Towards Thermalization in Heavy Ion Collisions

Stellenbosch, South Africa, February 2012

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Outline

1. **Initial state factorization**
2. **Final state evolution**

In collaboration with :

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T. Epelbaum	(IPhT)
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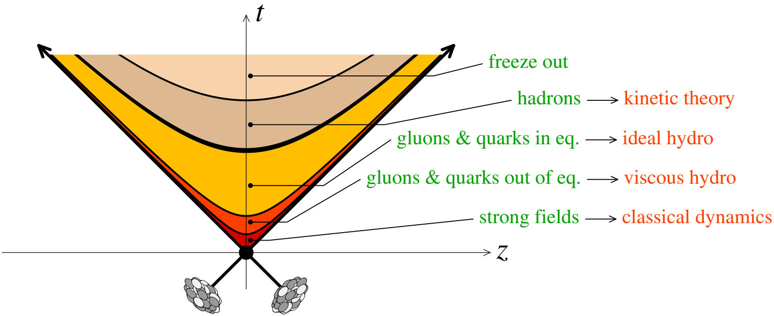
Introduction

Stages of a collision



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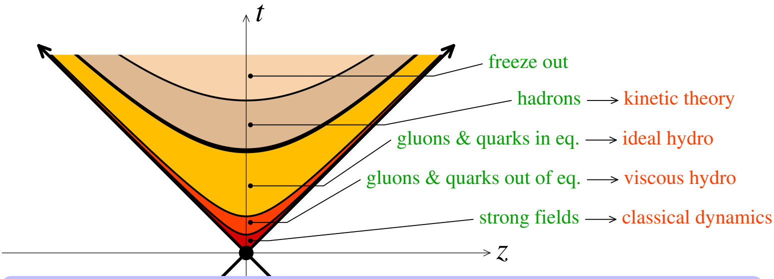
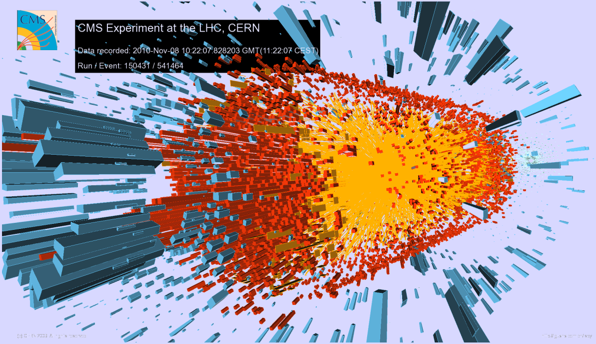


This talk : evolution up to times ~ 1 fm/c

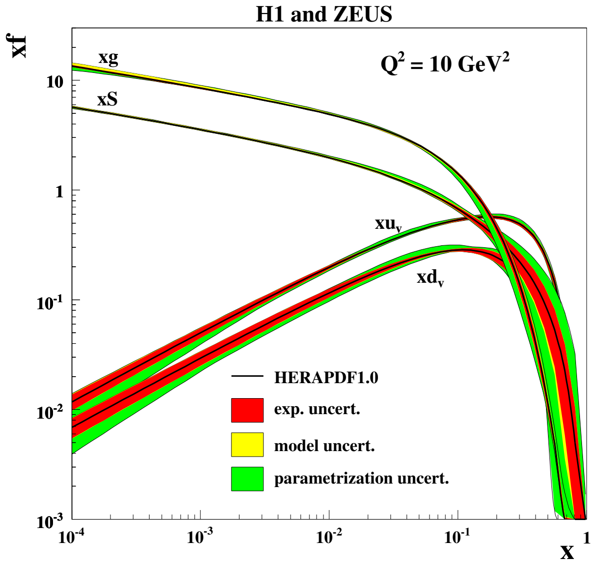
- **i.** Partonic content of high energy nuclei
- **ii.** Gluon production in the collision
- **iii.** Evolution shortly after the collision, Thermalization

Kinematics



- Low typical final state transverse momentum $p_\perp \lesssim 1$ GeV
- Incoming partons have low momentum fractions $x \sim p_\perp / E$
  - $x \sim 10^{-2}$ at RHIC ($E = 200$ GeV)
  - $x \sim 4.10^{-4}$ at the LHC ($E = 2.76 - 5.5$ TeV)

Nucleon parton distributions



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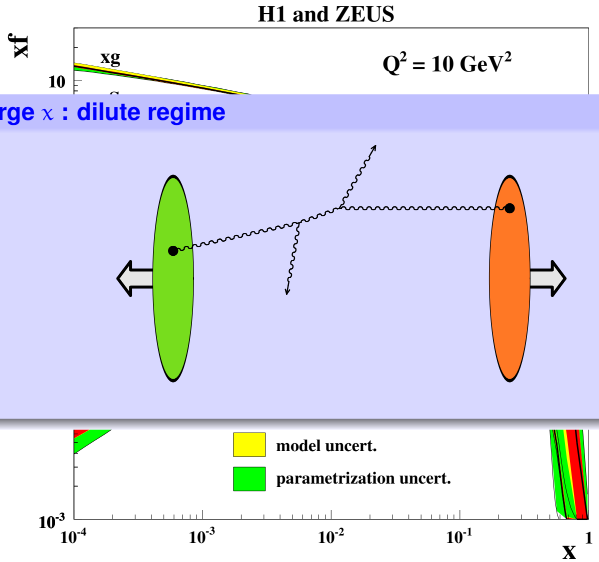

Large x : dilute regime

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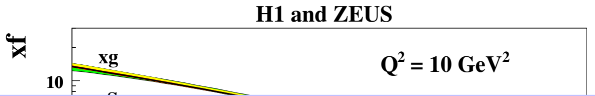
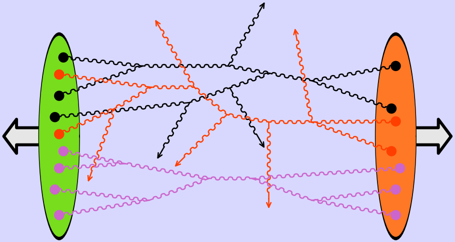
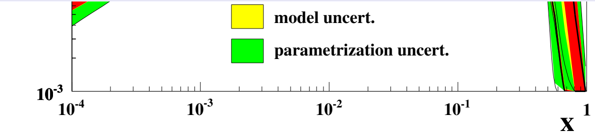
Nucleon parton distributions



Small x : dense regime, gluon saturation





Color Glass Condensate = effective theory of small x gluons

[McLerran, Venugopalan (1994), Jalilian-Marian, Kovner, Leonidov, Weigert (1997), Iancu, Leonidov, McLerran (2001)]

- The fast partons ($k^+ > \Lambda^+$) are frozen by time dilation
  ▷ described as static color sources on the light-cone :

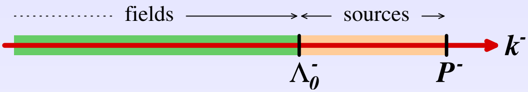
$$J^\mu = \delta^{\mu +}\rho(x^-, \vec{x}_\perp) \qquad (0 < x^- < 1/\Lambda^+)$$

- The color sources ρ are random, and described by a probability distribution $W_{\Lambda^+}[\rho]$

- Slow partons ($k^+ < \Lambda^+$) may evolve during the collision
  ▷ treated as standard gauge fields
  ▷ eikonal coupling to the current J^μ : $J_\mu A^\mu$

$$\mathcal{S} = \underbrace{-\frac{1}{4}\int F_{\mu\nu}F^{\mu\nu}}_{\mathcal{S}_{YM}} + \int \underbrace{J^\mu A_\mu}_{\text{fast partons}}$$

Renormalization group evolution, JIMWLK equation



- The cutoff between the sources and the fields is not physical, and should not enter in observables
- Loop corrections contain logs of the cutoff
- These logs can be cancelled by letting the distribution of the sources depend on the cutoff

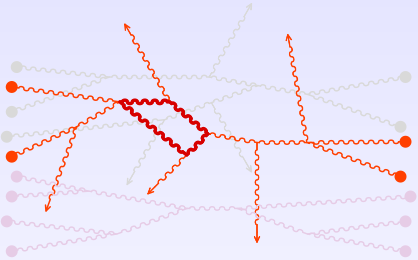
$$\Lambda \frac{\partial W[\rho]}{\partial \Lambda} = \mathcal{H}\left(\rho, \frac{\delta}{\delta\rho}\right) W[\rho] \qquad \text{(JIMWLK equation)}$$

Initial State Factorization

[FG, Venugopalan (2006)]

[FG, Lappi, Venugopalan (2008)]

Power counting



In the saturated regime: $J \sim g^{-1}$

$$g^{-2}\ g^{\#\text{ of external legs}}\ g^{2\times(\#\text{ of loops})}$$

- No dependence on the number of sources J
  - ▷ infinite number of graphs at each order

Inclusive gluon spectrum

Inclusive gluon spectrum to all orders

$$\frac{dN_1}{d^3\vec{p}} \sim \int d^4x d^4y \; e^{ip\cdot(x-y)} \; \square_x \square_y \Big[A_+(x) A_-(y) + G_{+-}(x,y) \Big]$$

$A_\pm, G_{+-}$ = Schwinger-Keldysh 1- and 2-point functions

- Structure of the expansion in g^2 :

$$A_\pm = \frac{1}{g}\Big[\underbrace{a_0}_{\text{tree}} + \underbrace{a_1 g^2}_{\text{1-loop}} + \cdots\Big] \qquad G_{+-} = \underbrace{b_0}_{\text{tree}} + \underbrace{b_1 g^2}_{\text{1-loop}} + \cdots$$

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Leading Order

- LO : we need only $A_+(x)$ and $A_-(y)$, at tree level
- These functions obey the classical equation of motion :

$$\square\mathcal{A} + V'(\mathcal{A}) = J$$

- Boundary conditions : retarded, with $\mathcal{A} \to 0$ at $x_0 = -\infty$

Inclusive spectra at LO

$$\left.\frac{dN_1}{d^3\vec{p}}\right|_{LO} \sim \int d^4x d^4y\; e^{ip\cdot(x-y)}\;\square_x\square_y\;\mathcal{A}(x)\,\mathcal{A}(y)$$

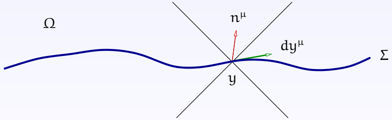
$$\left.\frac{dN_n}{d^3\vec{p}_1\cdots d^3\vec{p}_n}\right|_{LO} = \left.\frac{dN_1}{d^3\vec{p}_1}\right|_{LO}\cdots\left.\frac{dN_1}{d^3\vec{p}_n}\right|_{LO}$$

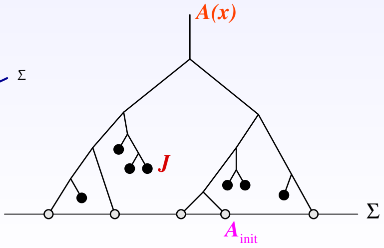
Cauchy problem for classical fields

- In some situations, one needs to express the classical field in terms of the source J and its value on a surface Σ

Green's formula

$$\mathcal{A}(x) = i \int_{y\in\Omega} G_R^0(x,y)\,\Big[J(y) - V'(\mathcal{A}(y))\Big] + i \int_{y\in\Sigma} G_R^0(x,y)\,(n\cdot \overleftrightarrow{\partial}_y)\,\mathcal{A}_{\rm init}(y)$$





Small perturbations of a classical field

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Disturbance propagating over a classical background

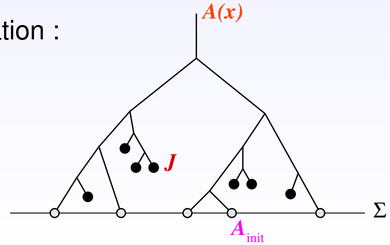
$$\Big[\square_x + V''(\mathcal{A}(x))\Big]\, a(x) = 0 \quad , \quad a(x) = \alpha(x) \ \text{ on } \ \Sigma$$

Formal solution

$$\big[\alpha\,\mathbb{T}\big]_y \equiv \alpha(y)\,\frac{\delta}{\delta\mathcal{A}_{\rm init}(y)} + (n\cdot\partial\alpha(y))\,\frac{\delta}{\delta(n\cdot\partial\mathcal{A}_{\rm init}(y))}$$

$$a(x) \equiv \int\limits_{y\in\Sigma} \big[\alpha\,\mathbb{T}\big]_y \ \ \mathcal{A}(x)$$

- Diagrammatic interpretation :



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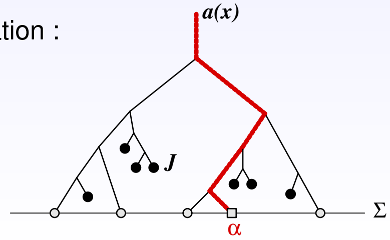


Next to Leading Order

- What do we need at NLO?

$$A_\pm = \frac{1}{g}\left[a_0 + \underline{\underline{a_1 g^2}} + \cdots\right] \qquad G_{+-} = \underline{\underline{b_0}} + b_1 g^2 + \cdots$$

- These two subleading quantities can be expressed in terms of perturbations to the retarded classical field

- For instance, at tree level:

$$G_{+-}(x,y) = \int \frac{d^3k}{(2\pi)^3 2k}\, a_k(x)\, a_k^*(y)$$

$$\left[\square_x + V''(\mathcal{A}(x))\right] a_k(x) = 0 \qquad , \qquad \lim_{x_0 \to -\infty} a_k(x) = e^{ik\cdot x}$$

Next to Leading Order

Master relation between LO and NLO

$$\left.\frac{dN_1}{d^3\vec{p}}\right|_{NLO} = \left[\frac{1}{2}\int_{u,v\in\Sigma}\int_k \left[a_k\,\mathbb{T}\right]_u\left[a_k^*\,\mathbb{T}\right]_v + \int_{u\in\Sigma}\left[\alpha\,\mathbb{T}\right]_u\right]\left.\frac{dN_1}{d^3\vec{p}}\right|_{LO}$$

- Valid for all inclusive multi-gluon spectra, and for the energy-momentum tensor
- Valid for any Cauchy surface Σ
- Not specific to scalar theories
- In the CGC, upper cutoff on the loop momentum : $k^\pm < \Lambda$, to avoid double counting with the sources $J_{1,2}$
  ▷ large logarithms of the cutoff

Initial state logarithms

Central result

$$\frac{1}{2}\int_{u,v\in\Sigma}\int_{k}\left[a_{k}\,\mathbb{T}\right]_{u}\left[a^{*}_{k}\,\mathbb{T}\right]_{v}+\int_{u\in\Sigma}\left[\alpha\,\mathbb{T}\right]_{u}=$$

$$=\log\left(\Lambda^{+}\right)\,\mathcal{H}_1+\log\left(\Lambda^{-}\right)\,\mathcal{H}_2+\text{terms w/o logs}$$

$\mathcal{H}_{1,2}=$ JIMWLK Hamiltonians of the two nuclei

- No mixing between the logs of Λ^{+} and Λ^{-}
- Since the LO↔NLO relationship is the same for all inclusive observables, these logs have a universal structure

Factorization of the logarithms

- By integrating over $\rho_{1,2}$'s, one can absorb the logarithms into universal distributions $W_{1,2}[\rho_{1,2}]$
- $\mathcal{H}$ is a self-adjoint operator :

$$\int [D\rho]\, W\, (\mathcal{H}\,\mathcal{O}) = \int [D\rho]\, (\mathcal{H}\,W)\,\mathcal{O}$$

Single inclusive gluon spectrum at Leading Log accuracy

$$\left\langle \frac{dN_1}{d^3\vec{p}} \right\rangle_{\text{Leading Log}} = \int \left[D\rho_1\; D\rho_2\right] W_1\left[\rho_1\right] W_2\left[\rho_2\right] \underbrace{\left.\frac{dN_1[\rho_{1,2}]}{d^3\vec{p}}\right|_{LO}}_{\text{fixed } \rho_{1,2}}$$

- Logs absorbed into the evolution of $W_{1,2}$ with the scales

$$\Lambda \frac{\partial W}{\partial \Lambda} = \mathcal{H}\,W \qquad \text{(JIMWLK equation)}$$

Multi-gluon correlations at Leading Log

- The previous factorization can be extended to multi-particle inclusive spectra :

$$\left\langle \frac{dN_n}{d^3\vec{\mathbf{p}}_1 \cdots d^3\vec{\mathbf{p}}_n} \right\rangle_{\text{Leading Log}} =$$

$$= \int \left[D\rho_1\, D\rho_2\right] W_1\left[\rho_1\right] W_2\left[\rho_2\right] \; \frac{dN_1[\rho_{1,2}]}{d^3\vec{\mathbf{p}}_1} \cdots \frac{dN_1[\rho_{1,2}]}{d^3\vec{\mathbf{p}}_n}\bigg|_{\text{LO}}$$

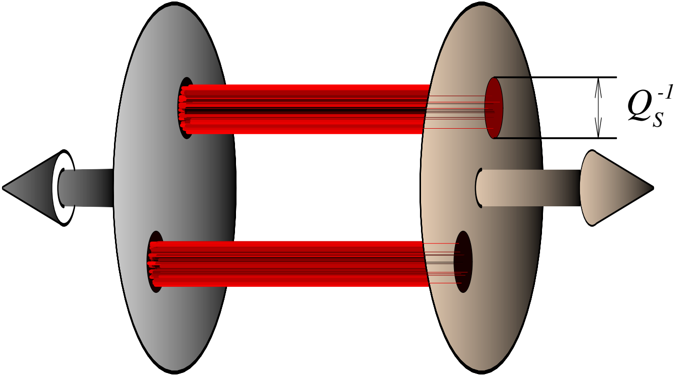
- At Leading Log accuracy, all the rapidity correlations come from the evolution of the distributions $W[\rho_{1,2}]$
  ▷ they are a property of the pre-collision initial state

- Predicts long range ($\Delta y \sim \alpha_s^{-1}$) correlations in rapidity

Final state evolution

[Dusling, Epelbaum, FG, Venugopalan (2010)]
[Dusling, FG, Venugopalan (2011)]
[Epelbaum, FG (2011)]

Energy momentum tensor at LO



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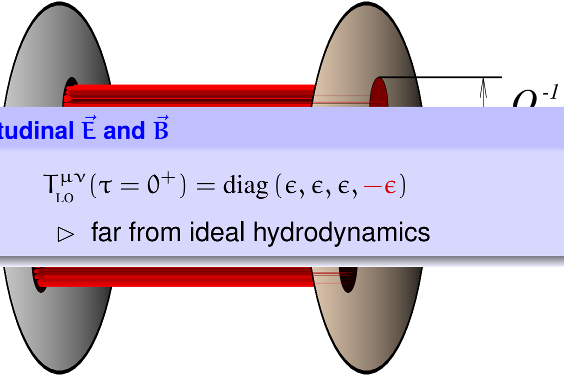


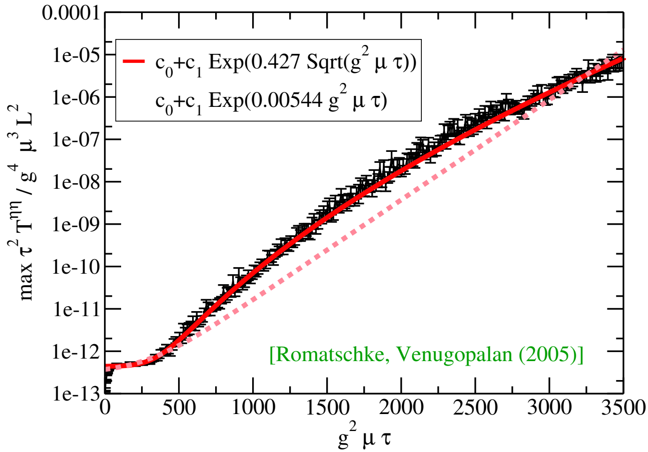
$T^{\mu\nu}$ for longitudinal $\vec{E}$ and $\vec{B}$

$$T^{\mu\nu}_{LO}(\tau = 0^+) = \mathrm{diag}\,(\epsilon, \epsilon, \epsilon, -\epsilon)$$

▷ far from ideal hydrodynamics

Weibel instabilities for small perturbations

[Mrowczynski (1988), Romatschke, Strickland (2003), Arnold, Lenaghan, Moore (2003), Rebhan, Romatschke, Strickland (2005), Arnold, Lenaghan, Moore, Yaffe (2005), Romatschke, Rebhan (2006), Bodeker, Rummukainen (2007),...]



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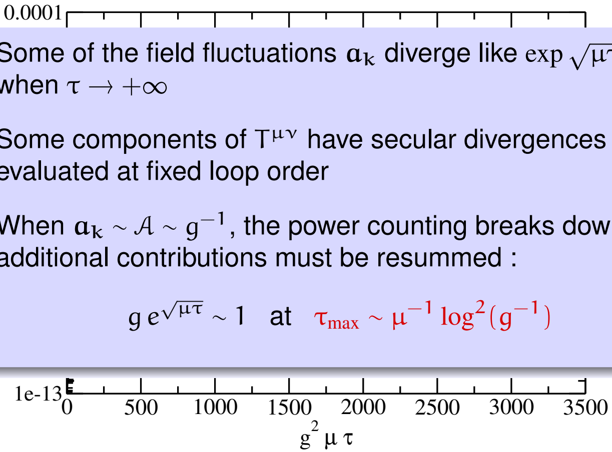
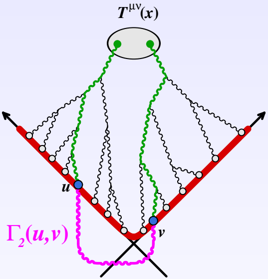


- Some of the field fluctuations a_k diverge like $\exp\sqrt{\mu\tau}$ when $\tau \to +\infty$
- Some components of $T^{\mu\nu}$ have secular divergences when evaluated at fixed loop order
- When $a_k \sim \mathcal{A} \sim g^{-1}$, the power counting breaks down and additional contributions must be resummed :

$$g\, e^{\sqrt{\mu\tau}} \sim 1 \quad \text{at} \quad \tau_{max} \sim \mu^{-1} \log^2(g^{-1})$$

Improved power counting

$$\text{Loop} \sim g^2 \qquad , \qquad \mathbb{T}_{\boldsymbol{u}} \sim e^{\sqrt{\mu\tau}}$$



- 1 loop : $(g e^{\sqrt{\mu\tau}})^2$

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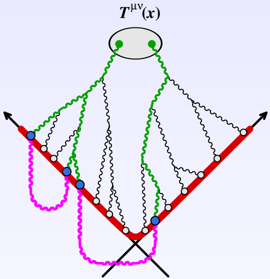

- 1 loop : $(g e^{\sqrt{\mu\tau}})^2$
- 2 disconnected loops : $(g e^{\sqrt{\mu\tau}})^4$

Improved power counting

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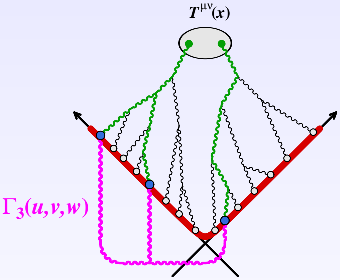

- 1 loop : $(ge^{\sqrt{\mu\tau}})^2$
- 2 disconnected loops : $(ge^{\sqrt{\mu\tau}})^4$
- 2 nested loops : $g(ge^{\sqrt{\mu\tau}})^3$ ▷ subleading

Leading terms at τ_{max}

- All disjoint loops to all orders
  ▷ exponentiation of the 1-loop result

Resummation of the leading secular terms

$$T^{\mu\nu}_{\text{resummed}} = \exp\left[\frac{1}{2}\int_{u,v\in\Sigma}\underbrace{\int_{k}[a_k\mathbb{T}]_u[a_k^*\mathbb{T}]_v}_{\mathcal{G}(u,v)} + \int_{u\in\Sigma}[\alpha\mathbb{T}]_u\right] T^{\mu\nu}_{\text{LO}}[\mathcal{A}_{\text{init}}]$$

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Resummation of the leading secular terms

$$T^{\mu\nu}_{\rm resummed} = \exp\left[\frac{1}{2}\int_{u,v\in\Sigma} \underbrace{\int_k [a_k\mathbb{T}]_u [a_k^*\mathbb{T}]_v}_{\mathcal{G}(u,v)} + \int_{u\in\Sigma} [\alpha\mathbb{T}]_u\right] T^{\mu\nu}_{\rm LO}[\mathcal{A}_{\rm init}]$$

$$= \int [D\chi]\,\exp\left[-\frac{1}{2}\int_{u,v\in\Sigma} \chi(u)\mathcal{G}^{-1}(u,v)\chi(v)\right] T^{\mu\nu}_{\rm LO}[\mathcal{A}_{\rm init}+\chi+\alpha]$$

- The evolution remains classical, but we must average over a Gaussian ensemble of initial conditions
- Note : the constant shift α can be absorbed into a redefinition of $\mathcal{A}_{\rm init}$

More on this resummation

- The Gaussian fluctuations around the classical field $\mathcal{A}_{\rm init}$ promote it to a coherent quantum state
(they add $1/2$ particle to every mode)

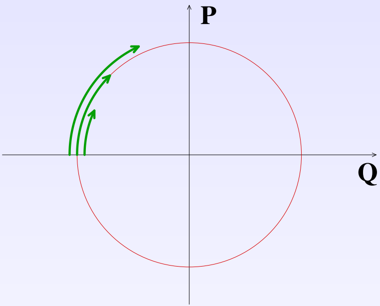
- Dual formulation of QM in the classical phase-space :

Density	$\widehat{\rho}$		$W(Q,P)$
Evolution	$\partial_t\widehat{\rho}+i[\widehat{H},\widehat{\rho}]=0$	$\xrightarrow[\text{trans.}]{\text{Wigner}}$	$\partial_t W+\{\{W,H\}\}=0$
Initial condition	$\big\vert\mathcal{A}_{\rm init}\big\rangle\big\langle\mathcal{A}_{\rm init}\big\vert$		$\exp-\frac{1}{2}\int\chi\mathcal{G}^{-1}\chi$

Approximations :
  - Moyal bracket $\{\{\cdot,\cdot\}\}$ replaced by classical Poisson bracket
  - Non-gaussianities of the initial distribution are ignored

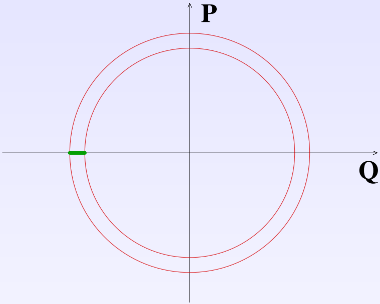
- Independent (and anterior..) uses of this scheme :
  - Cosmology [Polarski, Starobinsky (1995), Son (1996), Khlebnikov, Tkachev (1996)]
  - Cold atoms [Davis, Morgan, Burnett (2002), Norrie, Ballagh, Gardiner (2004)]

Anharmonicity and decoherence



- The oscillation frequency depends on the initial condition

Anharmonicity and decoherence



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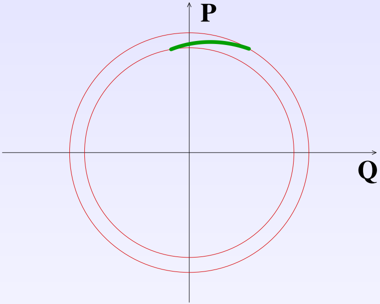
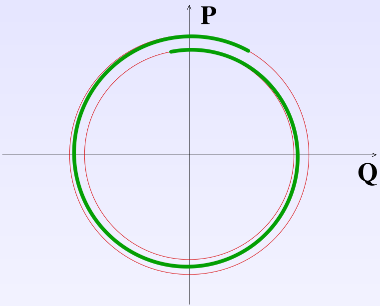


- The oscillation frequency depends on the initial condition
- An ensemble of initial configurations spreads in time

Anharmonicity and decoherence



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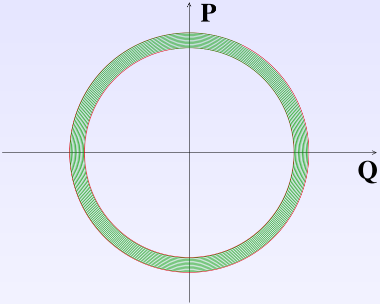

- The oscillation frequency depends on the initial condition
- An ensemble of initial configurations spreads in time
- At large times, the ensemble fills densely all the region allowed by energy conservation

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Similar problem in a simpler toy model

ϕ^4 field theory coupled to a source

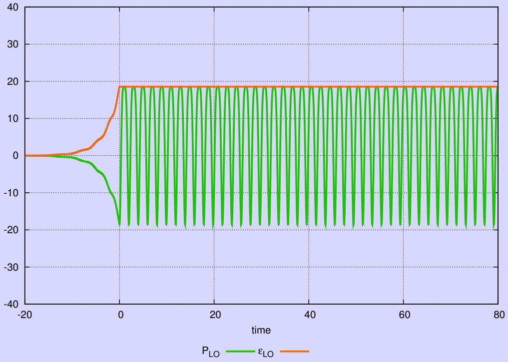
$$\mathcal{L} = \frac{1}{2}(\partial_\alpha \phi)^2 - \frac{g^2}{4!}\phi^4 + J\phi$$

$$J \quad \propto \quad \theta(-x^0)\,\frac{Q^3}{g}$$

- In 3+1-dim, g is dimensionless, and the only scale in the problem is Q, provided by the external source
- The source is active only at $x^0 < 0$, and is turned off adiabatically when $x^0 \to -\infty$
- This theory has unstable modes (parametric resonance)

Secular divergences in fixed order calculations

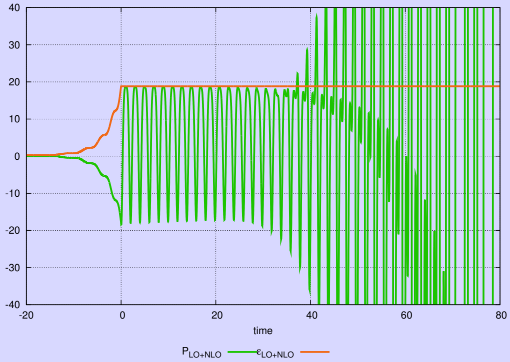
Tree



- Oscillating pressure at LO : no equation of state

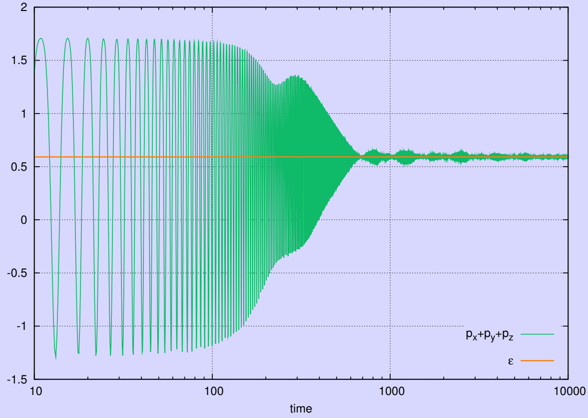
Secular divergences in fixed order calculations

Tree + 1-loop



- Oscillating pressure at LO : no equation of state
- Small NLO correction to the energy density (protected by energy conservation)
- Secular divergence in the NLO correction to the pressure

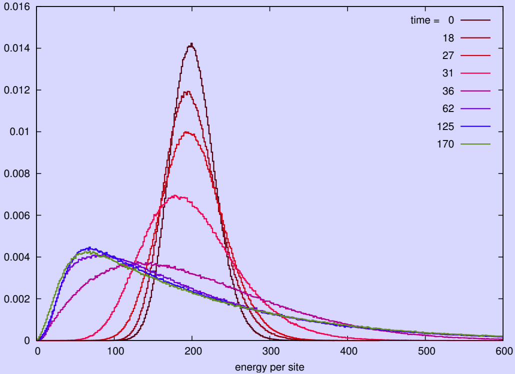
Resummed energy momentum tensor



- No secular divergence in the resummed pressure
- The pressure relaxes to the equilibrium equation of state

Energy fluctuations in a small subvolume

Probability distribution $P(e)$ ($e =$ energy on one site, $g = 0.5$)



- At $t = 0$, narrow Gaussian fluctuations
- Very rapid change of shape
- Shape close to that expected from the canonical ensemble

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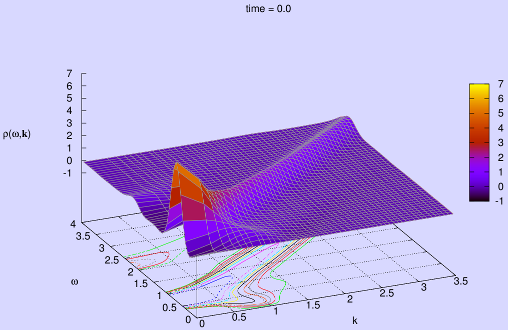
Spectral density

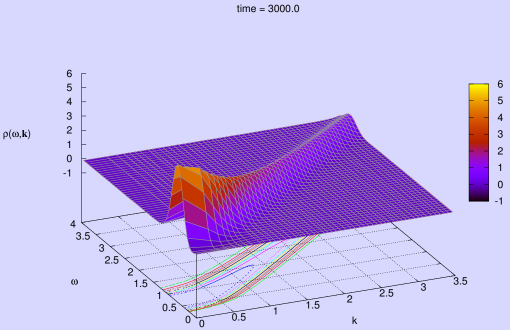
$\tau = 0$



- Complicated spectral density at early times

Spectral density

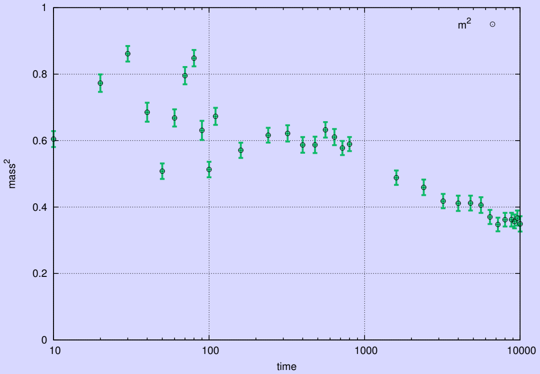
$\tau = 3000$



- Complicated spectral density at early times
- Single quasiparticle peak at late times

Medium induced mass

Fit of the spectral peak by $\omega^2 = k^2 + m^2$



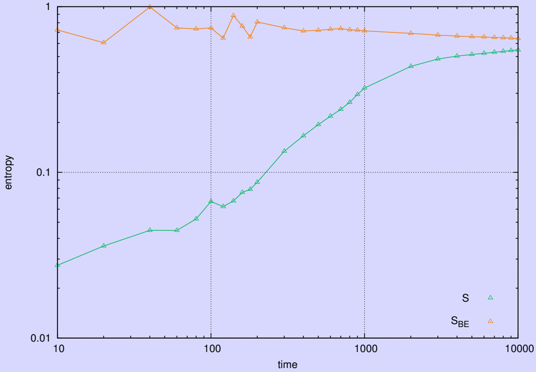
- Note : at weak coupling, the mass fitted from the spectral peak agrees with

$$m^2 = \frac{g^2}{2}\left\langle\phi^2\right\rangle$$

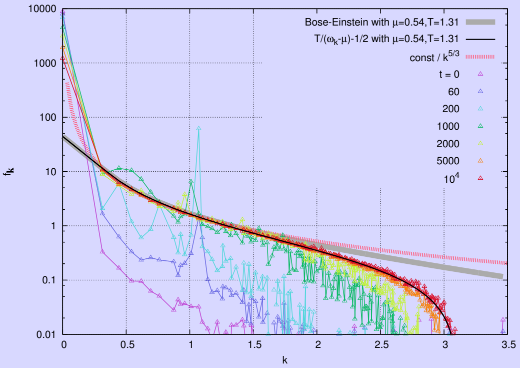
Entropy production

$$\mathcal{S} \equiv \int_{\boldsymbol{k}} \Big[(1 + f_{\boldsymbol{k}}) \log(1 + f_{\boldsymbol{k}}) - f_{\boldsymbol{k}} \log(f_{\boldsymbol{k}}) \Big]$$

Time evolution of the entropy

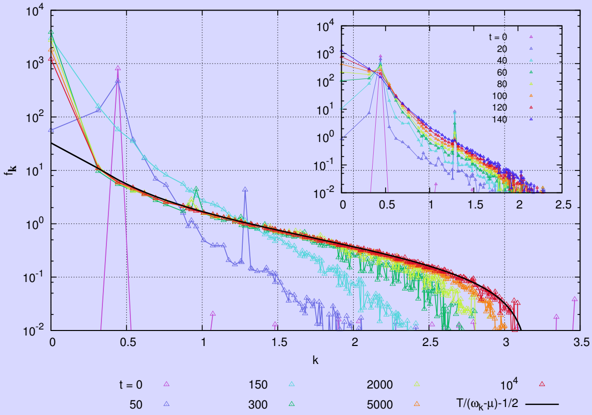


Time evolution of the occupation number



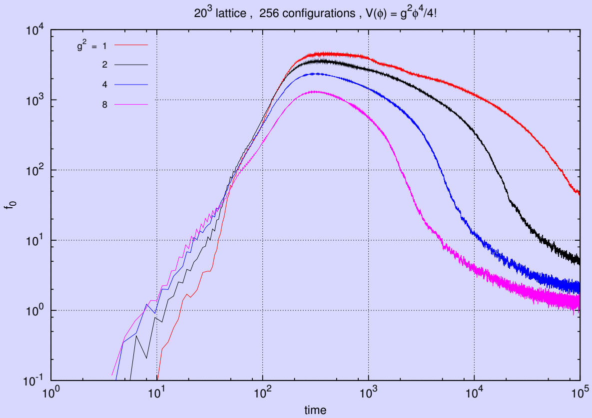
- Resonant peak at early times
- Turbulent Kolmogorov spectrum in the intermediate k-range?
- Late times : classical equilibrium with a chemical potential
- $\mu \approx m$ + excess at $k = 0$: Bose-Einstein condensation?

Bose-Einstein condensation



- Start with the same energy density, but an empty zero mode
- Very quickly, the zero mode becomes highly occupied
- Same distribution as before at late times

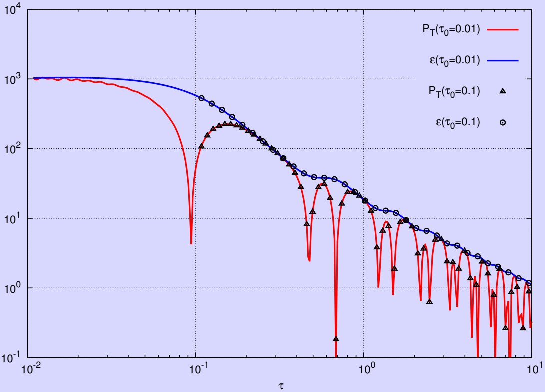
Evolution of the condensate



- Formation time almost independent of the coupling
- Condensate lifetime much longer than its formation time
- Smaller amplitude and faster decay at large coupling

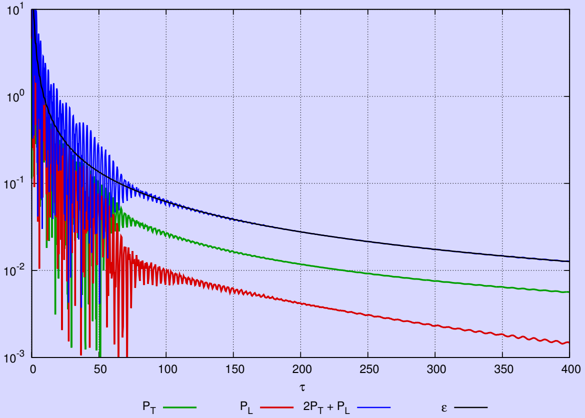
Effect of longitudinal expansion

- The EoM is singular when $\tau \to 0$: one must start at $\tau_0 \neq 0$
- With the proper spectrum of field fluctuations (that depends on τ_0) and zero point subtraction, the result does not depend on the initial τ_0



Effect of longitudinal expansion

- After some time, the pressures relax and we have the expected equation of state : $\epsilon = 2P_T + P_L$
- However : $P_T \neq P_L$

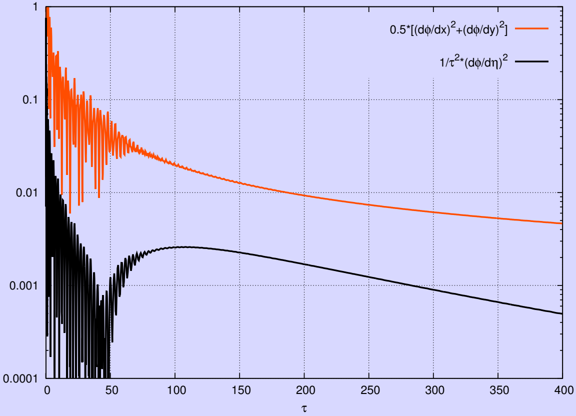


Effect of longitudinal expansion

- $P_T = P_L$ requires

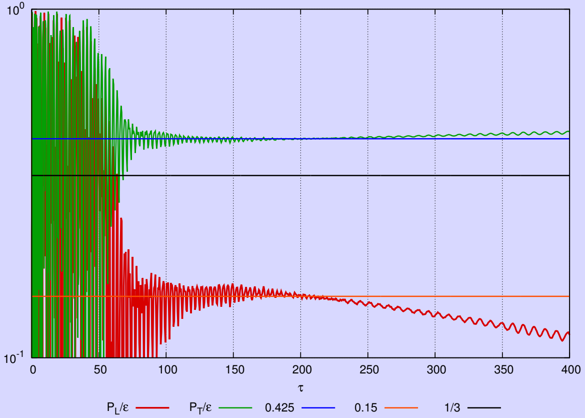
$$\frac{1}{\tau^2}\left(\frac{\partial\phi}{\partial\eta}\right)^2 = \frac{1}{2}\left[\left(\frac{\partial\phi}{\partial x}\right)^2 + \left(\frac{\partial\phi}{\partial y}\right)^2\right]$$

But instead...



Effect of longitudinal expansion

- Constant anisotropy (the drop of P_L/ϵ at $\tau \geq 200$ is likely a lattice artifact)



Summary and Outlook

Summary

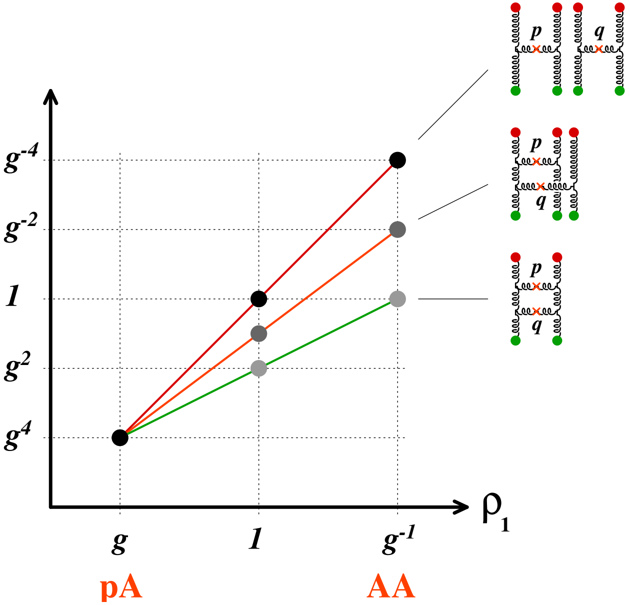
- Factorization of high energy logarithms in AA collisions
  - limited to inclusive observables
  - controls the rapidity dependence of correlations
  - links nucleus-nucleus collisions to other reactions (pA, DIS)
- Resummation of secular terms in the final state evolution
  - stabilizes the NLO calculation
  - leads to the equilibrium equation of state
  - full thermalization on much longer time-scales
  - Bose-Einstein condensation for overoccupied initial state
  - ϕ^4 theory : instabilities too weak to resist against expansion

Outlook

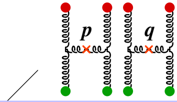
- thermalization in QCD, w/ longitudinal expansion?
- if a BEC is formed, phenomenological implications?

Extra

Dense-dilute collisions



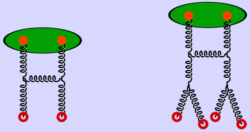
Dense-dilute collisions



Expected complications

- More diagrams to consider even at Leading Order
- More terms in the evolution Hamiltonian if $\rho \sim g$:

$$g^2 \rho^2 \left(\frac{\partial}{\partial\rho}\right)^2 \sim g^4 \rho^2 \left(\frac{\partial}{\partial\rho}\right)^4$$



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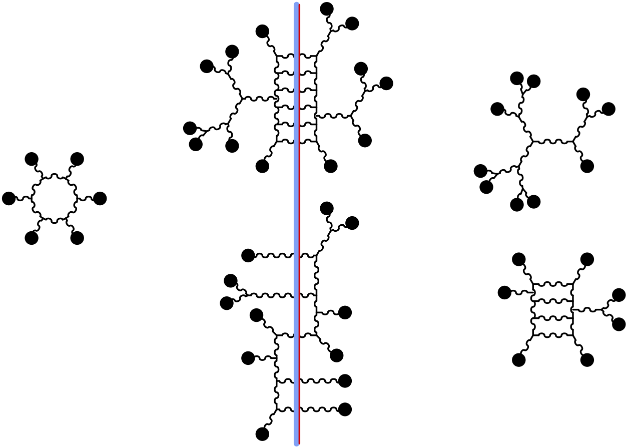
Exclusive processes

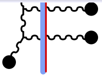


Exclusive processes

Example : differential probability to produce 1 particle at LO

$$\left.\frac{dP_1}{d^3\vec{p}}\right|_{LO} = F[0] \times \int d^4x d^4y \; e^{ip\cdot(x-y)} \, \square_x \square_y \, \mathcal{A}_+(x)\mathcal{A}_-(y)\Big|_{z=0}$$

- The vacuum-vacuum graphs do not cancel in exclusive quantities : $F[0] \neq 1$ (in fact, $F[0] = \exp(-c/g^2) \ll 1$)
- $\mathcal{A}_+$ and $\mathcal{A}_-$ are classical solutions of the Yang-Mills equations, but with non-retarded boundary conditions

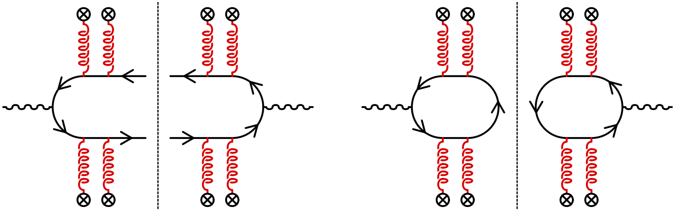


François Gelis

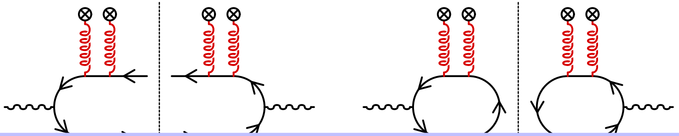
Thermalization in Yang-Mills theory

- Recent analytical work : Kurkela, Moore (2011)
- Going from scalars to gauge fields :
  - More fields per site (3 Lorentz components $\times$ 8 colors)
  - More complicated spectrum of initial conditions
  - Expansion : UV overflow on a fixed grid in η

BEC and dilepton production



BEC and dilepton production



Two topologies for virtual photons at LO

Connected	$\omega \sim M_{inv} \sim Q_s$	$k_\perp \sim Q_s$
Disconnected	$\omega \sim M_{inv} \sim Q_s$	$k_\perp \ll Q_s$

▷ excess of dileptons with $k_\perp \ll M_{inv}$

Links to Quantum Chaos

- Quantum Chaos : how does the chaos at the classical level manifests itself in quantum mechanics?

- Berry's conjecture [M.V. Berry (1977)]

  High lying eigenstates of such systems have nearly random wavefunctions. The corresponding Wigner distribution is almost uniform on the energy surface

- Srednicki's eigenstate thermalization hypothesis [M. Srednicki (1994)]

  For sufficiently inclusive measurements, these high lying eigenstates look thermal. If the system starts in a coherent state, decoherence is the main mechanism to thermalization