Searching for Dark Matter with Two-Stage Atomic Transitions

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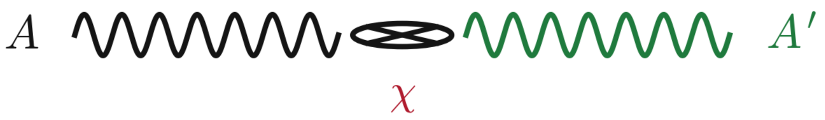
Dark Photon

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



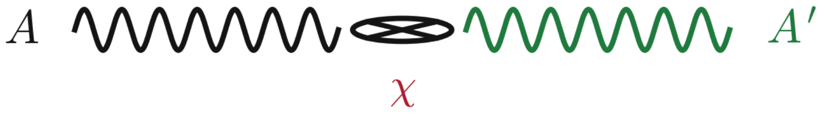
Partner to photon with nonzero mass

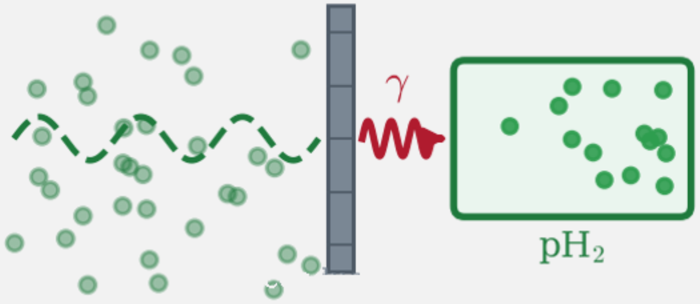
Photon can transition to dark photon and vice versa

i. Could make up bulk of dark matter mass
ii. Could be a mediator between SM and DM
iii. Could just exist

Dark Photon Searches

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





From the Halo

Dark Photon Searches

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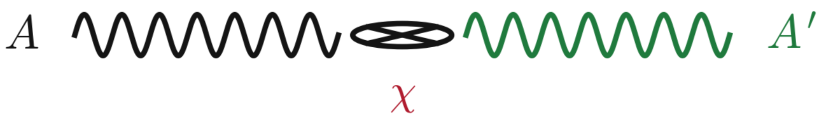
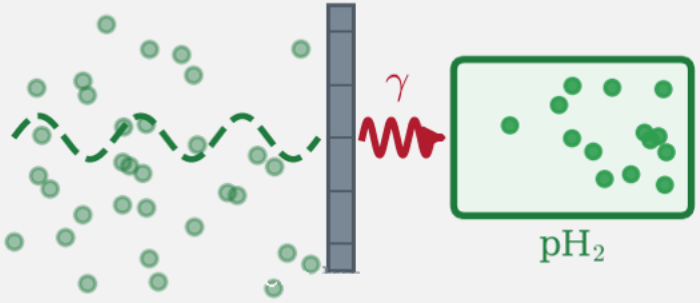
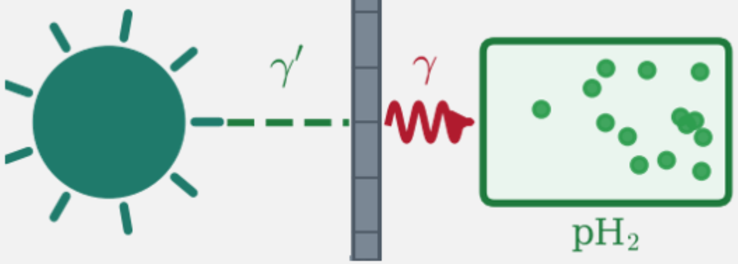
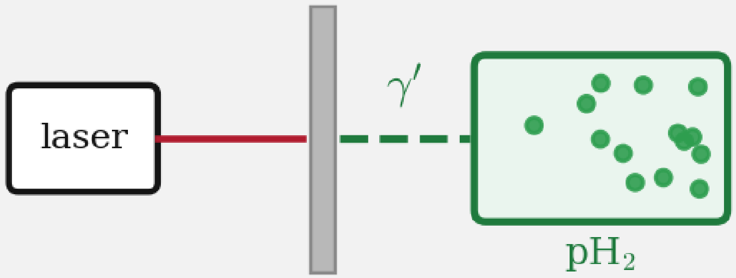




From the Halo



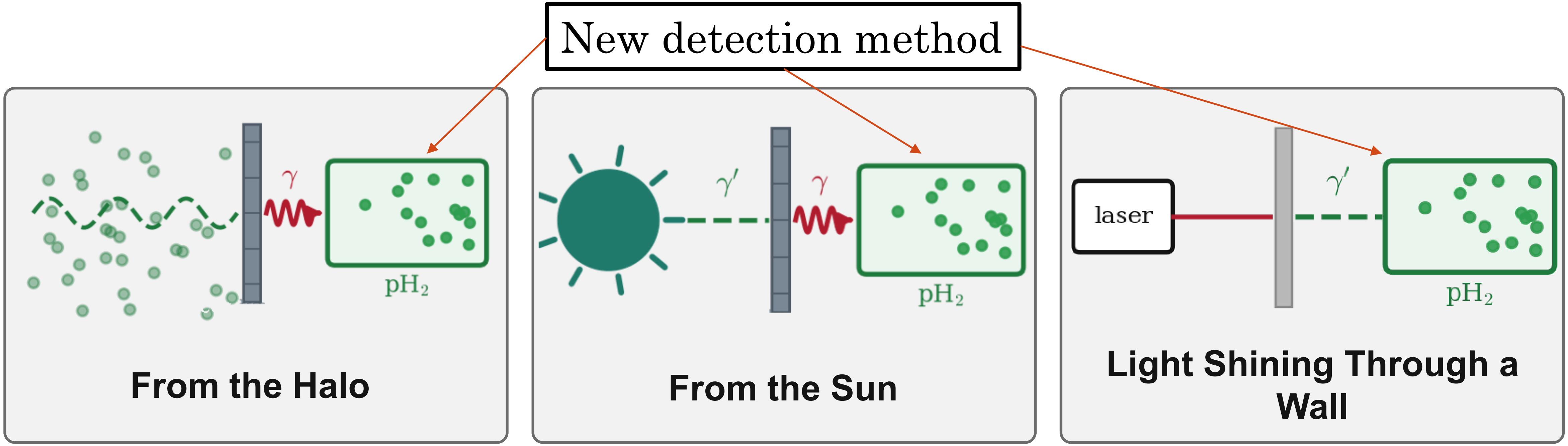
From the Sun



Light Shining Through a Wall

Dark Photon Searches

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

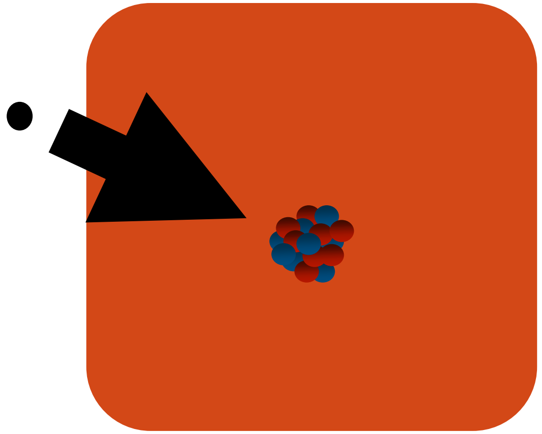


Quantum Detection

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

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

- Can we get better scaling with N?



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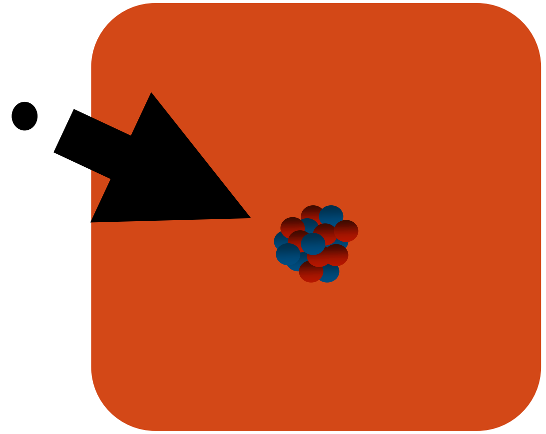

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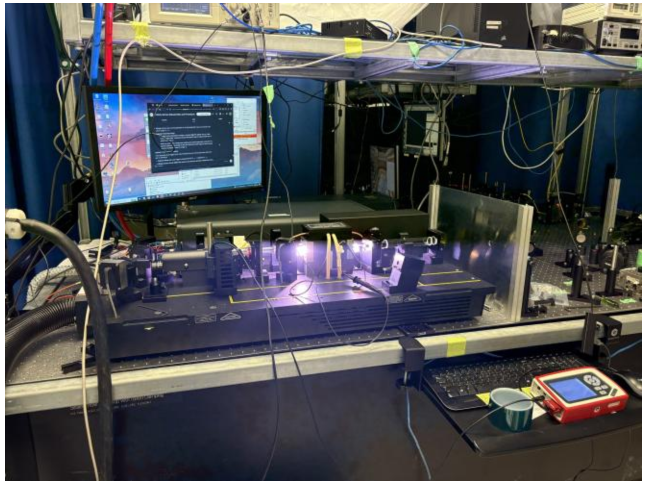
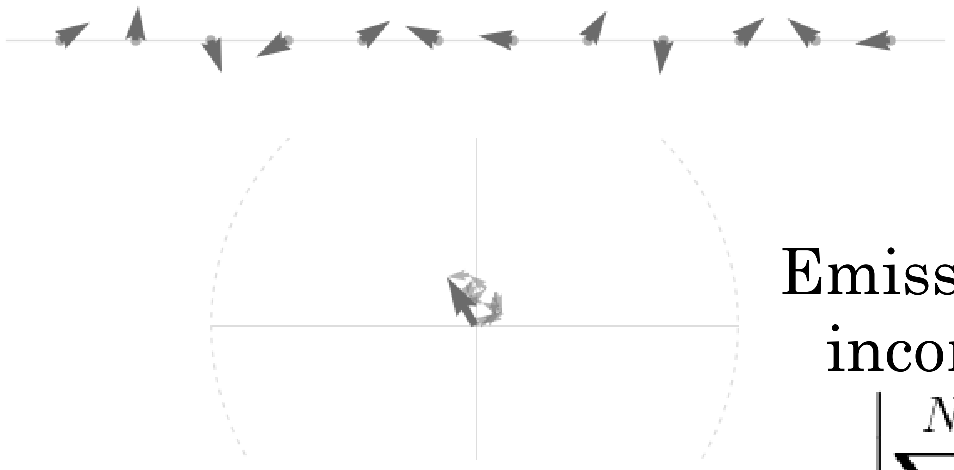


- Quantum effects can make signal $\sim N^2$.
- CATCHY (Coherent Atomic Transition from Counter-pulsed Hydrogen)

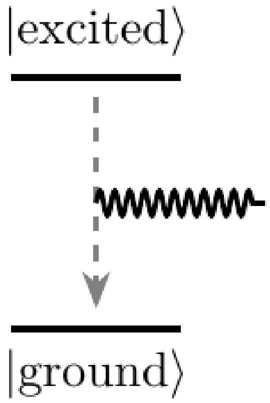
Detects dark photons with a quantum detector

Coherent Atomic Emission

RANDOM QUANTUM PHASES



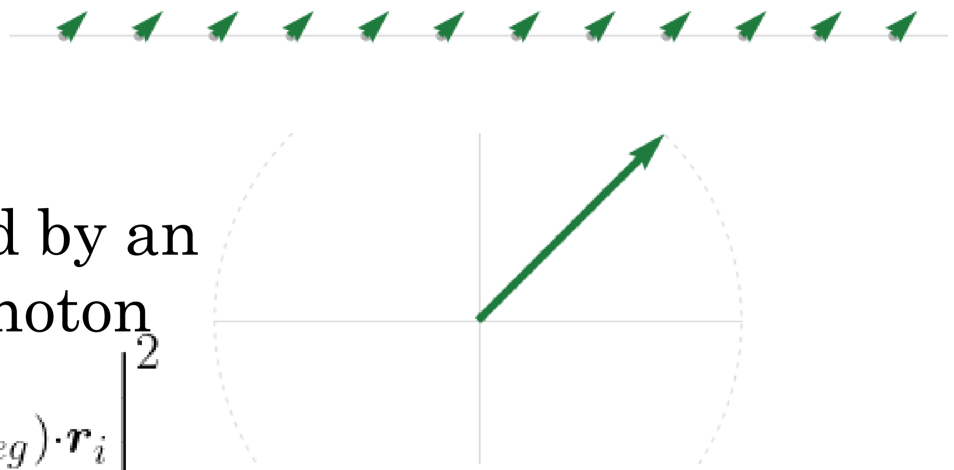
$$\Gamma \propto N$$



Emission triggered by an incoming dark photon

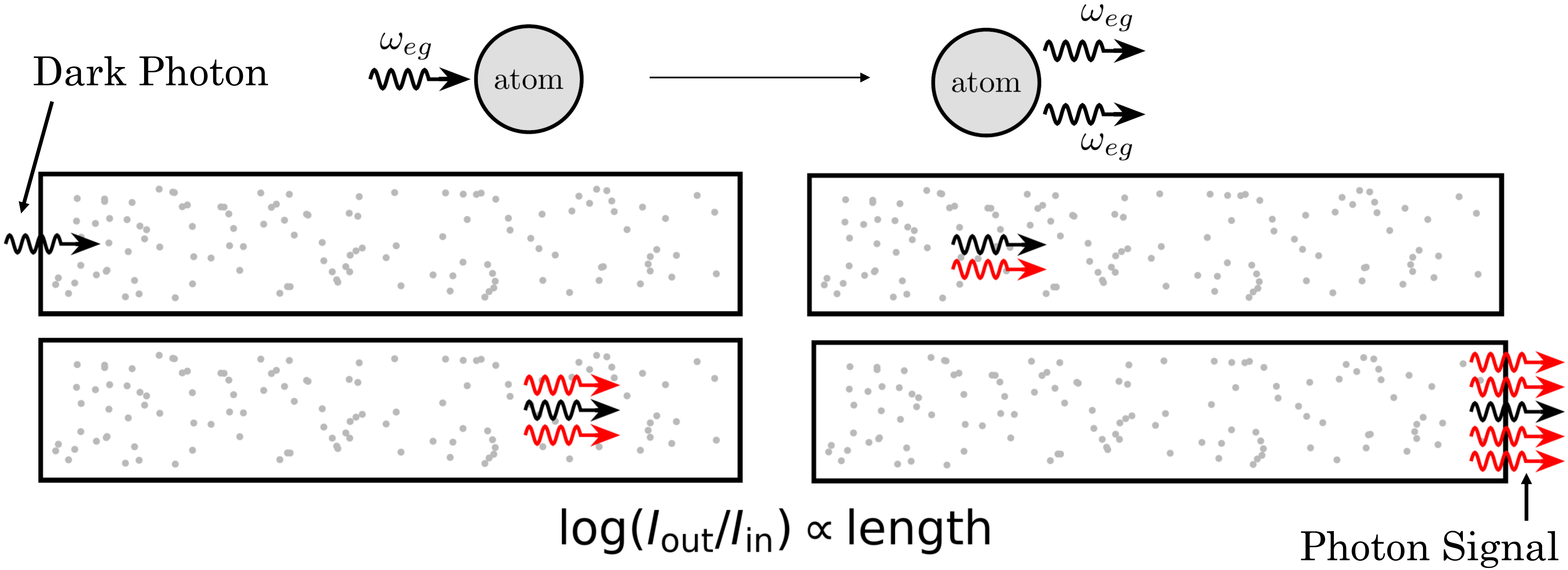
$$\Gamma \propto \left| \sum_{i=1}^{N} \mathcal{M} e^{-i(\boldsymbol{k}-\boldsymbol{k}_{eg})\cdot\boldsymbol{r}_i} \right|^2$$

LOCKED QUANTUM PHASES

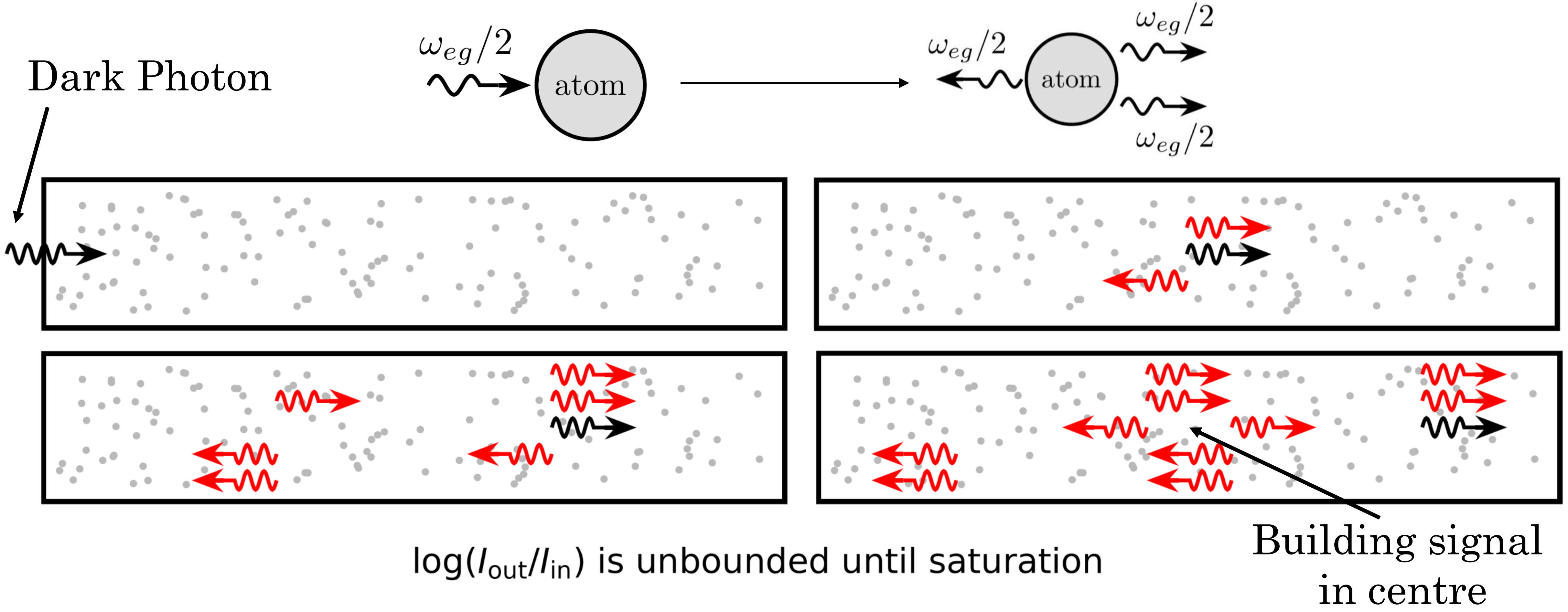


$$\Gamma \propto N^2$$

Stimulated One-Photon Emission



Stimulated Two-Photon Emission

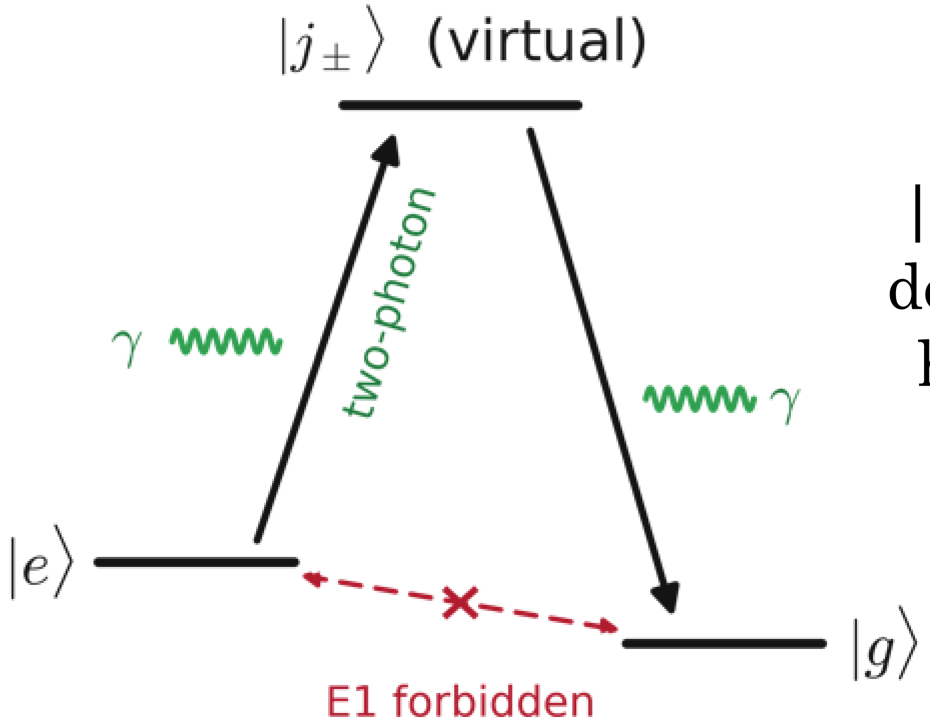


$\log(I_{out}/I_{in})$ is unbounded until saturation

Two-Stage Emission

Need atom/molecule with this structure

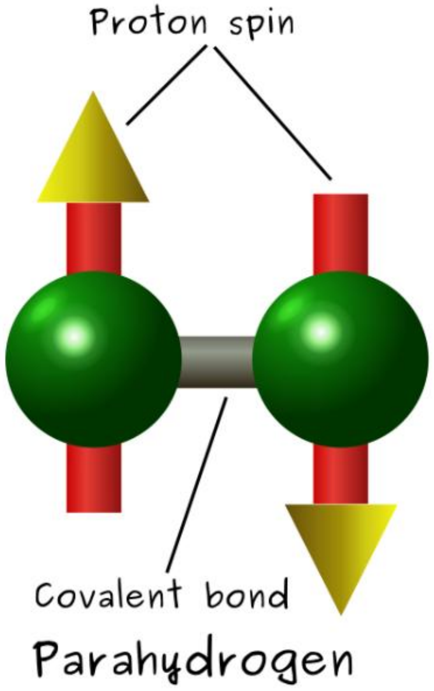
$\omega_{eg} \ll \omega_{jg}, \omega_{je}$



$|e\rangle \rightarrow |g\rangle$ is two-photon dominated and does not happen spontaneously

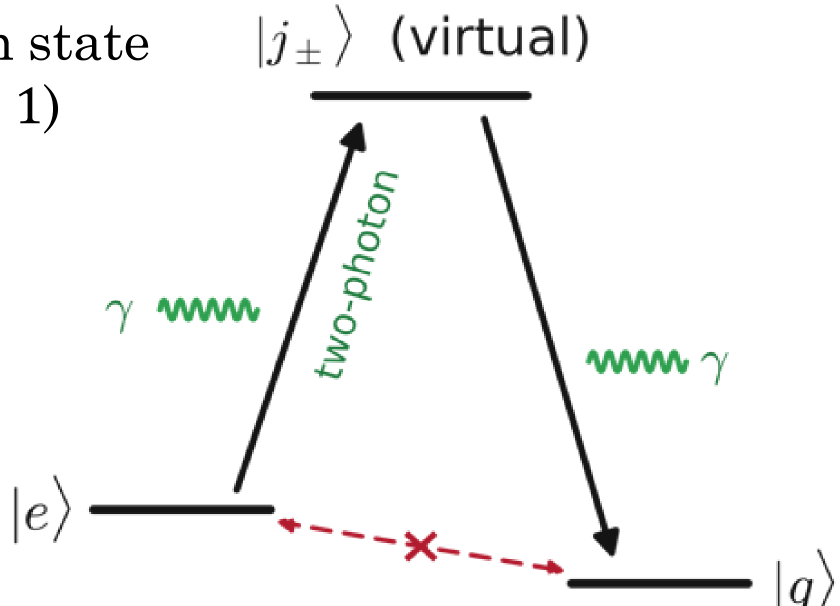
A Candidate: Parahydrogen

H_2 molecule with opposite proton spins



$T_{\text{spontaneous}} = 100$ Myr

First excited electron state ($J = 1$)



First excited vibrational proton state ($J = 0$)

Ground state ($J = 0$)

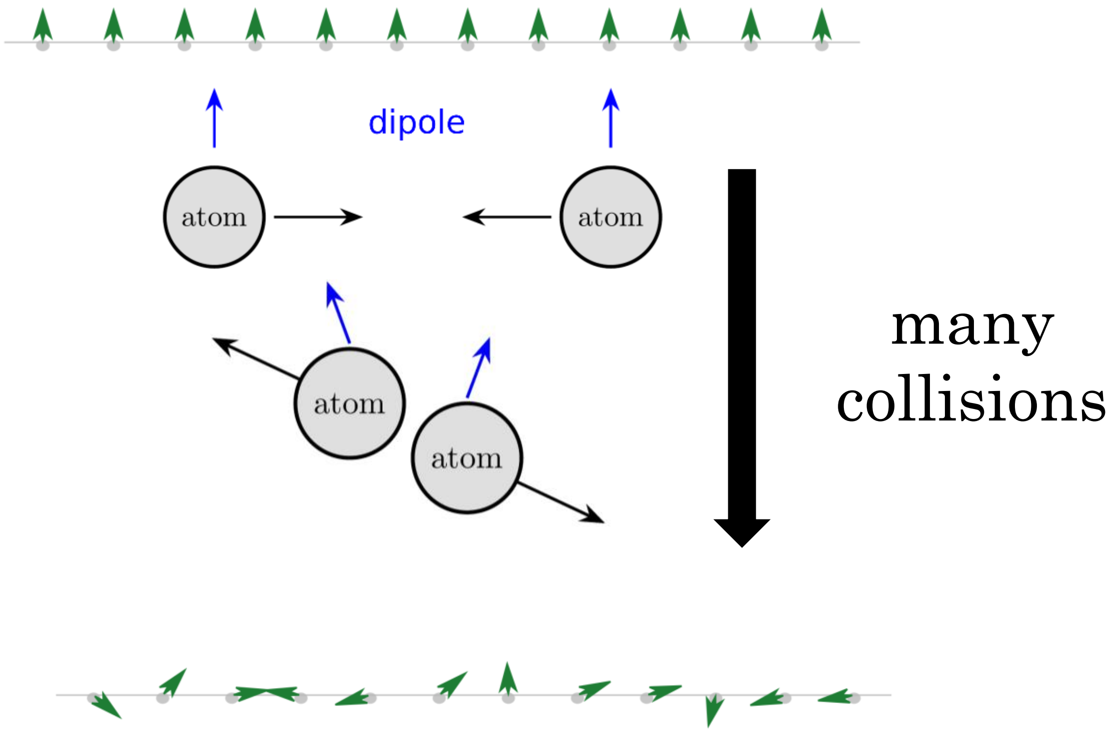
$\omega_{jg} \approx 10$ eV

$\omega_{eg} \approx 0.5$ eV

Collisional Decoherence

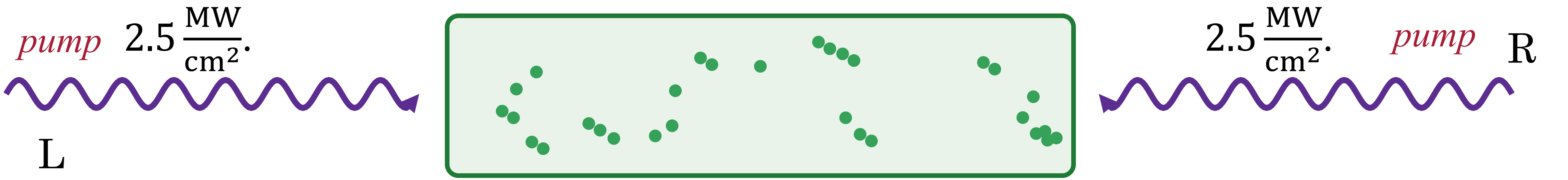
- Atoms collide and their dipoles misalign
- Enough collisions kill the overall coherent signal
- No infinite gain
- Want to minimize temperature—

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

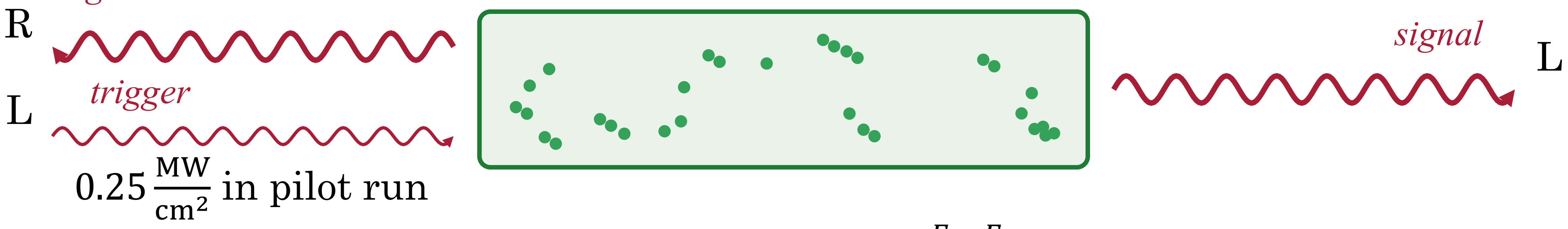


The Protocol

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

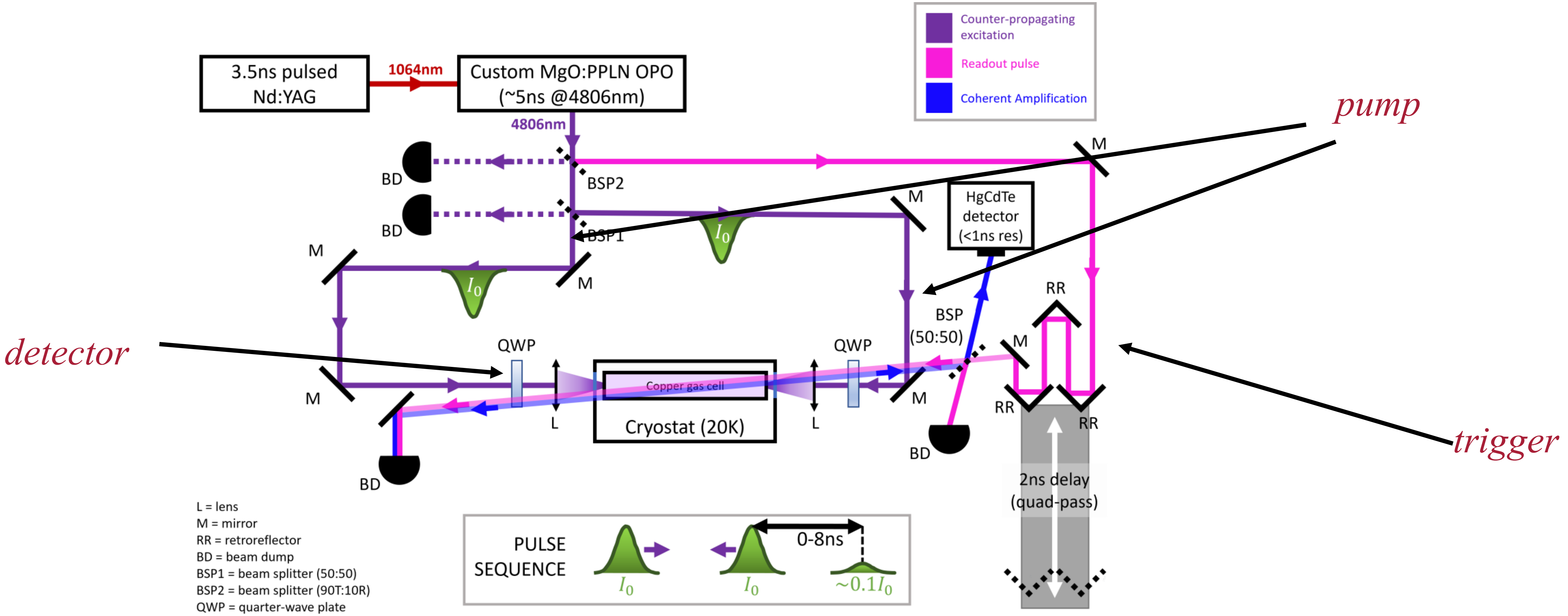


(b) Trigger Phase — a trigger laser deexcites the sample



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

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

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

The Importance of Phase Alignment

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

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

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

condense field equations
Ignore dark photon,
Set $E_2 \propto E_1^*$.

$$(\partial_t - \partial_z)E_1 = i\Omega n\rho_{ge}E_1$$

ρ is 2x2 density matrix
n is num. dens.

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condense field equations
Ignore dark photon,
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$$(\partial_t - \partial_z)E_1 = i\Omega n \rho_{ge} E_1$$

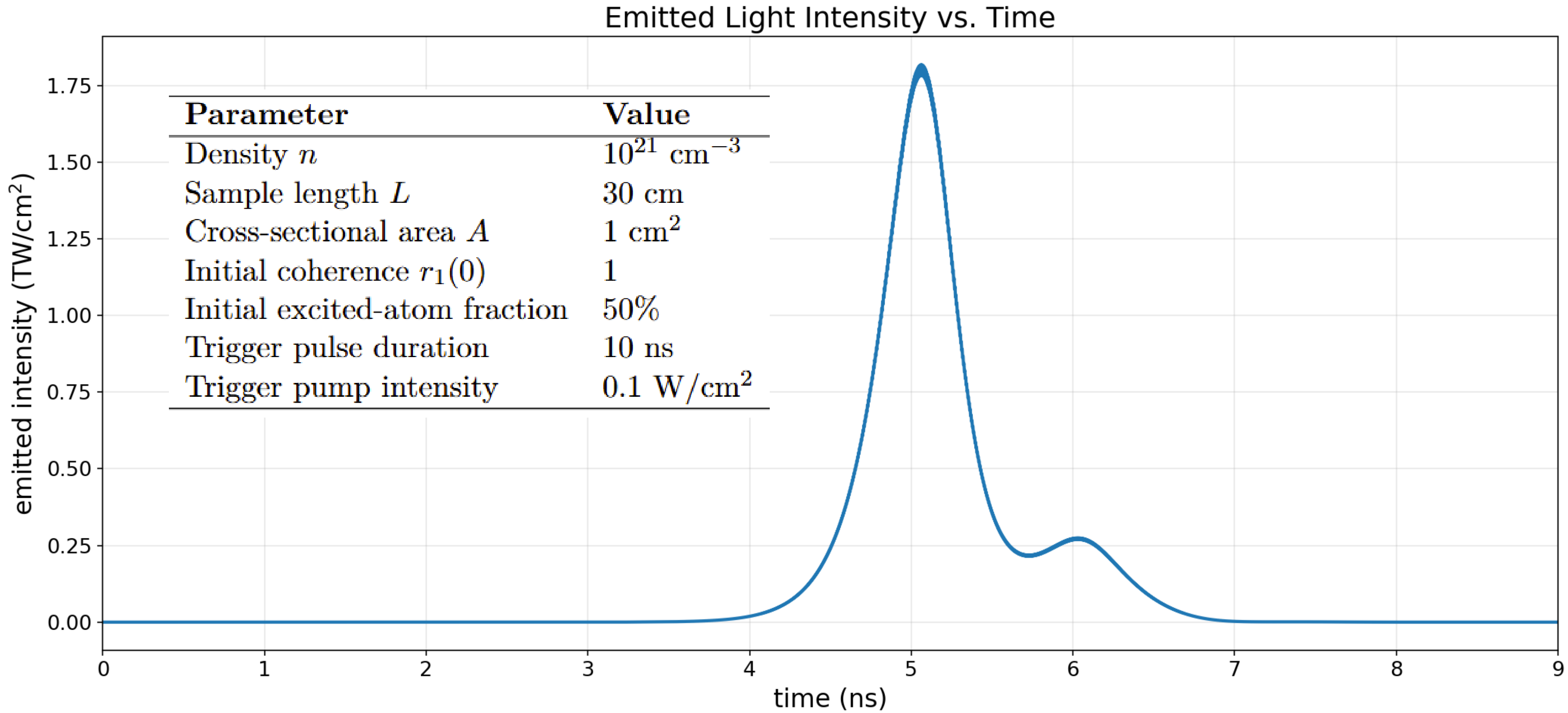
ρ is 2x2 density matrix
n is num. dens.

$$E_1 \propto \exp\left[\frac{i\Omega n}{2}\int \rho_{ge}\, d(z-t)\right]$$

Phases of ρ_{ge} must be aligned along the photon's path.

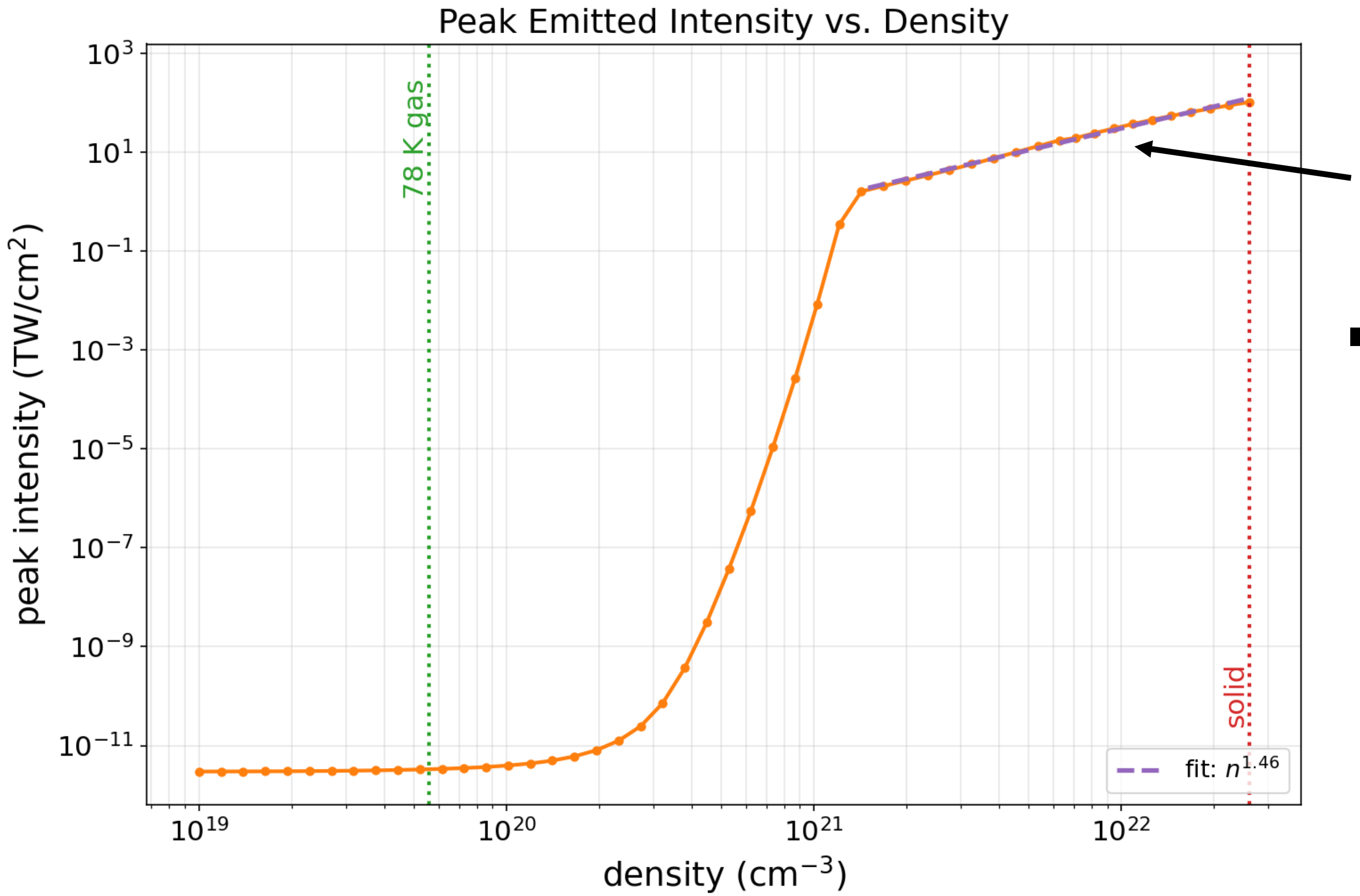
ρ_{ge}

The Intensity Spike from Laser Trigger



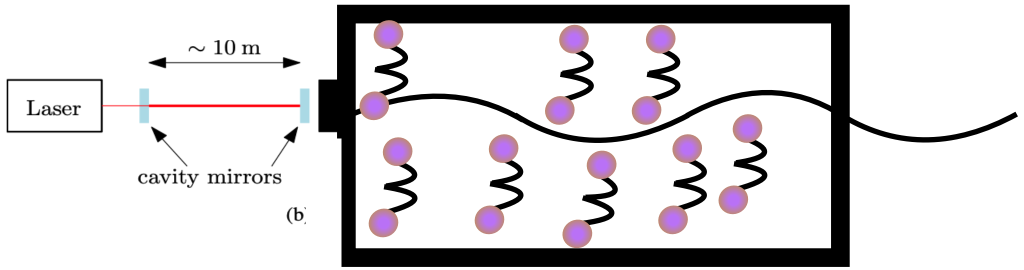
Parameter	**Value**
Density n	10^{21} cm^{-3}
Sample length L	30 cm
Cross-sectional area A	1 cm^2
Initial coherence $r_1(0)$	1
Initial excited-atom fraction	50%
Trigger pulse duration	10 ns
Trigger pump intensity	0.1 W/cm^2

Is the Sensitivity N^2?



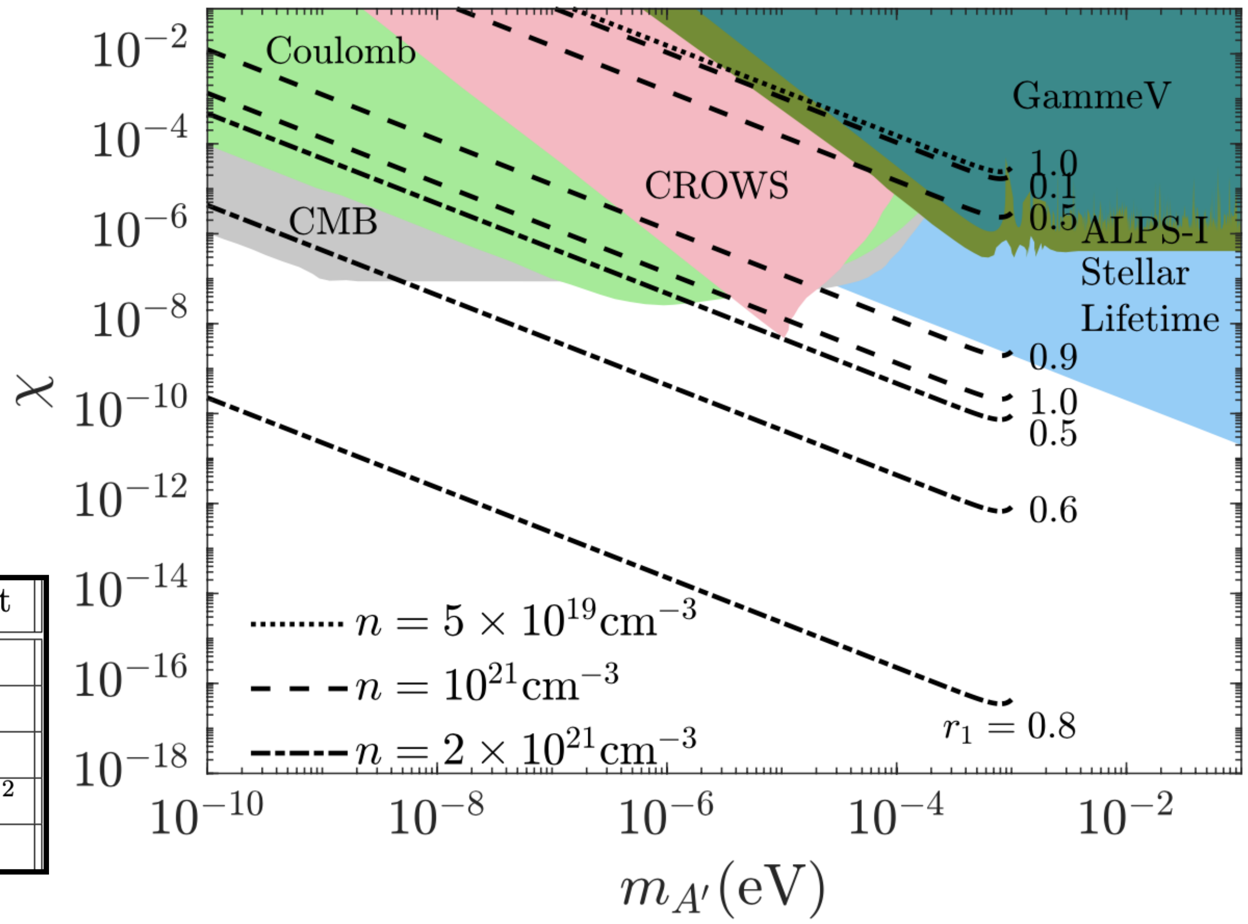
- Max intensity is super-linear for fixed length
- Reminiscent of other quantum coherent processes (e.g. Dicke Superadiance)
- Neglects collisional dephasing of pH_2 molecules

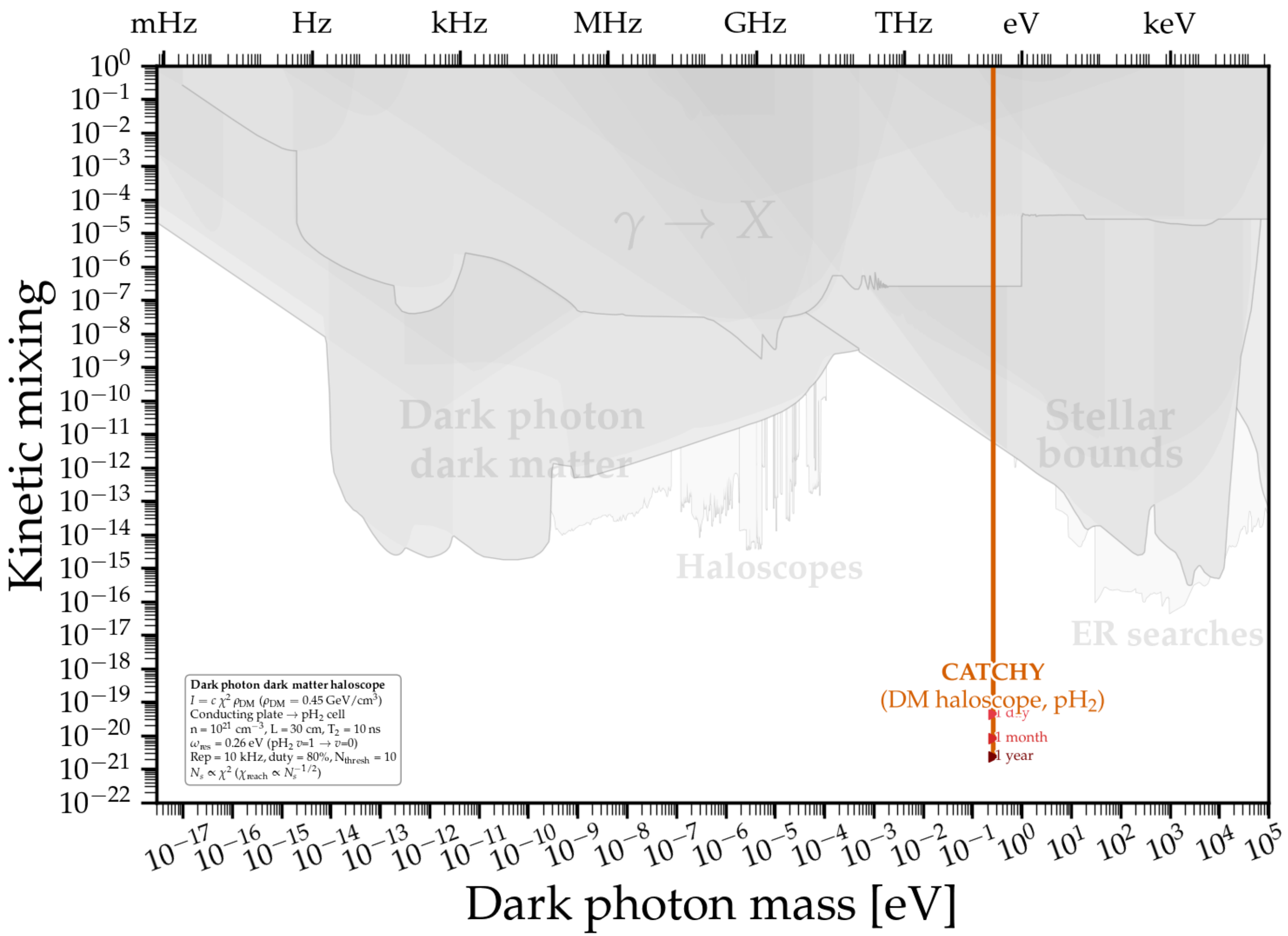
Prospective LSW Sensitivity



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

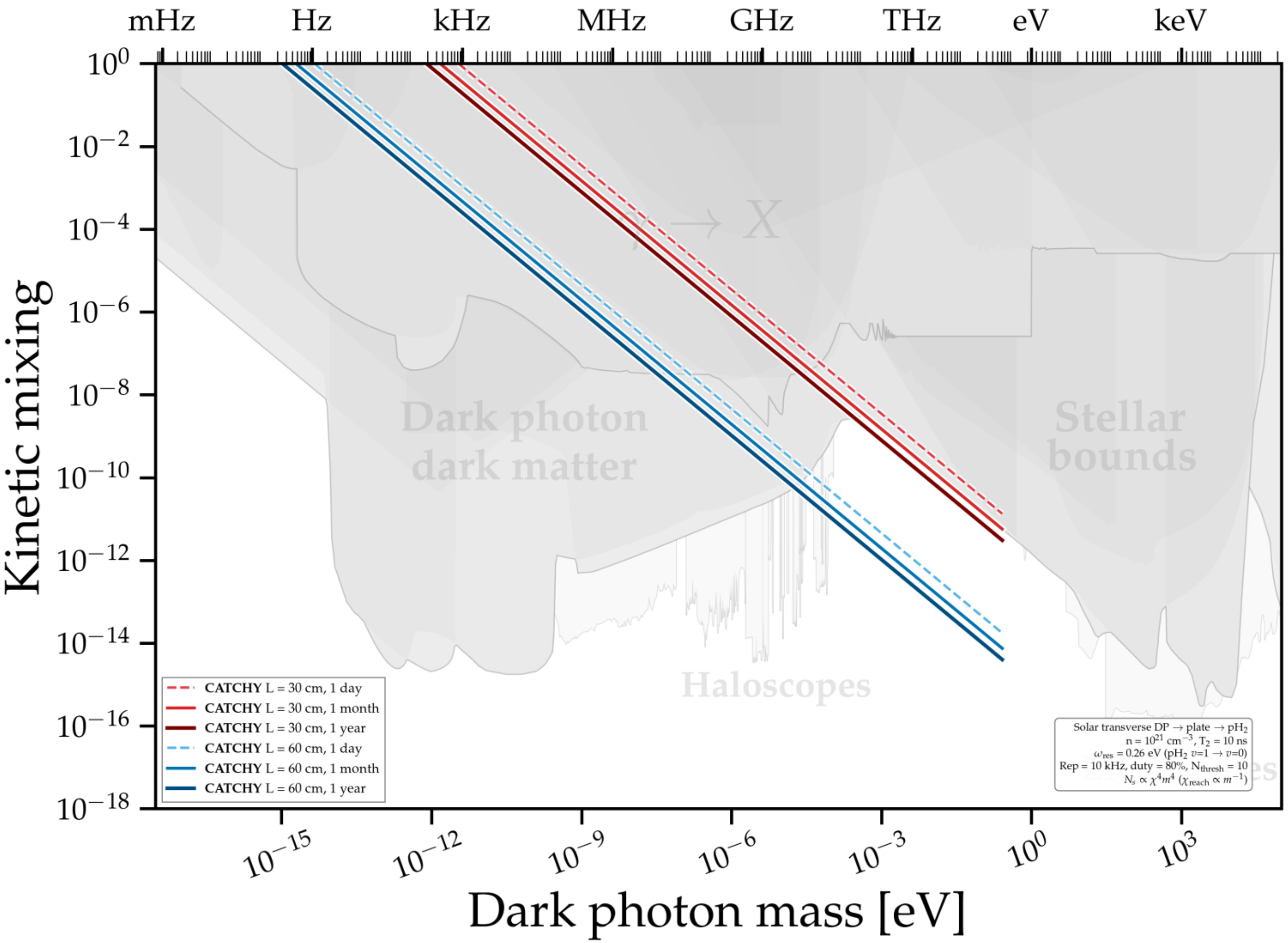
Dark Photon Generating Cavity	Superradiant Parahydrogen Target
Cavity Length $l = 50$ cm	Sample Length $L = 30$ cm
Cavity Reflections $N_{\text{pass}} = 2 \times 10^4$	pH_2 Density $n = 10^{21}$ cm^{-3}
Cavity Laser Freq. $\omega' = 0.26$ eV	Pump Laser Freq. $\omega_1 = 0.26$ eV
Cavity Laser Power $P_L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





Prospective Haloscope Sensitivity

Prospective Helioscope Sensitivity

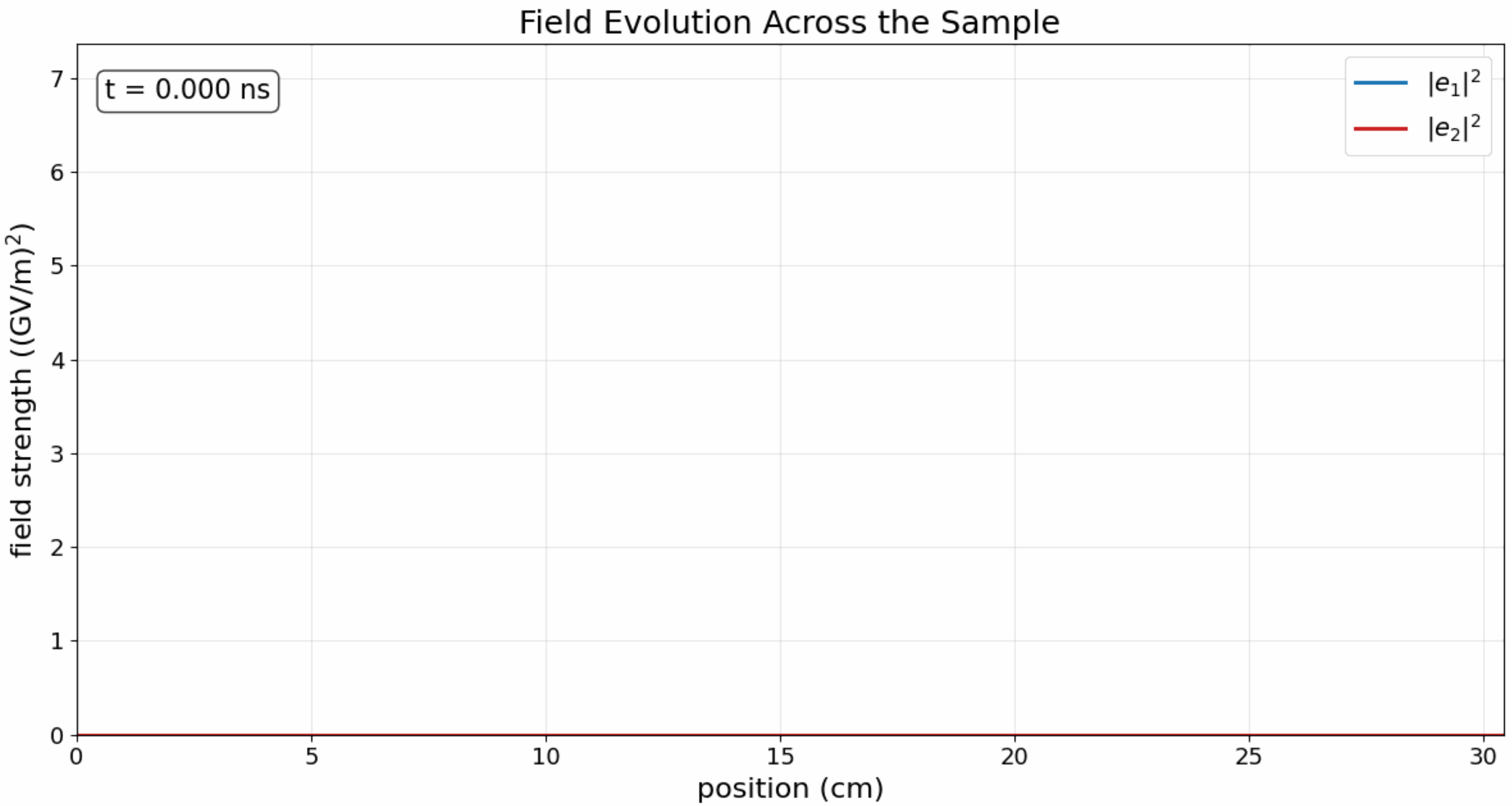


Conclusion

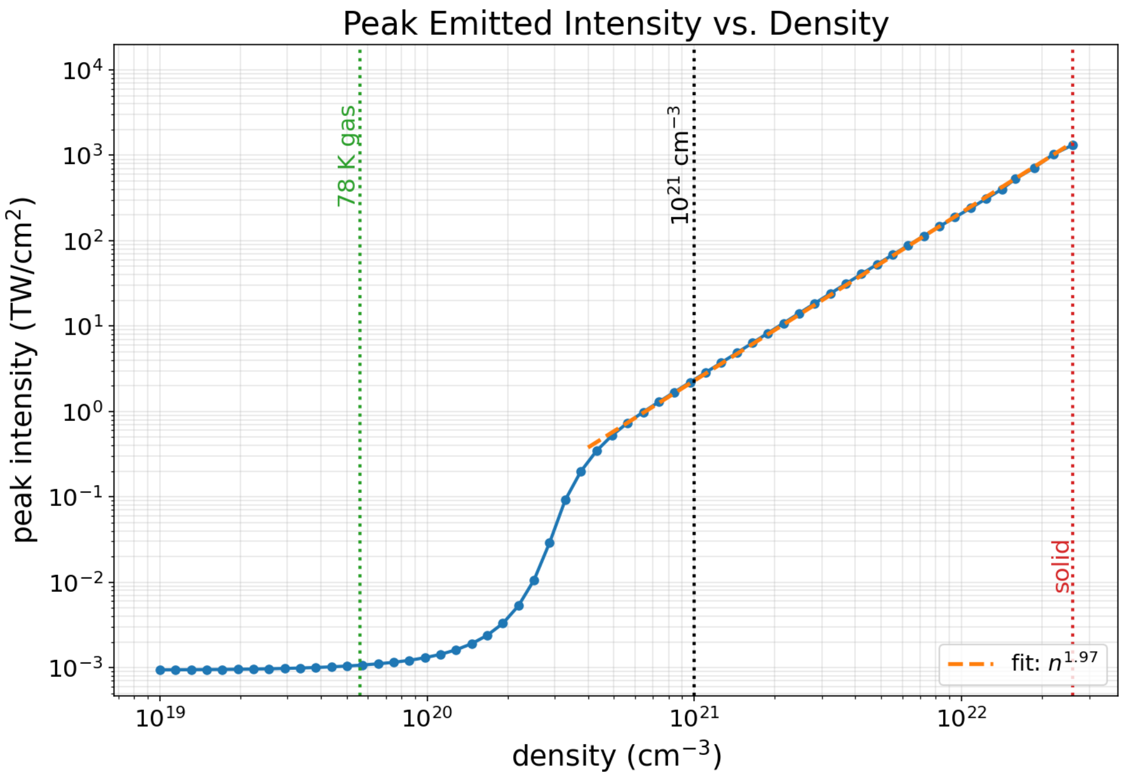
- CATCHY: ongoing project for a new kind of quantum detection at Queen's University
- Search for dark photons with coherently prepared parahydrogen
- An incoming dark photon produces a cascade of two-photon emissions, producing an observable spike in intensity
- Sensitivity limits scales super-linearly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

EXTRA SLIDES

Evolution of the Electric Field (GIF)



The Power Law Depends on Trigger Strength



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

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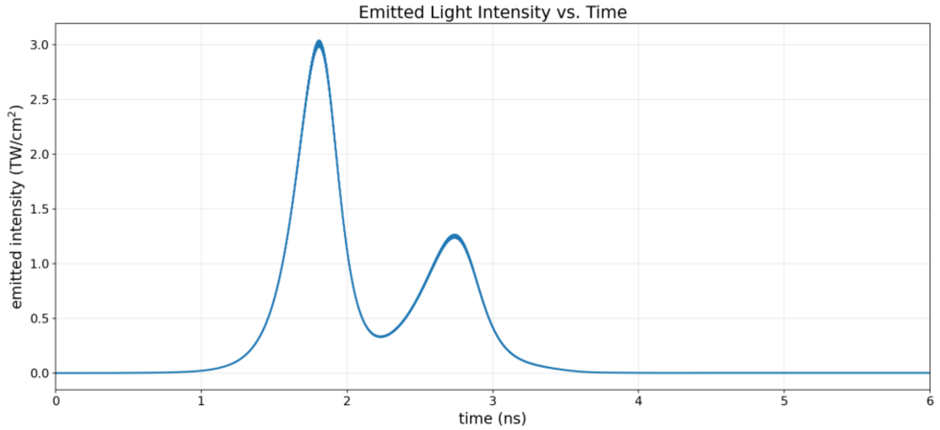
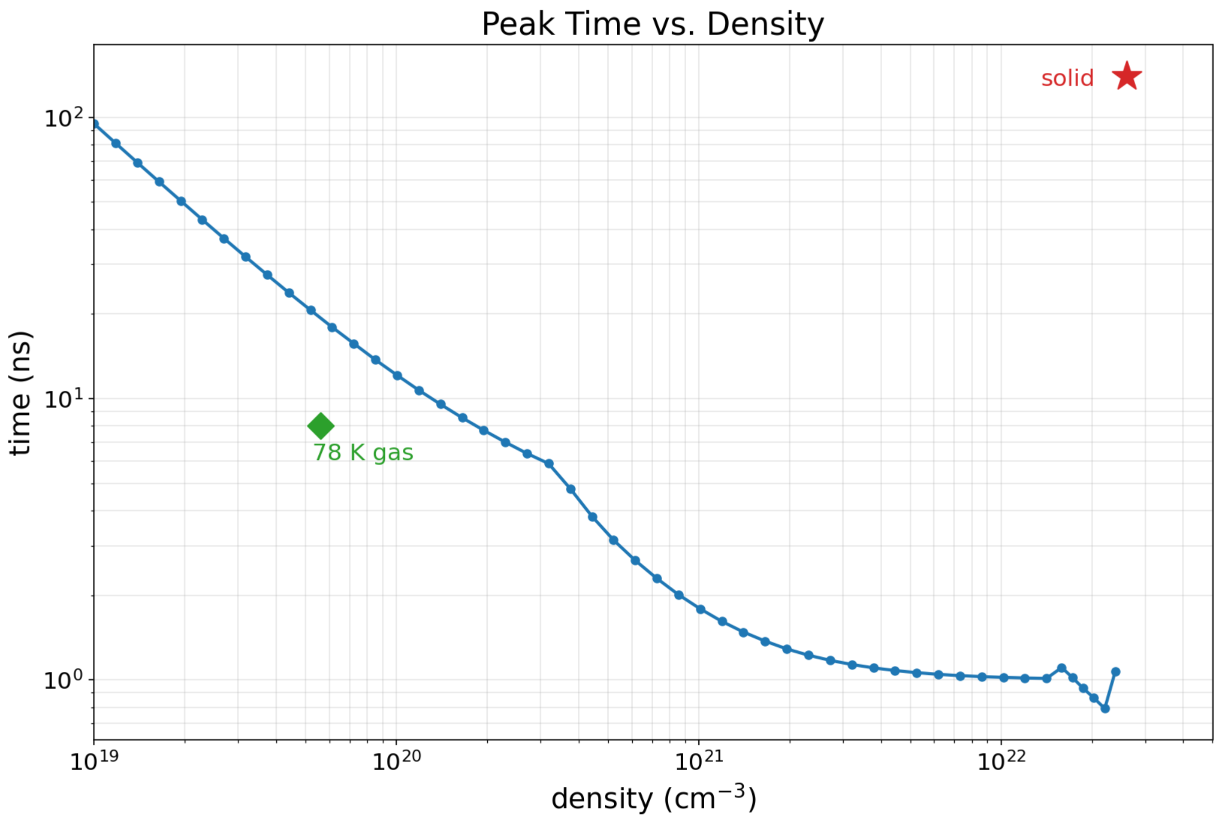
Trigger pulse duration	10 ns
Trigger pump intensity	1 GW/cm^2



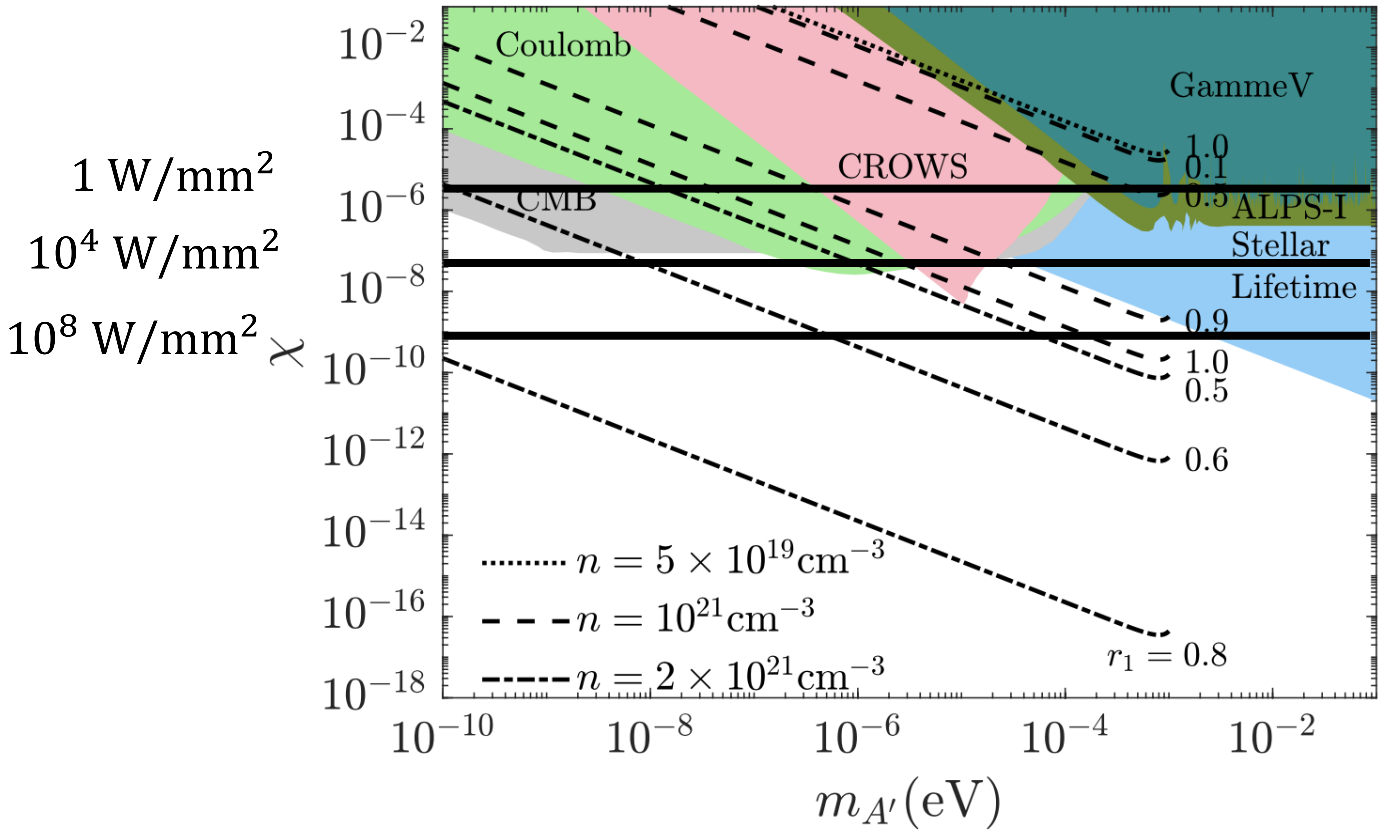
Peak Times vs. Density



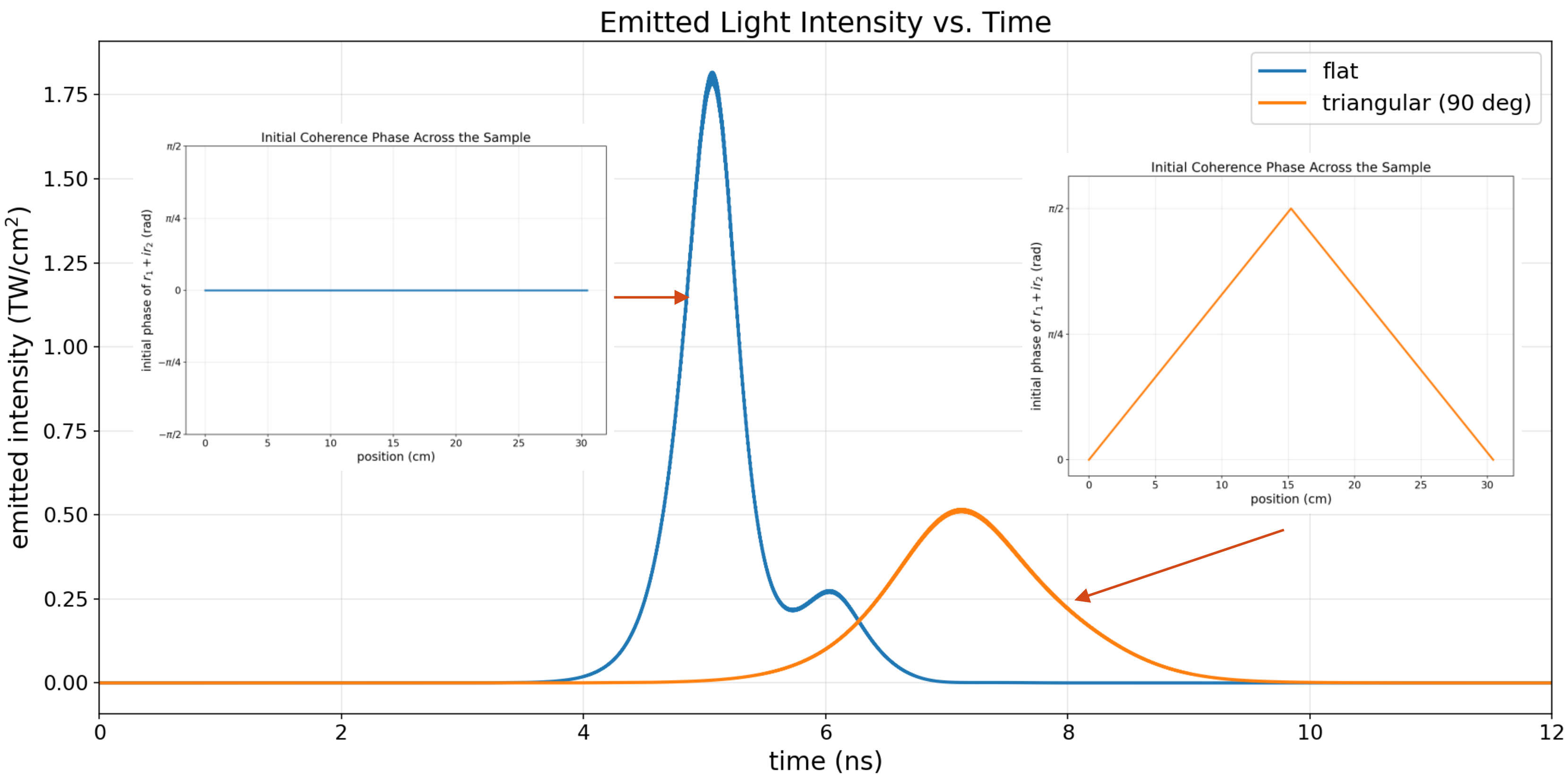
- Time of peak intensity vs density (idealized no decoherence)
- Can safely ignore decoherence if $t_{\text{peak}} < t_{\text{dec}}$
  - Collisional decoherence matters a bit for gaseous pH_2 and not at all for solid pH_2

Quantum Noise

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



Dependence on Signal on Constant Phase



More aligned dipoles give stronger signal

Random dipoles completely destroy signal