Title: The emerging theory of Strong Coupled quark-gluon Plasma

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Abstract:

The emerging theory of Strongly coupled Quark-Gluon Plasma (sQGP)

Edward Shuryak
Department of Physics and Astronomy
State University of New York
Stony Brook NY 11794 USA

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Outline

- emerging theory of strongly coupled quark-gluon plasma (sQGP) at T=200-400 MeV, RHIC domain
  (bits of history and brief summary of main arguments)
- classical molecular dynamics (MD) of Non-Abelian plasma => eqn describing rotation of color vectors
- electric and magnetic quasiparticles (EQPs and MQPs) are fighting for dominance
- Comparison to AdS/CFT correspondence

(Between strongly coupled N=4 SYM and classical MD):

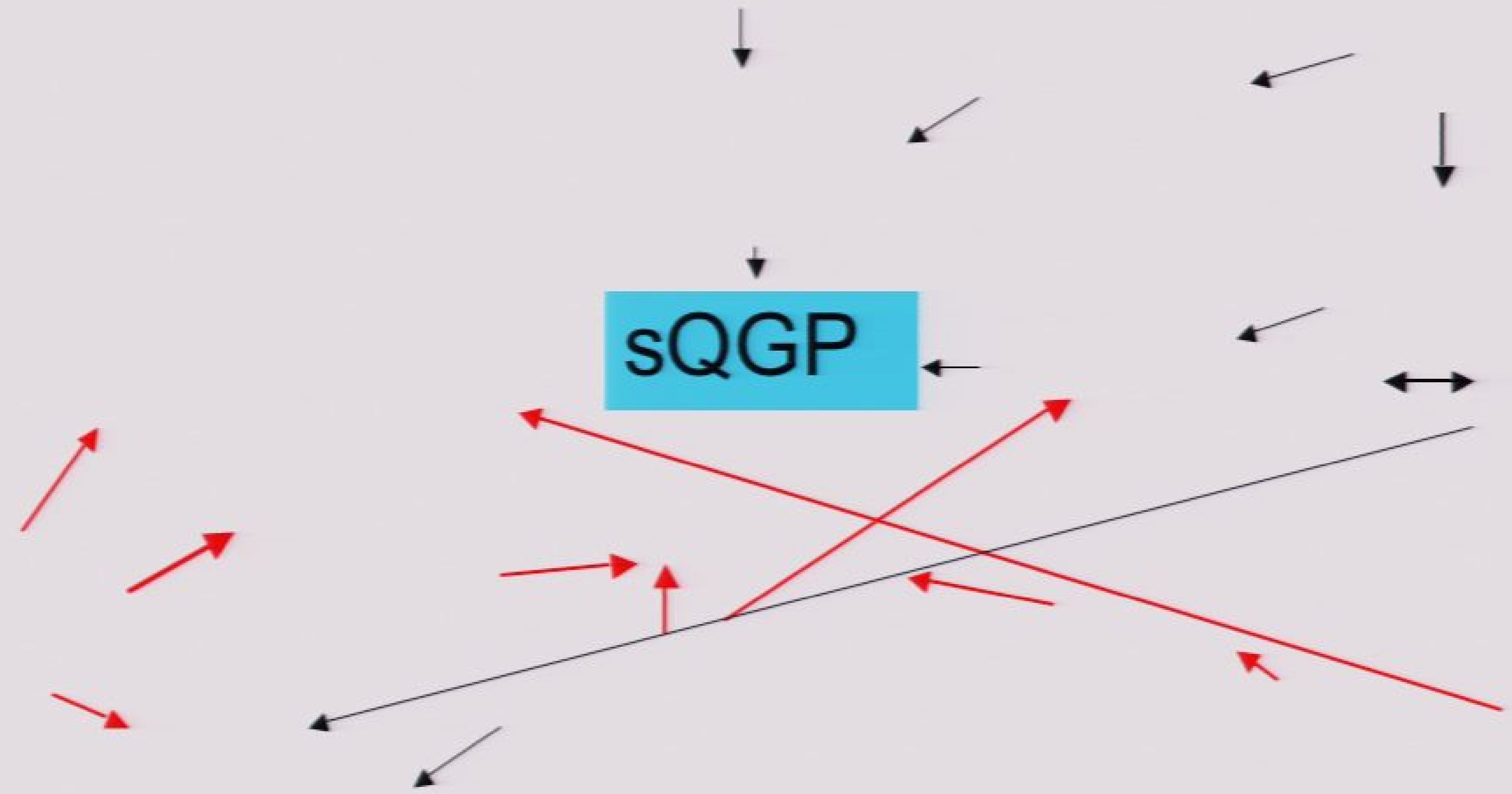
(based on 3 papers: B.Gelman, I.Zahed,ES, PRC74,044908,044909 (2006)

J.F.Liao,ES, hep-ph/0611131,PRC 07

E/M duality=>Flux tubes; (J.F.Liao,ES, in progress)

Monopole condensation theory (M.Cristoforetti,ES)

The emerging theory of sQGP



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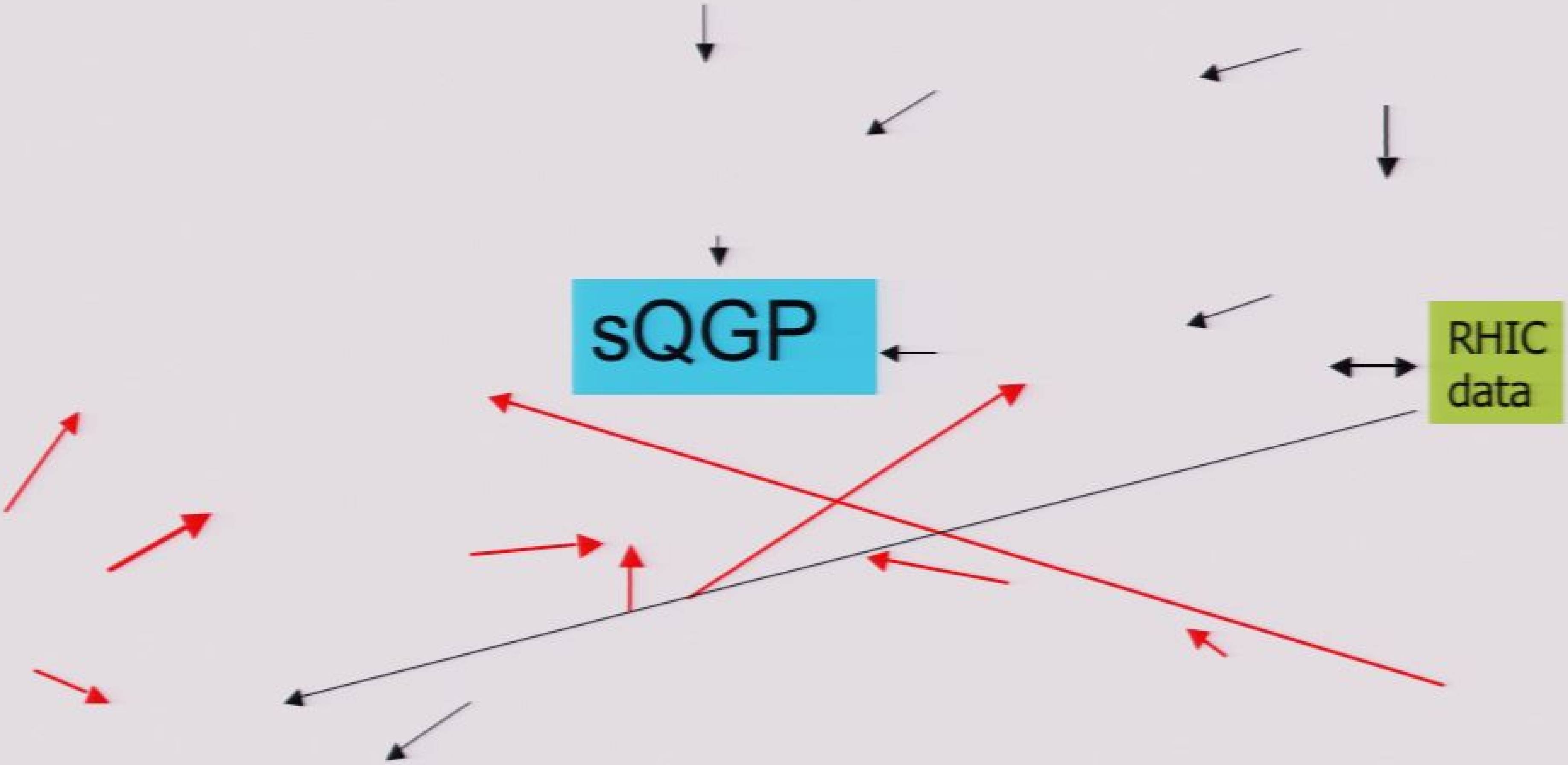

sQGP

RHIC data

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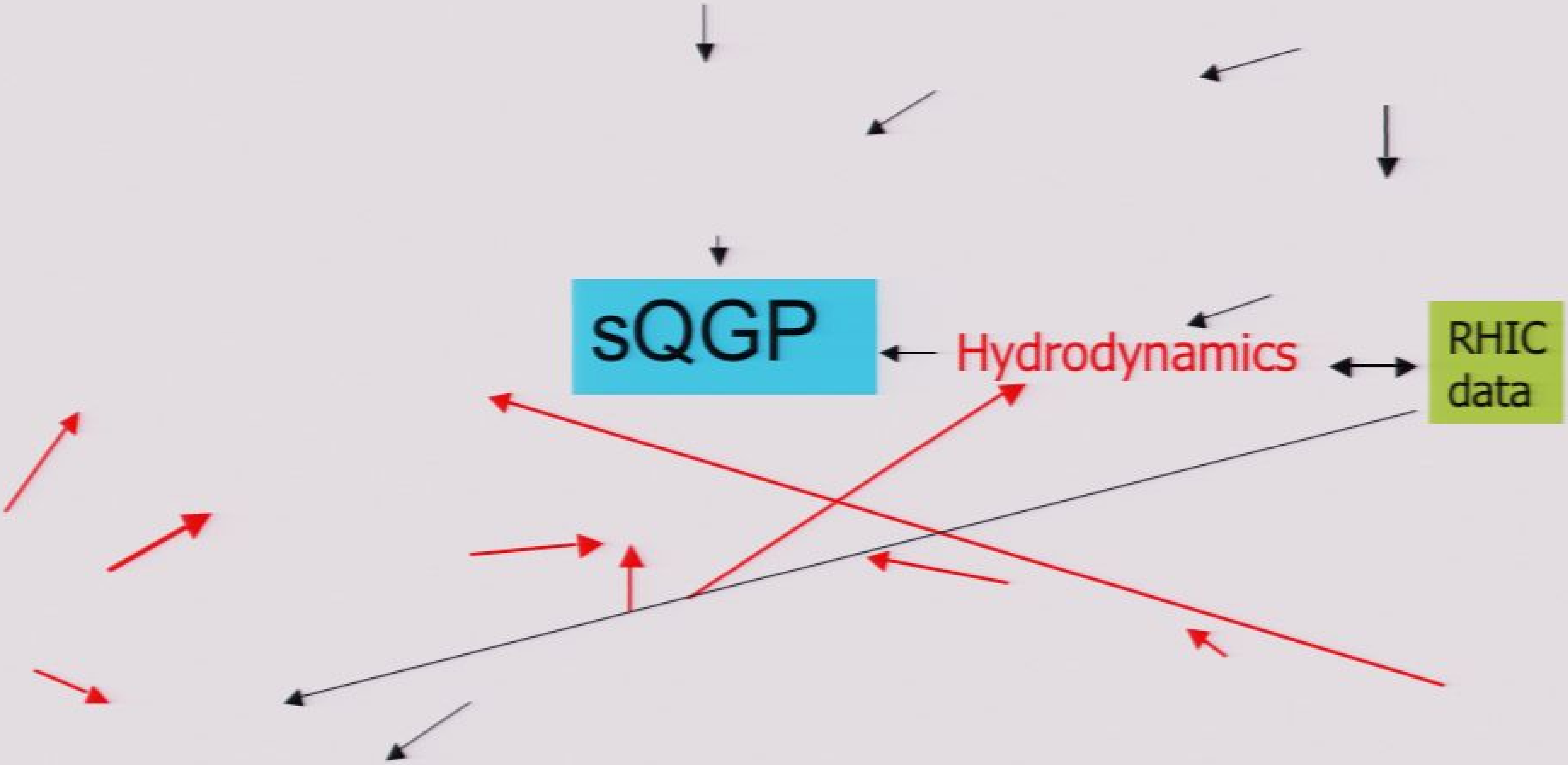

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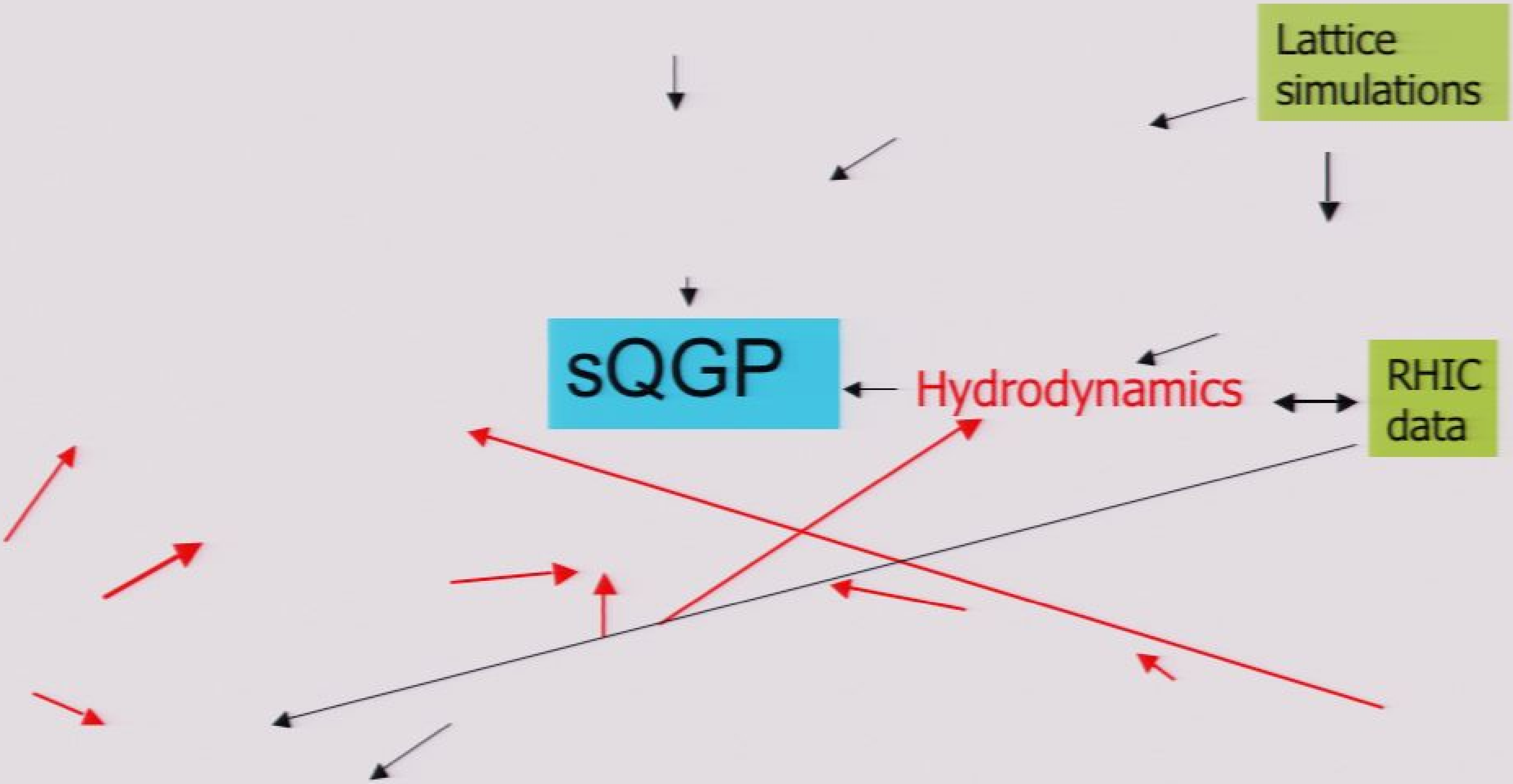

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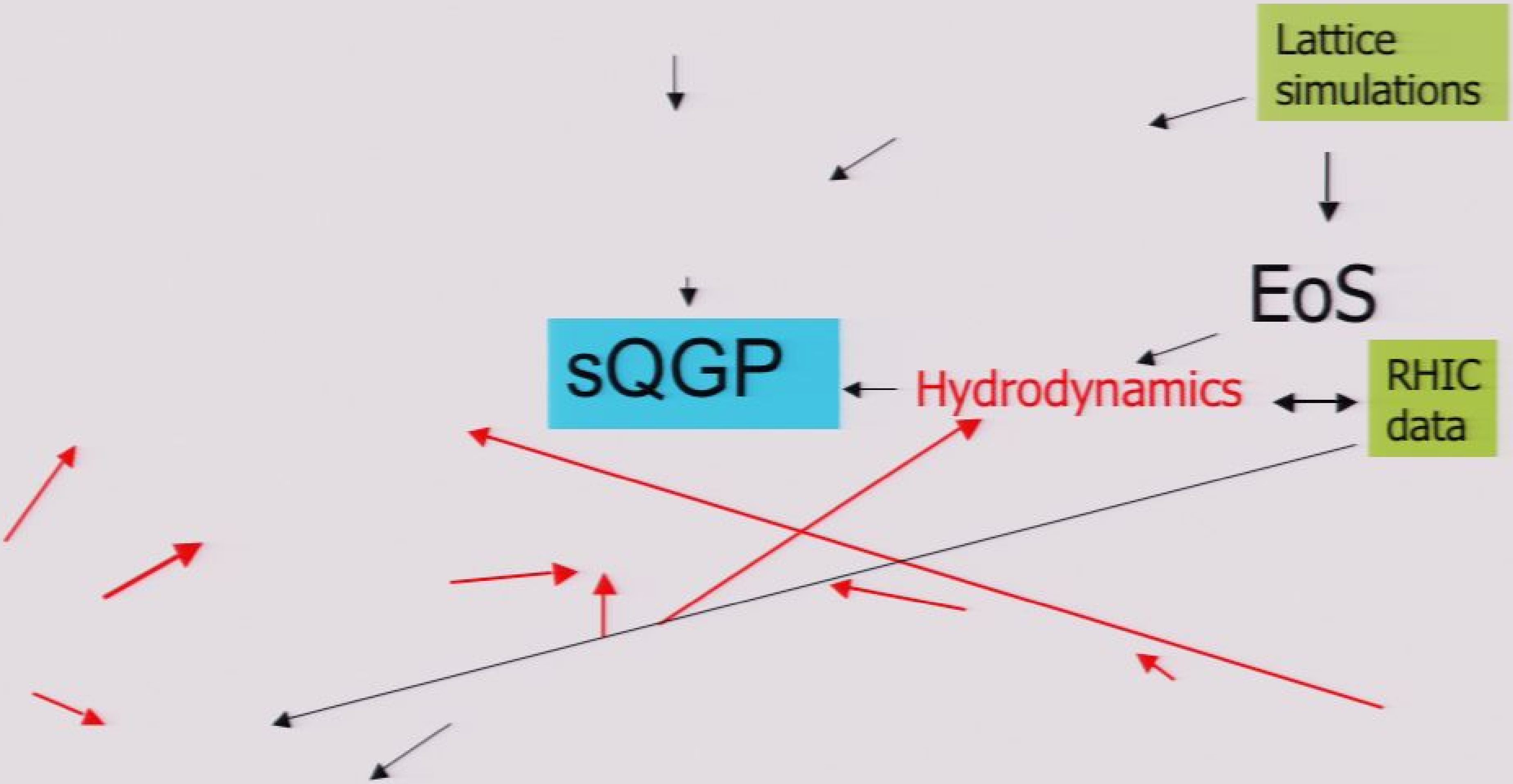

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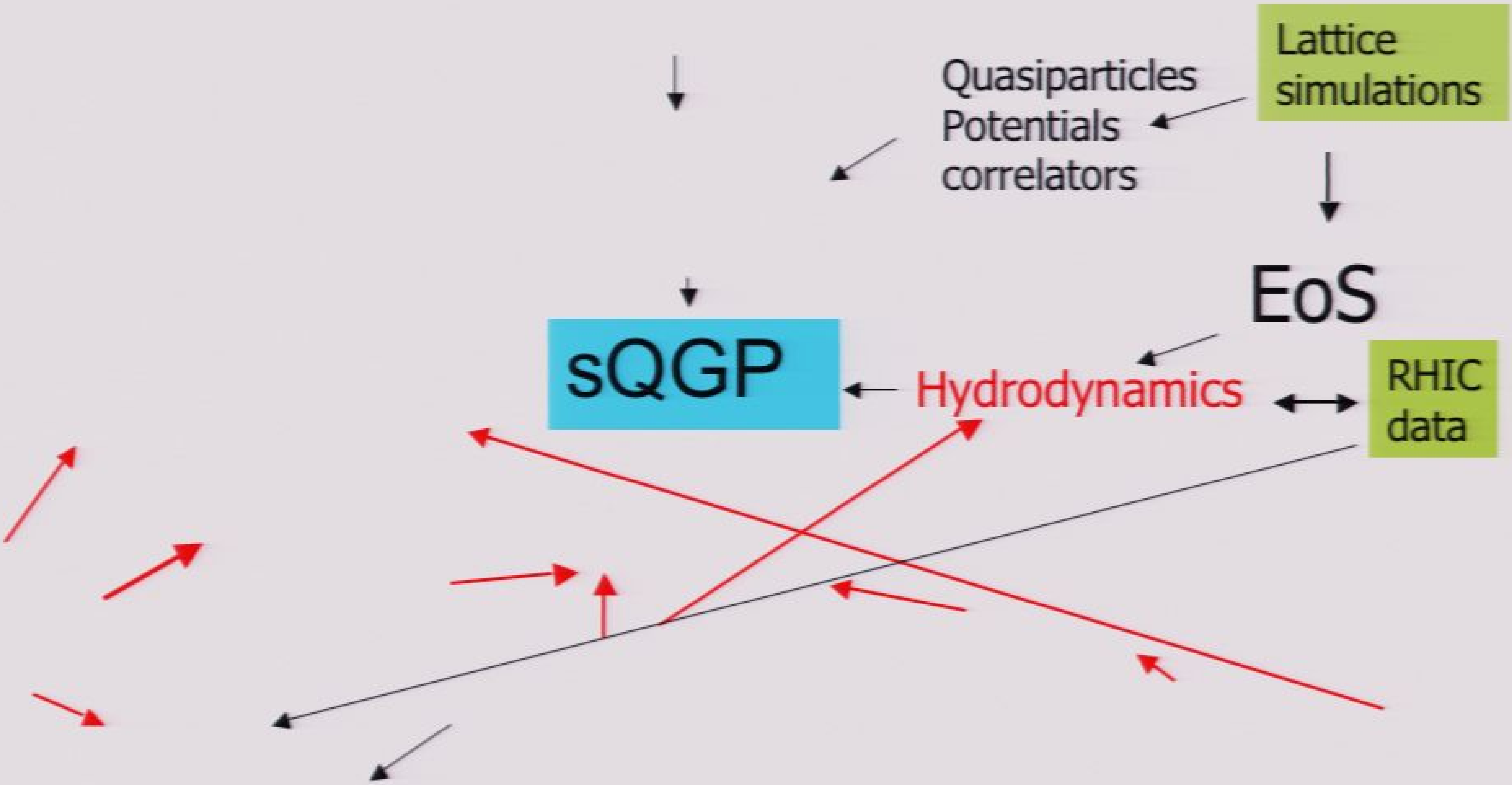

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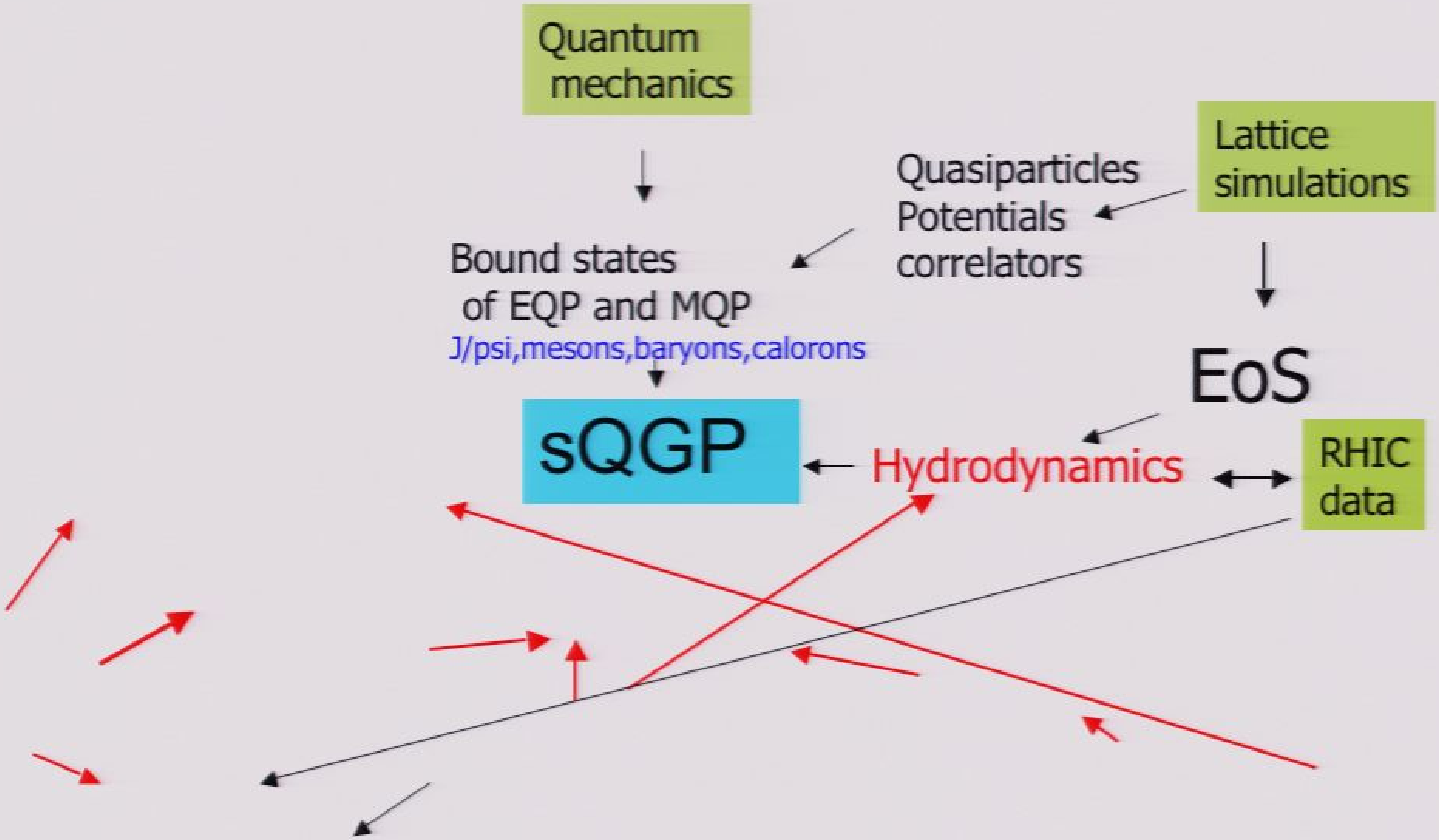

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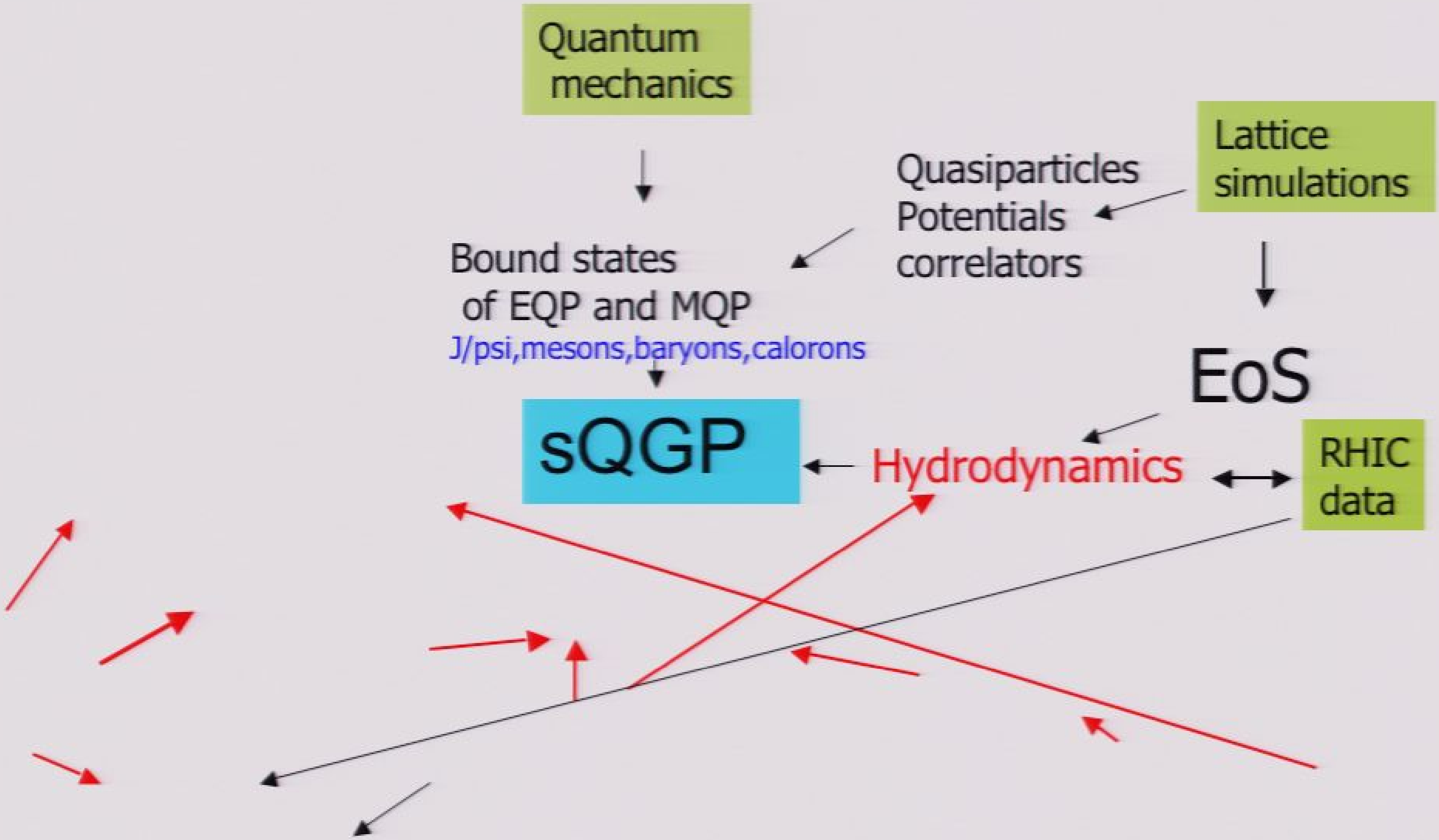

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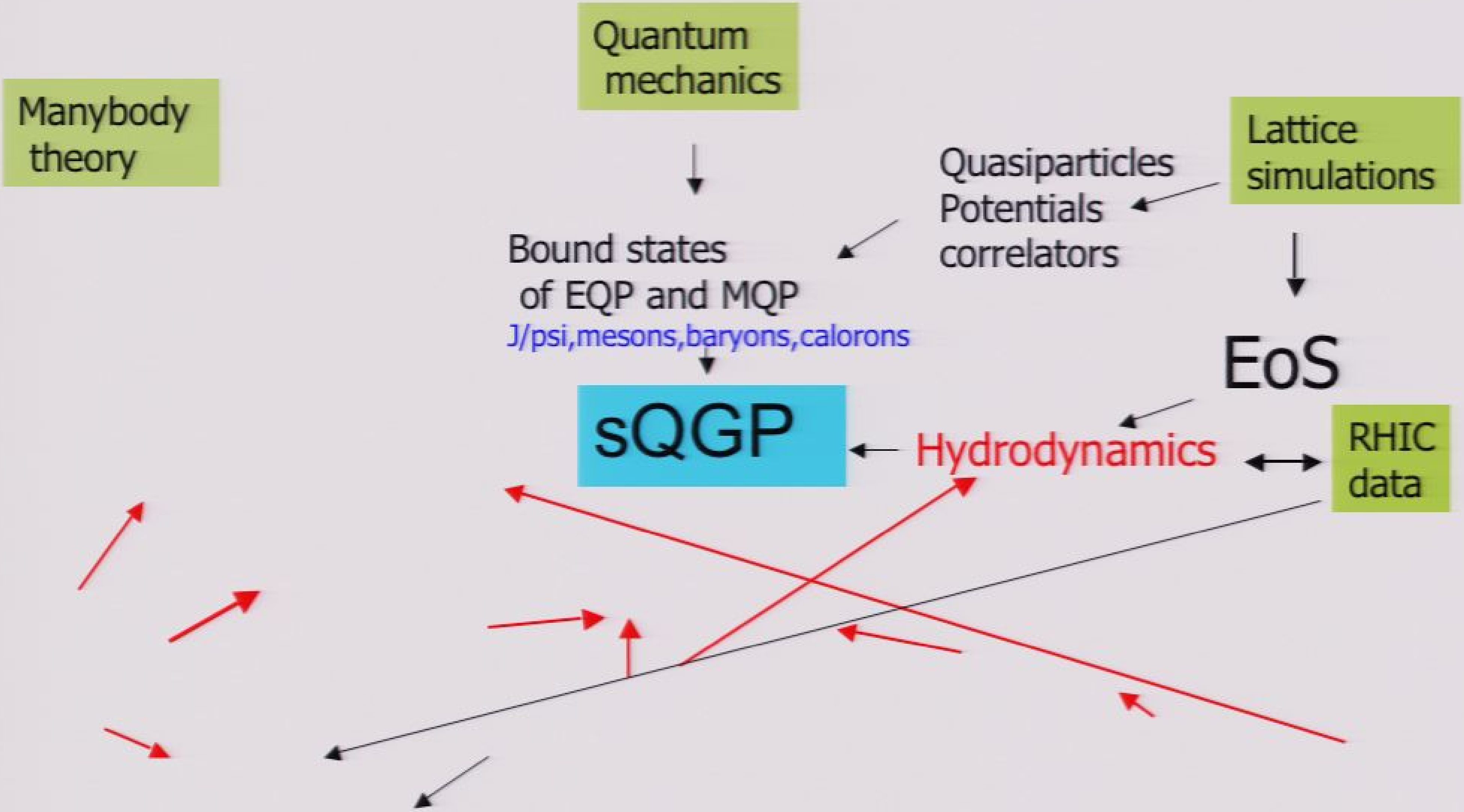

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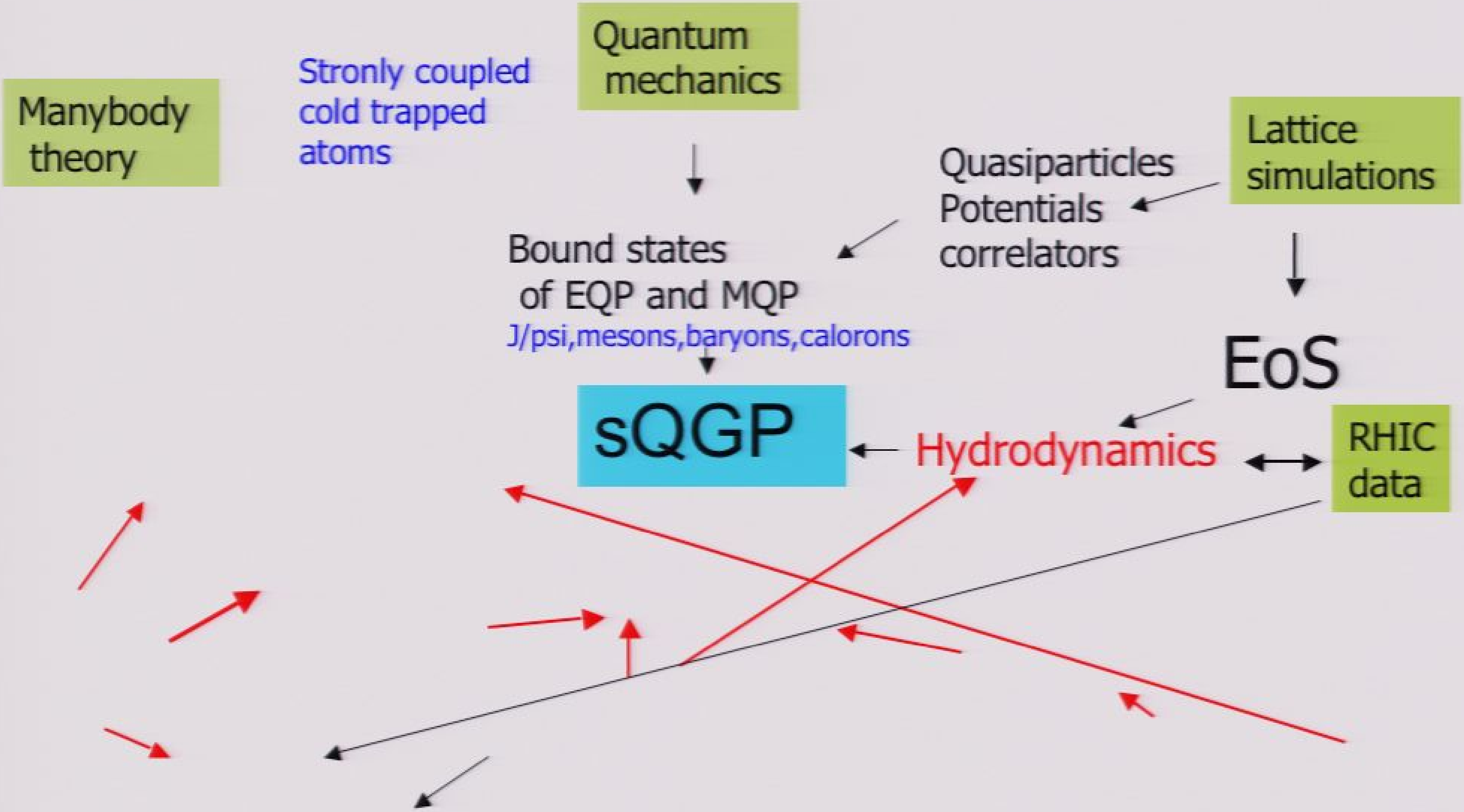

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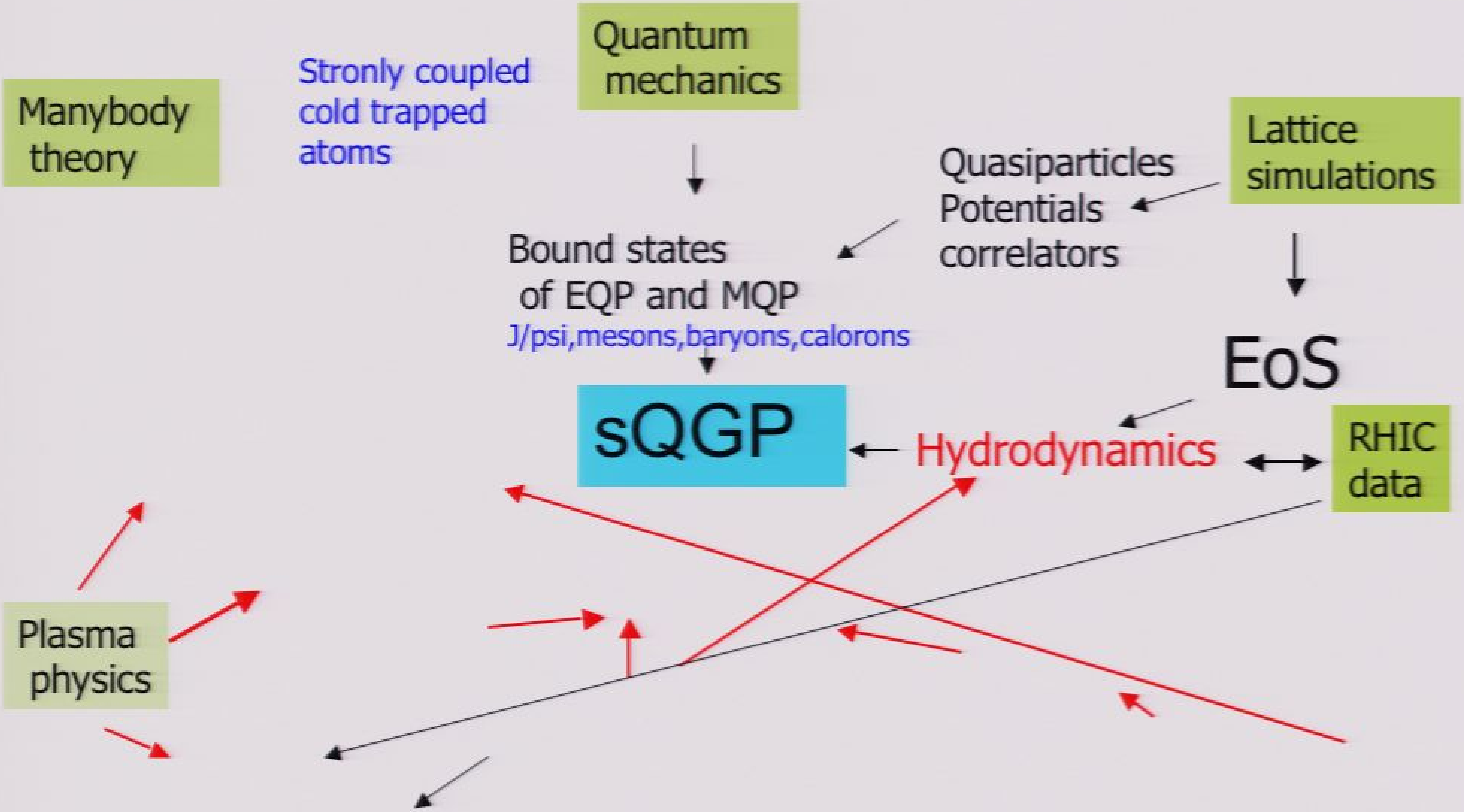

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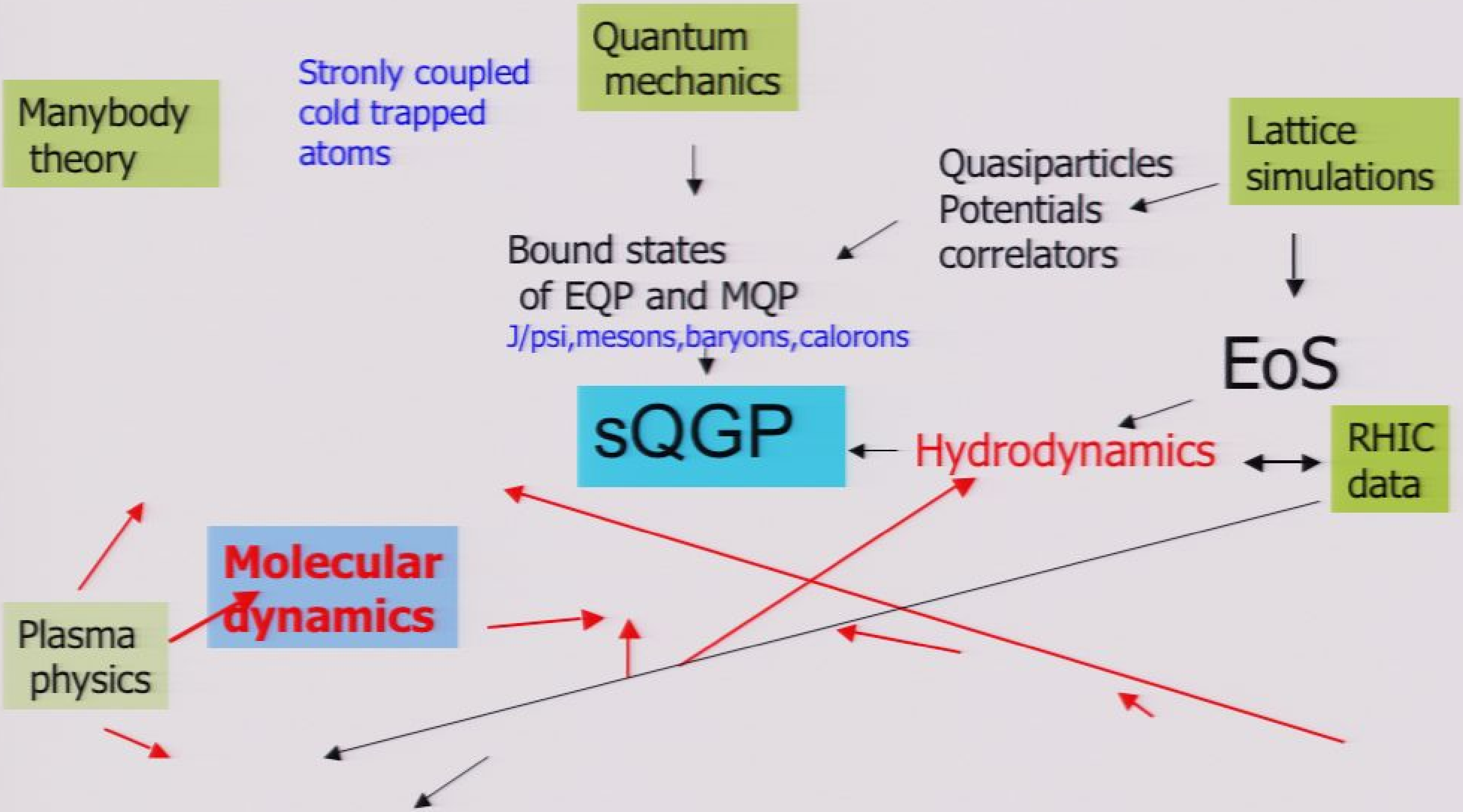

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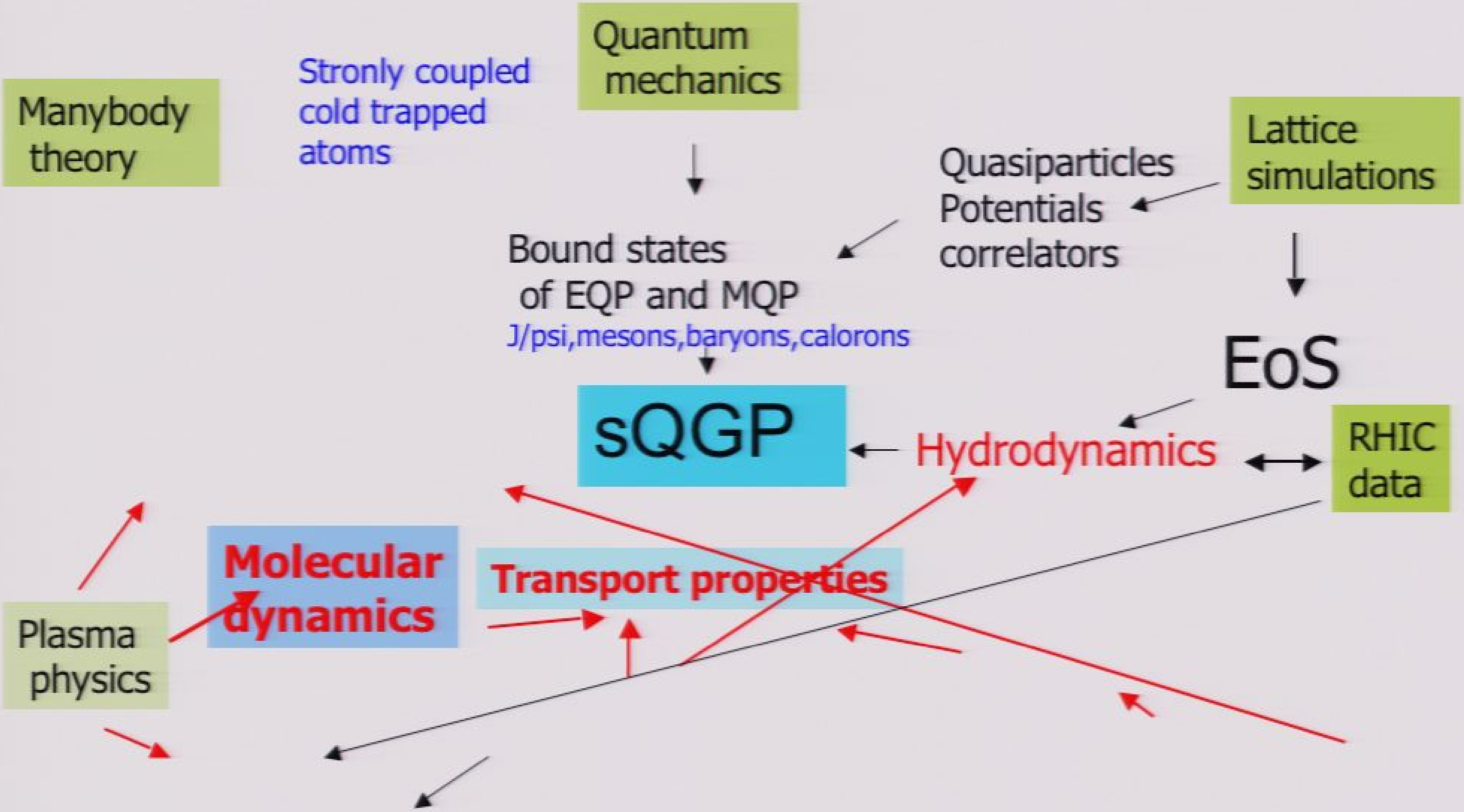

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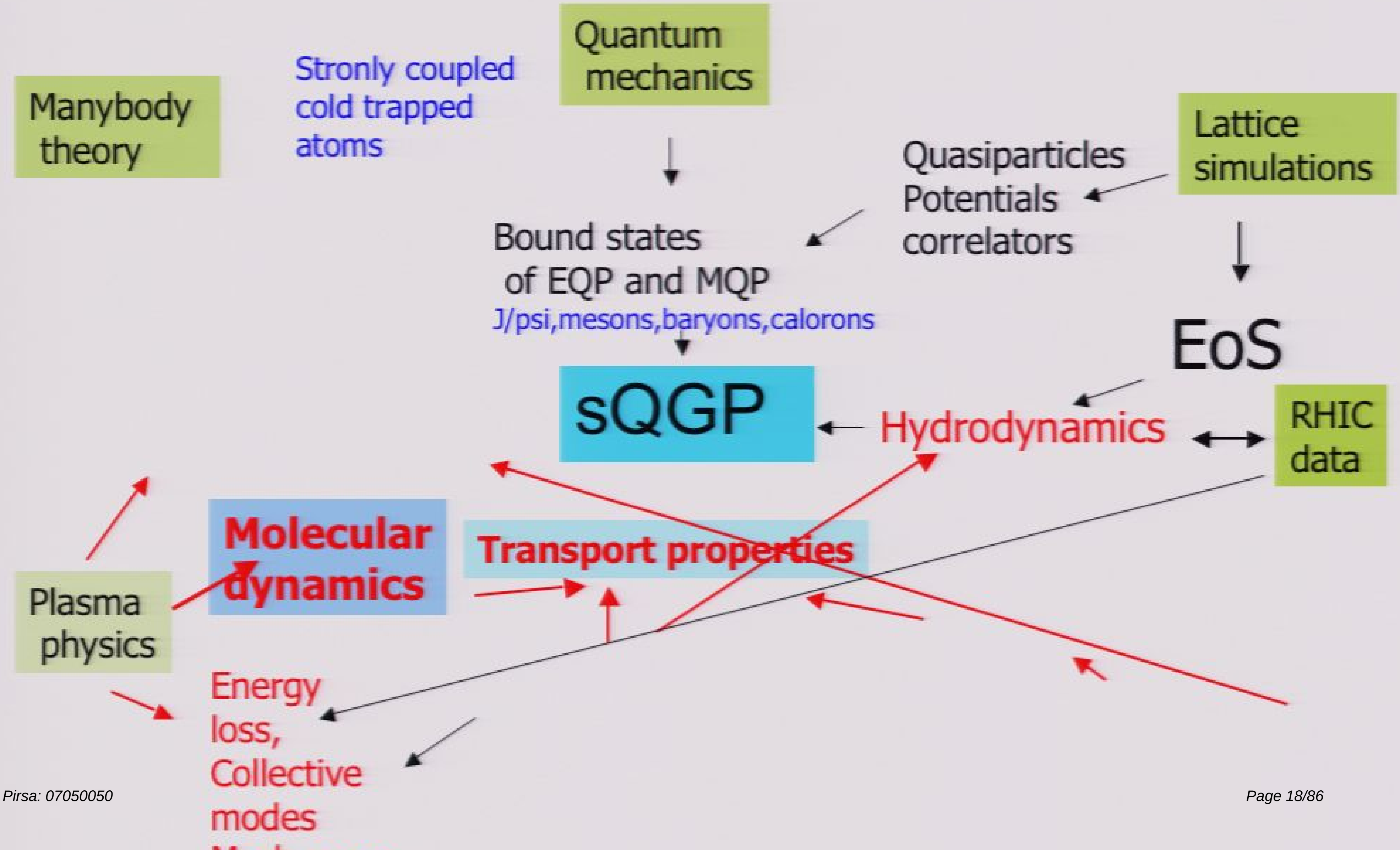

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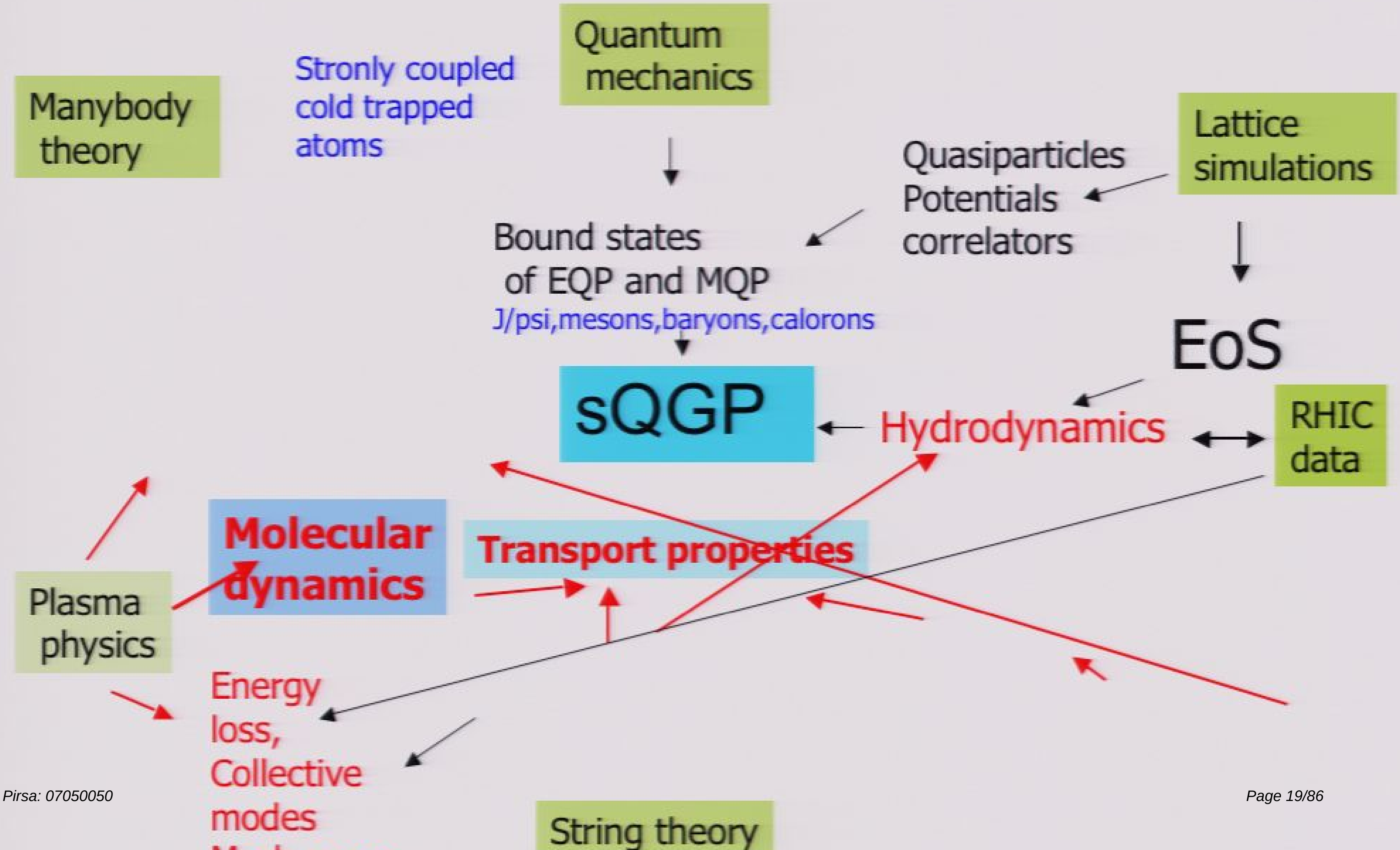

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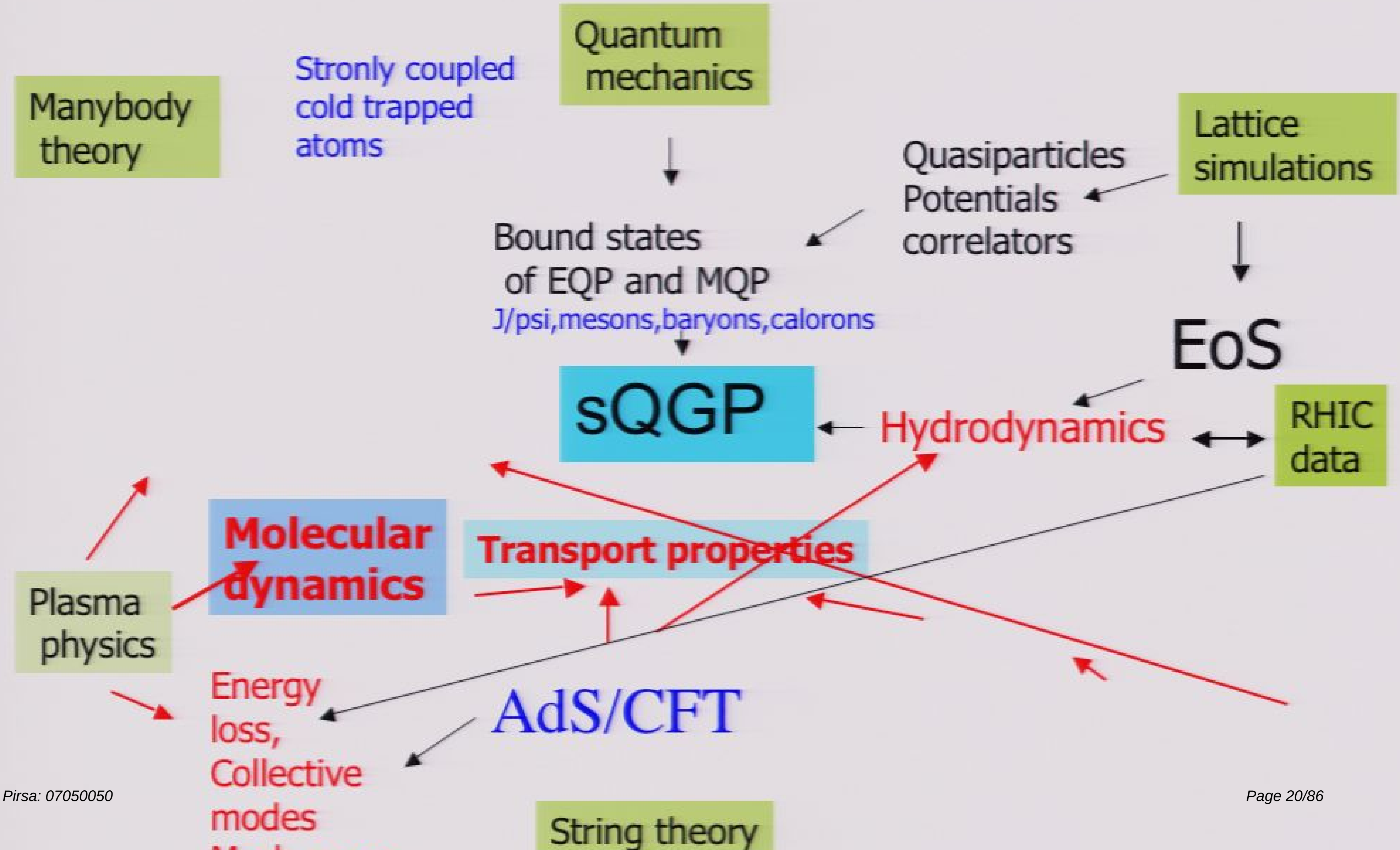

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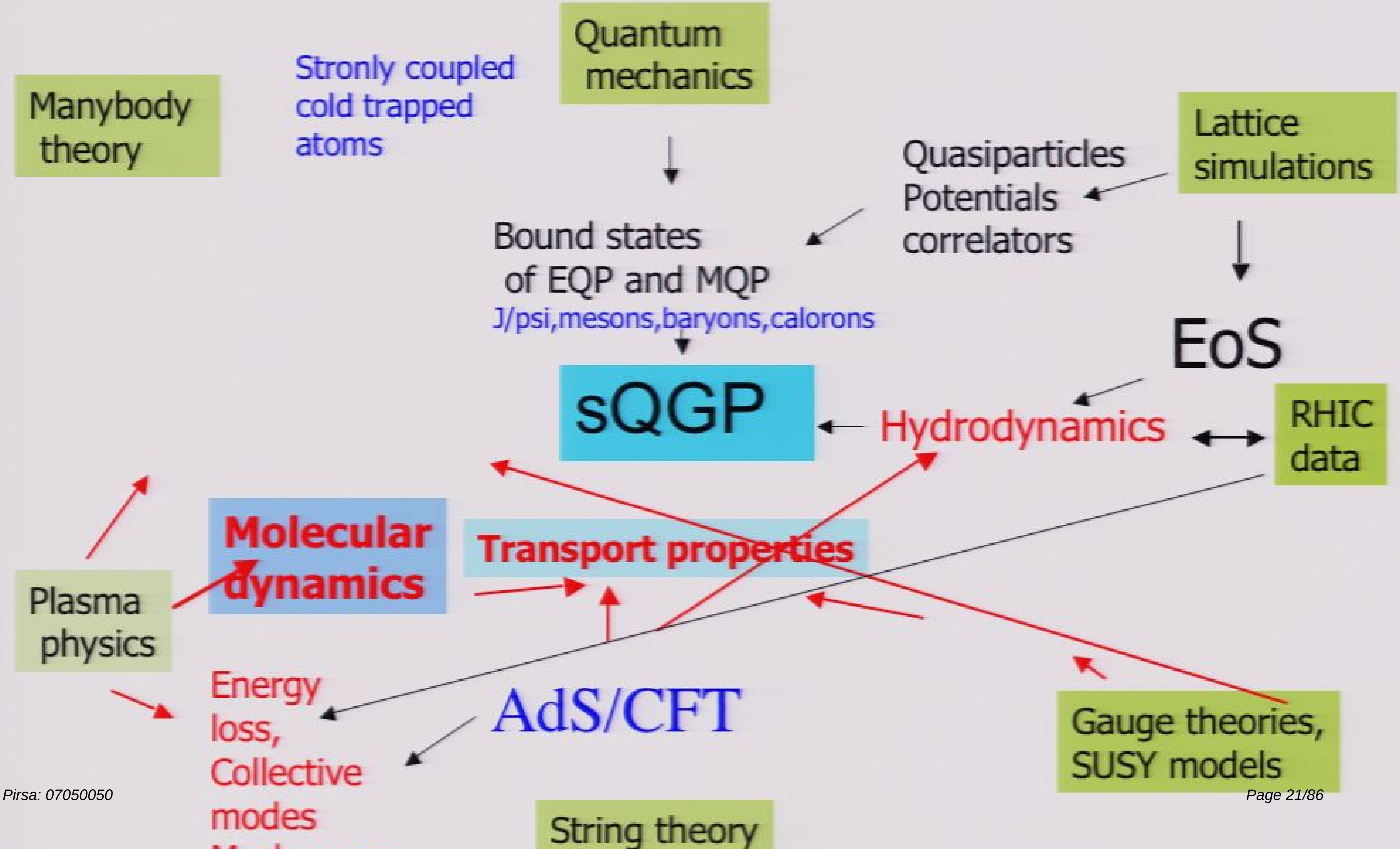

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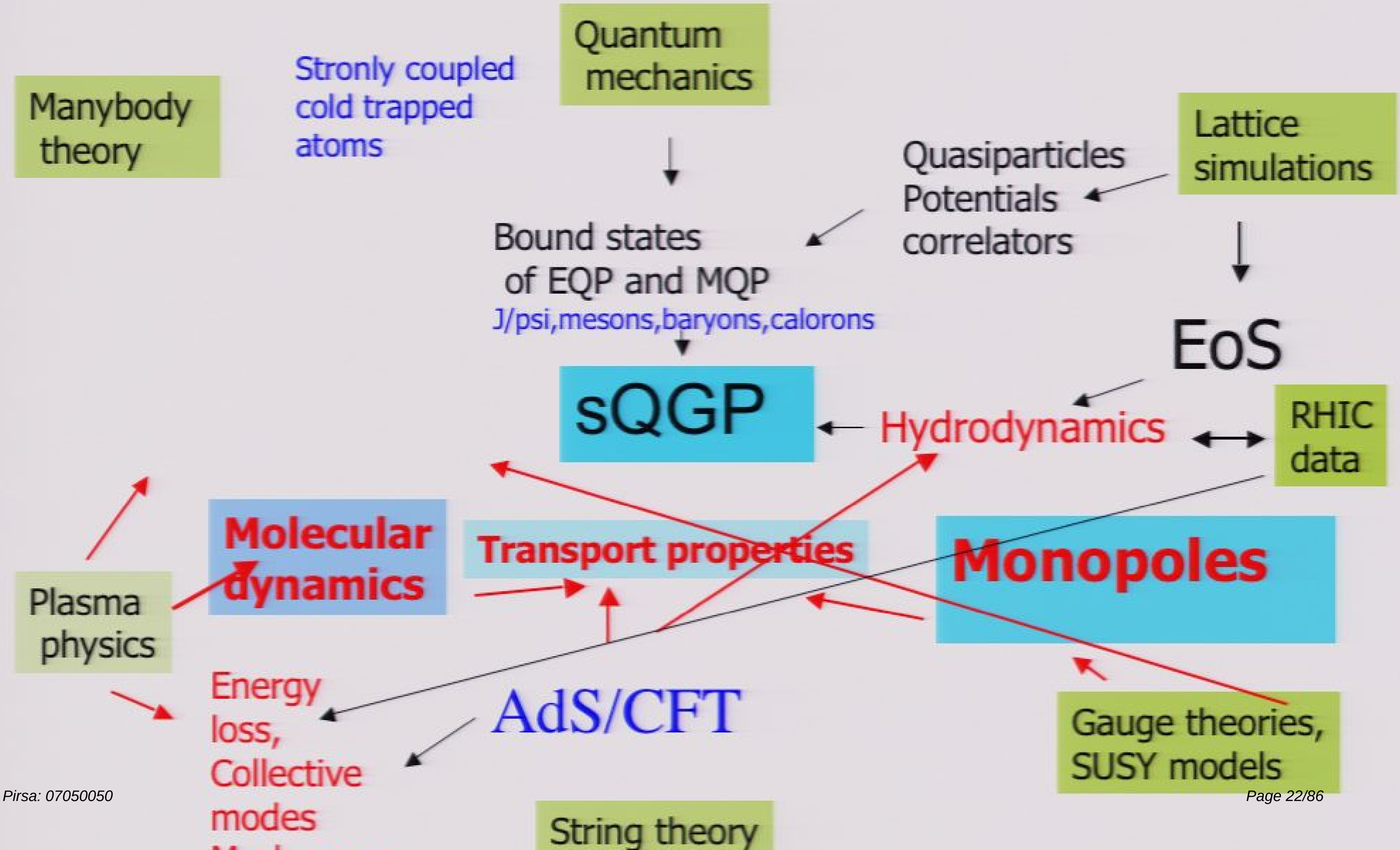

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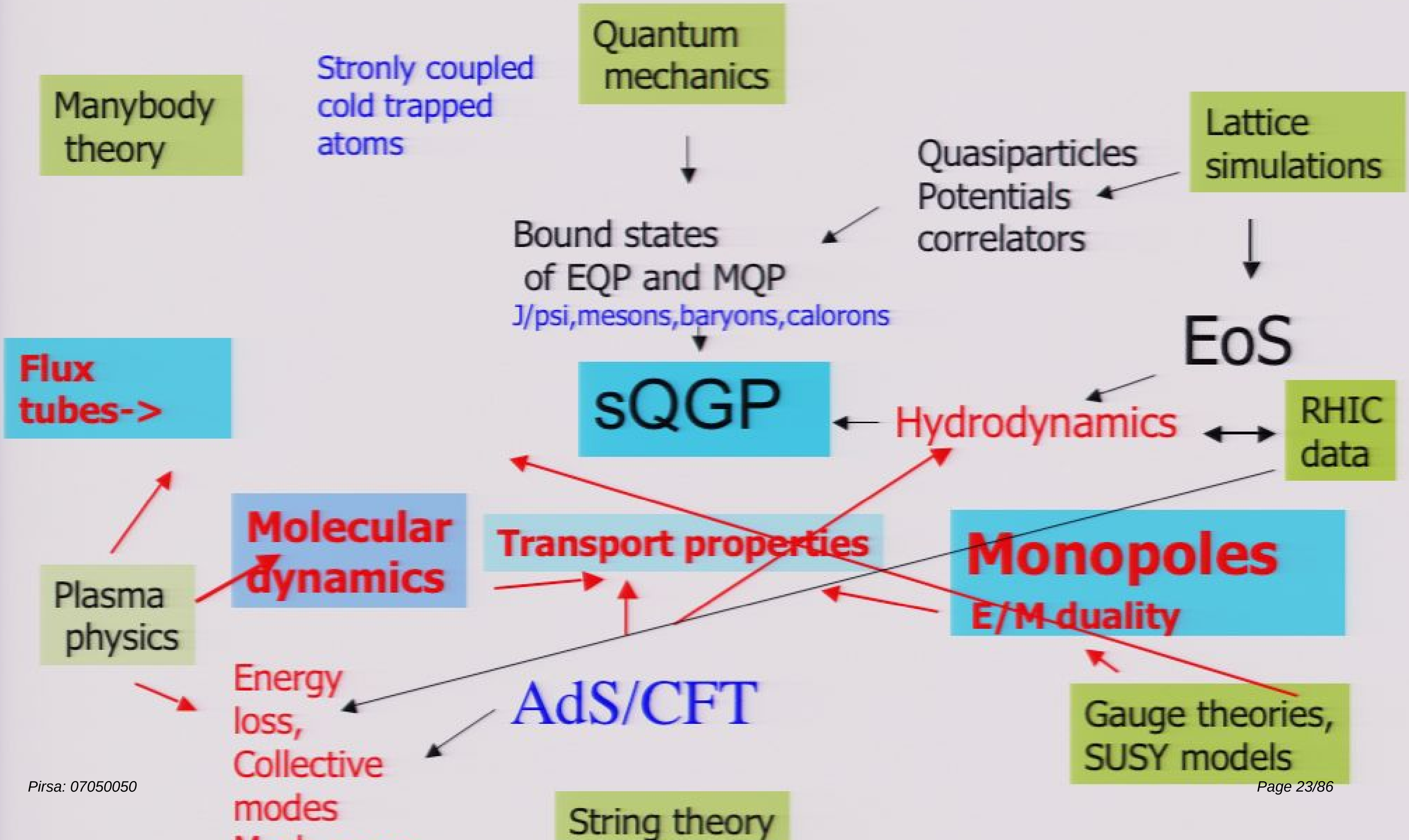

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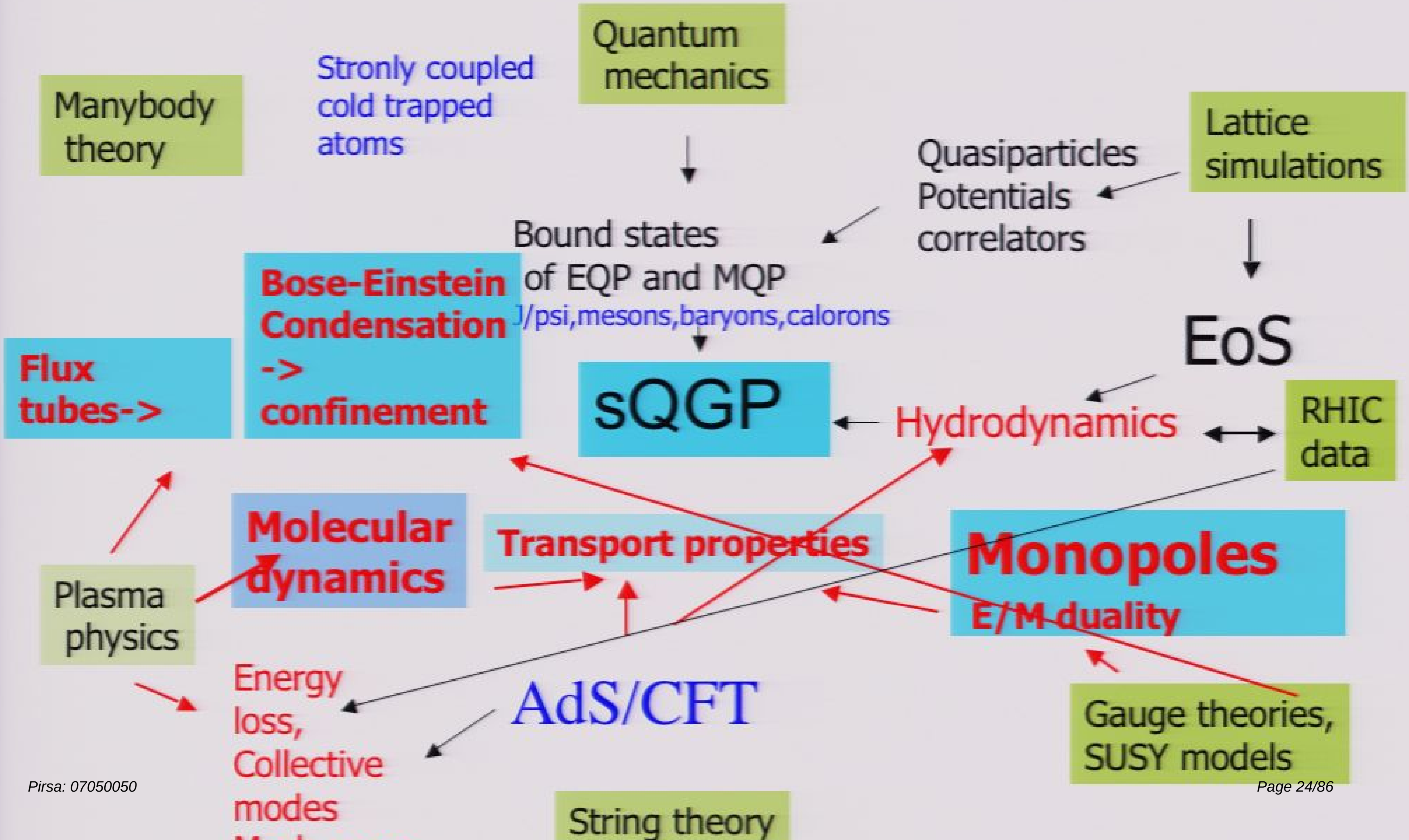

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Bose-Einstein Condensation -> confinement

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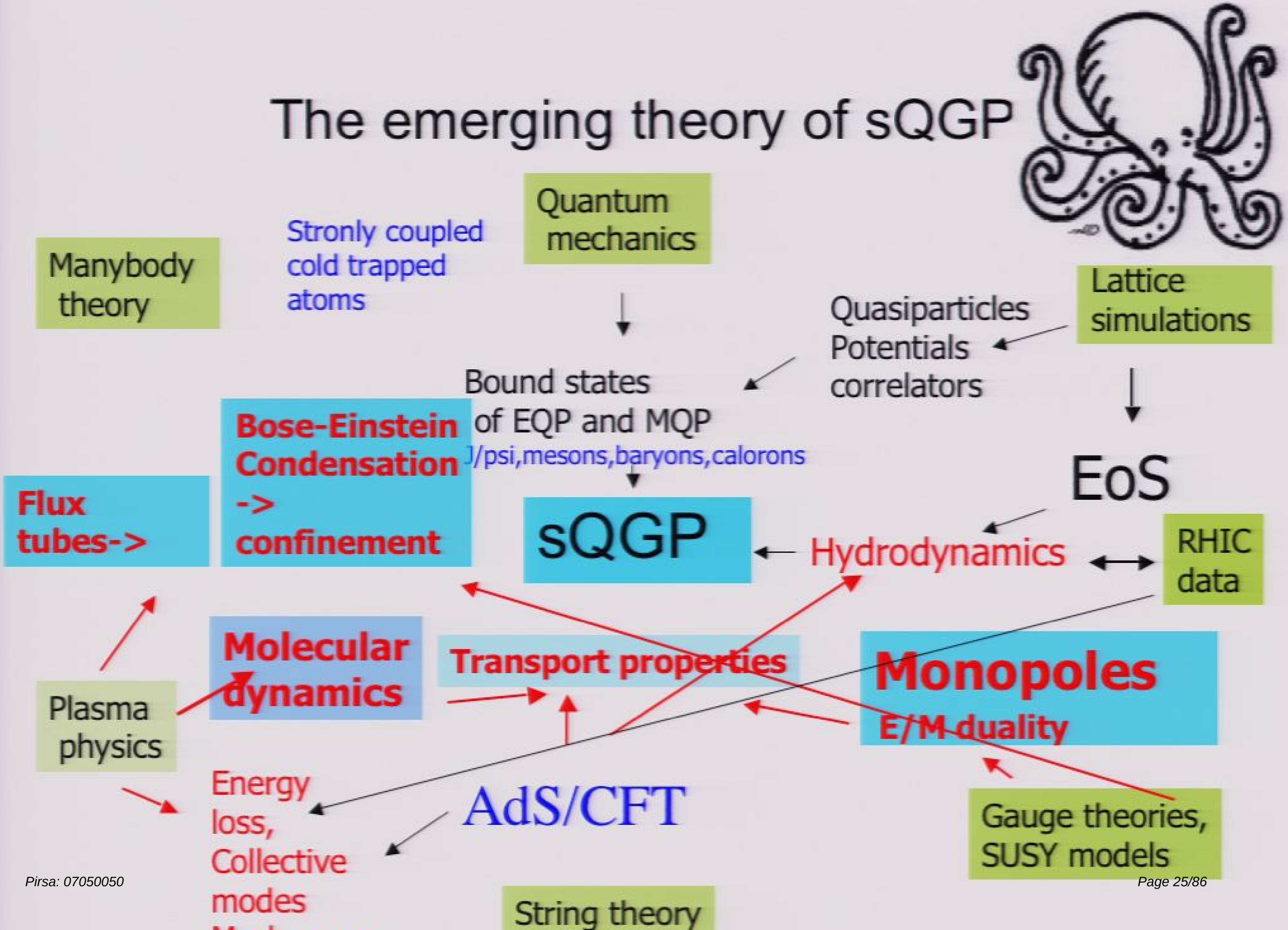

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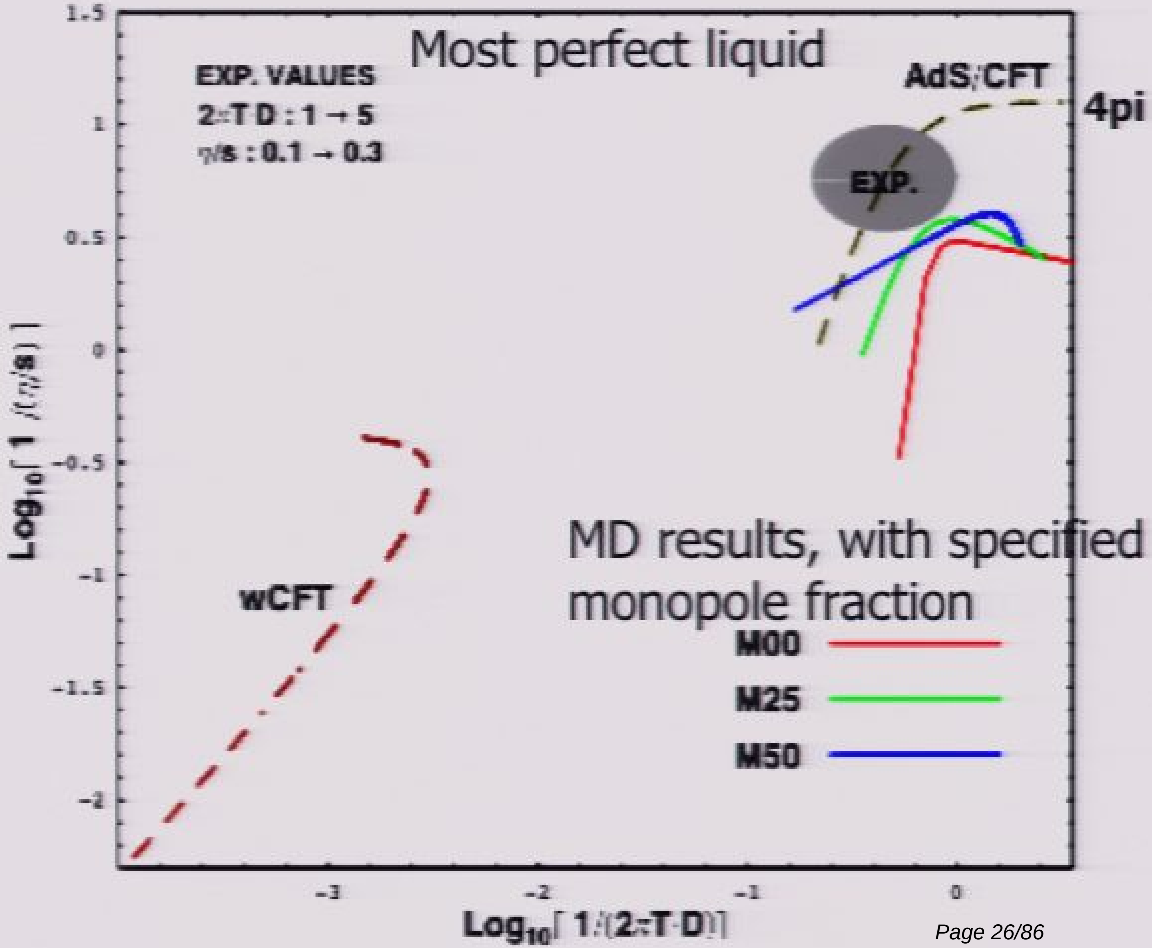
short transport summary

log(inverse viscosity s/eta)- vs. log(invesre diffusion const D*2piT) (avoids messy discussion of couplings)

- RHIC data: very small viscosity and D
- vs theory - AdS/CFT and MD(soon to be explained)



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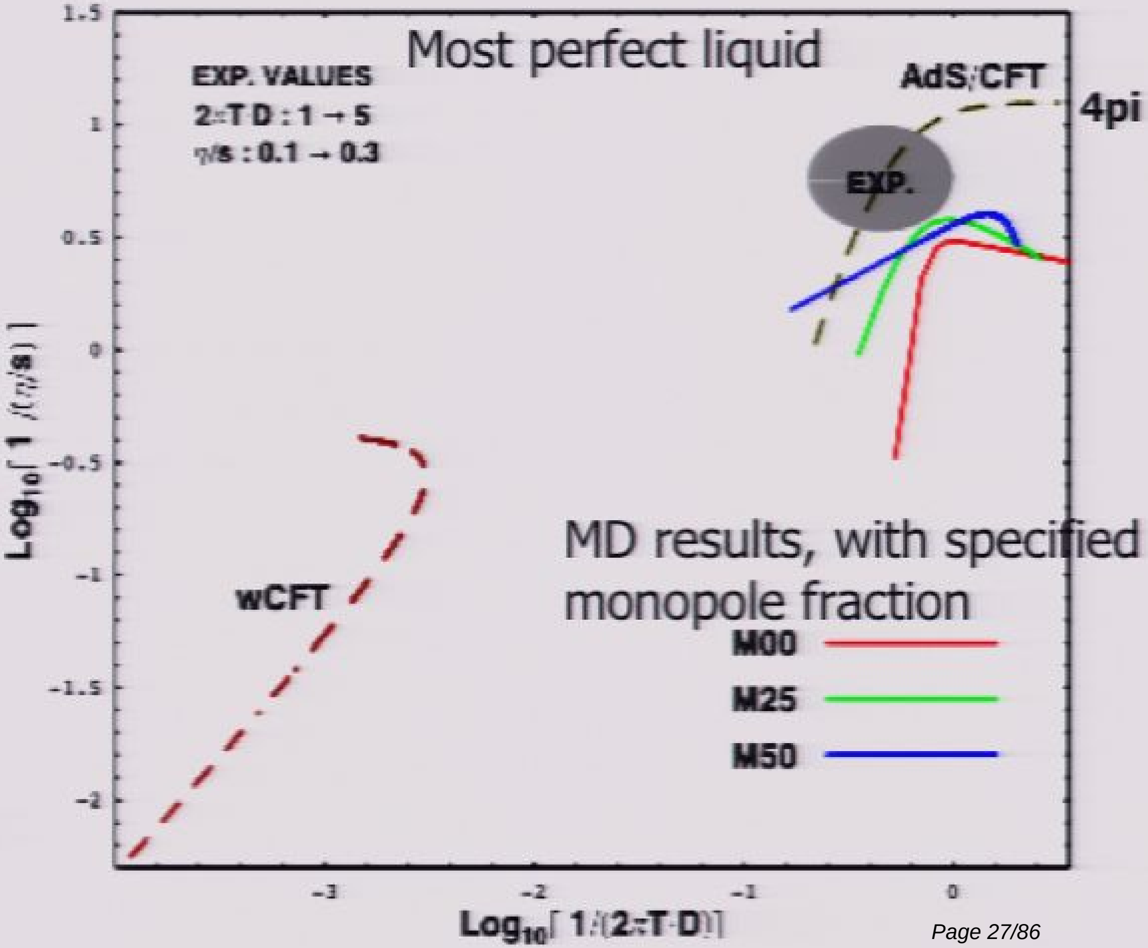
Most perfect liquid

MD results, with specified monopole fraction

Weak coupling end =>
(Perturbative results shown here)
Both related to mean free path

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->Stronger coupled ->

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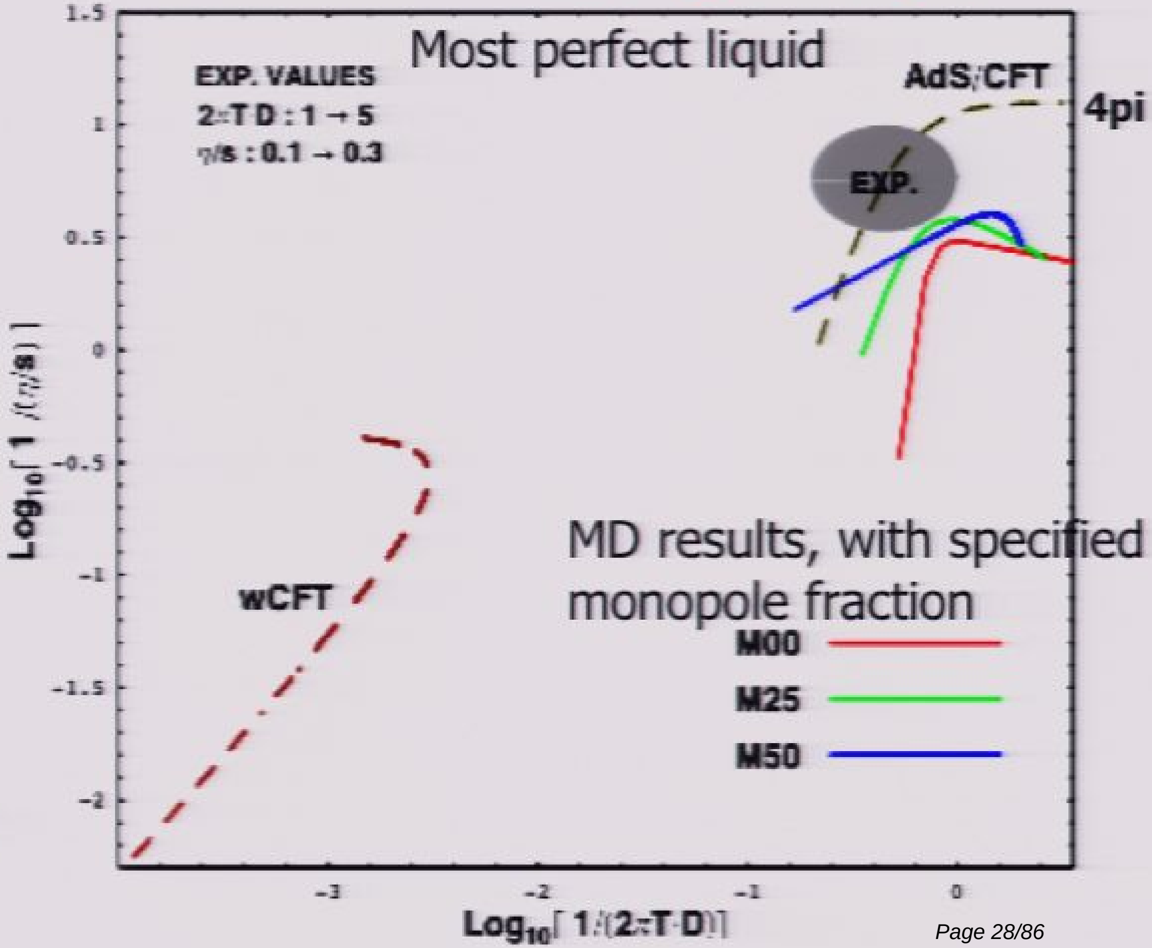

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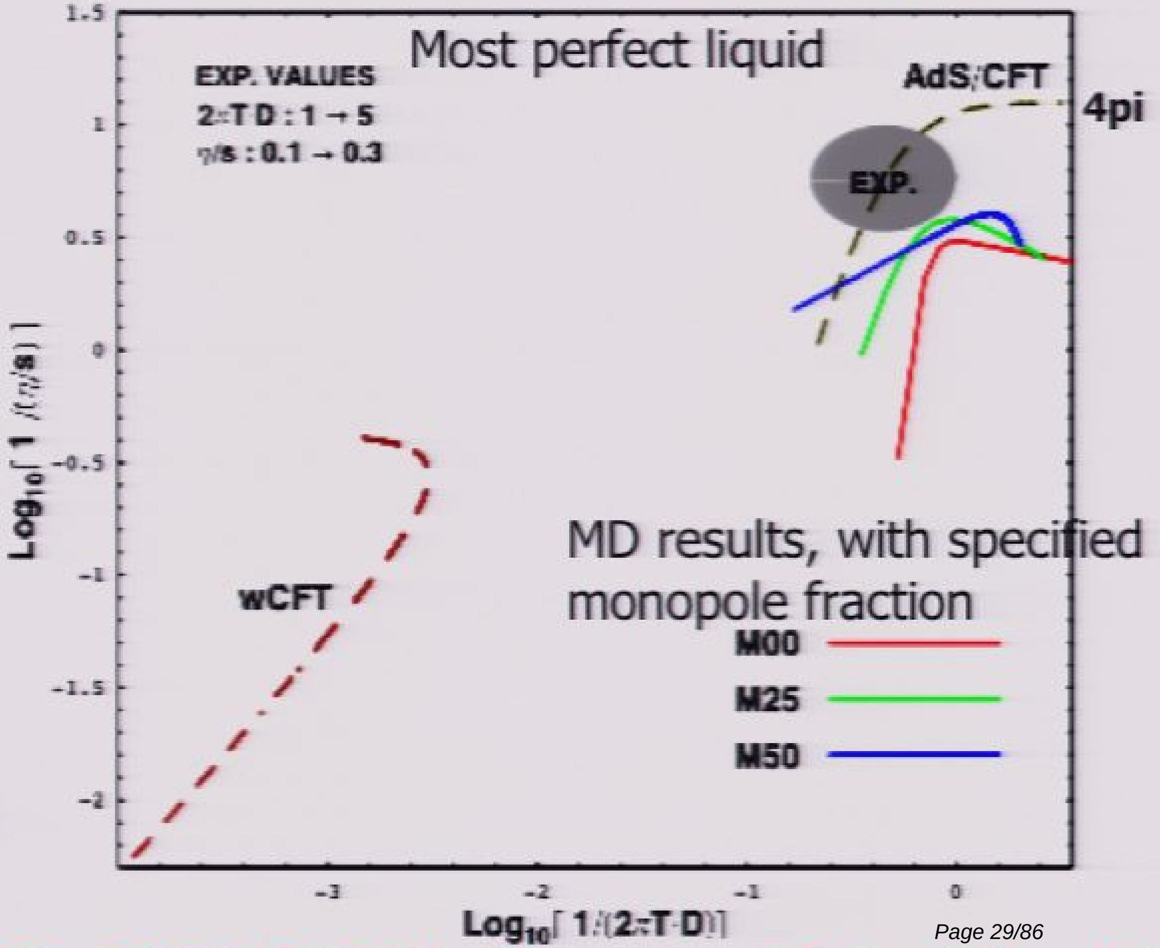

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50-50% E/M is the most ideal liquid

Magdeburg hemispheres 1656

Air:
P=p(inside)-p(atm)
QCD:
P=#(n.d.f)T^4-B

- "We cannot pump the QCD vacuum out, but we can pump in something else, namely the Quark-Gluon Plasma" my arguments from 1970's

- QGP was expected to be much simpler than the QCD vacuum, weakly coupled. We now see it is also quite complicated => sQGP...

My hydro history

- Hydro for e+e- as a spherical explosion (ES,PLB 34 (1971) 509)

=> killed by AF in 73 and discovery of jets in e+e- in 76

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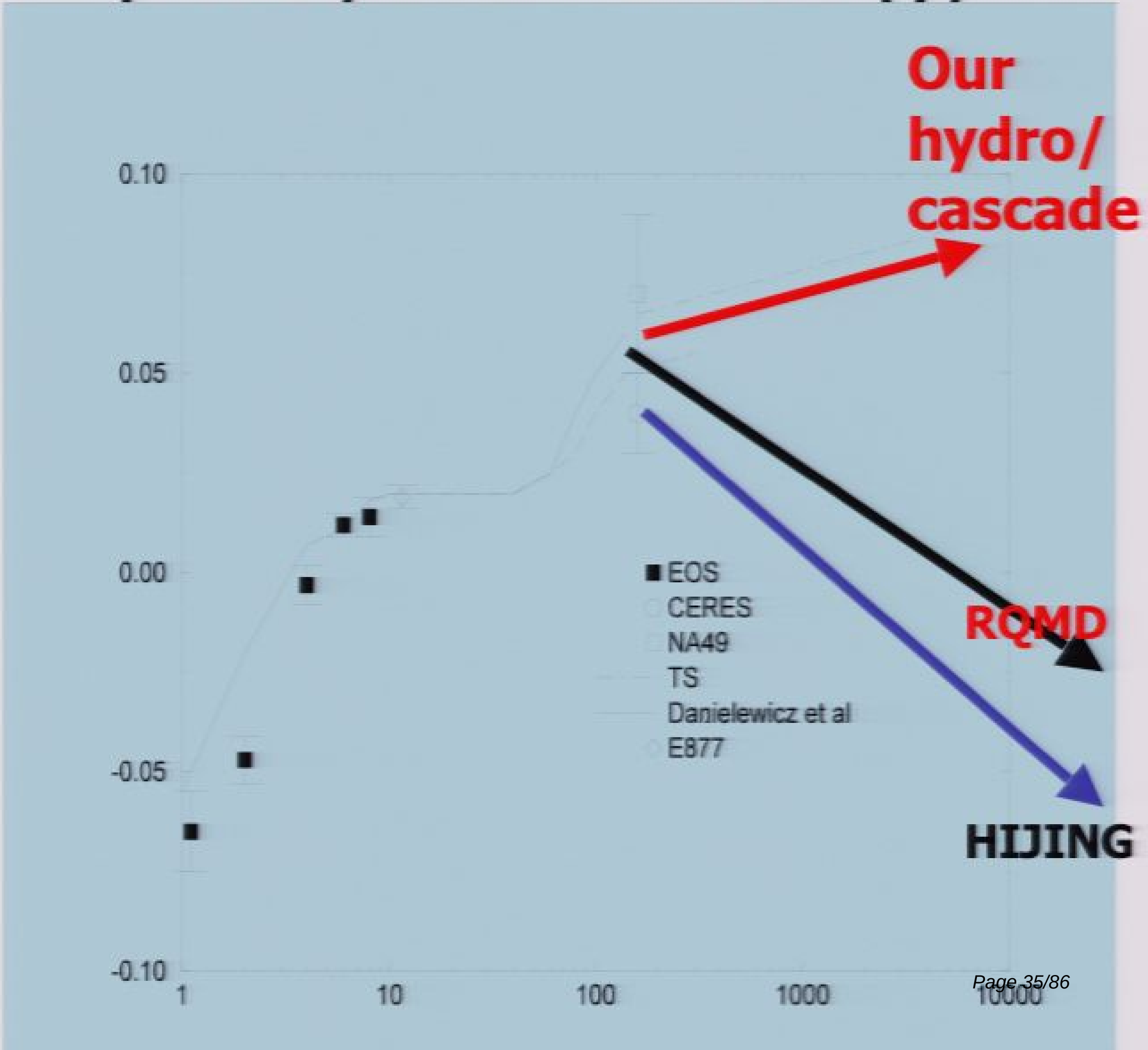
ES+Hung, prc57 (1998) 1891, radial flow at PbPb at SPS (with separate freezeout surfaces) worked! (but nobody cared as cascades did the same)

✓ ES+D.Teaney (99-01) radial and elliptic flows at RHIC worked like a clock!

From my QM99 (``RHIC predictions") talk, the ellipticity v2 vs energy

Qualitative difference with string cascades (RQMD) and parton cascades (HIJING)



Sonic boom from quenched jets

Casalderrey,ES,Teaney, hep-ph/0410067; H.Stocker…

- **the energy deposited by jets into liquid-like strongly coupled QGP goes into conical shock waves and flow to Mach angle**
- **One can solve relativistic hydrodynamics and got the flow picture, not too close to the head**
- **AdS/CFT allows complete treatement (not yet done in full)**

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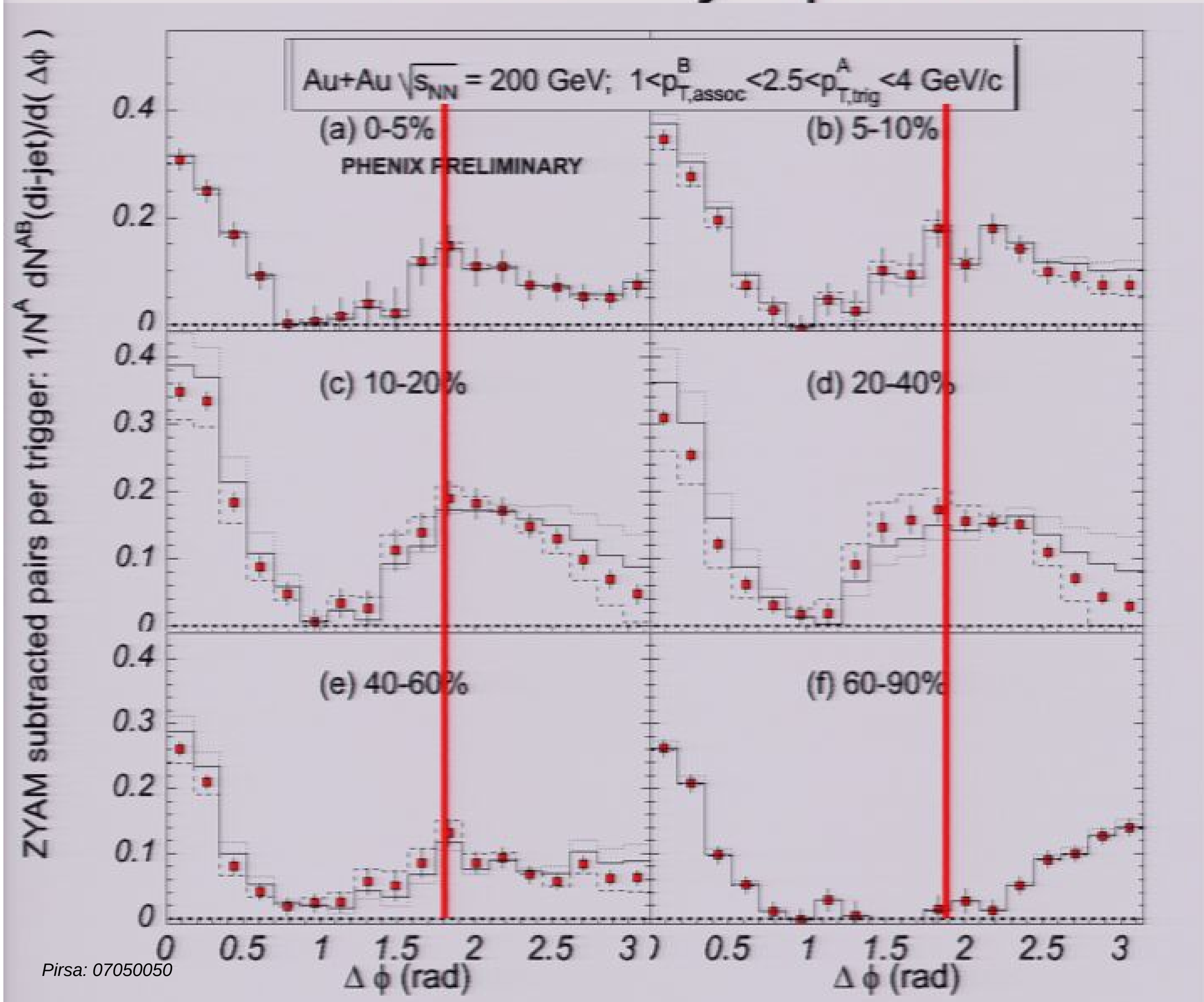
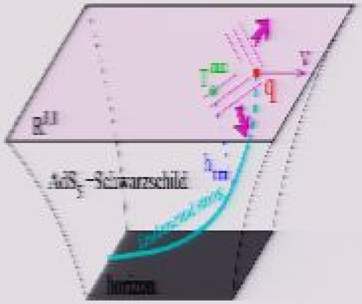
PHENIX jet pair distribution



Note: it is only projection of a cone on phi

Red line - expected Mach directiton for <Cs>=.3

Freiss,Gubser et al: Mach cone from jets in AdS/CFT



subsonic

⇒no cone
⇒(as in b-tagged jets
⇒ – Antinori,ES, nucl-th/0507046)

Supersonic
Note how angle moves as v->cs

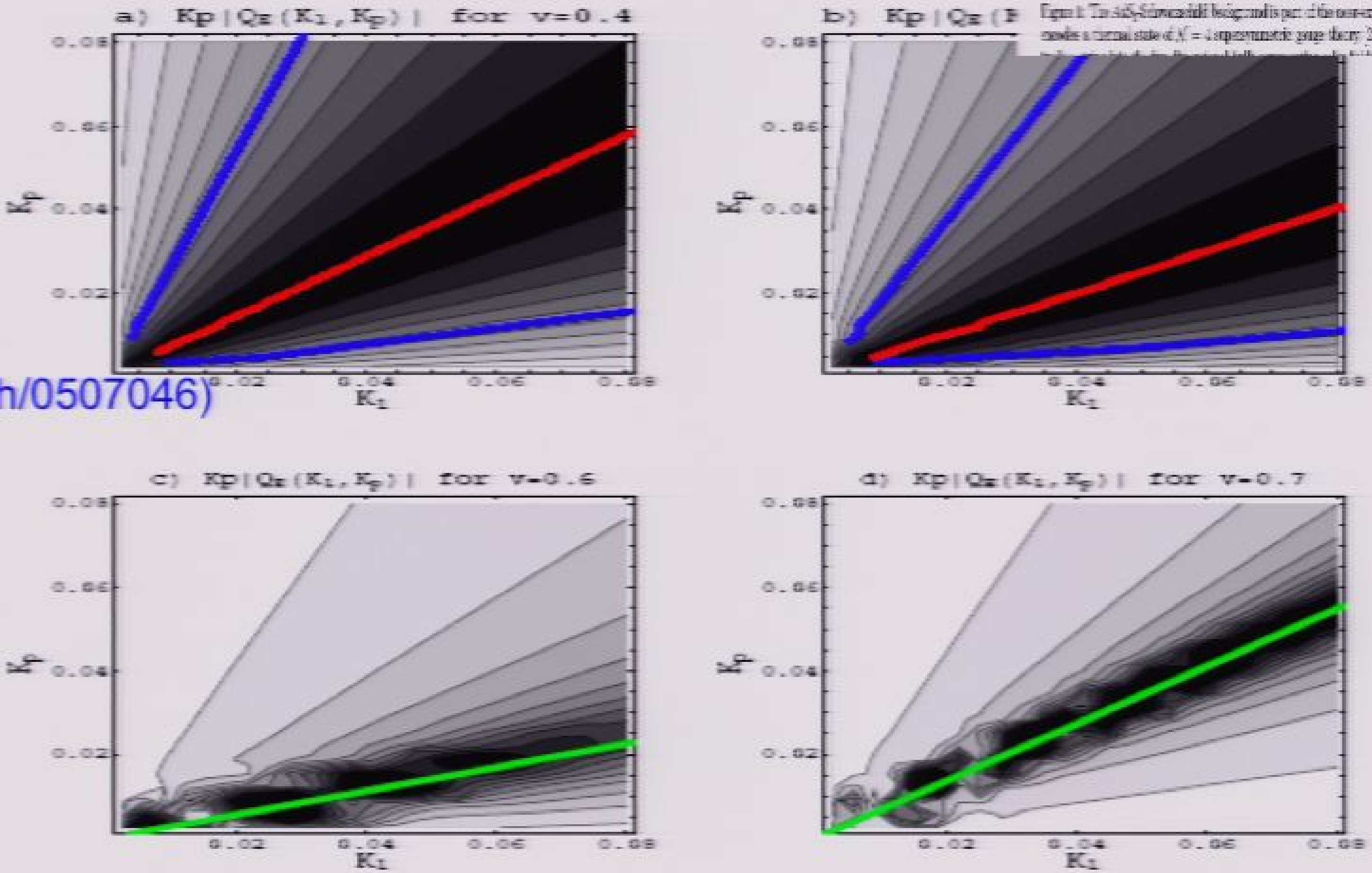


Figure 4: Contour plots of $K_\perp|Q_E^K|$ for various values of v at low momenta. The
line shows the Mach angle. The red curve shows where $K_\perp|Q_E^K|$ is maximized fo
$K=\sqrt{K_1^2+K_\perp^2}$. The blue curves show where $K_\perp|Q_E^K|$ takes on half its maximum va

2 Mach cones in strongly coupled plasmas

(thanks to B.Jacak)

PHYSICAL REVIEW E 68, 056409 (2003)

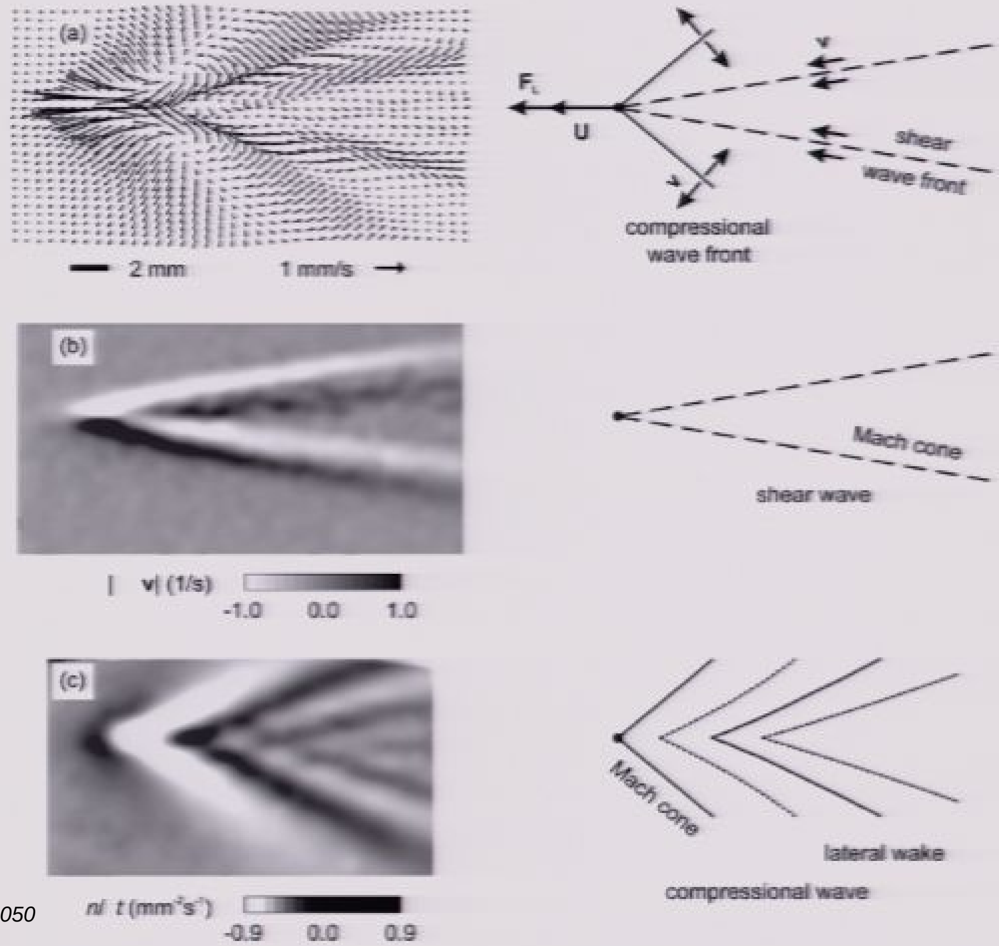
Compressional and shear wakes in a two-dimensional dusty plasma crystal

V. Nosenko,* J. Goree,† and Z. W. Ma
Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242, USA

D. H. E. Dubin
Department of Physics, University of California at San Diego, La Jolla, California 92093, USA

A. Piel
Institut für Experimentelle und Angewandte Physik, Christian-Albrechts Universität, Kiel, Germany

(Received 9 July 2003; published 24 November 2003)



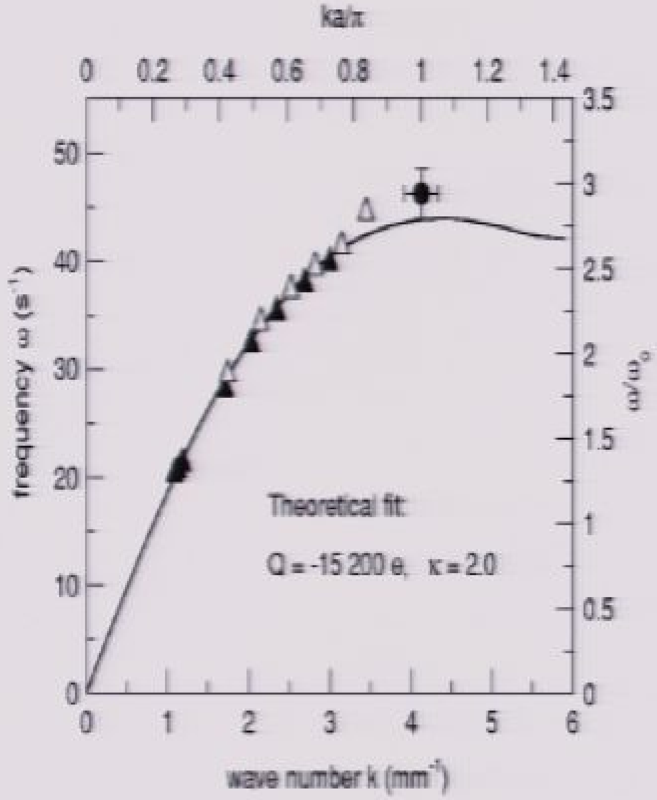


FIG. 13. Experimentally measured dispersion relation of compressional waves. The points were calculated using the theoretical

FIG. 4. The compressional- and shear-wave Mach cones, excited simultaneously. The scanning speed U is higher than the sound speed

Two main differences between sQGP and electrodynamical plasmas:

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- Electrons have the same charge -e at all time, but our quasiparticles (quarks, gluons,…) have colors which **vary in time** =>

Gelman,Zahed,ES: Wong eqn for color vectors

Two main differences between sQGP and electrodynamical plasmas:

Electrons have the same charge -e at all time, but our quasiparticles (quarks, gluons,…) have colors which **<u>vary in time</u>** =>

Gelman,Zahed,ES: Wong eqn for color vectors

There are not only ``electric" but also **magnetically charged** quasiparticles, monopoles and dyons =>

- For $SU(2)$ charge Q is a unit vector, $\vec{Q} = (Q^1, Q^2, Q^3)$

$$dx_i/dt = p_i/m,$$
$$dp_i/dt = (g^2/4\pi) \sum \vec{Q}_i \cdot \vec{Q}_j / r_{ij}^2,$$
$$d\vec{Q}_i/dt = (g^2/4\pi) \sum \vec{Q}_i \times \vec{Q}_j / |r_{ij}|$$

- Note: $d\vec{Q}_i^2/dt = 0$

Wong eqn can be rewritten as x-p canonical pairs, 1 pair for SU(2), 3 for SU(3), etc. known as Darboux variables. We did SU(2) color => Q is a unit vector on O(3)

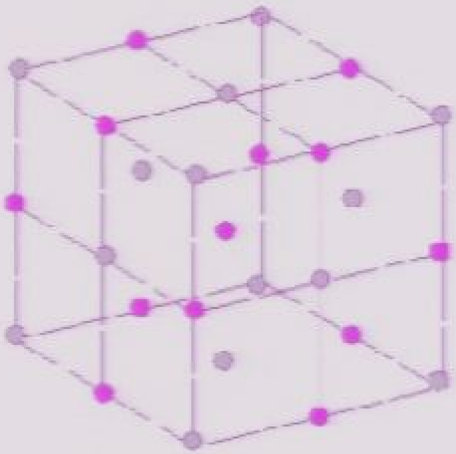
Classical strongly coupled plasmas

As **Gamma= <|Epot|>/<Ekin>** grows

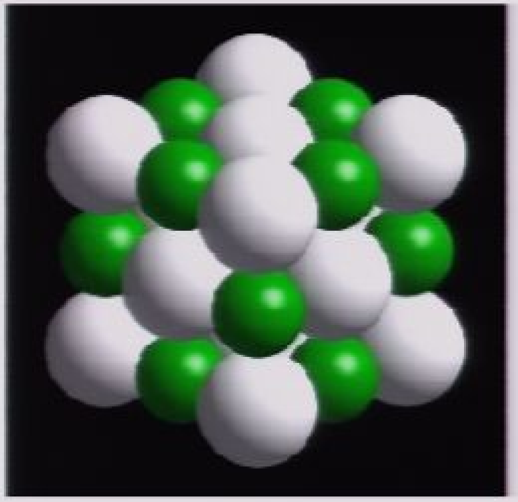
gas => liquid => solid

- **This is of course for +/- Abelian charges,**
- **But ``green" and ``anti-green" quarks do the same!**

NaCl Structure



NaCl Structure with
Face Centered Cubic Bravais Lattice



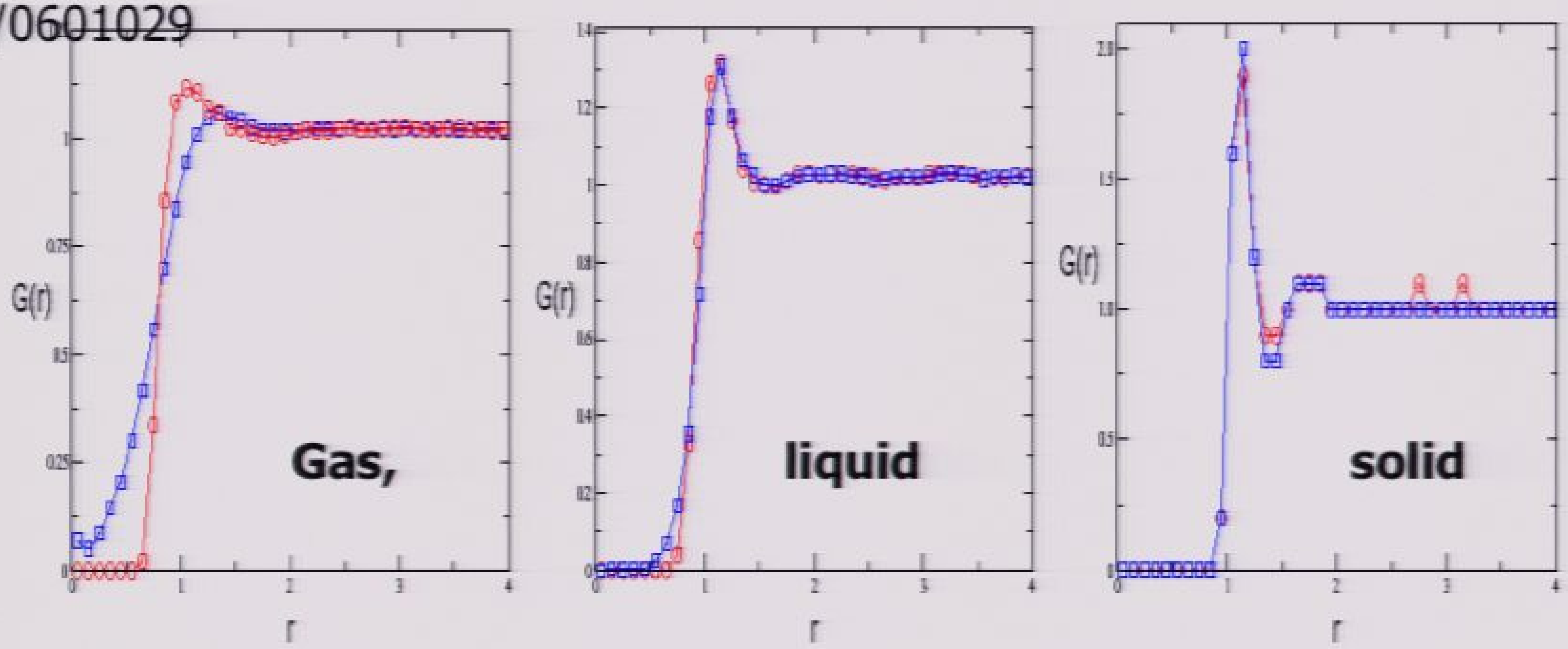
•local order would be preserved in a liquid also,

as it is in molten solts (strongly coupled Two-Component Plasma with <pot>/<kin>=O(60)) (which is an order of magn. larger than in sQGP)

Structure factor for cQGP

Gelman,ES, Zahed,nucl-th/0601029

With a non-Abelian color => Wong eqn



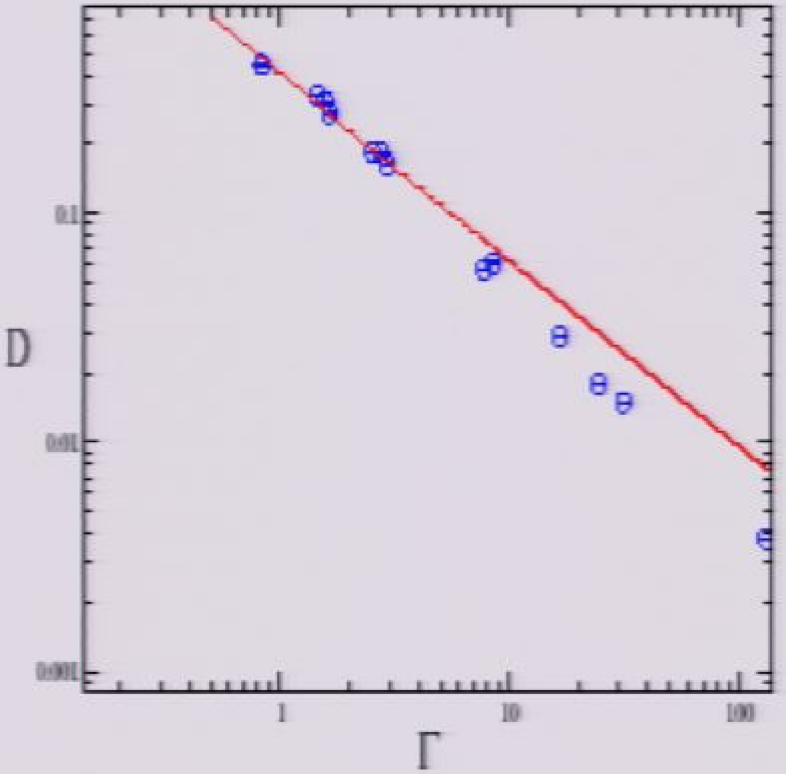
- G_d correlation function for $\Gamma = 0.83, 31.3, 131$, respectively; red circles correspond to $t^* = 0$, and blue squares correspond to $t^* = 6$
- $\Gamma = 0.83$ is a weak correlation between the particles; relaxes rather quickly with time
- The correlation is more robust for $\Gamma = 31.3$ (*liquid*)
- For $\Gamma = 131$ correlation is very stable (*solid*)

The stronger is coupling, the smaller is diffusion const!

$$D(\tau) = \frac{1}{3N}\left\langle \sum_{i=1}^{N} \vec{v}_i(\tau)\cdot\vec{v}_i(0)\right\rangle$$

$$D = \int_0^\infty D(\tau)\, d\tau$$

$$D \approx \frac{0.4}{\Gamma^{4/5}}$$



(Compare it to AdS/CFT result by Casalderrey-Teaney D\sim 1/lambda^.5)

Shear viscosity

- Green-Kubo relation for viscosity

$$\eta = \int_0^\infty \eta(\tau)\, d\tau$$

$$\eta(\tau) = \frac{1}{3\,TV} \left\langle \sum_{x<y} \sigma_{xy}(\tau)\, \sigma_{xy}(0) \right\rangle$$

$\sum_{x<y}$—a sum over the three pairs of distinct tensor components (xy, yz and zx); the stress-energy tensor are given by

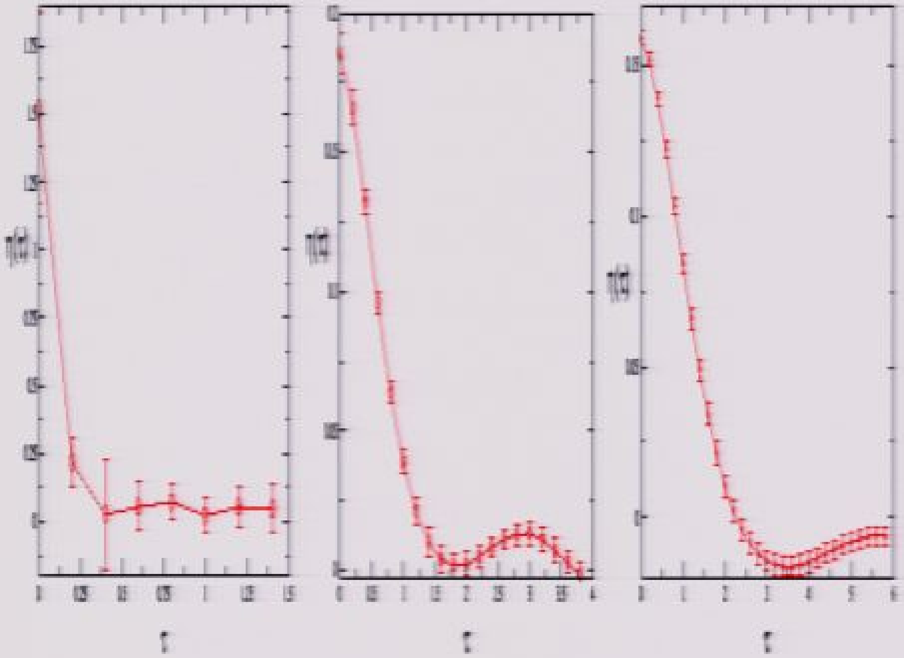
$$\sigma_{xy} = \sum_{i=1}^{N} m_i v_{ix} v_{iy} + \frac{1}{2} \sum_{i \neq j} r_{ij,x} F_{ij,y}$$

$\vec{F}_{ij}$ is the force on particle *i* due to particle *j*

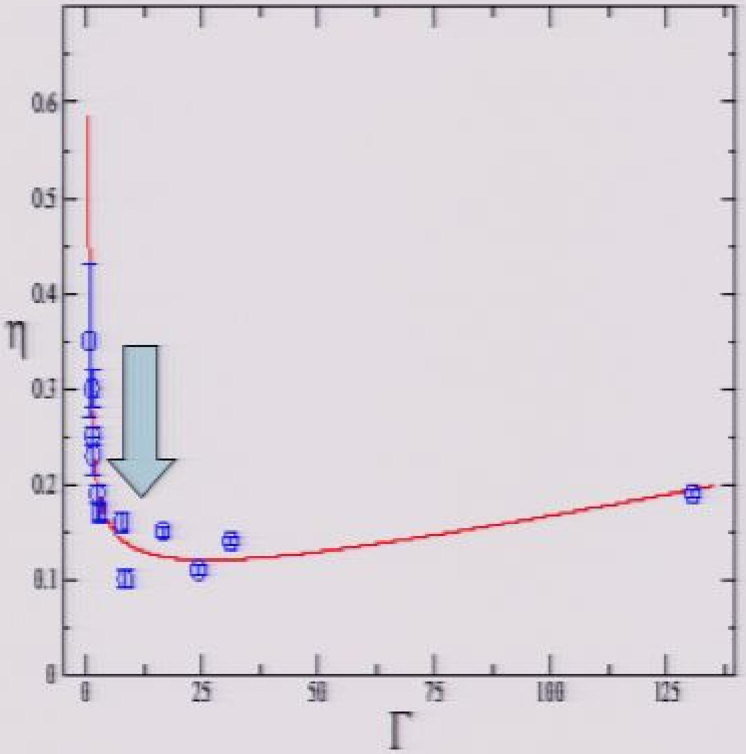
Viscosity does **not** disappear but has a **minimum**

QGP coupling (blue arrow) seems to be about the best liquid one can possibly make

translated to sQGP => eta/s= 3 or so <<1



- Stress-tensor autocorrelation correlation function $\eta(t)$ for Γ = 0.83, 31.3, 131



$$\eta \approx 0.001\,\Gamma + \frac{0.242}{\Gamma^{0.3}} + \frac{0.072}{\Gamma^{2}}$$

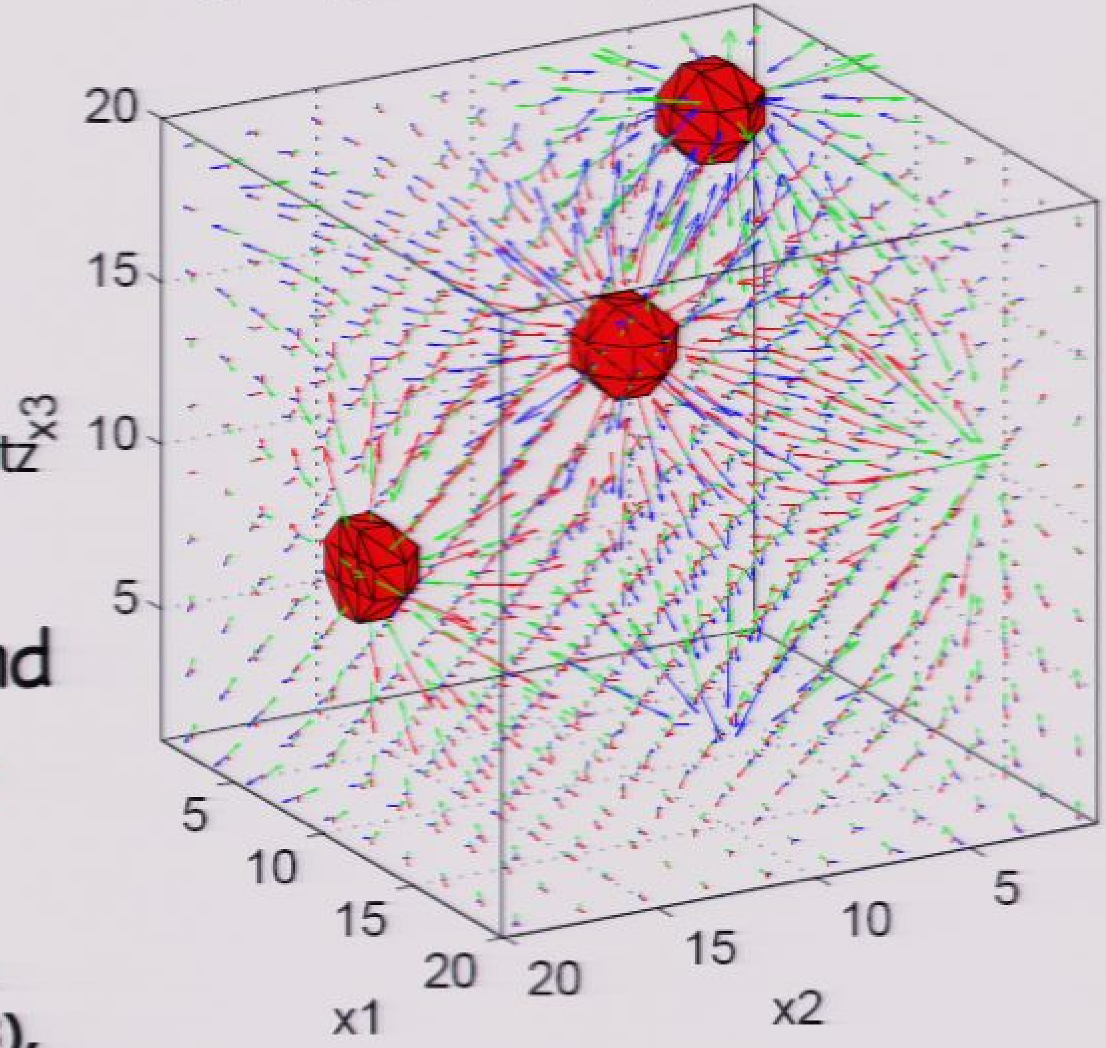
sQGP= new type of plasma, containing competing electric / magnetic quasiparticles

sQGP= new type of plasma, containing competing electric / magnetic quasiparticles

Why Higgsing and monopoles?

- SUSY gauge theories have large degenerate moduli spaces with Energy=0, with rich variety of Higgsing and magnetic objects
- QCD at T can be viewed as a **superposition as all of them**, with some weight W(<A_0>)
- Magnetic screening mass is nonzero: in fact lattice told us it exceeds electric for T<1.4Tc
- Monopoles/dyons can be traced on the lattice directly, especially while Nc of them make calorons (finite T instantons)

One can see monopoles/dyons In lattice gauge theory simulations



Berlin group - Ilgenfritz et al

Red, blue and green U(1) fields

3 dyons with corresp. Field strengths, **SU(3), Each (1,-1,0) charges**

New (compactified) phase diagram describing an electric-vs-magnetic competition

Dirac condition (old units e^2=alpha)

$$\frac{eg}{\hbar c} = \frac{n}{2}$$

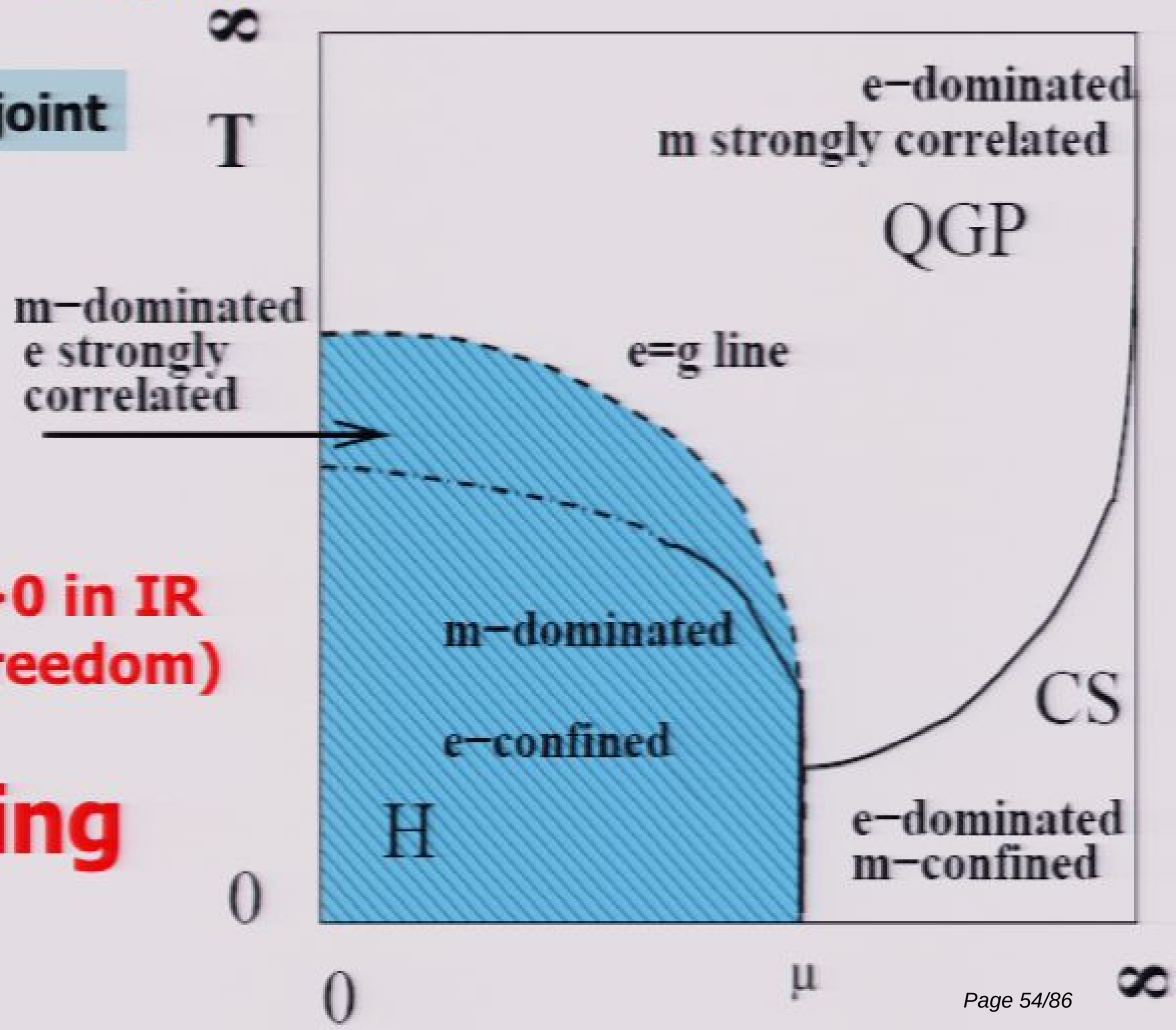
<- n=2 adjoint

Thus at the e=g line

$$e^2/\hbar c = g^2/\hbar c = 1$$

Near deconfinement line g->0 in IR (Landau's U(1) asymptotic freedom)

=> **e-strong-coupling**



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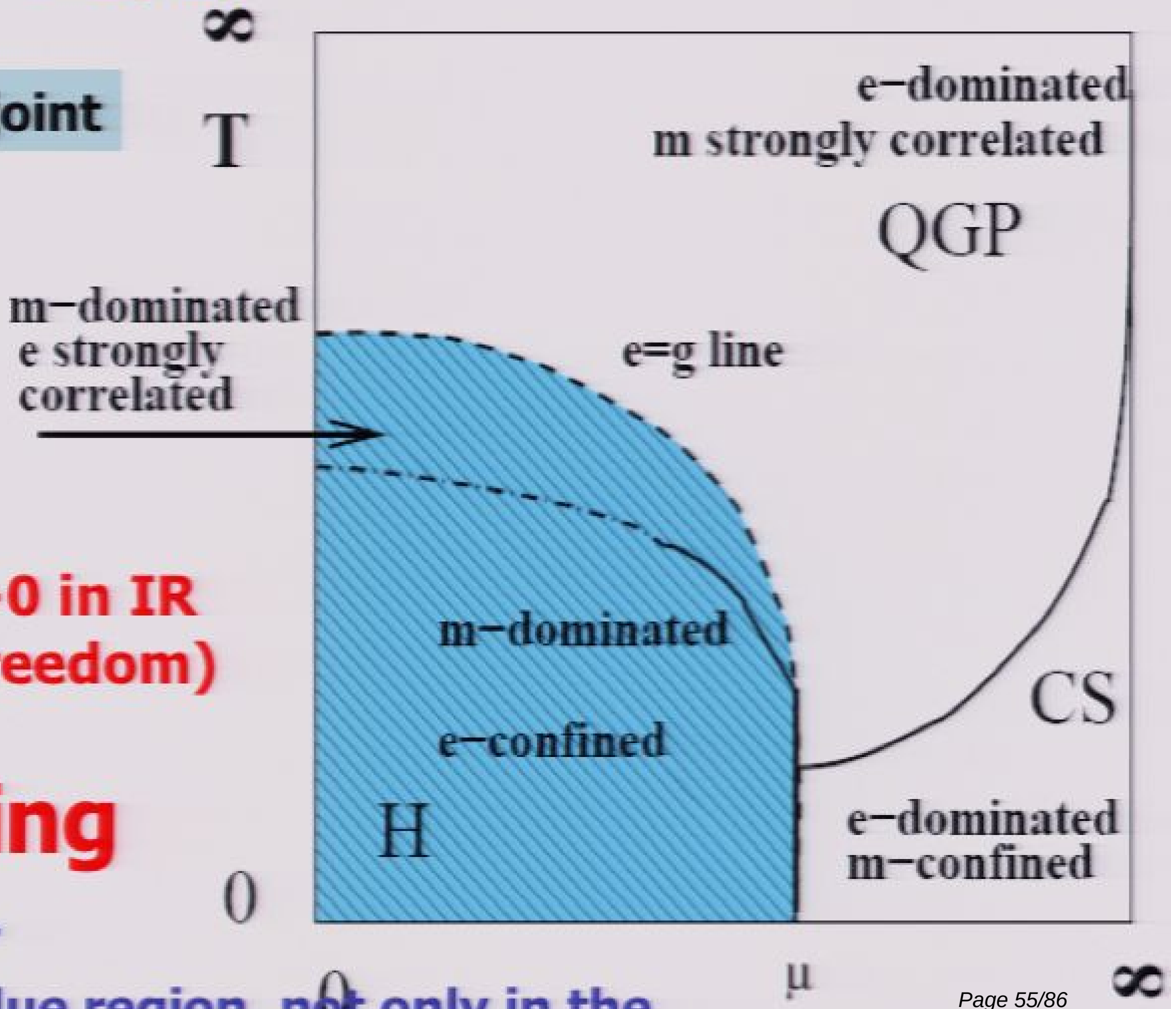

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Why is this diagram better? =>

There are e-flux tubes in all blue region, not only in the confined phase! In fact, they are maximally enhanced at Tc

How MQPs+EQPs move?

(2 pedagogical examples before we deal with a plasma)

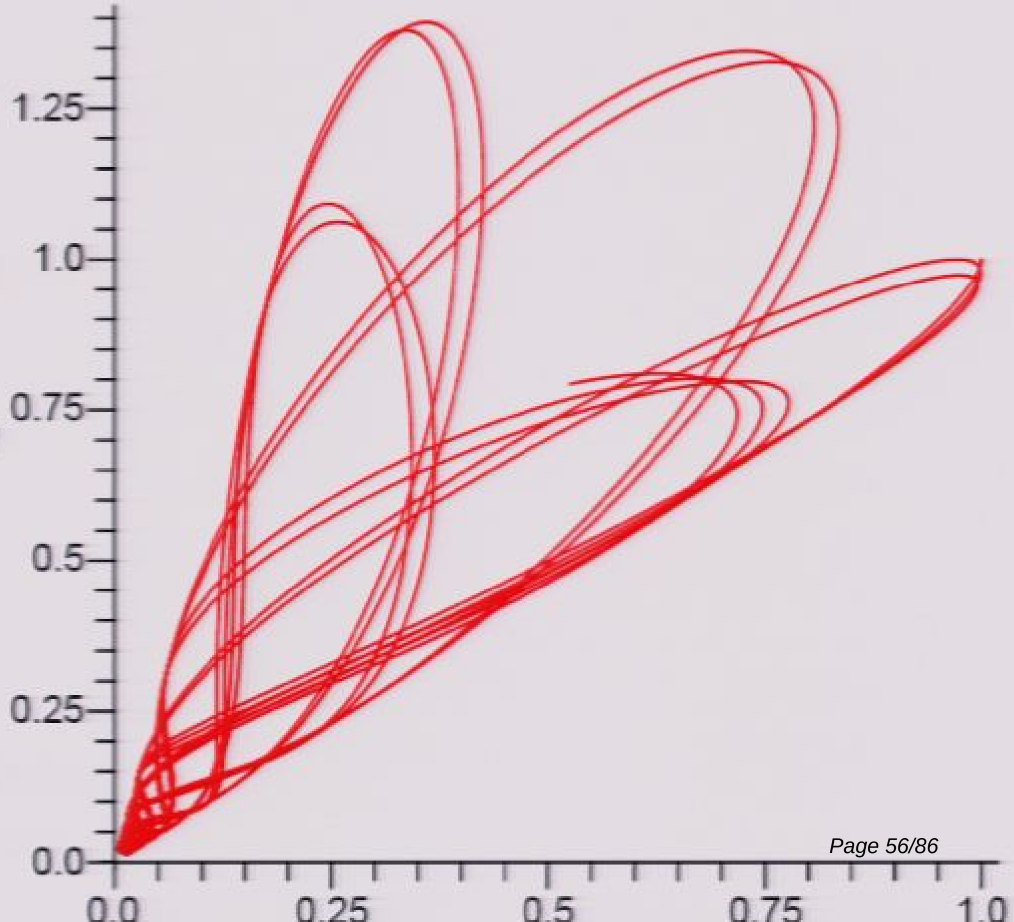
(1) one MQP (dyon)+one static e-charge

A.Poincare => the motion is restricted to a cone

- **angular momentum of the field J from ExB|| to r J=hbar*(n/2) <= Dirac g_e g_m/hbar c=N/2**

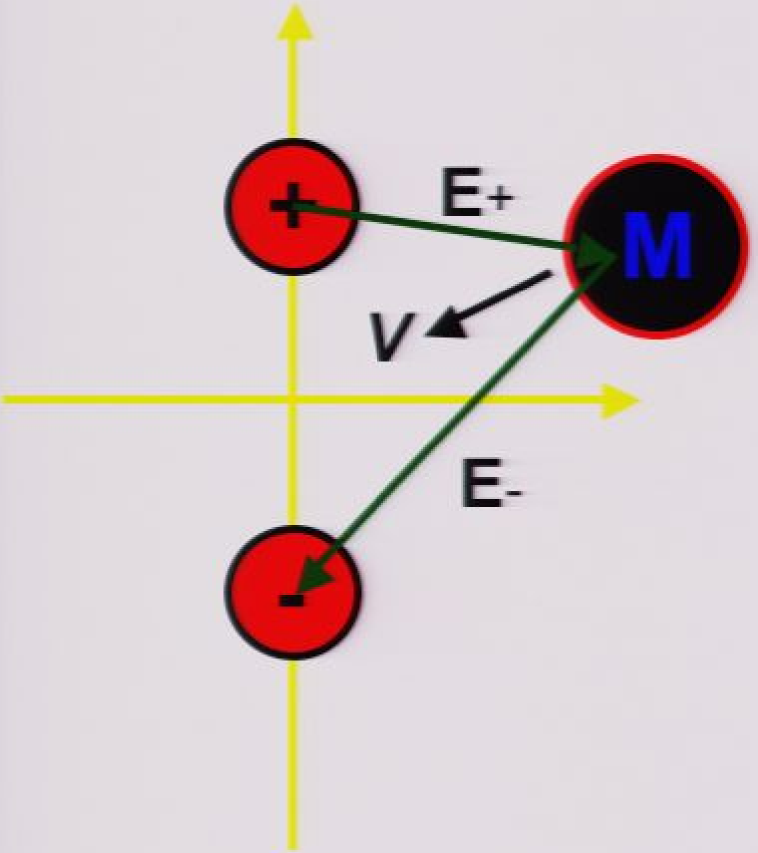
=>Monopoles of any sign **repel from a charge because Their rotation makes a repelling dipole**

(also think of quantum mech.=> localization energy!



Here is my solution for a dyon (with attractive e-charge, preventing the escape to large r)

Second (and now entirely new) problem: static eDipole+MPS

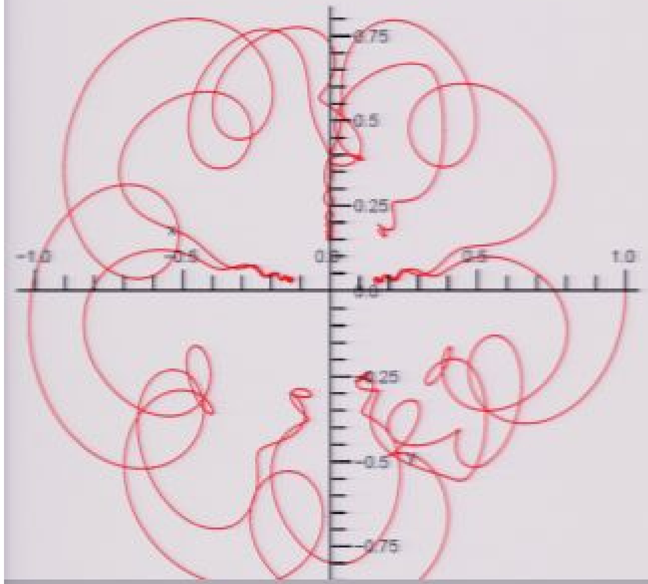


Note that Lorentz force is O(v)!

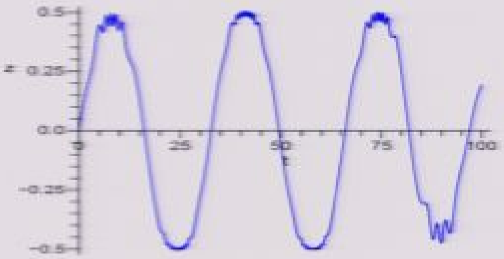
$$M\frac{d^2\vec{r}}{dt^2} = \frac{g}{c}\vec{E}\times\frac{d\vec{r}}{dt}$$

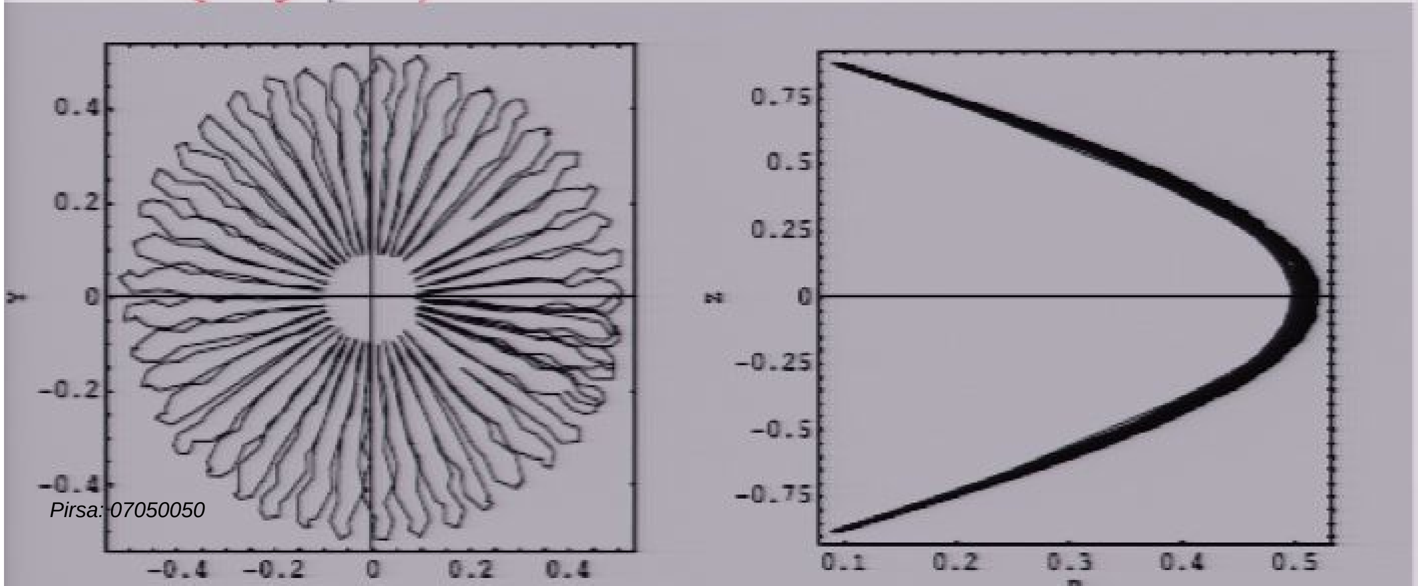
$$\vec{E} = e\,[\frac{\vec{r}-a\vec{z}}{|\vec{r}-a\vec{z}|^3} - \frac{\vec{r}+a\vec{z}}{|\vec{r}+a\vec{z}|^3}]$$

We found that **two charges** play ping-pong by a monopole without even moving!



Chaotic, regular and escape trajectories for a monopole, all different in initial condition by 1/1000 only!





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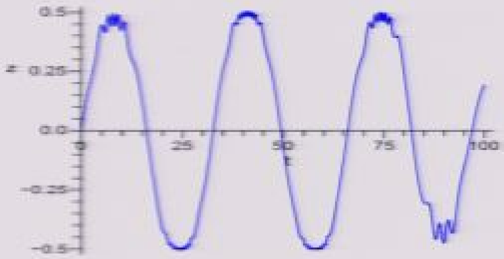
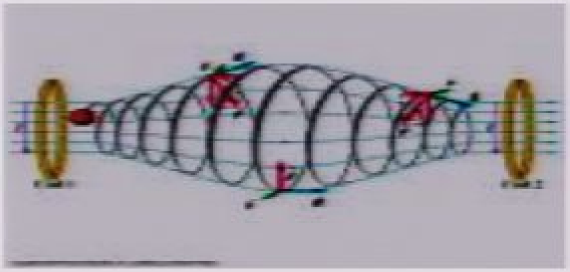
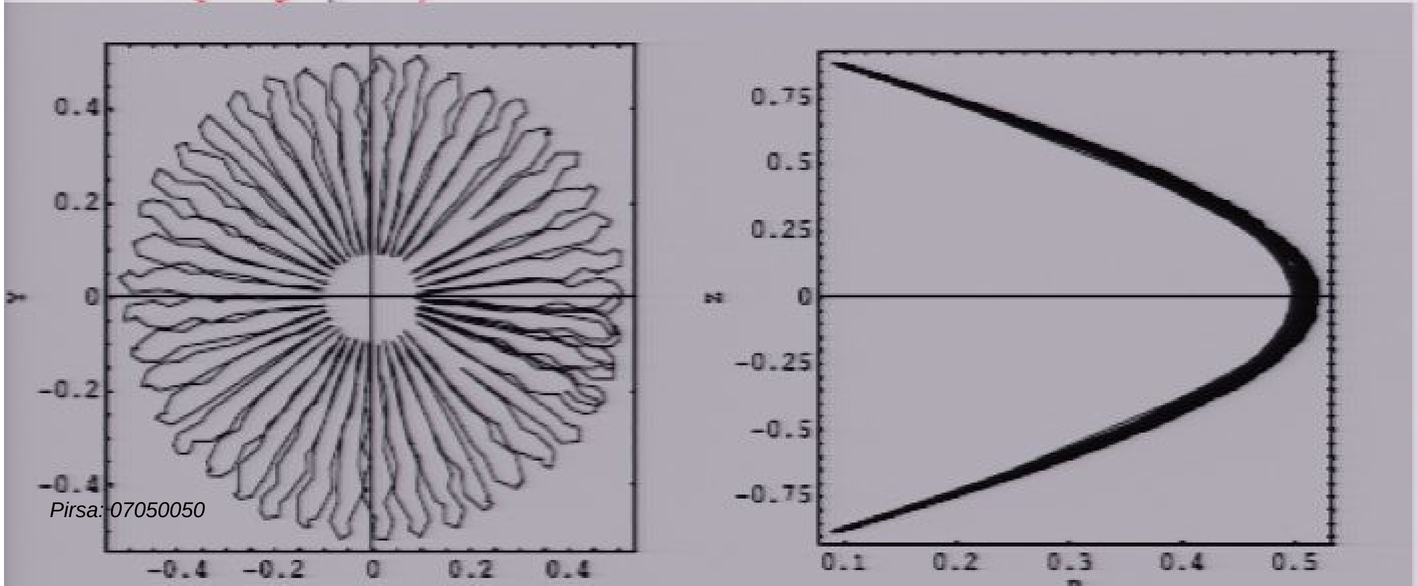


Dual to Budker's magnetic bottle





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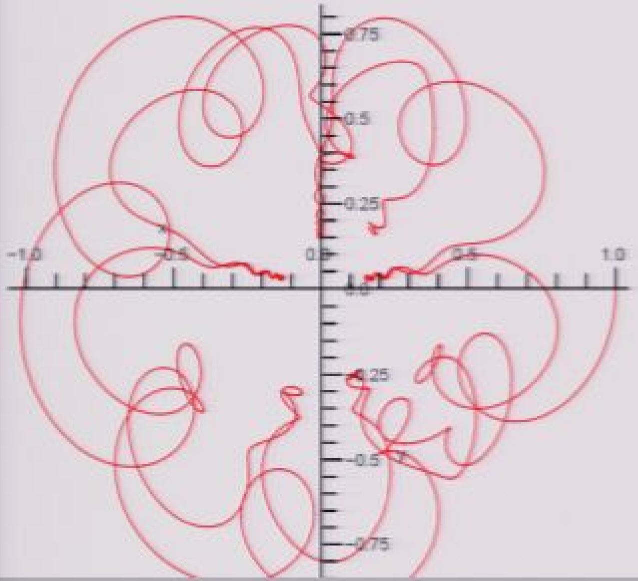
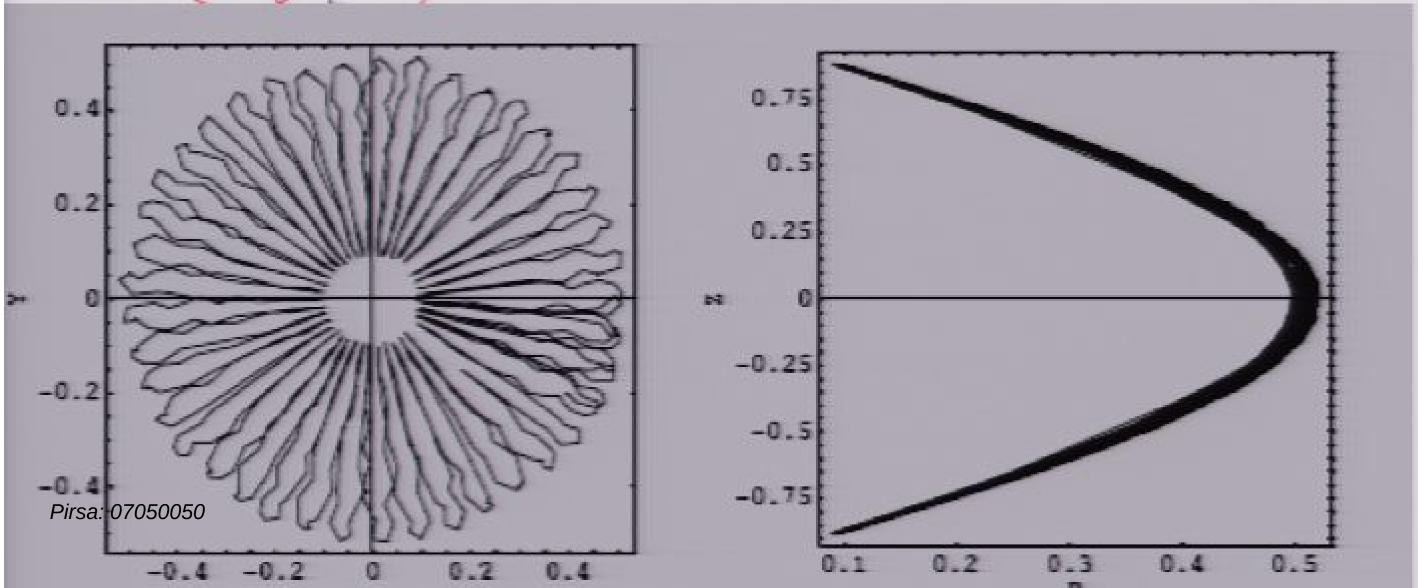
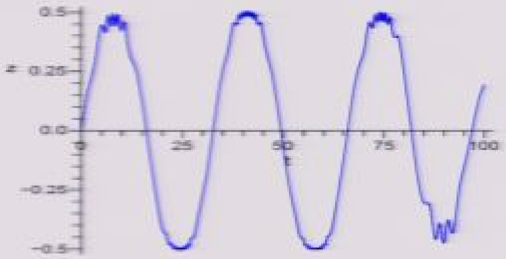


Chaotic, regular and escape trajectories for a monopole, all different in initial condition by 1/1000 only!





Dual to Budker's magnetic bottle

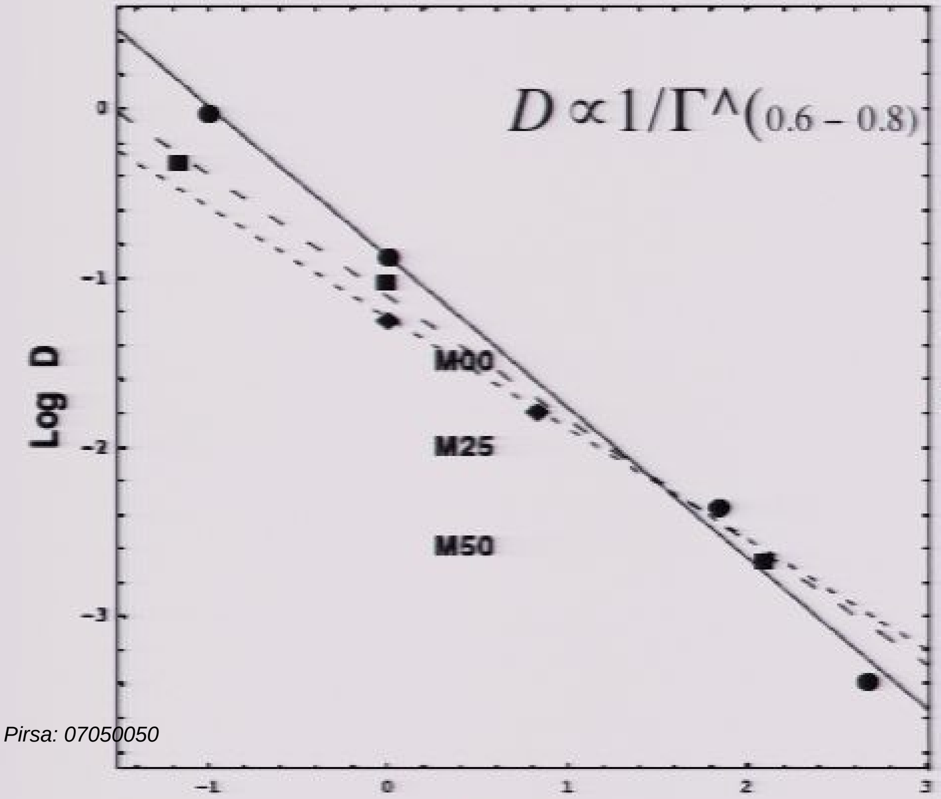
MD simulation for plasma with monopoles

(Liao,ES hep-ph/0611131)

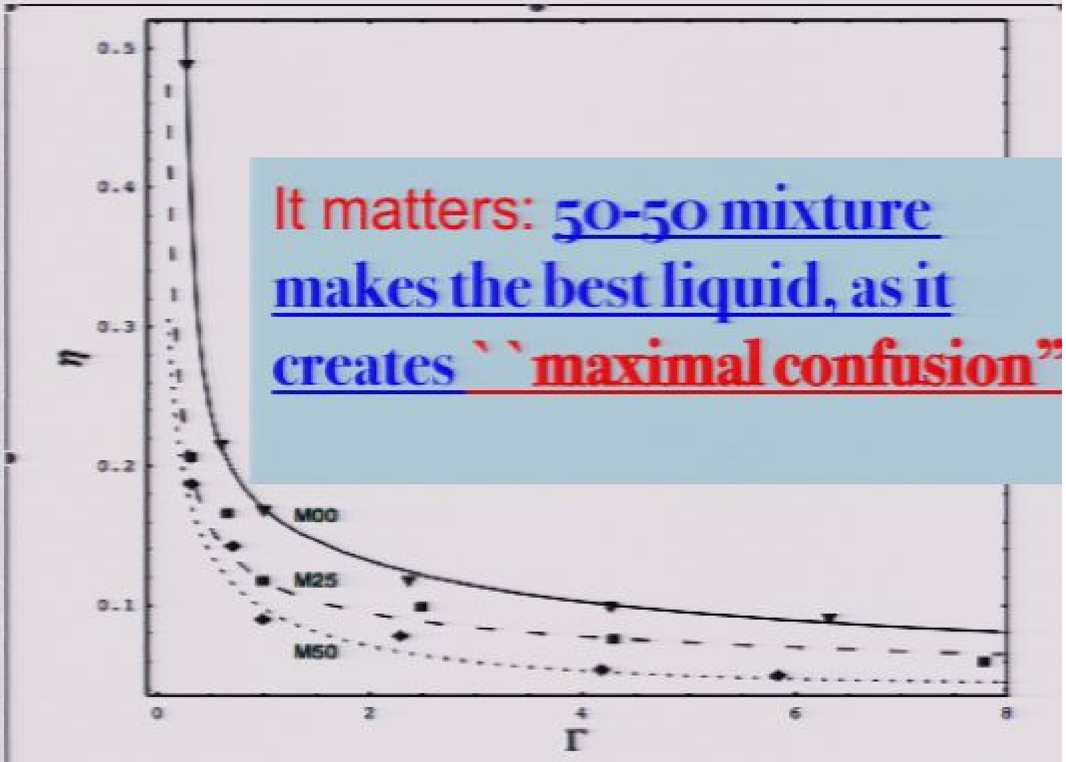
monopole admixture M50=50% etc

again diffusion decreases indefinitely, viscosity does not

$$D(\tau) = \frac{1}{3N} < \sum_{i=1}^{N} \vec{v}_i(\tau) \cdot \vec{v}_i(0) >$$



$D \propto 1/\Gamma\wedge(0.6 - 0.8)$



It matters: **50-50 mixture makes the best liquid, as it creates ``maximal confusion"**

FIG. 16. Shear viscosity η calculated at different plasma parameter Γ for M00(circle), M25(square), and M50(diamond) plasma respectively.

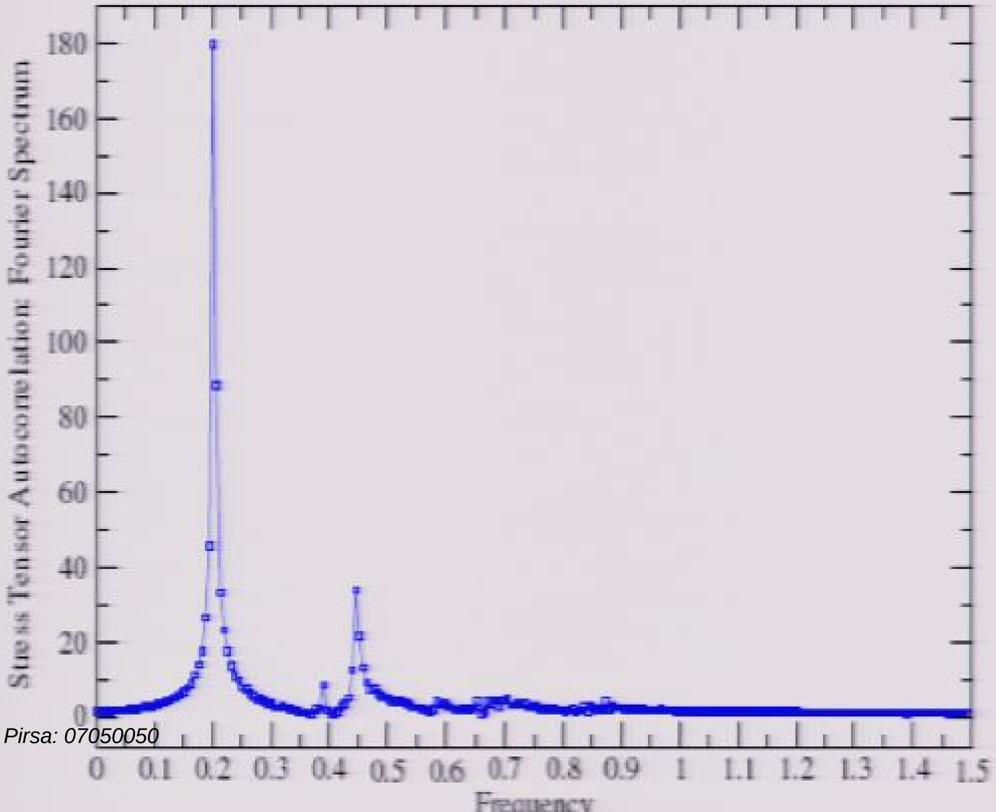
We identified 3 collective modes

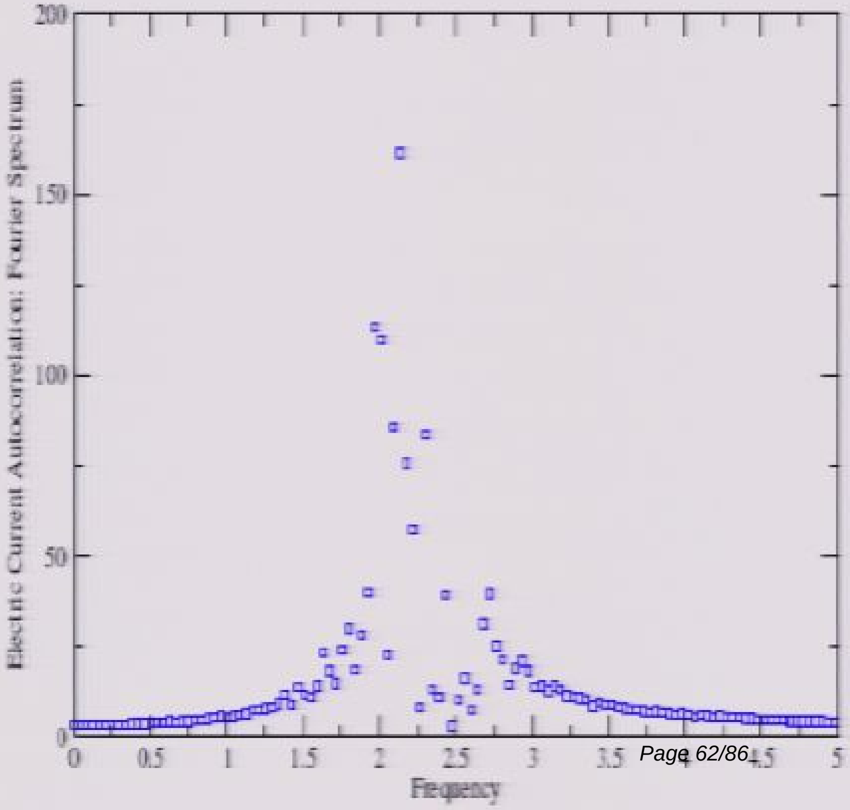
(1000 particles in a stable spherical drop)

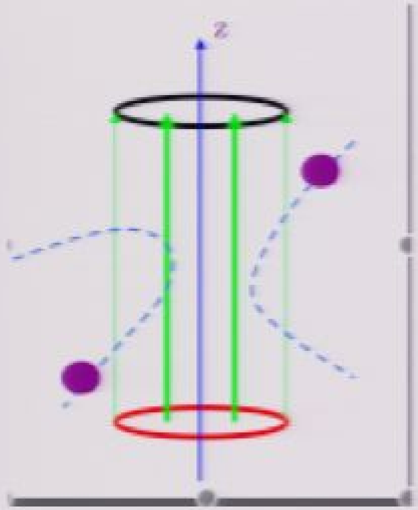
l=0 breathing =>diffusion; l-2 quadrupole => shear viscosity,
l=1 plasmon => conductivity

and studied the dependence of their fequencies and <u>widths</u> **on coupling…**

Quadrupole (phonon) and plasmon

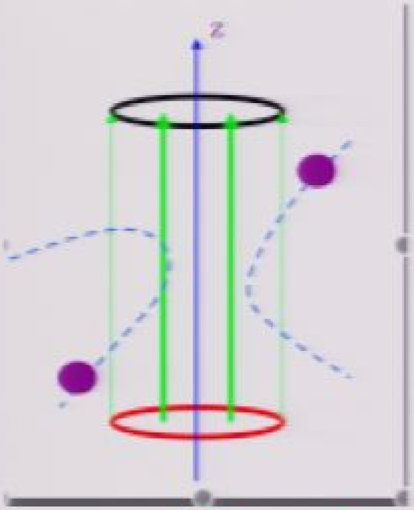






e-flux tubes in QGP?

(with J.F.Liao)



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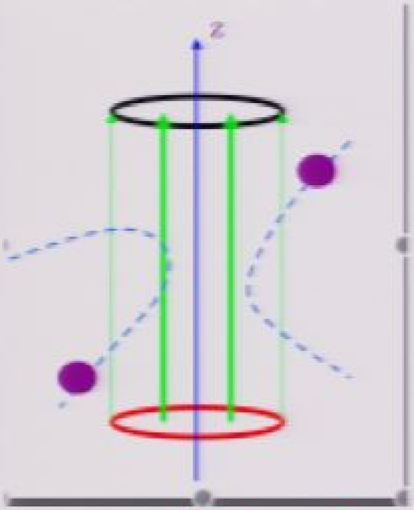

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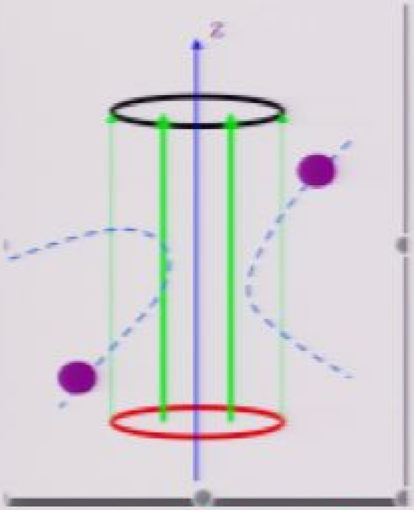

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magnetic flux tubes at the Sun,

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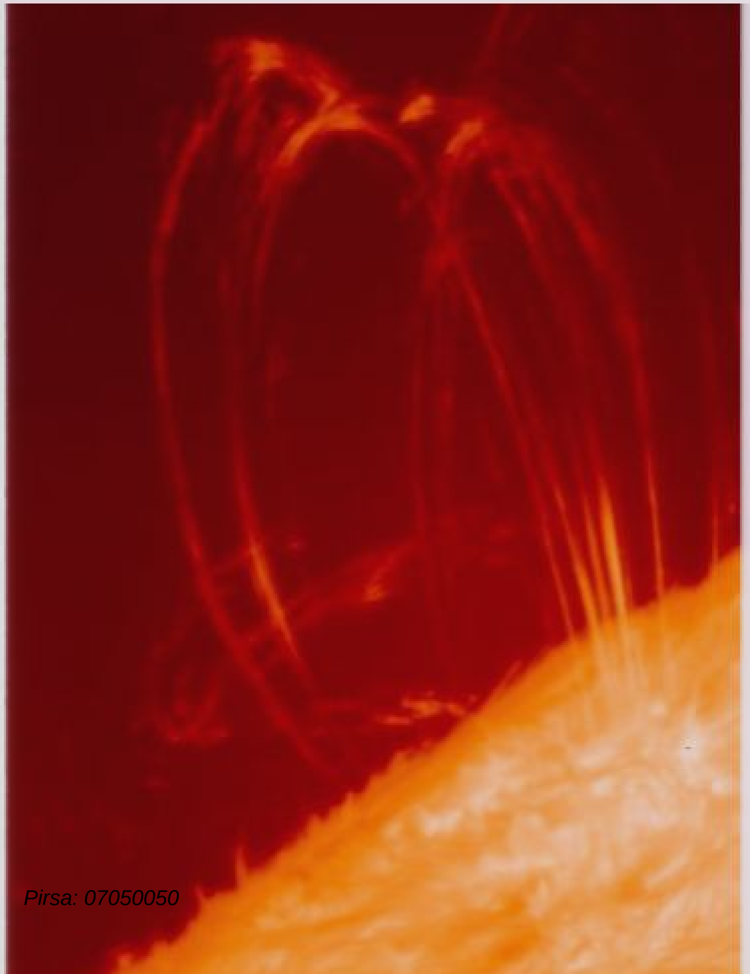

where classical electrons rotate around it

- B: about 1 kG,
- Lifetime: few months

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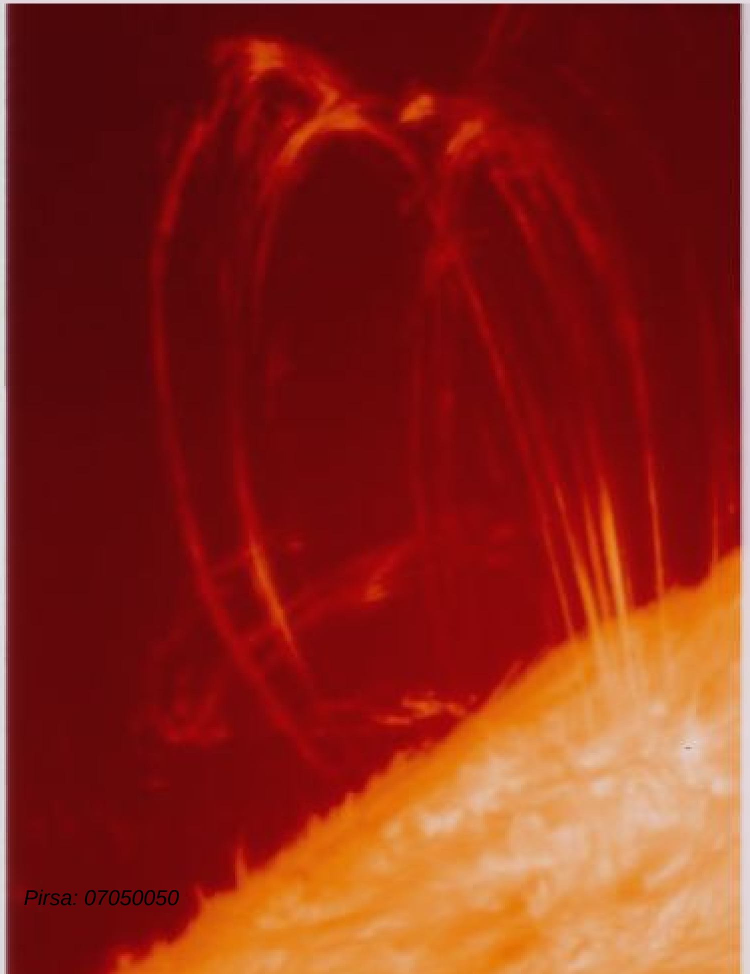

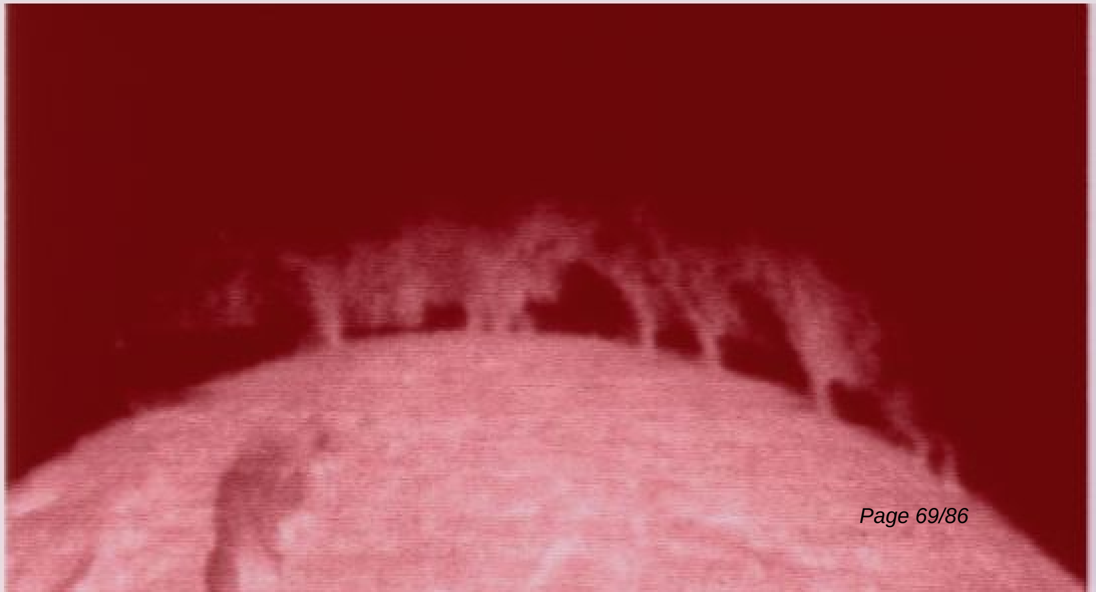

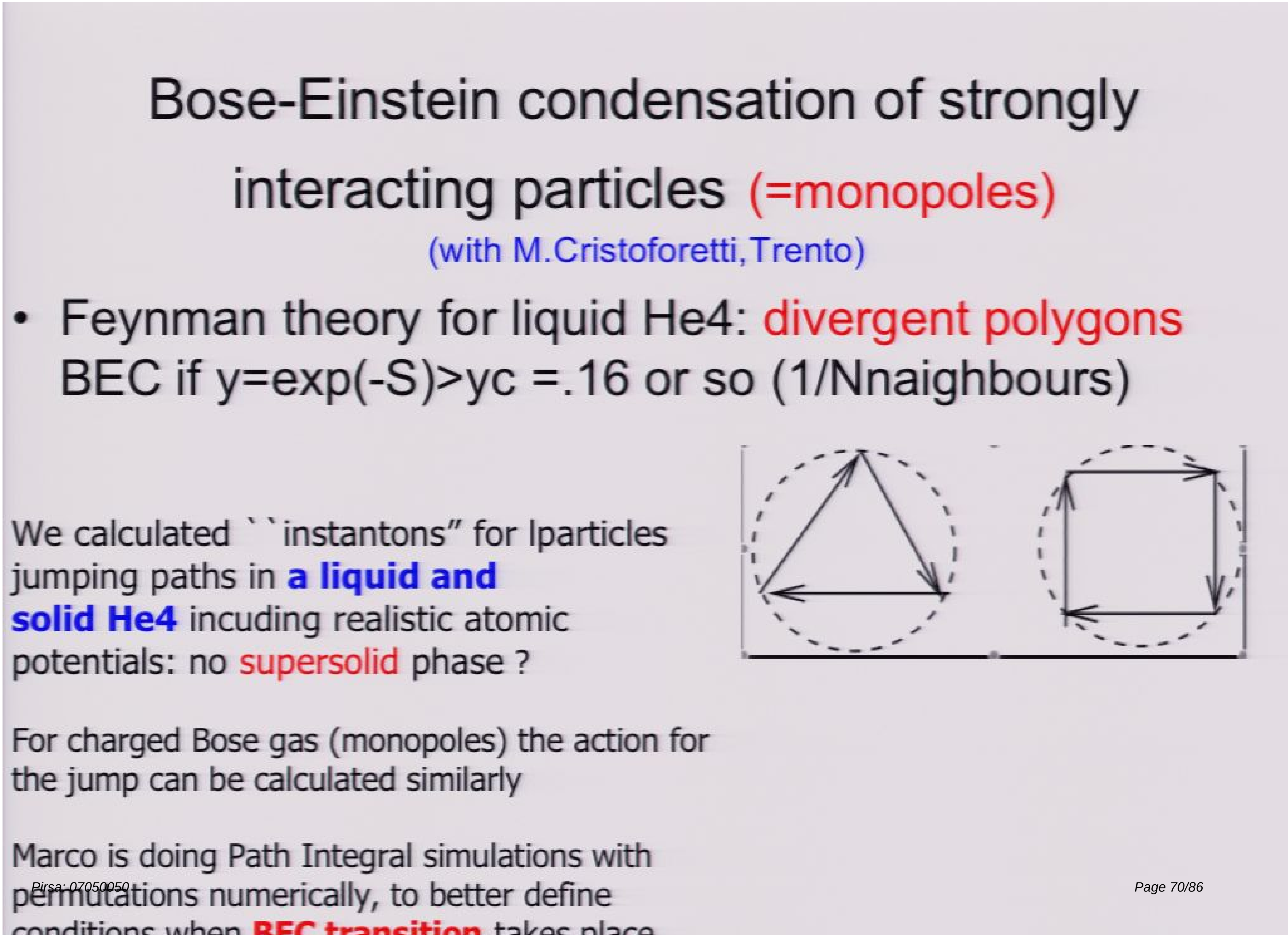

Bose-Einstein condensation of strongly interacting particles (=monopoles)

(with M.Cristoforetti, Trento)

- Feynman theory for liquid He4: divergent polygons BEC if y=exp(-S)>yc =.16 or so (1/Nnaighbours)

We calculated ``instantons” for lparticles jumping paths in **a liquid and solid He4** incuding realistic atomic potentials: no supersolid phase ?

For charged Bose gas (monopoles) the action for the jump can be calculated similarly

Marco is doing Path Integral simulations with permutations numerically, to better define conditions when **BEC transition** takes place

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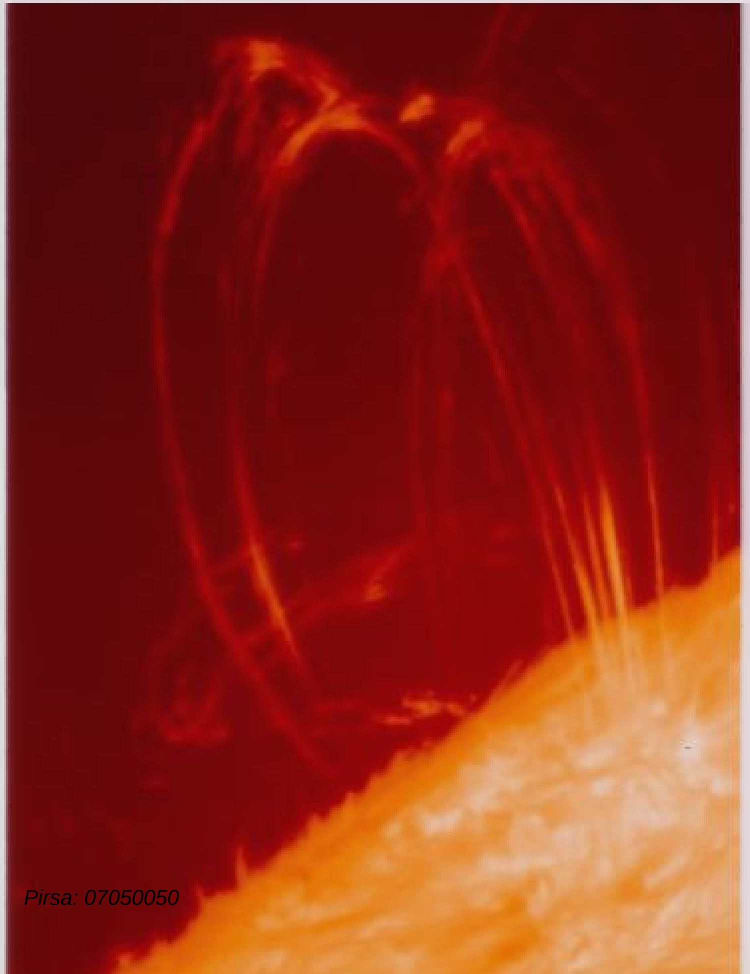

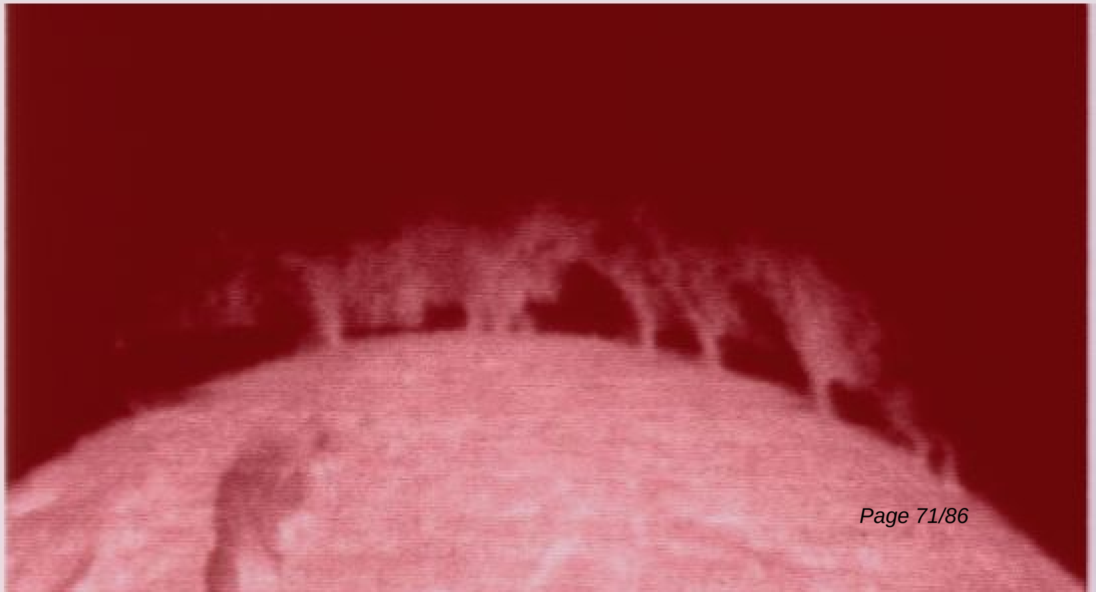

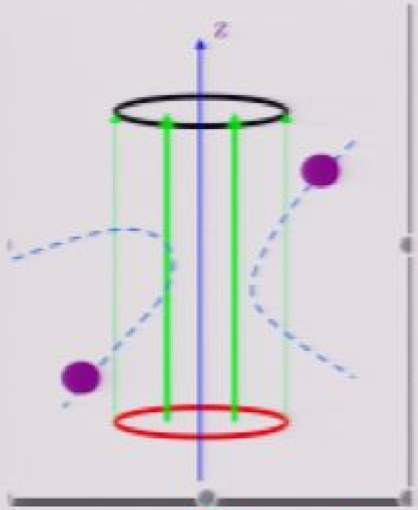

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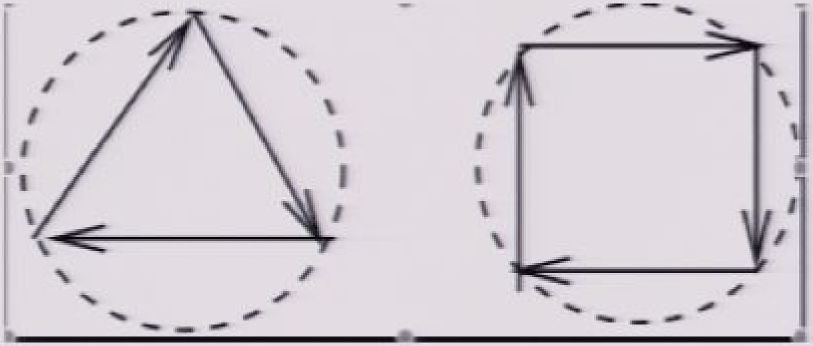

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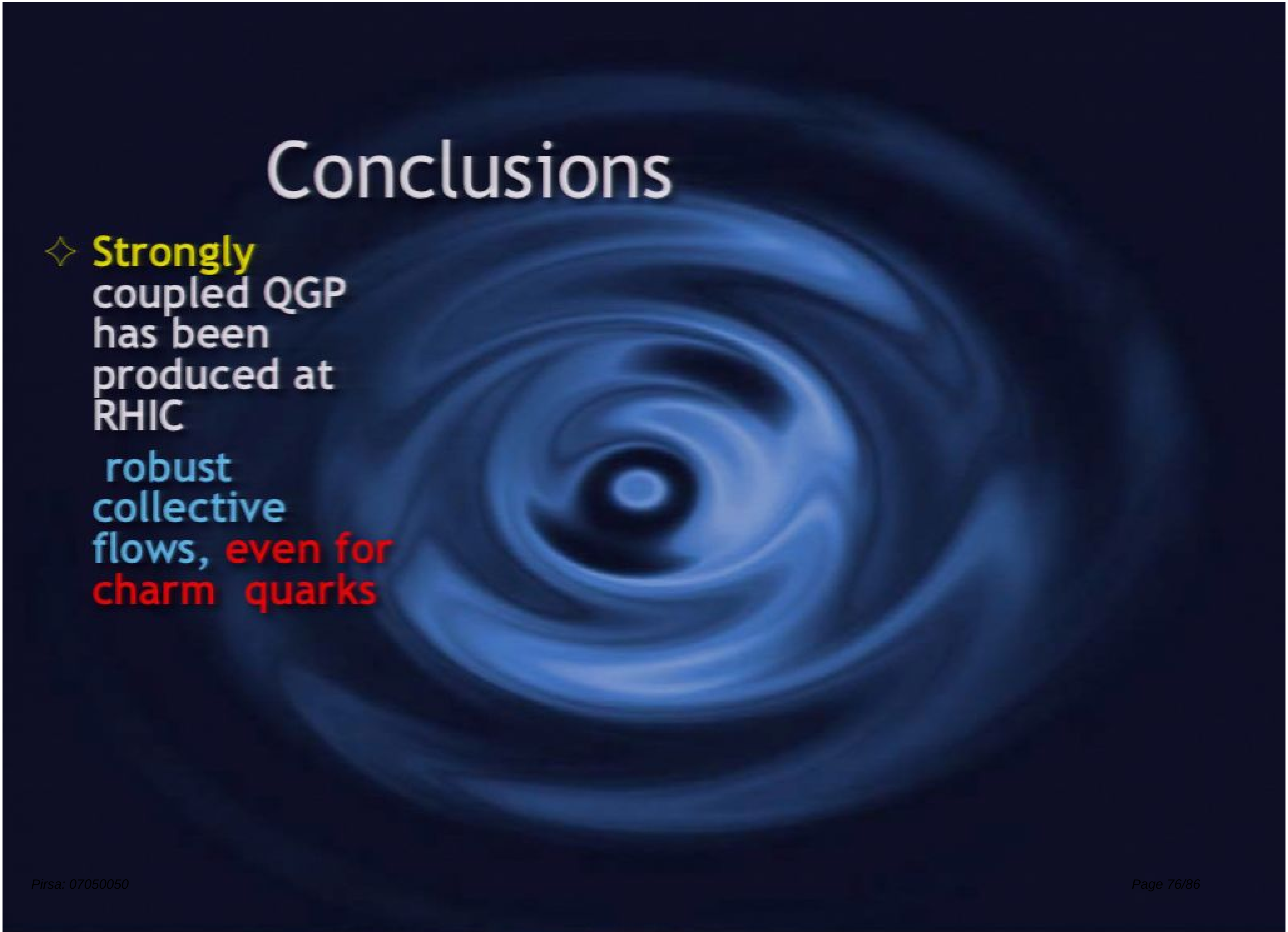

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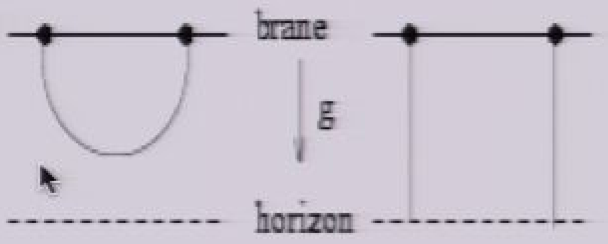
RHIC data on transport (eta,D), ADS/CFT and classical MD all

ely

A gift by the string theorists: AdS/CFT correspondence, the only way to calculate at VERY strong coupling

- The $\mathcal{N}=4$ SUSY Yang Mills gauge theory is conformal (CFT) (the coupling does not run). At finite T it is a QGP phase at ANY coupling. If it is weak it is like high-T QCD => gas of quasiparticles. What is it like when the coupling gets strong $\lambda = g^2 N_c \gg 1$?
- AdS/CFT correspondence by Maldacena turned the strongly coupled gauge theories to a classical problem of gravity in 10 dimensions
- Example: a modified Coulomb's law (by Maldacena)



$$V(L) = -\frac{4\pi^2}{\Gamma(1/4)^4}\frac{\sqrt{\lambda}}{L}$$

- becomes a sreened potential at finite T

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