Coupling nuclear structure and relativistic hydrodynamic calculations: collectivity in small systems

Benjamin Bally

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Motivations

- Interface between low- and high-energy nuclear physics
  - ◇ Nuclear structure recognized as important to understand heavy-ion collisions

    Giacalone *et al.*, PRL 127, 242301 (2021)

    Zhang *et al.*, PRL 128, 022301 (2022)

    Jia *et al.*, PRL 131, 022301 (2023)

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- $^{16}\mathrm{O} + {}^{16}\mathrm{O}$ already performed at RHIC (2021) and is scheduled at LHC (2025)
- New proposal for a future LHC run (not before 2029)

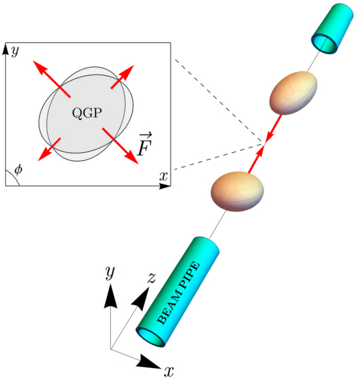
Preprint: arXiv:2402.05995

CERN-TH-2024-021

The unexpected uses of a bowling pin: exploiting ^{20}Ne isotopes for precision characterizations of collectivity in small systems

Giuliano Giacalone,[1,*] Benjamin Bally,[2] Govert Nijs,[3] Shihang Shen,[4] Thomas Duguet,[5,6] Jean-Paul Ebran,[7,8] Serdar Elhatisari,[9,10] Mikael Frosini,[11] Timo A. Lähde,[12,13] Dean Lee,[14] Bing-Nan Lu,[15] Yuan-Zhuo Ma,[14] Ulf-G. Meißner,[10,16,17] Jacquelyn Noronha-Hostler,[18] Christopher Plumberg,[19] Tomás R. Rodríguez,[20] Robert Roth,[21,22] Wilke van der Schee,[3,23,24] and Vittorio Somà[5]

- Large collaboration of theorists
- From low- and high-energy nuclear physics communities
  - Heavy-ion collisions
  - Nuclear structure (PGCM)
  - Nuclear structure (NLEFT)


y
QGP
$\vec{F}$
ϕ
x
y
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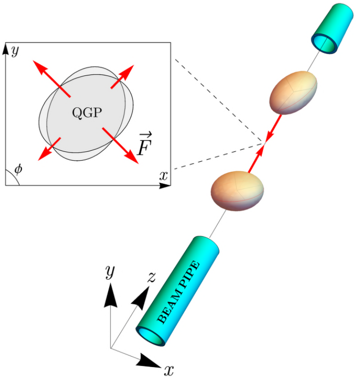
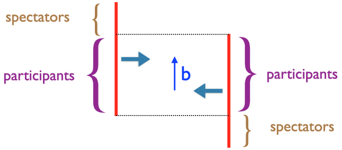
BEAM PIPE
x

Phenomenology of heavy-ion collisions I





Ollitrault, EPJA 59, 236 (2023)

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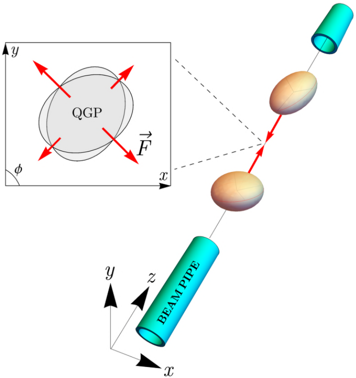

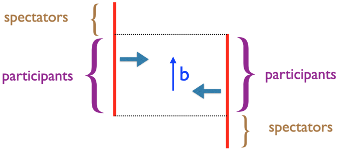

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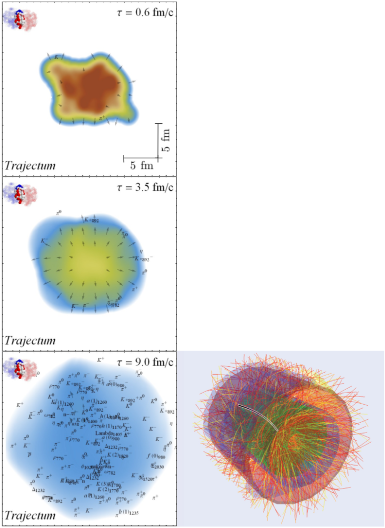
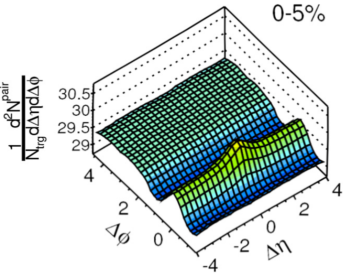


Giacalone *et al.*, PRL 131, 202302 (2023)

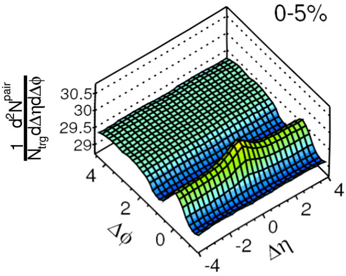
ALICE collaboration

Phenomenology of heavy-ion collisions II



credit: CMS collaboration

Phenomenology of heavy-ion collisions II



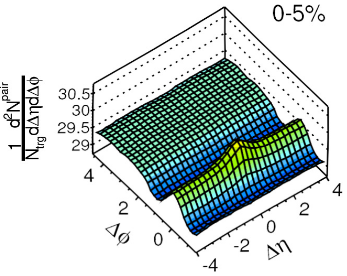
credit: CMS collaboration

- Probability distribution of particle emission

$$P(\phi,\eta) = P(\phi) = \frac{1}{2\pi} \sum_{n=-\infty}^{+\infty} V_n e^{-in\phi}$$

$V_2 \equiv$ elliptic flow, $V_3 \equiv$ triangular flow, . . .

Phenomenology of heavy-ion collisions II



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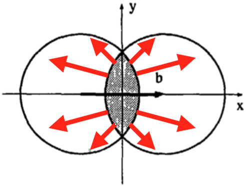
$$V_2 \equiv \text{elliptic flow},\ V_3 \equiv \text{triangular flow}, \ldots$$

- Average of pair distribution

$$\left\langle \frac{dN_{\text{pair}}}{d\Delta\eta d\Delta\phi} \right\rangle = \langle P(\phi) P(\phi + \Delta\phi) \rangle == \frac{1}{2\pi} \left(1 + 2 \sum_{n=1}^{+\infty} \langle |V_n|^2 \rangle \cos(n\Delta\phi) \right)$$

Phenomenology of heavy-ion collisions III



Ollitrault, PRD 46, 229 (1992)

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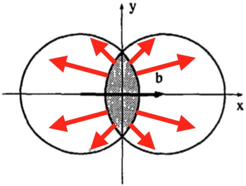

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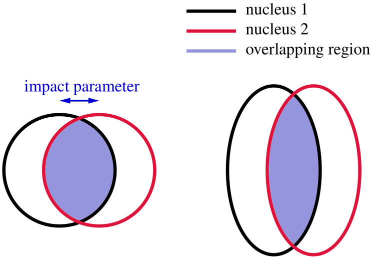

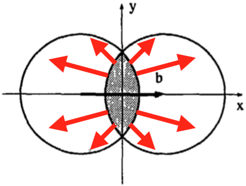

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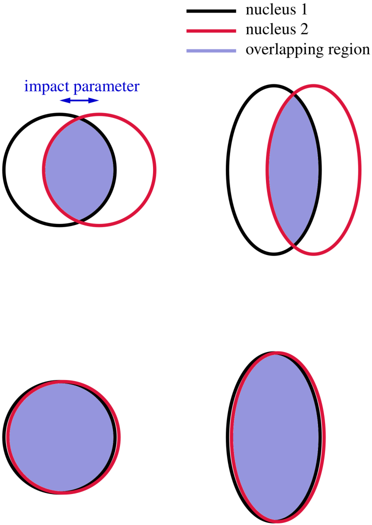
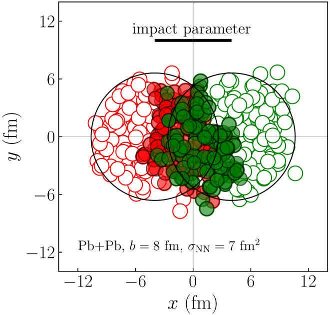
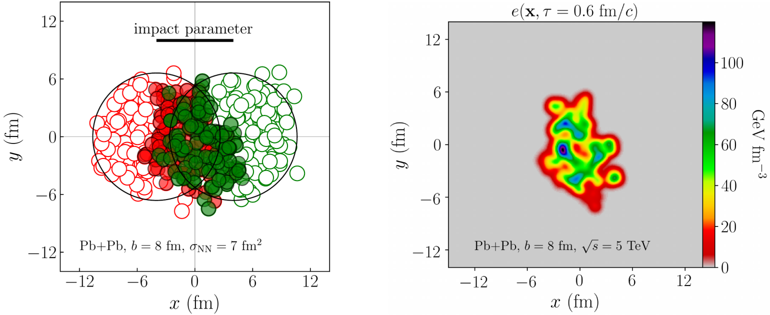




Courtesy of G. Giacalone

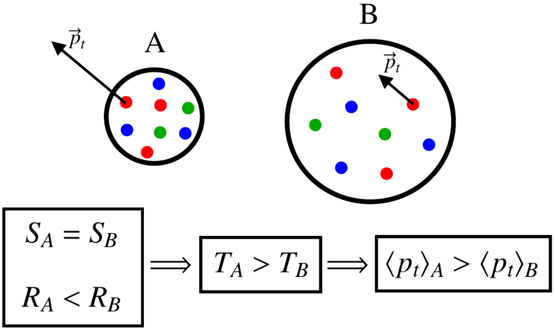
- Nucleons sampled using a model (often simply a Woods-Saxon density)

Phenomenology of heavy-ion collisions IV



Courtesy of G. Giacalone

- Nucleons sampled using a model (often simply a Woods-Saxon density)
- Participant nucleons translated into energy density using a prescription, e.g., T$_{\mathrm{R}}$ENTo model
- Run relativistic hydrodynamic simulations



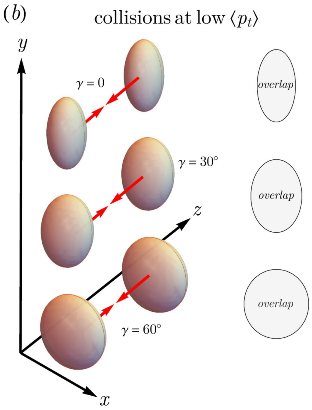
Courtesy of G. Giacalone

- $\langle p_t \rangle$ is the average transverse momentum of particles
- Looking at low $\langle p_t \rangle$ $\Rightarrow$ looking at larger nuclear overlaps

Phenomenology of heavy-ion collisions VI

- Pearson correlation coefficient

$$\rho(v_2^2, \langle p_t \rangle) = \frac{\left\langle \delta v_2^2 \delta \langle p_t \rangle \right\rangle}{\sqrt{\left\langle \left(\delta v_2^2 \right)^2 \right\rangle \left\langle \left(\delta \langle p_t \rangle \right)^2 \right\rangle}} \quad \text{where } \delta o = o - \langle o \rangle$$



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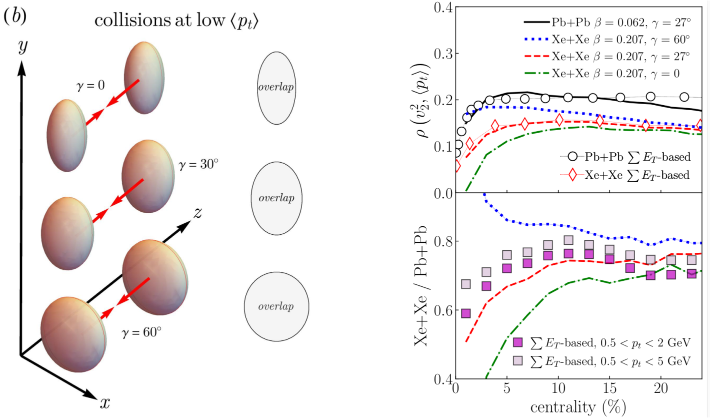

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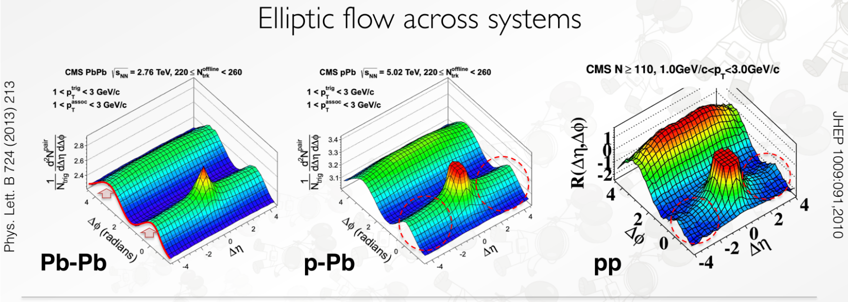

Chinellato, Quark Matter 2023

- Collectivity appears in *small systems* (p+p, p+A, d+A, . . .)
- Is it the same mechanism? Is hydrodynamic the correct description?
- How small can a QGP be?

The proposal

- Experimental methods exist but have also limitations
  - $p + {}^{197}Au$ *versus* $d + {}^{197}Au$
  - Central ${}^{16}O + {}^{16}O$ *versus* peripheral ${}^{208}Pb + {}^{208}Pb$

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- **New idea: central ^{16}O + ^{16}O *versus* central ^{20}Ne + ^{20}Ne**
  - Systems with similar A
  - Same centrality class
  - Overlap region well-defined

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  ⇒ **Test hydrodynamic description in a small systems**

LHC schedule

https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

- ion+ion collisions scheduled 1 month/year until the end of operation

Tools and workflow

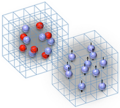
EFT → **Nuclear structure** → **Relativistic hydrodynamic** → **Hadron transport** → **Nucl-th**

χEFT N3LO

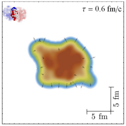
TAURUS

PGCM

$\not\pi$EFT LO



NLEFT



Trajectum

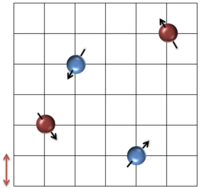
smash

arXiv:2402.05995

- TAURUS: `https://github.com/project-taurus`
- *Trajectum*: `https://sites.google.com/view/govertnijs/trajectum`
- SMASH: `https://github.com/smash-transport/smash`

NLEFT calculations

- Nuclear Lattice Effective field Theory (NLEFT)
  Lee, Front. in Phys. 8, 174 (2020)
  Lähde and Meißner, Lectures Notes in Phys., Springer (2019)



- Mesh with 8 sites and spacing $a = 1.315$ fm

- Minimal pionless EFT Hamiltonian with SU(4) symmetry

- Pin-hole algorithm → nucleon positions
  Elhatisari *et al.*, PRL 119, 222505 (2017)

⇒ see Dean's presentation

PGCM calculations

- Projected Generator Coordinate Method (PGCM)

$$|\Theta_{\epsilon}^{\sigma M}\rangle = \sum_{qK} f_{\epsilon}^{\sigma M}(q, K) P_{MK}^{\sigma} |\Phi(q)\rangle \quad \text{where} \quad \sigma \equiv Z, N, J, \pi$$

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- Full method: PGCM + Perturbation Theory

  Frosini *et al.*, EPJA 58, 62 (2022)

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- Model space: $e_{\text{max}} = 6$, $e_{3\text{max}} = 18$, $\hbar\omega = 12$

  Hamiltonian: Hüther N3LO

  Hüther *et al.*, PLB 808, 135651 (2019)

  Reference states $|\Phi\rangle$: real general Bogoliubov (VAPNP mininization)

  Collective coordinates q: $\beta_{20}, \beta_{22}, \beta_{30}, \beta_{32}$

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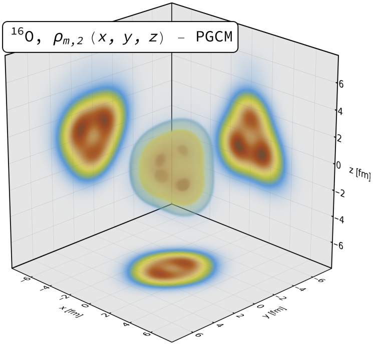
⇒ **see Andrea's presentation & my presentation of last year**

PGCM-based densities



- Determine average deformation of PGCM ground state: $\bar{q}$
- One-body density: $\rho_m(x,y,z) = \sum_{st} \frac{\langle \Phi(\bar{q}) | a^{+}_{xyzst} a_{xyzst} P^Z P^N | \Phi(\bar{q}) \rangle}{\langle \Phi(\bar{q}) | P^Z P^N | \Phi(\bar{q}) \rangle}$
- Sample directly ρ_m or assuming α clusters

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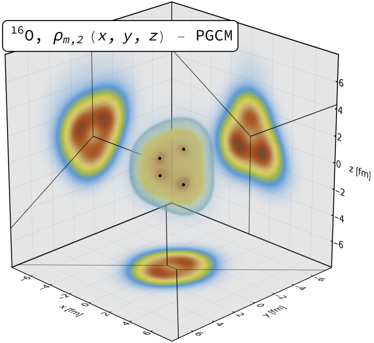

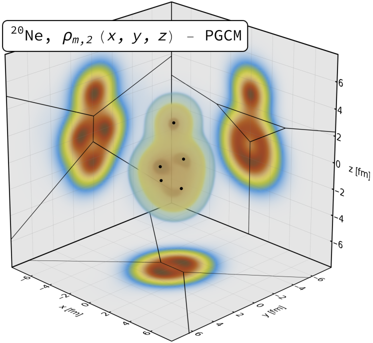

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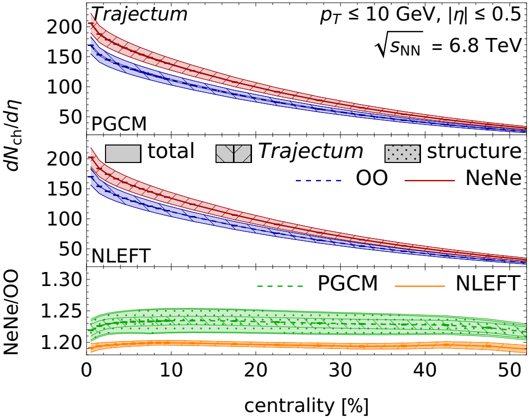
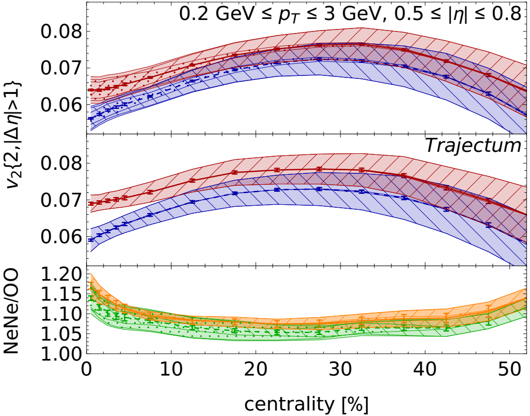
Results: multiplicity



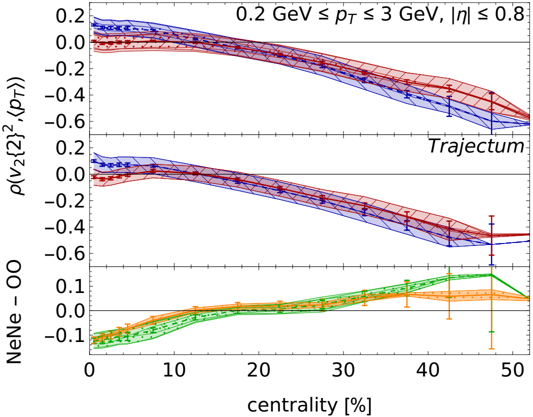
Results: elliptic flow $v_2\{2\}^2$



- In the 0-1% events:

$$\frac{v_2\{2\}_{\mathrm{NeNe}}}{v_2\{2\}_{\mathrm{OO}}} = \begin{cases} 1.170(8)_{\mathrm{stat.}}(30)^{\mathit{Traj.}}_{\mathrm{syst.}}(0)^{\mathrm{str.}}_{\mathrm{syst.}} & (\mathrm{NLEFT}) \\ 1.139(6)_{\mathrm{stat.}}(27)^{\mathit{Traj.}}_{\mathrm{syst.}}(28)^{\mathrm{str.}}_{\mathrm{syst.}} & (\mathrm{PGCM}) \end{cases}$$

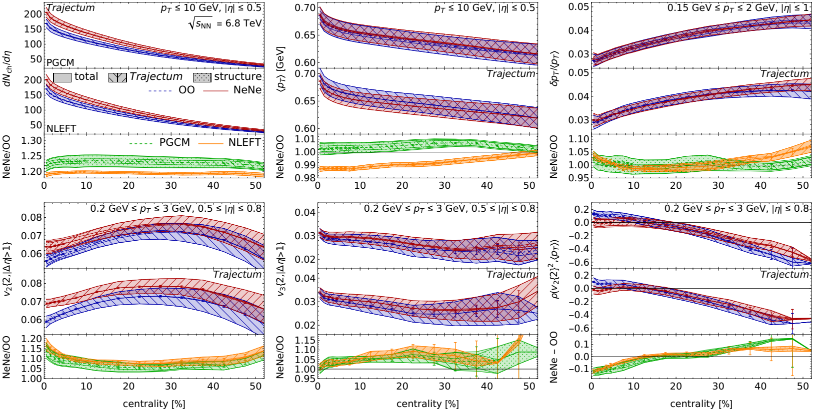
Results: Pearson coefficient $\rho(v_2\{2\}^2, \langle p_T \rangle)$



- Suppression of ρ due to the large deformation of ^{20}Ne

$$\rho_{\mathrm{Ne+Ne}} - \rho_{\mathrm{O+O}} \propto \left(\beta^3_{2,{}^{16}\mathrm{O}} - \beta^3_{2,{}^{20}\mathrm{Ne}}\right)$$

Results: general comments



- Ratios/differences between ^{20}Ne + ^{20}Ne and ^{16}O + ^{16}O reduce uncertainties
- NLEFT and PGCM in good agreement

Conclusion

- Interface between low- and high-energy nuclear physics
  - Combines several state-of-the-art frameworks and software
  - NLEFT and PGCM give consistent results
  - Many things to understand or improve

    → PGCM: less phenomenological sampling of nucleon positions

    → more methods and interactions

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- We make **predictions** for the future **^{16}O + ^{16}O run at LHC in 2025**

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  - Combines several state-of-the-art frameworks and software
  - NLEFT and PGCM give consistent results
  - Many things to understand or improve

    → PGCM: less phenomenological sampling of nucleon positions

    → more methods and interactions

- We make **predictions** for the future **^{16}O + ^{16}O run at LHC in 2025**

- **Proposal: combine the ^{16}O + ^{16}O run with a ^{20}Ne + ^{20}Ne run**
  - Ratios/differences reduce considerably systematic uncertainties
  - Make use of the large ground-state deformation of ^{20}Ne

  ⇒ **Test hydrodynamic behavior in a small systems**