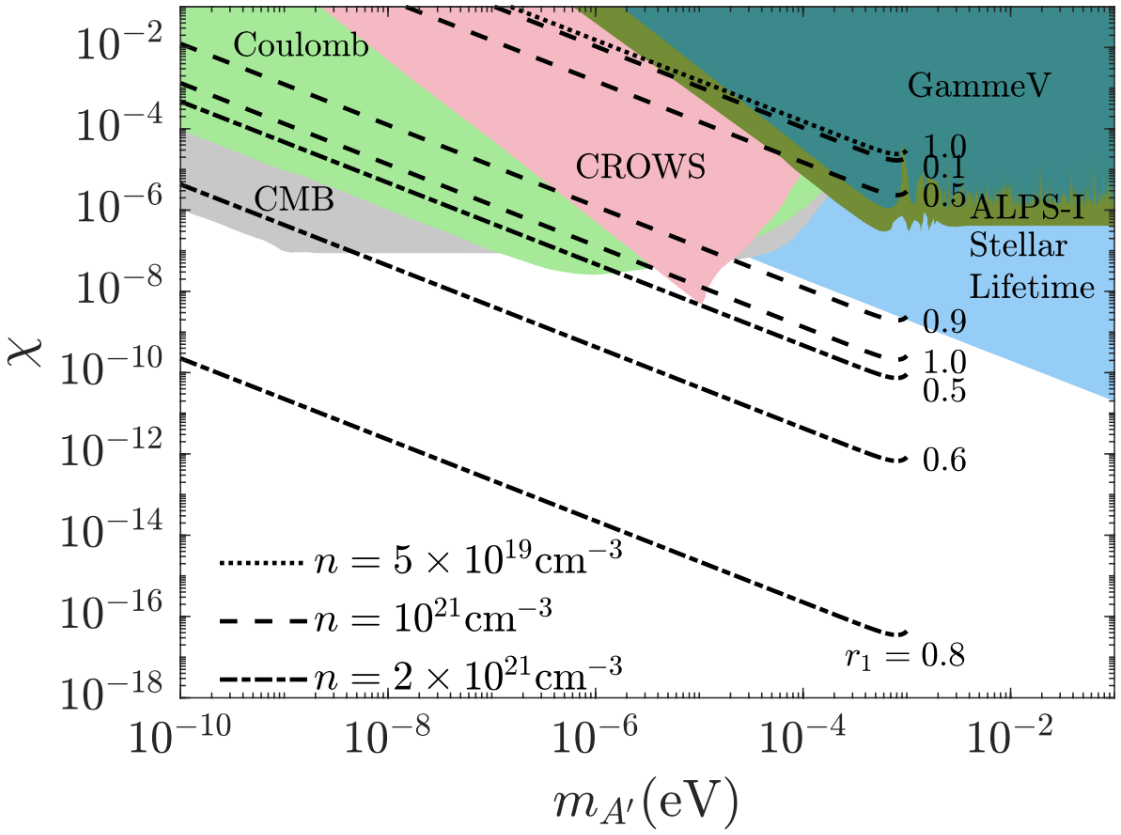
- Max intensity is super-linear for fixed length
- Reminiscent of other quantum coherent processes (e.g. Dicke Superadiance)
- Neglects collisional dephasing of pH_2 molecules (i.e. assumes $t_{\text{peak}} < t_{\text{dec}}$)

Prospective LSW Sensitivity



Improved reach as the number density of pH_2 or initial coherence r_1 increases.

Dark Photon Generating Cavity	Superradiant Parahydrogen Target
Cavity Length $l = 50$ cm	Sample Length $L = 30$ cm
Cavity Reflections $N_{\text{pass}} = 2 \times 10^4$	pH_2 Density $n = 10^{21}$ cm^{-3}
Cavity Laser Freq. $\omega' = 0.26$ eV	Pump Laser Freq. $\omega_1 = 0.26$ eV
Cavity Laser Power $P_L = 1$ W mm^{-2}	Pump Laser Power $\approx 10^9$ W mm^{-2}
–	pH_2 Sample Area $A = 1$ cm^2

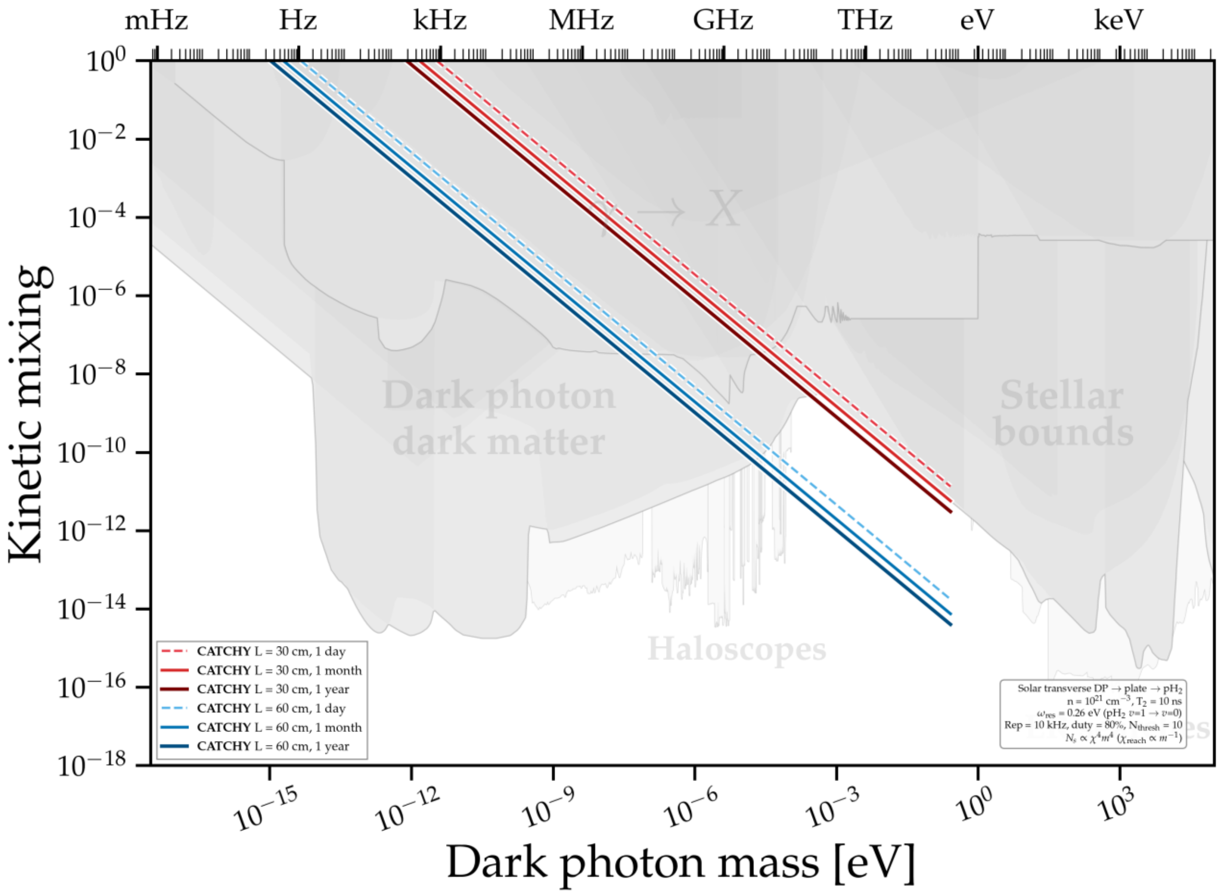


Conclusion

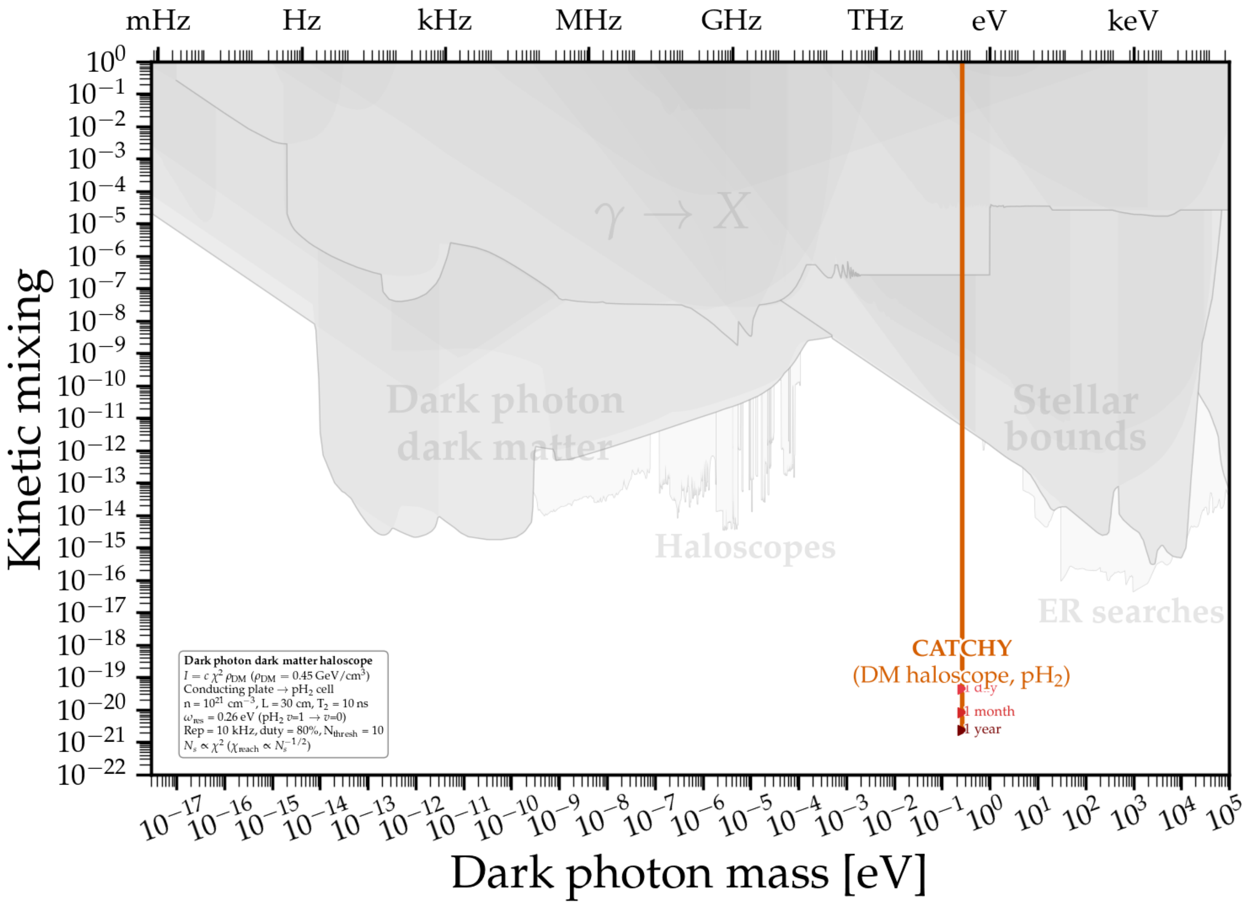
- CATCHY: ongoing project for a new kind of quantum detection at Queen’s University
- Search for dark photons with coherently prepared parahydrogen
- An incoming dark photon produces a cascade of two-photon emissions, producing an observable spike in intensity
- Sensitivity limits scales super-linearly with number density

EXTRA SLIDES

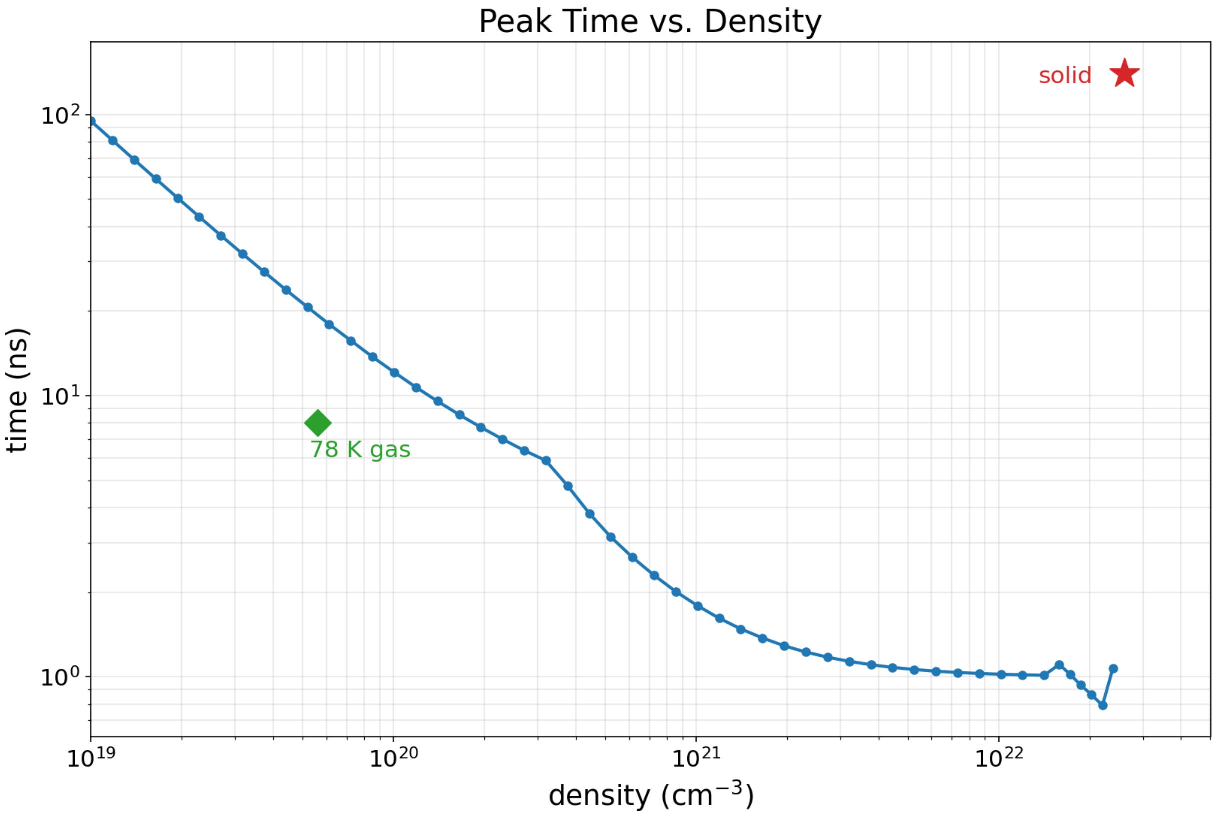
CATCHY as a Helioscope



CATCHY as a Haloscope



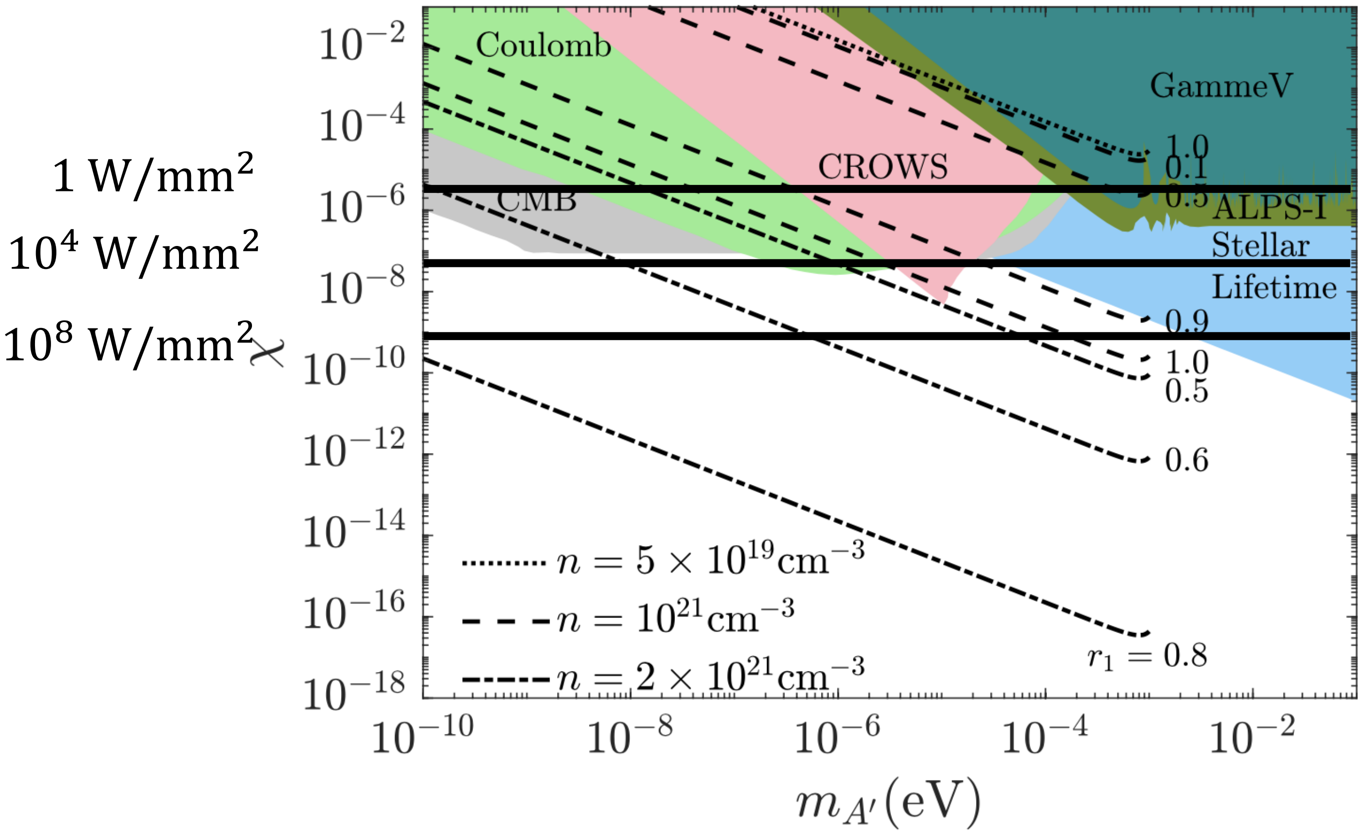
Peak Times vs. Density



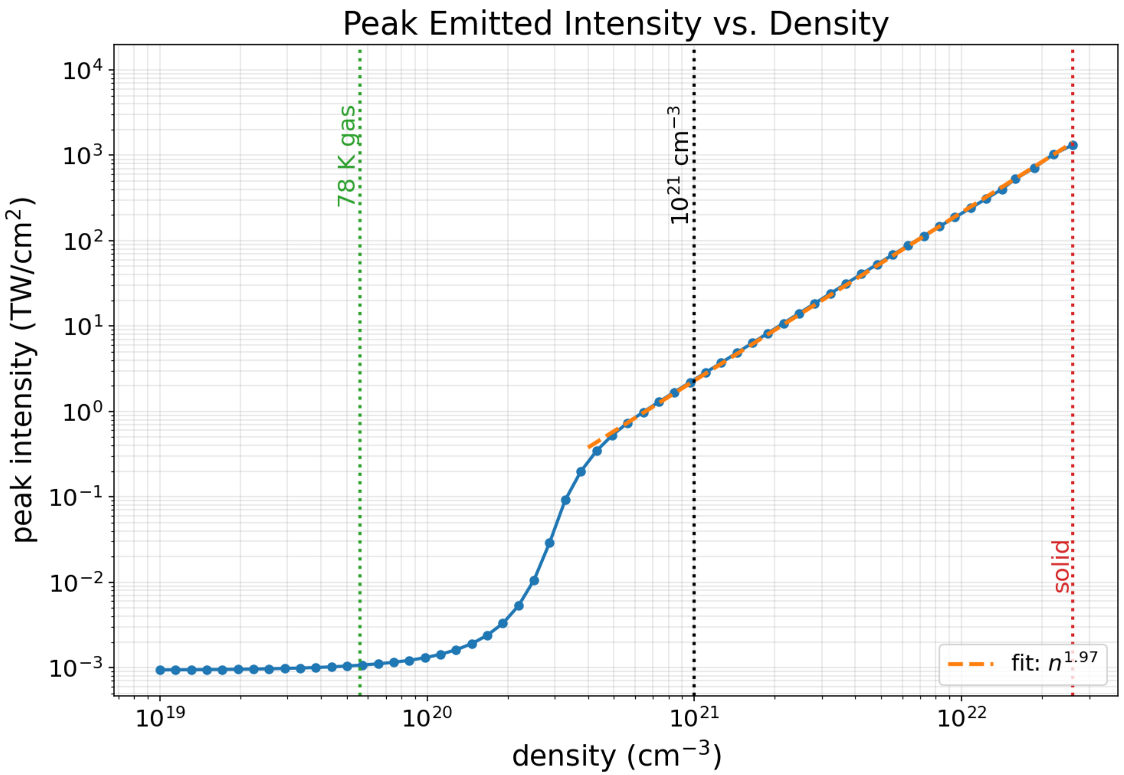
- Time of peak intensity vs density (idealized no decoherence)
- Can safely ignore decoherence if $t_{\text{peak}} < t_{\text{dec}}$
- Decohence matters a bit for gaseous pH_2 and not at all for solid pH_2

Quantum Noise

- Random vacuum fluctuations may trigger detector spontaneously
- Likely dominant background
- May be circumvented by using a stronger laser



The Power Law Depends on Trigger Strength



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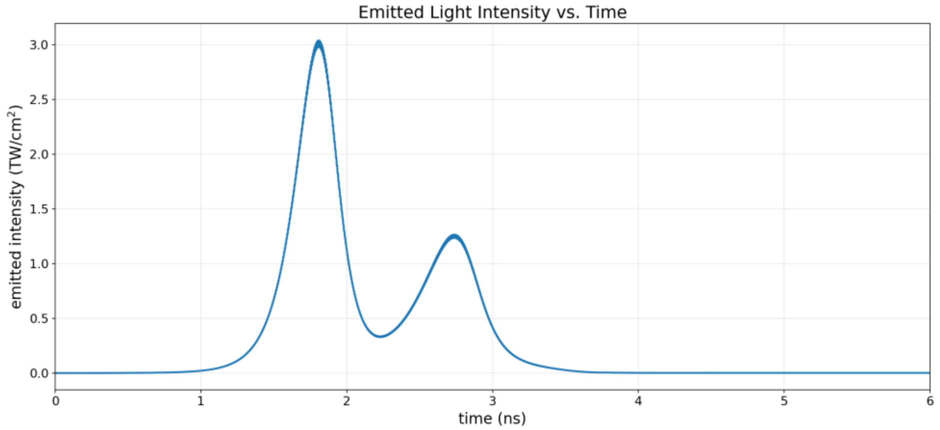
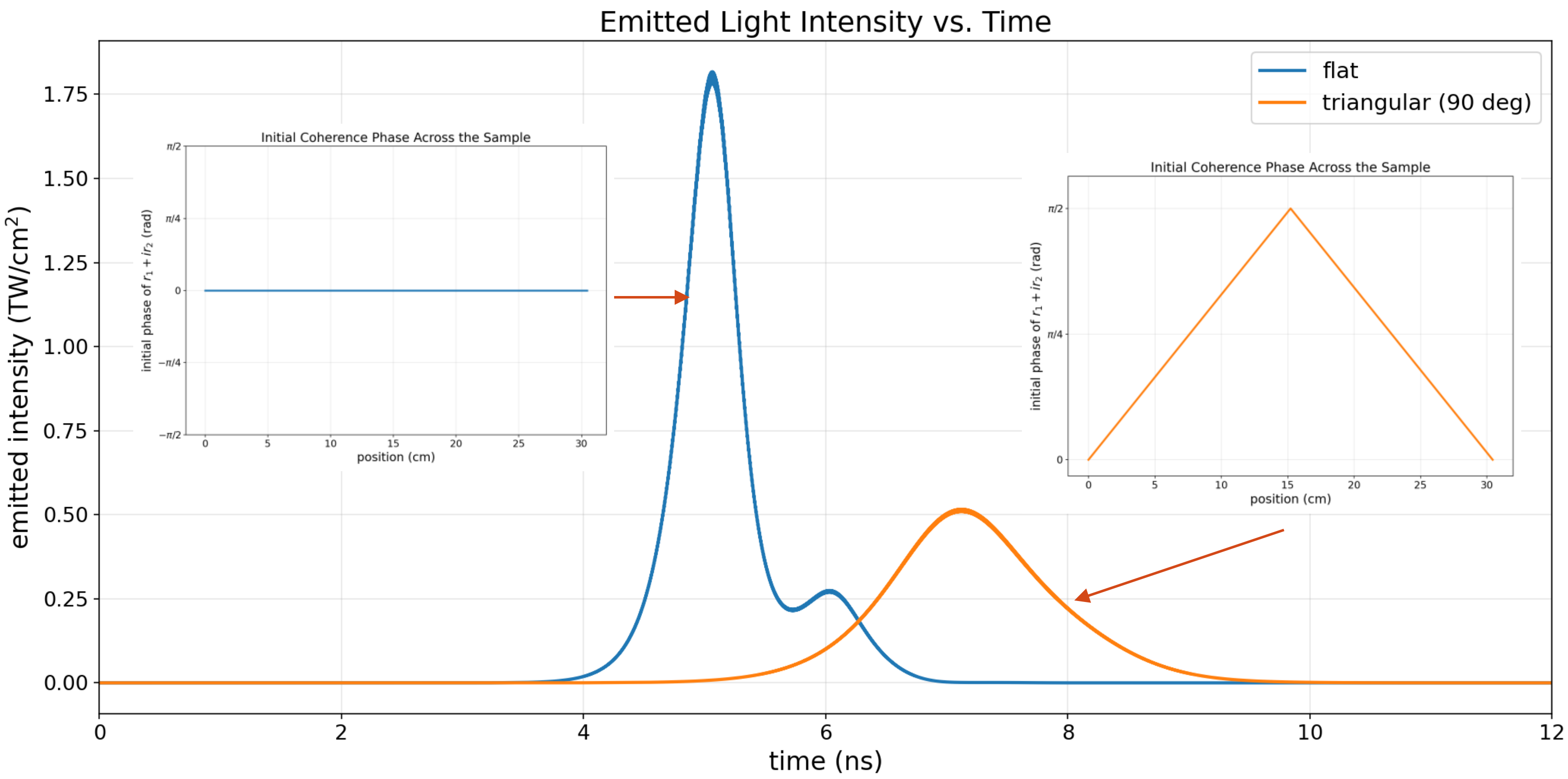


$n^{1.97}$ for strong field vs. $n^{1.46}$ for weak field

Dependence on Signal on Constant Phase



More aligned dipoles give stronger signal

Random dipoles completely destroy signal