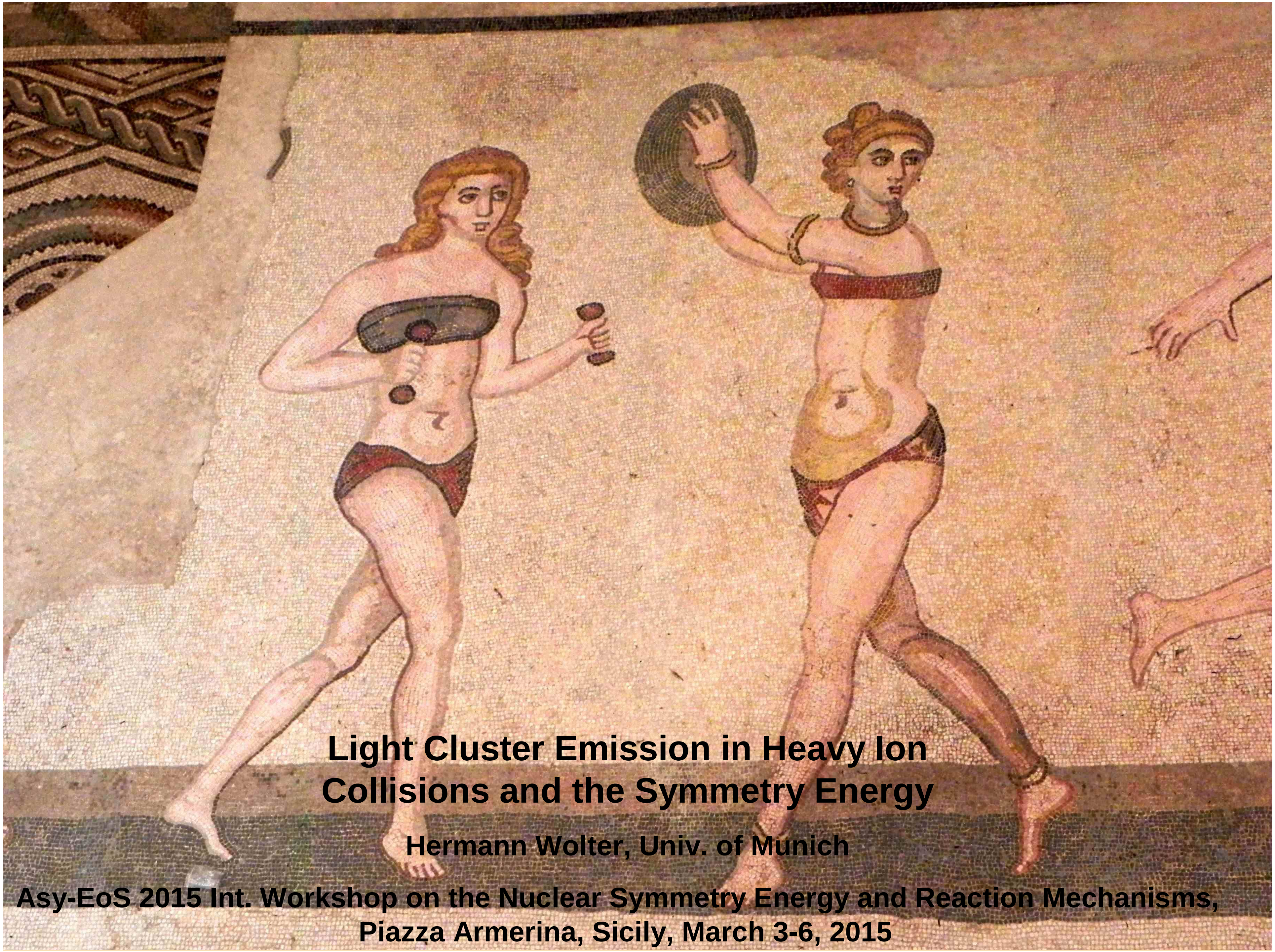


# Light Cluster Emission in Heavy Ion Collisions and the Symmetry Energy

**Hermann Wolter, Univ. of Munich**

**Asy-EoS 2015 Int. Workshop on the Nuclear Symmetry Energy and Reaction Mechanisms, Piazza Armerina, Sicily, March 3-6, 2015**

Organization of the following program points:

1. Comments on Light Cluster Emission
2. Open discussion on aspects of clustering in heavy ion collisions
3. Concluding remarks

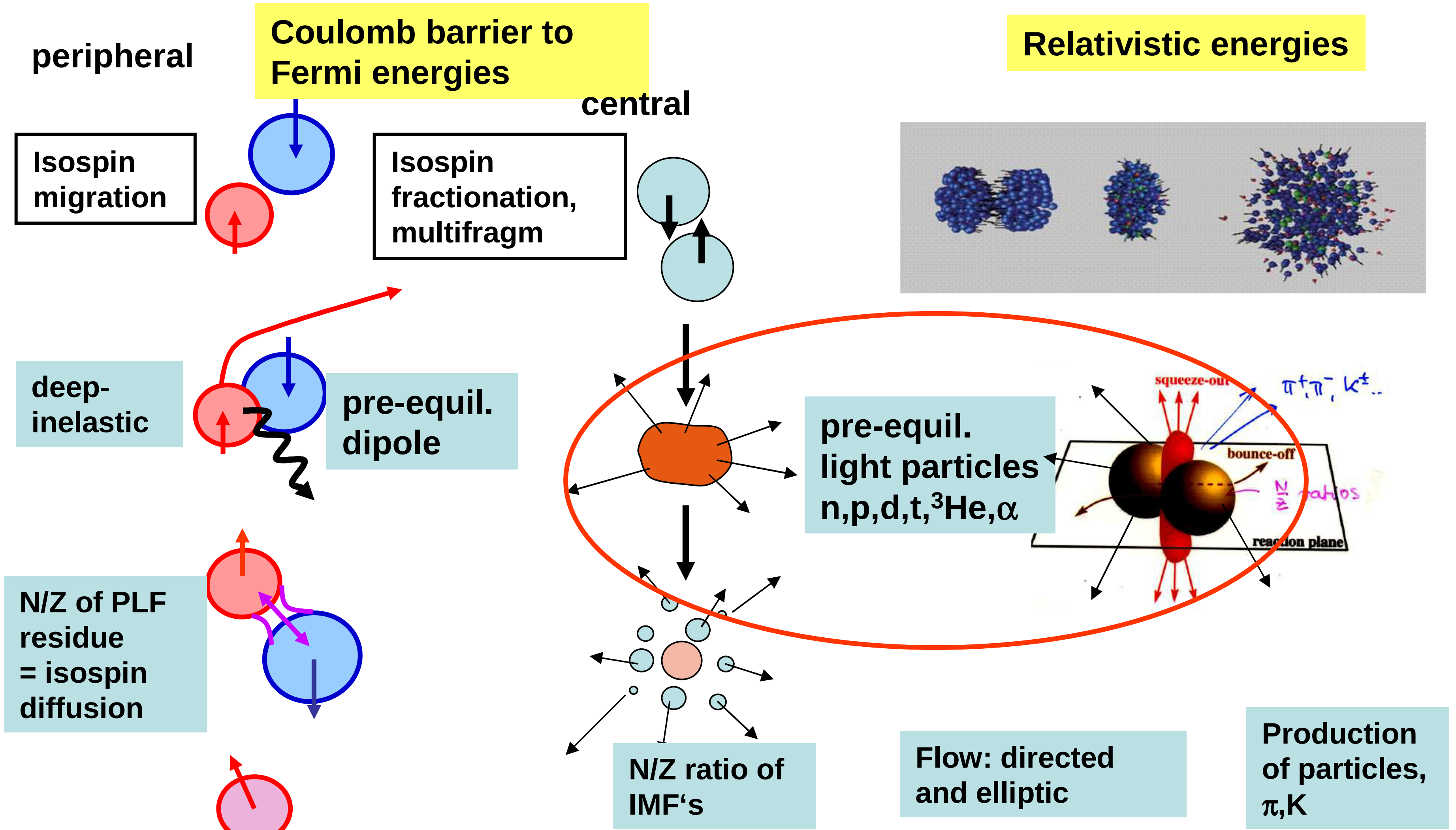
Outline for 1.:
- density and momentum dependence of the symmetry potential
- pre-equilibrium emission of nucleons and light clusters as a probe of the symmetry potential
- results from Xe+Sn (CT) and Sn+Sn (MSU)
- question of light cluster dynamics (→ following discussion)

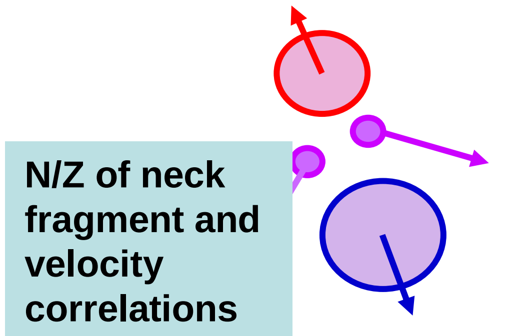
with
Malgorzata Zielinska-Pfabe, Piotr Decowski[+] (Smith Coll., USA),
Maria Colonna (LNS Catania),
with encouragement from Remi Bougault (LPC Caen), Abdou Chbihi (GANIL, Caen)
[+]deceased

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

TUM LMU Excellence Cluster Universe

# Isospin sensitive Observables in Heavy Ion Collisions




Symmetry energy effects are small absolutely (about 10%)
→ use differences or ratios of isospin dependent observables,
to eliminate uncertainties in the isoscalar sector.

# Symmetry energy and symmetry potentials (effective masses)

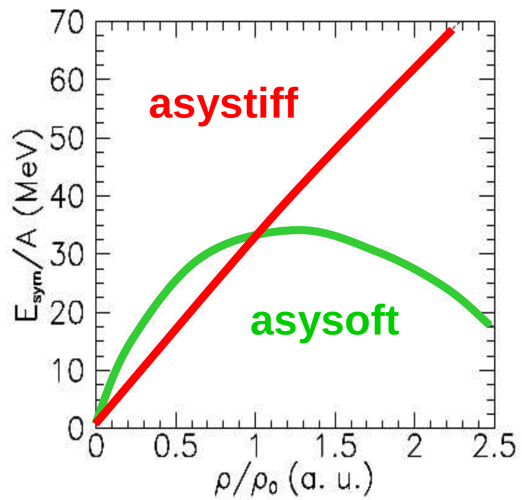
**Momentum dependence of symmetry potential (isoscalar and isovector)**

$$\varepsilon(\rho[f(\rho,k)];\delta) \rightarrow U(\rho,k;\delta) = \frac{\partial\varepsilon(\rho,\delta)}{\partial f(\rho,k)} = \underbrace{U_0(\rho,k) + U_{sym}(\rho,k)(\tau\delta)}_{U_\tau(\rho,k)} + \ldots$$

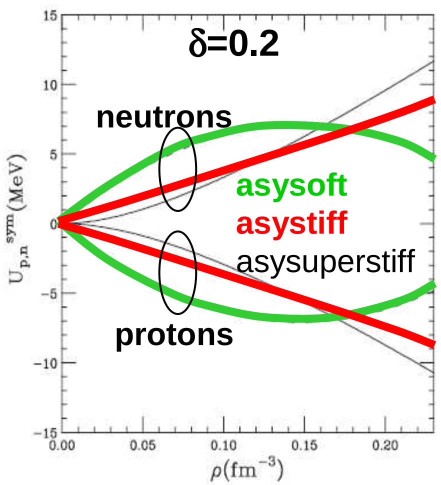
**Effective proton-neutron mass splitting**

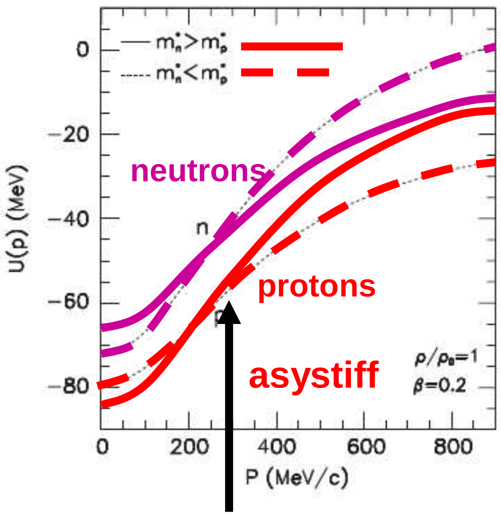
$$\frac{m^*_\tau}{m} = \left(1+\frac{m}{\hbar^2 k}\frac{\partial U_\tau}{\partial k}\right)^{-1}$$

**Symmetry energy**




**Neutron/proton potentials as a fct of density for $p=p_F$ (left) momentum for $\rho=\rho_0$ (right)**




**crossing of potentials**
**→ leads to crossing of emission spectra**

# Symmetry energy and symmetry potentials (effective masses)

**B.A. Li, X. Han, PLB727, 276 (2013)**

**establish a relation $\{E_{sym},L\} \leftarrow\rightarrow \{U_{sym},m^*_{n,p}\}$ using the Hugenholtz-Van Hove theorem**

$$E_{\mathrm{sym}}(\rho) = \frac{1}{3}\frac{\hbar^2 k_F^2}{2m_0^*} + \frac{1}{2}U_{\mathrm{sym}}(\rho, k_F),$$

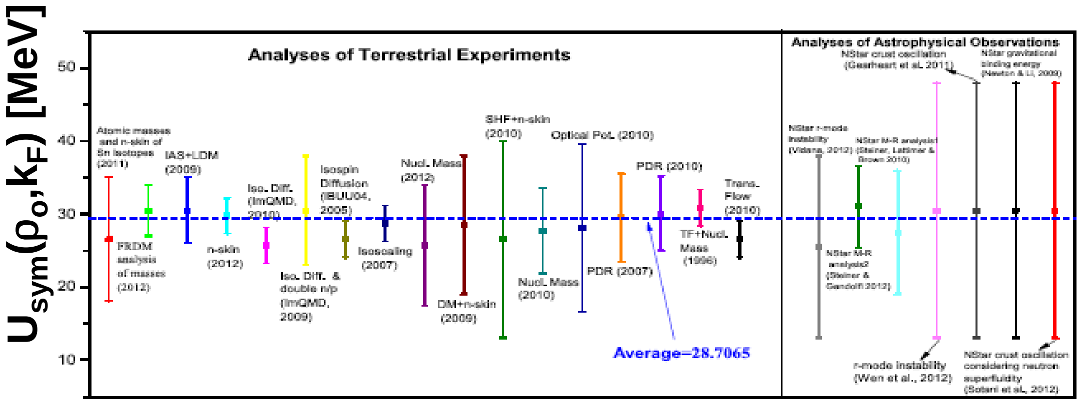
$$L(\rho) = \frac{2}{3}\frac{\hbar^2 k_F^2}{2m_0^*} + \frac{3}{2}U_{\mathrm{sym}}(\rho, k_F) + \frac{\partial U_{\mathrm{sym}}}{\partial k}|_{k_F} k_F,$$

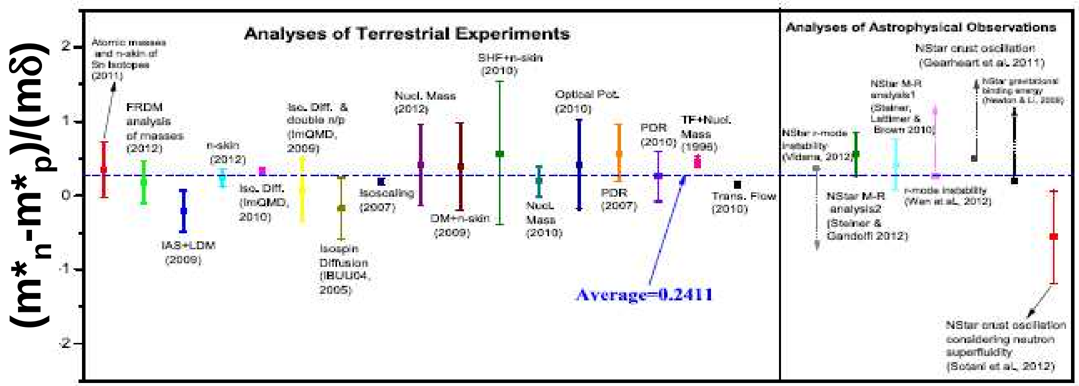
$\Longleftrightarrow$

$$U_{\mathrm{sym}}(\rho_0, k_F) = 2\left[E_{\mathrm{sym}}(\rho_0) - \frac{1}{3}\frac{m}{m_0^*}E_F(\rho_0)\right],$$

$$\left.\frac{dU_{\mathrm{sym}}}{dk}\right|_{k_F}(\rho_0) = \left[L(\rho_0) - 3E_{\mathrm{sym}}(\rho_0) + \frac{1}{3}\frac{m}{m_0^*}E_F(\rho_0)\right] \Big/ k_F,$$

**Use existing determinations in the literature for $\{E_{sym},L\}$ to obtain values for $\{U_{sym},m^*_{n,p}\}$**

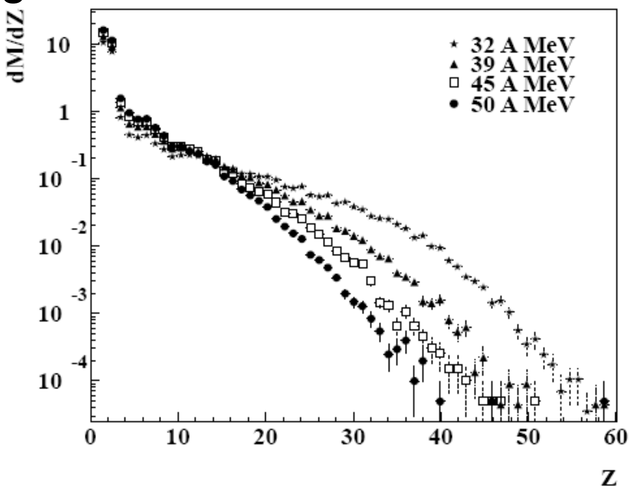


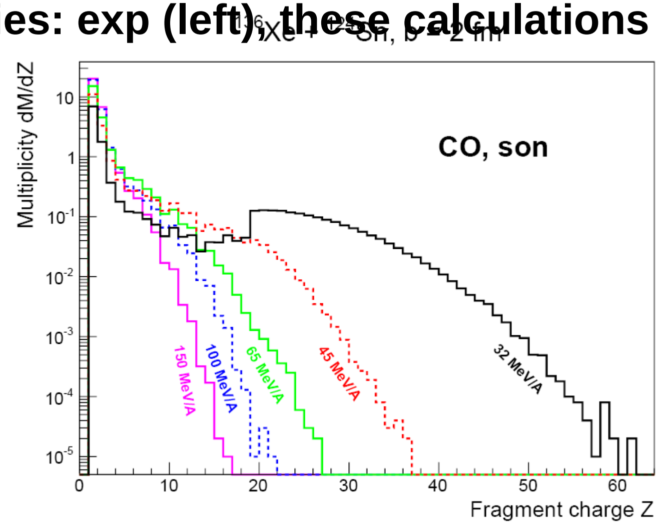

- **On the averge $m^*_n > m^*_p$,**
- **mainly determined by nuclear structure and astrophysics,**
- **however, error bars are large.**

# Study of Light Fragment Emission: $^{136,124}Xe+^{124,112}Sn$, E = 32,..,150 AMeV

**fragment distributions at different energies: exp (left), these calculations (right)**




S. Hudan, et al., PRC67, 064613




H.H. Wolter, et al., EPJ Web of Conf. &&, 03097 (2014)

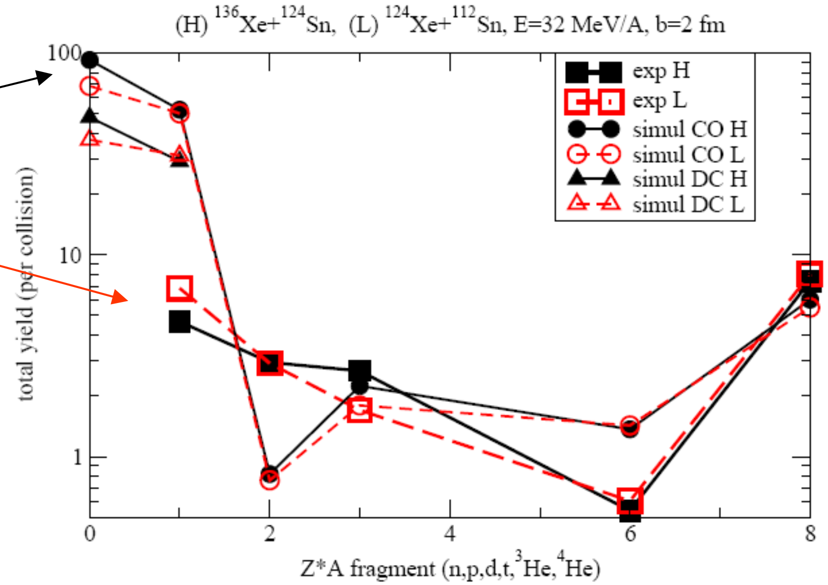
**Cluster recognition: (both a-posteriori)**

**DC: „density cut“ coordinate space coalescence with $\rho_c > \rho_0/8$**

**CO: „coalescence“ in coordinate and momentum space, $r_0$=1.6fm, $p_0$=1.3fm$^{-1}$**

**overpredict nucleons with CO**

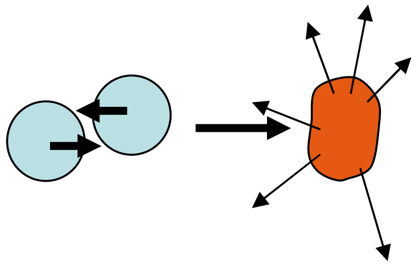
**data R. Bougault, A. Chbihi (Ganil, prelim, IWM11)**




**H: $^{136}Xe+^{124}Sn$**
**L: $^{124}Xe+^{112}Sn$**

**general pattern ok, but differences in detail**

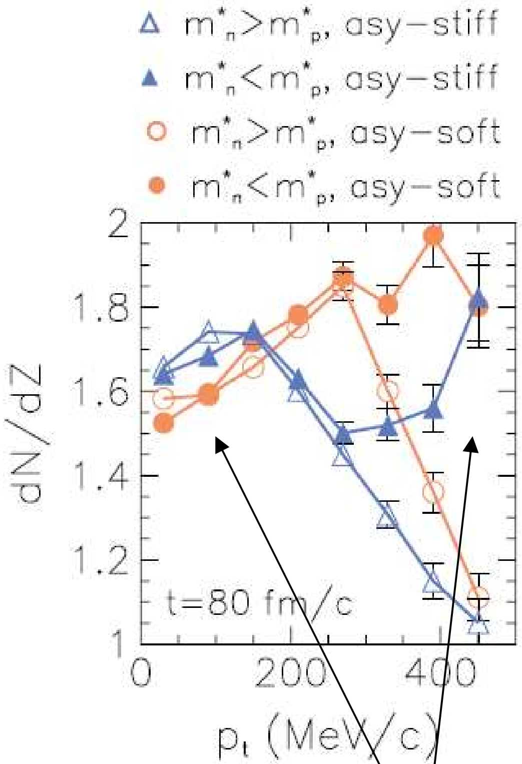
# Ratios of emitted pre-equilibrium particles in central collisions



**Early emitted neutrons and protons reflect difference in potentials in expanded source, esp. ratio Y(n)/Y(p).**

**Previous studies:**

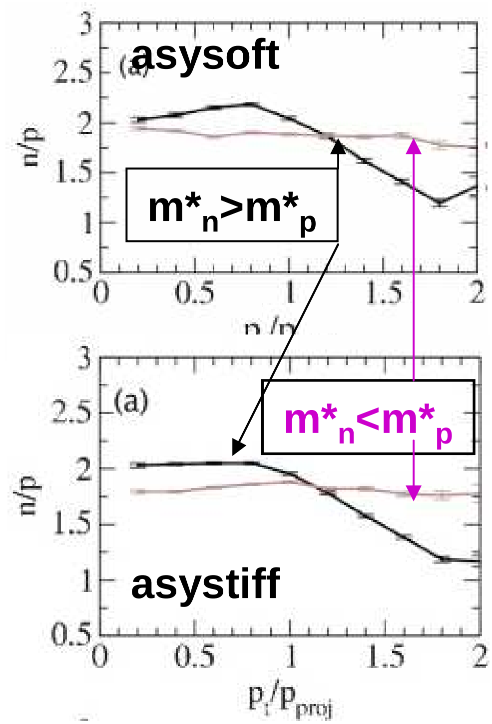
**$^{132}Sn+^{124}Sn$, 100 AMeV**




**splitting dep. on stiffness of symm energy resp. effect, mass**

**(J. Rizzo et al., PRC72,064609 (2005))**

**$^{197}Au+^{197}Au$. 600 AMeV**

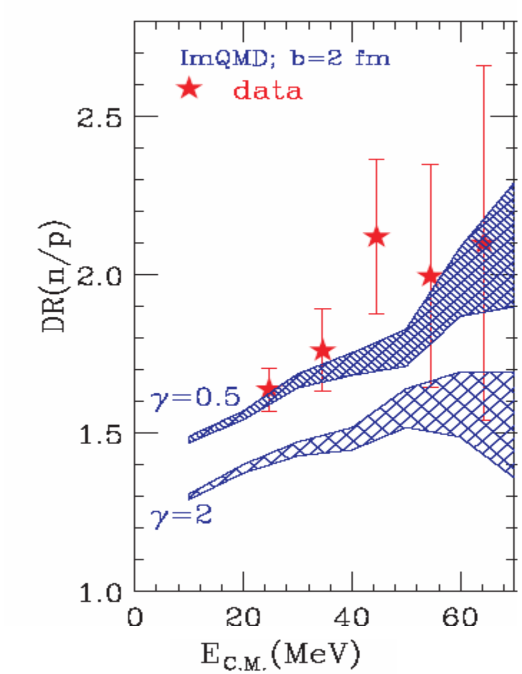



**essentially only dep. on eff. mass**

**V.Giordano, et al., PRC 81(2010))**

**Double Ratios** $\frac{^{124}Sn + ^{124}Sn}{^{112}Sn + ^{112}Sn}$

**50 AMeV**




**no effective mass depend.**

**M. Famiano, et al., PRL 97,052701 (06)**
**M.B.Tsang, et al., PRL 102, 122701 (09)**

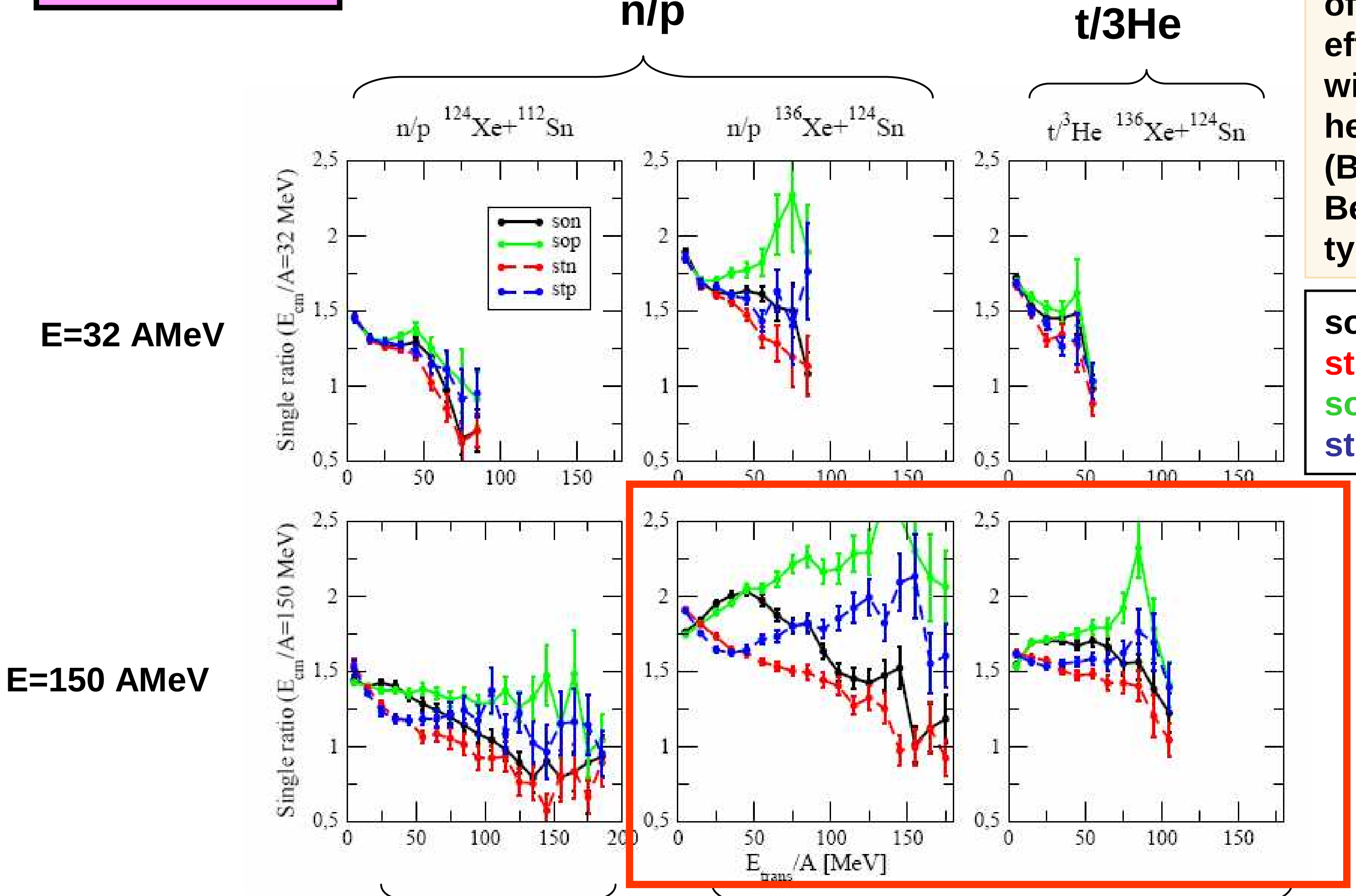
# Light Fragment Emission: $^{136,124}Xe+^{124,112}Sn$, E = 32,.,150 AMeV ,

**Single ratios**

effects smaller for heavier clusters,
but have to improve statistics

Variation
of density dep. and
effective mass splitting
with isoscalar potential
held fixed
(Bombaci-Gale-
Bertsch-DasGupta
type)

son: asysoft, $m_n^* > m_p^*$
stn: asystiff, $m_n^* > m_p^*$
sop: asysoft, $m_n^* < m_p^*$
stp: asystiff, $m_n^* < m_p^*$




look in more detail
on next page

neutron poor
$^{124}Xe+^{112}Sn$

neutron rich
$^{136}Xe+^{124}Sn$

effects smaller for neutron poor

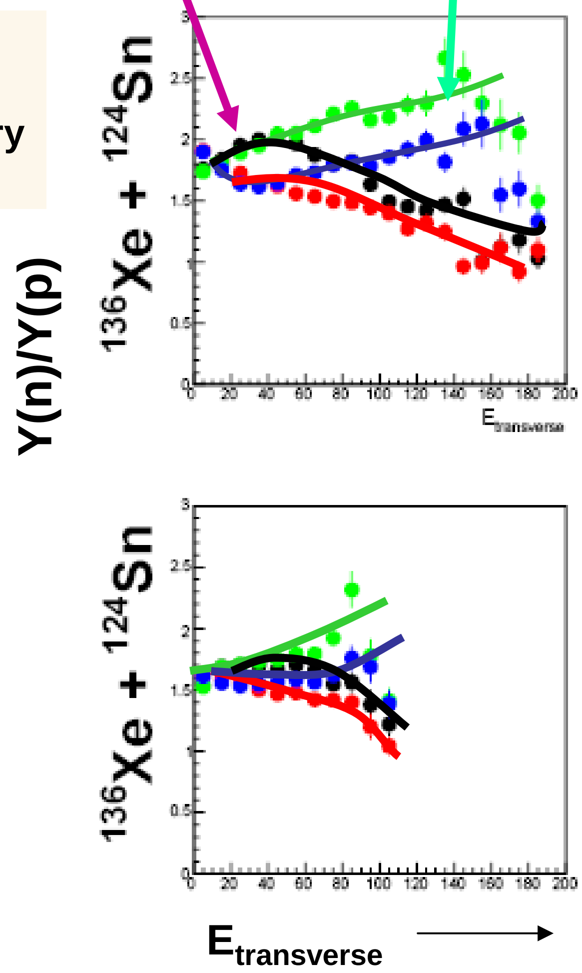
H.H. Wolter, et al.,
EPJ Web of Conf. &&, 03097 (2014)

**Asy-EOS dominates for slow particles; asysoft has larger repulsion at lower densities**

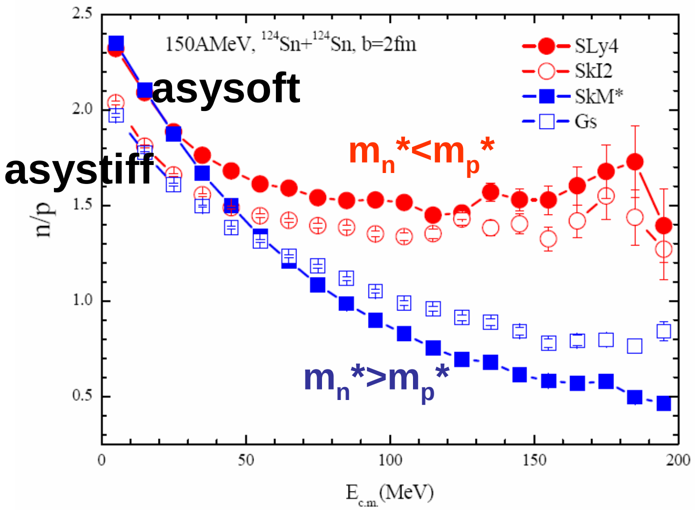
**Effective mass dominates for fast particles; smaller eff. mass favors emission**

**E=150 AMeV**

**Possibility to separate density and momentum dependence of symmetry energy**




**similar conclusions for Sn+Sn collisions (MSU)**




**Y. Zhang, M.B.Tsang, et al., PLB 732, 186 (2014)**

**Effect also exists for light clusters (easier to measure) but somewhat reduced**

**son: asysoft, $m_n^* > m_p^*$**
**stn: asystiff, $m_n^* > m_p^*$**
**sop: asysoft, $m_n^* < m_p^*$**
**stp: asystiff, $m_n^* < m_p^*$**

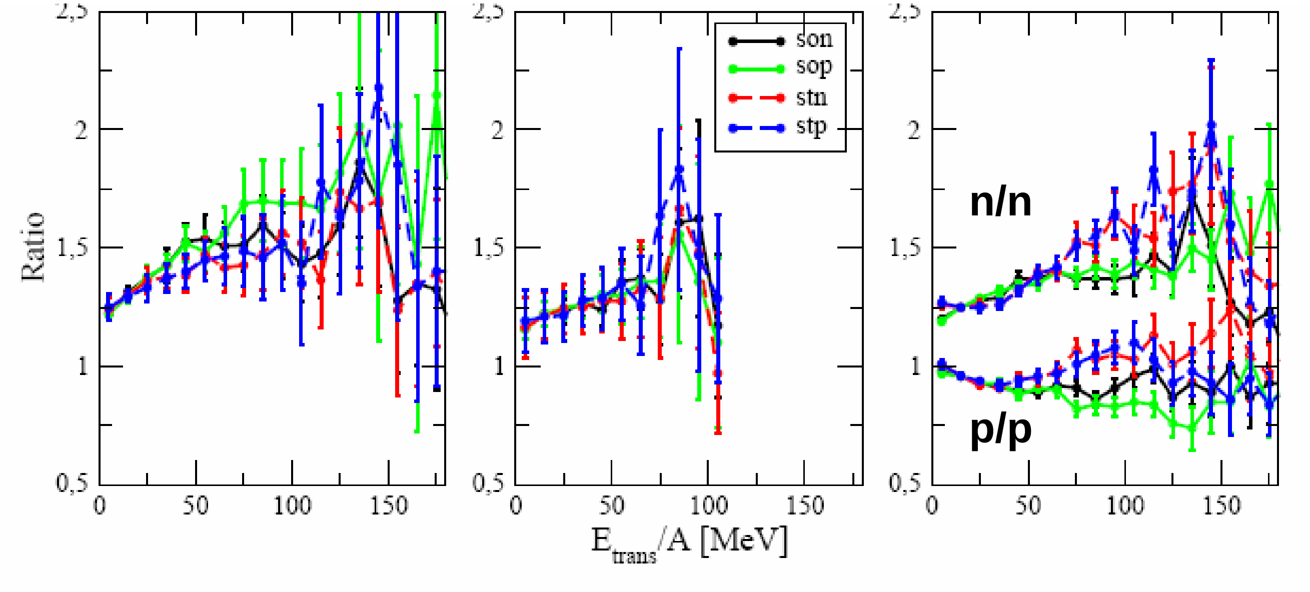
## Double Ratios

$$\frac{n/p\;_{^{136}Xe+^{124}Sn}}{n/p\;_{^{124}Xe+^{112}Sn}}$$

$$\frac{t/^{3}He\;_{^{136}Xe+^{124}Sn}}{t/^{3}He\;_{^{124}Xe+^{112}Sn}}$$

## Singe Ratios

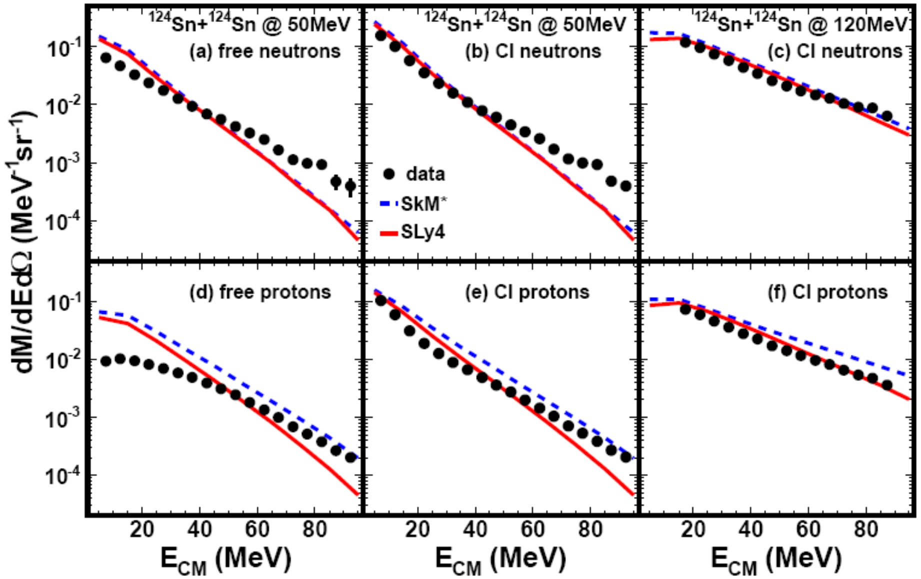
$$\frac{n_{^{136}Xe+^{124}Sn}}{n_{^{124}Xe+^{112}Sn}},\ resp.,\ \frac{p_{^{136}Xe+^{124}Sn}}{p_{^{124}Xe+^{112}Sn}}$$

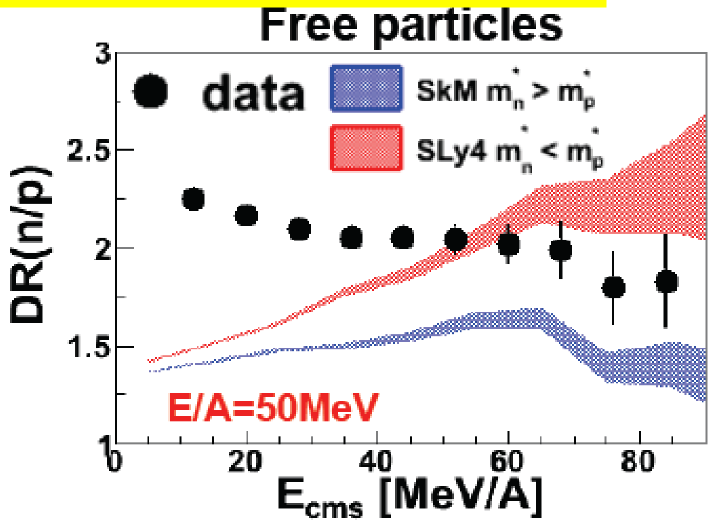


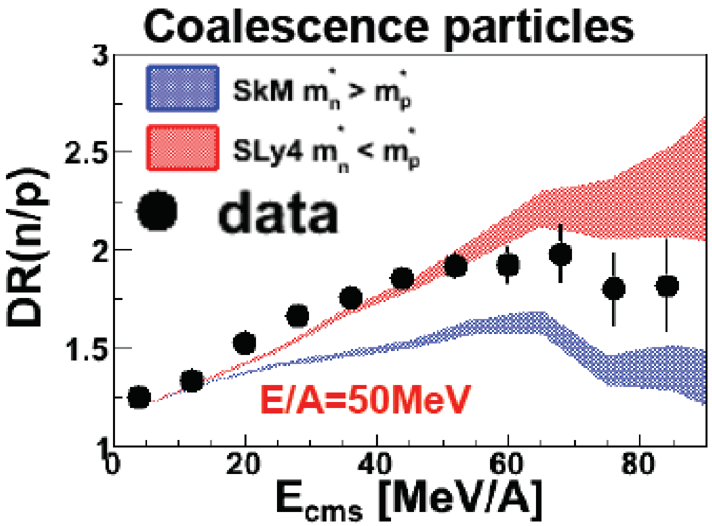

**sensitivity much smaller**

**sensitivity only to asy-stiffness**

## Comparison with data:
## problem of light cluster description in transport approaches
**(recent work from MSU)**



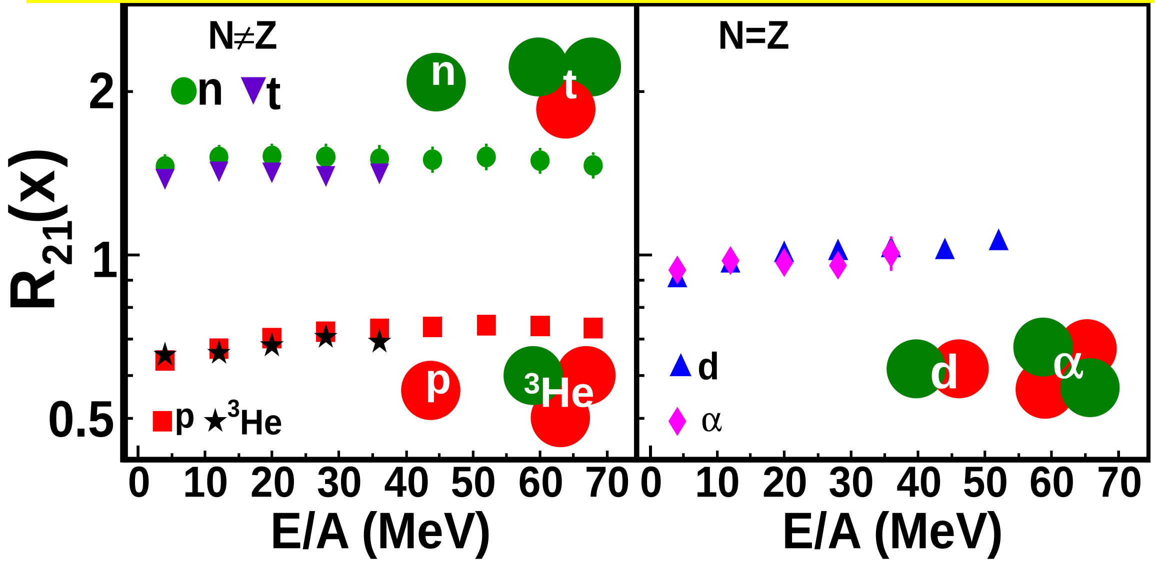




**coalescence invariant spectra agree better with experiment: A poor man's substitute for not treating light clusters properly in the simulation**

**favors slightly $m_n^*<m_p^*$ (in contrast to other analyses, see above)**
**→ more work required!**


Y.X. Zhang, M.B.Tsang,et al., PLB 732, 186 (2014)
D.D.S.Coupland, arXiv 1406.4546

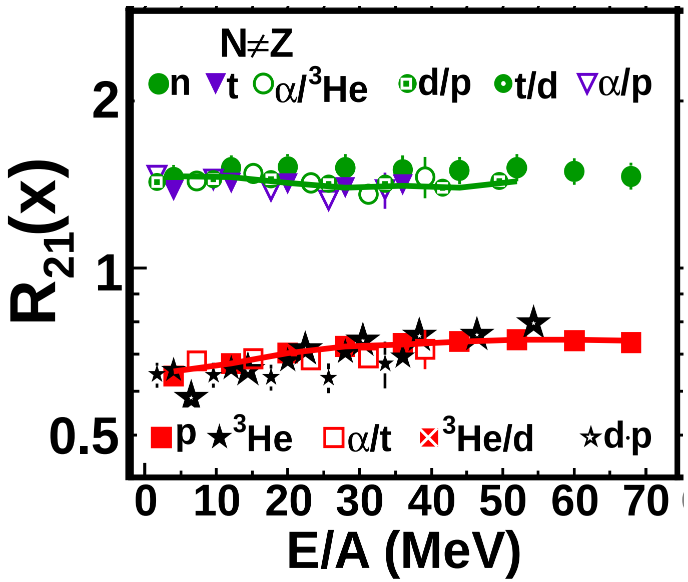
**An interesting note:**
**„Chemical potential scaling“ Z.Chajecki, et al., arXiv 1402.5216**

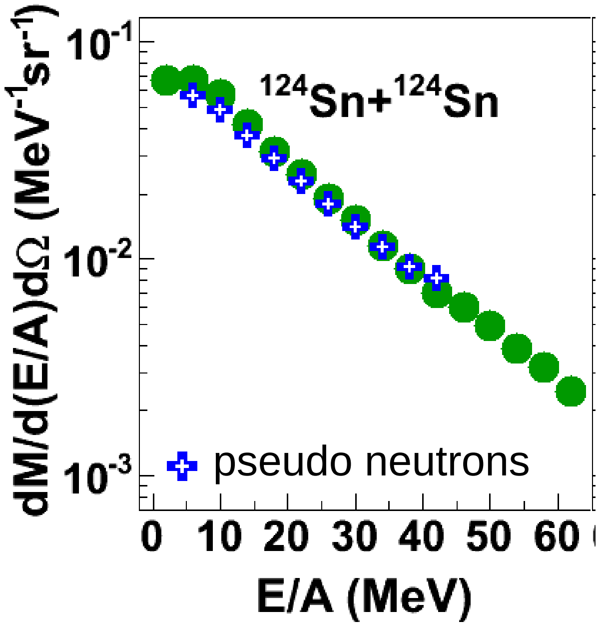



$$R_{21}(N,Z) = \frac{dM_2(N,Z)}{dM_1(N,Z)}$$

**expect from chemical potential dependence without correlation contributions**

$$R_{21}(N,Z) = \exp\left[\left(N\Delta\mu_n + Z\Delta\mu_p\right)/T\right]$$



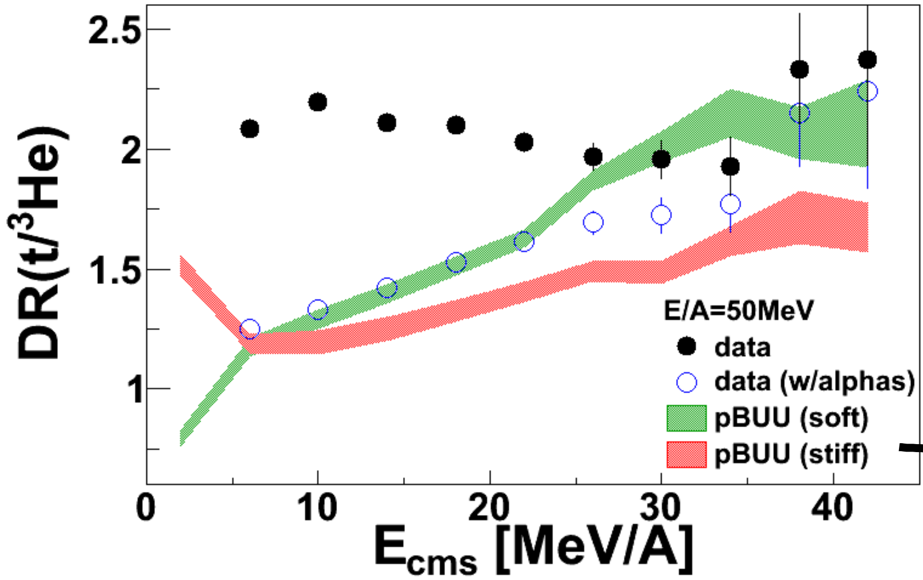

$$\Rightarrow Y(n) = \frac{Y(t)}{Y(^3He)} Y(p)$$

**“Pseudo neutron yields”**

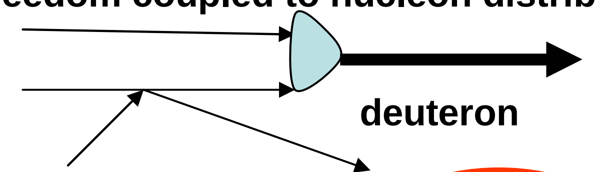
**correlation effects seem to be small for light cluster yields (?)**

# Interdependence of light cluster yields

W.Lynch, INPC, Florence, 2013:
$^{124,112}Sn+^{124,112}Sn$, 50 AMeV;
Z. Chajecki, NuSYM13




LC's as explicit degrees of freedom coupled to nucleon distribution functions by 3-body collisions of type NNN→ND




P. Danielewicz and Q. Pan, PRC 46 (1992): (d,t,$^3$He, but no α!) coupled transport eqs.

→ cluster yields depend on each other

## Conclusions:

**- pre-equilibrium nucleon and light cluster emission directly prpbe density and momentum dependence of symmetry potential**

**- the single ratio spectra may allow to separate this density and momentum dependence.**
**The energy range around 100 to 200 MeV is most sensitive. At higher energy sensitive mainly to momentum dependence**

**- more asymmetric systems and the n/p ratio are most sensitive. The t/3He ratio carries a similar information**

**- more precise data recently available, but not yet precise enough to determine effective masses (at some stress with other determinations)**

**- touches question of dynamical light cluster description in HIC**
**(→ see following discussion)**