

UNIFIED JET-MEDIUM TREATMENT IN LIGHT IONS AND THEIR AZIMUTHAL ANISOTROPIES

Kevin Possendoro Pala

Jacquelyn Noronha-Hostler

Isaac Long

Surkhab Kaur Virk

Isabella Danhoni

Christopher Plumberg

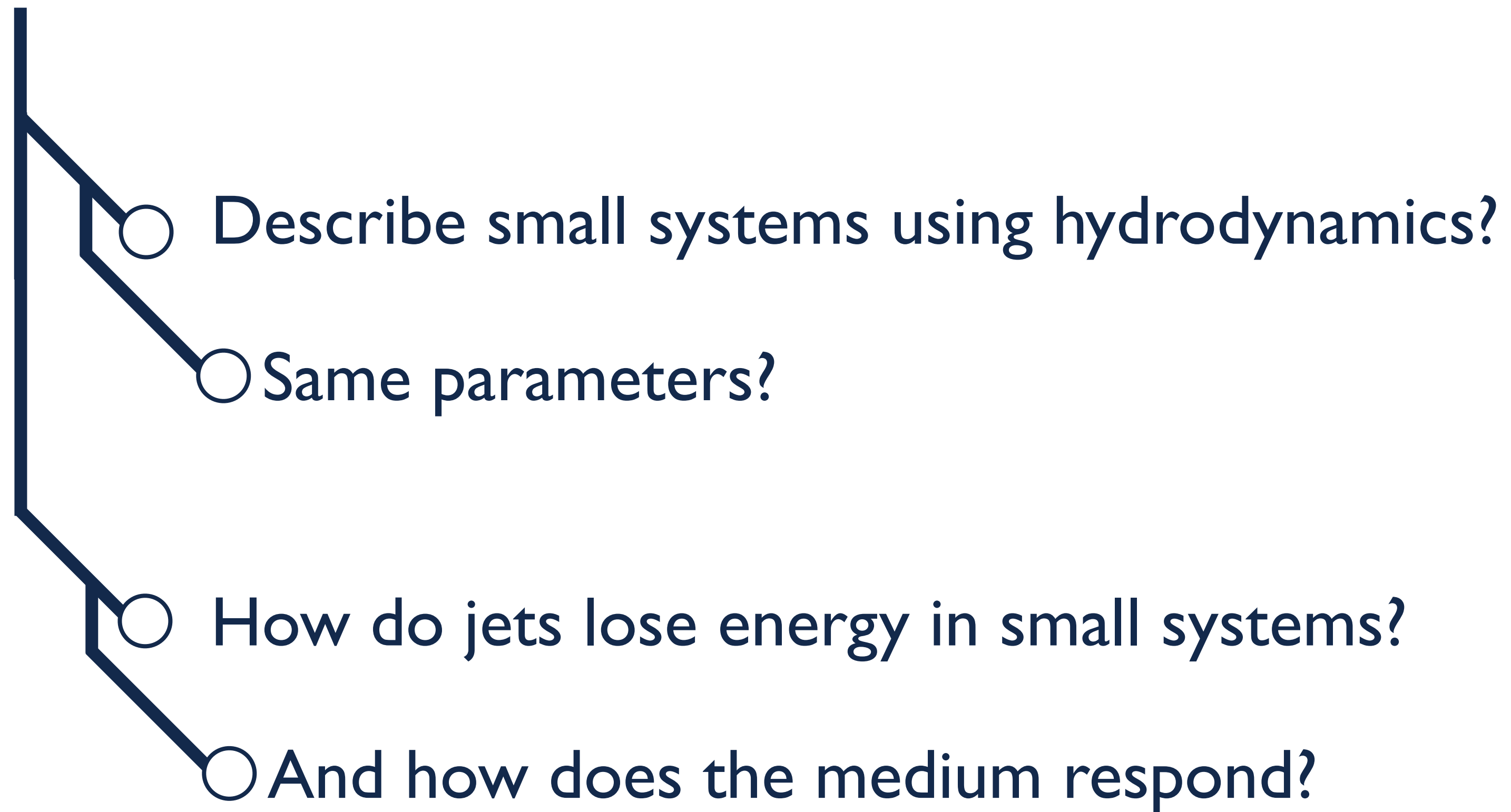
Fernando Gardim

Project 2020/15893-4

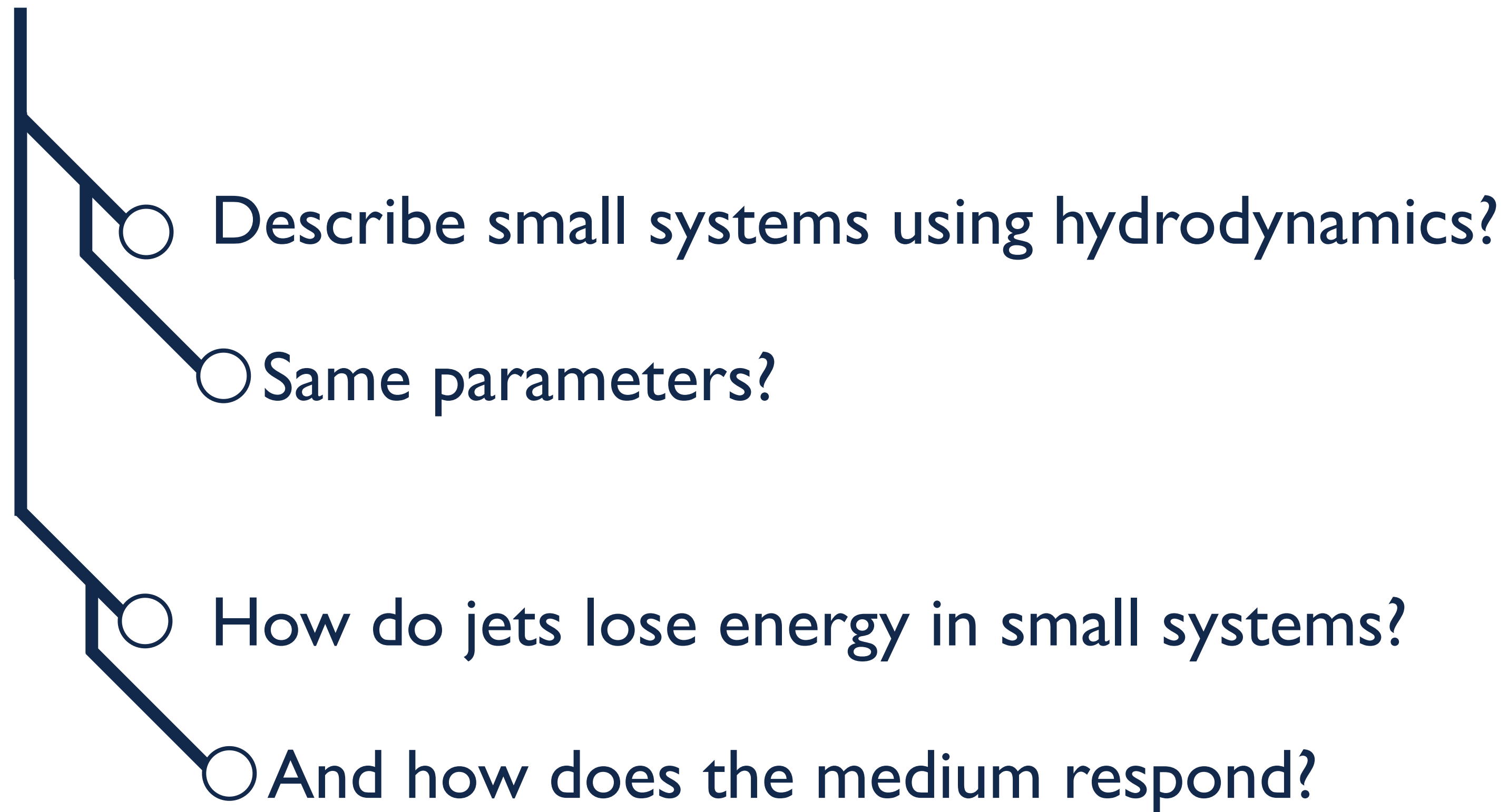
Project 2024/08903-4



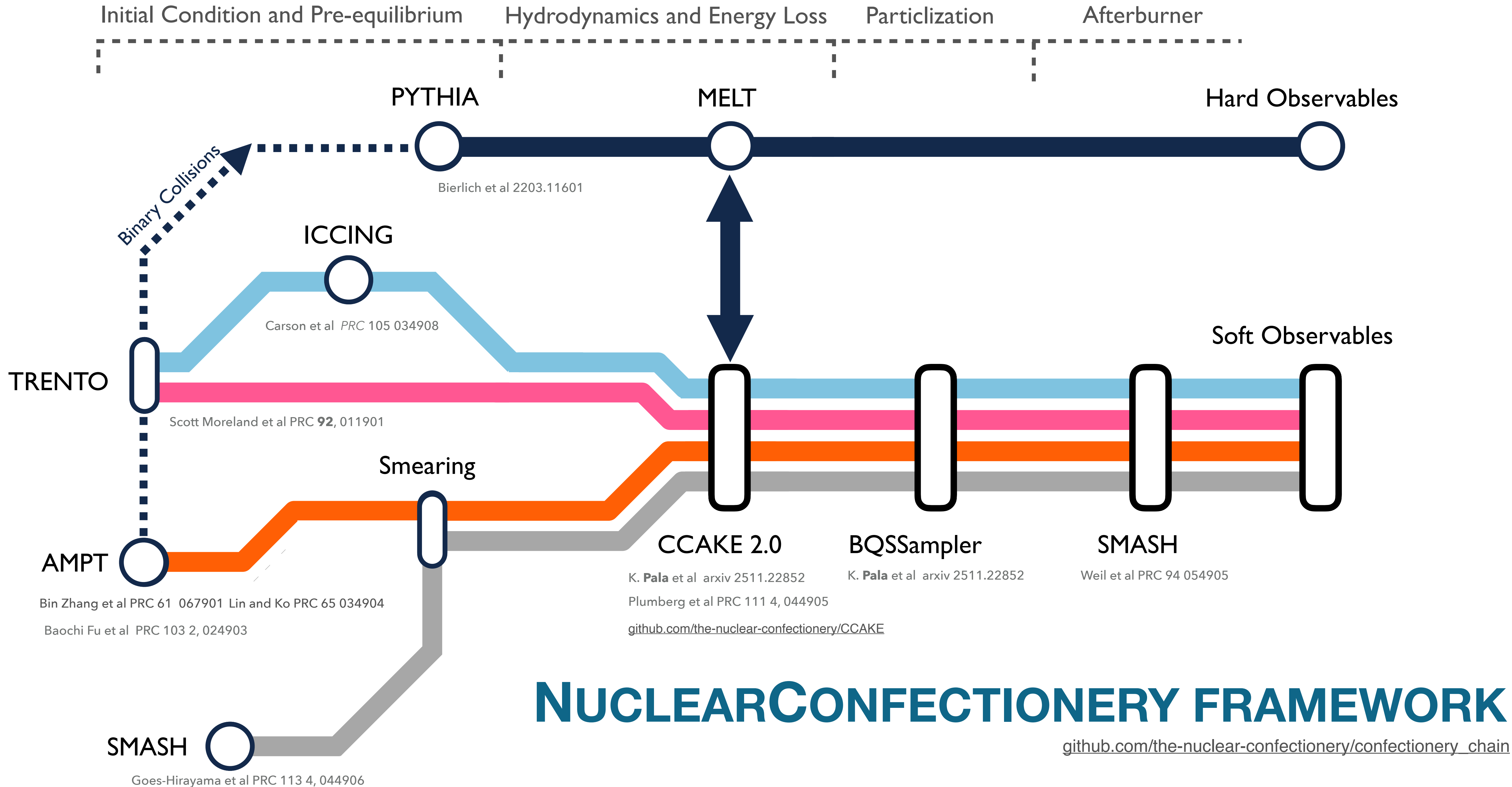
HYDRODYNAMICS, SMALL SYSTEMS AND JETS

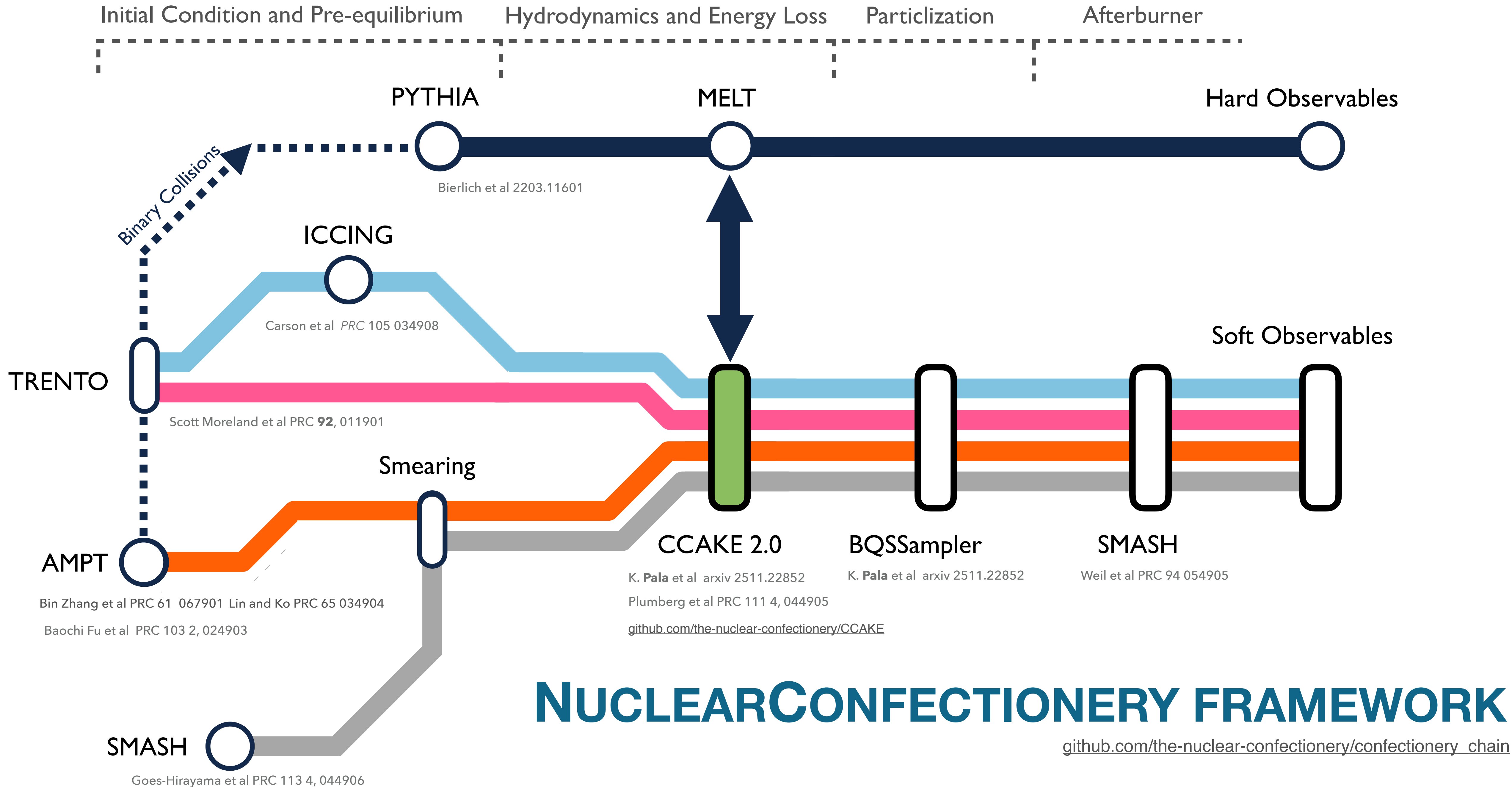


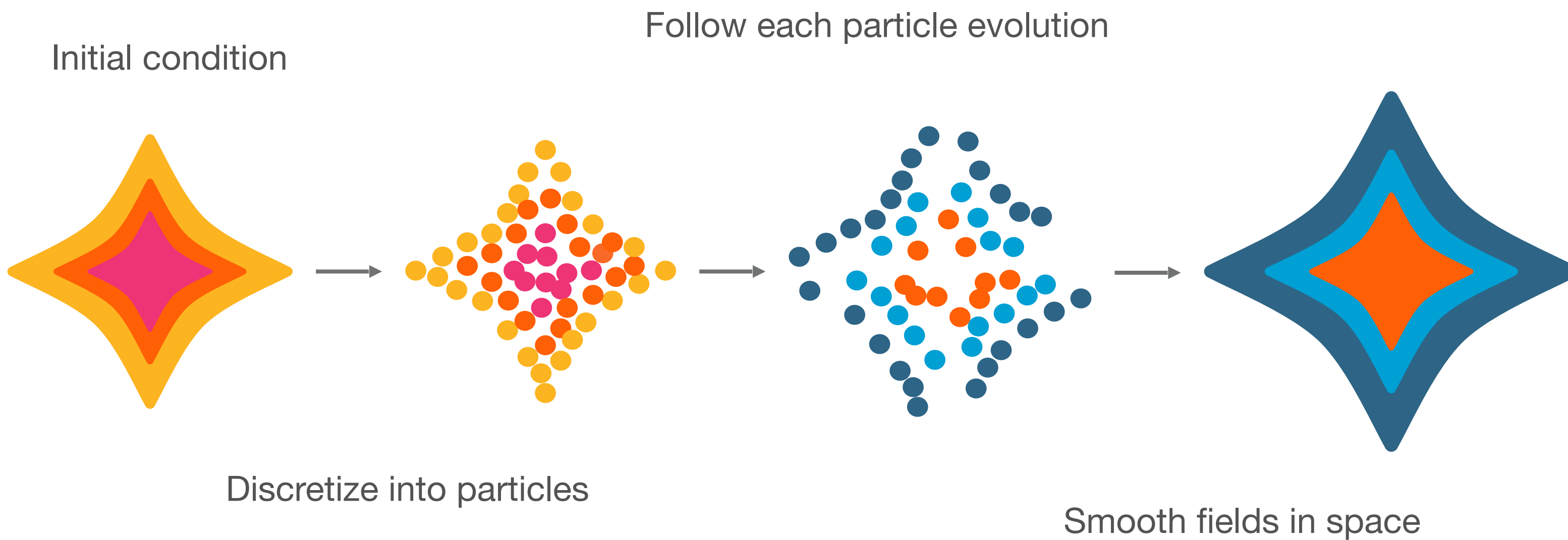
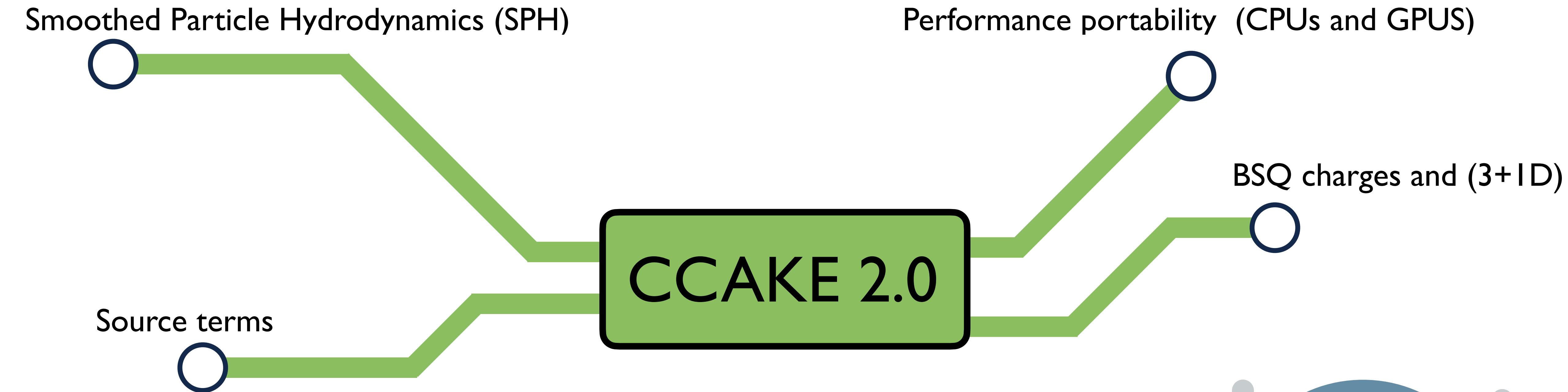
HYDRODYNAMICS, SMALL SYSTEMS AND JETS



Investigate using hybrid simulations







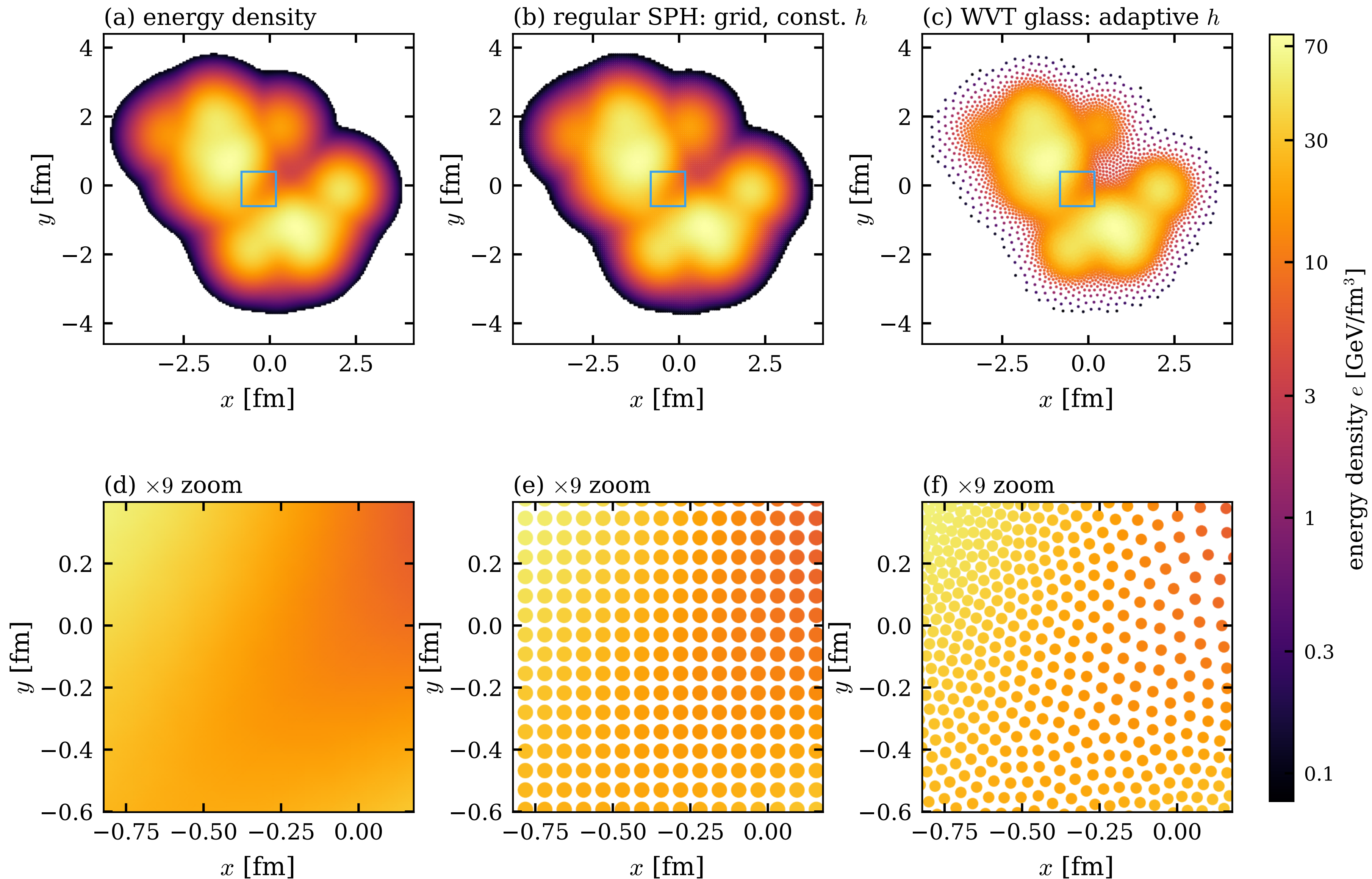
$$A(\mathbf{r}) = \sum_{i=1} A(\mathbf{r}_i) W(\mathbf{r}_i - \mathbf{r}, h) \Delta V_i$$

$$\nabla_j A(\mathbf{r}) = \sum_{i=1} A(\mathbf{r}_i) \nabla_j W(\mathbf{r}_i - \mathbf{r}, h) \Delta V_i$$

WVT - INITIAL CONDITION

$$N_{SPH} \propto \varepsilon$$

Fictitious force $\rightarrow$ glass-like



ADAPTIVE RESOLUTION

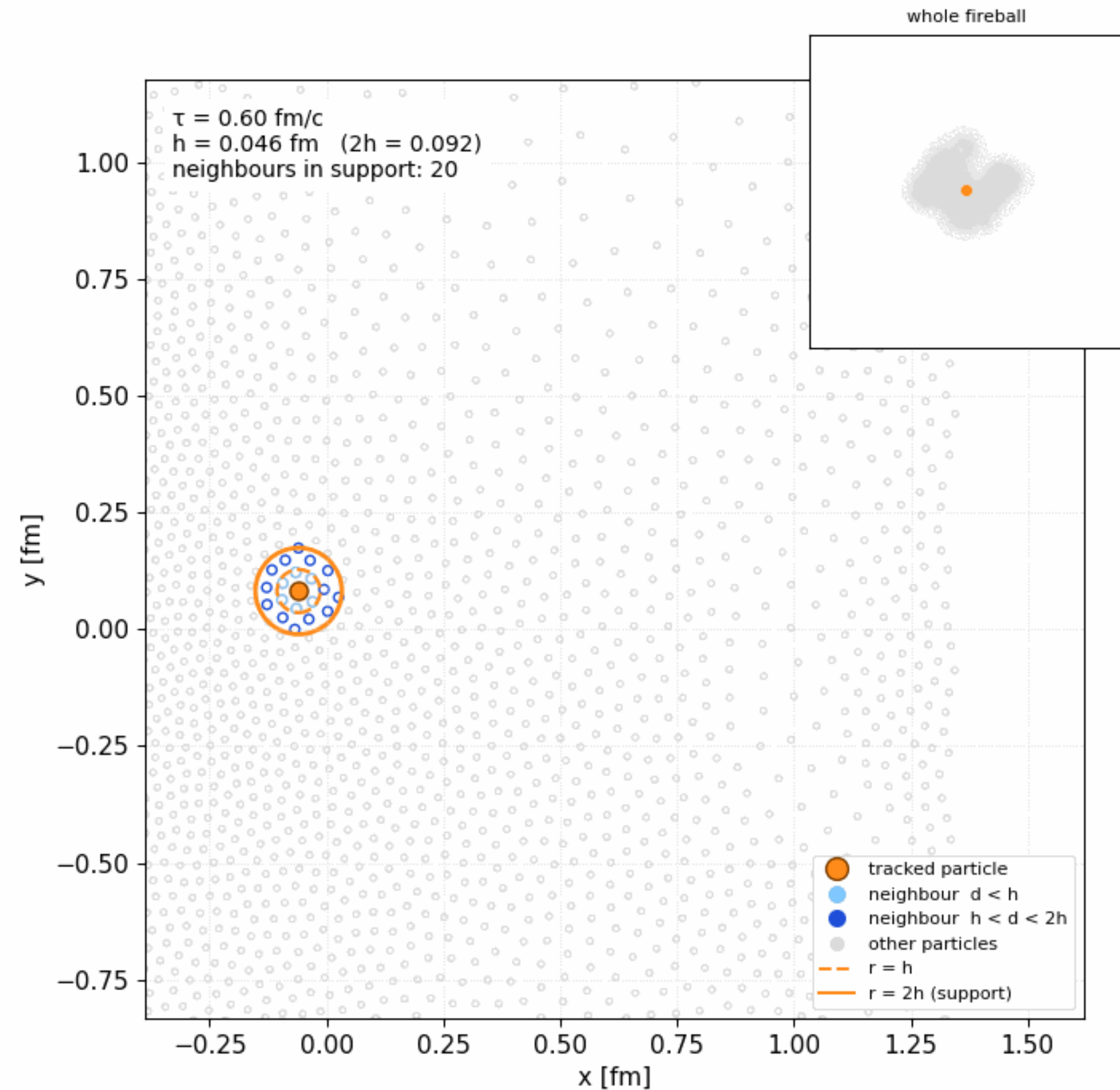
Resolution scales with density

$$h = 1.2 \left(\frac{1}{\sigma^*} \right)^D$$

SPH particle density

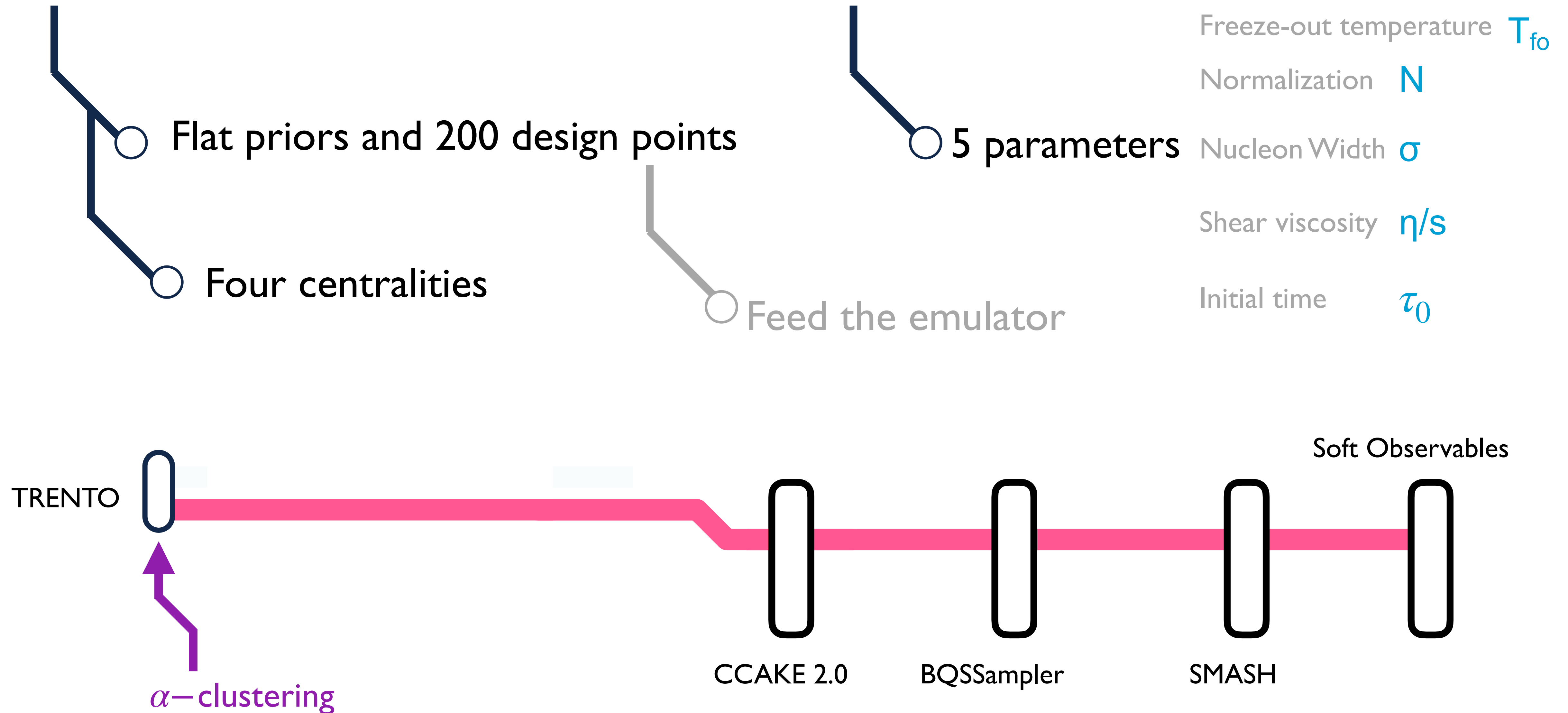
Adds a new equation

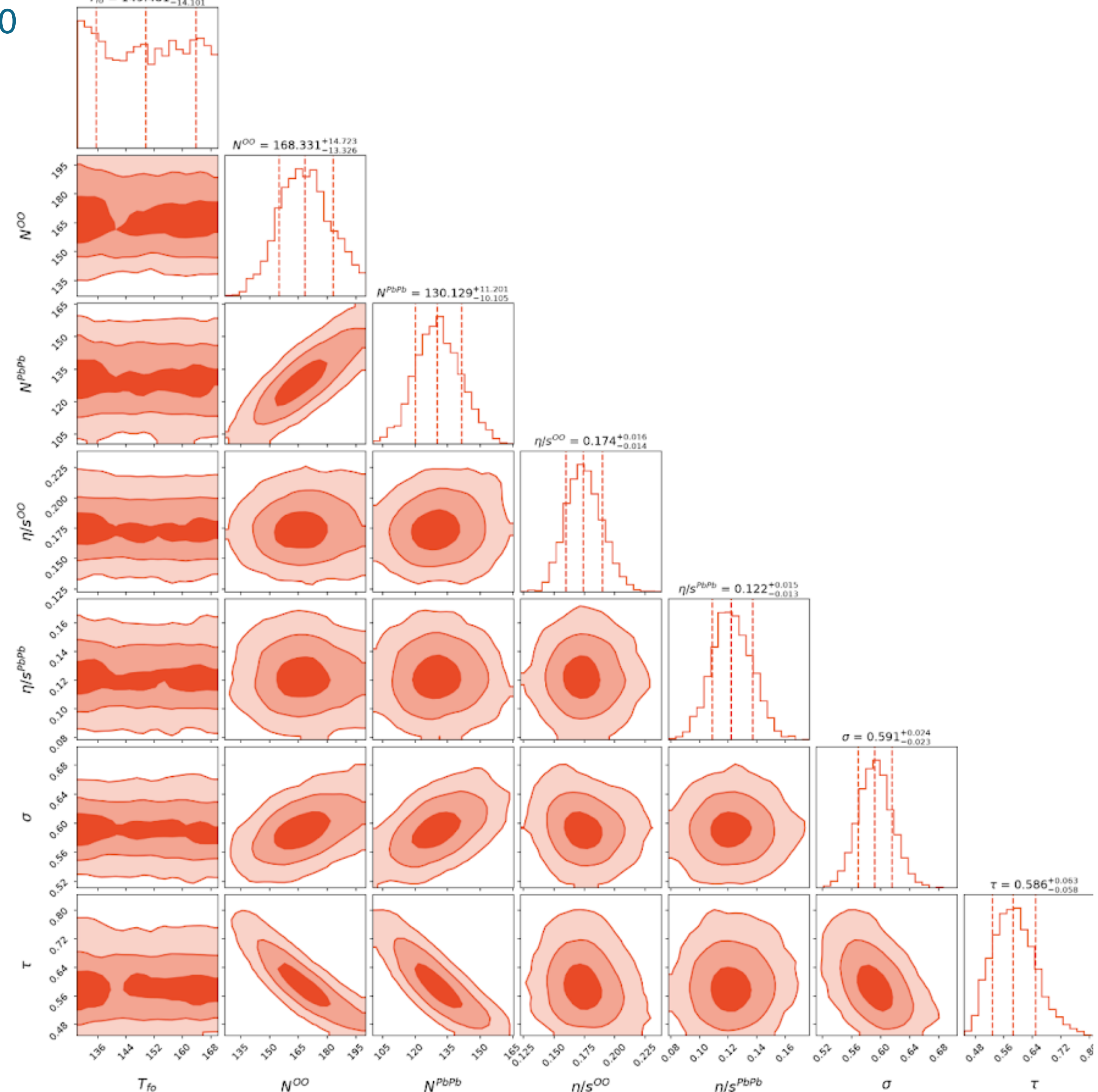
Keep track of $\frac{dh}{dt}$



Improvements to accuracy & efficiency

SMALL AND LARGE SYSTEM BAYESIAN





O + O · charged

M, <pT>

v₂{2}, v₃{2}

v₂{4} / v₂{2}

Pb + Pb · charged

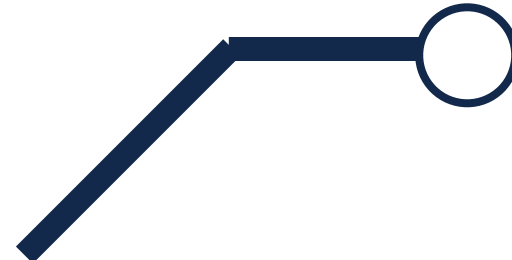
M, <pT>

v₂{2}, v₃{2}, v₄{2}

Pb + Pb · π, K, p

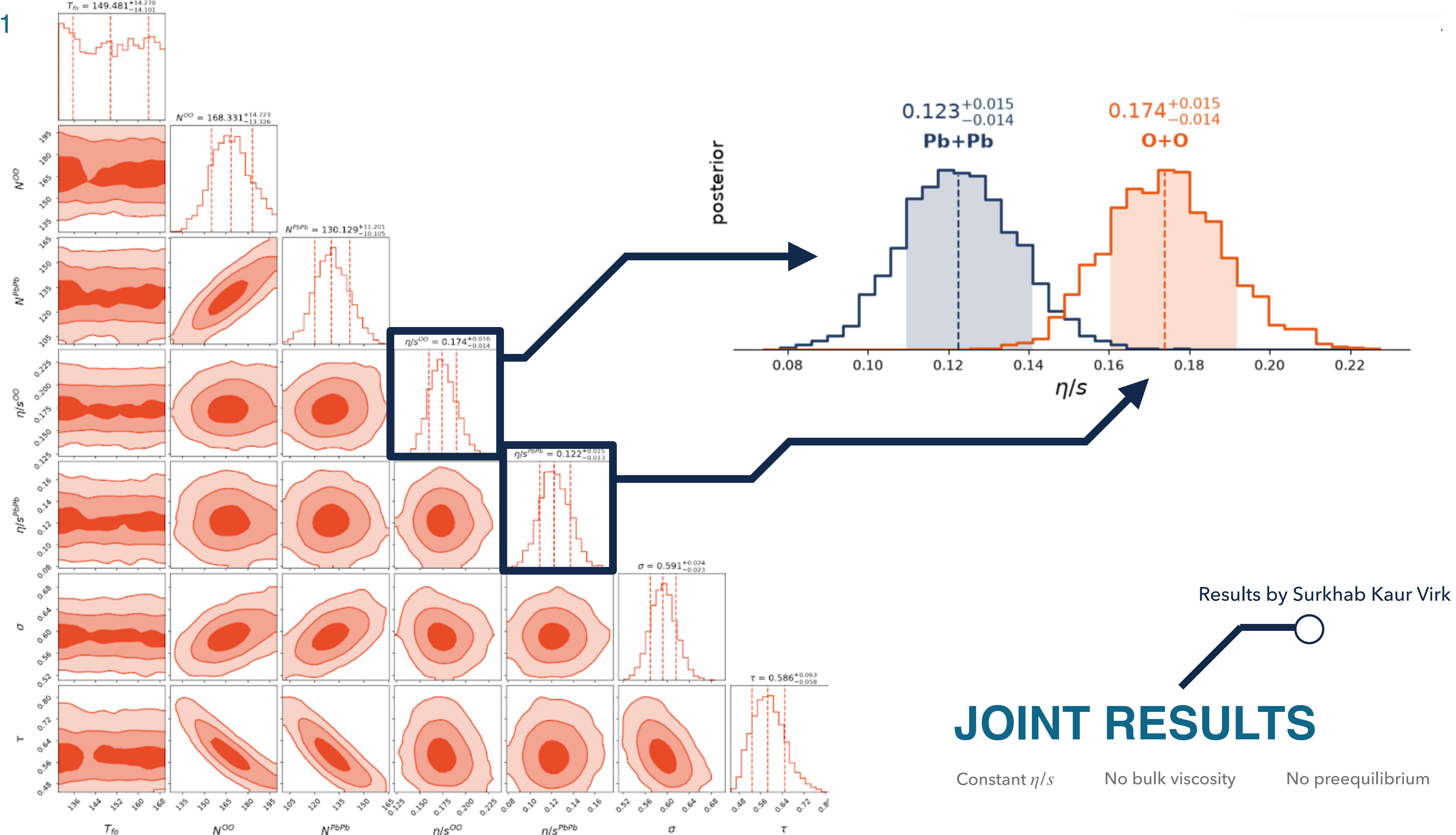
M, <pT>

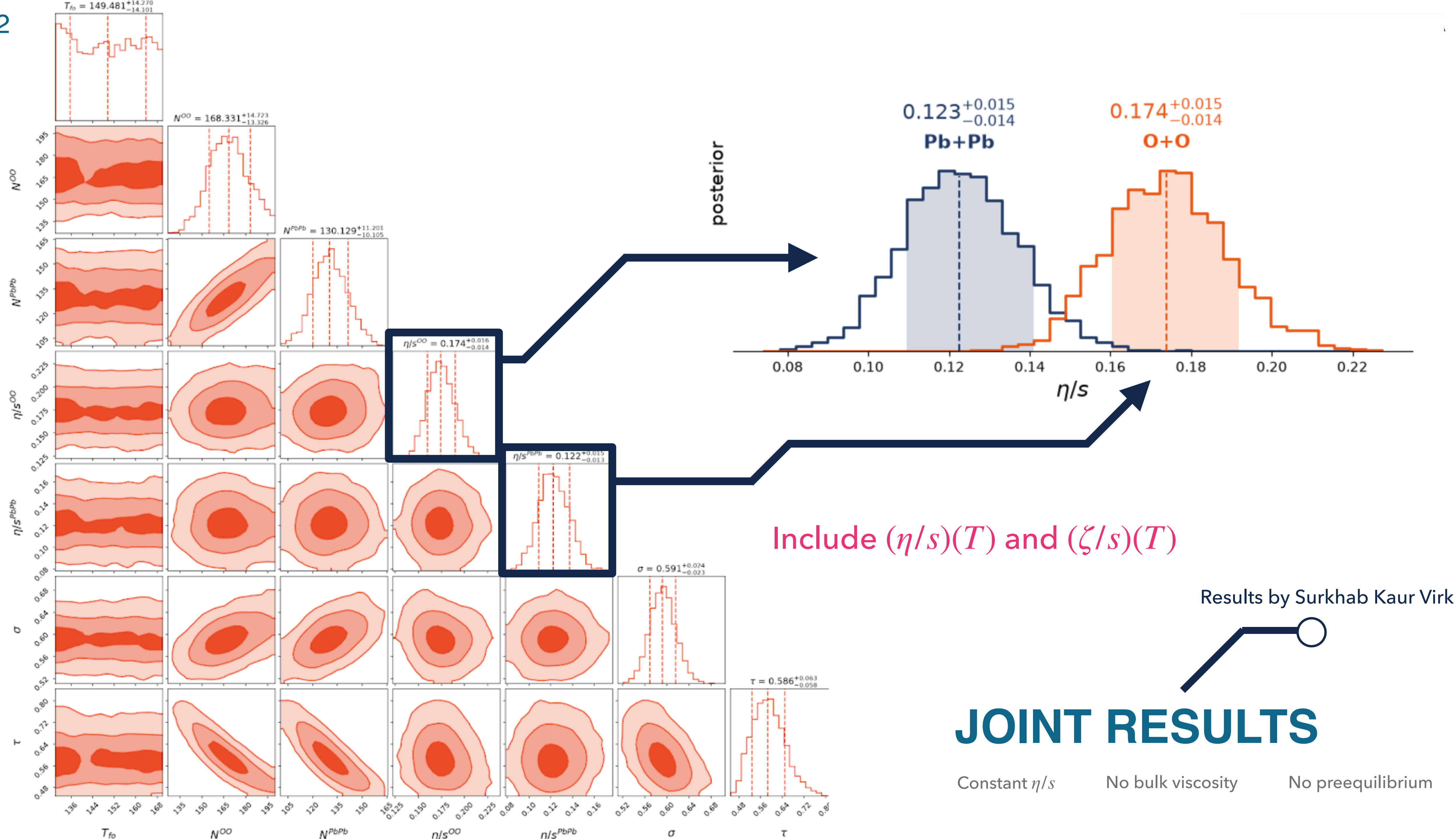
Results by Surkhab Kaur Virk

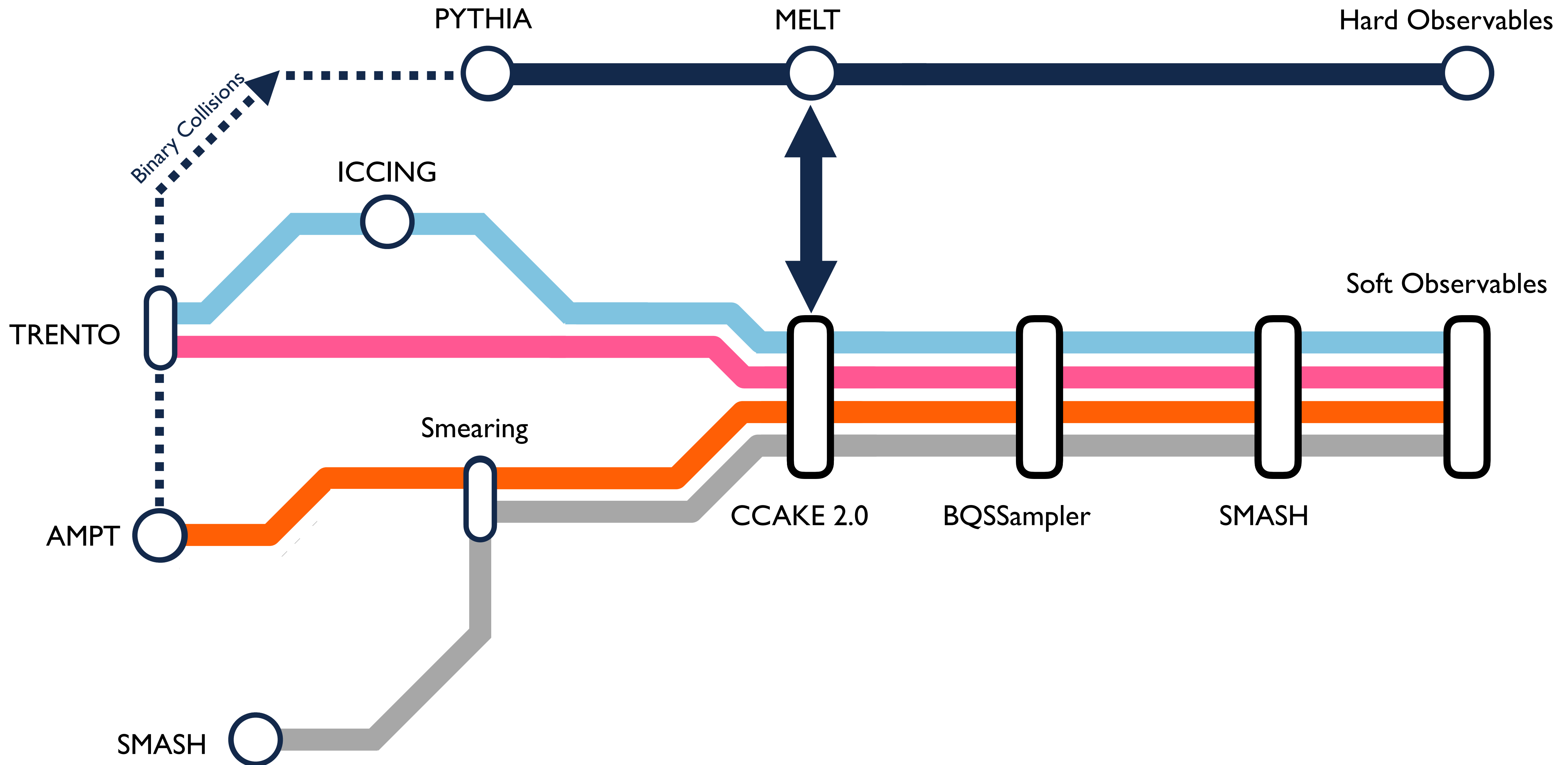


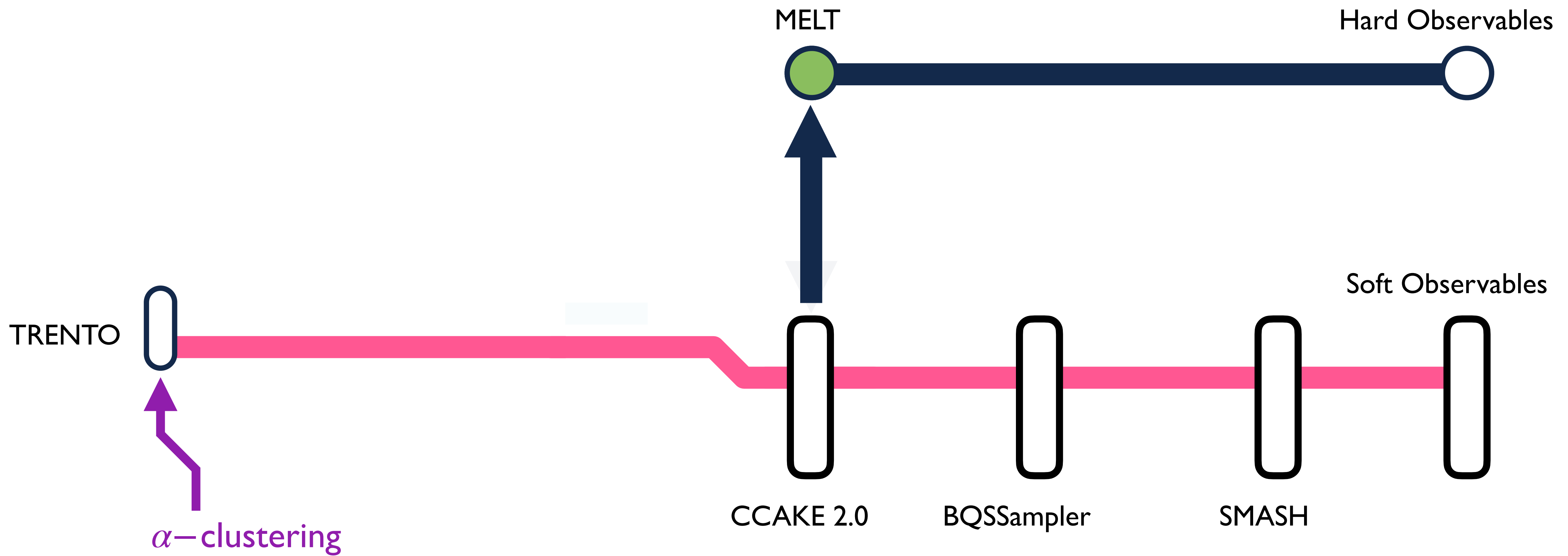
JOINT RESULTS

Constant η/s No bulk viscosity No preequilibrium

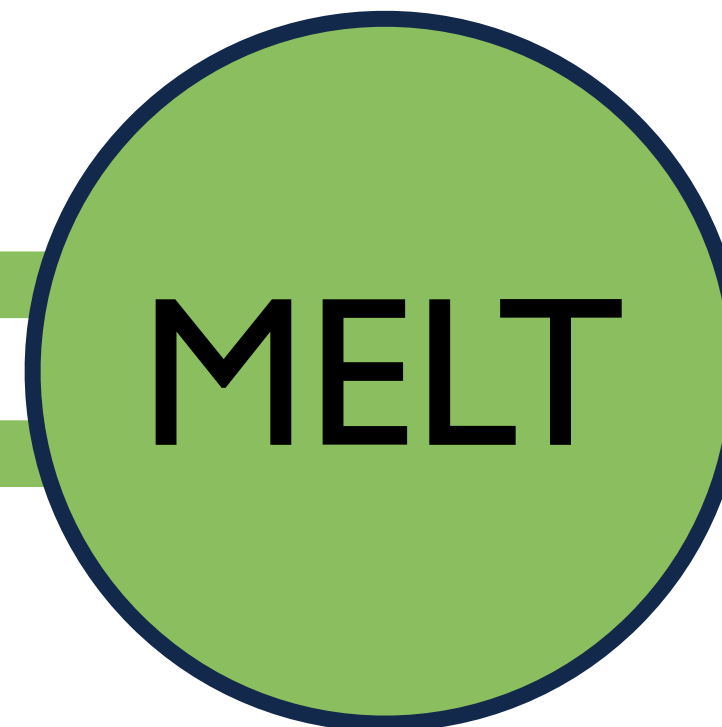








Modular Energy Loss Treatment



Massless parton at light speed



$$\mathbf{r}_{\text{jet}} = \mathbf{r}_{\text{jet}}^0 + t$$



B. Betz, M. Gyulassy JHEP 08 (2014) 090

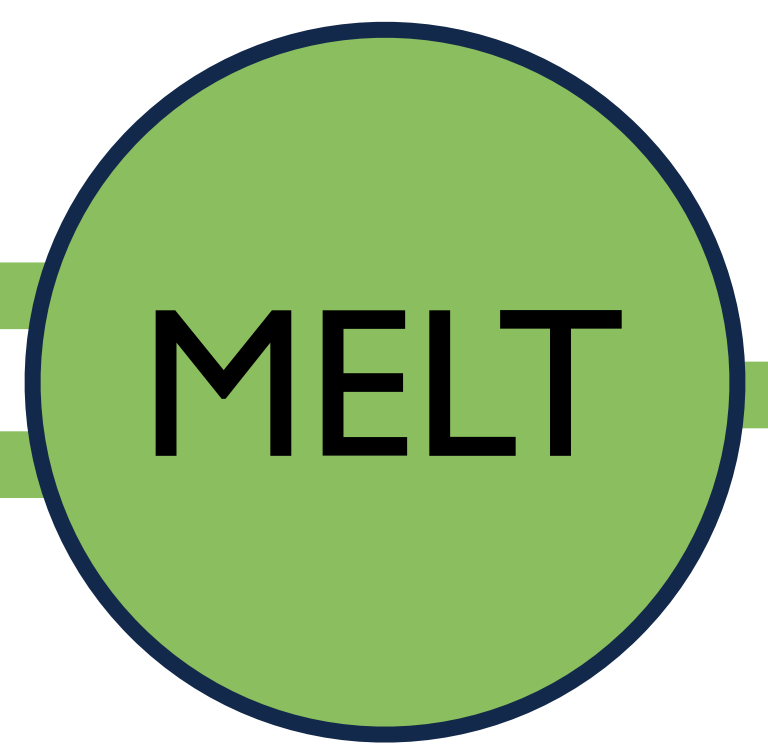
Based on BBMG model



Modular Energy Loss Treatment

Massless parton at light speed

$$\mathbf{r}_{\text{jet}} = \mathbf{r}_{\text{jet}}^0 + t$$



B. Betz, M. Gyulassy JHEP 08 (2014) 090

Based on BBMG model

Free parameters but must obey

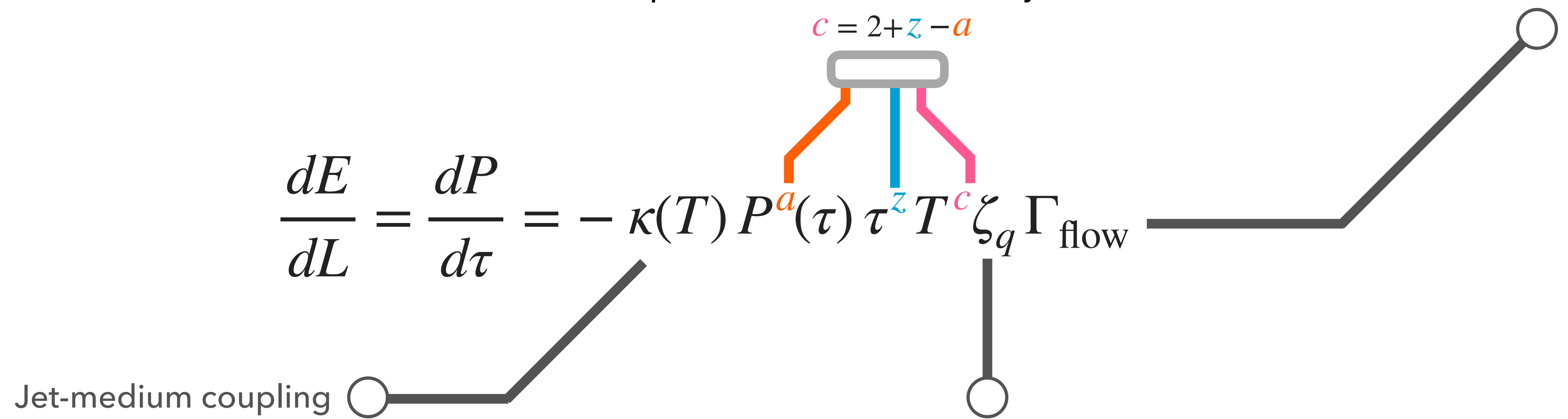
$$c = 2 + z - a$$

$$\frac{dE}{dL} = \frac{dP}{d\tau} = -\kappa(T) P^a(\tau) \tau^z T^c \zeta_q \Gamma_{\text{flow}}$$

$$\Gamma_{\text{flow}} = \gamma_{\text{flow}} \left(1 - \mathbf{v}_{\text{flow}} \cdot \hat{\mathbf{n}}_{\text{jet}} \right)$$

Jet-medium coupling

Fluctuations



Modular Energy Loss Treatment

Massless parton at light speed

$$\mathbf{r}_{\text{jet}} = \mathbf{r}_{\text{jet}}^0 + t$$

B. Betz, M. Gyulassy JHEP 08 (2014) 090

Based on BBMG model

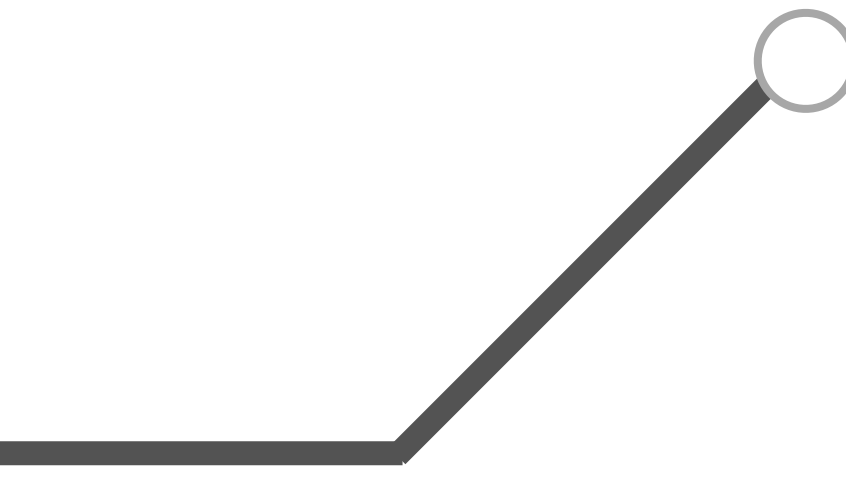


$$(c, z, a, q)$$

Until

$$E_{\text{jet}} = 0$$
$$T_{\text{jet}} < 150 \text{ MeV}$$

$$\frac{dE}{dL} = \frac{dP}{d\tau} = - \kappa(T) P^a(\tau) \tau^z T^c \zeta_q \Gamma_{\text{flow}}$$



Modular Energy Loss Treatment

Massless parton at light speed

$$\mathbf{r}_{\text{jet}} = \mathbf{r}_{\text{jet}}^0 + t$$

B. Betz, M. Gyulassy JHEP 08 (2014) 090

Based on BBMG model

- 1 → pQCD-like
- 2 → Strongly coupled



$$(c, z, a, q)$$

Until

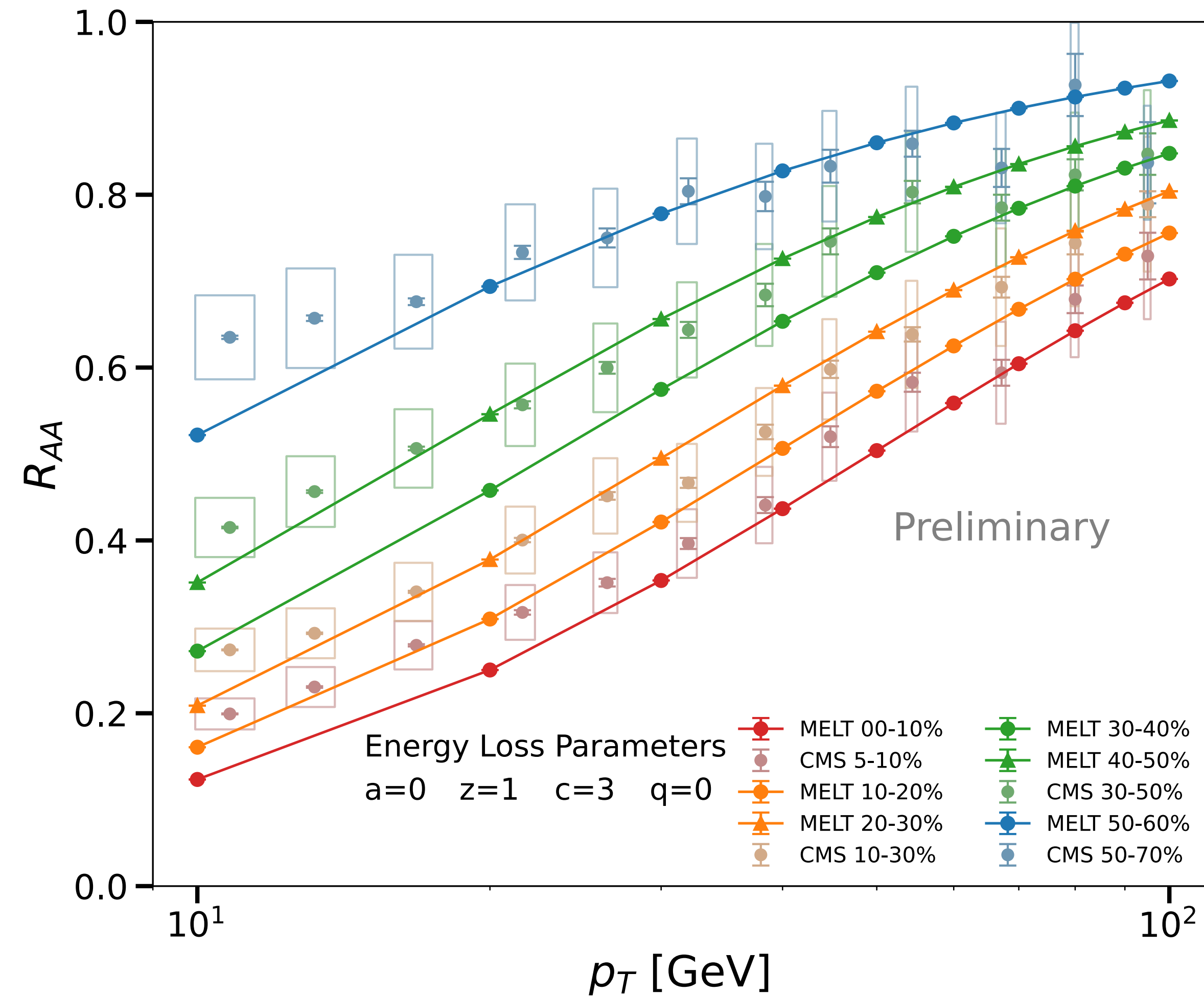
$$E_{\text{jet}} = 0$$
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JETS IN LARGE AND SMALL SYSTEMS

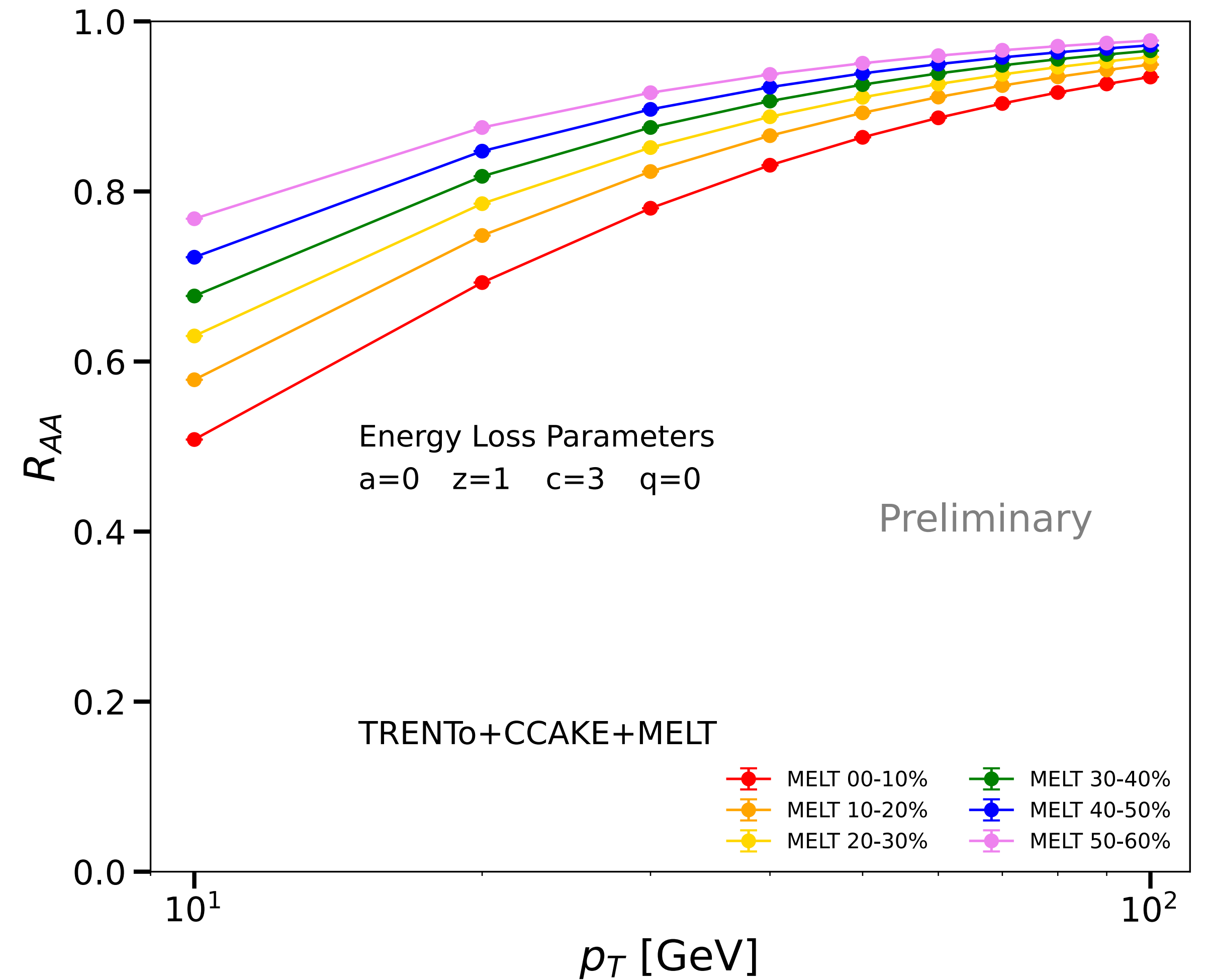
Results by Isaac Long

Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV



Pre-Bayesian parametrization

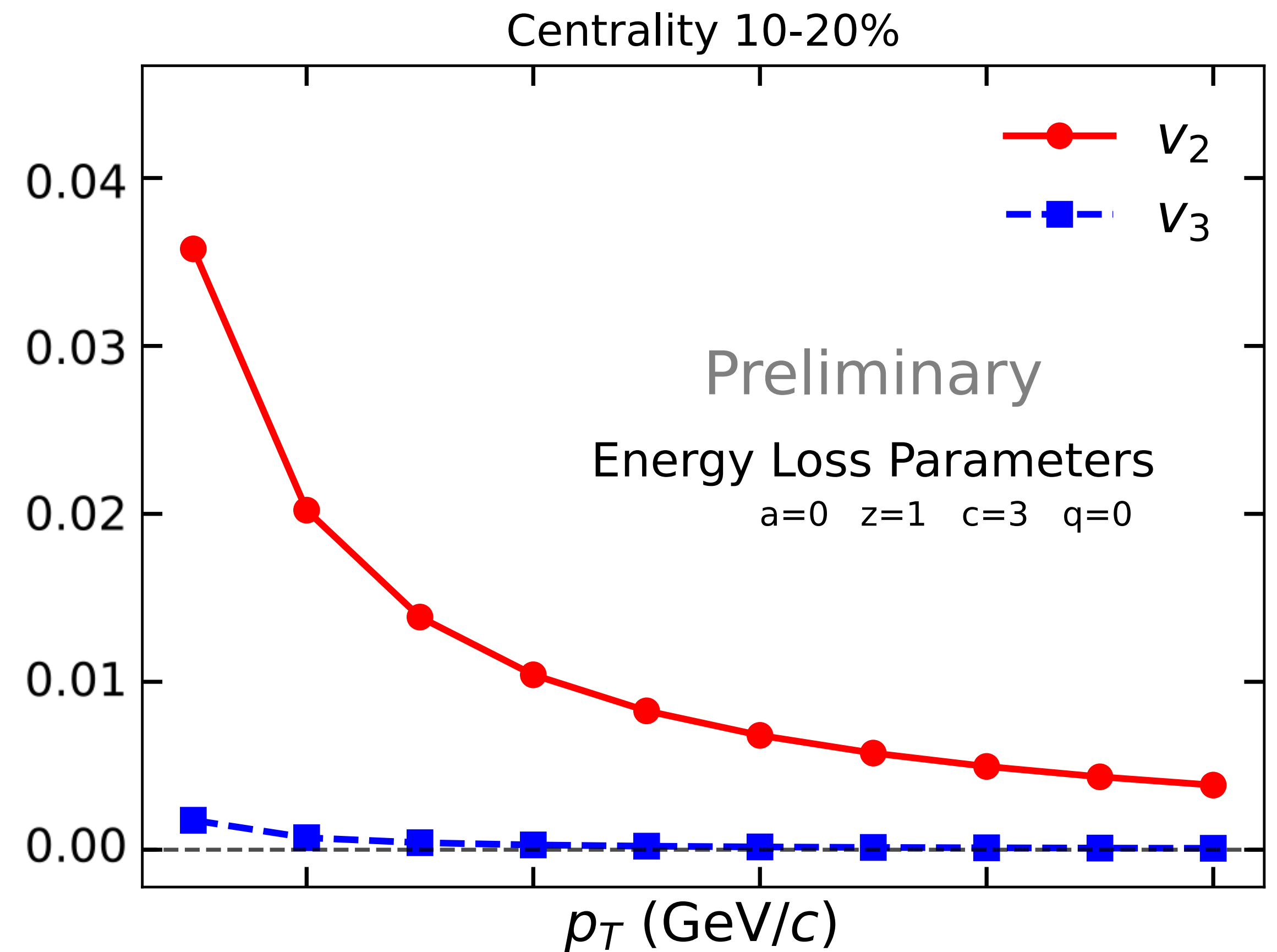
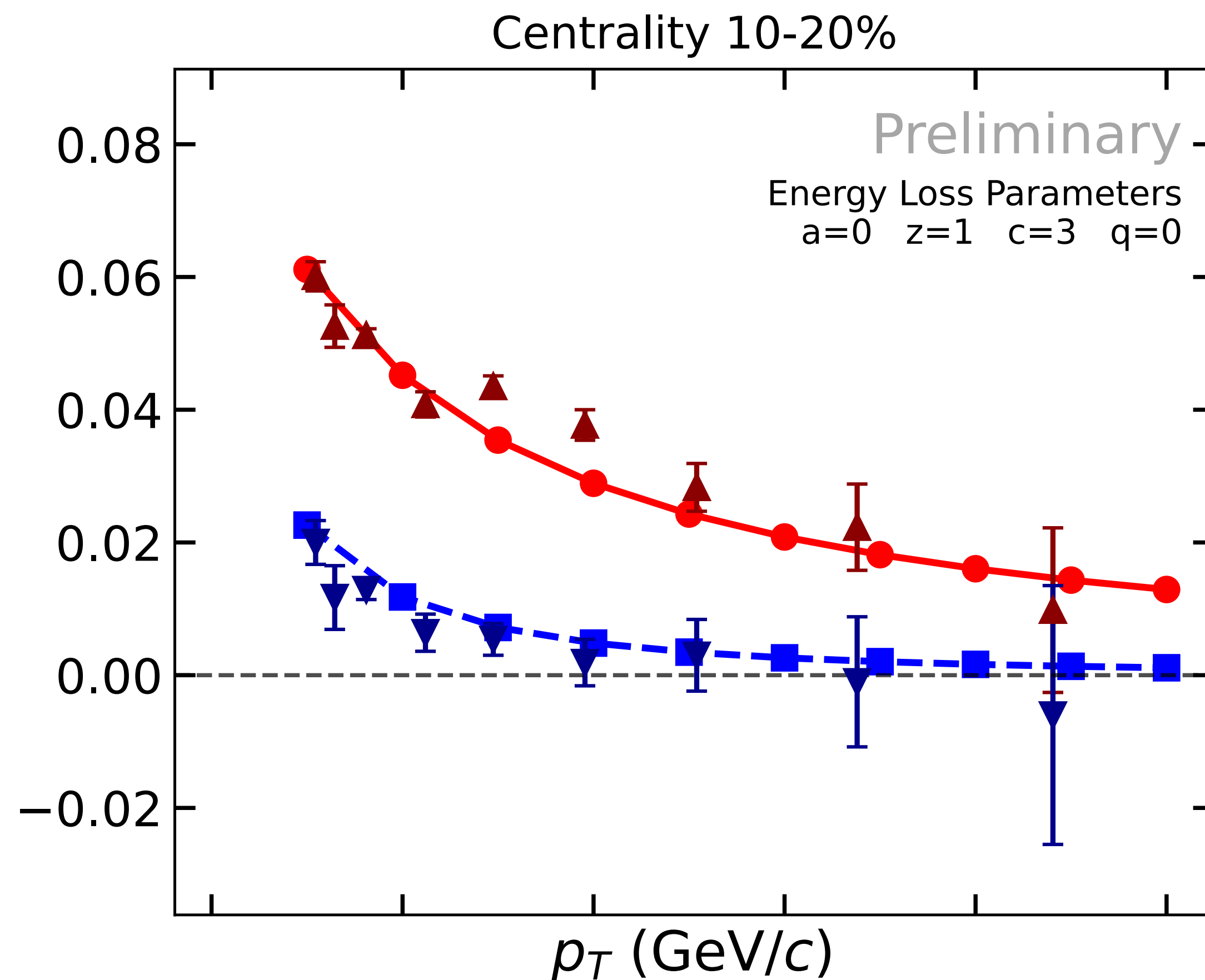
O+O $\sqrt{s_{NN}} = 5.36$ TeV



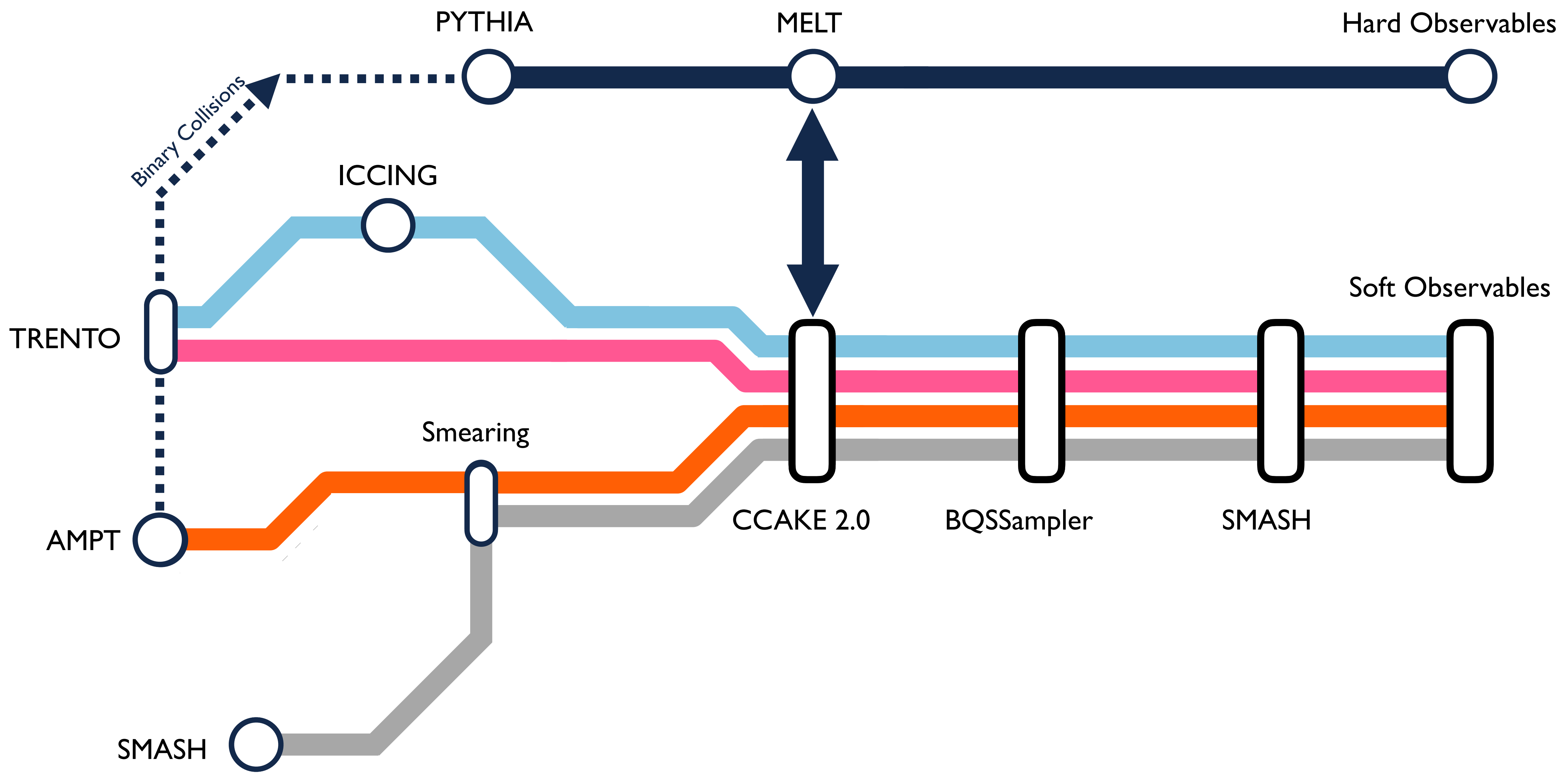
JETS IN LARGE AND SMALL SYSTEMS Results by Isaac Long

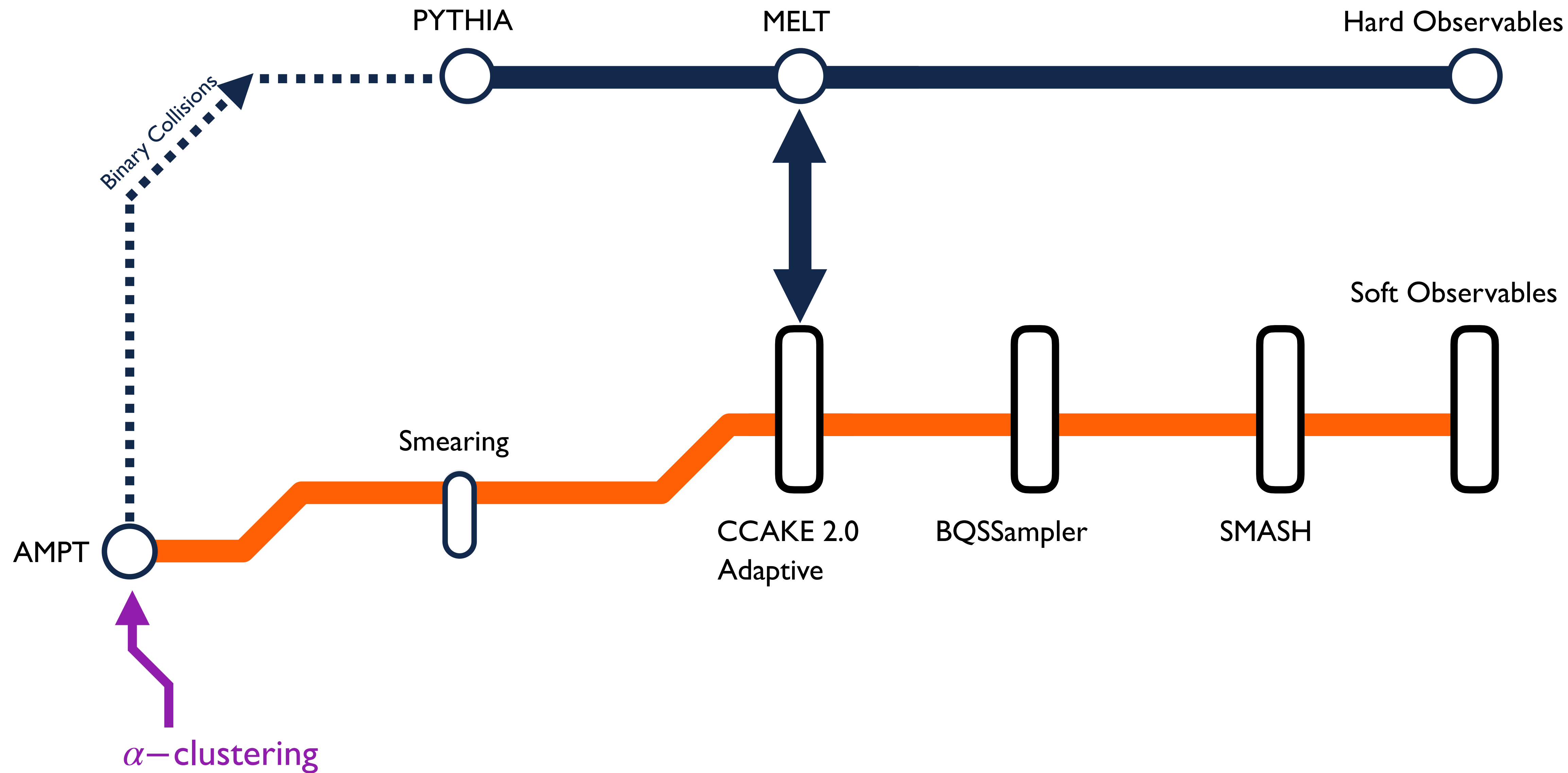
Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV

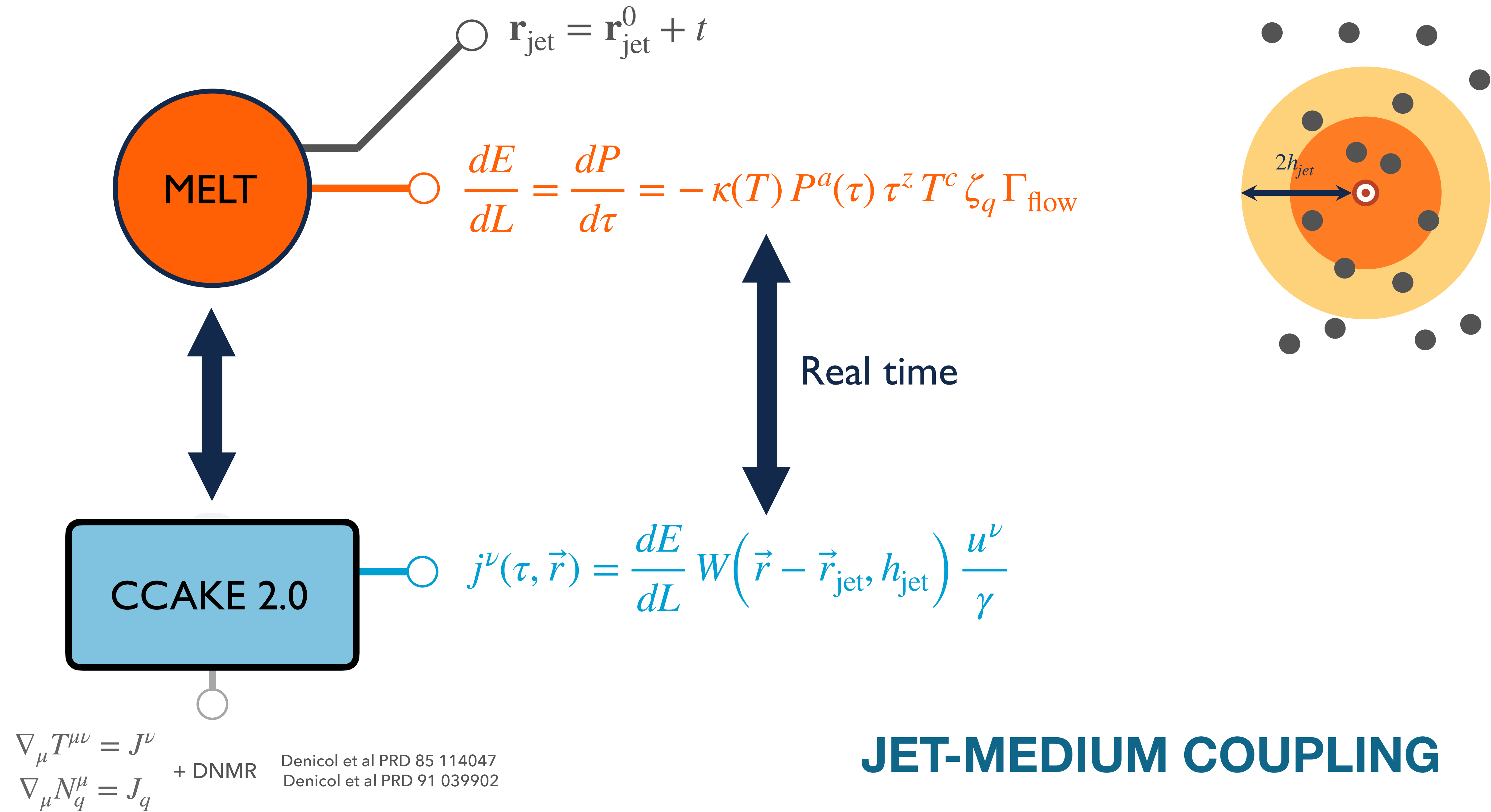
O+O $\sqrt{s_{NN}} = 5.36$ TeV



Pre-Bayesian parametrization

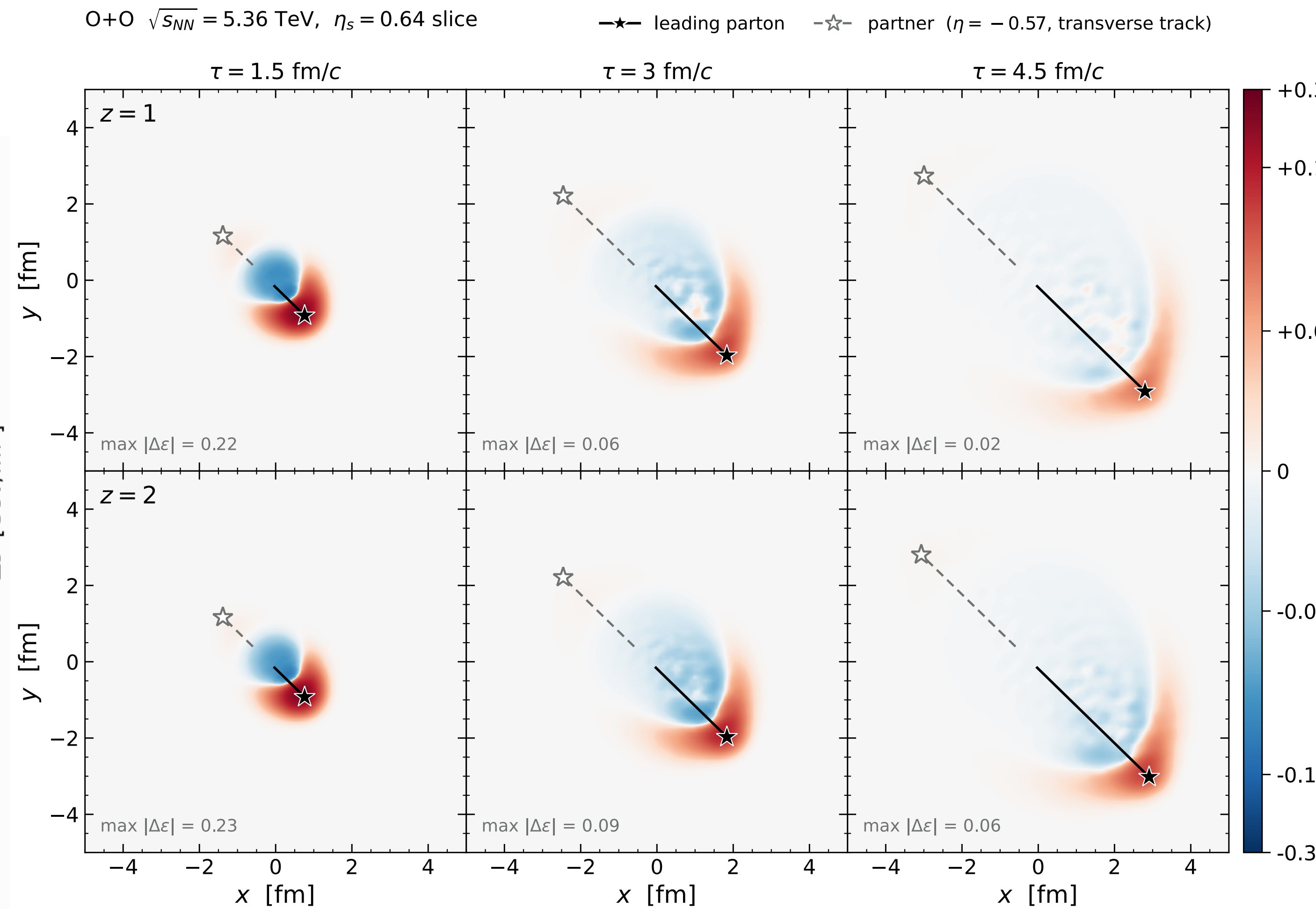
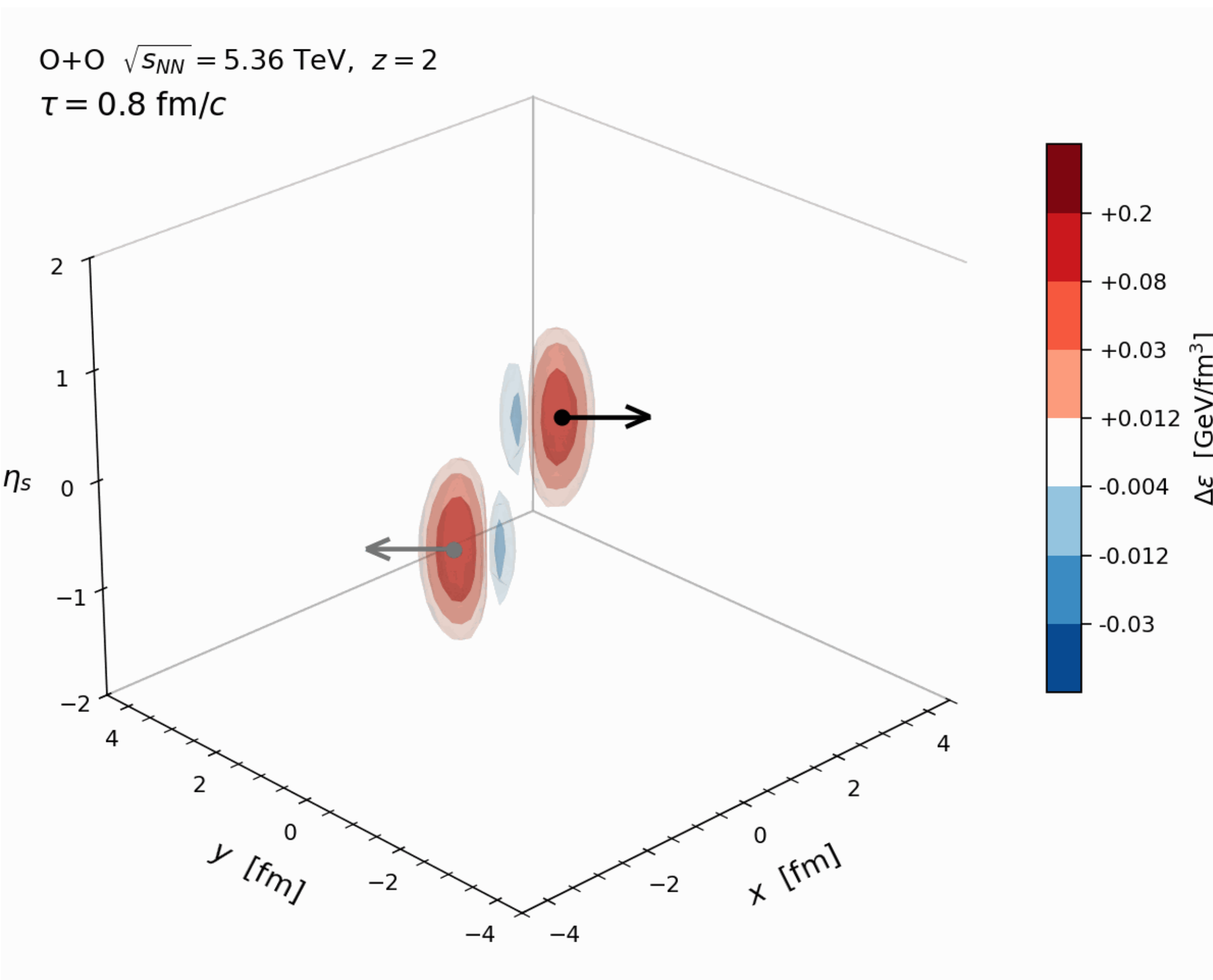


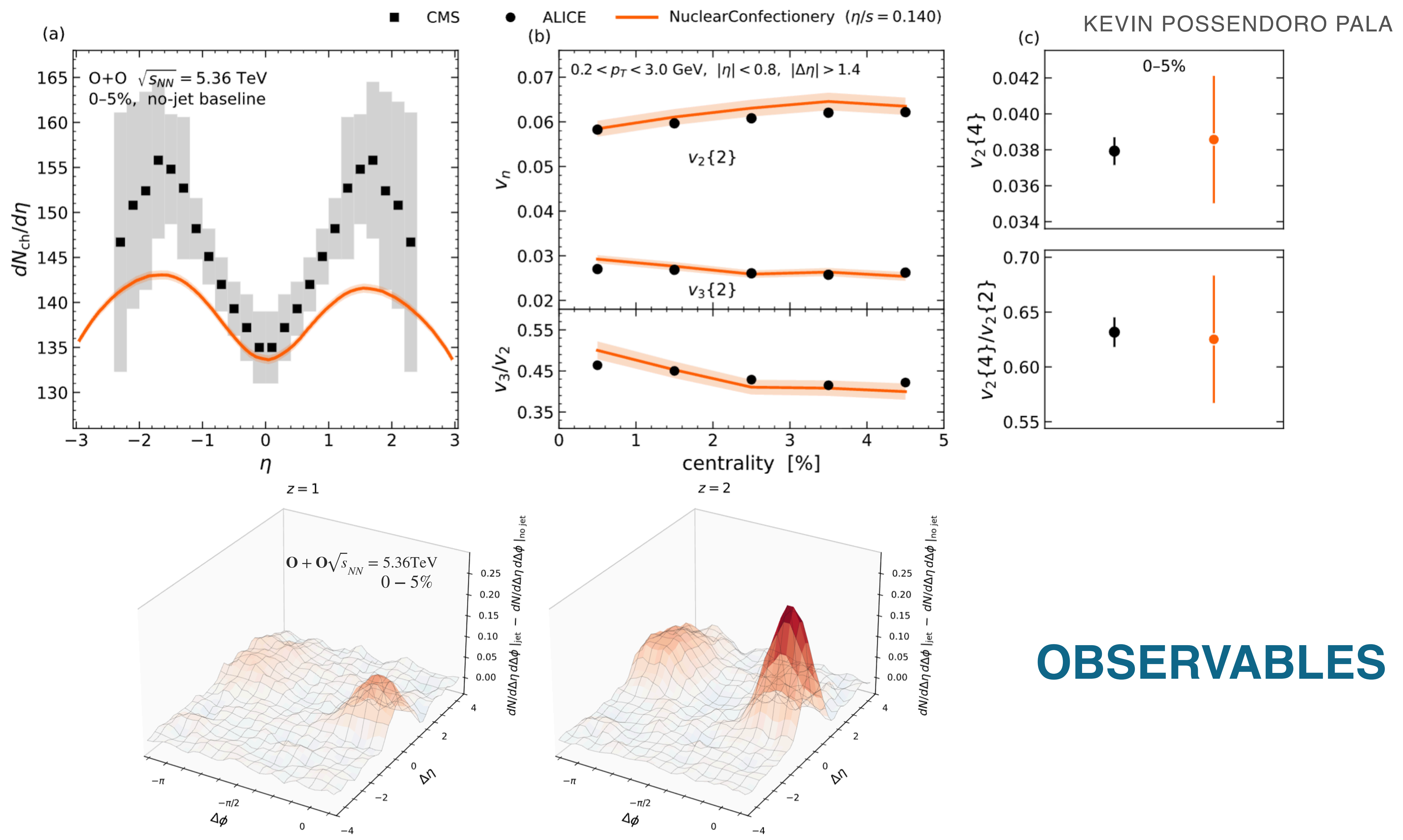




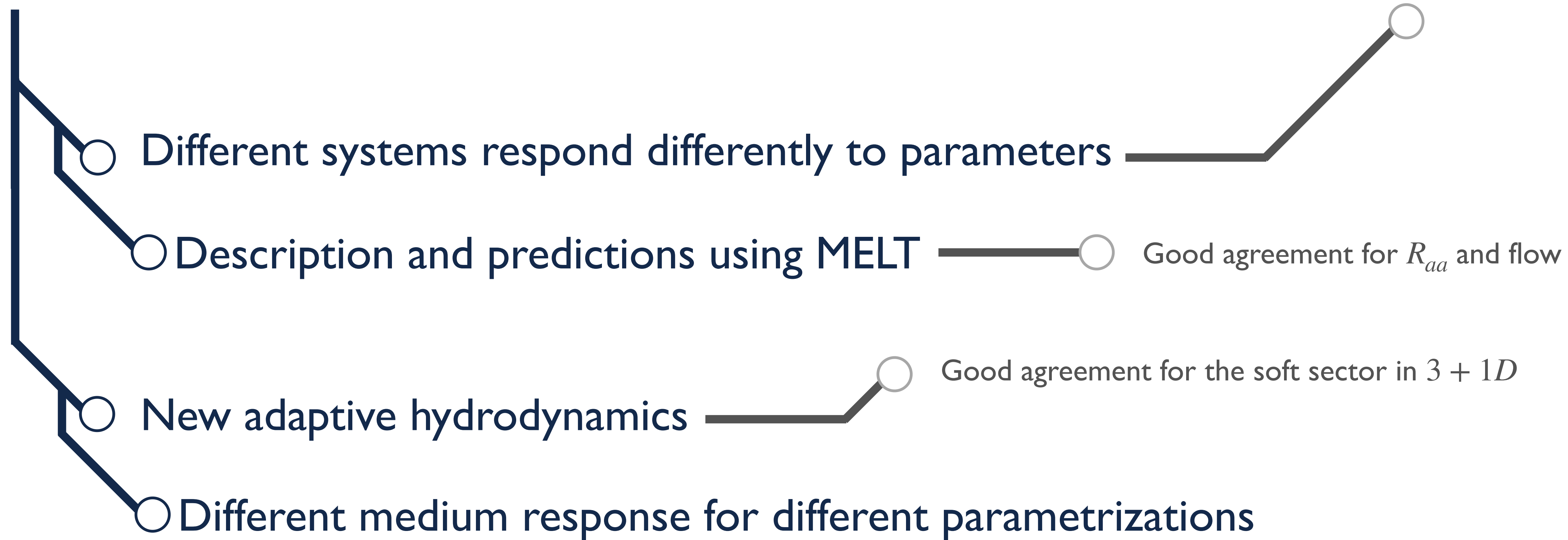
JET-MEDIUM COUPLING

$3 + 1D$



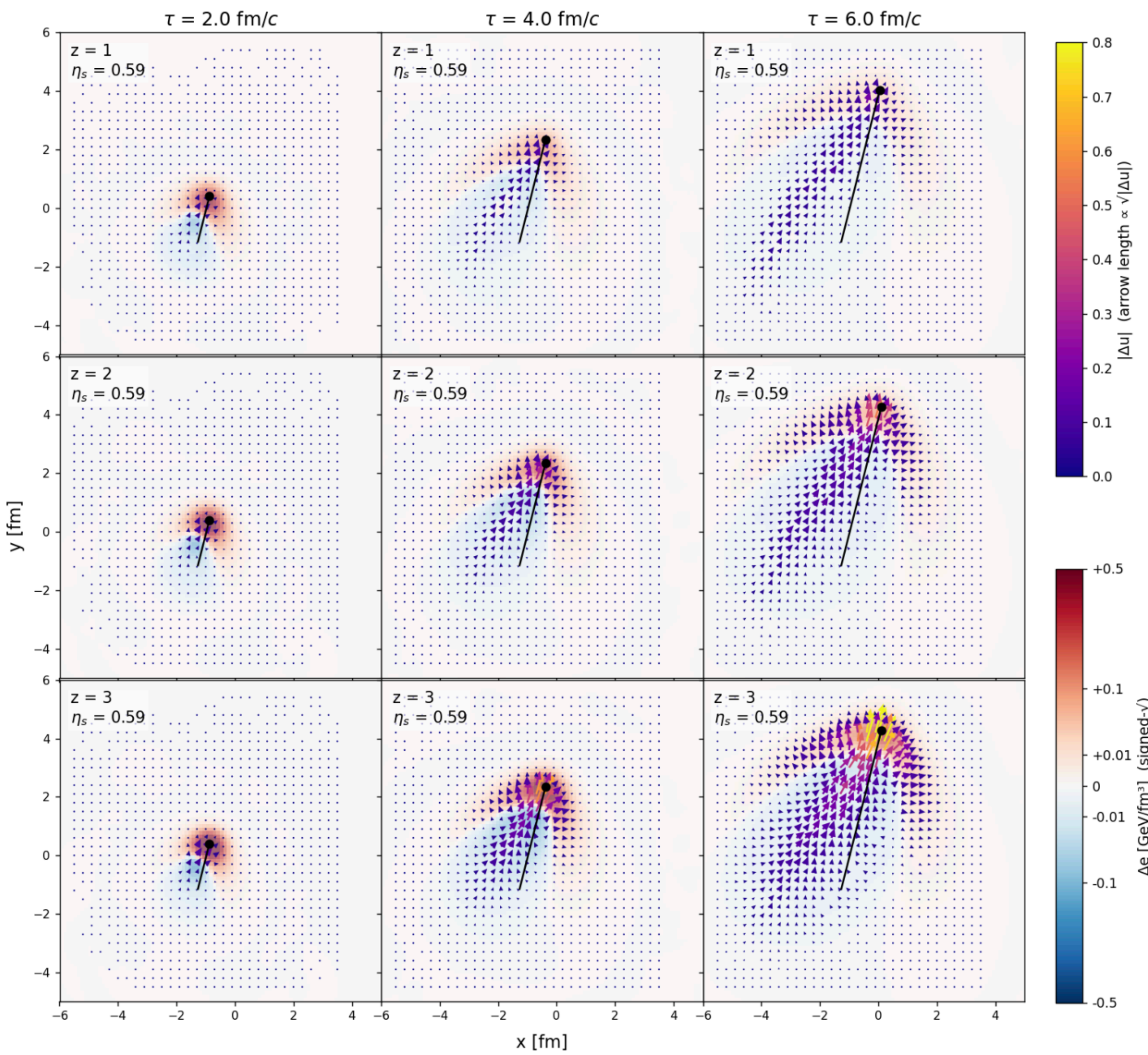
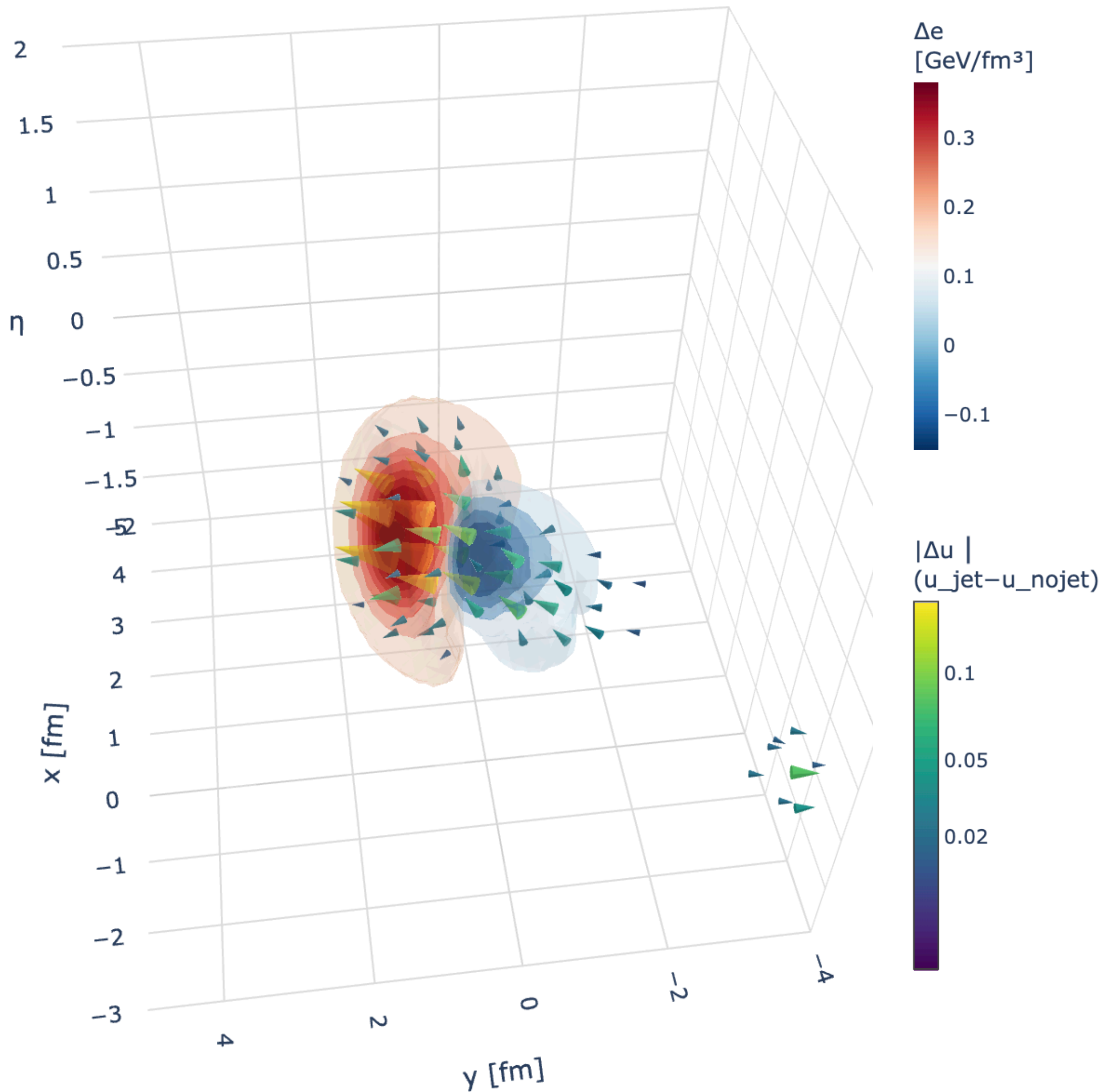


CONCLUSION



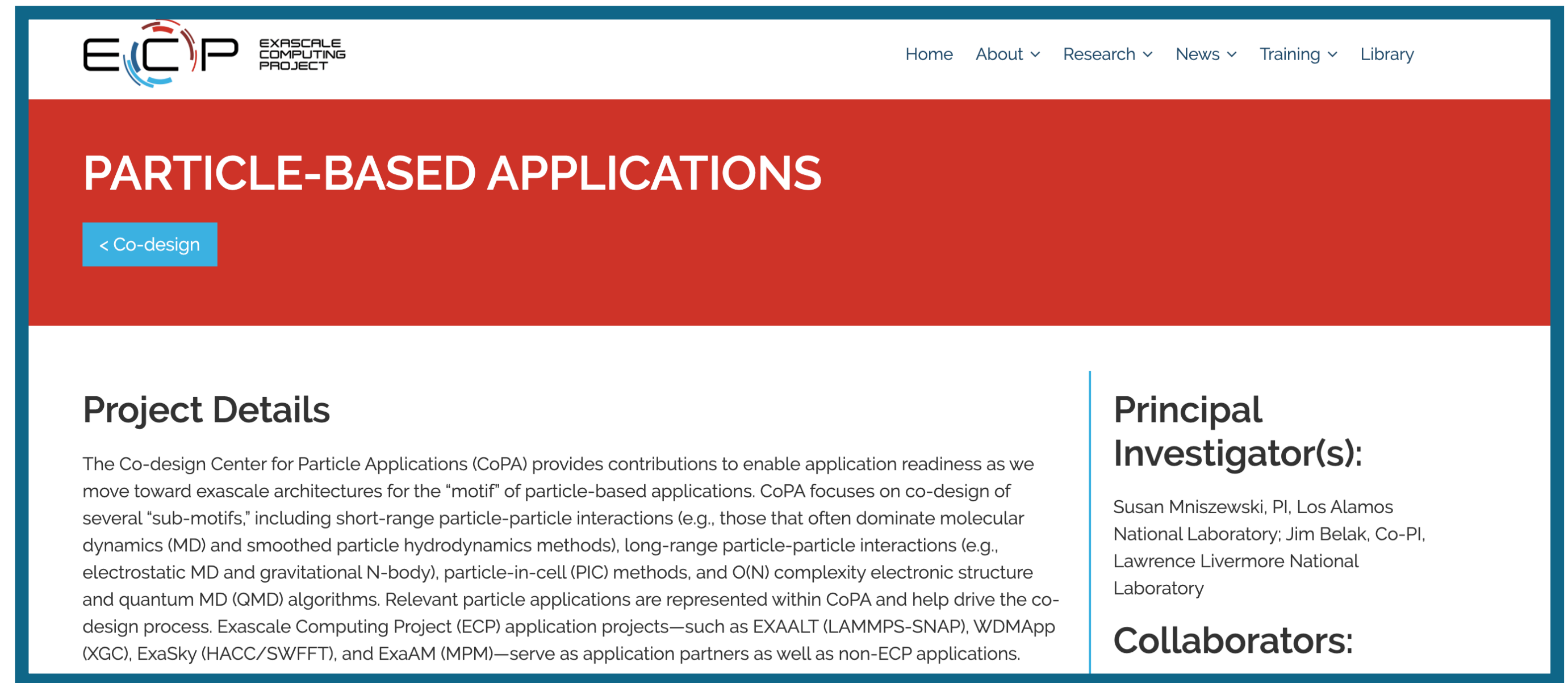
BACKUP

FLUID EVOLUTION



CCAKE CENTRAL LIBRARY

- ▶ Exascale Computing Project (ECP) - Co-design Center for Particle Applications (COPA)
- ▶ ECP-COPA/Cabana used in CCAKE
- ▶ Performance portability
 - ▶ - Personal Computers
 - ▶ - Workstations
 - ▶ - Clusters w/wo GPUs



The screenshot shows the 'PARTICLE-BASED APPLICATIONS' page of the Exascale Computing Project (ECP). The page has a red header with the ECP logo and navigation links (Home, About, Research, News, Training, Library). Below the header, there's a blue button labeled '< Co-design'. The main content area is divided into two columns. The left column, titled 'Project Details', describes the Co-design Center for Particle Applications (CoPA) and its focus on enabling application readiness for exascale architectures. The right column, titled 'Principal Investigator(s):', lists Susan Mniszewski, PI, and Jim Belak, Co-PI, from Los Alamos National Laboratory and Lawrence Livermore National Laboratory. Below this, the 'Collaborators:' section is partially visible.

ECP EXASCALE COMPUTING PROJECT

Home About ▾ Research ▾ News ▾ Training ▾ Library

PARTICLE-BASED APPLICATIONS

< Co-design

Project Details

The Co-design Center for Particle Applications (CoPA) provides contributions to enable application readiness as we move toward exascale architectures for the "motif" of particle-based applications. CoPA focuses on co-design of several "sub-motifs," including short-range particle-particle interactions (e.g., those that often dominate molecular dynamics (MD) and smoothed particle hydrodynamics methods), long-range particle-particle interactions (e.g., electrostatic MD and gravitational N-body), particle-in-cell (PIC) methods, and O(N) complexity electronic structure and quantum MD (QMD) algorithms. Relevant particle applications are represented within CoPA and help drive the co-design process. Exascale Computing Project (ECP) application projects—such as EXAALT (LAMMPS-SNAP), WDMApp (XGC), ExaSky (HACC/SWFFT), and ExaAM (MPM)—serve as application partners as well as non-ECP applications.

Principal Investigator(s):

Susan Mniszewski, PI, Los Alamos National Laboratory; Jim Belak, Co-PI, Lawrence Livermore National Laboratory

Collaborators:

<https://www.exascaleproject.org/research-project/particle-based-applications/>

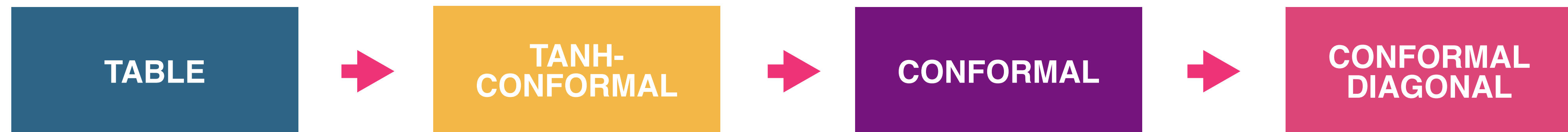
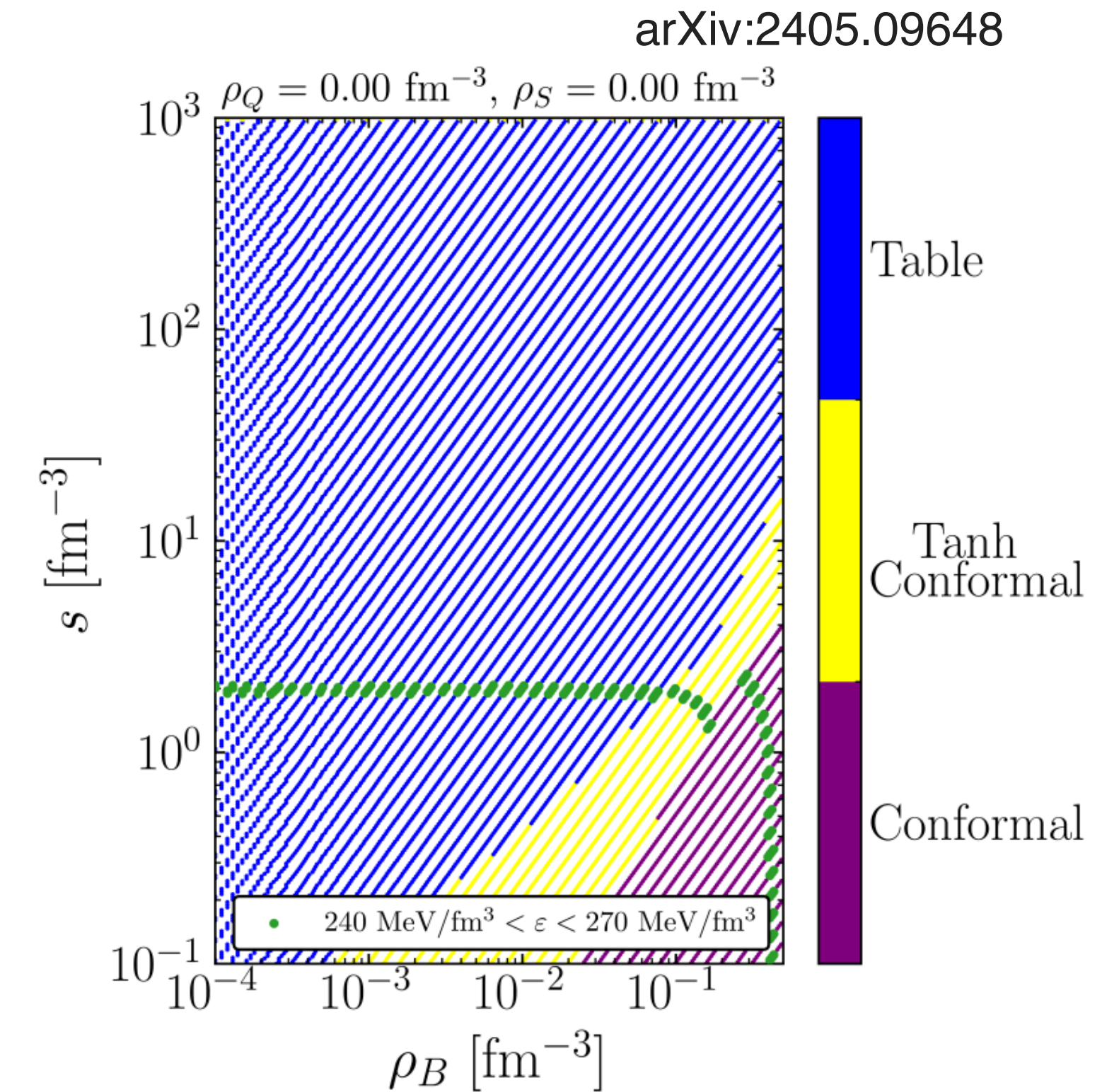
CCAKE: FREEZE-OUT SURFACE

- ▶ Surface $\varepsilon_{fo} = \varepsilon(x = (x^0, x^1, x^2, x^3))$

$$n_\mu = \frac{N_\mu}{\sqrt{|N_\mu N^\mu|}} = - \frac{\partial_\mu \varepsilon_{fo}(x)}{\sqrt{|\partial_\mu \varepsilon_{fo}(x) \partial^\mu \varepsilon_{fo}(x)|}}$$

CCAKE: EQUATION OF STATE

$$p(T, \vec{\mu}) = \frac{1}{2} A_0 T_0^4 \left[\left(\frac{T}{T_0} \right)^2 + \sum_X \left(\frac{\mu_X}{\mu_{X,0}} \right)^2 \right]^2$$



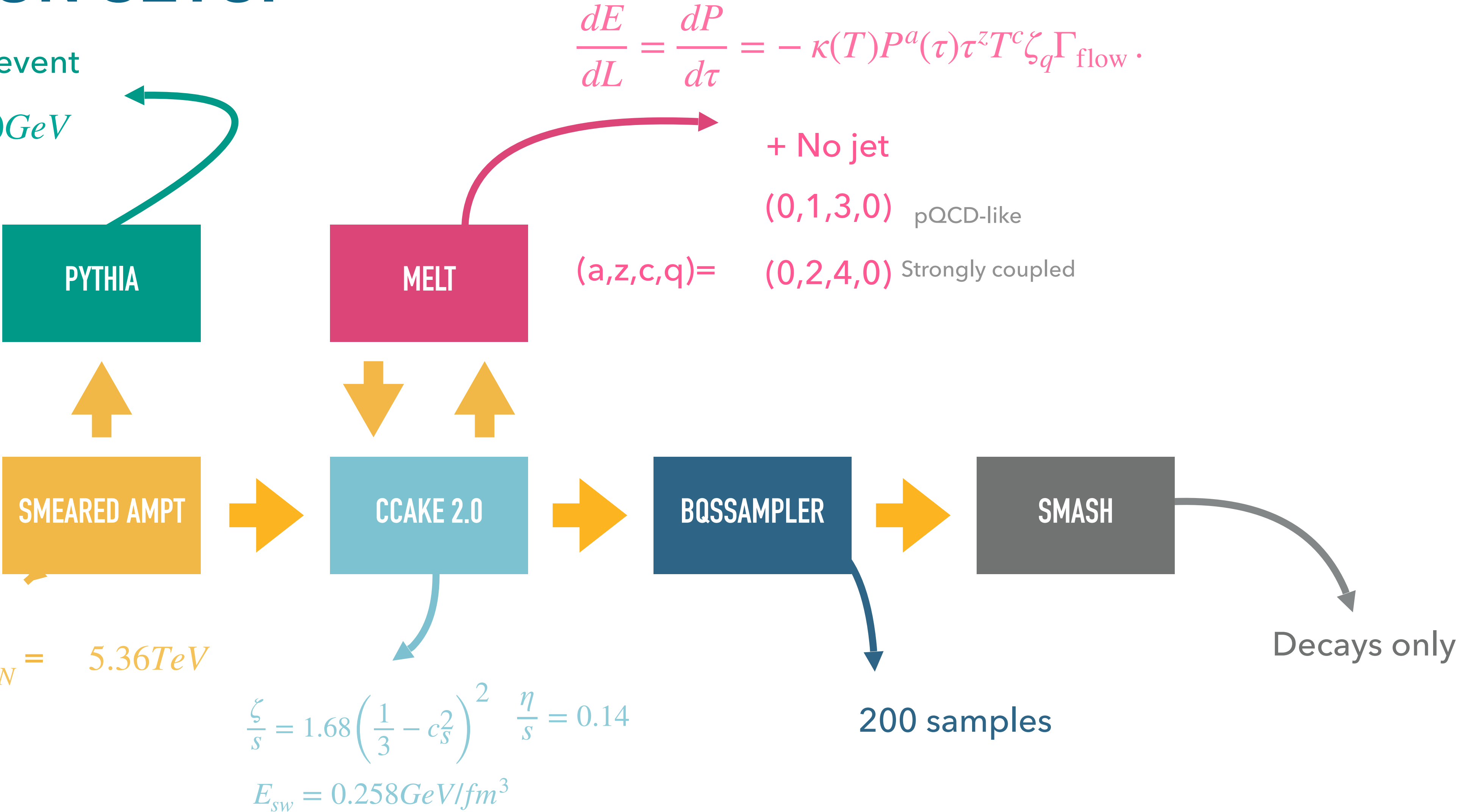
$$p(T, \vec{\mu}) = \frac{1}{2} A_0 T_0^4 \left(1 + \tanh \left(\frac{T - T_c}{T_s} \right) \right) \left[\left(\frac{T}{T_0} \right)^2 + \sum_X \left(\frac{\mu_X}{\mu_{X,0}} \right)^2 \right]^2$$

$$p(T, \vec{\mu}) = \frac{1}{2} A_0 T_0^4 \left[\left(\frac{T}{T_0} \right)^2 + \sum_X \left(\frac{\mu_X}{\mu_{X,0}} \right)^4 \right]^2$$

SIMULATION SETUP

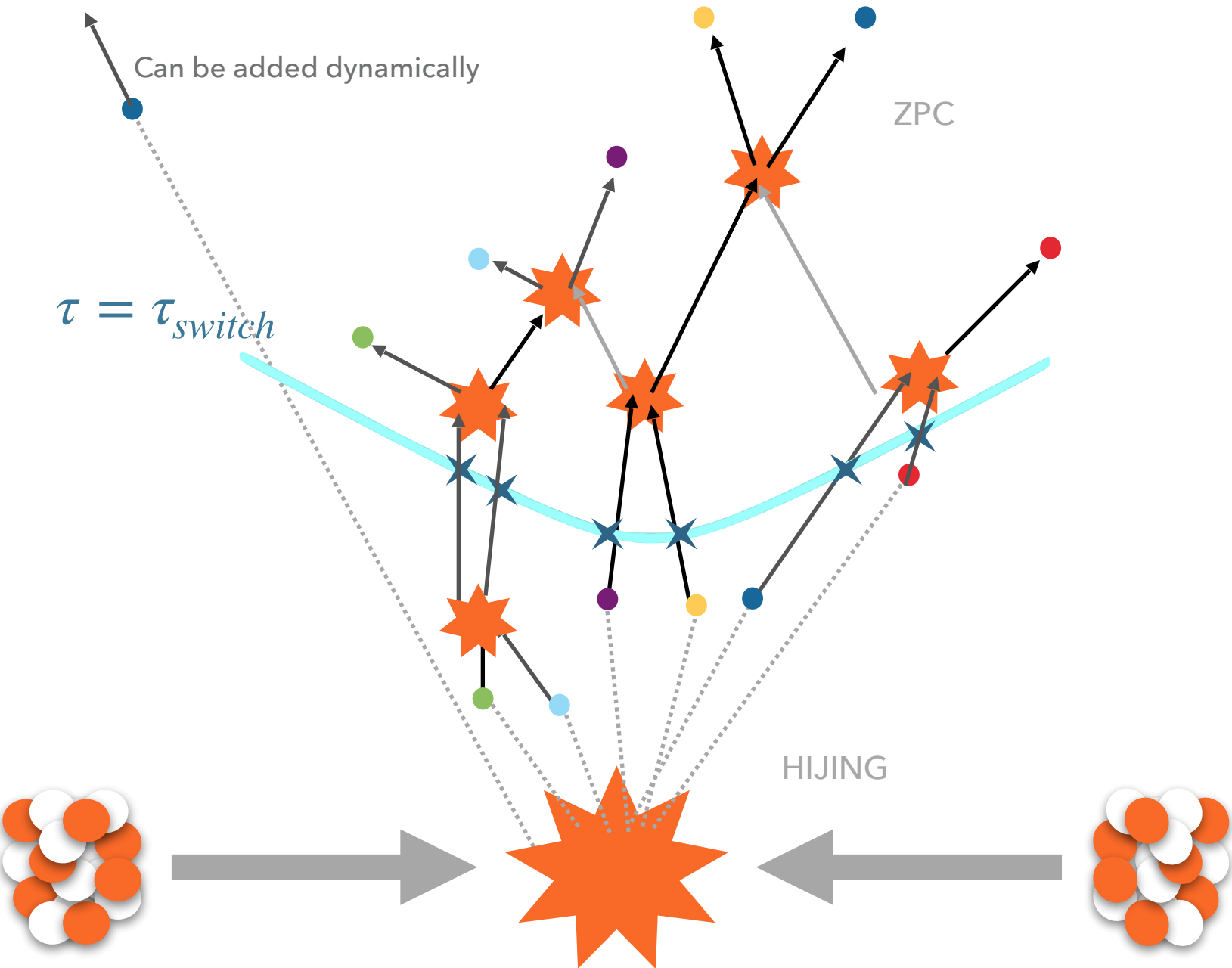
1 "Di-jet" pair/event
 $150 < p_T < 200 GeV$

00 0-5% $\sqrt{s_{NN}} = 5.36 TeV$
1500 events



INITIAL STATE

SMEARED AMPT



$$T^{\mu\nu}(x^1, x^2, x^3) = \sum_{i=\text{partons}} \frac{p_i^\mu p_i^\nu}{p_i^0} W_i(\vec{x}, \sigma_\perp, \sigma_3)$$

$$W(\vec{x}_i, \sigma_\perp, \sigma_3) = W(x_i^\perp, \sigma_\perp) W(x_i^3, \sigma_3)$$

Cubic spline with support σ_j

α-clustering nucleon distribution

Summerfield et al *PRC* 104 (2021) 4, L041901

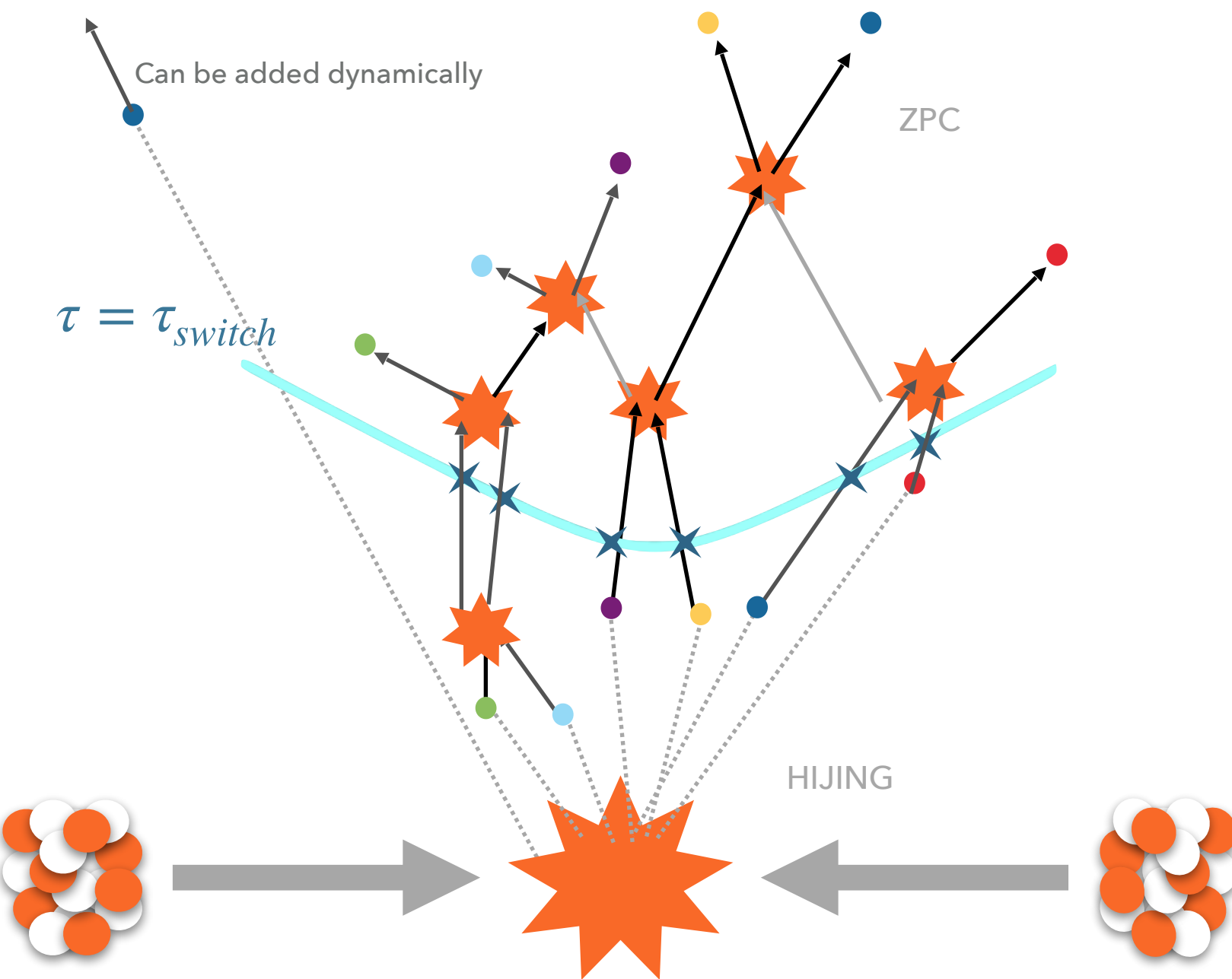
INITIAL STATE

Hard Parton moving through the medium
Jet sampling

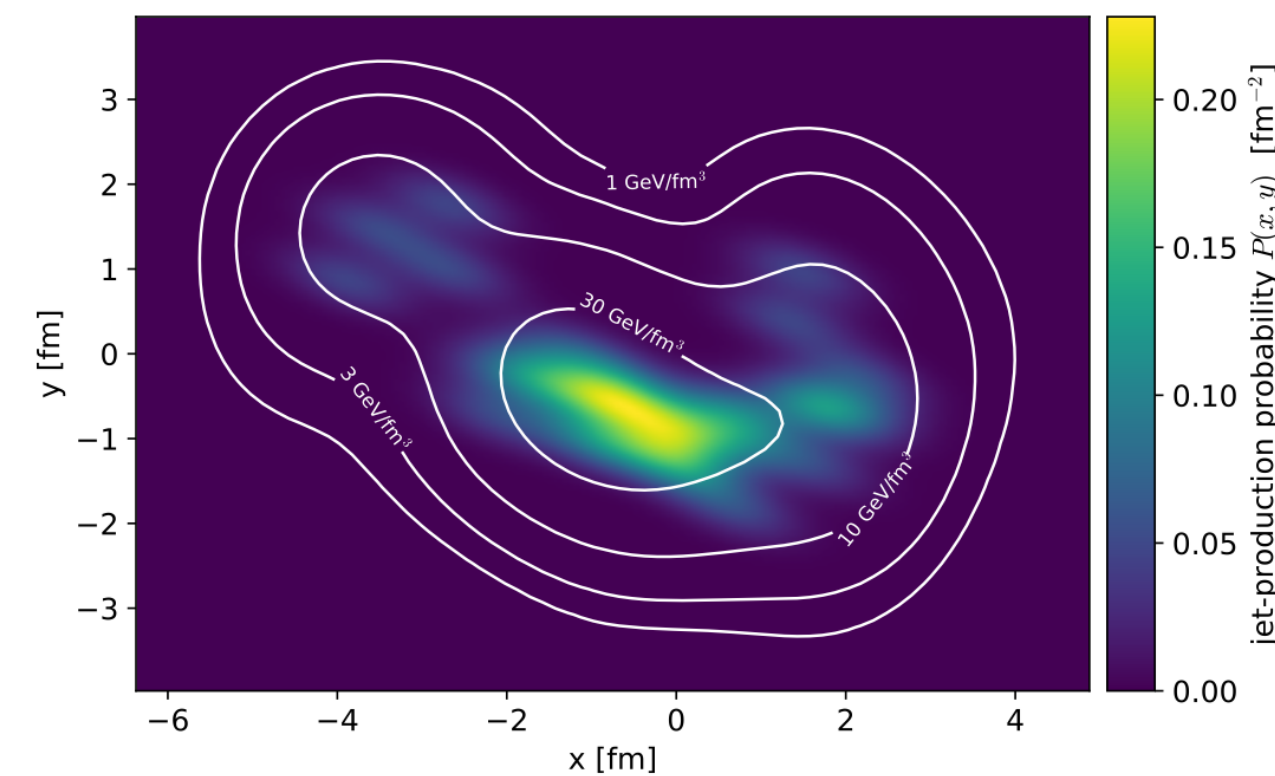
SMEARED AMPT

BINARY COLLISIONS

PYTHIA



Jet position



$$T^{\mu\nu}(x^1, x^2, x^3) = \sum_{i=\text{partons}} \frac{p_i^\mu p_i^\nu}{p_i^0} W_i(\vec{x}, \sigma_\perp, \sigma_3)$$

$$W(\vec{x}_i, \sigma_\perp, \sigma_3) = W(x_i^\perp, \sigma_\perp) W(x_i^3, \sigma_3)$$

Cubic spline with support σ_j

α -clustering nucleon distribution

Summerfield et al *PRC* 104 (2021) 4, L041901

INITIAL STATE

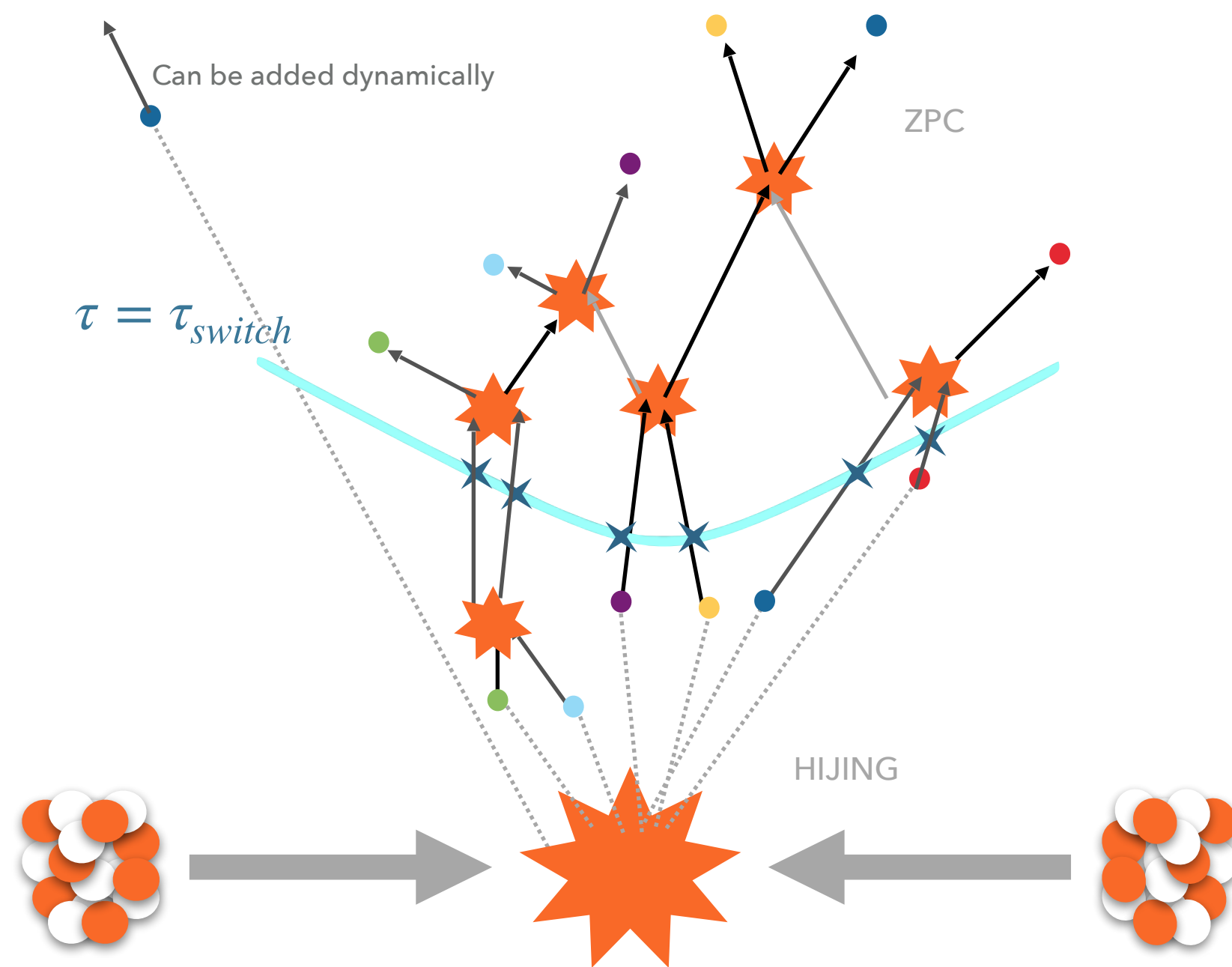
Hard Parton moving through the medium
Jet sampling

SMEARED AMPT

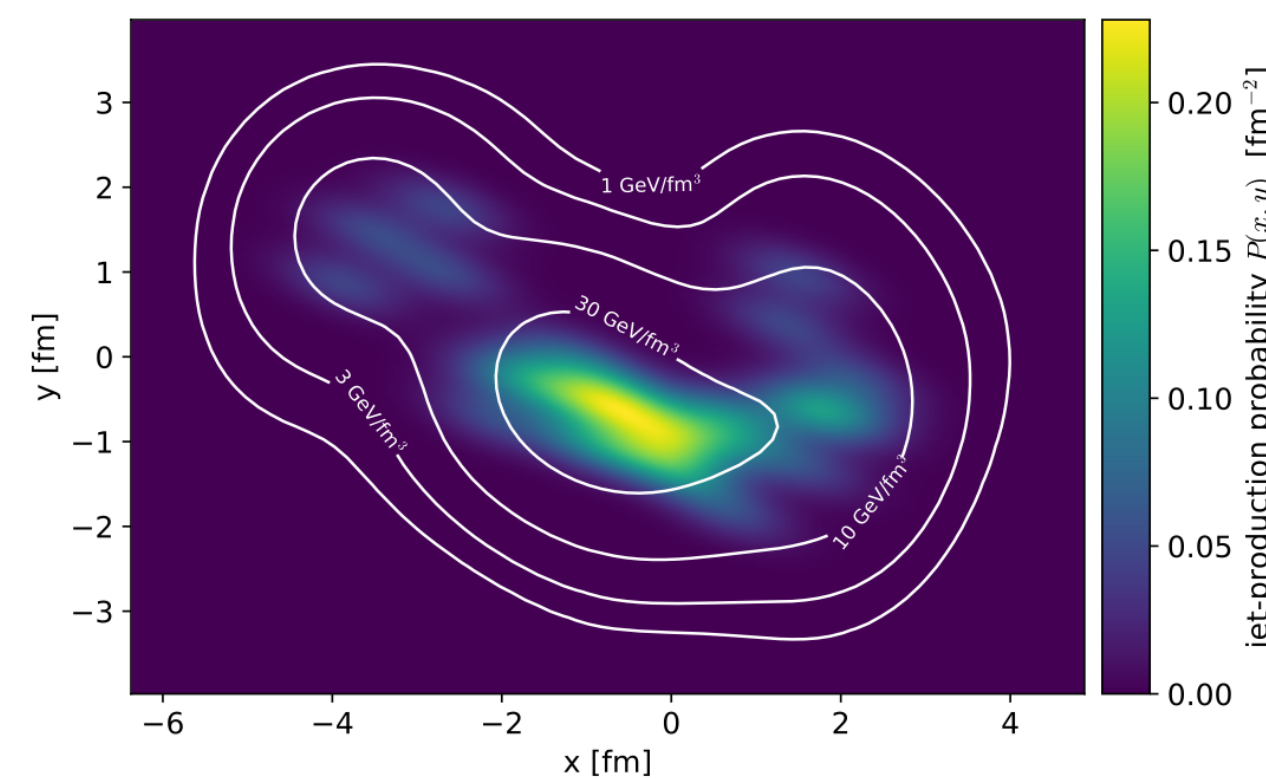
BINARY COLLISIONS

PYTHIA

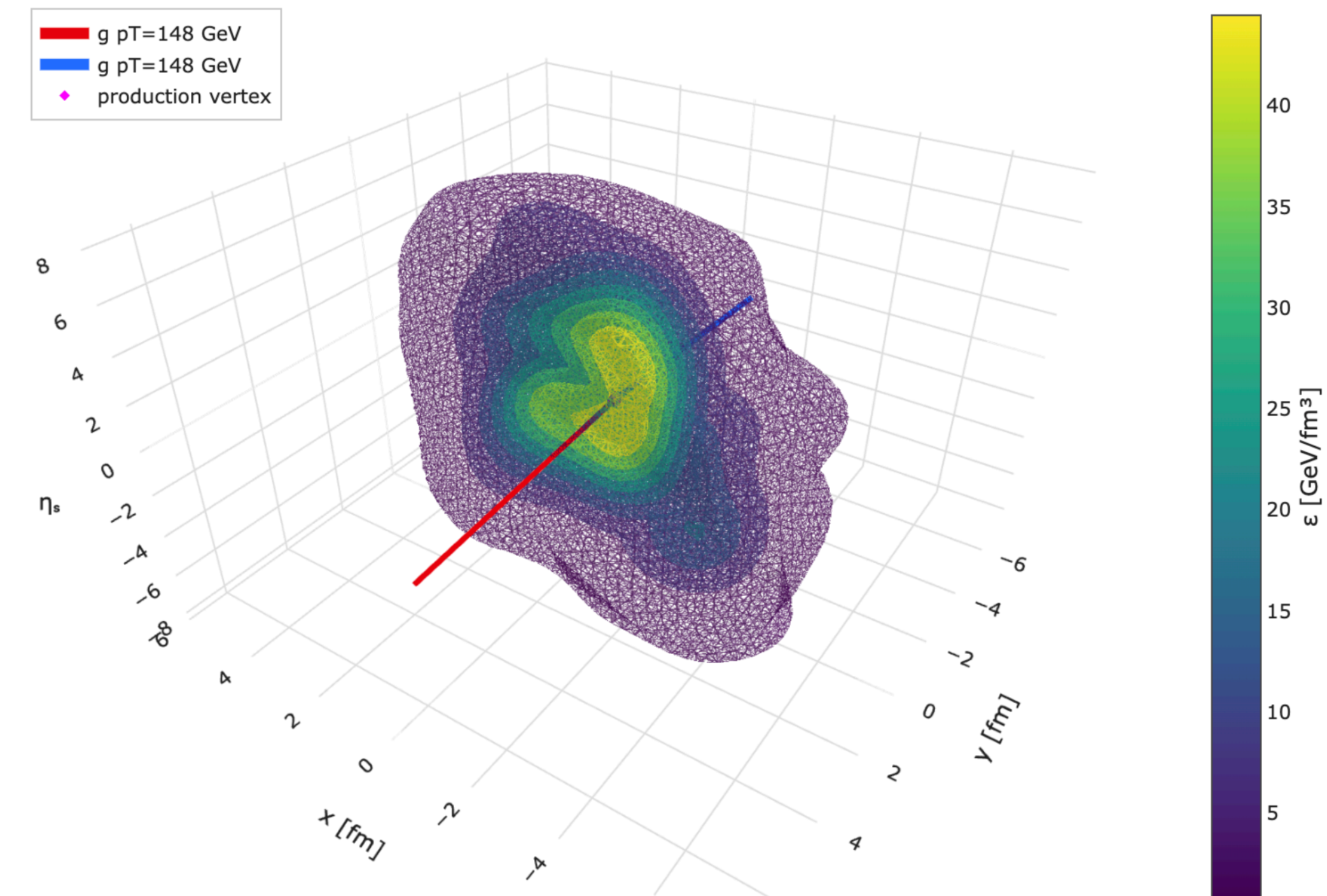
Jet momentum/composition



Jet position



$0 + 0 \sqrt{s_{NN}} = 5.36 \text{ TeV}$
 $0 - 5\%$



$$T^{\mu\nu}(x^1, x^2, x^3) = \sum_{i=\text{partons}} \frac{p_i^\mu p_i^\nu}{p_i^0} W_i(\vec{x}, \sigma_\perp, \sigma_3)$$

$$W(\vec{x}_i, \sigma_\perp, \sigma_3) = W(x_i^\perp, \sigma_\perp) W(x_i^3, \sigma_3)$$

Cubic spline with support σ_j

α -clustering nucleon distribution

Summerfield et al PRC 104 (2021) 4, L041901

BAYESIAN SETUP

PRIORS · FLAT

T_{fo}	130 – 170 MeV
N	100 – 200
η/s	0 – 0.3
σ	0.2 – 1.0 fm
τ	0.2 – 1.0 fm/c

DESIGN

200 design points
Centralities 0–5, 5–10, 20–30, 50–60%

OBSERVABLES

O + O · charged
M, $\langle pT \rangle$
 $v_2\{2\}$, $v_3\{2\}$
 $v_2\{4\} / v_2\{2\}$
Pb + Pb · charged
M, $\langle pT \rangle$
 $v_2\{2\}$, $v_3\{2\}$, $v_4\{2\}$
Pb + Pb · π , K, p
M, $\langle pT \rangle$

EMULATOR

PCA on the observable space
One GP per principal component
LOO cross-validation

SAMPLING

Parallel-tempered ensemble MCMC
→ joint posterior

SCOPE

5 parameters · 2 systems
4 centrality classes

JET SETUP

	Parameter	Value
Initial state	normalization N	190
	nucleon width w	0.3 fm
Hydrodynamics	initial time τ_0	0.6 fm/ c
	shear η/s (constant)	0.08
Jets	jets per event	4×10^5
	events per centrality	1100
	angular sampling bins	30

JET-MEDIUM SIMULATIONS SETUP

	Parameter	Value
Initial state	normalization K	0.749
	transverse smearing σ_r	1.25 fm
	longitudinal smearing σ_η	1.40
	initial time τ_0	0.4 fm/ c
Shear	η/s (constant)	0.14
Bulk	$\zeta/s = A (1/3 - c_s^2)^p$	$A = 1.4, p = 2$
Freeze-out	energy density e_{fo}	0.257 GeV/fm ³