Neutrino spectroscopy with atoms and laser
— toward detection of relic neutrino —

A. Yoshimi on behalf of SPAN-collaboration

Okayama University

SPAN = SPectroscopy of Atomic Neutrinos

Collaborators

Okayama university

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M. Yoshimura (Theory)
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A. Yoshimi (Nucl. Phys.)
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T. Hiraki (Particle Phys.)

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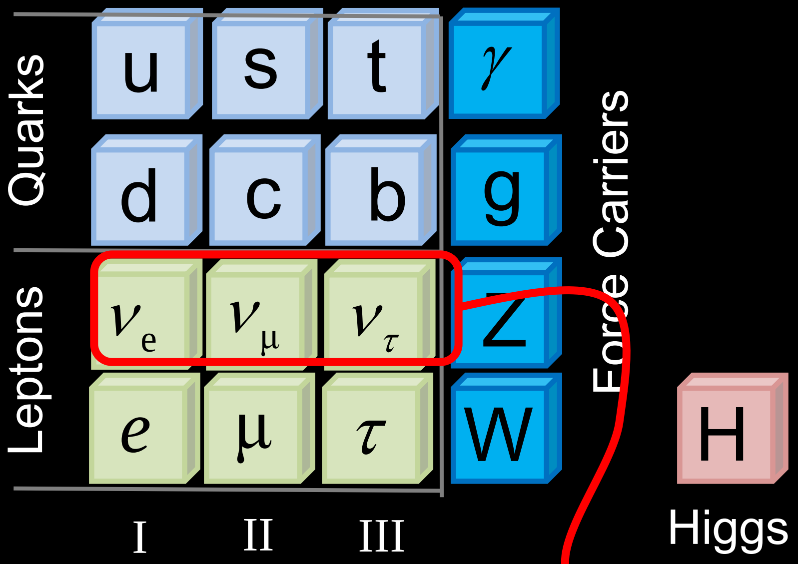
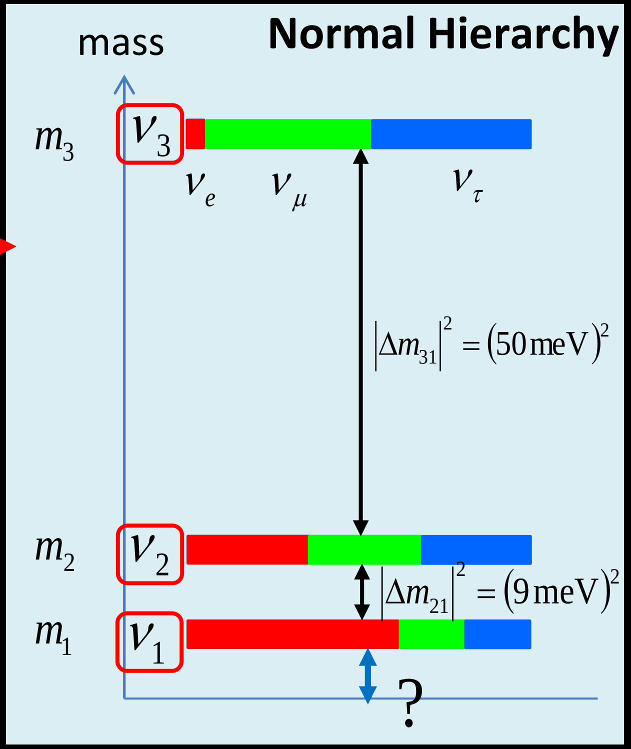
Okayama Univ.

Osaka Univ.
M. Tanaka (Theory)

Neutrino Physics



- Neutrino oscillation experiments have been successful, but ….
- The origin of quite smallness of neutrino mass ($m_{\nu e}$ / m_e < 10^{-5}) ?
- Is Matter/Anti-matter asymmetry relevant to neutrino properties ?



Must be clarified

- Absolute neutrino mass
- Dirac / Majorana distinction
- Mass hierarchy
- CP-violating parameters in Lepton sector
- Relic neutrino background

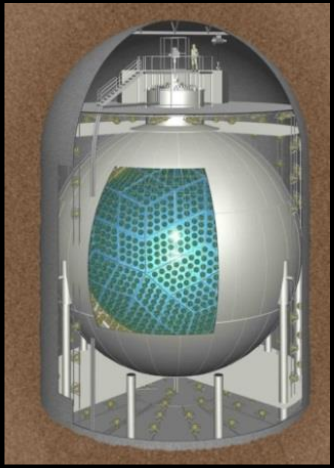
Neutrino Experiments

Neutrino oscillation experiment

Mass type, CP phase

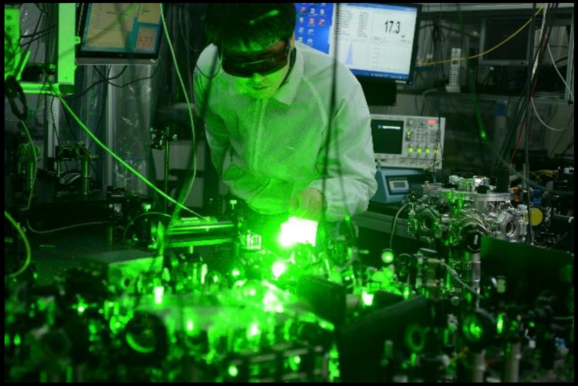
Neutrino-less ββ decay

- Majorana/Dirac
- Effective neutrino mass



Our method ; "Atomic neutrino" experiment

- Small table-top experiment



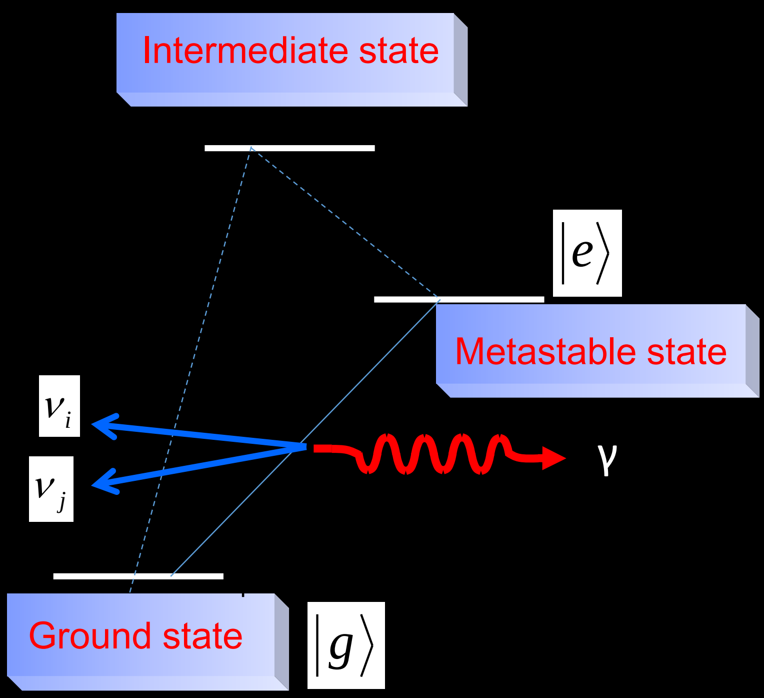
Direct mass measurement (3H β-decay)

- β-decay endpoint.

Neutrino emission from excited atom

- **Radiative emission of neutrino pair (RENP) from excited atoms decaying to ground state.**

$$|e\rangle \rightarrow |g\rangle + \gamma\nu\bar{\nu}$$



Meta-stable state

Low-order Ele-Mag transitions forbidden

Energy scale

eV ~ meV : neutrino mass scale

Associated photon

Spectrum includes information of neutrino-mass, mass-type, etc.

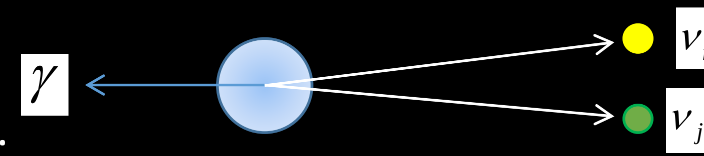
Systematic determination of neutrino properties

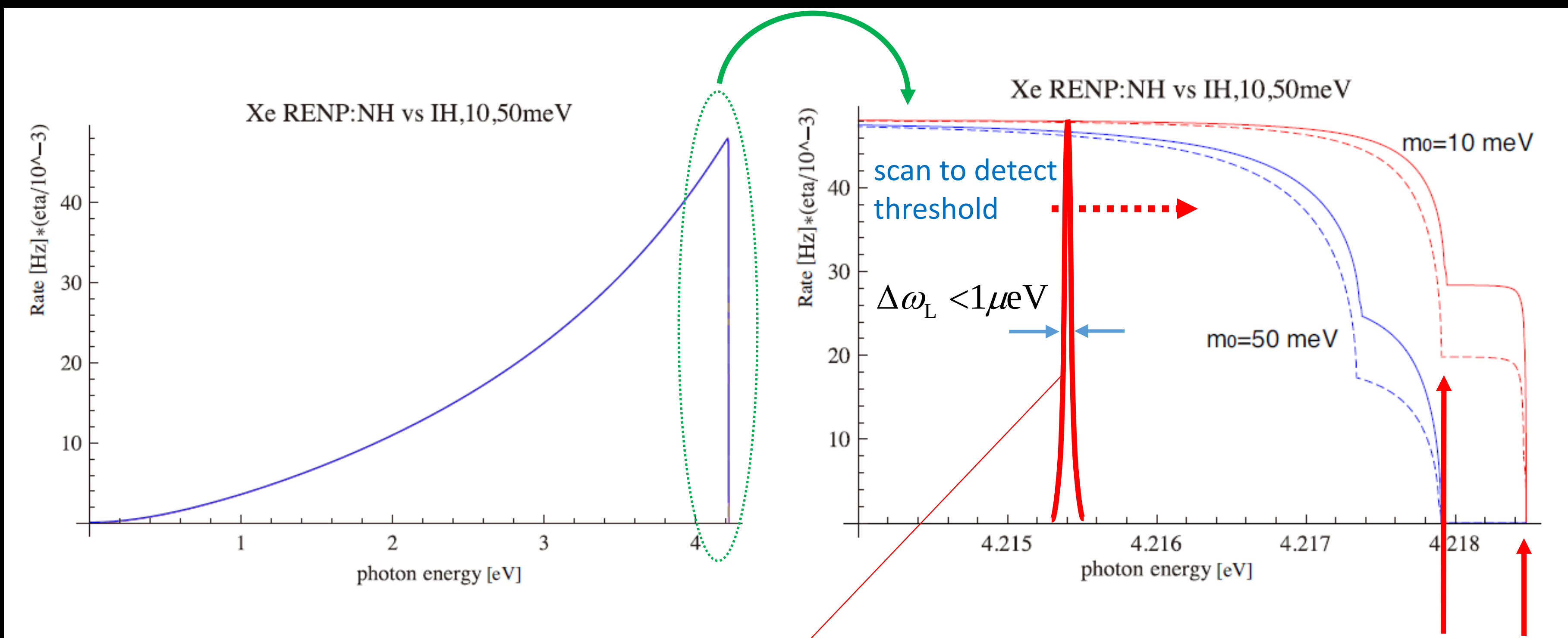
A. **Fukumi et al.,**
B. **Prog. Theor. Exp. Phys. (2012) 04D002.**

Neutrino absolute mass in photon spectrum

RENP photon spectrum

Overall spectrum is similar to muon decay at rest.



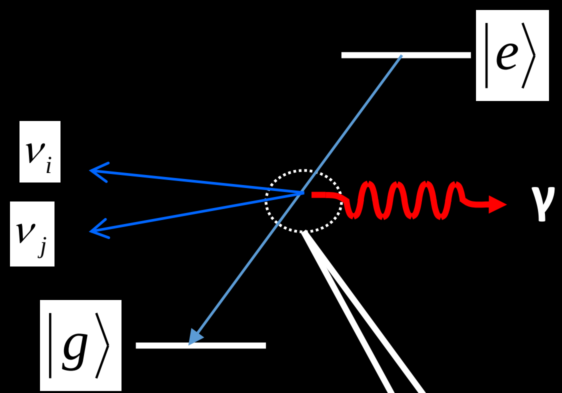


Trigger laser of 294nm (4.22eV) with 100MHz-width

$$\Delta m_i < 1\mu\text{eV}$$

Threshold: $$\omega_{ij} = \frac{\varepsilon_{eg}}{2} - \frac{(m_i + m_j)^2}{2\varepsilon_{eg}}$$

RENP process; within the Standard Model



Weak Interaction process

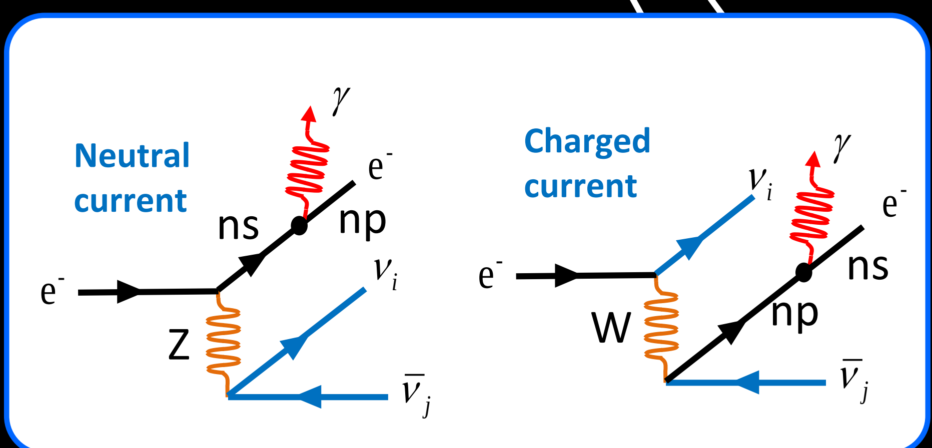
$$\Gamma_{\mathrm{RENP}} = \frac{1}{30\pi^3} G_F^2 (\Delta E)^5 \approx 10^{-34} [\mathrm{s}^{-1}]$$

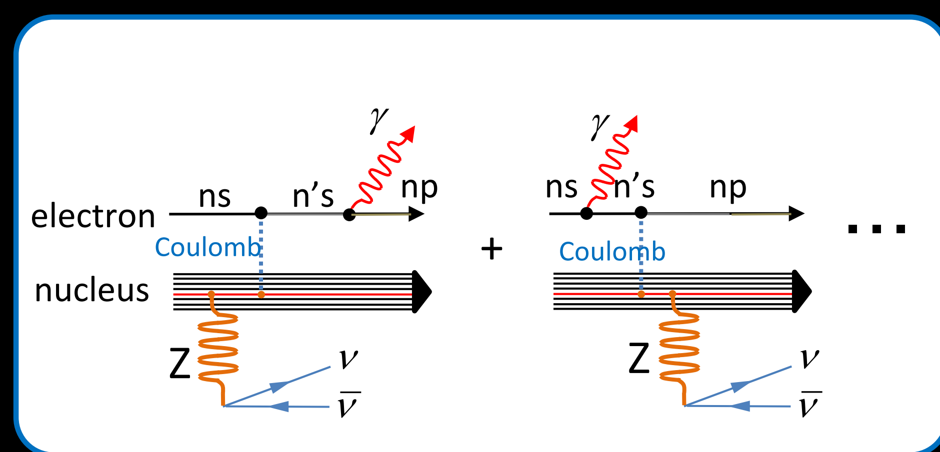
Rate enhancement
if macro-coherence achieved

$$\Gamma_{\mathrm{RENP}} \approx 50[\mathrm{Hz}] \cdot \left(\frac{n}{7\times 10^{20}\,\mathrm{cm}^{-3}} \right)^3 \left(\frac{V}{10^2\,\mathrm{cm}^{-3}} \right) \left(\frac{\eta}{10^{-3}} \right)$$

for $^3P_1$ (8.3eV) in Xe atom

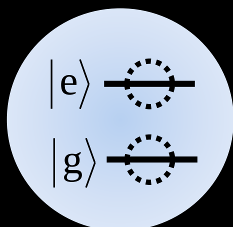
M.Yoshimura and N. Sasao, Phys.Rev.D 89, 053013 (2014)





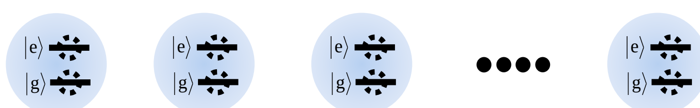
Atomic coherence and rate amplification

Superposition of |e> and |g>
in single atom



$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle + e^{i\theta}|e\rangle\right)$$

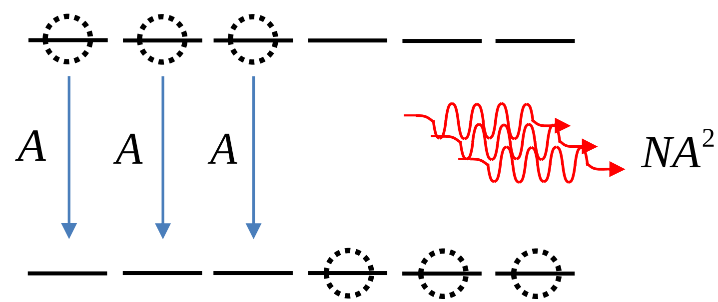
if many atoms have
a common phase.



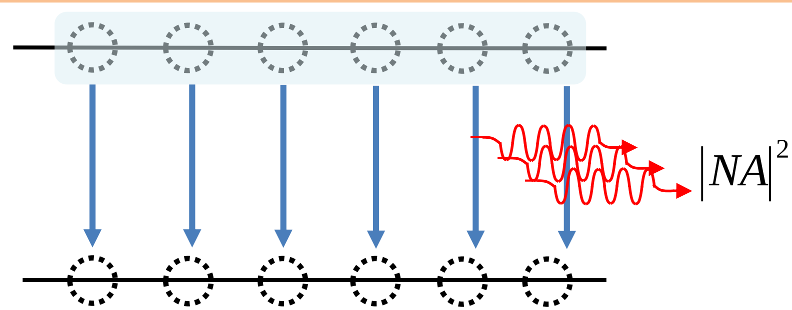
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle + e^{i\theta}|e\rangle\right) \quad \bullet\bullet\bullet\bullet \quad |\psi\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle + e^{i\theta}|e\rangle\right)$$

All atoms are identical !

Independent decays of non-identical atoms



Decays from quantum physically identical atoms

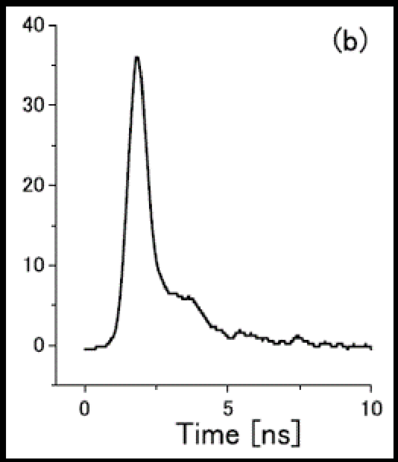


Decay rate is enhanced in the coherent decay

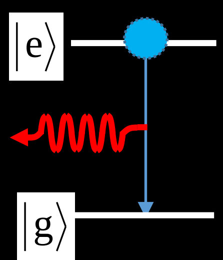
Rate amplification

Huge rate amplification becomes possible by Quantum-mechanical coherence in atoms

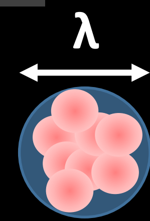
SR measurement
in Ba atoms



Super-radiance (SR); one-photon emission

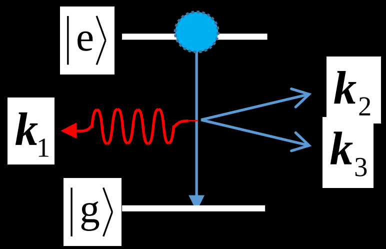


$$R \propto \left|\sum_{a}^{N} \exp\left(i\boldsymbol{k}\cdot\boldsymbol{r}_a\right) M_a\left(\boldsymbol{r},t\right)\right|^2 \propto N^2$$



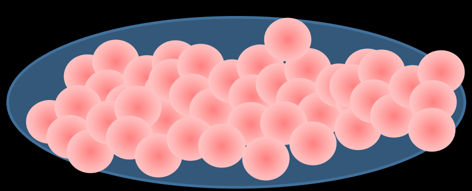
$\boldsymbol{k}\cdot\boldsymbol{r}_a << 1$ only limited volume

Macro-coherent amplification



$$R \propto \left|\sum_{a=1}^{N} \exp\left\{i\left(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3\right)\cdot\boldsymbol{r}_a\right\} M_a(\boldsymbol{r}_a,t)\right|^2 \propto N^2$$

"macroscopic "

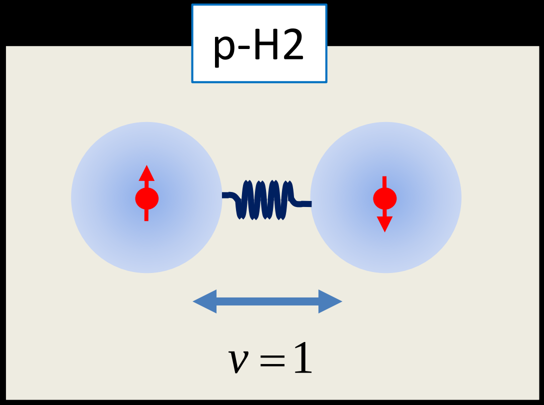


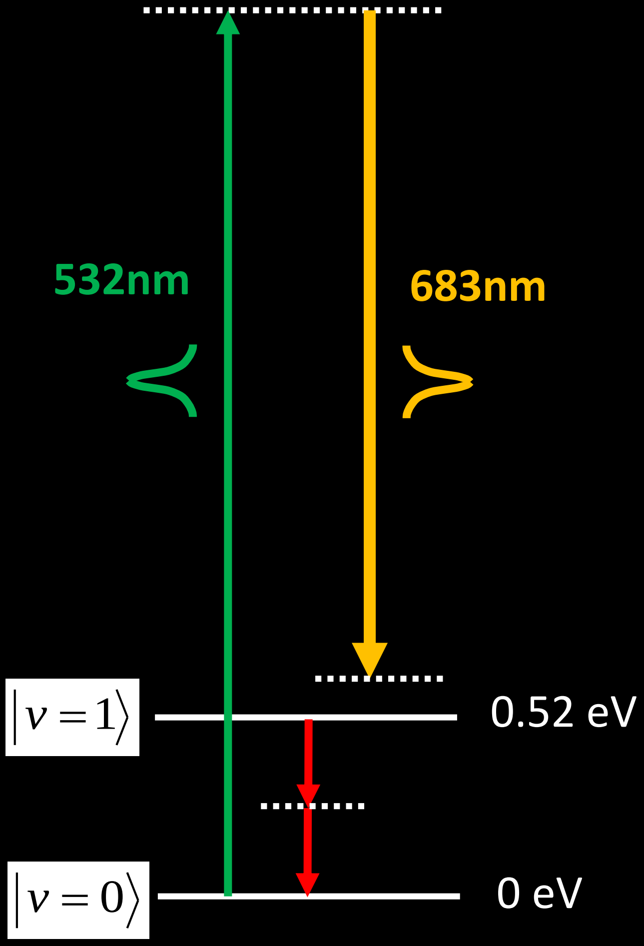
$\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3=0$ **momentum conservation**

Proof-of-principle of rate amplification in two-photon process

Metastable state in Para-Hydrogen molecule

- Vibrationally excited state to ground.
- E1 one-photon decay is forbidden.
- Two photon transition is allowed, but it is a rare process.





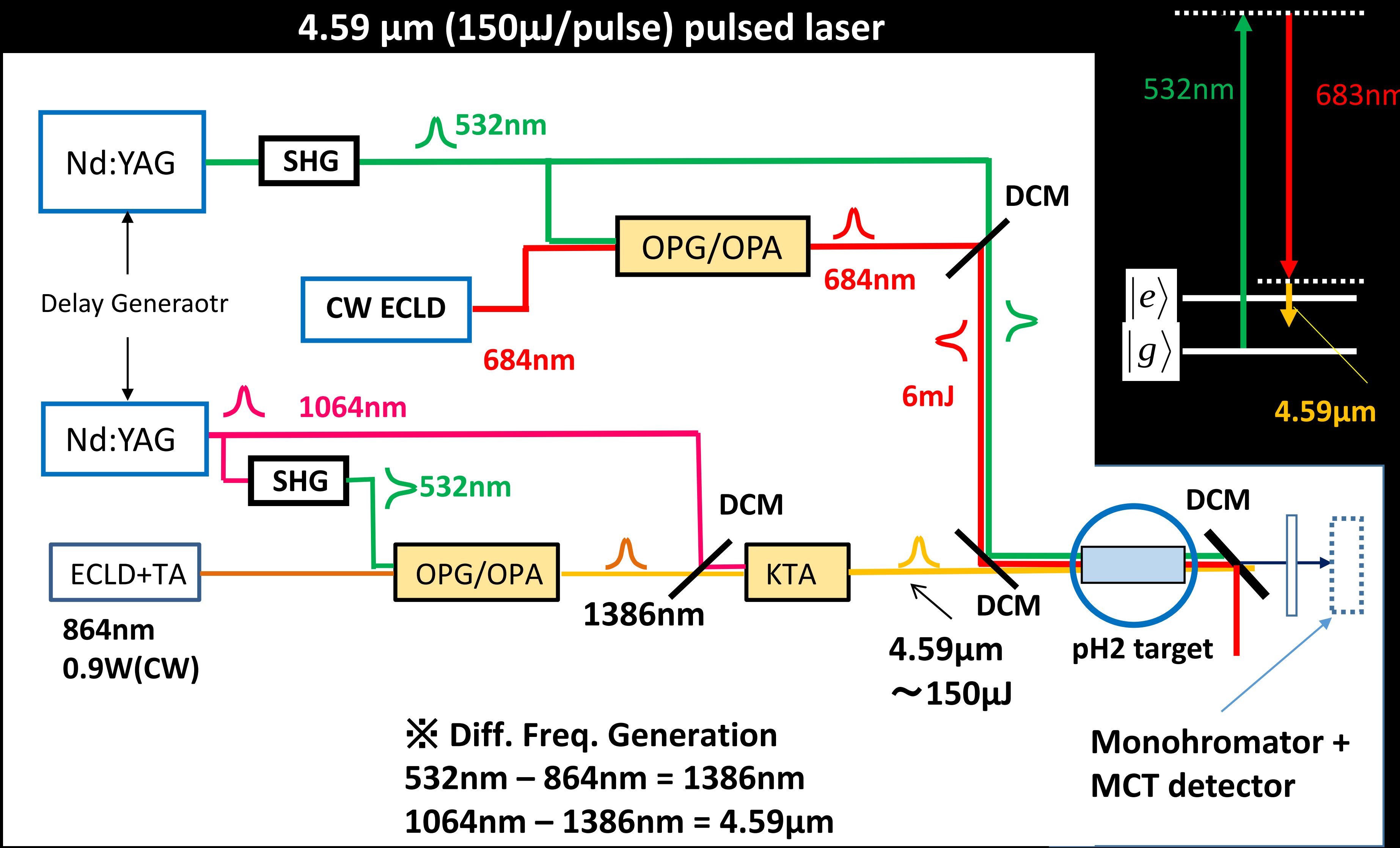
- Produce coherence between two states

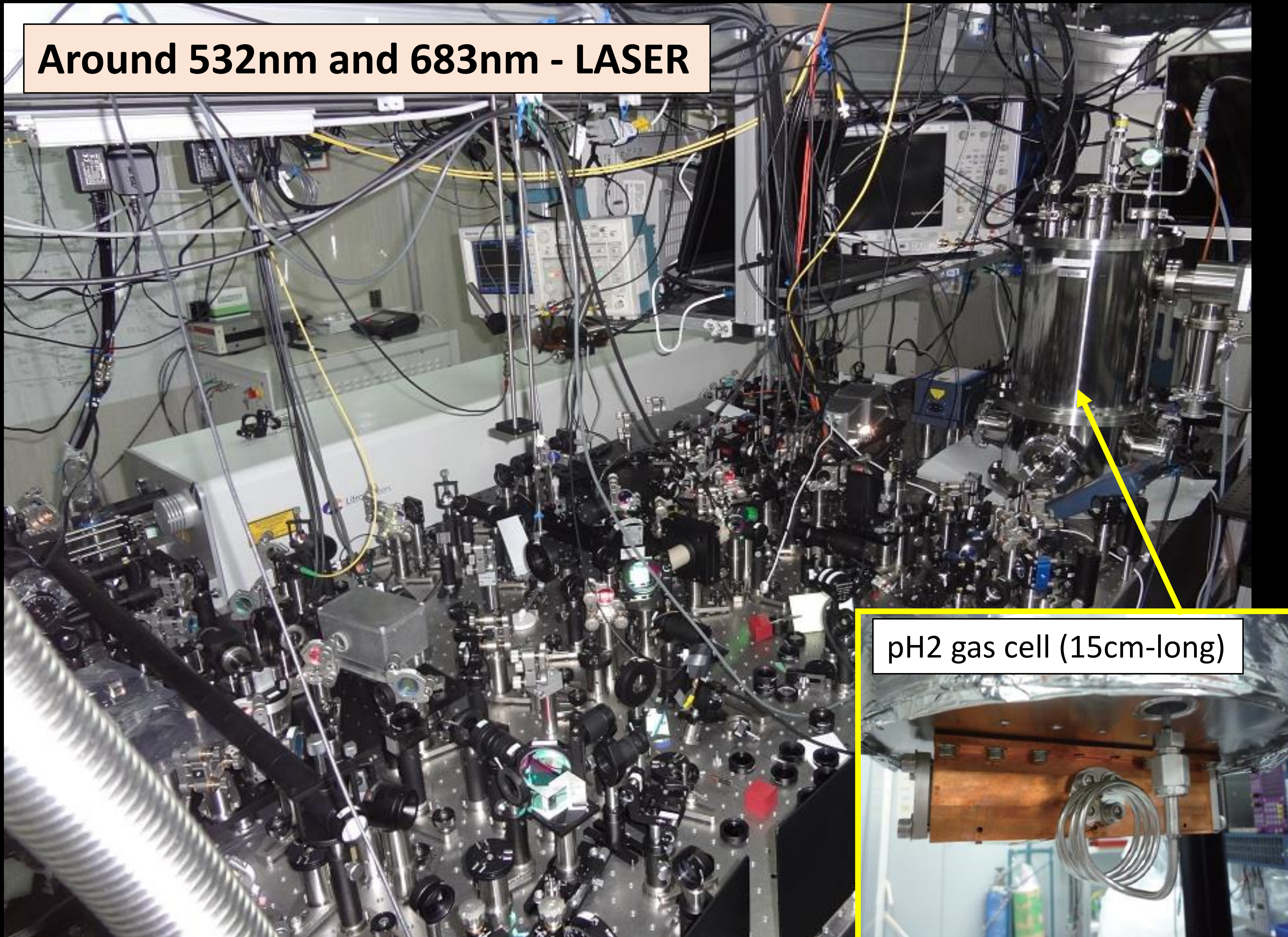
High-quality pulsed-Lasers

High-power, Narrow-width, good profile, …

Experimental setup

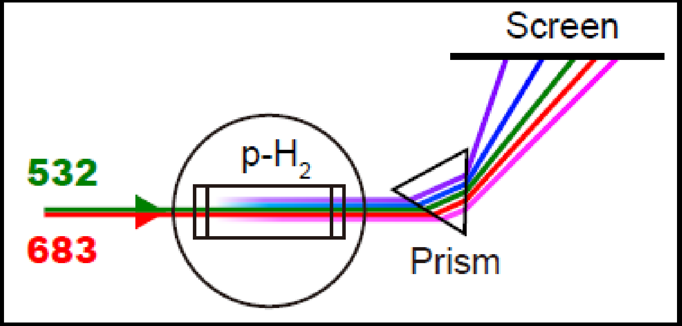
- **Development 683nm (6mJ/p, 100MHz) pulsed laser and 4.59 µm (150µJ/pulse) pulsed laser**

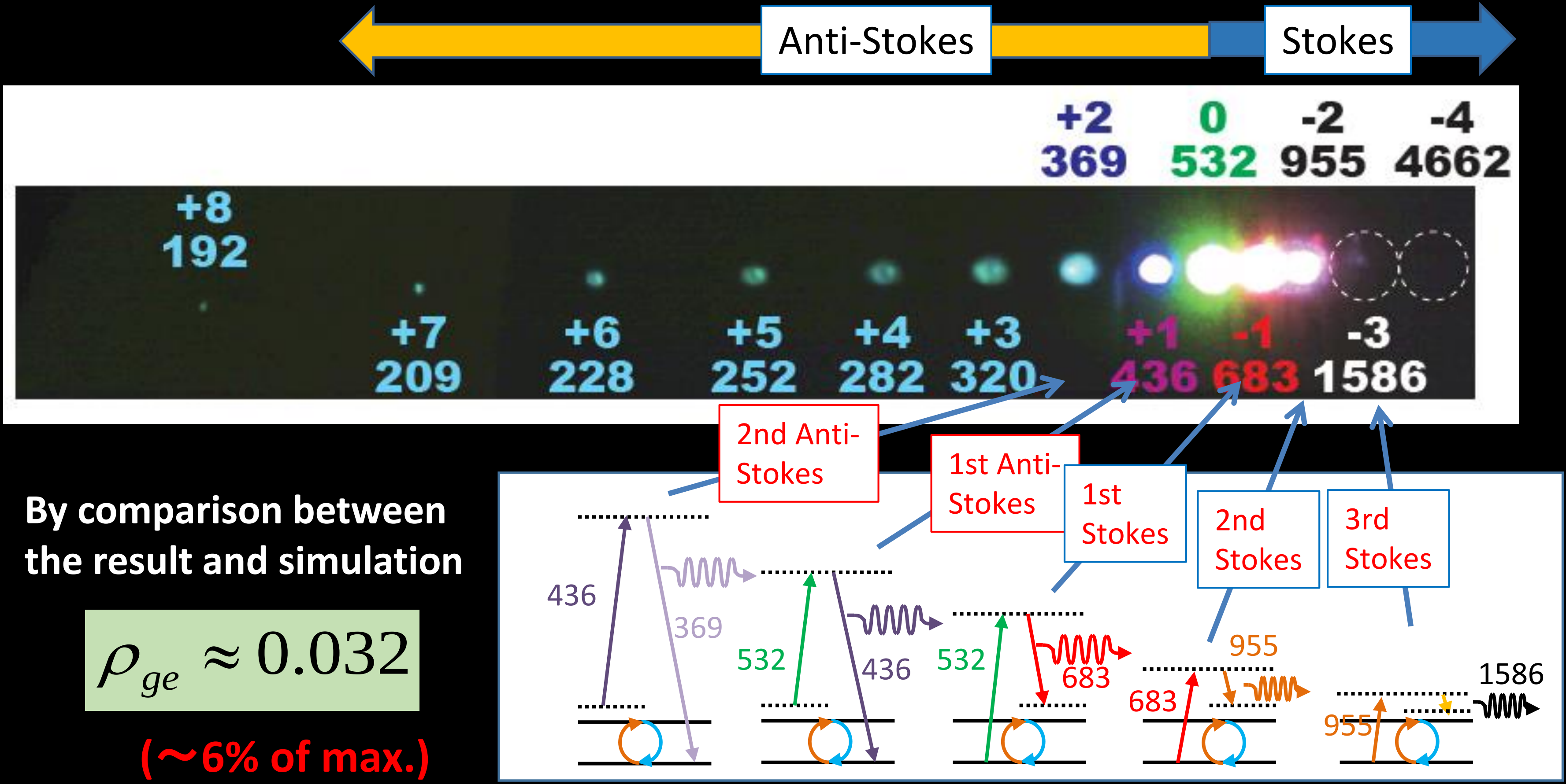



Around 532nm and 683nm - LASER
pH2 gas cell (15cm-long)

"Observation" of coherence

- **Raman sidebands observation**
- **Evidence of large coherence**



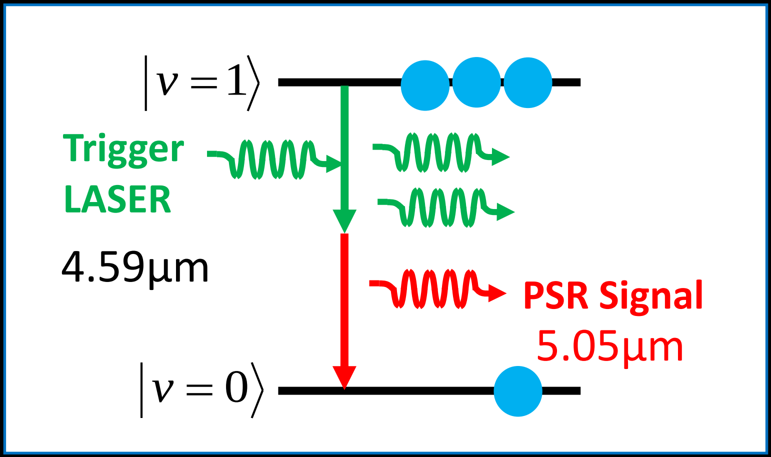


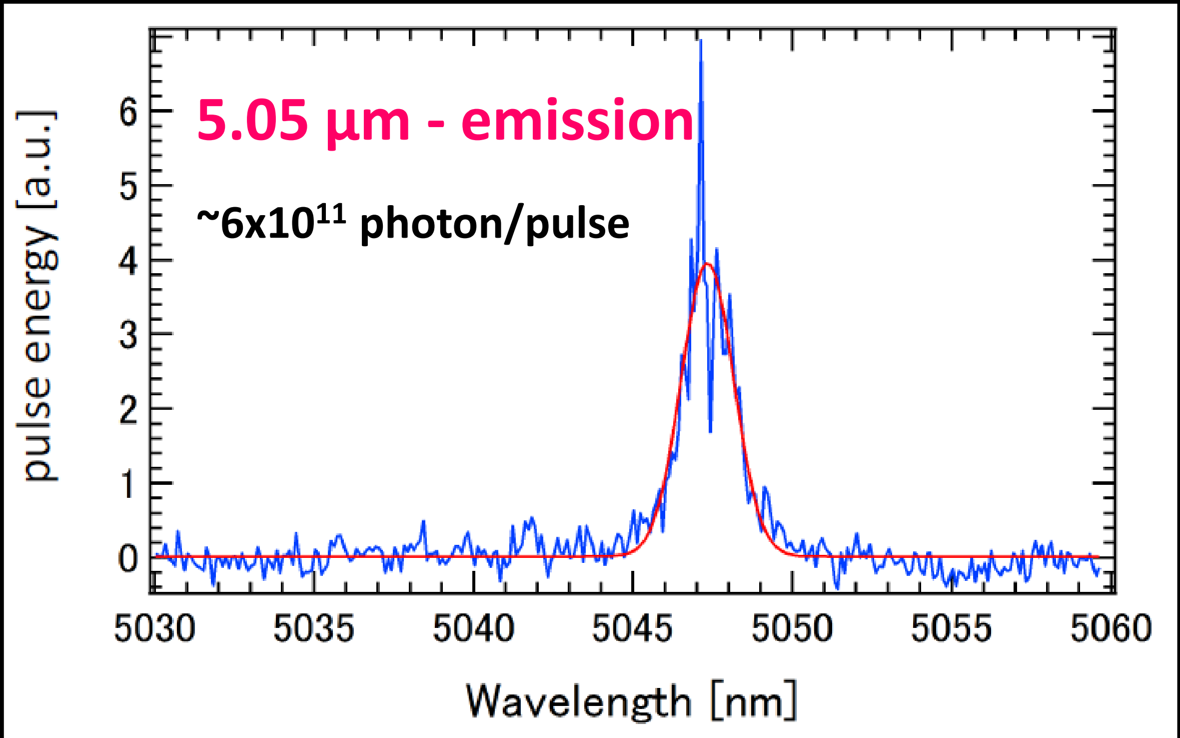
By comparison between the result and simulation

$$\rho_{ge} \approx 0.032$$

(~6% of max.)

Enhancement of two-photon emission rate





Spontaneous de-excitation

$$\tau \approx 0.3\times10^{11}\,[\mathrm{s}] \approx 950\,[\mathrm{y}]$$

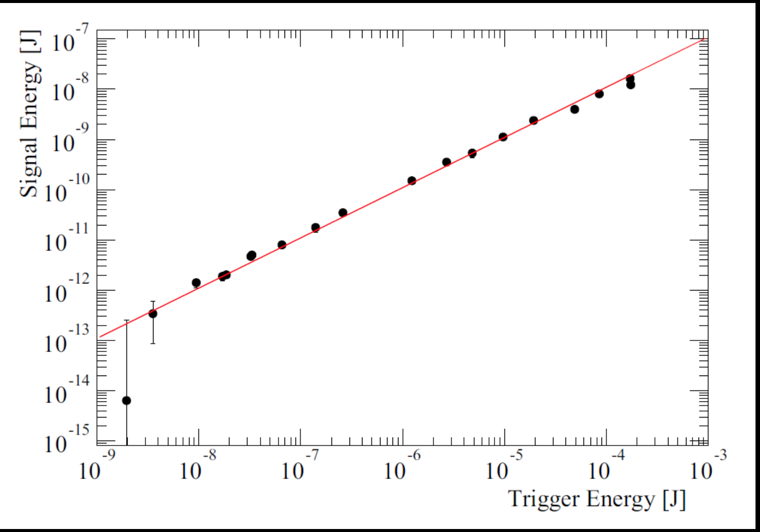
(1.6×10^{-8} photon/pulse)

Enhancement > 10^{18}

Y. Miyamoto et al.,
Prog. Theo. Exp. Phys. (2015) 081C01.
Prog. Theor. Exp. Phys. (2014) 113C01

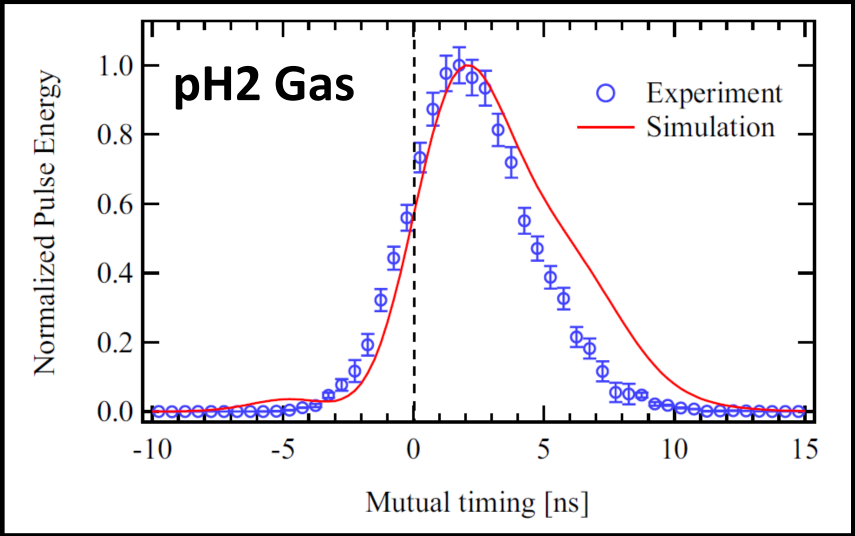
Systematic studies of coherence in pH2

Trigger intensity dependence

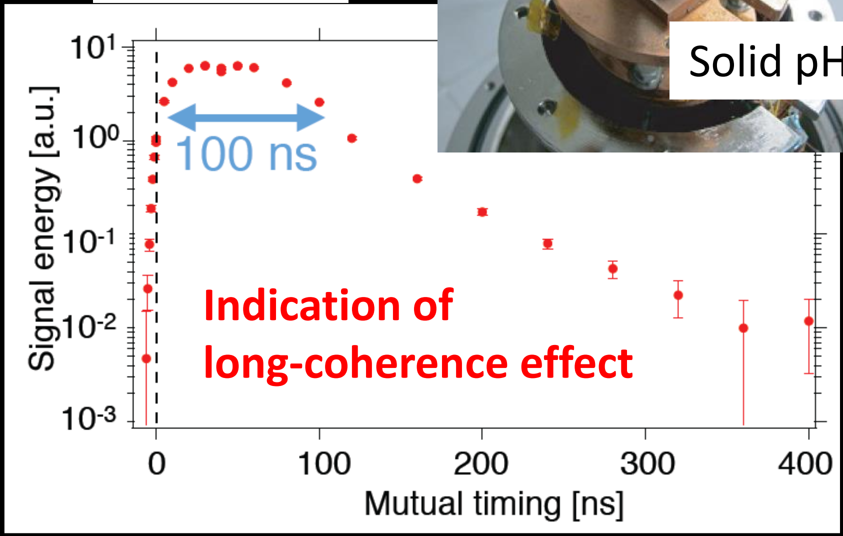


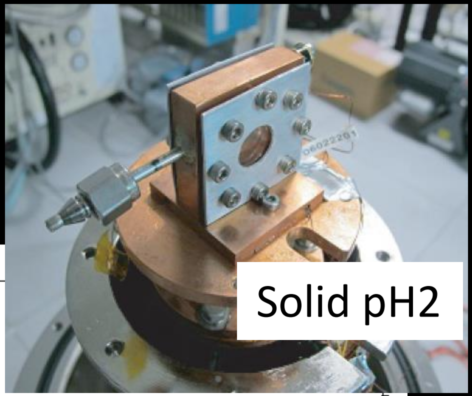
Linear dependence in 5-orders region

Coherence time profile



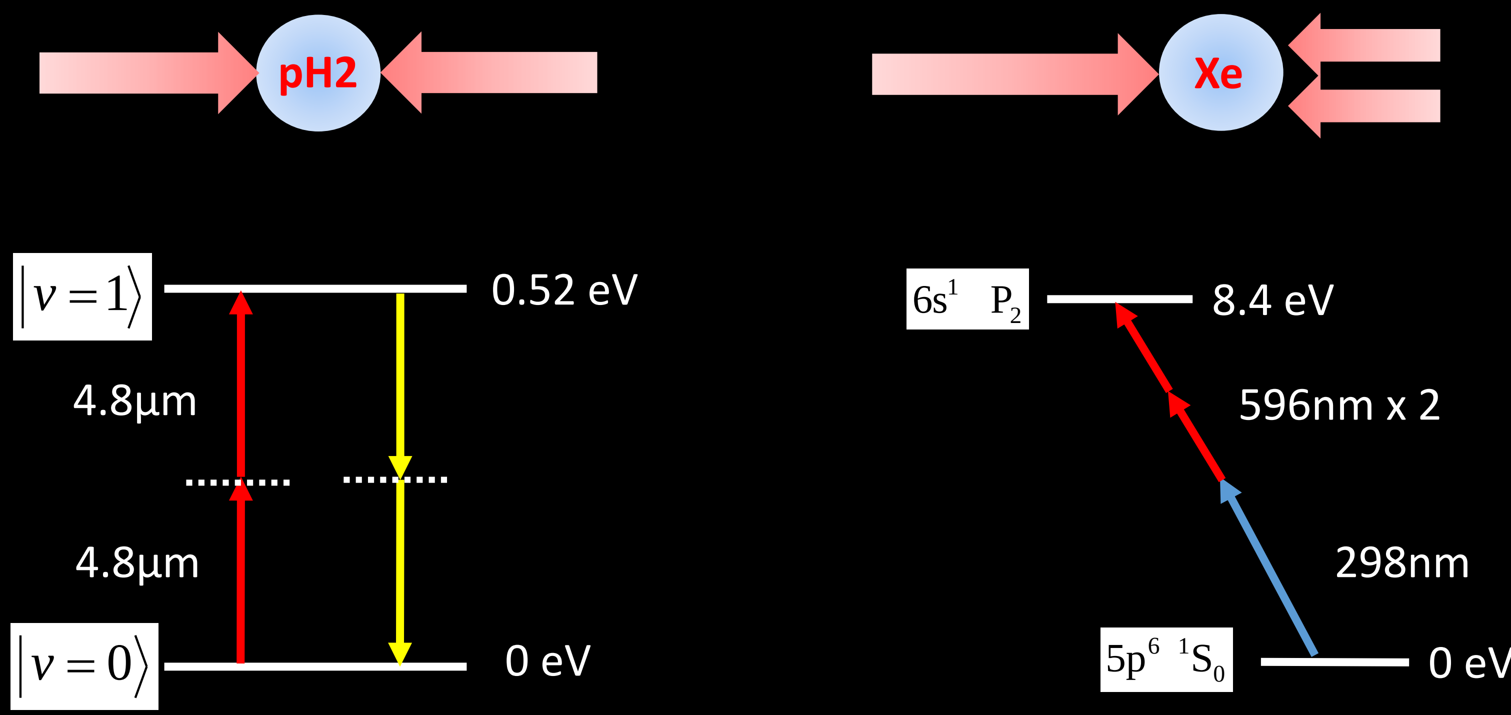
Solid-pH2





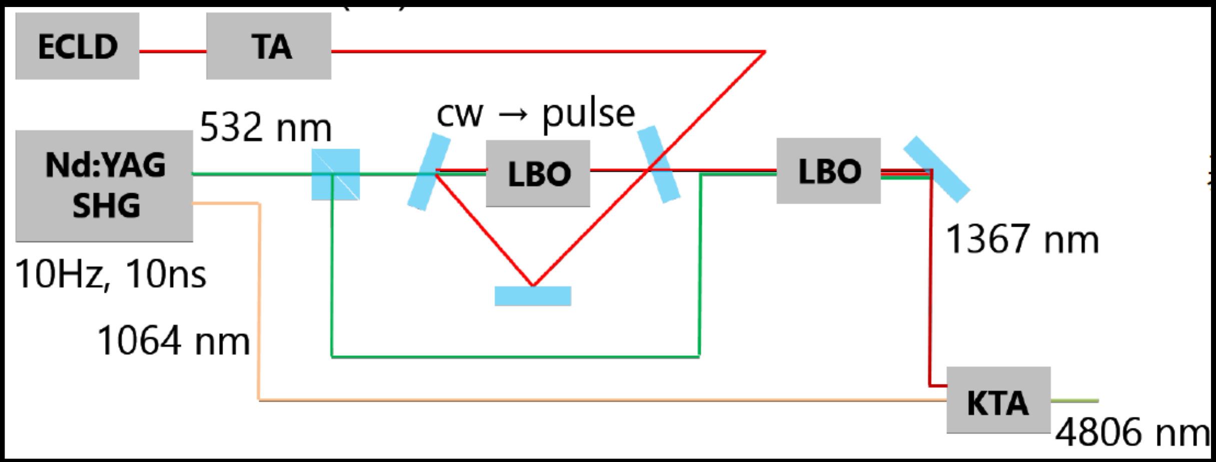
Ongoing items – counter-propagating experiments -

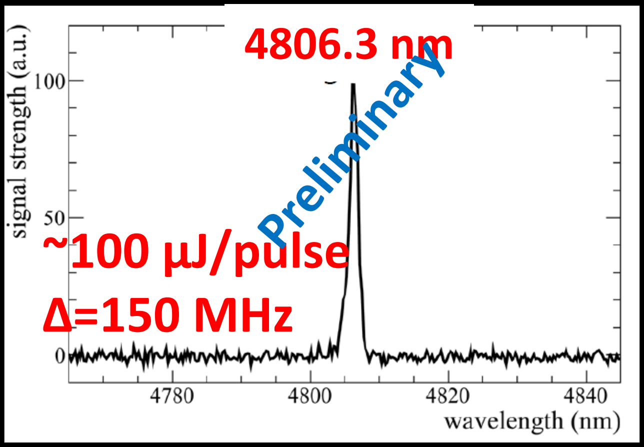
Two-lasers irradiation in counter-propagating direction

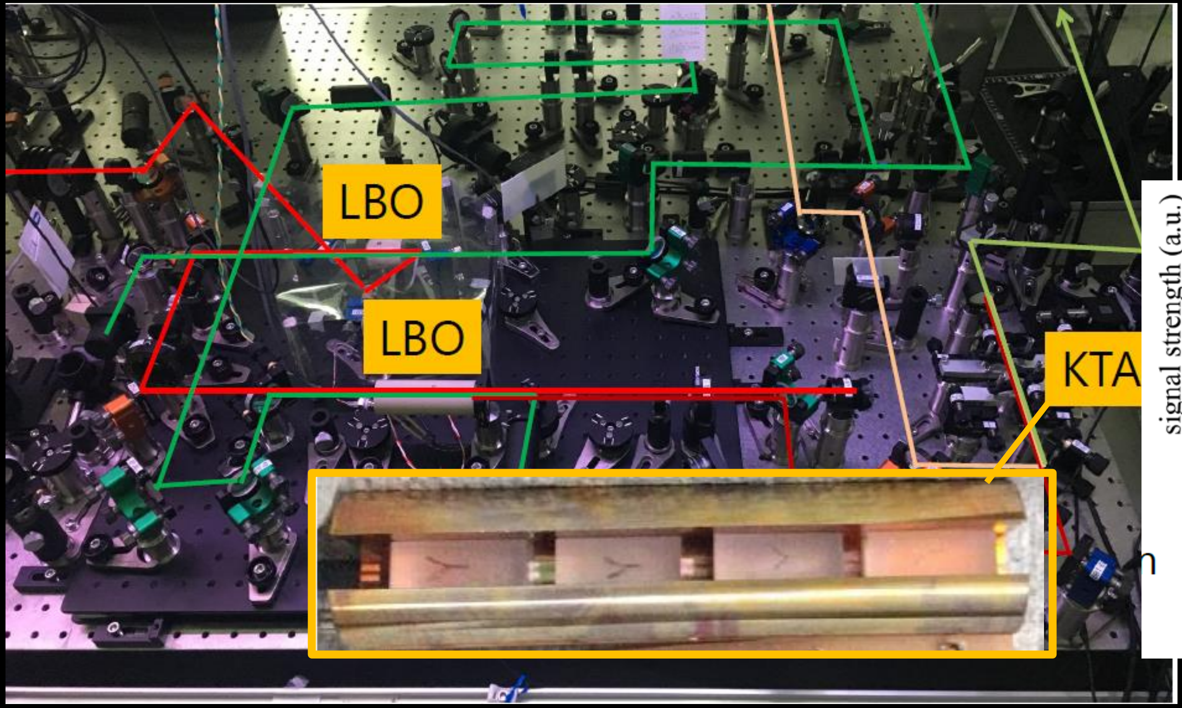


Massive neutrino pair and photon → **Momentum can be conserved in this scheme**

4.8 μm pulse laser developments

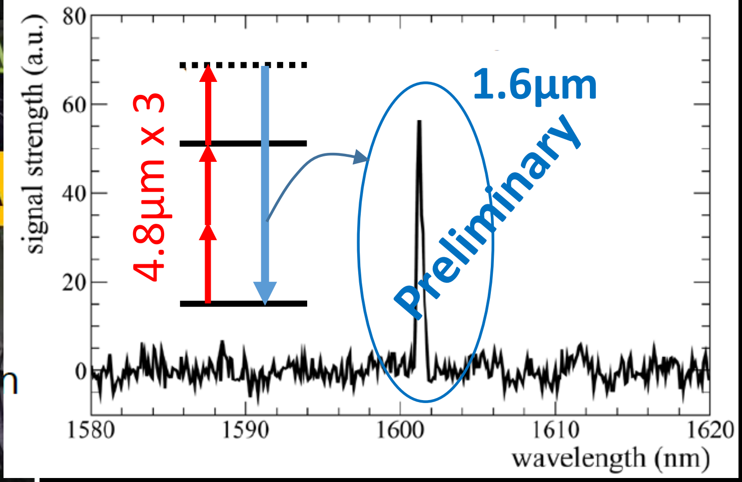






Now trying : → 10 mJ/p

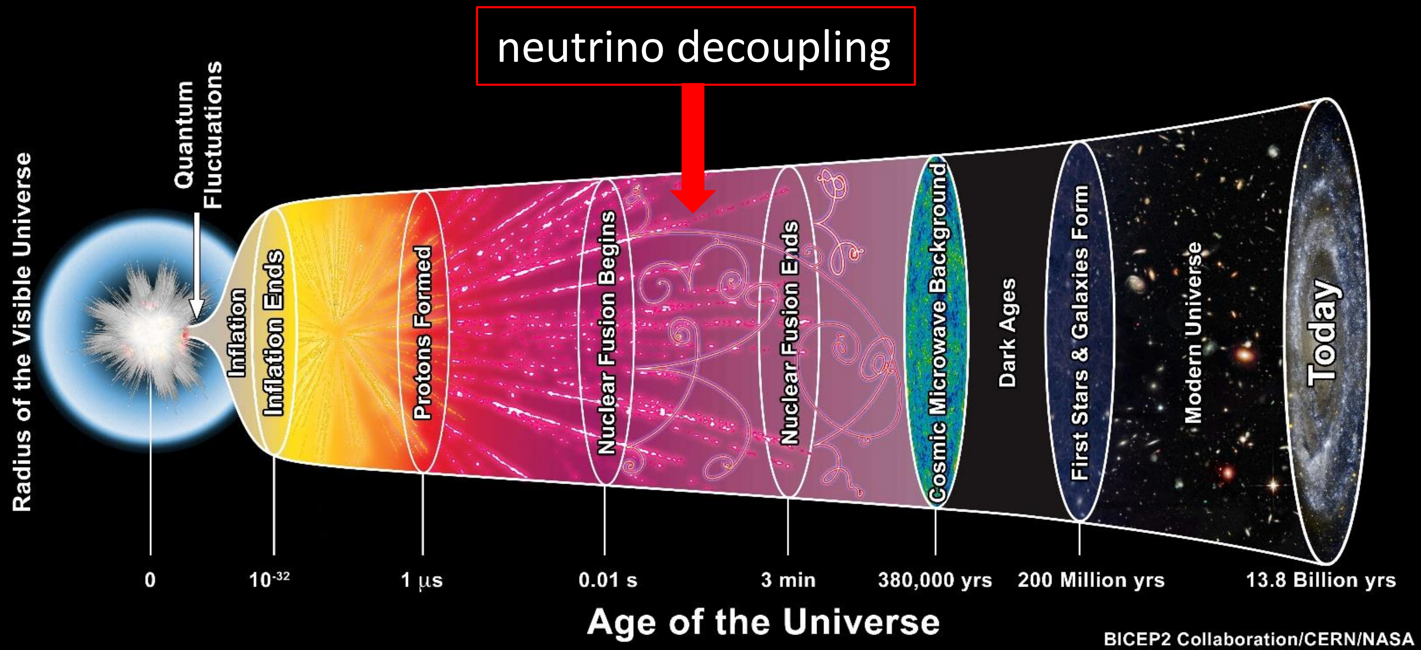
Test of Third Harmonic Generation



Y. Miyamoto et al., in preparation

Detection of relic neutrinos of 1.9 K

- Direct remnant at a few seconds after the big bang
  - earliest epoch of the universe
- Important basis of light element synthesis



- Neutrino temperature differs from 2.7 K of cosmic microwave B.G.

$$T_\nu^{(\mathrm{now})} = \left(\frac{4}{11}\right)^{1/3} T_\gamma^{(\mathrm{now})} \cong 1.9\,\mathrm{K}$$

$$n_\nu^{(\mathrm{now})} = 110/\mathrm{cm}^3$$

Detection of relic neutrinos of 1.9 K; in RENP spectrum

Relic neutrinos background

⇩

RENP rates are reduced by Pauli blocking factors

$$\Gamma_{\mathrm{RENP}} \to \left(1 - f_i\right)\left(1 - \bar{f}_j\right)\Gamma_{\mathrm{RENP}}$$

$$f_i(p) = \frac{1}{e^{p/T_\nu - \mu_d/T_d} + 1}$$

⇩

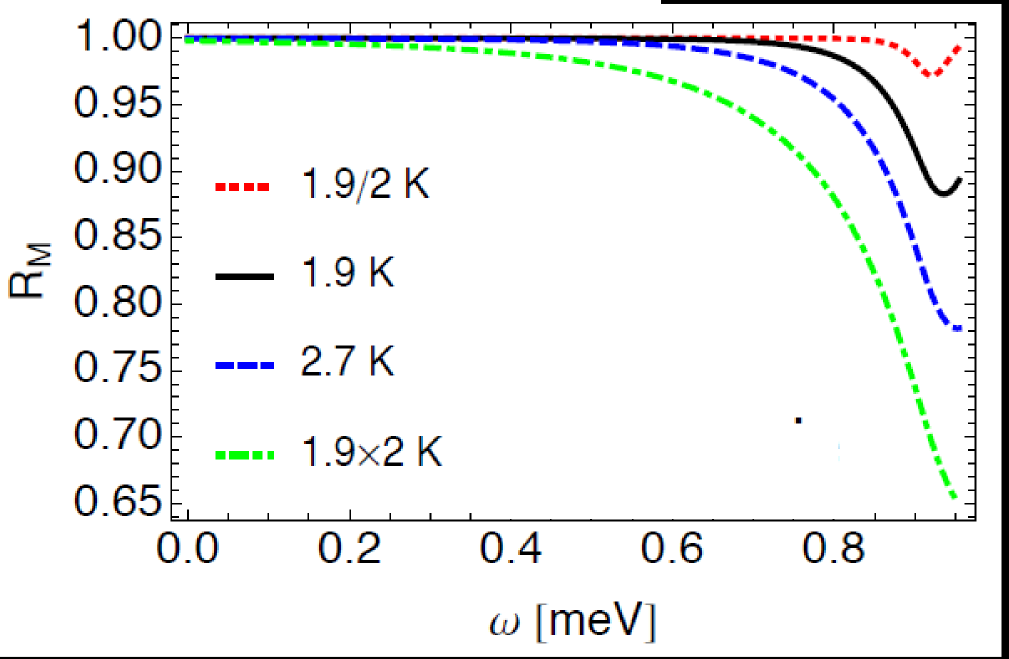
RENP spectrum shape is distorted

M. Yoshimura et al.,
Phys. Rev.D 91, 063516 (2015)

$\varepsilon_{\mathrm{eg}} = 11\,\mathrm{meV}$

$m_0 = 5\,\mathrm{meV}$

Ratio of RENP rates: with/without Pauli blocking



Summary and Future

- A new/systematic approach to the determination of unknown neutrino properties: absolute mass, M-D distinction, CP-phases and relic neutrinos.

- Two-photon emission in p-H2 was amplified up to 10^{18}, by coherence of ~6%

- Counter-propagating experiments are now in preparation: p-H2, Xe, …

- Other important studies:
  Background suppression of amplified higher-order QED
  Other atomic targets, ….