Superradiant Searches for Dark Photons in Two Stage Atomic Transitions

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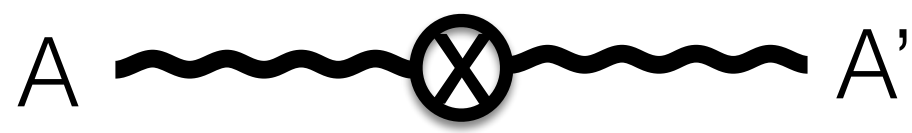
Dark photons

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



Galison, Manohar 1984
Holdom 1986

U(1) vectors mixed with the SM photon appear in many SM extensions

SUSY breaking sectors

Dienes Kolda March-Russell 1998

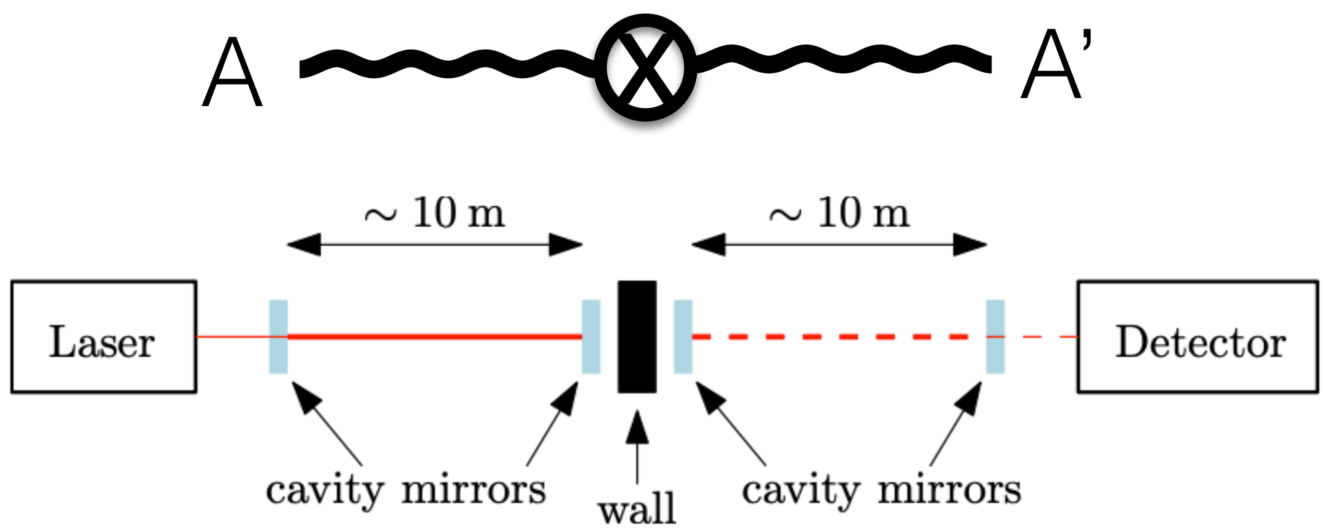
String compactifications

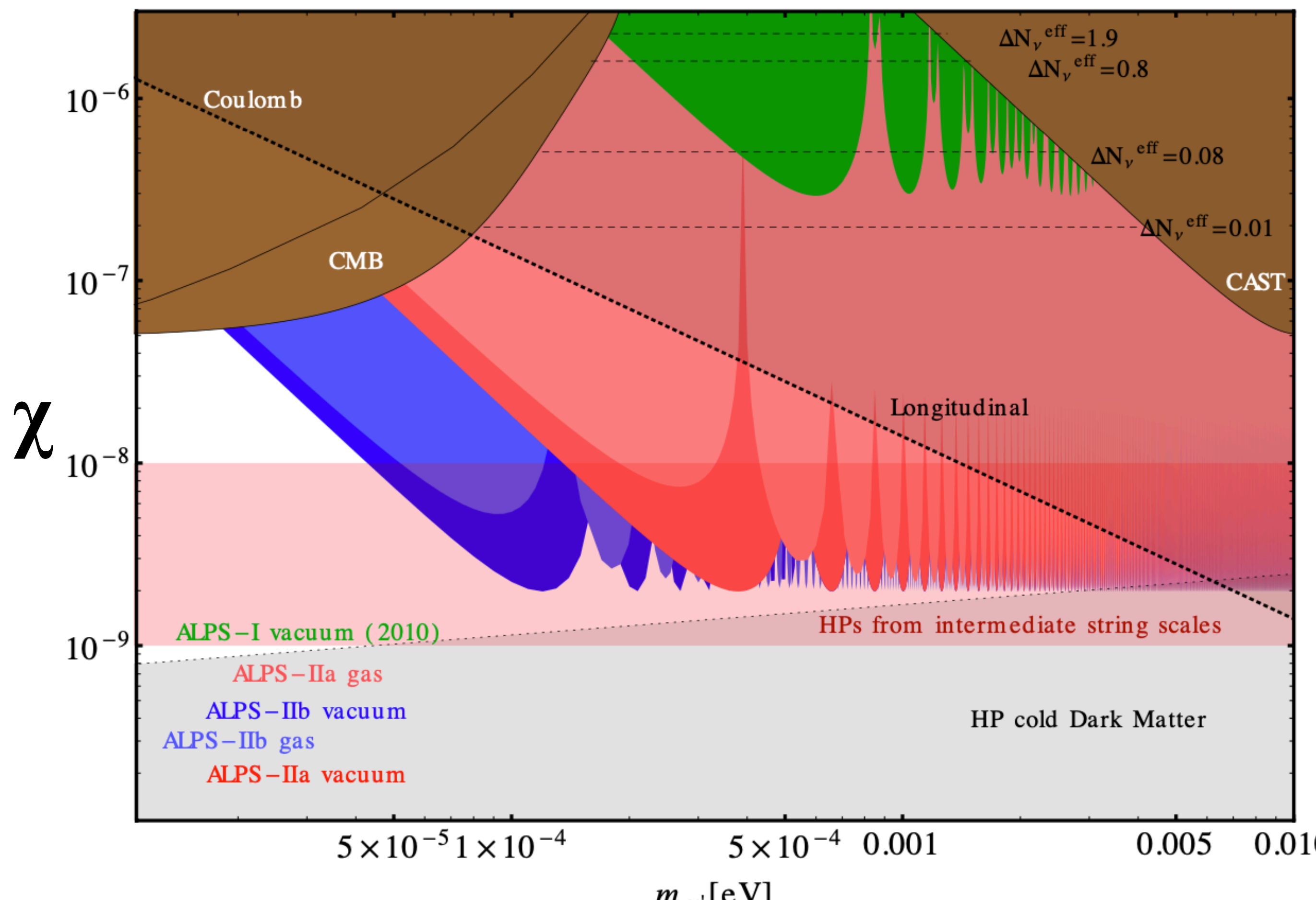
Goodsell Jaeckel Redondo Ringwald 2008

Dark sectors

Pospelov 2008
Arkani-Hamed Finkbeiner Slatyer Weiner 2008
Ackerman Buckley Carroll Kamionkowski 2008

Light Shining Through Walls

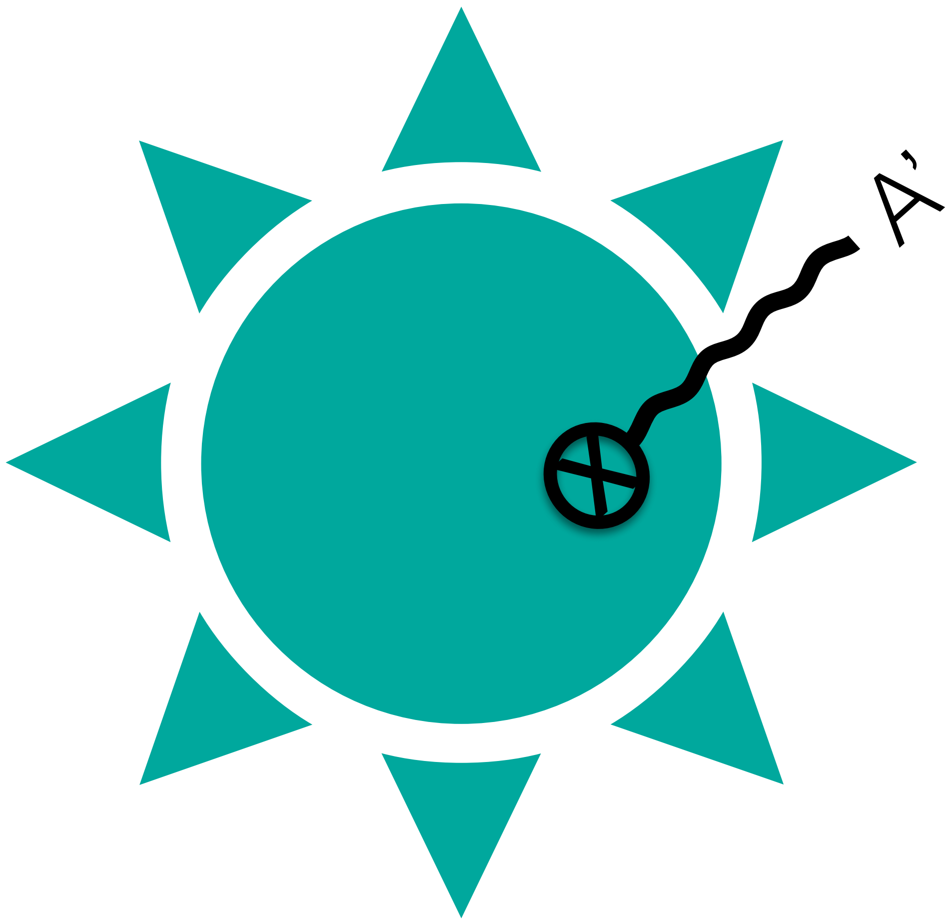


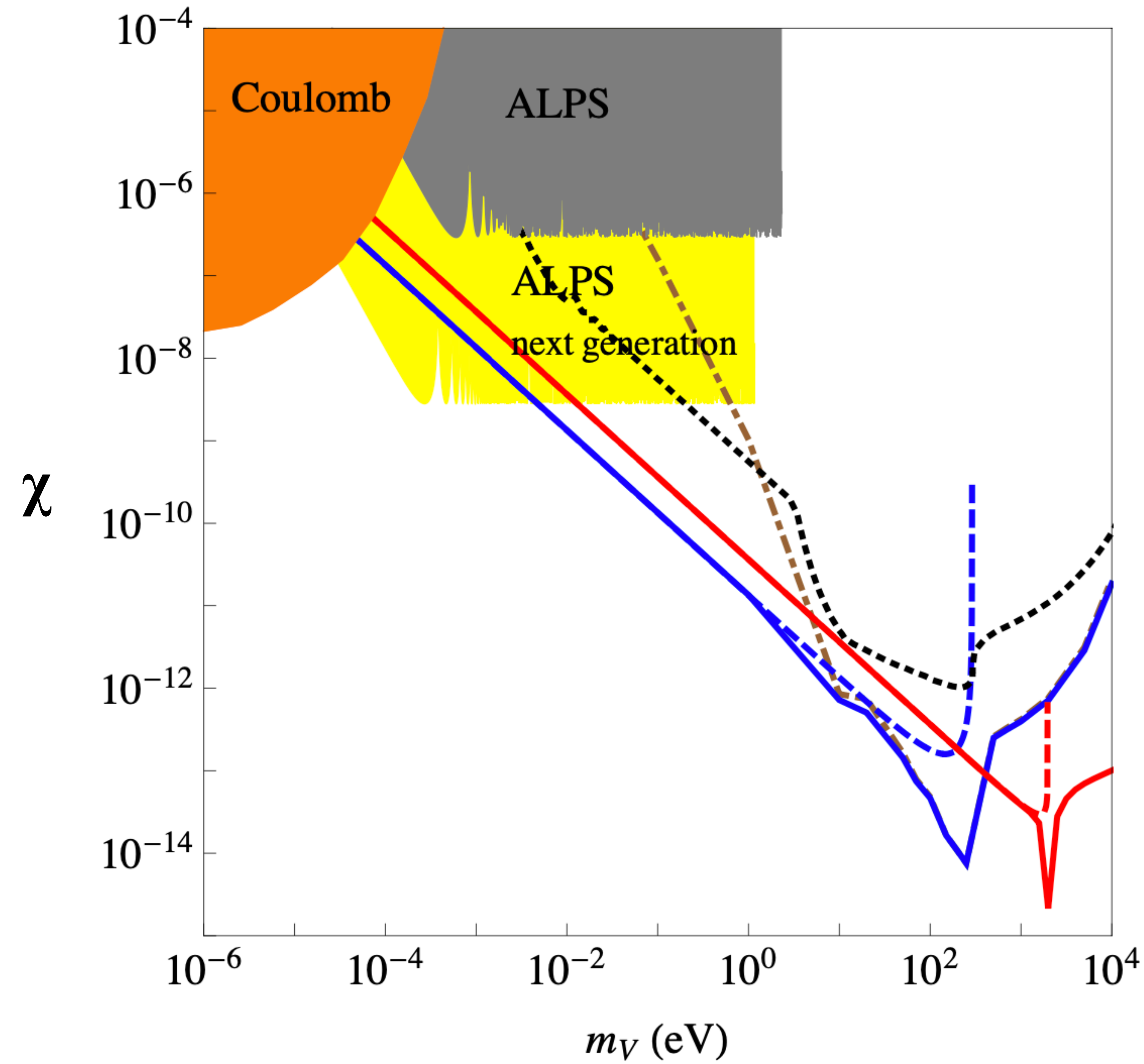


Searches for dark photons currently use cavities to detect the dark photons coming through the wall, (ALPS II).

ALPS II TDR 1302.5647

Stellar emission with longitudinal mode

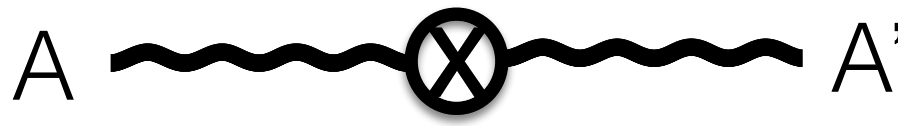


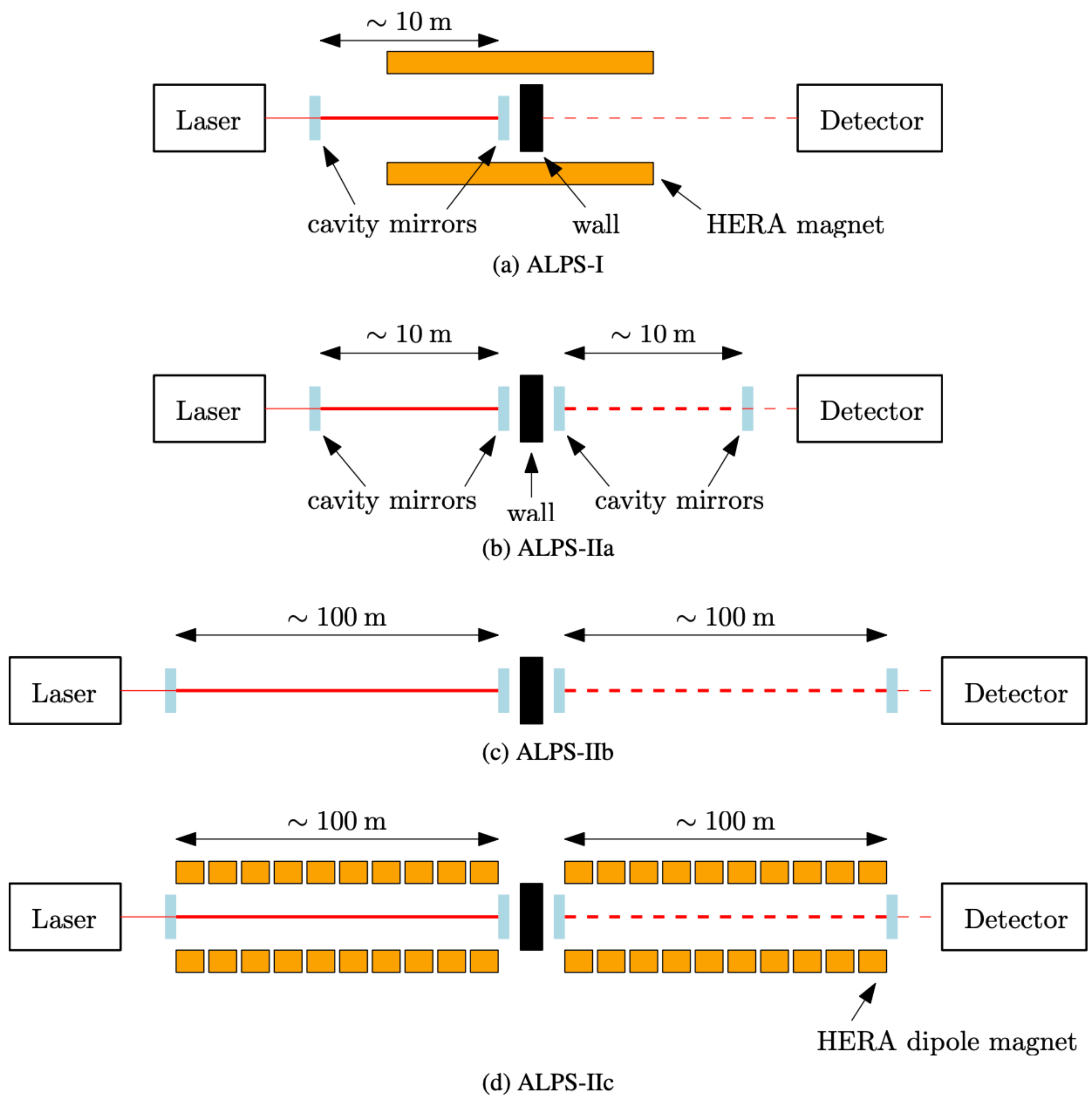


Stellar emission bounds currently leading for ~meV+.

An, Pospelov, Pradler 1302.3884
Raffelt 1996

Light Shining Through Walls





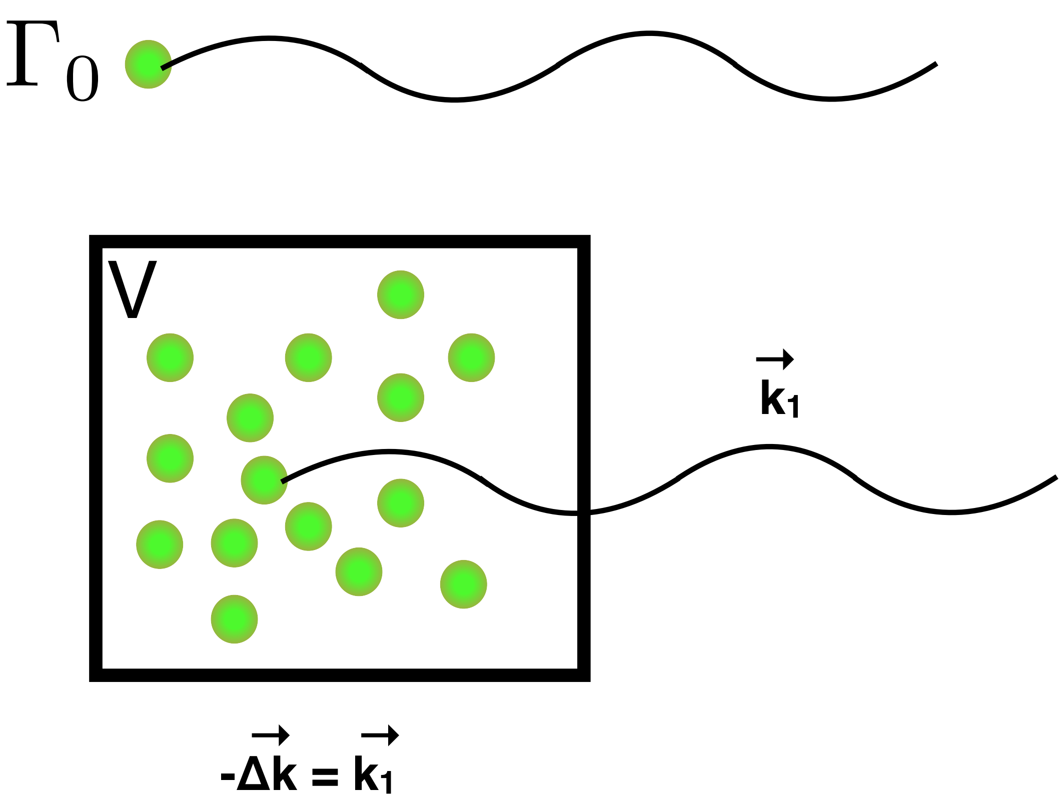
ALPS II focusing on axion detection.

ALPS II TDR 1302.5647

Classic Superradiance

Dicke 1954

Superradiance describes the collective (de-)excitation of atoms that emit or absorb photons coherently.



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

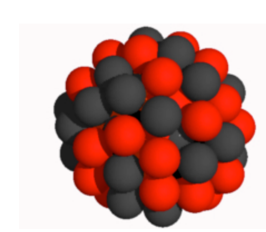
$$V \sim \frac{1}{k_1^3}$$ coherence volume momentum limited

$$\Gamma = nV\Gamma_0$$ No SR

$$\Gamma_{tot} = n^2 V^2 \Gamma_0$$ SR

Analogy to Spin-Independent Direct Detection: sum over emitters versus sum over nucleons in amplitude, squared.

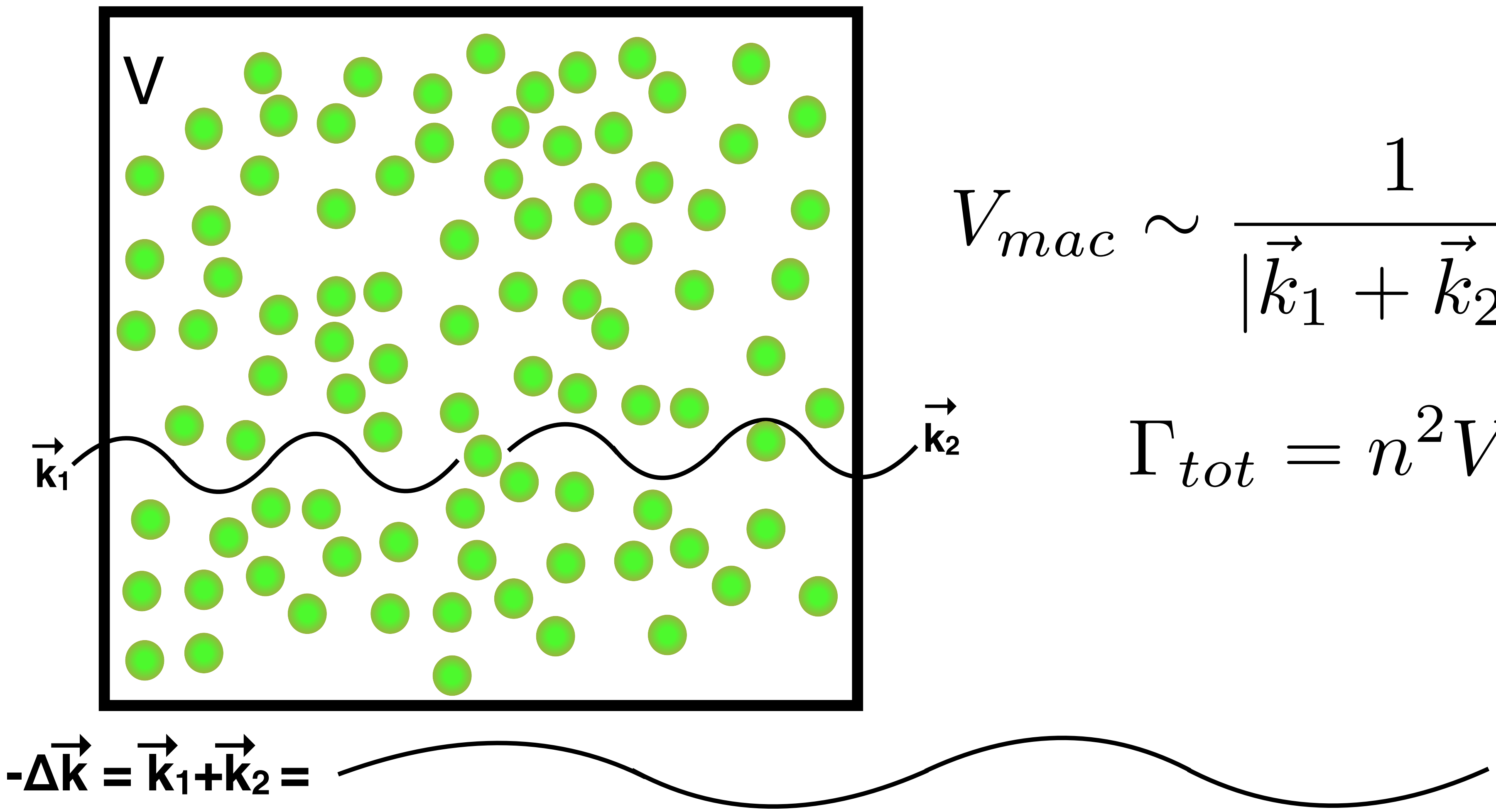
$$\sigma \propto N^2 \sigma_n$$



Macro Superradiance

Yoshimura 2006

Classic superradiance is limited by the frequency of the photon emitted. Macro superradiance minimizes the momenta of emitters with back-to-back two photon emission.



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

$$\Gamma_{tot} = n^2 V_{mac}^2 \Gamma_0$$ macro SR

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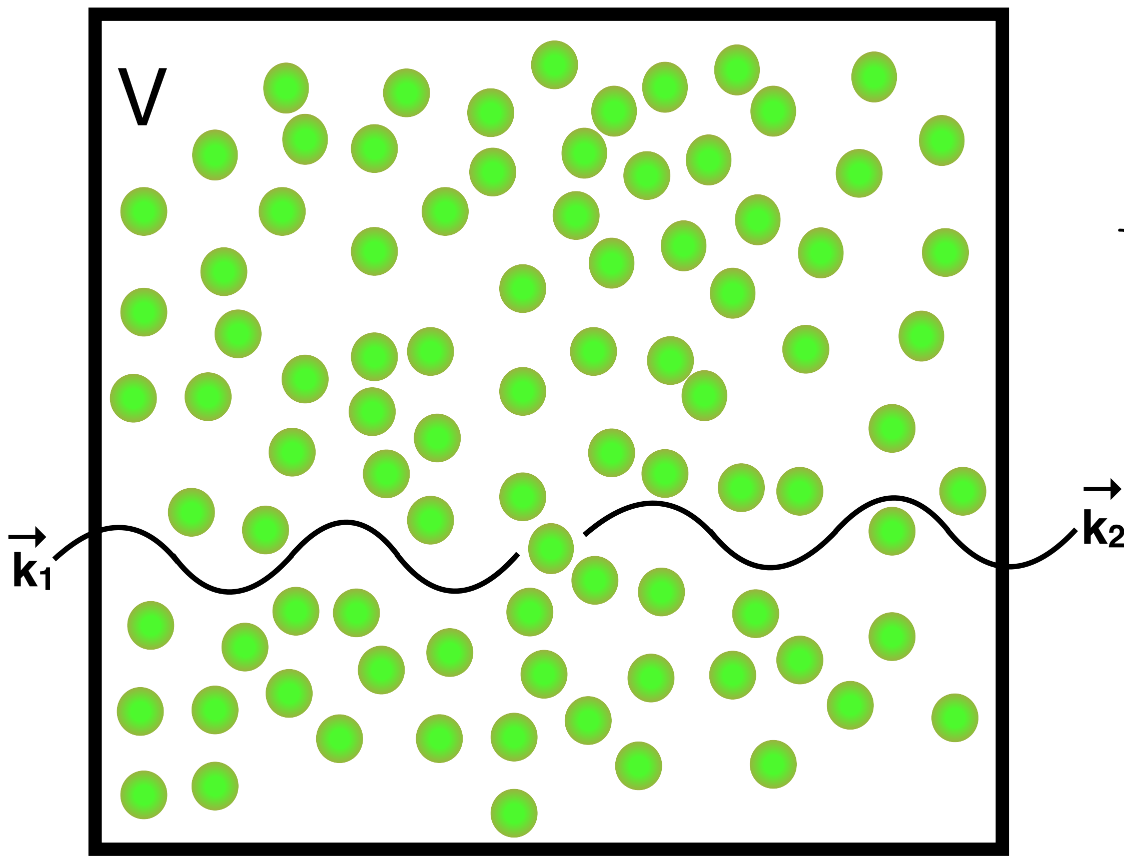

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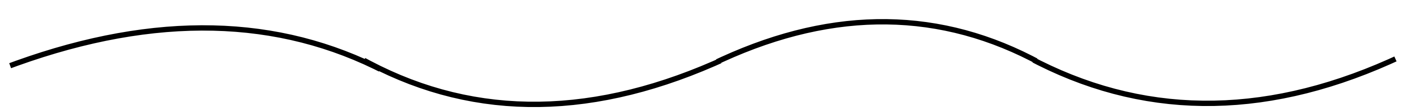
$$\Gamma_{tot} = n^2 V_{mac}^2 \Gamma_0$$ macro SR

$-\Delta\vec{k} = \vec{k}_1 + \vec{k}_2 =$

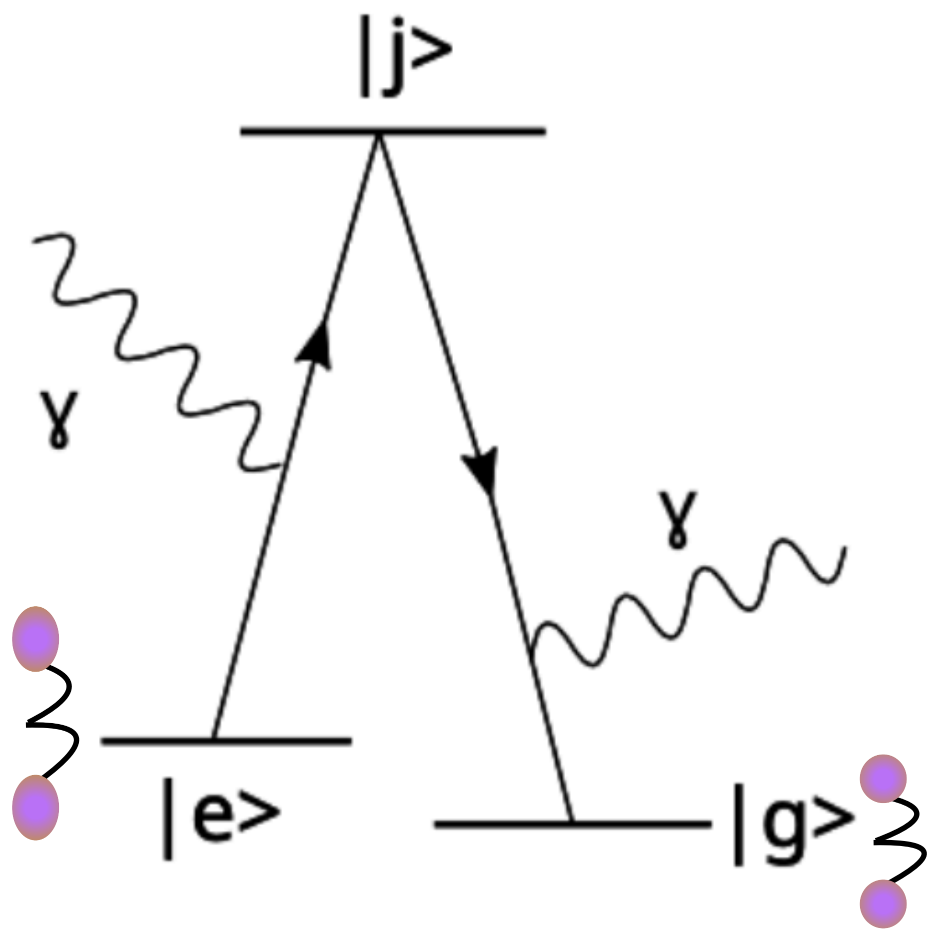


$$\Gamma_{\rm sp} = \int \frac{d^3k_1}{(2\pi)^3}\frac{d^3k_2}{(2\pi)^3}\left|\int d^3r \sum_{a=1}^{N} \frac{a_{eg}}{4}\sqrt{\frac{4\omega_1\omega_2}{V^2}}\, e^{-i(\vec{k}_1+\vec{k}_2-\vec{k}^a_{eg})(\vec{r}-\vec{r}_a)}\right|^2 2\pi\delta(\omega_{eg}-\omega_1-\omega_2)\,,$$

Macro-coherent when phase difference minimized, $|\vec{k}^a_{eg}| \ll |\vec{r} - \vec{r}_a|$.

Macro Coherence in Parahydrogen

pH_2's first vibrational excitation state
electric dipole (E1) transition parity forbidden,
leading transition is two photon (E1xE1).



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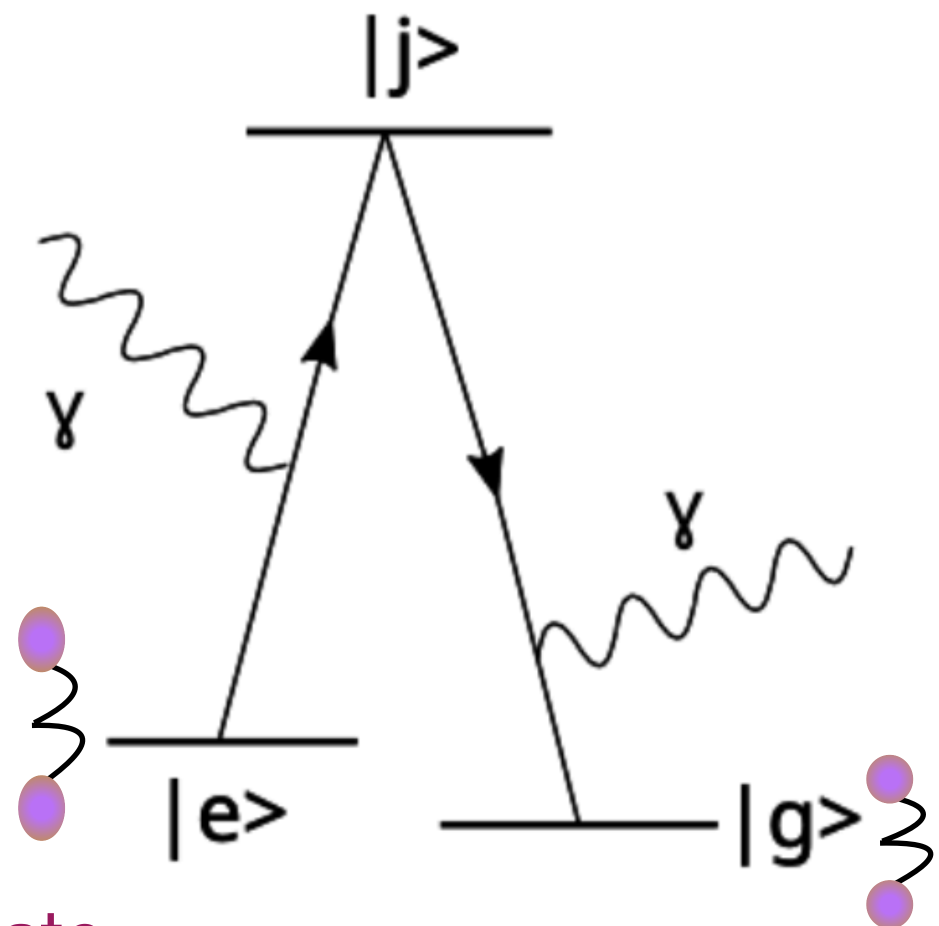
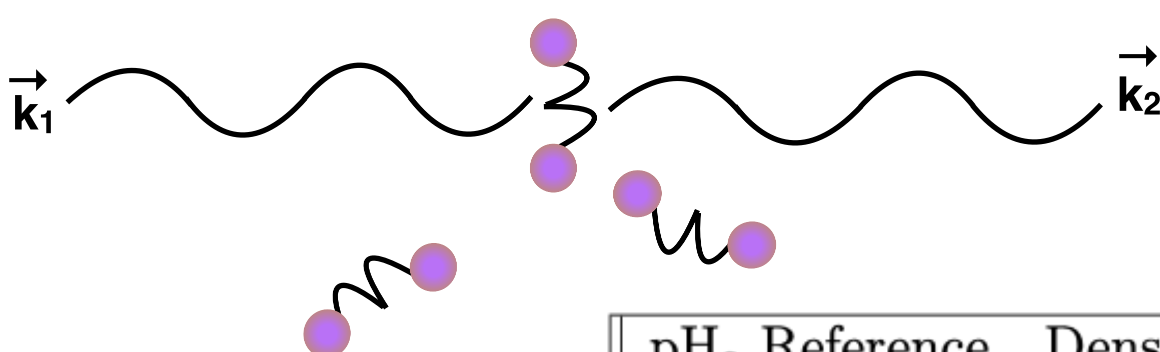


pH_2's first vibrational excitation state electric dipole (E1) transition parity forbidden, leading transition is two photon (E1xE1).

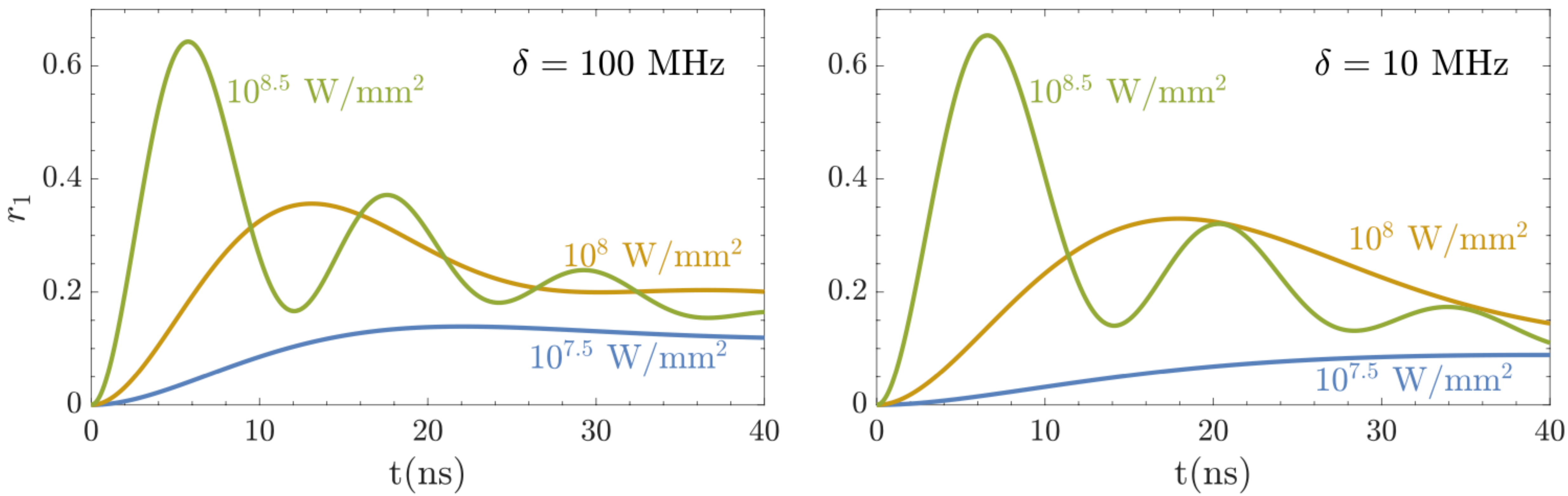
This ~0.5 eV vibrational mode is the lowest lying state, along with easily attainable 10 ns decoherence times, this makes pH_2 a good medium for macro coherence.

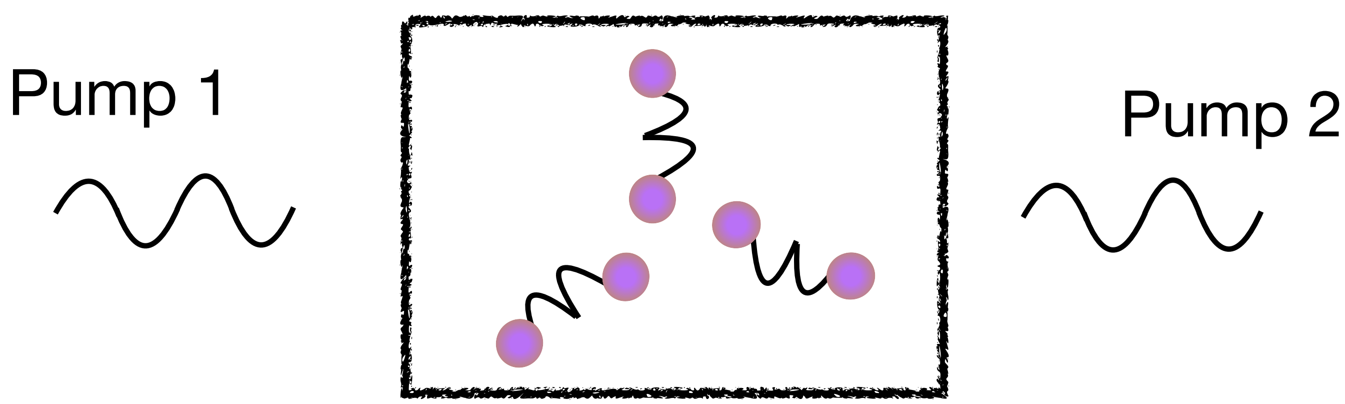


pH_2 Reference	Density (cm^{-3})	Temperature (K)	Decoherence Time (ns)
[57]	$10^{19} - 10^{20}$	80-500	~ 10
[42]	5.6×10^{19}	78	~ 8 (est)
[37]	$10^{19} - 5 \times 10^{20}$	78	~ 10 (est)
[58]	2.6×10^{22}	4.2	$\gtrsim 140$

Macro Coherence in Parahydrogen

r_1 is the |e>,|g> Bloch vector where $r_1 = 1$ defines fully coherent/in-phase atoms.
Our simulations assumed 10 ns decoherence times, and varied laser detuning δ.





Bhoonah, JB, Song 2019

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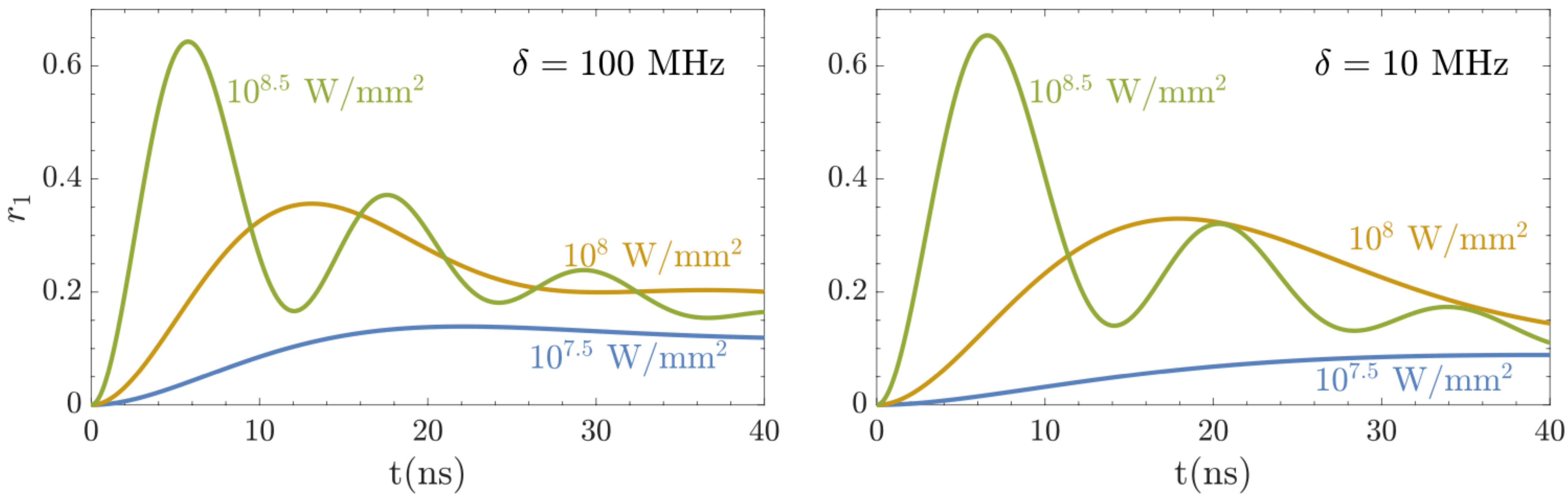

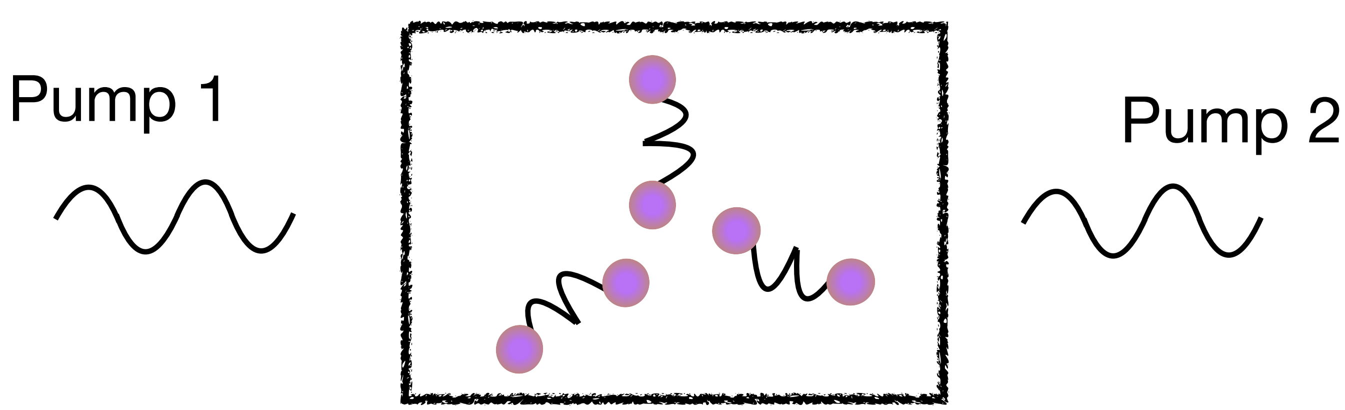

Superradiant Parahydrogen Target
Sample Length $L = 30$ cm
pH_2 Density $n = 10^{21}$ cm^{-3}
Pump Laser Freq. $\omega_1 = 0.26$ eV
Pump Laser Power $\approx 10^9$ W mm^{-2}

-Commercially available lasers have the pulse power necessary to excite ~mg of parahydrogen to full coherence.
-Current record is $r_1 \sim 0.068$.
Motohiko et al. 2015

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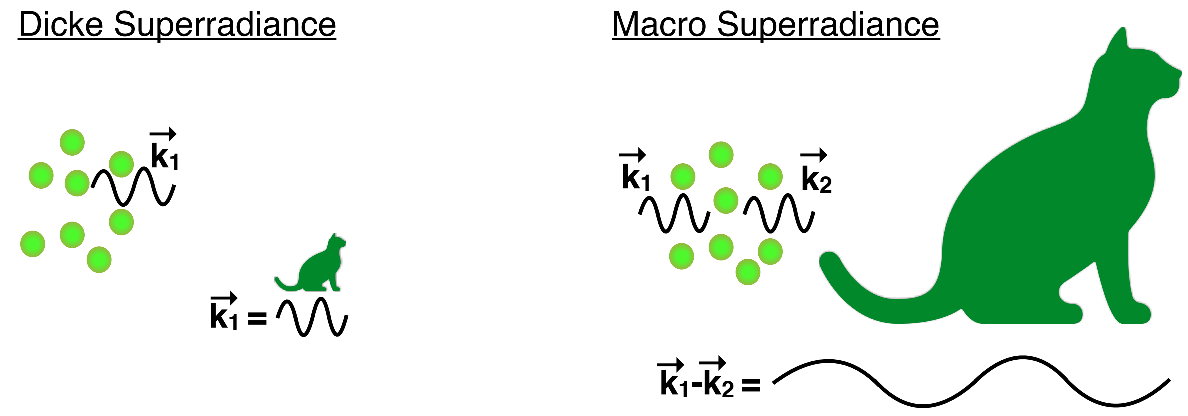
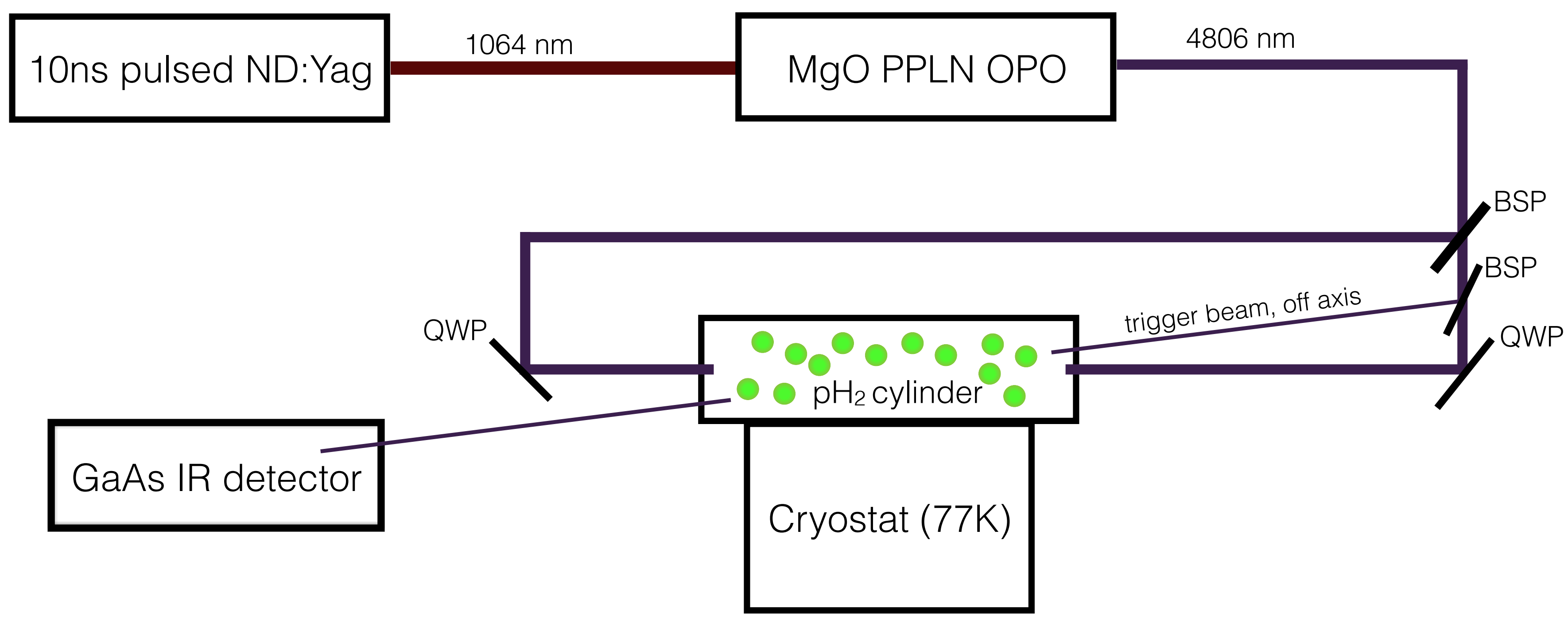
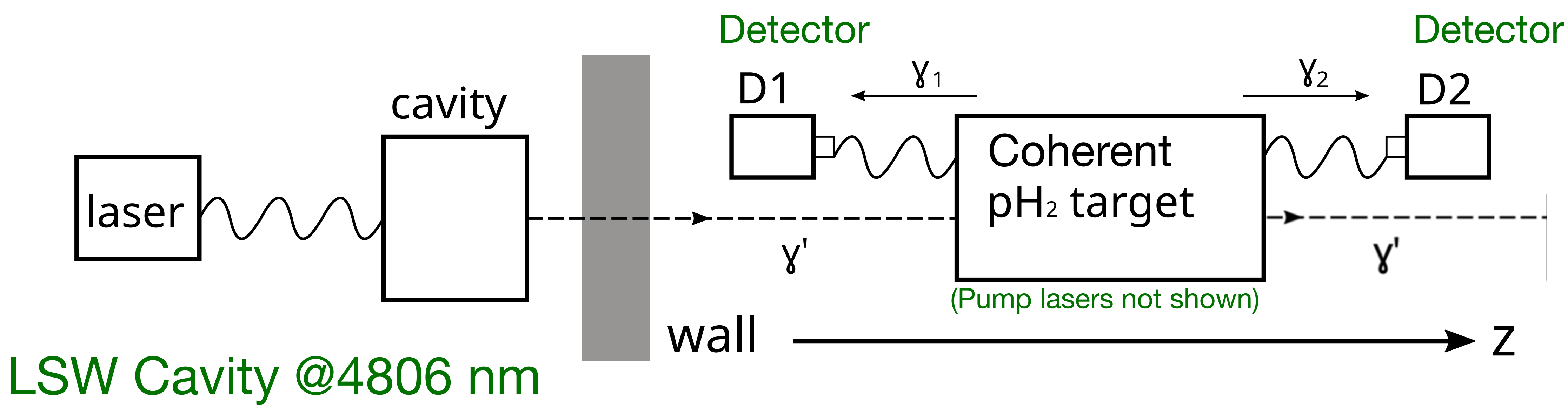
Macro Coherence at Queen's University





One technical challenge is generating enough 10 ns laser pulse power —looking into new methods for simplifying 1064 -> 4806 nm conversion.

Modified search for dark photons:
Use a macro-coherent sample of parahydrogen as a target for a light-shining-through-wall laser.

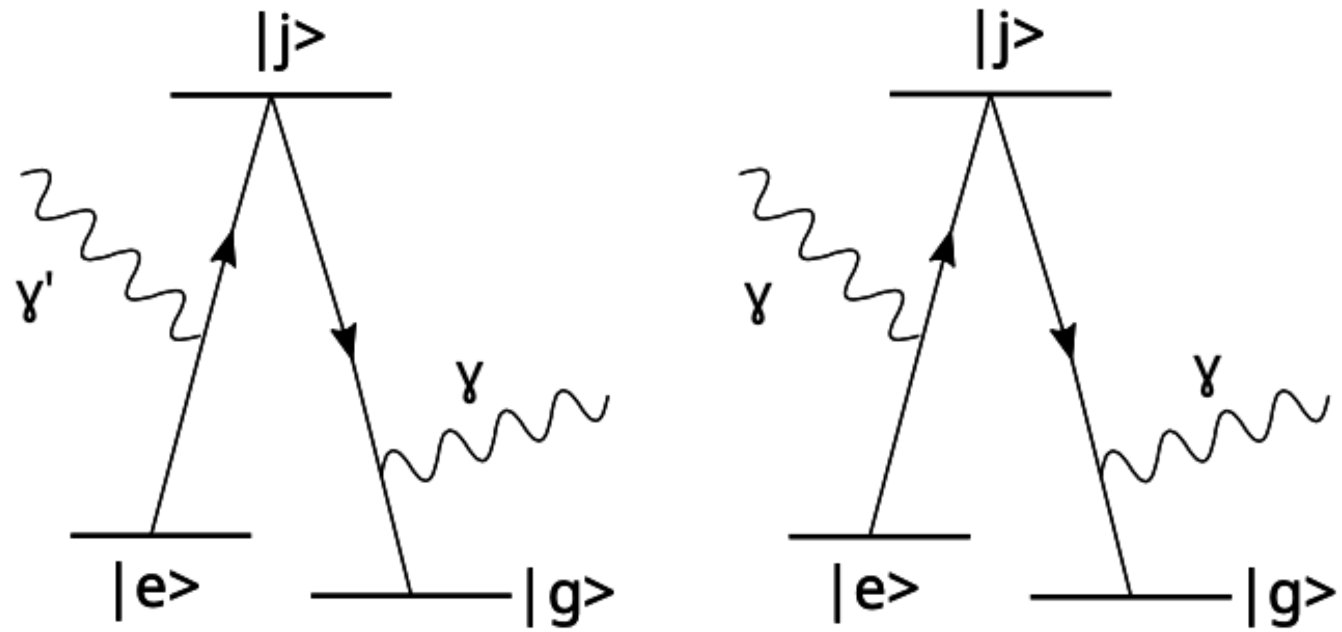


1. Excite hydrogen to coherent state with back-to-back lasers.
2. Run cavity-amplified light-through-wall laser at same frequency.
3. Look for deexcitation of pH_2 during 10 ns coherence window.
4. Calibrate coherence / response of pH_2 with cavity laser off.

The transitions for multi-photon emission, in the Standard Model and with a dark photon.

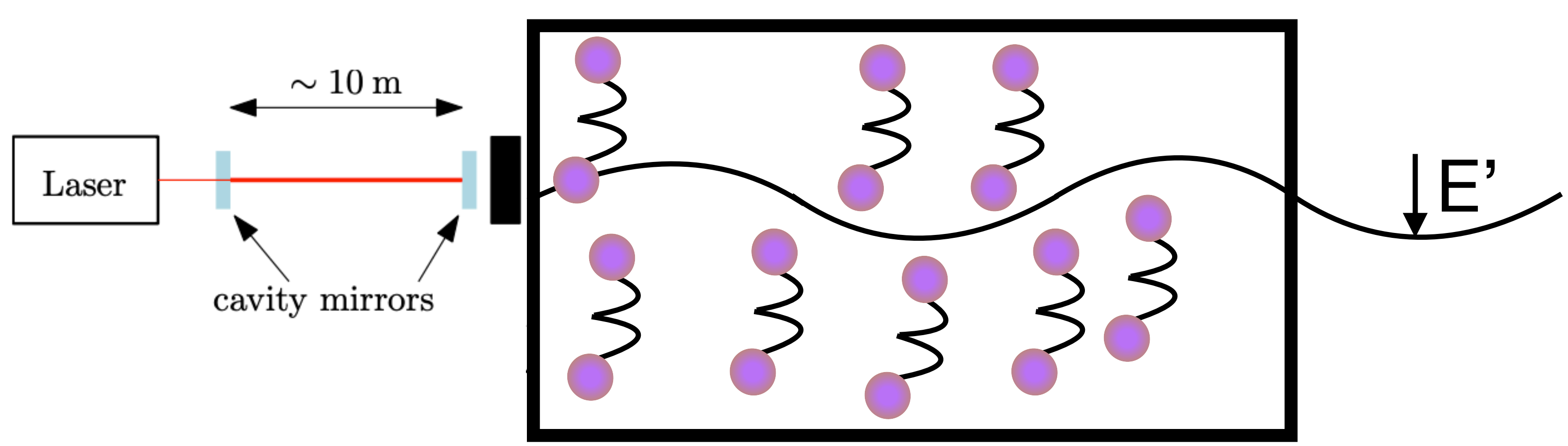
$$H_I = -\mathbf{d} \cdot (\tilde{E}_1 + \tilde{E}_2 + \chi \tilde{E}')$$

electric dipole
term from E'

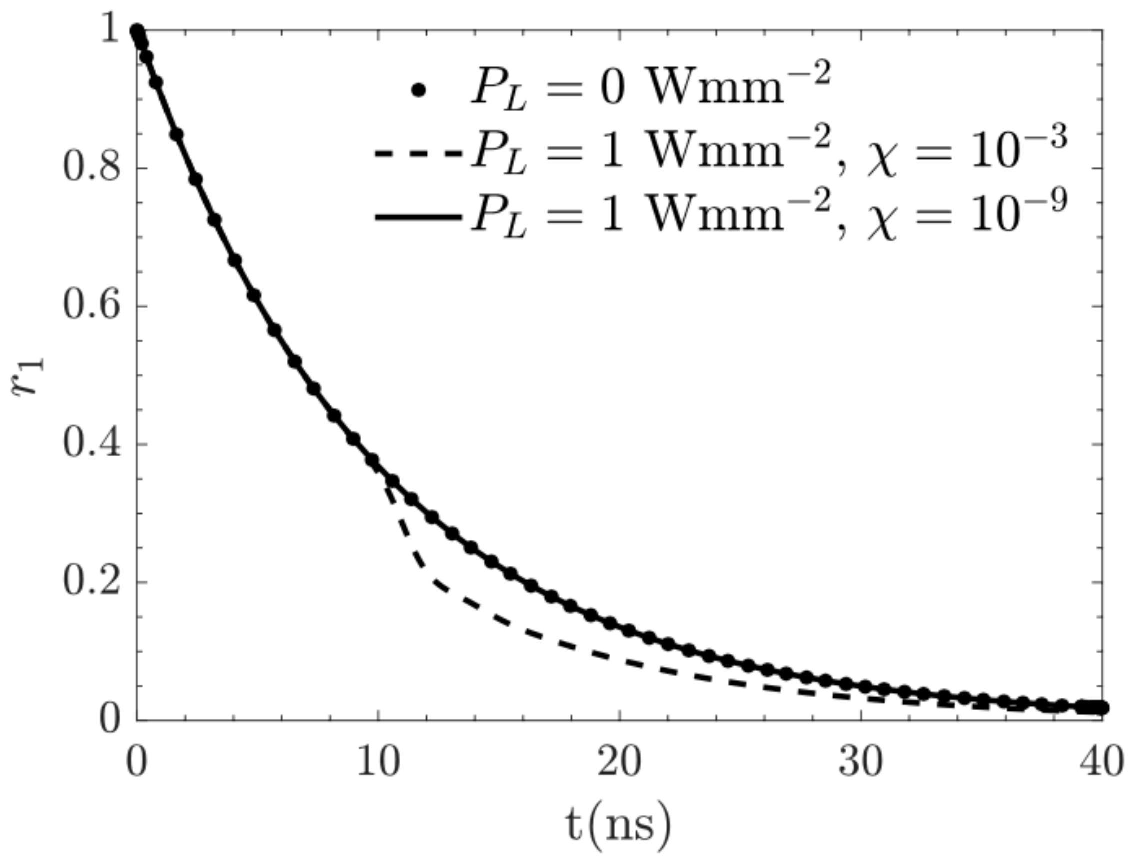


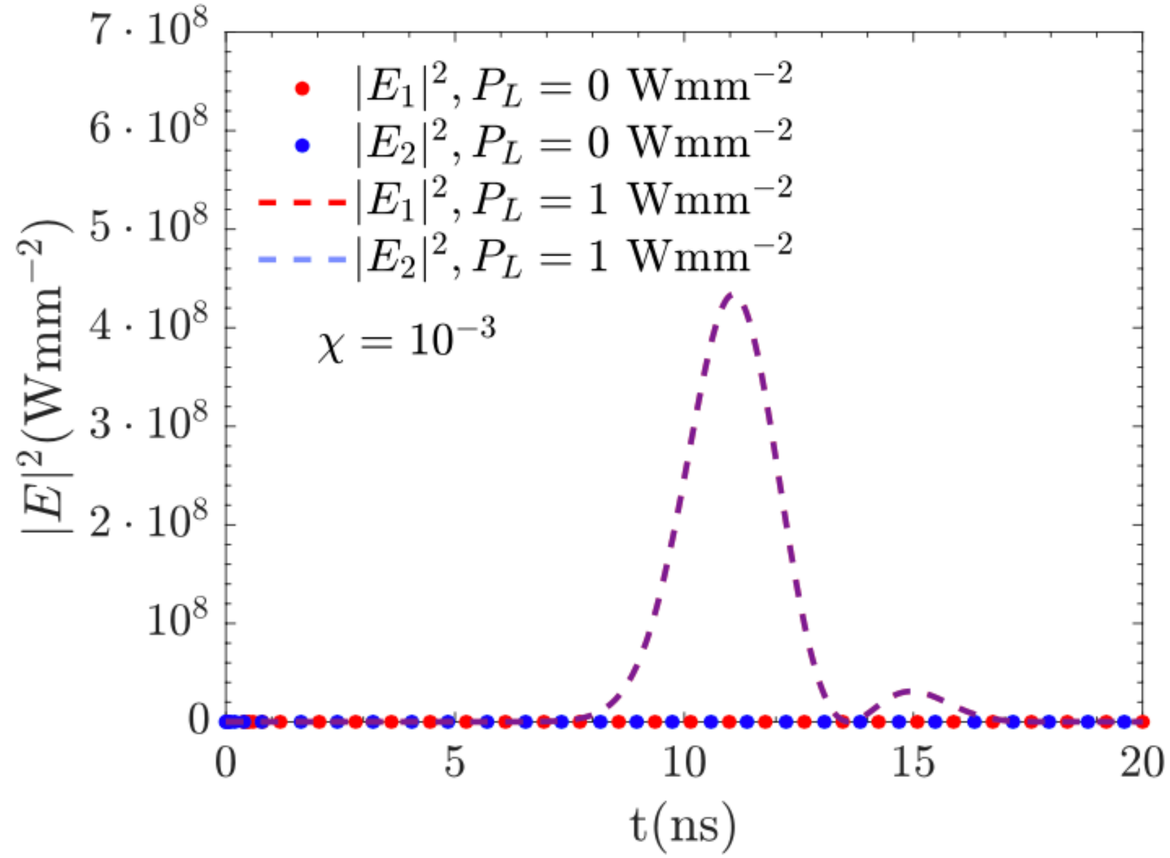
(a) $|e\rangle \to |g\rangle + \gamma' + \gamma$ (b) $|e\rangle \to |g\rangle + \gamma + \gamma$

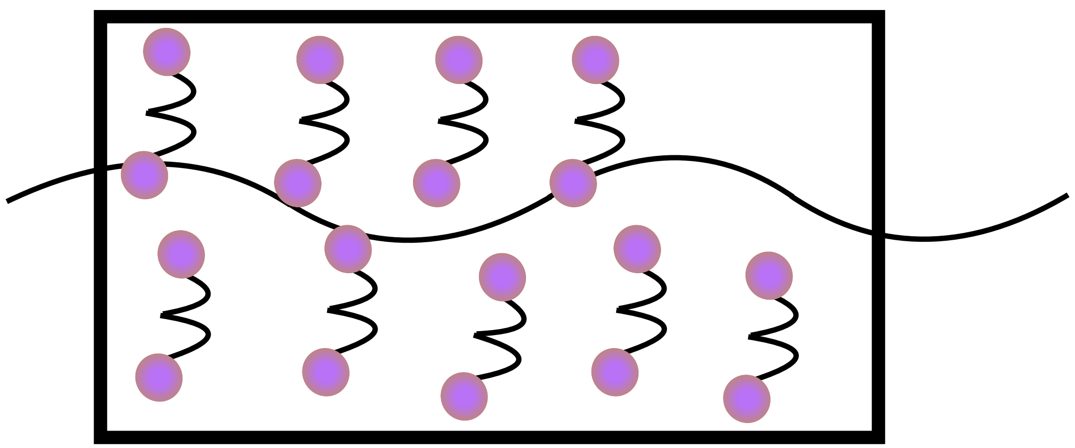
The gain over traditional light-shining-through-wall regeneration cavity is that the dark photon field acts as a trigger laser for two photon emission.



$$\Gamma = \frac{1}{8\pi} |a_{eg}|^2 |\rho_{ge}|^2 N^2 \omega_1^3 \boxed{|E'|^2}$$







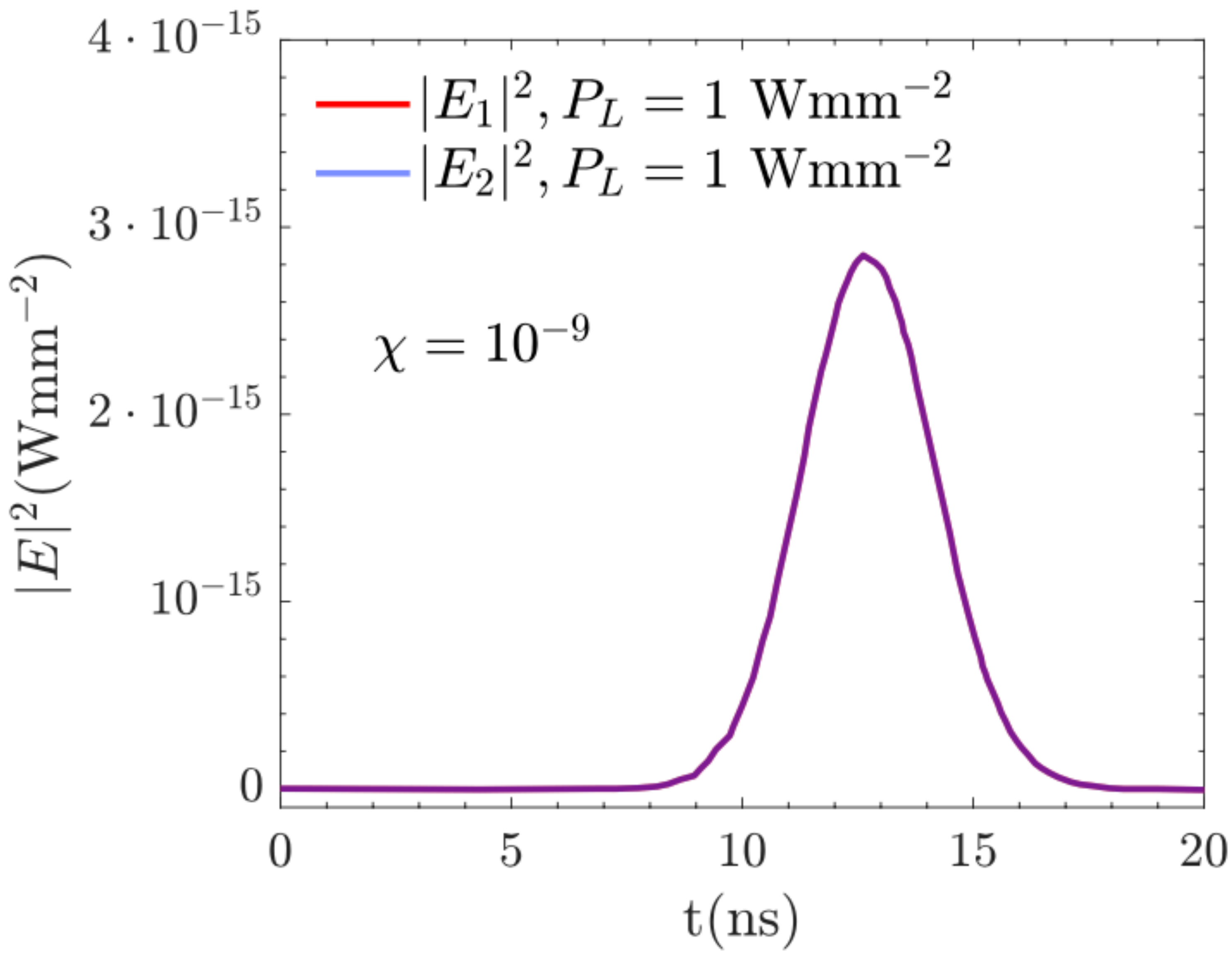
E’, E_1 , E_2

Maxwell’s equations with the E1xE1 transition Hamiltonian are integrated over the experimental volume to determine the power emitted in photons from the sample, start from $r_1 = 1$.

$$(\partial_t - \partial_z)E_1 = \frac{i\omega n}{2}\left[\left(\frac{a_{ee}+a_{gg}}{2} + \frac{a_{ee}-a_{gg}}{2}r_3\right)E_1 + a_{eg}(r_1 - ir_2)(E_2^* + \chi\eta E'^*)\right],$$

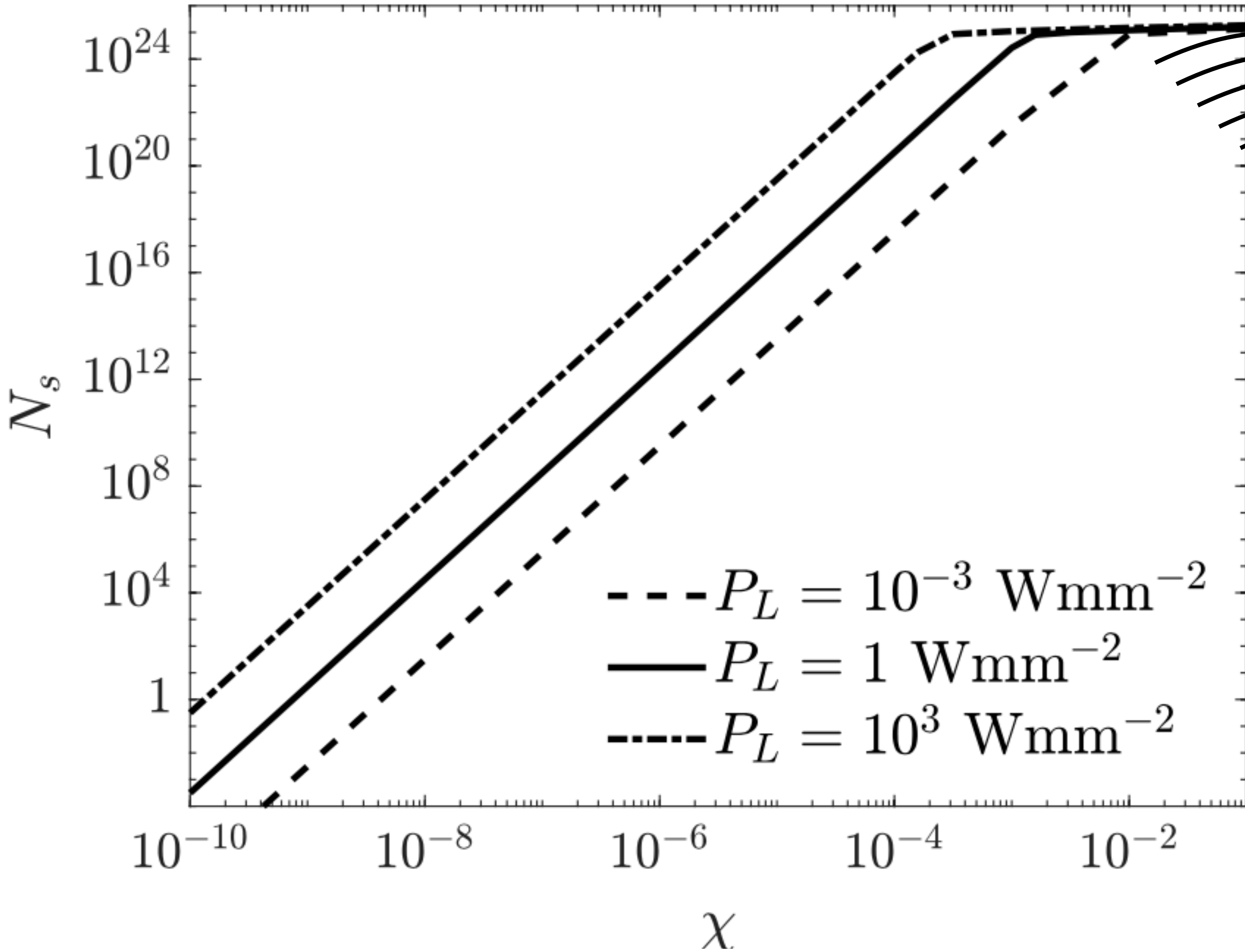
$$(\partial_t + \partial_z)E_2 = \frac{i\omega n}{2}\left[\left(\frac{a_{ee}+a_{gg}}{2} + \frac{a_{ee}-a_{gg}}{2}r_3\right)(E_2 + \chi\eta E') + a_{eg}(r_1 - ir_2)E_1^*\right],$$

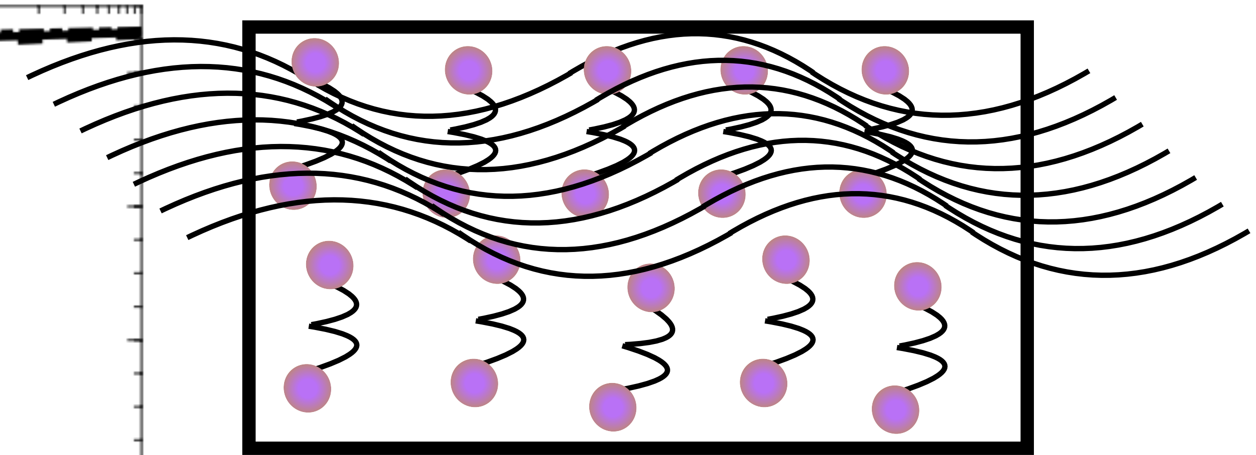
$$(\partial_t + \partial_z)E' = \frac{i\omega n}{2}\left[\left(\frac{a_{ee}+a_{gg}}{2} + \frac{a_{ee}-a_{gg}}{2}r_3\right)(2\chi^2\eta E' + \chi E_2) + a_{eg}(r_1 - ir_2)\chi\eta E_1^*)\right]$$



Using a cavity laser comparable to ALPS I, and a pH_2 macro coherence setup similar to a lower power test run [Hiraki et al. 2018], ~10 signal photons for $N_{rep} = 1000$, $m_{A'} = 0.1$ meV, $\chi = 10^{-9}$.

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





$$N_s \propto P_L N_{\rm rep} \chi^4 (N_{\rm pass} + 1) \sin^2\left(\frac{m_{A'}^2}{4\omega} l\right)$$

Signal photons scale the mixing parameter (until every atom is de-excited.)

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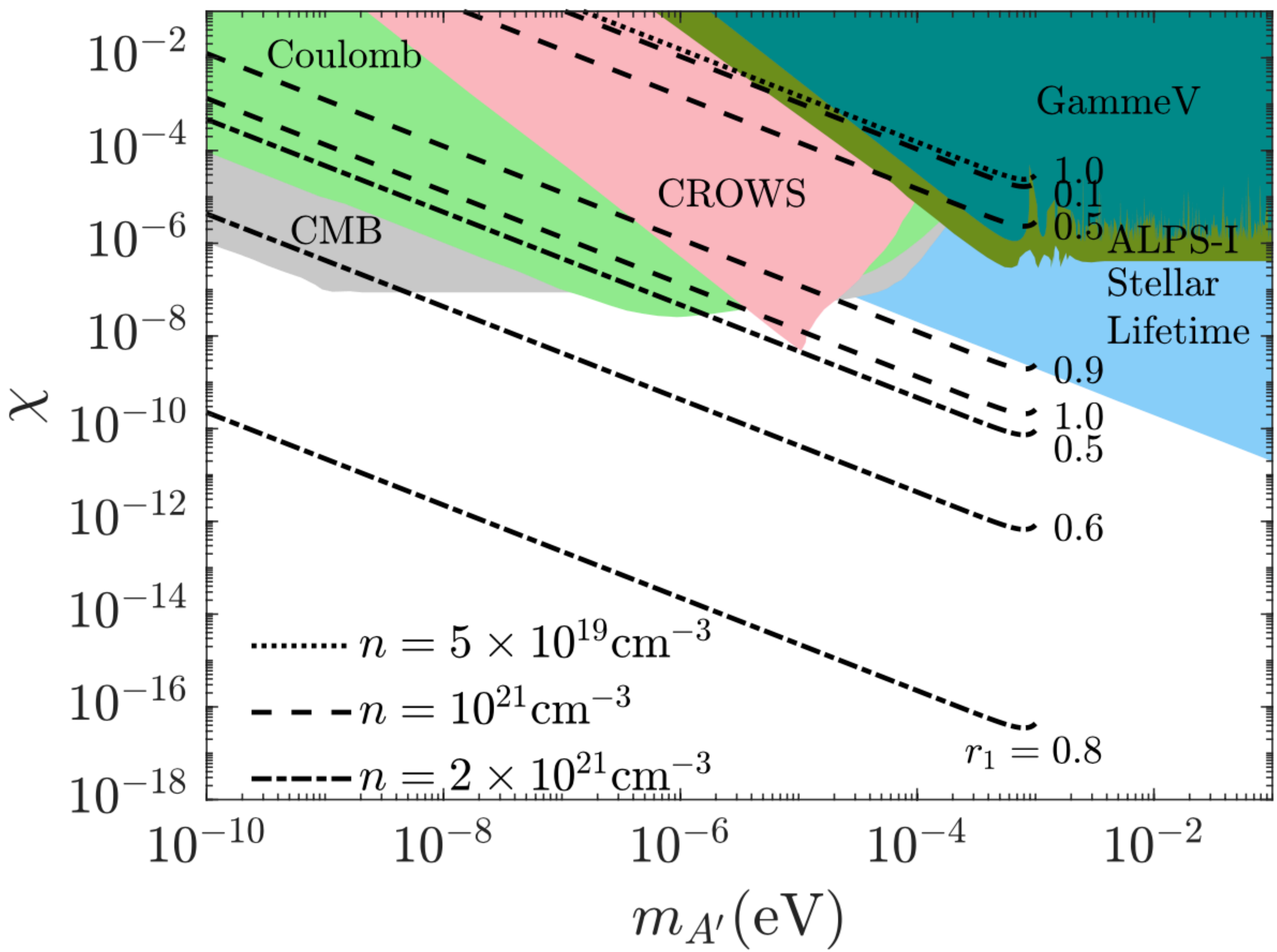
There is improved reach as the number density of pH_2 increases.



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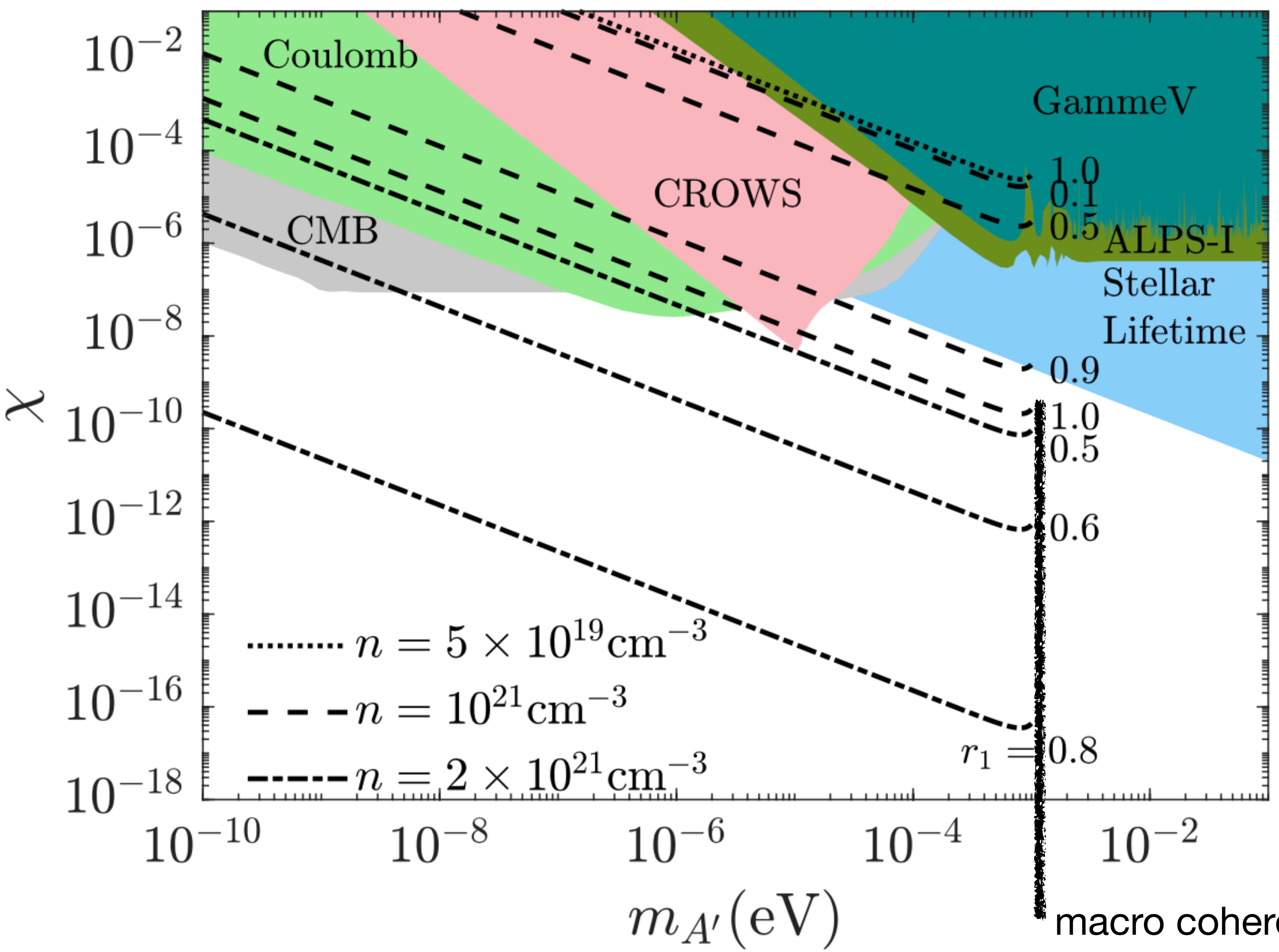
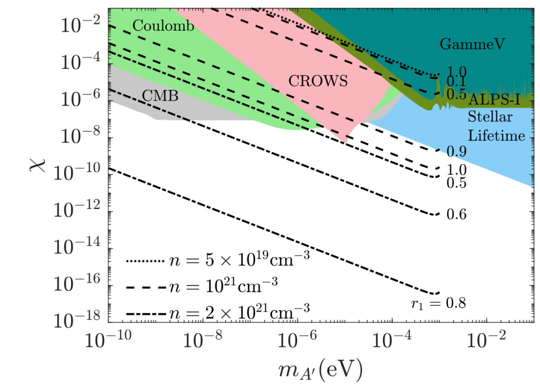


macro coherence condition

$$(\omega_{eg}/2 - k_{A'})L < 1$$

The extremely nonlinear sensitivity scaling with n (also L, t) can be understood quantitatively



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condense field equations, drop z, r_2, fix r_1 ⟶

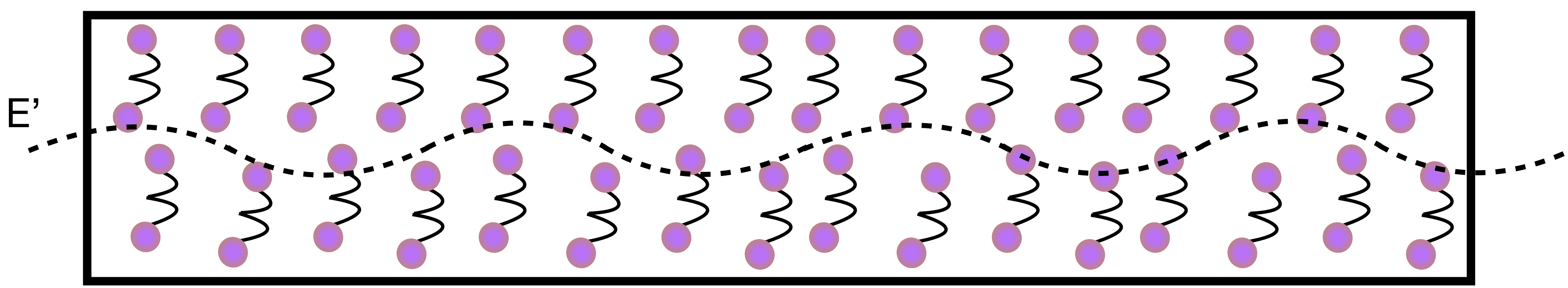
$$(\partial_t^2 - \partial_z^2)E_1 - n^2\Omega_r^2 E_1 = 0$$

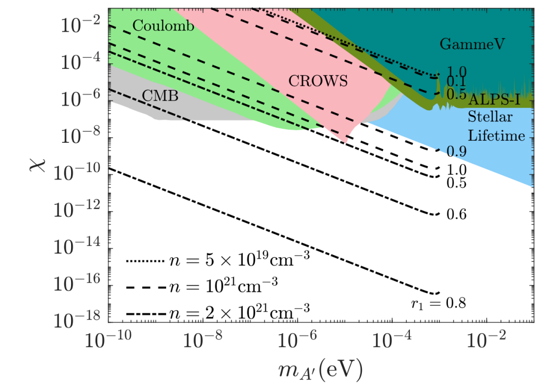
$$E_1 \propto e^{n\Omega_r t}$$

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

->Exponential dependence on n, t, r_1

and qualitatively





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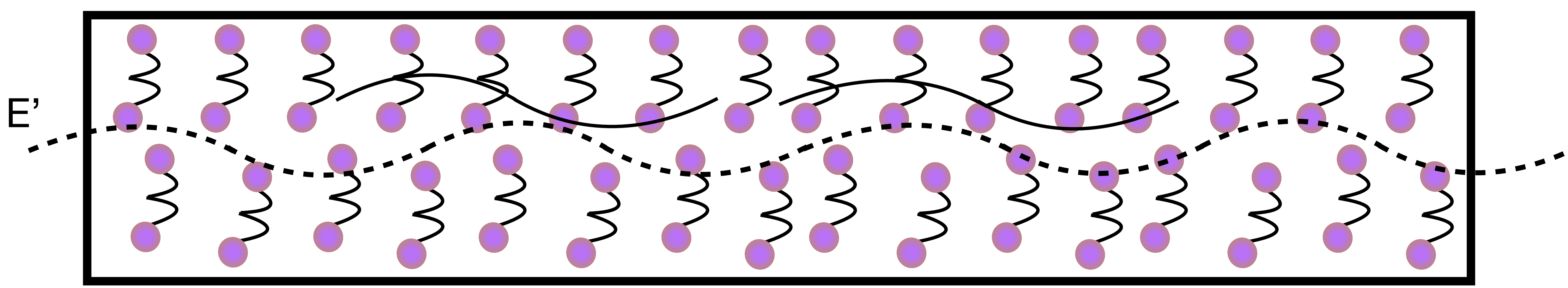

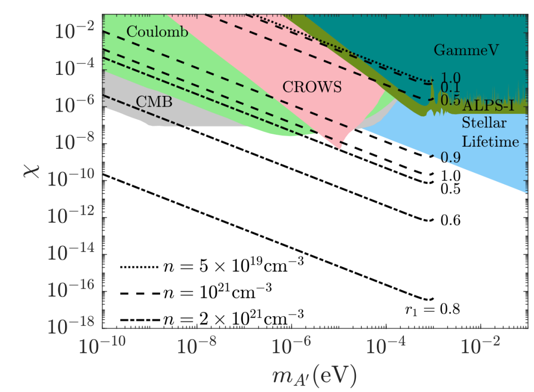

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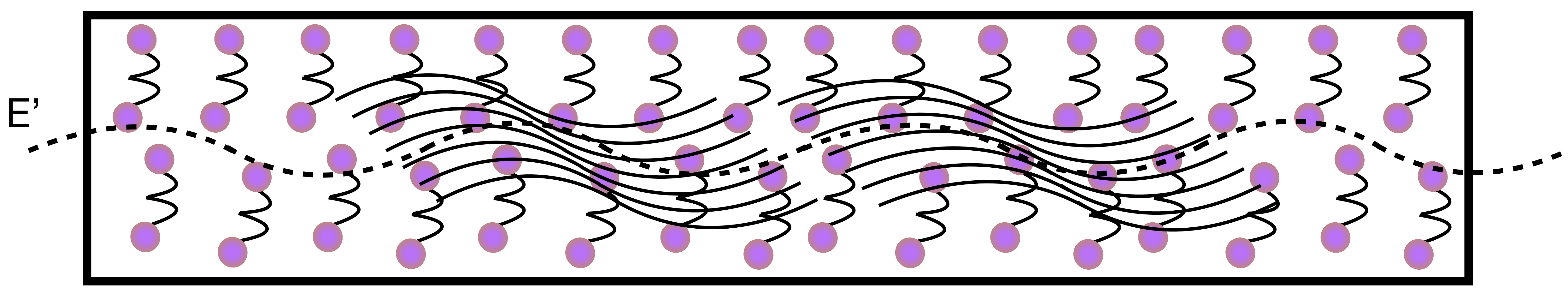
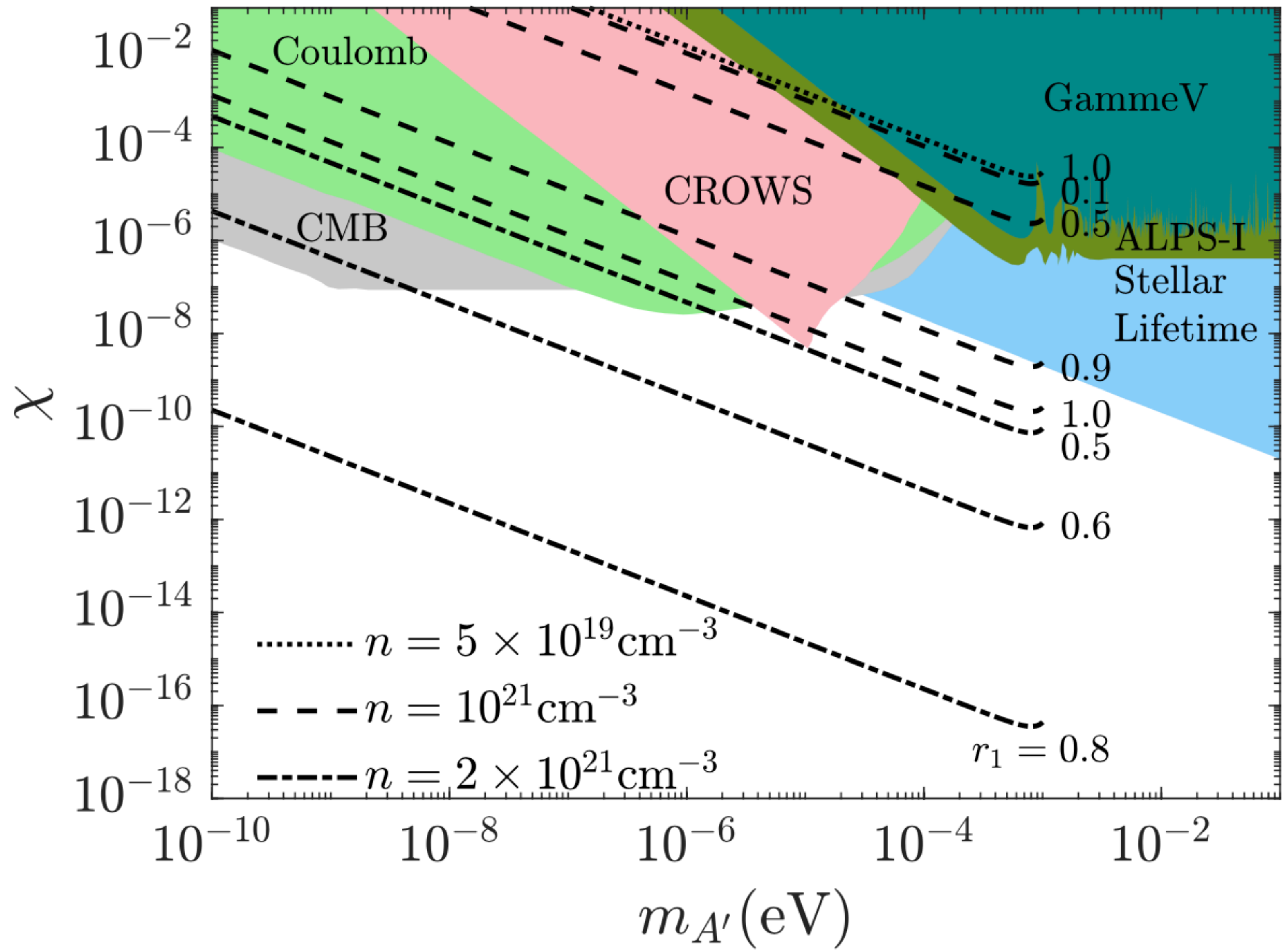
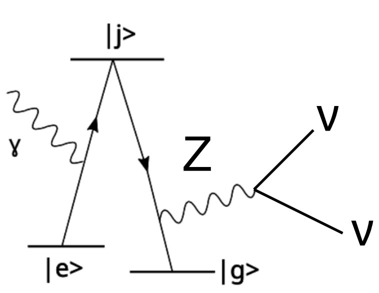




-Macro superradiance in parahydrogen can be used to look for weakly coupled fields

-Need to develop $r_1 \sim 1$ in a pH_2 sample, recent progress towards this goal

(maybe eventually find neutrino masses and detect cosmic neutrinos



Yoshimura et al. 2007-)