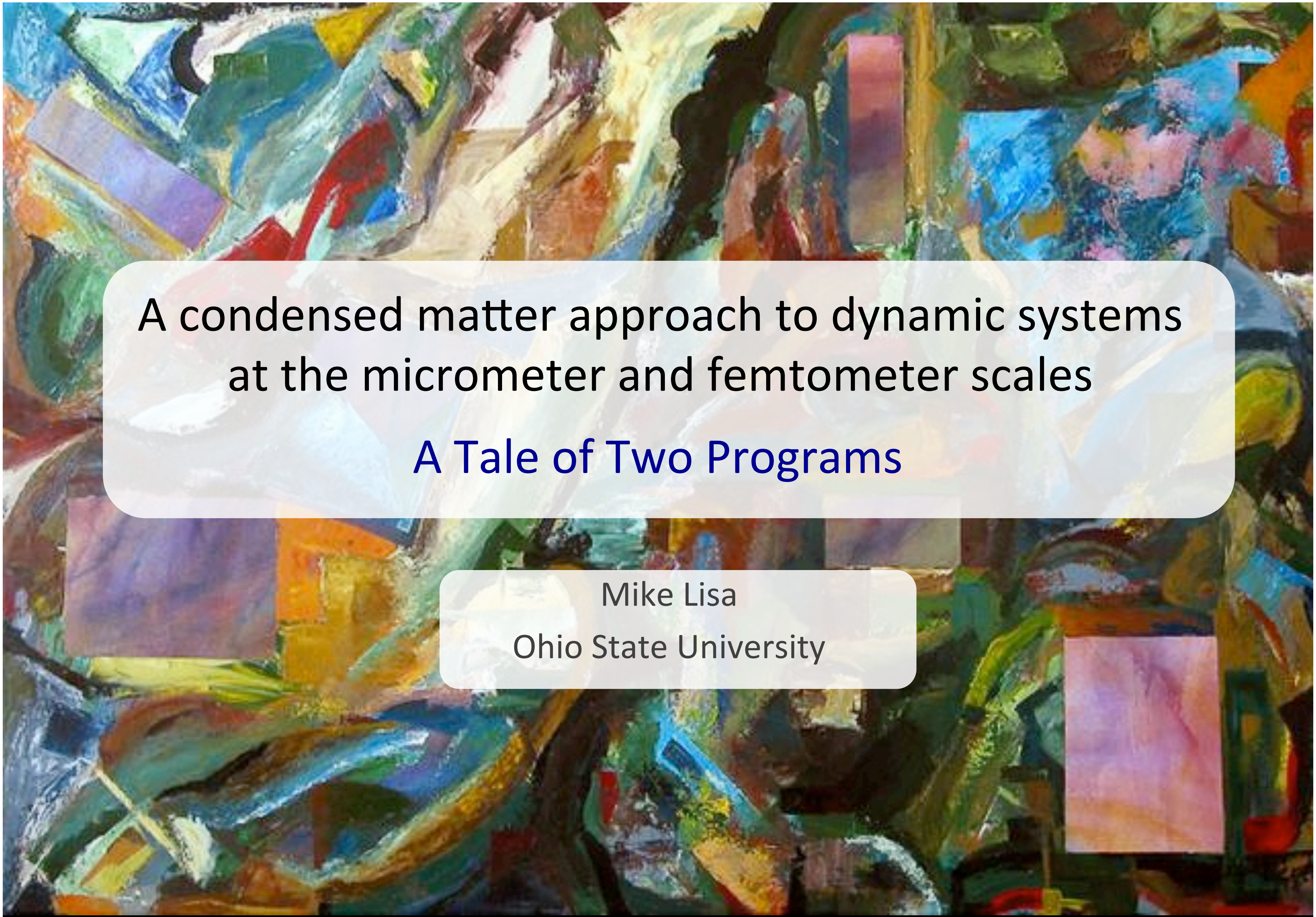


A condensed matter approach to dynamic systems at the micrometer and femtometer scales

A Tale of Two Programs

Mike Lisa
Ohio State University

Outline

- **Introduction to micro-explosions** – RHIC's big brother

- **Energy dependence of the anisotropic freezeout shape**
  - micro-explosions
  - femto-explosions
    - connection to QGP viscosity

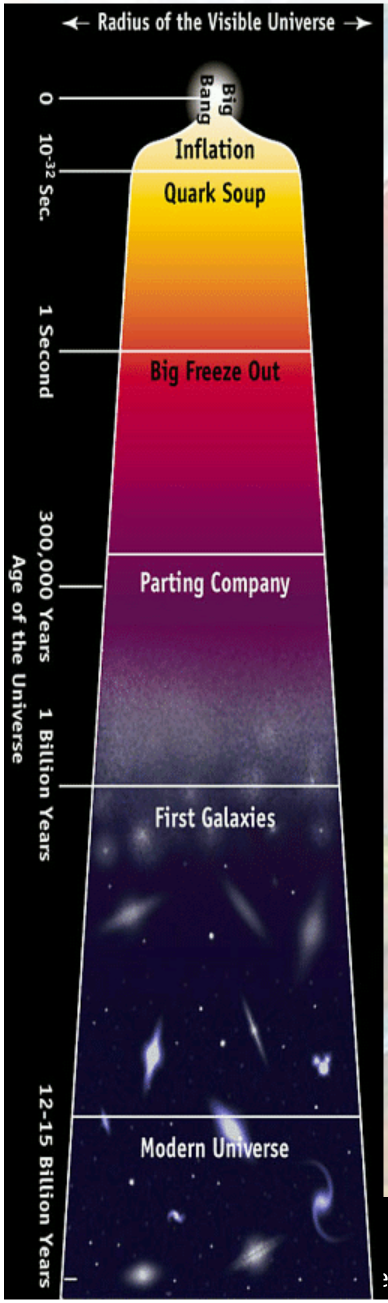
- **Geometric substructure of the shocked region, speciation**
  - femto-explosions
  - micro-explosions

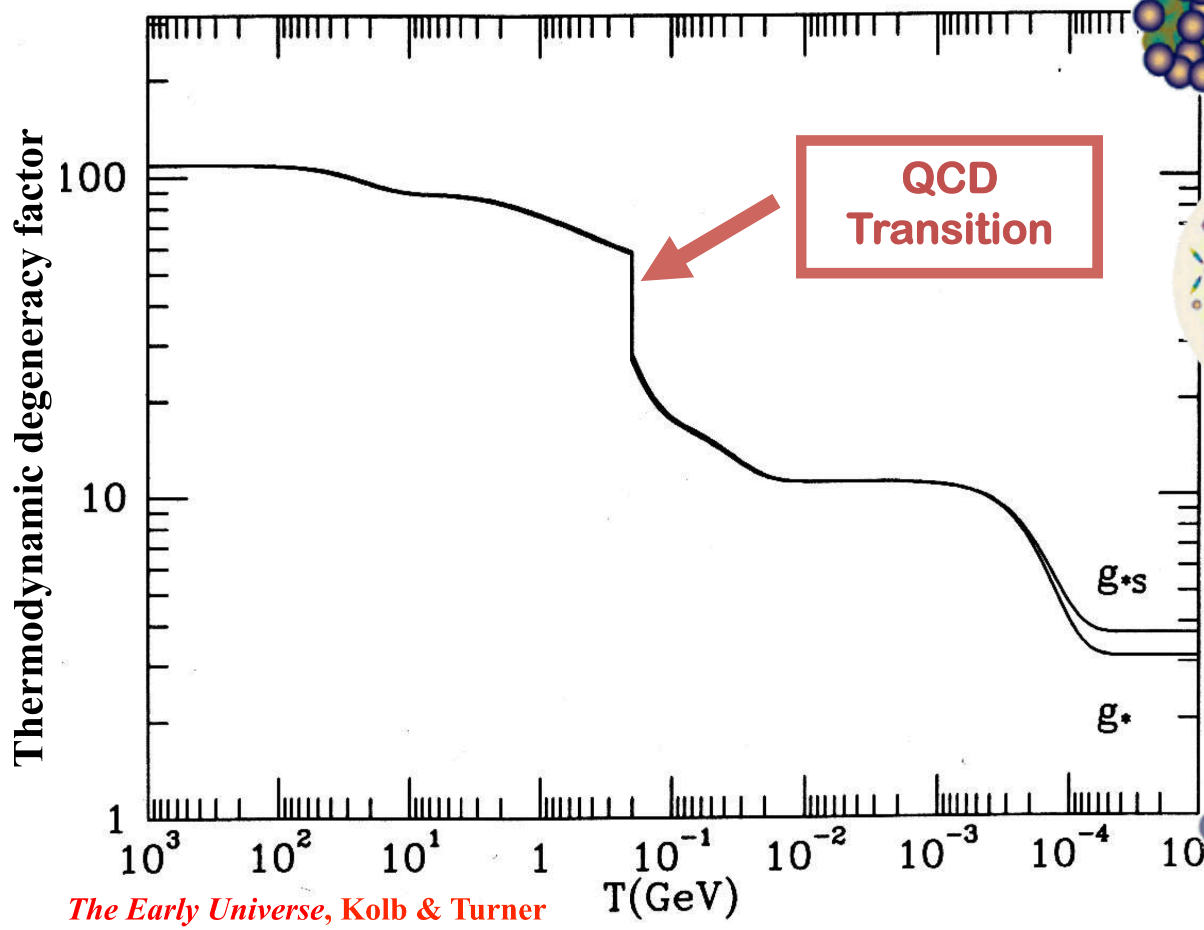
- **Blast creation of exotic, new forms of confined matter**
  - micro-explosions
  - femto-exploations

- Summary

Big bang

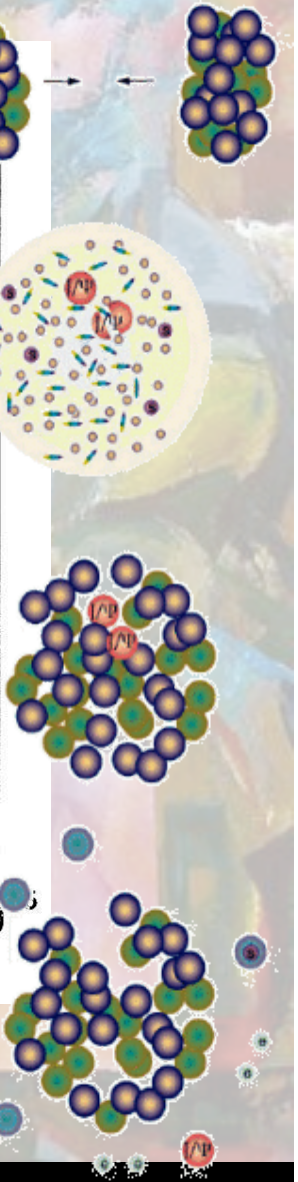
femto bangs



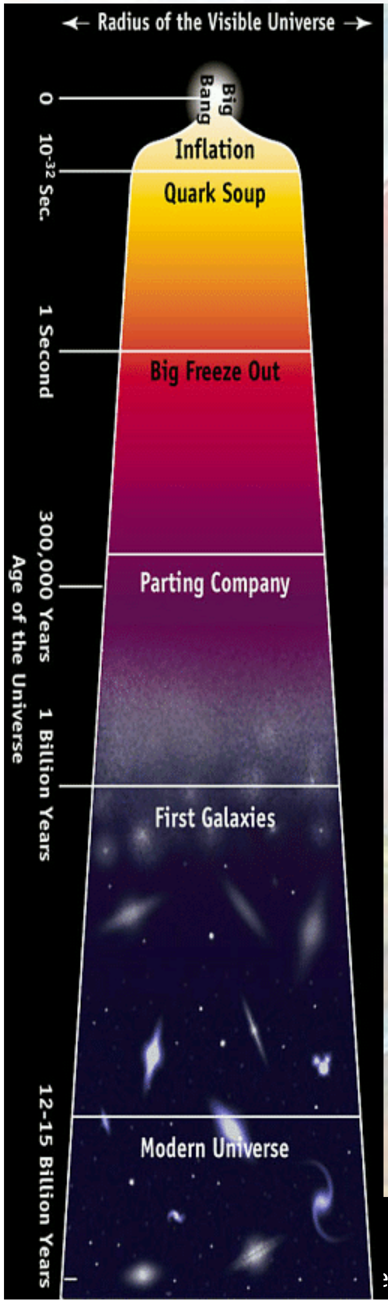


QCD Transition

The Early Universe, Kolb & Turner



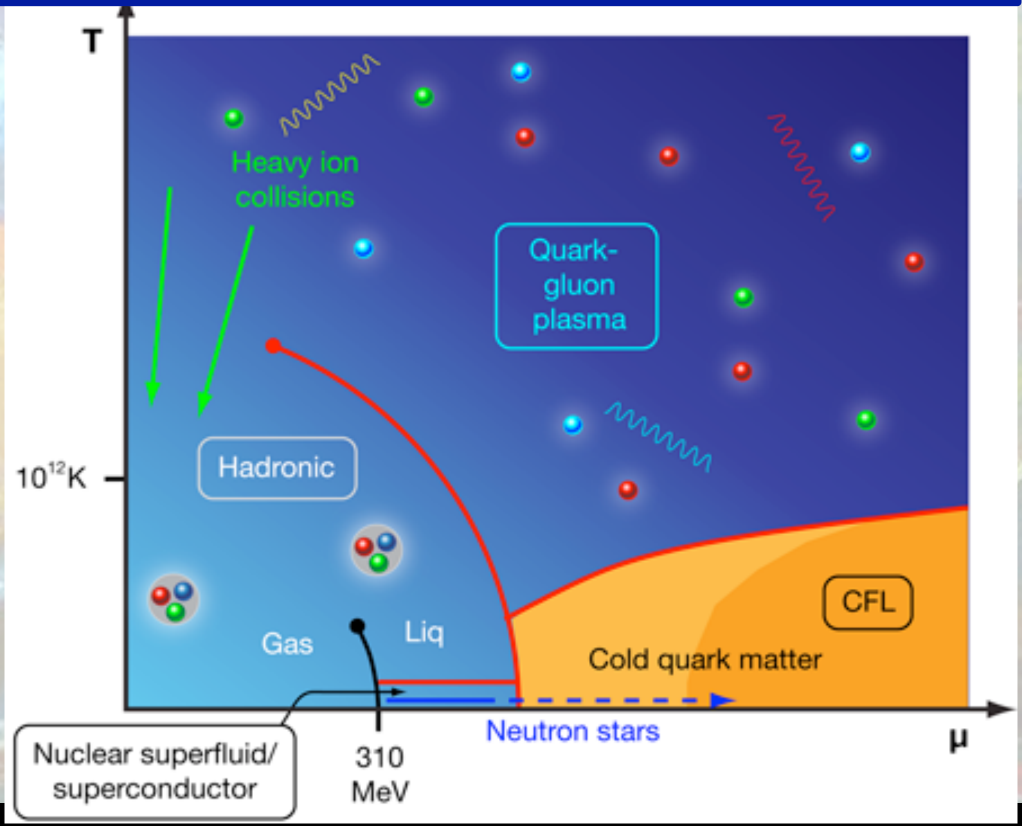
Big bang femto bangs



But it’s not *really* condensed matter physics.

Can such a **short-lived, dynamic** system be used to probe the phase diagram?

Is there a similar case where this is done?



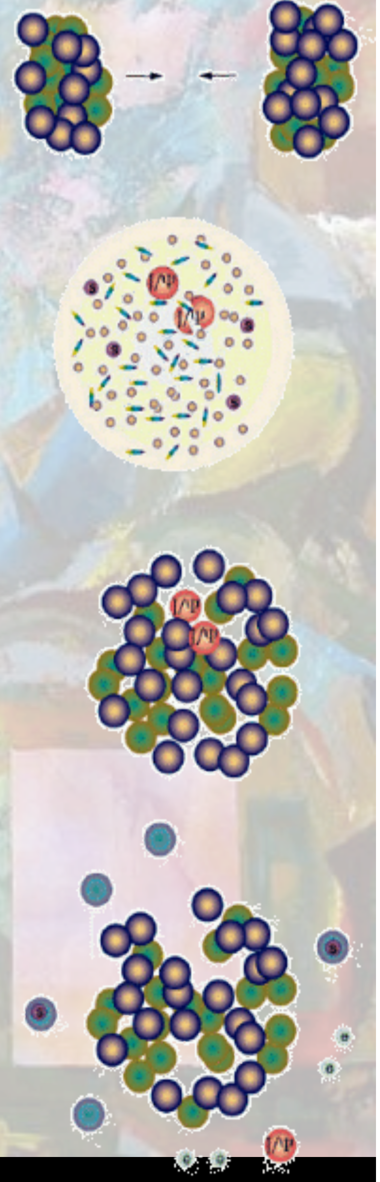
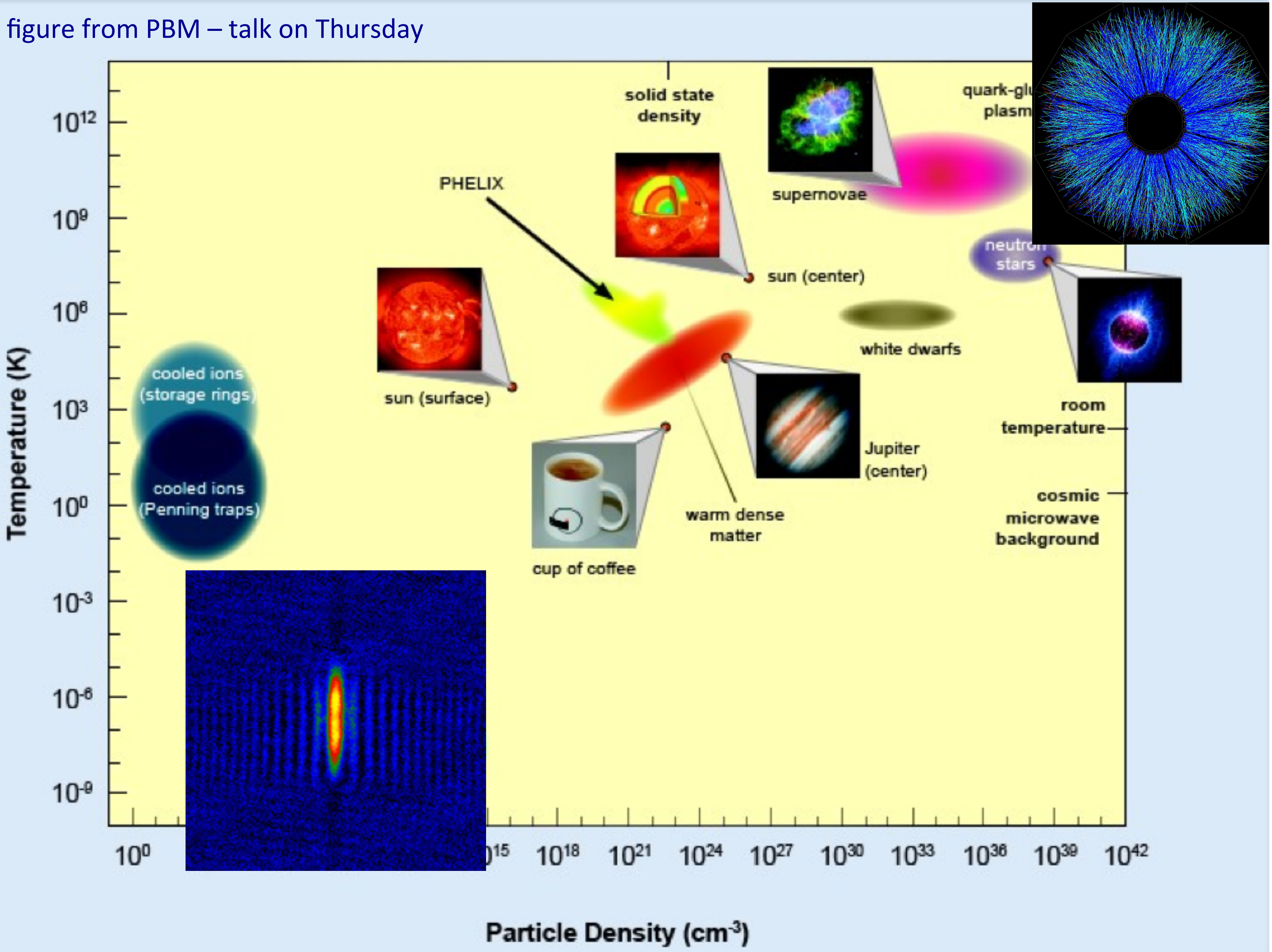
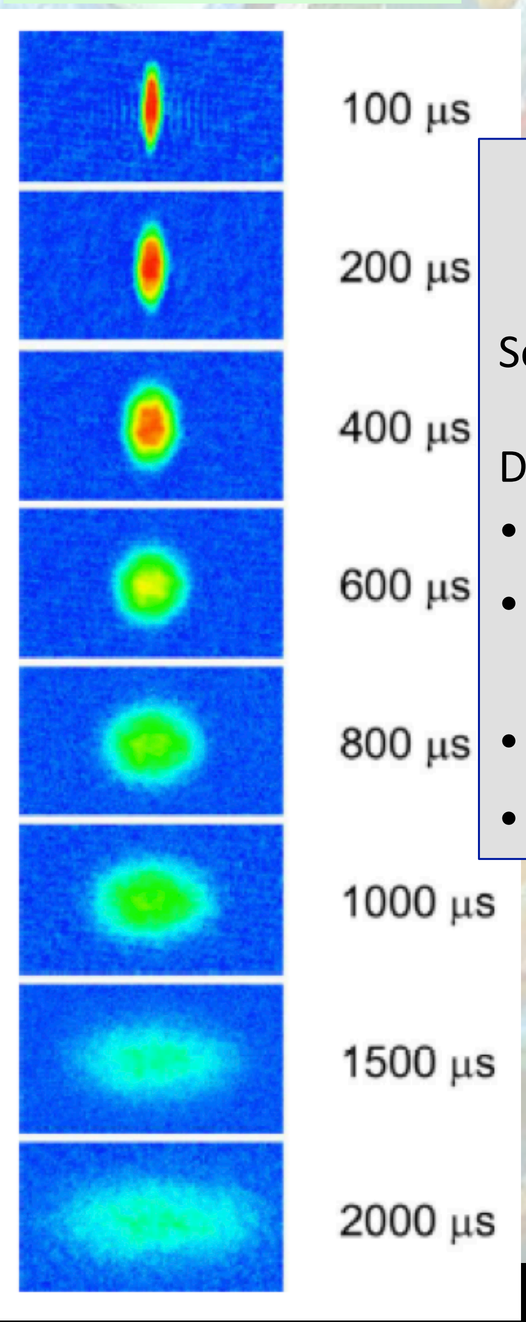


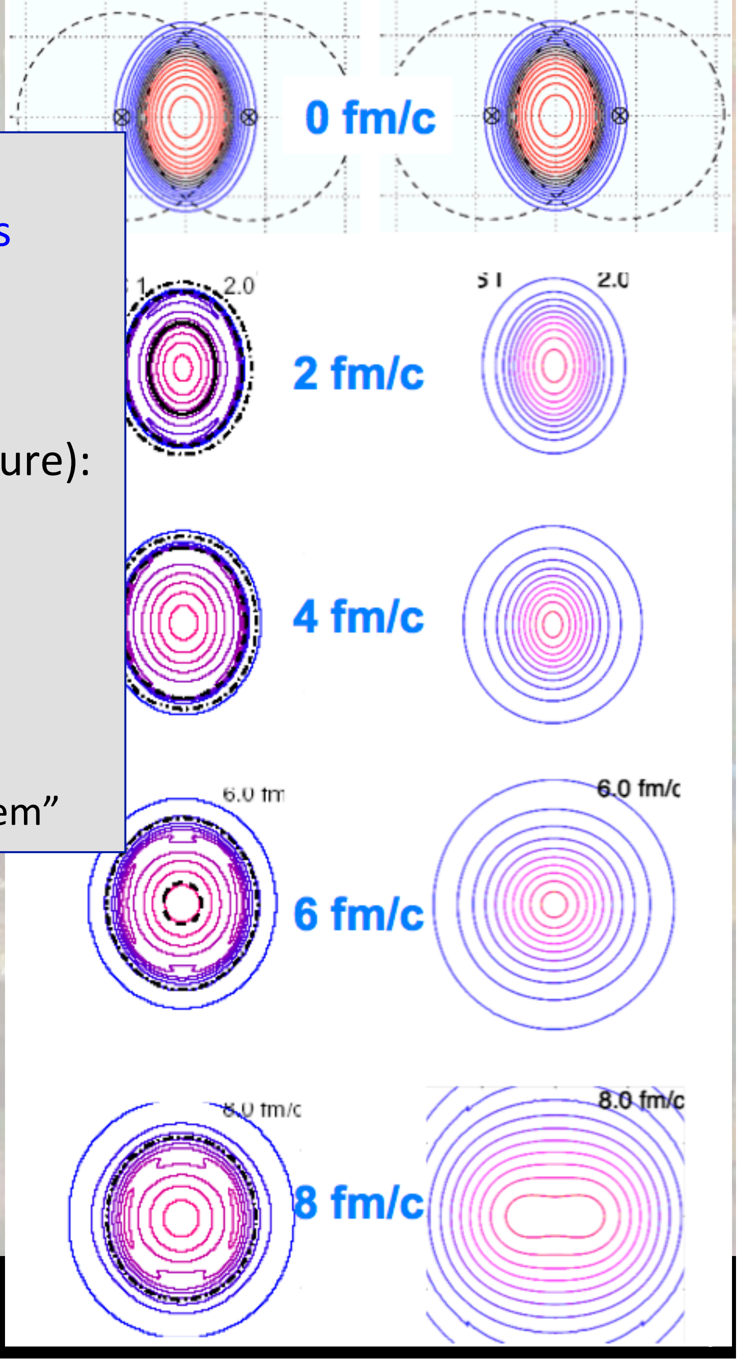
figure from PBM – talk on Thursday



Ultra-cold atomic gas



(model of) heavy ion collision



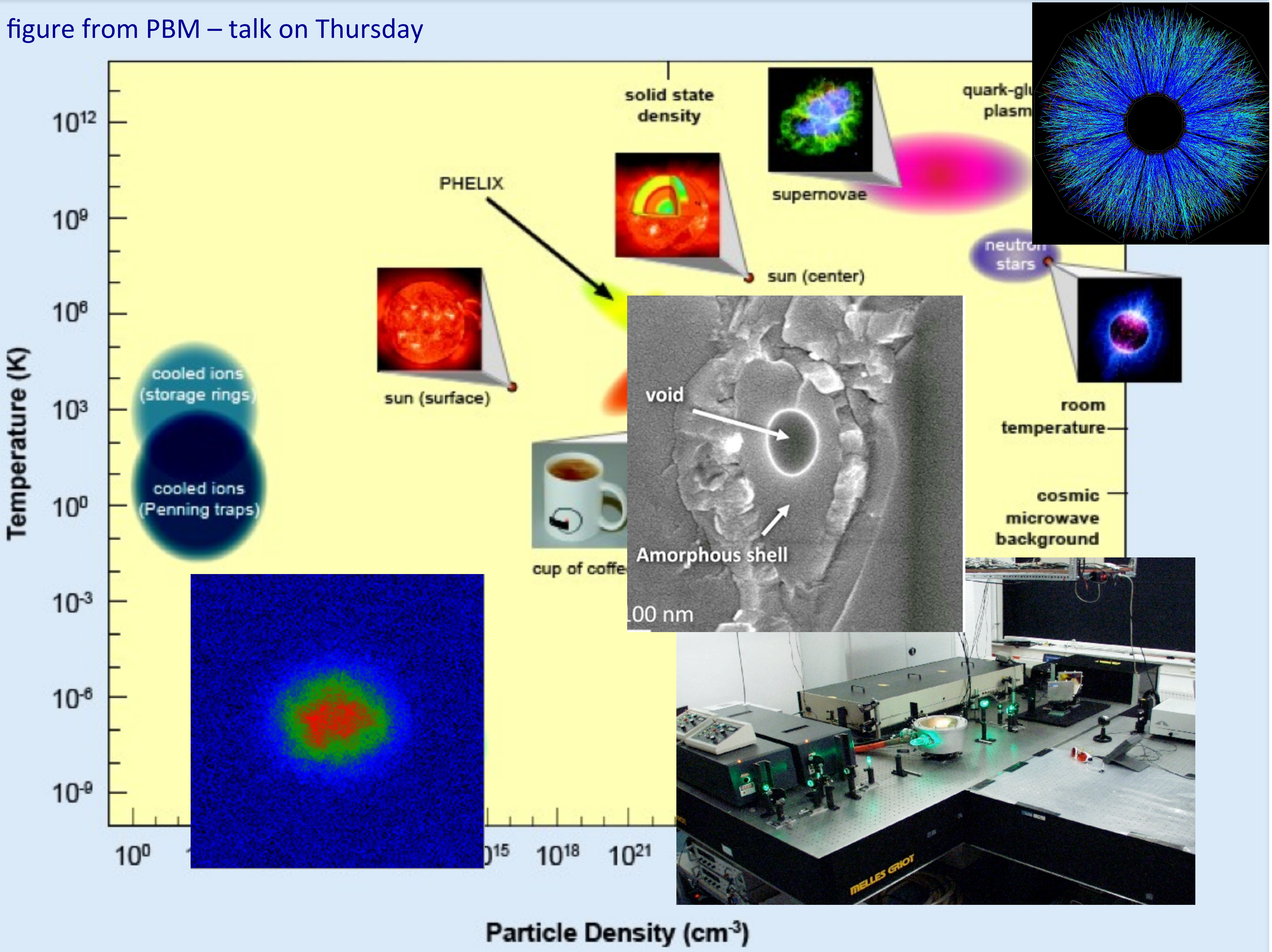
"Universal" elliptic flow of strongly-interacting systems

Sensitivity to phase structure?

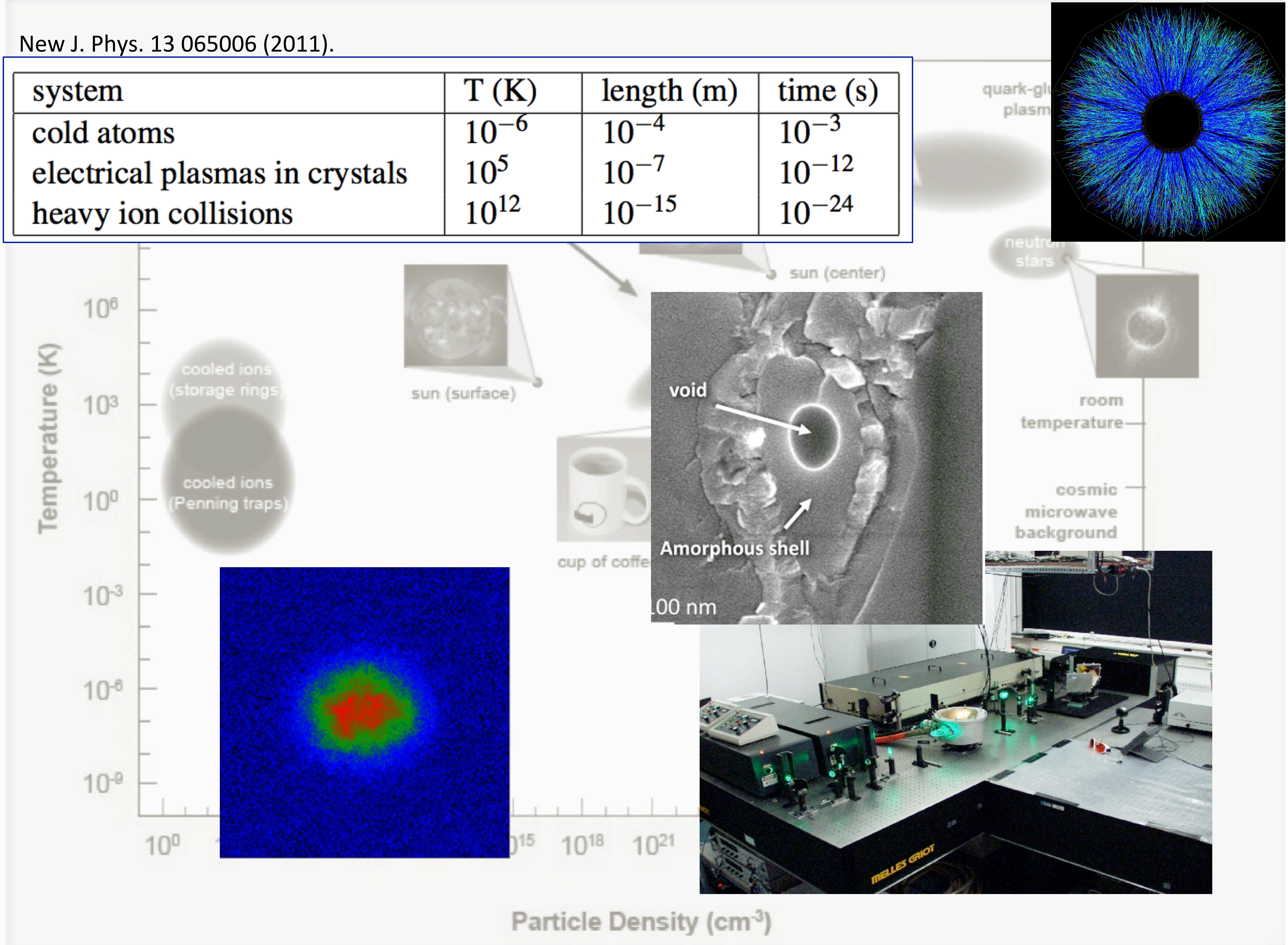
Differences (besides size, temperature):

- timescale
- initial state: violent vs prepared
    - thermalization?
- homo- vs hetero-geneous
- technique: "movie versus postmortem"

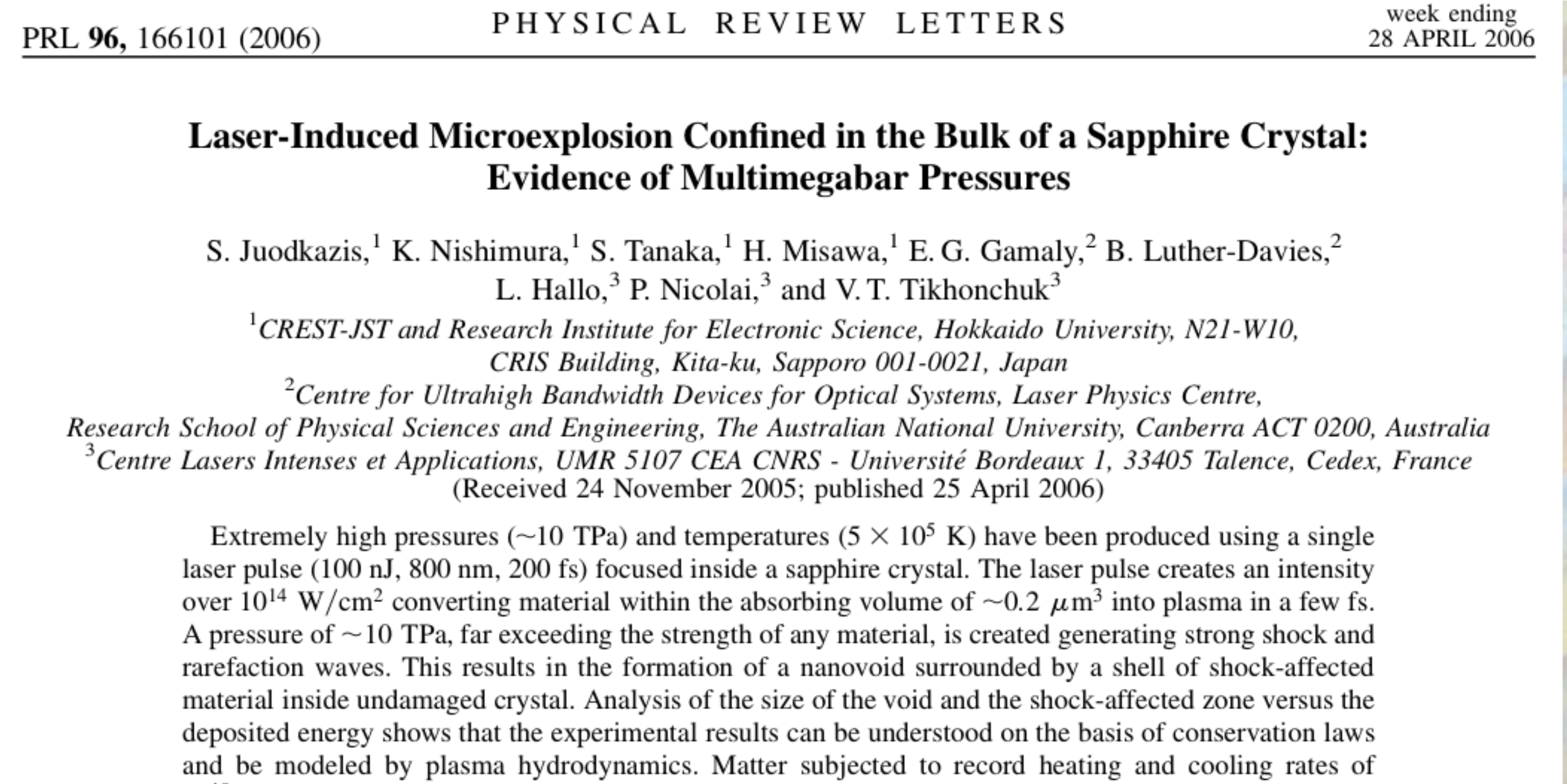
figure from PBM – talk on Thursday



New J. Phys. 13 065006 (2011).



system	T (K)	length (m)	time (s)
cold atoms	10^{-6}	10^{-4}	10^{-3}
electrical plasmas in crystals	10^{5}	10^{-7}	10^{-12}
heavy ion collisions	10^{12}	10^{-15}	10^{-24}



PRL **96,** 166101 (2006) PHYSICAL REVIEW LETTERS week ending 28 APRIL 2006

Laser-Induced Microexplosion Confined in the Bulk of a Sapphire Crystal: Evidence of Multimegabar Pressures

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L. Hallo,[3] P. Nicolai,[3] and V. T. Tikhonchuk[3]
[1]CREST-JST and Research Institute for Electronic Science, Hokkaido University, N21-W10, CRIS Building, Kita-ku, Sapporo 001-0021, Japan
[2]Centre for Ultrahigh Bandwidth Devices for Optical Systems, Laser Physics Centre, Research School of Physical Sciences and Engineering, The Australian National University, Canberra ACT 0200, Australia
[3]Centre Lasers Intenses et Applications, UMR 5107 CEA CNRS - Université Bordeaux 1, 33405 Talence, Cedex, France

(Received 24 November 2005; published 25 April 2006)

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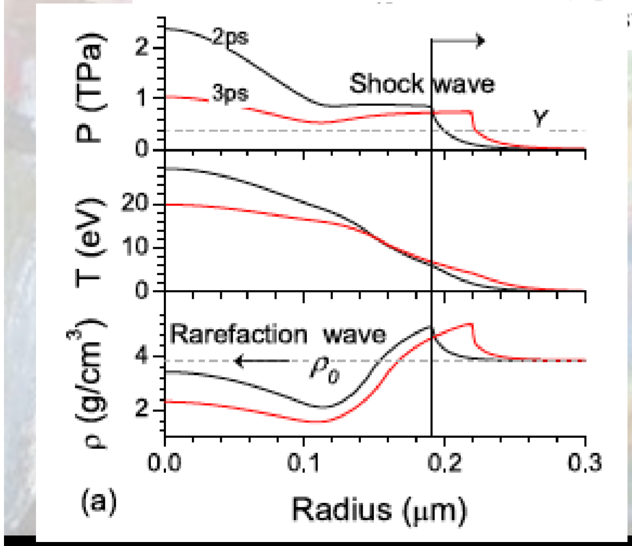

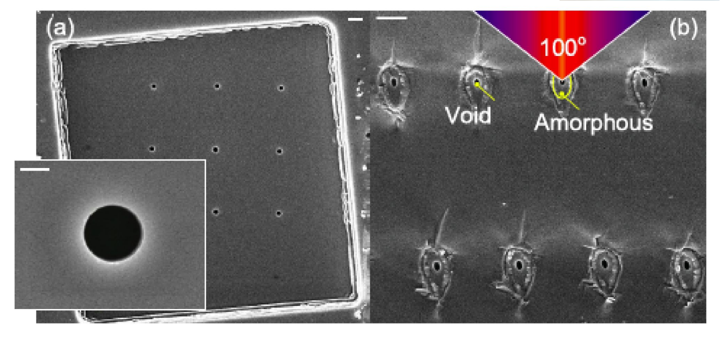

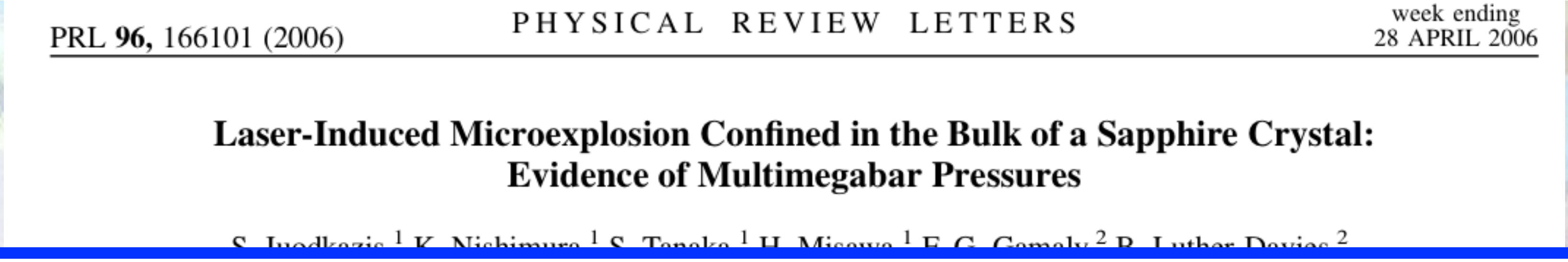

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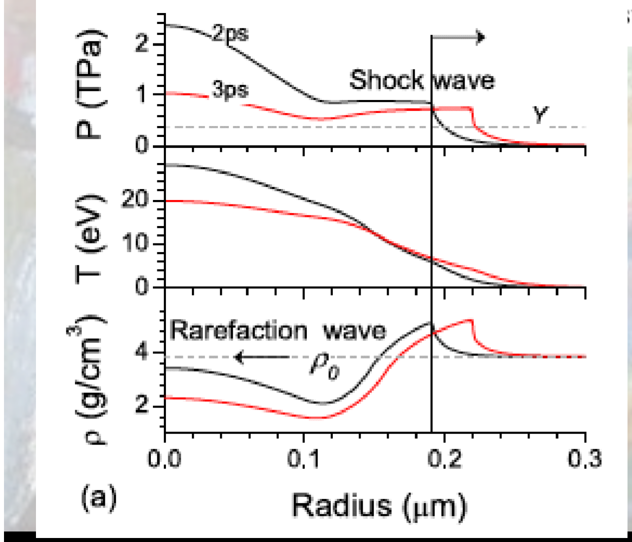

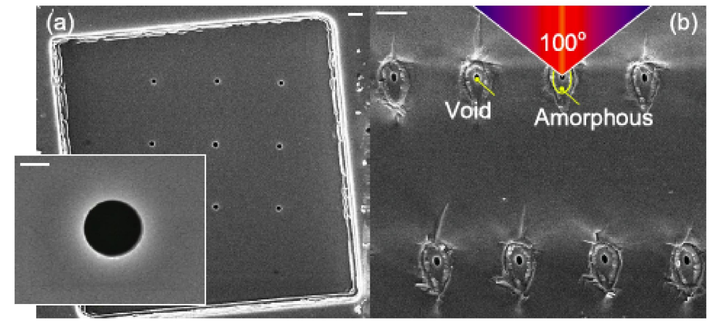

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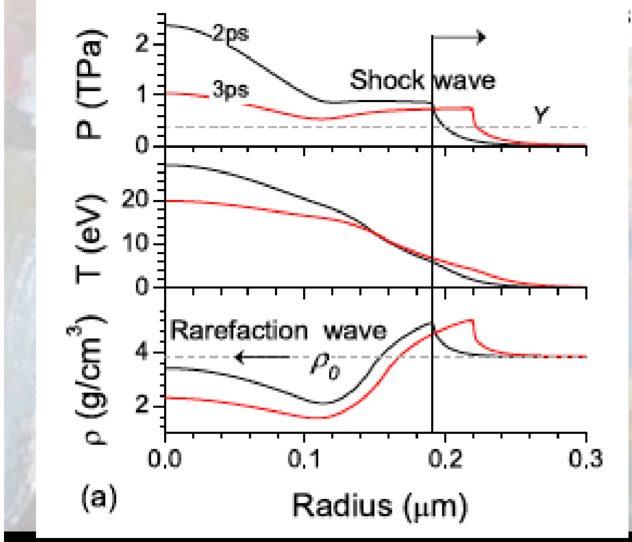

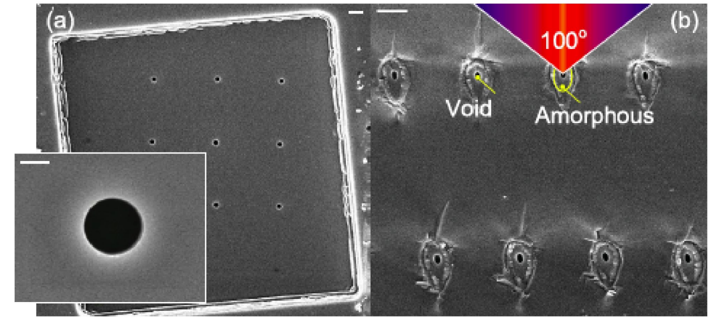

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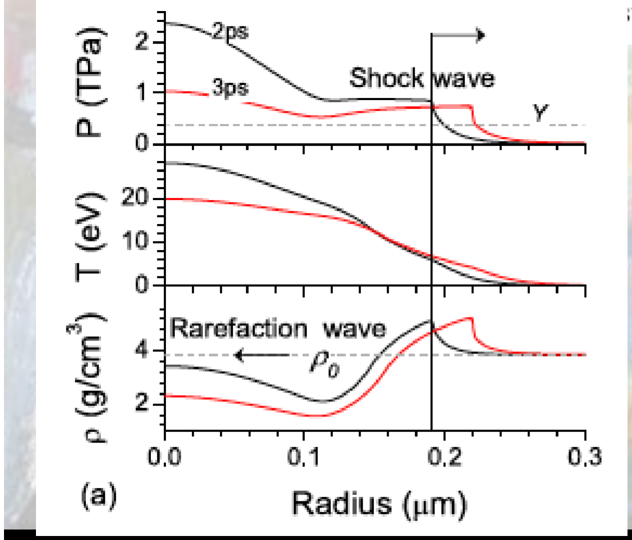

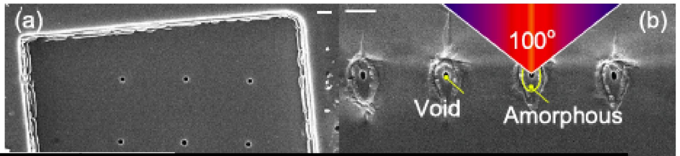

	Microexplosions	**Femtoexplosions**
√s		
ε	10^{17} J/m^3	5 GeV/fm^3 = 10^{36} J/m^3
T	10^6 K	200 MeV = 10^{12} K
rate	10^{18} K/sec	10^{35} K/s

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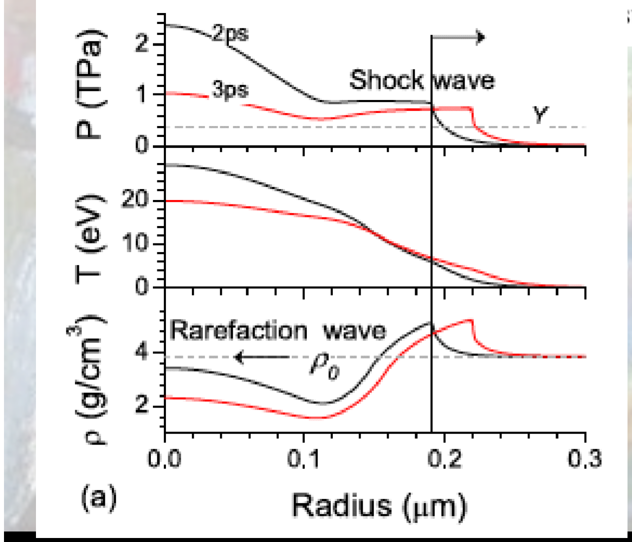

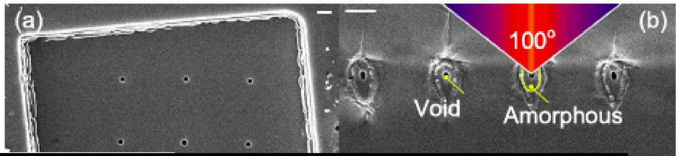

	Microexplosions	**Femtoexplosions**
√s	0.1 μJ	1 μJ
ε	10^{17} J/m^3	5 GeV/fm^3 = 10^{36} J/m^3
T	10^6 K	200 MeV = 10^{12} K
rate	10^{18} K/sec	10^{35} K/s

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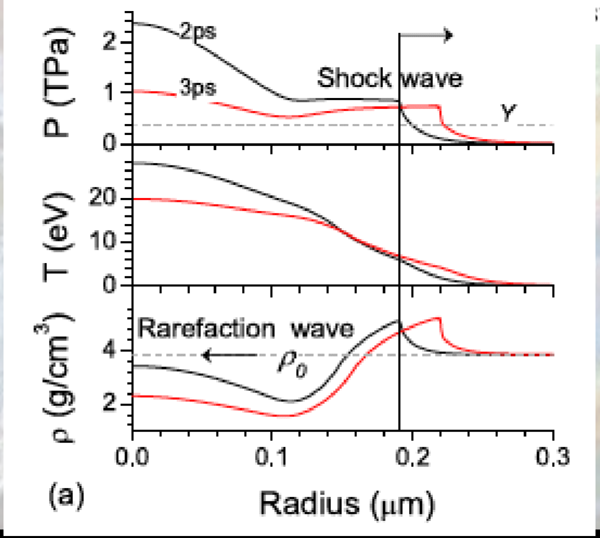
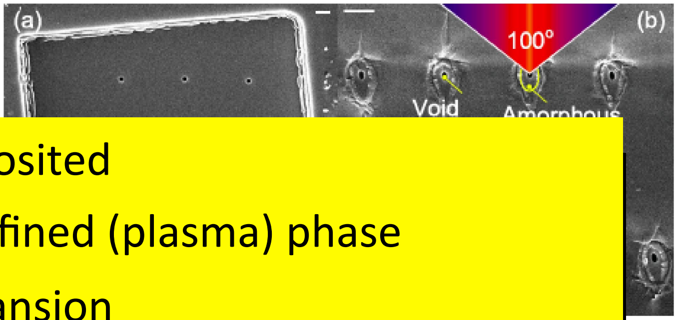
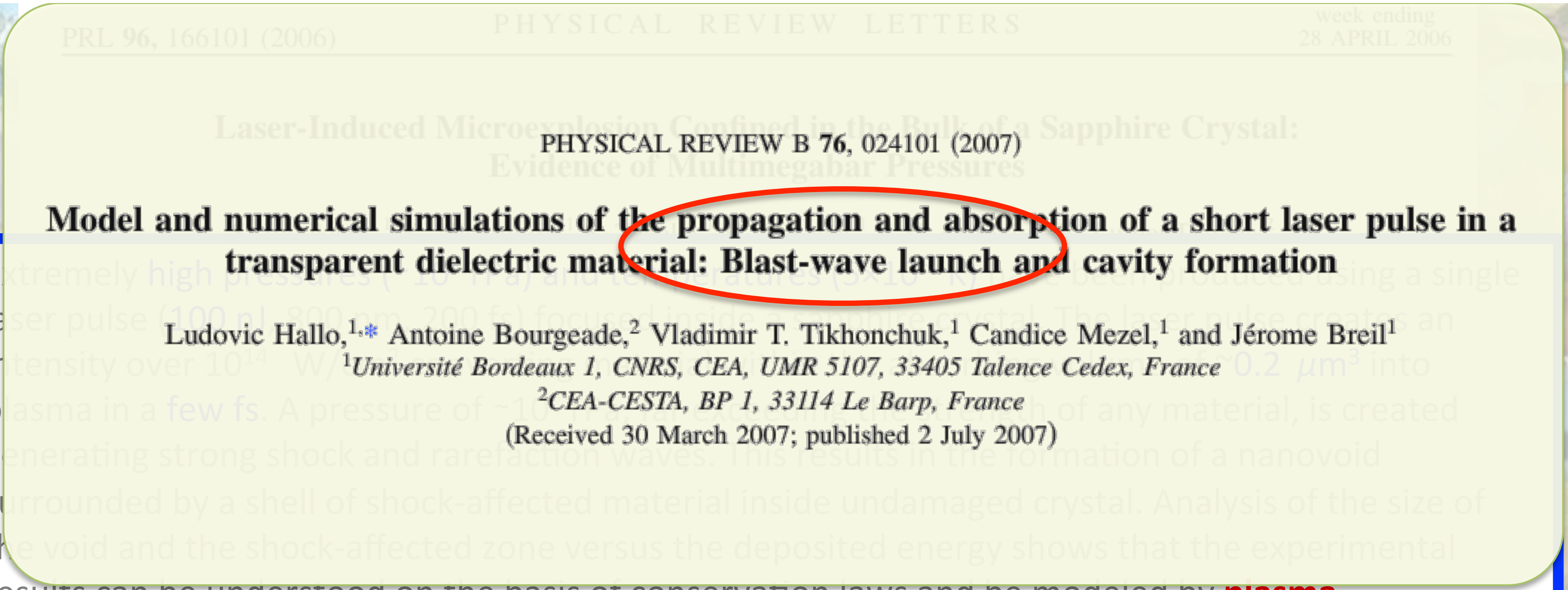




- energy quickly deposited
- transition to deconfined (plasma) phase
- hydrodynamic expansion
- cool back to confined (atomic) phase



PRL 96, 166101 (2006) PHYSICAL REVIEW LETTERS week ending 28 APRIL 2006

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PHYSICAL REVIEW B 76, 024101 (2007)

Model and numerical simulations of the propagation and absorption of a short laser pulse in a transparent dielectric material: Blast-wave launch and cavity formation

Ludovic Hallo,[1,*] Antoine Bourgeade,[2] Vladimir T. Tikhonchuk,[1] Candice Mezel,[1] and Jérome Breil[1]

[1]*Université Bordeaux 1, CNRS, CEA, UMR 5107, 33405 Talence Cedex, France*

[2]*CEA-CESTA, BP 1, 33114 Le Barp, France*

(Received 30 March 2007; published 2 July 2007)

Extremely high pressures (~10[illegible] TPa) and temperatures (5×10[illegible] K) [illegible] been produced using a single laser pulse (100 nJ, 800 nm, 200 fs) focused inside a sapphire crystal. The laser pulse creates an intensity over 10^{14} W/[illegible] into plasma in a few fs. A pressure of ~10[illegible] TPa, far exceeding the strength of any material, is created generating strong shock and rarefaction waves. This results in the formation of a nanovoid surrounded by a shell of shock-affected material inside undamaged crystal. Analysis of the size of the void and the shock-affected zone versus the deposited energy shows that the experimental results can be understood on the basis of conservation laws and be modeled by **plasma hydrodynamics**. Matter subjected to record heating and cooling rates of 10^{18} K/s can, thus, be studied in a well-controlled laboratory environment.

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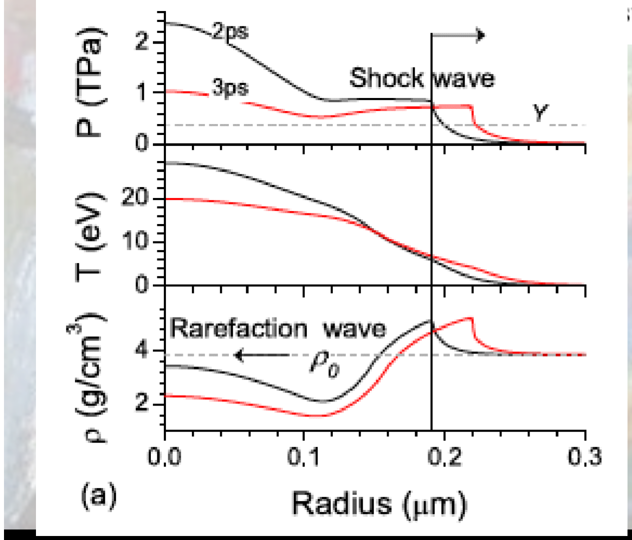

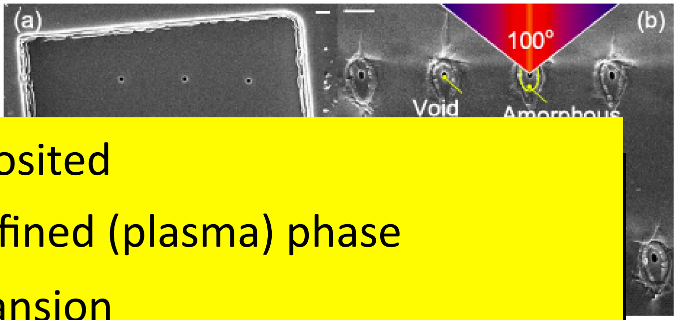

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- energy quickly deposited
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Appl Phys A (2008) 92: 837–841
DOI 10.1007/s00339-008-4580-5

Applied Physics A
Materials Science & Processing

Formation of nanocavities in dielectrics: influence of equation of state

L. Hallo · A. Bourgeade · C. Mézel · G. Travaillé · D. Hébert · B. Chimier · G. Schurtz · V.T. Tikhonchuk

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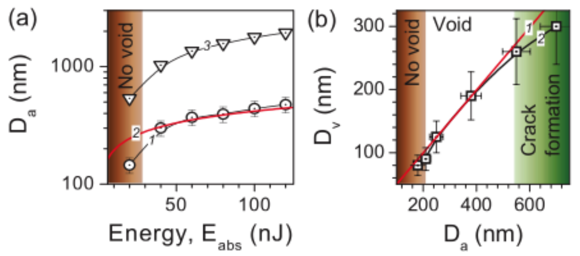

FIG. 3 (color). (a) The diameter (1) and length (3) of the amorphous region vs the absorbed pulse energy, E_{abs}. The voids were 20 μm beneath the surface. Curve (2) plotted by Eq. (1) with $l_a = 80$ nm. (b) Dependence of the void diameter on the diameter of amorphous part: (1) theory by Eq. (2) with $\delta = 1.14$; (2) experiment.

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data should allow a tuning of equations of state in main of extreme parameters

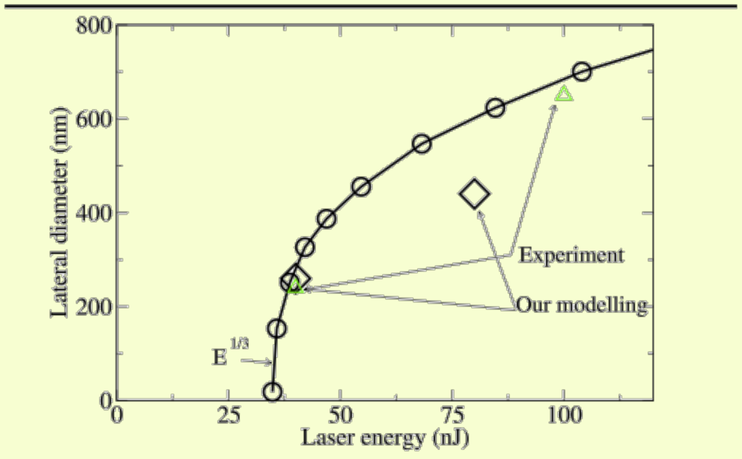

Fig. 9 Cavity diameter on the laser energy in silica, simple modeling (*circles*) [2], IL0005 EOS (*diamond shapes*) and experiment (*triangles*)

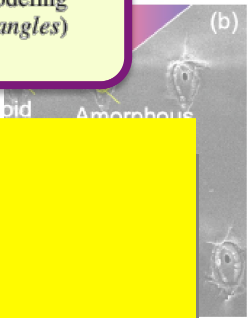

Table 1 SESAME 7387, QEOS and home-made IL type EOS parameters

EOS name	*G*	E_{sub} (MJ/kg)
QEOS	1.5	≈0.01
SESAME 7387	0.65	10
IL0005	0.03	17
IL0006	0.03	28
IL0007	0.03	8

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- cool back to confined (atomic) phase
- probe **EoS** under extreme conditions (**√s dep.**)
- examine final anisotropy of system

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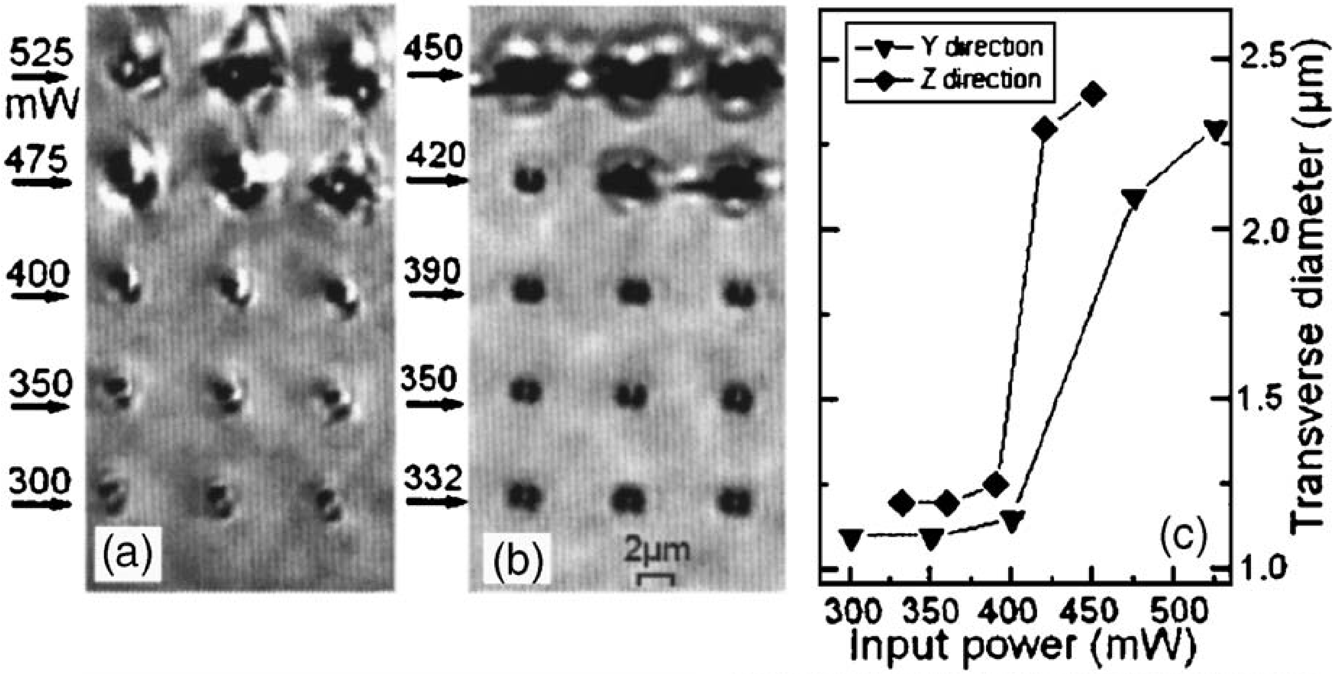
Applied Physics A

Zhou & Gu, App. Phys. Lett. **87** 241107 (2005)



Energy scan: threshold behaviour in size and anisotropy

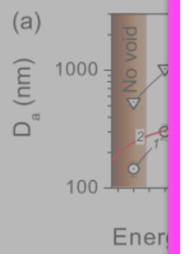
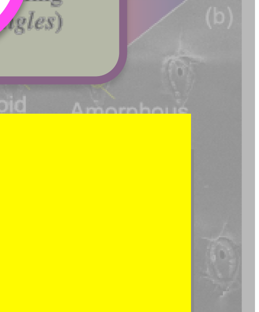


FIG. 3 (color). (a… amorphous region v… were 20 μm beneath… with $l_a = 80$ nm. (b) Dependence of the void diameter on the diameter of amorphous part: (1) theory by Eq. (2) with $\delta = 1.14$; (2) experiment.

…data should allow a tuning of equations of state in main of extreme parameters



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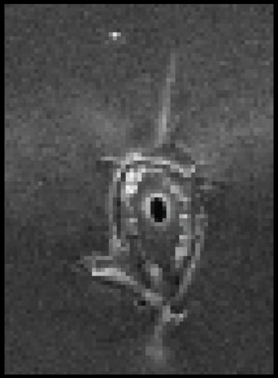
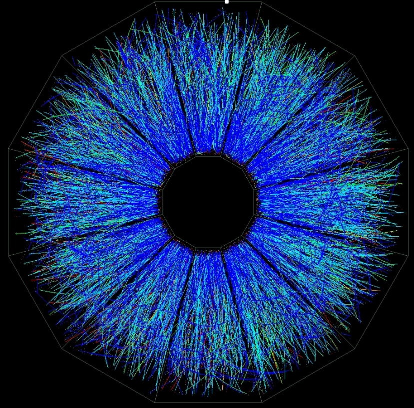
Applied Physics A

Microexplosion



measure geometry
infer momentum

Femtoexplosion



measure momentum
infer geometry

FIG. 3 (color). (a) The diameter (1) and length (3) of the amorphous region vs the absorbed pulse energy, E_{abs}. The voids were 20 μm beneath the surface. Curve (2) plotted by Eq. (1) with $l_a = 80$ nm. (b) Dependence of the void diameter on the diameter of amorphous part: (1) theory by Eq. (2) with $\delta = 1.14$; (2) experiment.

Fig. 9 Cavity diameter on the laser energy in silica, simple modeling (*circles*) [2], IL0005 EOS (*diamond shapes*) and experiment (*triangles*)

main of extreme parameters

Table 1 SESAME 7387, QEOS and home-made IL type EOS parameters

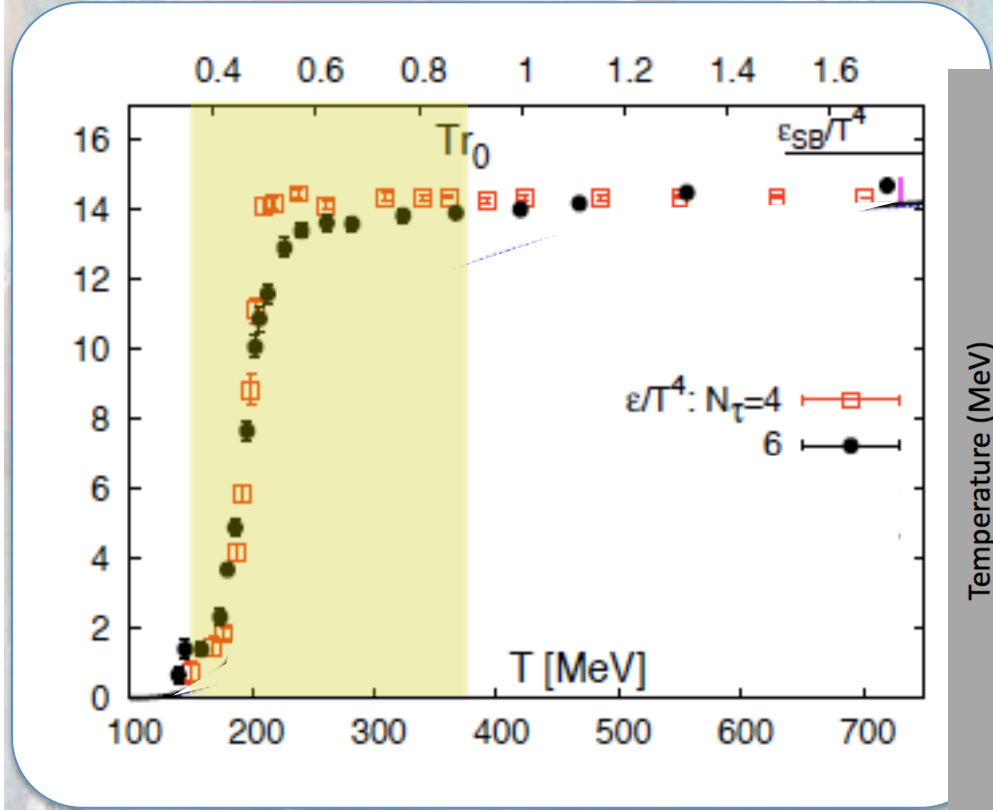
EOS name	G	E_{sub} (MJ/kg)
QEOS	1.5	≈0.01
SESAME 7387	0.65	10
IL0005	0.03	17
IL0006	0.03	28
IL0007	0.03	8

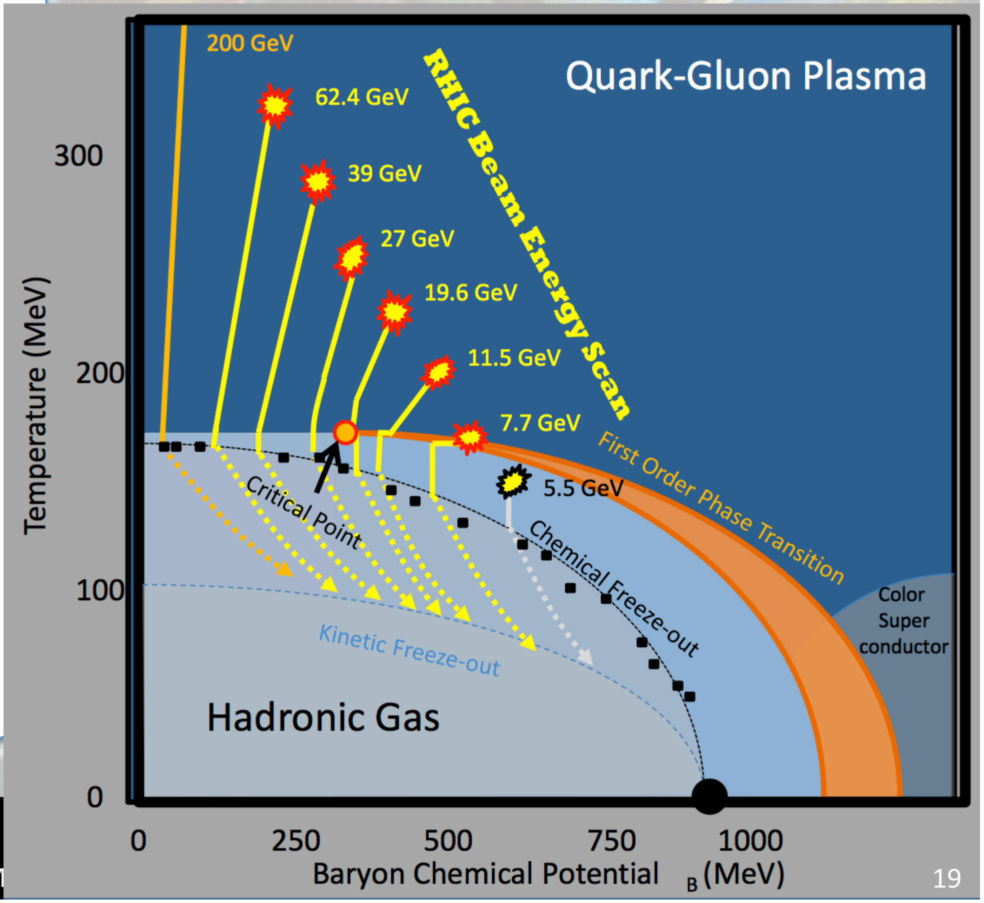
- energy quickly deposited
- transition to deconfined (plasma) phase
- hydrodynamic expansion
- cool back to confined (atomic) phase
- probe **EoS** under extreme conditions (**$\sqrt{s}$ dep.**)
- examine final anisotropy of system

RHIC BES-I

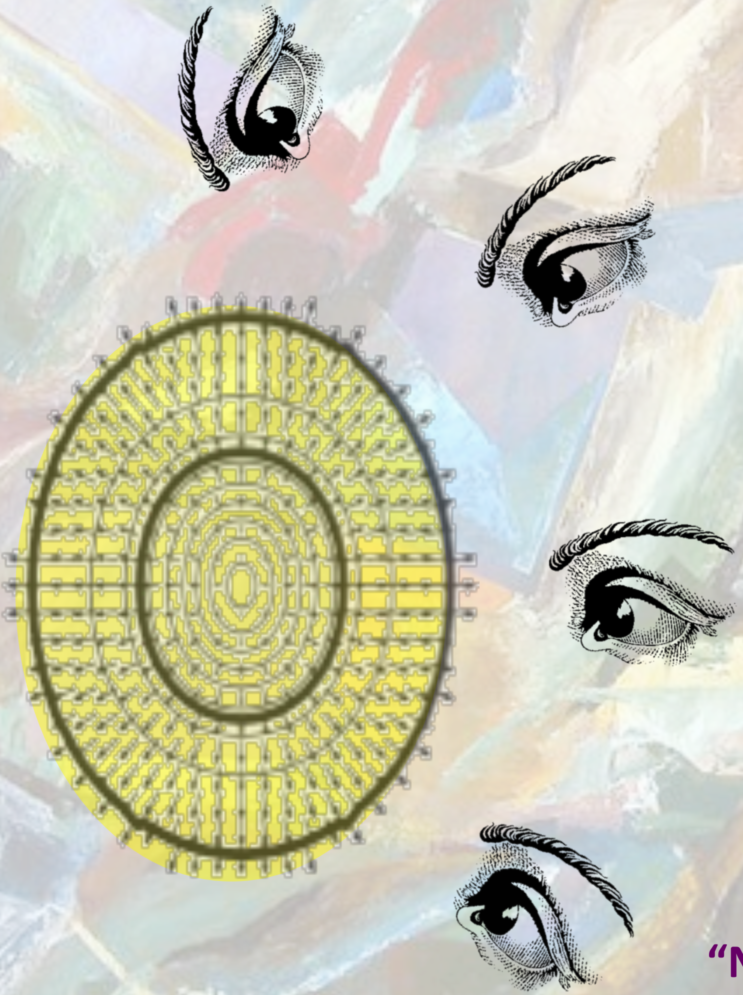
arXiv:1007.2613

Energies chosen to cover the interesting transition region **dictated by the scale of the theory** (not highest energy possible)

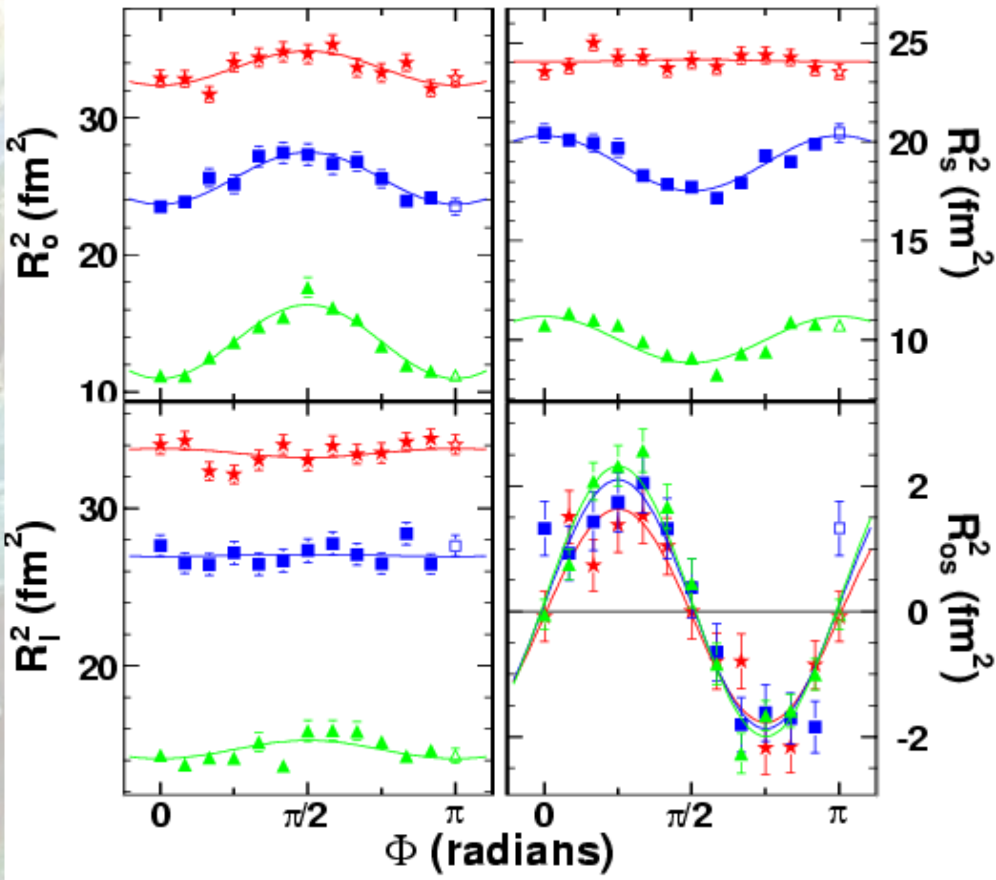




Azimuthal dependence of HBT radii at RHIC



STAR, PRL93 012301 (2004)

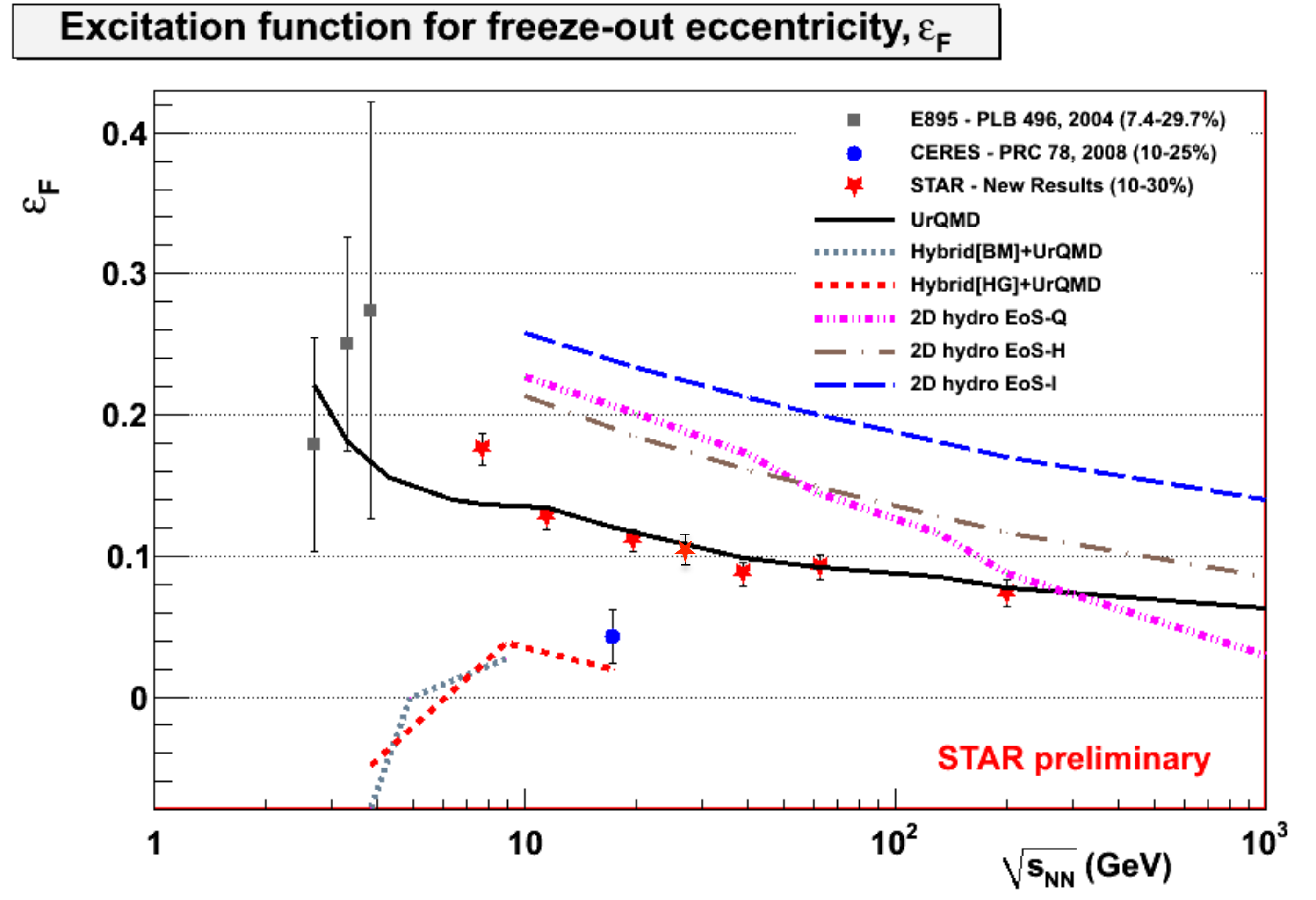


"No-flow formula" estimated good within ~ 30% (low pT)

$$R_{s,n}^2 \equiv \left\langle R_s^2(\phi) \cdot \cos(n\phi) \right\rangle \qquad \varepsilon \approx 2\frac{R_{s,2}^2}{R_{s,0}^2} \approx 2\frac{R_{os,2}^2}{R_{s,0}^2} \approx -2\frac{R_{o,2}^2}{R_{s,0}^2}$$

Retiere&MAL PRC70 (2004) 044907

STAR BES results [prelim]

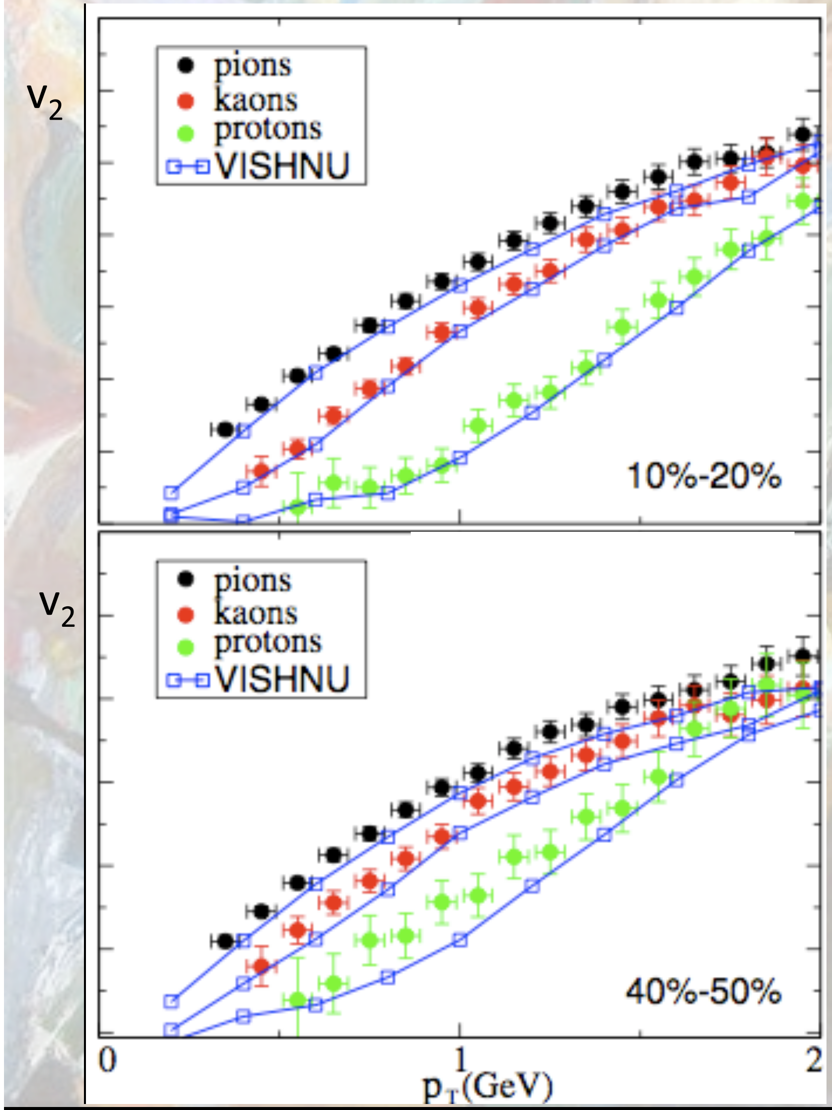


STAR, Quark Matter 2012

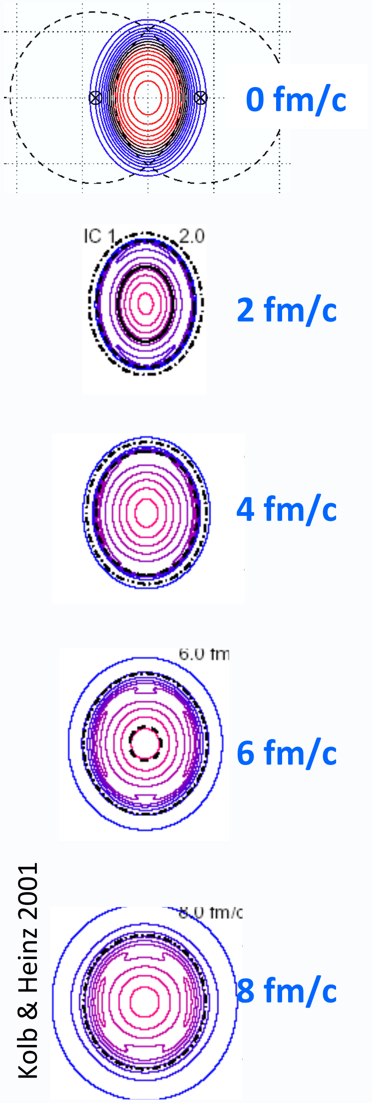
- no non-monotonic or threshold behaviour
- remarkably (depressingly) consistent with **pre**diction using soft hadronic EoS with realistic freezeout
- **But** results may provide the key to something at least as fundamental... (next)

Elliptic flow in a viscous hydro

Heinz, Chen, Song, arXiv:1108.5323



Plasma
hydrodynamics



Kolb & Heinz 2001

Hydrodynamics: conservation laws for long wavelength modes

$$\partial_\mu T^{\mu\nu} = 0$$

Generally:

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \pi^{\mu\nu}.$$

First order Navier Stokes theory:

$$\pi^{\mu\nu} = \pi^{\mu\nu}_{(1)} = \eta(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \tfrac{2}{3}\Delta^{\mu\nu}\nabla_\alpha u^\alpha).$$

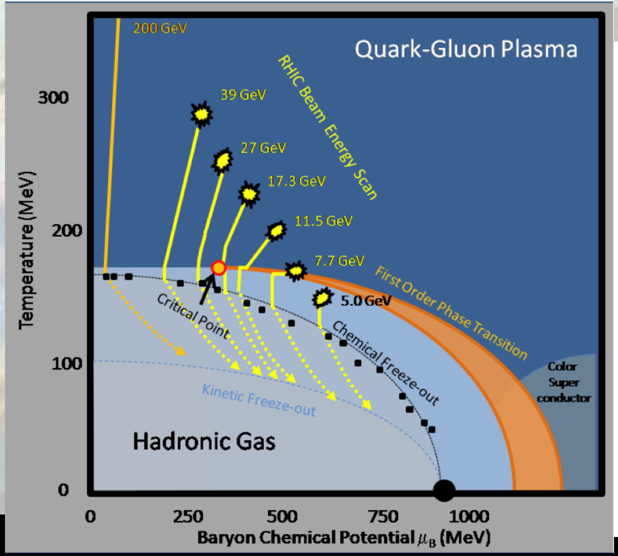
η: Shear viscosity

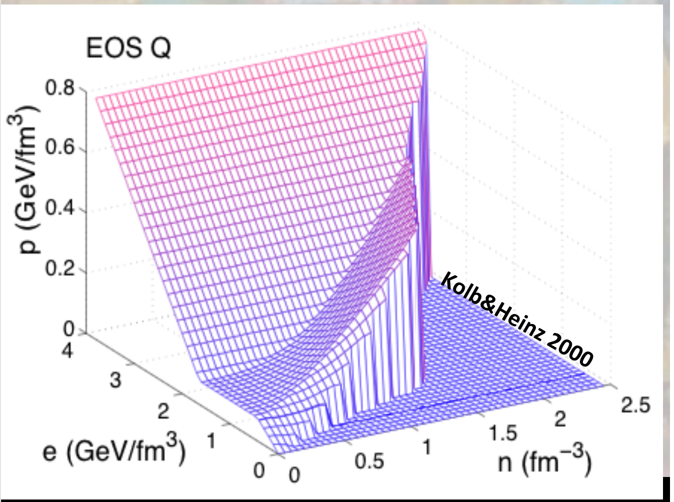
Large η = transport of momentum across fluid layers

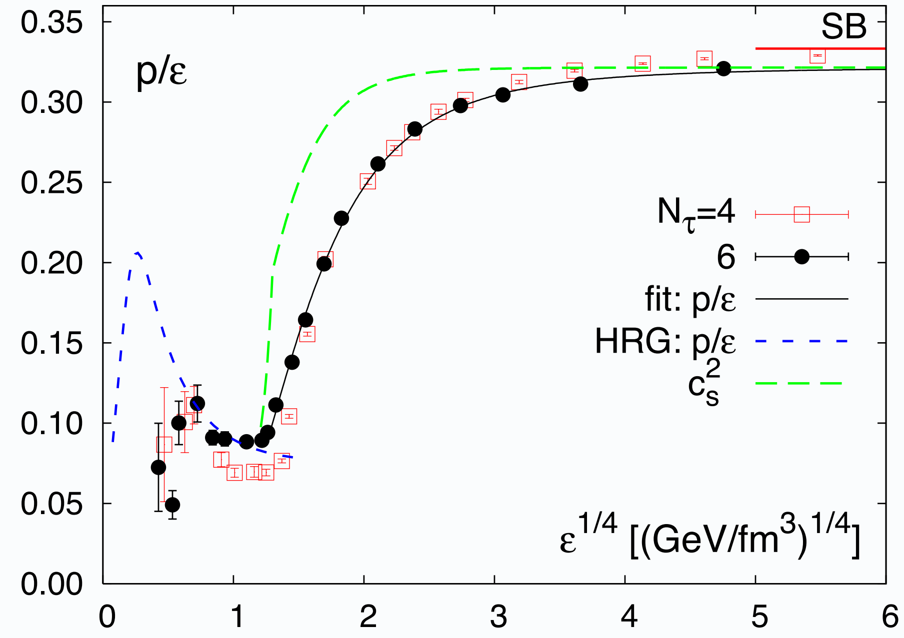
+ initial conditions
(nontrivial!)

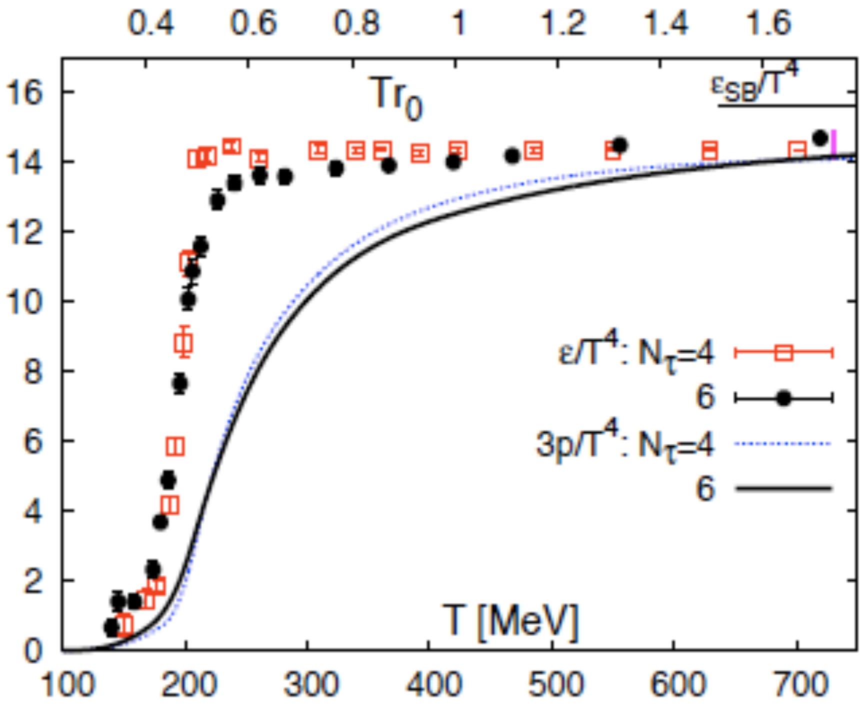
+ Equation of State
(fundamental)

walski, T. Lappi and R. Venugopalan, Phys.Rev.Lett. 100:022303









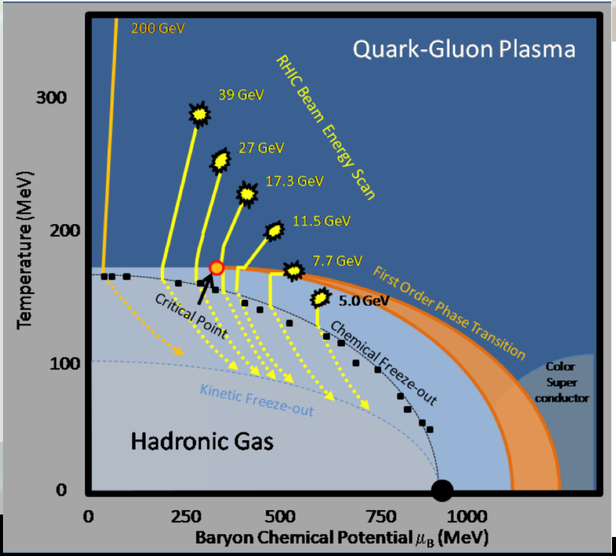
F. Karsch, arXiv:0711.0656 [hep-lat]

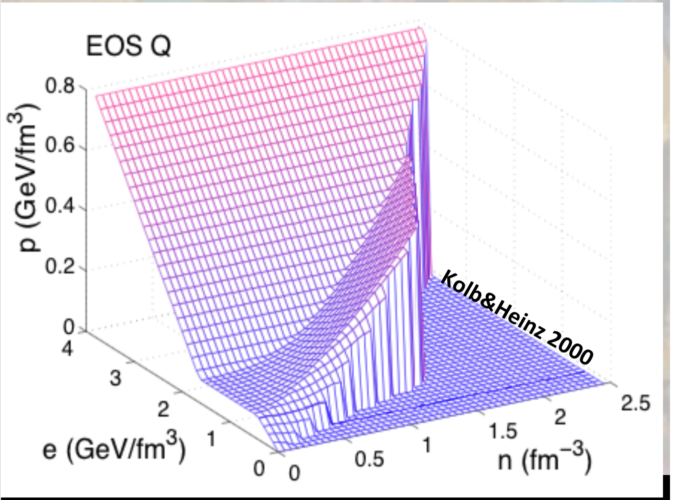
Data support

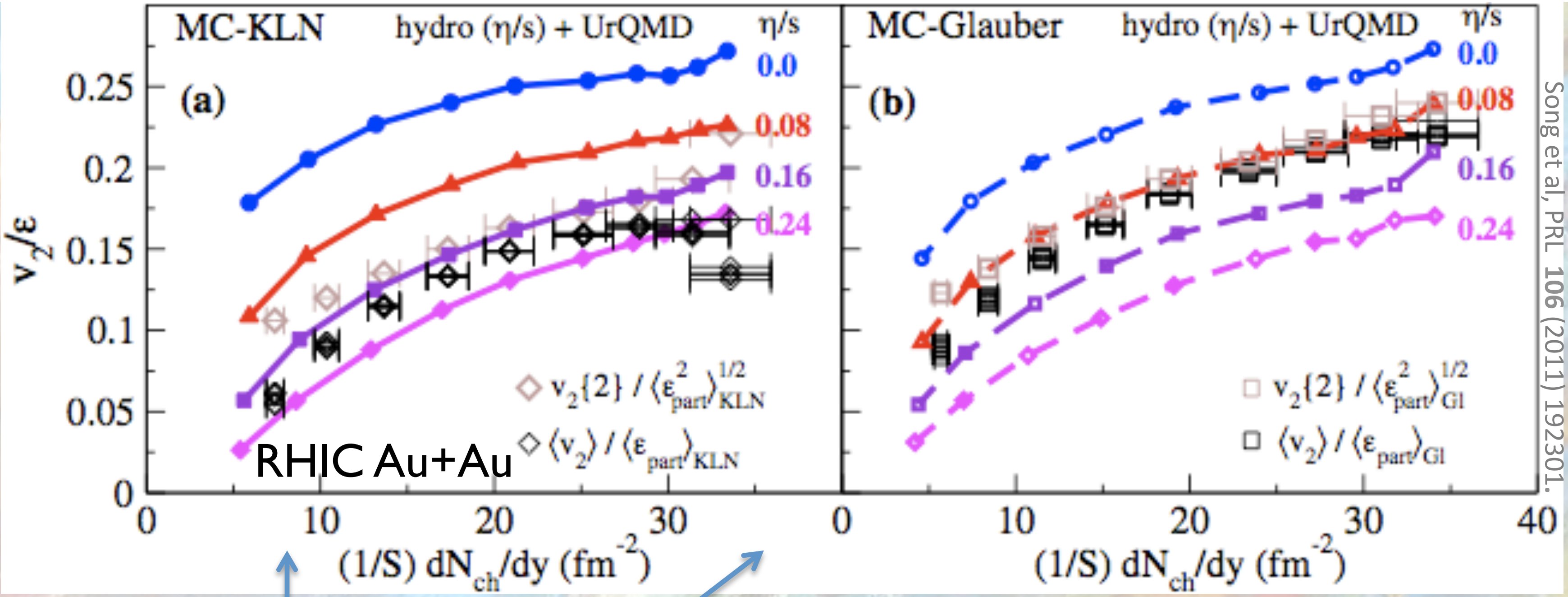
Lattice QCD EoS near zero net baryon density

- Cross-over transition.

Of great interest: viscosity

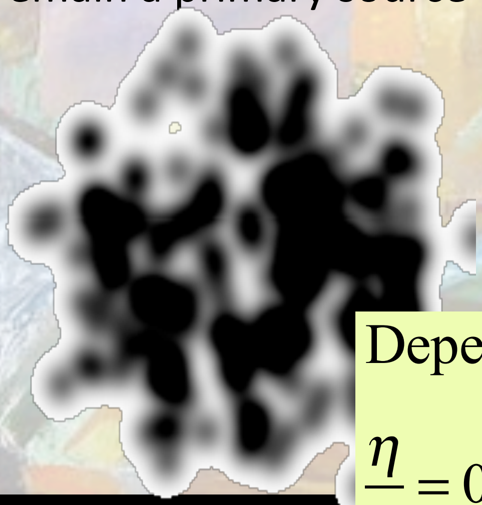




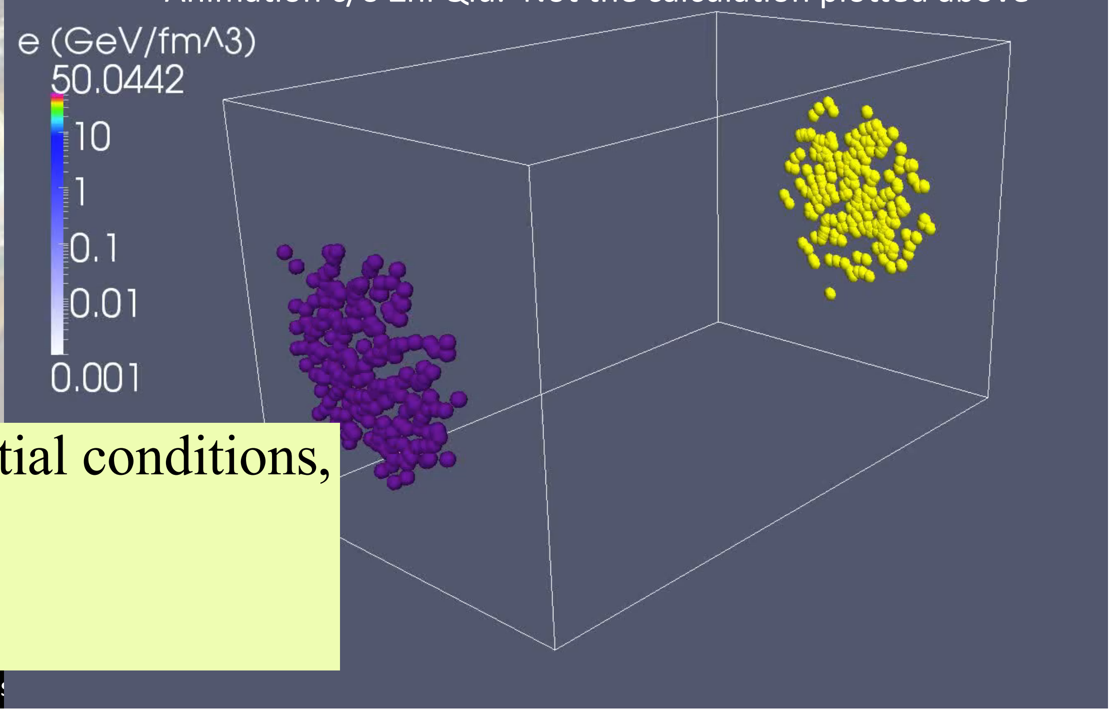


Song et al, PRL **106** (2011) 192301.

Ambiguity of initial configuration remain a primary source of uncertainty

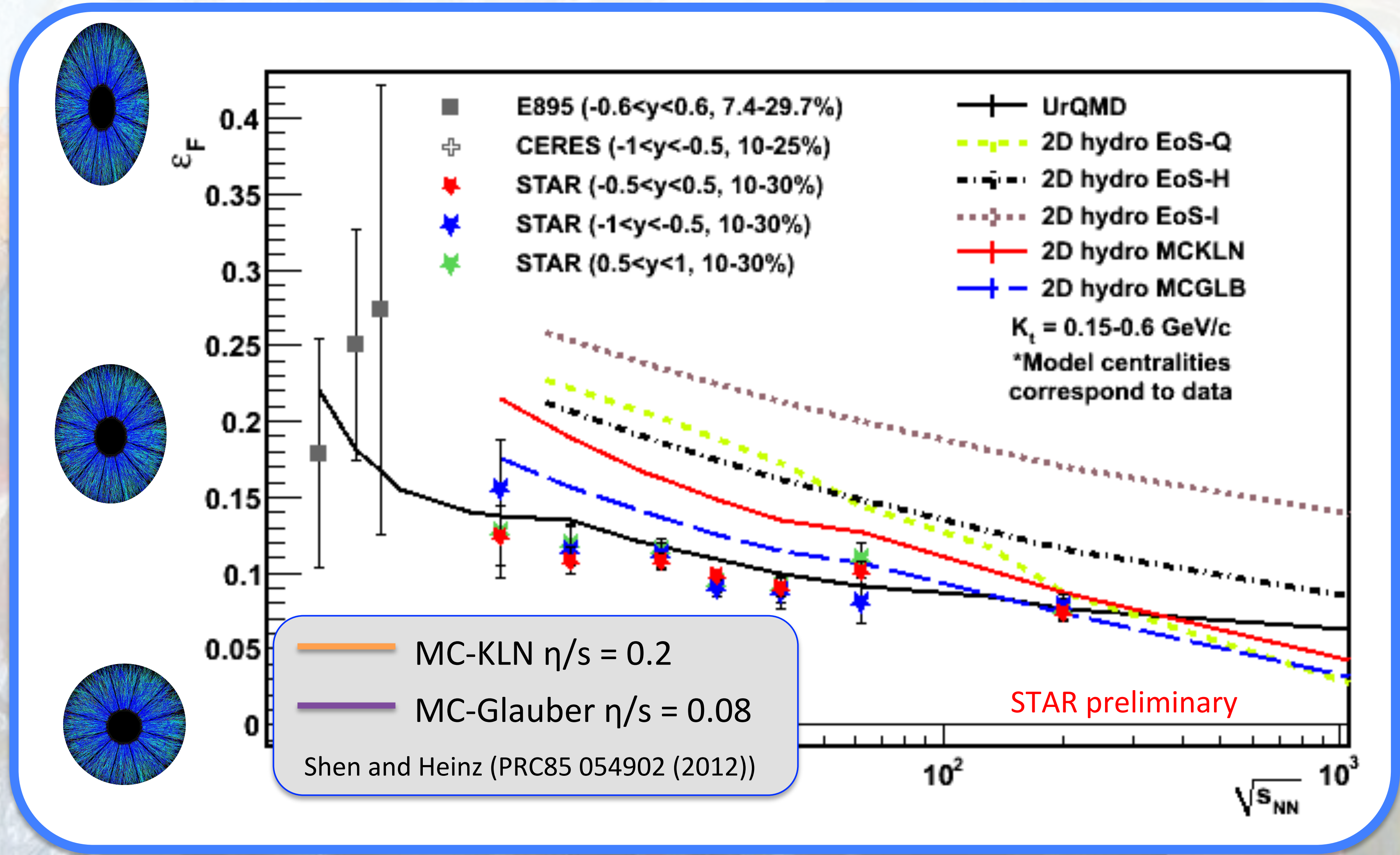


Animation c/o Zhi Qiu. Not the calculation plotted above



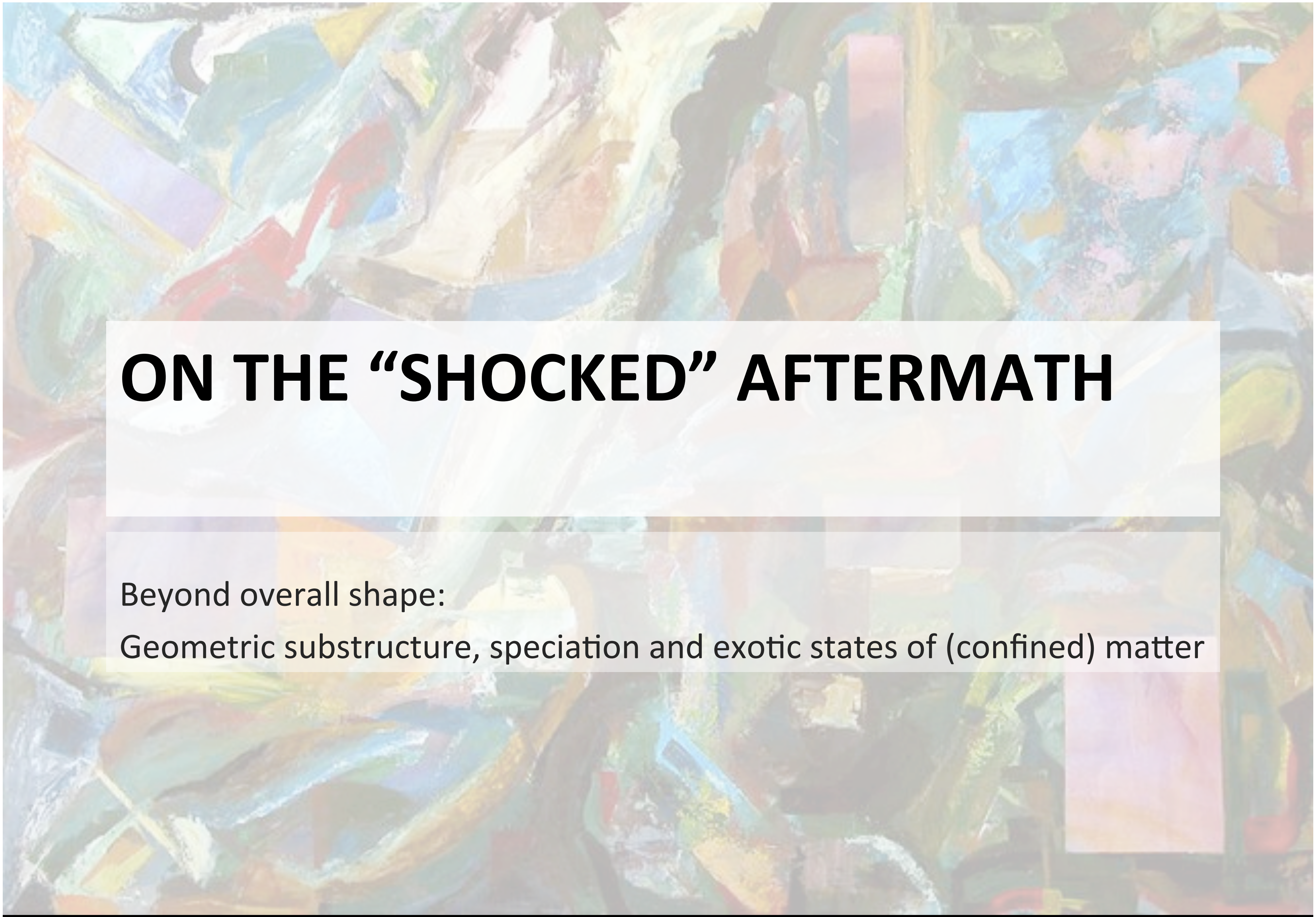
Depending on initial conditions,

$$\frac{\eta}{s} = 0.08 \div 0.2$$



Shen and Heinz (PRC85 054902 (2012))

- Two initial-state/viscosity combinations that give degenerate results in azimuthal *momentum* space, are **non-degenerate in azimuthal *coordinate* space**
    - an important handle on a fundamental QCD coefficient



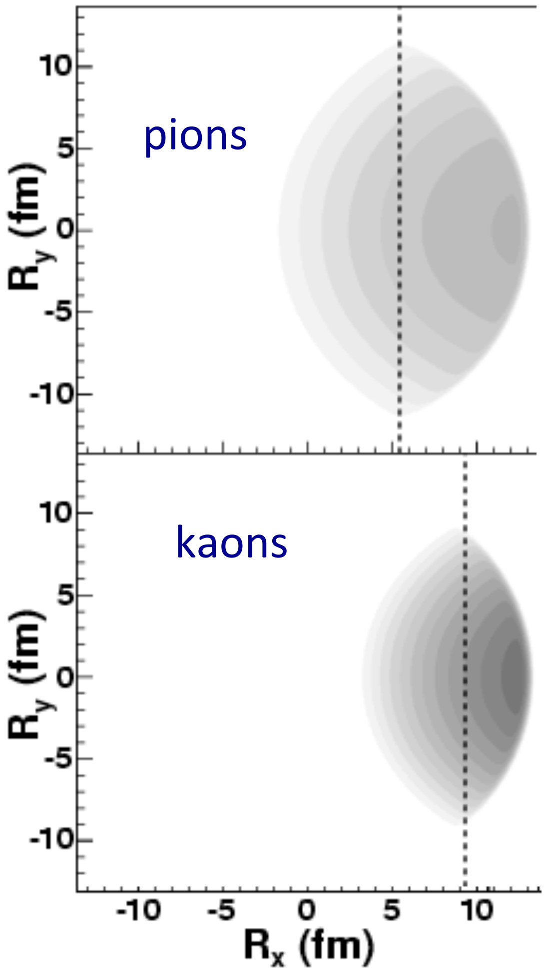
ON THE “SHOCKED” AFTERMATH

Beyond overall shape:

Geometric substructure, speciation and exotic states of (confined) matter

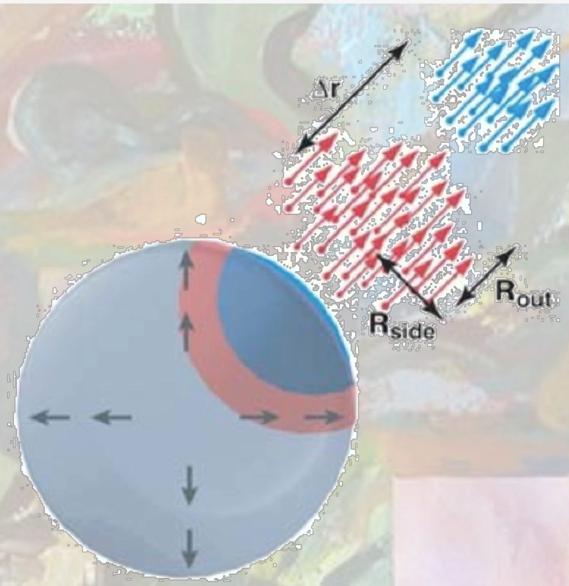
Speciation: Dynamics of separation distributions

Blast wave calculation
$v_x = 0.907c$



F. Retiere & MAL 2004

$$\underbrace{R(\vec{k}^*) = \frac{A(\vec{k}^*)}{B(\vec{k}^*)} - 1}_{\text{measured}} = \int d^3r\, \underbrace{S(\vec{r})}_{\text{wanted}}\, \underbrace{|\Psi(\vec{r},\vec{k}^*)|^2}_{\text{known}}$$



Collective flow generates separated emission regions ("homogeneity regions") for hadrons of different mass.

Speciation: Extracting the source characteristics

$$\underbrace{R(\vec{k}^*) = \frac{A(\vec{k}^*)}{B(\vec{k}^*)} - 1}_{\text{measured}} = \int d^3r \, \underbrace{S(\vec{r})}_{\text{wanted}} \, \underbrace{|\Psi(\vec{r}, \vec{k}^*)|^2}_{\text{known}}$$

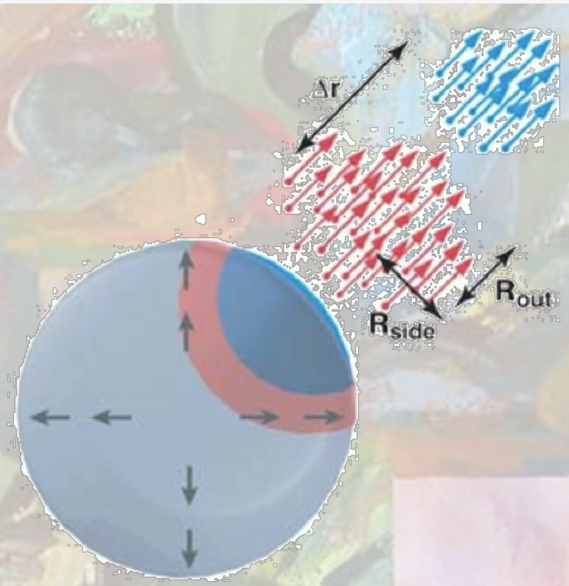
Spherical harmonic decomposition

$$R_{l,m}(|\vec{k}^*|) \equiv \int d\Omega \; R(\vec{k}^*) Y_{l,m}(\Omega)$$

$$S_{l,m}(|\vec{r}|) \equiv \int d\Omega \; S(\vec{r}) Y_{l,m}(\Omega)$$

$$R_{l,m}(|k^*|) = \int dr \; S_{l,m}(r) K_l(|k^*|, r)$$

Brown, Danielewicz, Pratt et al '05
Chajecki & Lisa '05
Brown & Kisiel '08



$R_{0,0}(|\vec{k}^*|)$ probes size

$\mathrm{Re}(R_{1,1}(|\vec{k}^*|))$ probes asymmetry

Speciation in 0-5% Central Au+Au @ 200 GeV

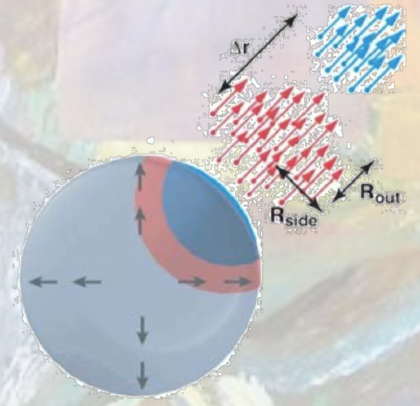
- Narrow Coulomb hole ← large source
- Significant asymmetry in correlation function

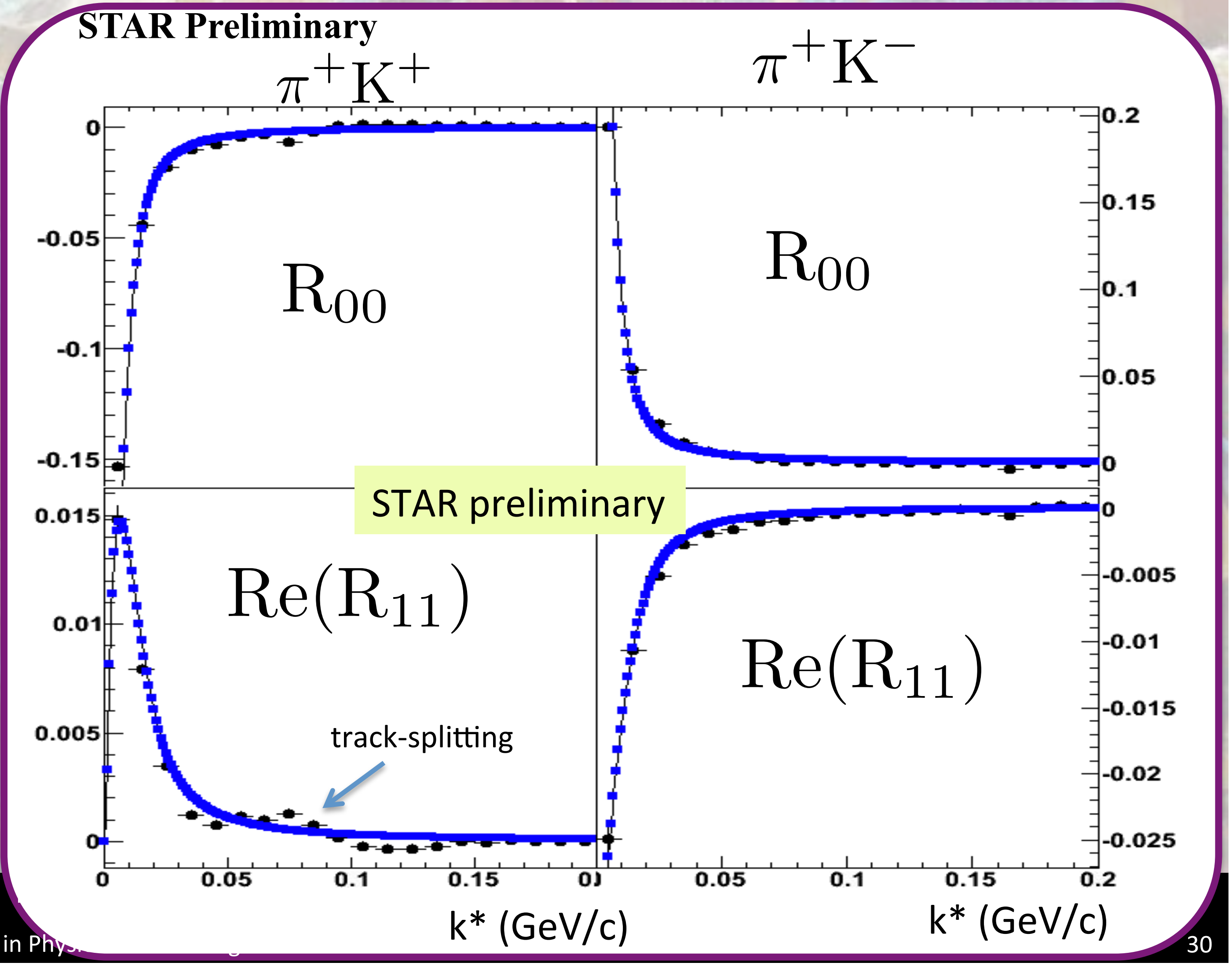
- First such high-quality data
- consistent with blast scenario

- data
- Gauss Source

$\sigma = 14.1\ \mathrm{fm}$

$d = 6\ \mathrm{fm}$

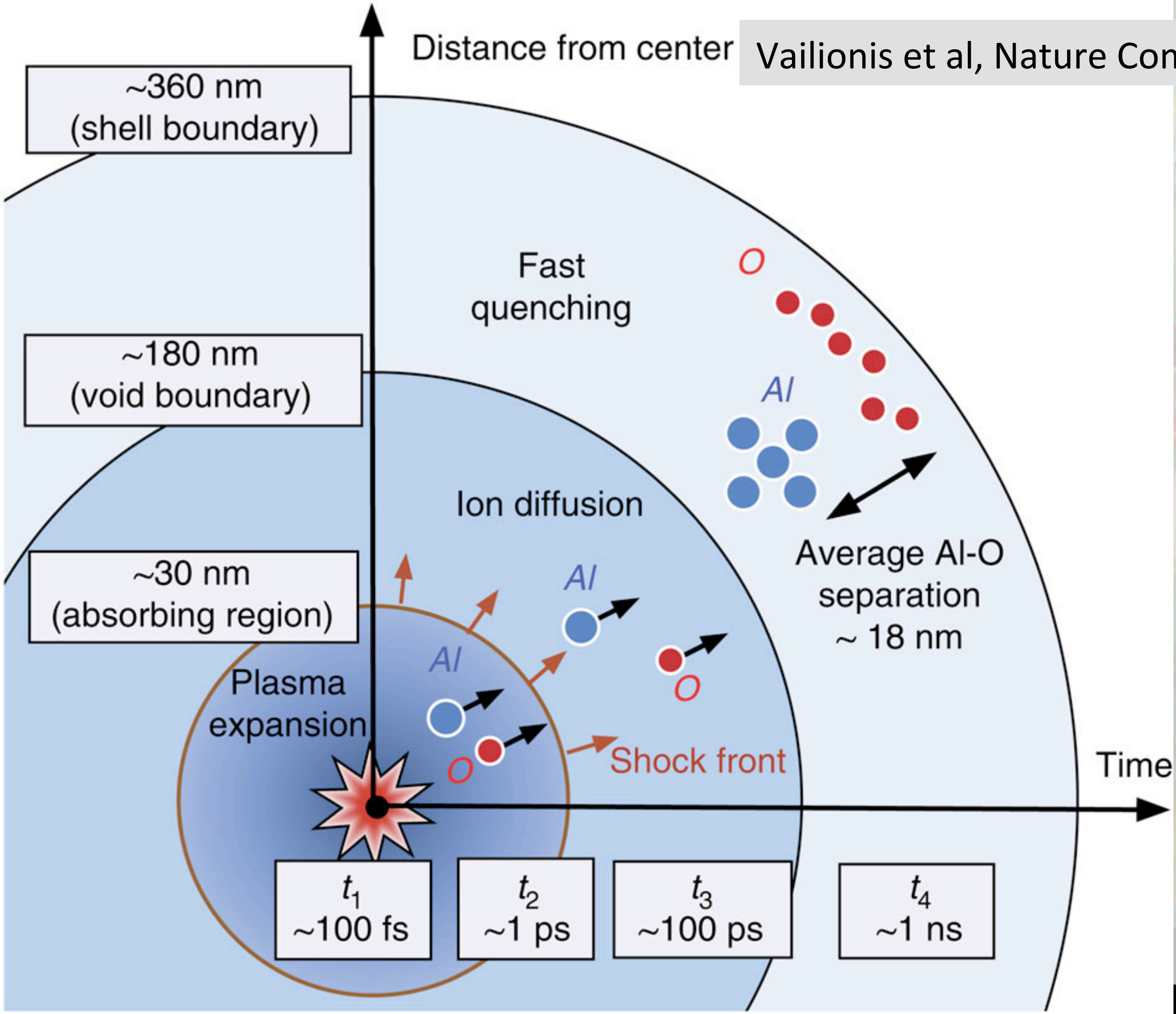




STAR, Quark Matter 2012

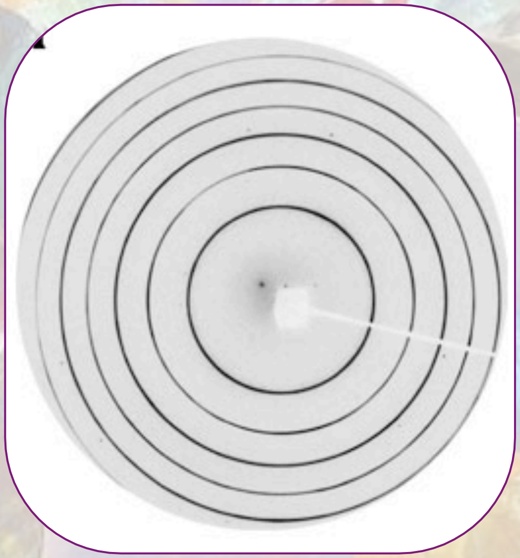
“Surprising speciation” substructure discovered in microexplosions in sapphire

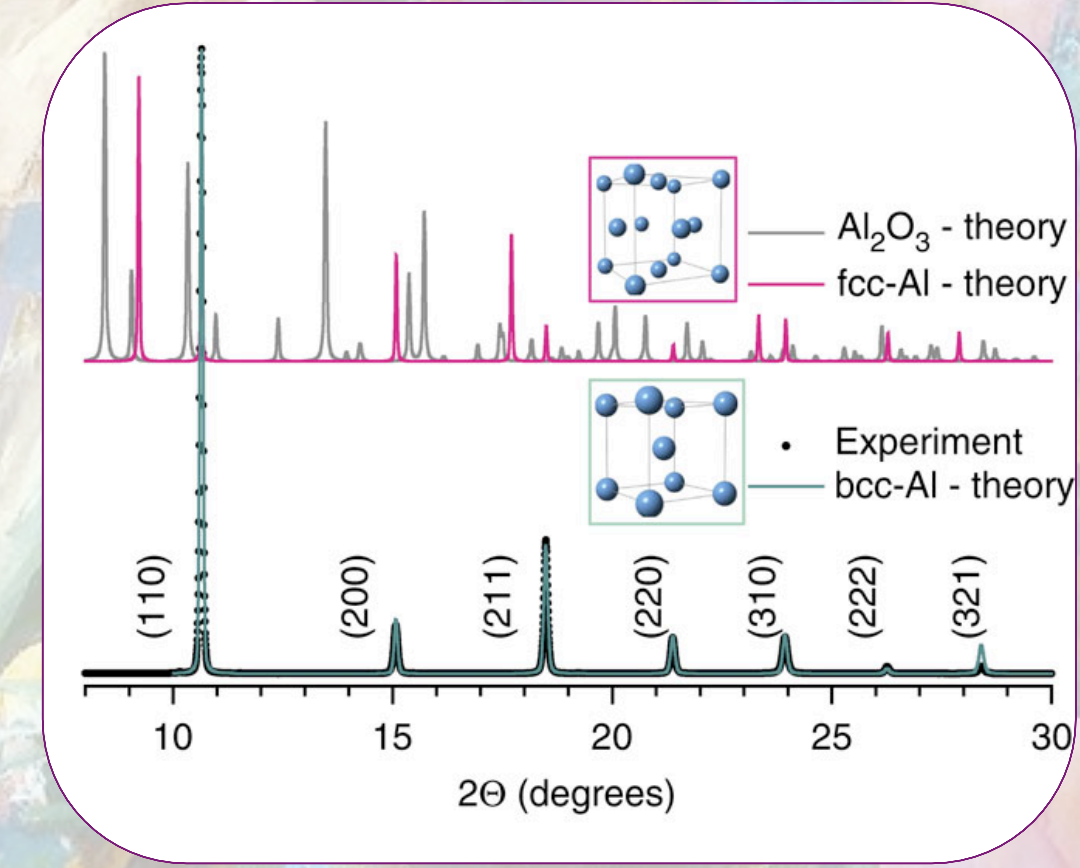
Vailionis et al, Nature Comm. DOI: 10.1038 (2011)



“exotic” bcc-Al from ultra-high pressure blast

(first observation; may play role in planetary core)



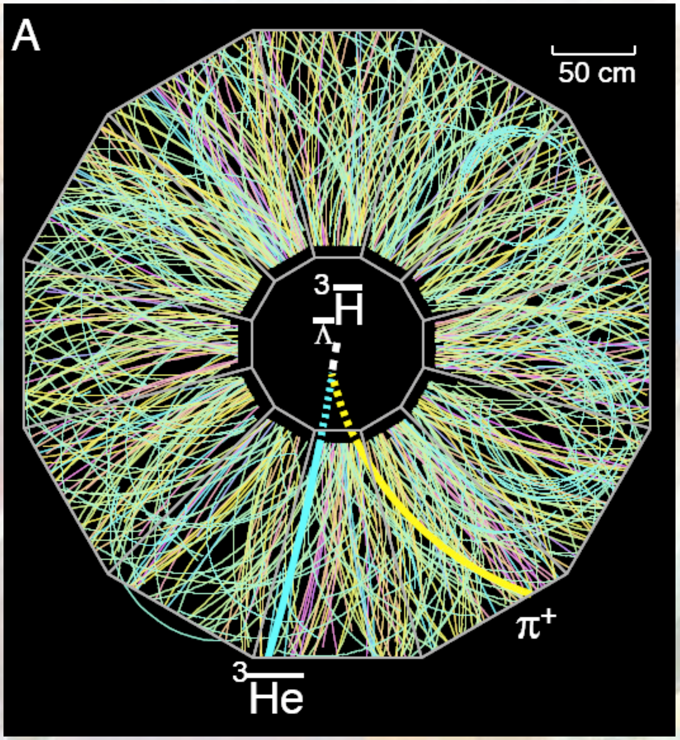


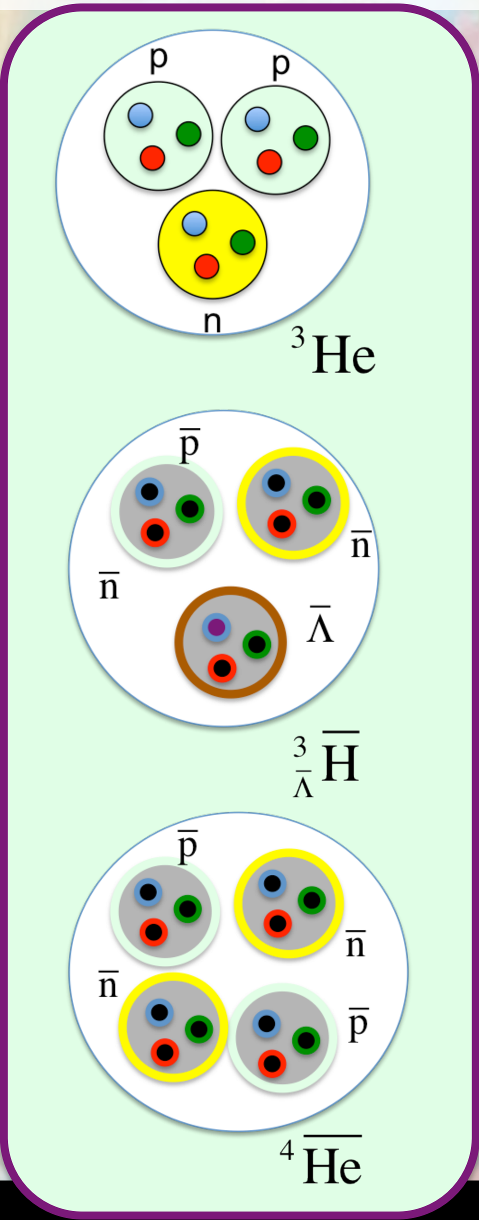
Micro-X-ray diffraction (µXRD) image of the shockwave compressed area

- peaks reveal essentially pure sample of new phase

Vailionis et al, Nature Comm. DOI: 10.1038 (2011)

Generation of novel, exotic form of stable matter in femtoexplosions





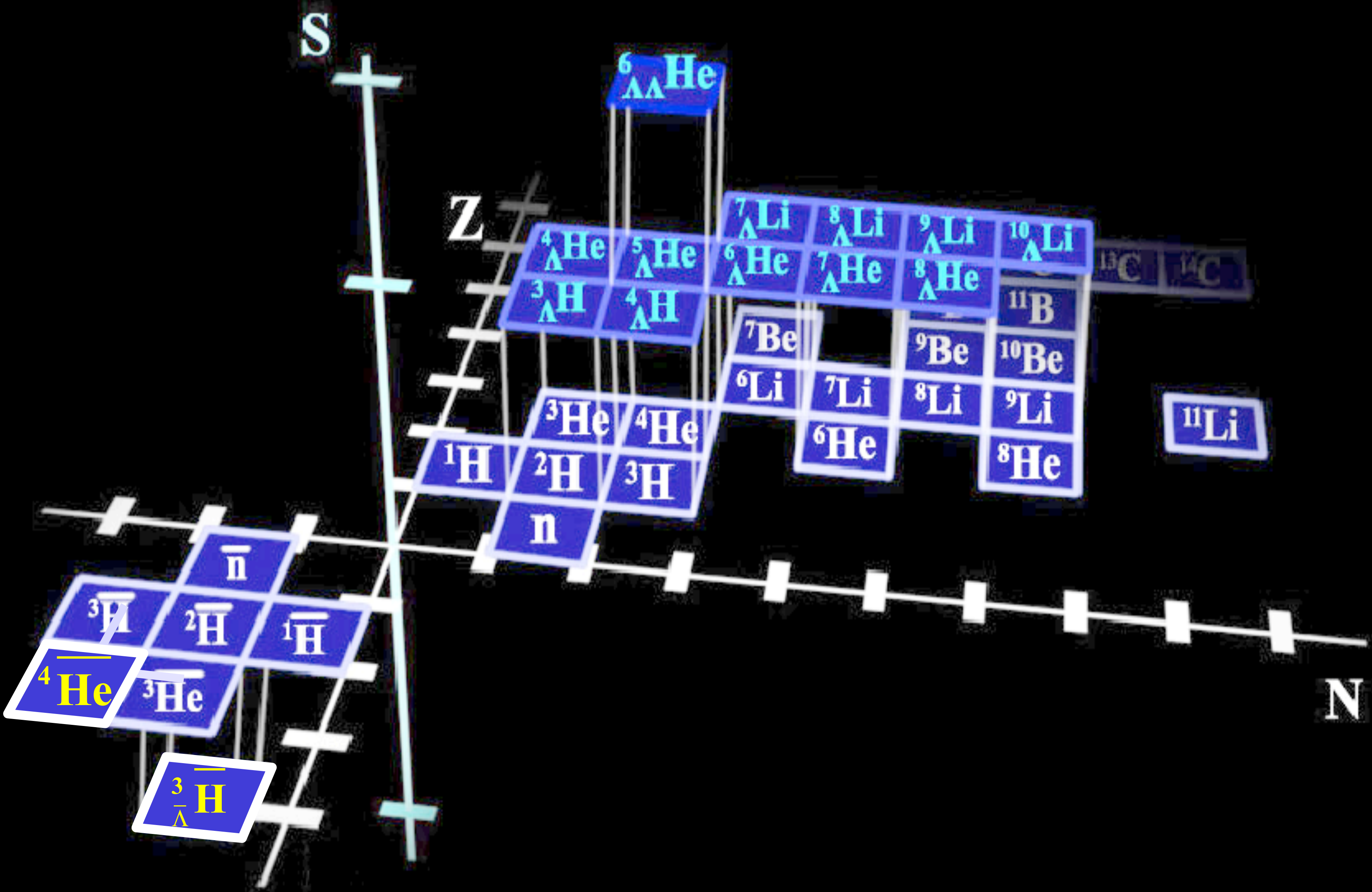
Science *Science* 328, 58 (2010)

STAR discovers the first anti-strange anti-nucleus

nature *Nature* 473, 353 (2011)

STAR discovers the heaviest anti-nucleus

Pushing the boundary of nuclear structure physics



Summary – Parallel programs & message from STAR

	micro-explosions	**femto-explosions**
in-principle relevance to larger systems	planets, inertial-confinement fusion	Big Bang

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threshold behaviour observed	✓	*see my talk Wednesday*
handle on viscosity	?	✓ *(not widely appreciated)*

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- Tremendous structure and physics in a condensed-matter approach to dynamic explosions.
- Can our fields learn more from each other?