Opportunities of strong-field physics in middle-energy heavy-ion collisions

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Plan

Middle-energy heavy-ion collisions $\sqrt{s_{\mathrm{NN}}} = O(2\text{ - }10\ \mathrm{GeV})$ is interesting not only to QCD but also to strong-field QED

1. Introduction to strong-field QED

2. Strong EM field in high-energy heavy-ion collisions

Strong but too short-lived ⇒ affects “non-perturbativeness” of strong-field processes

3. Strong EM field in middle-energy heavy-ion collisions

Estimation of EM field strength and spacetime volume with a hadron transport model (JAM)

⇒ “strong” O(50 MeV) and large spacetime volume $O((20\ \mathrm{fm})^4)$

⇒ a nice setup to study strong-field QED; non-negligible to hadronic/QCD processes as well

[Nishimura (Osaka), Ohnishi (Kyoto), HT, in progress]

4. Summary

1. Introduction to strong-field QED

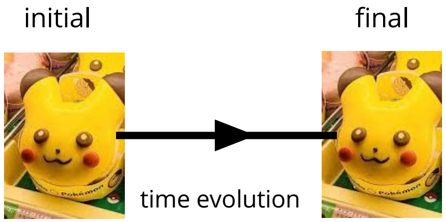
2. Strong EM field in high-energy HIC

3. Strong EM field in middle-energy HIC

[Nishimura (Osaka), Ohnishi (Kyoto), HT, to appear soon]

4. Summary

Strong-field QED



Vacuum
(= No EM field)

Strong-field QED

initial

time evolution

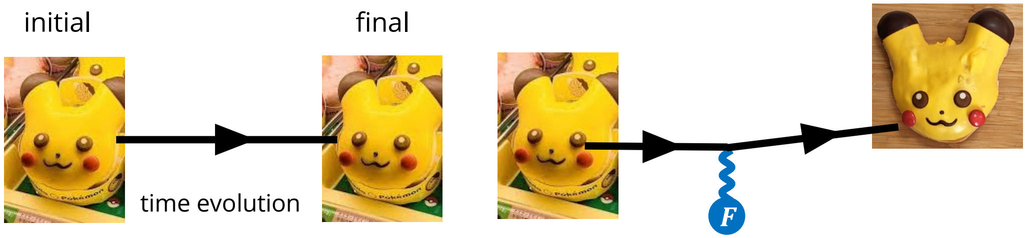
final

Vacuum
(= No EM field)

Weak EM field
$(eF/m^2 \lesssim 1)$

Strong EM field
$(eF/m^2 \gtrsim 1)$

Strong-field QED



Vacuum
(= No EM field)

Weak EM field
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Strong EM field
$(eF/m^2 \gtrsim 1)$

Almost the same

⇒ Perturbative

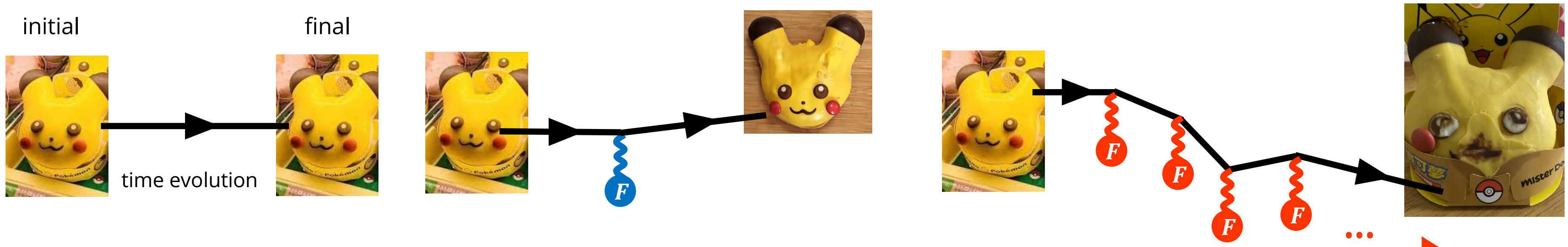
⇒ Understood

ex) Electron anomalous magnetic moment $a := \frac{g-2}{2}$

$a(\text{theor.}) = 1159652182.03\ldots \times 10^{-12}$ [Aoyama, Kinoshita, Nio (2017)]

$a(\text{exp.}) \quad = 1159652180.73\ldots \times 10^{-12}$

Strong-field QED



Vacuum
(= No EM field)

Weak EM field
$(eF/m^2 \lesssim 1)$

Strong EM field
$(eF/m^2 \gtrsim 1)$

Almost the same
⇒ Perturbative
⇒ Understood

Completely different
⇒ Non-perturbative
⇒ Not understood

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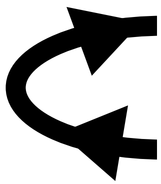
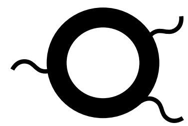
$a(\text{exp.}) = 1159652180.73 \ldots \times 10^{-12}$

Examples of strong-field phenomena

✔ Novel QED processes ($eF/m_e^2 \gtrsim 1$)

ex) Schwinger mechanism | Photon splitting | Vacuum birefringence (= Polarization dep. of reflective index)

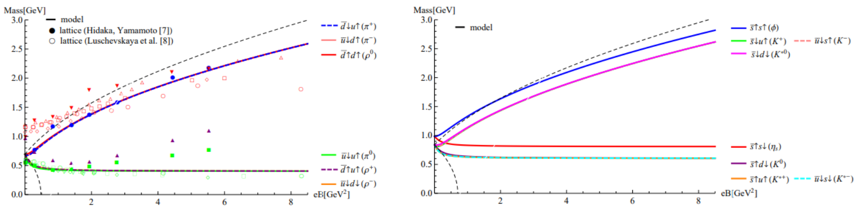




Review: [Fedotov, Ilderton, Karbstein, King, Seipt, HT, Torgrimsson (2022)]

✔ Impacts on QCD/hadron physics ($eF/\Lambda_{\rm QCD}^2 \gtrsim 1$)

[HT (2015)]



ex. 1) Hadron properties:

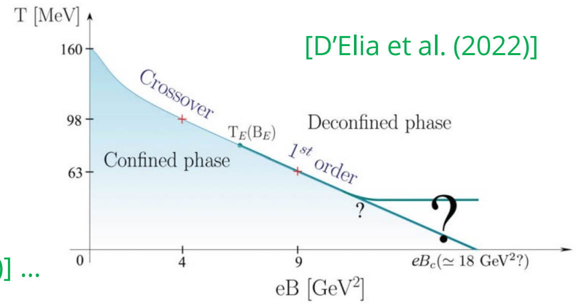
e.g., mass, charge dist., decay mode, …

See also recent review [Iwasaki, Oka, Suzuki (2021)]

ex. 2) QCD phase diagram

e.g., (inverse) magnetic catalysis, new phase, …

[D'Elia et al. (2022)]



ex. 3) Others: Anomalous transport,
(for color EM field) Glasma, string breaking, …

Many reviews, e.g., [Kharzeev, Liao, Voloshin, Wang (2016)] [Hattori, Huang (2017)] …

Many theoretical predictions, but never observed in experiments

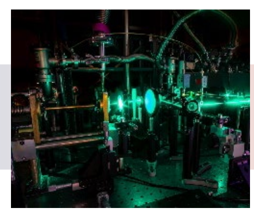
Need of EXTREMELY strong EM field

✔ Order of the magnitude:

QED: $eE, eB > m_e^2 = (0.511\ \mathrm{MeV})^2 \approx O(10^{29}\ \mathrm{W/cm^2})$

QCD: $> \Lambda_{\mathrm{QCD}}^2 = (200\ \mathrm{MeV})^2 \approx O(10^{39}\ \mathrm{W/cm^2})$

Our limit at the present

LED	Laser welding	Cond.-mat (THz laser)	Guiness record	???
				
			HERCULES @ USA (2008)	
$I \sim 10^{-5}\ \mathrm{W/cm^2}$	$10^6\ \mathrm{W/cm^2}$	$10^{10}\ \mathrm{W/cm^2}$	$10^{22}\ \mathrm{W/cm^2}$	$\mathbf{10^{29}\ W/cm^2}$
or $eE \sim 10^{-1}\ \mathrm{eV/cm}$	$10^4\ \mathrm{eV/cm}$	$10^6\ \mathrm{eV/cm}$	$10^{12}\ \mathrm{eV/cm}$	$\mathbf{10^{18}\ eV/cm}$
$\sim (10^{-3}\mathrm{eV})^2$	$(10^{-1}\mathrm{eV})^2$	$(1\ \mathrm{eV})^2$	$(1\ \mathrm{keV})^2$	$\mathbf{(10^6\ eV)^2}$

Daily life → Industry → Science

Impossible within the current tech. ⇒ New idea needed ⇒ HIC ?

1. Introduction to strong-field QED

2. Strong EM field in high-energy HIC

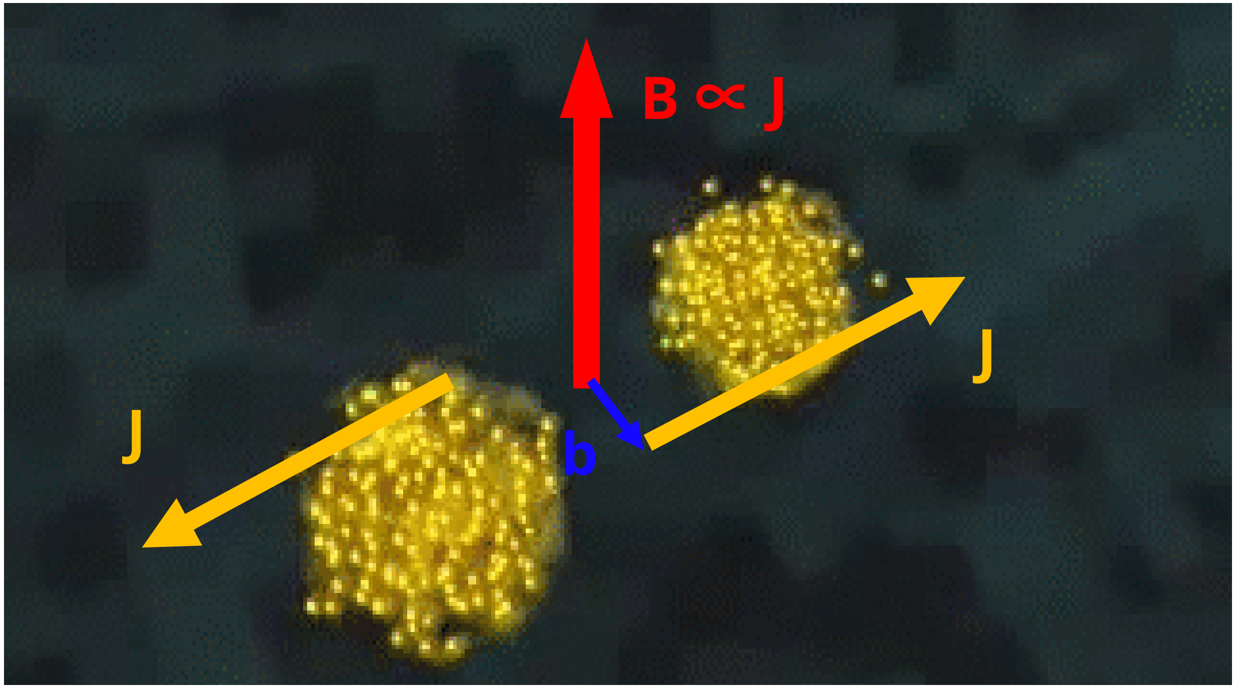
3. Strong EM field in middle-energy HIC

[Nishimura (Osaka), Ohnishi (Kyoto), HT, to appear soon]

4. Summary

Strong EM field at high-energy heavy-ion collisions

[See also talk by Xu]

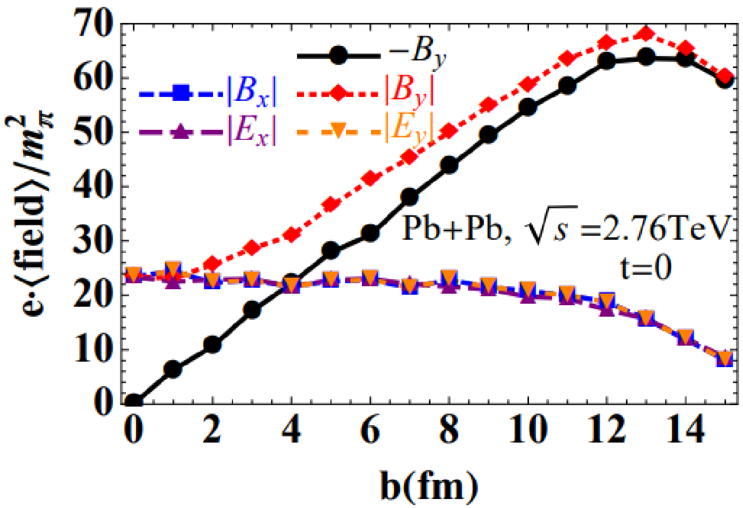


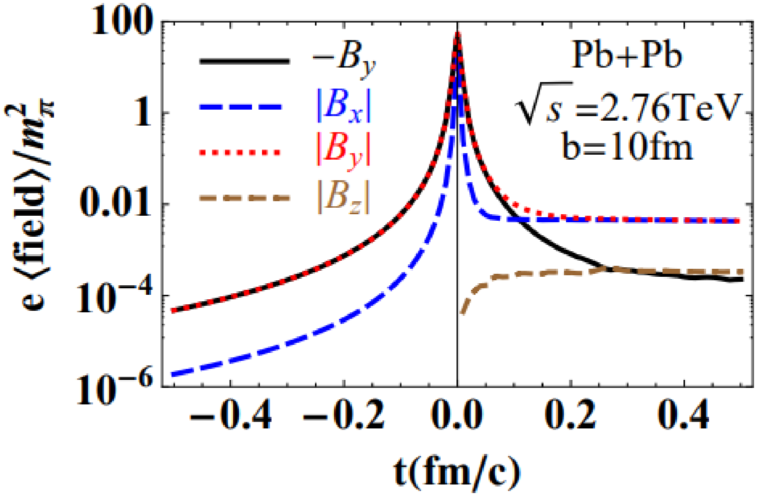
Animation stolen from Internet

✔ **Strong magnetic field is created**

Strong EM field at high-energy heavy-ion collisions

[See also talk by Xu]





[Deng, Huang (2012)]

See also [Bzdak, Skokov (2012)] [Hattori, Huang (2016)]

✔ **Strong magnetic field is created**

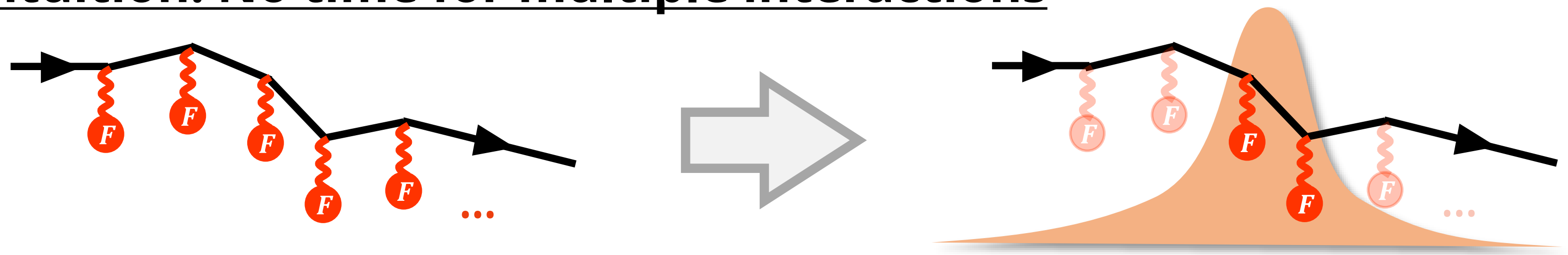
Pro: Super strong $eB \gg \Lambda_{\rm QCD}^2$

Cons: Extremely short-lived ($\tau \ll 1\ \mathrm{fm}/c$)

⇒ Affects "non-perturbativeness" of strong-field physics

Shorter lifetime ⇒ more perturbative

✔ Intuition: No time for multiple interactions



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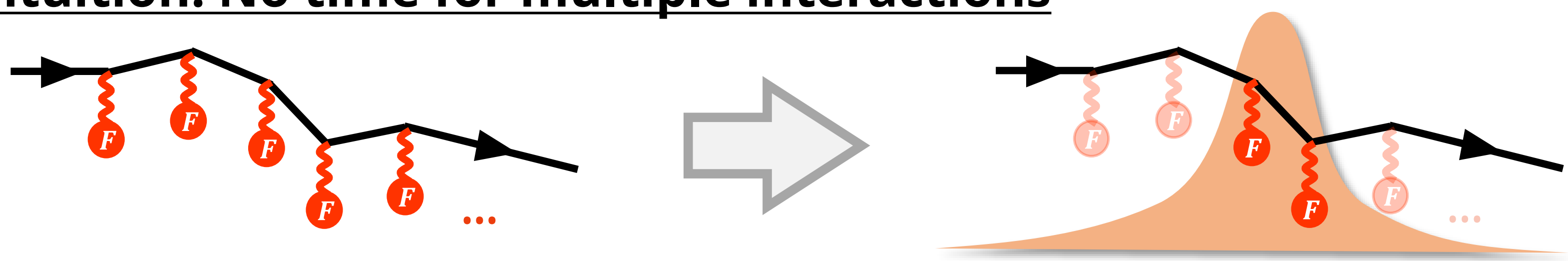


✔ "Phase diagram" of strong-field physics

[HT, Fujiii, Itakura (2014)]
[HT, Fujimori, Misumi, Nitta, Sakai (2021)]

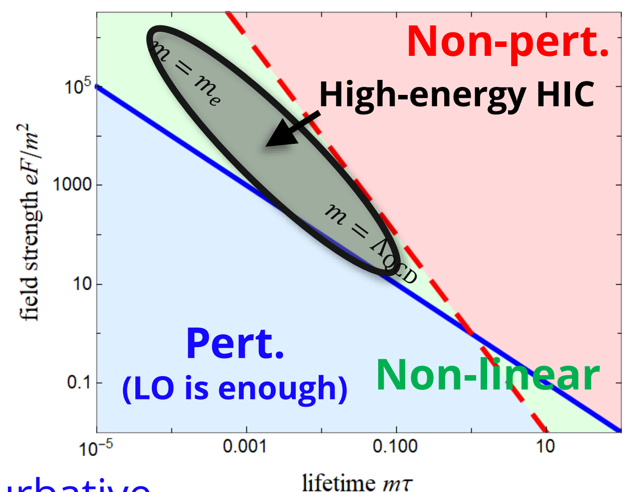
As example: Vacuum particle prod. by E field w/ finite lifetime

- Three dimensionful parameters in the system: eE, τ, m

  ⇒ Two dim.-less parameters determine the physics

$$\gamma = \frac{m}{eE\,\tau} = \frac{\text{(Typical energy)}}{\text{(Work by field)}}$$ ⇒ Characterize the magnitude of work

$$\nu = \frac{eE\,\tau}{1/\tau} = \frac{\text{(Work by field)}}{\text{(Photon energy)}}$$ ⇒ Characterize the number of photons



- $\boldsymbol{\gamma \ll 1\,, \nu \gg 1}$ ⇒ Non-perturbative v.s. $\boldsymbol{\gamma \gg 1\,, \nu \ll 1}$ ⇒ perturbative

- High-energy HIC: $eF \sim (1\ \text{GeV})^2\,,\ \tau \sim 0.1\ \text{fm}/c \Rightarrow \gamma \sim \begin{cases} 10^{-3}\ (m = \Lambda_{\text{QCD}}) \\ 10^{-5}\ (m = m_{\text{e}}) \end{cases},\ \nu \sim 0.1$

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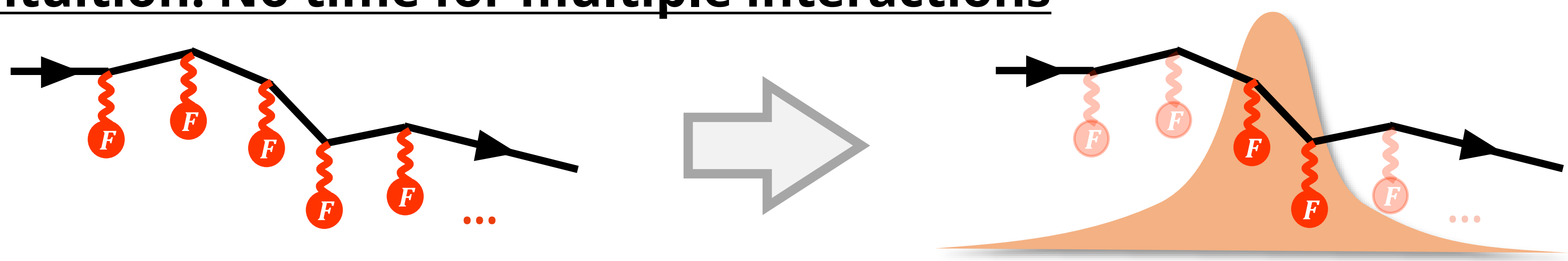

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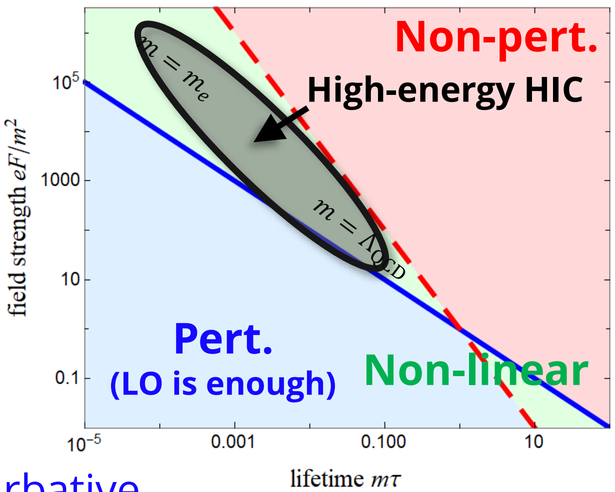

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High-energy HIC is short-lived ⇒ not useful for strong-field phys. in non-pert. regime

(actually, only NLO such as Breit-Wheeler have been observed in exp., with no signals of higher-order effects)

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3. **Strong EM field in middle-energy HIC**

[Nishimura (Osaka), Ohnishi (Kyoto), HT, to appear soon]

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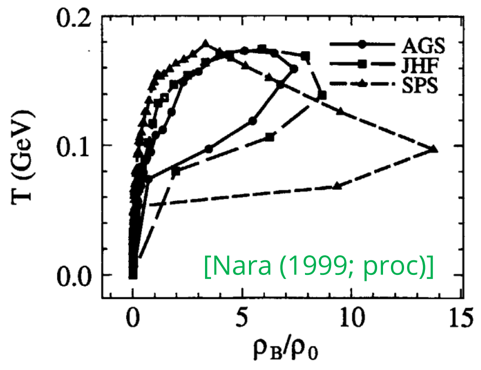
Strong EM field at middle-energy heavy-ion collisions

✔ Lower energy ⇒ Landau stopping picture

Numerical results with transport-model simulations

E = O(10 GeV/nucleon)



Time evolution of baryon density and effective temperature in Au+Au at 11.6AGeV/c from 0 fm/c to 20 fm/c 1.0 fm/c step, Au+Au at 25AGeV, and Pb+Pb at 158AGeV, respectively.

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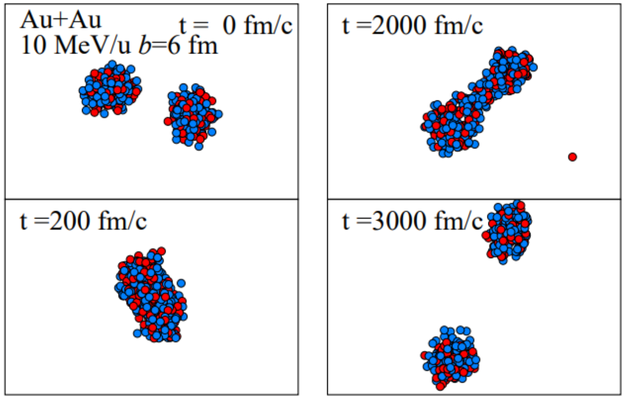

Figure 1. Snapshot of ^{197}Au + ^{197}Au at $E_{\rm lab}$ = 10 MeV/nucleon b = 6 fm. The time indicated in each panel is not from the contact of two nuclei but indicates only that of the simulation.

[Maruyama, Bonasera, Papa, Chiba (2002)]

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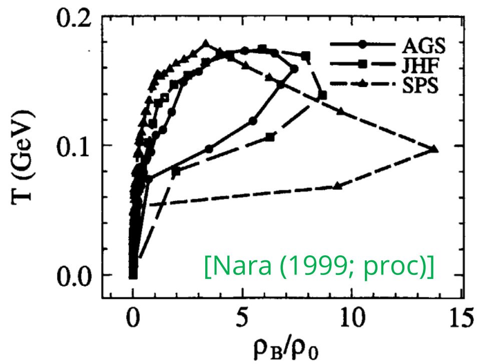

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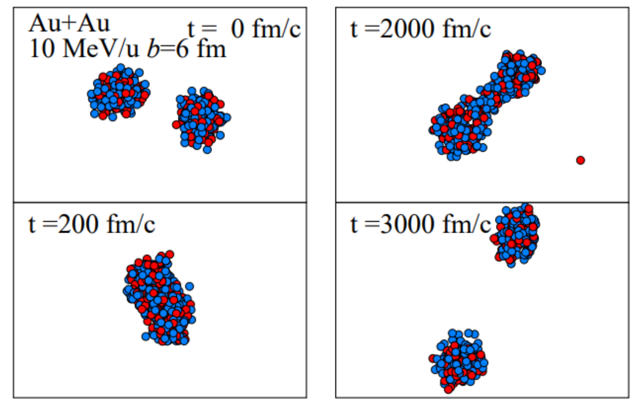

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⇒ Dense matter is formed for a long time $O(10 - 1000\ \mathrm{fm}/c)$

⇒ Charge density is also large ("High Z atom" s.t. $Z \gtrsim 1/\alpha$) ⇒ Strong Coulomb field

- High energy ⇒ Magnetic vs Low/middle energy ⇒ Electric
- Rough order estimate: $eE \sim \frac{Z\alpha}{r^2} \sim \Lambda_{\rm QCD}^2 \sim (100\ \mathrm{MeV})^2$

$$\Rightarrow \gamma = \frac{m}{eE\tau} \lesssim \begin{cases} 10^{-1}\ (m = \Lambda_{\rm QCD}) \\ 10^{-4}\ (m = m_{\rm e}) \end{cases} \sim 0.1,\ \nu = eE\tau^2 \gtrsim 10$$

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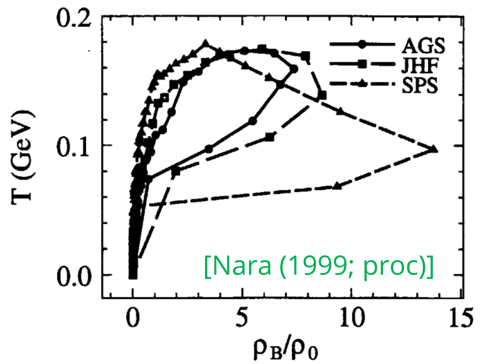

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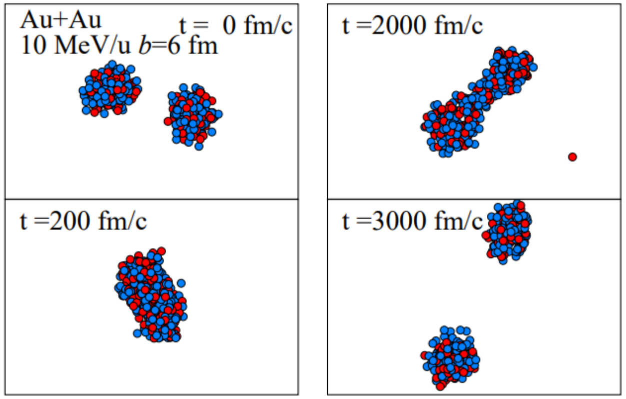

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⇒ Non.-pert both in QED & QCD $\begin{cases} \gamma \ll 1 \\ \nu \gg 1 \end{cases}$

∴ Interesting to strong-field physics. May affect QCD/hadron processes as well !
⇒ Let's think about this possibility seriously

Estimation with a hadron trans. model: JAM (1/4)

[Nishimura (Osaka), Ohnishi (Kyoto), HT, in progress]

✔ Simulation with JAM (Jet AA Microscopic transport model)

[Nara, Otsuka, Ohnishi, Nitta, Chiba (2000)]

- A transport-model simulation of heavy-ion collisions
  ⇐ superposition of two-body hadron scatterings + inelastic scattering processes
  (e.g., string breaking with PYTHIA)

- Anyway, **phase space distribution of charged particles** can be calculated

- Phase space dist. ⇒ EM field

From JAM

$$A^\mu(x^0, \boldsymbol{x}) = \frac{1}{4\pi} \int_{-\infty}^{+\infty} \mathrm{d}^3\boldsymbol{x}' \frac{J^\mu(x^0 - |\boldsymbol{x} - \boldsymbol{x}'|, \boldsymbol{x}')}{|\boldsymbol{x} - \boldsymbol{x}'|}$$

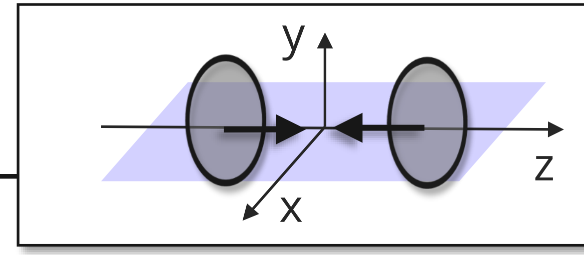
Detail 1: The following results are after N=100 event averaging: $\langle A \rangle = \frac{1}{N} \sum_{n=1}^{N} A_n$

Detail 2: I don't use Lienard-Wiechert potential for a point-like particle
⇐ LW pot. is inapplicable, since particles are produced / can decay during the evolution

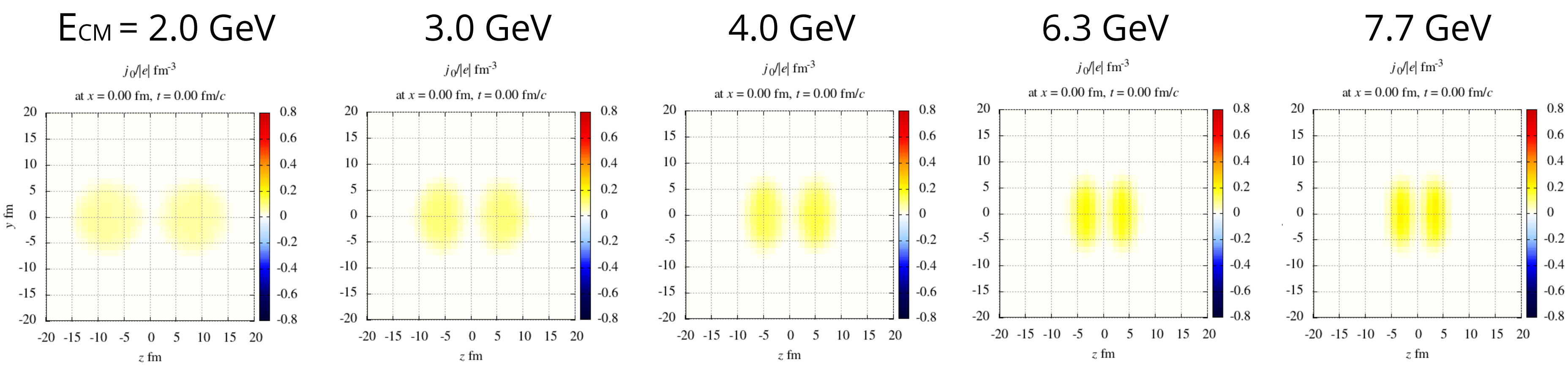
Detail 3: I smeared the point-like dist. of each hadron in JAM with
(relativistic) Gaussian smearing with smearing width 1fm

Estimation with a hadron trans. model: JAM (2/4)

[Nishimura (Osaka), Ohnishi (Kyoto), HT, in progress]



✔ Time evol. of charge density (central coll.) @ z=0

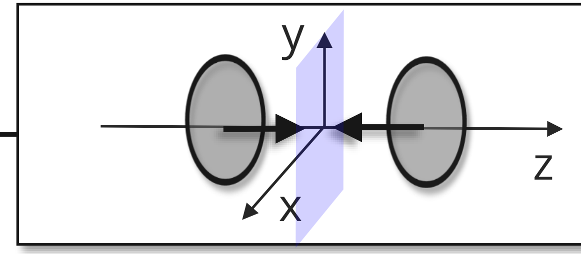


Huge charge density with a long lifetime time due to the stopping

- O(10) times bigger than charge density of a single static ion $\rho_{\rm charge} \sim \rho_{\rm nuclear} /2 \sim 0.08\ {\rm fm}^{-3}$ (nuclear saturation density)
- Lifetime ~ O(20 fm/c)

Estimation with a hadron trans. model: JAM (3/4)

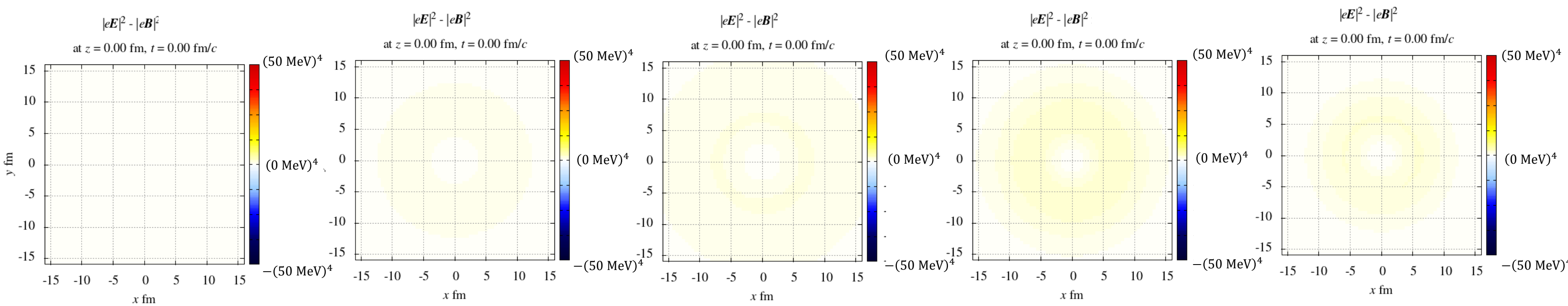
[Nishimura (Osaka), Ohnishi (Kyoto), HT, in progress]



✔ Time evolution of EM field (central coll. b=0) @ z=0

- Lorentz inv. $F \coloneqq E^2 - B^2$ (F>0: Electric, F<0: Magnetic)

E_{CM} = 2.0 GeV | 3.0 GeV | 4.0 GeV | 6.3 GeV | 7.7 GeV



Field strength can be strong as $e^2 F \sim (eE)^2 = O\big((50\ \mathrm{MeV})^4\big)$

⇒ • **Very strong for QED ($m_e = 0.511$ MeV)**

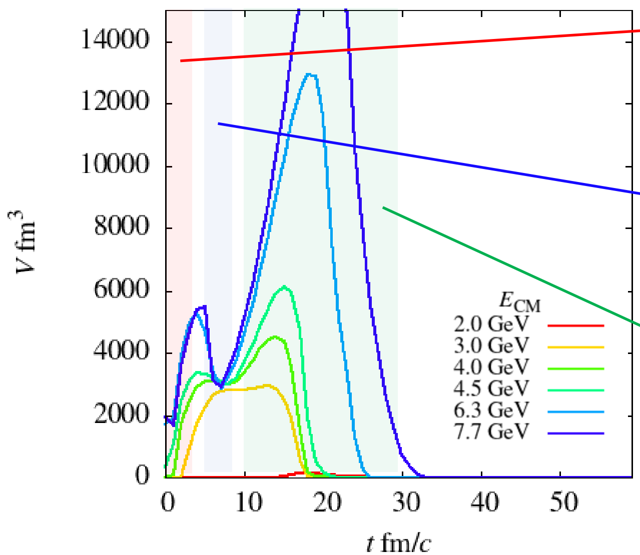
- **Weak for QCD ($\Lambda_{\mathrm{QCD}} = 200$ MeV), but should be non-negligible (if deconfined, very strong for current quark mass)**

Estimation with a hadron trans. model: JAM (4/4)

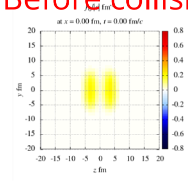
[Nishimura (Osaka), Ohnishi (Kyoto), HT, in progress]

✔ Spacetime volume of EM field (central coll. b=0)

Volume for $e^2F = |e\boldsymbol{E}|^2 - |e\boldsymbol{B}|^2 > (30\ \mathrm{MeV})^4$

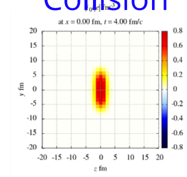


Before collision



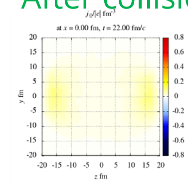
= Strength: so so
Volume: so so

Collision



= Strength: strongest
Volume: small

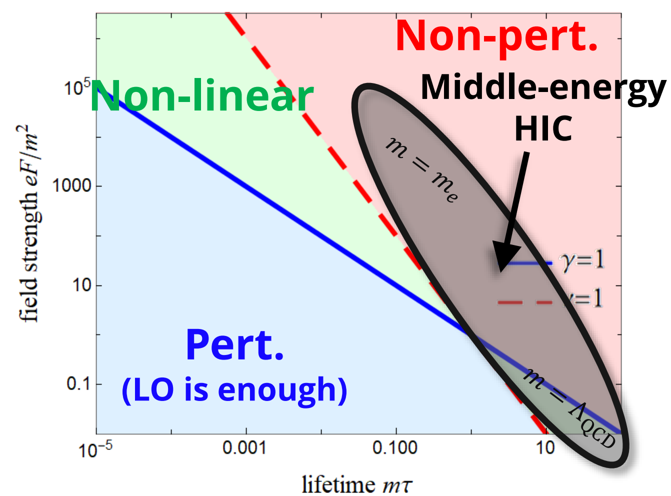
After collision



= Strength: weak
Volume: large

Strong E field with $e^2F \sim (eE)^2 \sim (30\ \mathrm{MeV})^2$,
lifetime $\tau \gtrsim 20\ \mathrm{fm}/c$, volume $V \gtrsim (15\ \mathrm{fm})^3$

⇒ **Non-pert** for QED. **Non-linear** for QCD



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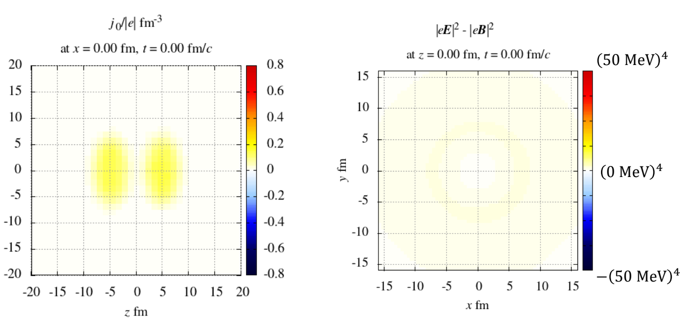
Summary

Middle-energy heavy-ion collisions $\sqrt{s_{\mathrm{NN}}} = O(1\text{-}10\ \mathrm{GeV})$ is interesting not only to QCD but also to strong-field QED

Estimation of EM field strength and spacetime volume with a hadron transport model (JAM)
⇒ "strong" O(50 MeV) and large spacetime volume O((20 fm)^4)
⇒ a nice setup to study strong-field QED; non-negligible to hadronic/QCD processes as well

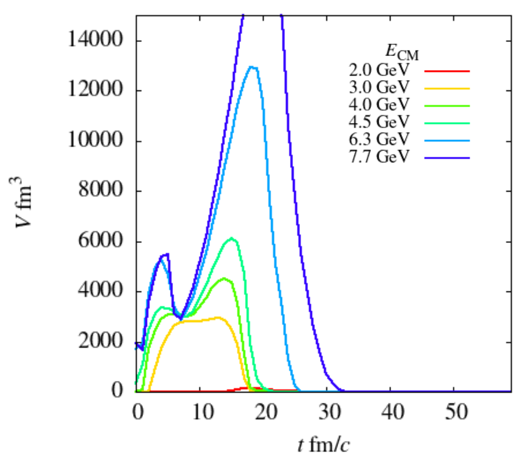
Realtime evolution of EM field

charge density ⇒ E field

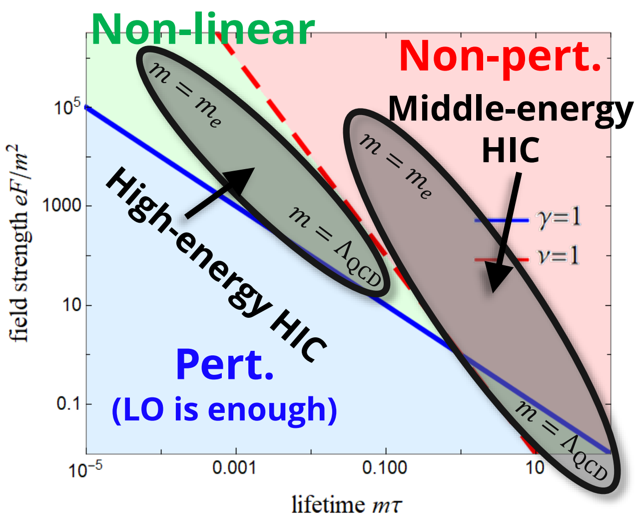


Spacetime volume of EM field

$e^2F = |e\boldsymbol{E}|^2 - |e\boldsymbol{B}|^2 > (30\ \mathrm{MeV})^4$

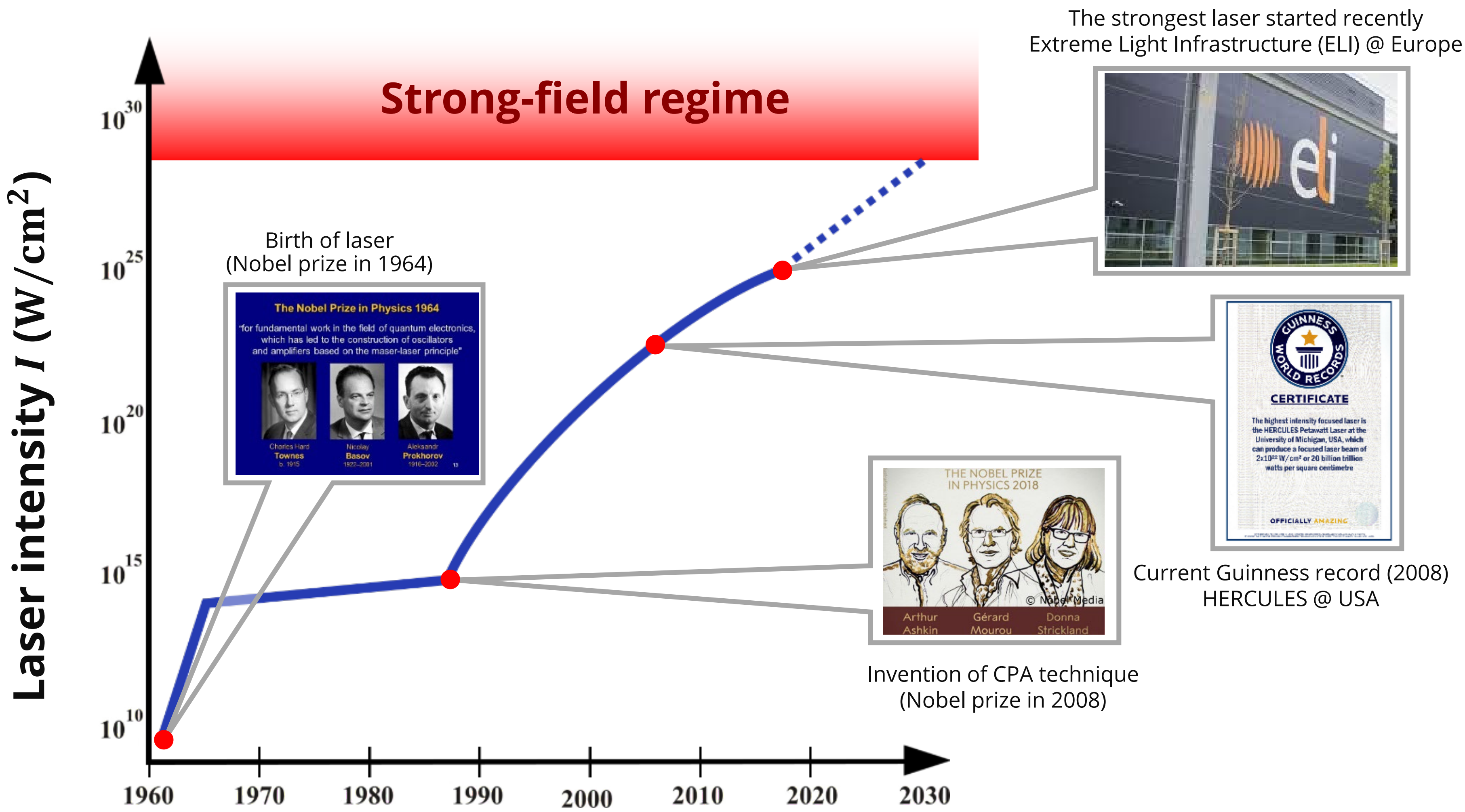


"Phase diagram" of strong-field physics



[Nishimura (Osaka), Ohnishi (Kyoto), HT, in progress]

The current status of high-power laser

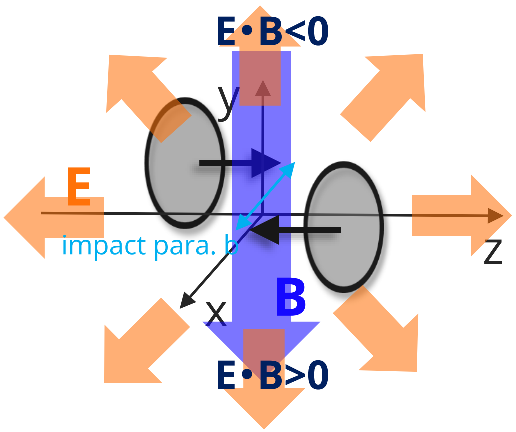


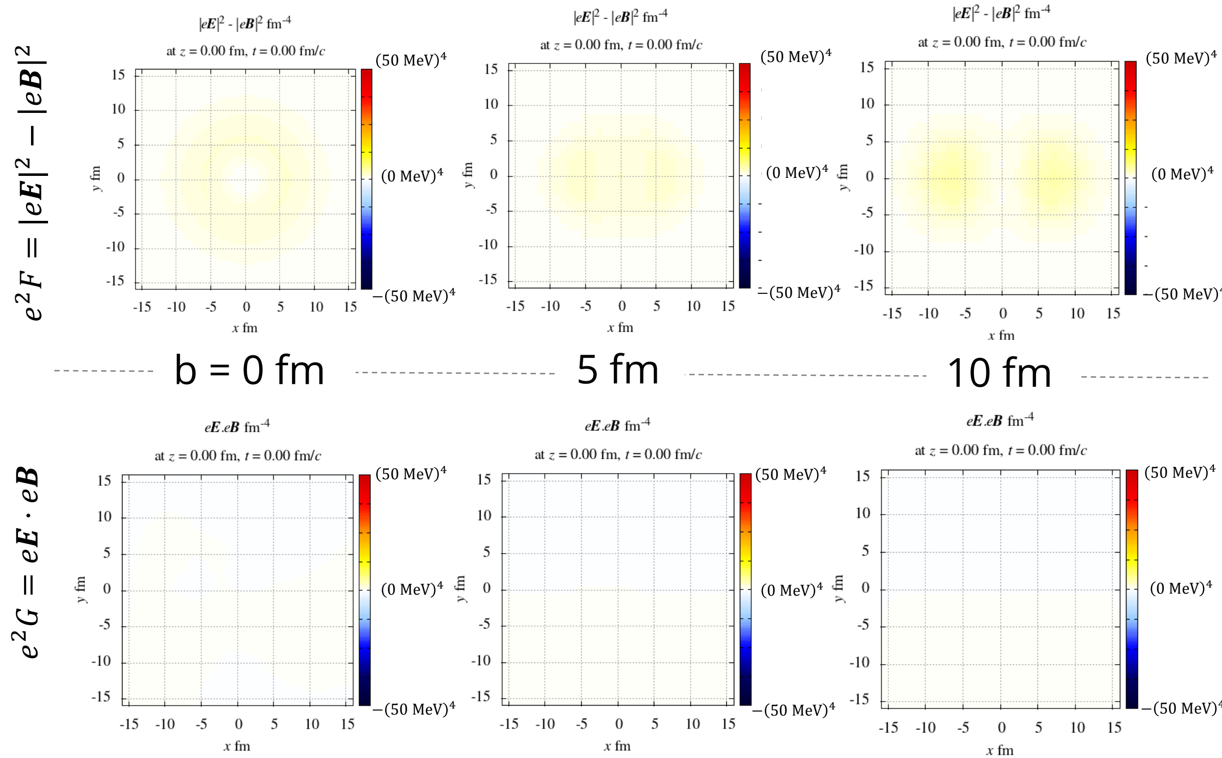
Weak !! Any nice idea ? ⇒ Heavy-ion collisions !

Estimation with a hadron trans. model: JAM (5/5)

[Nishimura (Osaka), Ohnishi (Kyoto), HT, in progress]

✔ Non-central collision ⇒ B & E•B are produced





Preliminary results

@ ECM = 7.7 GeV

- $e\boldsymbol{E}\cdot e\boldsymbol{B} = O((50\ \mathrm{MeV})^4)$ ⇒ Non-negligible for QCD (Enough strong for electron and current quarks)
- Perhaps, a nice place to study chiral-anomaly-related stuffs

ex) chirality production via the Schwinger mechanism $N_5 = VT\dfrac{e\boldsymbol{E}\cdot e\boldsymbol{B}}{2\pi^2}\exp\left[-\pi\dfrac{m^2}{eE}\right]$