# Constraining the nuclear matter equation of state around twice saturation density

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- Introduction.
- Analysis and results.
- Simulations: the scenario.
- Summary and discussion.

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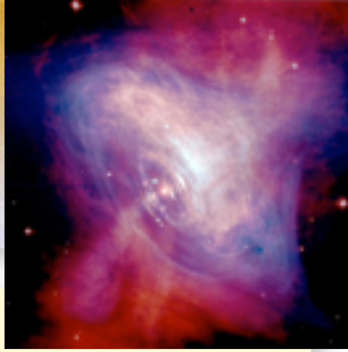
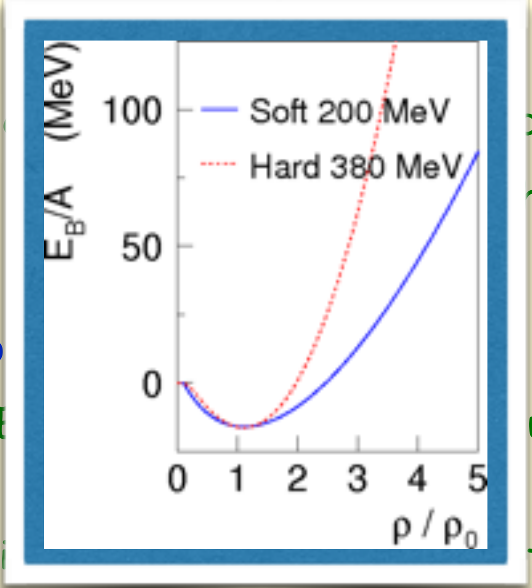
# Introduction



*NGC 1952, Crab Nebula pulsar neutron star imaged by the NASA/ESA Hubble Space Telescope*



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[1] J. M. Lattimer, Ann. Rev. Nucl. Part. Sci. 62 (2012) 485.
[2] A. Burrows, Rev. Mod. Phys. 85 (2013) 245.
[3] A. Gezerlis, I. Tews, E. Epelbaum, S. Gandolfi, K. Hebeler, A. Nogga, A. Schwenk, Phys. Rev. Lett. 111 (2013) 032501

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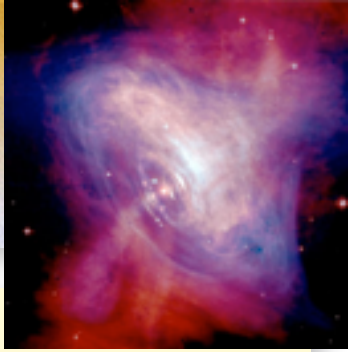

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- The equation of state (EOS) of nuclear matter:
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  - object of intense theoretical efforts since several decades
  - an important ingredient in modeling fascinating astrophysical phenomena such as:
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    - core collapse supernovae[2]
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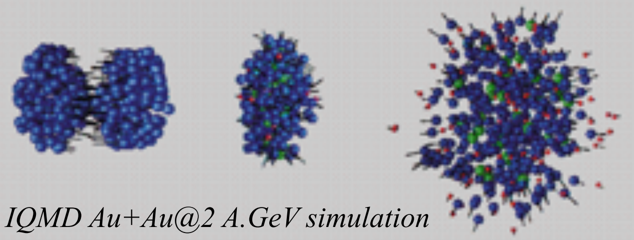

*IQMD Au+Au@2 A.GeV simulation*

- Alternative method: in earth laboratories, heavy ion collisions over a wide range of incident energies, system sizes and compositions.
  - flow method: limited to $E_{beam}<10$ A.GeV ⬅ some kind of a clock is available (sound velocity versus participant-spectator interaction).
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  - BEVALAC & AGS accelerators, proton flows versus transport theories -> $K_0$ = 167-200 MeV (soft) from $V_1$, $K_0$ = 300 MeV (semi-stiff) from $V_2$ -> contradictions.

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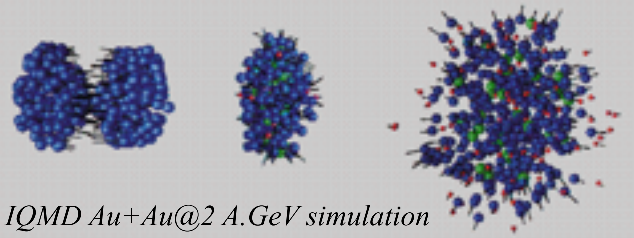
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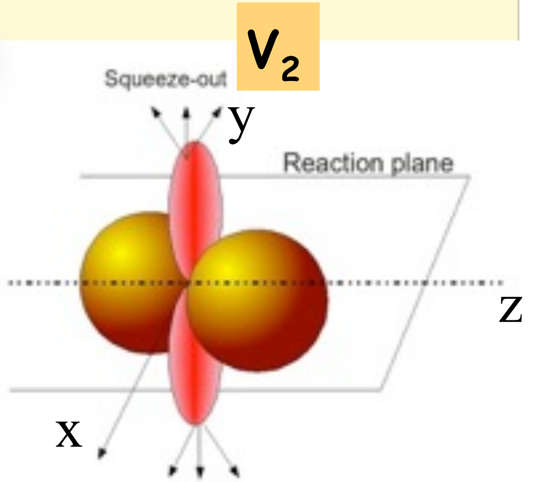
## Flows at high density in heavy-ion collisions

$$\frac{dN}{d(\phi-\phi_R)}(y,p_t)=\frac{N_0}{2\pi}\left(1+2\sum_{n\ge1} v_n\cos n(\phi-\phi_R)\right)$$

Y = rapidity

$p_t$ = transverse momentum

$\Phi_R$ = reaction plane azimuthal angle



$V_1$ = 'side/directed flow', $\cos(\Phi-\Phi_R)$ mode

$$V_2(y,p_t)=\left\langle\frac{p_x^2-p_y^2}{p_t^2}\right\rangle$$

'Elliptic flow': $\cos(2(\Phi-\Phi_R))$ mode, competition between 'in-plane' ($V_2$>0) and 'out-of-plane' ejection ($V_2$<0).

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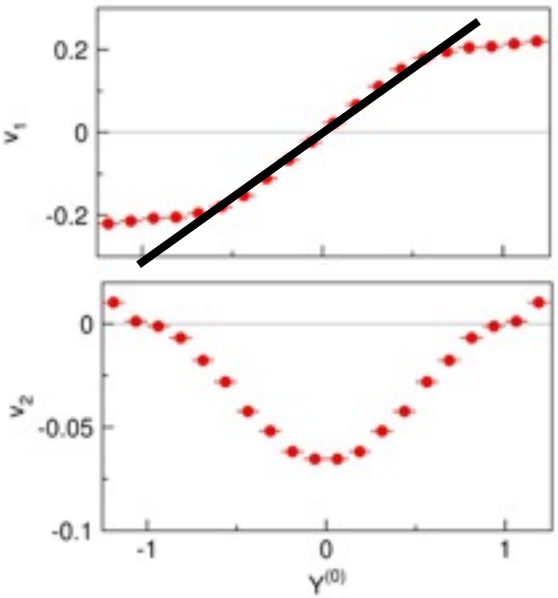

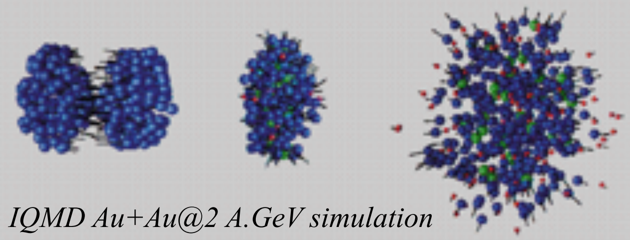
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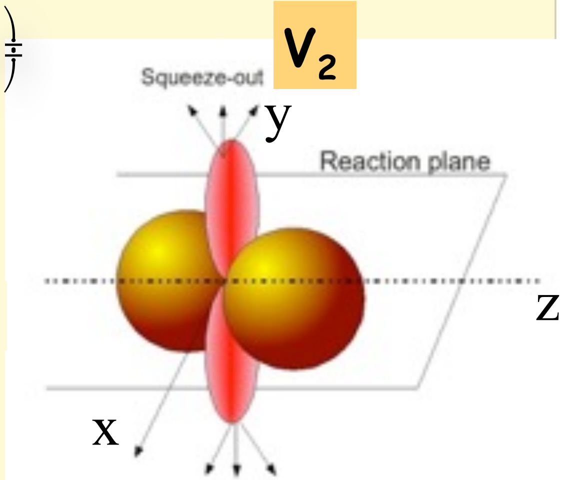

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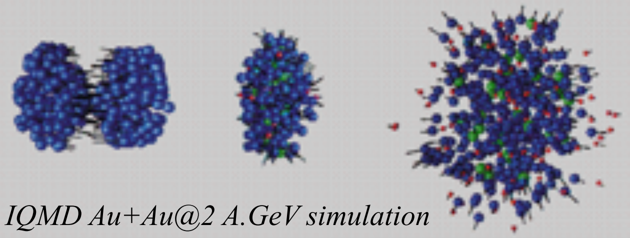
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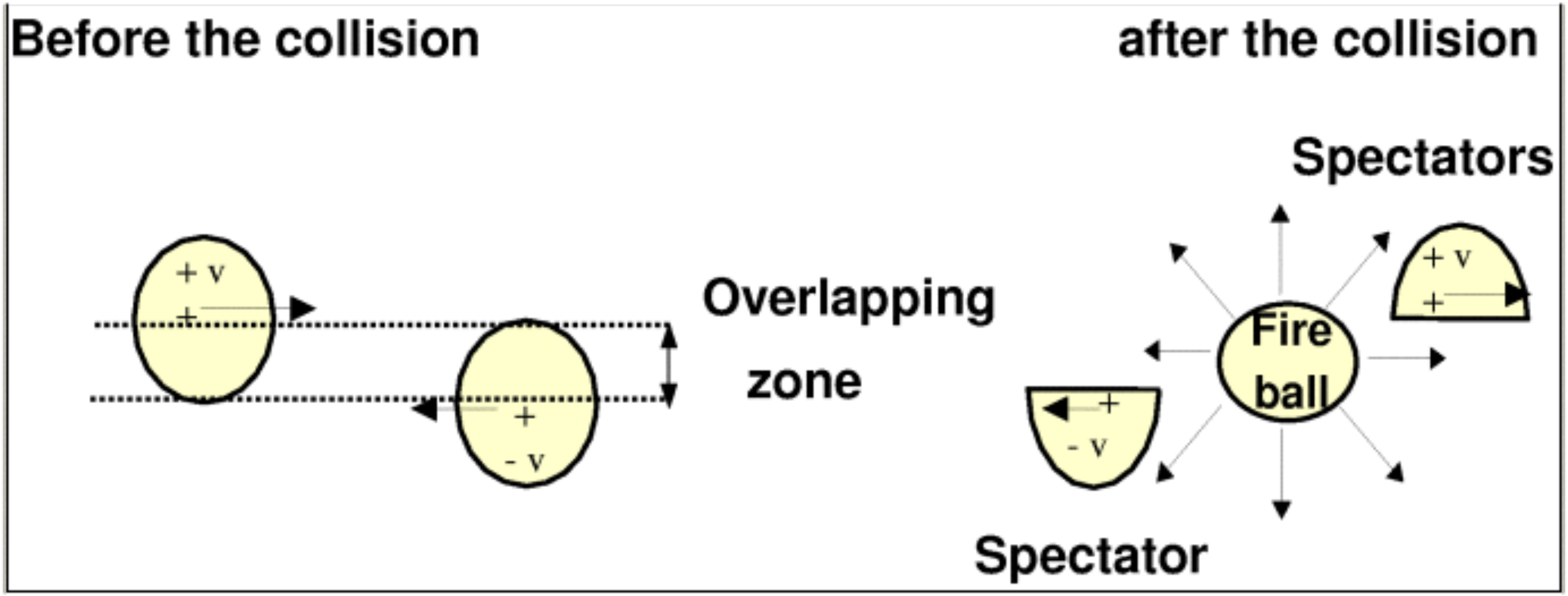

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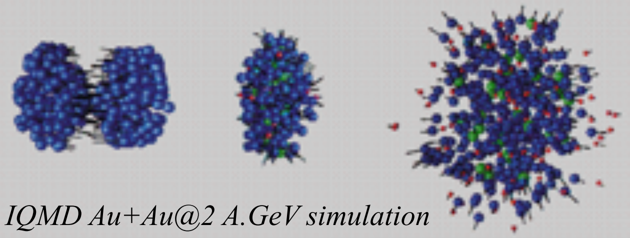

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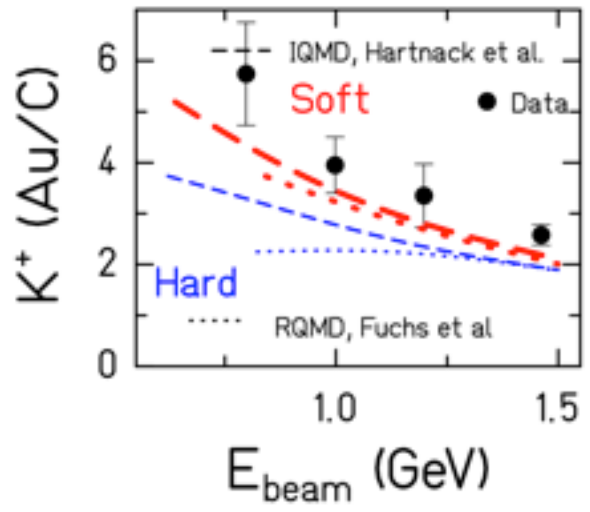

Data: C. Sturm et al., PRL 86 (2001) 39

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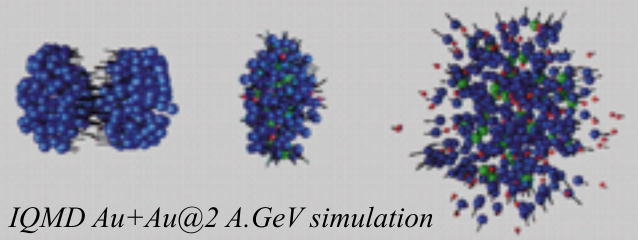
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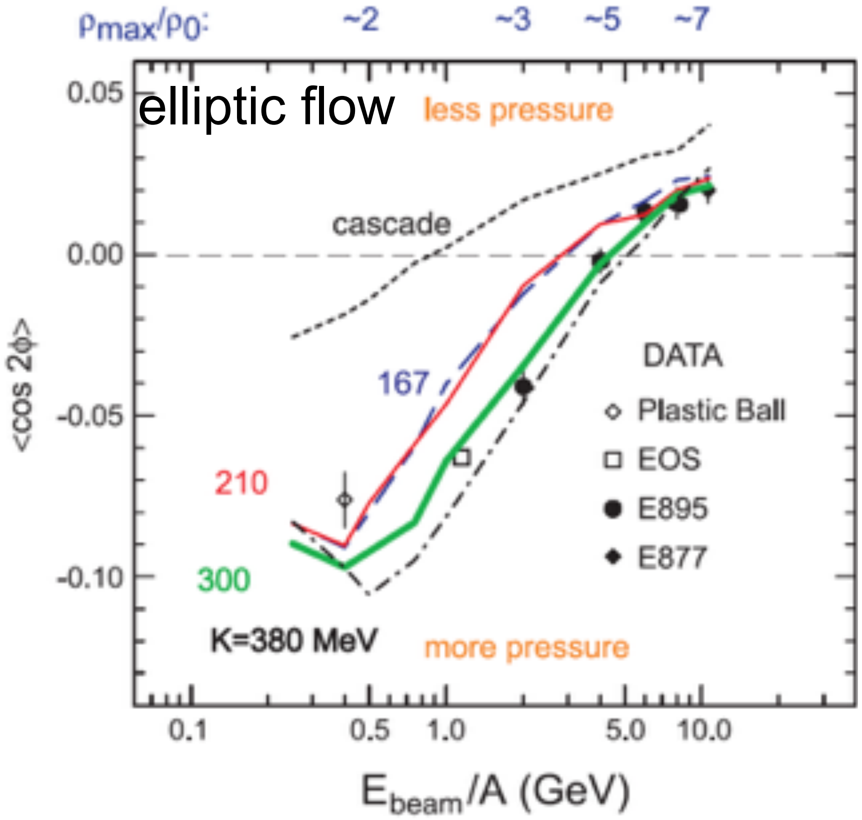
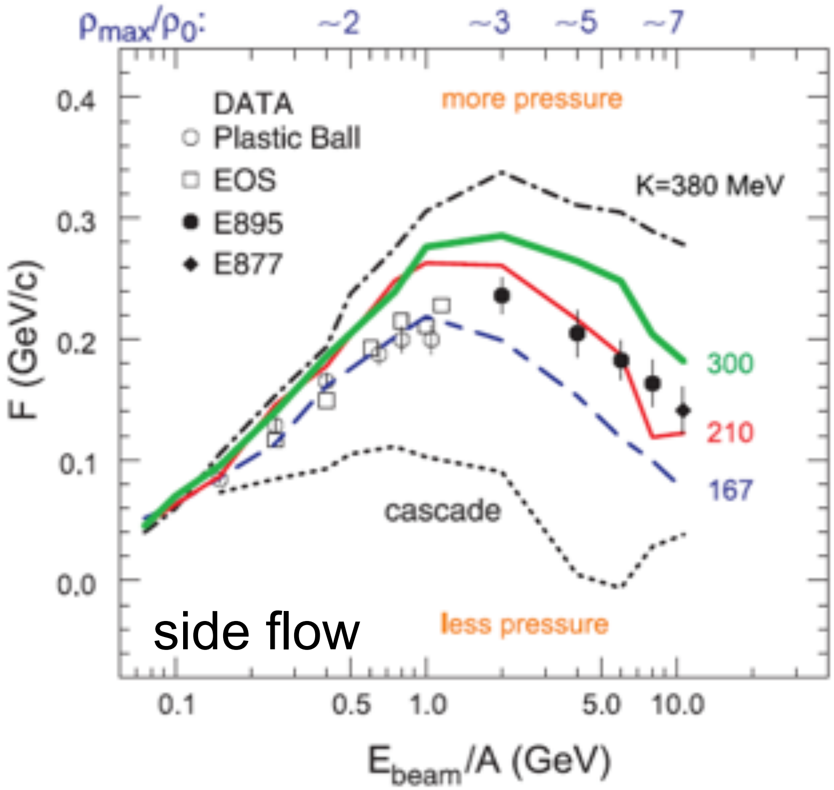
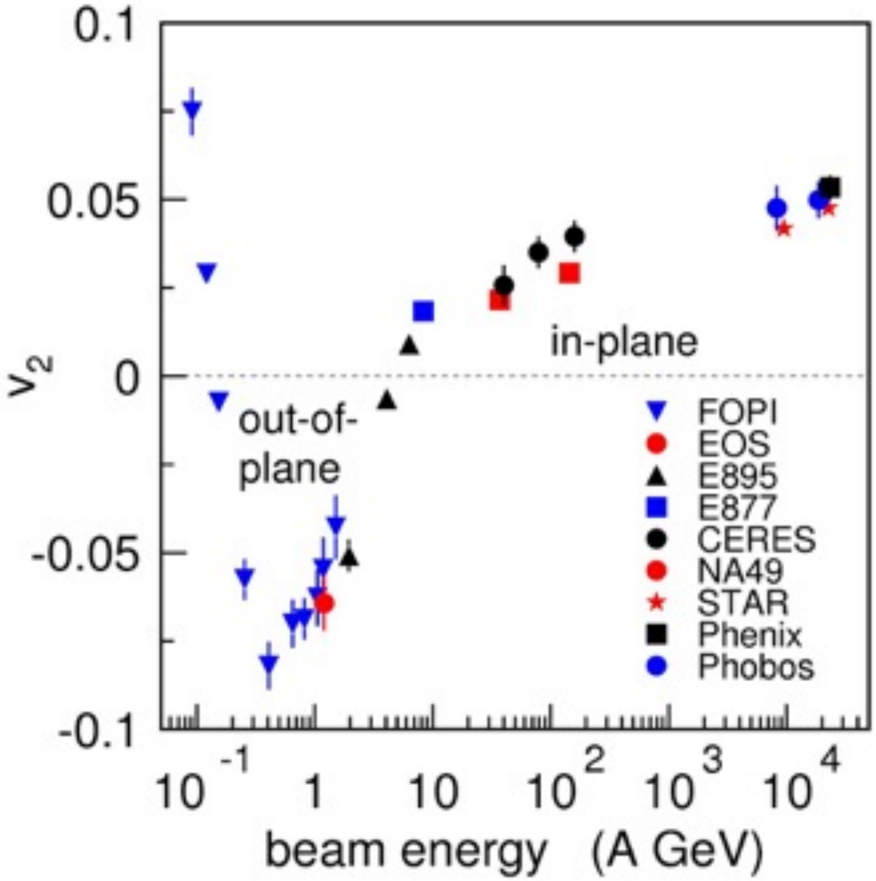
# Elliptic flow and the nuclear matter EOS





P. Danielewicz et al.
Science 298, 1592 (2002)

# Beam energy dependence of elliptic flow



elliptic flow

- ➢ pressure gradient of compression zone
- ➢ shadowing of spectators
- ➢ at low energies
  - attraction due to mean field of nucleons
- ➢ at high energies
  - lacking shadowing of spectators

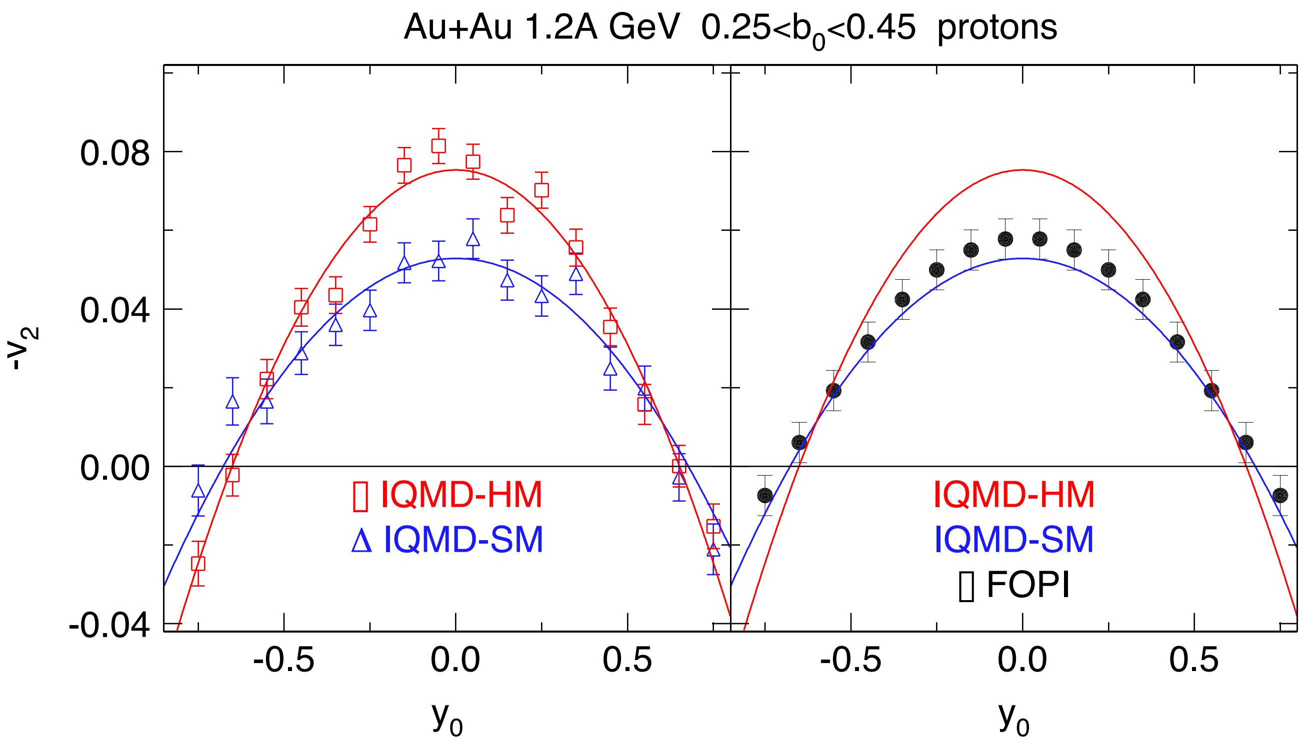
# Introduction

- Present work: improve the situation in the 1 A.GeV regime, from extensive flow data published recently by the FOPI Collaboration (Au+Au @ 0.4-1.5 A.GeV) [4]
  ➜ close look at the elliptic flow data with improvements:
  - 1) not only protons: d, t, $^3$He $^4$He having larger flow signals than single nucleons.
  - 2) not only mid-rapidity data: 80% of the target- projectile rapidity gap.

[4] W. Reisdorf, et al. (FOPI Collaboration), Nucl. Phys. A 876 (2012) 1.

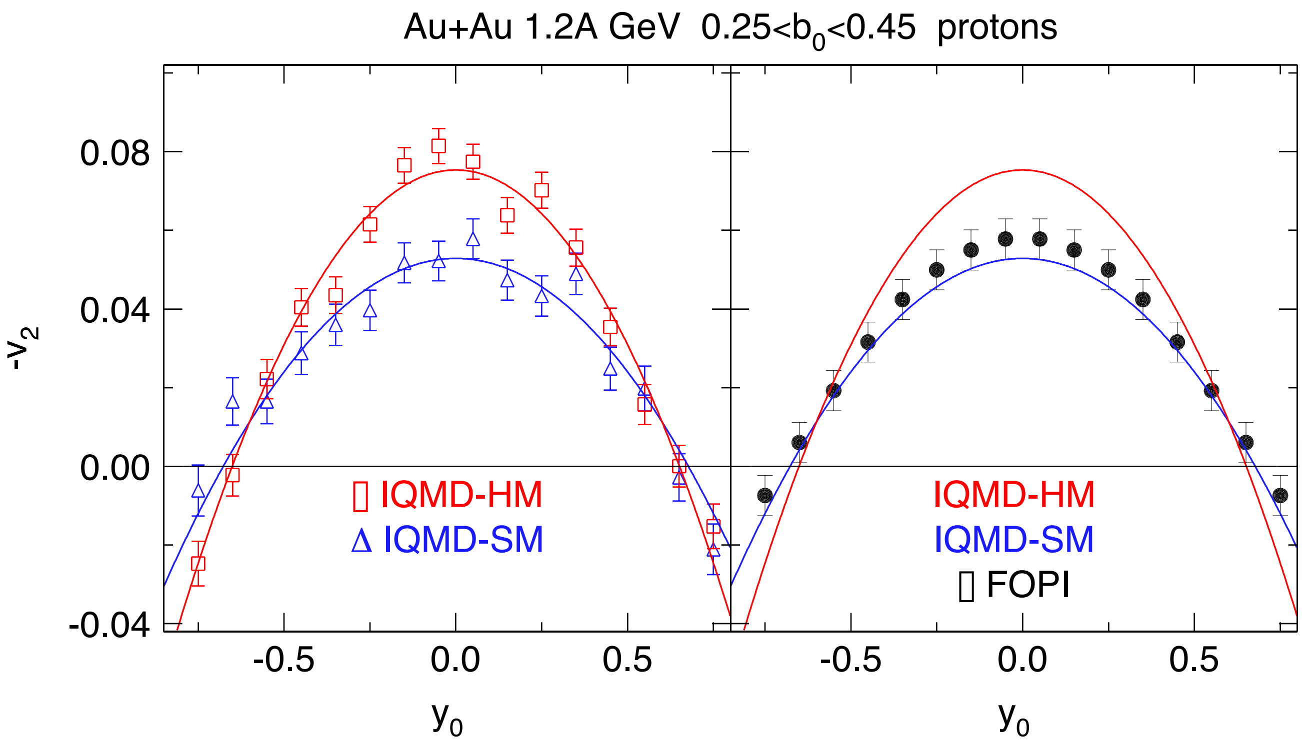
# Analysis and results

Elliptic flow



# Analysis and results

## Elliptic flow

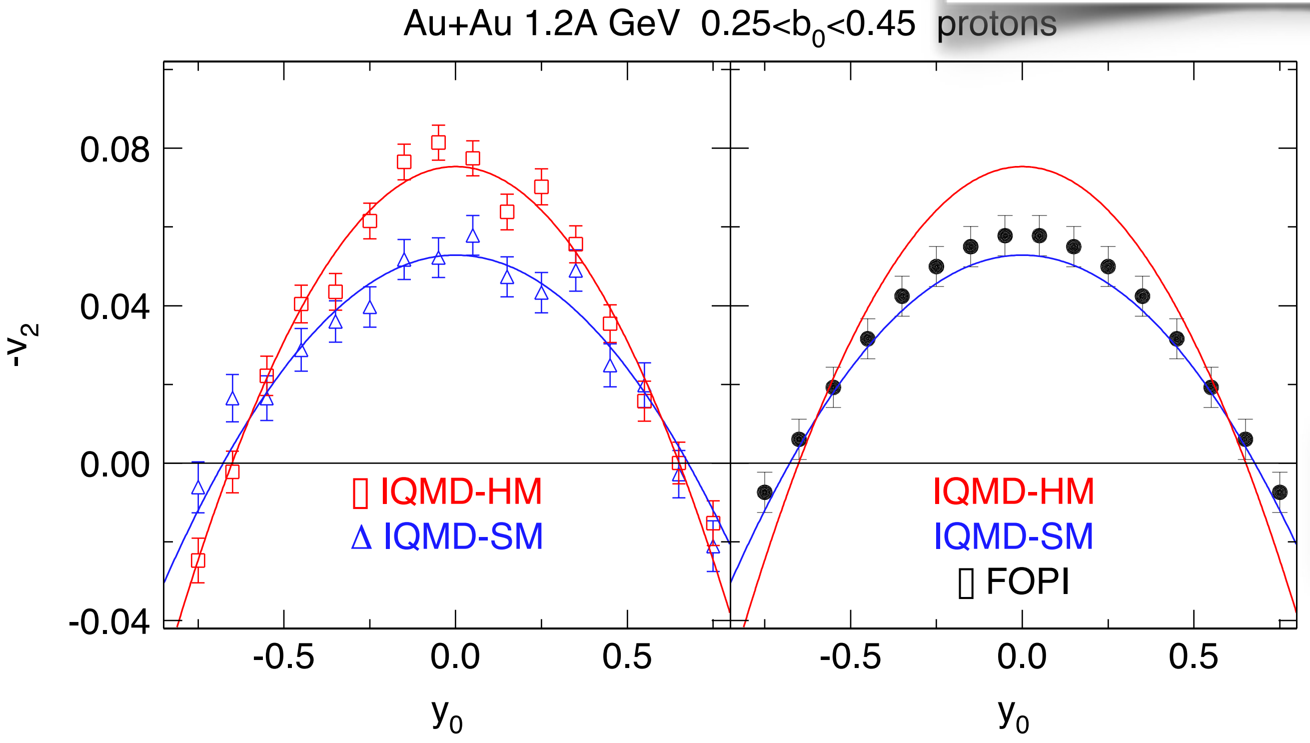


$K_0$ =
380 MeV (‘stiff’)
200 MeV (‘soft’)

# Analysis and results

Complete shape of $v_2(y_0)$:
a new observable:
$v_{2n} = |v_{20}| + |v_{22}|$,
from fit
$v_2(y_0) = v_{20} + v_{22} . y_0^2$

Elliptic flow



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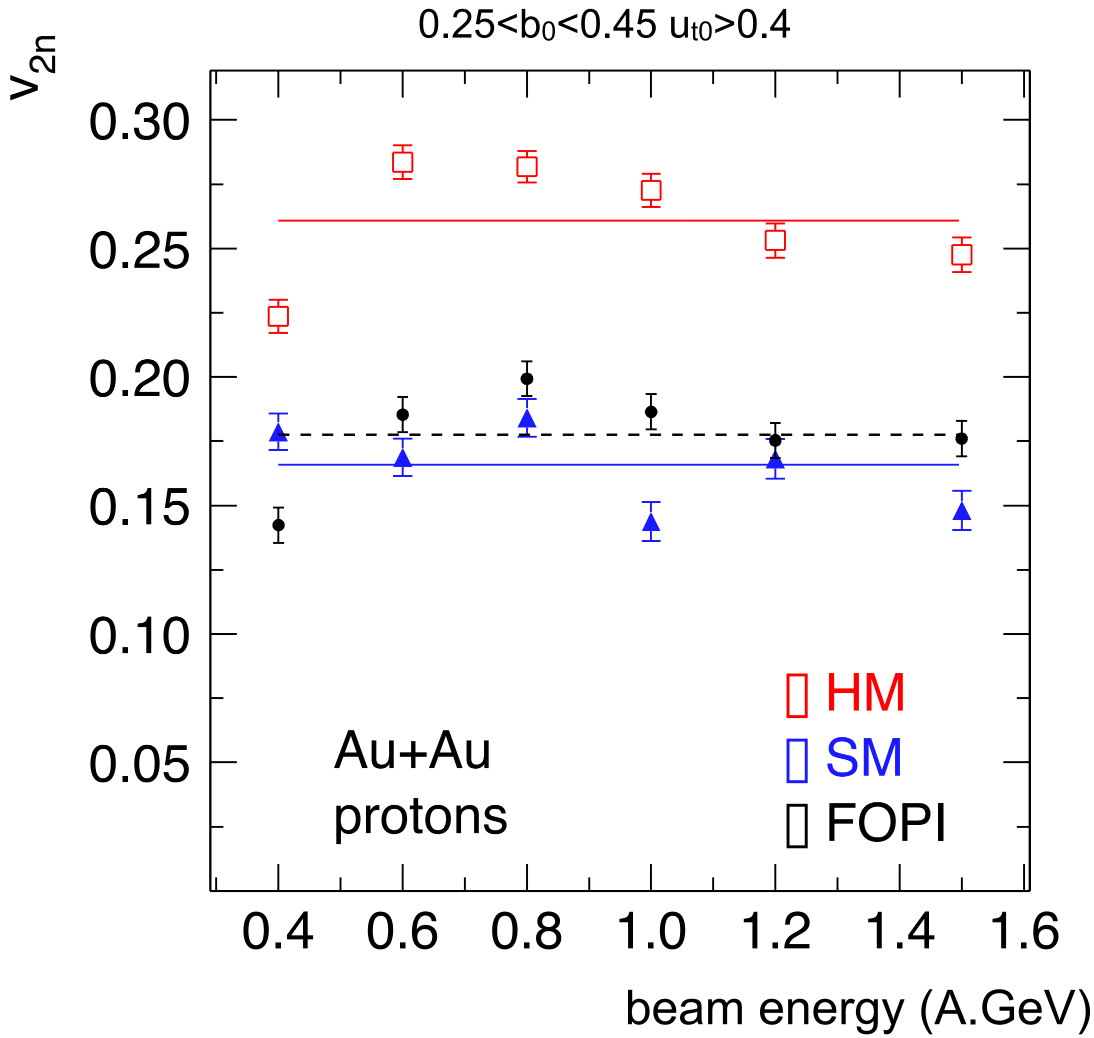
➜ $v_{2n}(E_{beam})$ varies by a factor ≈1.6, >> measured uncertainty (≈1.1)



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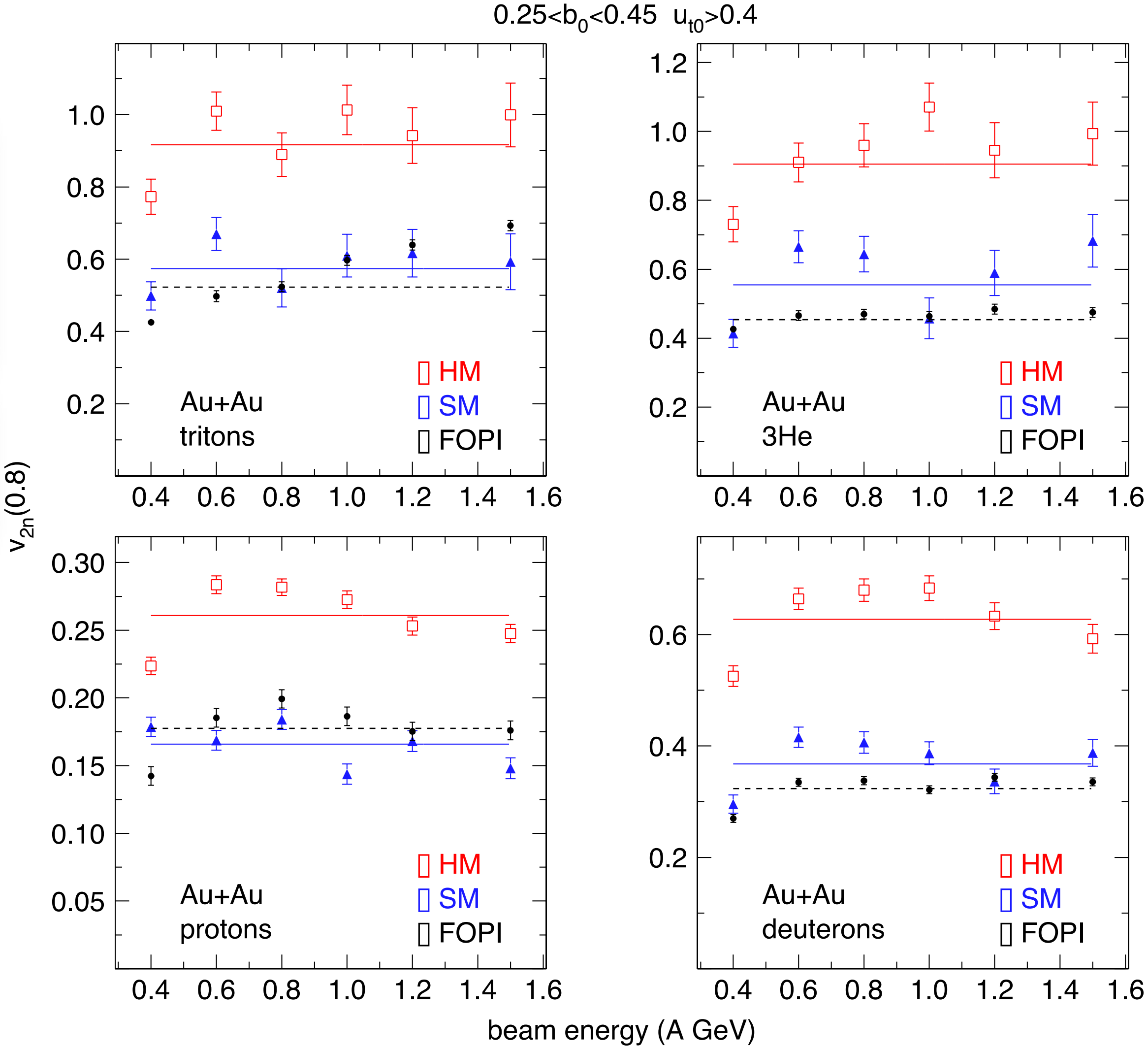
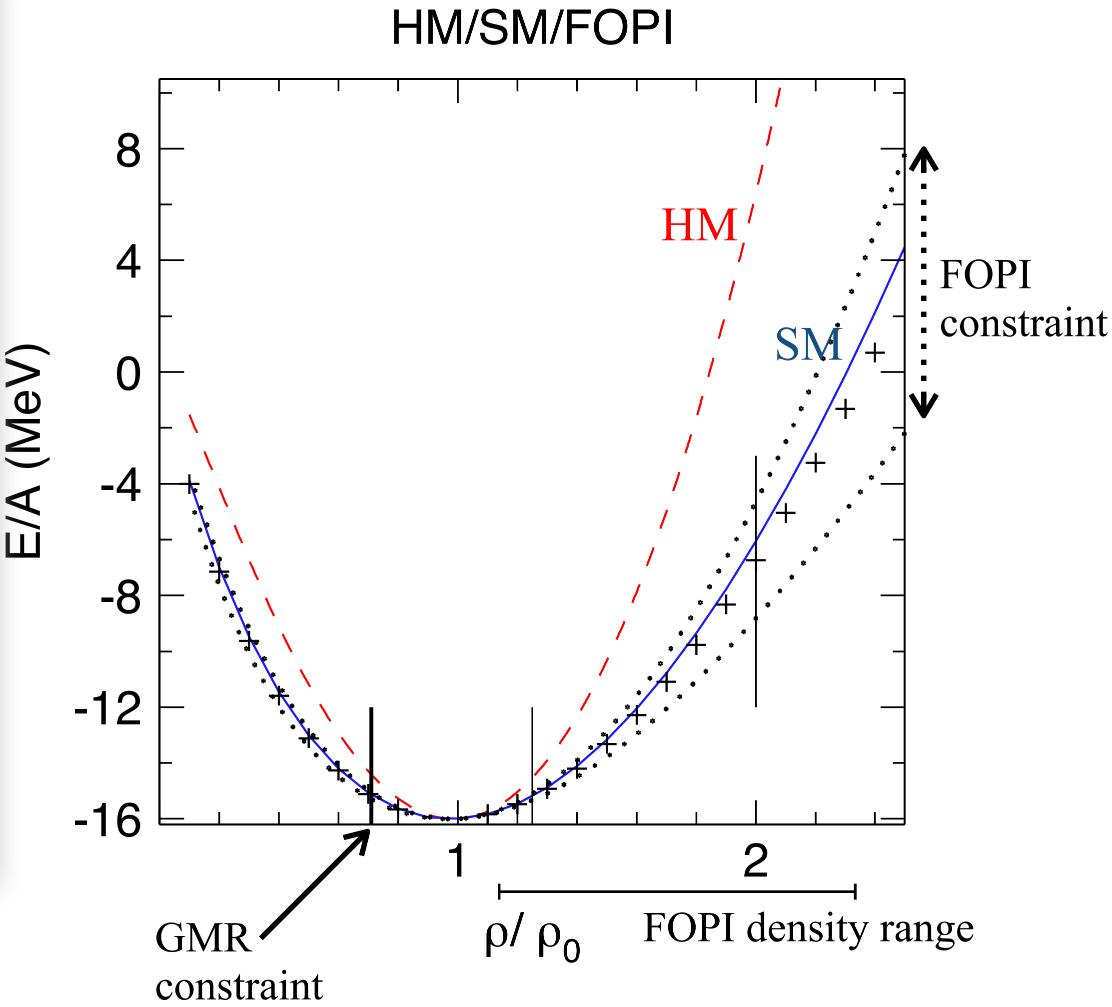
➜ $v_{2n}(E_{beam})$ varies by a factor ≈1.6, >> measured uncertainty (≈1.1)

➜ clearly favors a 'soft' EOS : $K_0$ = 190 +/- 30 MeV



# Analysis and results

- Phenomenological EOS
  HM and SM include the saturation point at $\rho/\rho_0 = 1$,
  $E/A = -16$ MeV by construction.
- ➜ fixes the absolute position of the curves:
- the heavy ion data are only sensitive to the shape, i.e. the pressure (derivative).
- ➜ a stiff EOS, characterised by $K_0 = 380$ MeV is not in agreement with the flow data in the incident energy range 0.4 - 1.5 A.GeV.



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IQMD transport model[5,6] various phenomenological EOS's:
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Here: protons in Au+Au at 1.5 A.GeV, b=3 fm

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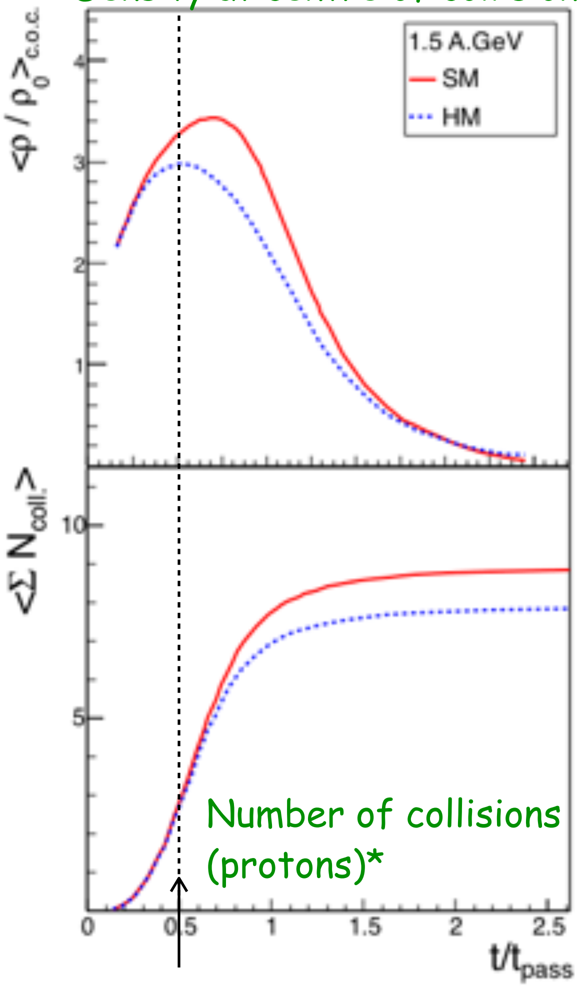
Density at centre of collision

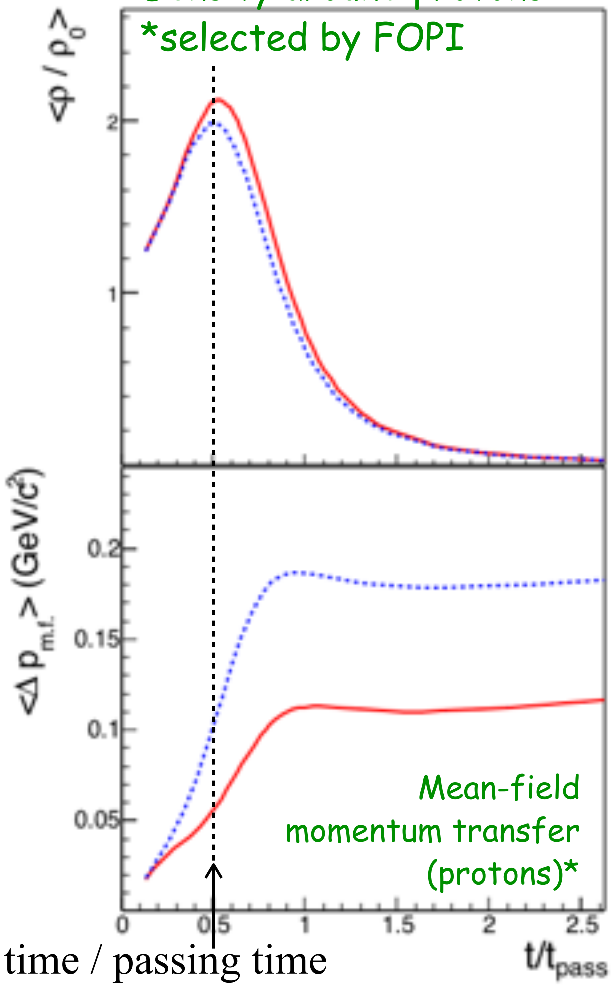


Number of collisions (protons)*

full target-projectile overlap

Density around protons*

*selected by FOPI



Mean-field momentum transfer (protons)*

$t/t_{pass}$ = time / passing time

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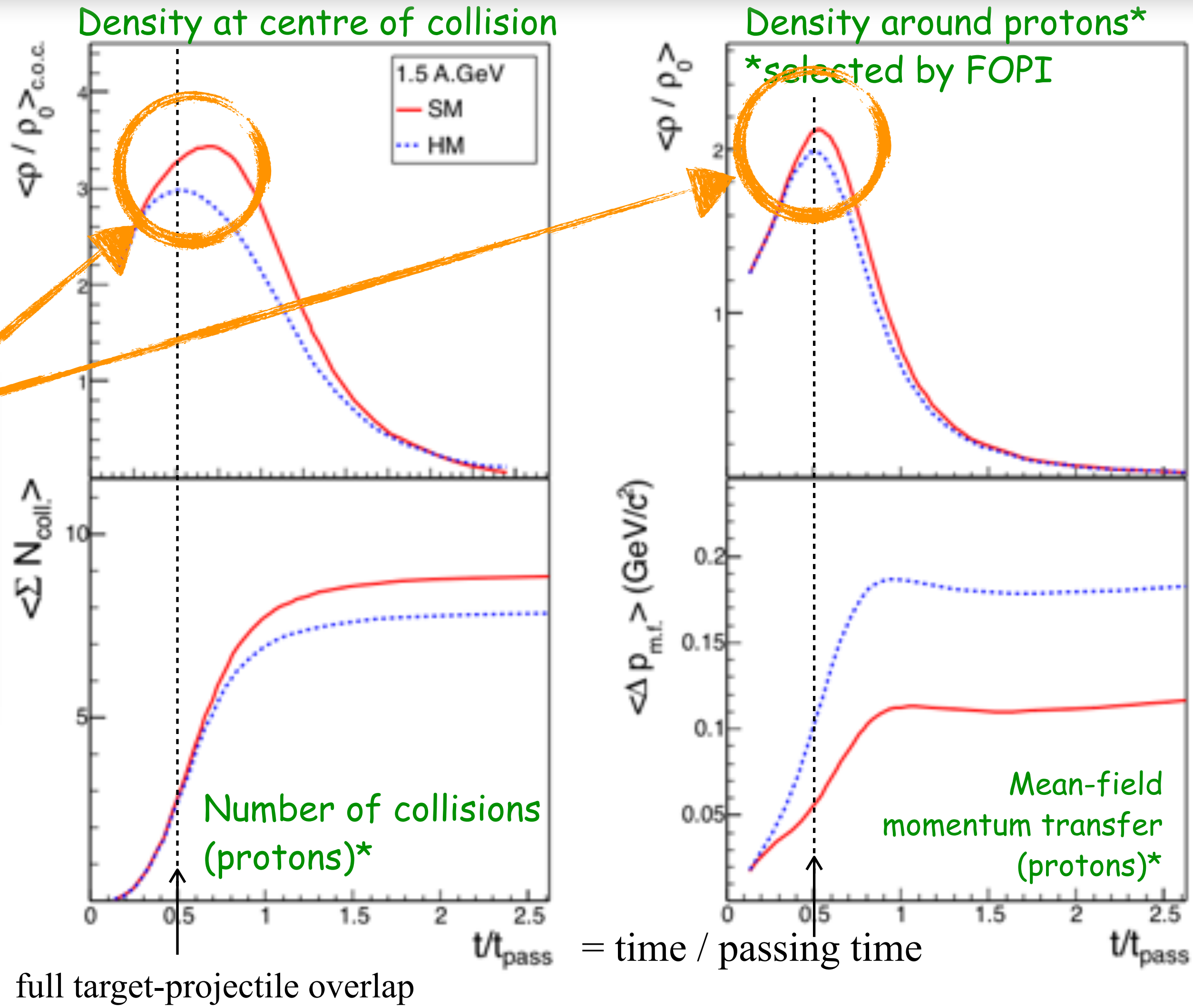
The highest density phase initiates the high pressure, hence the flow.

Tested: a high density cut-off in the EOS => no elliptic flow.



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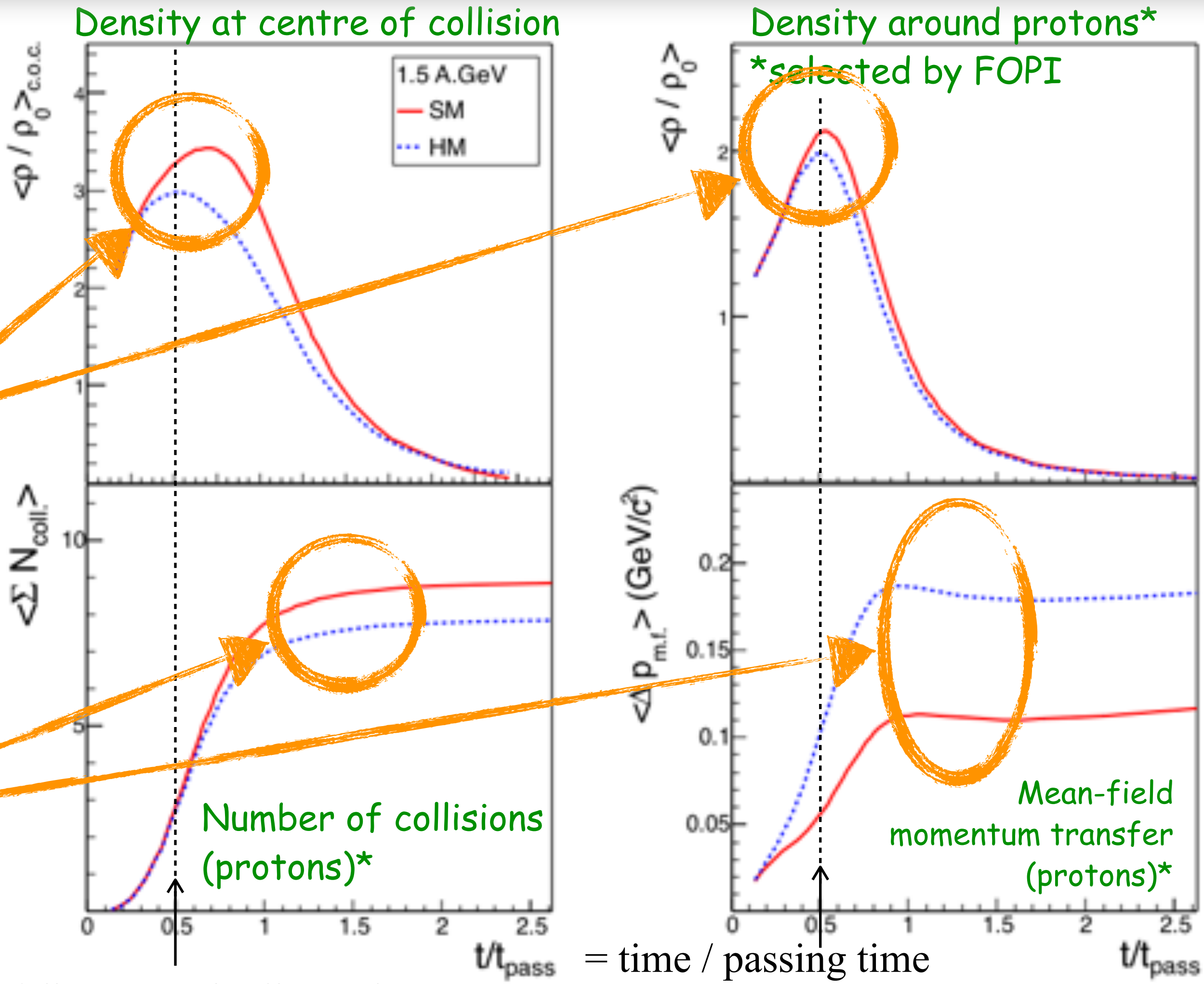
The (flow) dynamics develops up to later times, hence lower densities.



Density at centre of collision

Density around protons*

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Number of collisions (protons)*

Mean-field momentum transfer (protons)*

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full target-projectile overlap

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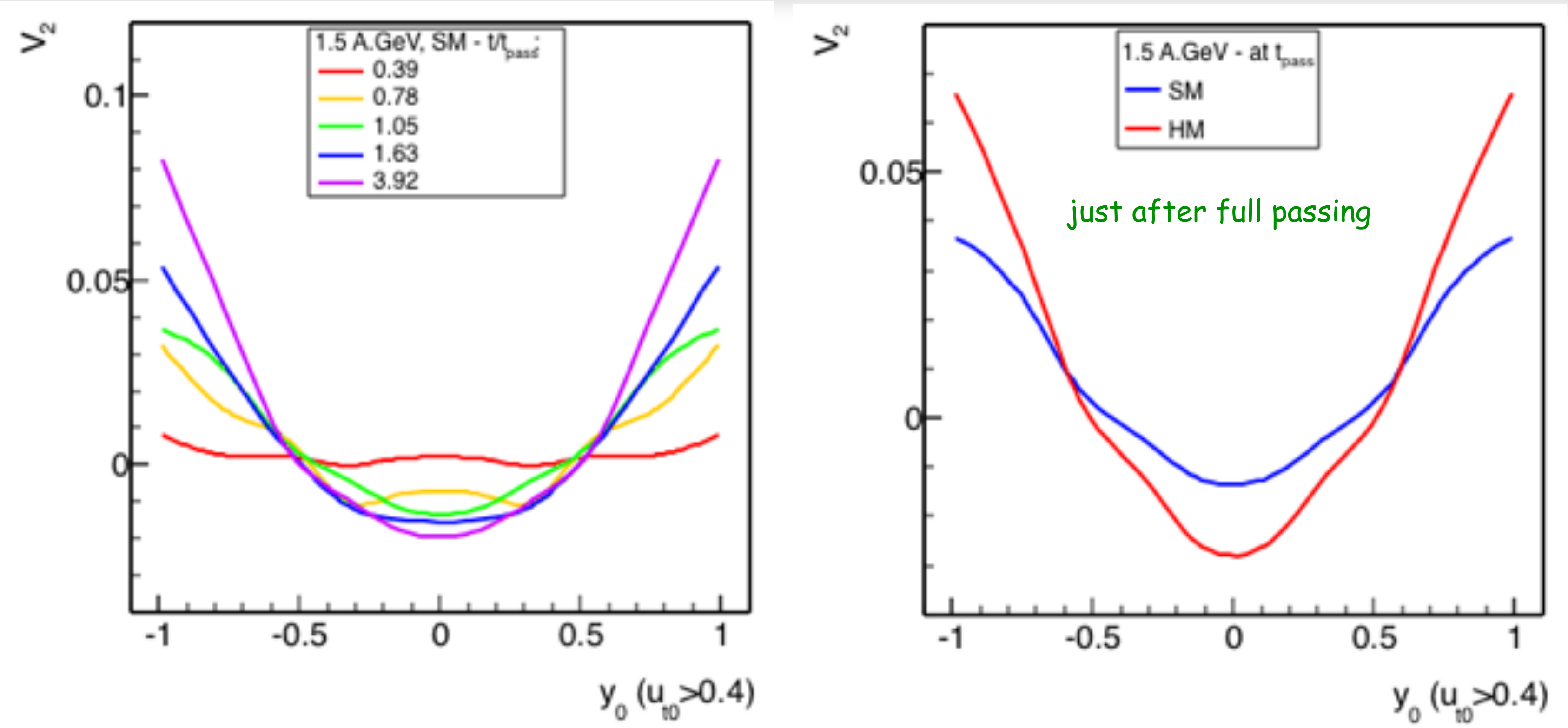

just after full passing

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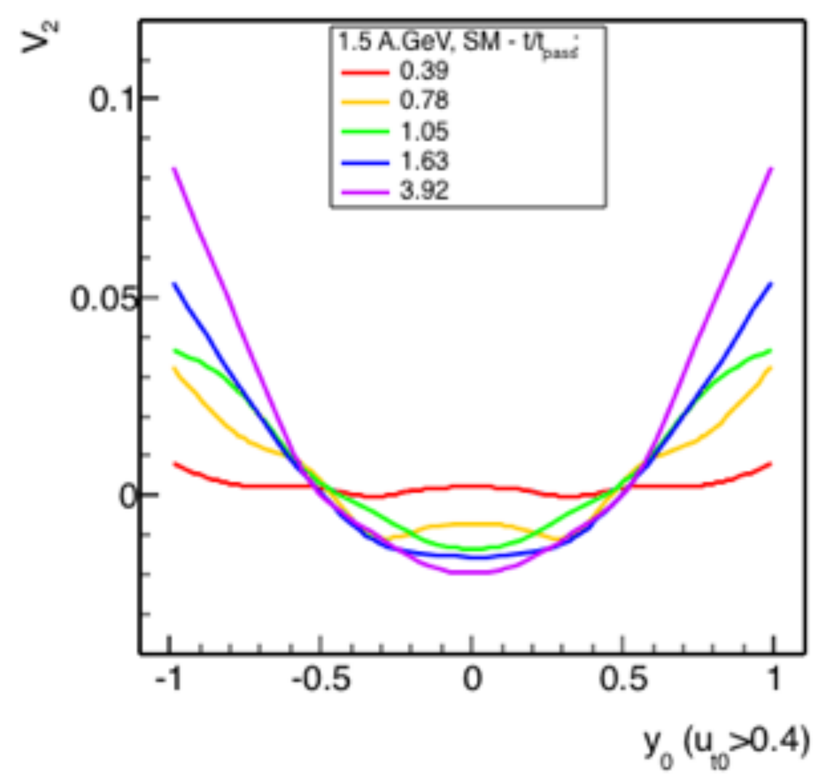
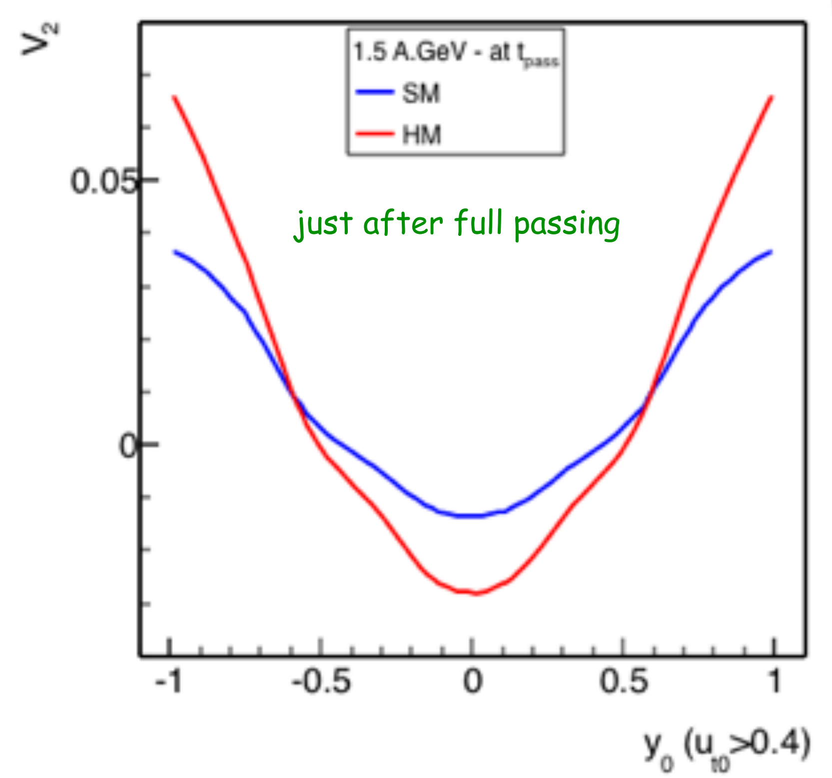
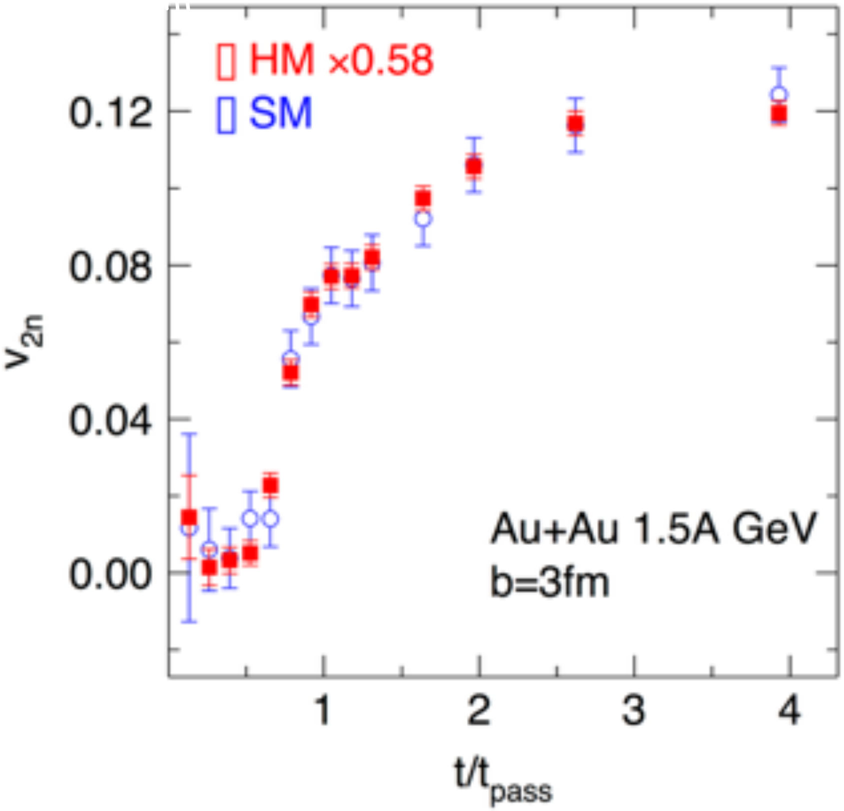




just after full passing

- The elliptic flow at mid-rapidity develops fast: already stabilised at the passing time.
- At $t_{pass}$, the elliptic flow, in its rapidity dependance, depends already strongly on the EOS.
- The elliptic flow around the spectators (|y0| close to 1) stabilises twice slower.

# Simulations: the scenario



- The shape of its rapidity dependance shows a universality with the EOS's (through scaling).

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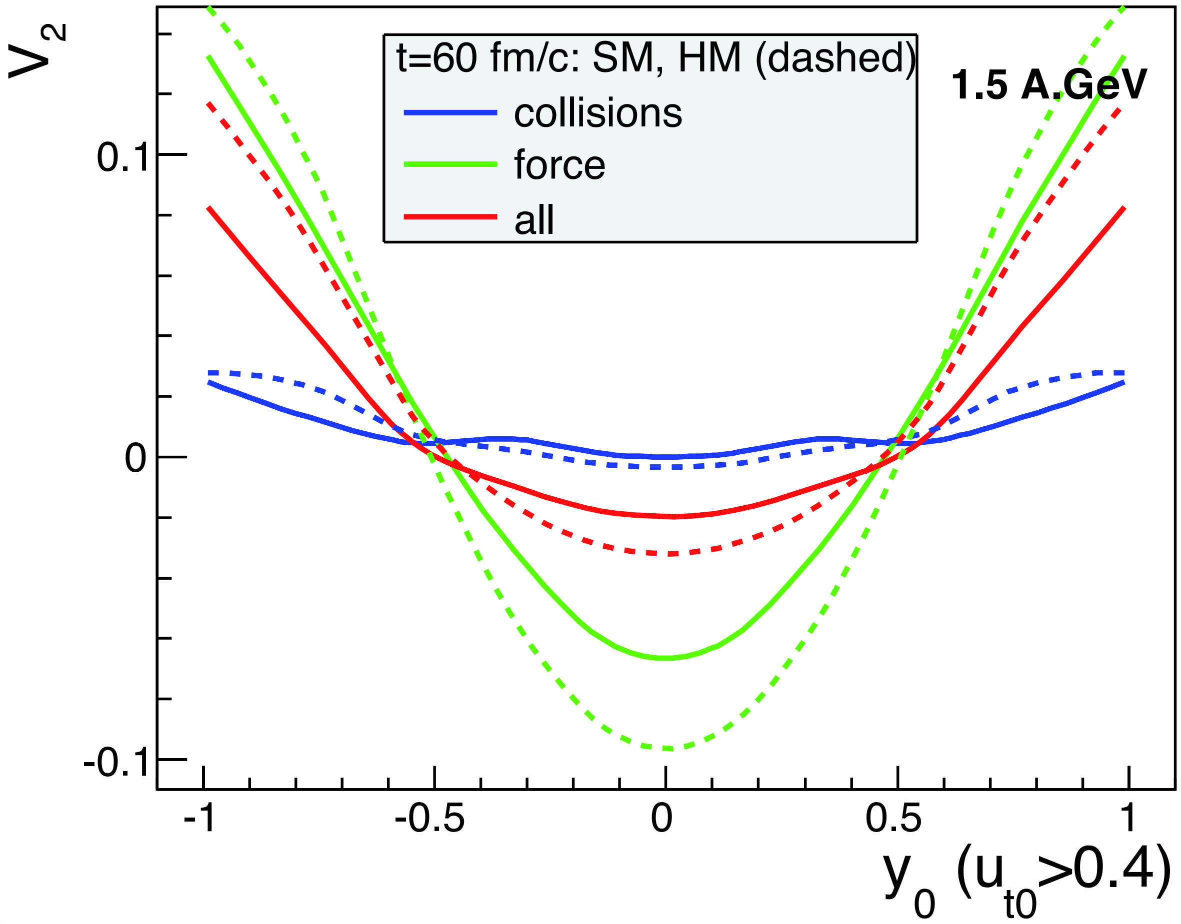
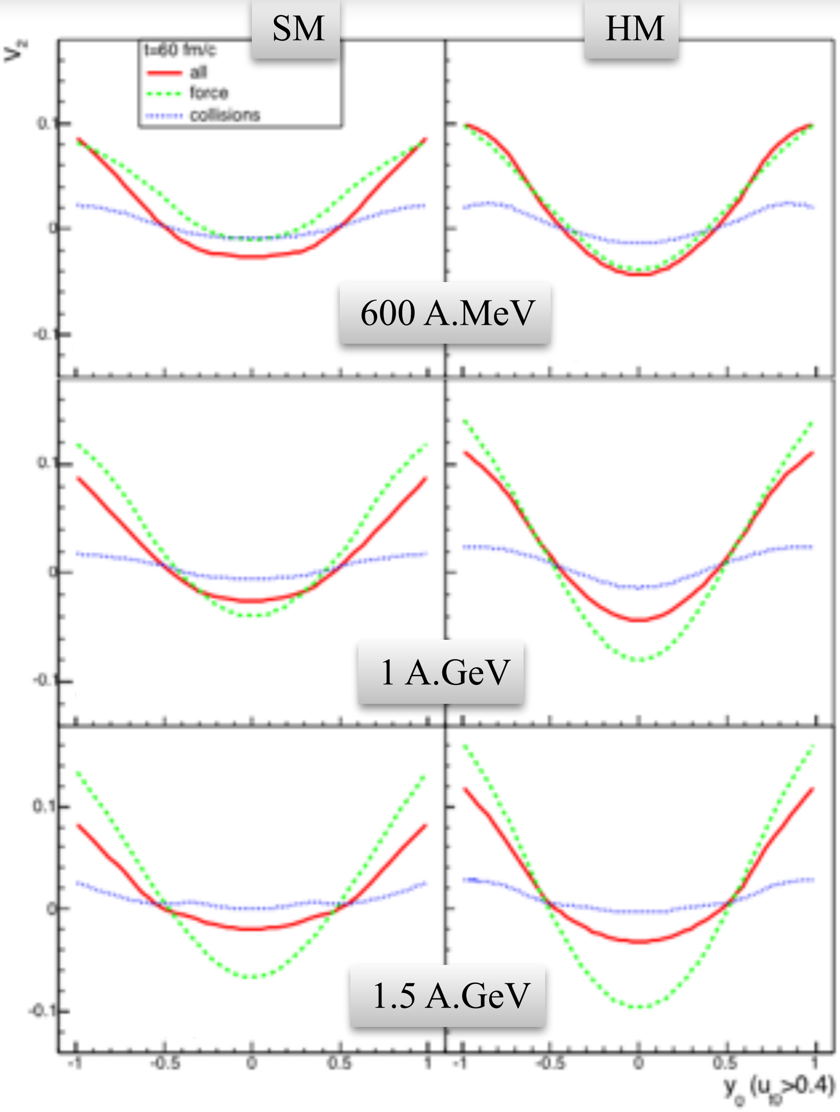


# Simulations: the scenario

- The elliptic flow in strength and shape is mostly influenced by the force of the mean field (hence EOS).
- A 'mean' density characterising the development of the elliptic flow can be built from the mean value weighted by this force up to around the passing time.



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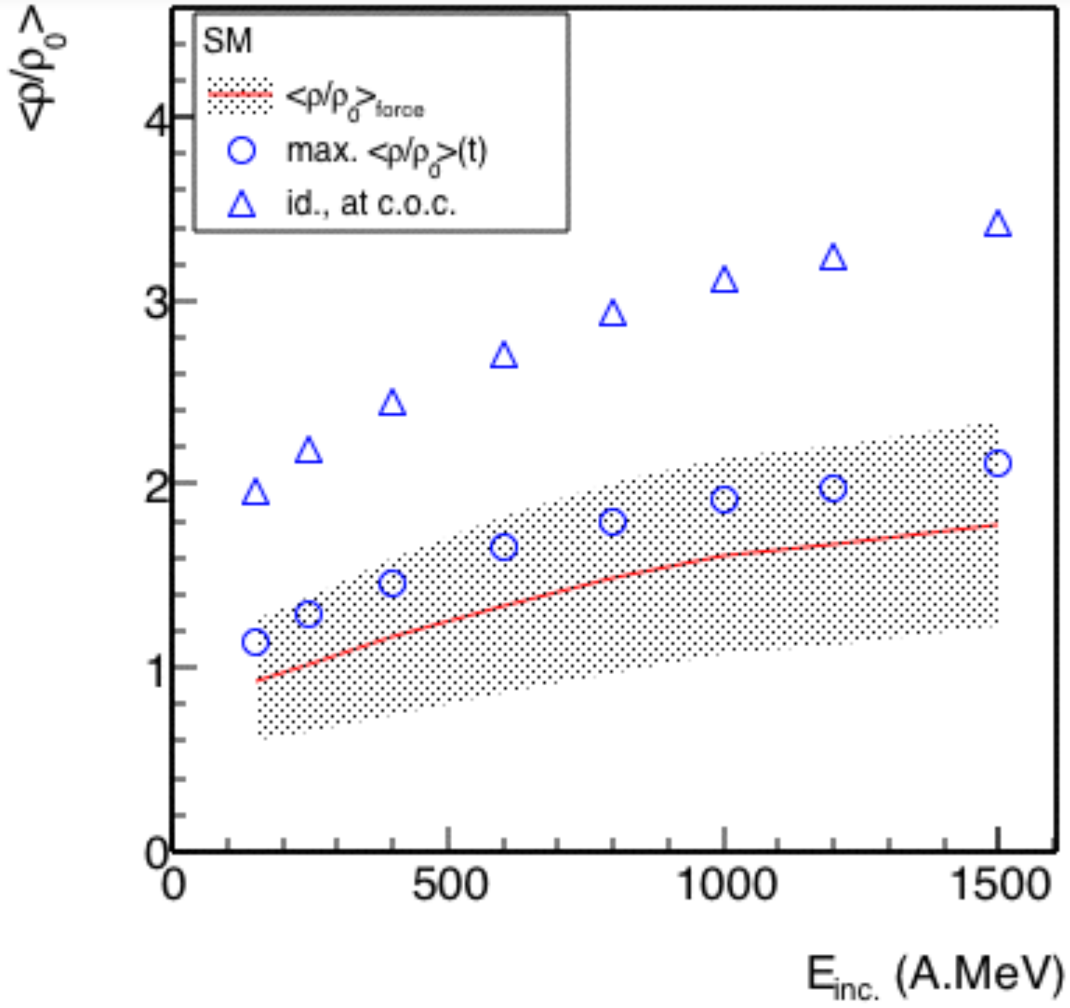

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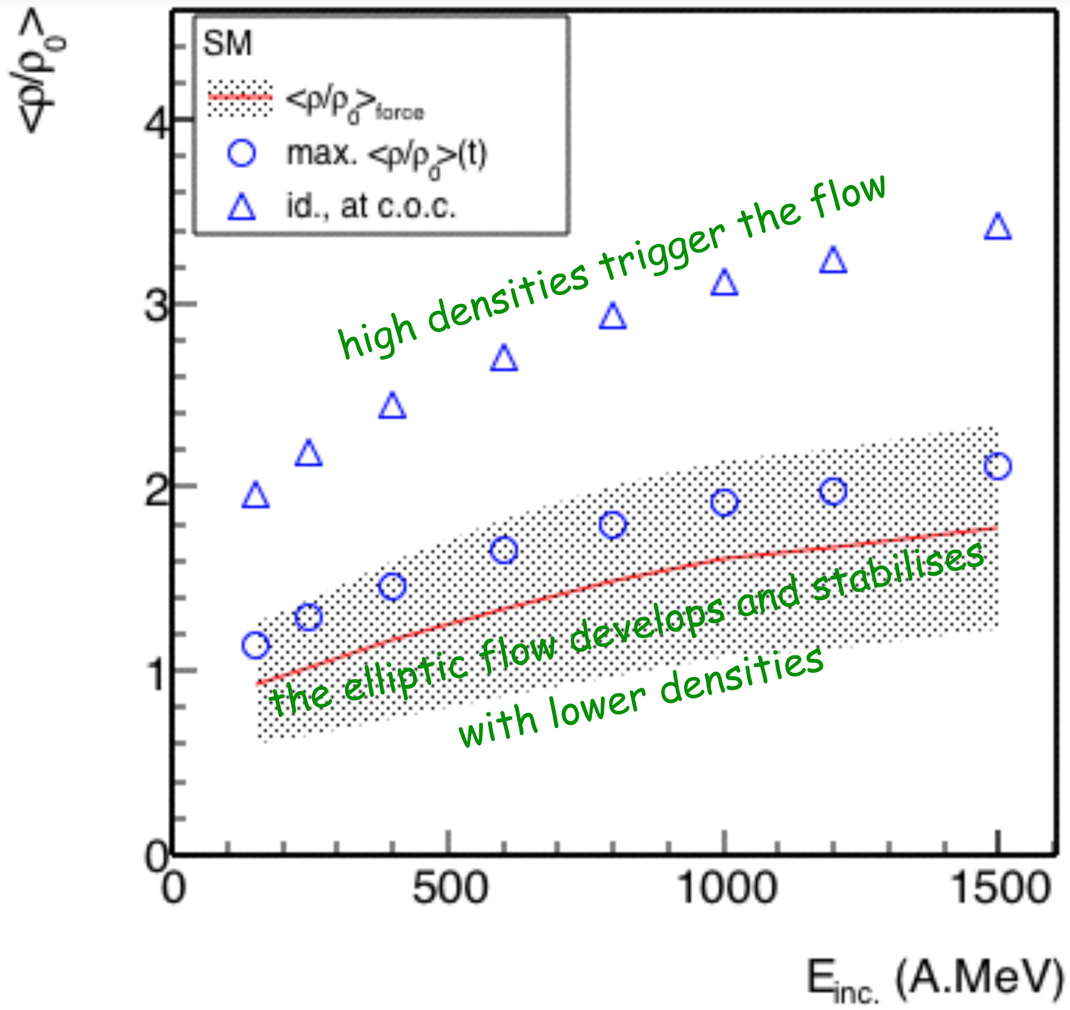

- In the QMD model, the EOS must be correct over a broad range of densities in order to predict the observed elliptic flow.
- The density range, relevant to the EOS evidenced by the FOPI Collaboration, spans in the range $\rho \simeq (1 - 3)\, \rho_0$.

# Summary and discussion

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- A single parameter $v_{2n}$, characterising the elliptic flow over a large rapidity interval, for protons and other light isotopes -> clear discrimination for soft EOS.

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- Pion yields: differ only by about 10% between HM and SM options, imply high experimental accuracy and better transport model predictions (elementary pion cross sections not precisely known).

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*Thank you for your attention!*

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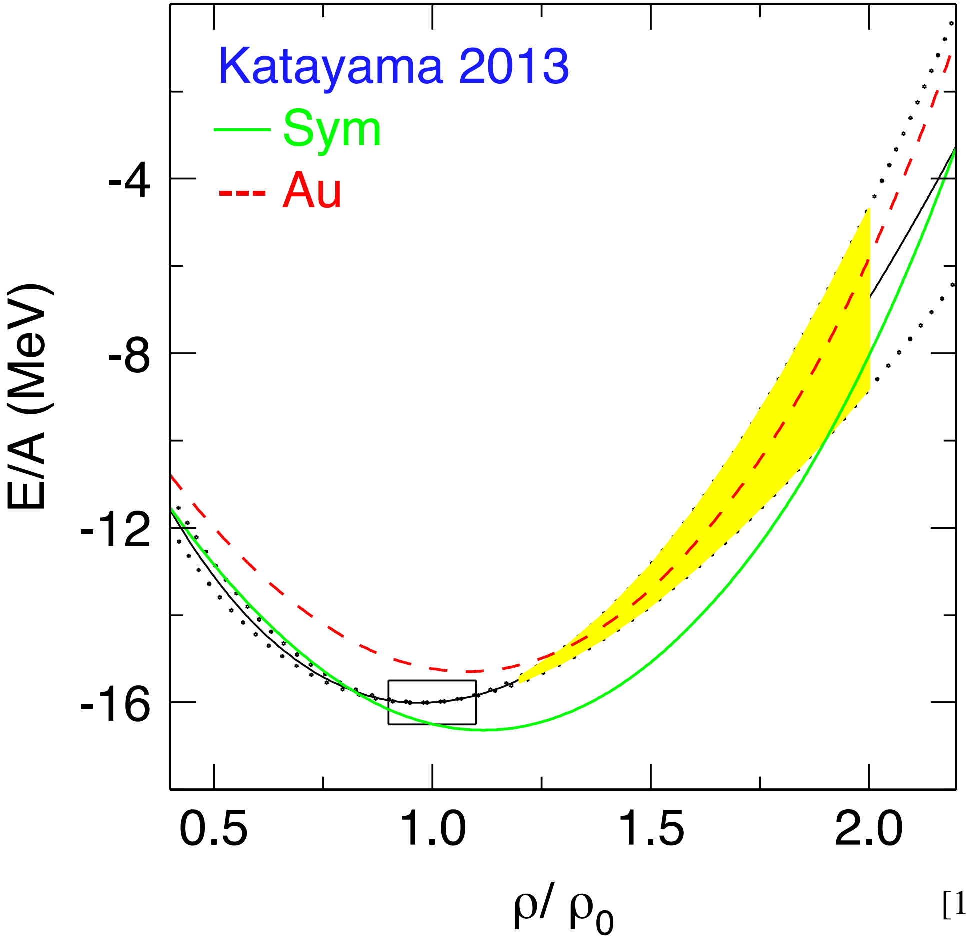
# Comparison to microscopic calculations

(three representative microscopic calculations compared with our new constraints)



Dirac-Brueckner-Hatree-Fock (DBHF) calculation[10] using the Bonn A[11] nucleon-nucleon potential

[10] R. Brockmann, R. Machleidt, Phys. Rev. C 42 (1990) 1965.

[11] T. Katayama, K. Saito, Phys. Rev. C 88 (2013) 035805.

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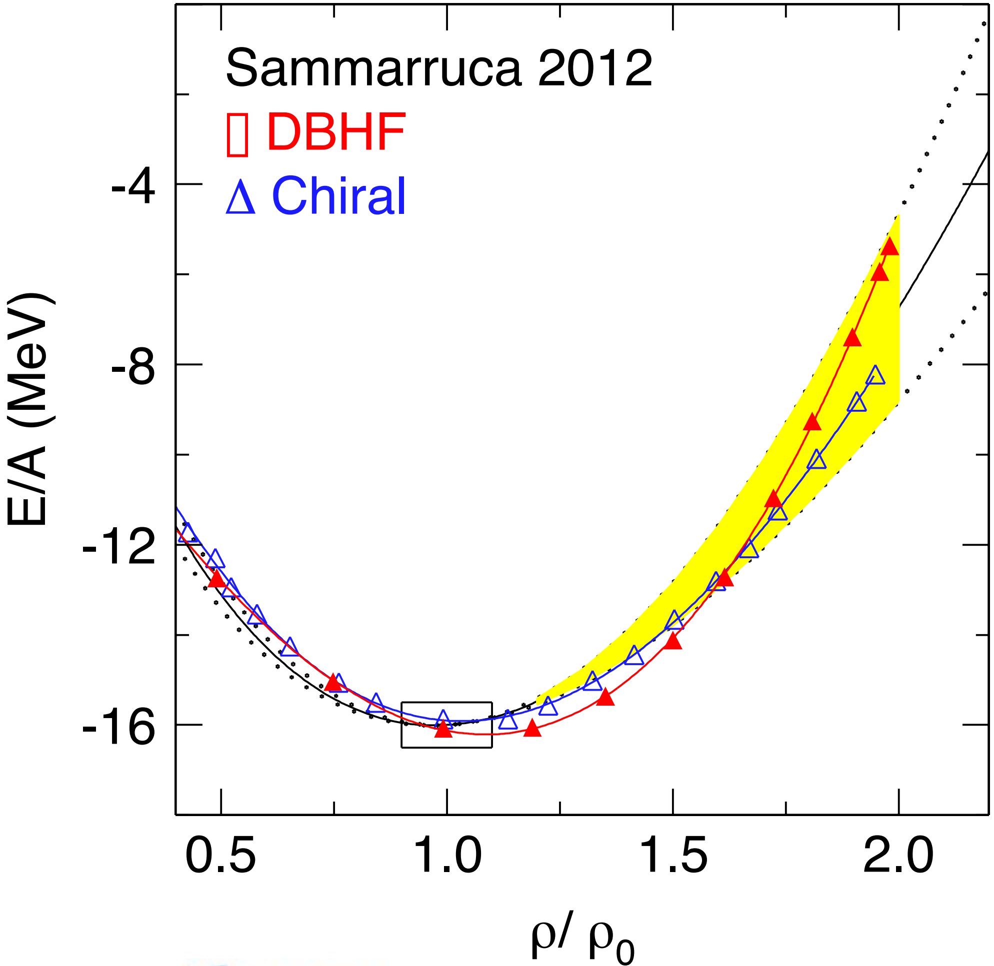

2 symmetric nuclear matter EOS's from [12]:

1) 'DBHF' = meson theoretic potential together with the DBHF method

2) 'Chiral'= use of effective field theory (EFT) with density dependent interactions derived from leading order chiral three-nucleon forces.

[12] P. Danielewicz, G. Odyniec, Phys. Lett. B 157 (1985) 168.

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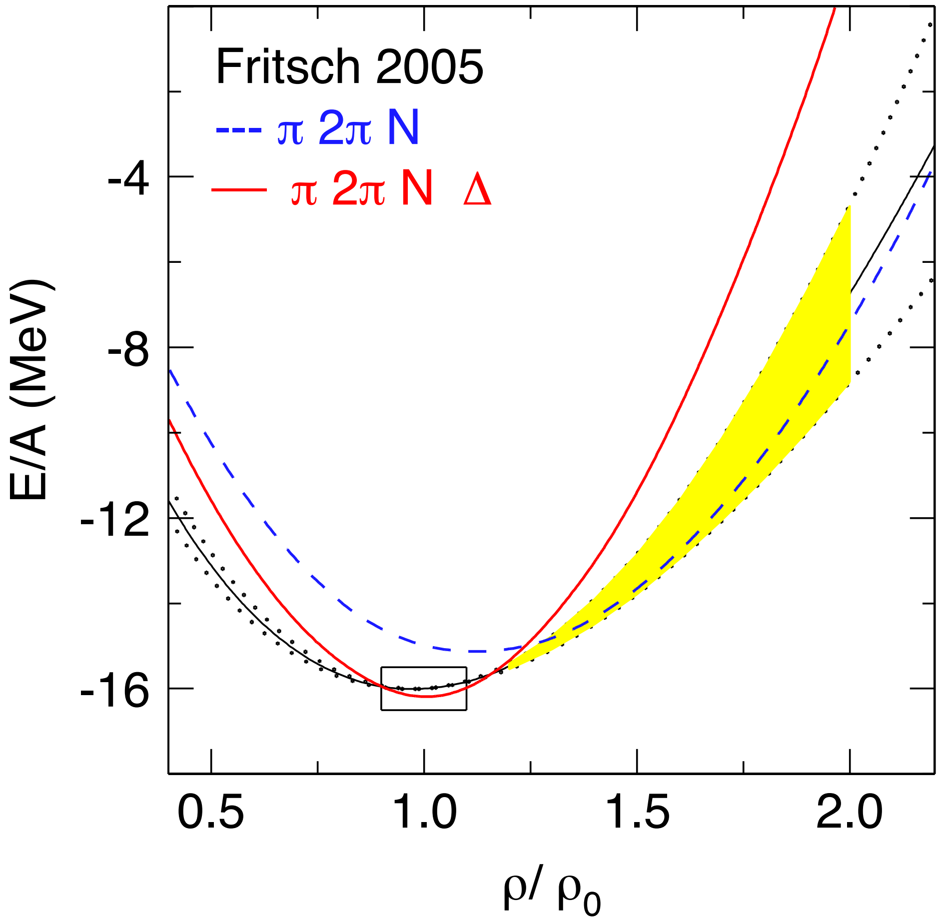

Using the chiral approach[13]: 2 rather different EOS's including or not virtual Δ excitations.

- » the virtual Δ-excitations help locate the EOS at the right horizontal place around ρ = 0.16 fm−3.
- » the Δ leads to a rather marked stiffening of the EOS (K0 = 304 MeV)
- » because 'cold' EOS ?
- » finite temperature in the reaction => the Δ are real rather than virtual. The theoretical 'Δ stiffness' could then be a dispersion effect rapidly changing with temperature.

[13] S. Fritsch, N. Kaiser, W. Weise, Nucl. Phys. A 750 (2005) 259.