N^2 Enhanced Quantum Detection and the CATCHY experiment

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CETUP, June 29, 2026

Queen's University

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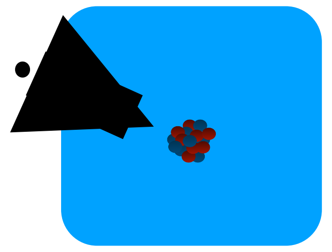
N^2 detection and CATCHY

Motivation and comparison with traditional detectors



CATCHY: Bhardwaj, Buchanan JB, Fraser, Godfrey, Kulkarni, Song





Light boson searches using coherent atoms

Bhoonah, JB, Song 1909.07387

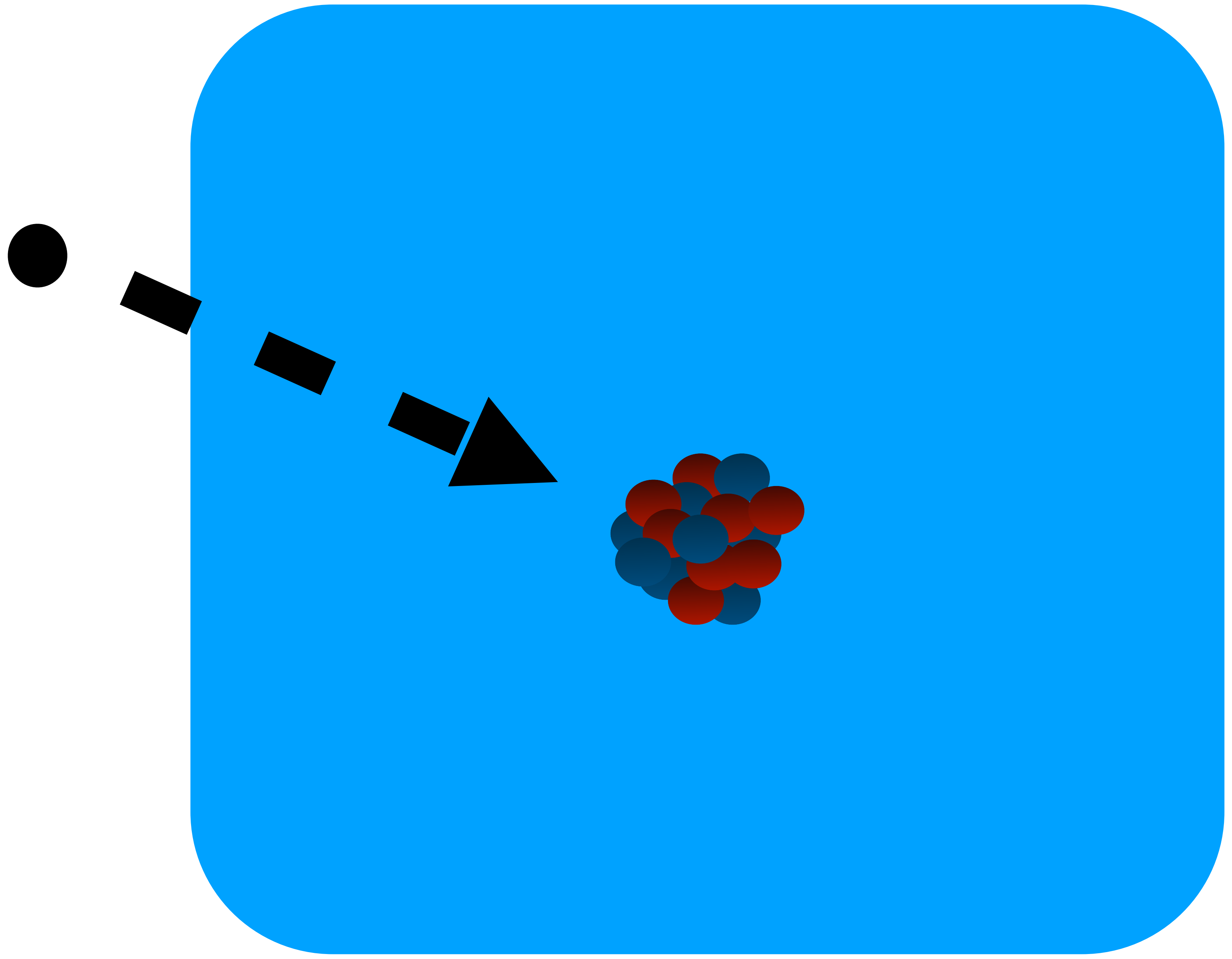
JB, Kulkarni, Song 260x.xxxxx

Godfrey PhD: https://www.proquest.com/docview/3161889593

Detection, volume frontier

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

$$\Gamma \approx n_x v_x A^4 \sigma_{nx}$$



$$N = \#\text{Argon, Xenon}$$

$$A = 40{,}130$$

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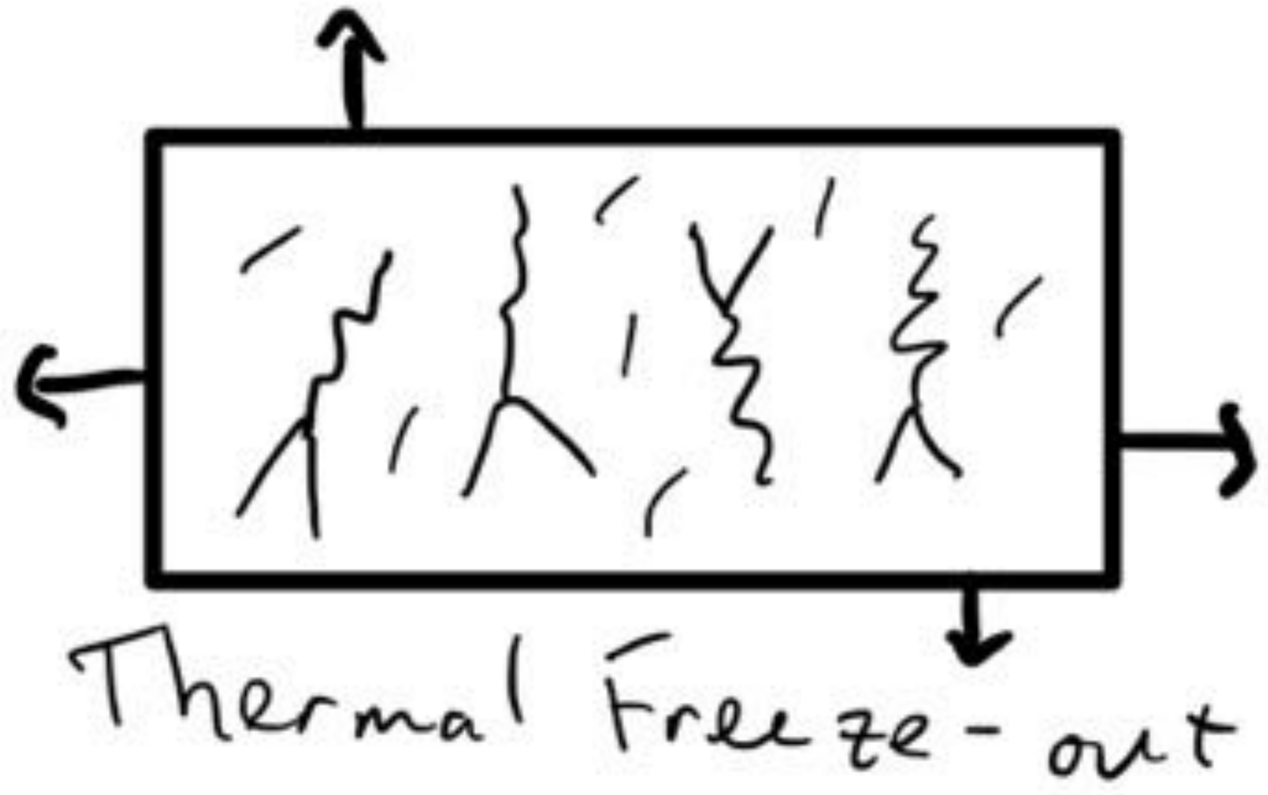
High mass dark matter - WIMPs

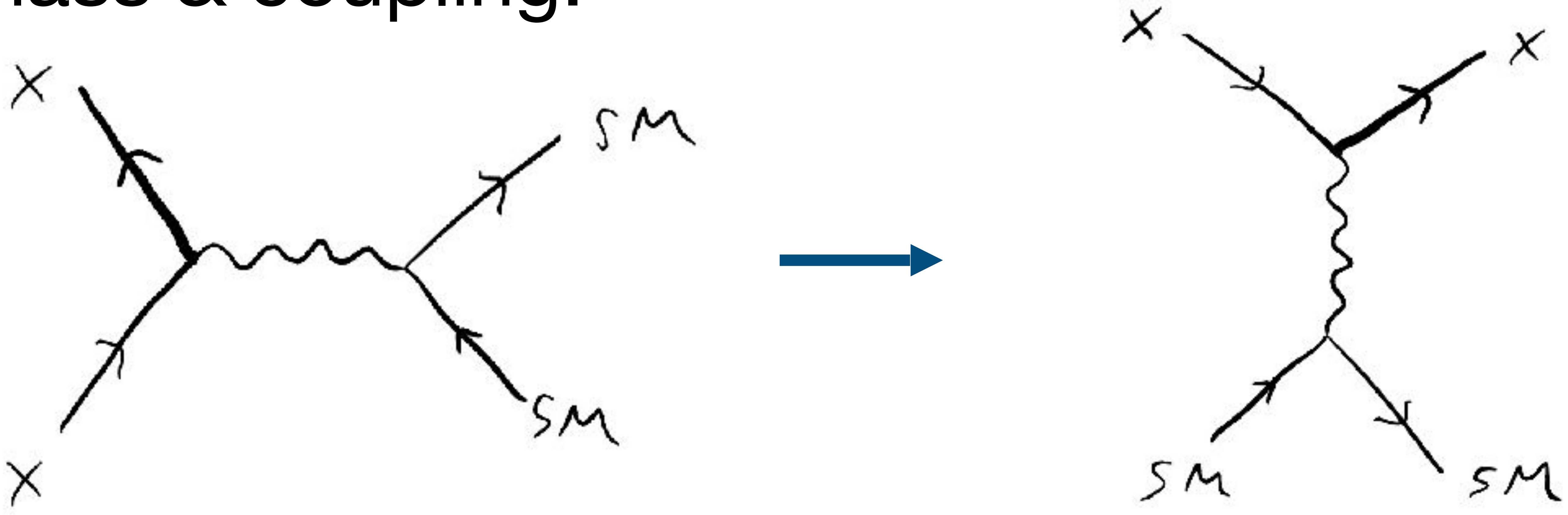


Universe cools, dark matter falls out of thermal equilibrium, large portion annihilates to SM particles

$$\frac{m_x n_x}{n_\gamma} \sim \frac{x_f}{m_{pl}\langle\sigma_a v\rangle} \qquad x_f \sim \log[m_x^3 \langle \sigma_a v \rangle / H]$$

Observed DM abundance for annihilation cross-section matching weak scale mass & coupling.

$$\Omega_x h^2 \sim 0.1 \left(\frac{m_{\rm v}}{100 \text{ GeV}}\right)^2 \left(\frac{0.03}{\alpha_w}\right)^2$$



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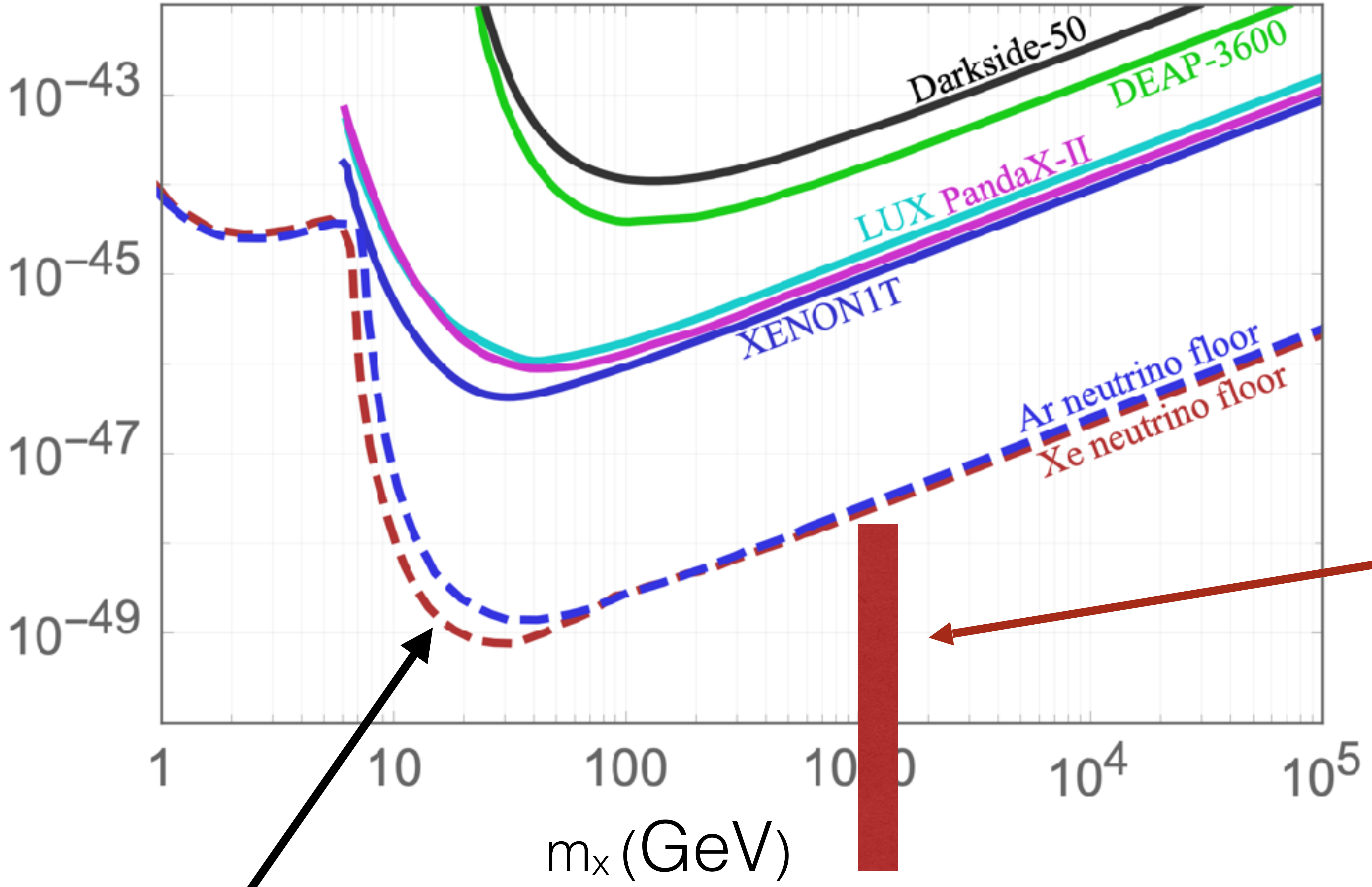
Underground dark matter detection, WIMP searches

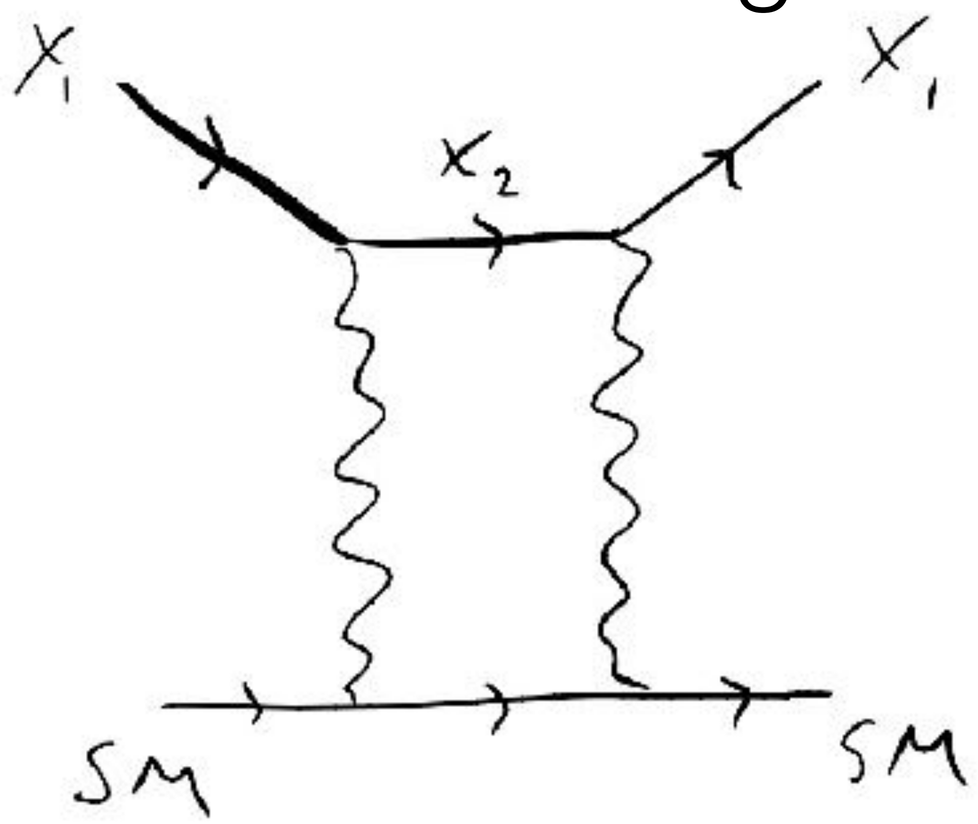
$$\sigma_n \approx \frac{\alpha_W^2 \mu_{nX}^2}{M_Z^4}$$

σ_n (cm²) → **10^{-39} cm²**



Interaction forbidden at v ~ 0.001c by $X_1 \leftrightarrow X_2$ mass gap → $\delta \sim \mathrm{GeV}\left(\frac{\mathrm{TeV}}{M_1}\right)$

Loop suppressed scattering



Neutrino floor/fog

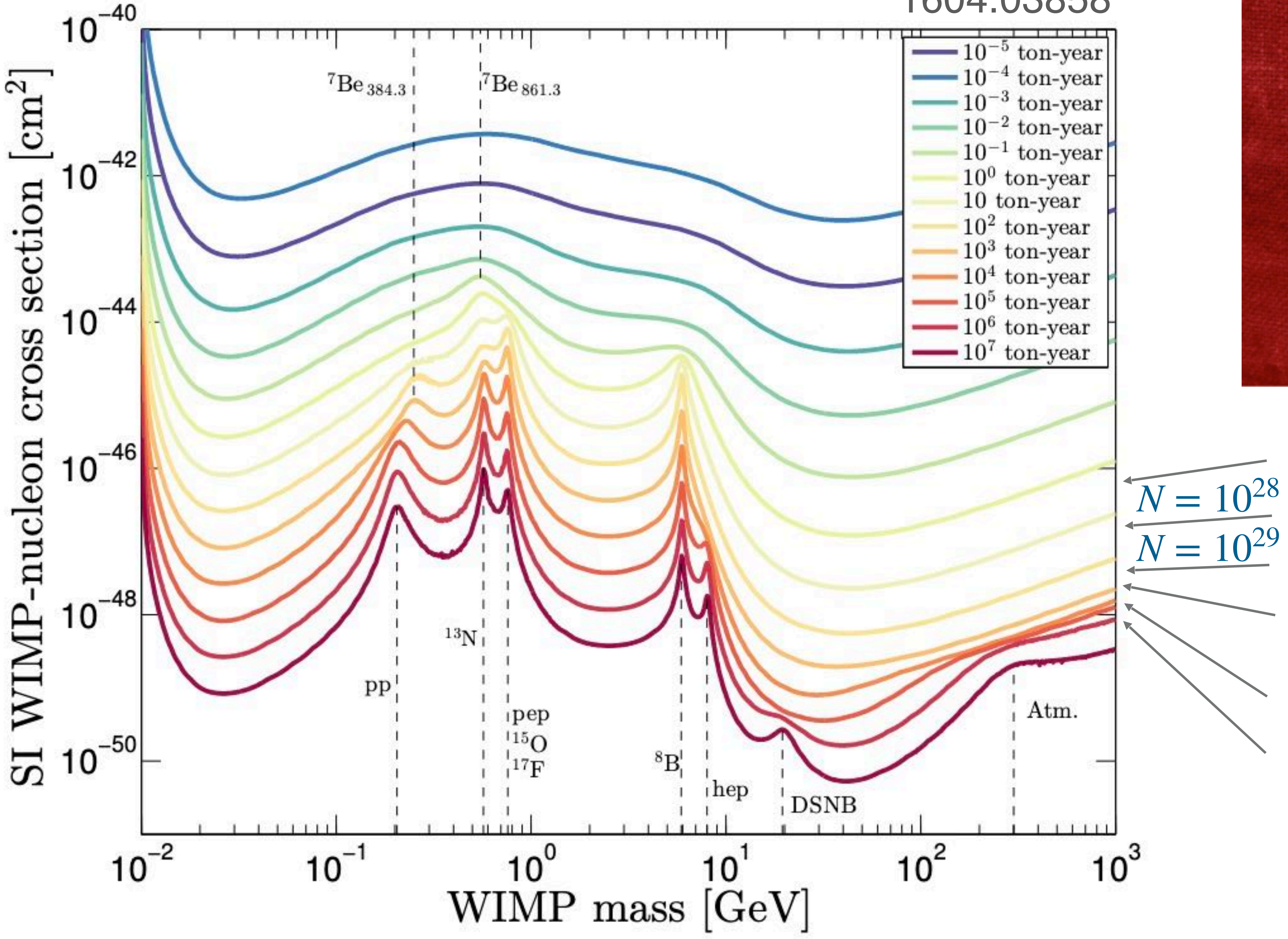
1307.5458, Billard, Strigari, Figueroa-Feliciano

Higgsino Dark Matter Loops

Hisano et. al. 2013
Hill and Solon 2013
Chen and Hill 2019

THE ELEPHANT

Ciaran O'Hare
1604.03858



THE ELEPHANT

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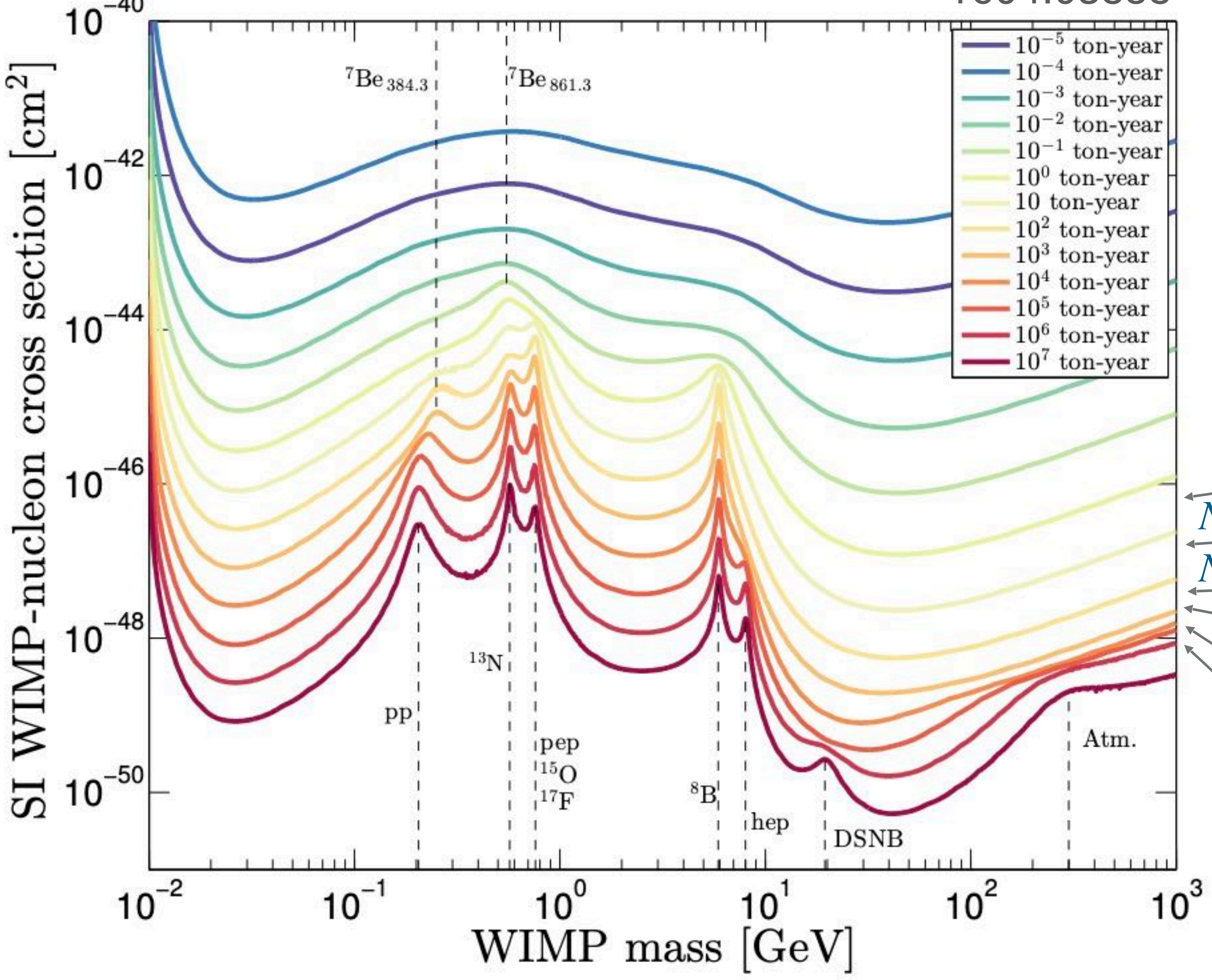

$N = 10^{28}$

$N = 10^{29}$

~$20 mil DEAP, LUX, XENON100

~$100 mil LZ, X1t, PandaX-4t, Darkside

~$0.5 bil XLZD, PandaX-nT, ARGO

~$10 bil?

~$100 bil?

~$1 tril?

Signal = $N\Gamma t$

Upper bound on fundamental science projects: 0.1% of GDP

EU: 17 t, USA: 30 t, China: 19 t, Canada 2.2 t, Australia 1.8 t

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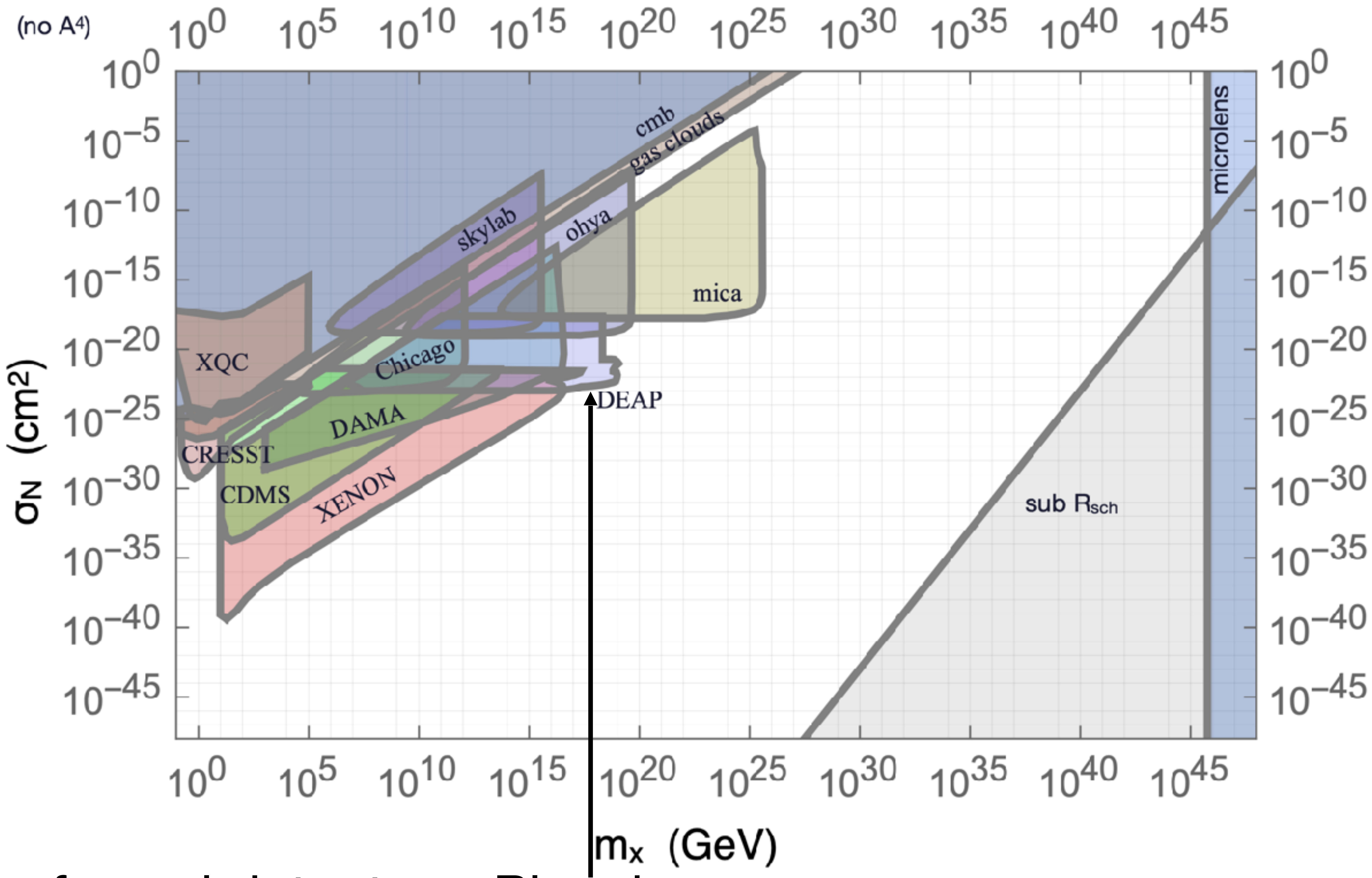
High mass dark matter searches



-Limit of usual detectors: Planck mass
(coincidence - DM flux through meter squared in a year)

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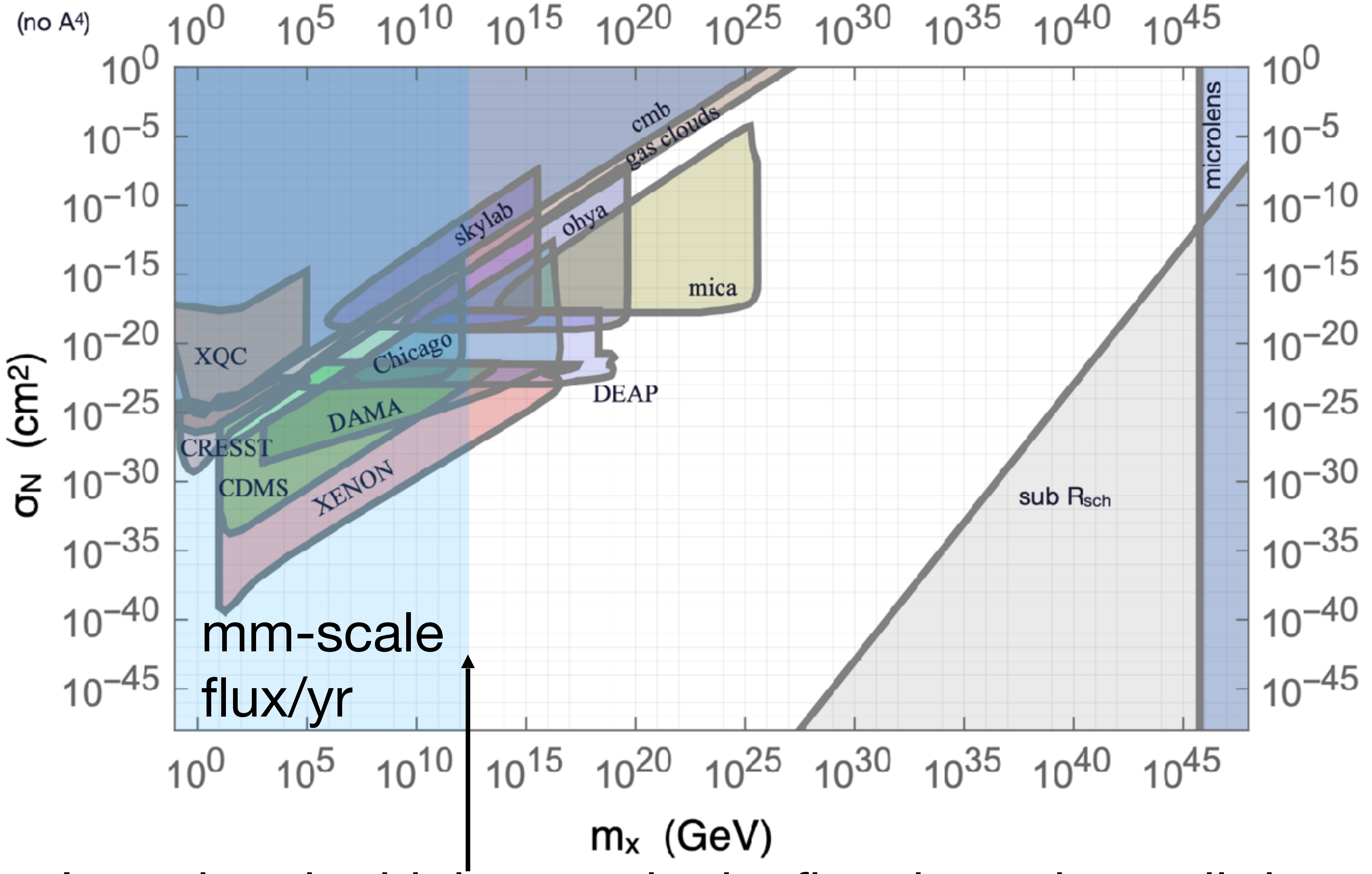
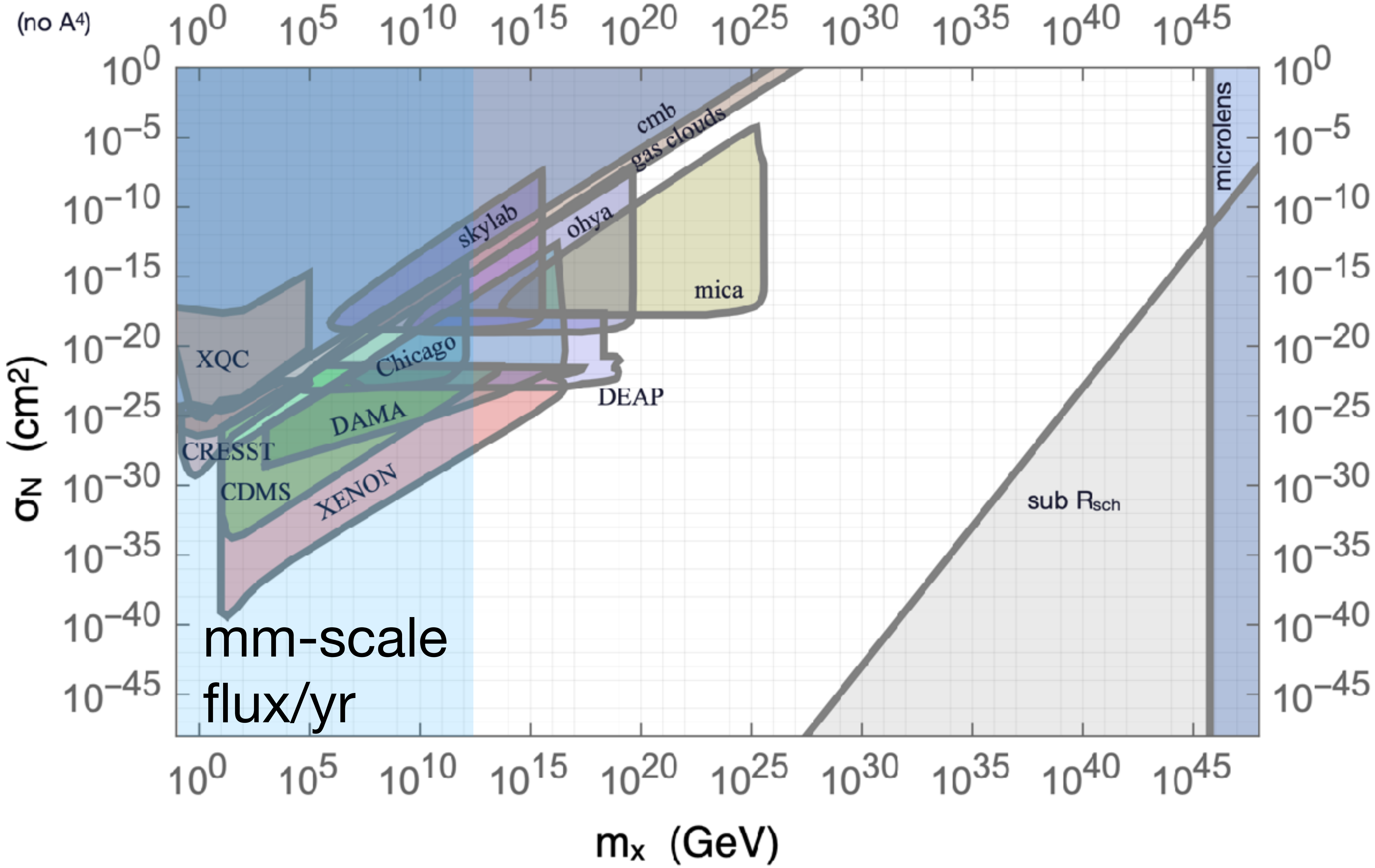
Dark matter, quantum detection

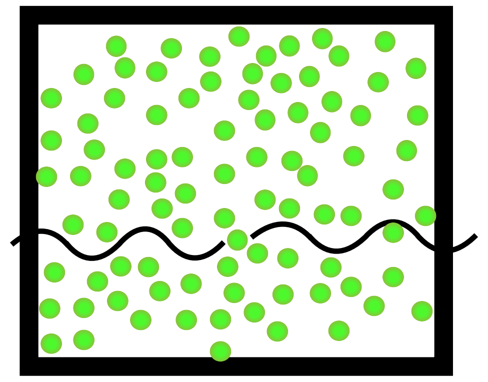


Inverting the high mass logic, flux through small detectors isn't a no-go for particle dark matter — detector response is the key

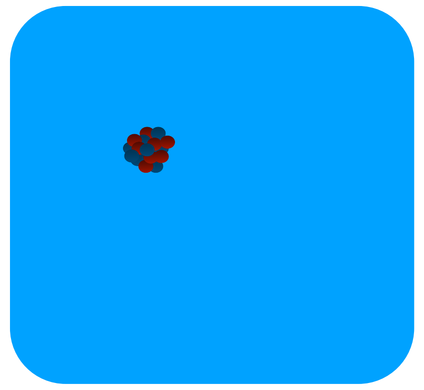
Dark matter, quantum detection



$$\text{QSignal} = N^2\Gamma t$$



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



Need N ~ 10^{18} (coherently excited H_2) to match classic NA^4 detectors.

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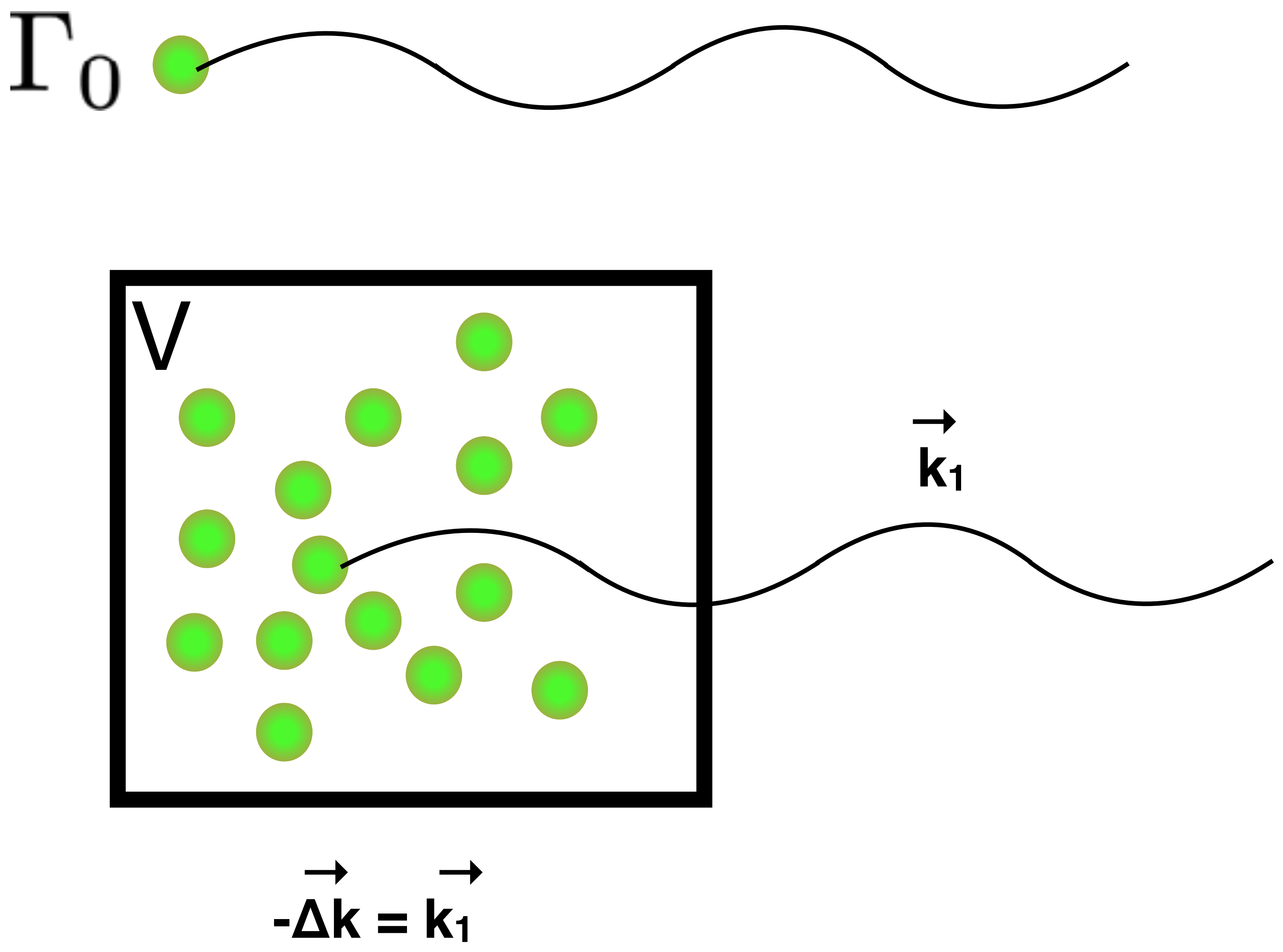
Superradiance

Dicke 1954
Gross and Haroche 1982

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



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

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

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

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

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

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

<- different: a charge distribution limited by de Broglie wavelength

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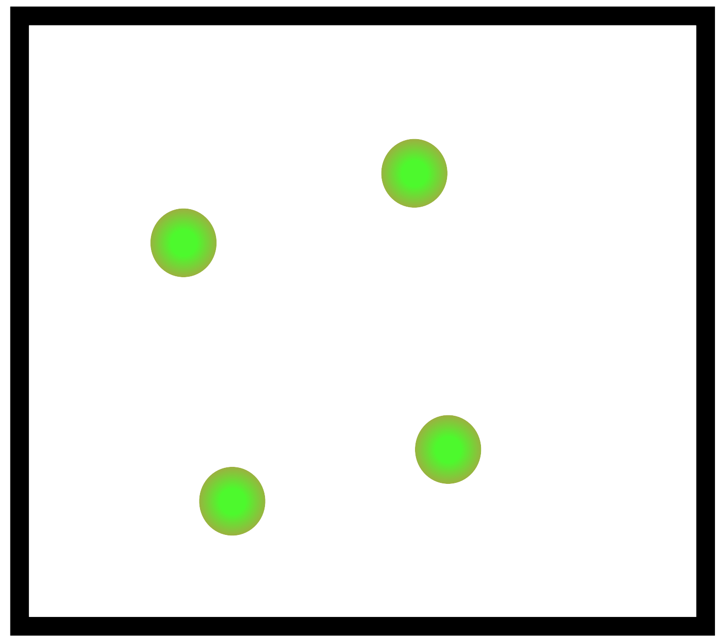
Superradiance: more detail



The dipole operator for a single atom

$$\widehat{\mathscr{D}} = (\sigma^{+} + \sigma^{-}) d \cdot \hat{\epsilon}$$

Generalized dipole operator over N atoms

$$J \equiv \sum_{i}^{N} \sigma_i^{\pm}$$

$$|J, M = J\rangle \equiv |e, e, \ldots, e\rangle$$
$$|J, M = J-1\rangle \equiv S[|g, e, \ldots, e\rangle]$$
$$|J, M = J-2\rangle \equiv S[|g, g, e, \ldots, e\rangle]$$

Calculations for N dipole emission follow ladder operator algebra (i.e. angular momentum algebra).

$$\left|J, M = 0\right\rangle \equiv S[|\underbrace{g, g, \ldots, g}_{N/2}, \underbrace{e, \ldots, e, e}_{N/2}>]$$

$$\Gamma_{dipole} \propto \left\langle J^{+} J^{-} \right\rangle = (J + M)(J - M + 1)$$

$$|J, M = -J+1\rangle \equiv S[|g, g, g, \ldots, e\rangle]$$
$$|J, M = -J\rangle \equiv |g, g, g, \ldots, g\rangle$$

This rate peaks at

$$M = 0$$
$$\Gamma_{dipole} \propto J(J+1)$$

→ 1/2 excited dipoles

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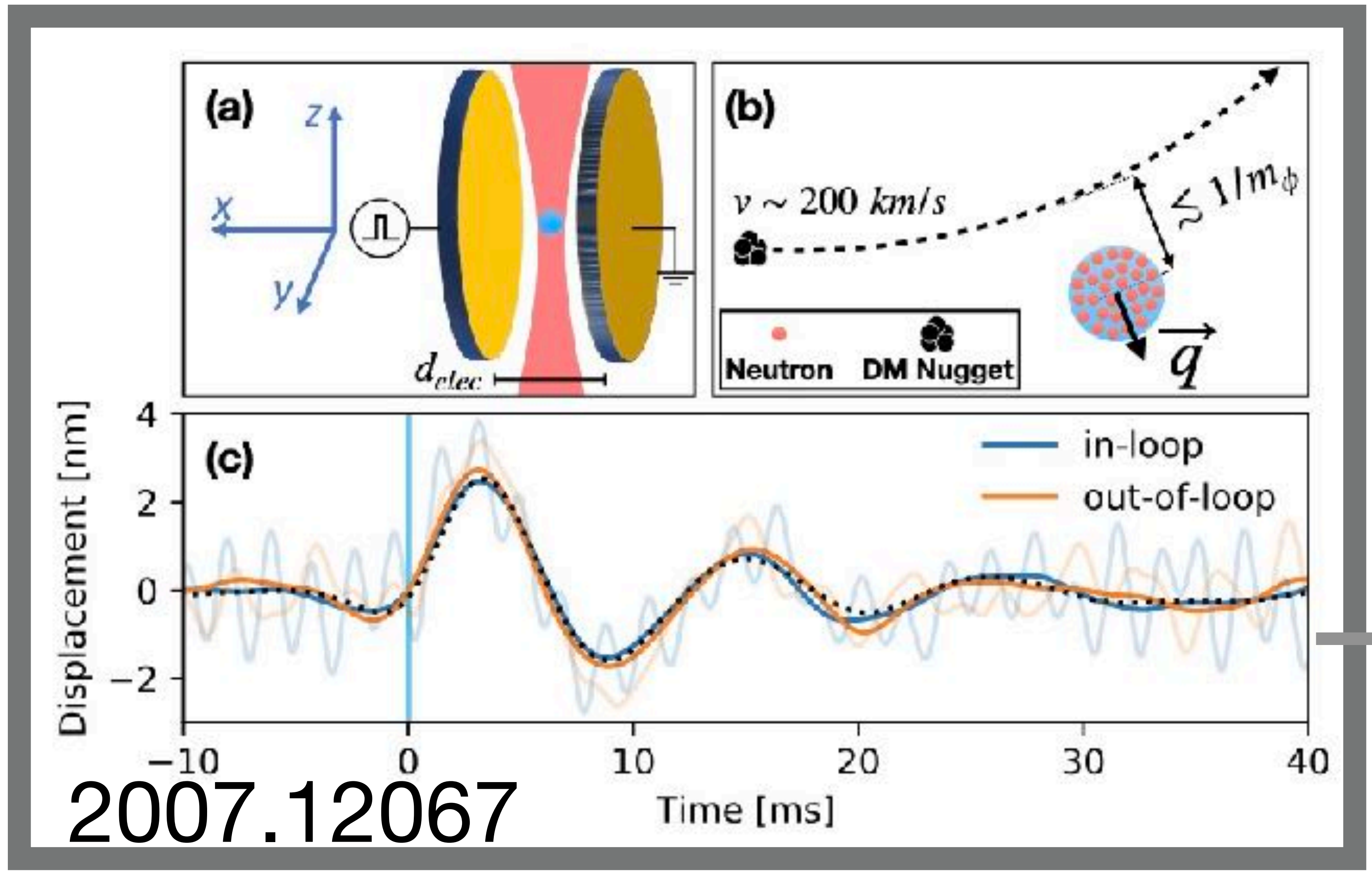
Quantum N^2 sensitive detectors

(we have to build them)



2007.12067

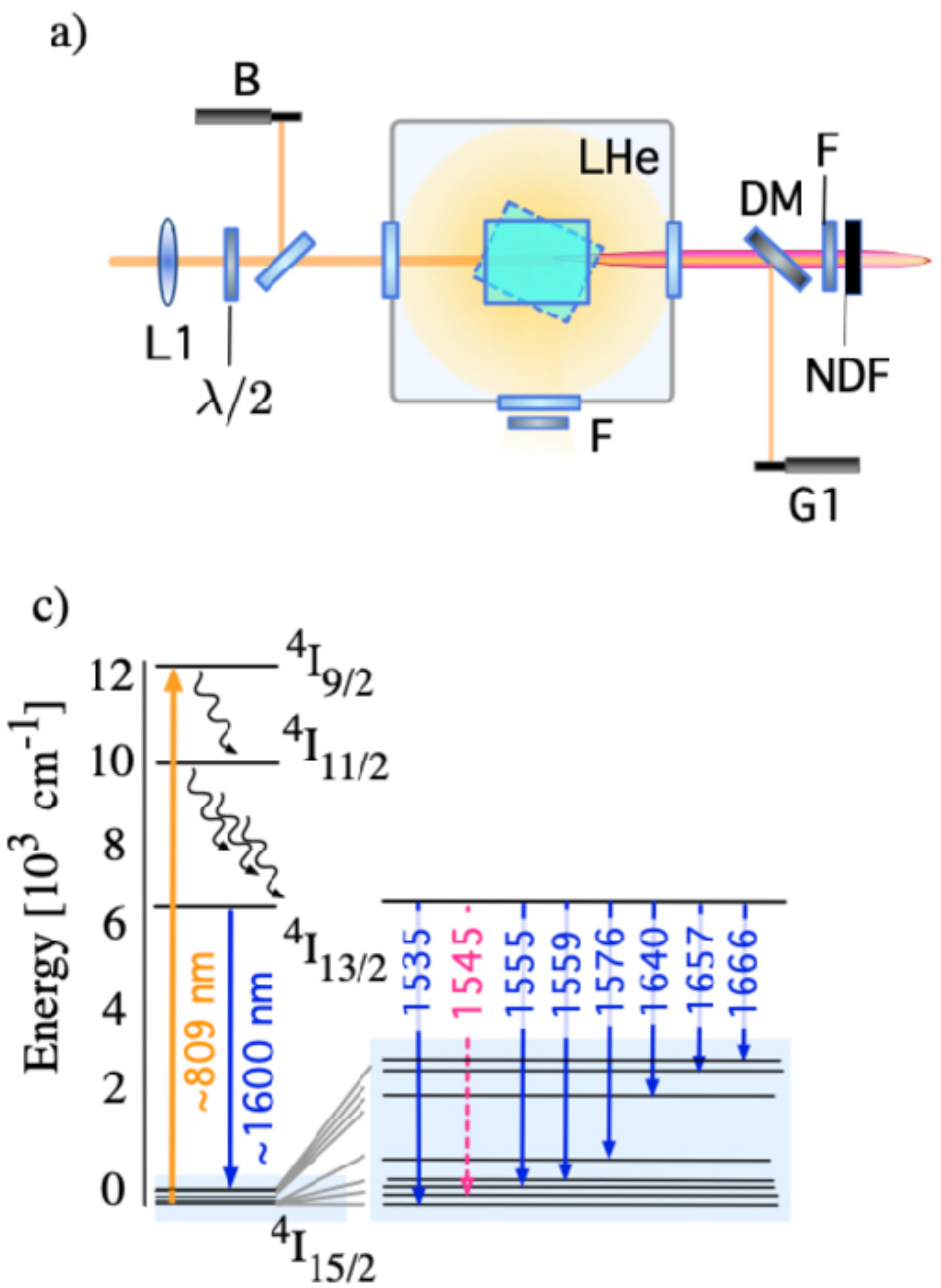
Other quantum detectors:

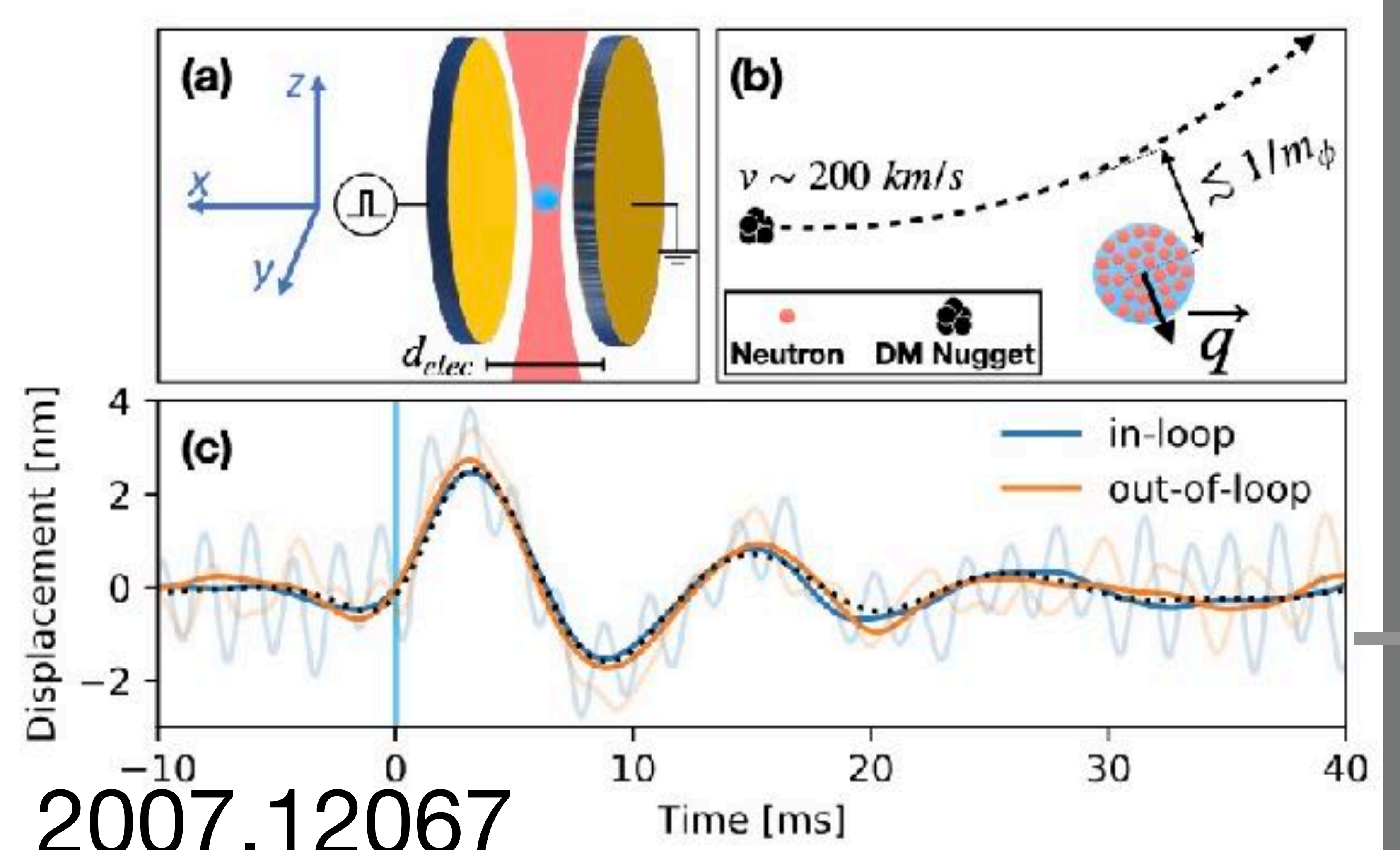
- Levitated silicon sphere Carney, Leach, Moore 2207.05883 2007.12067 (experimental bound on DM-nuclear scattering)

- WINDCHIME project 2203.07242

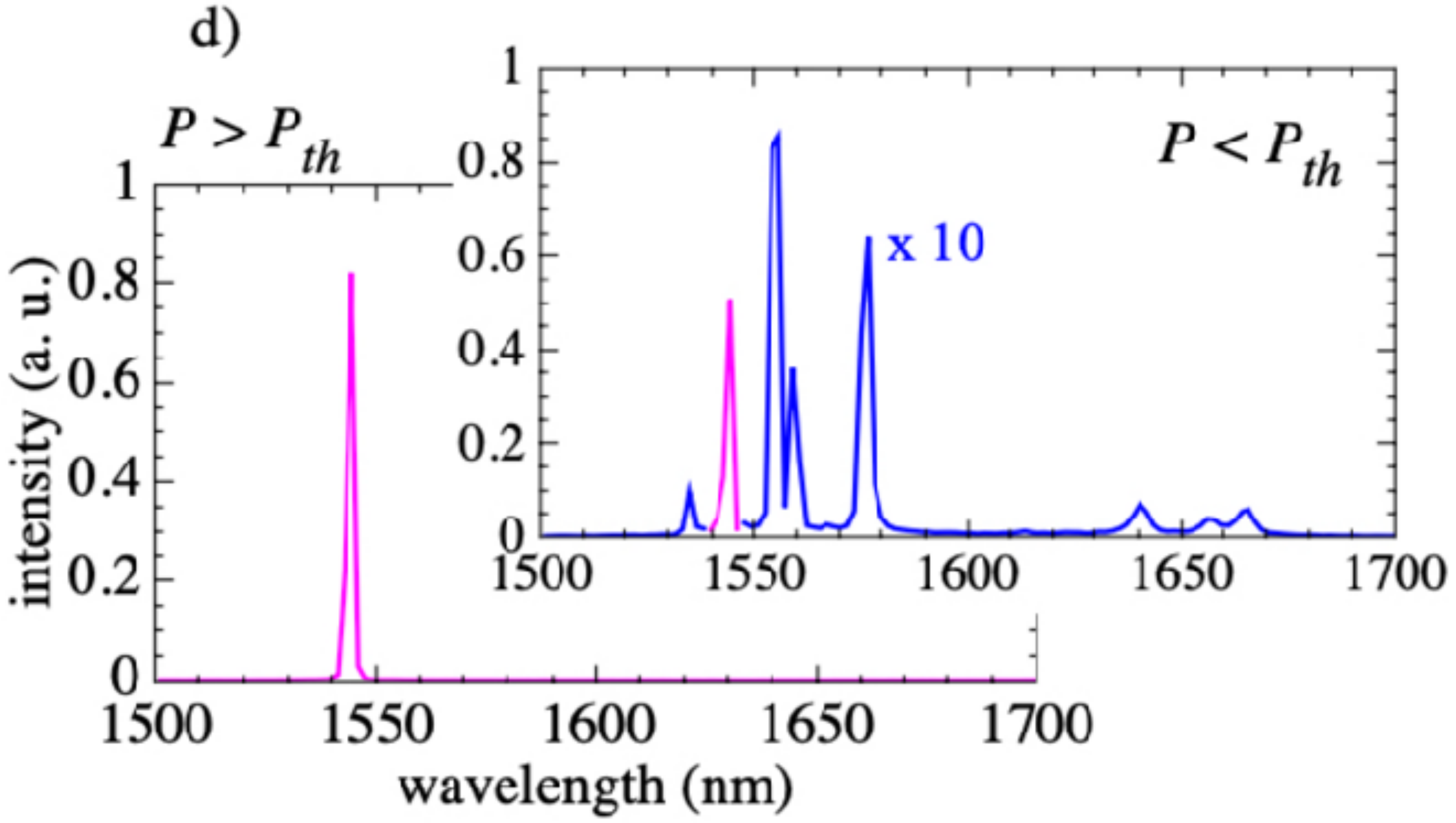
Quantum N^2 sensitive detectors

Superradiant record so far





2007.12067



Braggio et al. 1909.00999

Other quantum detectors:

- Levitated silicon sphere
  Carney, Leach, Moore
  2207.05883
  2007.12067 (experimental bound on DM-nuclear scattering)

- WINDCHIME project
  2203.07242

Current crystal-based superradiance has achieved N~10^12 erbium atoms collectively de-exciting in cryogenic erbium- doped yttrium orthosilicate

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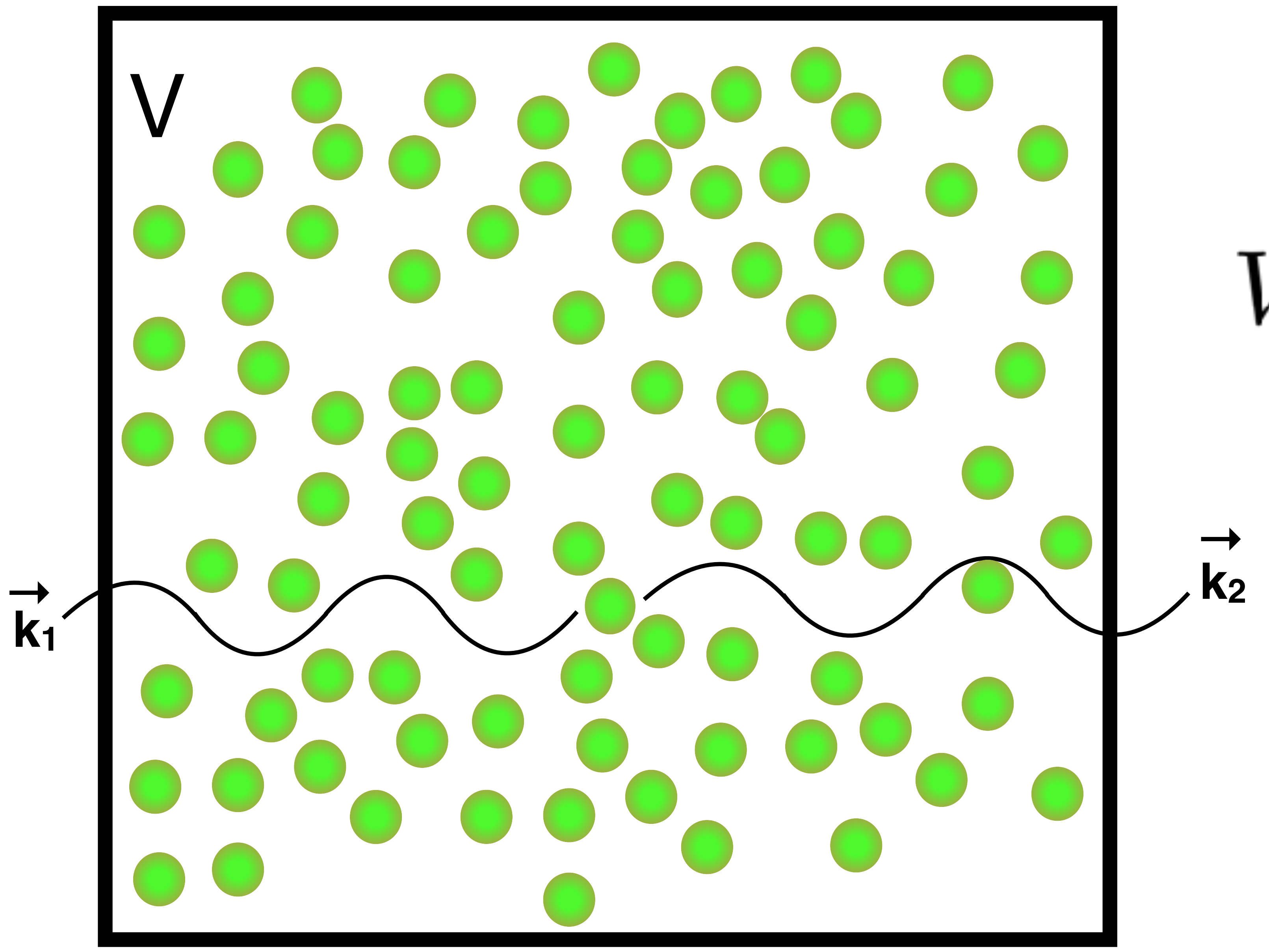
Two-Photon Superradiance

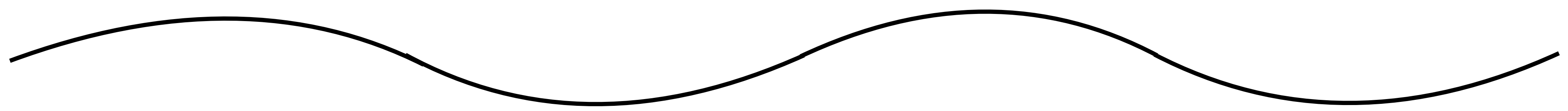
Bhoonah, JB, Song 1909.07387
Hiraki et al. 2019



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

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

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



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

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

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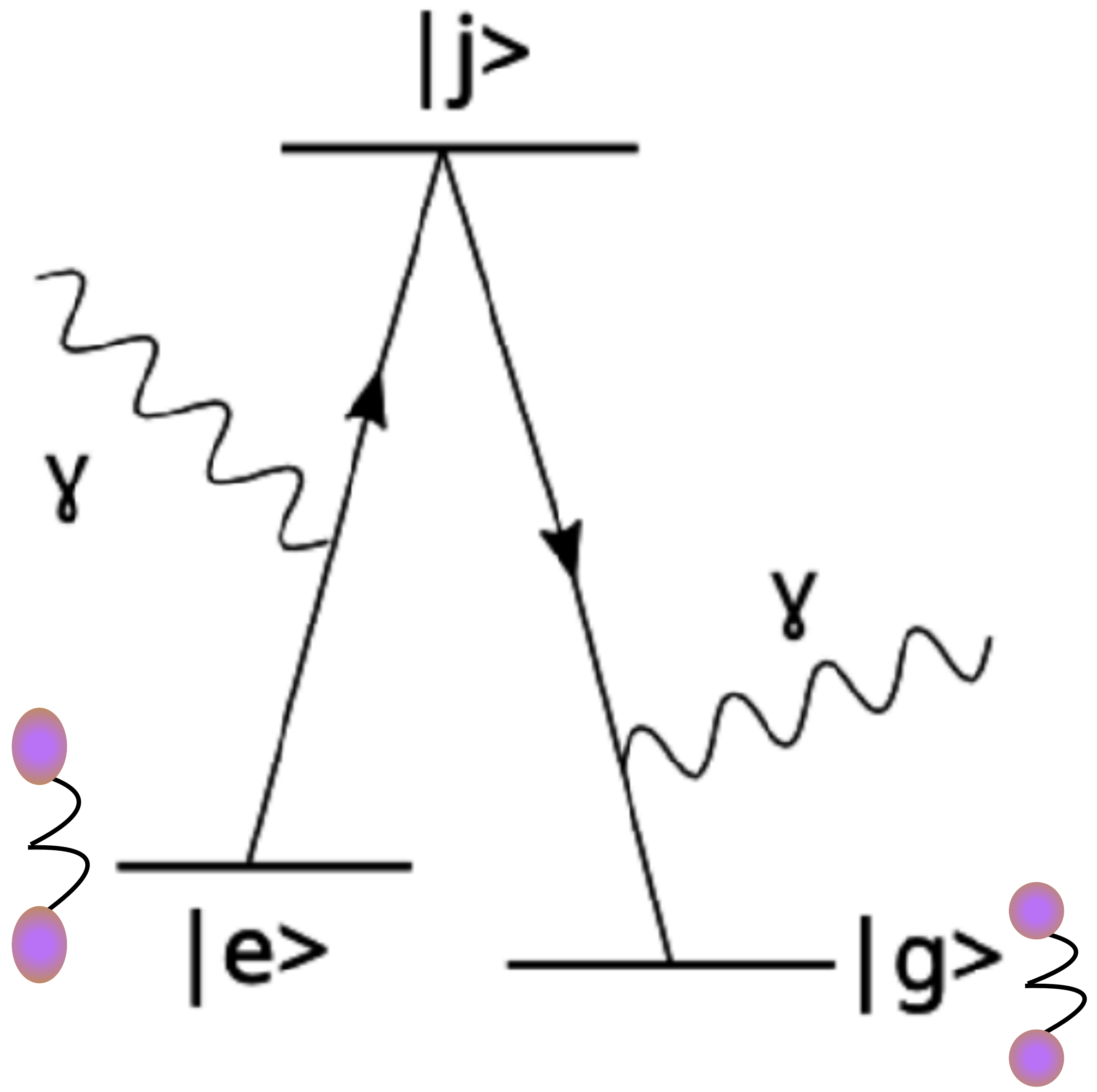
Macro Coherence in Parahydrogen

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



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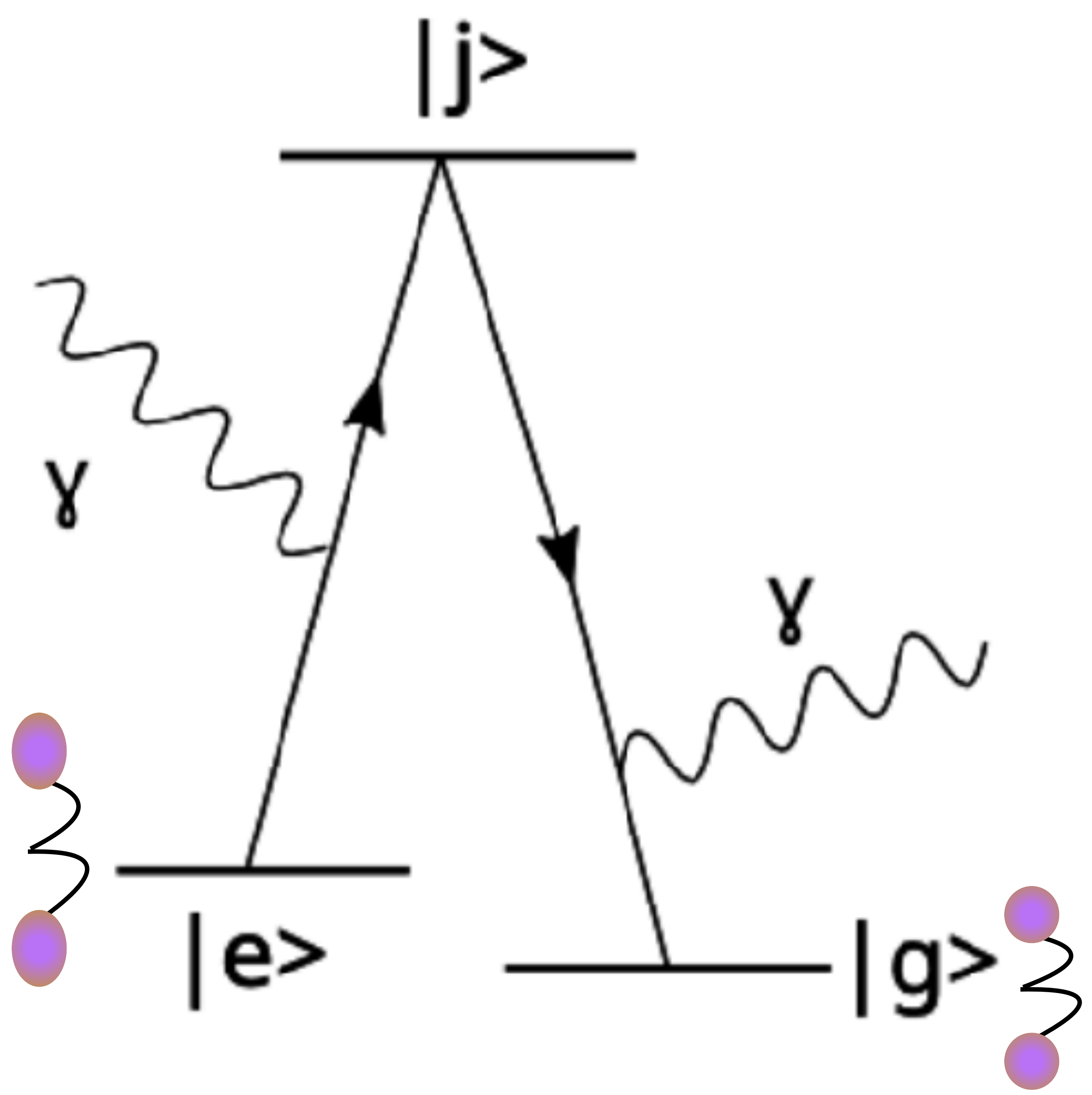

$$H = H_0 + H_I \qquad H_I = -\mathbf{d}\cdot(\tilde{E}_1 + \tilde{E}_2)$$

$$|\psi\rangle = c_g e^{-i\omega_g t}|g\rangle + c_e e^{-i(\omega_e+\delta)t}|e\rangle + c_{j+}e^{-i\omega_j t}|j_+\rangle + c_{j-}e^{-i\omega_j t}|j_-\rangle$$

$$i\partial_t c_{j+} = \frac{1}{2}(d_{jg}c_g e^{i\omega_{jg}t} + d_{je}c_e e^{i(\omega_{je}-\delta)t})(\bar{E}_1 e^{-i\omega t} + \bar{E}_2^* e^{i\omega t})$$
$$i\partial_t c_{j-} = \frac{1}{2}(d_{jg}c_g e^{i\omega_{jg}t} + d_{je}c_e e^{i(\omega_{je}-\delta)t})(\bar{E}_1^* e^{i\omega t} + \bar{E}_2 e^{-i\omega t})$$
$$i\partial_t c_g = \frac{1}{2}d_{gj}e^{-i\omega_{jg}t}[c_{j+}(\bar{E}_1^* e^{i\omega t} + \bar{E}_2 e^{-i\omega t}) + c_{j-}(\bar{E}_1 e^{-i\omega t} + \bar{E}_2^* e^{i\omega t})]$$
$$i\partial_t c_e = \frac{1}{2}d_{ej}e^{-i(\omega_{je}-\delta)t}[c_{j+}(\bar{E}_1^* e^{i\omega t} + \bar{E}_2 e^{-i\omega t}) + c_{j-}(\bar{E}_1 e^{-i\omega t} + \bar{E}_2^* e^{i\omega t})]$$

$$d_{jg} \equiv \langle j_+| - \mathbf{d}\cdot\epsilon_r|g\rangle = \langle j_-| - \mathbf{d}\cdot\epsilon_l|g\rangle$$
$$d_{je} \equiv \langle j_+| - \mathbf{d}\cdot\epsilon_r|e\rangle = \langle j_-| - \mathbf{d}\cdot\epsilon_l|e\rangle$$

The Schrodinger equation for left/right-going plane wave E_1/E_2 fields, and their dipole interactions with parahydrogen excitations… (including virtual j states)

Macro Coherence in Parahydrogen

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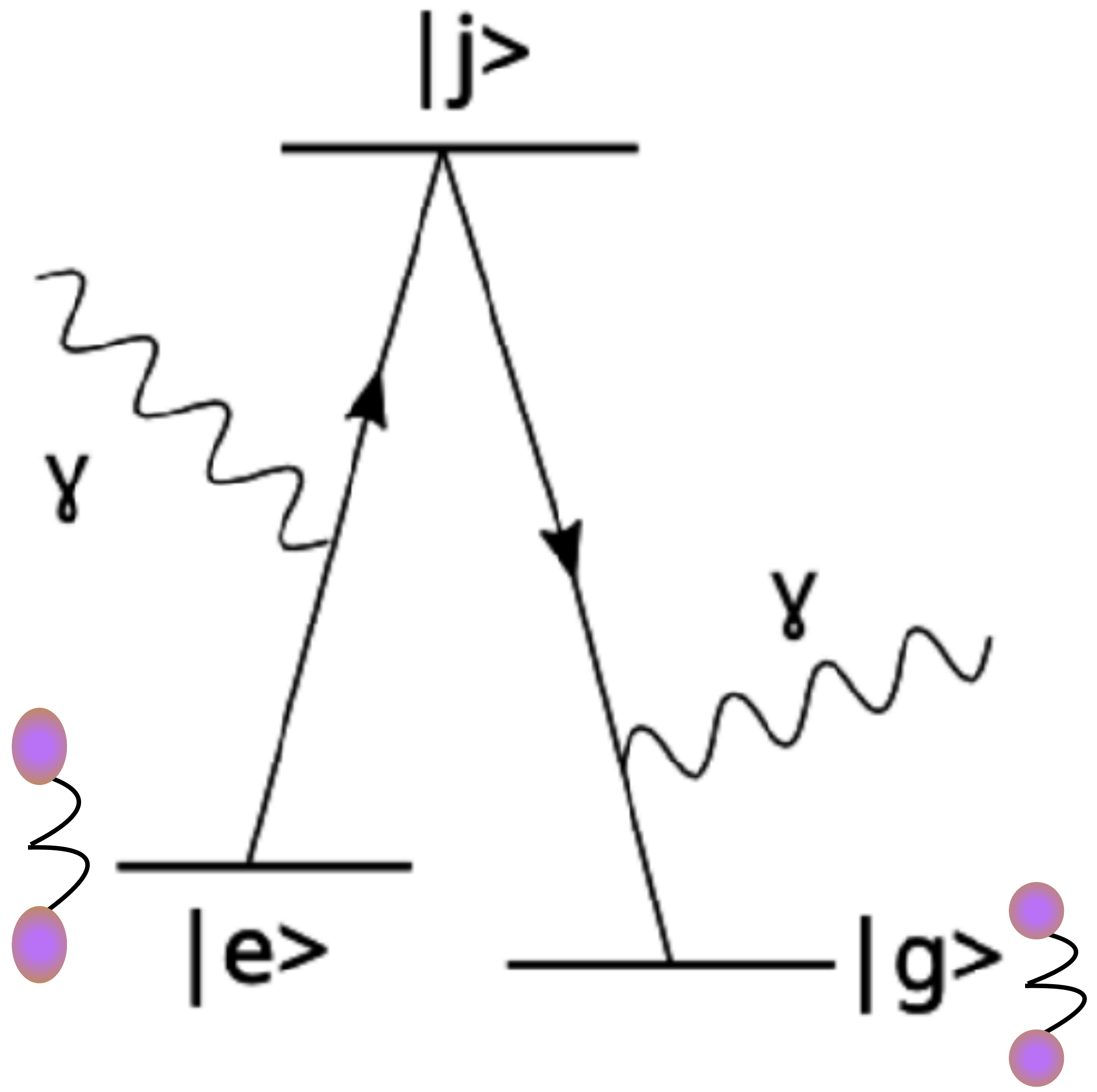

Simplified state

$$|\psi\rangle = c_g e^{-i\omega_g t}|g\rangle + c_e e^{-i(\omega_e+\delta)t}|e\rangle + c_{j+}e^{-i\omega_j t}|j_+\rangle + c_{j-}e^{-i\omega_j t}|j_-\rangle$$

$$i\partial_t \begin{pmatrix} c_e \\ c_g \end{pmatrix} = H_{eff}\begin{pmatrix} c_e \\ c_g \end{pmatrix} = \begin{pmatrix} \Omega_{ee} & \Omega_{eg} \\ \Omega_{ge} & \Omega_{ee} \end{pmatrix}\begin{pmatrix} c_e \\ c_g \end{pmatrix}$$

$$\bar{E}_1 = E_1 e^{-i\omega z}$$

$$\Omega_{ee} = \frac{a_{ee}}{4}\left(|\bar{E}_1|^2 + |\bar{E}_2|^2\right)$$
$$\Omega_{gg} = \frac{a_{gg}}{4}\left(|\bar{E}_1|^2 + |\bar{E}_2|^2\right)$$
$$\Omega_{eg} = \Omega_{ge}^* = \frac{a_{ge}}{2}\bar{E}_1\bar{E}_2\,,$$

$$a_{ee} = \sum_j |d_{je}|^2\left(\frac{1}{\omega_{je}-\delta-\omega} + \frac{1}{\omega_{je}-\delta+\omega}\right)$$

$$a_{gg} = \sum_j |d_{jg}|^2\left(\frac{1}{\omega_{jg}-\omega} + \frac{1}{\omega_{jg}+\omega}\right)\,,$$

$$a_{eg} = a_{ge}^* = \sum_j \frac{d_{je}d_{gj}}{\omega_{je}-\delta+\omega}\,.$$

…re-organized in terms of Rabi oscillation terms (2x2 matrix)…

Macro Coherence in Parahydrogen

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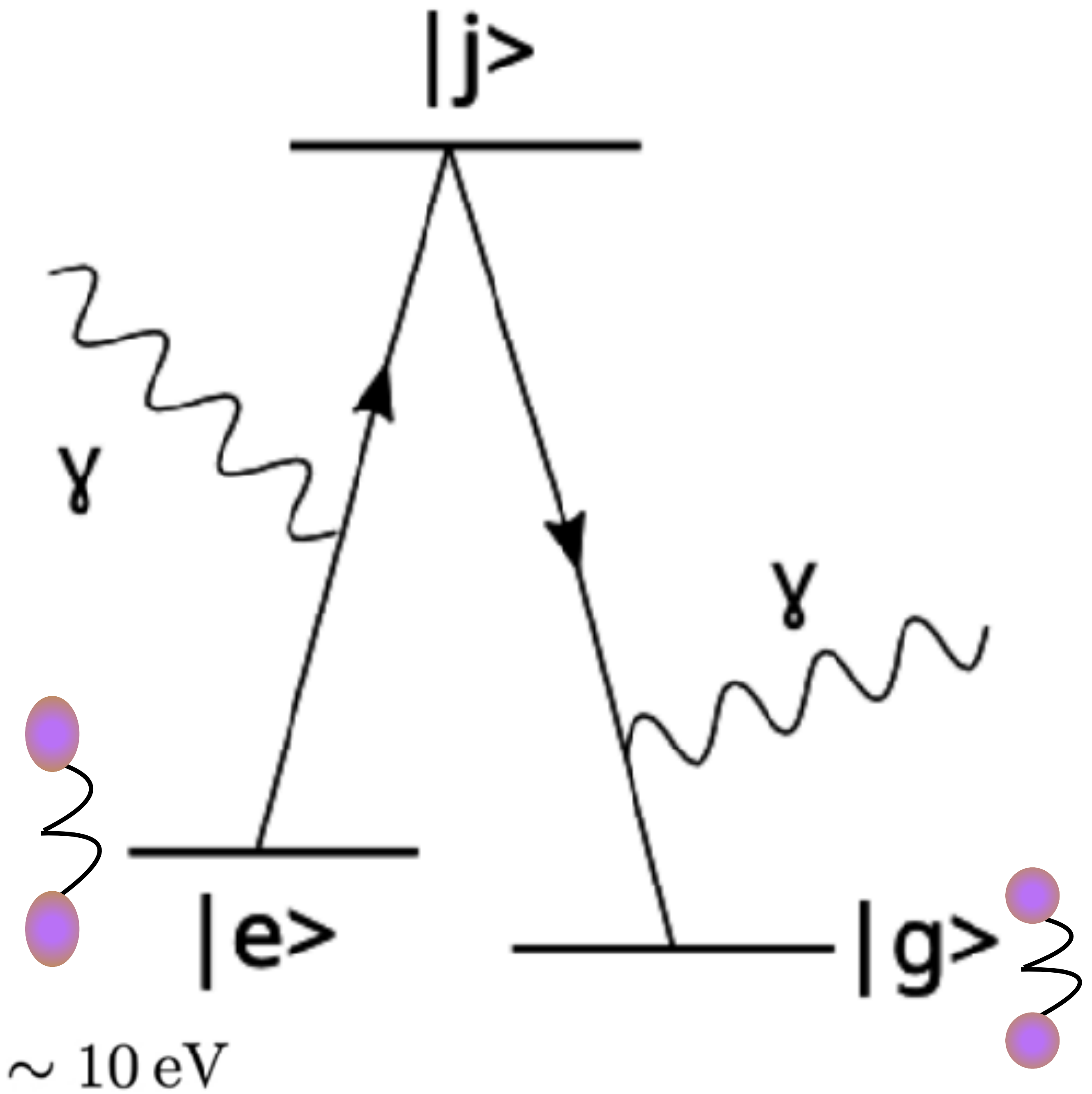


<u>Simplified state</u>

$$|\psi\rangle = c_g e^{-i\omega_g t}|g\rangle + c_e e^{-i(\omega_e+\delta)t}|e\rangle + c_{j+}e^{-i\omega_j t}|j_+\rangle + c_{j-}e^{-i\omega_j t}|j_-\rangle$$

markov - treat c_e, c_g constant - $\omega_{eg} \sim 0.5$ eV $\quad \omega_{je}, \omega_{jg} \sim 10$ eV

slowly varying envelope - $e^{i(\omega_{je}-\delta+\omega)t} \approx e^{i(\omega_{jg}+\omega)t} \approx e^{i(\omega_{je}-\delta-\omega)t} \approx e^{i(\omega_{jg}-\omega)t} \approx 0$

<u>Maxwell-Bloch</u> **...re-organized in terms of Bloch vectors...**

$$\partial_t r_1 = \left[-\frac{a_{gg}-a_{ee}}{4}(|\bar{E}_1|^2+|\bar{E}_2|^2)+\delta\right] r_2 + a_{eg}\,\mathrm{Im}(\bar{E}_1\bar{E}_2) r_3 - \frac{r_1}{T_2},$$

$$\partial_t r_2 = \left[\frac{a_{gg}-a_{ee}}{4}(|E_1|^2+|E_2|^2)-\delta\right] r_1 + a_{eg}\,\mathrm{Re}(\bar{E}_1\bar{E}_2) r_3 - \frac{r_2}{T_2},$$

$$\partial_t r_3 = -a_{eg}[\mathrm{Im}(\bar{E}_1\bar{E}_2) r_1 + \mathrm{Re}(\bar{E}_1\bar{E}_2) r_2] - \frac{1+r_3}{T_1},$$

$r_1 = \rho_{ge} + \rho_{eg}$, 1=phase coherence

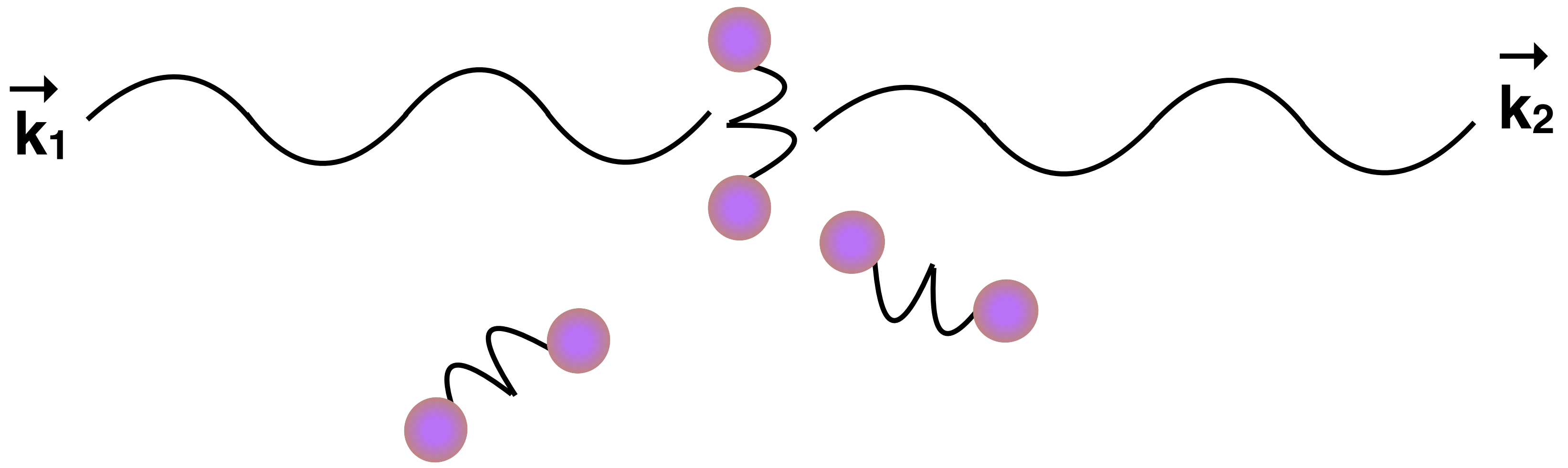
$r_2 = i(\rho_{eg} - \rho_{ge})$, other phase

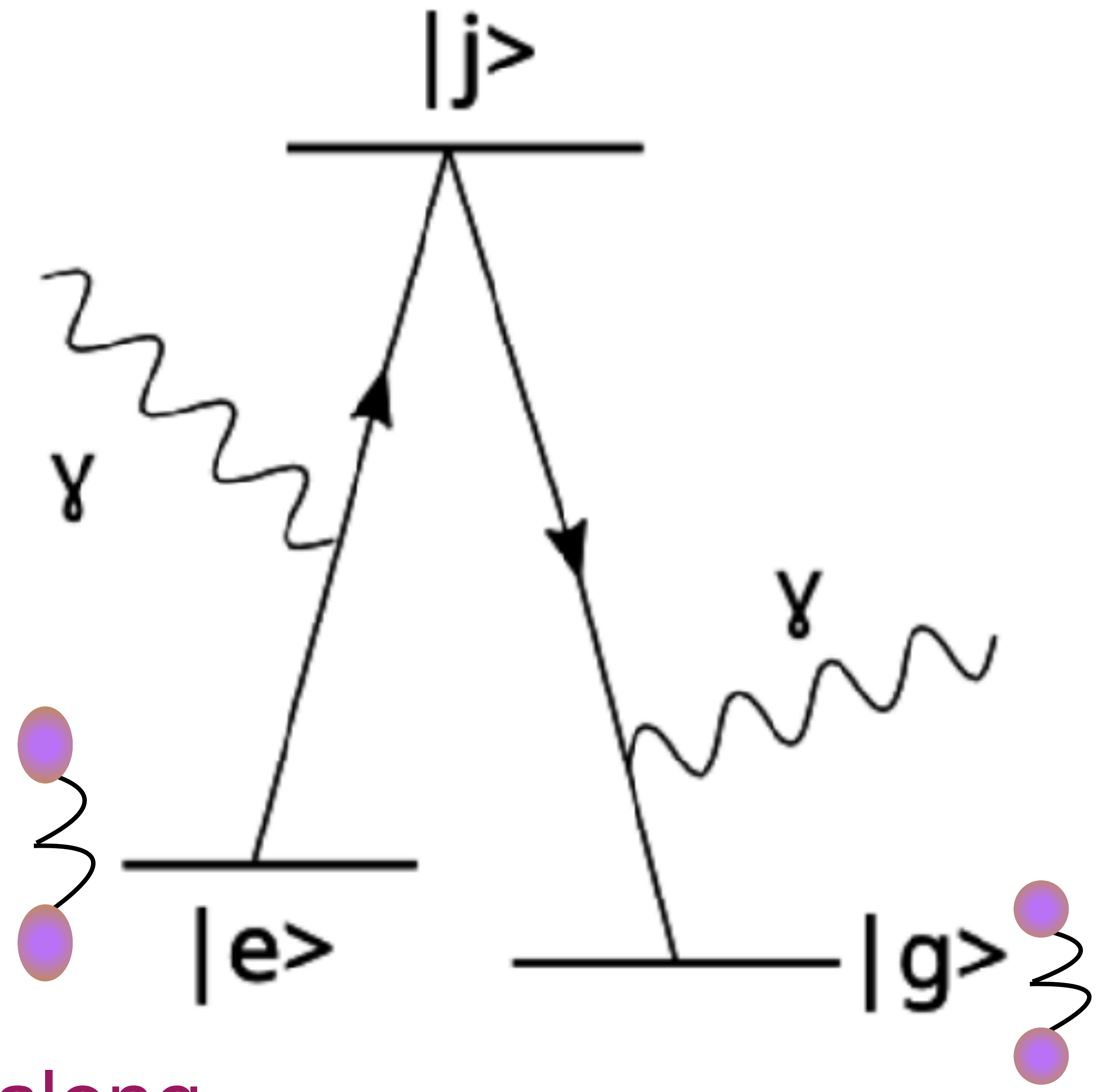
$r_3 = \rho_{ee} - \rho_{gg}$. +1=all excited, -1= all ground

T_1 = spontaneous decay time $\qquad$ T_2 = decoherence time

Macro Coherence in Parahydrogen

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

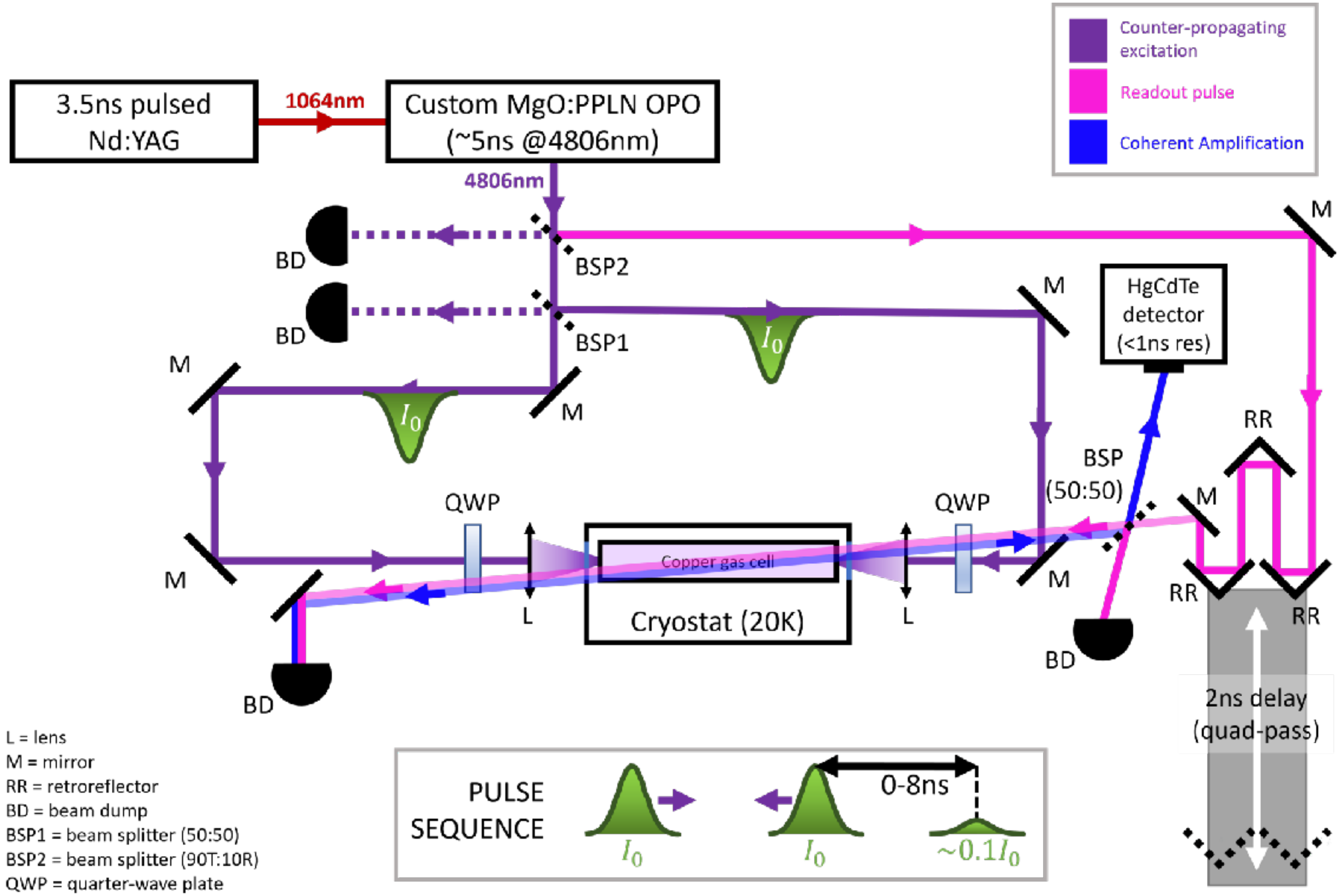




This ~0.5 eV vibrational mode is the lowest lying state, along with attainable 10 ns decoherence times, this makes pH_2 a good medium for testing macro coherence.

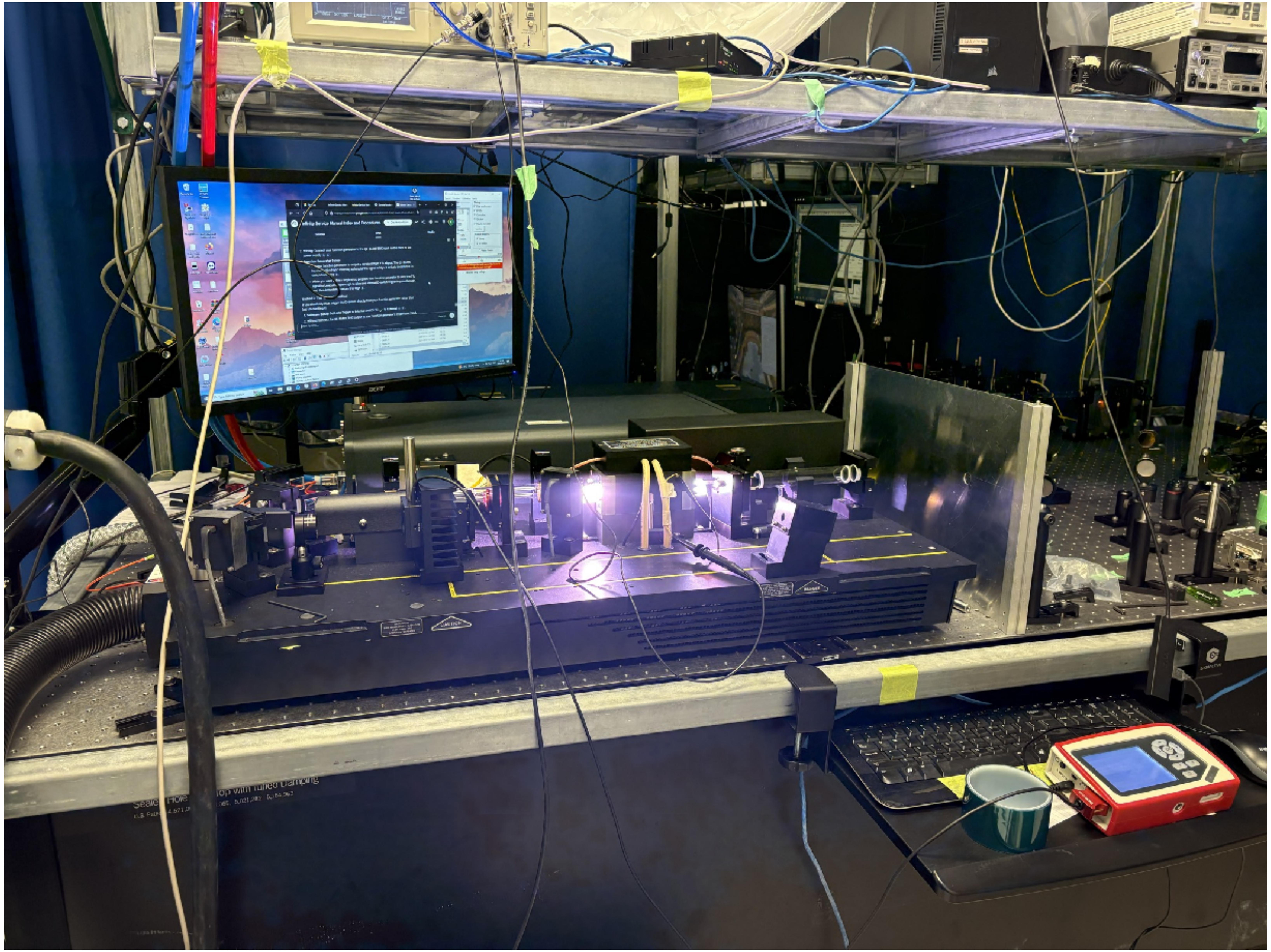
pH_2 Reference	Density (cm^{-3})	Temperature (K)	Decoherence Time (ns)
[57]	$10^{19} - 10^{20}$	80-500	~ 10
[42]	5.6×10^{19}	78	~ 8 (est)
[37]	$10^{19} - 5 \times 10^{20}$	78	~ 10 (est)
[58]	2.6×10^{22}	4.2	$\gtrsim 140$

CATCHY - Coherent Atomic Transition from Counter-pulsed HYdrogen



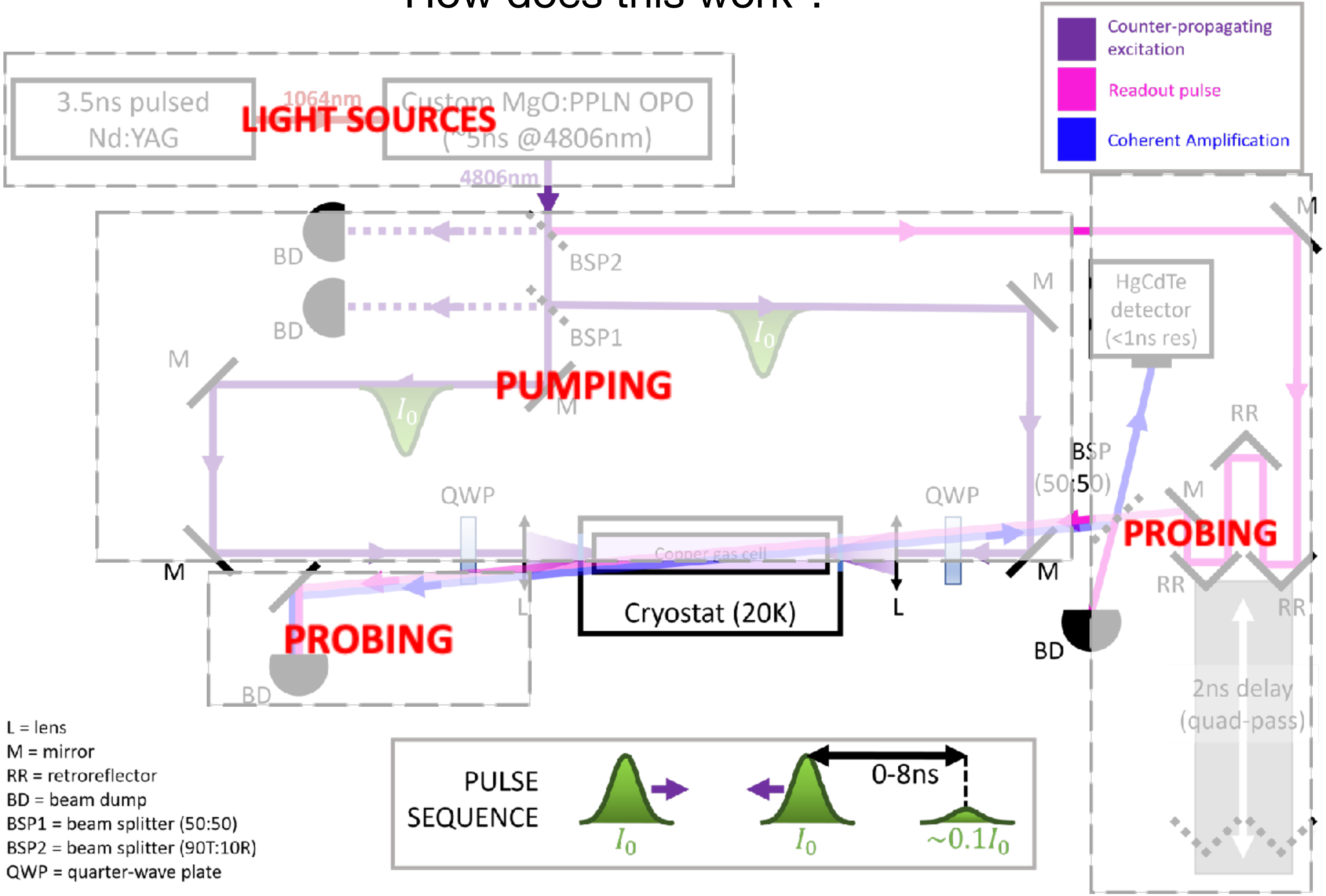
Goal is first coherence measurement for N^2 excitation of first vibrational mode of parahydrogen

CATCHY - Coherent Atomic Transition from Counter-pulsed HYdrogen



Goal is first detection of N^2 excitation of first vibrational mode of parahydrogen

How does this work ?



L = lens
M = mirror
RR = retroreflector
BD = beam dump
BSP1 = beam splitter (50:50)
BSP2 = beam splitter (90T:10R)
QWP = quarter-wave plate

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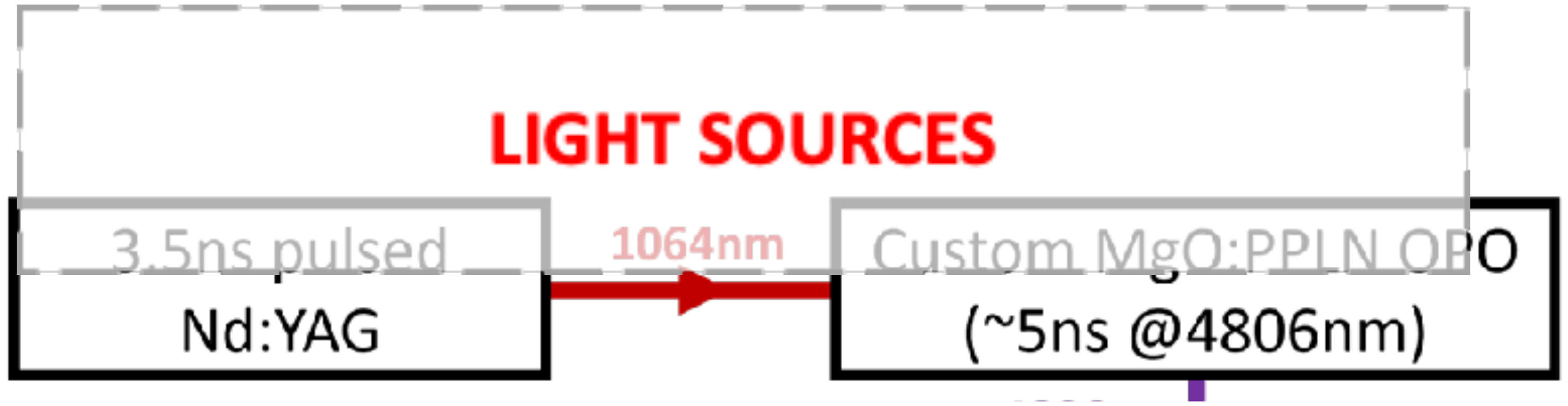
Generation of 4.826 micron narrow bandwidth light



Damage threshold studies for crystal

Laser specifications for 1064nm

Max Rep Rate: 100Hz

Max pulse energy: 500mJ

Shot to shot noise: 1%

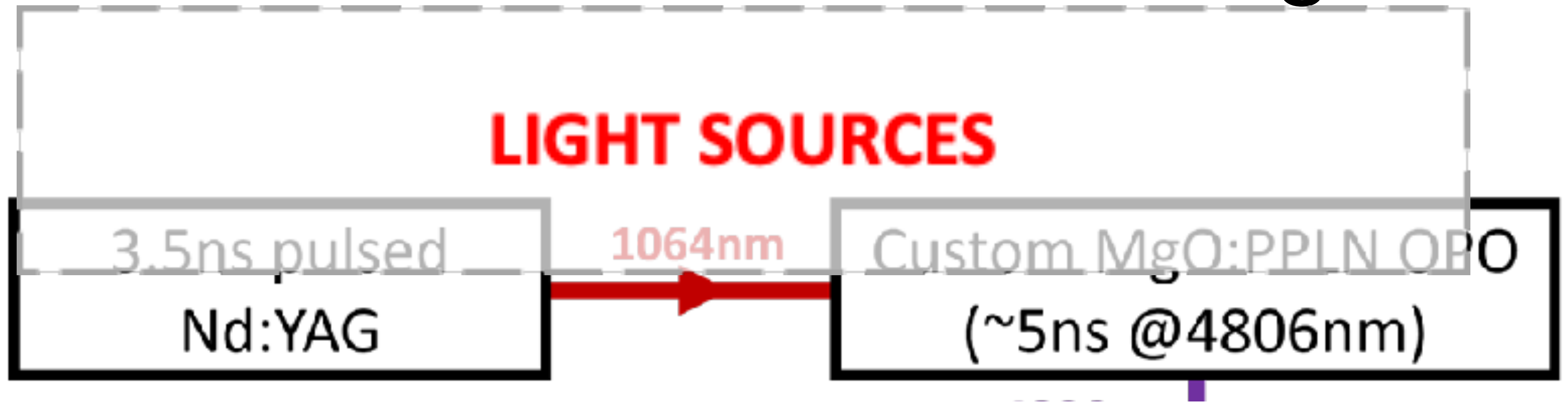
Bandwidth: 250 MHz

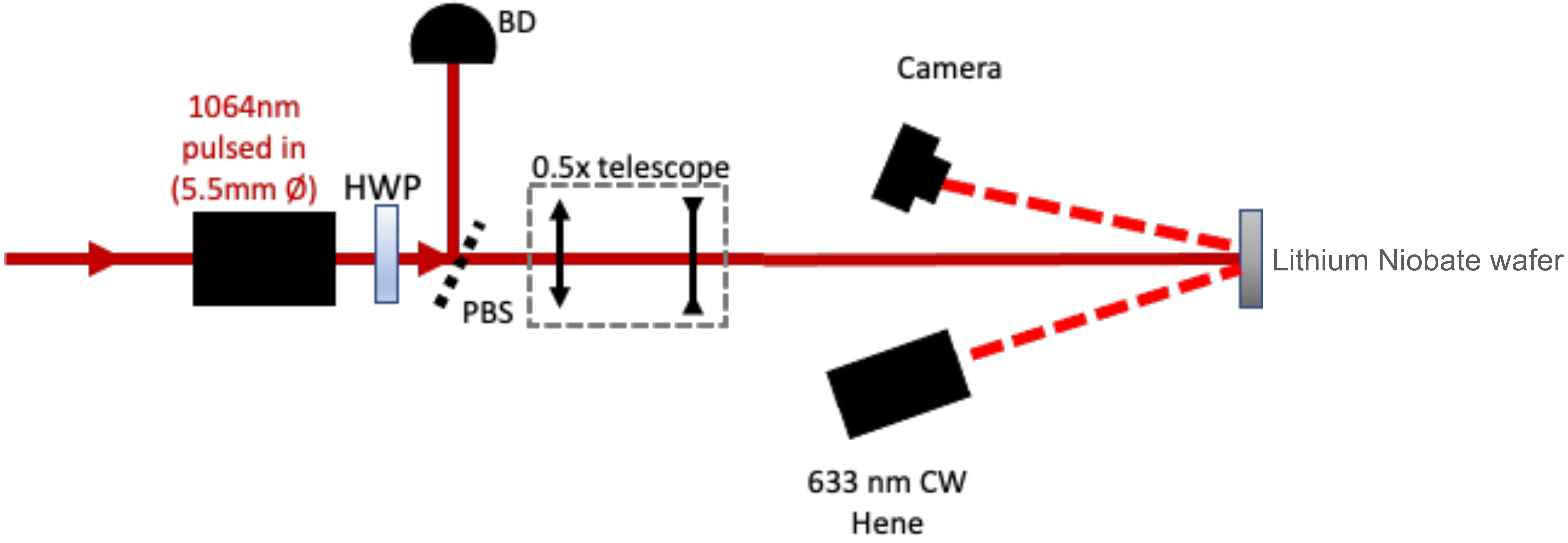
Damage threshold value from supplier

2J/cm^2 single shot @ 1064nm,

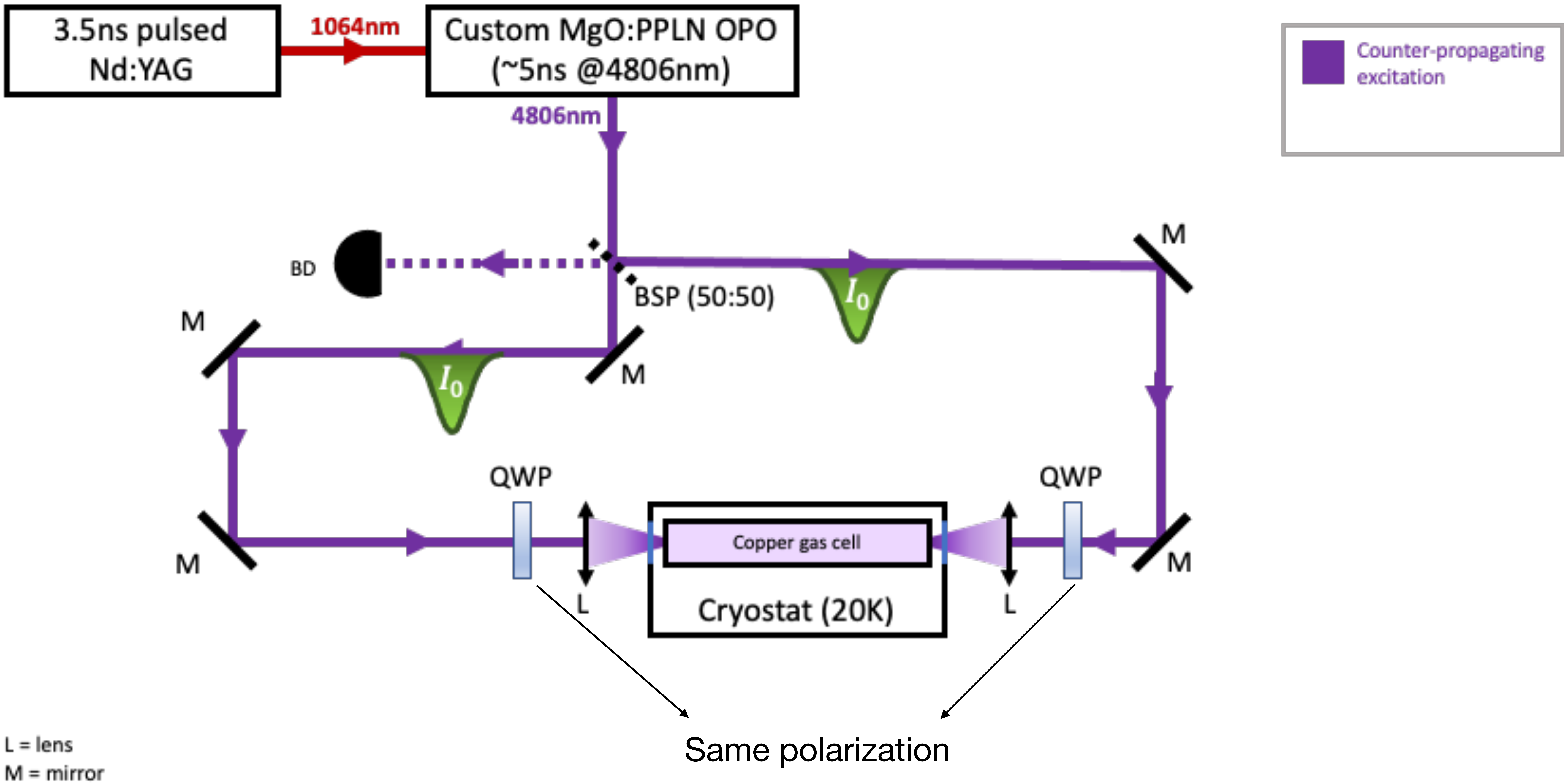
21Hz nanosecond pulsed laser

Characterizing damage of PPLN crystal





How to get centimetres of molecules excited ?



L = lens
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BD = beam dump
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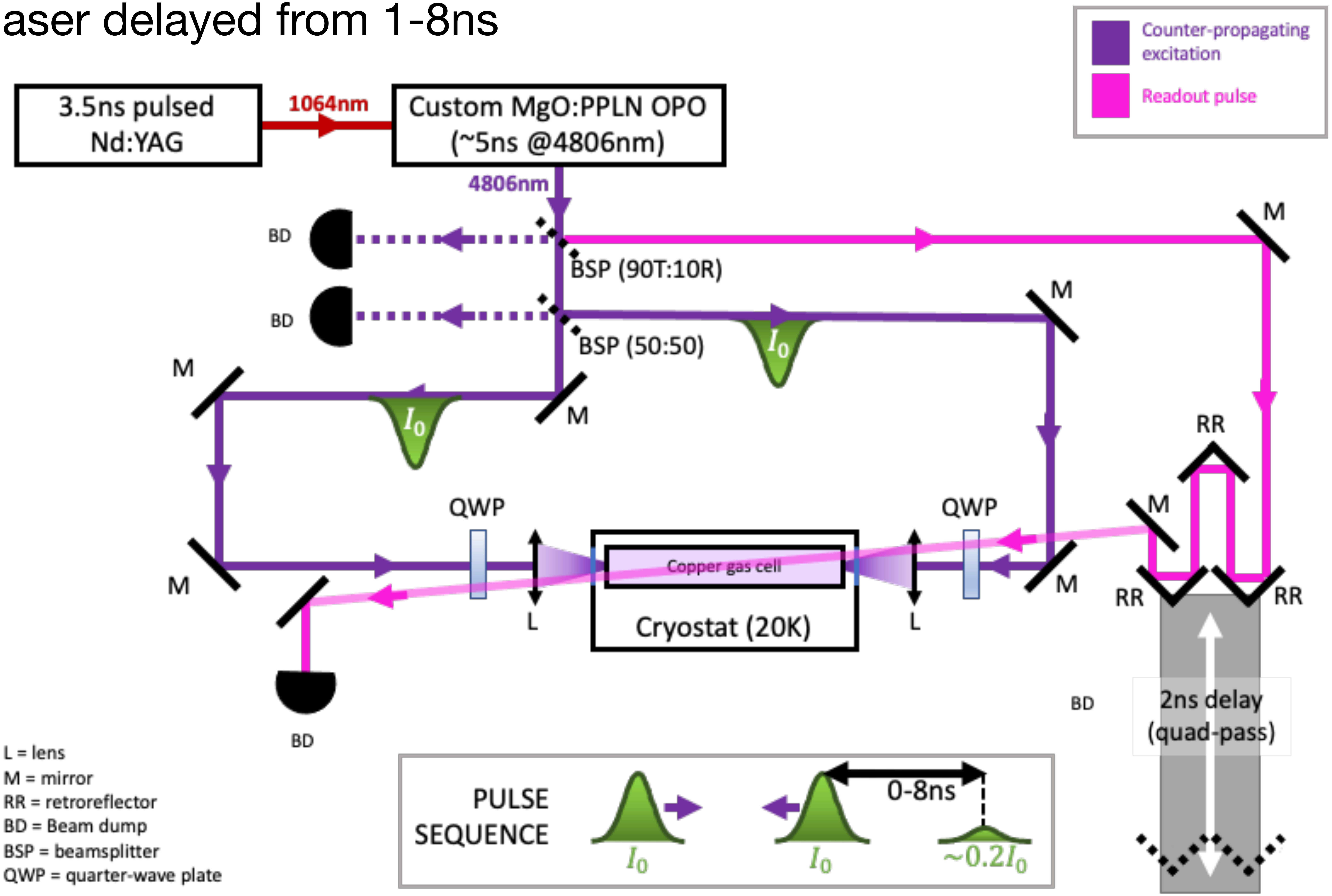
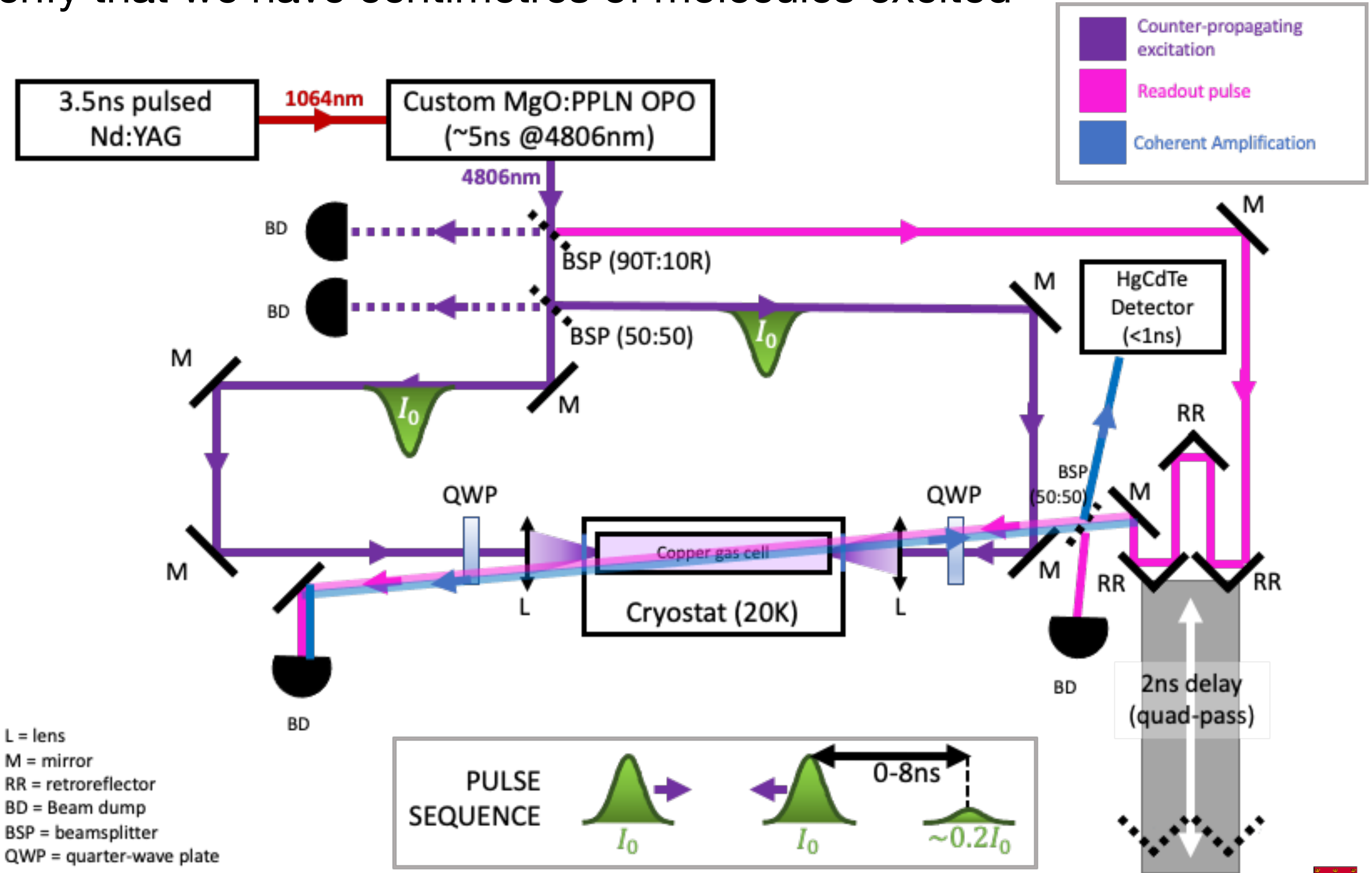
QWP = quarter-wave plate

How to verify that we have centimetres of molecules excited

Trigger laser delayed from 1-8ns

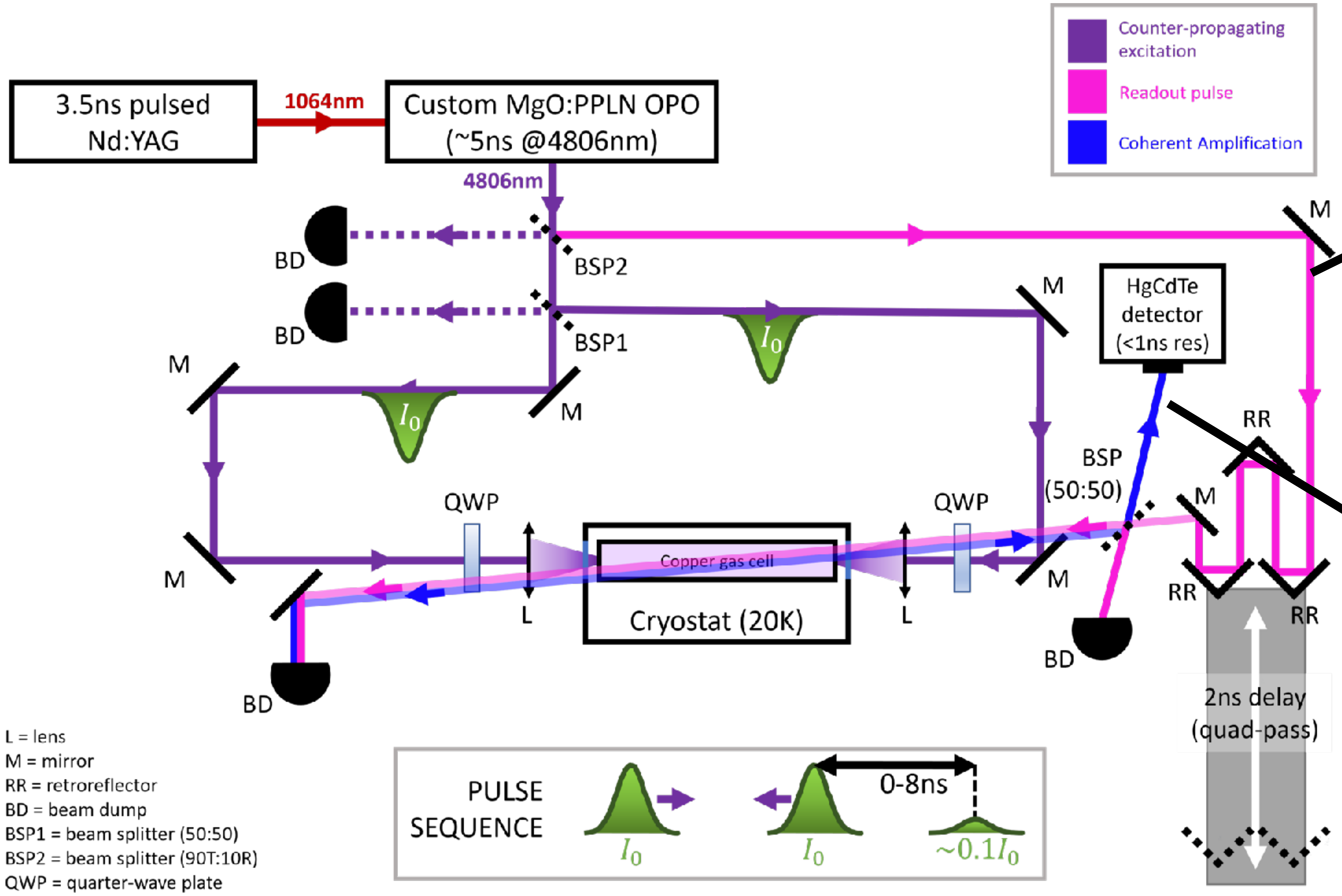


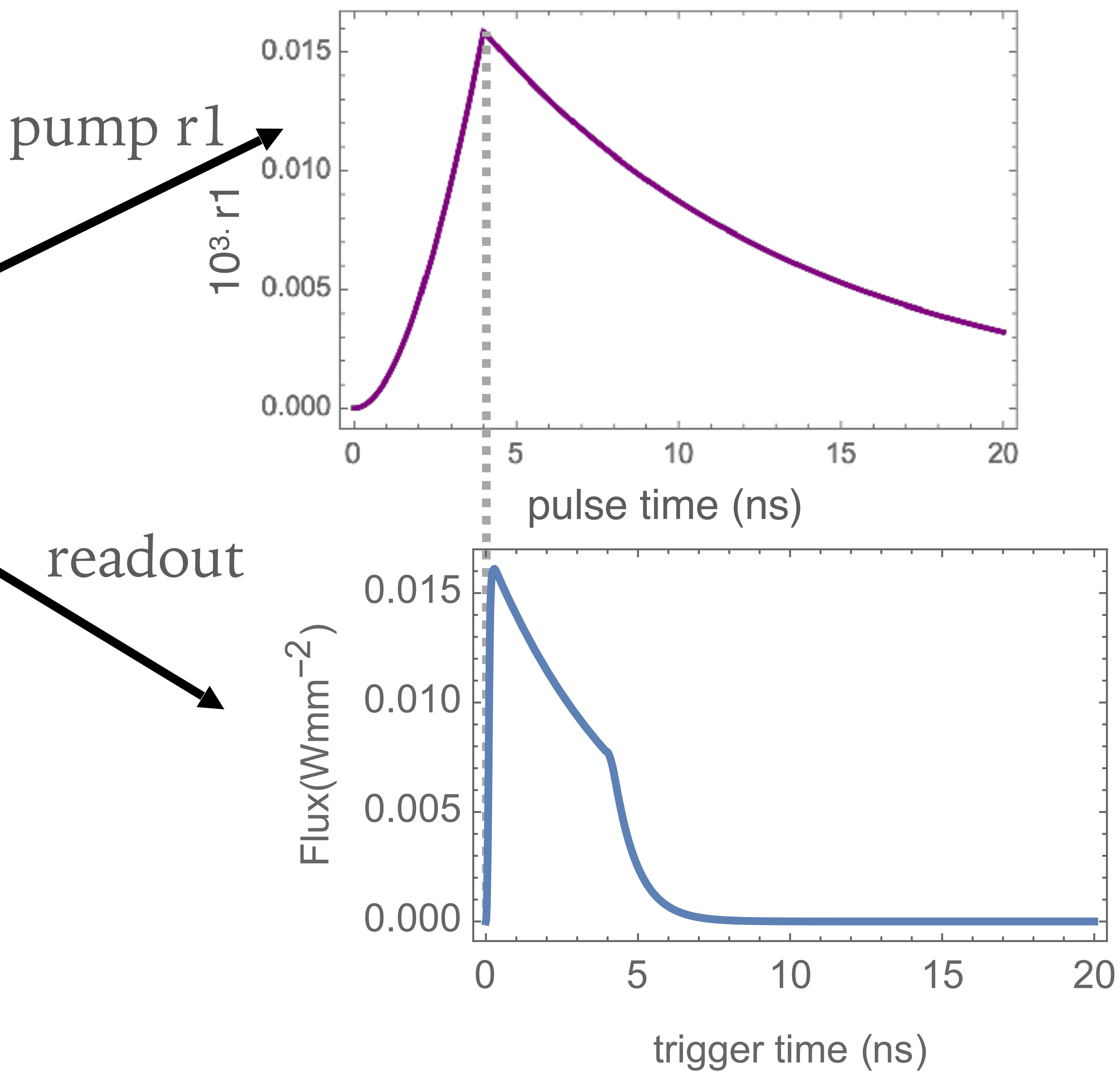
How to verify that we have centimetres of molecules excited



CATCHY - Coherent Atomic Transition from Counter-pulsed HYdrogen

1. pump pulse
excites pH2 in copper cell





Readout along opposite direction of trigger laser

2. trigger pulse stimulates
de-excitation of cell

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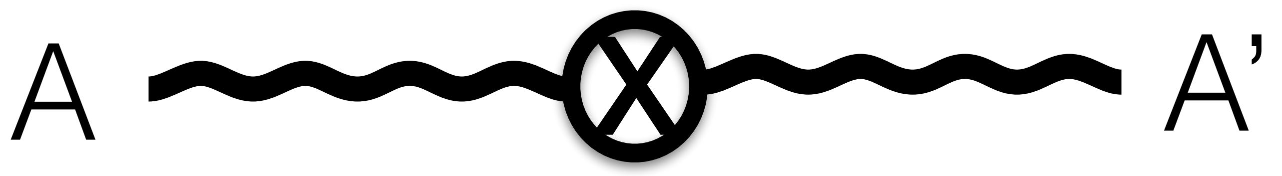
The Dark Photon!

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



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

Batra Delgado Kaplan Tait 2003

String compactifications

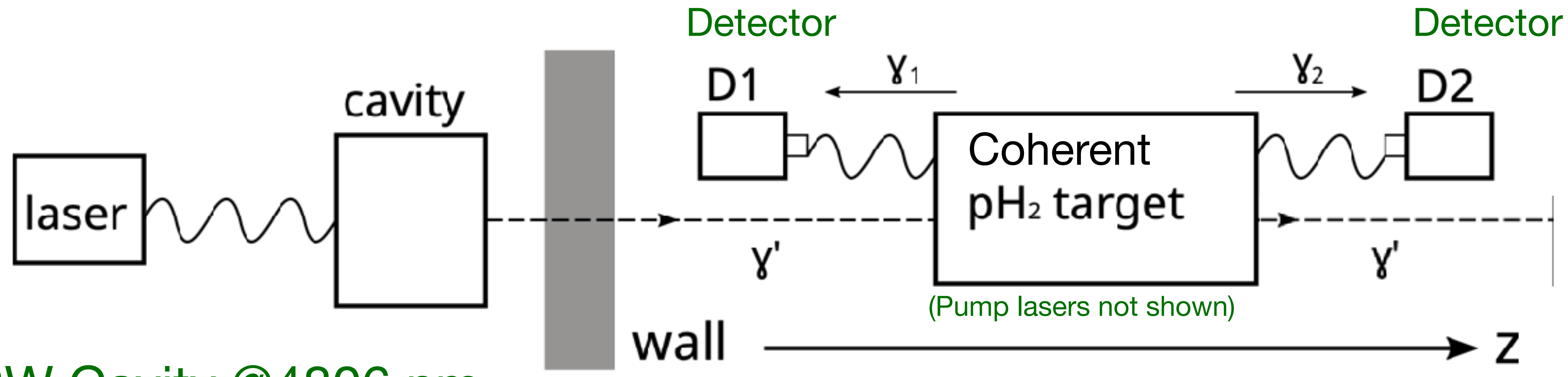
Goodsell Jaeckel Redondo Ringwald 2008

Dark sectors

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

Light-Shining-through-Wall Search for Dark Photons

Use a macro-coherent sample of parahydrogen as a target

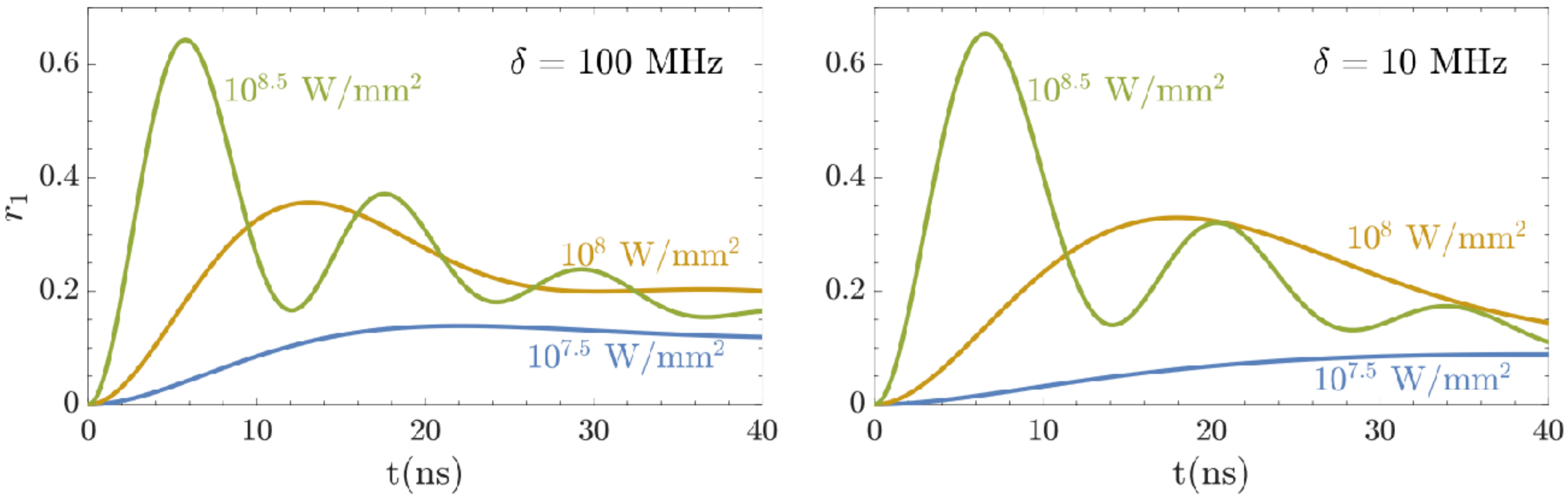


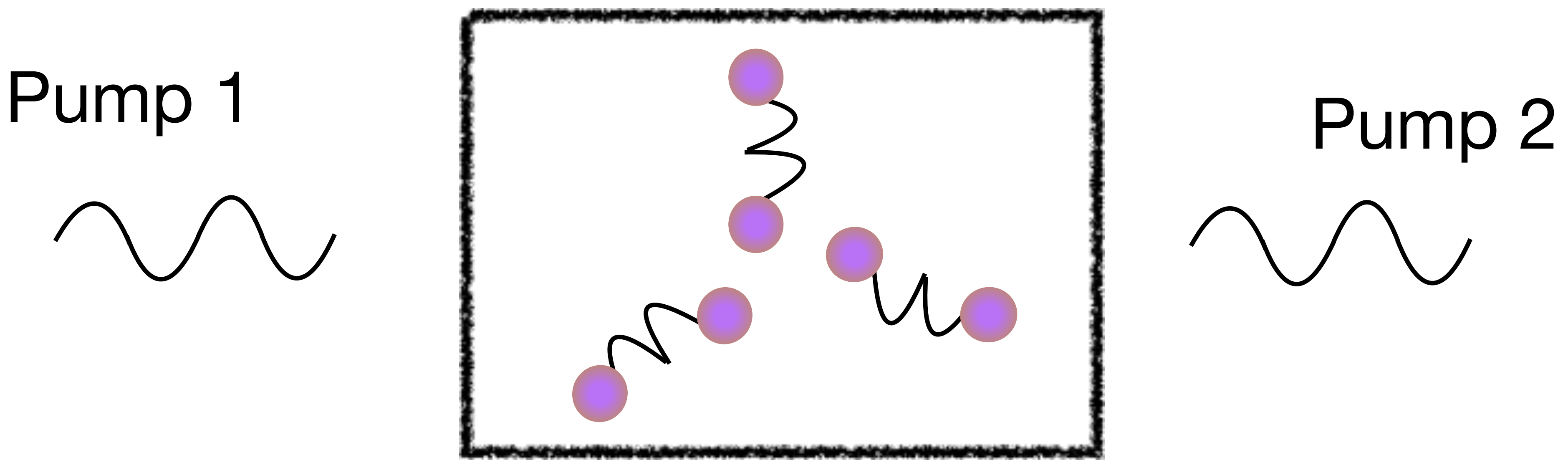
LSW Cavity @4806 nm

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.

Macro Coherence in Parahydrogen

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





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}

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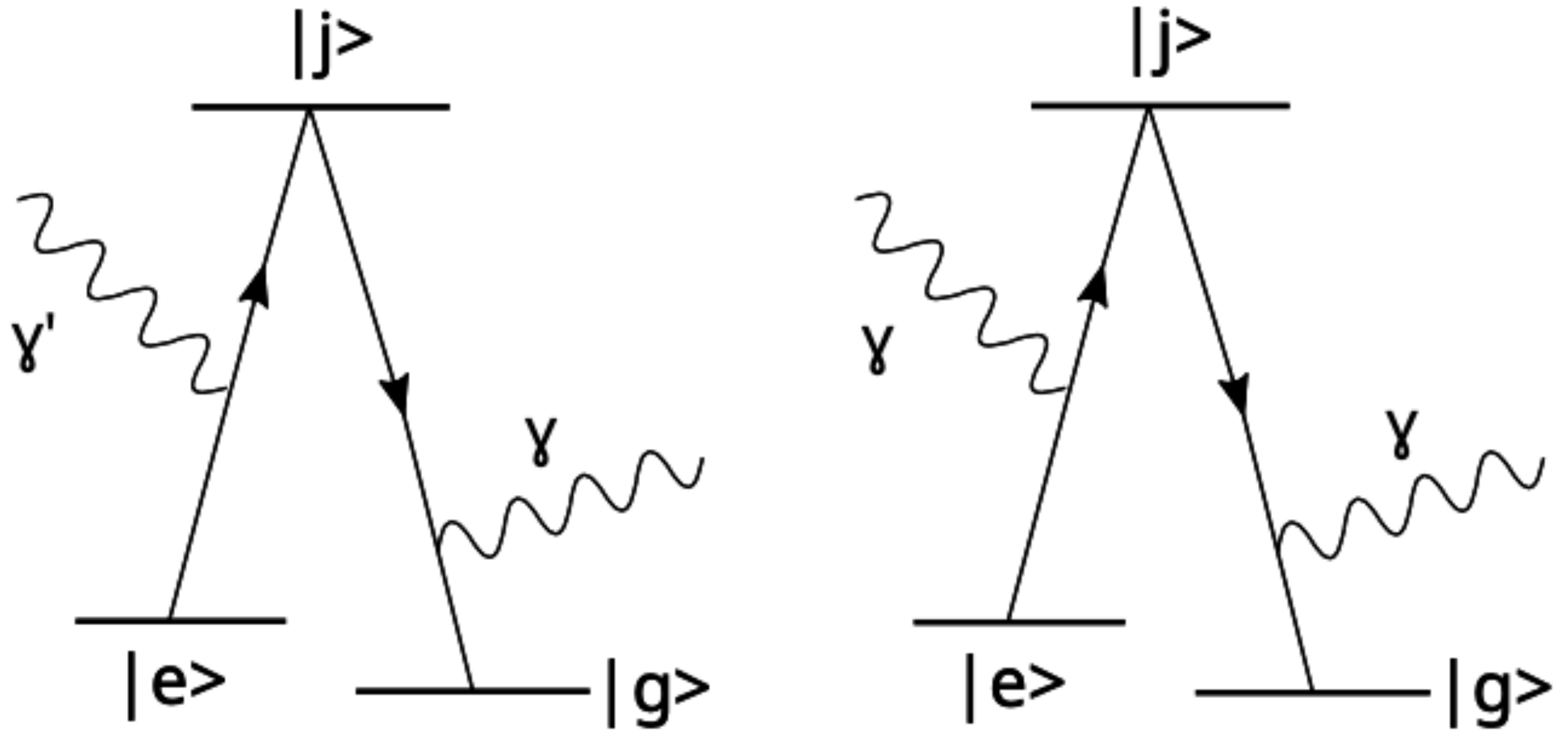
The transitions for multi-photon emission, in the Standard Model and with a dark photon.

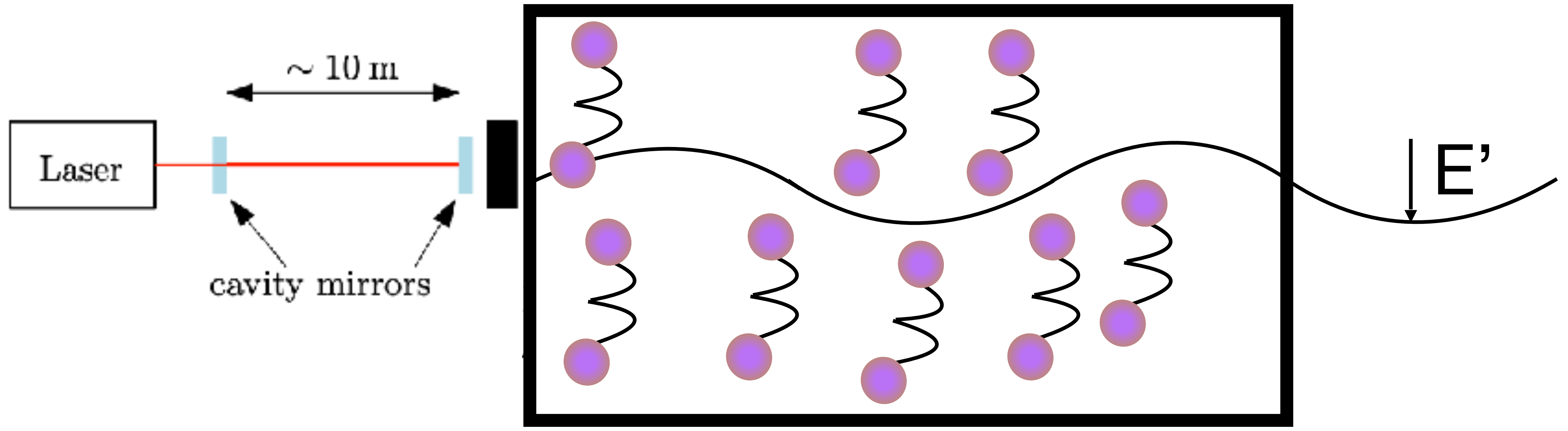
$$H_I = -\mathbf{d} \cdot (\tilde{E}_1 + \tilde{E}_2 + \chi \tilde{E}')$$

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.



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

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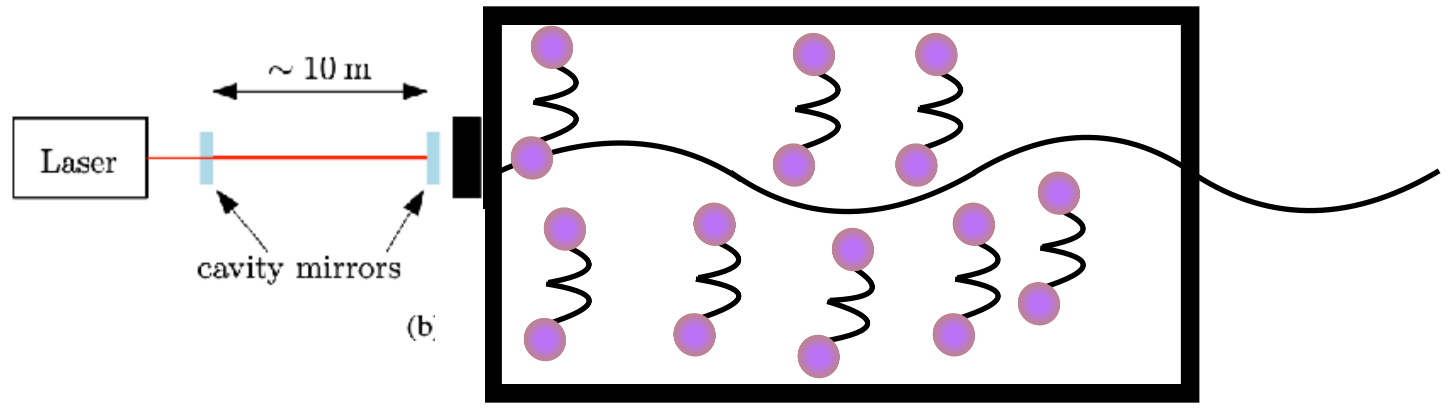
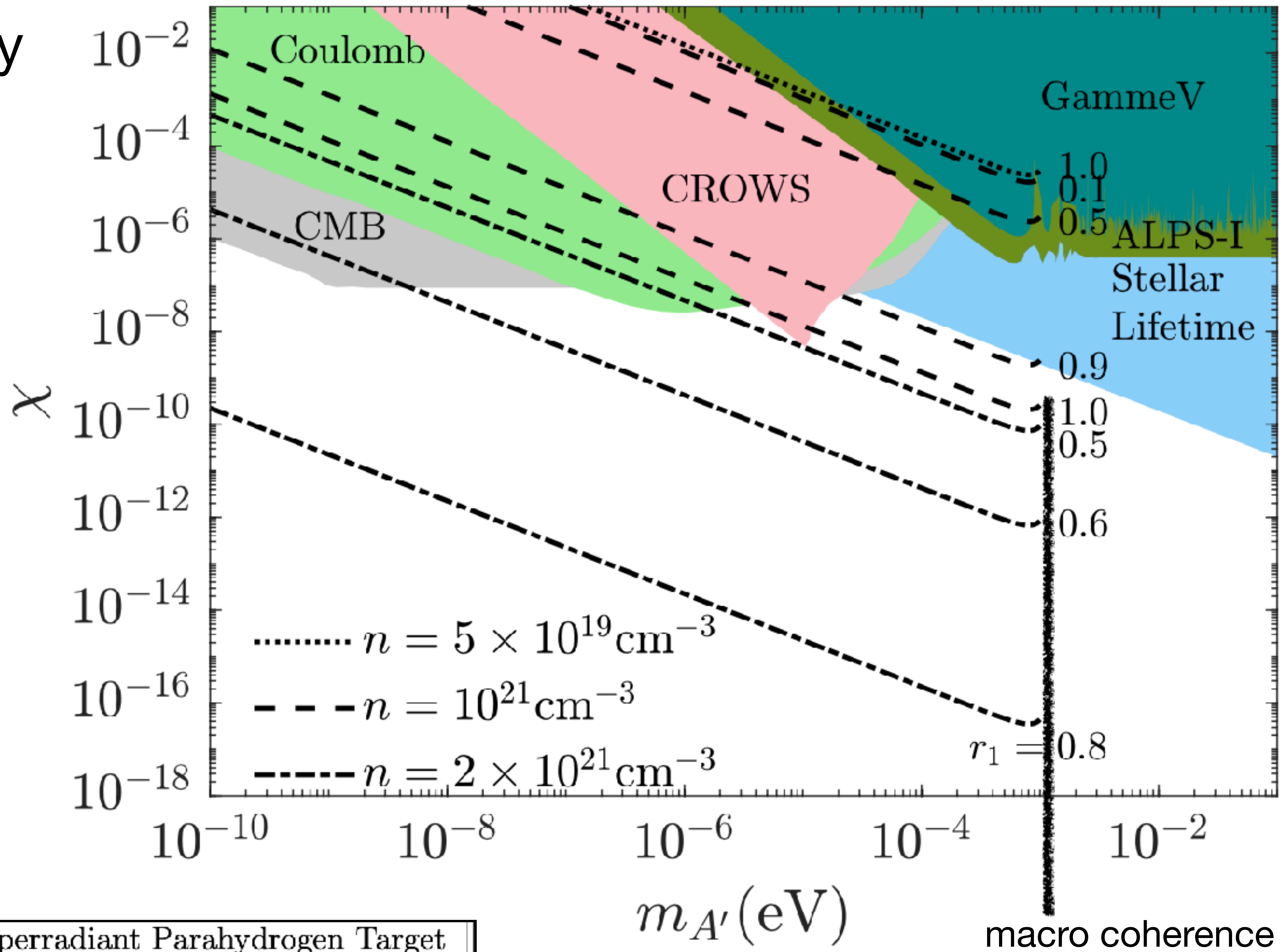
CATCHY+ LSW Sensitivity



Improved reach as the number density of pH_2, r_1 increases.



macro coherence condition

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

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

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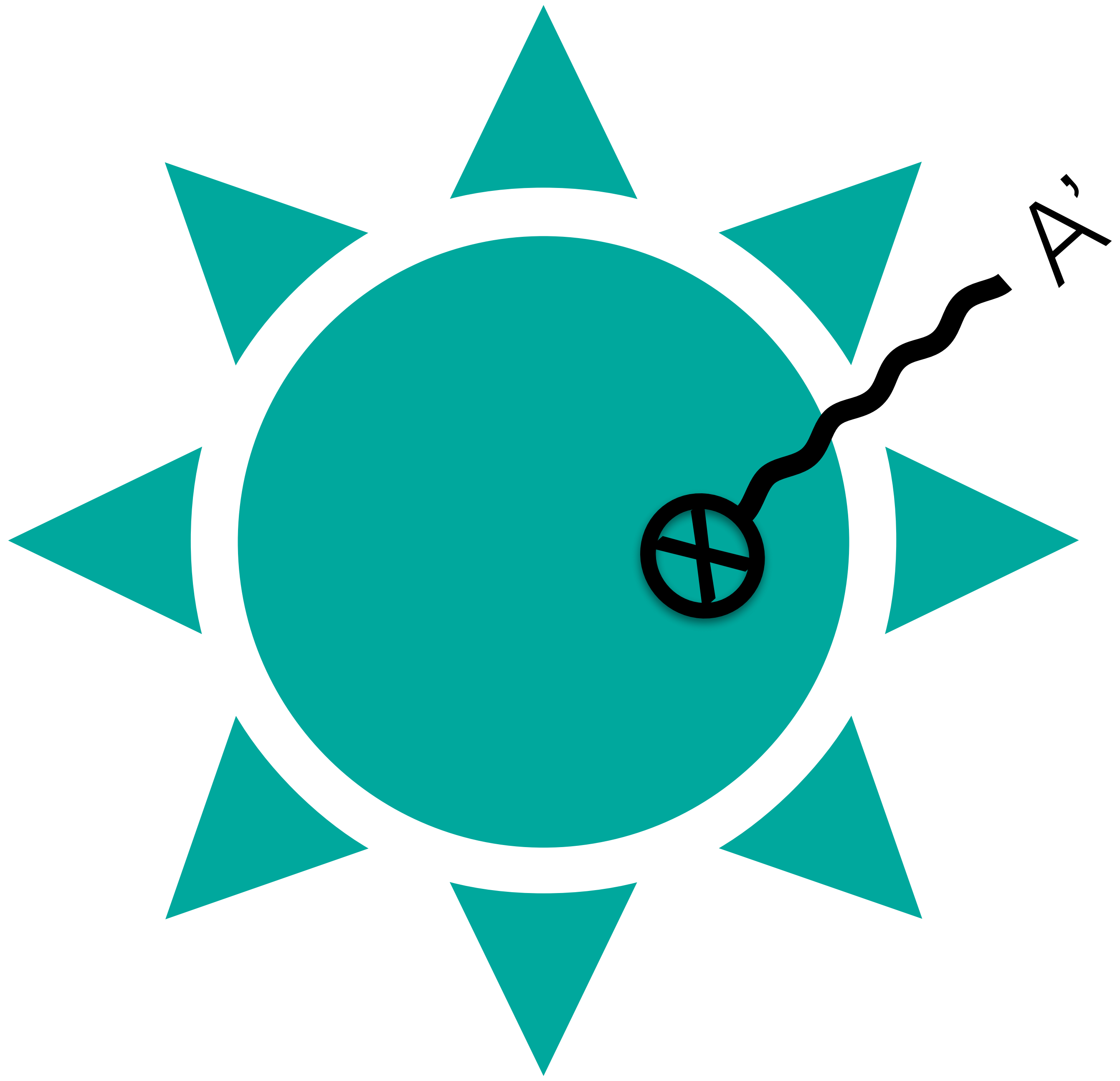
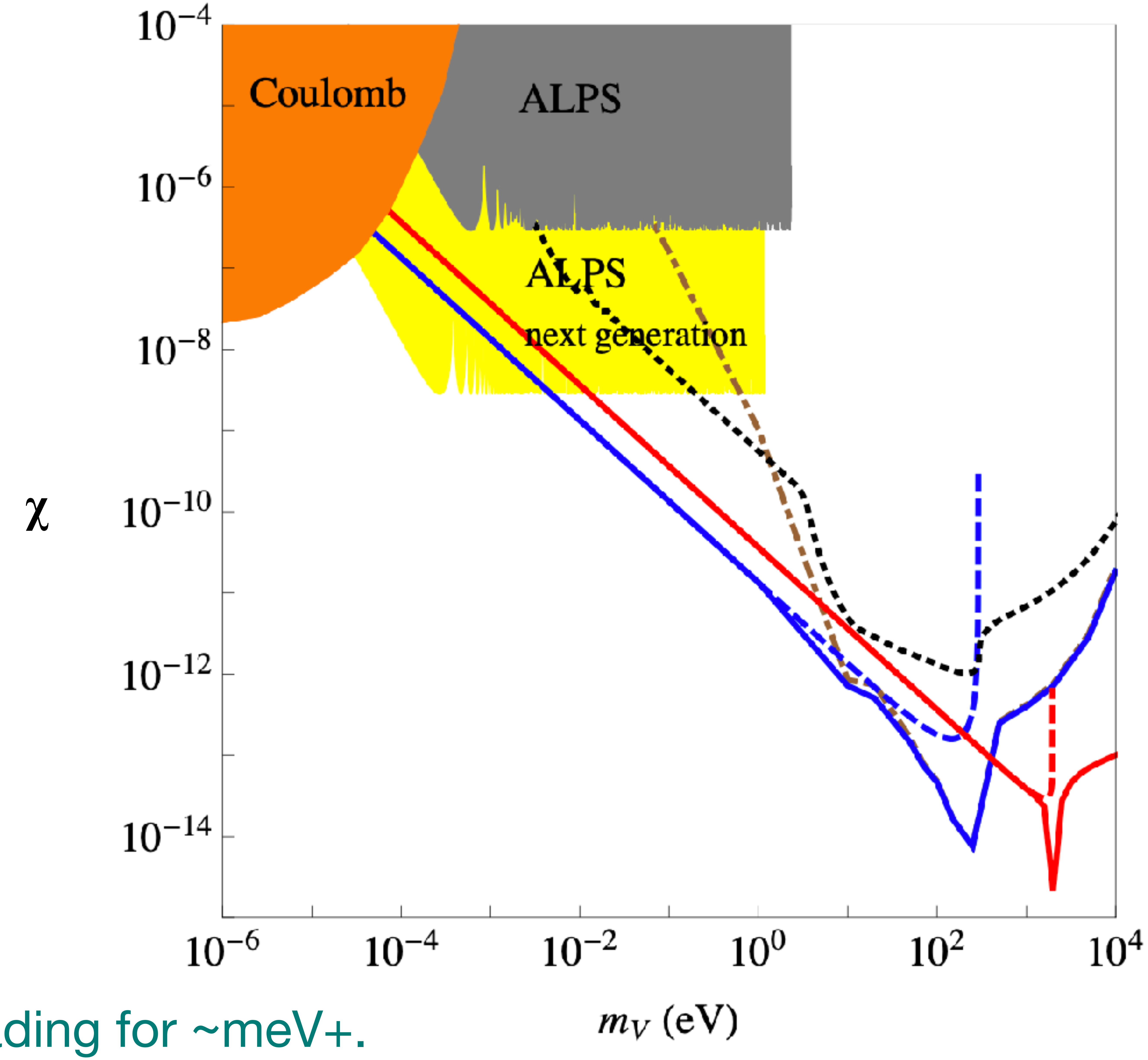
Stellar emission with longitudinal mode





Stellar emission bounds currently leading for ~meV+.

An, Pospelov, Pradler 1302.3884
Raffelt 1996

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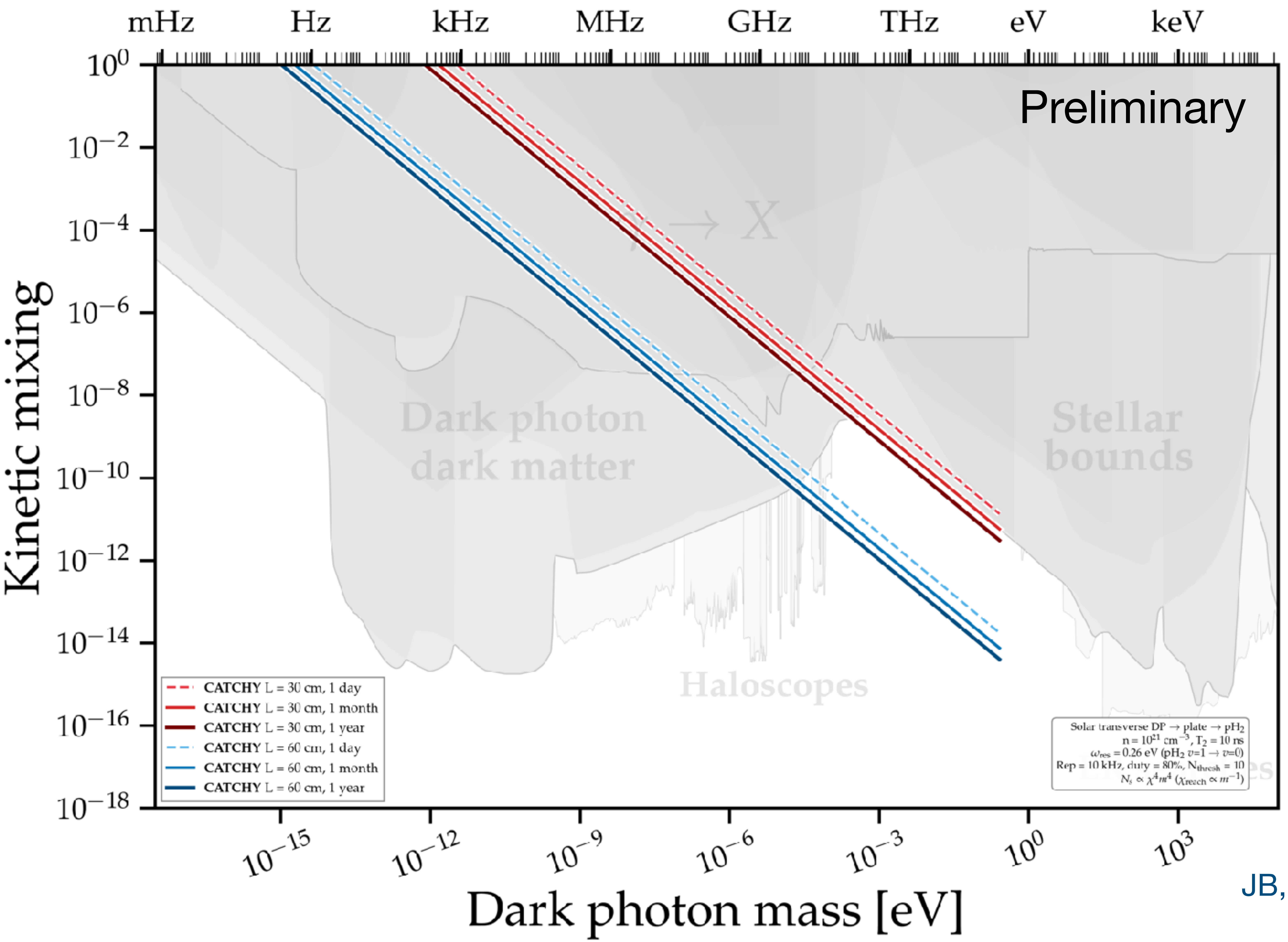

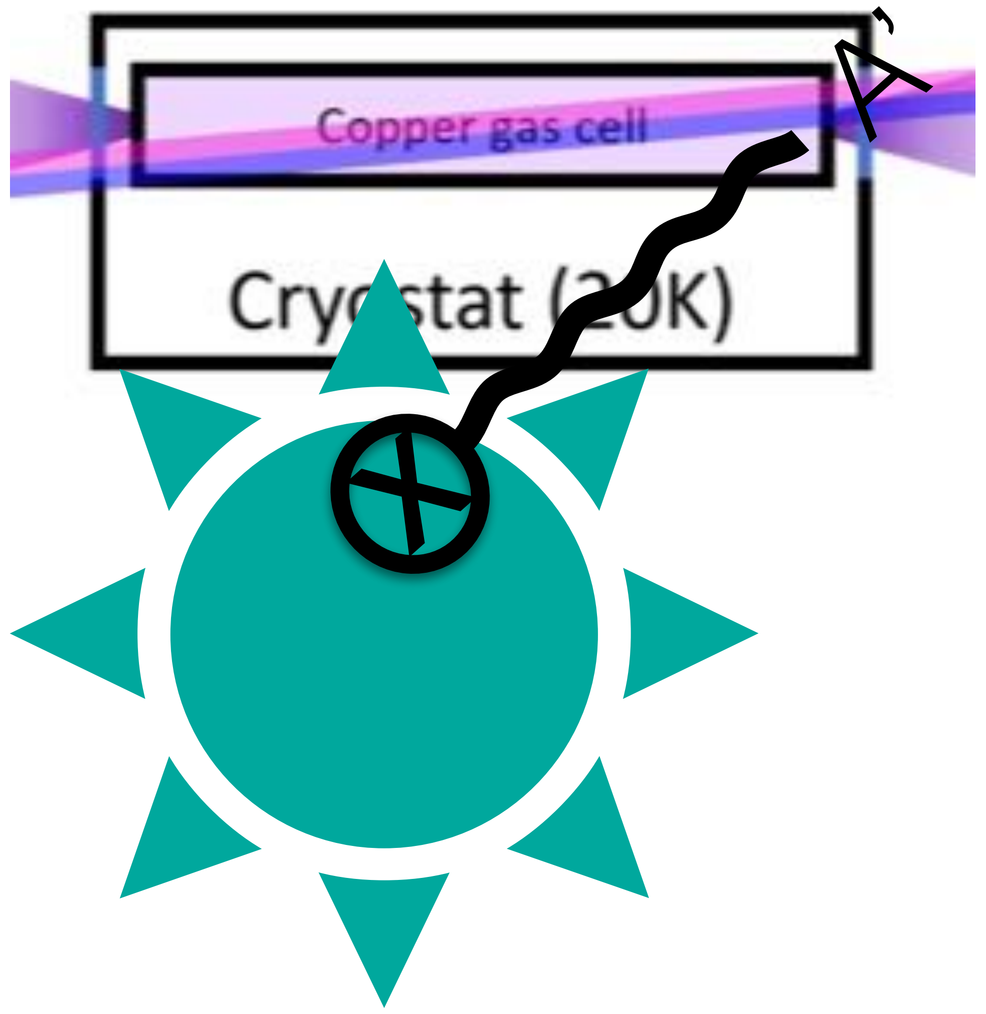

$$\left(\frac{dP}{dA}\right)_{\text{SolarDP}} = \frac{W_{\gamma'}}{4\pi d_\odot}\langle\cos^2\alpha\rangle\chi^2$$

JB, Jaeckel, Kulkarni, Song 260x.xxxxx

CATCHY works out of the box as a helioscope - sensitivity scales dramatically with N.

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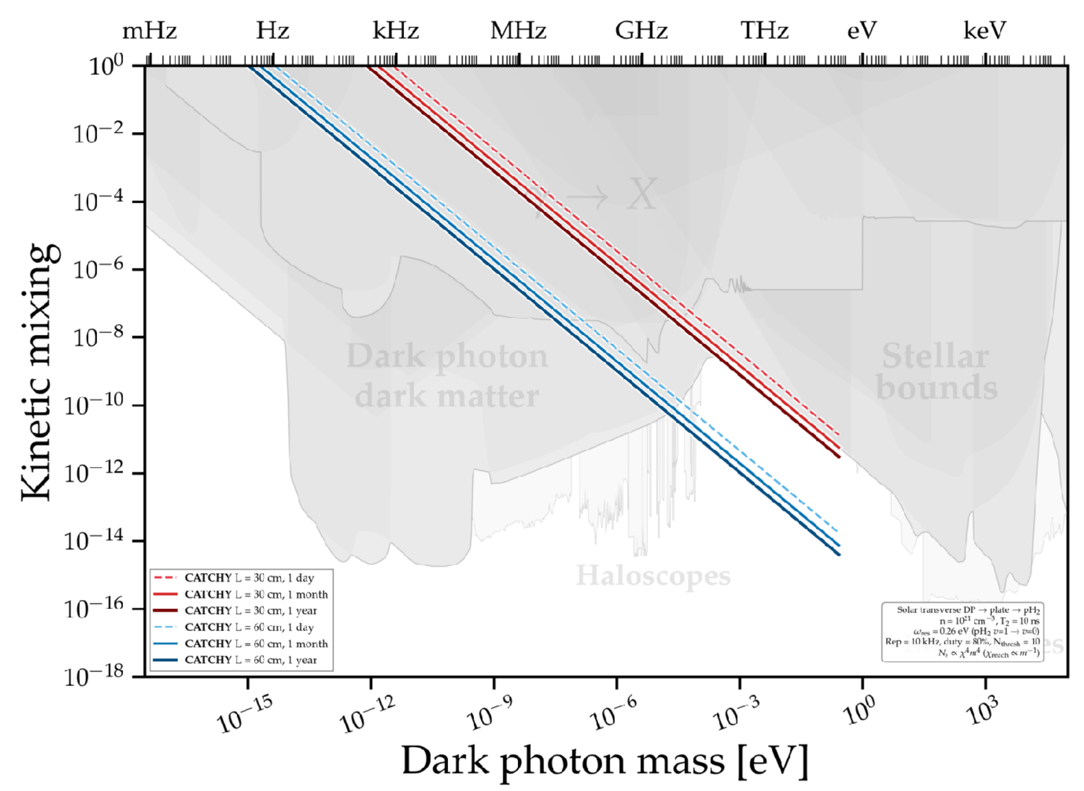
The nonlinear sensitivity (to A’ or A) scales with n (also L, t) and can be understood quantitatively



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

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

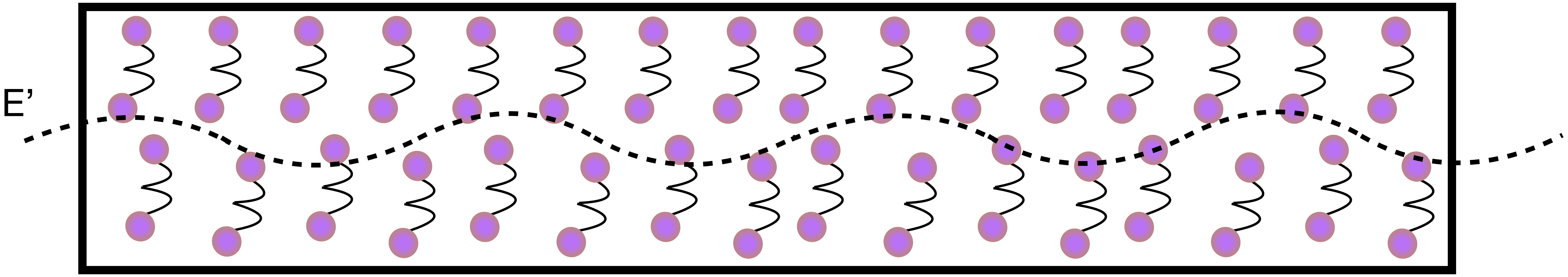
$$(\partial_t^2 - \partial_z^2)E_1 - n^2\Omega_r^2 E_1 = 0$$

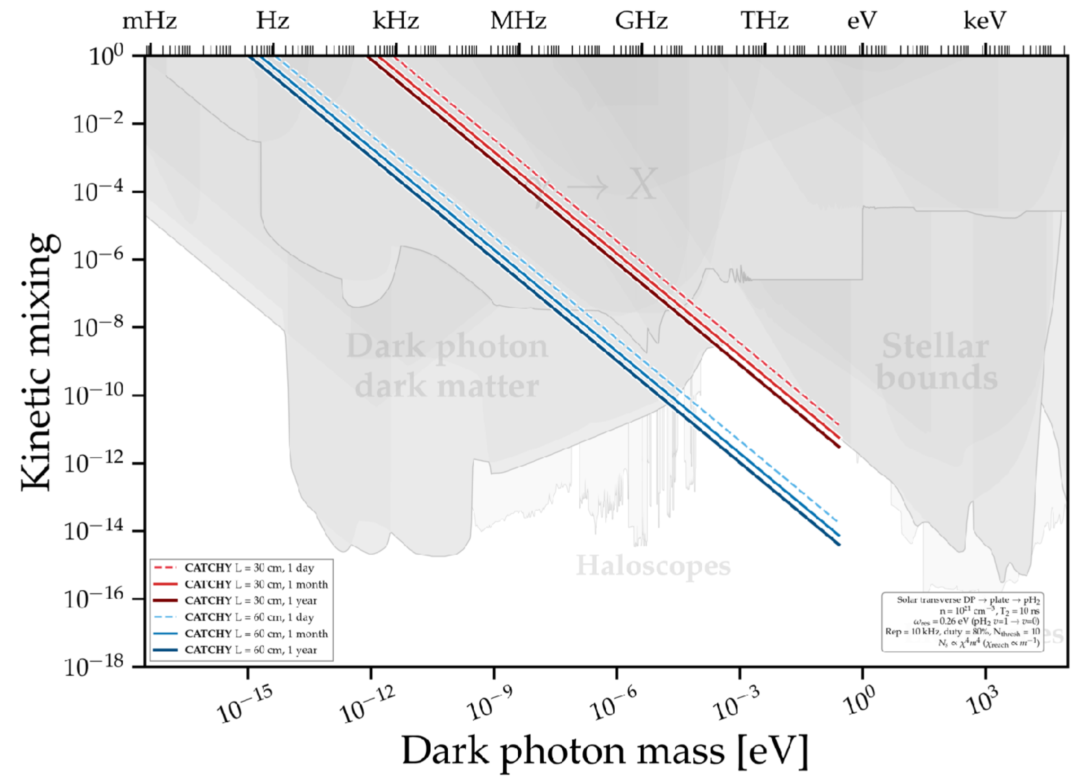
$$E_1 \propto e^{n\Omega_r t}$$

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

->Exponential dependence on n, t, r_1

and qualitatively





The nonlinear sensitivity (to A' or A) scales with n (also L, t) and can be understood quantitatively

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

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

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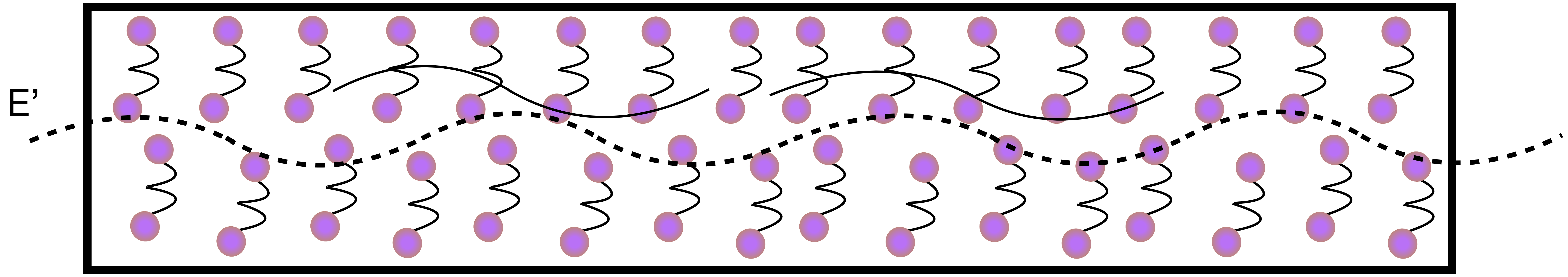

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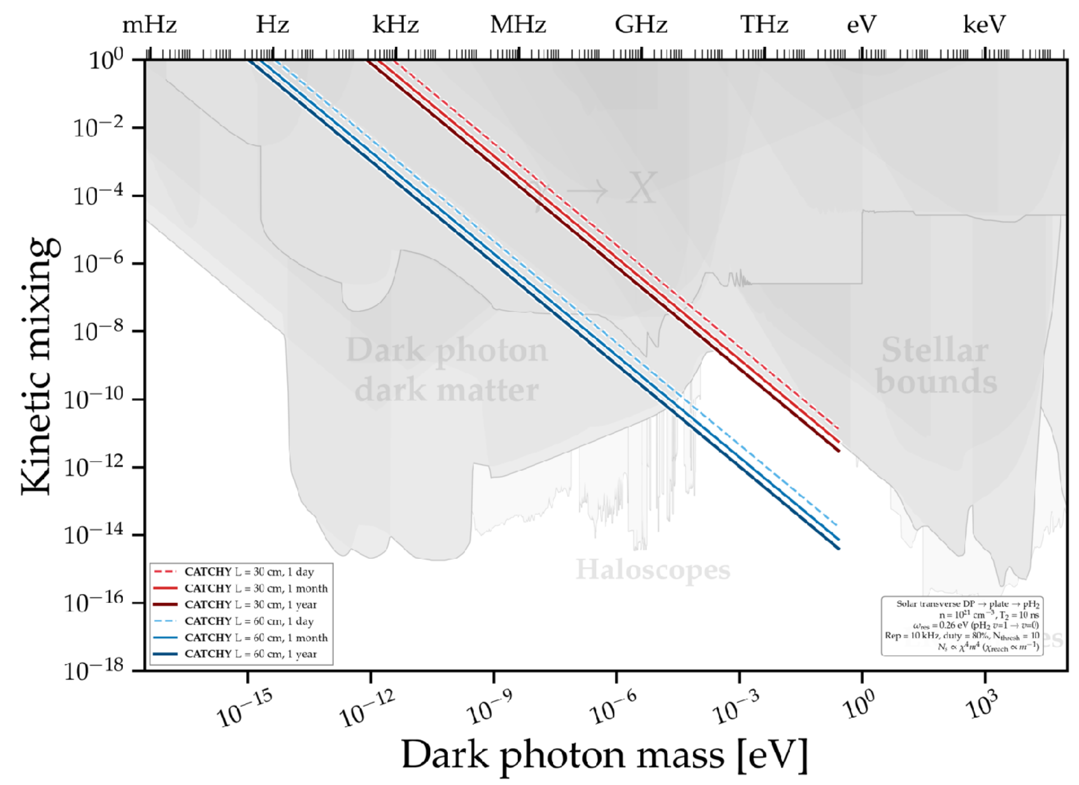
The nonlinear sensitivity (to A’ or A) scales with n (also L, t) and can be understood quantitatively



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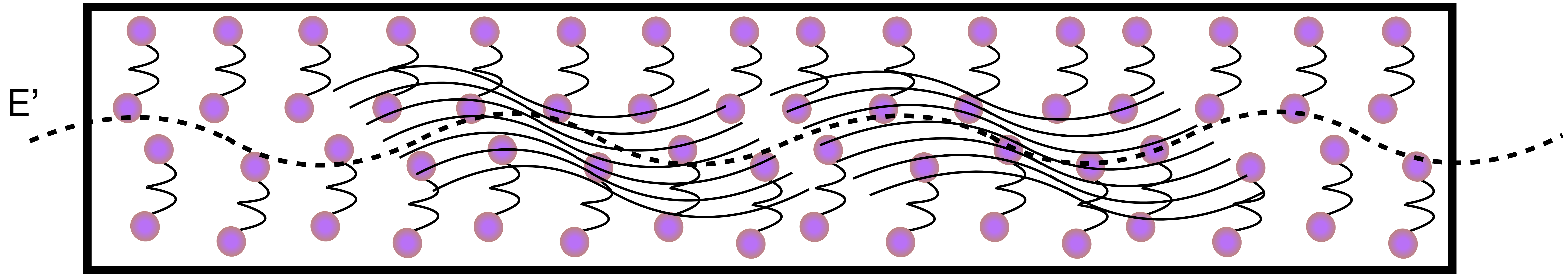
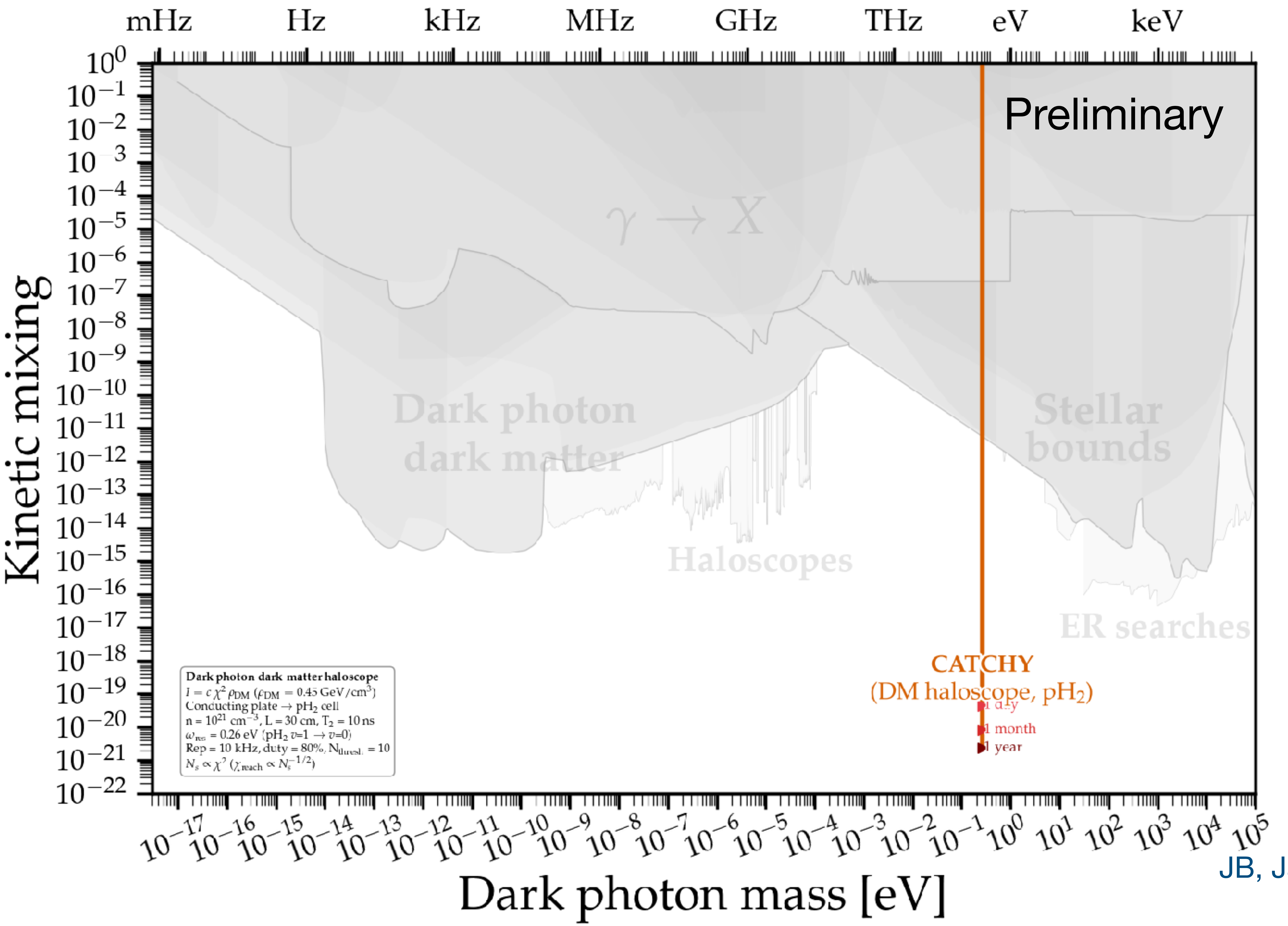
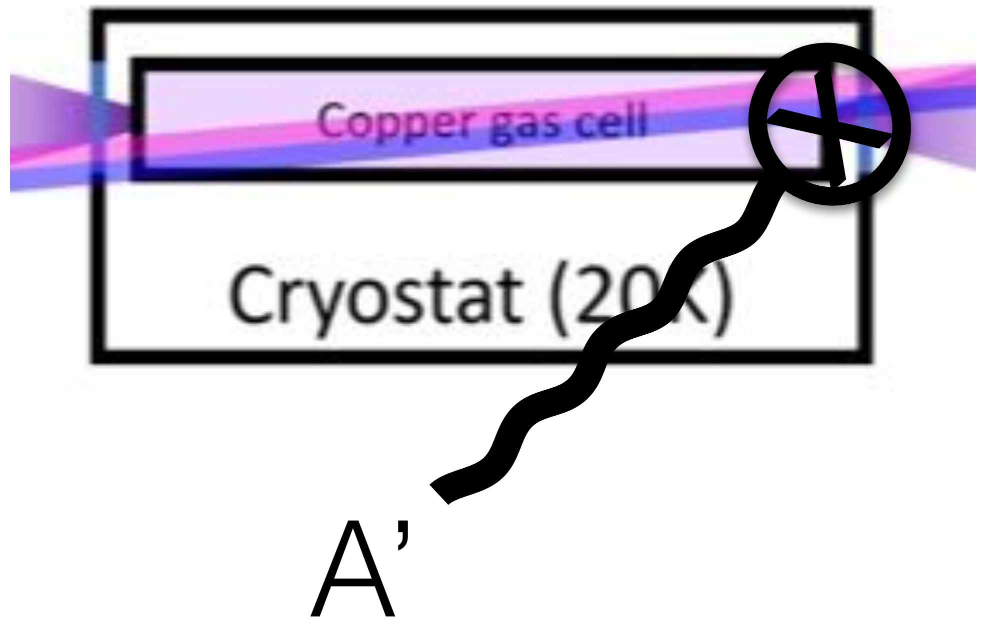
and qualitatively



(it’s a quantum avalanche detector)





$$\left(\frac{dP}{dA}\right)_{DP} = \langle \cos^2 \alpha \rangle \chi^2 \rho_{CDM}$$

JB, Jaeckel, Kulkarni, Song 260x.xxxxx

Catchy also works as a (very) limited haloscope.

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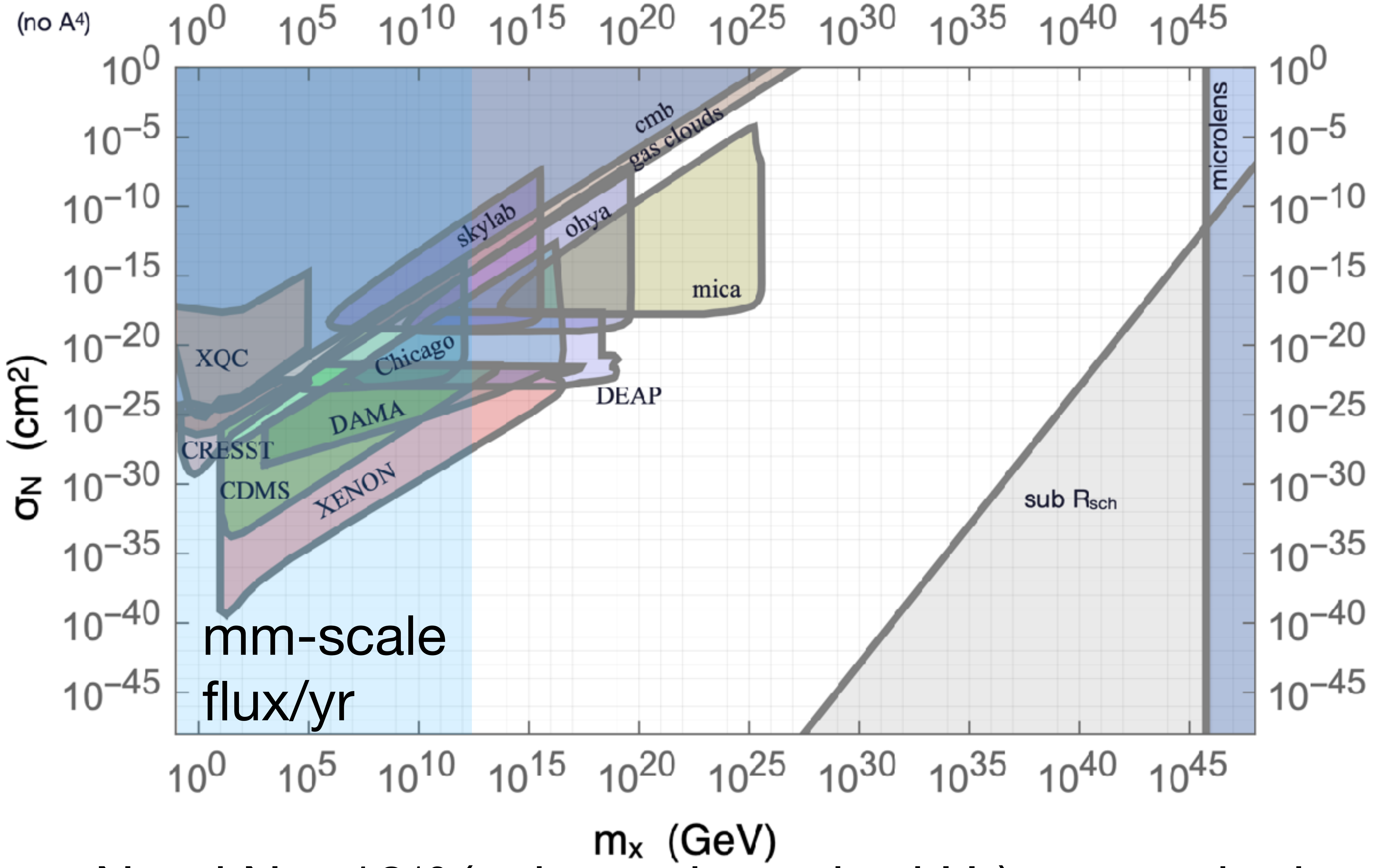
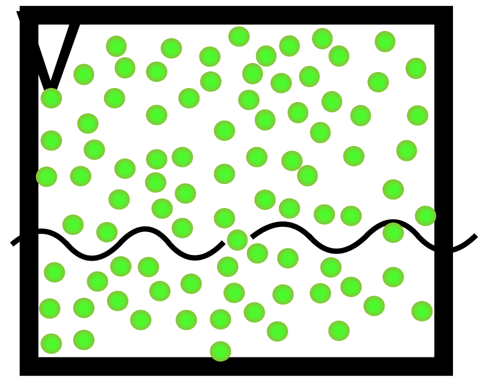
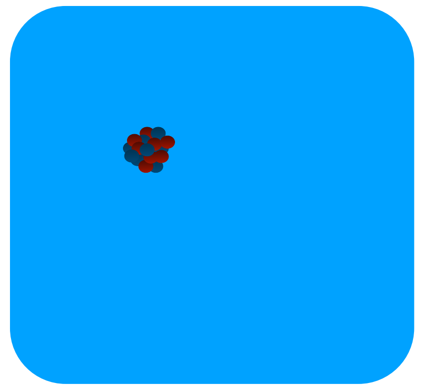
Dark matter, quantum detection



$$\text{QSignal} = N^2\Gamma t$$



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



Need N ~ 10^{18} (coherently excited H_2) to match classic NA^4 for WIMPs.

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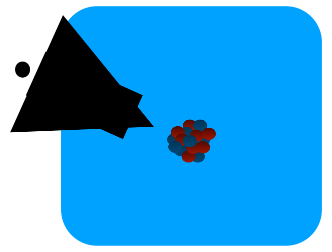
N^2 detection and CATCHY

Motivation and comparison with traditional detectors



CATCHY: Bhardwaj, Buchanan JB, Fraser, Godfrey, Kulkarni, Song





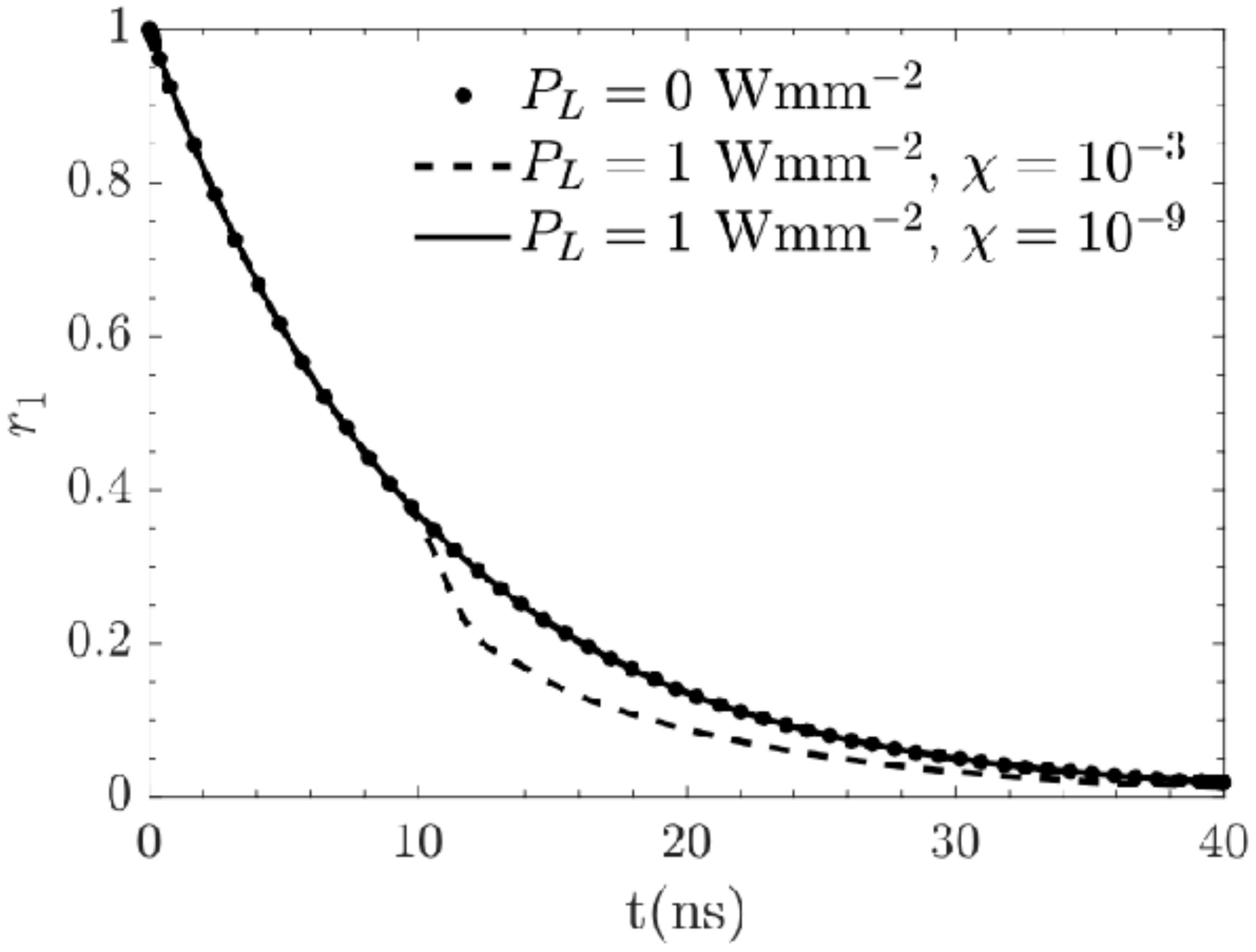
Light boson searches using coherent atoms

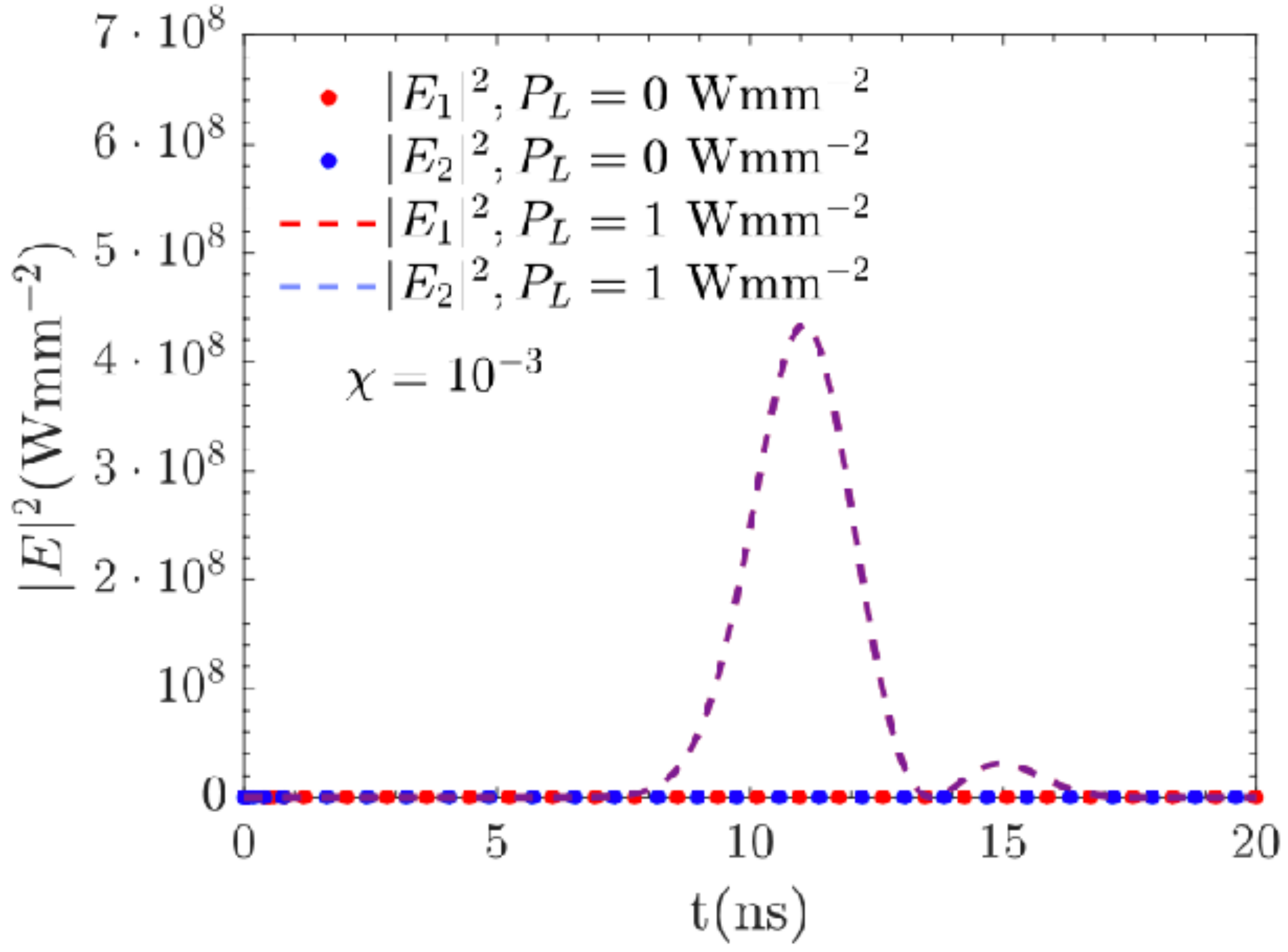
Bhoonah, JB, Song 1909.07387

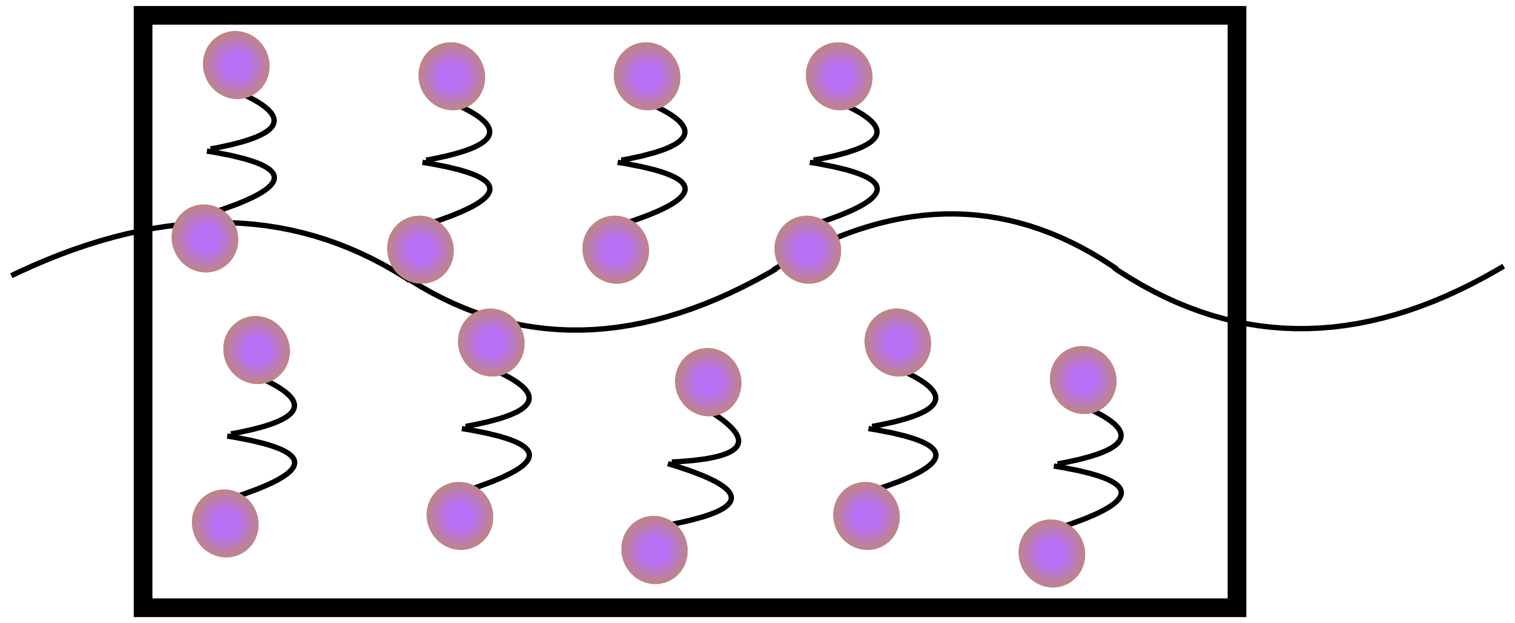
JB, Kulkarni, Song 260x.xxxxx

Godfrey PhD: https://www.proquest.com/docview/3161889593

Thanks! Questions?







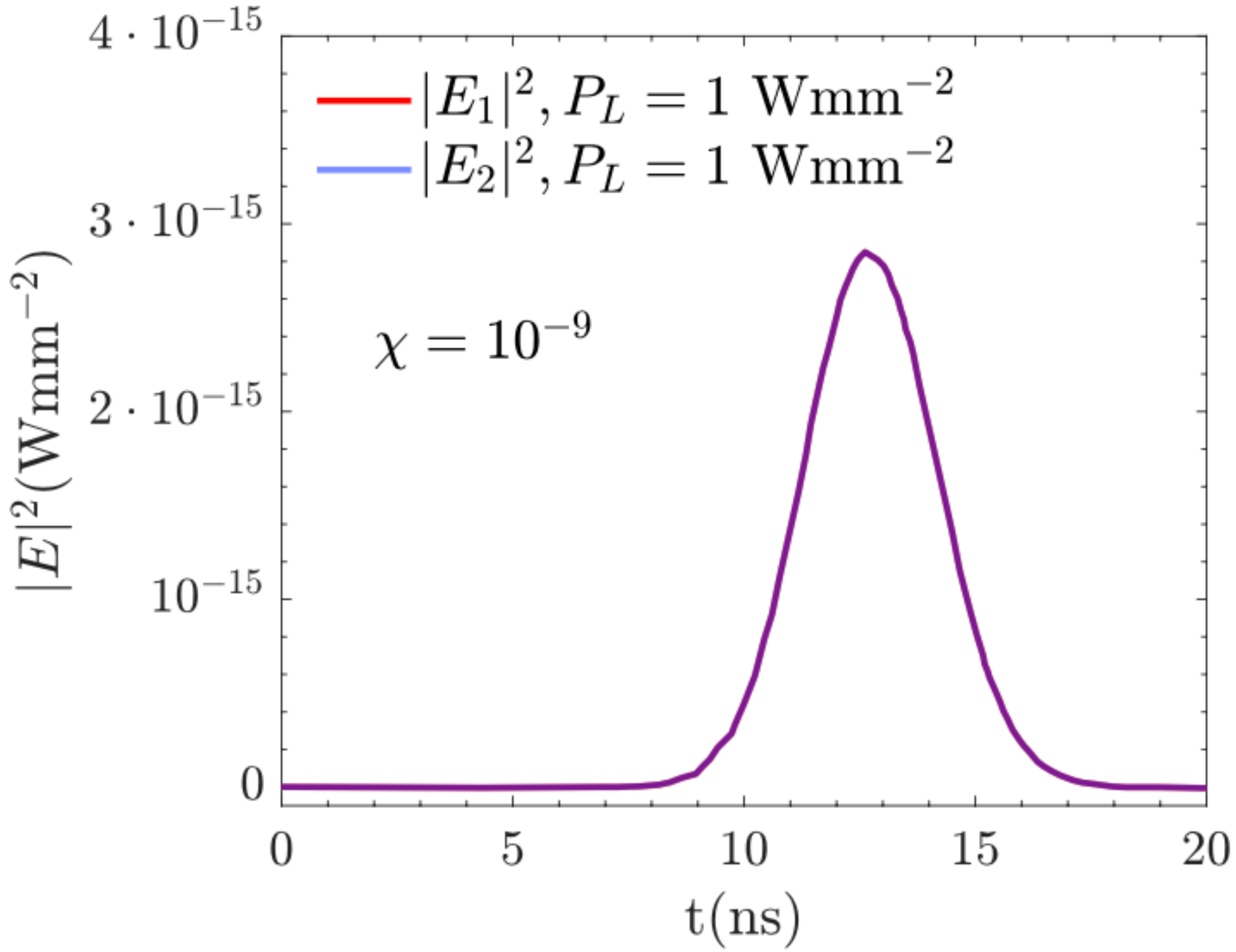
E’, E_1 , E_2

Maxwell-Bloch equations with the E1xE1 transition Hamiltonian integrated over experimental volume to find power emitted in photons from the sample, start from $r_1 = 1$.

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

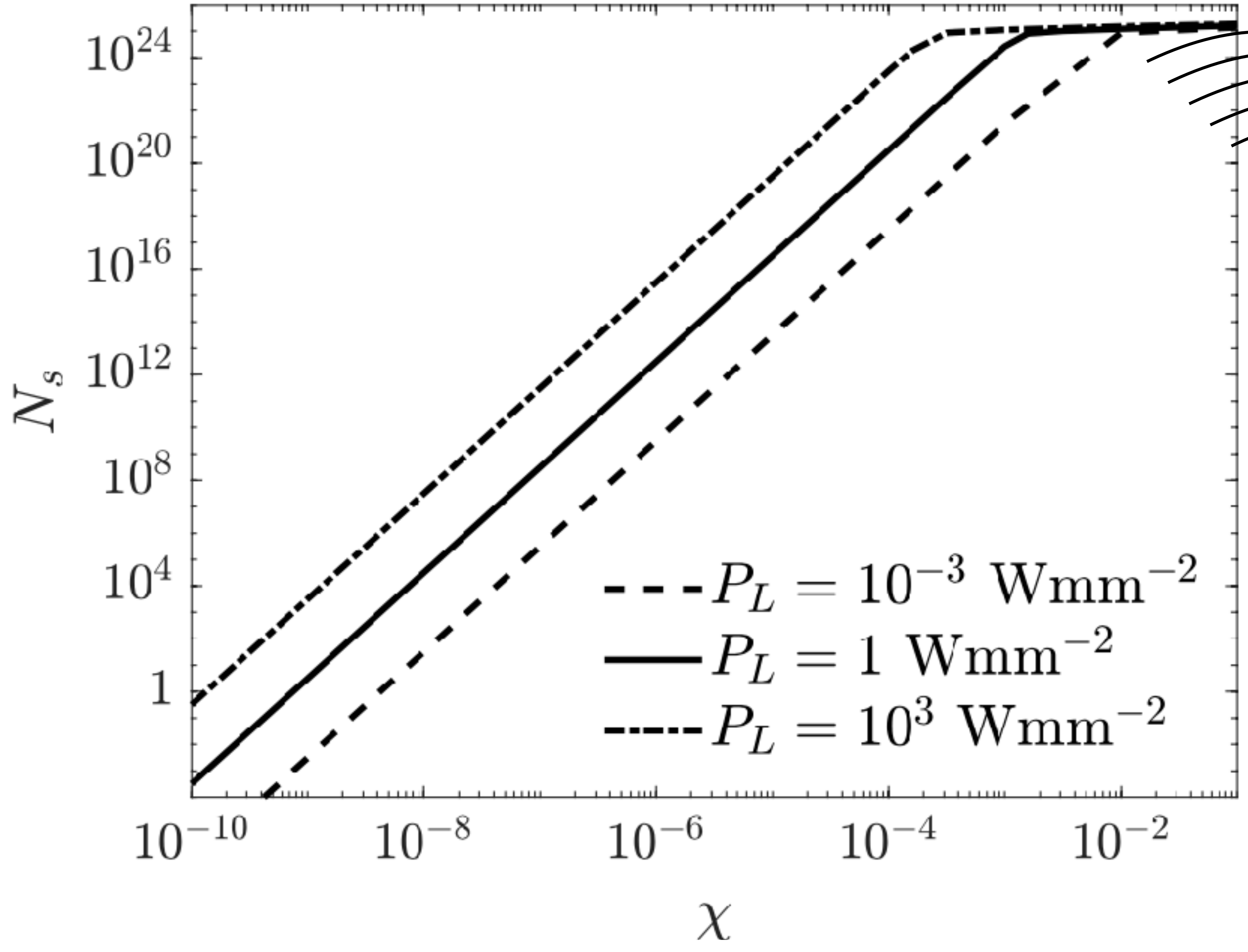
$$(\partial_t + \partial_z)E_2 = \frac{i\omega n}{2}\left[(\frac{a_{ee}+a_{gg}}{2} + \frac{a_{ee}-a_{gg}}{2}r_3)(E_2 + \chi\eta E') + a_{eg}(r_1 - ir_2)E_1^*\right],$$

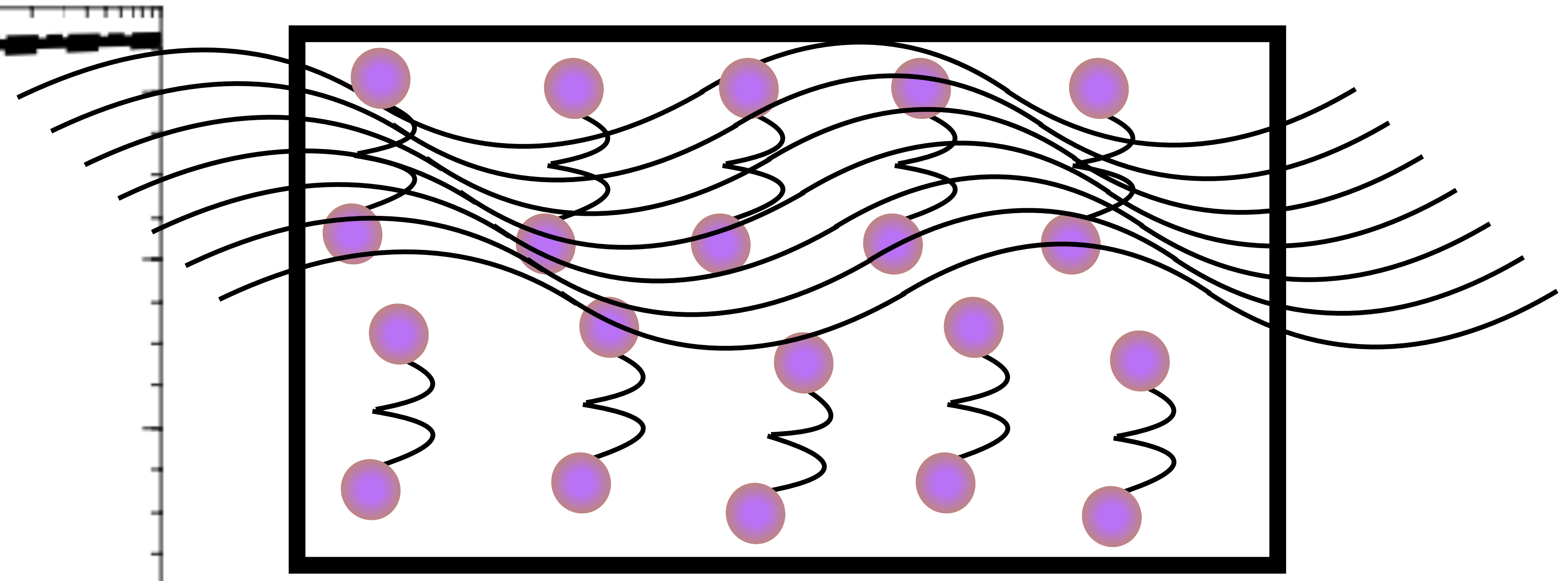
$$(\partial_t + \partial_z)E' = \frac{i\omega n}{2}\left[(\frac{a_{ee}+a_{gg}}{2} + \frac{a_{ee}-a_{gg}}{2}r_3)(2\chi^2\eta E' + \chi E_2) + a_{eg}(r_1 - ir_2)\chi\eta E_1^*)\right]$$



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 $N_{\rm pass} = 2 \times 10^4$	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





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

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

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
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