Constraining models of initial conditions with flow data

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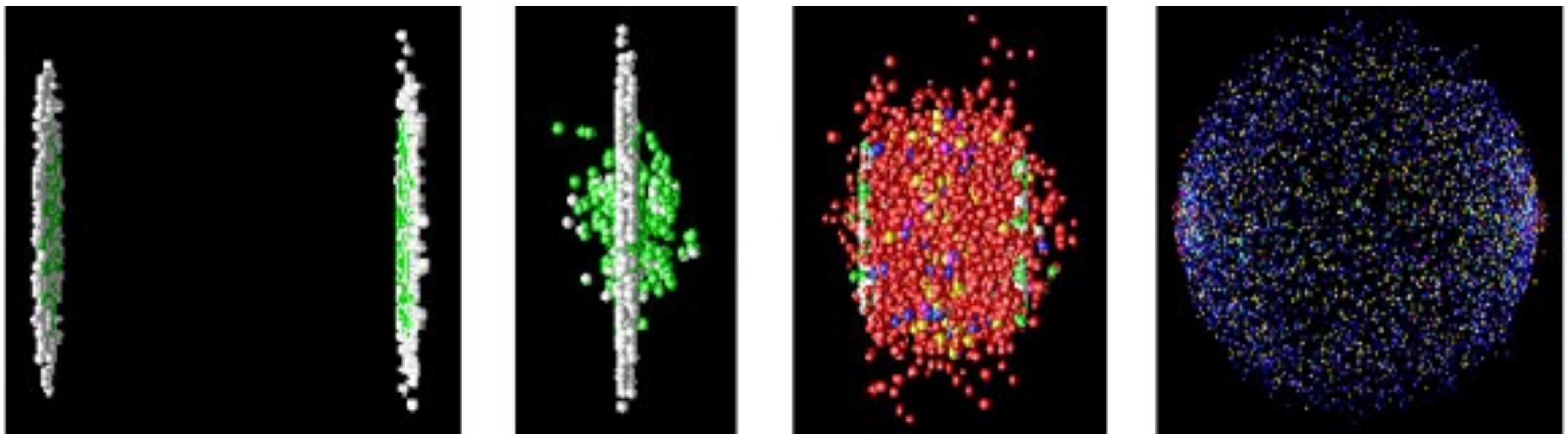
http://ipht.cea.fr

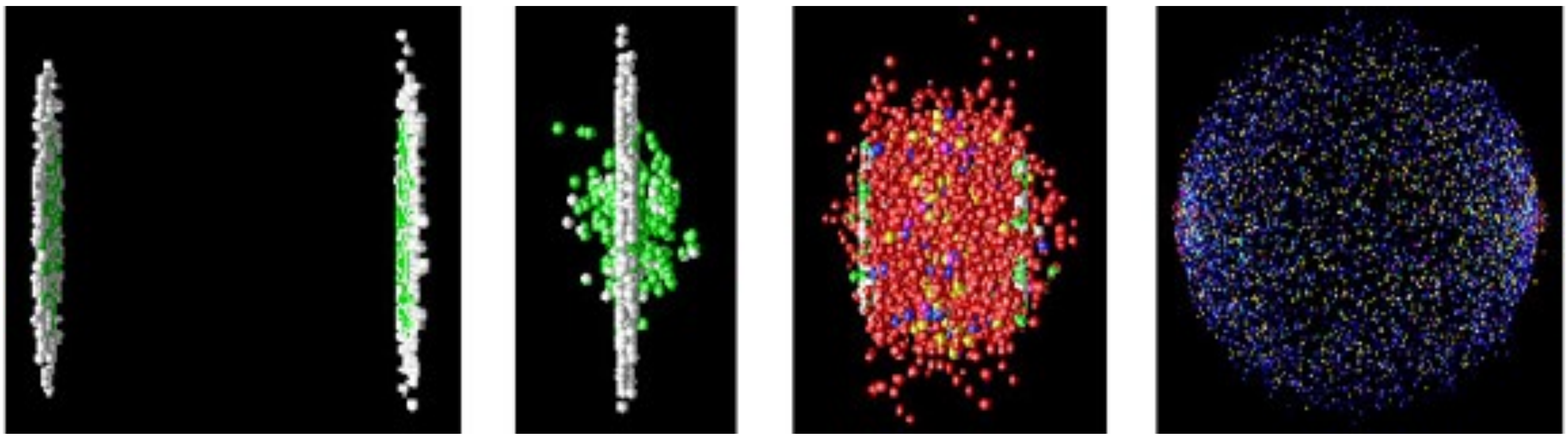
based on: Retinskaya Luzum JYO, 1311.5339

Ultrarelativistic nucleus-nucleus collisions



1. Initial conditions

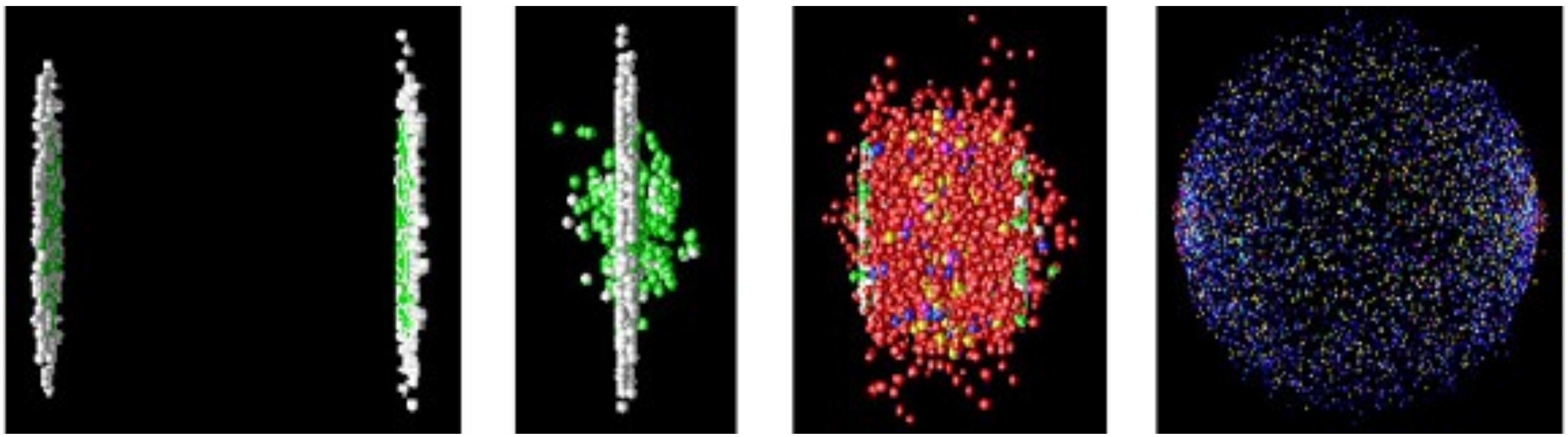
Ultrarelativistic nucleus-nucleus collisions



1. Initial conditions

2. Hydrodynamic expansion

Ultrarelativistic nucleus-nucleus collisions

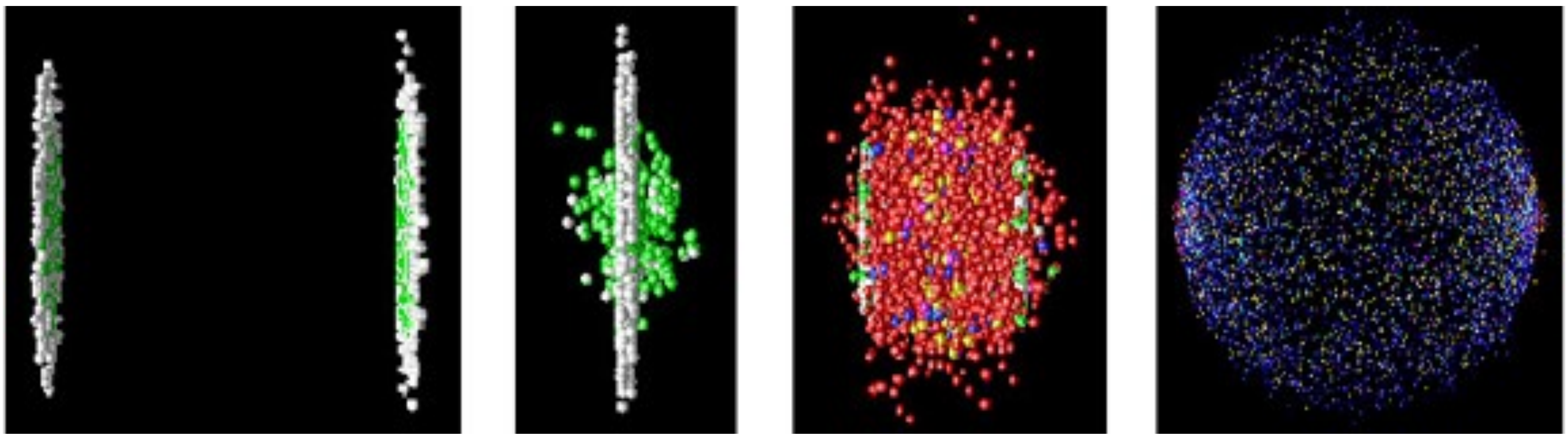


1. Initial conditions

2. Hydrodynamic expansion

3. Particles $\rightarrow$ detectors

Ultrarelativistic nucleus-nucleus collisions



1. Initial conditions

2. Hydrodynamic expansion

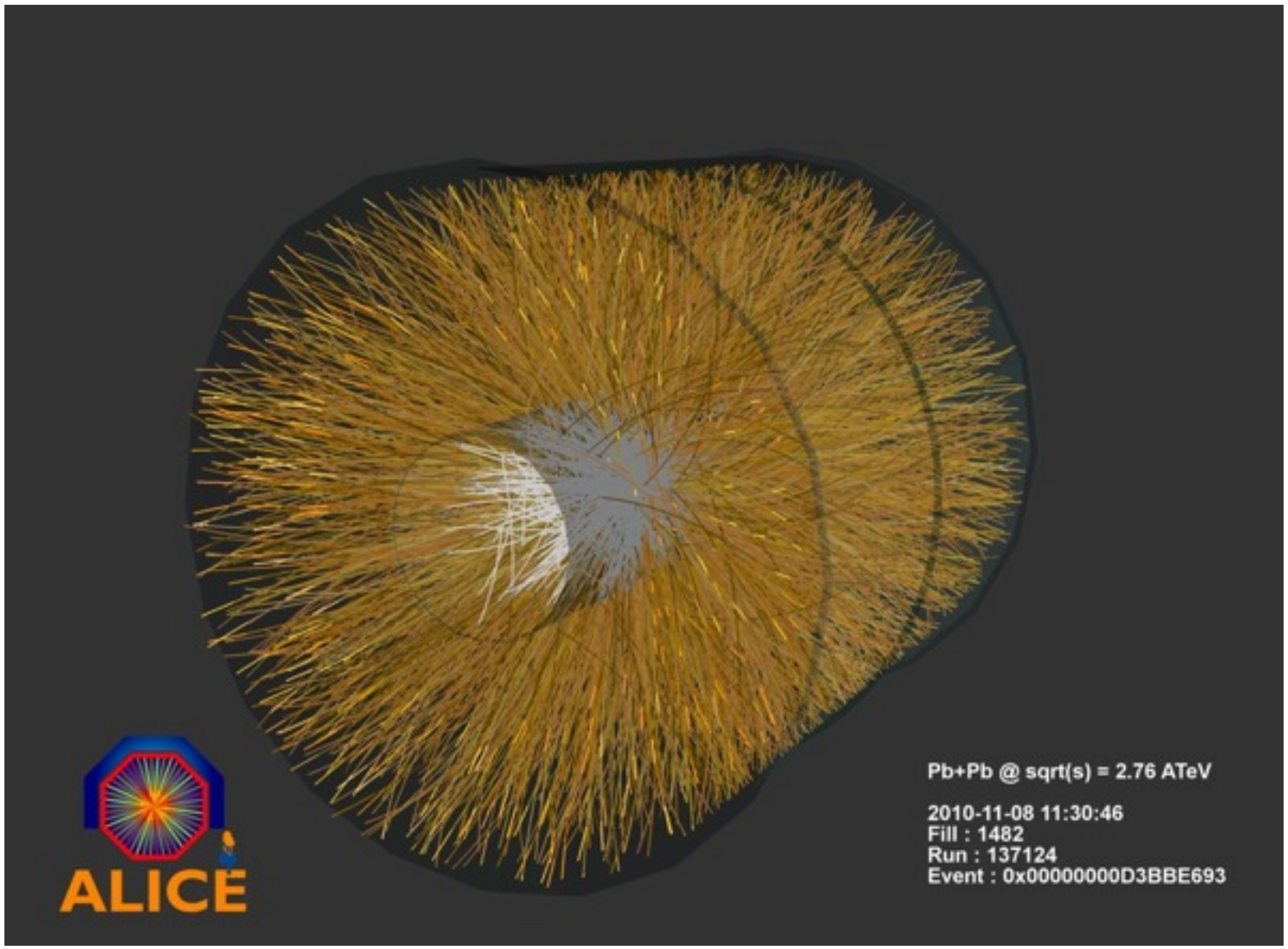
3. Particles → detectors

Goal: constrain models of initial conditions from data

Outline

- Observables: correlations and *how we understand them as anisotropic flow*
- Anisotropic flow as a hydrodynamic response to the initial geometry
- Systematic method for constraining models of initial conditions
- Results for RHIC and LHC

What we see: (1) particles



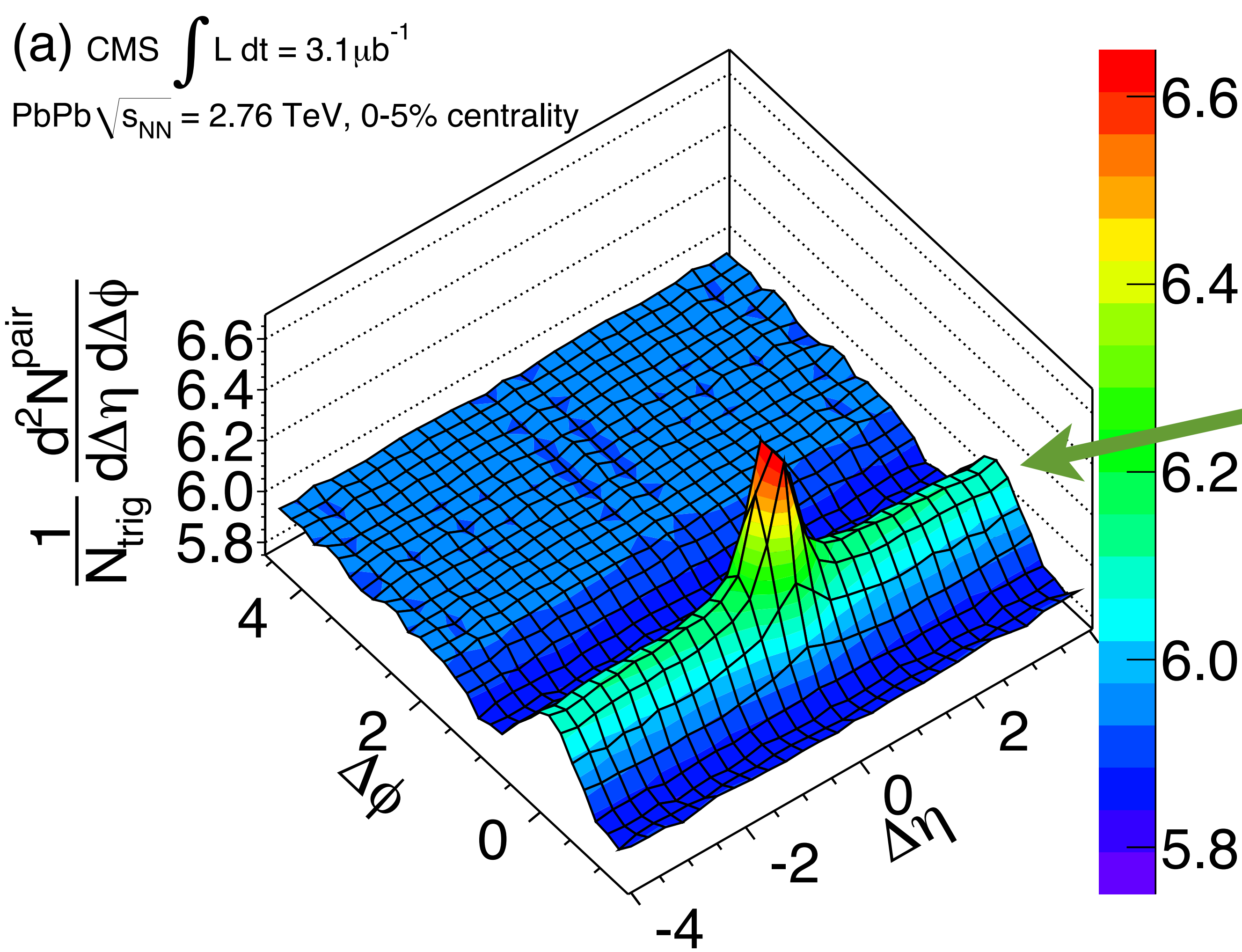
Trajectories of charged particles:

polar angle θ
(or pseudorapidity η=-ln tan θ/2)

azimuthal angle ϕ

What we see: (2) correlations

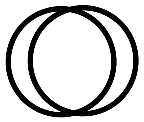
Number of pairs of particles versus relative azimuthal angle and pseudorapidity in central Pb-Pb collisions at LHC



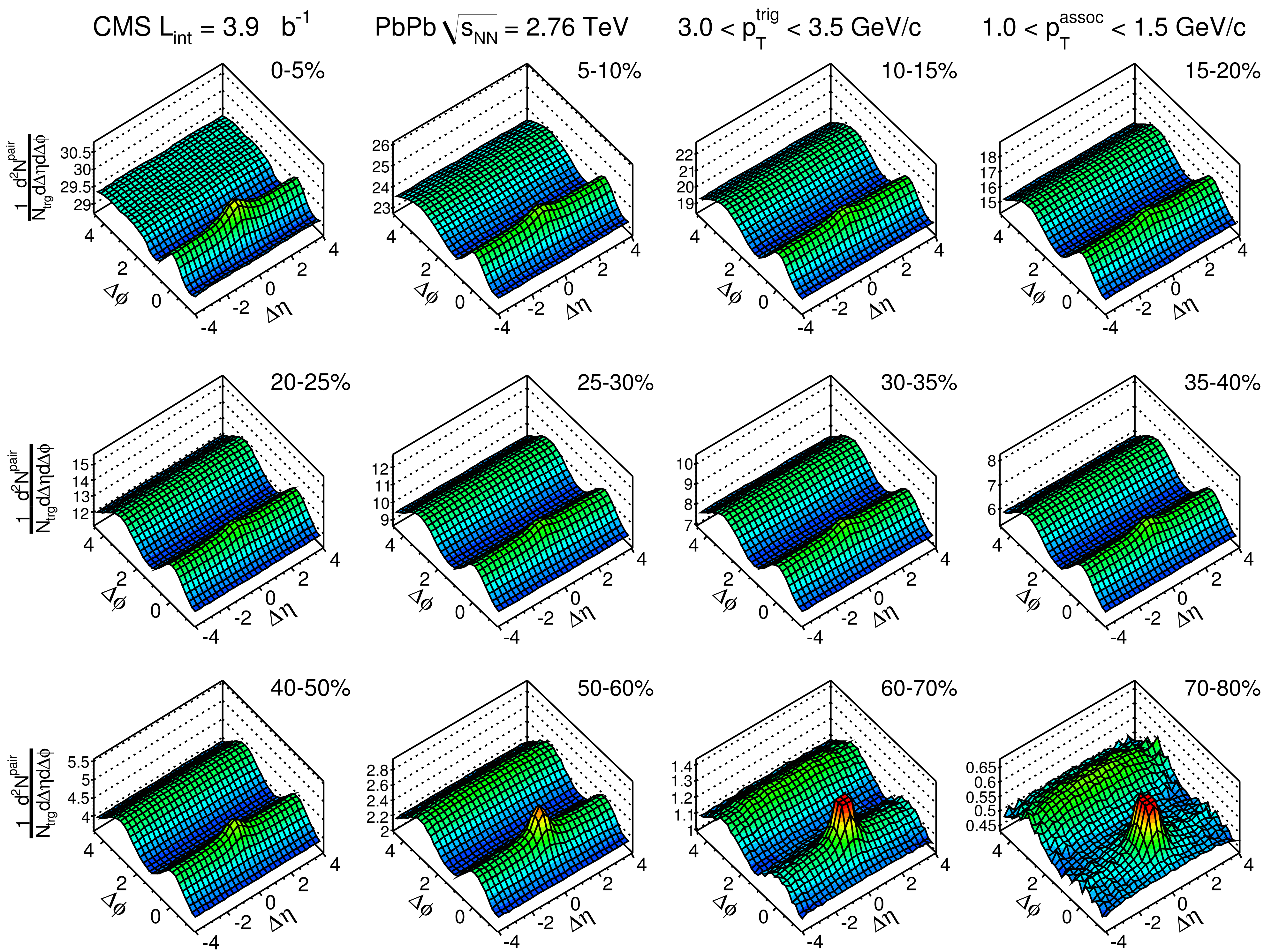
CMS 1105.2438

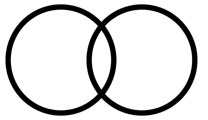
- Characteristic wave structure of long-range correlations
- *Current theory status:* particles emitted independently with probability depending on *azimuth,* not on rapidity.

Central to peripheral collisions



central





peripheral

CMS 1201.3158

Anisotropic flow

- All information is contained in the single-particle momentum distribution, in particular the azimuthal (ϕ) distribution

$$dN/d\phi=\sum_n V_n e^{in\phi}$$

- $V_n \equiv$ anisotropic flow
  $V_2 \equiv$ ***elliptic flow****: largest Fourier harmonic*
  $V_3 \equiv$ ***triangular flow****: next-to-largest*

- The observed pair correlation is the convolution of two single-particle distributions, averaged over initial geometries: $\langle \cos n\Delta\phi \rangle = \langle |V_n|^2 \rangle$

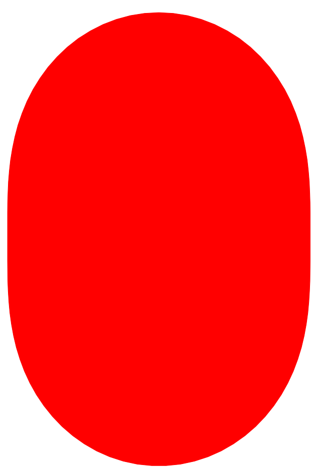
Hydro calculations

- Use some model for the initial density profile
- Solve relativistic hydrodynamics using this initial condition (involves equation of state & viscosity)
- Transform the continuous fluid into discrete, independent particles, and compute V_n

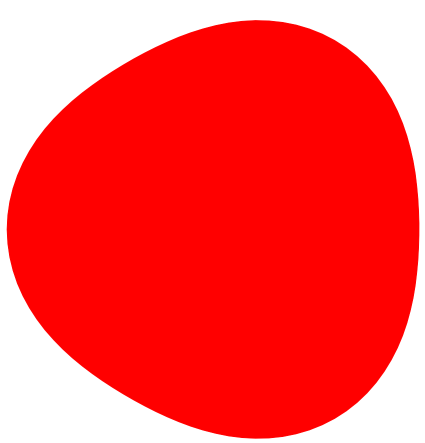
Symmetries and flow

Initial profile

Final distribution



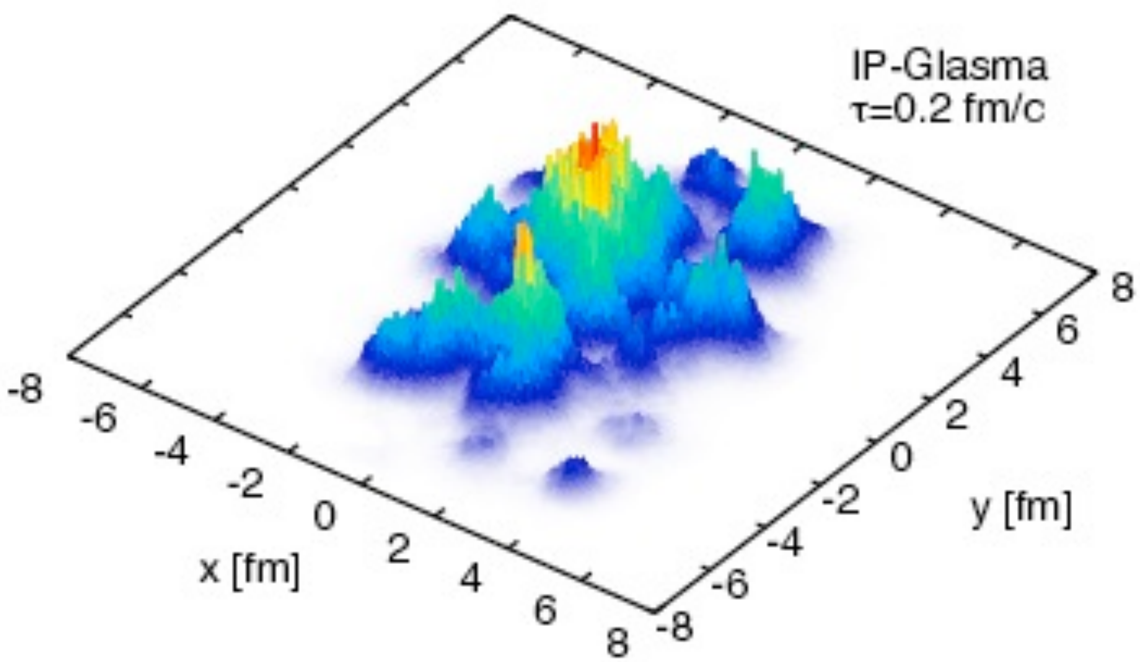
$\phi \to \phi + \pi$ symmetry: only V_2, V_4, V_6



$\phi \to \phi + 2\pi/3$ symmetry: only V_3, V_6

From initial anisotropies to anisotropic flow

A particular Monte-Carlo model typically predicts in every event an irregular initial transverse density profile $\rho(x,y)$



Gale Jeon Schenke 1301.5893

Fourier transform $\rho(x,y)$:

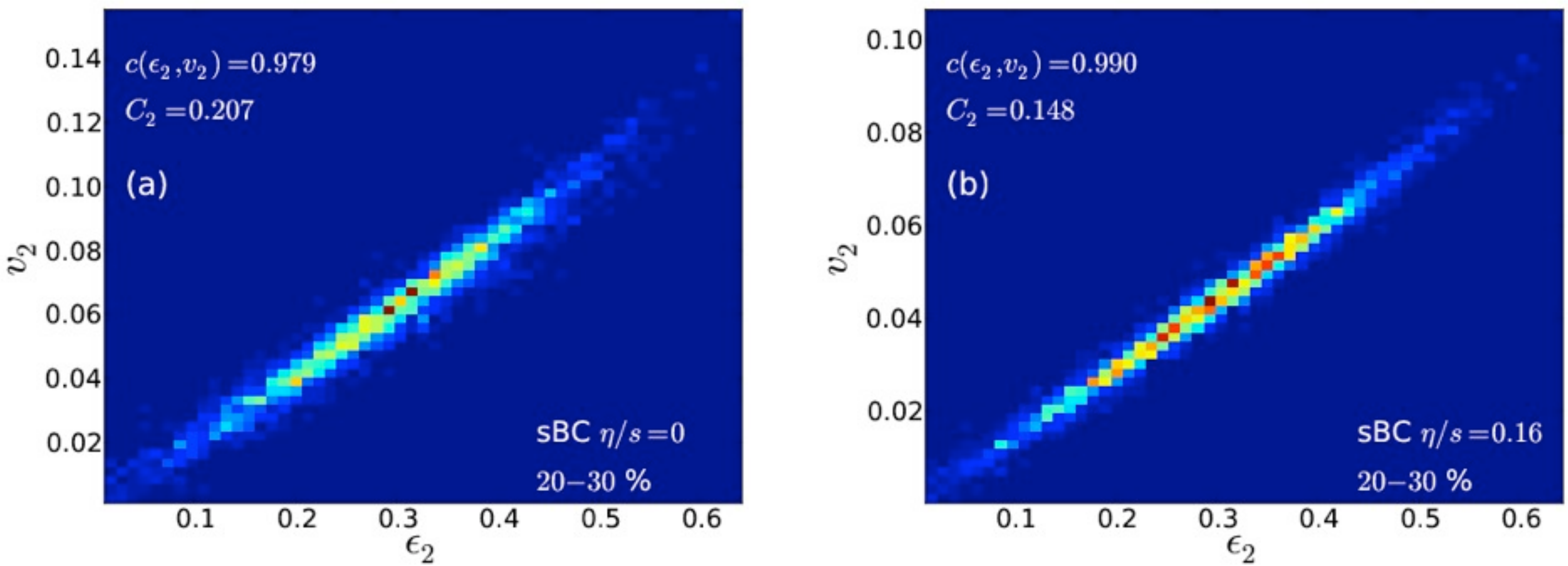
$$\varepsilon_n \equiv \frac{\int r^n e^{in\phi} \rho(r,\phi) r dr d\phi}{\int r^n \rho(r,\phi) r dr d\phi}$$

$\varepsilon_2 \equiv$ initial *eccentricity*

$\varepsilon_3 \equiv$ initial *triangularity*

By symmetry, one expects that v_n scales *approximately* like ε_n

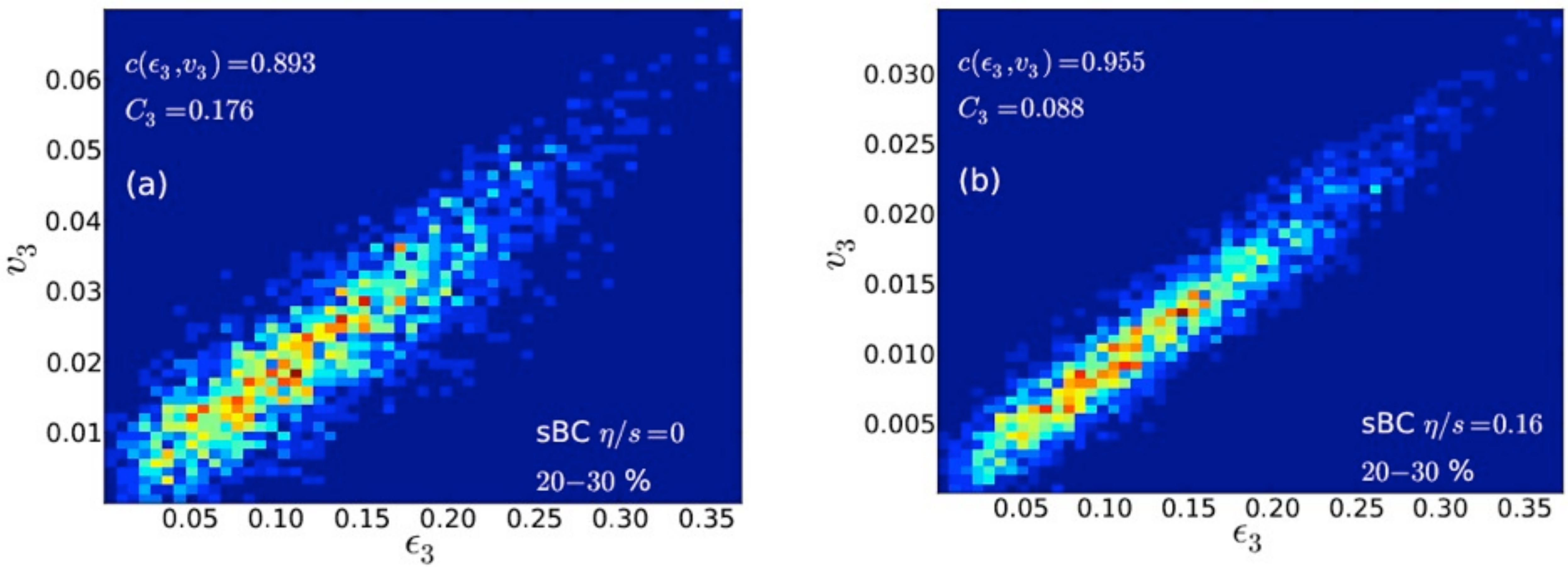
Elliptic flow v_2 versus initial eccentricity ε_2



Niemi Denicol Holopainen Huovinen 1212.1008

v_2 is almost perfectly linear in ε_2

Triangular flow v_3 versus initial triangularity ε_3



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v_3 is also strongly correlated with ε_3

Linear-response hydro

$$v_2 \approx C_2\ \varepsilon_2$$

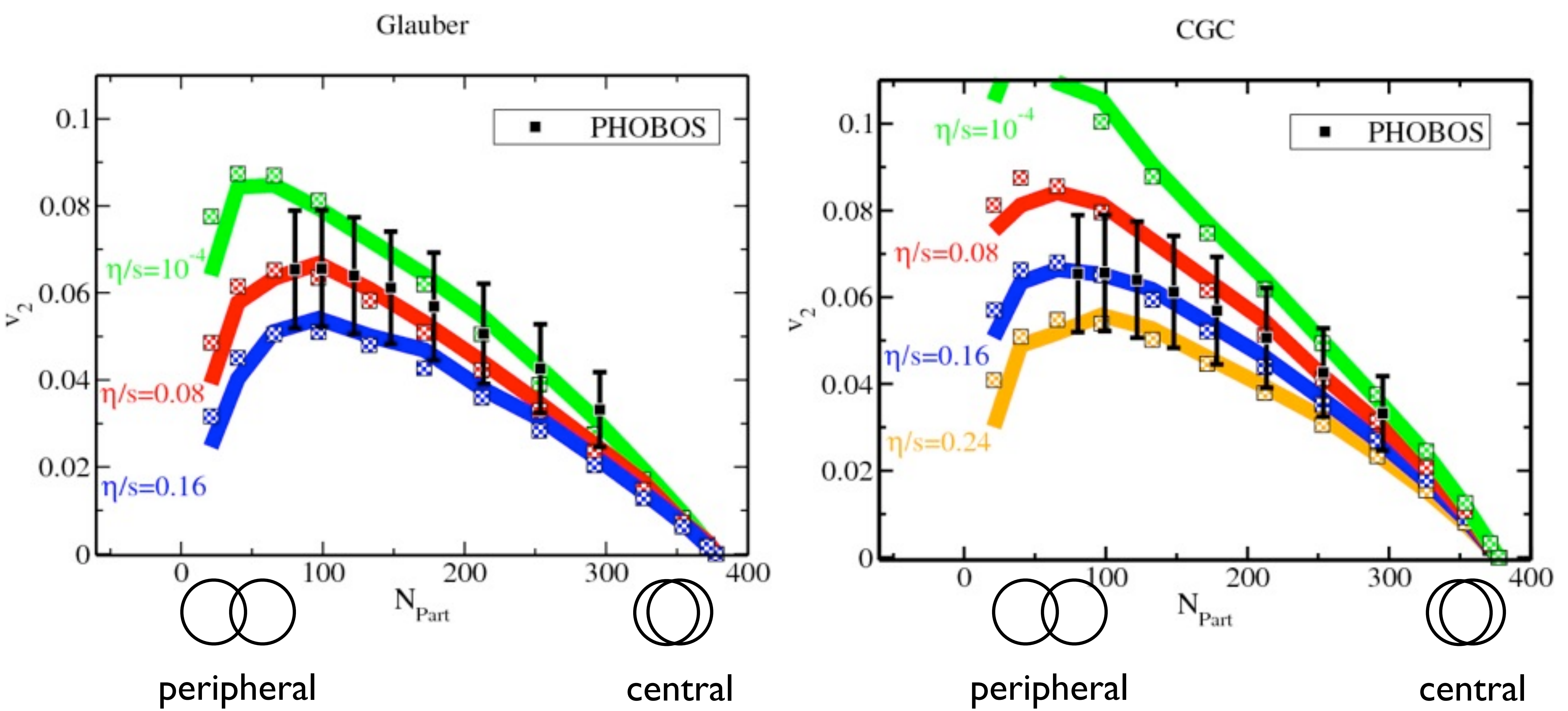
$$v_3 \approx C_3\ \varepsilon_3$$

Is a good approximation to the numerical solution of hydrodynamics with an arbitrary initial profile

Relates the initial profile to the measured flow through a hydrodynamic response which decreases with viscosity

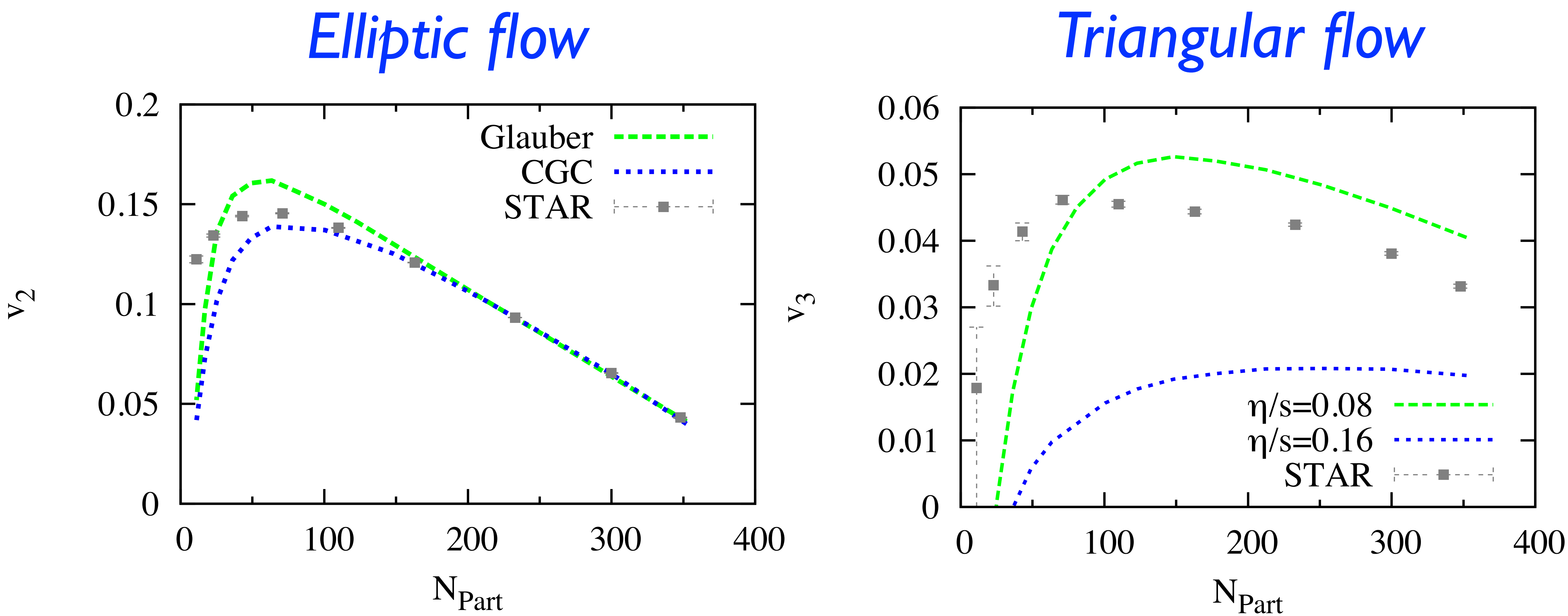
Viscous hydro versus RHIC data

Luzum Romatschke 0804.4015



Two different models of initial conditions reproduce v_2 data equally well, at the expense of tuning the viscosity

Combining v_2 and v_3, one can rule out models of initial conditions



Alver Gombeaud Luzum JYO 1007.5469

Once the viscosity is adjusted to match v_2, some models of initial conditions reproduce v_3 data, ***others don't***.

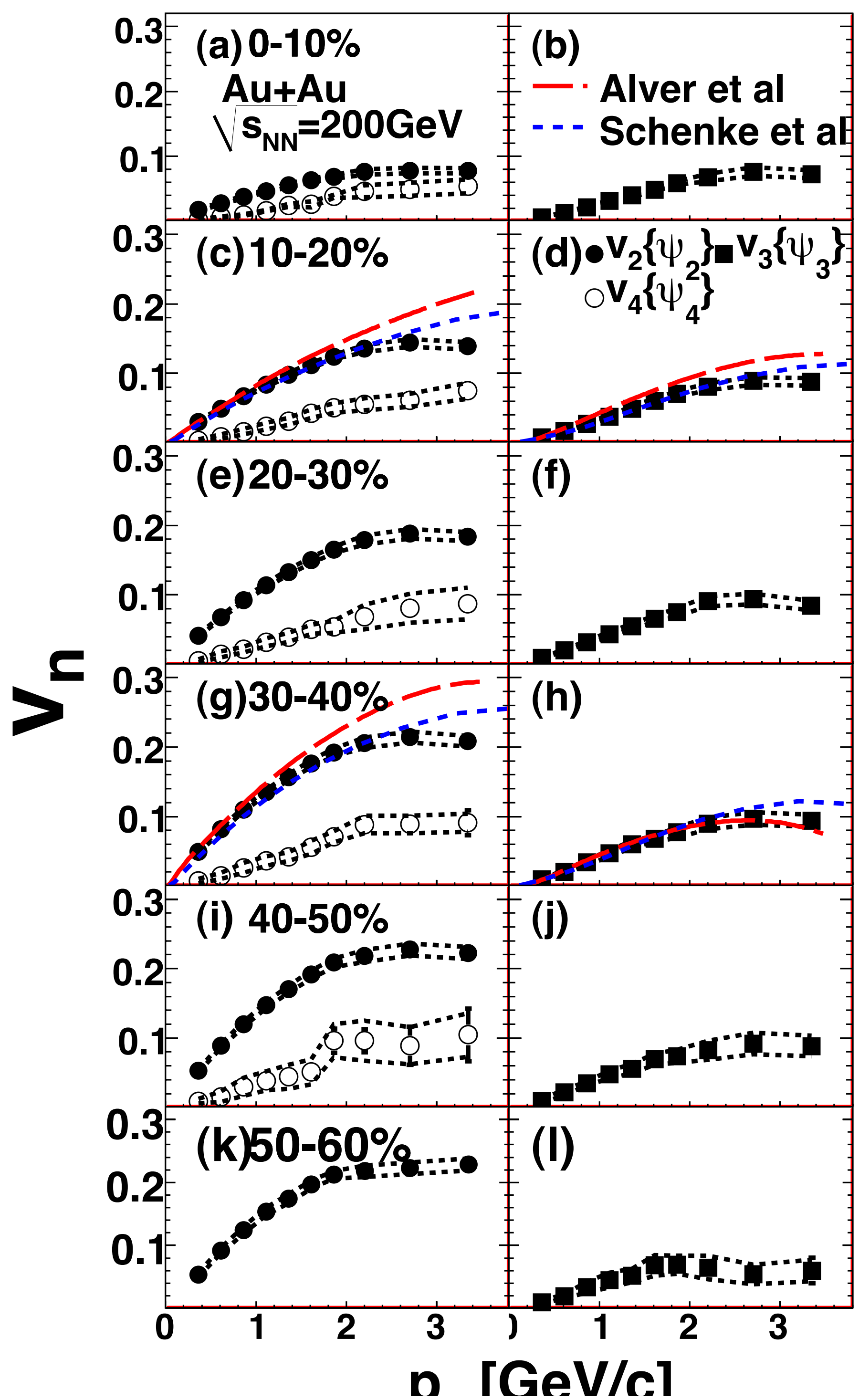
Systematic test of initial-state models

- We just invert the linear response:

$$\varepsilon_2 \approx v_2/C_2$$
$$\varepsilon_3 \approx v_3/C_3$$

- Take v_2, v_3 from measurements at RHIC and LHC
- Compute C_2, C_3 using viscous hydrodynamics
- Carefully estimate the uncertainty on C_2, C_3 by varying arbitrary parameters in the hydro calculation
- Obtain the allowed area in the (ε_2,ε_3) plane
- Compute (ε_2,ε_3) for several initial-state models, see if they fall within allowed area.

RHIC (200 GeV) & LHC (2.76 TeV) data



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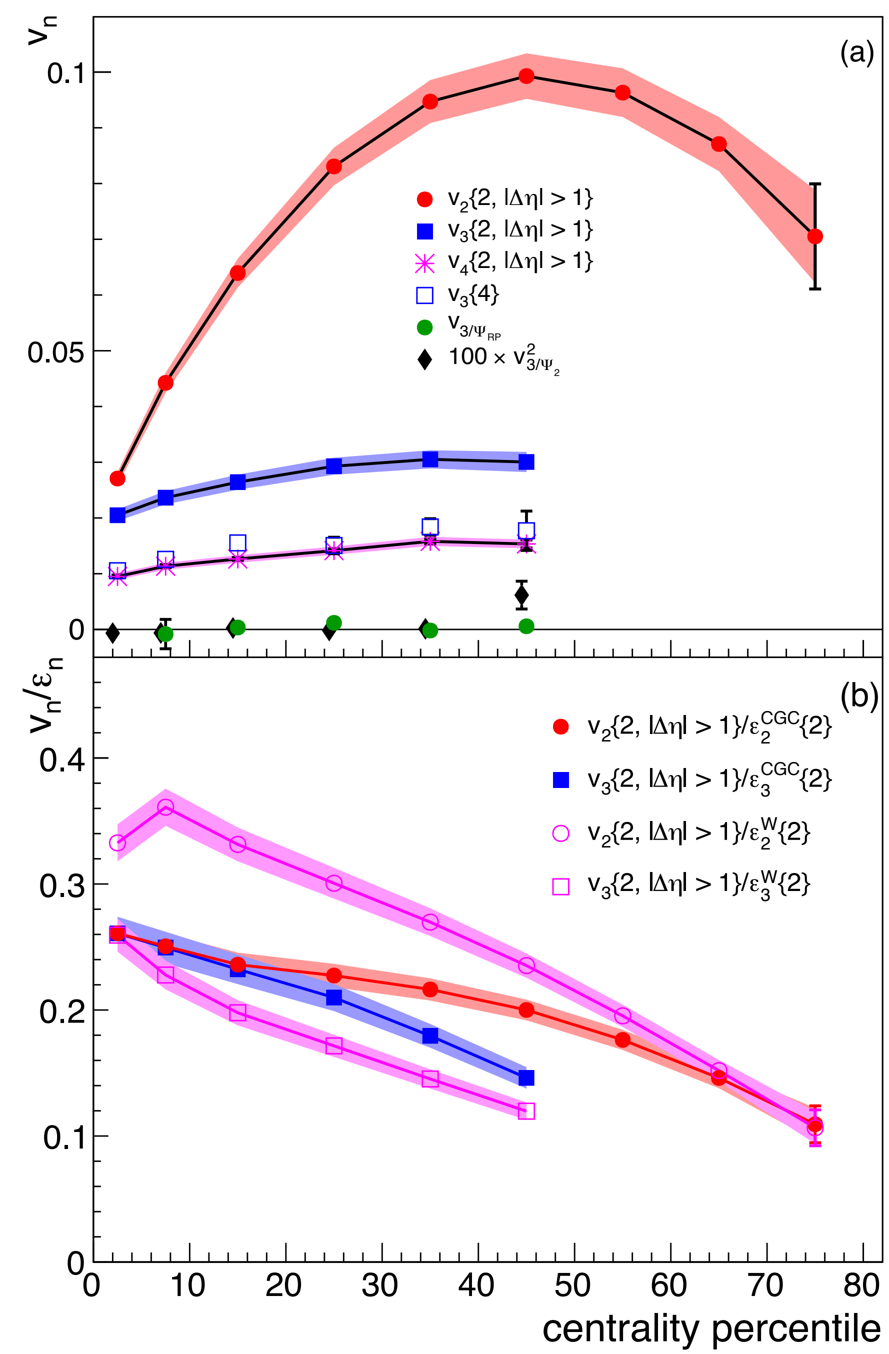


ALICE 1105.3865

Data: technical details

- Experiments measure all charged hadrons, each with its own kinematic cuts (in centrality, p_t, η, $\Delta\eta$).
- Data are averaged over *many* events. Averages of v_2, v_3 are rms averages, therefore our results for ε_2, ε_3 also pertain to rms averages: $\sqrt{\langle(\varepsilon_2)^2\rangle}$, $\sqrt{\langle(\varepsilon_3)^2\rangle}$.

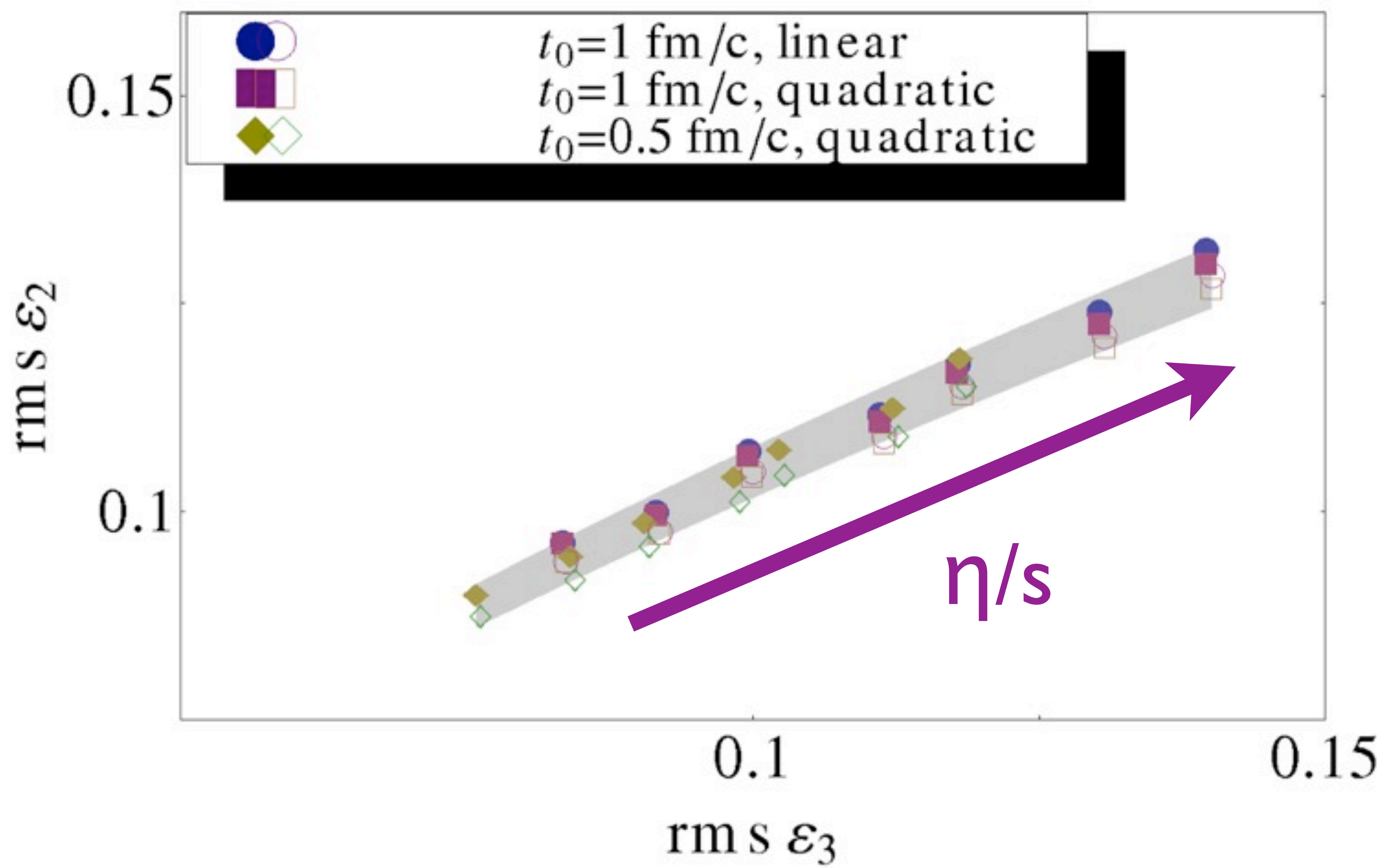
Hydro: technical details

- We use the 2+1d viscous hydro by
  Romatschke & Romatschke 0706.1522
- Smooth initial conditions (e.g. optical Glauber for v_2, deformed optical Glauber for v_3)
- Initial temperature and freeze-out temperature adjusted to match observed multiplicity and $\langle p_t \rangle$
- After freeze-out, hadronic decays but no rescattering.

Sources of uncertainty

- Viscosity over entropy ratio η/s
- Initial time (~initial flow)
- Initial profile: we compute ε_n with entropy density and energy density weighting.
- Viscous (=off-equilibrium) correction to the momentum distribution at freeze-out (linear vs. quadratic ansatz).

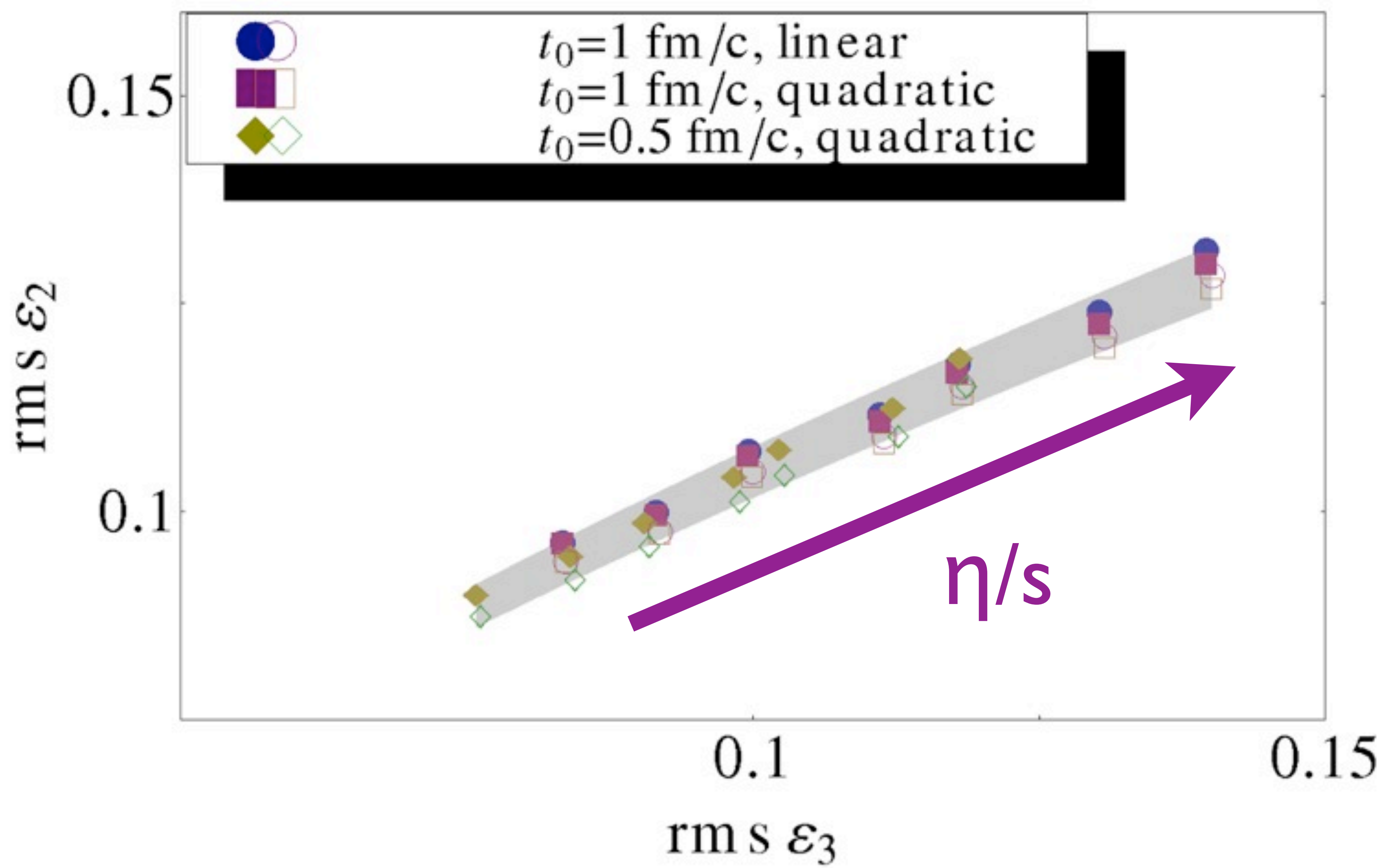
Uncertainties in the hydro response
(central Pb-Pb at LHC)



Each symbol = different hydro calculation → uncertainty band

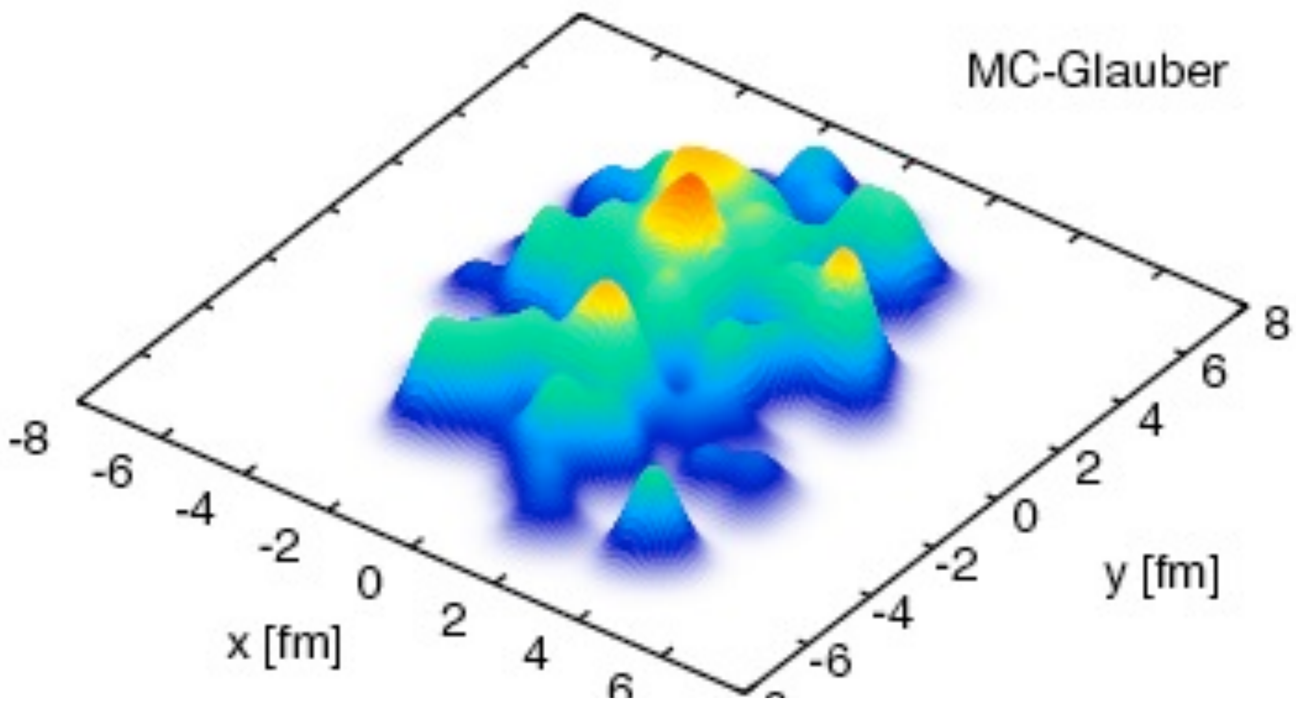
Uncertainties in the hydro response

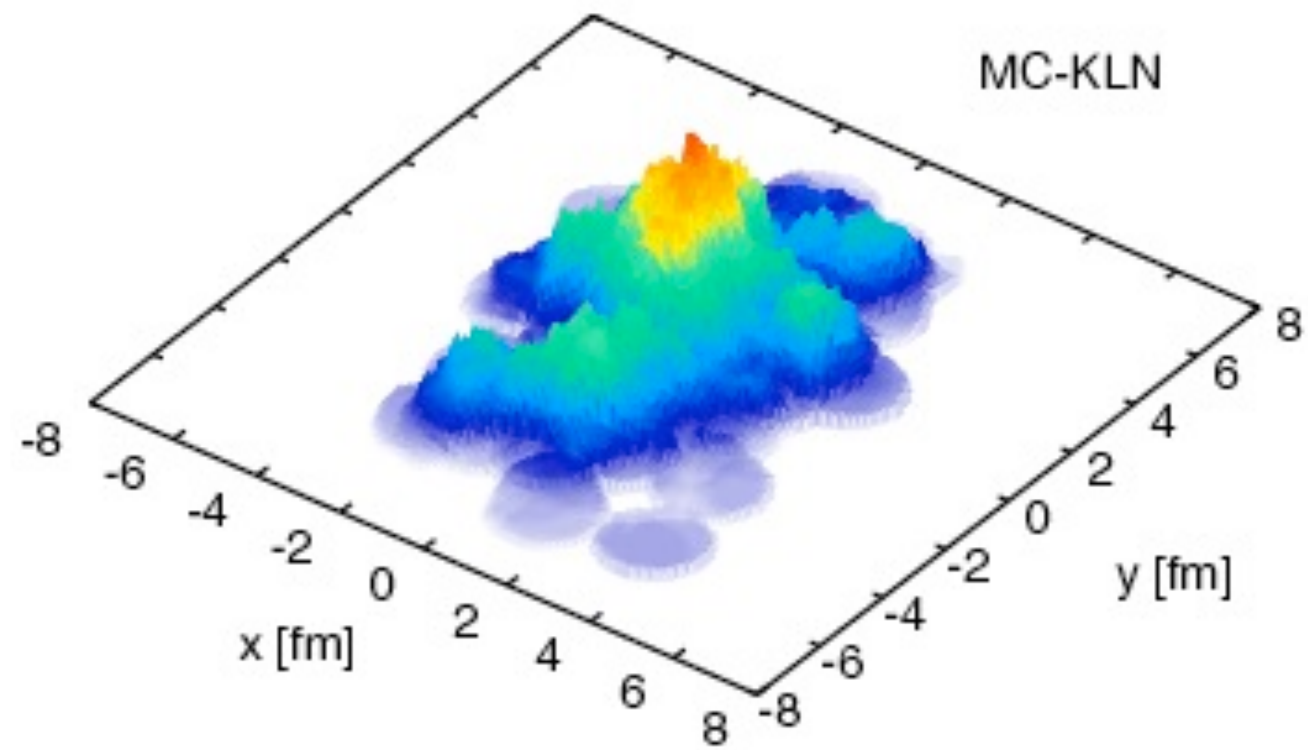
(central Pb-Pb at LHC)

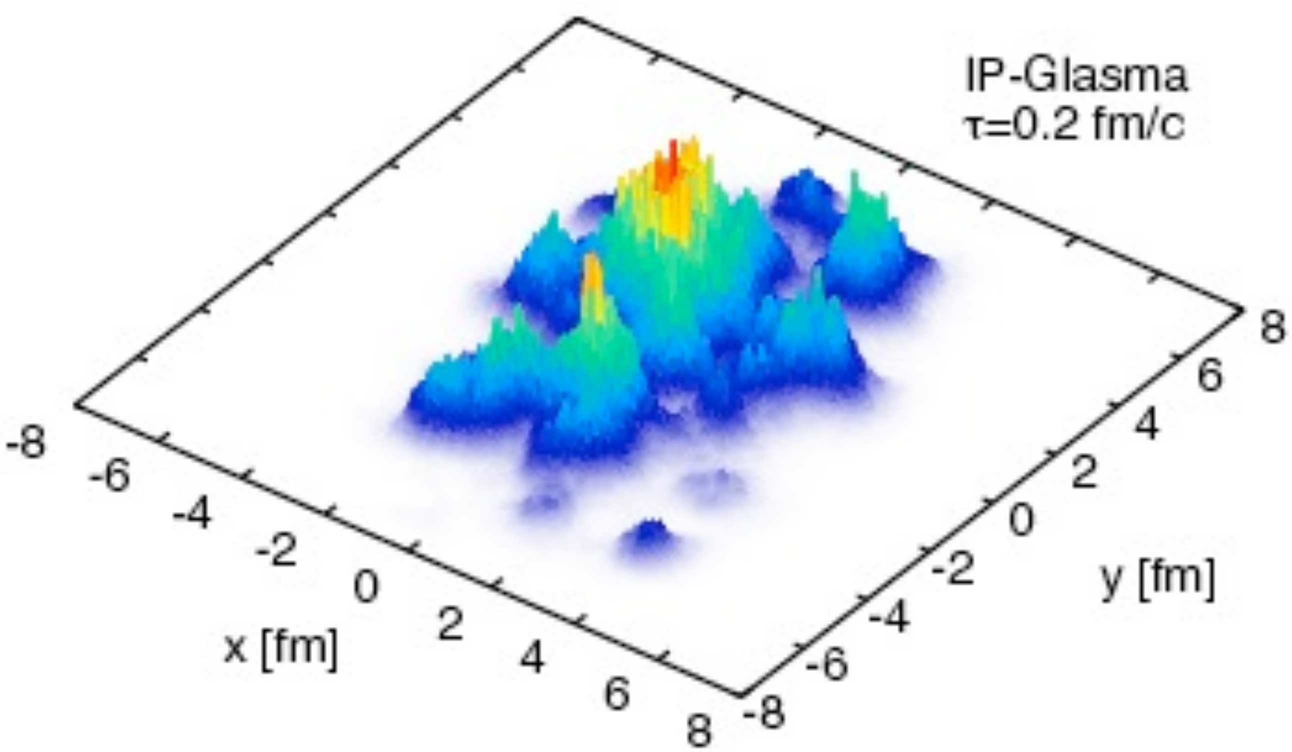


Allowed band: $\varepsilon_2/(\varepsilon_3)^{0.6} \approx$ constant

Initial-state models







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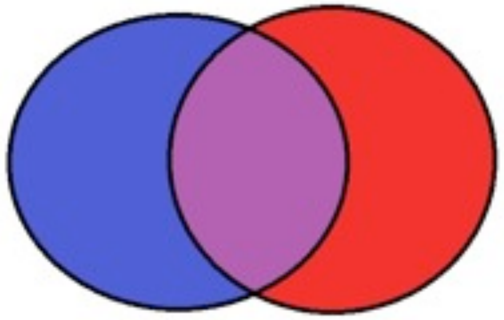
Initial-state models

- What matters here is not the detailed structure, but just:
- $\varepsilon_2 \sim$ eccentricity of the overlap area
- $\varepsilon_3 \sim$ magnitude of fluctuations



Initial-state Monte-Carlo models

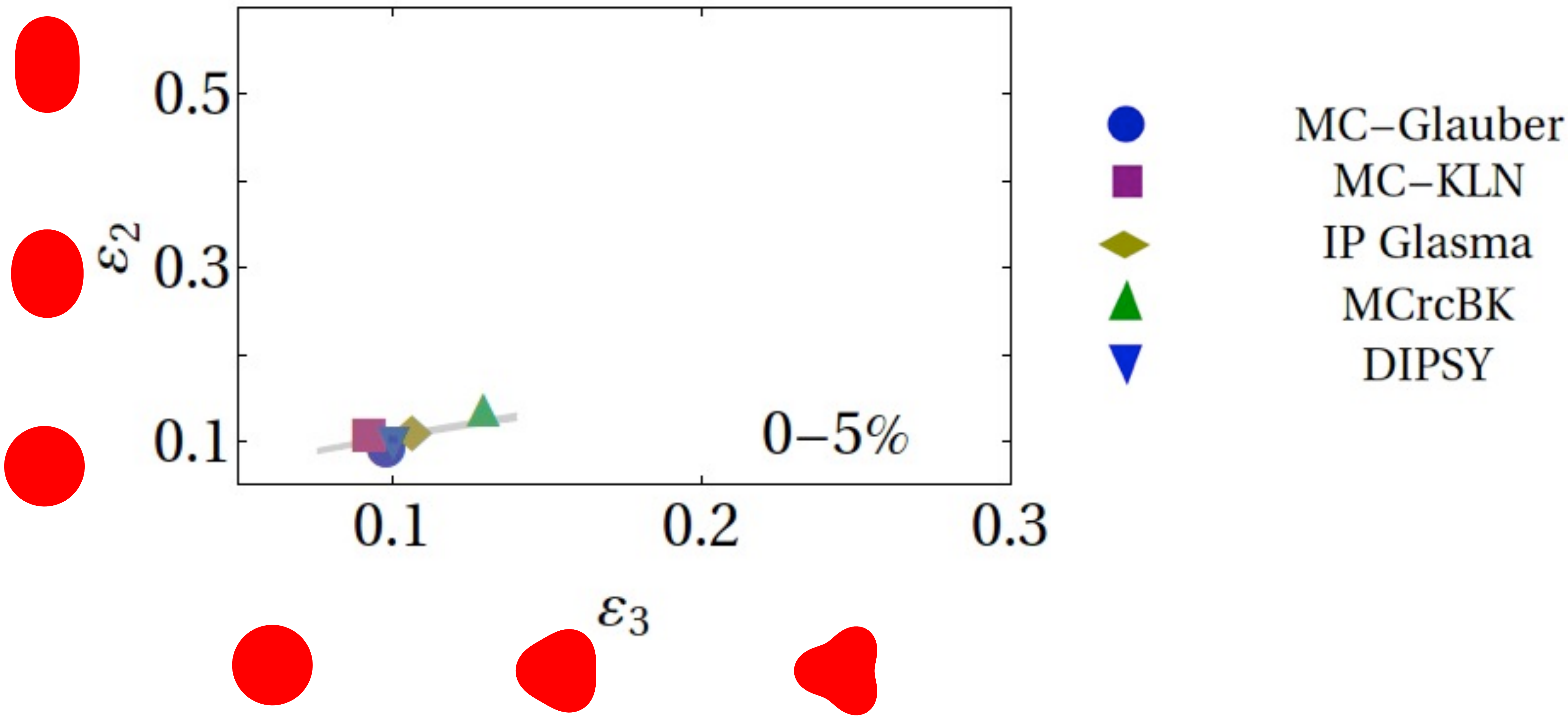
- MC-Glauber: energy typically localized around participant nucleons.
- QCD-inspired models: generally predict larger ε_2.

  Lappi Venugopalan nucl-th/0609021

  Hirano et al nucl-th/0511046

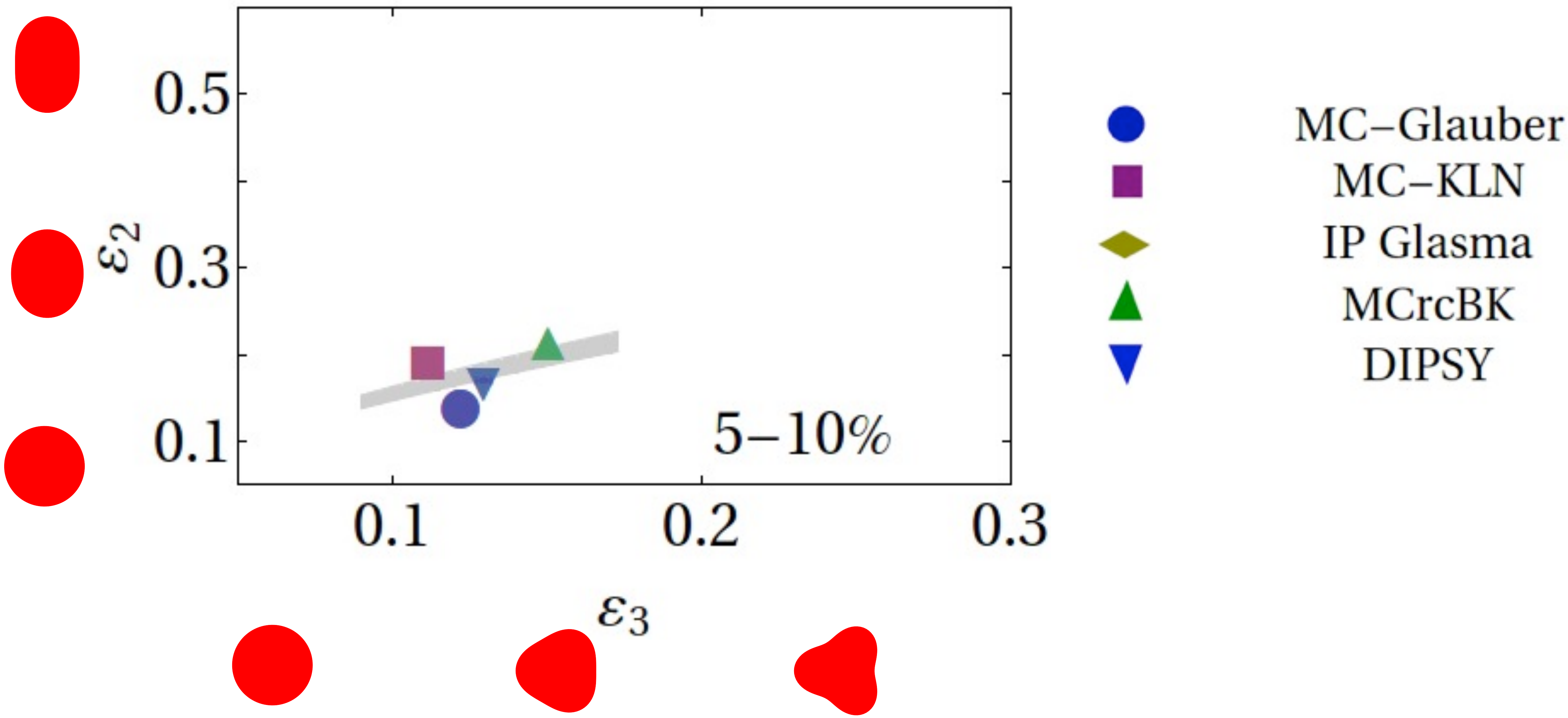
- Several QCD-inspired models:
  - MC-KLN (aka CGC) *Drescher Nara nucl-th/0611017*
  - MC-rcBK *Albacete Dumitru 1011.5161*
  - IP-Glasma *Schenke Tribedy Venugopalan 1202.6646*
  - DIPSY *Flensburg 1108.4862*

Constraining initial-state models at LHC



Constraining initial-state models at LHC

Strong increase of ε_2 driven by geometry of overlap area
Mild increase of ε_3 driven by decrease in system size $\propto 1/\sqrt{N}$



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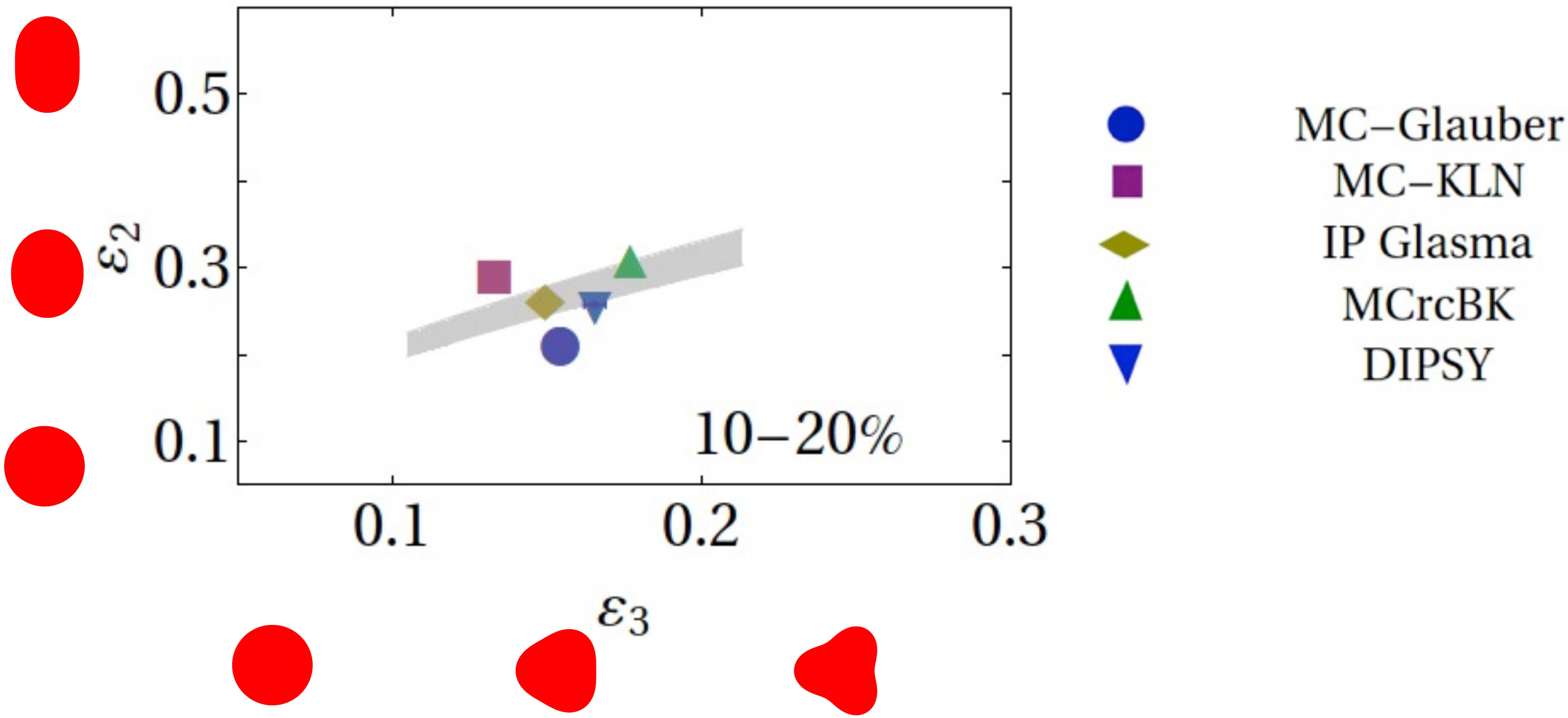

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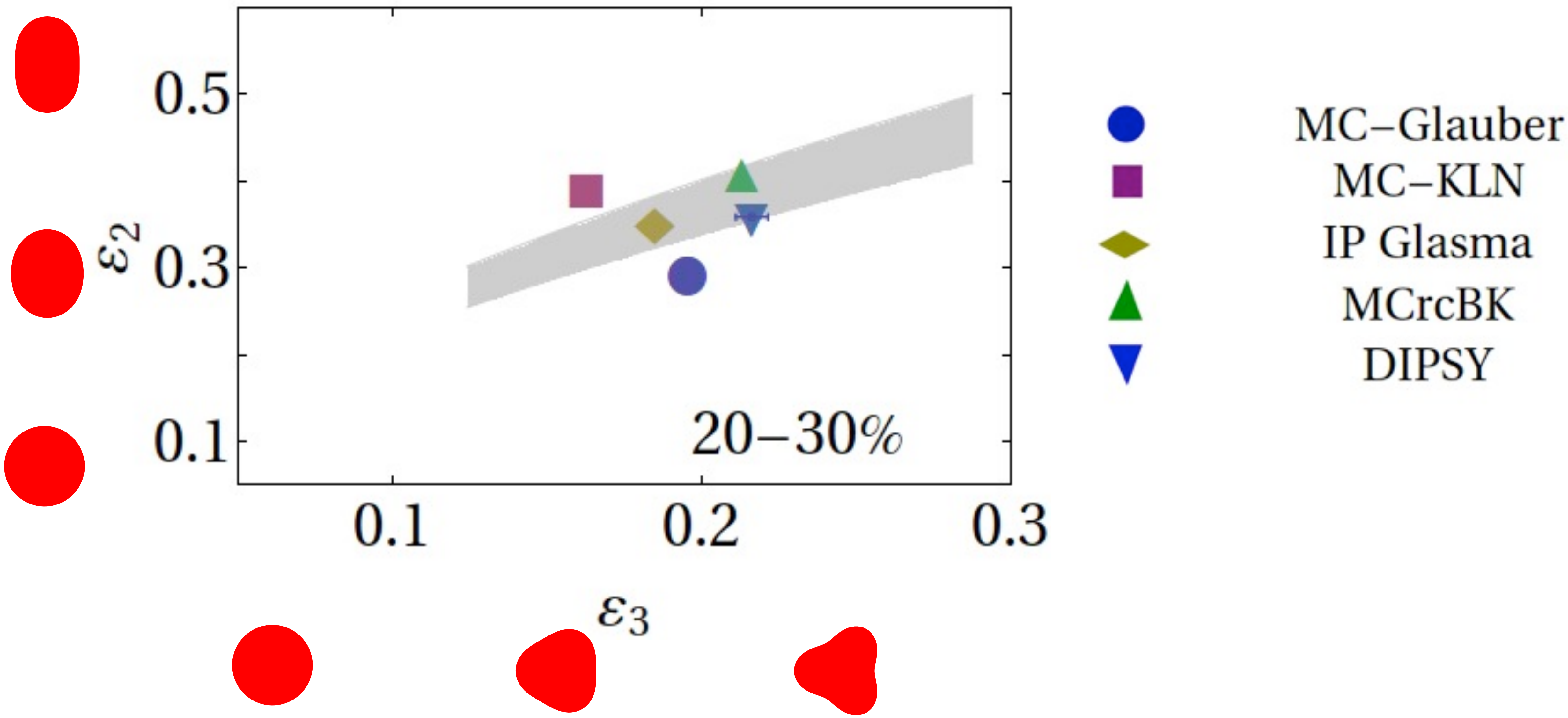

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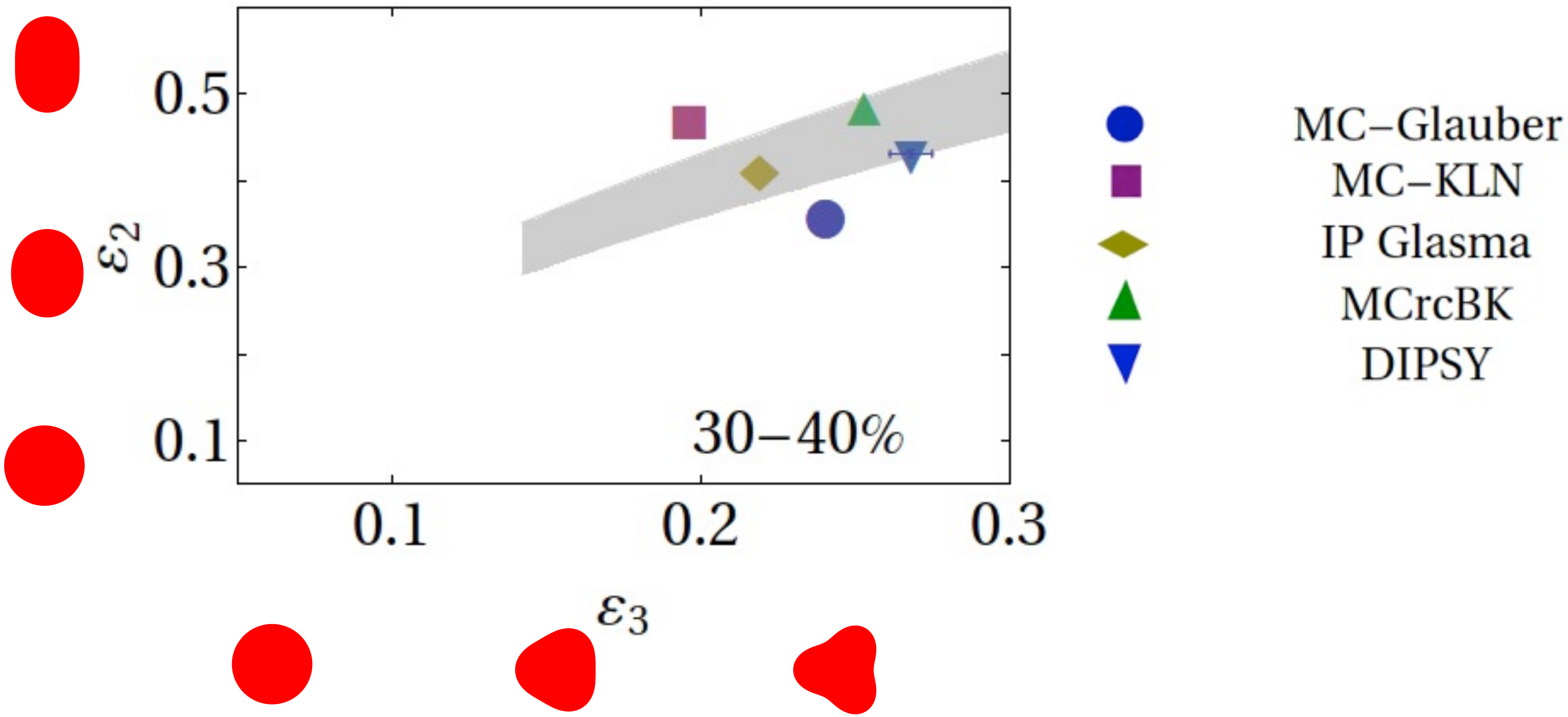

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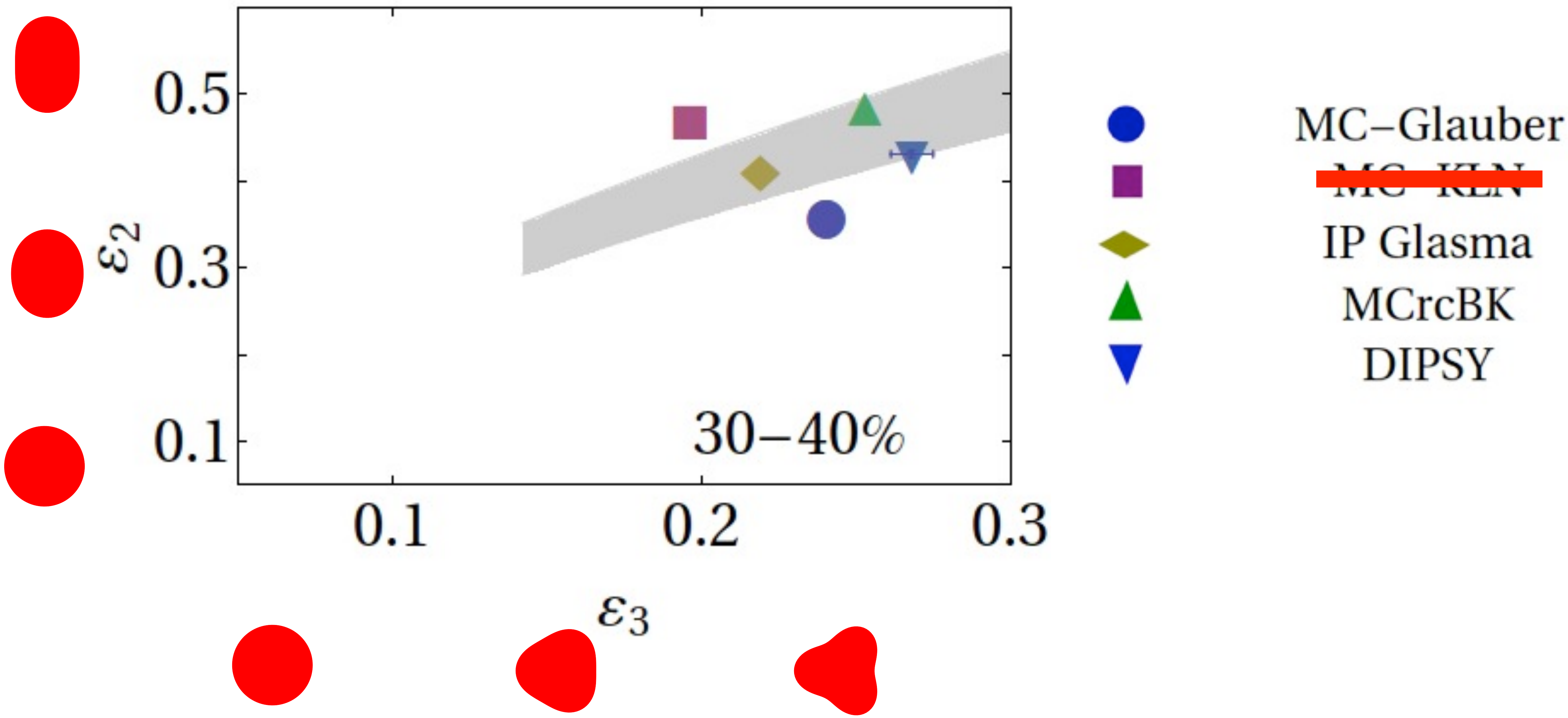

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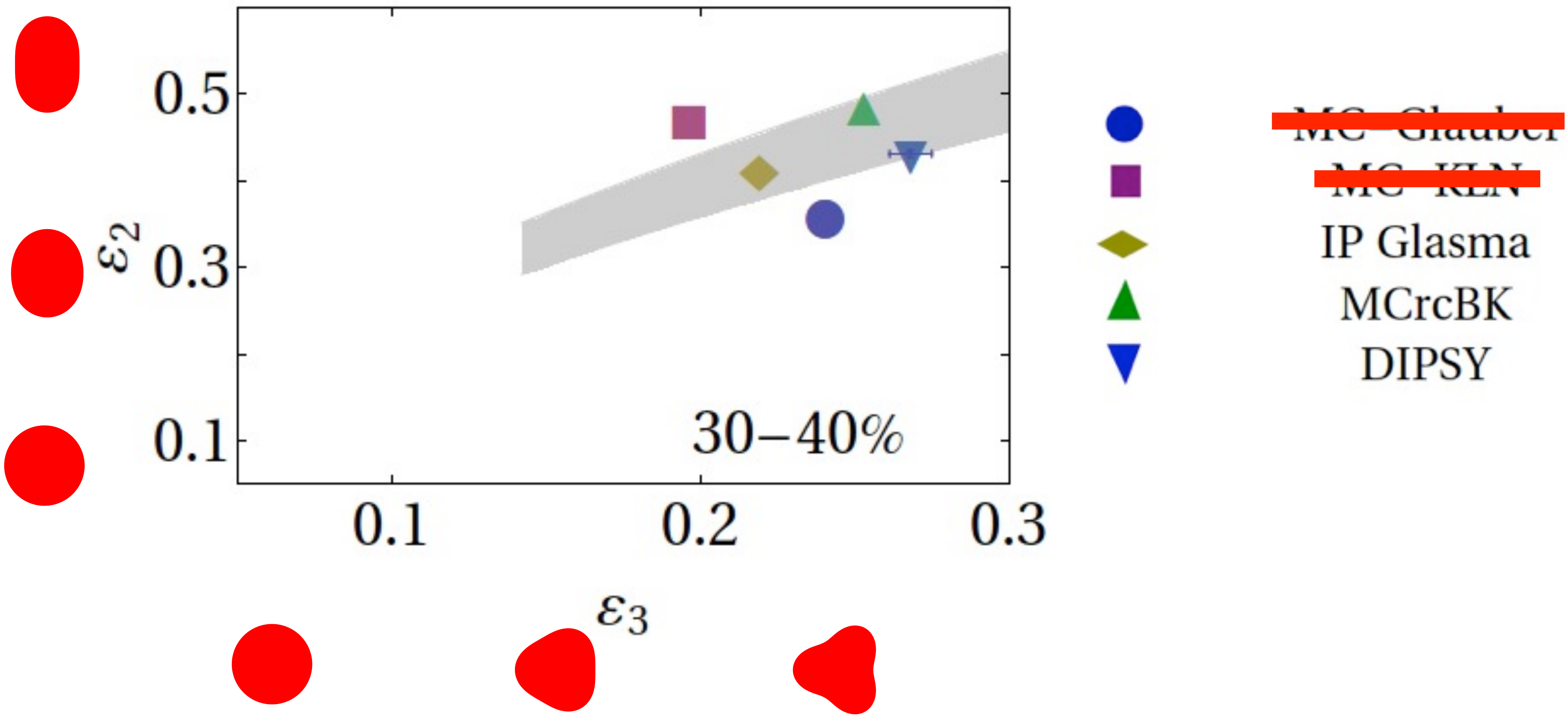
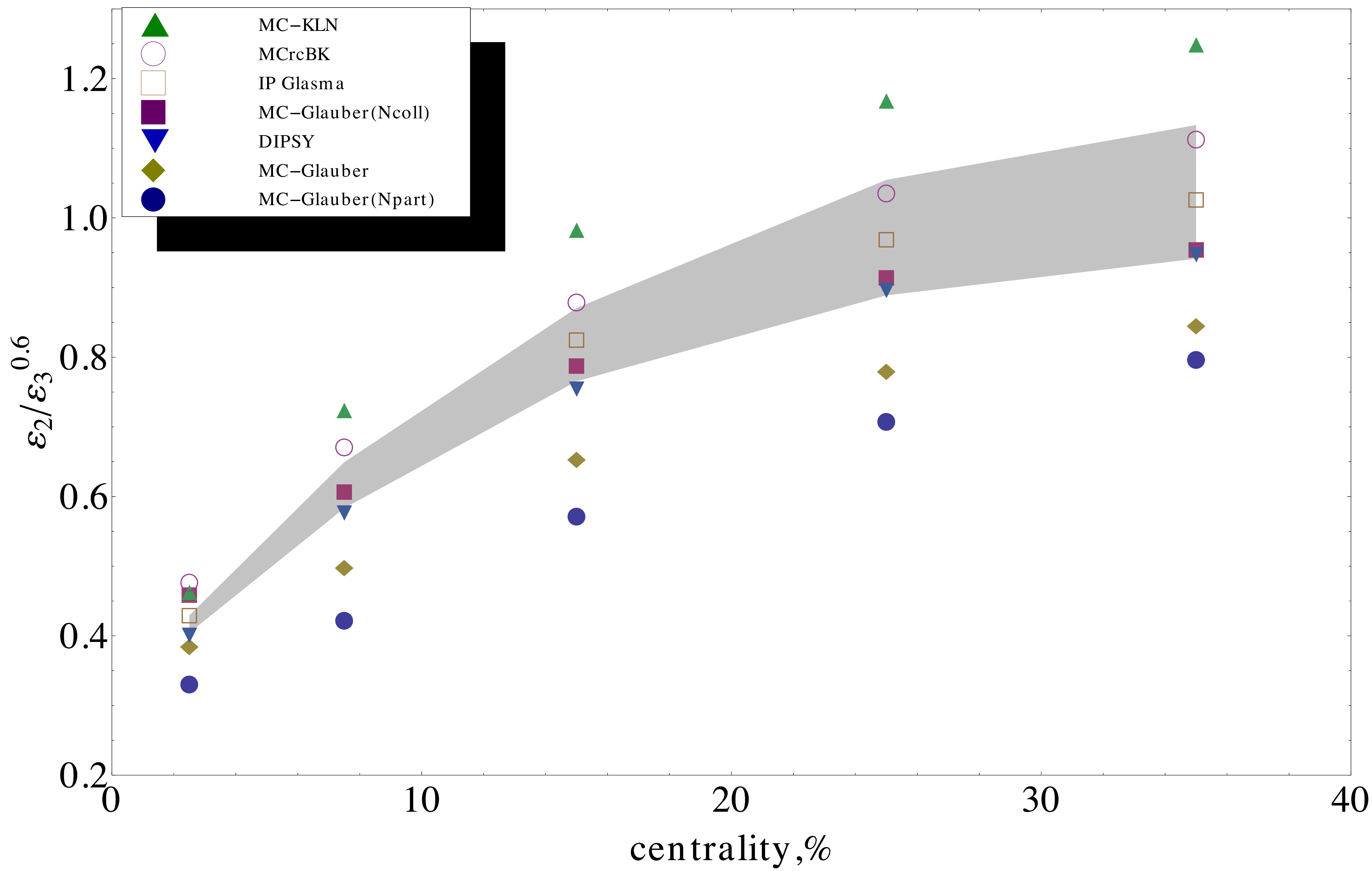
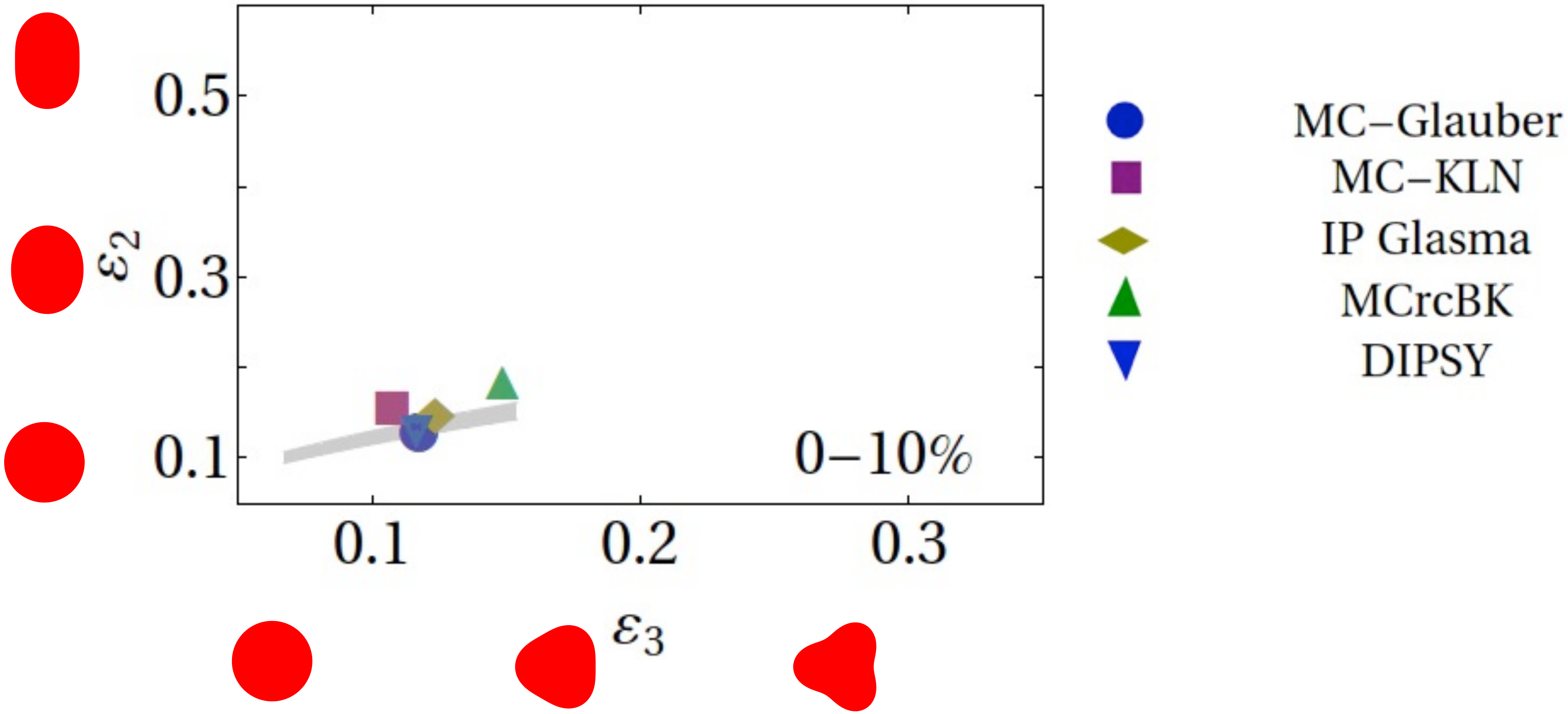


All centralities at once: testing the ratio $\varepsilon_2/(\varepsilon_3)^{0.6}$



Constraining initial-state models at RHIC



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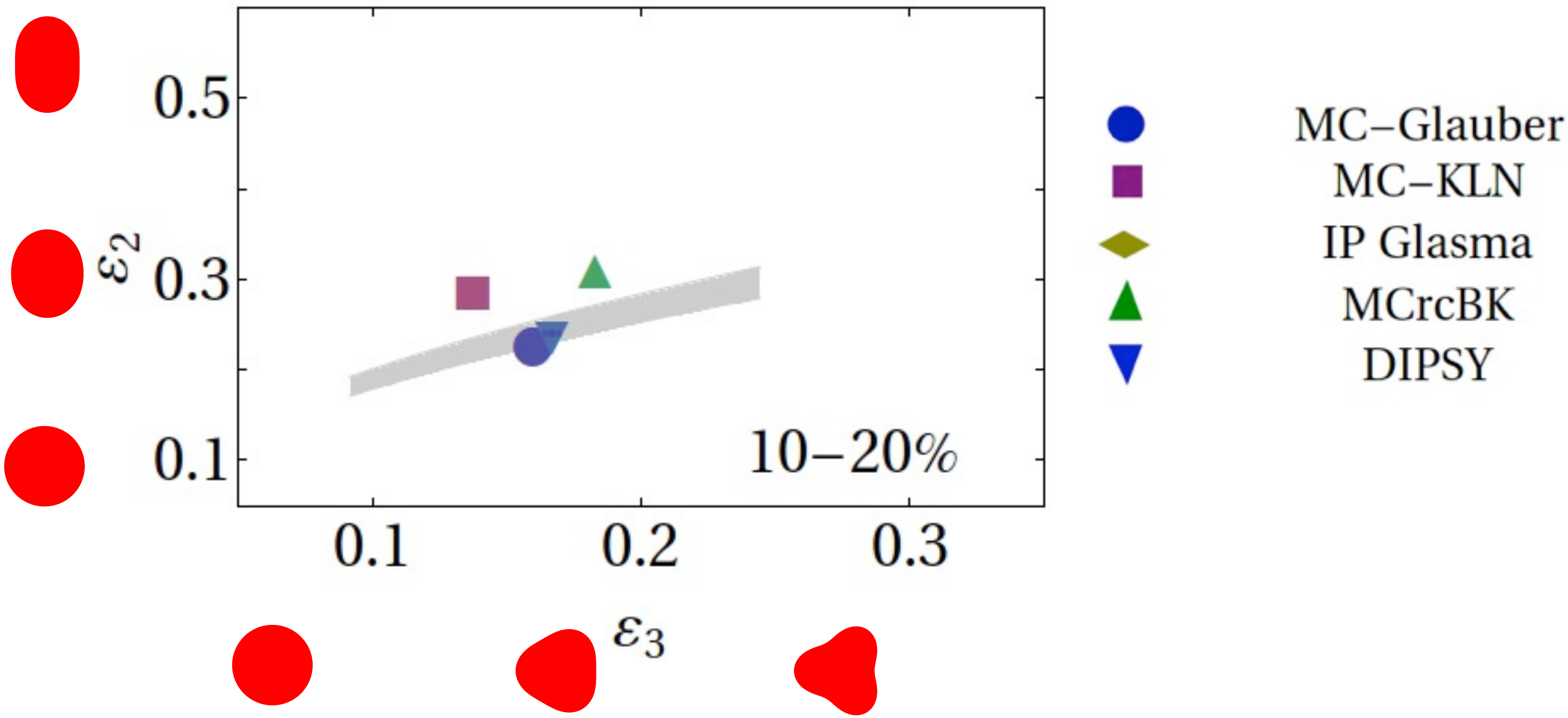

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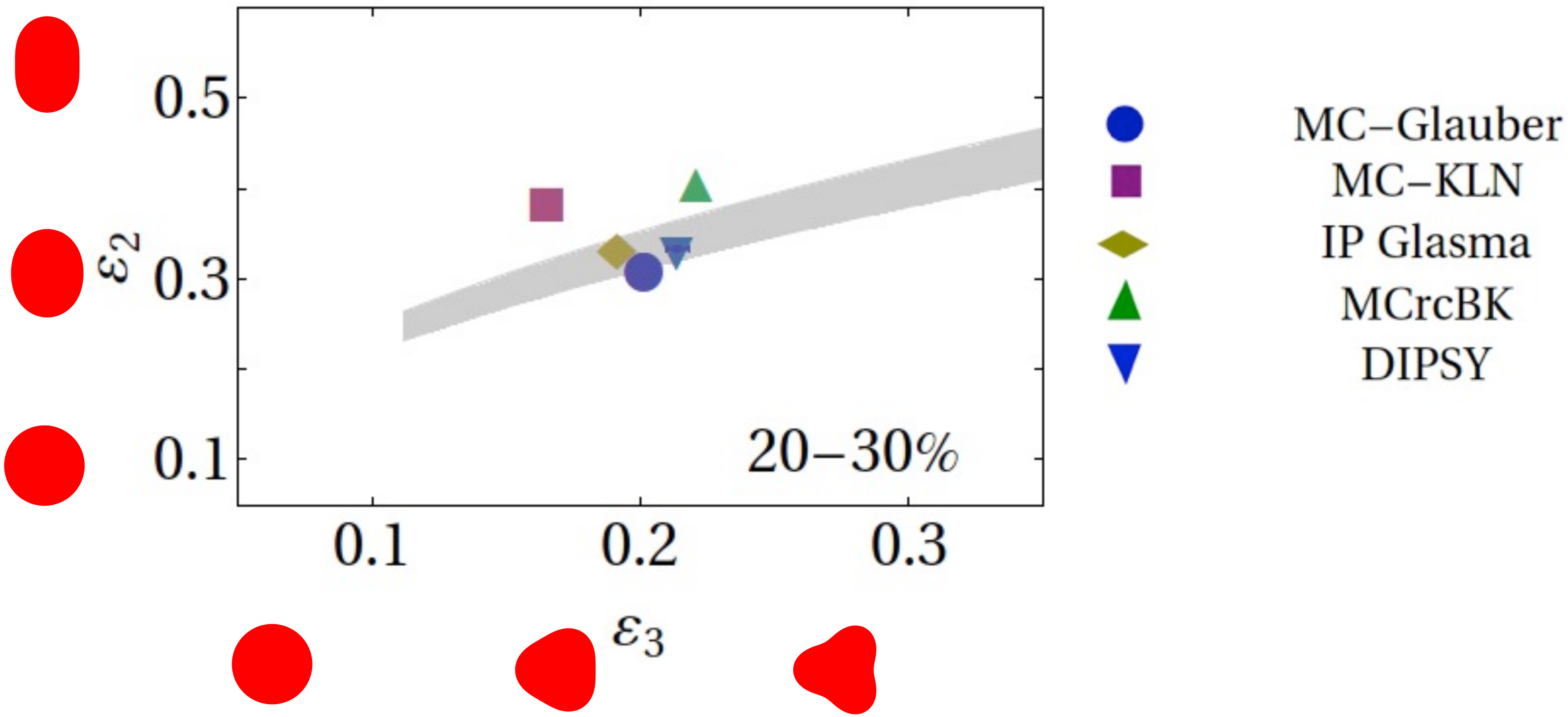

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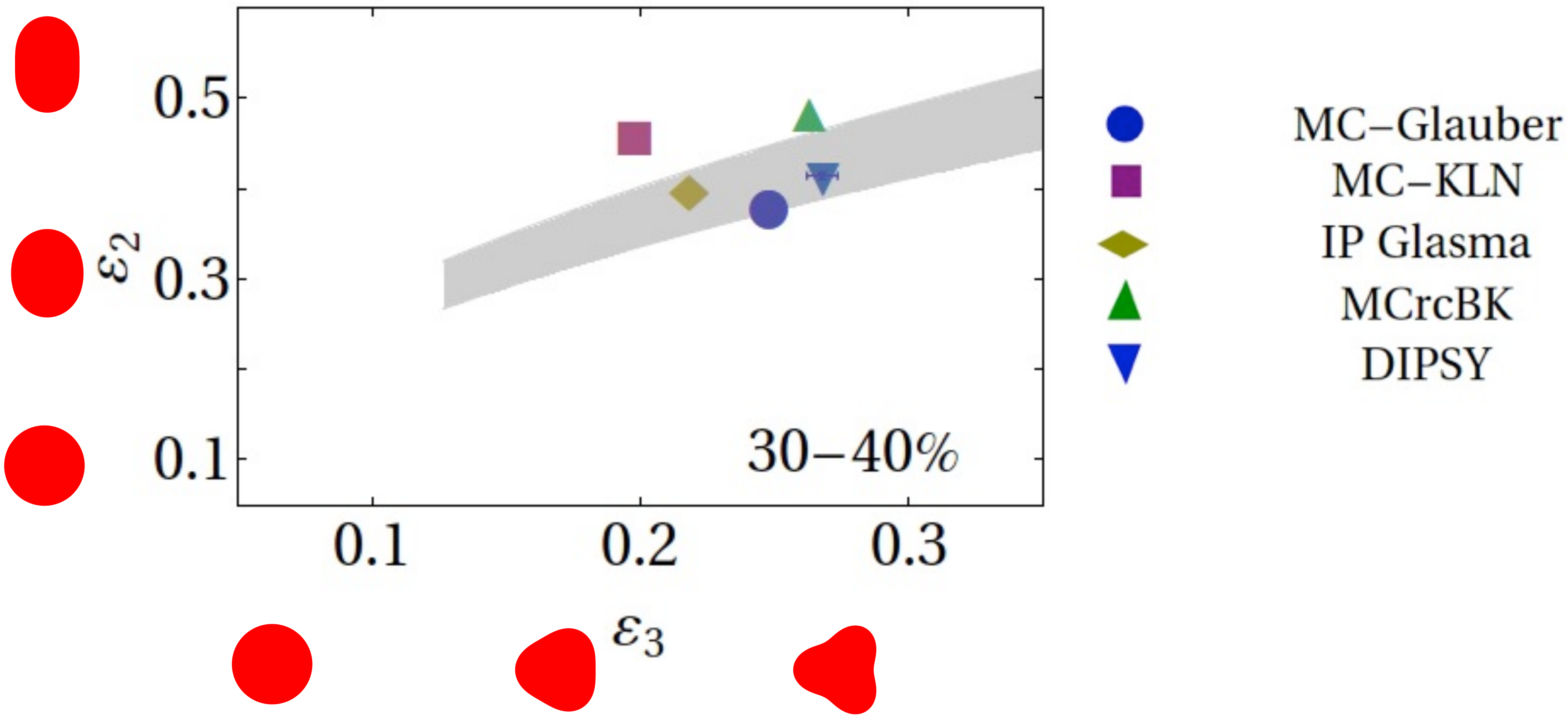

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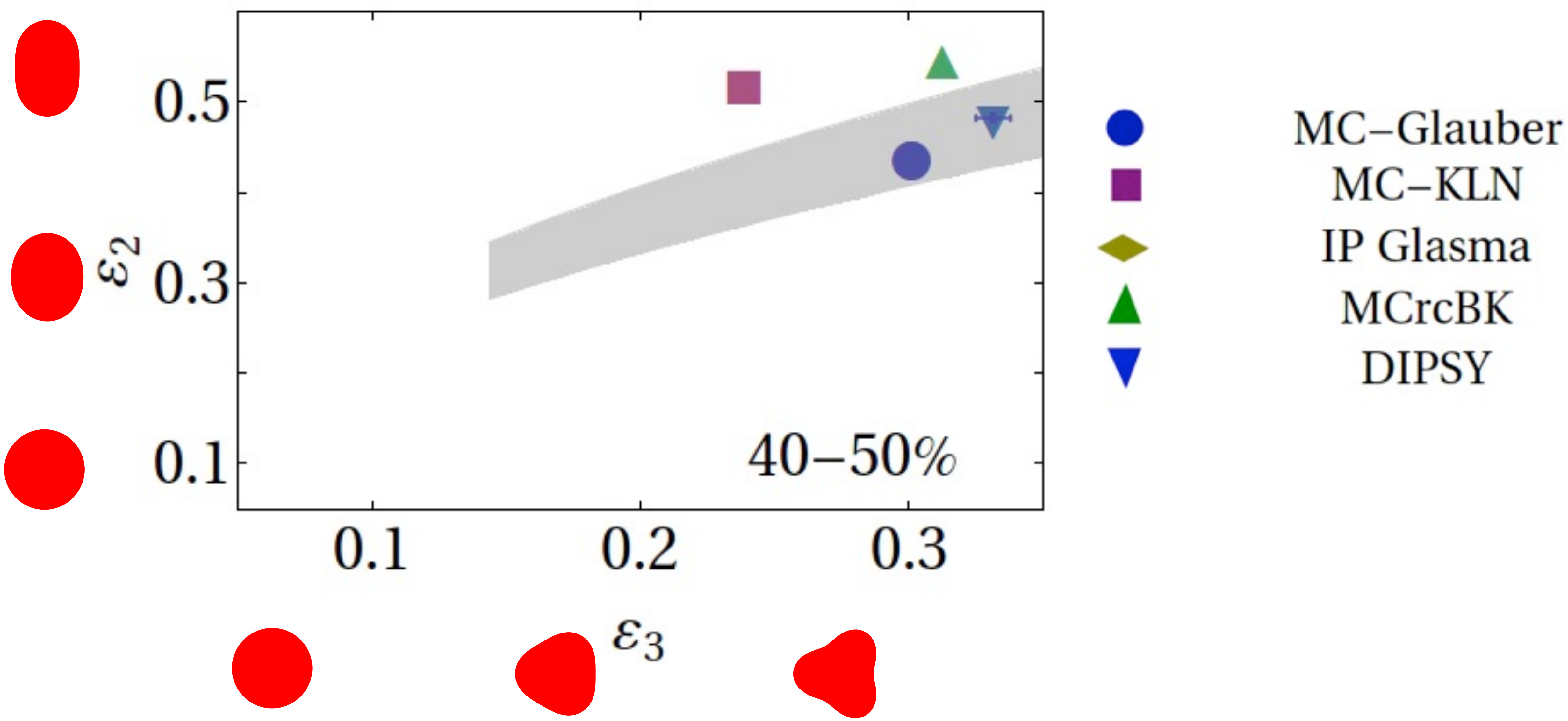

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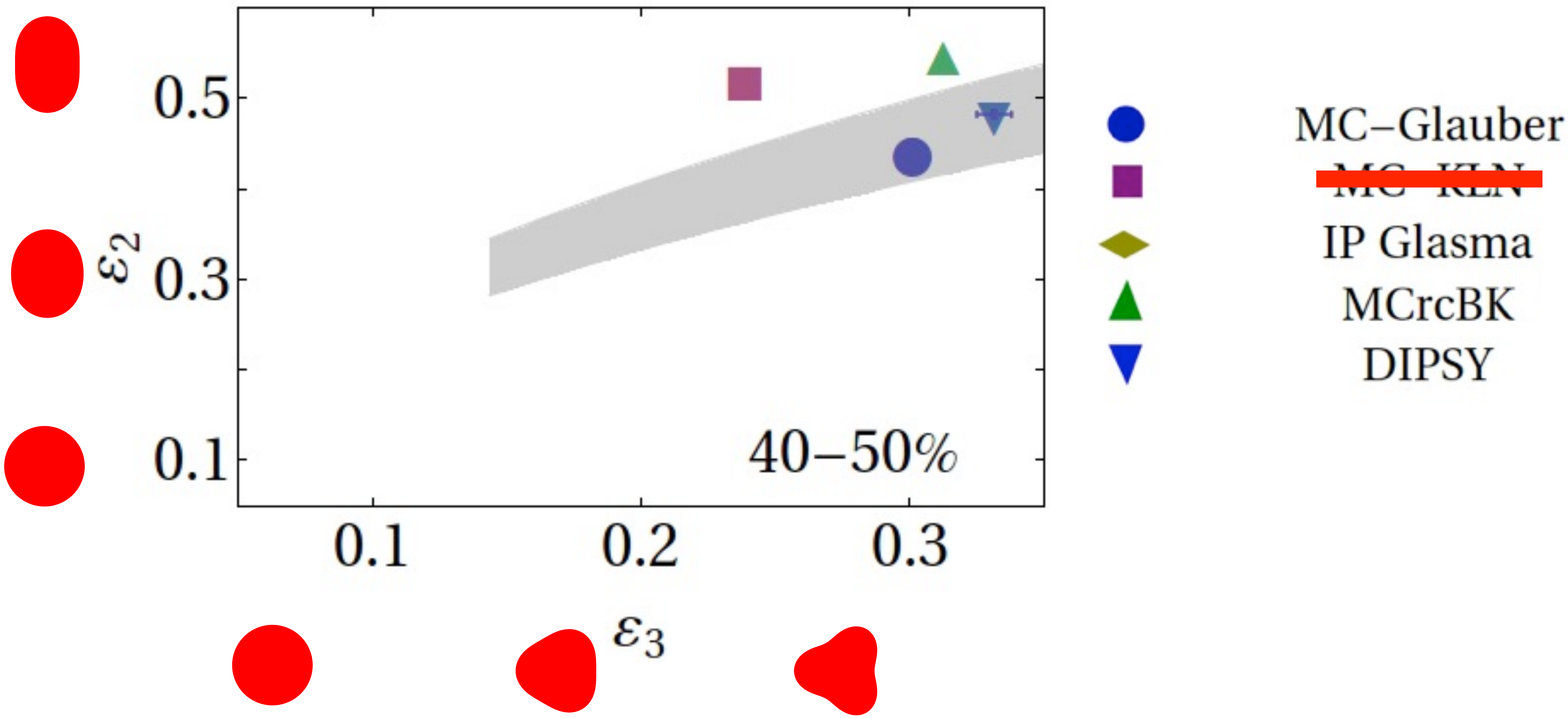

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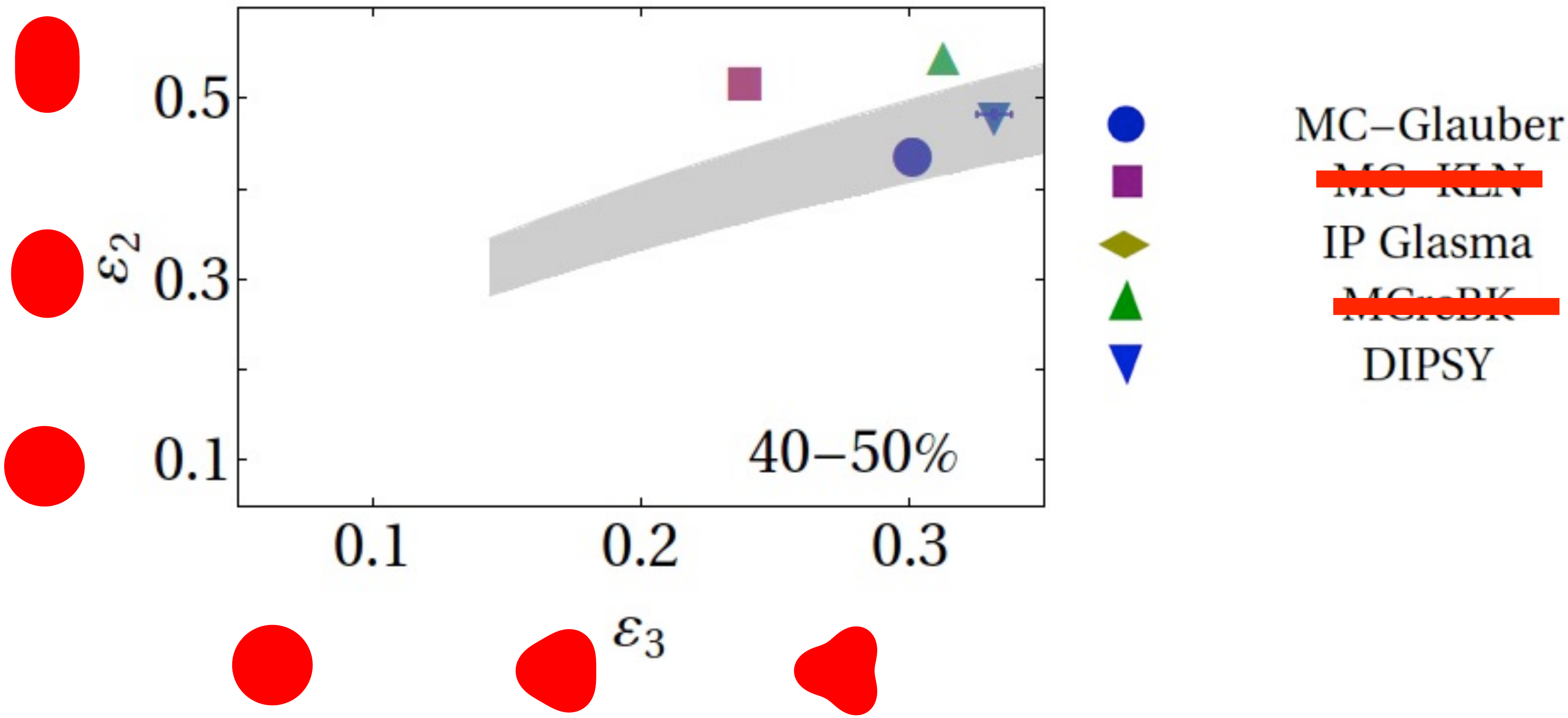

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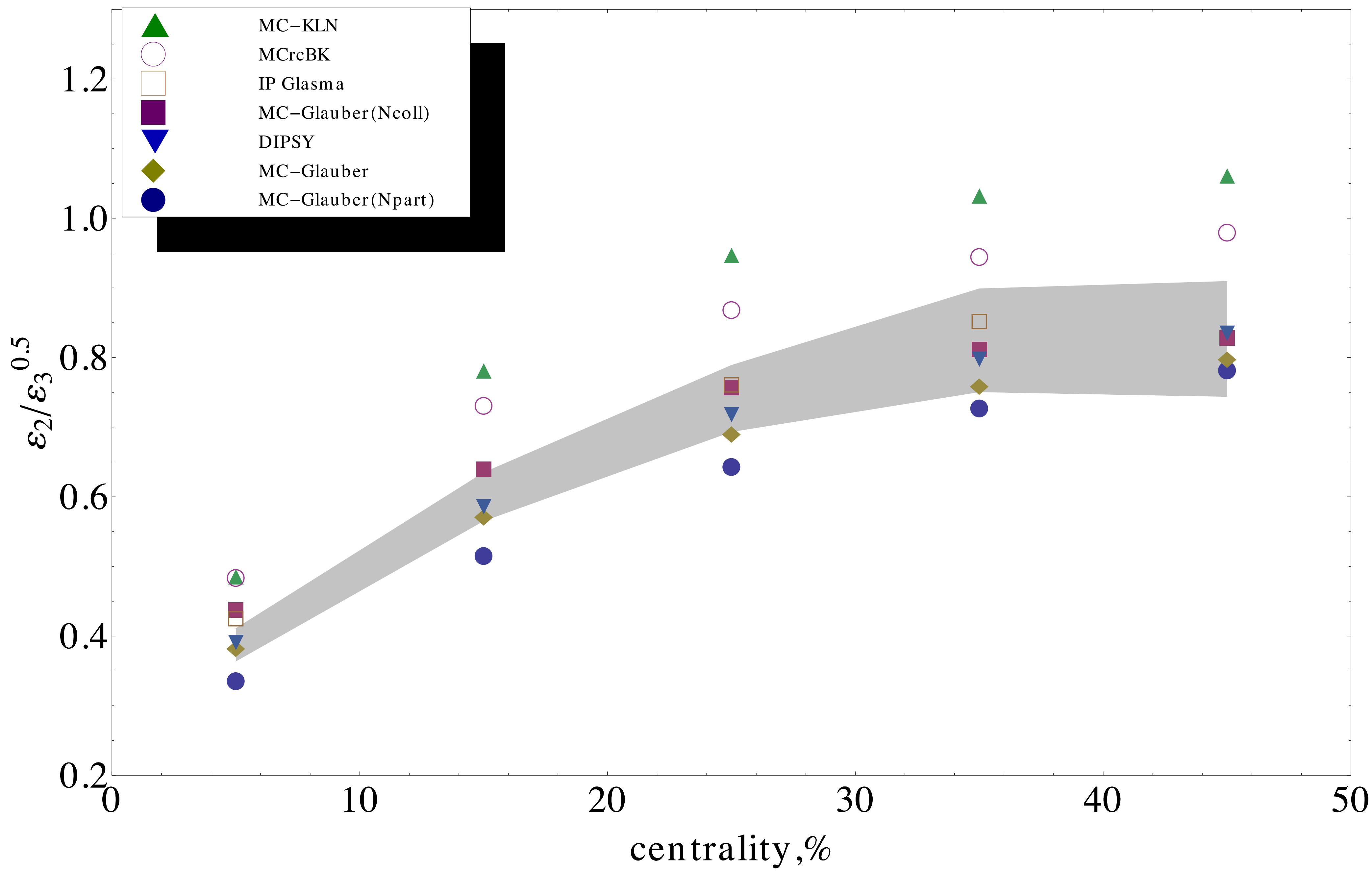


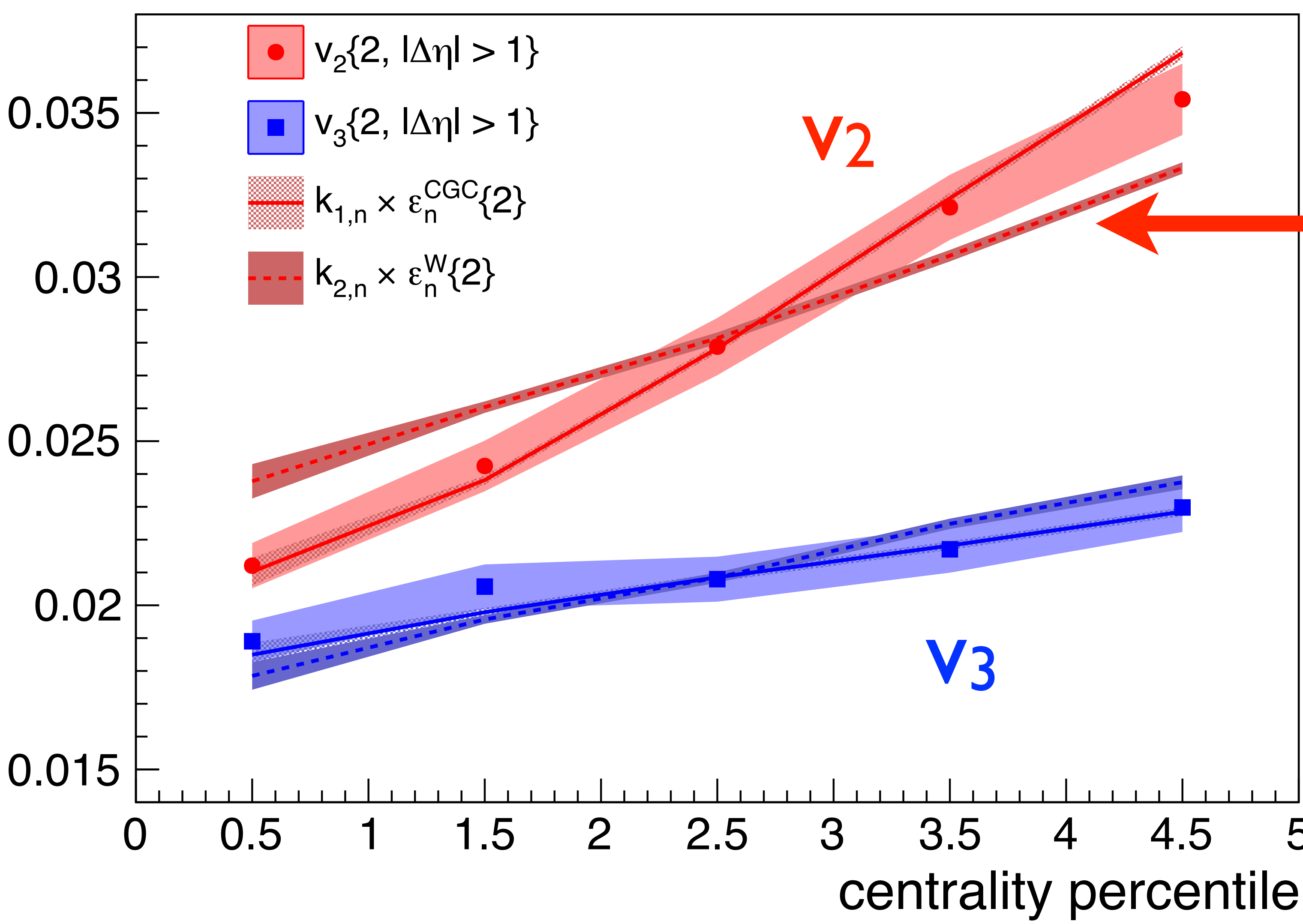
Summary

- Simple test for initial-state models at LHC: numerical value of $\varepsilon_2/(\varepsilon_3)^{0.6}$
- All models in the ballpark but some can already be excluded.
- Error bar can be reduced by improving the hydro calculation, in particular by taking a more realistic initial profile

Backup

Zooming into central collisions

Between 0 and 5%, hydro response ≈ constant
only ε_2 and ε_3 can change



MC-Glauber excluded by v_2 data alone

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