Yoctosecond light flashes from the quark-gluon plasma

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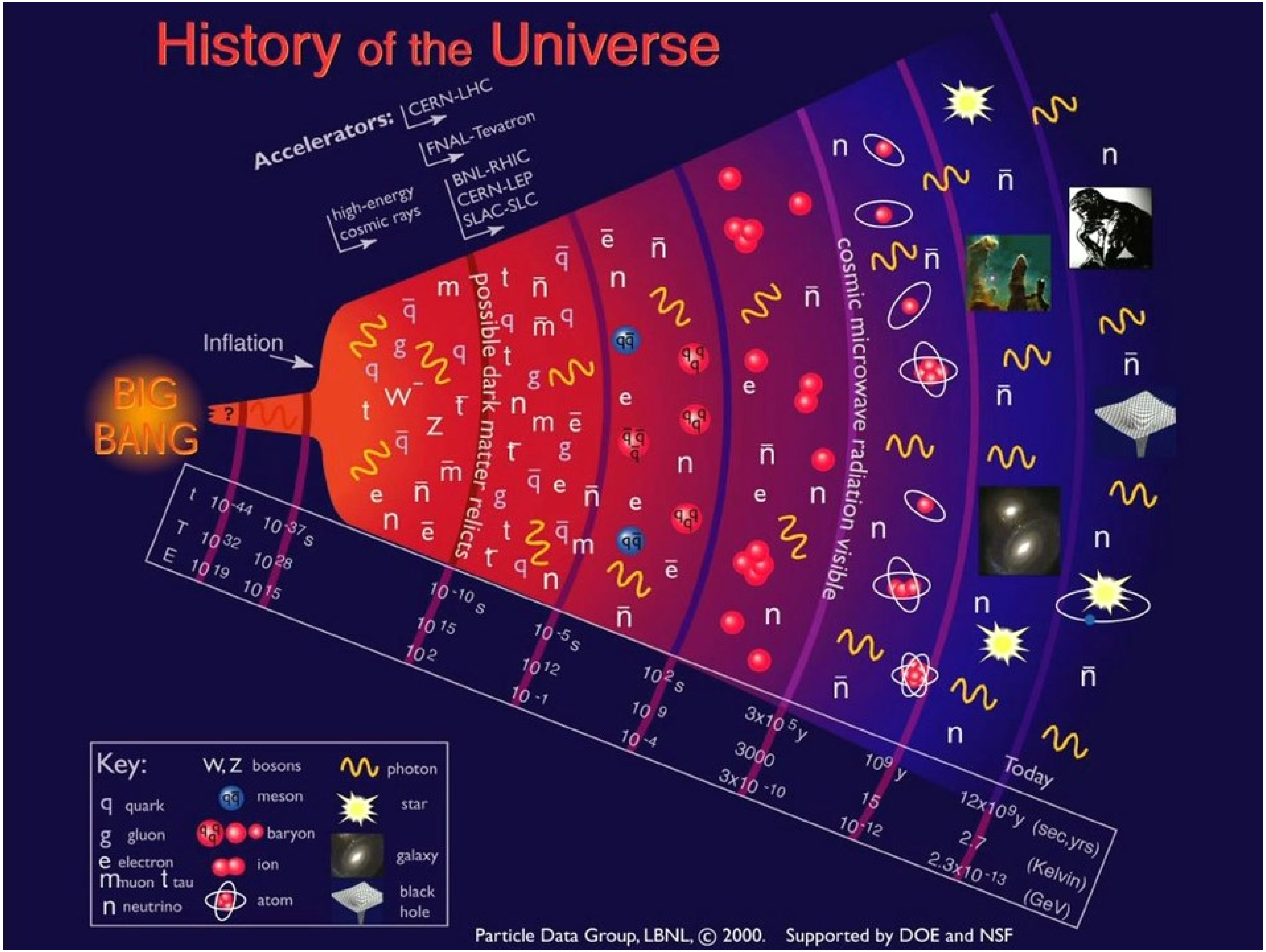
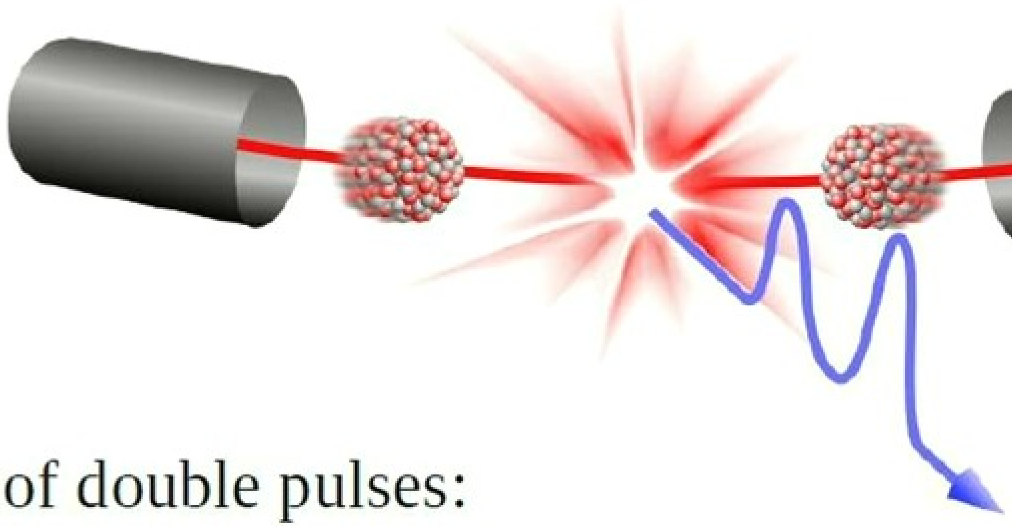
Vienna Theory Lunch Club, Nov 10, 2009

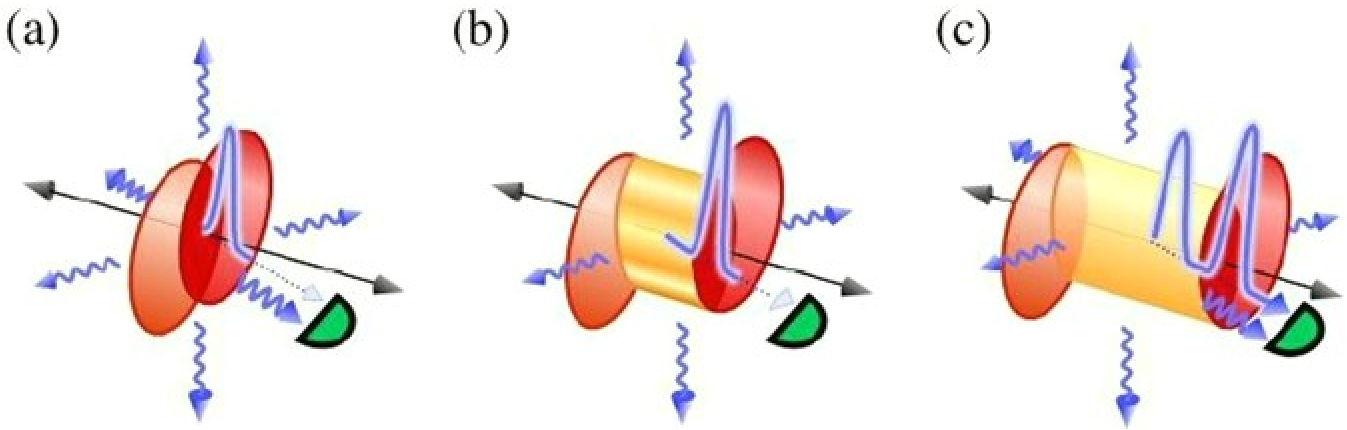

History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s 10^-10 s 10^-5 s 10^2 s 3x10^5 y 10^9 y Today 12x10^9 y (sec,yrs)
T 10^32 10^28 10^15 10^12 10^9 3000 15 2.7 (Kelvin)
E 10^19 10^15 10^2 10^-1 10^-4 3x10^-10 10^-12 2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Yoctosecond photon pulses

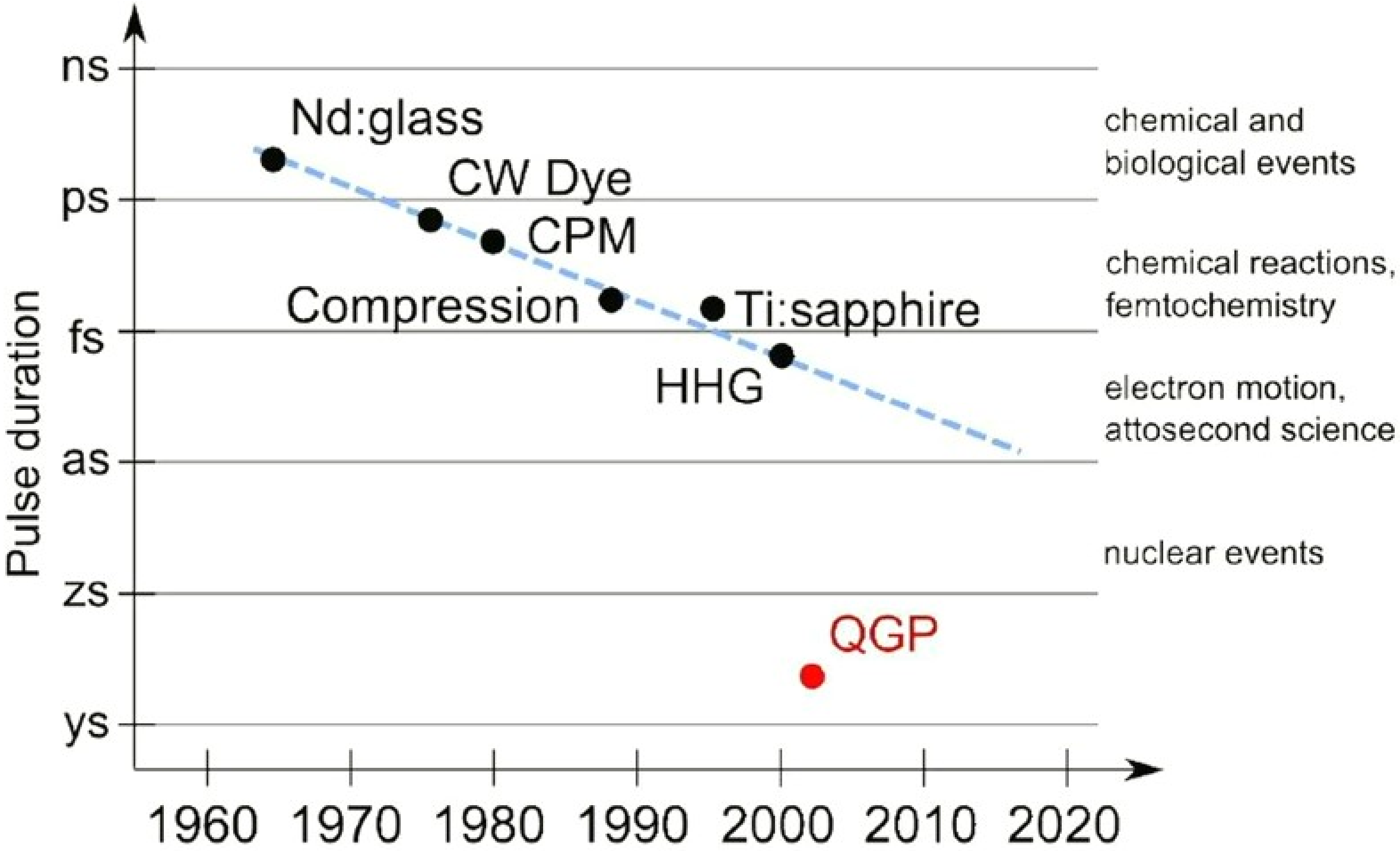
Yoctosecond photon pulses from heavy ion collisions:



Possibility of double pulses:



History of light pulse duration



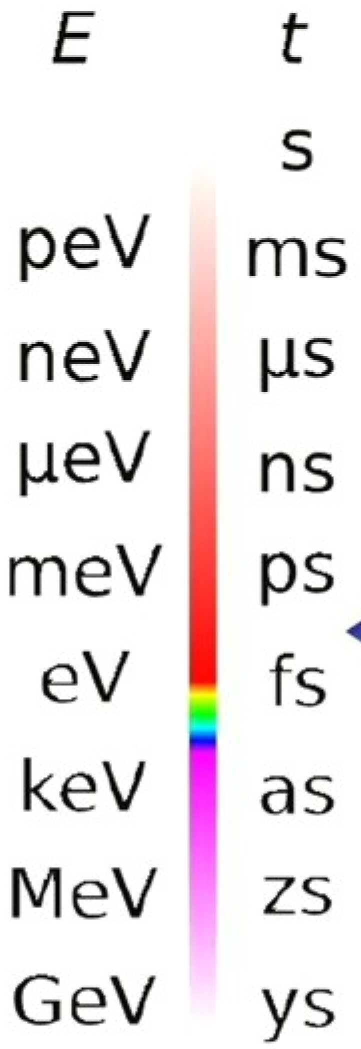
Nd:glass: Neodymium glass laser
CW Dye: Continuous Wave Dye laser
CPM: Colliding Pulse-Mode locked dye laser

Ti:sapphire: Titanium sapphire laser
HHG: High-Harmonic Generation
QGP: Quark Gluon Plasma

Outline

- Introduction
  - Time scales down to yoctosecond
  - Quark-gluon plasma (QGP)
- Yocto-second pulses from the QGP
  - Time evolution of heavy ion collisions
  - Possibility of double pulses

Pump probe spectroscopy



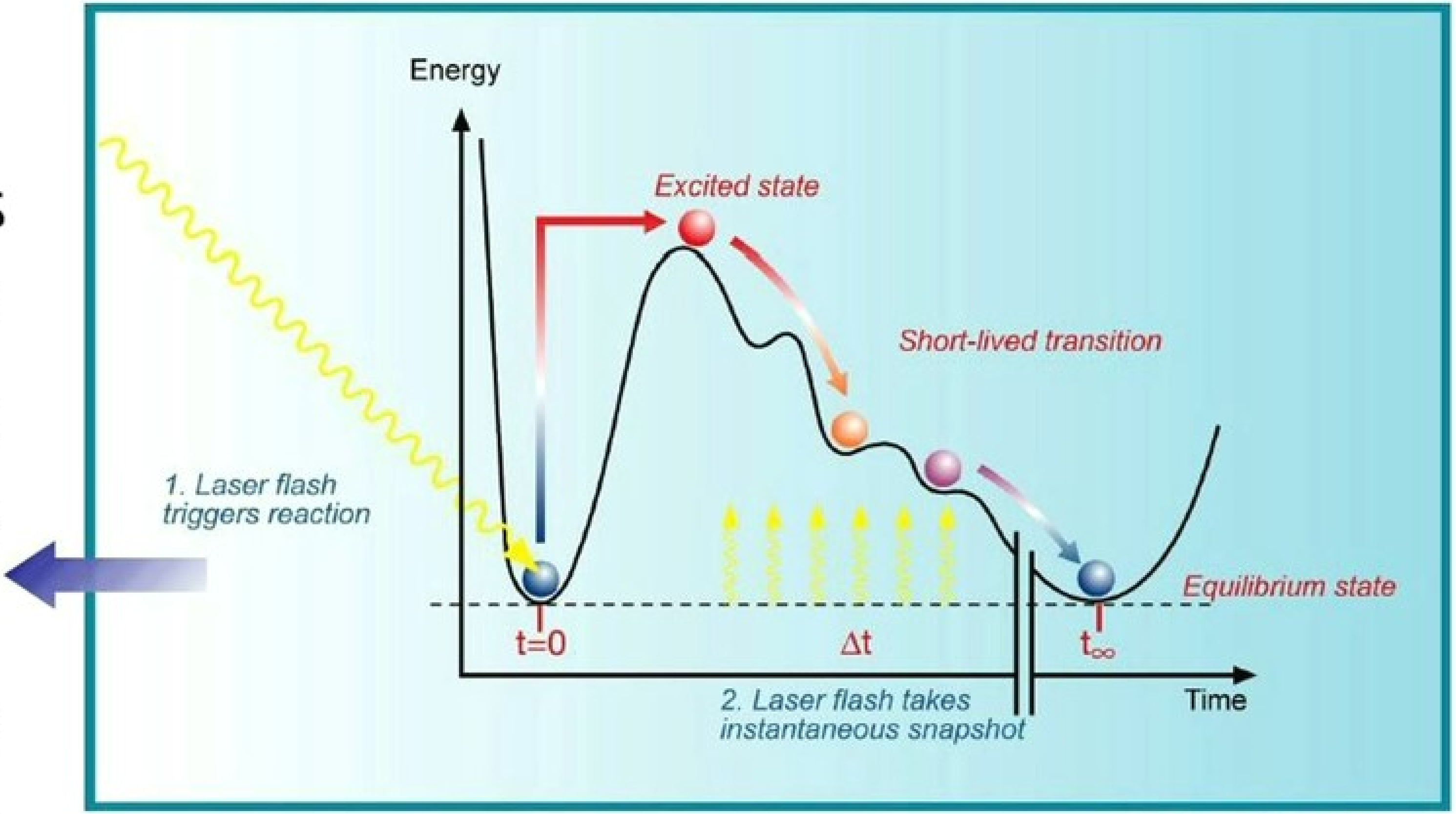
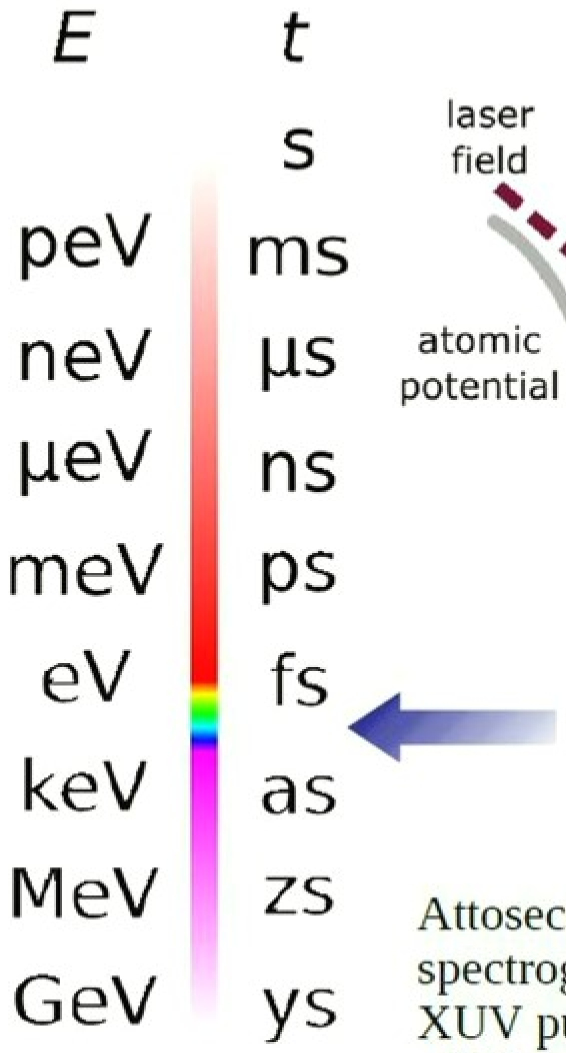


Image: DESY / XFEL

- First laser flash triggers chemical reaction.
- Second laser pulse takes snapshot of intermediate state.
- By varying interval between pulses, a movie can be created.

Attosecond technology



High harmonic generation

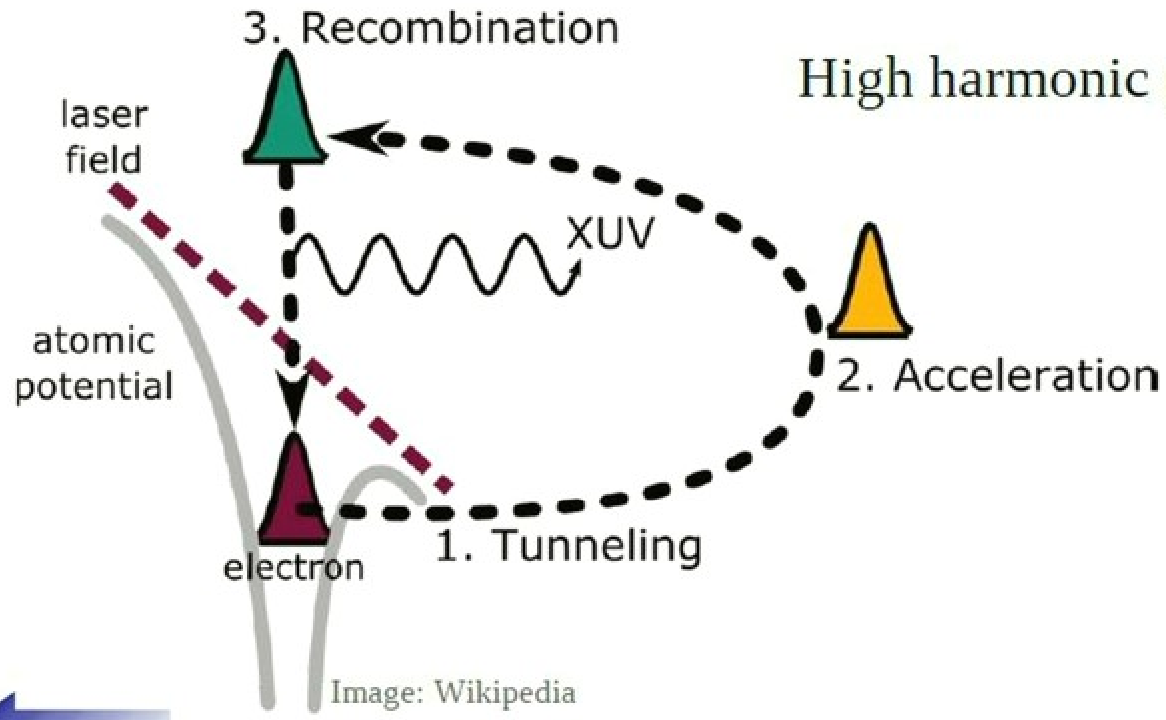
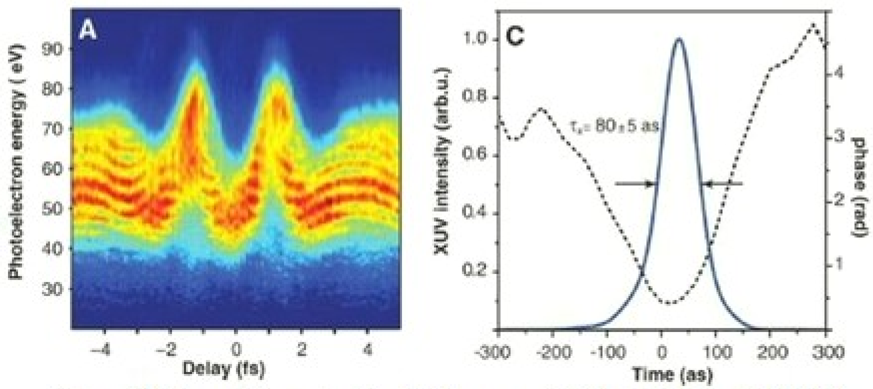


Image: Wikipedia

Attosecond streaking spectrogram measures XUV pulse duration of 80 as.



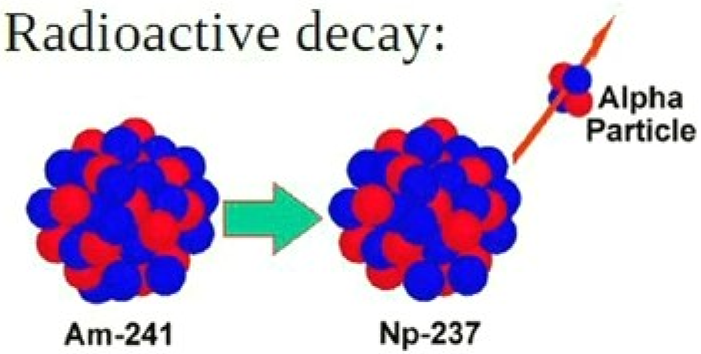
Goulielmakis et al, Science 320, 1614 (2008)

Zeptosecond

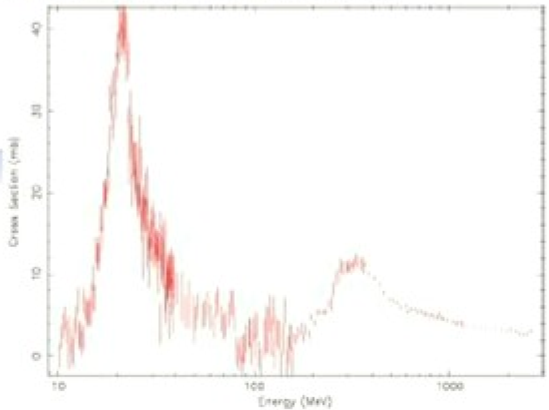
E	*t*
	s
peV	ms
neV	µs
µeV	ns
meV	ps
eV	fs
keV	as
MeV	zs
GeV	ys

Movie of nucleons in nuclei?

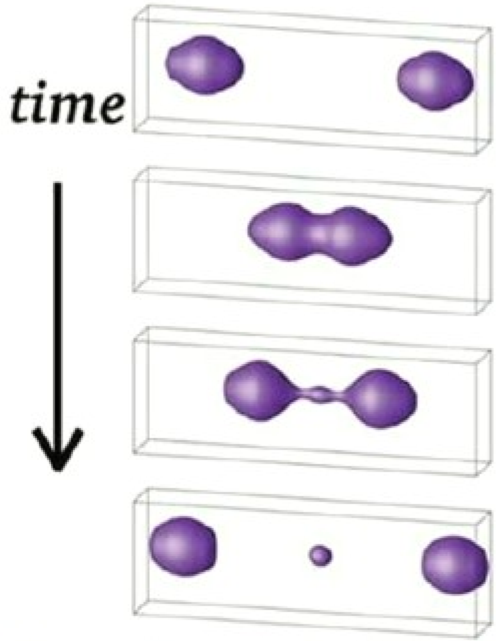
Radioactive decay:



Nuclear resonances:



Colliding nuclei:



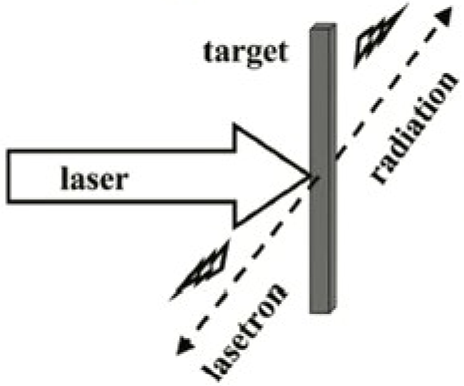
Zeptosecond snapshots of two 238U nuclei colliding at 900 MeV, resulting in three primary fragments.

Golabek, Simenel,
Phys. Rev. Lett. 103, 042701 (2009)

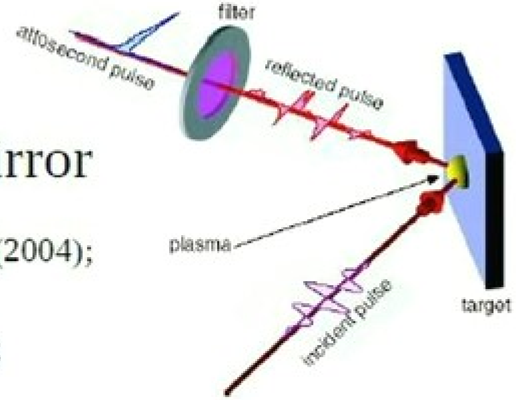
Zeptosecond

E	t
	s
peV	ms
neV	µs
µeV	ns
meV	ps
eV	fs
keV	as
MeV	zs
GeV	ys

Suggestions for creating zs pulses:

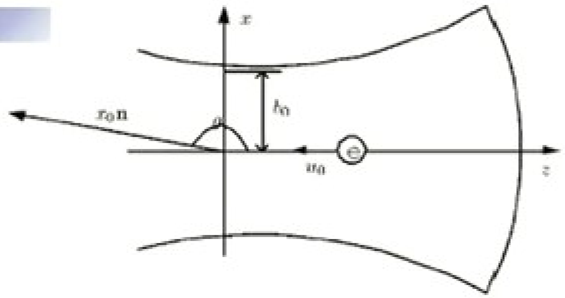


„Lasetron“
Kaplan, Shkolnikov,
PRL 88, 074801 (2002)



Plasma mirror
Gordienko et al.,
PRL 93, 115002 (2004);

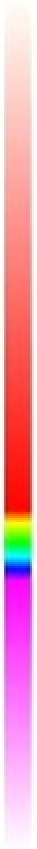
Tsakiris *et al.*,
NJP 8, 19 (2006);



Nonlinear Thomson backscattering
Lan *et al.*,
Phys. Rev. E 72, 06501 (2005)

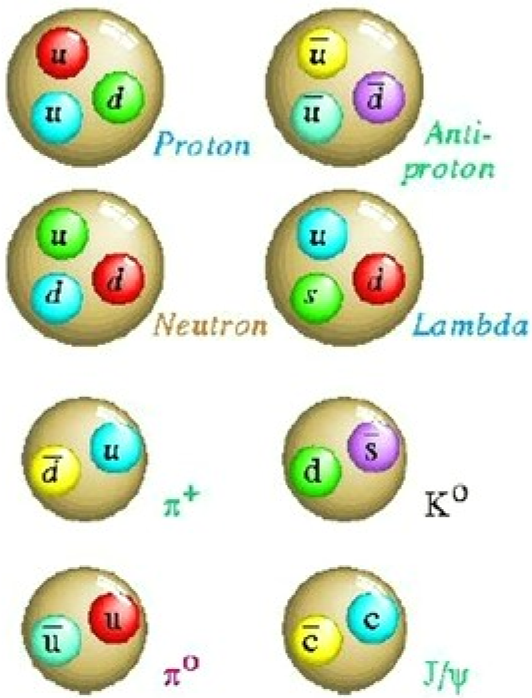
Yoctosecond

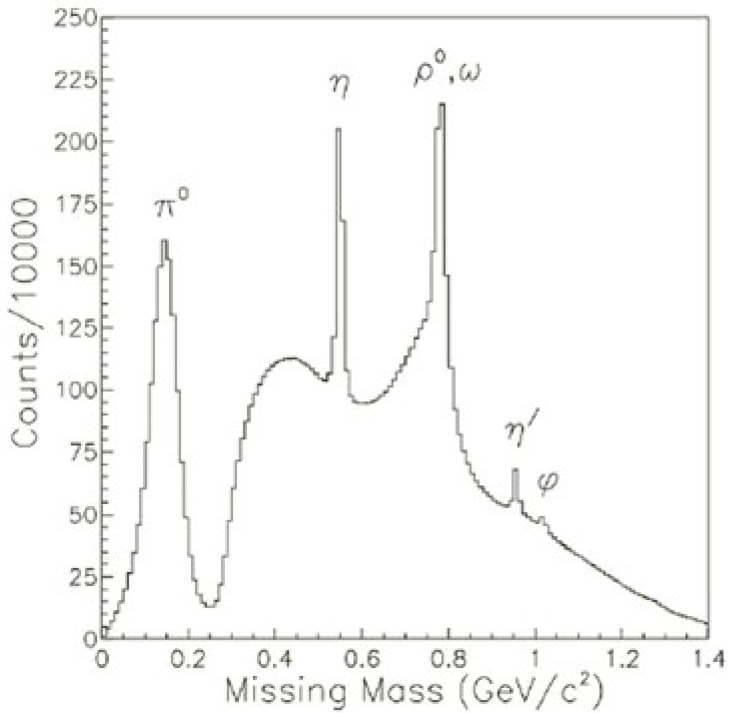
E	*t*
	s
peV	ms
neV	µs
µeV	ns
meV	ps
eV	fs
keV	as
MeV	zs
GeV	ys



$1\ \mathrm{ys} = 10^{-24}\ \mathrm{s}$

Movie of quarks in hadrons?



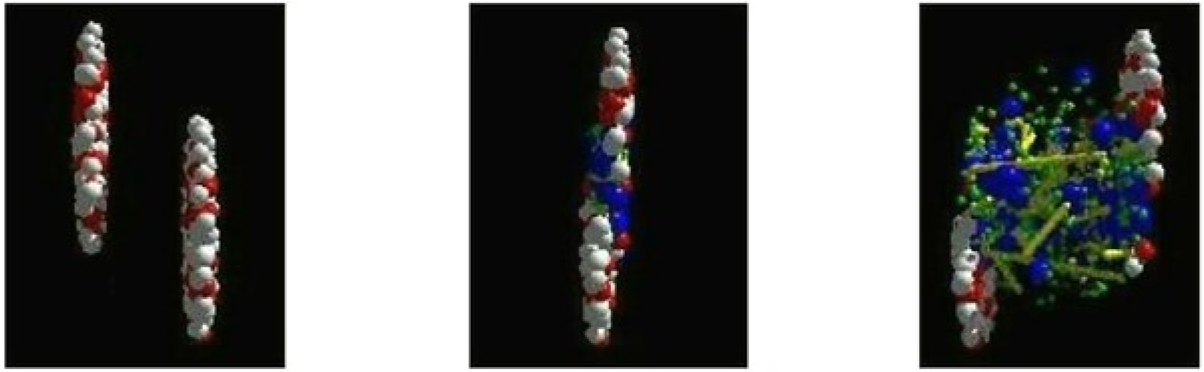


Photoproduction on proton

Dugger et al.,
Phys. Rev. C 76, 025211 (2007)

Yoctosecond

E	t
	s
peV	ms
neV	µs
µeV	ns
meV	ps
eV	fs
keV	as
MeV	zs
GeV	ys

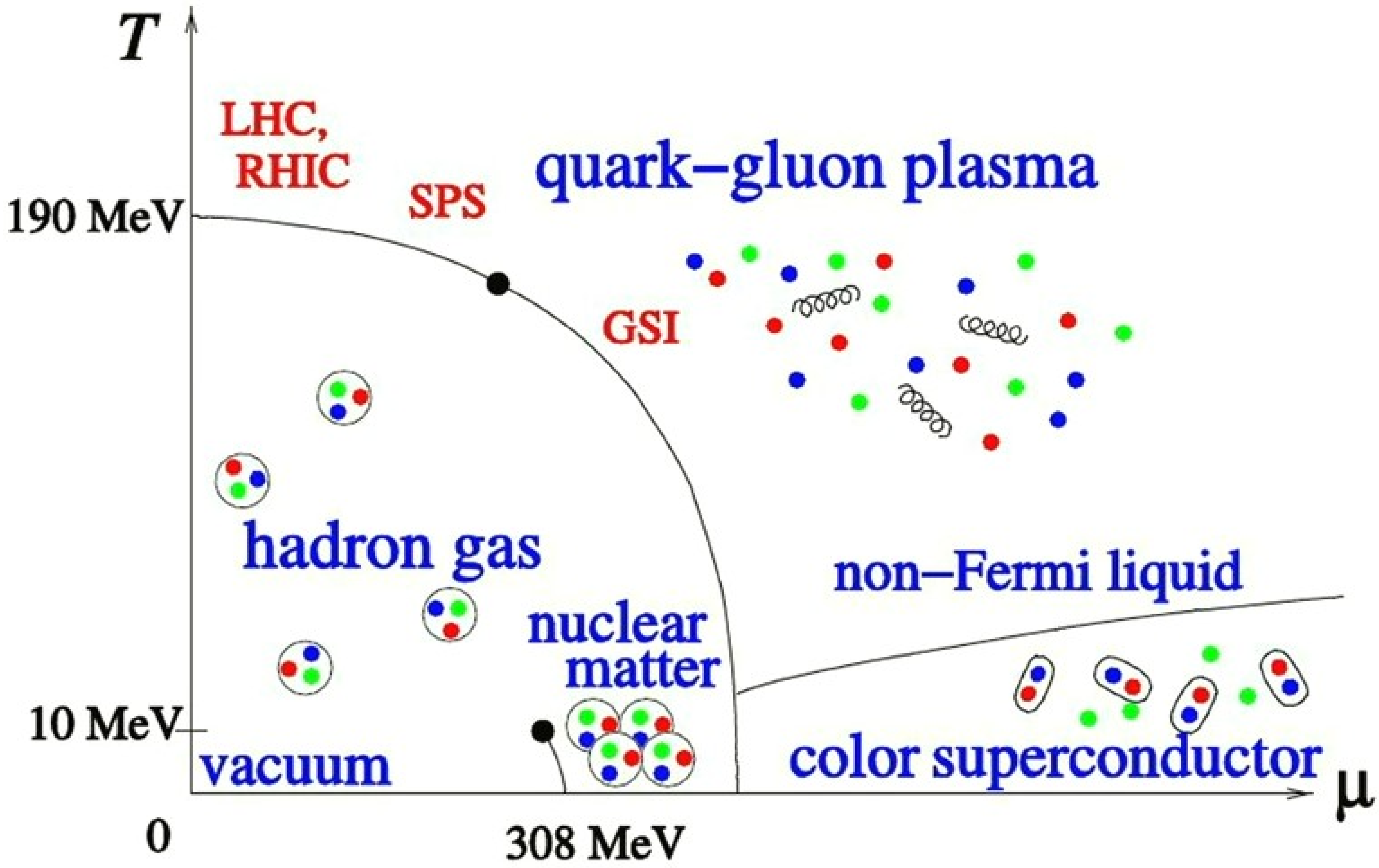


(Simulation by UrQMD group, Frankfurt)

- Heavy ion nuclei (gold, lead) (d~14 fm)
- formation time of QGP: t~1 fm/c ≈ 3 ys
- QGP phase: RHIC 5 fm/c, LHC 7.5 fm/c
- good agreement with hydrodynamic simulations,
  'perfect liquid' news 2005

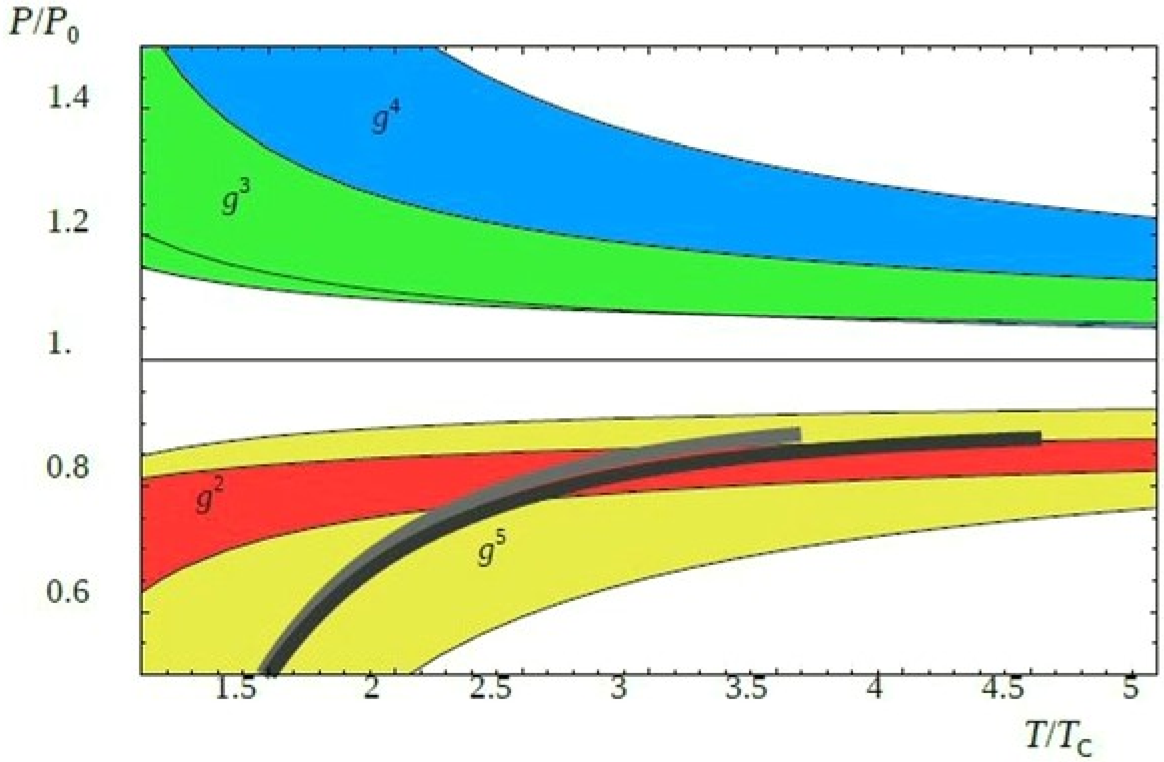
1 ys = 10^{-24} s

QCD phase diagram



QCD pressure

Perturbative expansion of QCD pressure converges badly



Lattice data: G. Boyd et al. (1996); M. Okamoto et al. (1999).

Perturbation theory:

g^2: Shuryak; Chin (1978)

g^3: Kapusta (1979)

g^4 ln g: Toimela (1983)

g^4 : Arnold, Zhai (1994)

g^5 : Zhai, Kastening (1995),
Braaten, Nieto (1996)

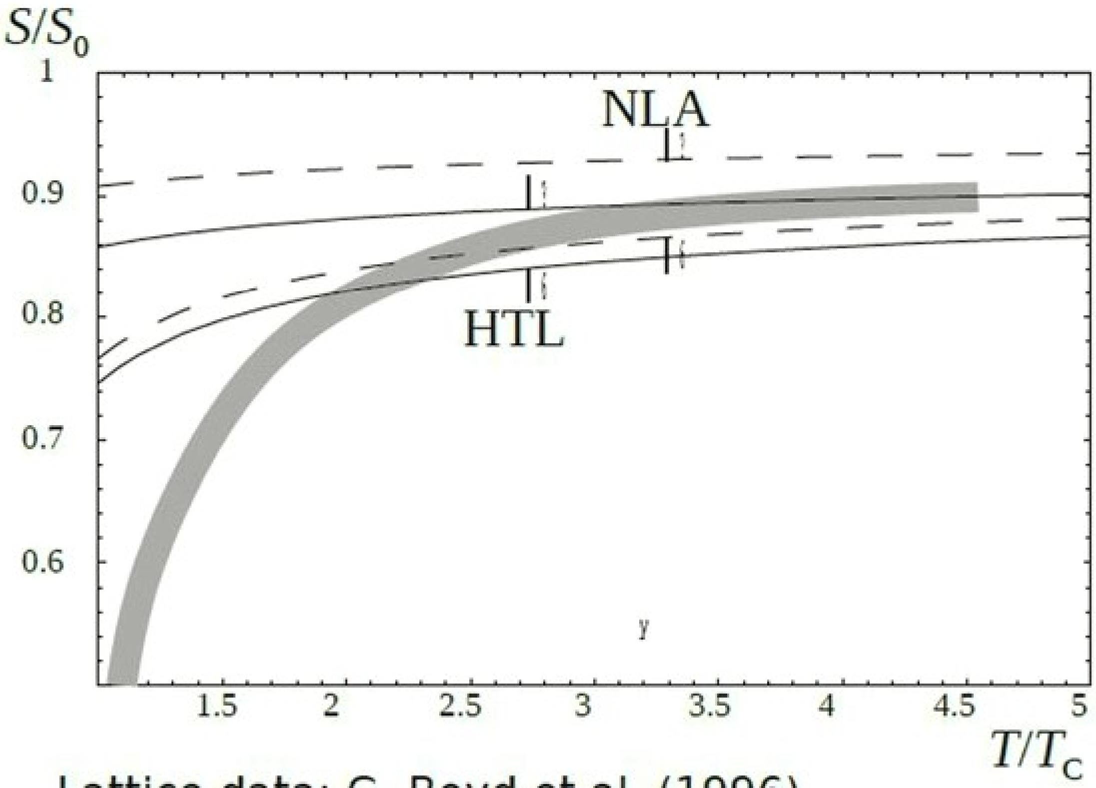
g^6 ln g: Kajantie, Laine,
Rummukainen, Schröder (2002)

g^6 (partly): Di Renzo, Laine, Miccio,
Schröder, Torrero (2006)

$N_f^3\, g^6$: Gynther, Kurkela, Vuorinen
(2009)

QCD pressure

Self–consistent 2PI resummation works for $T \geqslant 2.5\,T_c$



Lattice data: G. Boyd et al. (1996).

Φ -derivable approximation

Blaizot, Iancu, Rebhan, PRD63 (2001)

tested at large N_f

Blaizot, AI, Rebhan, Reinosa, PRD72 (2005)

For ϕ^4, exact renormalization group gives comparable results

Blaizot, AI, Mendez-Galain, Wschebor, NPA (2007)

RHIC

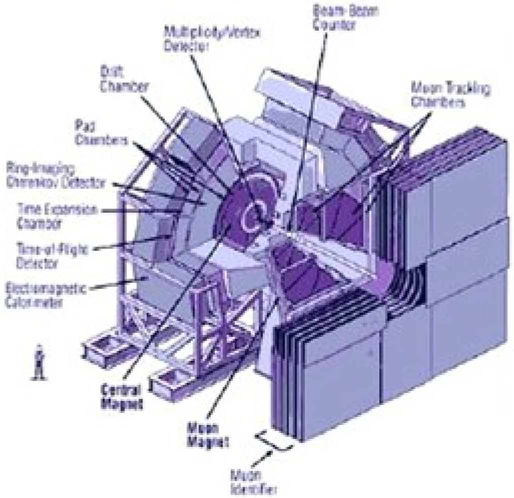
Relativistic heavy ion collider: experimental sites

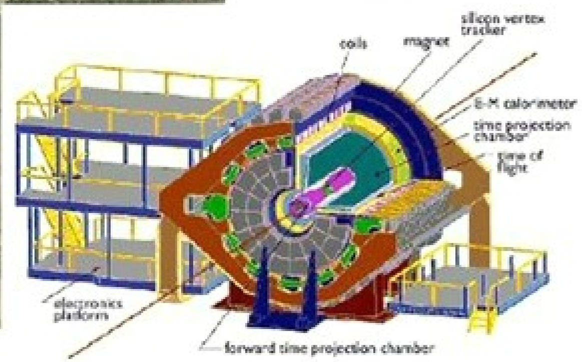
PHOBOS

PHENIX

BRAHMS

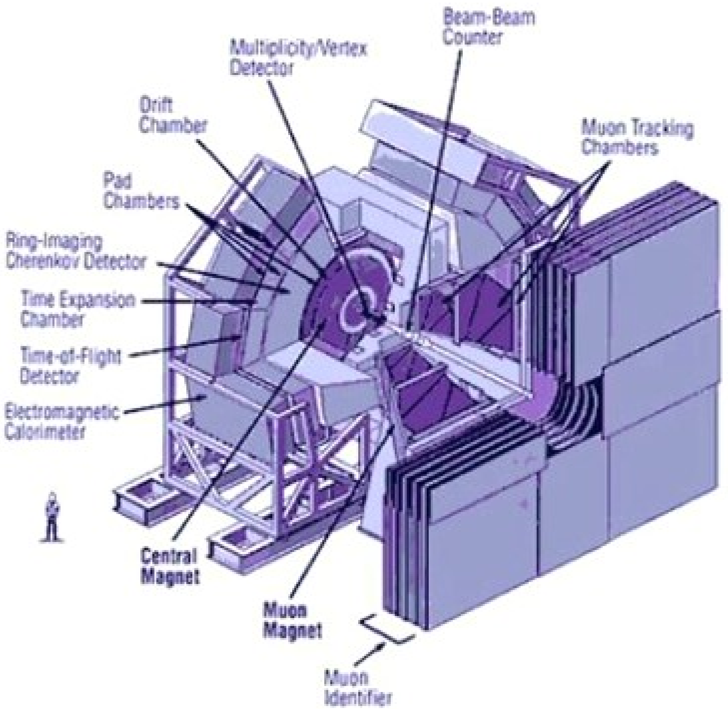
STAR

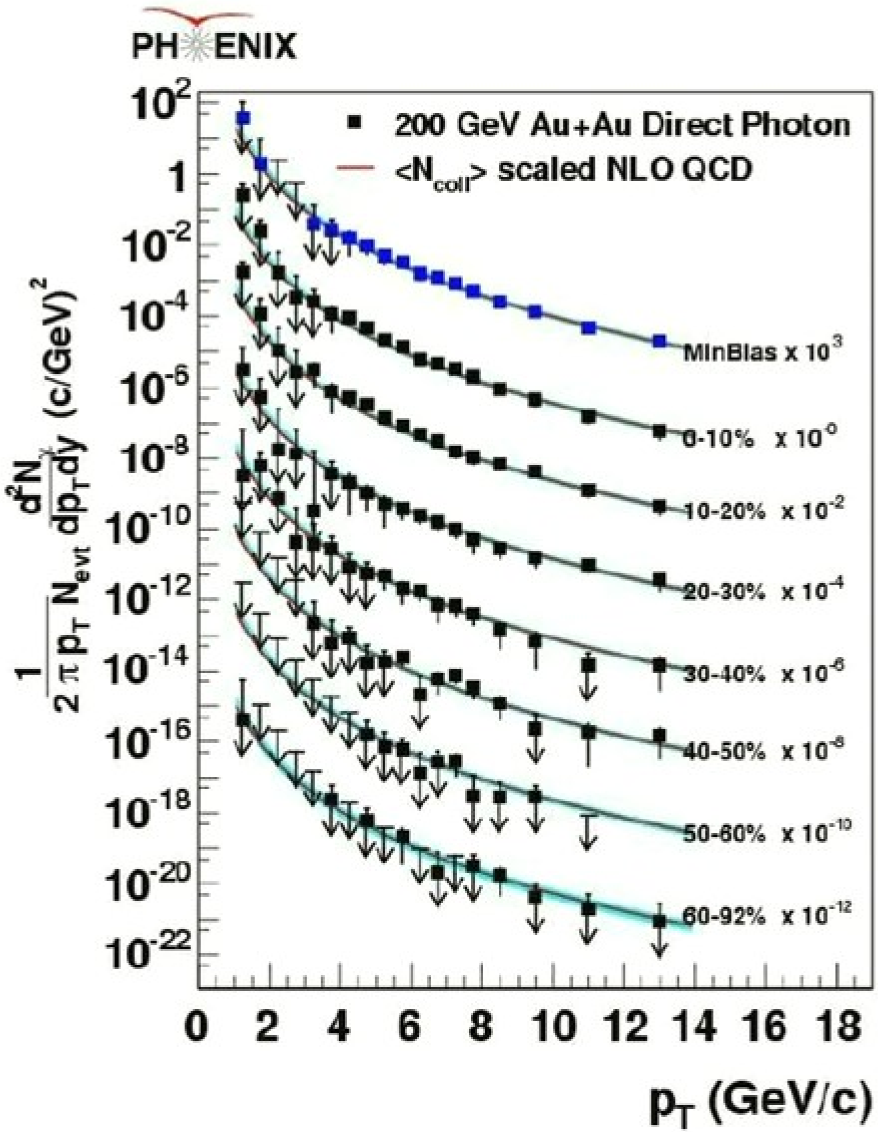




Photon spectrum

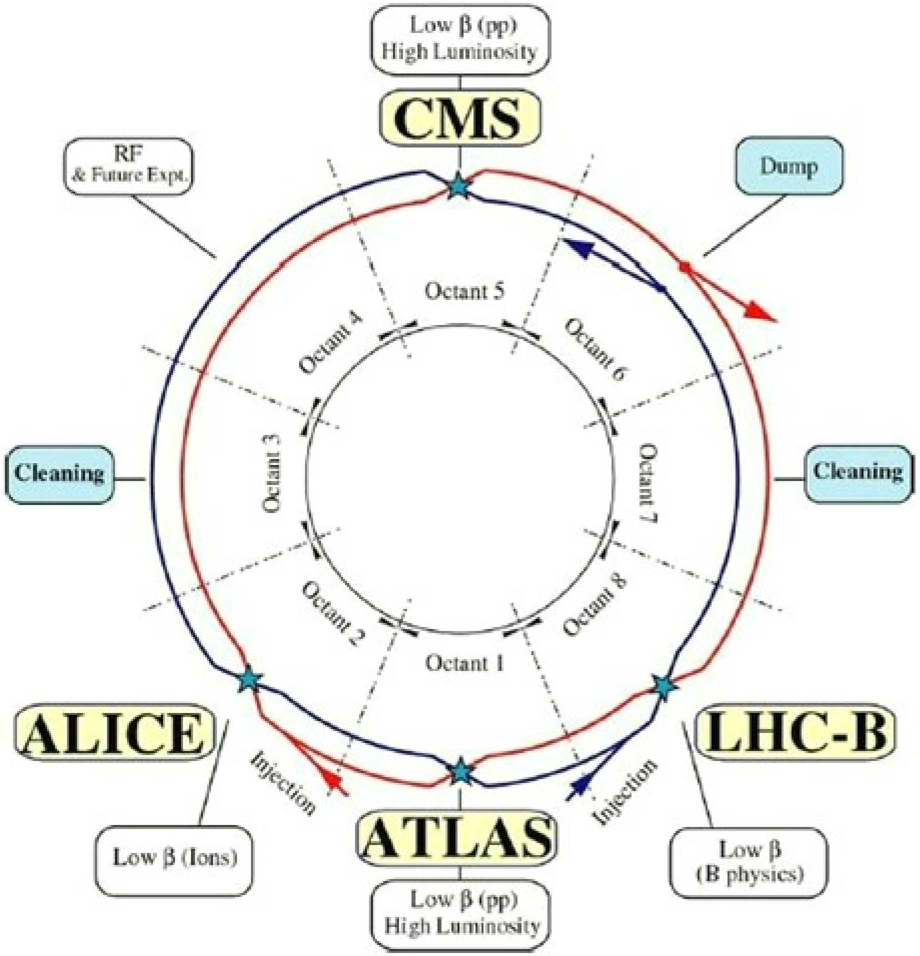
PHENIX data
for direct photons



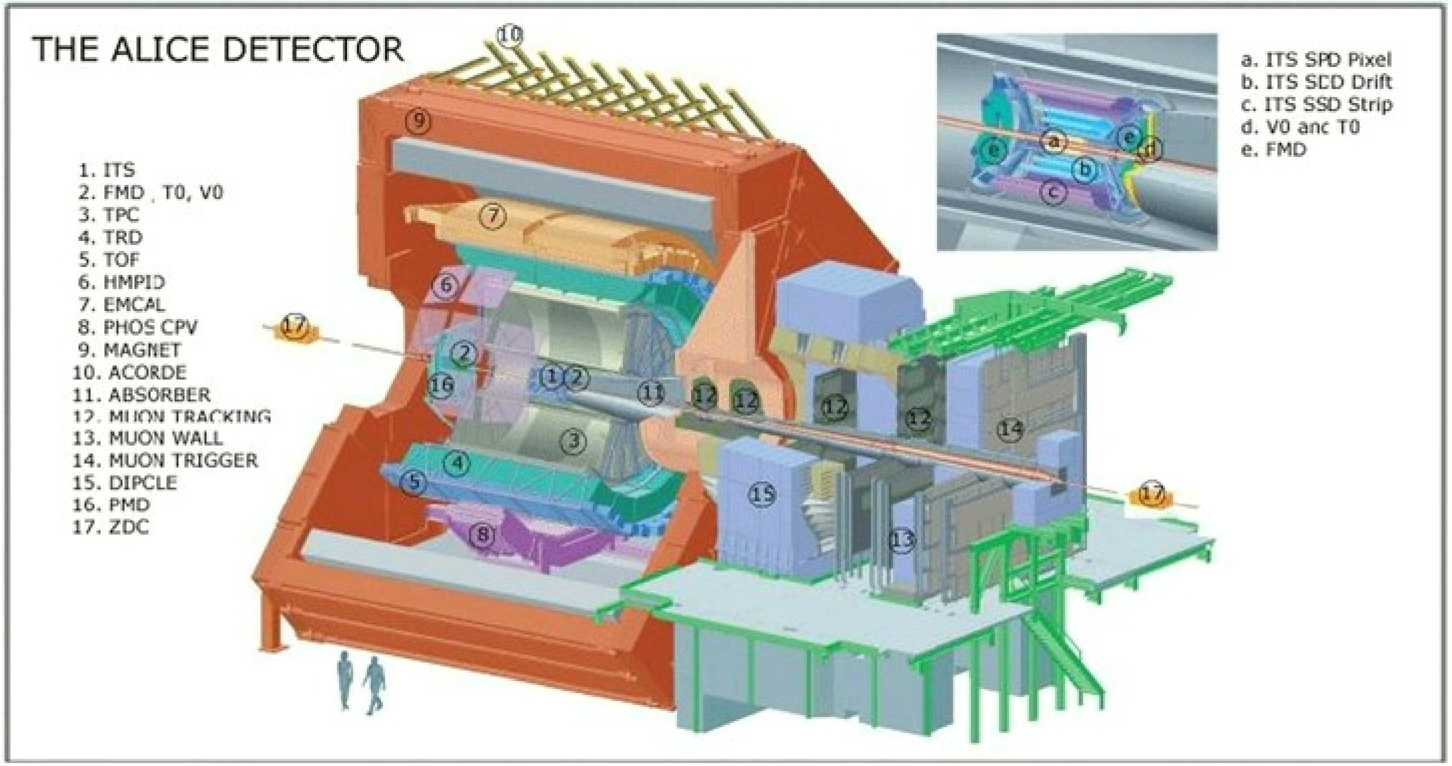


LHC

Large Hadron Collider



PHOS (PHOton Spectrometer)



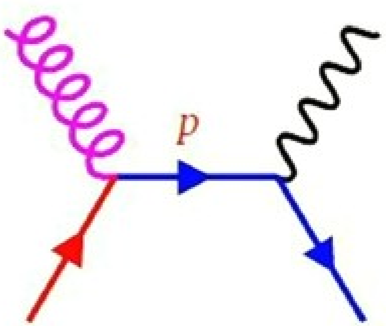
- PHOS is an electromagnetic calorimeter made of lead-tungstate crystals ($PbWO_4$).
- Detects photons (of ~ 0.5 - 10 GeV/c), π^0's (of ~ 1 - 10 GeV/c) and η mesons (of ~ 2 - 10 GeV/c).

Photon production in the QGP

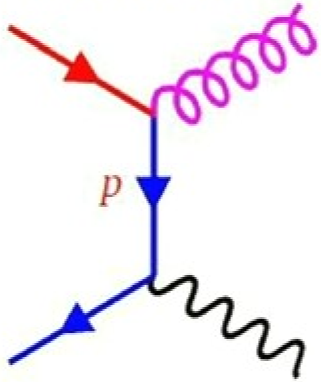
"Hard" contributions: $T \sim p \geqslant k_c$

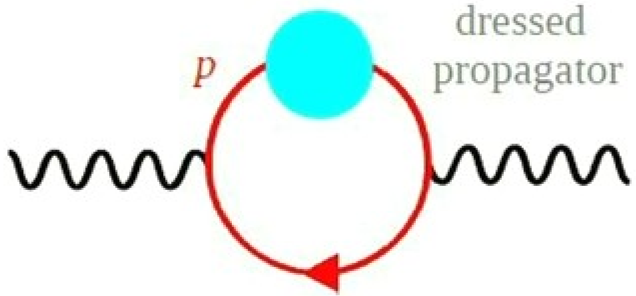
"Soft" contributions: $gT \sim p \leqslant k_c$

Compton scattering:



Quark-antiquark annihilation:





need to use dressed propagators

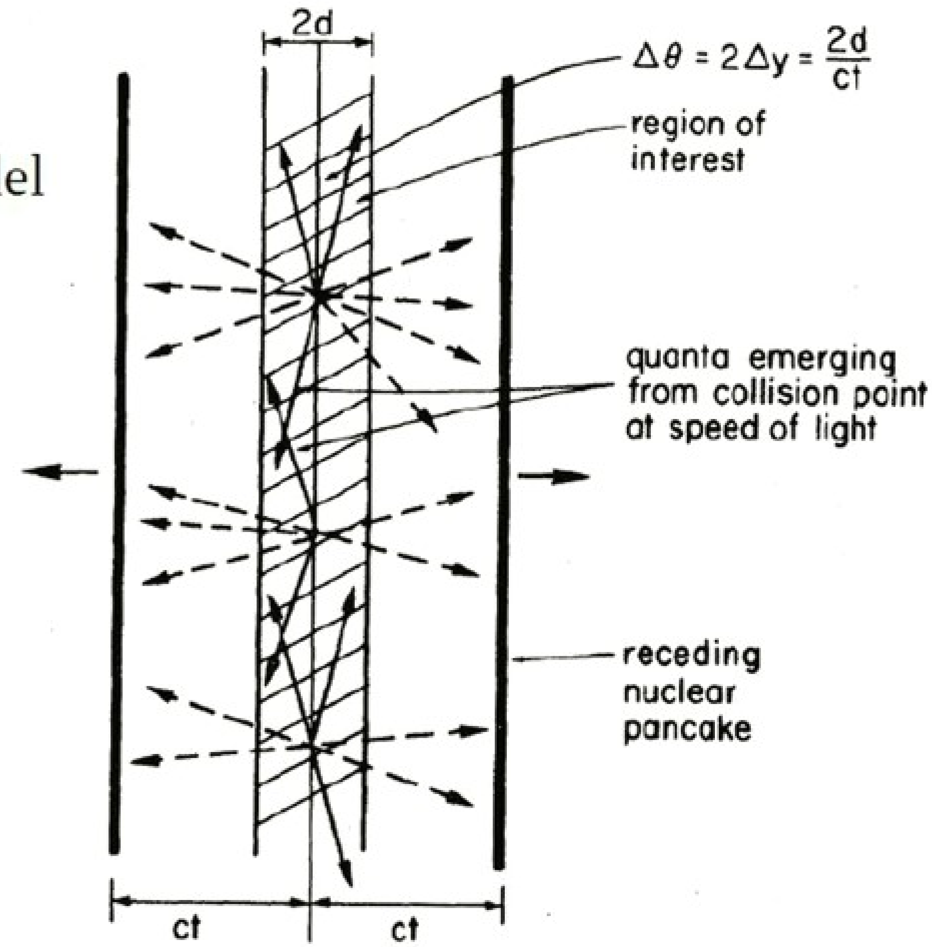
Final result should be independent of intermediate cutoff $k_c \sim \sqrt{g}\,T$

Integrate over thermal distribution functions.

Kapusta, Lichard, and Seibert, Phys. Rev. **D44**, 2774 (1991)

Expanding plasma

Bjorken expansion model

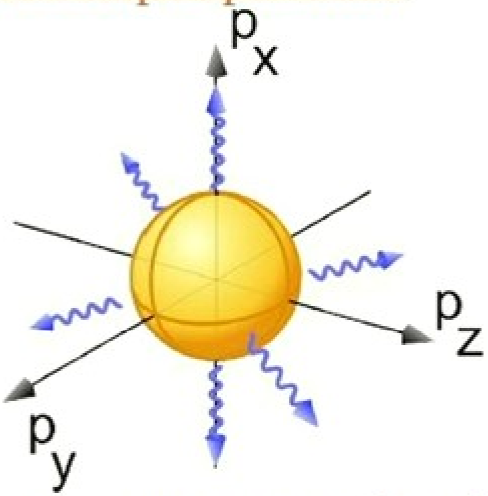


J. D. Bjorken, PRD 27, 140 (1983)

Momentum space anisotropy

anisotropy in momentum space

Isotropic plasma:



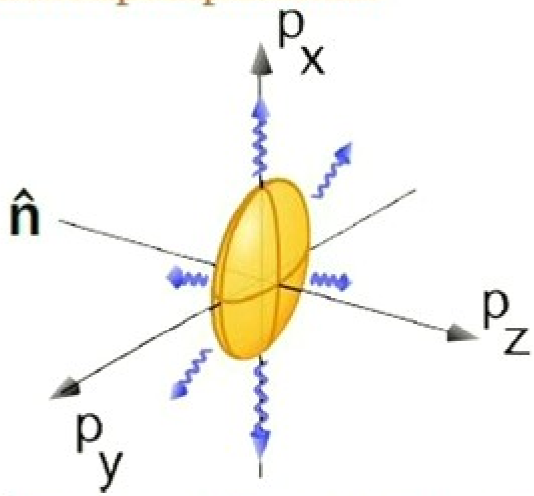
gluons: Bose-Einstein distribution

$$f^B(\mathbf{q}) = \frac{1}{e^{|\mathbf{q}|/T} - 1}$$

quarks: Fermi-Dirac distribution

$$f^F(\mathbf{q}) = \frac{1}{e^{|\mathbf{q}|/T} + 1}$$

Anisotropic plasma:



stretch or compress isotropic distribution along axis $:\hat{\mathbf{n}}$

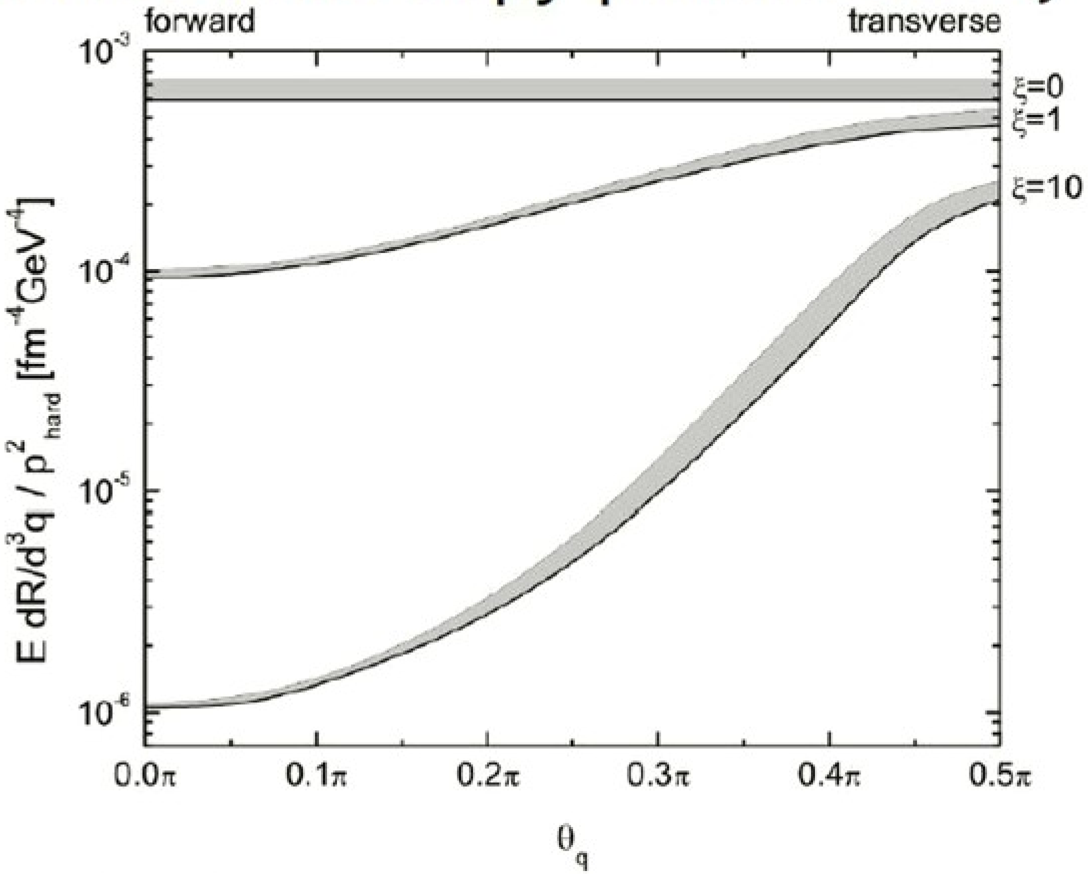
$$f_\xi(\mathbf{q}) = f_{iso}\left(\sqrt{\mathbf{q}^2 + \xi(\mathbf{q}\cdot\hat{\mathbf{n}})^2}\right)$$

ξ..anisotropy parameter

Schenke and Strickland,
Phys. Rev. **D76**, 025023 (2007)

Photon rate

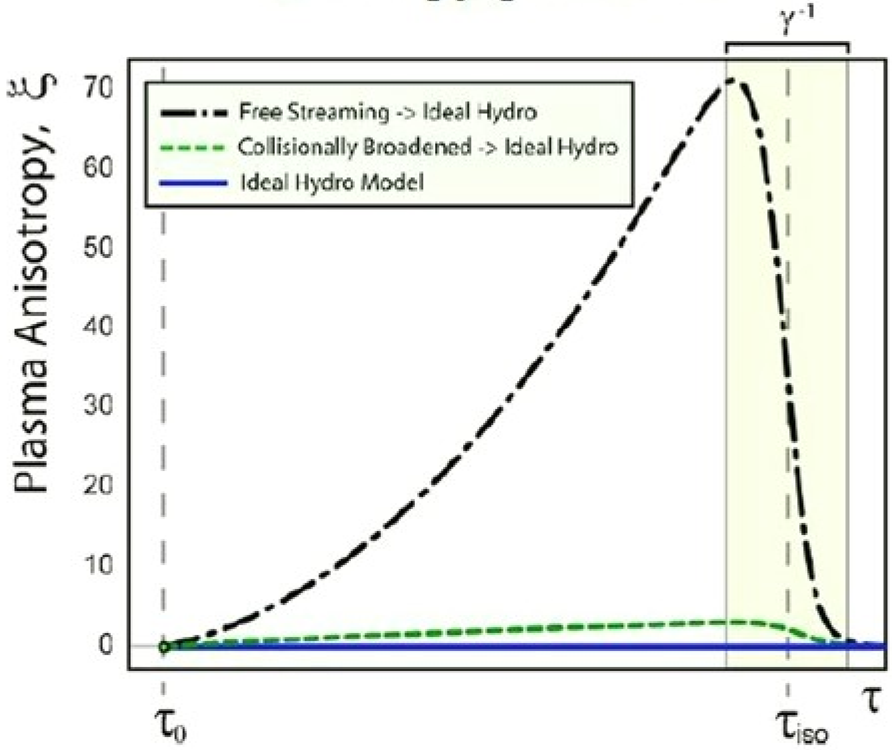
- Photon rate as function of emission angle θ_q for various anisotropy parameters ξ



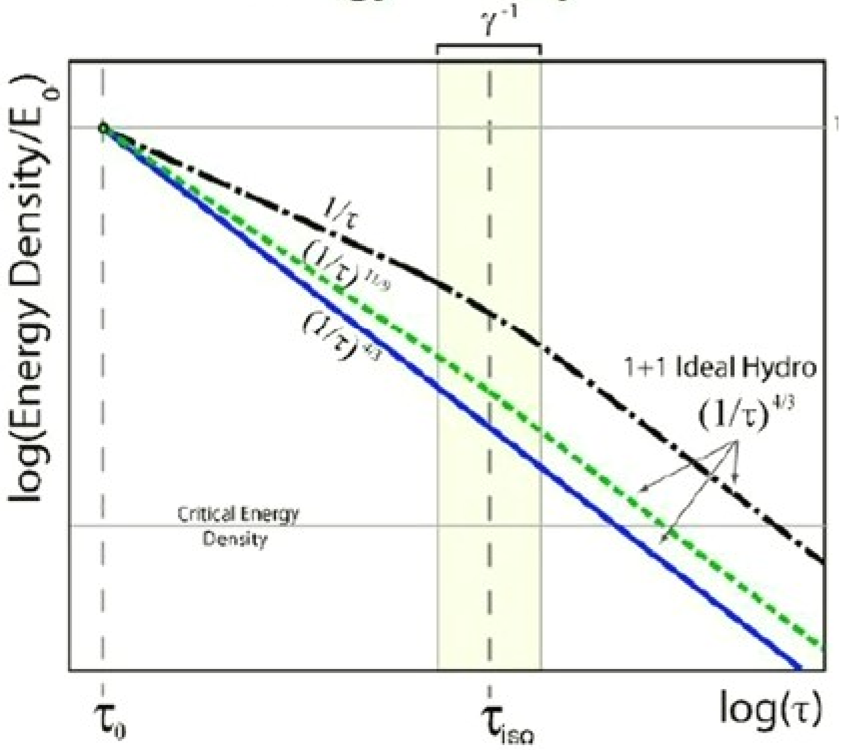
Schenke, Strickland, Phys. Rev. D76:025023, 2007.

Model for time-evolution

Anisotropy parameter



Energy density

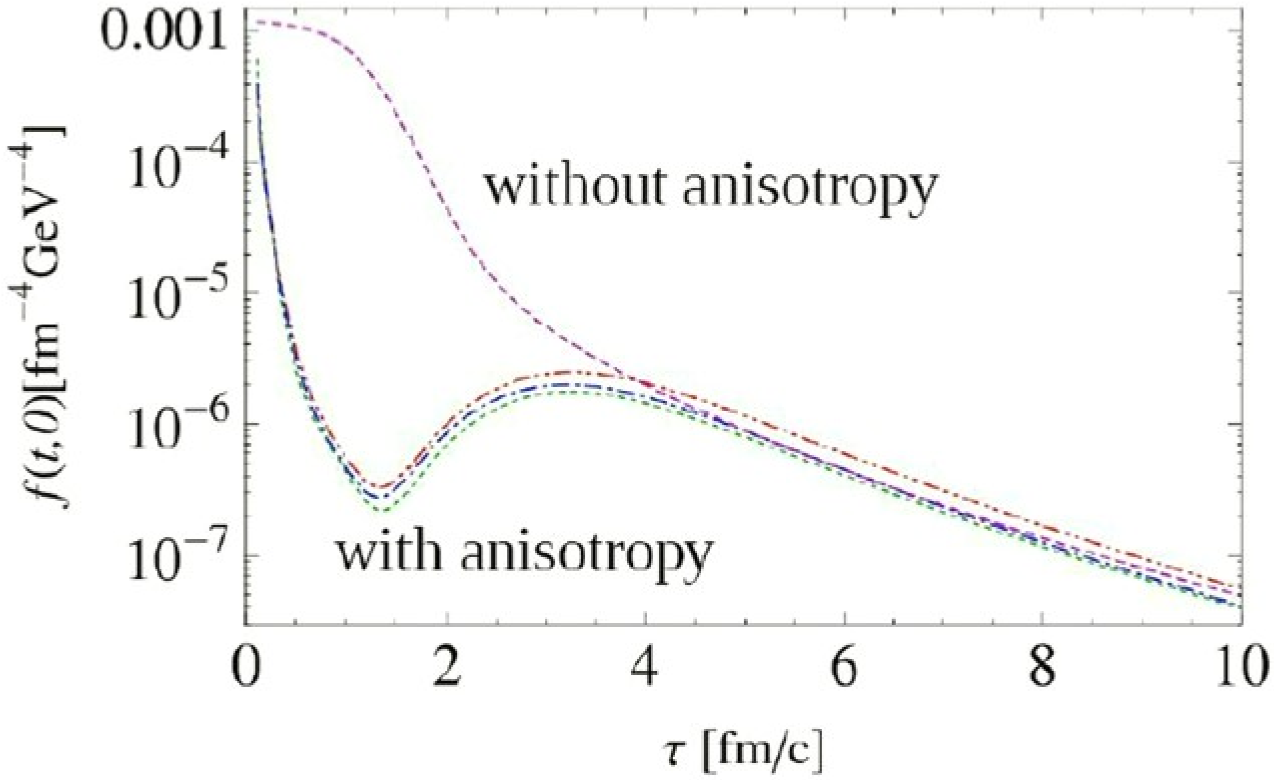


Isotropization time τ_{iso}

Martinez, Strickland, Phys. Rev. C78:034917, 2008.

Differential photon emission rate

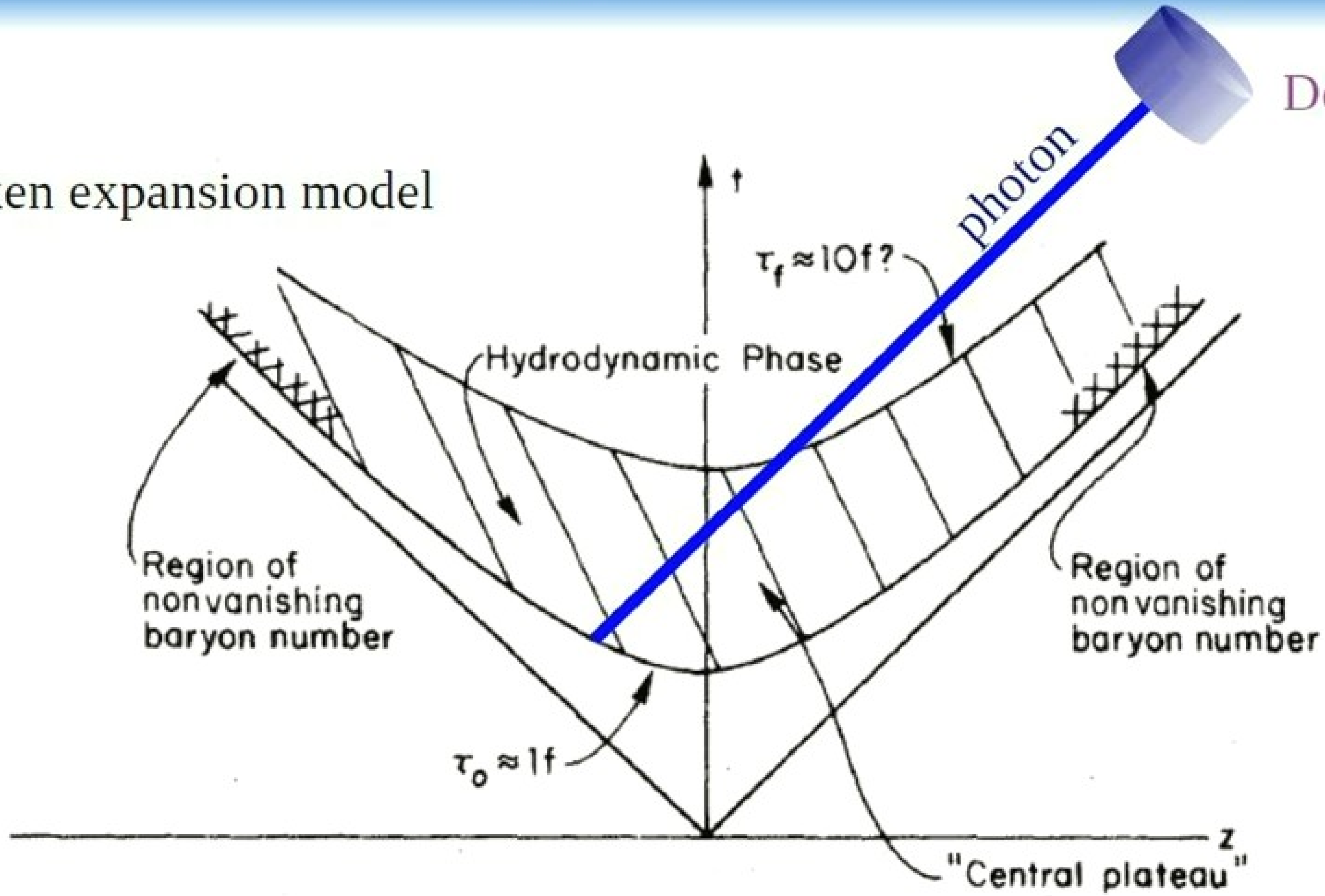
Photon rate in forward direction in the plasma rest frame:



Suppression of differential photon rate can lead to double peak structure, but this still needs to be integrated over space-time.

Space-time diagram of the collision

Bjorken expansion model

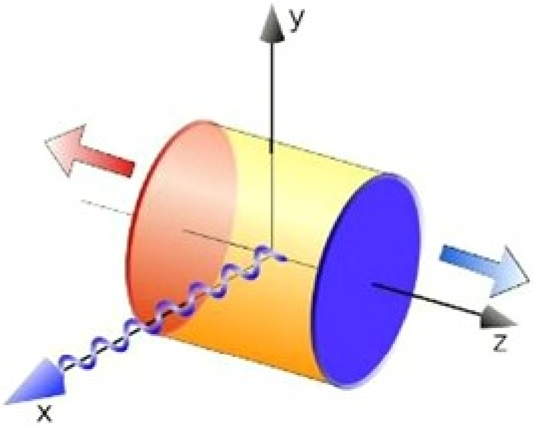


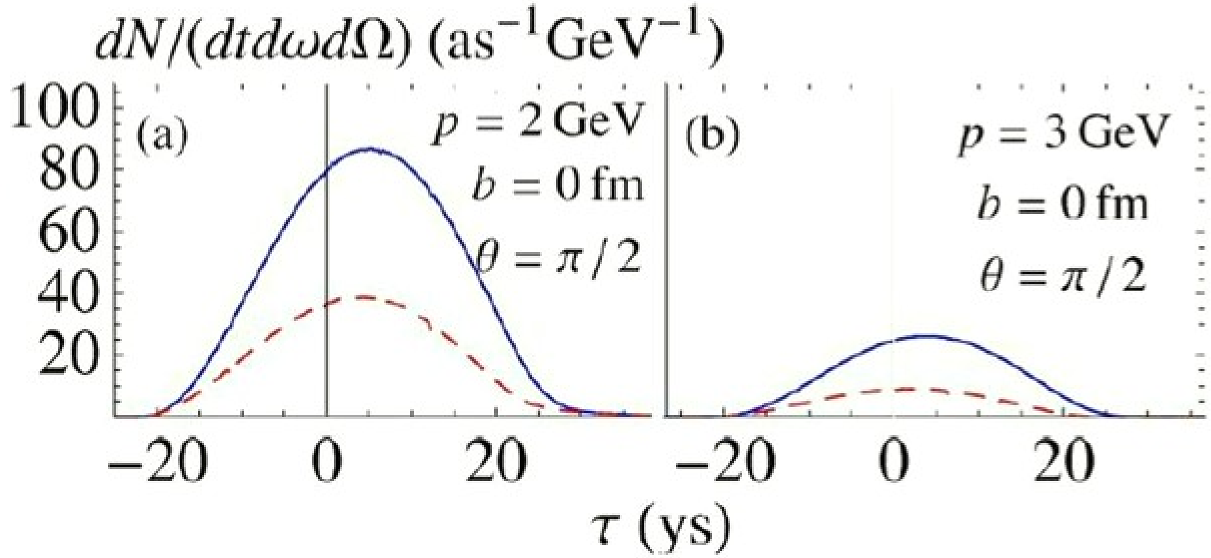
J. D. Bjorken, PRD 27, 140 (1983)

See also: possibility of plasma instabilities in anisotropically expanding plasma:
Romatschke, Rebhan (2006); Rebhan, Strickland, Attems (2008);
Rebhan, Steineder (in preparation)

Emission transverse to beam axis

Time evolution of photon emission





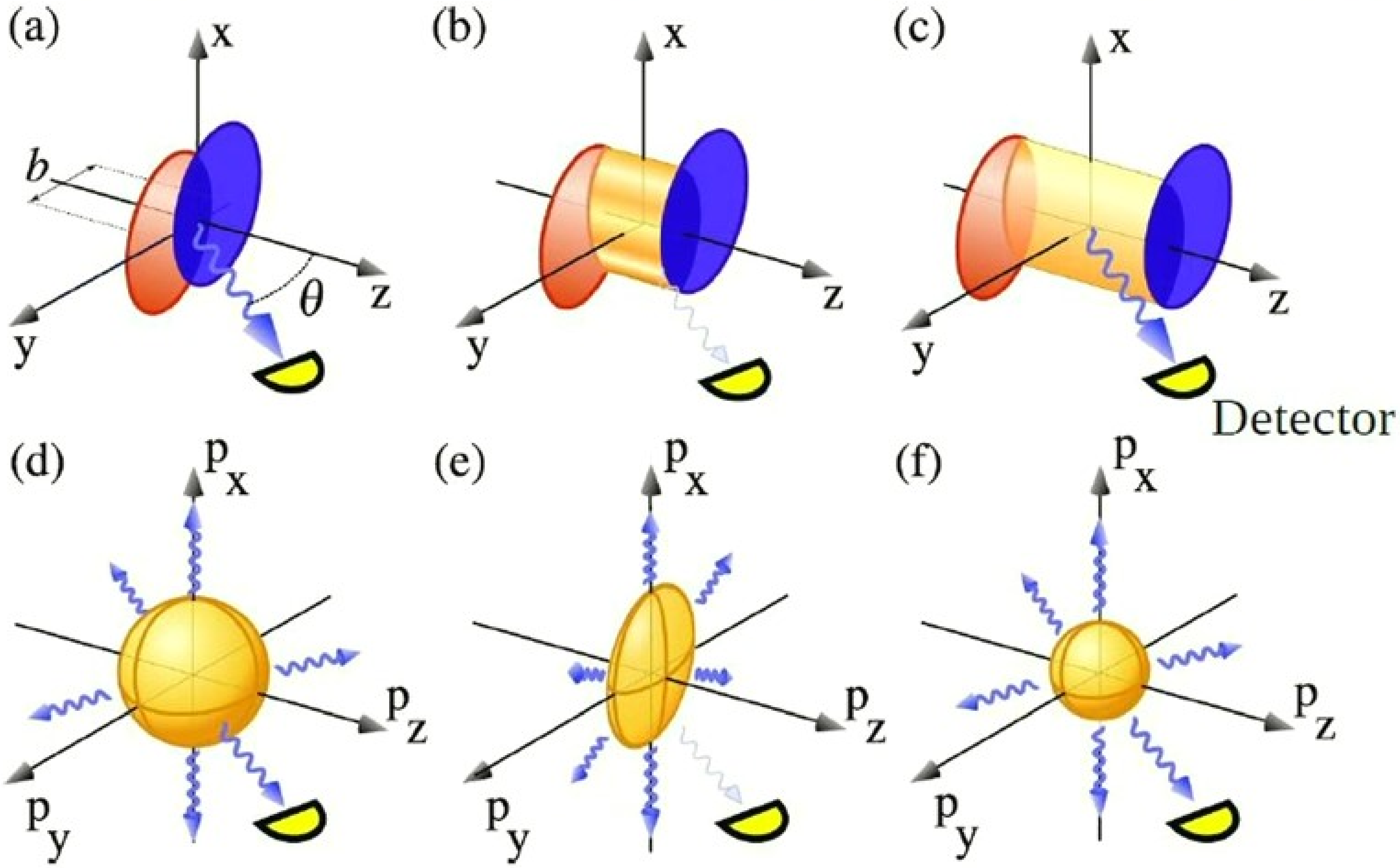
Structure of peak fully dominated by geometry.

Double peak structure washed out.

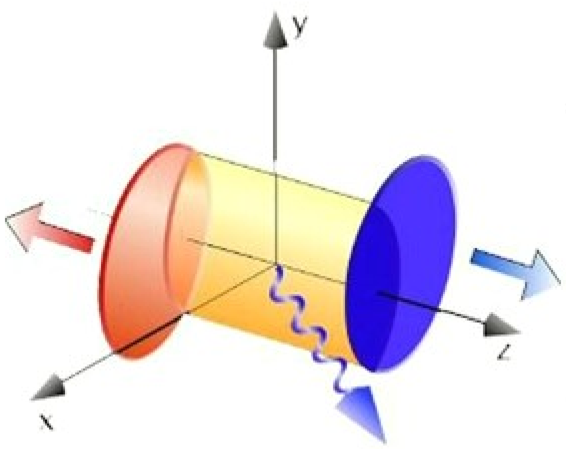
Non-central collisions

In order to see double peaks, one needs:

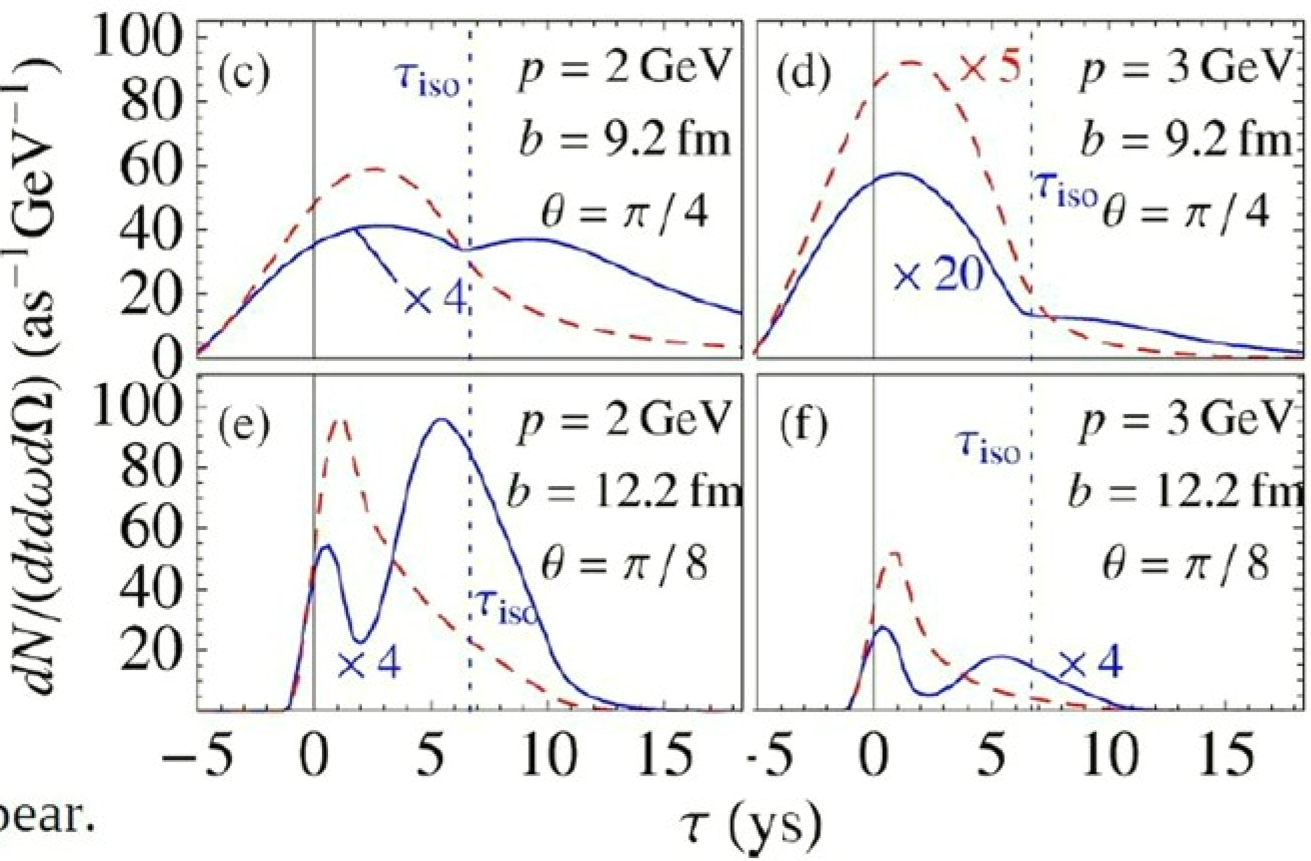
- non-central collisions (to decrease physical size of QGP)
- detector in forward direction (to increase effect of momentum anisotropy)



Non-central + forward direction



Time evolution of photon emission



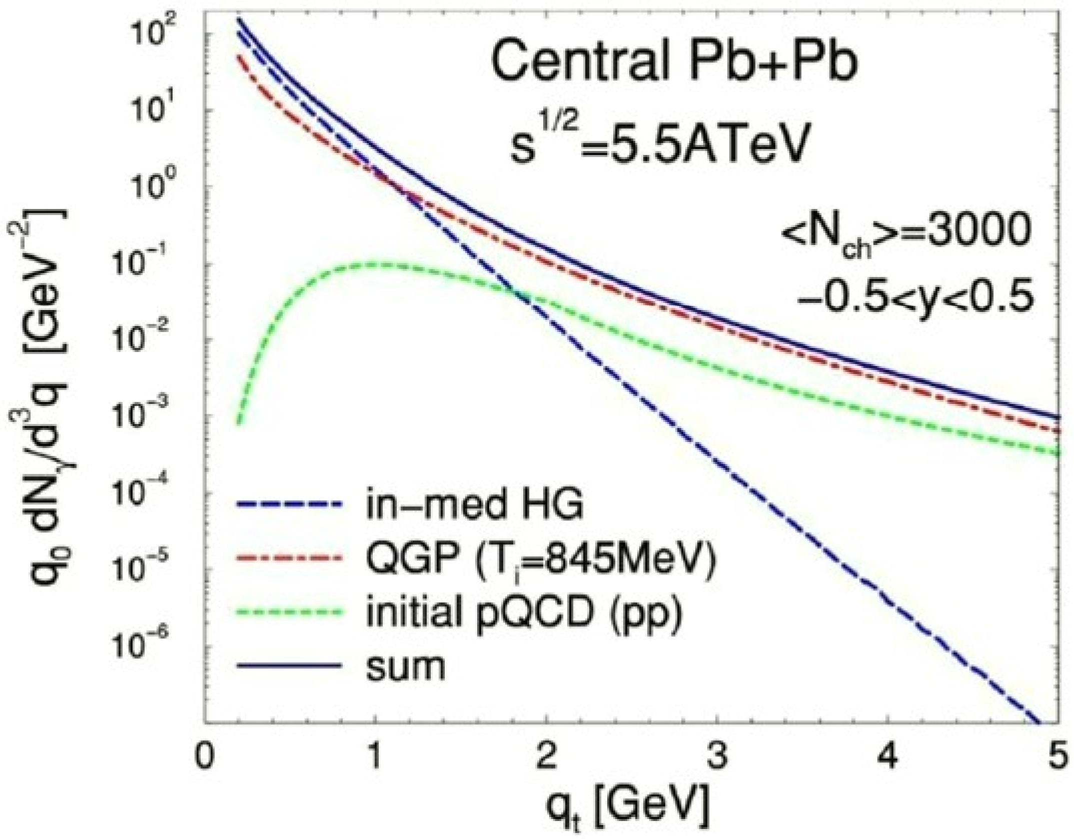
Intermediate angle:
a double peak may appear.

(but: large model uncertainties)

Pump probe experiments at the yocto-second time-scale?

Photon properties

- Other photon sources:

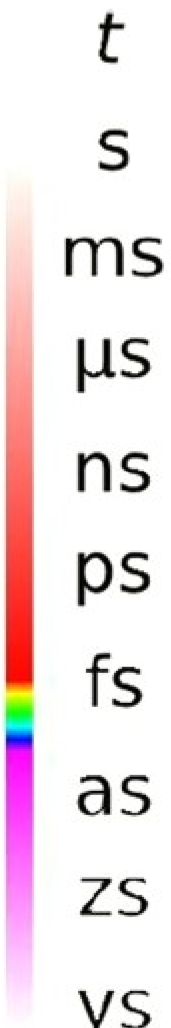


Turbide, Rapp, and Gale, PRC **69**, 014903 (2004)

- Only few GeV photons emitted per collision.
- 1 GeV photon per 10 ys:
  pulse energy: ~100 pJ
  pulse power: ~10 TW
- Single photon per pulse in principle sufficient to reconstruct nontrivial pulse shape.

Keller *et al.*, Nature 431, 1075 (2004)
Kolchin *et al.*, PRL 101, 103601 (2008)

Summary



- Timescales down to yoctosecond
  - Different systems accessible at different scales
- Quark gluon plasma and photons
  - Direct photons are good probe of QGP
- Time evolution of photon production
  - double peak structure may appear
  - novel experiments at yoctosecond timescale?