# Physical conditions in intermediate-energy heavy-ion collisions: Estimates from JAM

**Hidetoshi Taya**
**( Keio U. )**

Based on: [HT, Nishimura, Ohnishi, 2402.17136]
[HT, Jinno, Kitazawa, Nara, 2409.07685]
[HT, 2501.18171]

# Plan of the talk

**Messages:**

**(1) What is the BEST energy range to study high baryon-density physics ? $\Rightarrow$ $\sqrt{s_{NN}} = 3 \sim 5$ GeV**

**(2) Such an intermediate-energy regime is also EXTREMELY interesting for studying physics of strong electromagnetic field**

**Contents:**

1. Introduction: High-density QCD and intermediate-energy HIC

2. Best energy range for high density physics

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4. Summary

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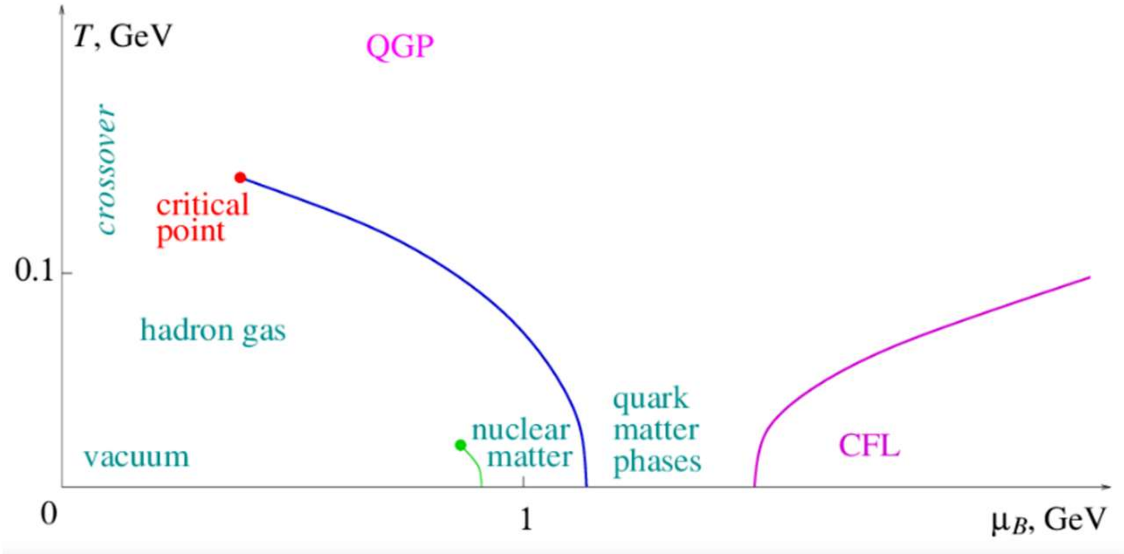
# Q: Matter under extreme condition

- ✔ **Conditions: Temperature, density, …**
- ✔ **Current expectation: QCD phase diagram**




[Stephanov (2006)]

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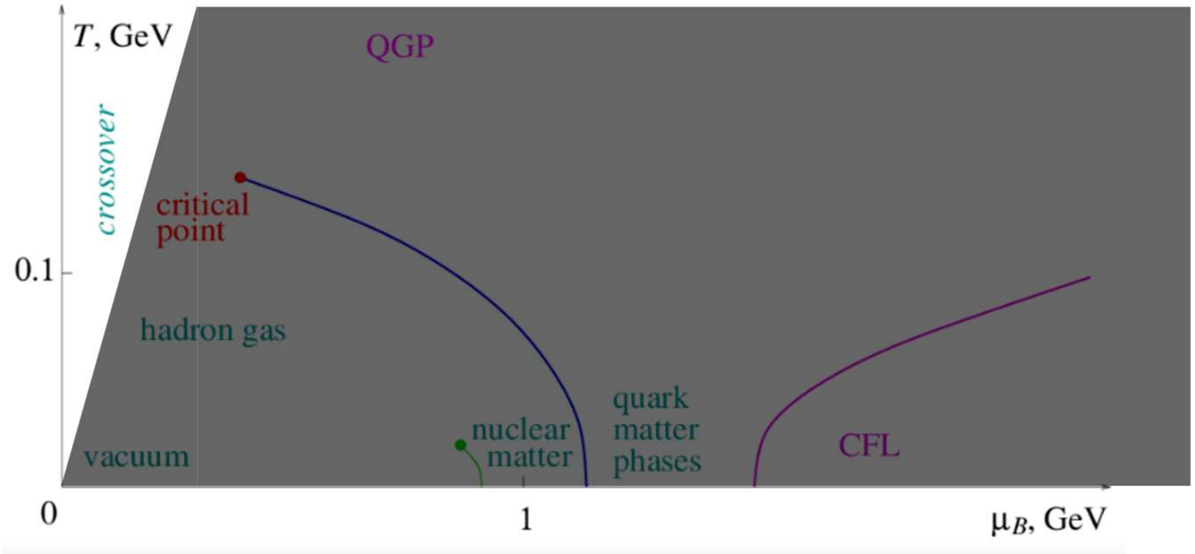


[Stephanov (2006)]

- Certain for the left (low density region)
  ⇐ theory: lattice QCD exp.: high-energy heavy-ion coll.

- Huge uncertainties in the right (high density region) [See also Yamamoto's talk]
  ⇒ need exp. Inputs: **intermediate-energy heavy-ion collisions**

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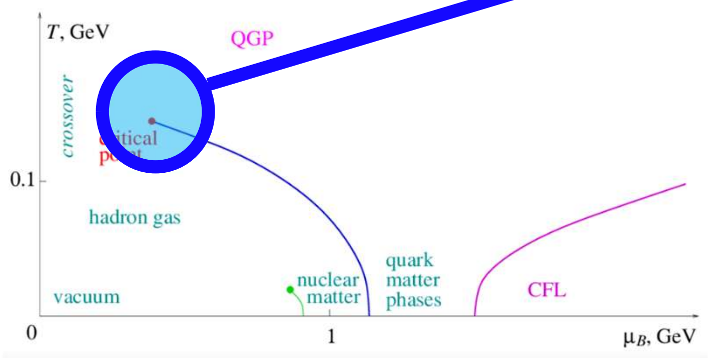


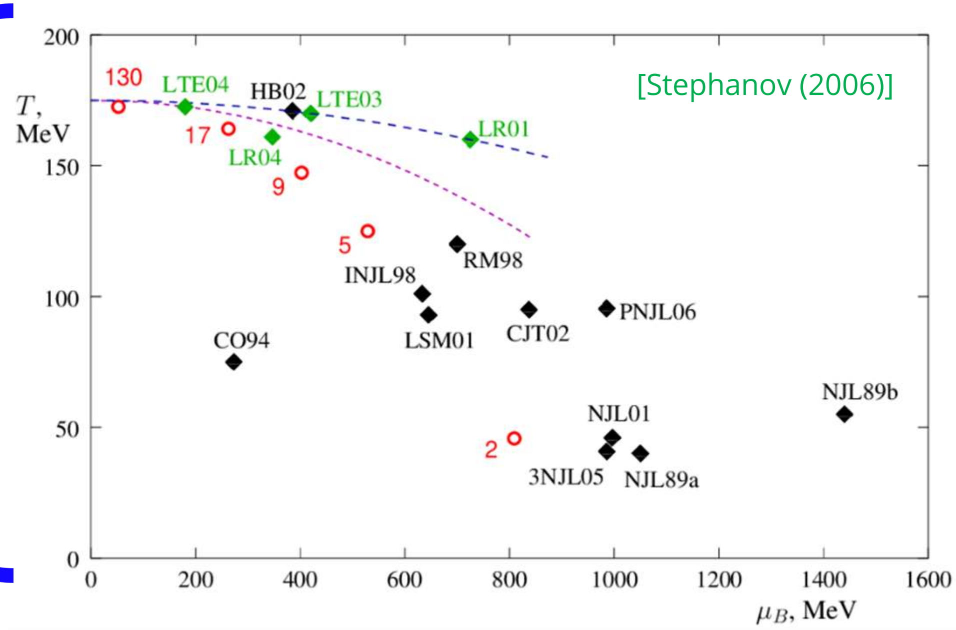


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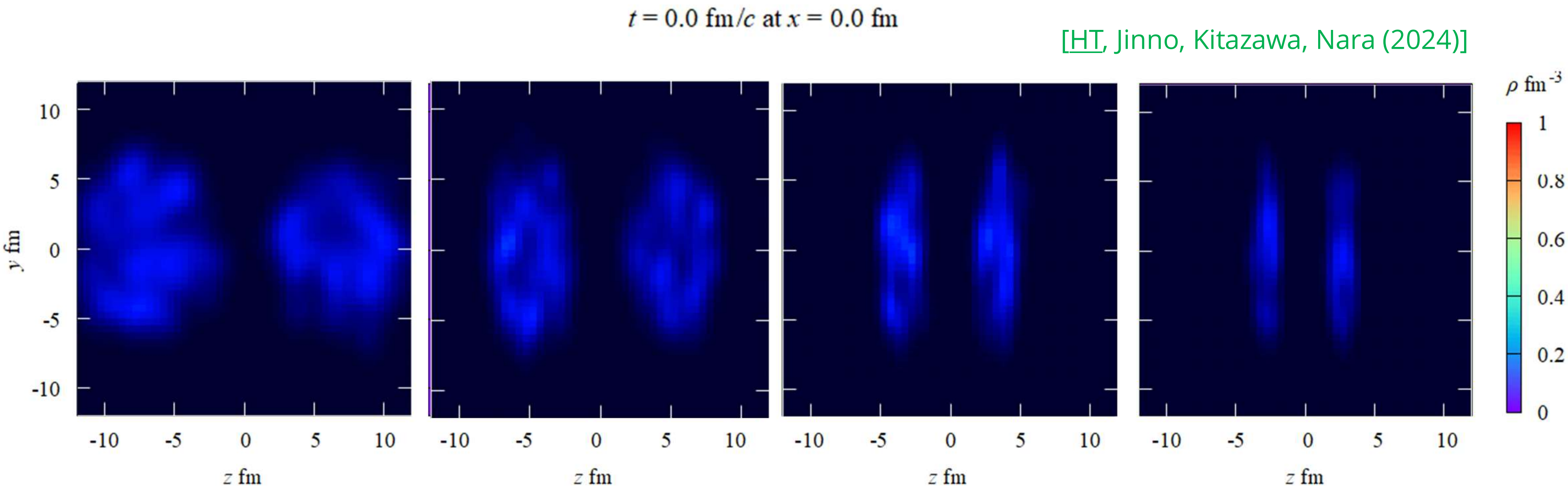
# Intermediate-energy HIC

✔ **Heavy-ion collisions at $\sqrt{s_{NN}} = O(2-10\ \mathrm{GeV})$** [AGS, SPS, RHIC BES, FAIR, NICA, HIAF, J-PARC-HI, …]
expected to be the only means to create "high density matter" in lab.

[HT, Jinno, Kitazawa, Nara (2024)]




$\sqrt{s_{NN}} = 2.4$ GeV　　3.9 GeV　　7.2 GeV　　11.5 GeV

Stopping (Landau) ⟷ Penetration (Bjorken)

Idea: baryon stopping at lower energies ⇒ dense matter [See also Wolf's talk]

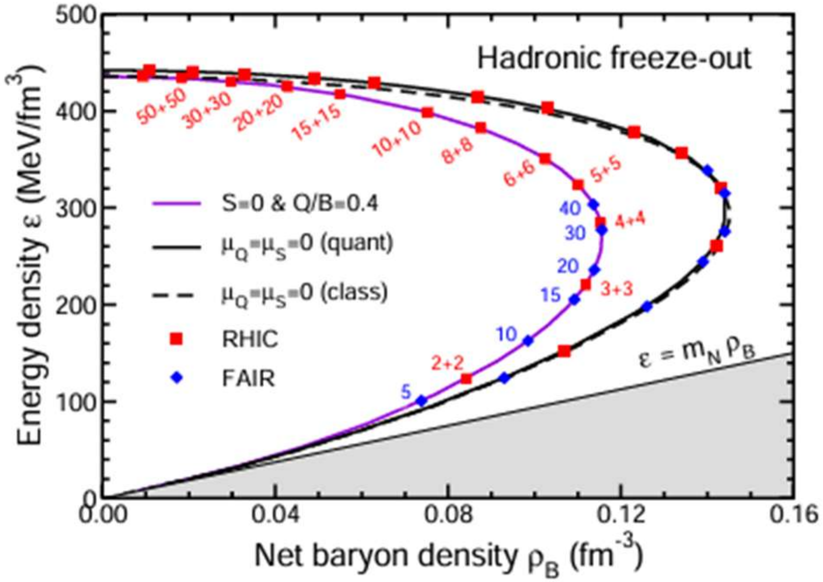
# Contents

# Preceding thy. work on intermediate-energy HIC

✔ **There exist many but highlight two:**

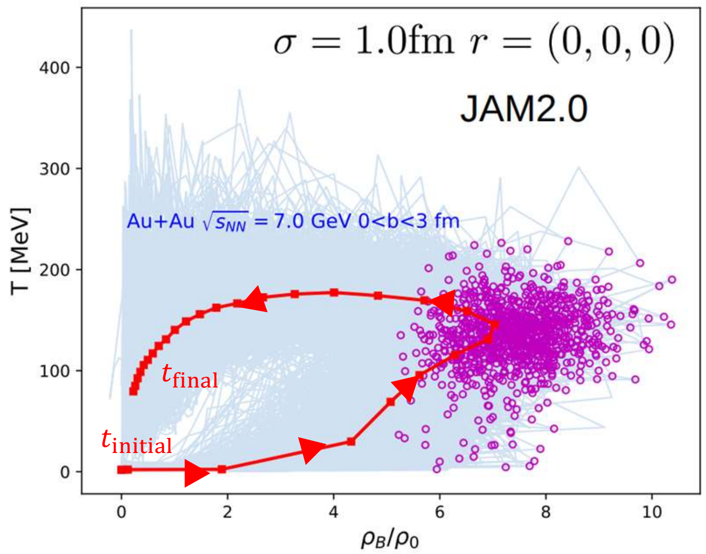
- Statistical model: [Randrup, Cleymans (2006)]

  ⇒ estimate from exp. particle yields at the freeze out




- Transport model: “Ohnishi plot” by A. Ohnishi (~2010)

  ⇒ time evolution of density (at the center cell)




$(\rho_0 \approx 0.17\ \mathrm{fm}^{-3})$

⇒
- the best energy range seems to be $\sqrt{s_{NN}} = 6 \sim 10\ \mathrm{GeV}$
- high density $\rho = (6 \sim 10) \times \rho_0$ can be realized

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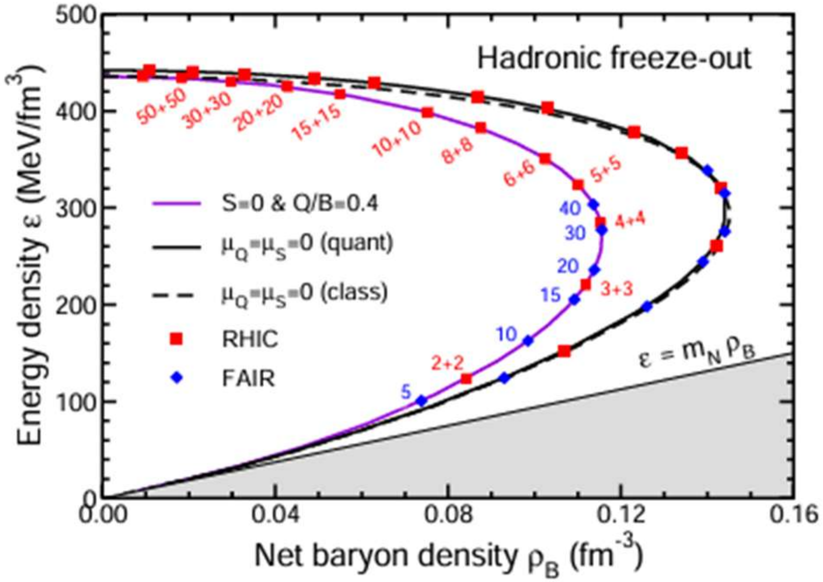


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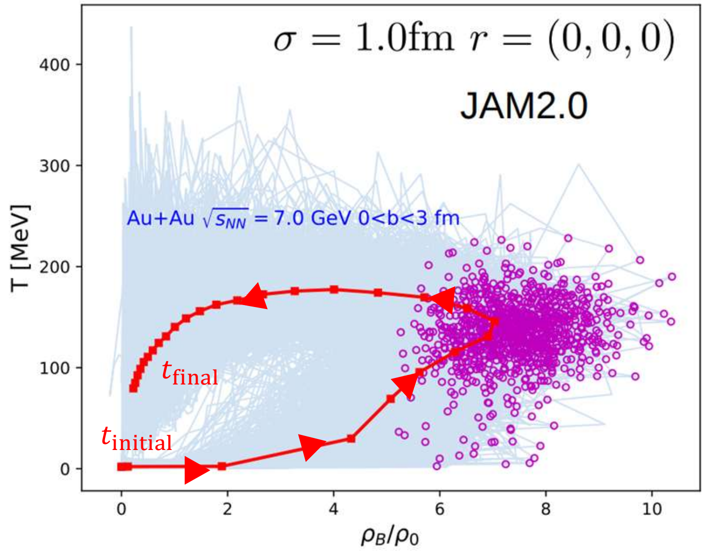


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⇒ • the best energy range seems to be $\sqrt{s_{NN}} = 6 \sim 10$ GeV
• high density $\rho = (6 \sim 10) \times \rho_0$ can be realized

✔ **Problem: Volume of the dense region ?**

⇒ **Purpose:**
- **can the dense region have sufficiently large volume?**
- **what is the best energy to simultaneously maximize density & volume?**

# Method

✔ **Microscopic transport model:**
**JAM (Jet AA Microscopic transport model)**

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

- A successful model to simulate the realtime dynamics of heavy-ion collisions, reproducing various data (v1, yields, ...)

- Basic idea: superposition of collisions of individual hadrons

(incl. inelastic ones such as resonance, string breaking, mini-jet)

- Anyway, the phase-space of each hadron $(x_i^\mu, p_i^\mu)$ can be obtained

⇒ integration of it gives physical observables

e.g.) baryon current in the local rest frame ($J^0_{\mathrm{LRF}} =: \rho$ gives the baryon density):

$$J^\mu_{\mathrm{LRF}} = \Lambda^\mu{}_\nu J^\nu_{\mathrm{lab}} = \Lambda^\mu{}_\nu \sum_{i:\,\mathrm{all\ hadrons}} \rho(\boldsymbol{x}_i)\, Q_i \frac{p_i^\mu}{p_i^0}$$

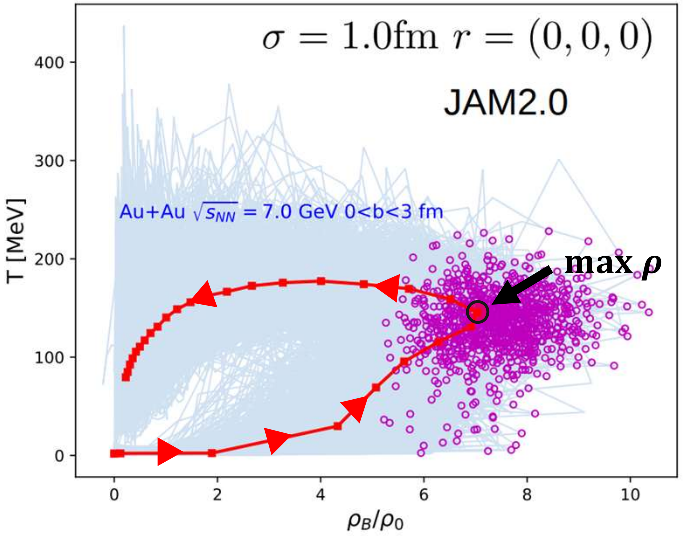
Boost matrix (move to Eckart frame)

Gaussian smearing (σ=1fm)

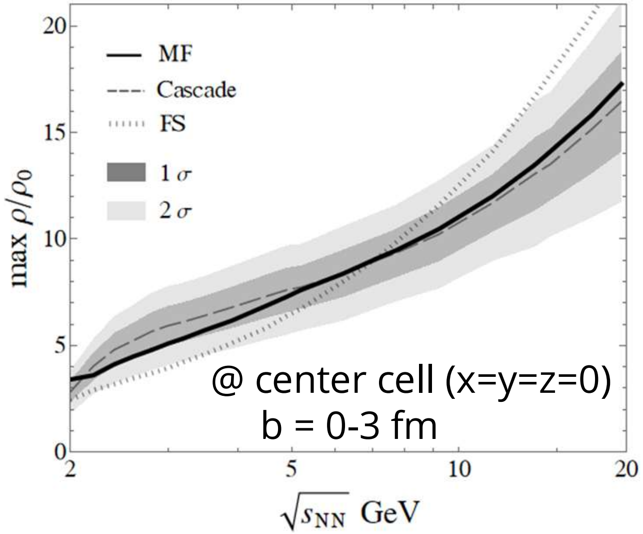
# Result (1/3): maximum density @ center cell ($x = 0$)

✔ **Consistency check w/ Ohnishi plot: calculate $\max \rho := \max_t J^0_{\mathrm{LRF}}$**

Ohnishi plot




This work




⇒ At $\sqrt{s_{NN}}$ = 7 GeV, $\max \rho \approx 7\rho_0$ and is **fluctuating by ~30%**

⇒ Consistent w/ Ohnishi plot (the time evo. is also consistent)

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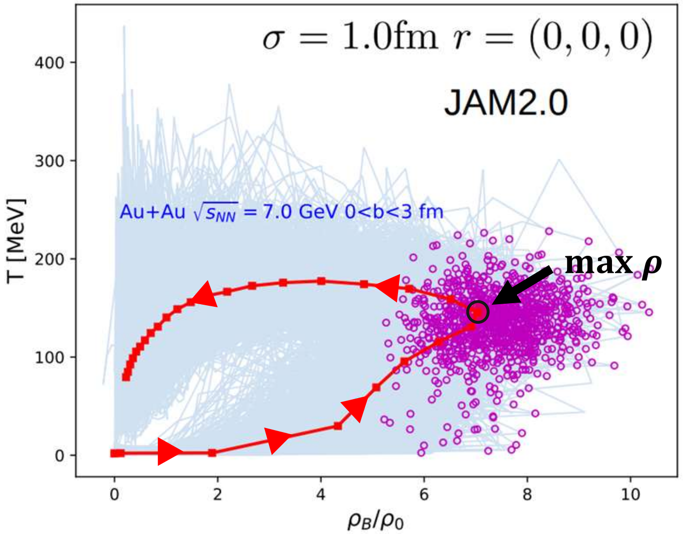


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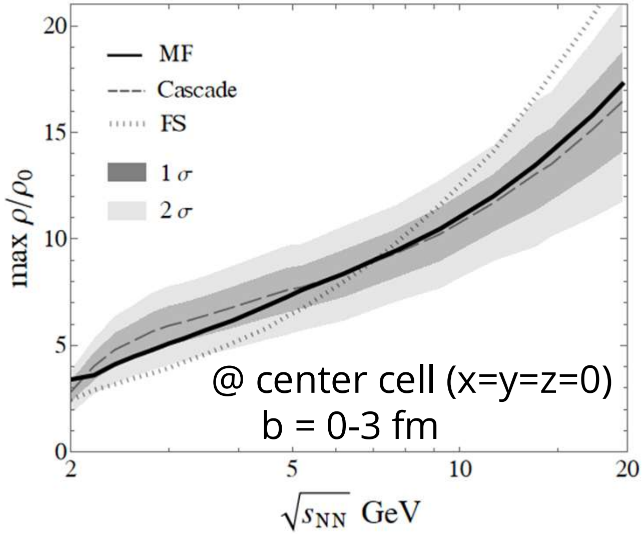


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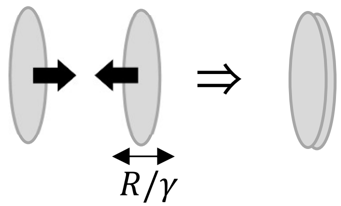
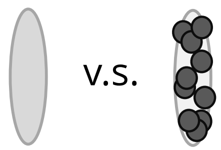
- **Basic: Classical physics = Overlapping of Lorentz contracted "uniform" nuclei**
  max density is at the maximally overlap
  ⇒ roughly: $\max \rho = 2 \times \rho_0 \gamma \approx \sqrt{s_{\mathrm{NN}}}\,[\mathrm{GeV}] \times \rho_0$

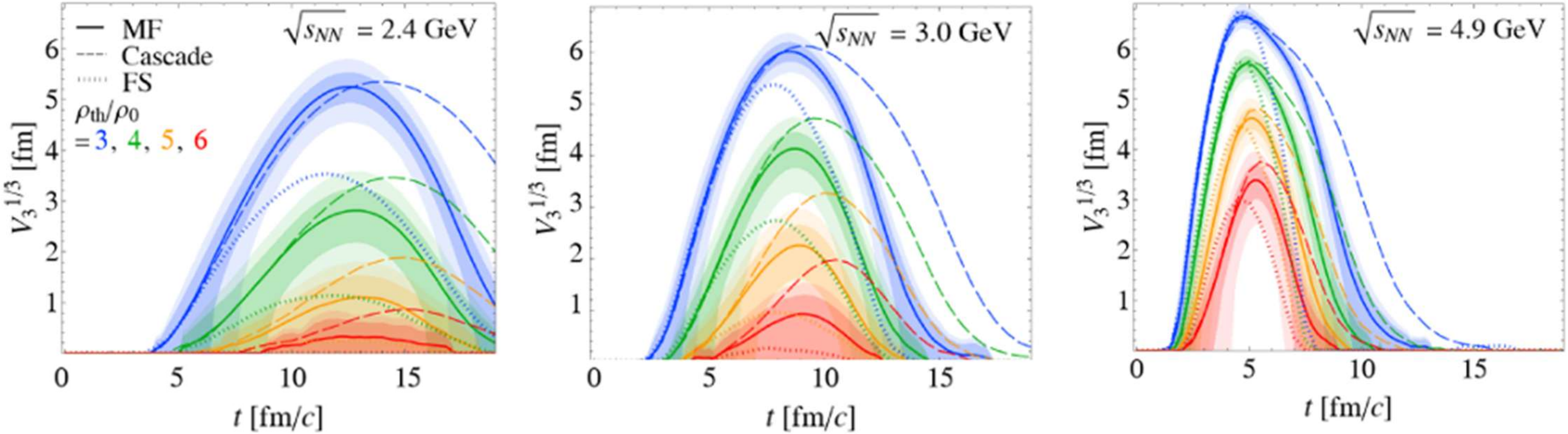



- **Reality: A nucleus is not uniform but is fluctuating**
  happen to overlap more/less ⇒ denser/diluter ⇒ ~30% fluctuation
  - fluctuation is important for creating a dense region (e.g., top 10% of 7.7 GeV reaches 10 x ρ0)
  - the dense region should be "local" = cannot extend over the whole overlapping region

# Result (2/3): spatial volume $V_3$

✔ **Spatial volume in the local rest frame:** $V_3(t) \coloneqq \int_{\rho(t,x)>\rho_{\mathrm{th}}} \mathrm{d}^3x\,\gamma(t,x)$



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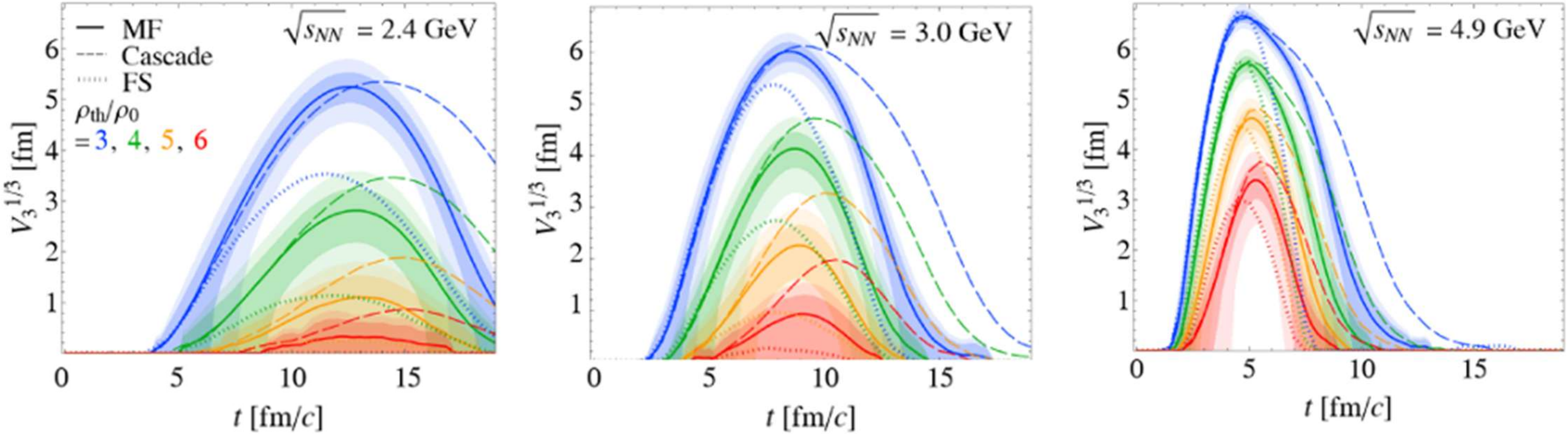



- **Super-dense region originates from nucleons fluct. ⇒ volume ~ nucleon size $V_3 = O((1\ \mathrm{fm})^3)$**
  - event selection enables us to go to higher densities, but it's not matter (i.e., not macroscopically large)
  - even if such a super-dense local region $V_3 = O((1\ \mathrm{fm})^3)$ were giving a nontrivial signal, it's buried in the other signals by other regions $V_3 = O((5\ \mathrm{fm})^3)$

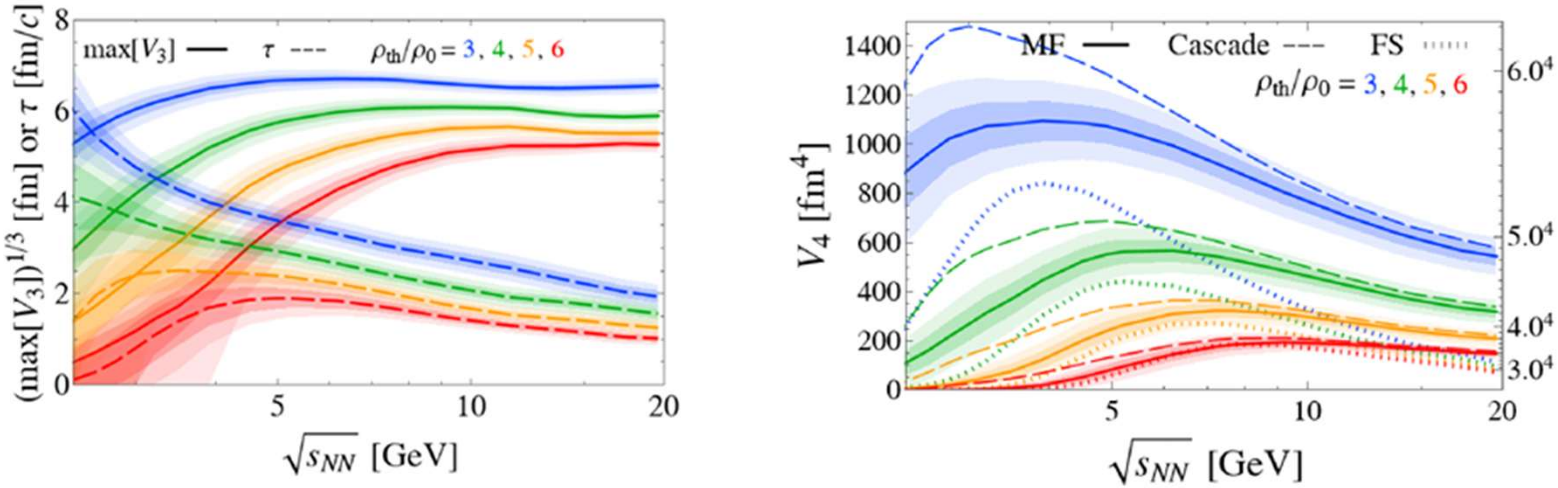
- **"Relatively" dense region $\rho \approx \sqrt{s_{NN}}\,[\mathrm{GeV}] \times \rho_0$ that is created by the naïve overlapping of two uniform nuclei can have sufficiently large volume ~ nucleus size $V_3 = O((6\ \mathrm{fm})^3)$**
  - under the requirement of large $V_3 = O\left((6\ \mathrm{fm})^3\right)$, the achievable density is limited to $\rho \approx \sqrt{s_{NN}}\,[\mathrm{GeV}] \times \rho_0$
  - Q: Larger $\sqrt{s_{NN}}$ is better for creating a high dense matter?

    A: No because the lifetime becomes shorter

    ⇒ Q: what is the best energy $\sqrt{s_{NN}}$ that maximize the volume and lifetime simultaneously, with keeping a high density ?

# Result (3/3): lifetime and four volume

✔ **Four volume and lifetime:** $V_4 \coloneqq \int_{\rho(t,x)>\rho_{\rm th}} \mathrm{d}t\mathrm{d}^3x$ **&** $\tau \coloneqq V_4/\max_t V_3$



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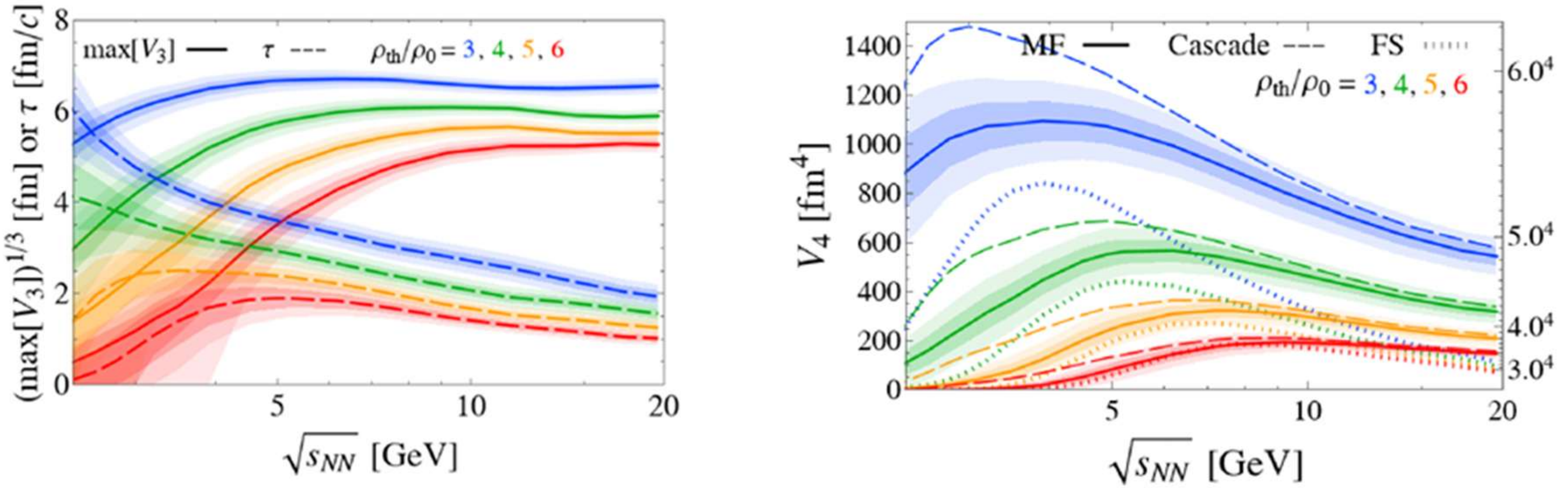


- $\sqrt{s_{NN}} \nearrow \Rightarrow V_3 \curvearrowright$ & $\tau \searrow$
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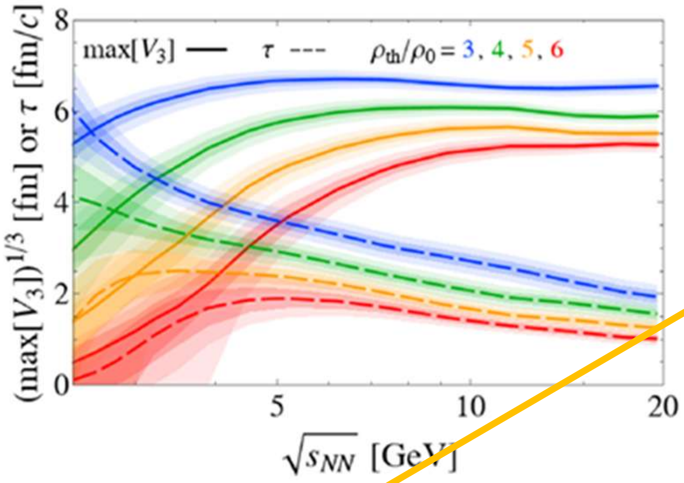
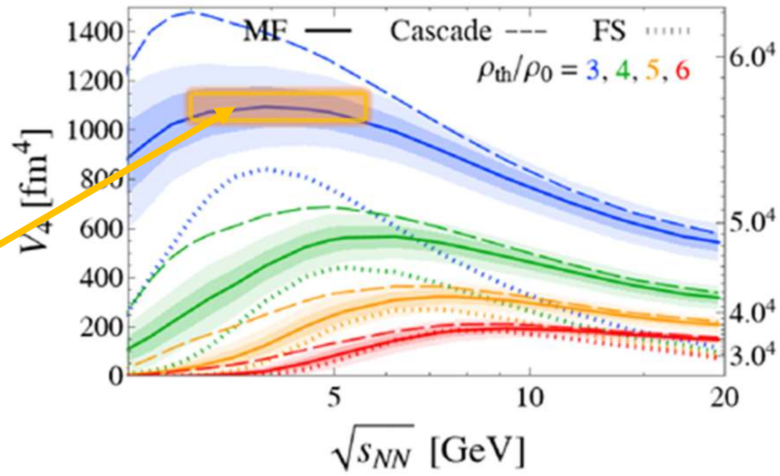


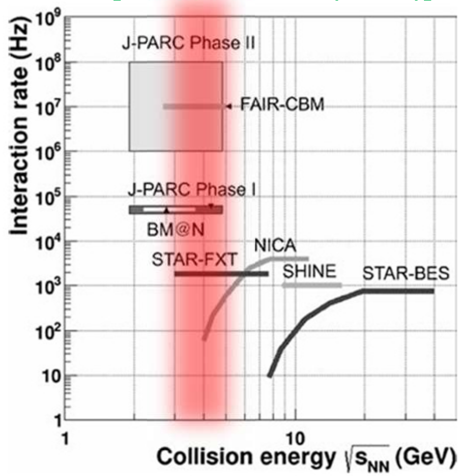




- $\sqrt{s_{NN}} \nearrow \Rightarrow V_3 \curvearrowright$ **&** $\tau \searrow$
- $V_4$ **has a plateau where lifetime and volume are simultaneously "maximized"**

  **⇒ interpreted as "the best energy range for creating high dense matter i.t.o. spacetime vol."**

  - for $\rho > 3\rho_0$ it's $\sqrt{s_{NN}} = 3 \sim 5$ GeV
  - the range can also be identified for even higher densities like $\rho > 5\rho_0$, for which however $V_4$ is no longer large (e.g., $V_4 \sim ((4\text{ fm})^4)$ for $\rho > 5\rho_0$ )

[Sako, Harada (2024)]




**∴ The best energy range is $\sqrt{s_{NN}} = 3 \sim 5$ GeV where you can explorer $\rho > 3\rho_0$**

Comment 1: should be contrasted w/ the existing result [Randrup, Cleymans (2006)]
$\sqrt{s_{NN}} = 6 \sim 10$ GeV and $\rho = (6 \sim 10) \times \rho_0$ [Ohnishi plot (~2010)]

Comment 2: the future experiments like FAIR-CBM & J-PARC-HI will exactly cover this regime with great statistics !

# Contents

# Motivation (1/2): Strong-field physics

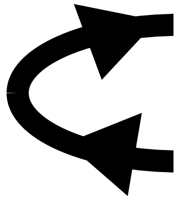
✔ **Matter under extreme conditions: temperature, density, EM field, …**

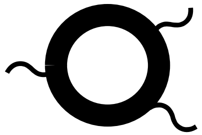
- Not only at the QCD scale but also even at the QED scale, many nontrivial non-perturbative phenomena expected (=: strong-field physics)

Review: [Fedotov, Ilderton, Karbstein, King, Seipt, HT, Torgrimsson (2022)]
[Hattori, Itakura, Ozaki (2023)]

Novel QED processes ($eE, eB \gtrsim m_e^2$)

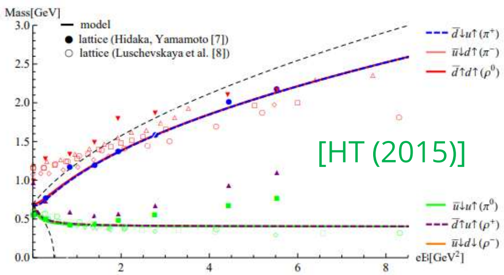
e.g.) Schwinger effect    Photon splitting    Vacuum birefringence





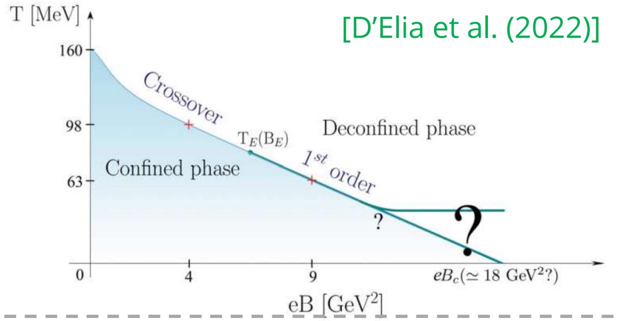

Impacts on QCD/hadron physics ($eE, eB \gtrsim \Lambda_{\mathrm{QCD}}^2$)

- Hadron properties
  (e.g., mass, charge density, decay mode, …)




[HT (2015)]

- QCD phase diagram
  (e.g., new phase, magnetic catalysis, …)



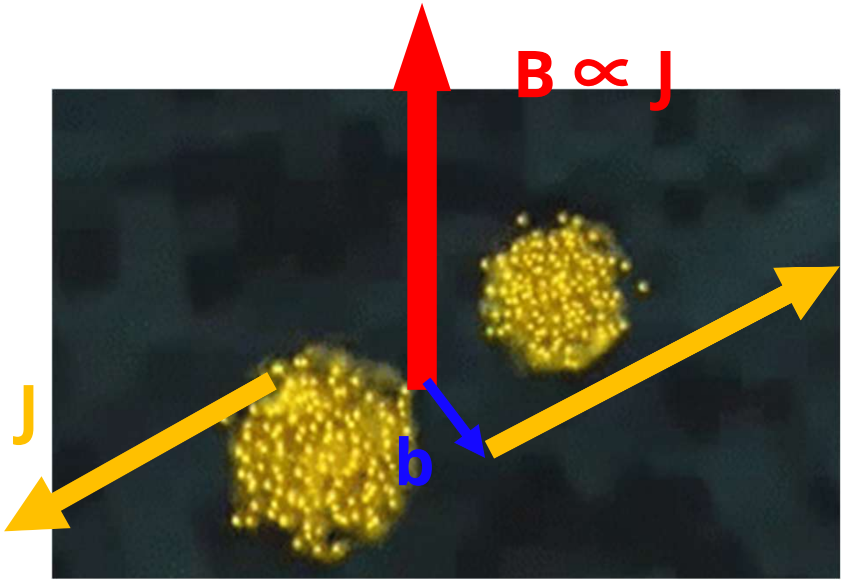

[D'Elia et al. (2022)]

- However, NO experimental verification

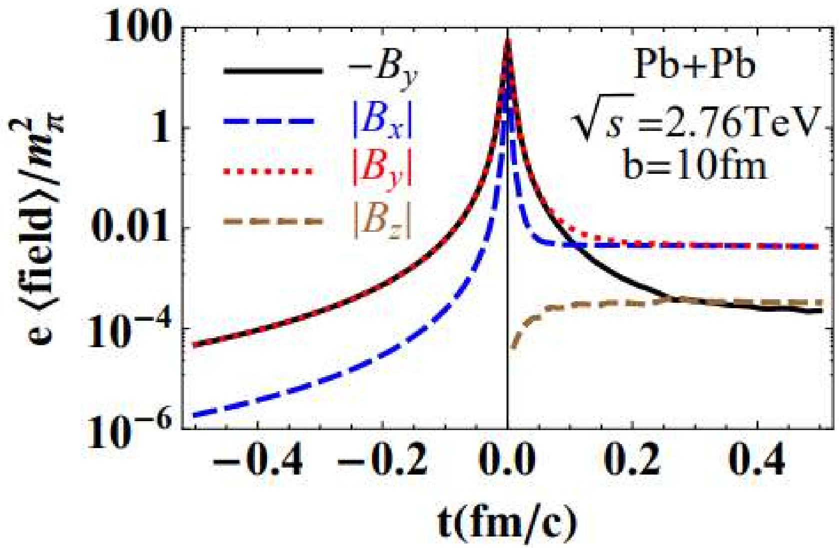
  ∵ no exp. to realize strong field ⇒ New idea/approach strongly needed !

# Motivation (2/2): Use of HIC

- Such a possibility has been discussed at high energies $\sqrt{s_{NN}} = O(100 - 1000\ \mathrm{GeV})$ over the past decade




[Deng, Huang (2012)]



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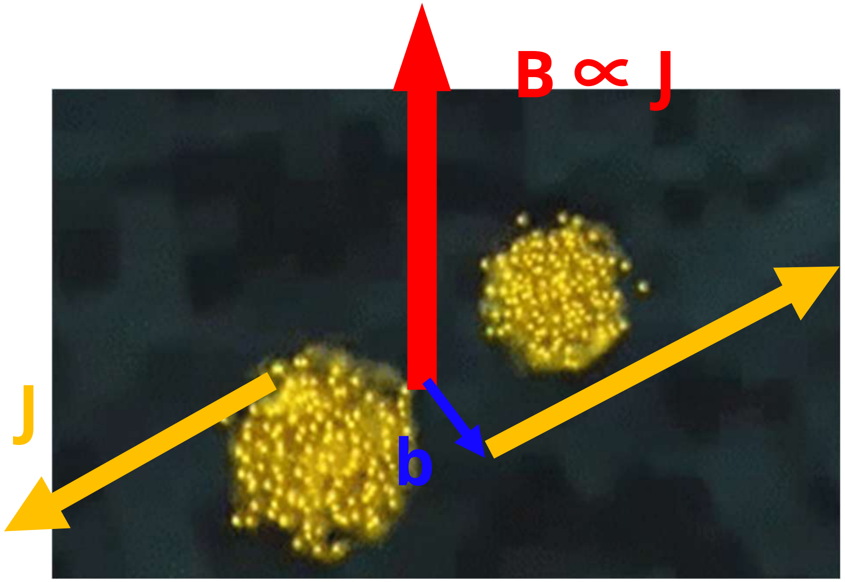


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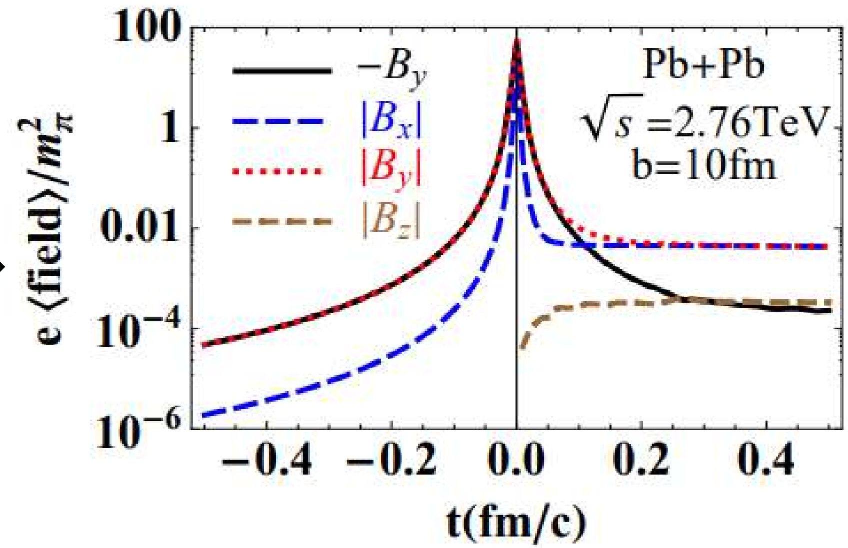
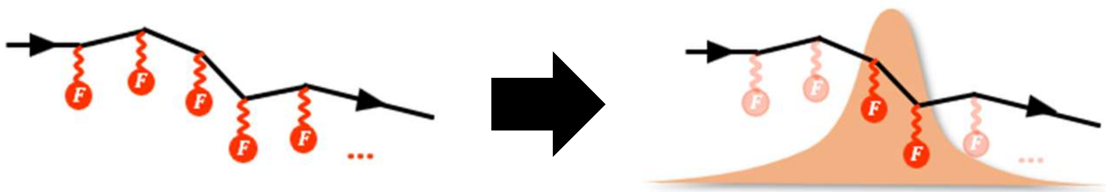
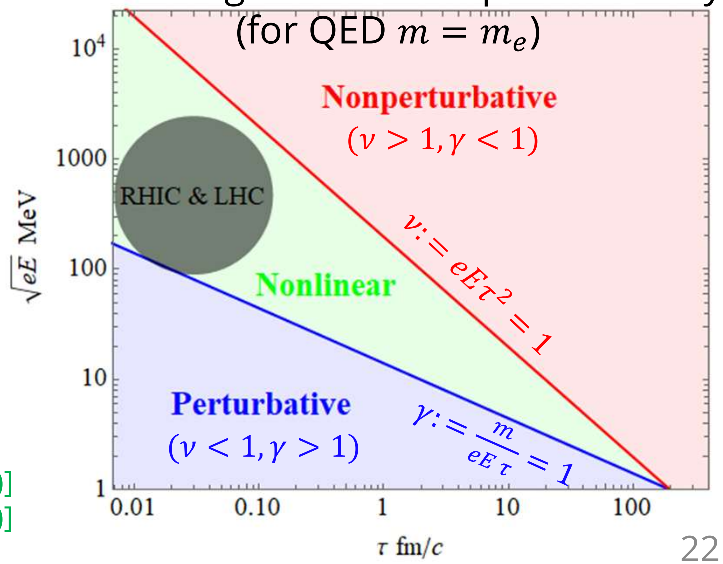



- But, extremely short-lived, so not interesting for non-perturbative strong-field physics

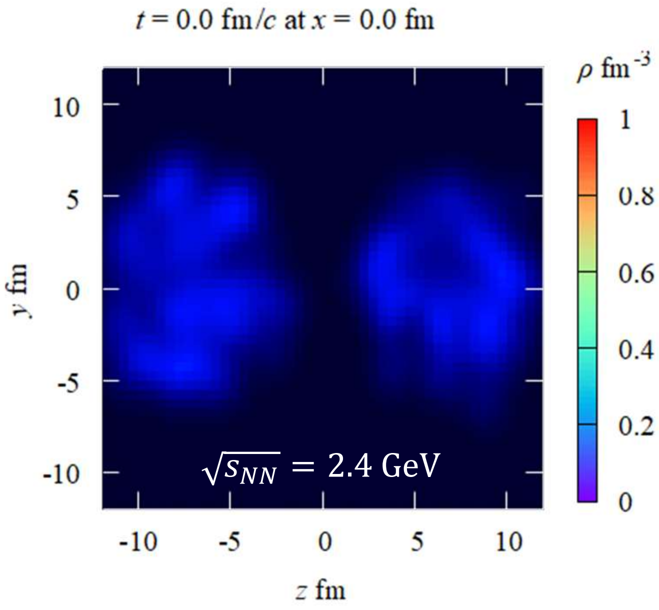


[HT, Fujiii, Itakura (2014)]
[HT, Fujimori, Misumi, Nitta, Sakai (2021)]

"Phase diagram" of "non-perturbativity" (for QED $m = m_e$)



# Idea: Intermediate energy should be useful




## ✔ Baryon stopping at intermediate energies

- high density is realized = large "atomic" number Z~200

  ⇒ strong Coulomb field $eE \sim \frac{Z\alpha}{r^2} \sim \Lambda_{\rm QCD}^2 \sim (100\ \mathrm{MeV})^2$

  ⇒ much stronger than the QED scale and is still comparable to QCD

- sticks together for a long time O(10 fm/c)

  ⇒ created Coulomb field should also be long-lived $\tau \sim 10\ \mathrm{fm}/c$ (more than 100 times longer than high energy)

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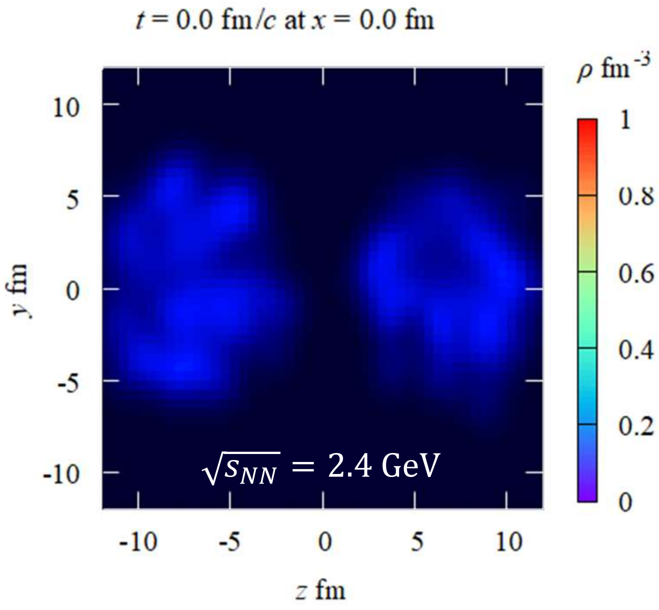


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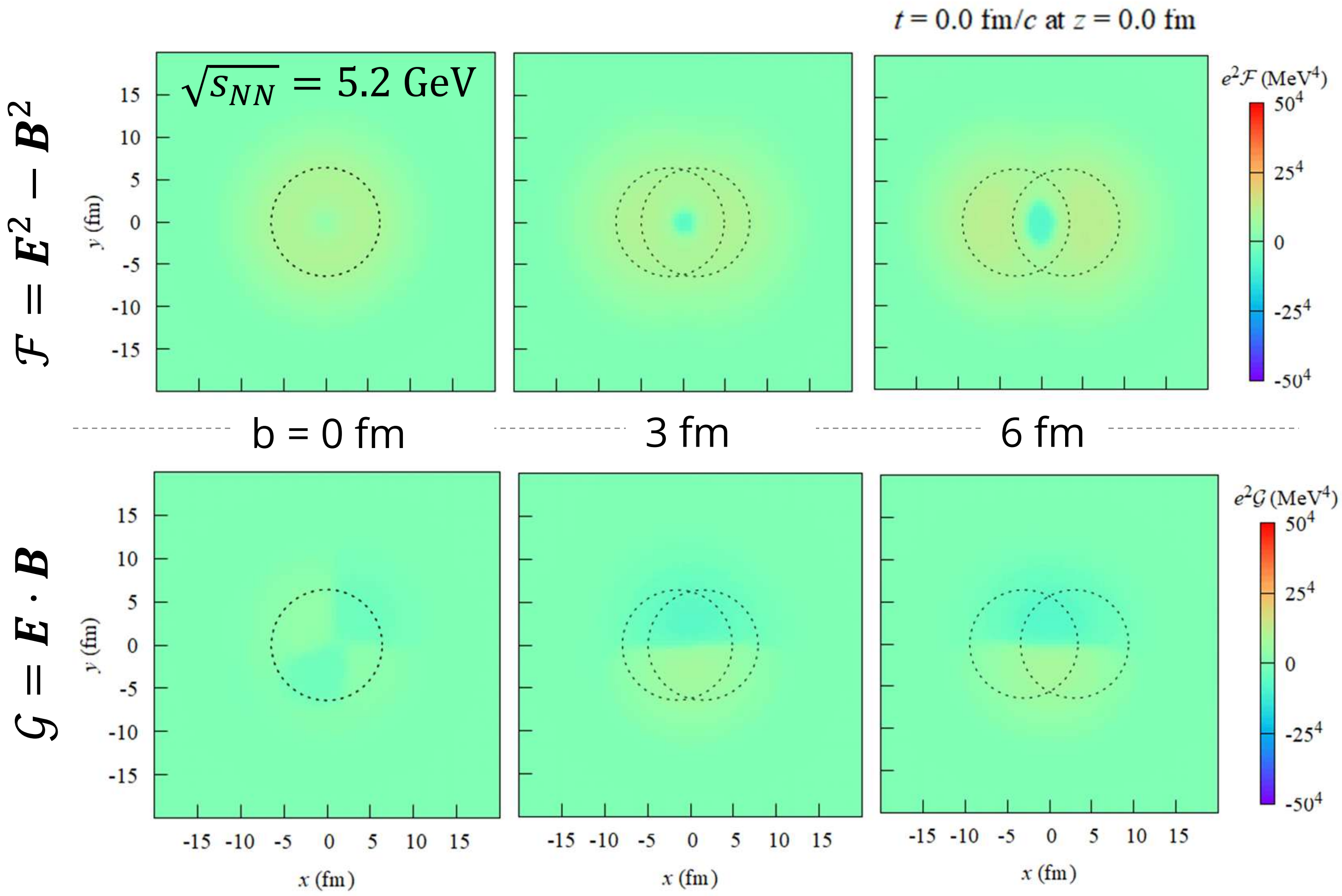
  ⇒ may resolve the issue of lifetime of high-energy HIC

**∴ can be a new tool to study strong-field physics; should also affect QCD**

**⇒ Purpose: Let's check if this is correct/wrong by using JAM**

# Result (1/2): Spacetime profile of EM field

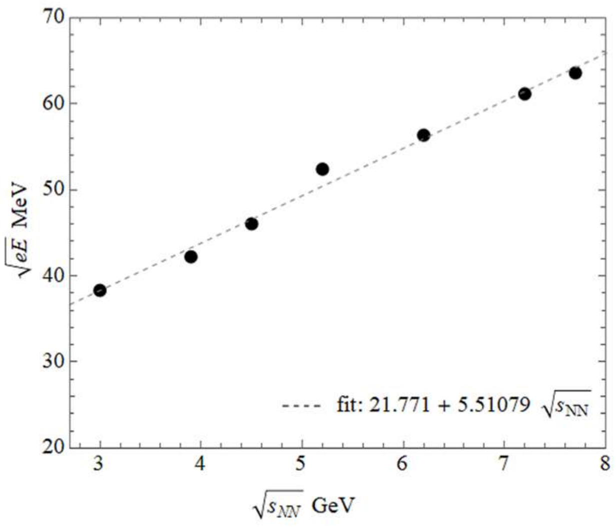


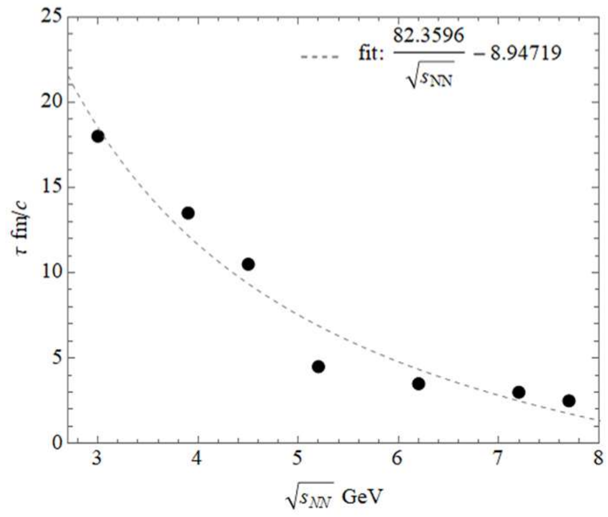

- B field appears w/ going to more peripheral but E field is always larger in space
  $\Rightarrow$ E field would be more important than B field in intermediate energies

- "topological" EM field configuration such that $\mathcal{G} = \boldsymbol{E} \cdot \boldsymbol{B} \neq 0$
  $\Rightarrow$ can be a source of chiral physics $\partial_\mu J_5^\mu \propto E \cdot B$

# Result (2/2): More quantitative analysis

✔ **Peak E-field strength and lifetime (FWHM)** **(at central coll. b=0)**




- **"strong" O(50 MeV) and long-lived O(10 fm/c) realized**

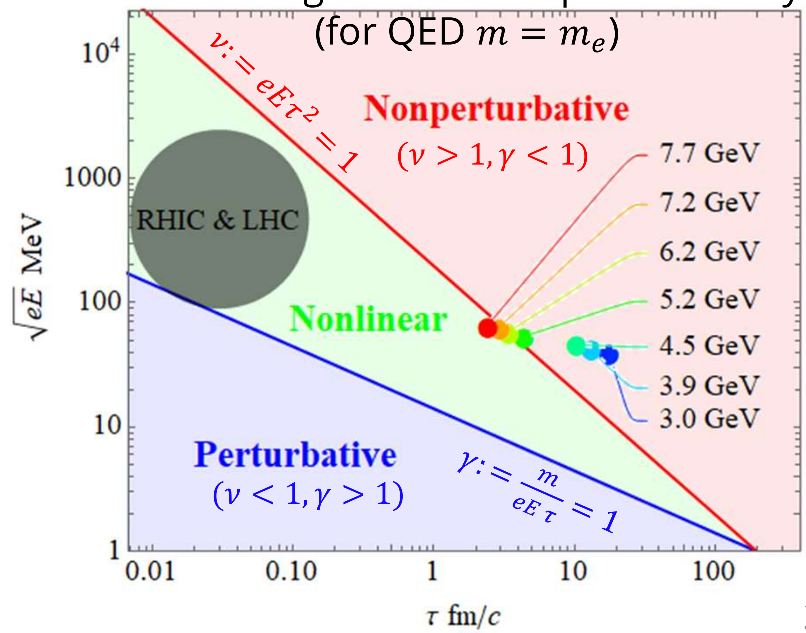
- can cover non-pert. regime

  ∴ **Intermediate-energy HIC must be useful as a new tool to study strong-field physics**

- non-negligible to QCD/hadron scale

  ⇒ should affect, e.g., EM probe

"Phase diagram" of "non-perturbativity" (for QED $m = m_e$)



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**4. Summary**

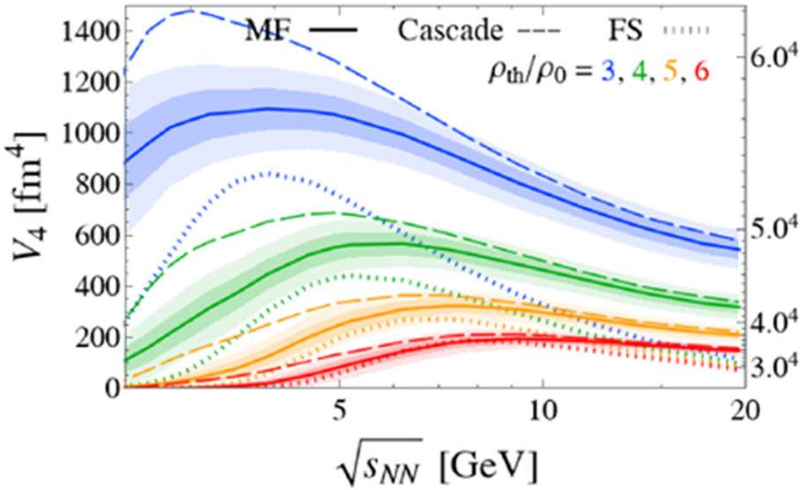
# Summary

- ✔ **I discussed physical conditions realized in intermediate-energy heavy-ion collisions by using a hadron transport model JAM**

- ✔ **Two take-home messages:**

(1) What is the BEST energy range to study high baryon-density physics ? ⇒ $\sqrt{s_{NN}} = 3 \sim 5$ GeV

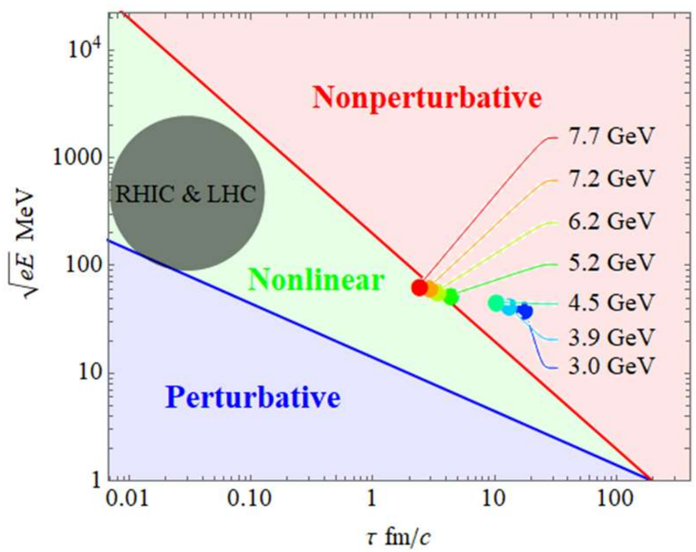
[HT, Jinno, Kitazawa, Nara, 2409.07685]




(2) Such an intermediate-energy regime is also EXTREMELY interesting for studying physics of strong EM field

[HT, Nishimura, Ohnishi, 2402.17136]

[HT, 2501.18171]



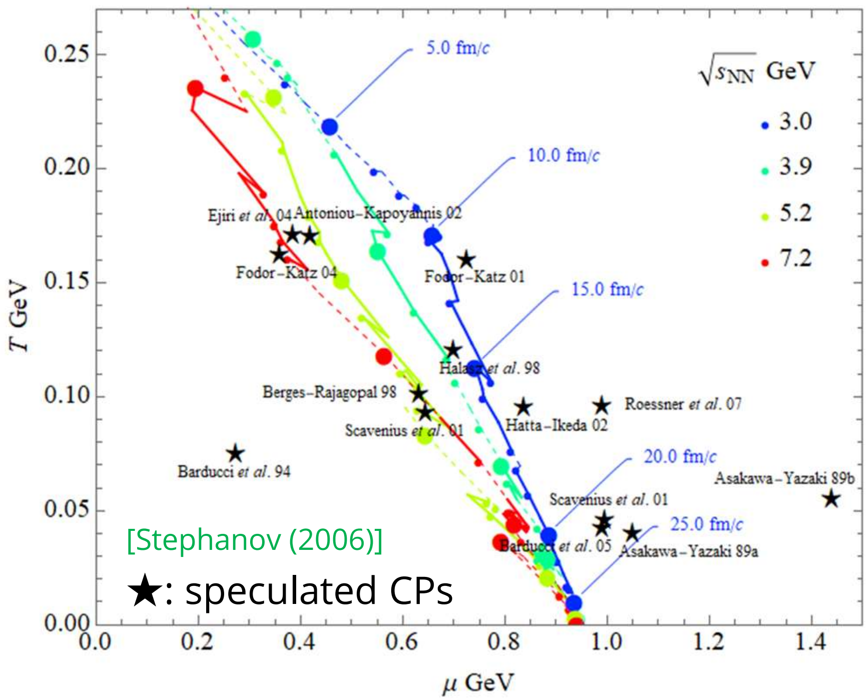
# Backup

# T and μ

✔ **What are the corresponding temperature T and chemical potential μ ?**

Naïve estimate from the classical ideal gas EoS, e.g., $P = nT$:

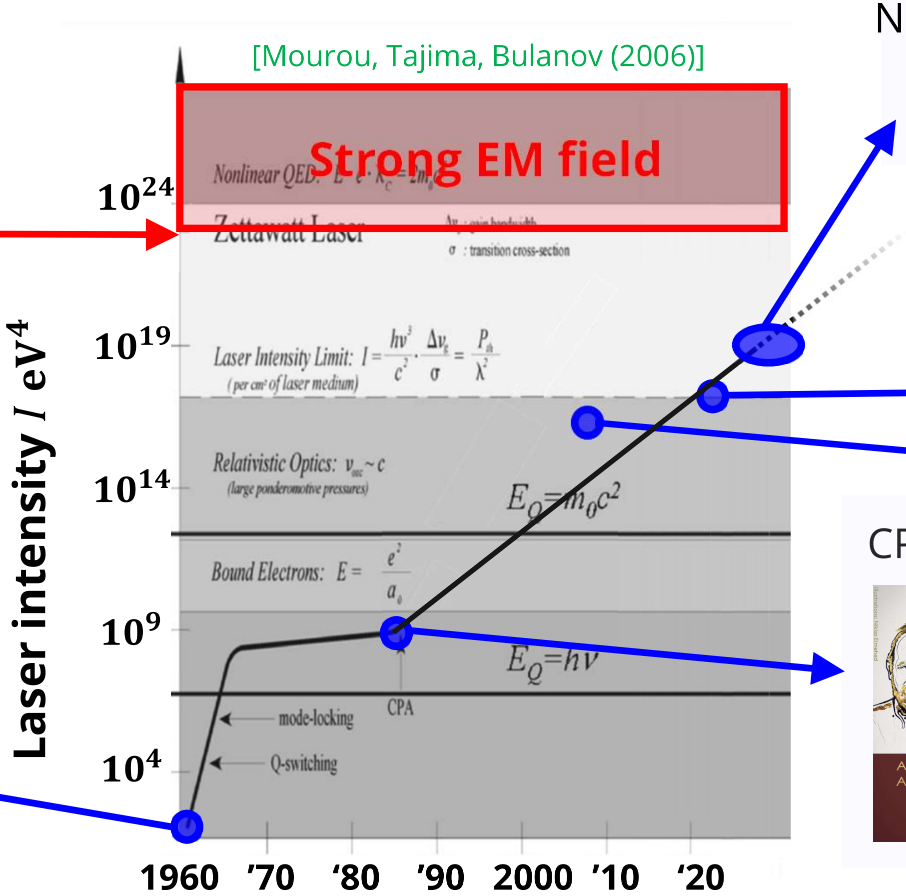
(⇐ no visible changes from those obtained by the numerical fit of the spectrum with Fermi dist)




⇒ Good news for critical-point search:

the trajectories pass the speculated critical points in the best energy range

# Development of intense laser



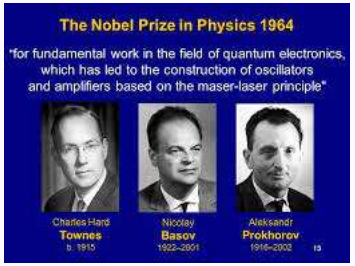

$eE, eB \sim (511\ \text{keV})^2$

Now started operation
$I > 10^{18}\ \text{eV}^4$
e.g., ELI @ Europe

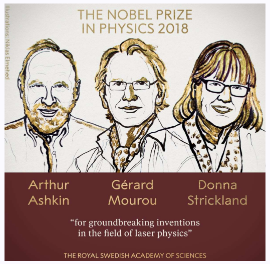
Current strongest
$I > 10^{17}\ \text{eV}^4$
CoReLS @ Korea
[Yoon et al., (2021)]

$I \sim 10^{16}\ \text{eV}^4$
HERUCLES @ USA
[Yanovsky et al., (2008)]

Birth of laser




CPA technique



# How E•B≠0 emerges