Core-crust transition in neutron stars

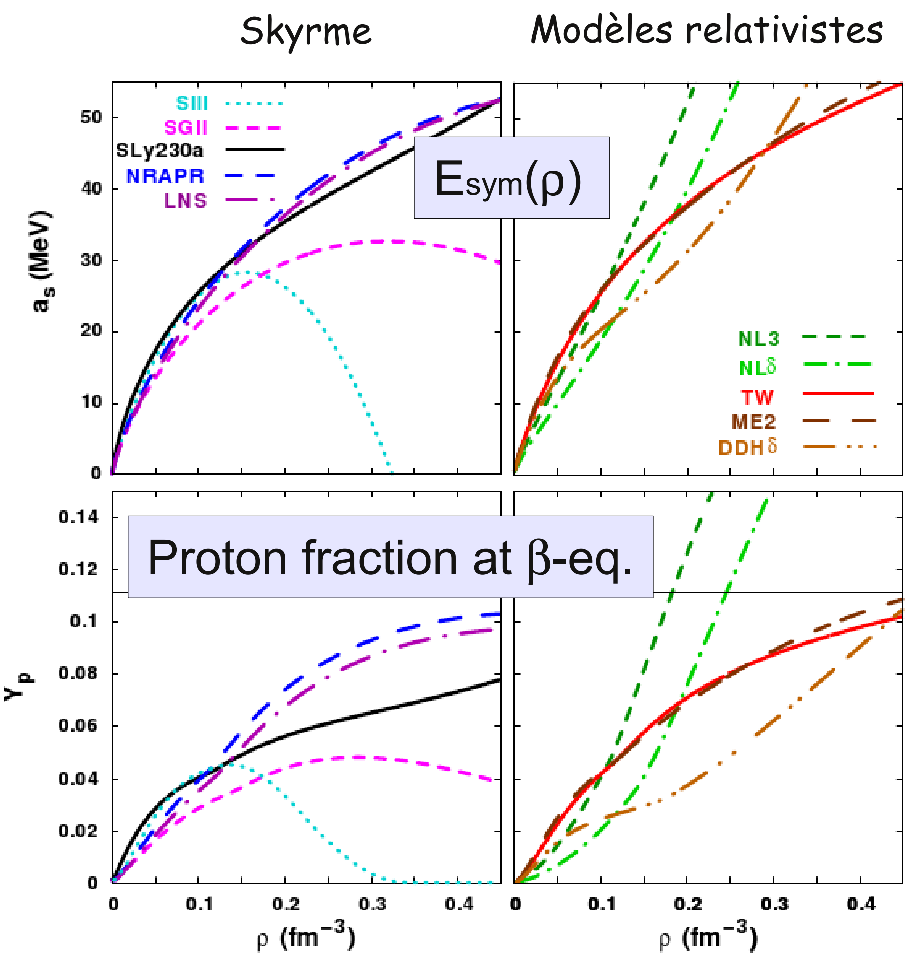
Camille Ducoin
Universidade de Coimbra - Centro de Física Computacional

Collaborators:

FCF - Coimbra : C. Providência, I. Vidaña
IPN - Orsay, France : J. Margueron

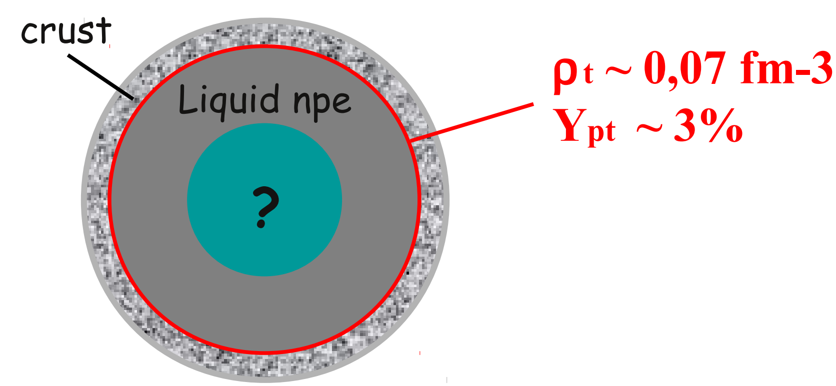
Introduction

asy-EOS : a crucial issue for compact-star physics



C. D. et al., PRC 78 (2008)

Focus : core-crust transition



asy-EOS affects:

- ✗ Transition density ρ_t
- ✗ Transition pressure P_t

} Mass + Width of the crust

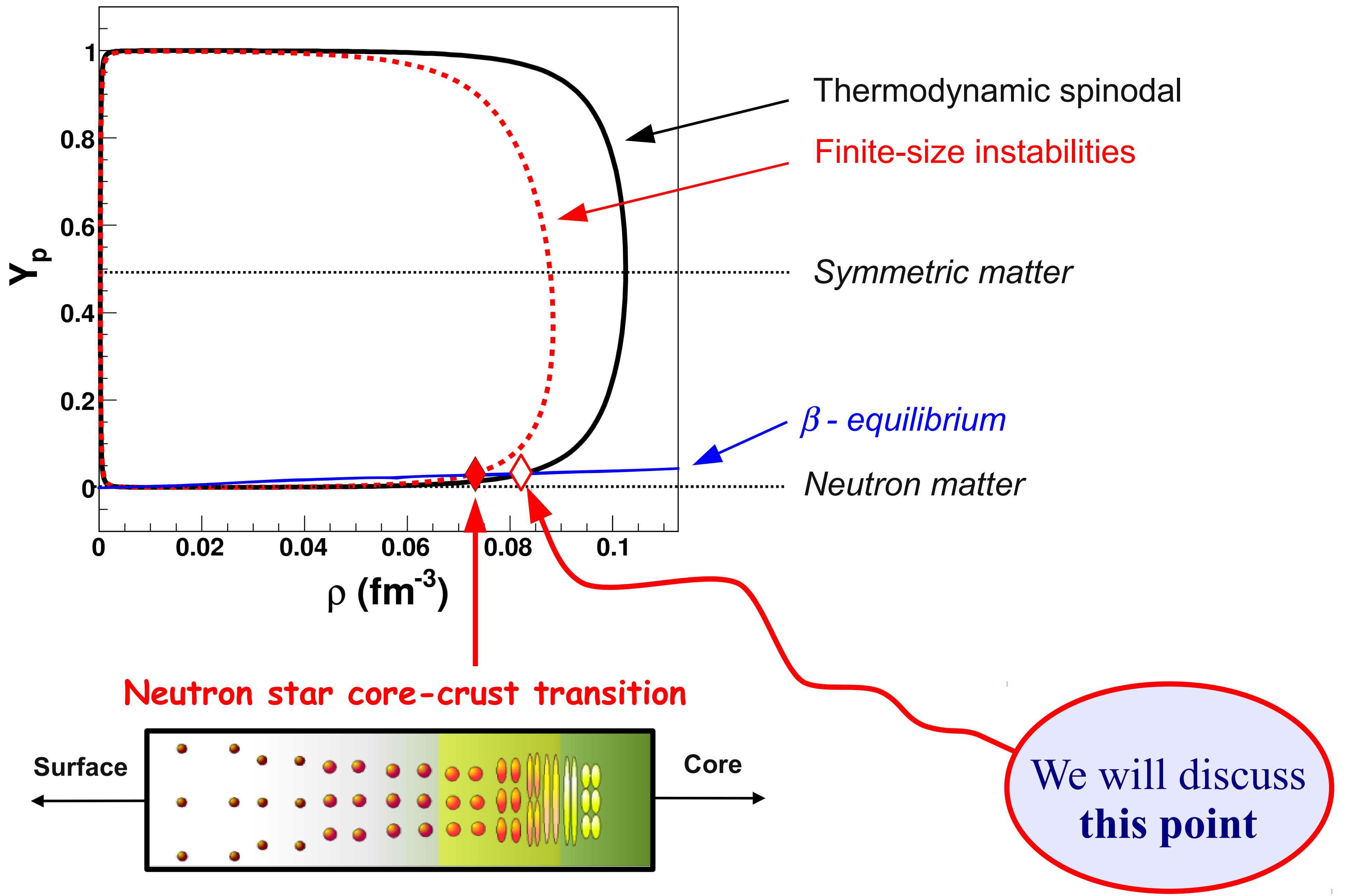
Observations: *glitches, X-ray transcients, …*

This work :
how the **symmetry-energy slope** at saturation affects transition **position** and **pressure** using Skyrme + Relativistic effective models

Symmetry-energy slope L and position of the core-crust transition

$$L = 3\rho_0 \frac{\partial E_{sym}}{\partial \rho}(\rho_0)$$

Core-crust transition : β-spino crossing



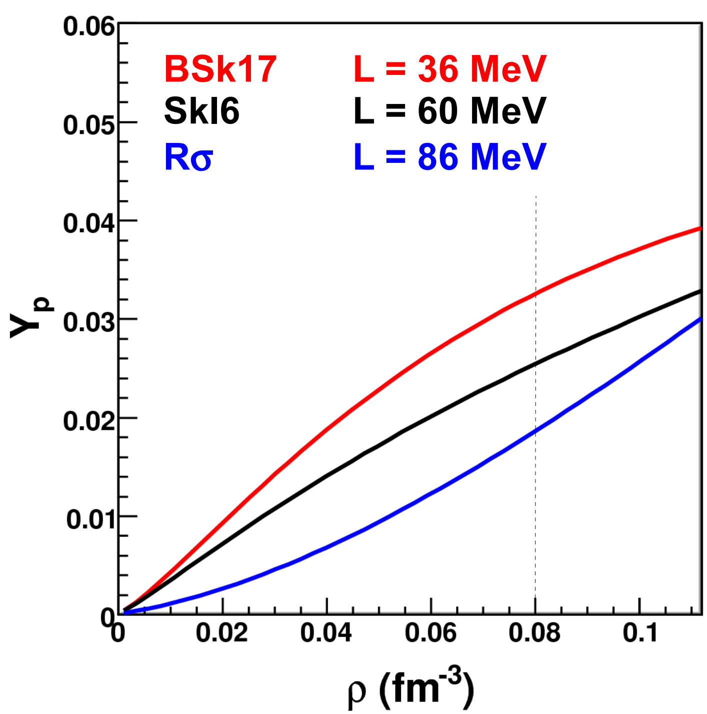
Effect of L on the proton fraction Y_p

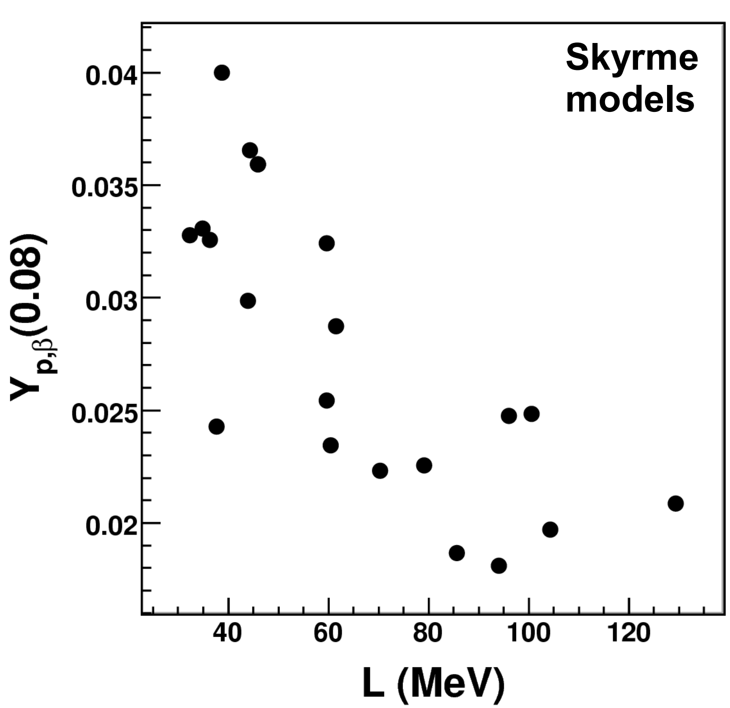
β-equilibrium : $p + e^- \rightarrow n\,(+\nu_e)$ $\qquad (\mu_n - \mu_p) + (\mu_e - \mu_\nu) = 0$

$(\mu_n - \mu_p) \sim 4\,E_{sym}(\rho) * (1-2Y_p)$

$$L = 3\rho_0 \frac{\partial E_{sym}}{\partial \rho}(\rho_0)$$

Higher **L** → Lower **E_{sym} ($\rho<\rho_0$)** → Higher **Y_p ($\rho<\rho_0$)**

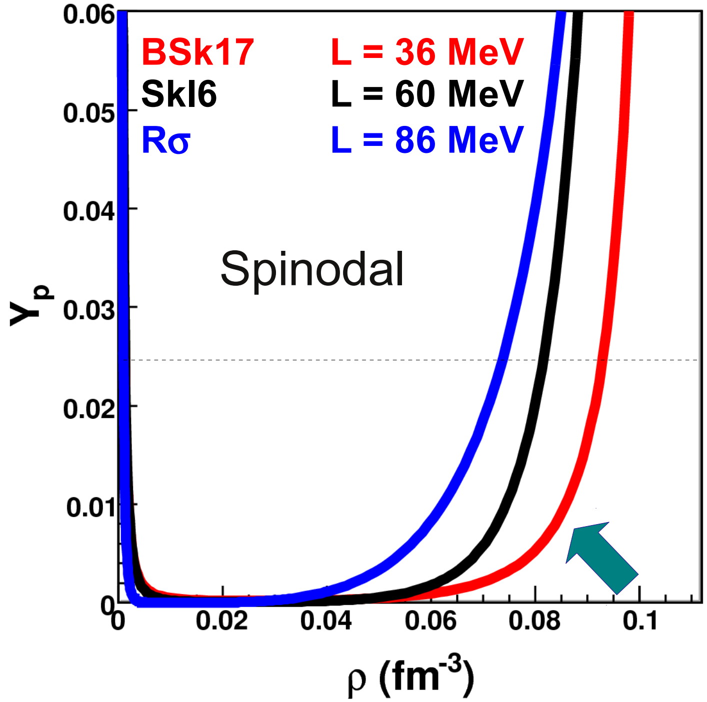


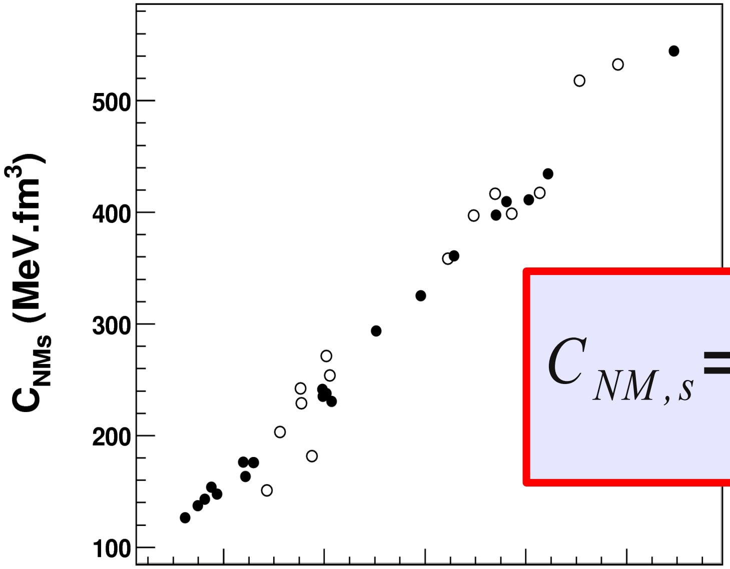


Effect of L on the spinodal border

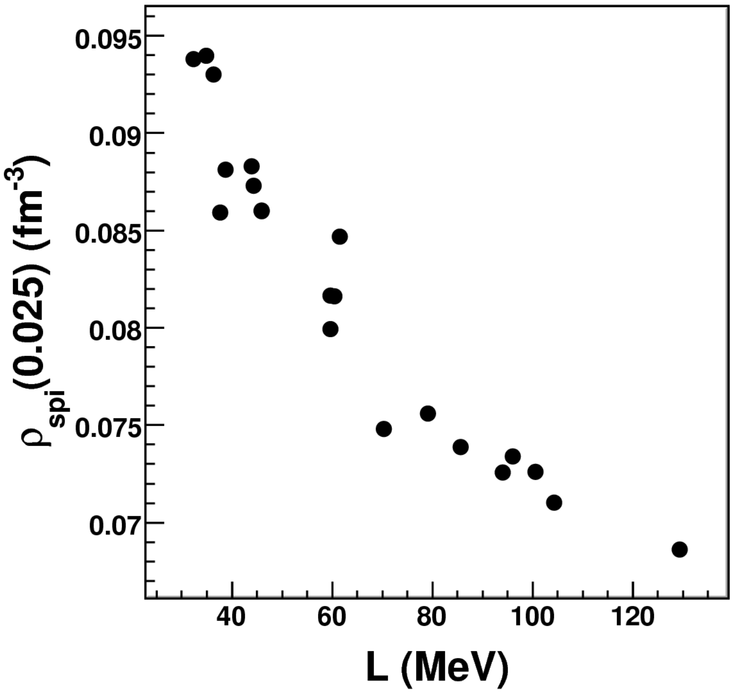
$C_{NM,s}$ = Energy-density curvature of neutron matter at spinodal density ($\sim 0.1\ fm^{-3}$)

Higher **L**
→ Higher **$C_{NM,s}$**
→ Lower **ρ_t**





$$C_{NM,s} = \frac{2L}{3\rho_0} + \ldots$$

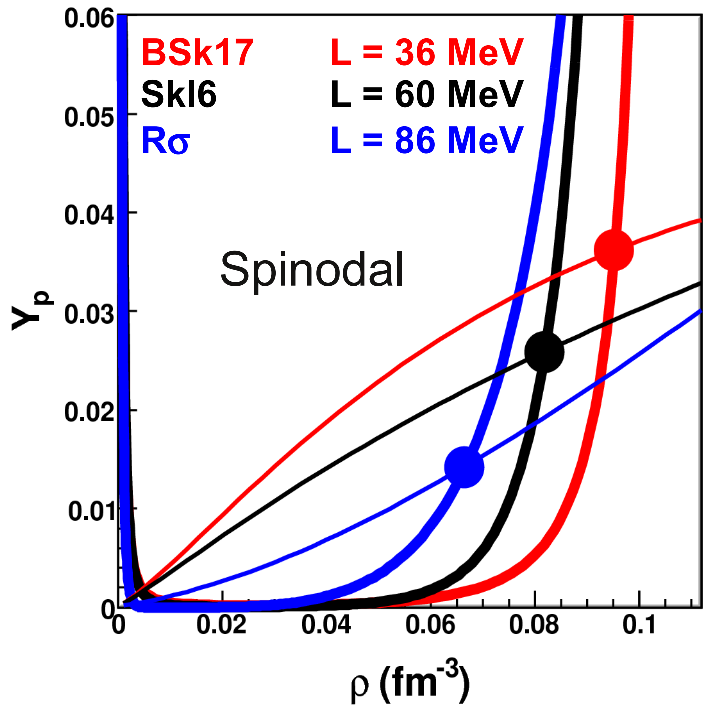


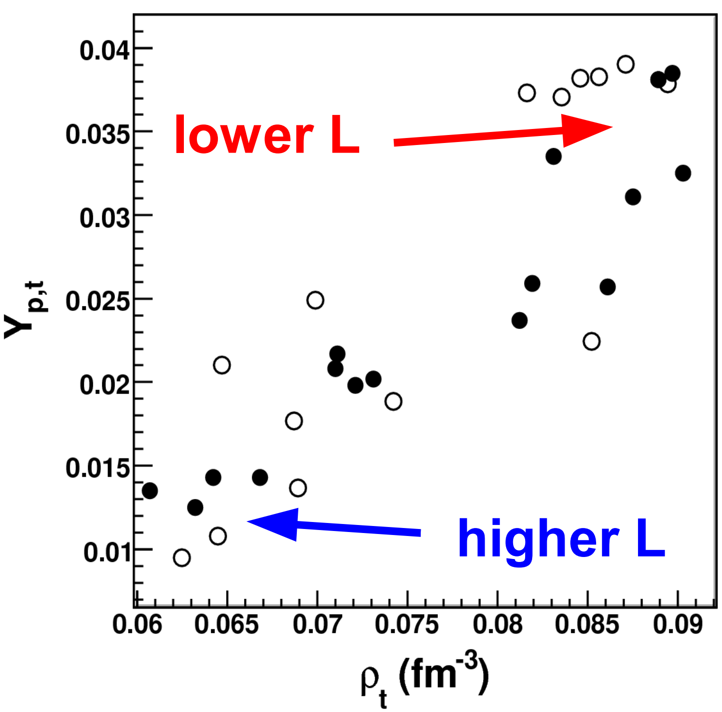
Effect of L on the transition point

Crossing between β-equilibrium and spinodal border:

L affects $Y_{p,\beta}(\rho)$
L affects $\rho_{spino}(Y_p)$

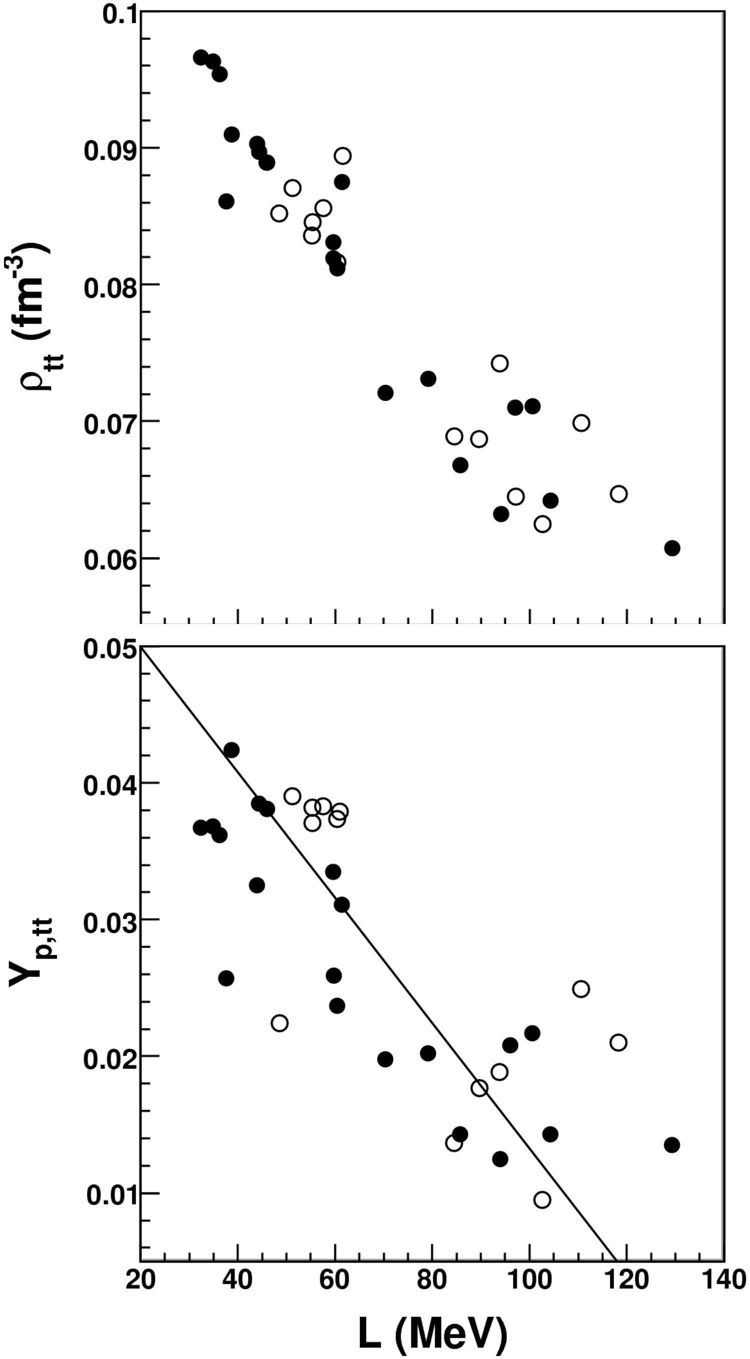
Conjonction of the 2 effects ⇒ Higher **L**, Lower $\mathbf{Y_{p,t}}$, Lower $\boldsymbol{\rho_t}$





Skyrme + Relativistic models

Effect of L on the transition point

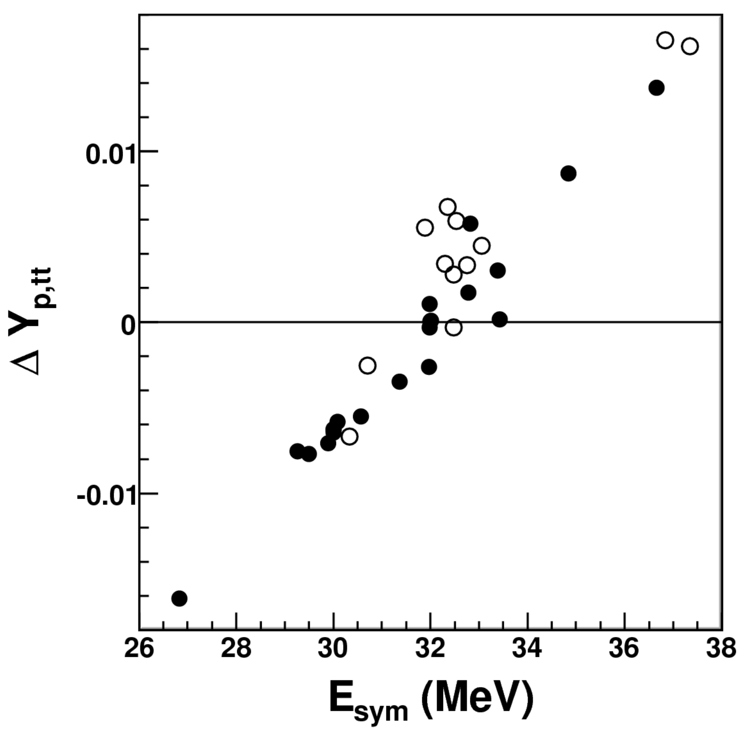


✓ **Clear decreasing correlations**

Higher **L** ⇒ { Lower **ρ_t**, Lower **$Y_{p,t}$** }

✓ **Important dispersion for $Y_{p,t}$**

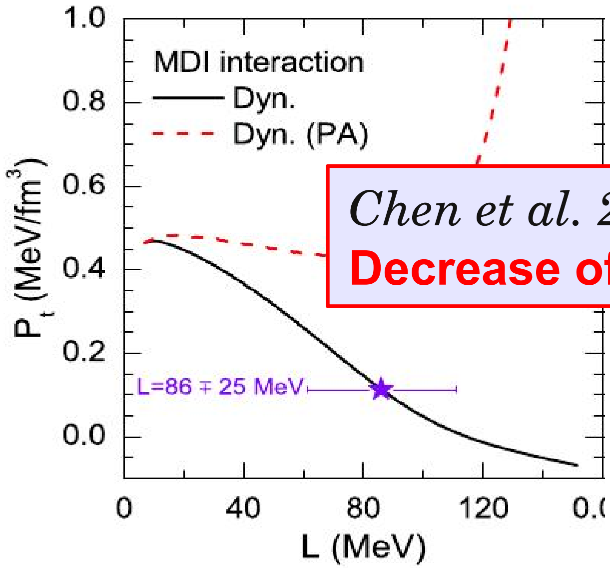
Linked to dispersion for $E_{sym}(\rho_0)$



Symmetry-energy slope L
and core-crust transition pressure

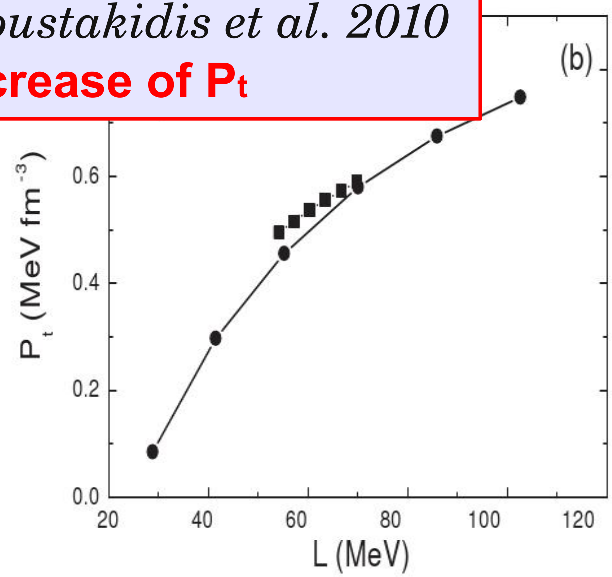
$$L = 3\rho_0 \frac{\partial E_{sym}}{\partial \rho}(\rho_0)$$

Effet of L on the transition pressure

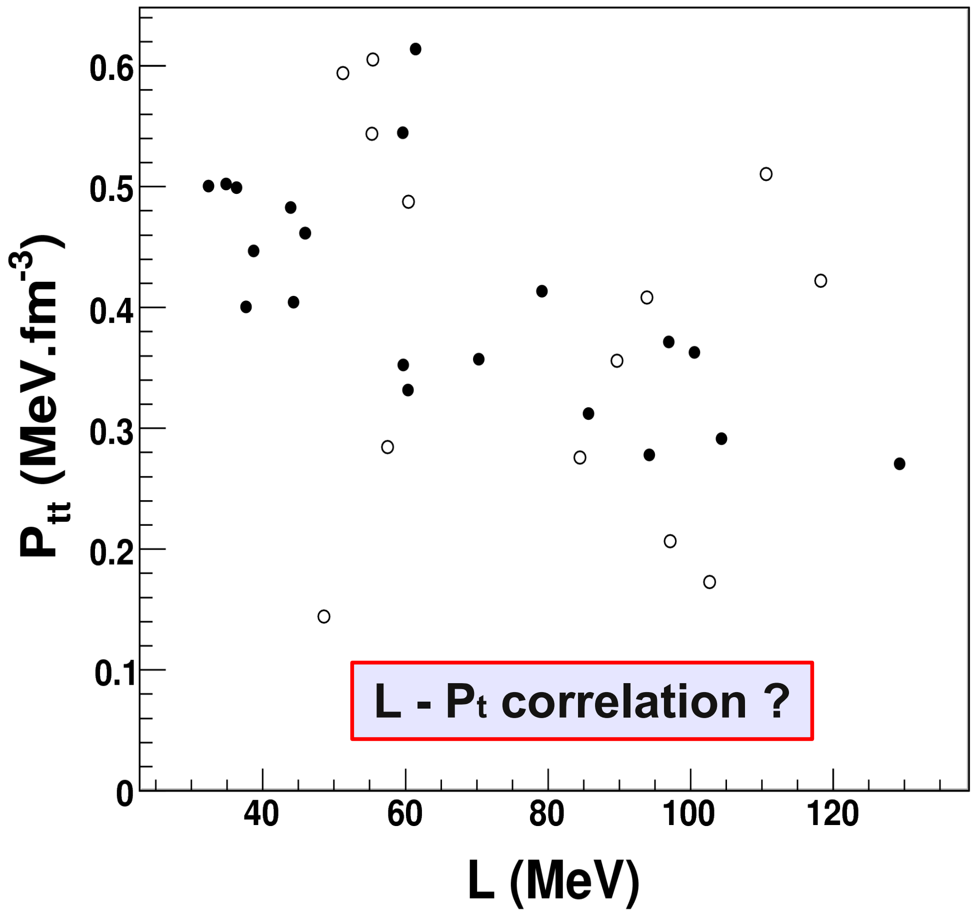


Chen et al. 2009
Decrease of P_t

Moustakidis et al. 2010
Increase of P_t



Skyrme + Relativistic effective models

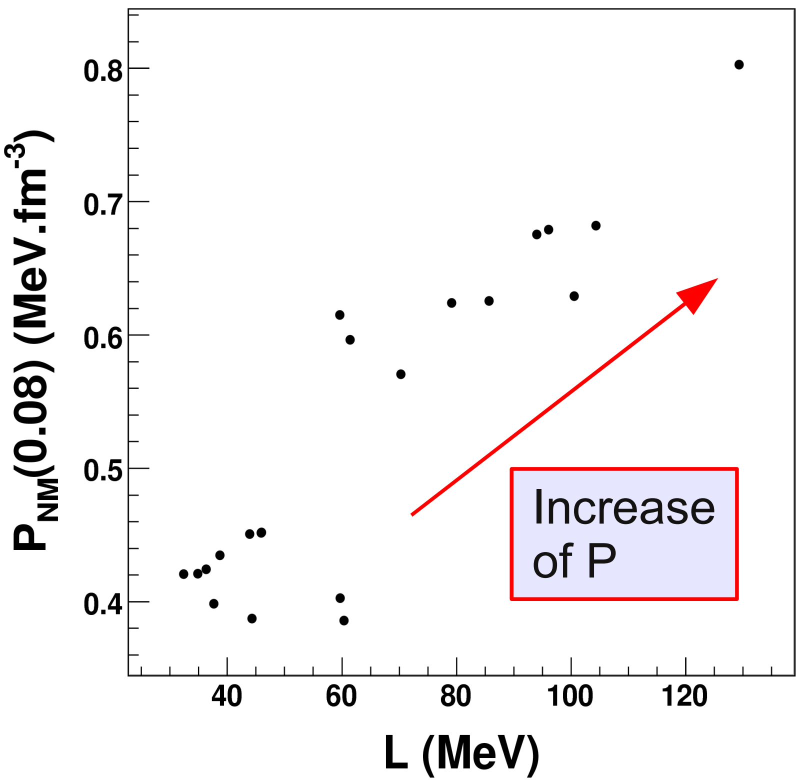


L - P_t correlation ?

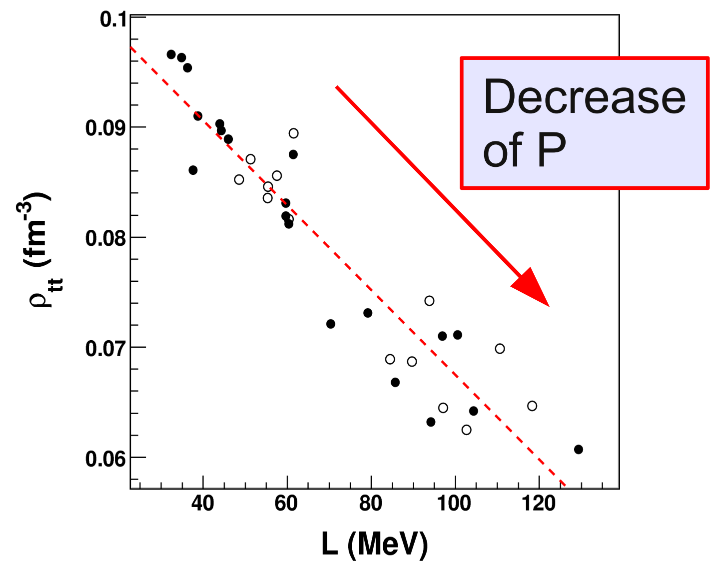
$P_t(L)$: what should we expect ?

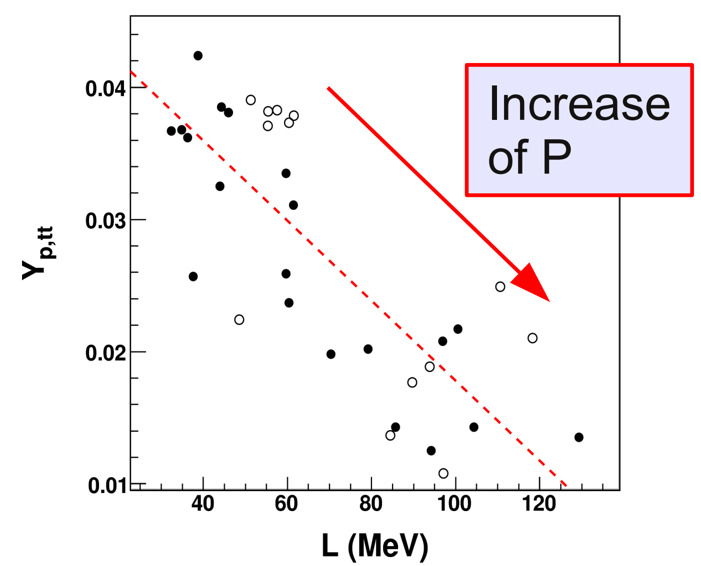
In n-rich matter, for a fixed density:
P increases with L

$$P(\rho, y) = \frac{\rho^2}{3\rho_0}\left[L y^2 + (K_0 + K_s y^2)\frac{\rho - \rho_0}{3\rho_0} + \ldots\right]$$



But the transition point moves...





Transition pressure: different contributions

$$P(\rho,y)=\frac{\rho^2}{3\rho_0}\left[L y^2+(K_0+K_s y^2)\frac{\rho-\rho_0}{3\rho_0}+\ldots\right]$$

Opposite contributions

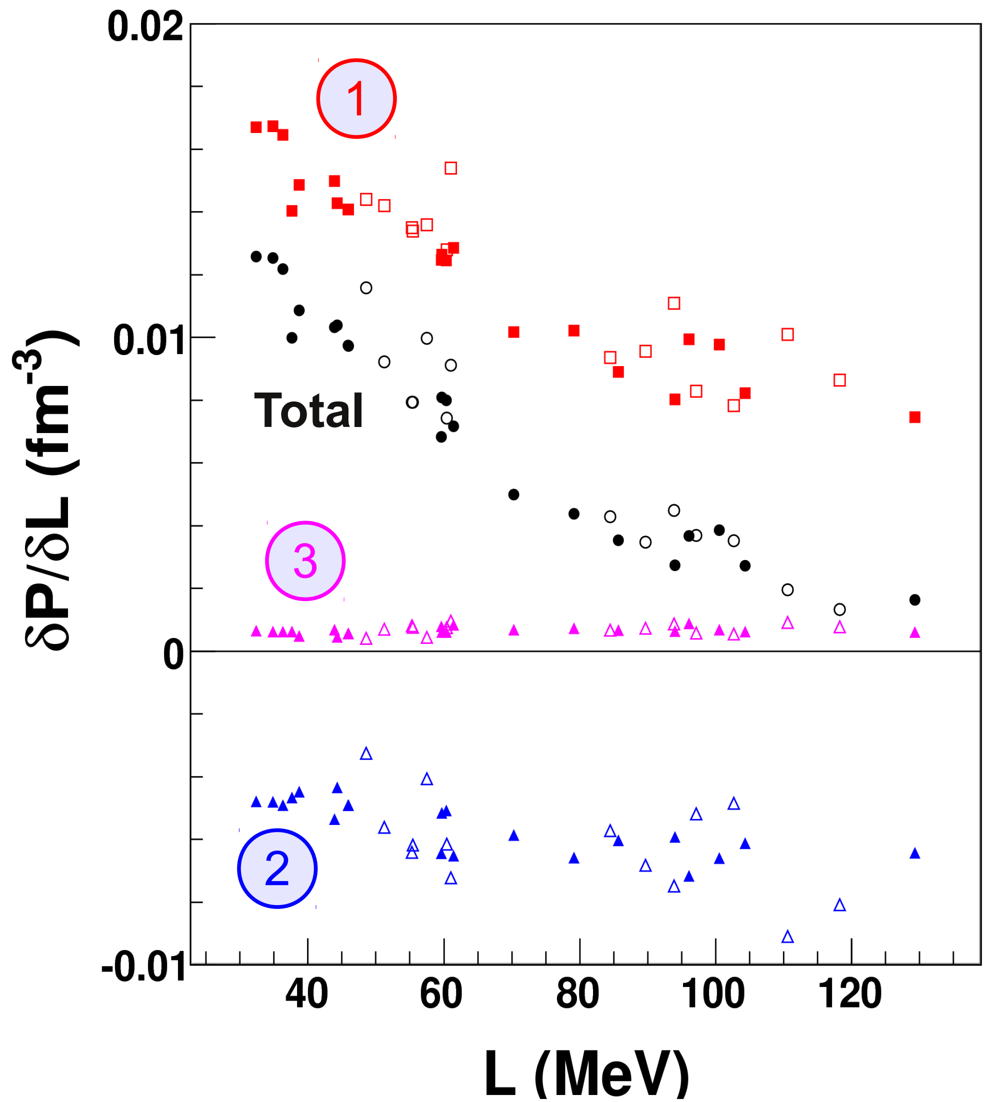
Total ➔ $P_t(L)$ increases

Variations due to δL :

1. $\left(\frac{\partial P}{\partial L}\right)_{\rho,y}(\rho_t,y_t)$

2. $\left(\frac{\partial P}{\partial \rho}\right)_{y,L}(\rho_t,y_t) * \frac{\delta \rho_t}{\delta L}$

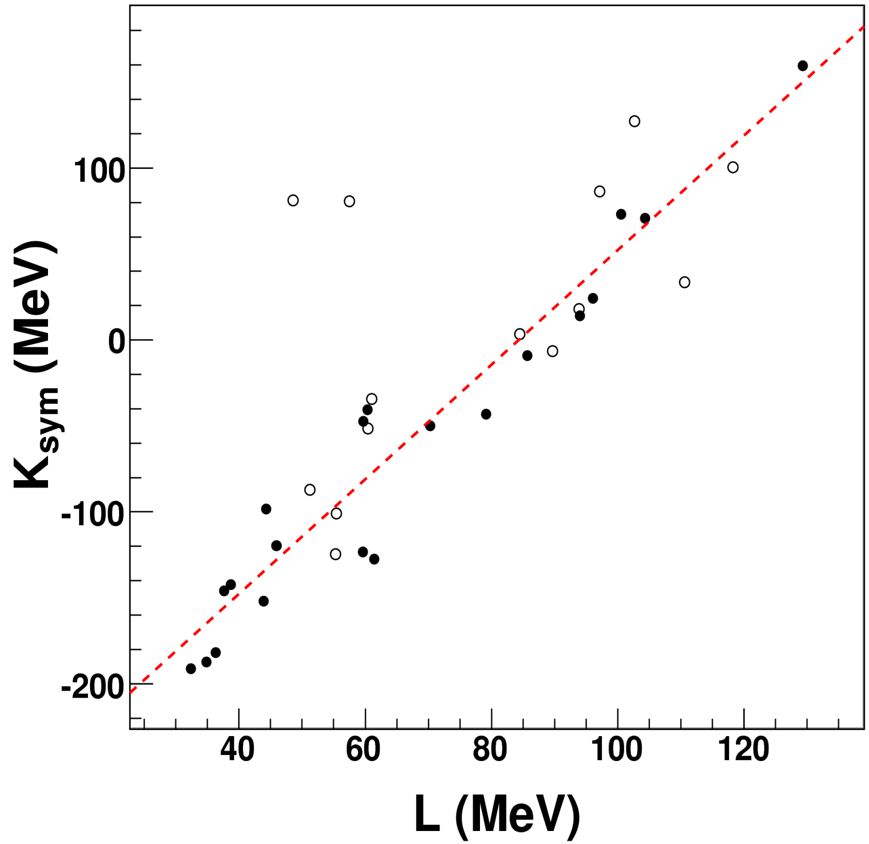
3. $\left(\frac{\partial P}{\partial y}\right)_{\rho,L}(\rho_t,y_t) * \frac{\delta y_t}{\delta L}$



Role of the correlation $K_{sym}(L)$

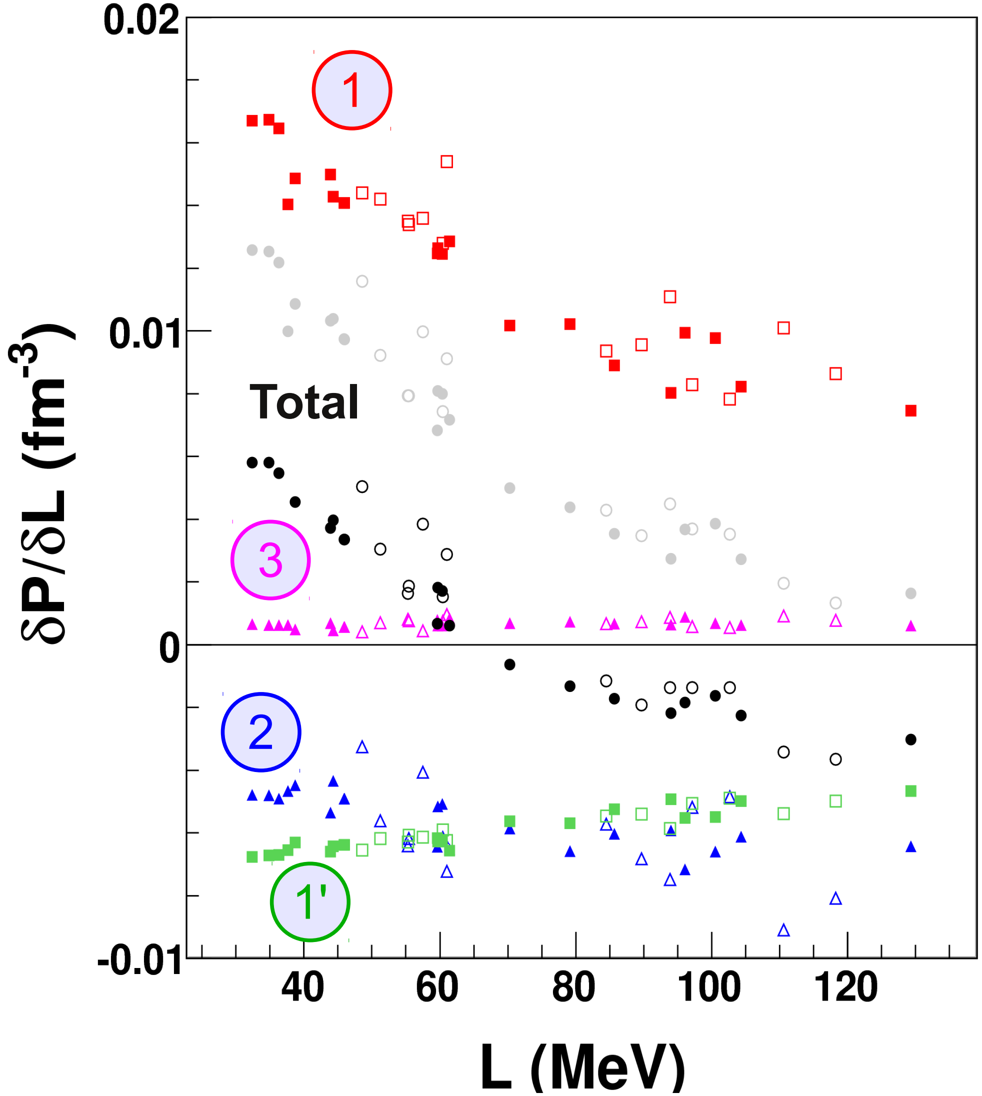
$$P(\rho, y) = \frac{\rho^2}{3\rho_0}\left[L y^2 + (K_0 + K_s y^2)\frac{\rho - \rho_0}{3\rho_0} + \dots\right]$$

1' $\left(\frac{\partial P}{\partial K_s}\right)_{\rho, y, L}(\rho_t, y_t) \ * \ \frac{\delta K_s}{\delta L}$



Opposite contributions

Total ➔ P_t (L) in/decreases



Previsions of a schematic model

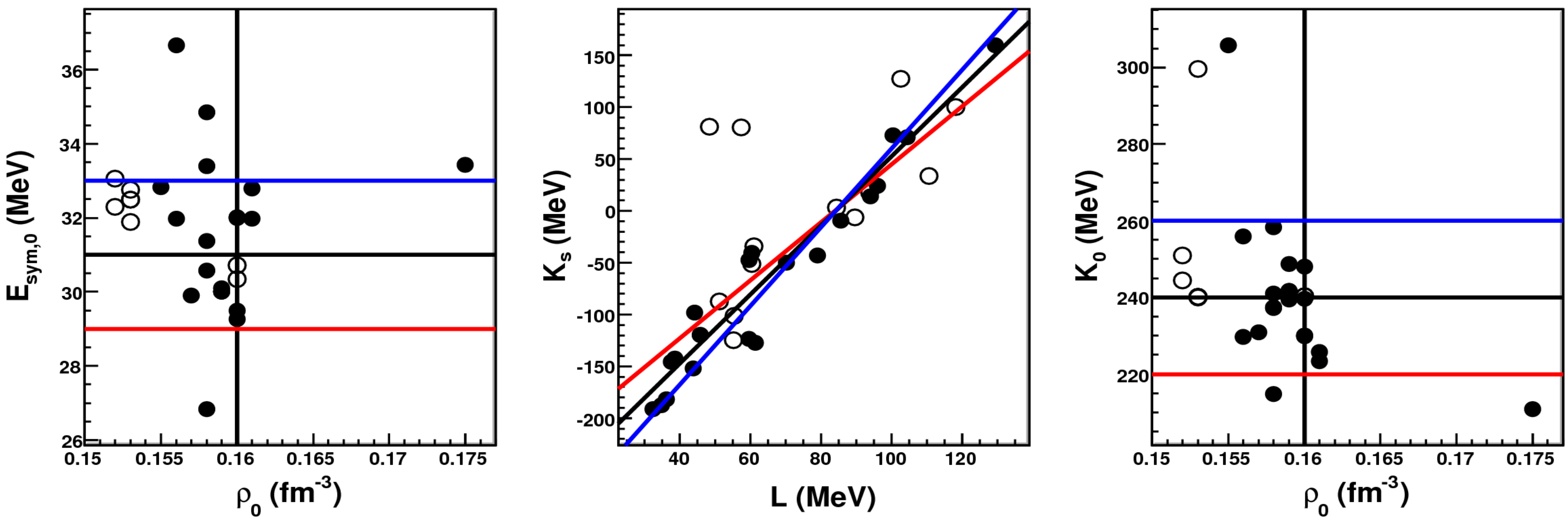
$$E = E_0 + E_s y^2 + L y^2 \frac{\rho-\rho_0}{3\rho_0} + (K_0 + K_s y^2)\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + (Q_0 + Q_s y^2)\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3 + \ldots$$

Typical values (isoscalar):

ρ_0 = 0.16 fm-3 ;
E_0 = -16 MeV ;
K_0 = 240 MeV ;
Q_0 = -350 MeV

Typical values (isovector):

E_s = 31 MeV
L = [40-100] MeV
K_s = 3.33 * L - 281 MeV
Q_s = -6,63 * L + 765 MeV

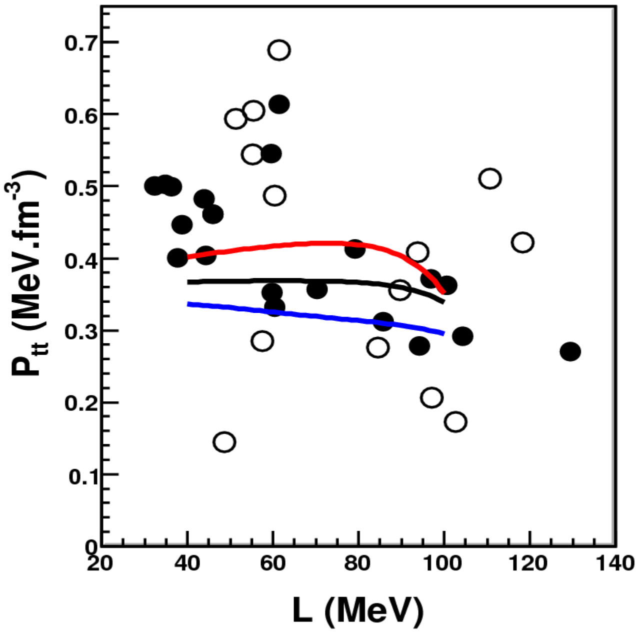


Previsions of a schematic model

$$E = E_0 + E_s y^2 + L y^2 \frac{\rho-\rho_0}{3\rho_0} + (K_0 + K_s y^2)\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + (Q_0 + Q_s y^2)\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3 + \ldots$$

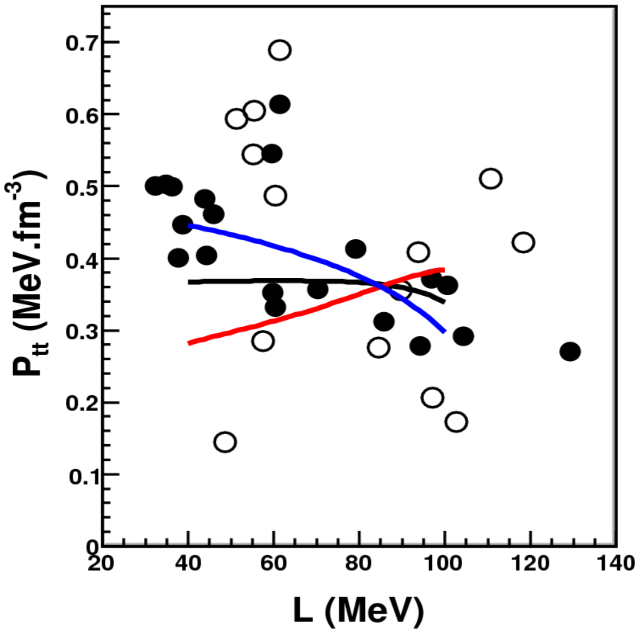
Different E_s (MeV):

29 - 31 - 33



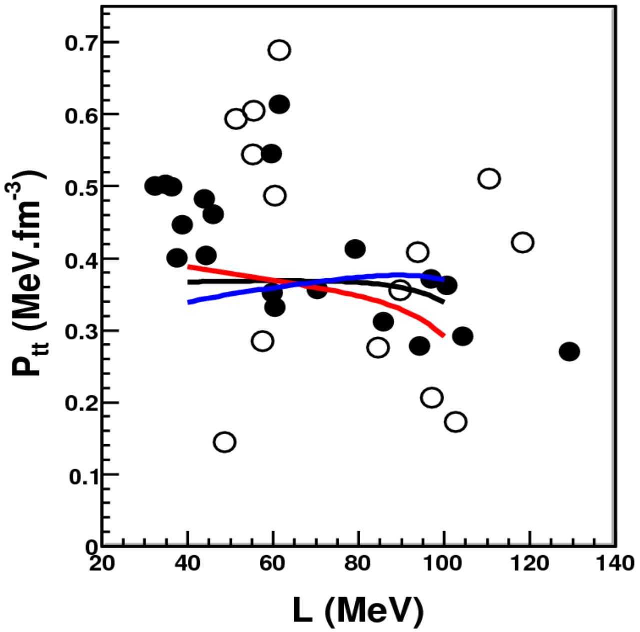
Different dK_s/dL:

2.8 - 3.3 - 3.8



Different K_0 (MeV):

220 - 240 - 260



Conclusion

Summary

- **Robust correlation between symmetry-energy slope L and core-crust transition position (rt, Yp,t) :**
  - ✗ Good correlation L - ρ_t
  - ✗ Correlation L - $Y_{p,t}$: dispersion due to different $E_{sym}(\rho_0)$

- **Delicate link between L and the transition pressure P_t :**
  - ✗ Opposite contributions : no qualitative prediction is possible
  - ✗ Important role of L-K_{sym} correlation

Outlook

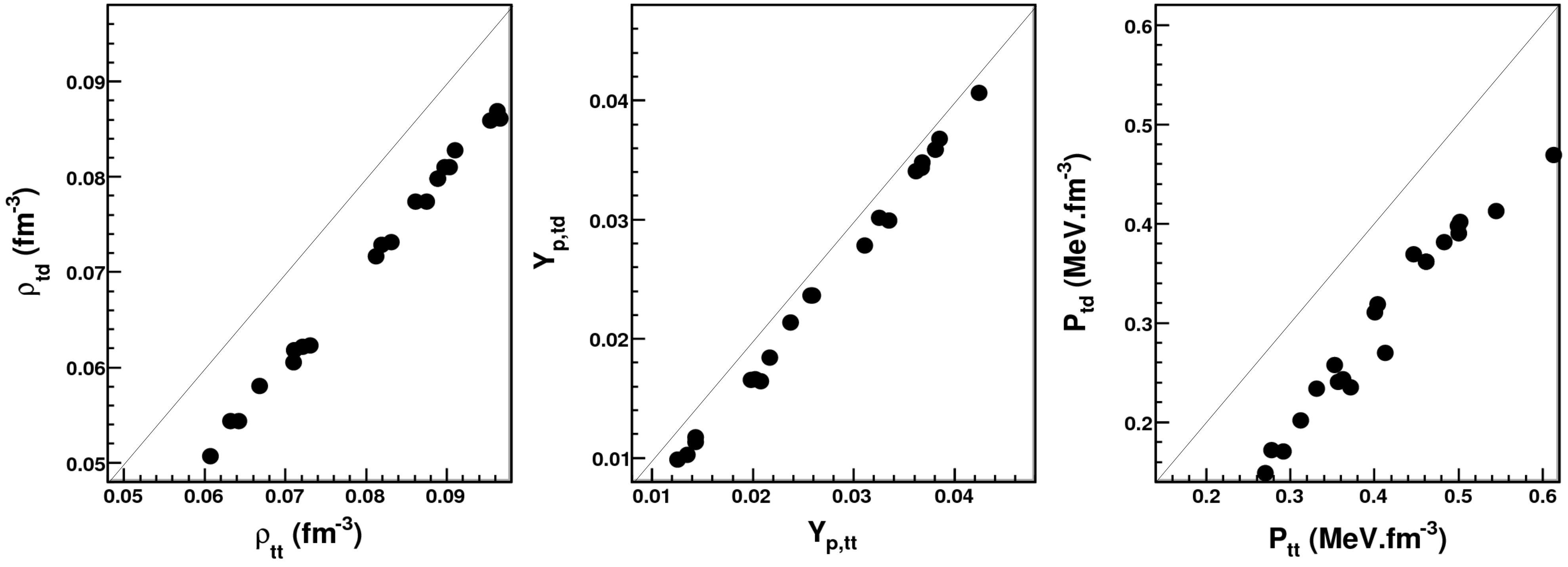
How can we obtain lab-experimental constraints on Pt ?
What model-independence can be reached?

- **Understanding the correlations** between coefs of the asy-EOS expension (such as L-Ksym-Qsym)
- **Constraining the n-rich fonctional at lower density points** (~0.1 fm^{-3}) instead of ρ_0 through relevant observables (neutron skin, multifragmentation, isospin diffusion...)

Grazie

Dynamic versus Thermodynamic

Skyrme models



Generalized Liquid Drop Model (GLDM)

$$x = \frac{\rho - \rho_0}{3\rho_0}$$

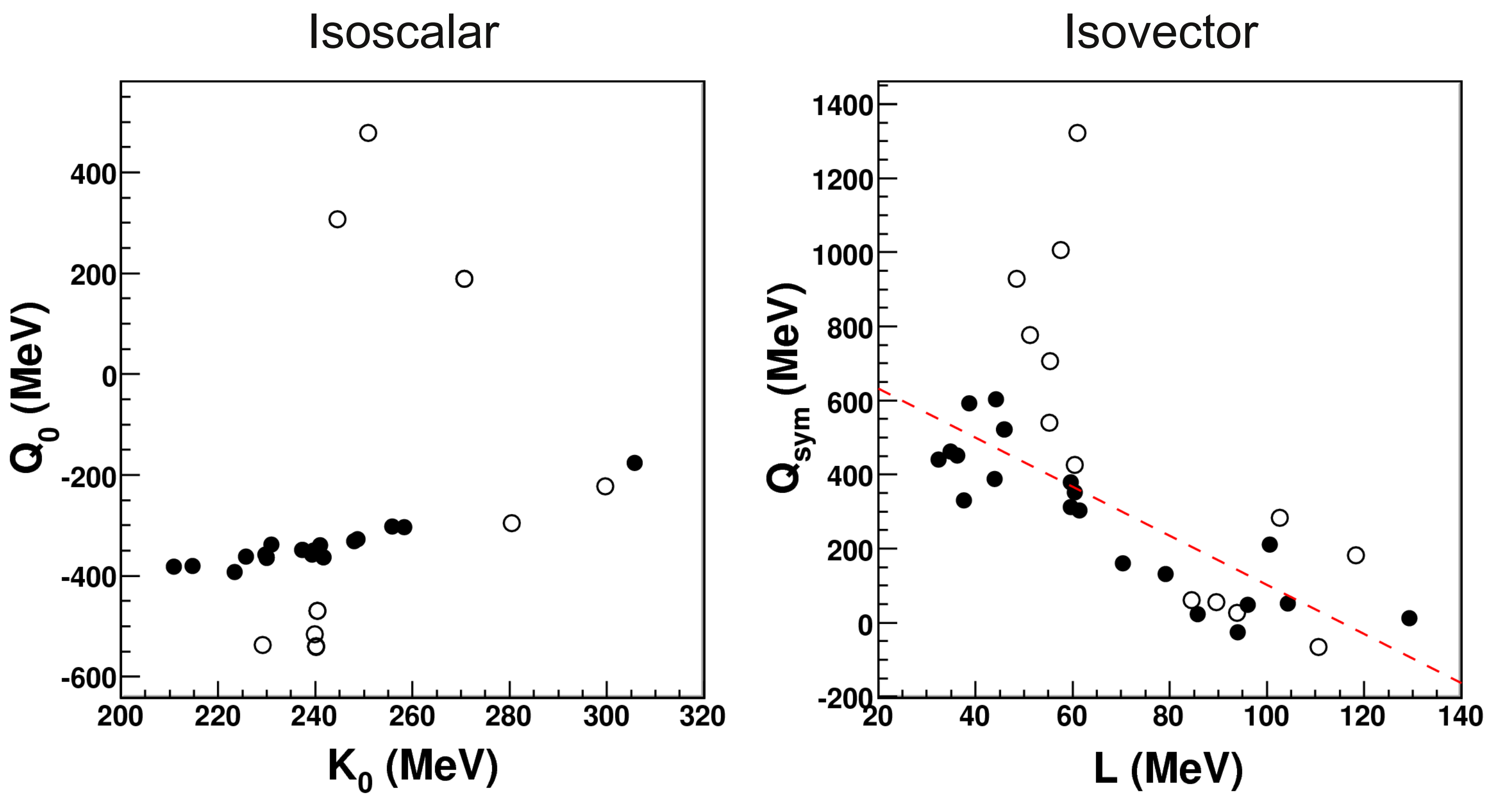
$$E(\rho, y) = \sum_{n \geq 0} \left(c_{IS,n} + c_{IV,n} y^2\right) \frac{x^n}{n!} \quad + \quad \left(E_{kin} - E_{kin}^{para}\right)$$

$$P(\rho, y) = \frac{\rho^2}{3\rho_0} \left[L y^2 + \sum_{n \geq 2} \left(c_{IS,n} + c_{IV,n} y^2\right) \frac{x^{n-1}}{(n-1)!} \right] \quad + \quad \rho^2 \frac{\partial \left(E_{kin} - E_{kin}^{para}\right)}{\partial \rho}$$

$$C_{NM,s} = \frac{2L}{3\rho_0} + \frac{1}{3\rho_0} \sum_{n \geq 2} c_{IV,n} \frac{x^{n-2}}{(n-2)!} \underbrace{\left[\frac{n+1}{n-1} x + \frac{1}{3} \right]}_{0 \text{ for } n=2,\ \rho/\rho_0 = 2/3} \quad + \quad \frac{\partial^2 \left[\rho \left(E_{kin} - E_{kin}^{para} \right) \right]}{\partial \rho^2}$$

0 for n=2, $\rho/\rho_0=2/3$

Third order of the GLDM



Skyrme data fit:
$Q_{sym} = -6{,}63 * L + 765$

Modele	ρ_0	E_0	K_0	Q_0	$E_{\rm sym}$	L	$K_{\rm sym}$	$Q_{\rm sym}$
BSk14	0.159	−15.9	239.4	−358.8	30.0	43.9	−152.0	388.3
BSk16	0.159	−16.1	241.7	−363.7	30.0	34.9	−187.4	461.9
BSk17	0.159	−16.1	241.7	−363.7	30.0	36.3	−181.9	450.5
G_σ	0.158	−15.6	237.3	−348.8	31.4	94.0	14.0	−26.8
R_σ	0.158	−15.6	237.4	−348.5	30.6	85.7	−9.1	22.2
LNS	0.175	−15.3	210.8	−382.7	33.4	61.5	−127.4	302.5
NRAPR	0.161	−15.9	225.7	−362.6	32.8	59.6	−123.3	311.6
RATP	0.160	−16.1	239.6	−349.9	29.3	32.4	−191.3	440.7
SV	0.155	−16.1	305.8	−175.9	32.8	96.1	24.2	48.0
SGII	0.158	−15.6	214.7	−381.0	26.8	37.6	−145.9	330.4
SkI2	0.158	−15.8	241.0	−339.8	33.4	104.3	70.7	51.6
SkI3	0.158	−16.0	258.2	−304.0	34.8	100.5	73.1	211.5
SkI4	0.160	−15.9	248.0	−331.3	29.5	60.4	−40.5	351.1
SkI5	0.156	−15.9	255.9	−302.1	36.6	129.3	159.6	11.7
SkI6	0.159	−15.9	248.6	−327.4	30.1	59.7	−47.3	379.0
SkMP	0.157	−15.6	230.9	−338.2	29.9	70.3	−49.8	159.4
SkO	0.160	−15.8	223.4	−393.0	32.0	79.1	−43.2	131.1
SLy230a	0.160	−16.0	229.9	−364.3	32.0	44.3	−98.2	602.9
SLy230b	0.160	−16.0	230.0	−363.2	32.0	46.0	−119.7	521.5
SLy4	0.160	−16.0	230.0	−363.2	32.0	45.9	−119.7	521.6
SLy10	0.156	−15.9	229.7	−358.4	32.0	38.7	−142.2	591.3
NL3	0.148	−16.2	270.7	188.8	37.3	118.3	100.5	182.6
TM1	0.145	−16.3	280.4	−295.4	36.8	110.6	33.6	−65.2
GM1	0.153	−16.3	299.7	−222.1	32.5	93.9	17.9	25.8
GM3	0.153	−16.3	239.9	−515.5	32.5	89.7	−6.5	55.9
FSU	0.148	−16.3	229.2	−537.4	32.5	60.4	−51.4	426.6
NL$\omega\rho$(025)	0.148	−16.2	270.7	188.8	32.4	61.1	−34.4	1322.0
NL$\rho\delta$(0)	0.160	−16.1	240.4	−470.2	30.3	84.5	3.3	61.4
TW	0.153	−16.3	240.2	−541.0	32.8	55.3	−124.7	539.0
DDME1	0.152	−16.2	244.5	307.6	33.1	55.4	−101.0	706.3
DDME2	0.152	−16.1	250.9	478.3	32.3	51.2	−87.2	777.1
DDHDI-25	0.153	−16.3	240.2	−540.3	25.6	48.6	81.1	928.3
DDHDII-30	0.153	−16.3	240.2	−540.3	31.9	57.5	80.7	1005.0
NL$\rho\delta$(2.5)	0.160	−16.1	240.4	−470.2	30.7	102.7	127.2	282.9