Can heavy quarkonia be used as thermometers in heavy-ion collisions?

Nicolas BORGHINI

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- Opening open doors: a few reminders on time scales
- Quantifying a qualitative intuition: adiabatic theorem
- Proposing a solution: quarkonia in a QGP as open quantum systems

N.B. & Nirupam Dutta, arXiv:1206.2149;
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A piece of common lore…

… well, at least in the heavy-ion community

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J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

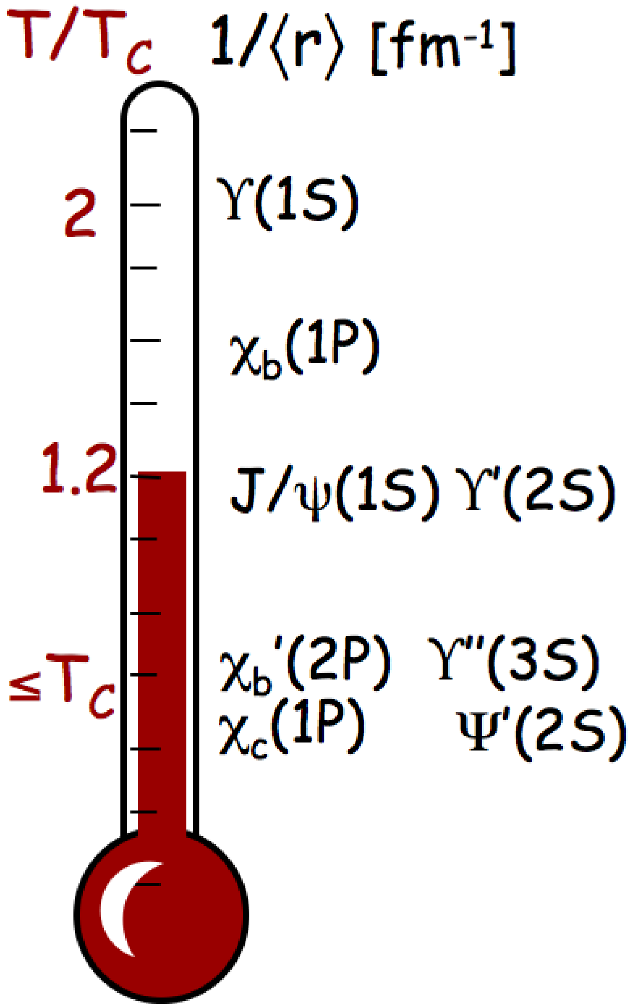
H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, …

☛ Later generalized to the higher charmonium states (ψ', χ_c) and to bottomonia ($\Upsilon(nS)$, χ_b).

A piece of common lore: “Sequential melting of quarkonia”



- The different heavy-quarkonium states are destroyed at different temperatures:
  - potential models;
  - spectral functions.

thermometer by Á.Mócsy,
Eur. Phys. J. C **61** (2009) 705

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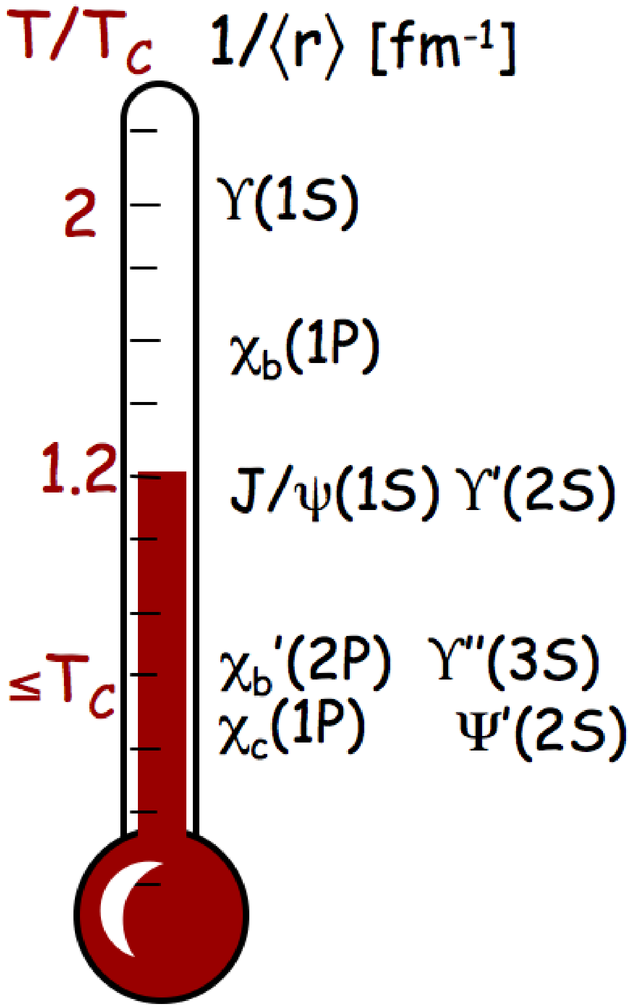
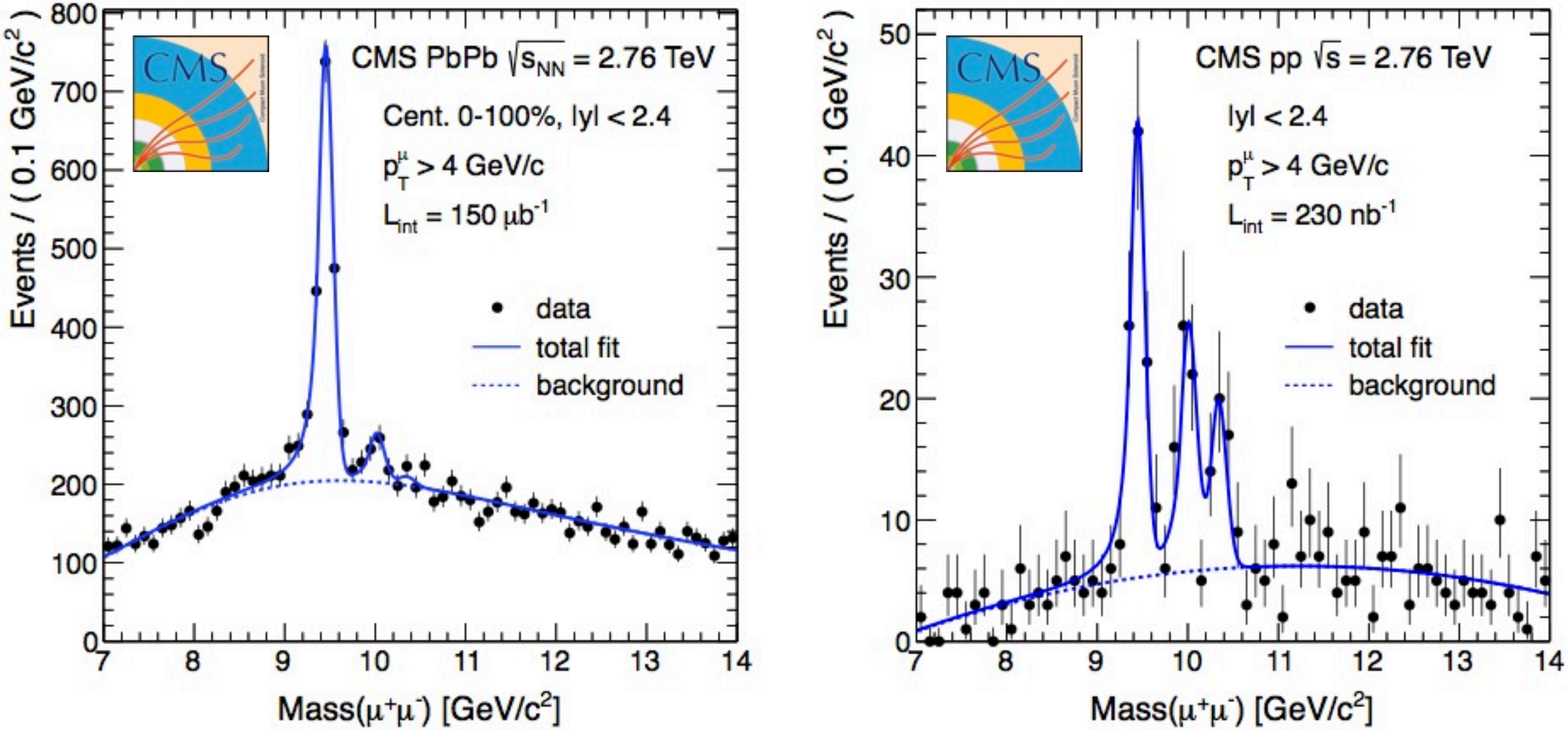


- The different heavy-quarkonium states are destroyed at different temperatures:
  - potential models;
  - spectral functions.
- Conversely, by investigating which states survive and which have been "melted", one can pin down the temperature reached by the medium created in a heavy-ion collision:

heavy quarkonia as "thermometers"

thermometer by Á.Mócsy,
Eur. Phys. J. C **61** (2009) 705

Sequential suppression of bottomonia(?)



$$
\begin{aligned}
\Upsilon(2S)/\Upsilon(1S)|_{pp} &= 0.56 \pm 0.13\,(\text{stat.}) \pm 0.02\,(\text{syst.}),\\
\Upsilon(2S)/\Upsilon(1S)|_{PbPb} &= 0.12 \pm 0.03\,(\text{stat.}) \pm 0.02\,(\text{syst.}),\\
\Upsilon(3S)/\Upsilon(1S)|_{pp} &= 0.41 \pm 0.11\,(\text{stat.}) \pm 0.04\,(\text{syst.}),\\
\Upsilon(3S)/\Upsilon(1S)|_{PbPb} &= 0.02 \pm 0.02\,(\text{stat.}) \pm 0.02\,(\text{syst.})
\end{aligned}
$$

CMS Collaboration, arXiv:1208.2826

A second piece of common lore...

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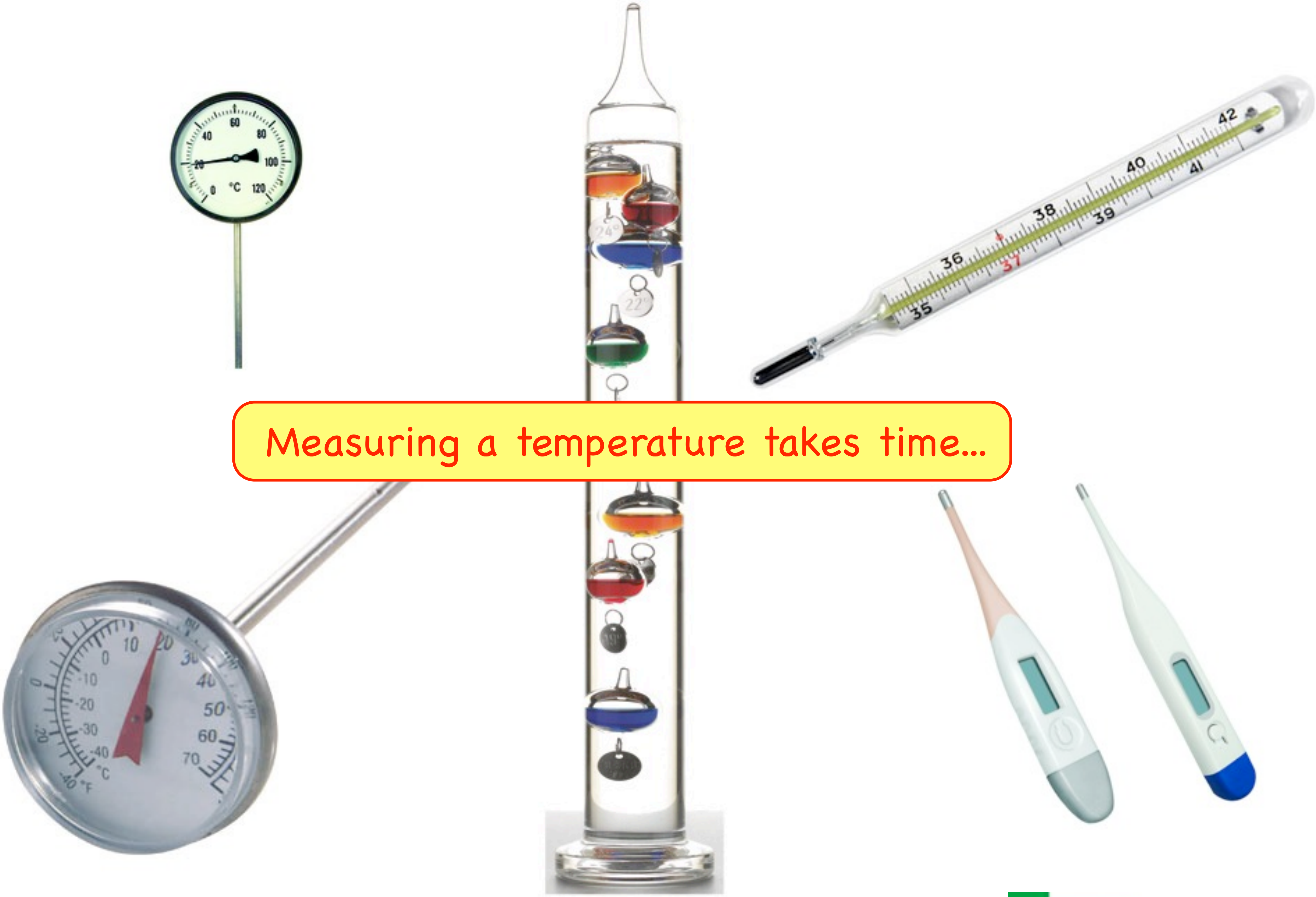

Measuring a temperature takes time...

A second piece of common lore...

Measuring a temperature takes time, because the thermometer has to equilibrate with the body whose temperature is taken.

☛ the thermometer has to reach thermodynamical equilibrium

This is automatic for quarkonia in lattice gauge theory computations.

Is this also true in a heavy-ion collision?

(Additionally, the thermometer should be much smaller than the body whose temperature it measures, so as not to modify its temperature...)

Some time scales

Mean radius of Υ-states: $\langle r\rangle \sim$ 0.35–0.8 fm

Velocity of the b/$\bar{\text{b}}$-quarks: $v \sim 0.3\,c$

☛ duration of an "orbit" $\sim$ 5—10 fm/c

...to be compared with the lifetime of the QGP created in a heavy-ion collision, which is at most 10 fm/c at the LHC.

That is, the time it takes for a b$\bar{\text{b}}$-pair to "realize" that it is in a given Υ-state is of the same order as the QGP lifetime.

Can we really expect bottomonia to reach thermodynamical equilibrium so as to obey the sequential-melting picture and thereby provide an easily used thermometer?

Can heavy quarkonia be used as thermometers in heavy-ion collisions?

- Opening open doors: a few reminders on time scales
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Time evolution & effective potential

Can one quantify these back-of-the-envelope estimates?

Idea: use in-medium quark–antiquark potential, as provided e.g. by fits to lattice data

Kaczmarek & Zantow, Phys. Rev. D **71** (2005) 114510

$$V(r) \sim \frac{\frac{4}{3}\alpha_s(T)}{r}\,\mathrm{e}^{-A\sqrt{1+N_f/6}\,T g_{2\,\mathrm{loop}}(T)\,r}$$

so as to compute the energy eigenstates.

For that, take the medium temperature T at... When actually?

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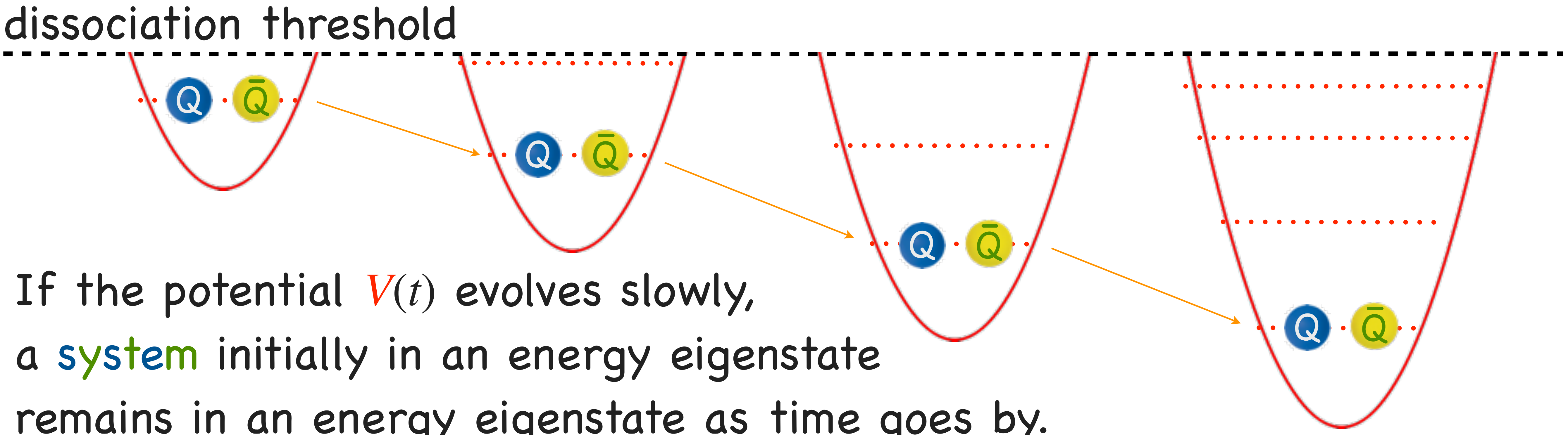
For that, take the medium temperature T at... When actually?

The Hamiltonian is in fact time-dependent, $H(t) = H_0 + V(t)$, and so are its instantaneous eigenstates $|\psi_n(t)\rangle$.

New question: if the system starts in a given instantaneous eigenstate $|\psi_n(0)\rangle$ will it remain in that eigenstate $|\psi_n(t)\rangle$ as time goes by?

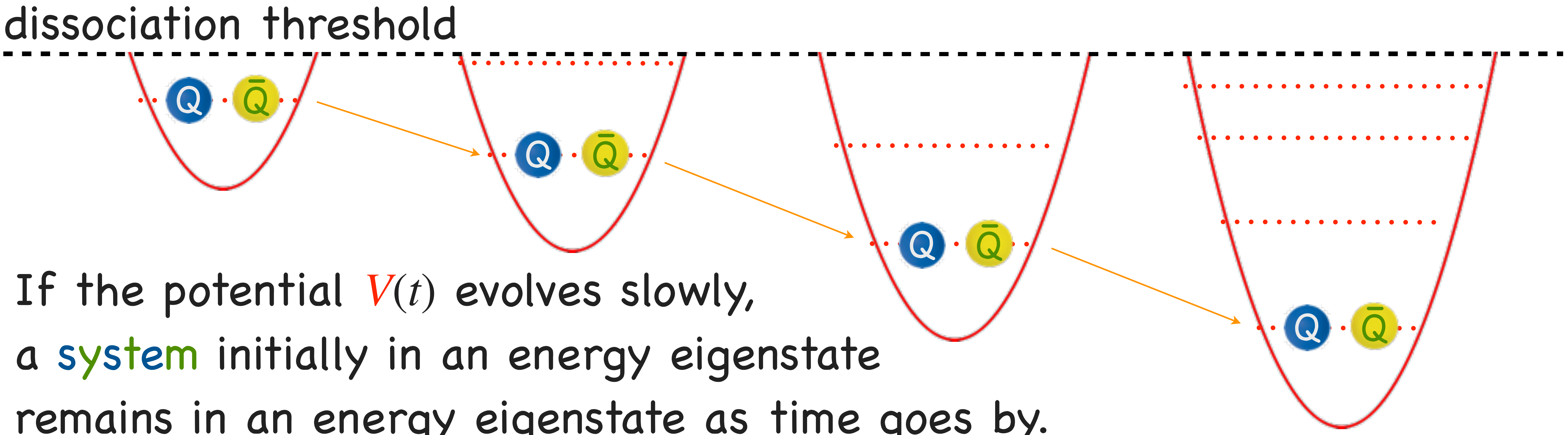
Is the evolution of the in-medium potential slow enough (= adiabatic)?

Slowly vs. fast evolving potential



If the potential $V(t)$ evolves slowly,
a system initially in an energy eigenstate
remains in an energy eigenstate as time goes by.

Slowly vs. fast evolving potential



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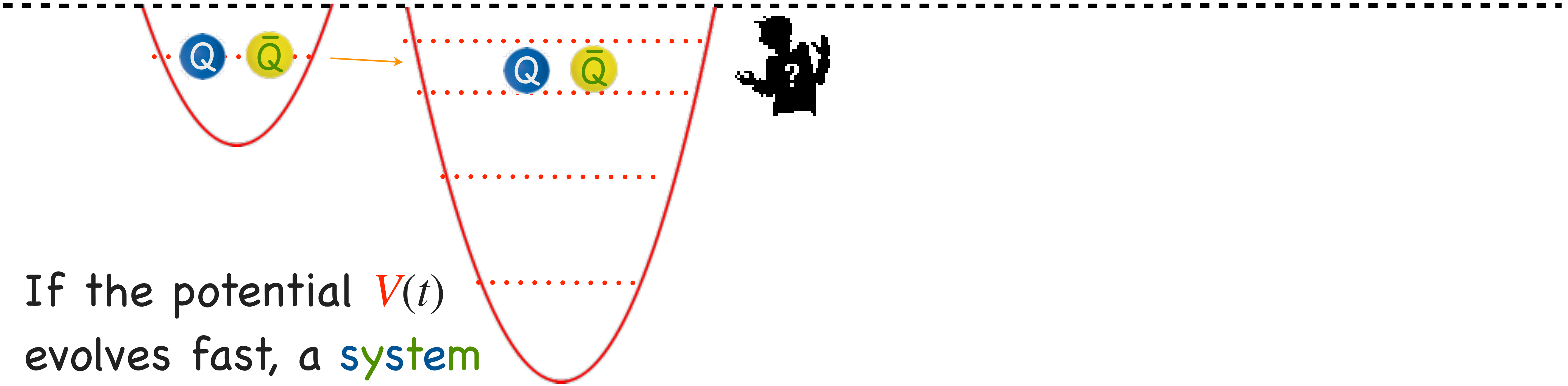
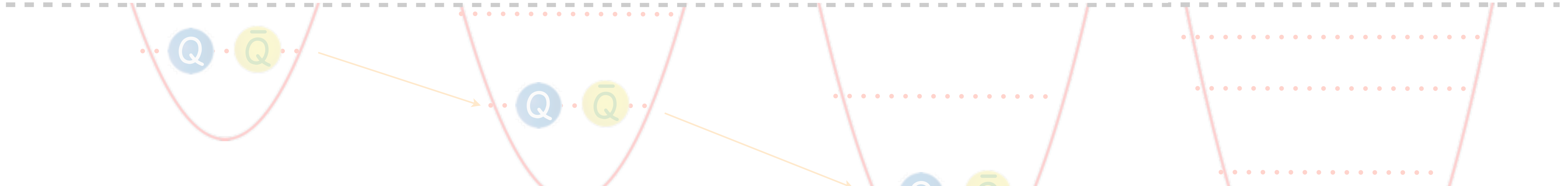


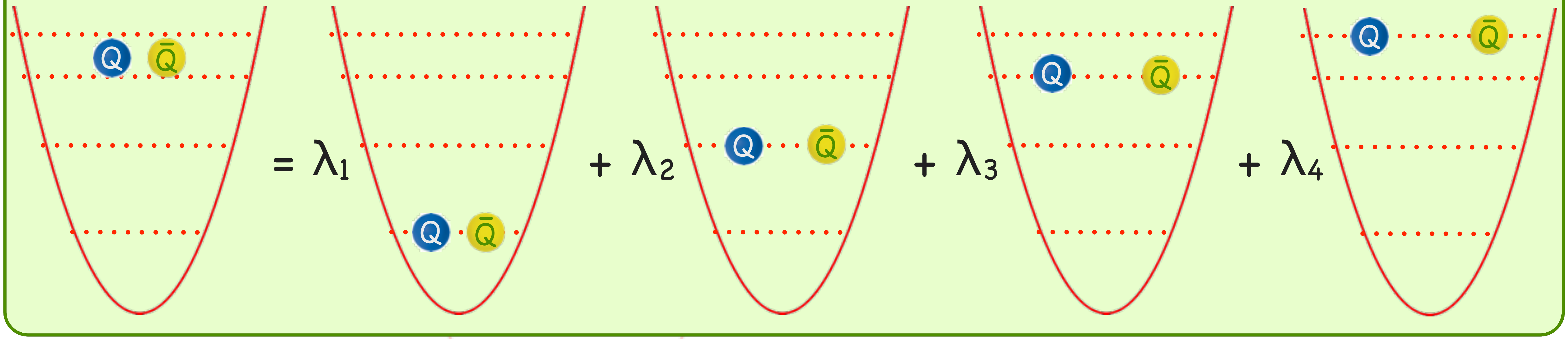
If the potential $V(t)$
evolves fast, a system
initially in an eigenstate cannot follow the change...

Slowly vs. fast evolving potential

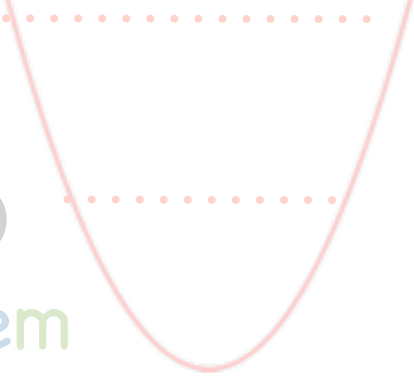
dissociation threshold



Quantum mechanics: project on eigenstates!



$$= \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4$$



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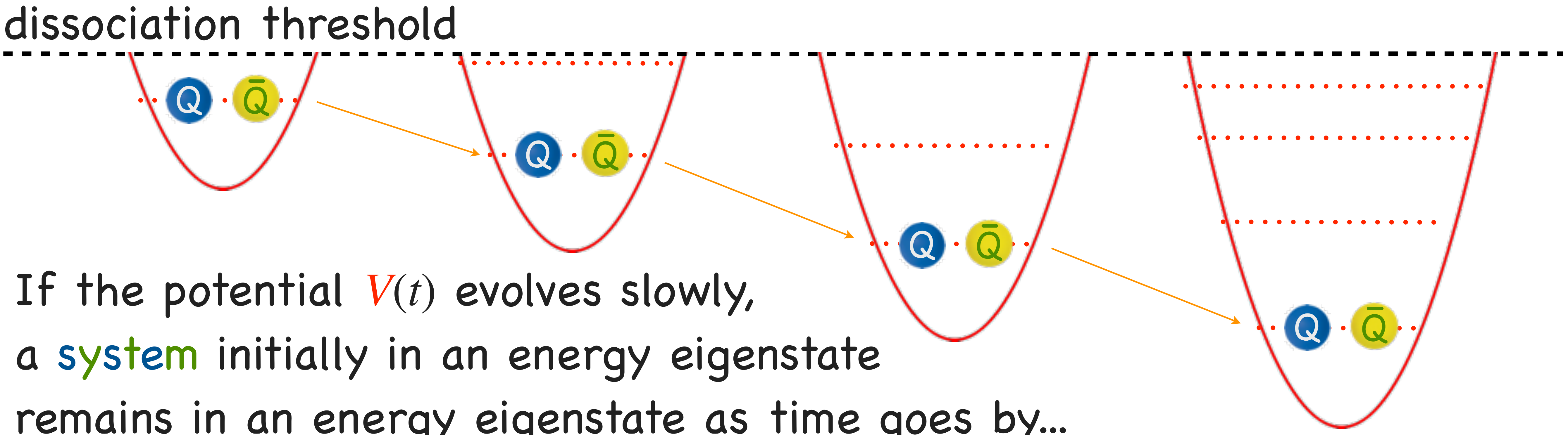

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a system initially in an energy eigenstate
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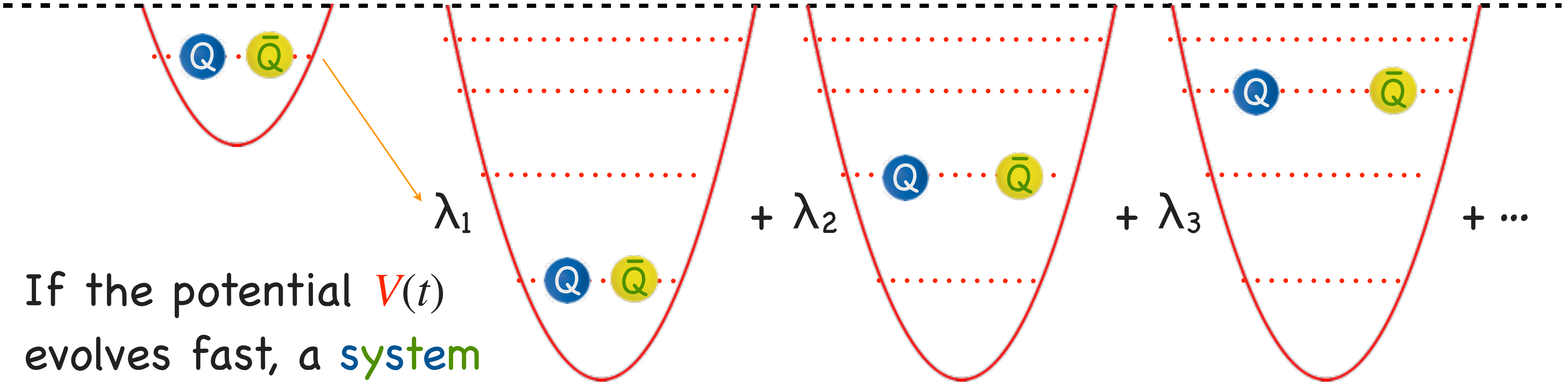

If the potential $V(t)$
evolves fast, a system
initially in an eigenstate is “reshuffled” over the final eigenstates.

Slow evolution: adiabatic theorem

A useful criterion* to decide whether the rate of change of the Hamiltonian is small enough that a system initially in an instantaneous eigenstate $|\psi_n(t)\rangle$ stays in the corresponding instantaneous eigenstate is

$$\frac{\left|\langle\psi_{n'}(t)|\,\dot{H}(t)\,|\psi_n(t)\rangle\right|}{\left[E_n(t)-E_{n'}(t)\right]^2} \ll 1 \quad \text{for all } n' \neq n$$

where $E_n(t)$ denotes the eigenenergy.

cf. your favorite QM textbook, e.g. Messiah chap.XVII or Griffiths chap.10

---

* this is a necessary, yet not a sufficient condition, cf. Rabi oscillations.

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Here, the time derivative $\dot{H}(t)$ depends on the rate of change of $T(t)$.

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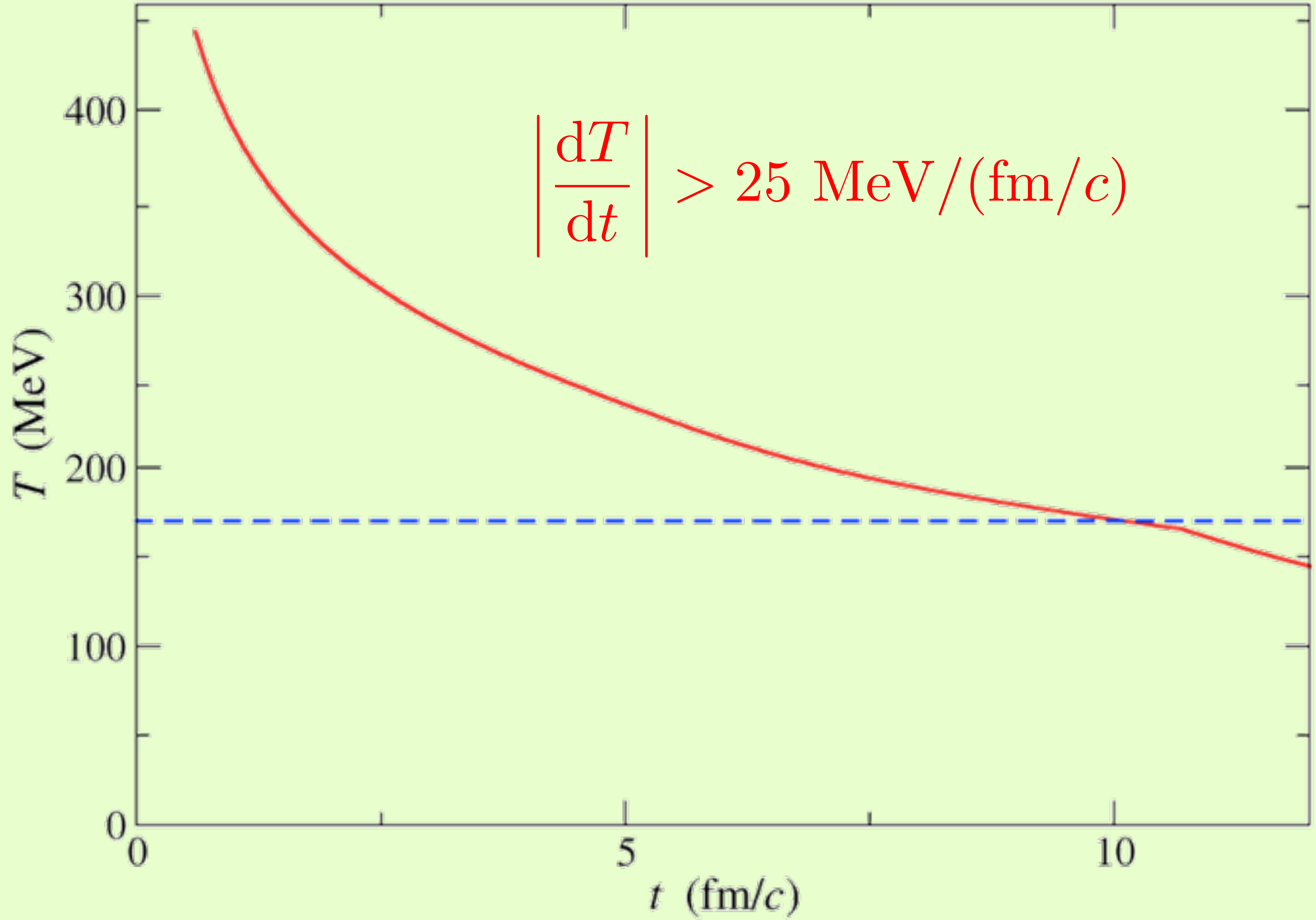
Slow evolution: adiabatic theorem

At the center of the hydrodynamically expanding fireball created in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV



Shen, Heinz, Huovinen & Song, Phys. Rev. C **84** (2011) 044903

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Here, the time derivative $\dot{H}(t)$ depends on the rate of change of $T(t)$.

☛ for $b\bar{b}$-pairs $\dfrac{\left|\langle\psi_{n'}(t)|\,\dot{H}(t)\,|\psi_n(t)\rangle\right|}{\left[E_n(t)-E_{n'}(t)\right]^2} \sim 0.1-1$ according to the channel

* this is a necessary, yet not a sufficient condition, cf. Rabi oscillations.

Quarkonia in a medium & adiabatic theorem

The temperature of the medium created in a nucleus–nucleus collision might be dropping too sharply to ensure the adiabatic evolution of the instantaneous bound eigenstates of an in-medium $b\bar{b}$-potential.

This would mean that a $b\bar{b}$-pair created in e.g. the 2S state would not remain in that state as the QGP cools down, but would have a finite probability to transition to e.g. the 1S- or 3S-state, yielding in the end an Υ or an Υ''.

☛ The simple sequential-melting picture is then blurred by the rapid evolution of the QGP, and the role of quarkonia as straightforward thermometers becomes questionable...

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OK, can I be constructive now,
instead of only being negative?

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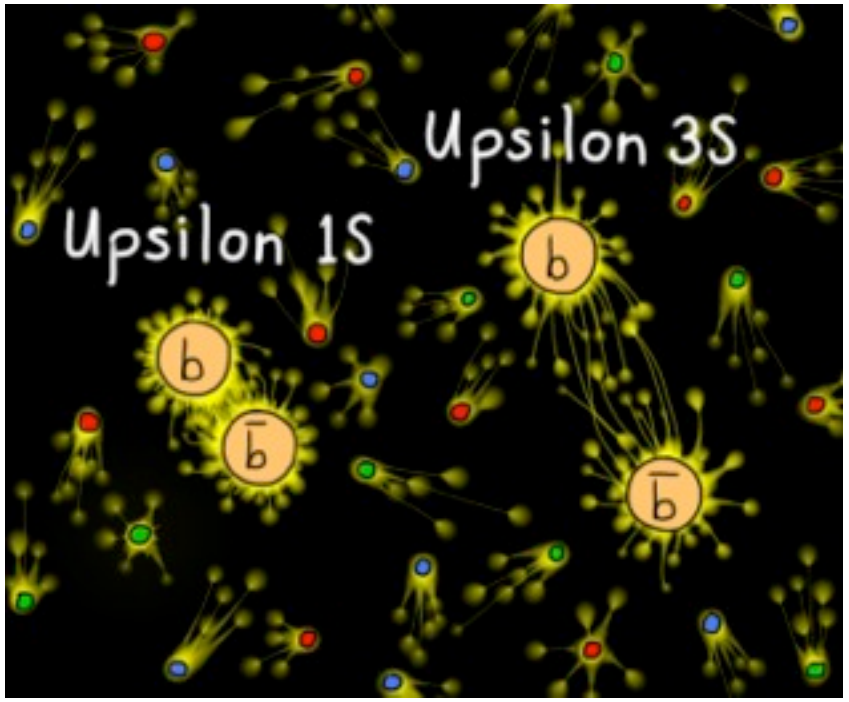
\+ work by Akamatsu & Rothkopf

A naïve picture...

Quarkonia ➡ few internal degrees of freedom: "small system"

almost no influence



big effect

Quark-gluon plasma ➡ many degrees of freedom

Medium can transfer energy & momentum to the quarkonium without being significantly affected: **small system** in contact with a **reservoir**.

Paradigm setup of **dissipative quantum systems**.

☛ Might be useful to study the real-time dynamics of quarkonia.

Dissipative quantum systems: generic setup & properties

- Small system $\mathcal{S}$ + reservoir $\mathcal{R}$ constitute a closed total system:

Hermitian Hamiltonian $$H = \underset{\text{free small system}}{\underset{\nearrow}{H_{\mathcal{S}}}} + \underset{\text{free reservoir}}{\underset{\uparrow}{H_{\mathcal{R}}}} + \underset{\text{interaction}}{\underset{\nwarrow}{V}}$$ ⇒ unitary evolution

- The reservoir/bath dynamics are "uninteresting": the corresponding degrees of freedom are integrated out.

⇒ non-unitary effective evolution ($(H_{\mathcal{S}})_{\text{eff}}$) of the small system:

open, dissipative quantum system.

Reservoir influence encoded in non-Hermitian $(H_{\mathcal{S}})_{\text{eff}}$.

Can heavy quarkonia be used as thermometers in heavy-ion collisions?

- The explosive evolution of the QGP created at RHIC or LHC may make the interpretation of heavy quarkonia yields (even) more difficult than usually thought.

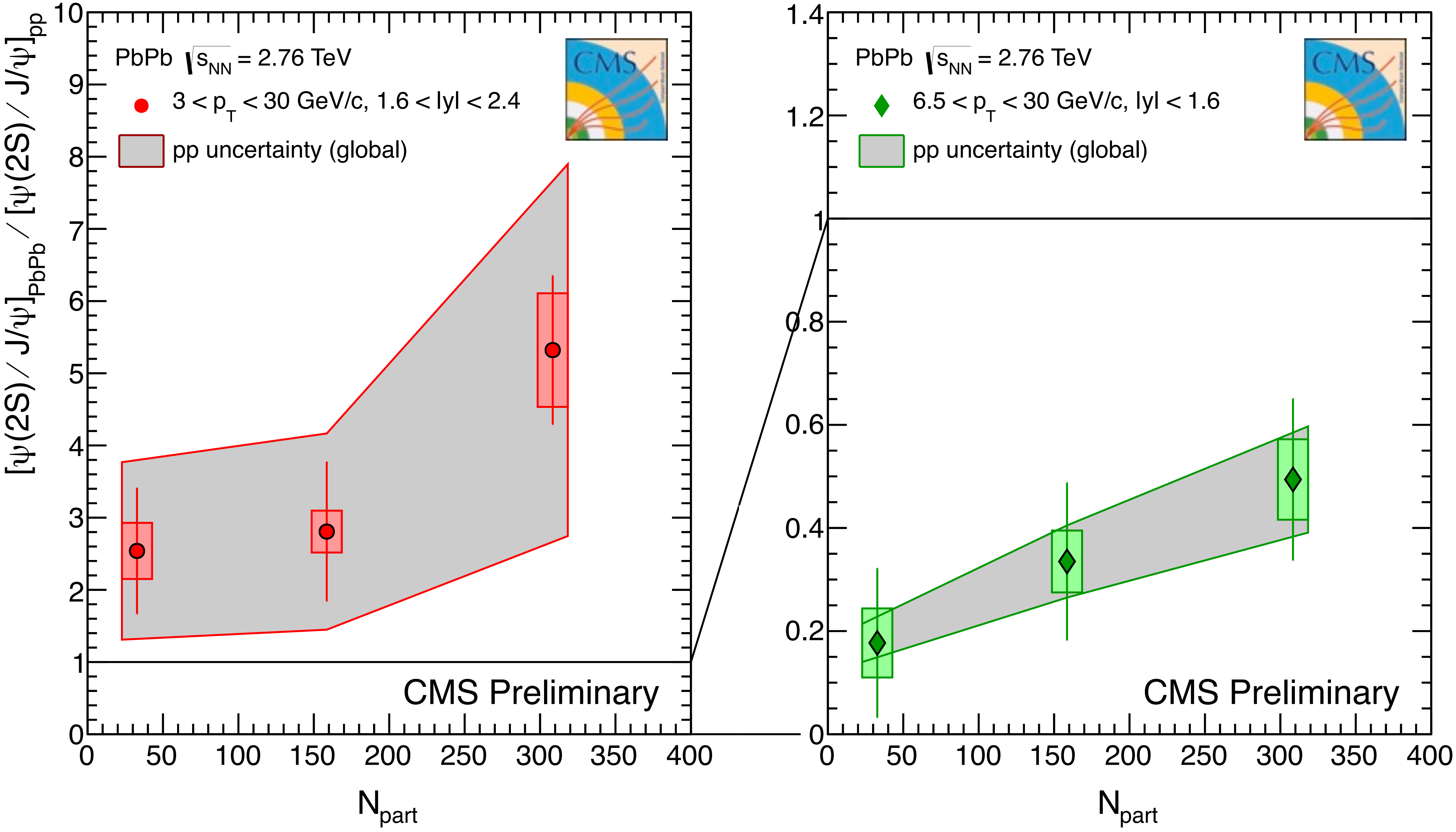
  ☛ open question (missing study...): does the adiabatic criterion give different results for bottomonia and charmonia, so as to “explain” the surprising preliminary CMS results on ψ' vs. J/ψ?

- In order to still be able to use heavy quarkonia as fruitful probes of nucleus–nucleus collisions, one may describe then as open quantum systems.

  ☛ until the day we have full-scale Monte Carlo simulations...

extra slide

CMS on charmonia



CMS Collaboration, PAS-HIN-12-007