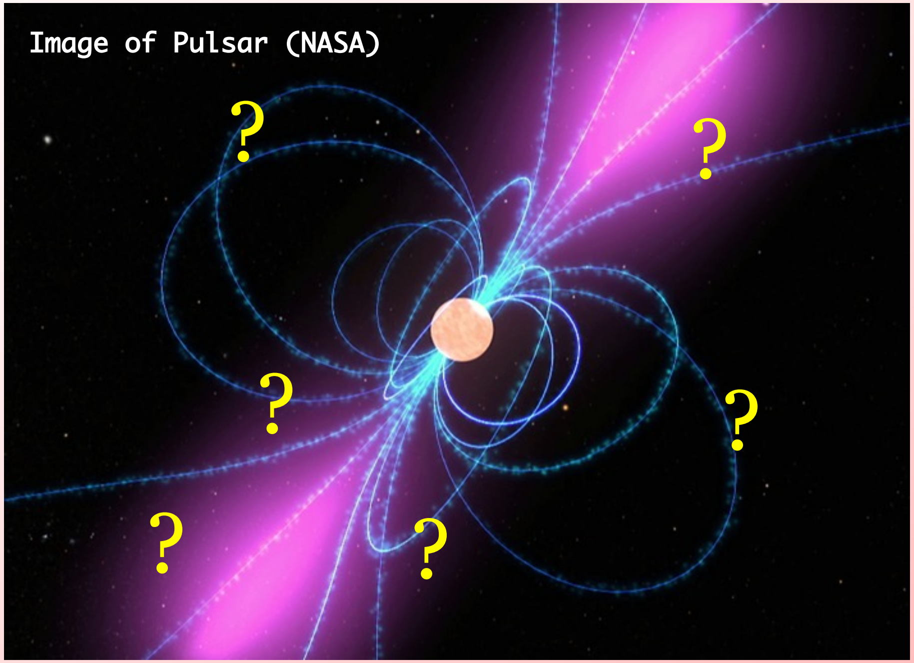
J-KAREN P レーザーを用いた誘導コンプトン散乱実験の初期報告

田中周太 (PI, 青学)

蔵満康浩(阪大)、福田祐仁(QST関西研)

浅井孝文(神戸大)、郡英輝、境健太郎、岩崎滉、姫野公輔、田口智也(阪大)、近藤康太郎(QST関西研)、神野智史(東大)、金崎真聡(神戸大)、時安敦史(東北大)、南卓海、安倍勇輝、檜原崇正(阪大)

山崎了(青学)、坂和洋一(阪大)



Induced Compton Scattering

Induced Compton Scattering

Interaction between rarefied plasma & bright radiation

- Rarefied plasma ($\lambda < \lambda_\mathrm{D}$, $\omega > \omega_\mathrm{pe}$)
  - Scattering of photons by an electron
  - Cross section is given by Klein-Nishina formula
- Bright radiation ($k_\mathrm{B}T_\mathrm{b} \gg m_\mathrm{e}c^2$)
  - $k_\mathrm{B}T_\mathrm{b}(\nu) \equiv h\nu\, n_\mathrm{ph}(\nu) \equiv E/(\Delta t\Delta\nu)$
  - $n_\mathrm{ph} > 2$ is possible for Boson ⇔ induced process rather than exclusion one! $n_\mathrm{ph} \sim 10^{27}$ for pulsar!!

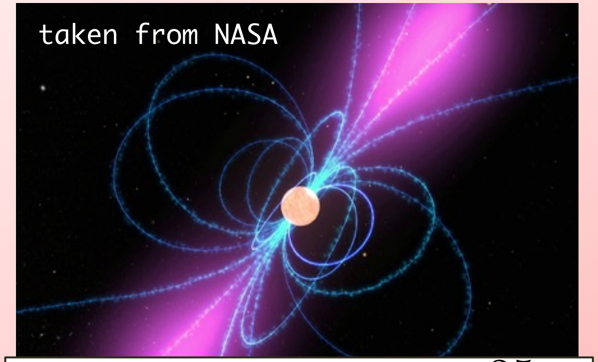
$$\boxed{\frac{dn_\mathrm{ph}(\nu)}{dt} \propto n_\mathrm{ph}(\nu_+)(\underline{1+n_\mathrm{ph}(\nu)}) - n_\mathrm{ph}(\nu)(\underline{1+n_\mathrm{ph}(\nu_-)})}$$

spontaneous + induced terms

🟥 $n_\mathrm{ph}(\nu_+)$

⬛ $n_\mathrm{ph}(\nu)$

🟦 $n_\mathrm{ph}(\nu_-)$



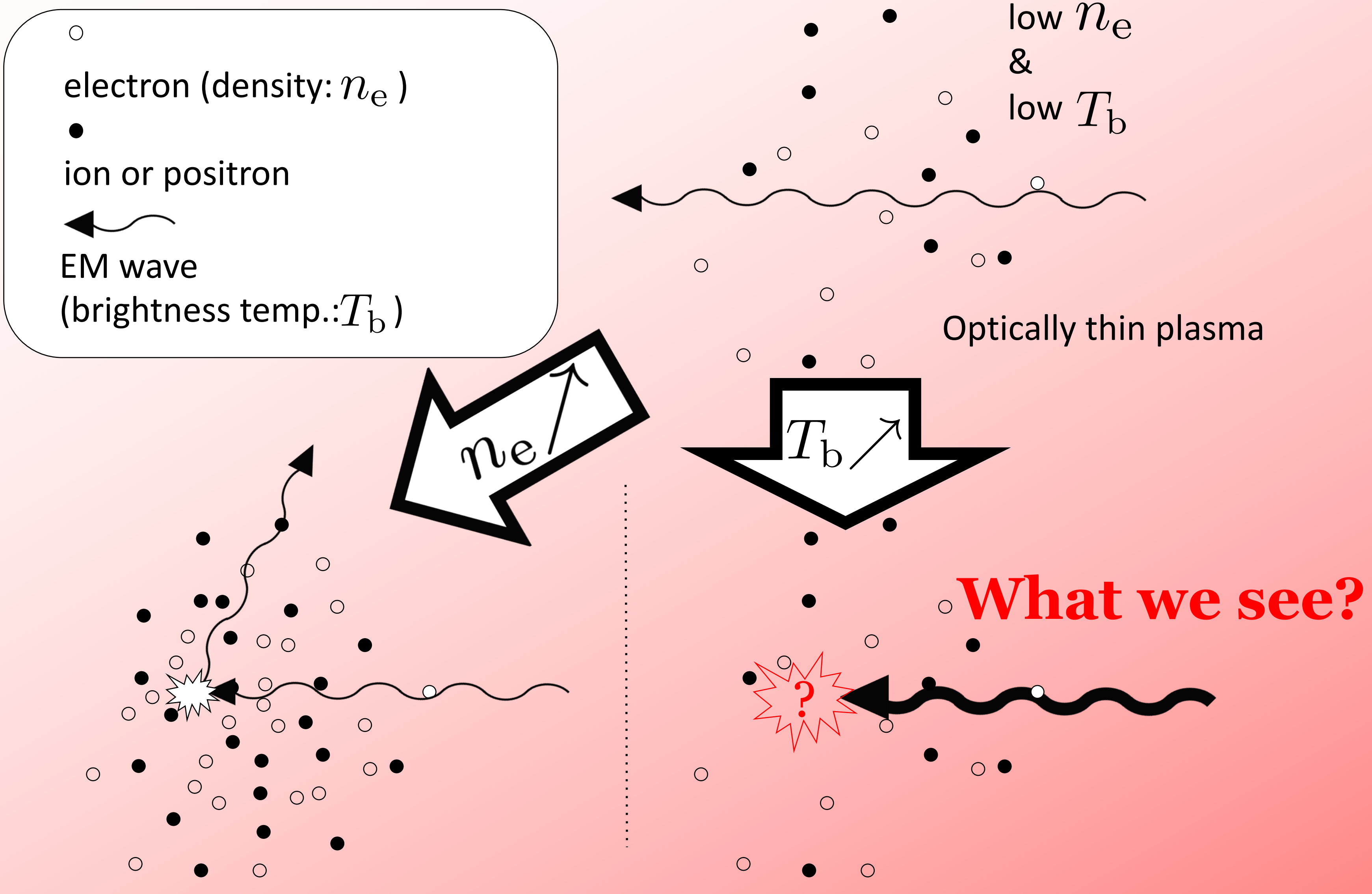
$$\boxed{T_\mathrm{b}(100\ \mathrm{MHz}) \gtrsim 10^{25}K}$$

Pulsed radio emission

$$\boxed{T_\mathrm{b}(100\ \mathrm{THz}) \gtrsim 10^{20}K}$$

Laser facilities

Spontaneous vs. Induced



○ electron (density: n_{e})

● ion or positron

EM wave
(brightness temp.: T_{b})

low n_{e}
&
low T_{b}

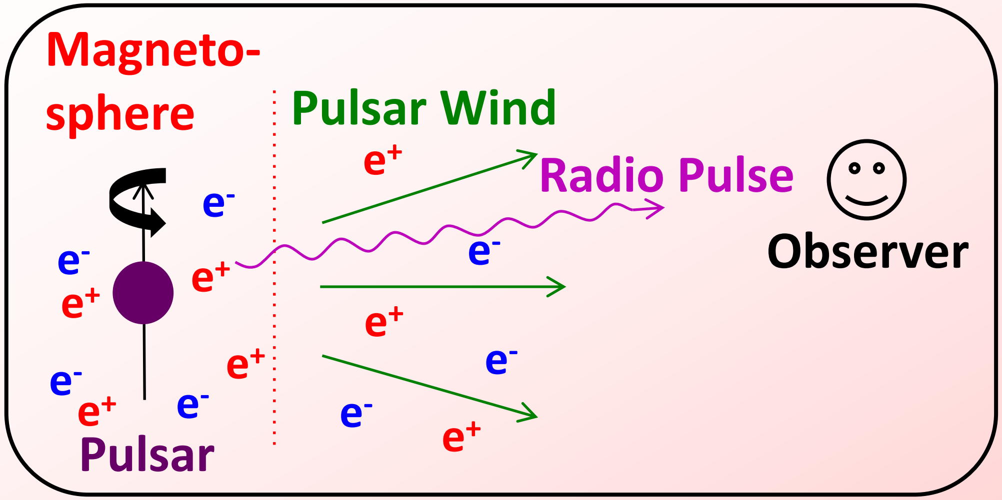
Optically thin plasma

What we see?

Thomson scattering

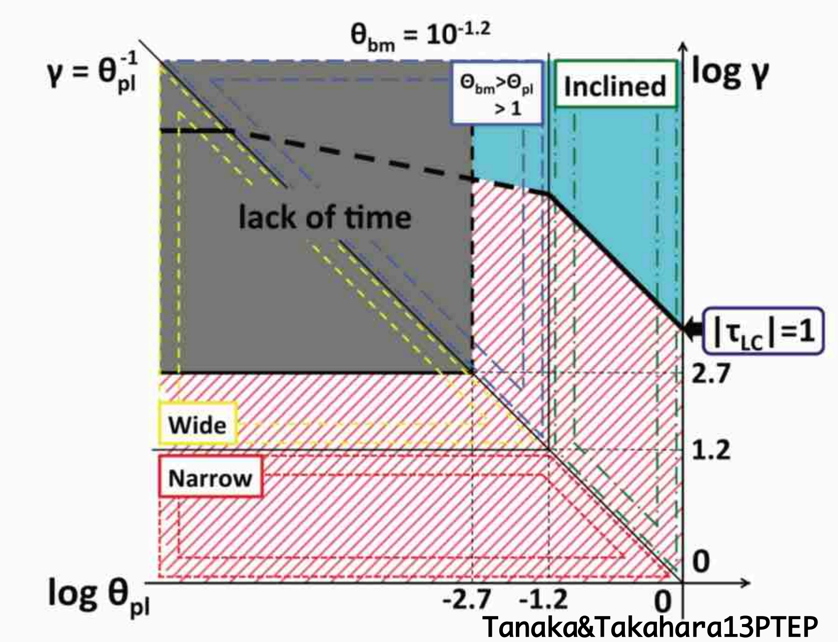
Induced Compton scattering

ICS & PSR



e.g., Tanaka&Takahara13PTEP

Interaction between radio pulse (laser) and pulsar wind (plasma).
=> Characteristic signature?



Tanaka&Takahara13PTEP

ICS has potential to constrain

$\dot{N}$: particle number flux

σ: magnetization

γ: bulk Lorentz factor

of the pulsar wind

$$L_{\text{spin}} = \dot{N}(1+\sigma)\gamma m_e c^2$$

Basic Equation

Kinetic Equation for Photon

Compton scattering off photons $n_{\mathrm{ph}}(\boldsymbol{k})$ by plasmas $f(\boldsymbol{p})$.

$$\left(\frac{\partial}{\partial t} + c\boldsymbol{\Omega}\cdot\boldsymbol{\nabla}\right) n(\boldsymbol{k}) = c n_{\mathrm{pl}} \int d^3\boldsymbol{p} f(\boldsymbol{p}) \int d^3\boldsymbol{k}_1$$

$$\times \left[\sigma_{\mathrm{KN}}(\boldsymbol{k}_1, \boldsymbol{k}, \boldsymbol{p}) n(\boldsymbol{k}_1)(1 + \underline{n(\boldsymbol{k})}) - \sigma_{\mathrm{KN}}(\boldsymbol{k}, \boldsymbol{k}_1, \boldsymbol{p}) n(\boldsymbol{k})(1 + \underline{n(\boldsymbol{k}_1)})\right]$$

Boltzmann-Uehling-Uhlenbeck Equation

induced term

Cross-section for Compton scattering (Klein-Nishina formula)

$$\sigma_{\mathrm{KN}}(\boldsymbol{k}_{\mathrm{i}}, \boldsymbol{k}_{\mathrm{f}}, \boldsymbol{p}) = \frac{r_{\mathrm{e}}^2}{2\gamma^2 k_{\mathrm{i}} k_{\mathrm{f}}} \boxed{\delta\left(k_{\mathrm{f}} D_{\mathrm{f}} - k_{\mathrm{i}} D_{\mathrm{i}} + \frac{k_{\mathrm{i}} k_{\mathrm{f}}(1-\mu)}{\gamma}\right)}$$

$$\times \left[1 + \left(1 - \frac{1-\mu}{\gamma^2 D_{\mathrm{i}} D_{\mathrm{f}}}\right)^2 + \frac{k_{\mathrm{i}} k_{\mathrm{f}} (1-\mu)^2}{\gamma^2 D_{\mathrm{i}} D_{\mathrm{f}}}\right]$$

Compton effect: not symmetric about $k_{\mathrm{i}} \Leftrightarrow k_{\mathrm{f}}$

$$D_{\mathrm{i,f}} = 1 - \boldsymbol{\beta}\cdot\boldsymbol{\Omega}_{\mathrm{i,f}} \quad \mu = \boldsymbol{\Omega}_{\mathrm{i}}\cdot\boldsymbol{\Omega}_{\mathrm{f}}$$

Kompaneets equation

uniform + isotropic + 1st order in hν << m_ec^2, k_BT_e << m_ec^2

Kompaneets 1957

$$\boxed{\frac{\partial n(x)}{\partial y} = \frac{1}{x^2}\frac{\partial}{\partial x}x^4\left(n(x) + n^2(x) + \frac{\partial n(x)}{\partial x}\right)}$$

$$\boxed{x \equiv \frac{h\nu}{k_\mathrm{B}T_\mathrm{pl}}, y \equiv \frac{k_\mathrm{B}T_\mathrm{pl}}{m_\mathrm{e}c^2}n_\mathrm{pl}\sigma_\mathrm{T}ct}$$

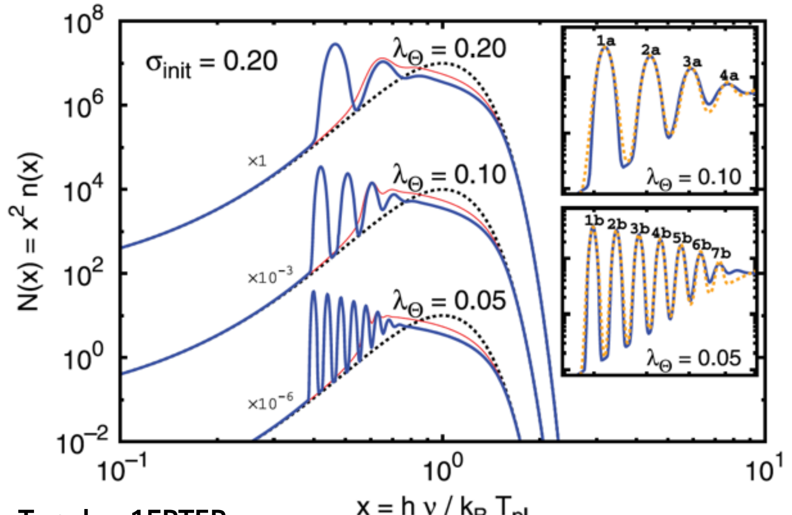
- Photon number conservation
- Bose-Einstein distribution as equilibrium solution
- No Thomson scatt. (0th order) because of isotropy.
- 1st term = Compton effect (energy loss for photon)
- 2nd term = Induced Compton (energy loss for photon)
- 3rd term = Inverse Compton (energy gain for photon)

$$\tau_\mathrm{Comp} \approx \sigma_\mathrm{T} l n_\mathrm{pl} \times \frac{h\nu}{m_\mathrm{e}c^2}$$

$$\tau_\mathrm{ind} \approx \sigma_\mathrm{T} l n_\mathrm{pl} \times \frac{k_\mathrm{B}T_\mathrm{b}(\nu)}{m_\mathrm{e}c^2}$$

$$\tau_\mathrm{IC} \approx \sigma_\mathrm{T} l n_\mathrm{pl} \times \frac{k_\mathrm{B}T_\mathrm{e}}{m_\mathrm{e}c^2} \approx y$$

The case for $n_{\rm ph} >> 1$



Tanaka+15PTEP

$$\boxed{n\Theta \times \min(1, x) \gg 1}$$

$$\boxed{\frac{\partial g}{\partial y} - 2g\frac{\partial g}{\partial x} = 0}$$

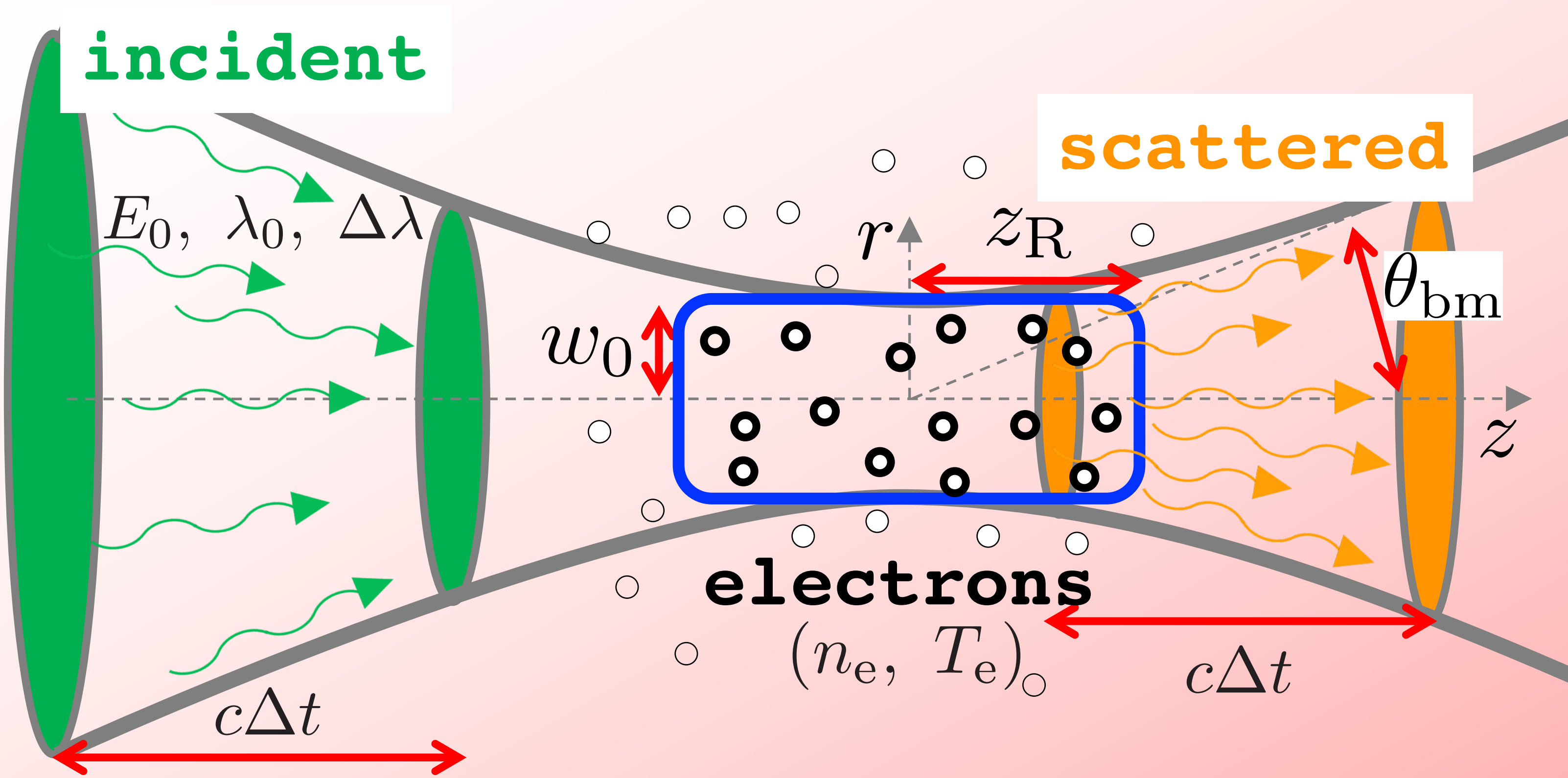
2nd order

$$\boxed{\frac{\partial g}{\partial y} - 2g\frac{\partial g}{\partial x} + \frac{17\Theta}{5} g \frac{\partial}{\partial x} g = \frac{14\Theta}{5}(xg)\frac{\partial^3}{\partial x^3}(xg)}$$

$$x = \frac{h\nu}{k_{\rm B}T_{\rm e}}, \quad \Theta = \frac{k_{\rm B}T_{\rm e}}{m_{\rm e}c^2}, \quad g(x) = x^2 n(x)$$

$$\frac{\partial g}{\partial y} - 2g\frac{\partial g}{\partial x} \approx \underbrace{\frac{14\Theta}{5}(xg)\frac{\partial^3}{\partial x^3}(xg)}_{\text{order of } (h\nu)\Theta/(m_e c^2)^2}$$

Solitary structures in spectrum



Predictions in Experiments

Four Constraints on Plasma

- Typical optical depth for ICS (blue)

$$\tau_{\mathrm{ICS}} > 0.1 \quad \Rightarrow \quad \boxed{n_{\mathrm{e}} > 0.1 \times \frac{16\pi^3 m_{\mathrm{e}} c^2 \Delta t \Delta\nu w_0^2}{6\sigma_{\mathrm{T}} E \lambda^3}}$$

- Doppler width (λ_Θ) of solitary waves (green)

$$\frac{\lambda_\Theta}{2} < \frac{\Delta\nu}{\nu} \quad \Rightarrow \quad \boxed{k_{\mathrm{B}} T_{\mathrm{e}} < \frac{3m_{\mathrm{e}}(w_0 \Delta\nu)^2}{2}}$$

- No screening effect (e.g., Galeev & Syunyaev 1973) (red)

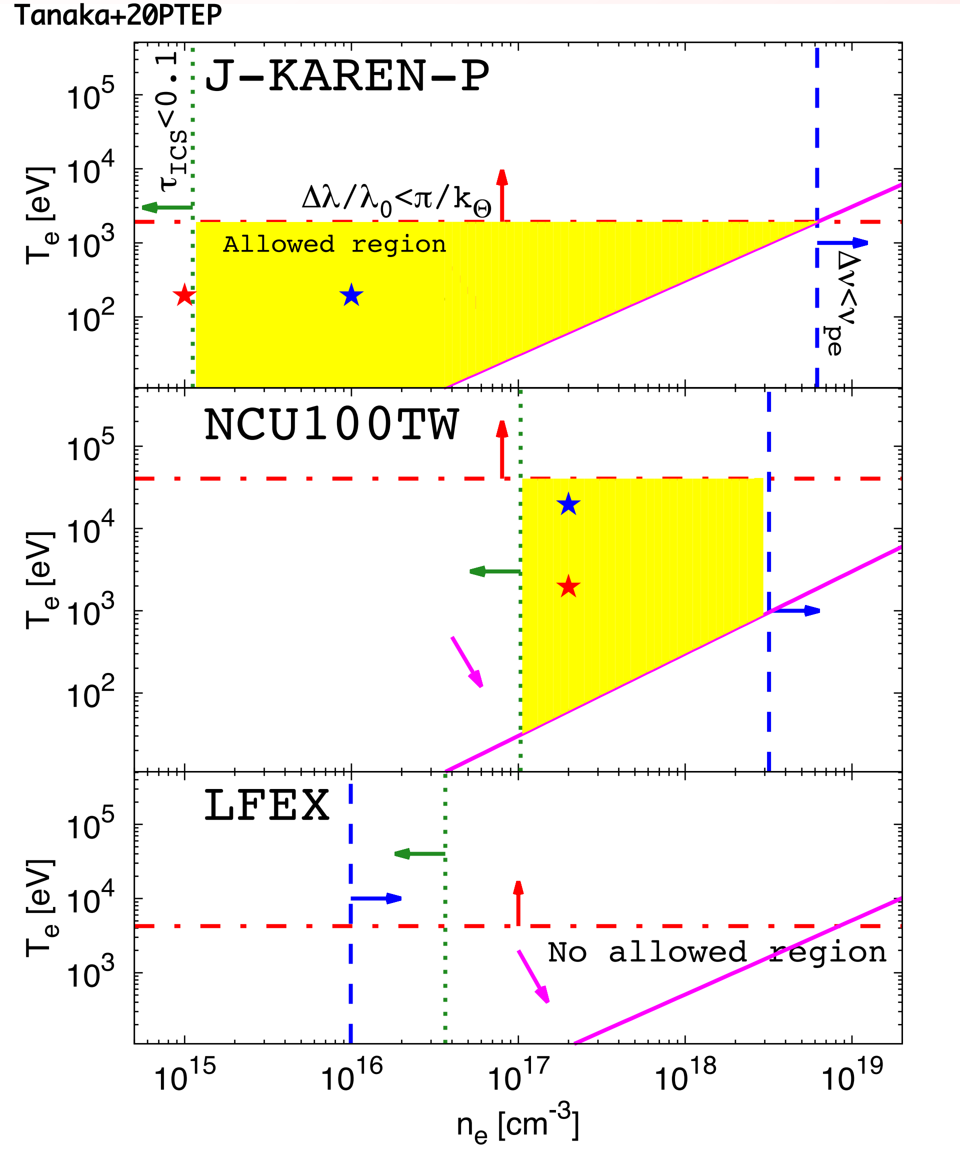
$$\Delta\nu > \nu_{\mathrm{pe}} \quad \Rightarrow \quad \boxed{n_{\mathrm{e}} < \frac{\pi m_{\mathrm{e}} \Delta\nu^2}{e^2}}$$

- Non-collective scattering (yellow)

$$\lambda < \lambda_{\mathrm{D}} \quad \Rightarrow \quad \boxed{k_{\mathrm{B}} T_{\mathrm{e}} > 4\pi e^2 \lambda^2 n_{\mathrm{e}}}$$

Laser Facilities

Tanaka+20PTEP



Allowed plasma parameters are found in yellow region.

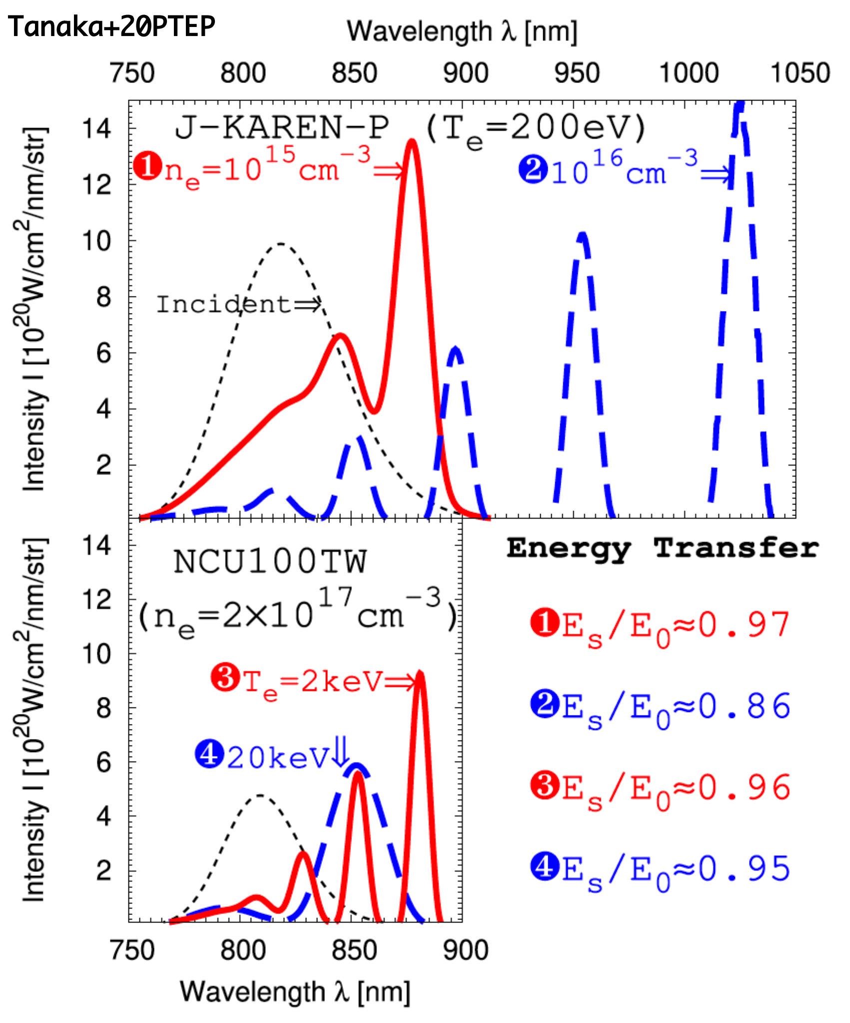
High-power short pulse laser is favored for ICS experiments rather than high (total) energy laser.

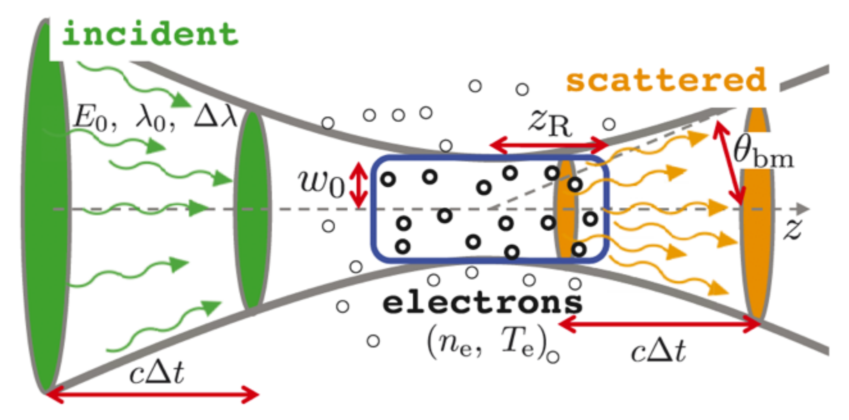
We can draw the same plot for other facilities of the given parameters!

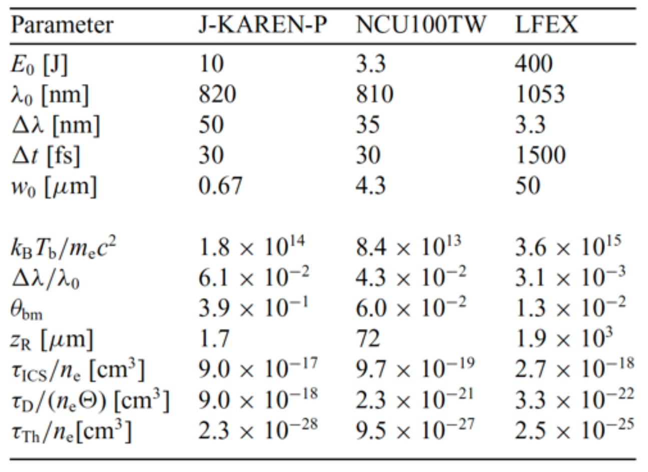
- *E*: total energy
- *Δt*: pulse width
- *Δν*: band width
- w_o: minimum waist
- λ: central wavelength

Predictions

Spectra of transmitted (scattered) light


Tanaka+20PTEP



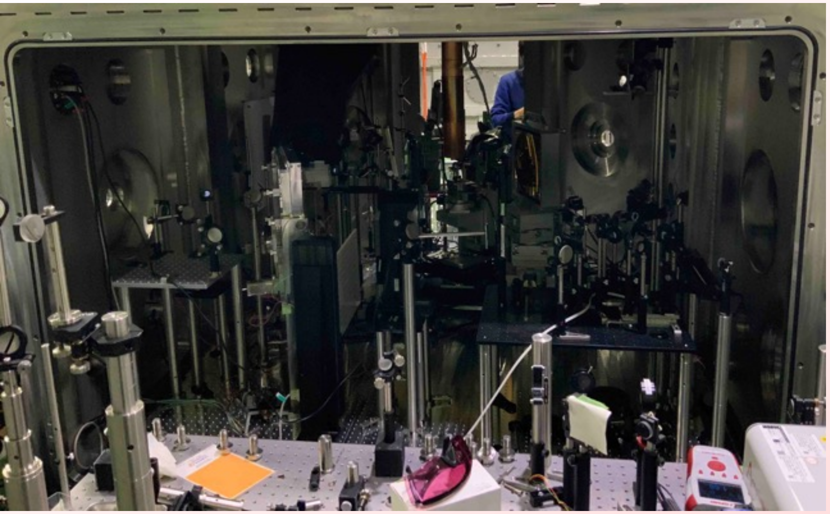


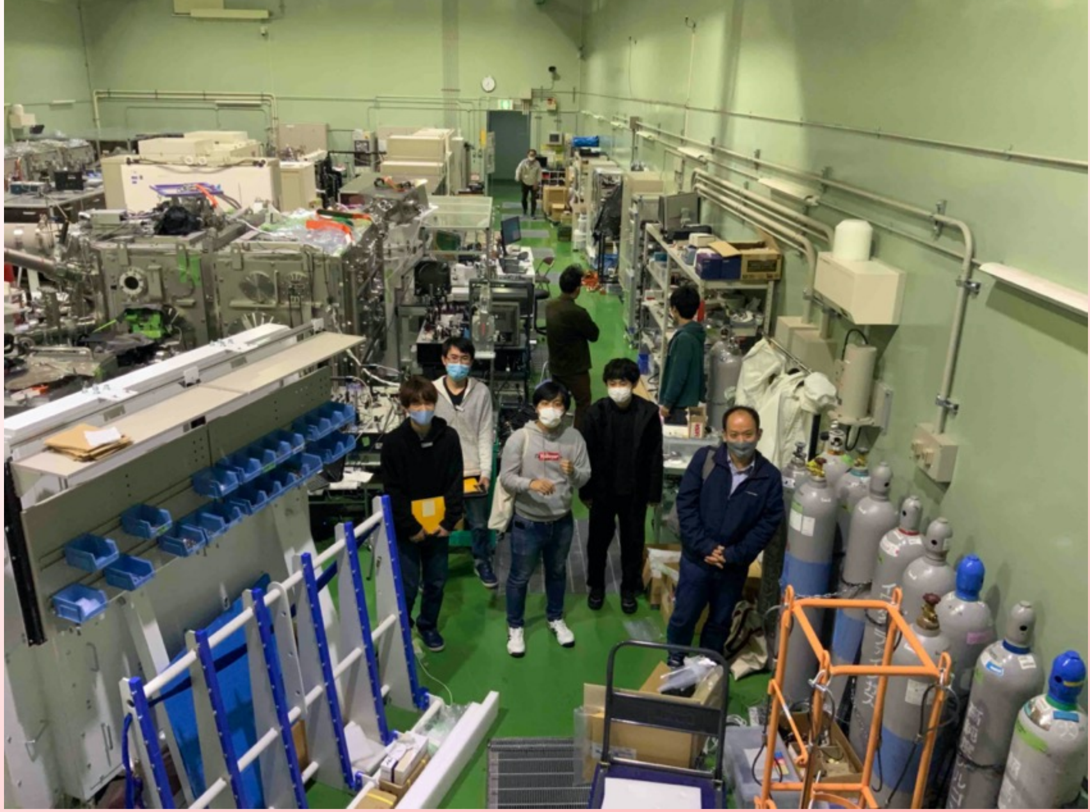
Parameter	J-KAREN-P	NCU100TW	LFEX
E_0 [J]	10	3.3	400
λ_0 [nm]	820	810	1053
$\Delta\lambda$ [nm]	50	35	3.3
Δt [fs]	30	30	1500
w_0 [μm]	0.67	4.3	50
$k_B T_b/m_e c^2$	1.8×10^{14}	8.4×10^{13}	3.6×10^{15}
$\Delta\lambda/\lambda_0$	6.1×10^{-2}	4.3×10^{-2}	3.1×10^{-3}
θ_{bm}	3.9×10^{-1}	6.0×10^{-2}	1.3×10^{-2}
z_R [μm]	1.7	72	1.9×10^3
τ_{ICS}/n_e [cm^3]	9.0×10^{-17}	9.7×10^{-19}	2.7×10^{-18}
$\tau_D/(n_e\Theta)$ [cm^3]	9.0×10^{-18}	2.3×10^{-21}	3.3×10^{-22}
τ_{Th}/n_e[cm^3]	2.3×10^{-28}	9.5×10^{-27}	2.5×10^{-25}

Only $\pi w_o^2\ 2z_R\ n_e \sim 10^4$ electrons at Rayleigh region

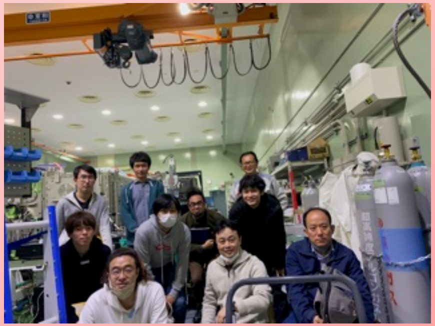
They would attain ~ PeV which is rad. reaction limited

$$\frac{dE}{dx} \approx \frac{3}{2}\frac{m_e c^2}{r_e} \approx 2 \times 10^{14}\ \mathrm{MeV/m} = 0.2\ \mathrm{PeV}/\mu\mathrm{m}$$



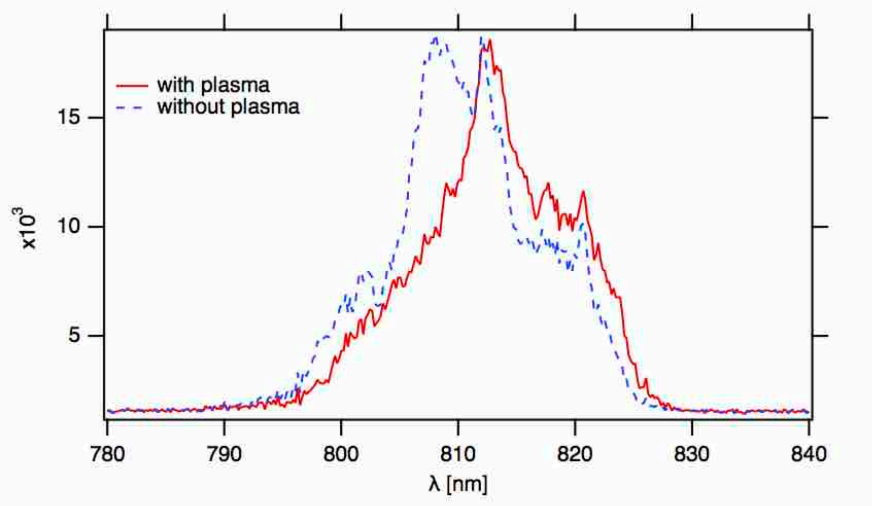


J-KAREN Experiment
2020/12/2, 3

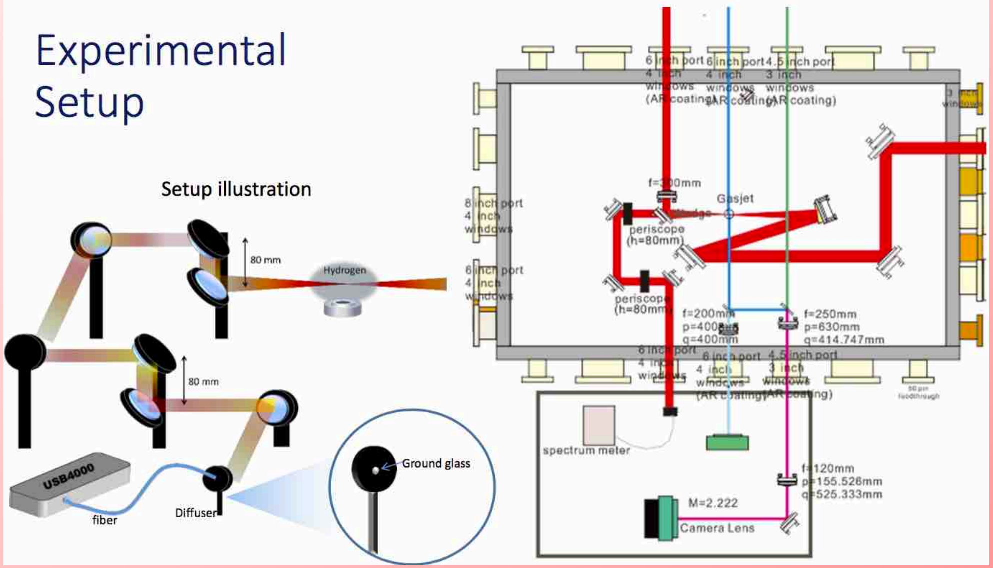


Initial Experiment

July 2017, National Central University @ Taiwan



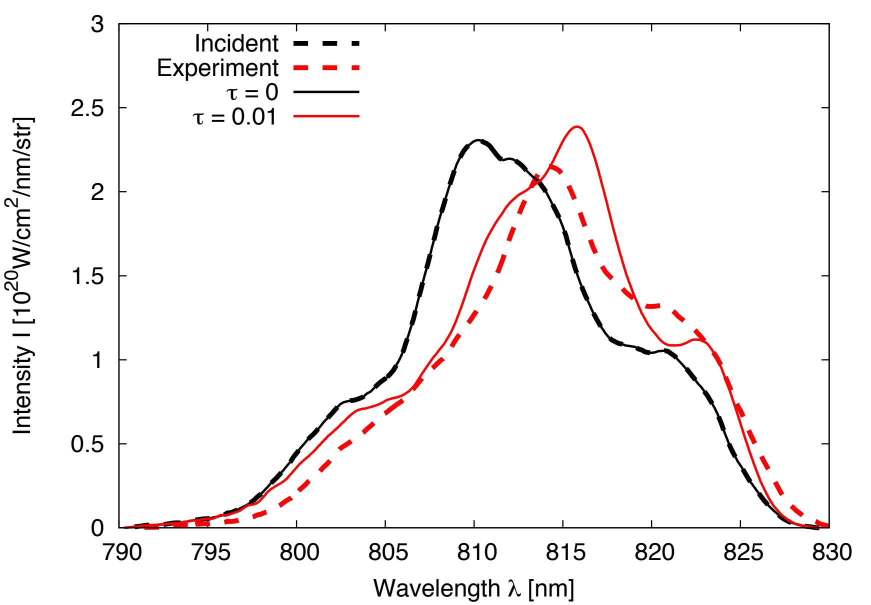
Detection?



Experimental Setup

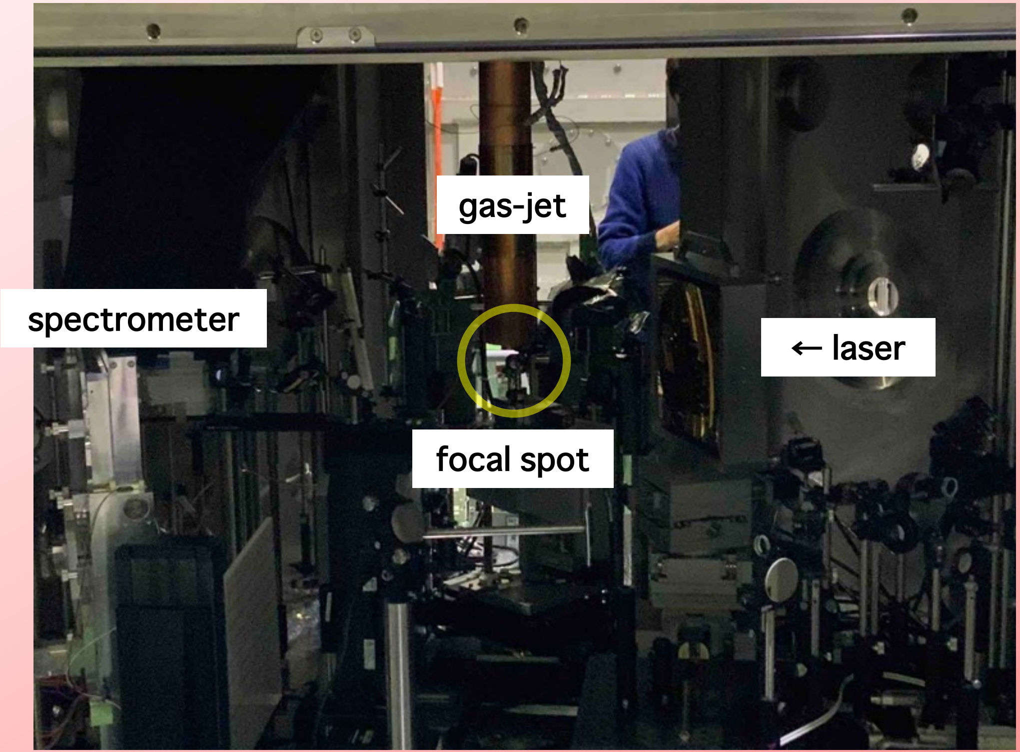
Setup illustration

Produced by Kuramitsu-san



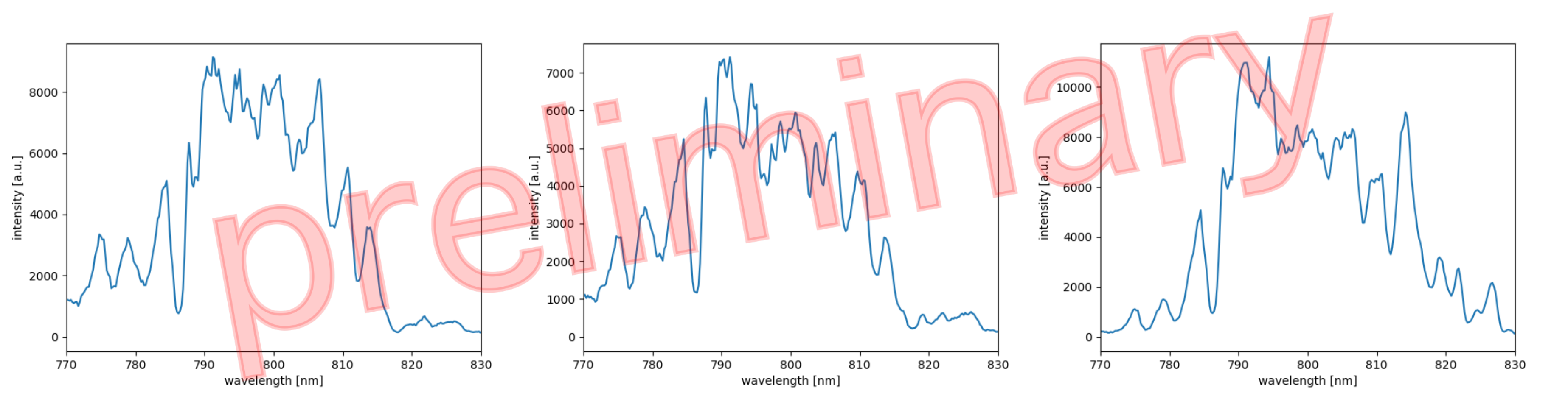
J-KAREN experiment

- What do we try to observe?
  - spectrum of scattered light (redshifted compared with incident one)
  - no side- & back-scattering, no change of polarization
  - dependence on electron density (optical depth)
  - dependence on electron temperature
  - acceleration of electrons (radiation reaction limited)

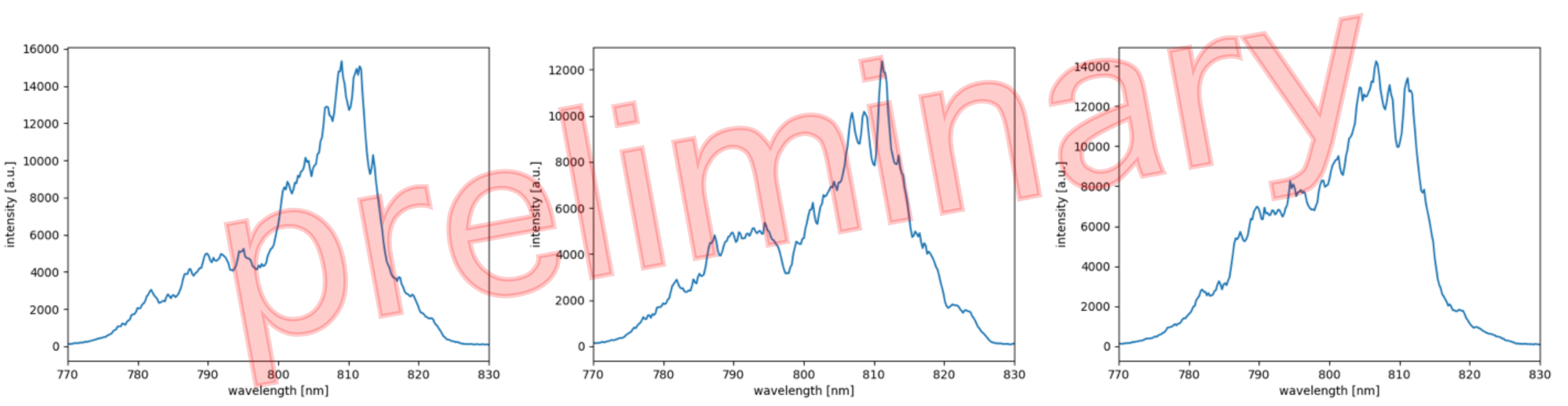


Spectrometer

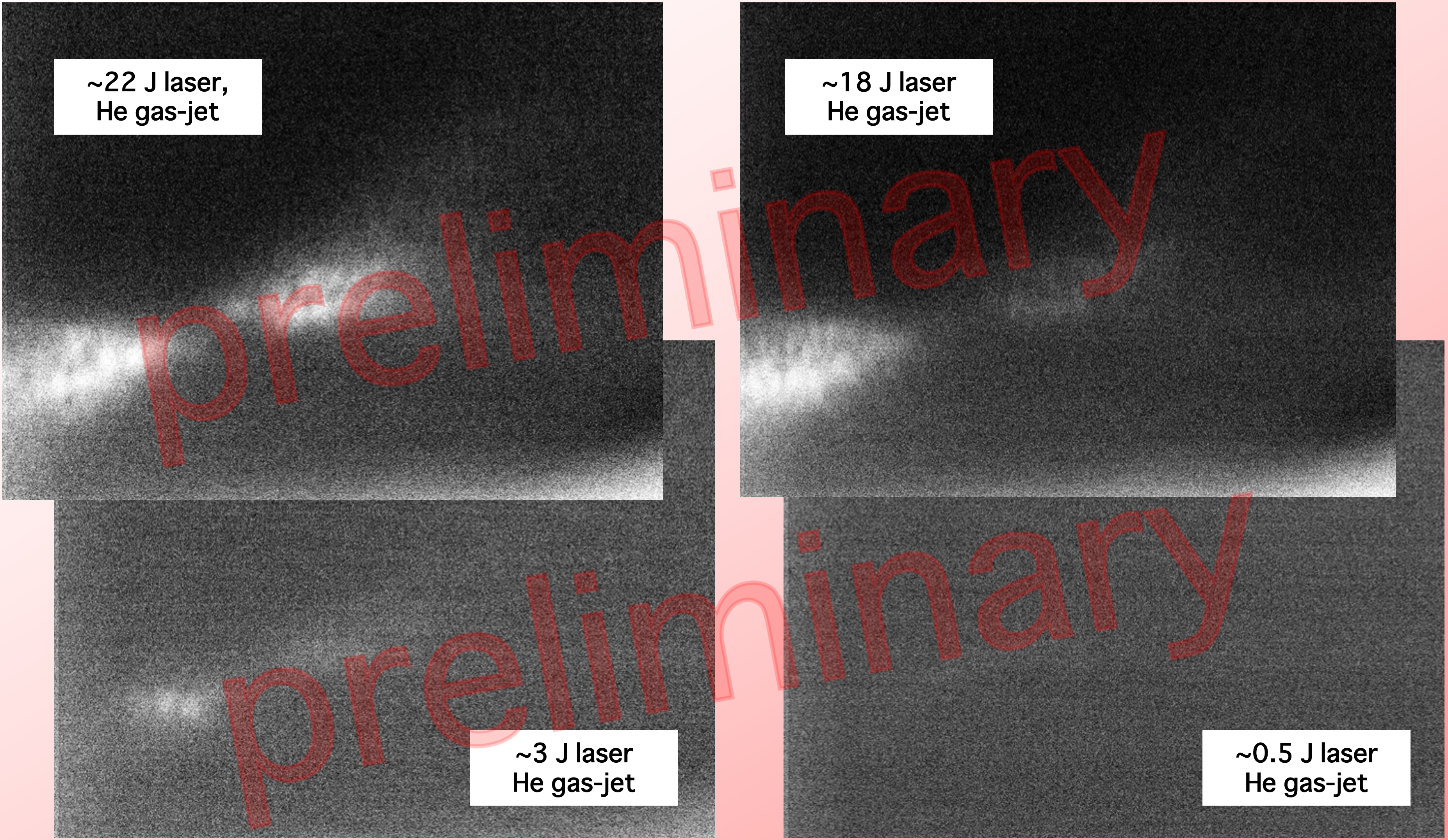
He gas-jet



gas-jet off



Imaging (Thomson scattering)



Summary

- J-KAREN Pレーザーを用いた誘導コンプトン散乱の実験を行った。
- Spectrometer: 透過光スペクトルを解析中だが、誘導コンプトン散乱による明確なスペクトル変調はまだ確認できていない。
- Imaging (Thomson scattering): 集光点付近にプラズマがいない可能性がある。
- 2021年1月に分光器とガス密度の校正実験を行う。
- 系統的に解析を進めて次の実験に繋げる!

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Various light scattering processes

- Geometric optics limit: $R > \lambda$, R = size of scatterer, λ = light wavelength
- Mie scattering: $R \sim \lambda$
- Rayleigh scattering: $R < \lambda$
- Brillouin scattering: Phonon, ion acoustic wave
- Raman scattering: Plasmon, vibration and/or rotational level of a molecule
- Compton scattering: an electron $\gamma + e \rightarrow \gamma + e$
  - Thomson scattering: classical limit of Compton (h = 0, elastic)
  - Induced Compton scattering: induced counterpart, redshift
  - Nonlinear Compton scattering: multiple photon absorption, blueshift

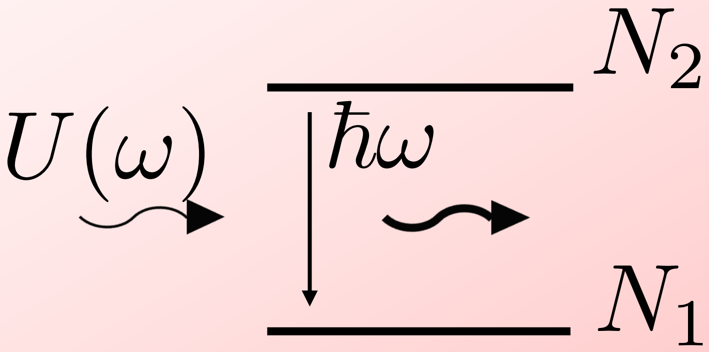
$$N\gamma + e \rightarrow \gamma + e$$

  - Double Compton scattering: photon splitting, redshift

$$\gamma + e \rightarrow 2\gamma + e$$

Induced effect in laser vs. ICS

- number in state *i*: N_i
- pumping rate to state *i*: Φ_i
- decay rate from state *i*: γ_i
- Einstein's *B* coefficient: B
- energy level between state 1 & 2: $\hbar\omega$
- photon energy density at *ω*: $U(\omega)$



$$\begin{aligned}\frac{dN_2}{dt} &= \Phi_2 - \gamma_2 N_2 \overbrace{- (N_2 - N_1)\, BU(\omega)}^{\text{induced term}} \\ \frac{dN_1}{dt} &= \Phi_1 - \gamma_1 N_1 + (N_2 - N_1)\, BU(\omega)\end{aligned}$$

$$\Updownarrow$$

$$\boxed{\frac{dn_{\rm ph}(\nu)}{dt} \propto \textcolor{red}{n_{\rm ph}(\nu_+)}(1 + n_{\rm ph}(\nu)) - n_{\rm ph}(\nu)(1 + \textcolor{blue}{n_{\rm ph}(\nu_-)})}$$

$$\Rightarrow \quad \frac{dn_{\rm ph}(\nu)}{dt} \propto n_{\rm ph}(\nu_+) - n_{\rm ph}(\nu) + (n_{\rm ph}(\nu_+) - n_{\rm ph}(\nu_-))\, n_{\rm ph}(\nu)$$