A Tour of eRHIC

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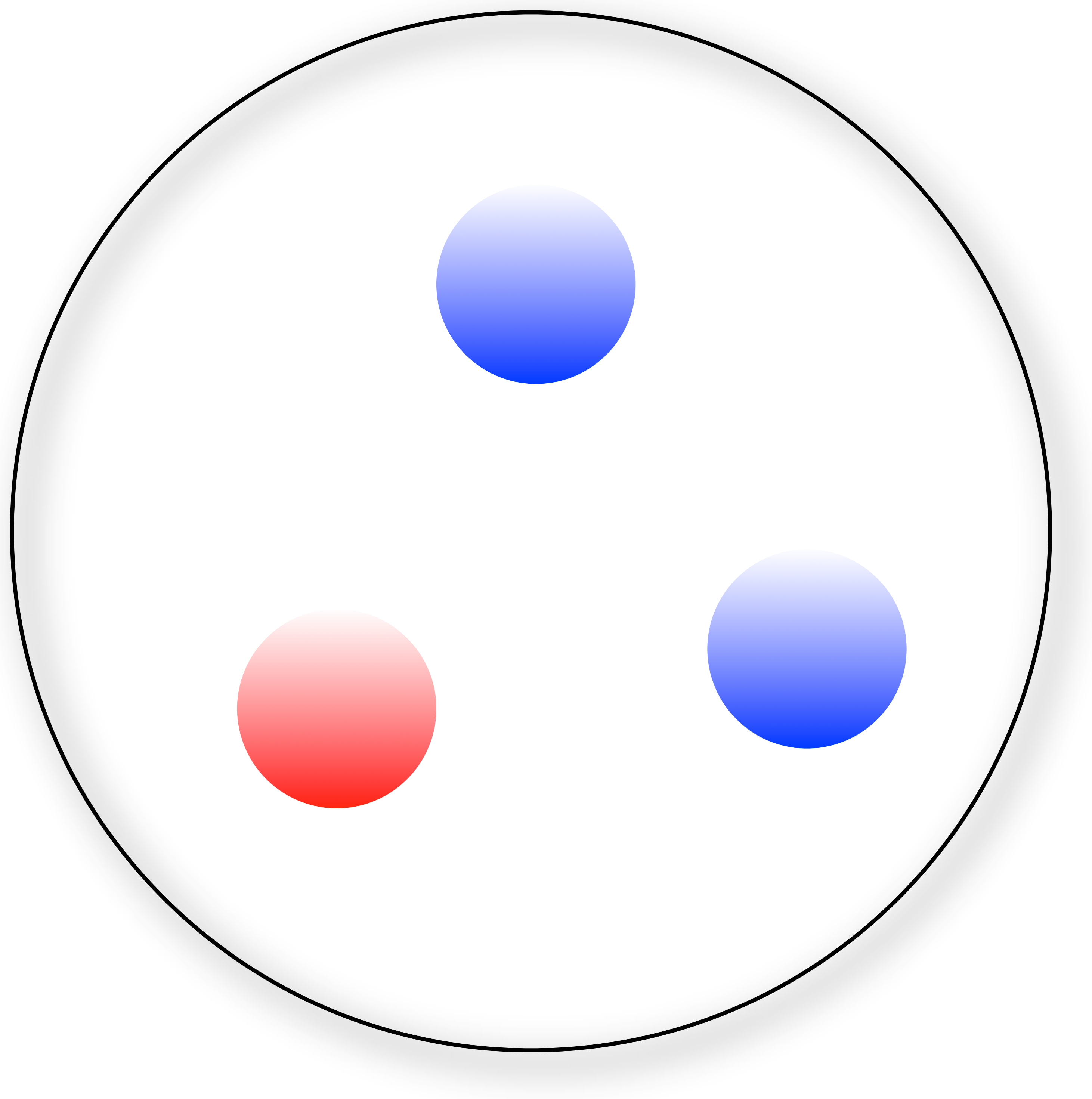
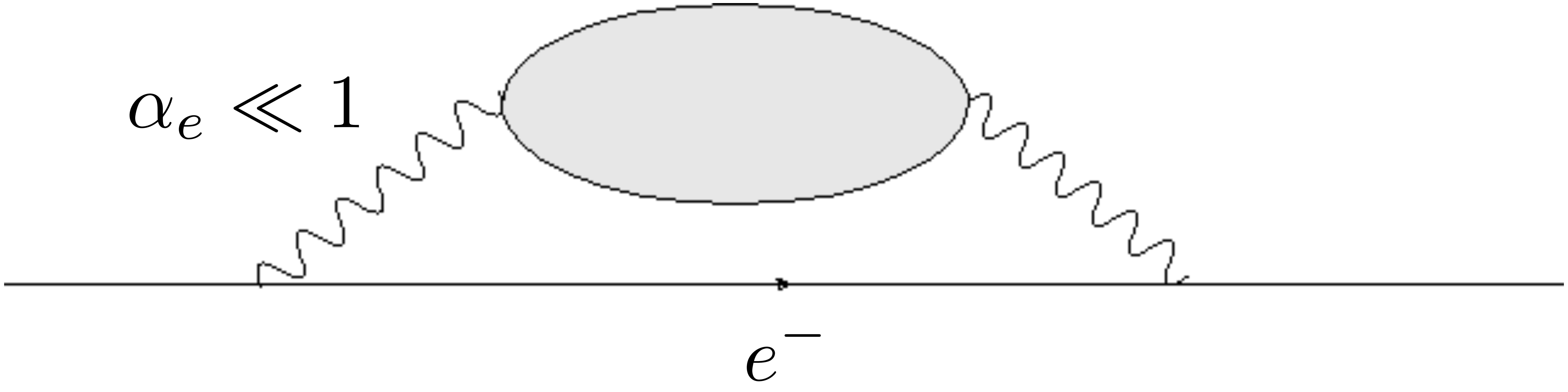
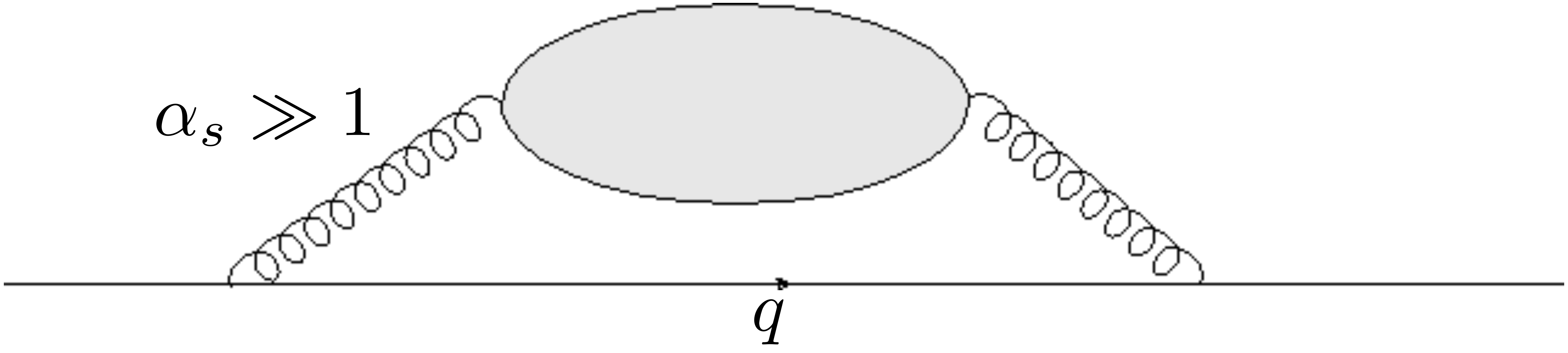


Parton Model



Parton Model



Parton Model

- Valence quarks determine quantum numbers
- Momentum carried mostly by virtual quarks & gluons
- Parton distribution function

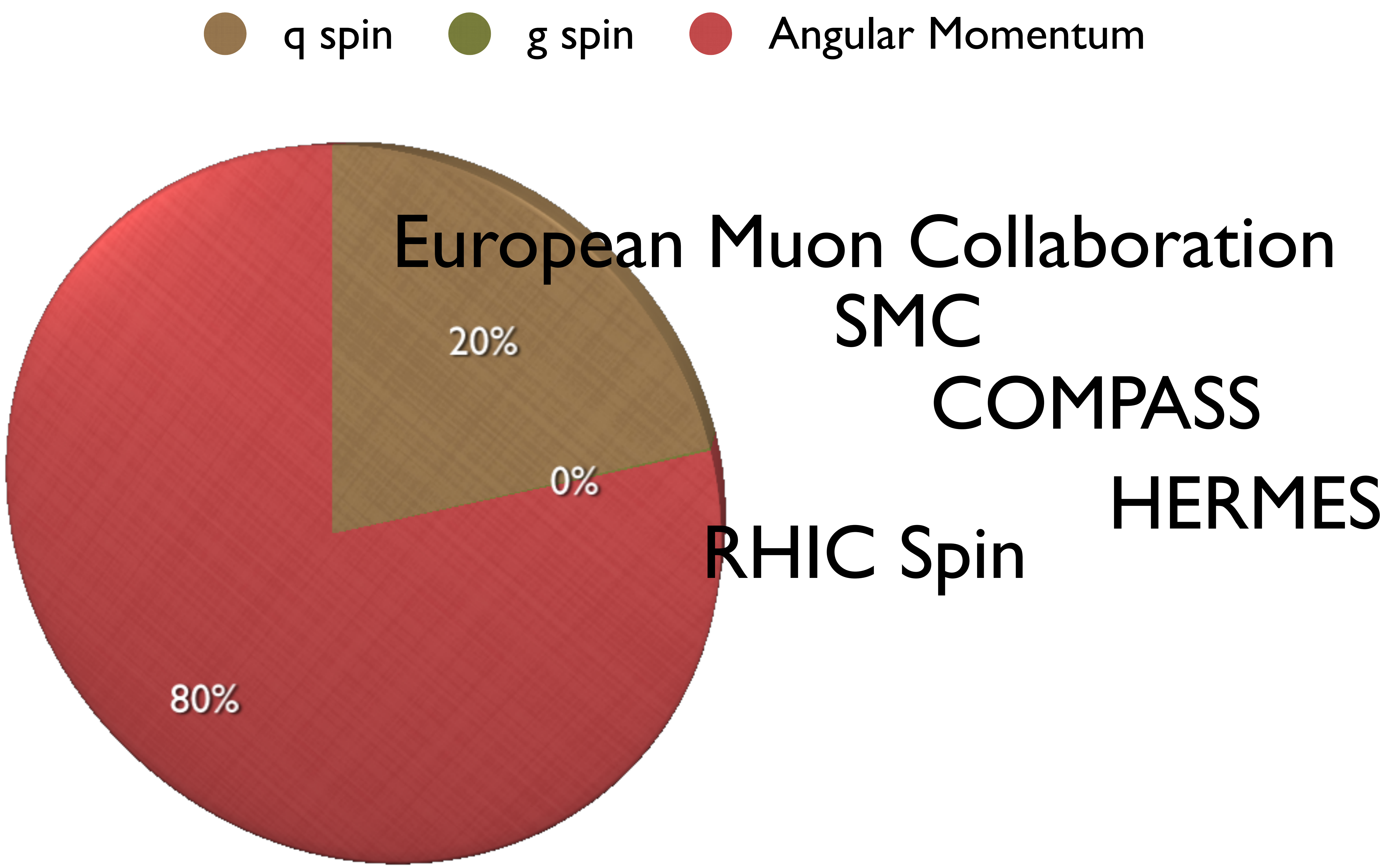
Spin Crisis

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G(Q^2) + L_q(Q^2) + L_g(Q^2)$$

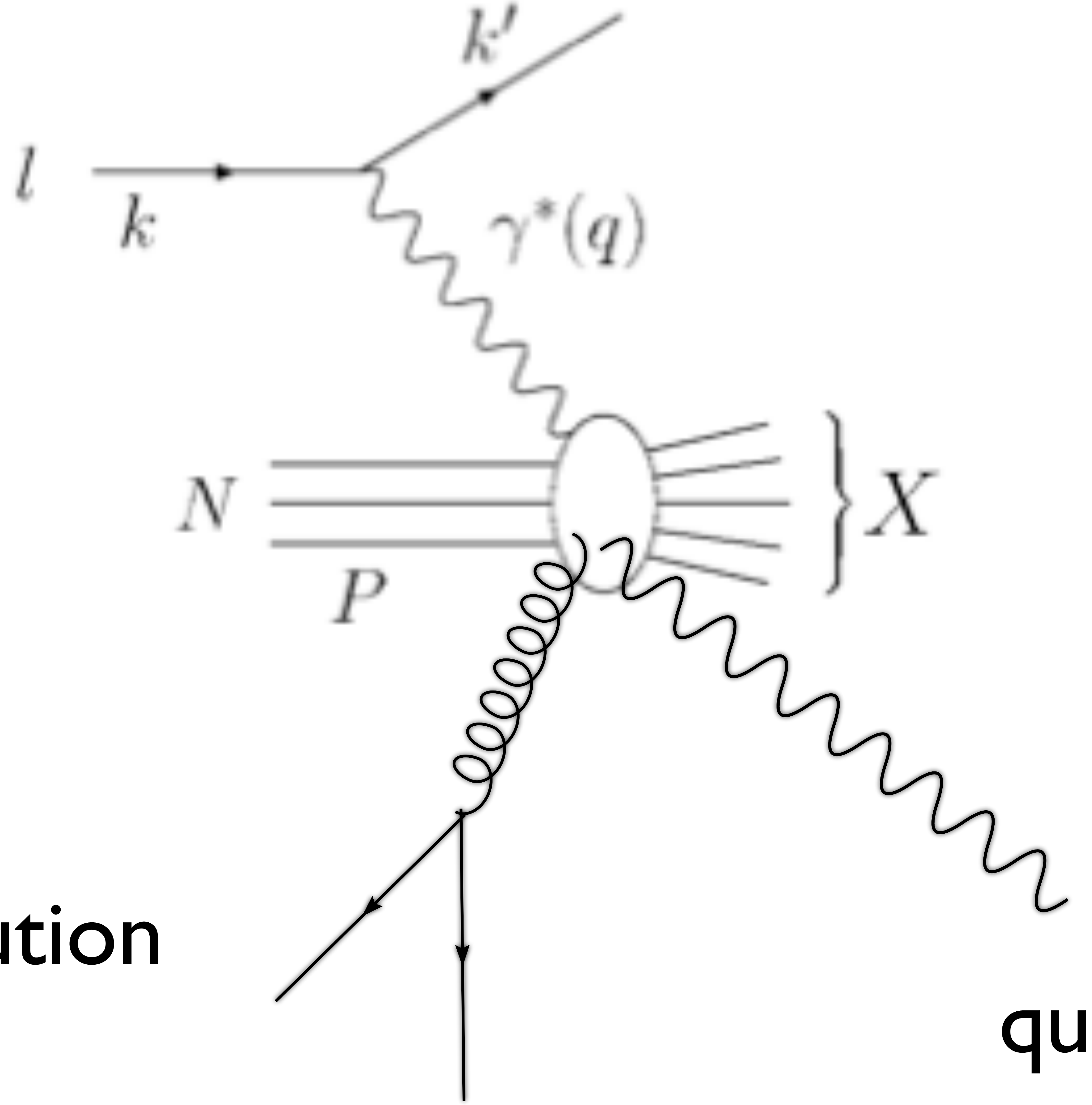
Quark Spin Gluon Spin Orbital Angular Momentum

Spin Crisis

- Spin of the quark: ~ 20%
- Spin of the gluons: ~ 0%
- Orbital angular momentum



Spin Crisis



Deeply Virtual
Compton Scattering

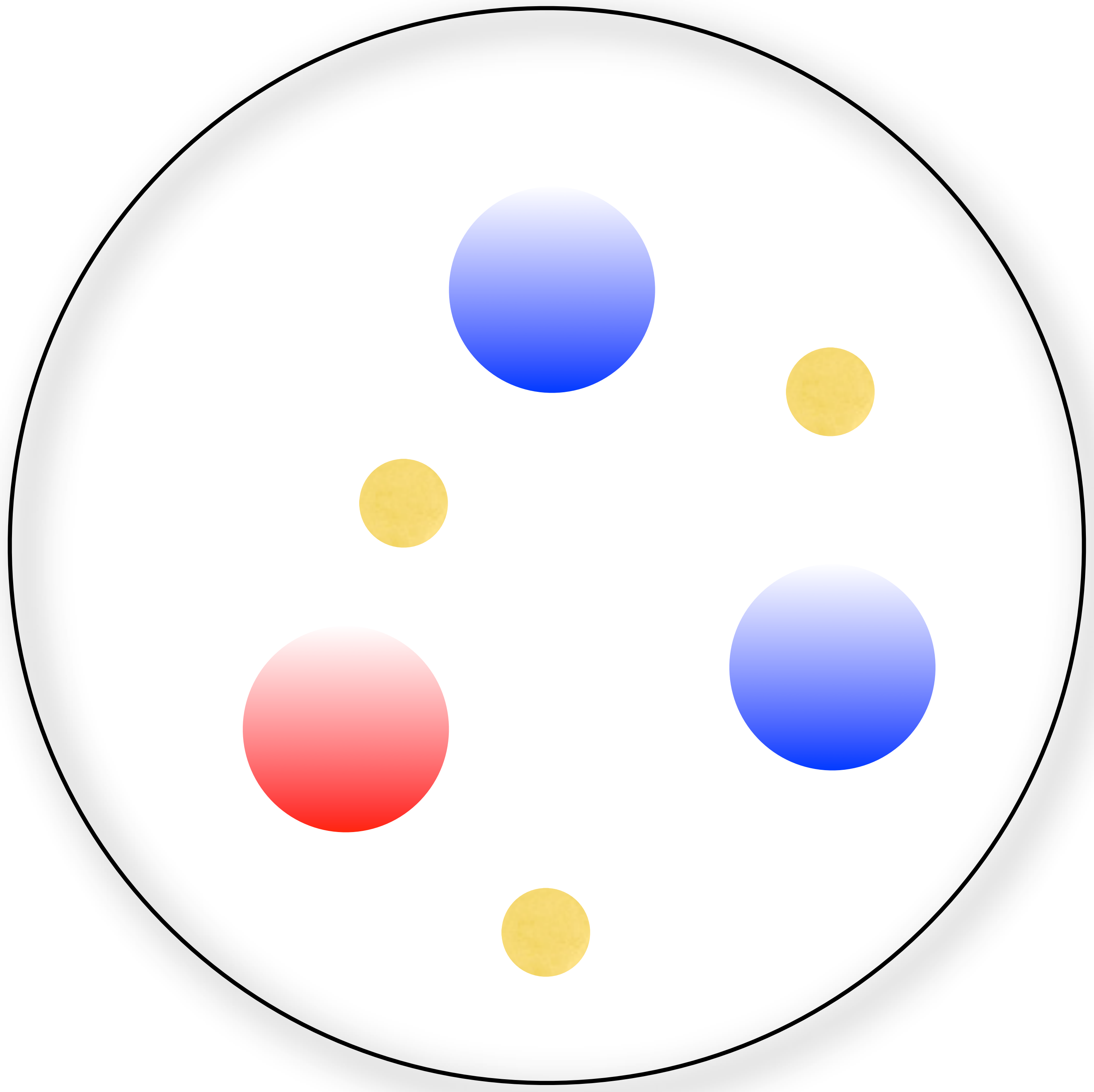
gluon distribution

Deeply Inelastic lepton-
nucleon scattering

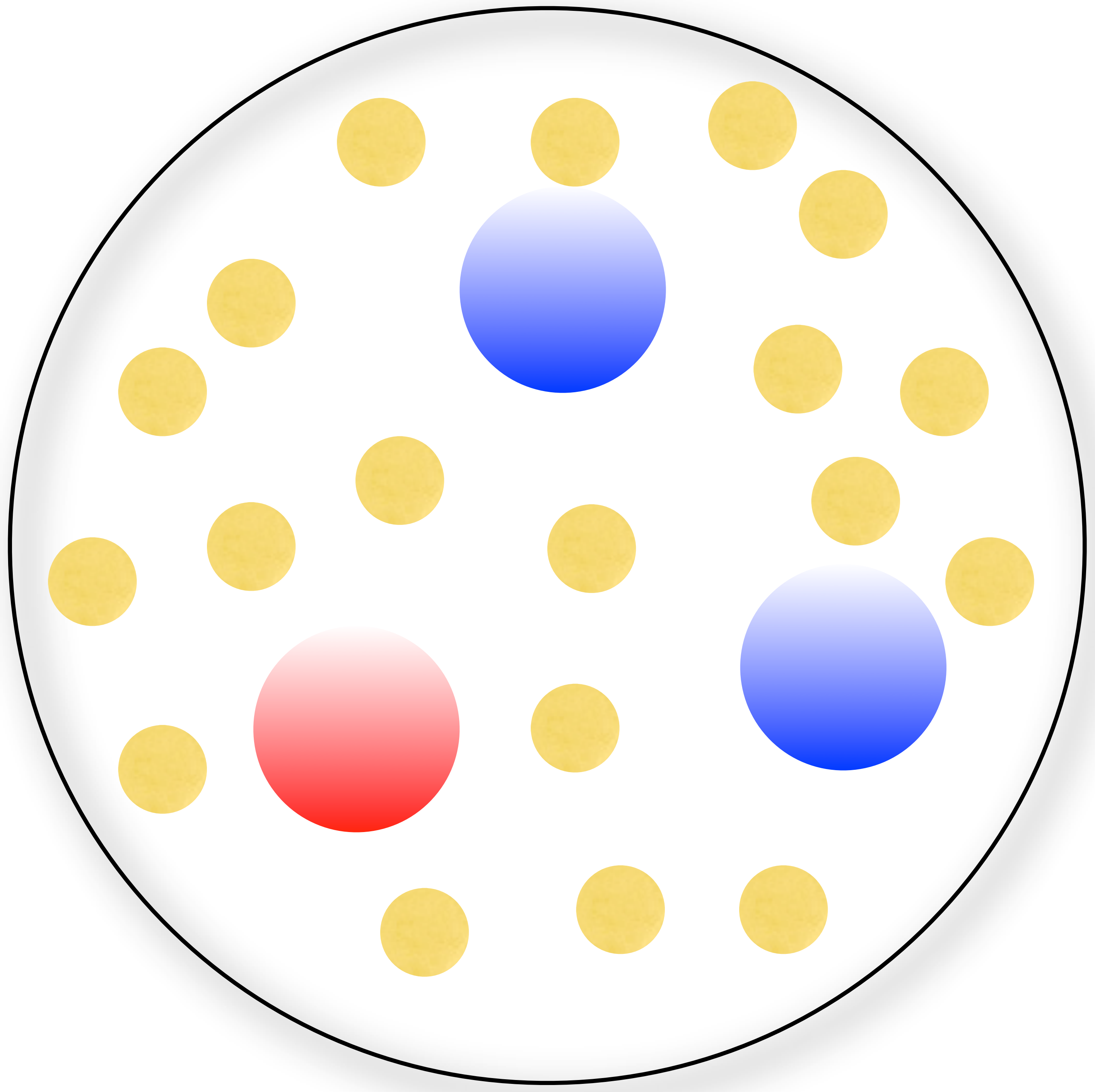
quark distribution

From Deshpande et al. Annu. Rev. Part. Sci. (2005)

Color Glass Condensate

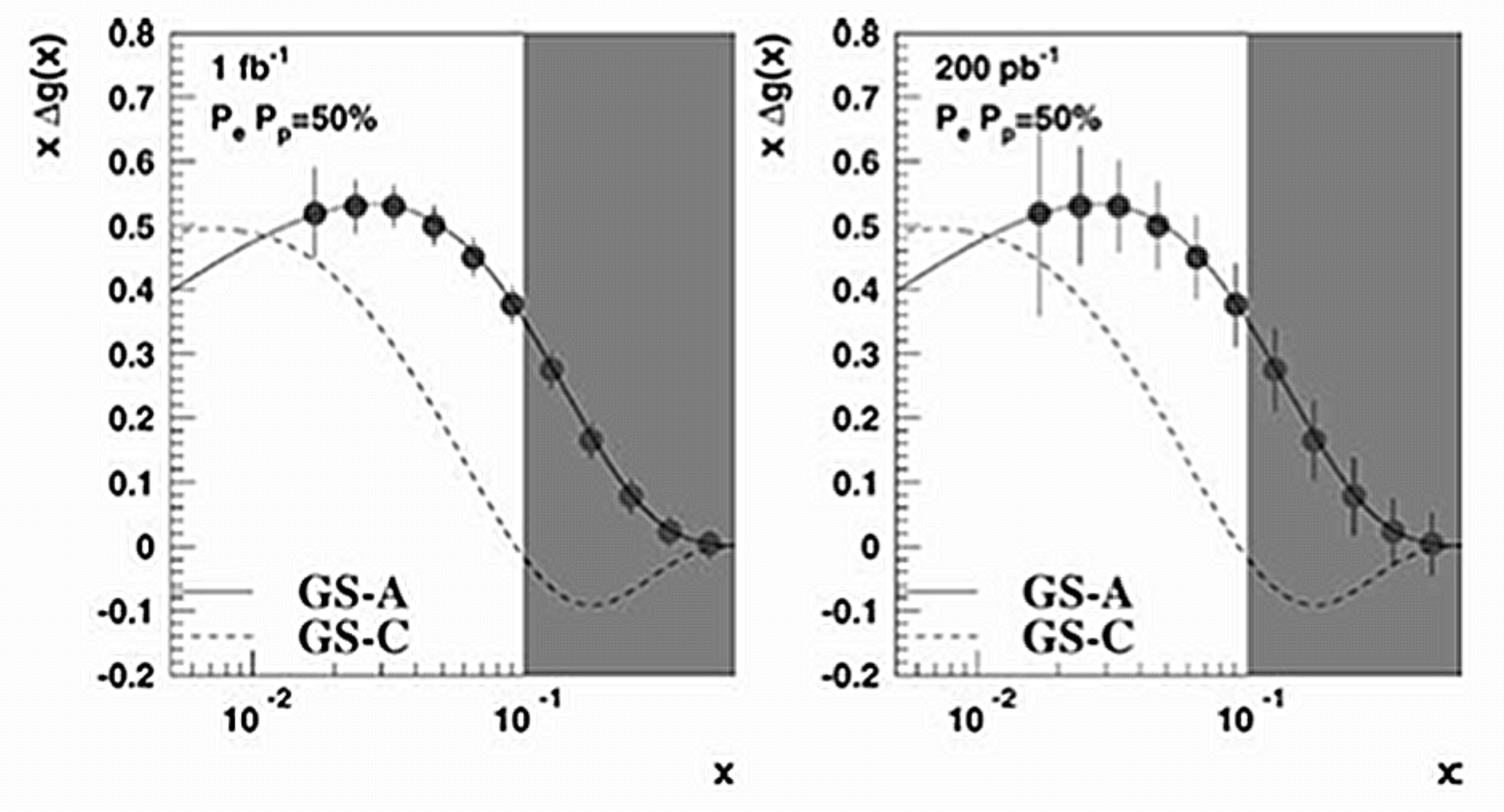


Large x



Small x

Gluon PDF



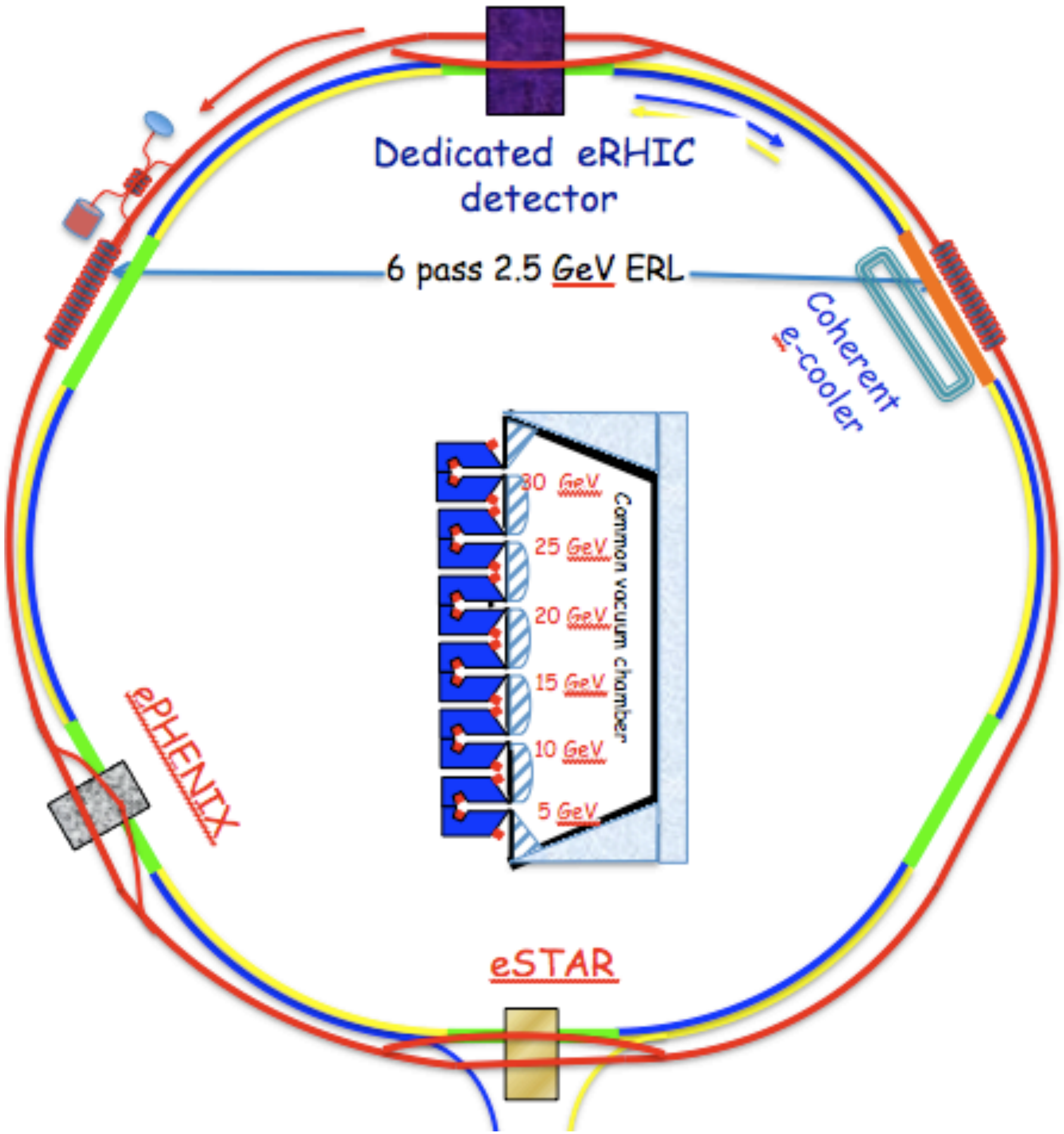
From Deshpande et al. Annu. Rev. Part. Sci. (2005)

Color Glass Condensate

- Saturation limit at infinite energy
- Accessible experimentally by heavy ions
- Allows condensed matter in QCD

eRHIC Requirements

- High luminosity
- High spin polarization

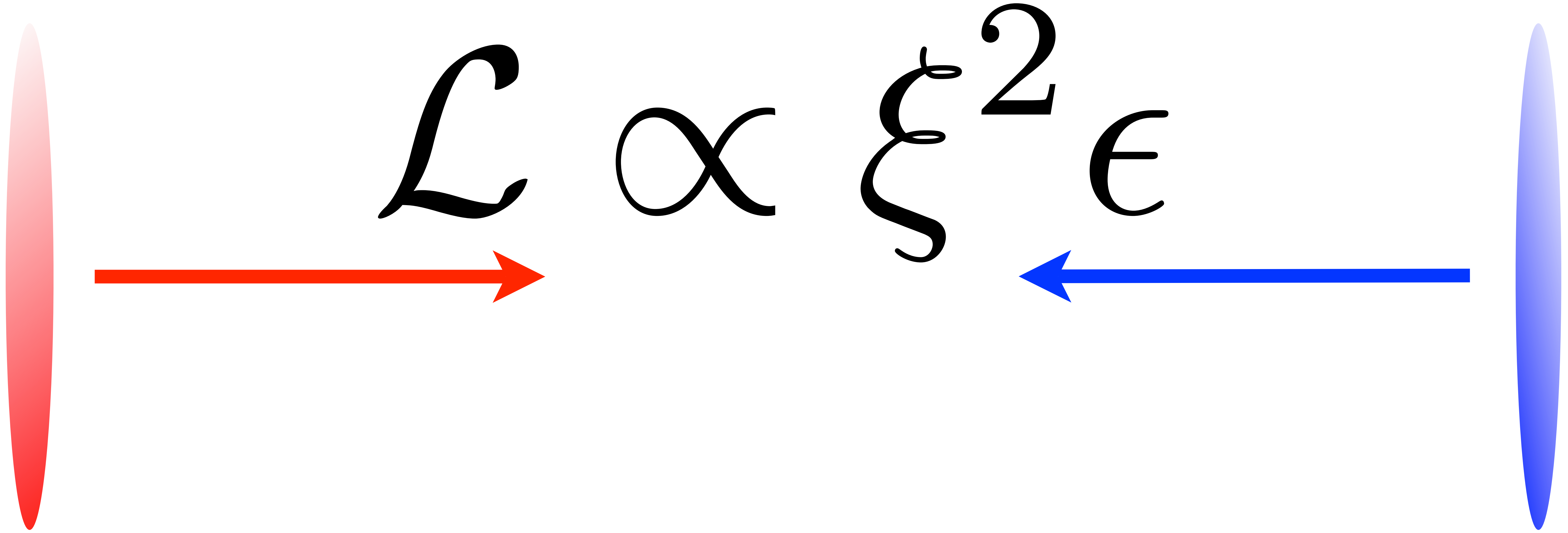


Shamelessly lifted from http://www.bnl.gov/cad/eRhic/

Luminosity

$$\mathcal{L} = \frac{N_e N_h}{4\pi\sqrt{\beta^* \epsilon}} f$$

Beam-beam Interaction



$$\mathcal{L} \propto \xi^2 \epsilon$$

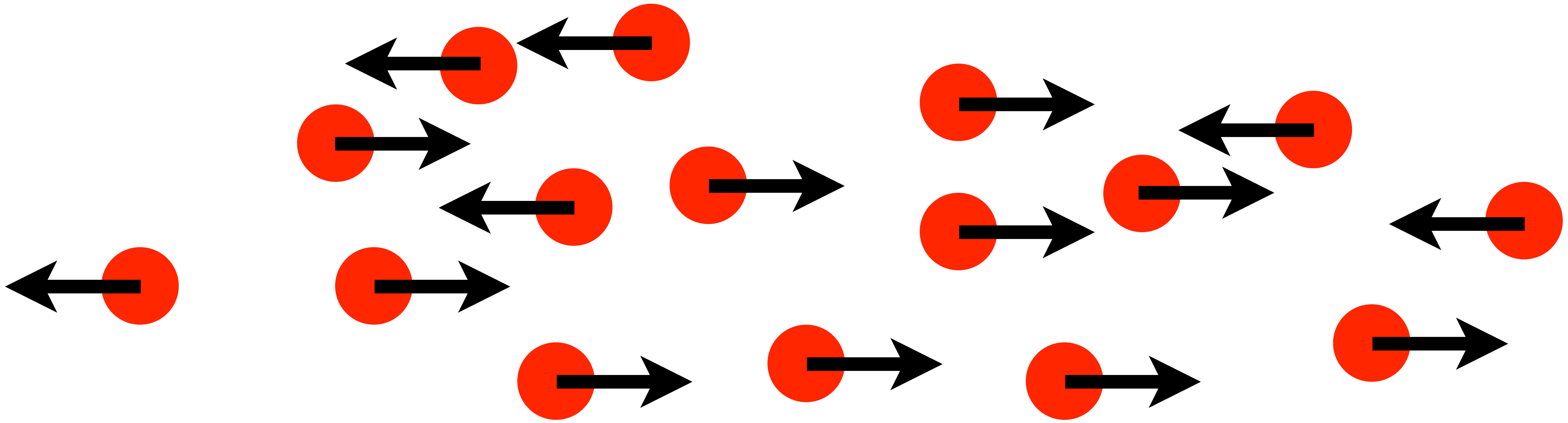
$$\xi_i^{\pm} = \frac{N^{\mp} r_e \beta_i^{0\pm}}{\gamma \, 2\pi \sigma_i^{\mp} (\sigma_x^{\mp} + \sigma_y^{\mp})}$$

$$\xi \sim \frac{N}{\epsilon}$$

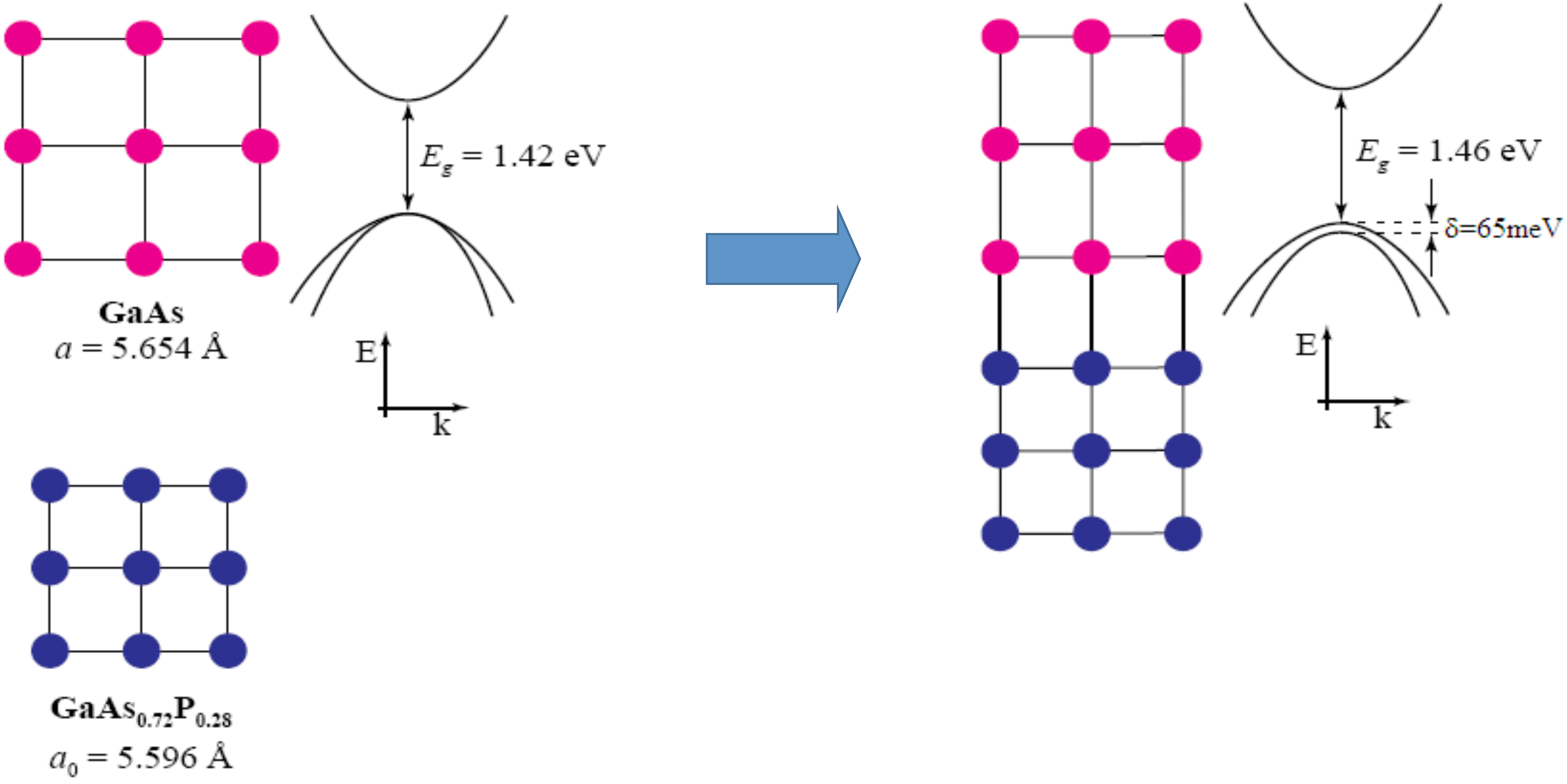
$$\xi \sim 0.05 - 0.10$$

Spin Polarization

$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

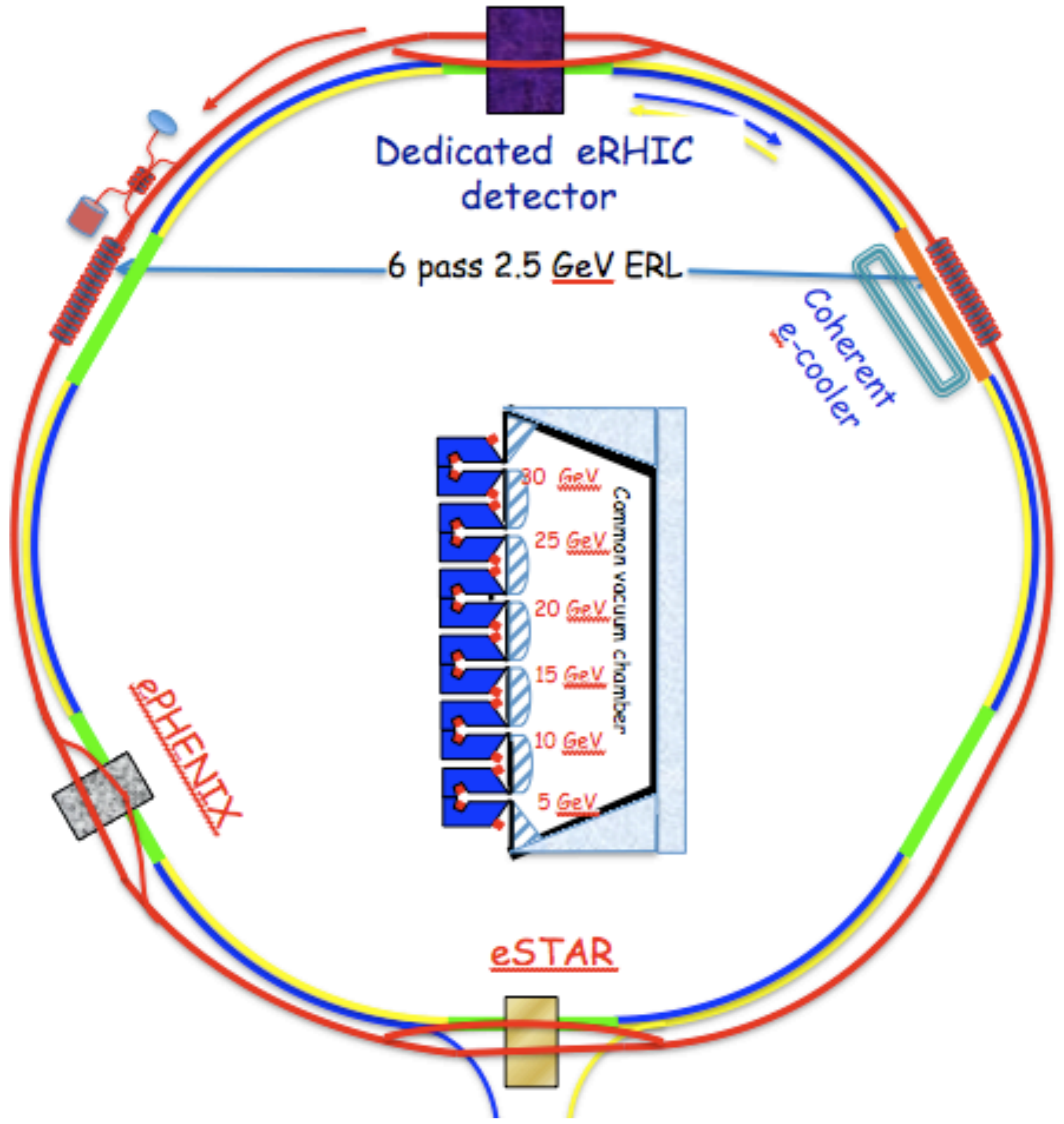


Spin Polarization



Shamelessly used courtesy of Erdong Wang

Energy Recovery Linac



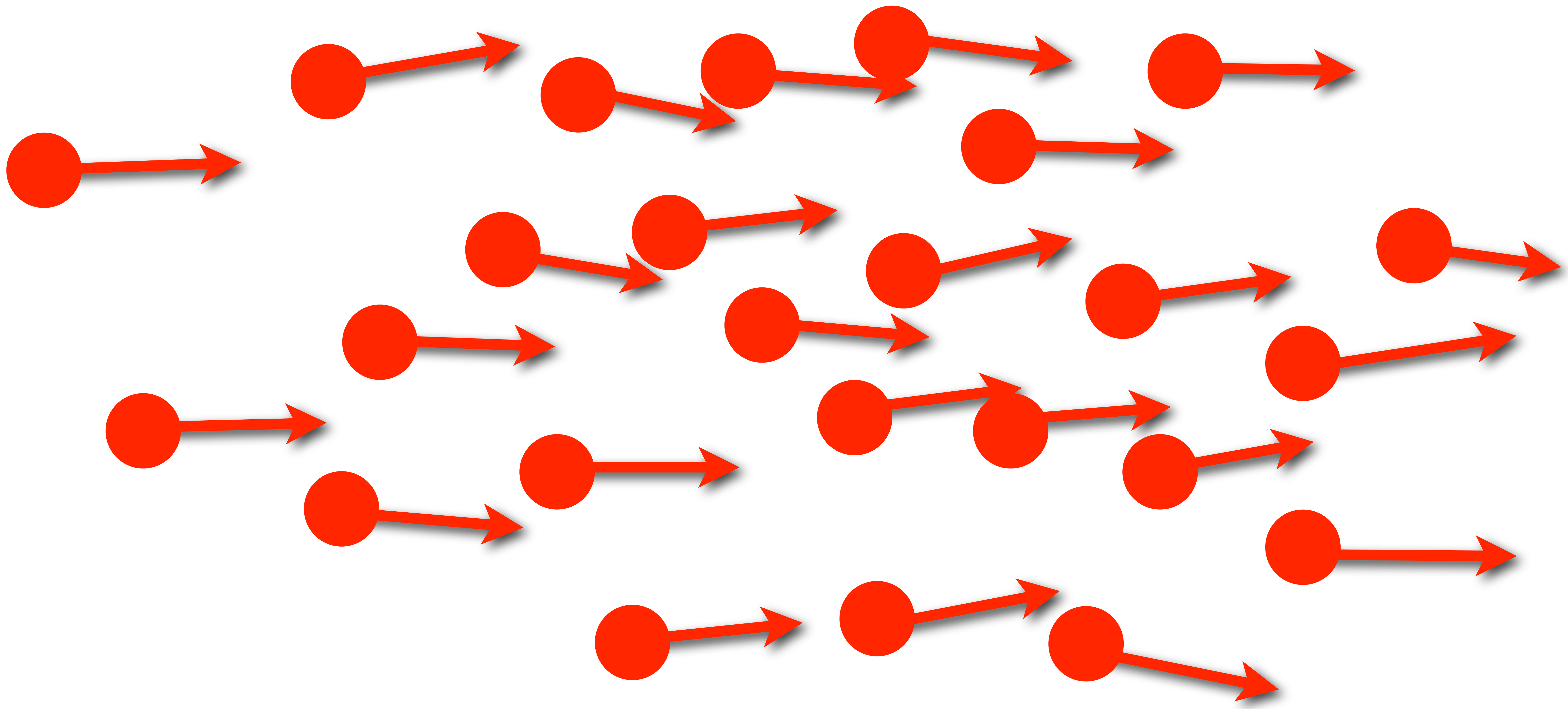
50 mA X 20 GeV = 1 GW

Richard M. Flynn Power Plant
Holtsville, NY
135 MW

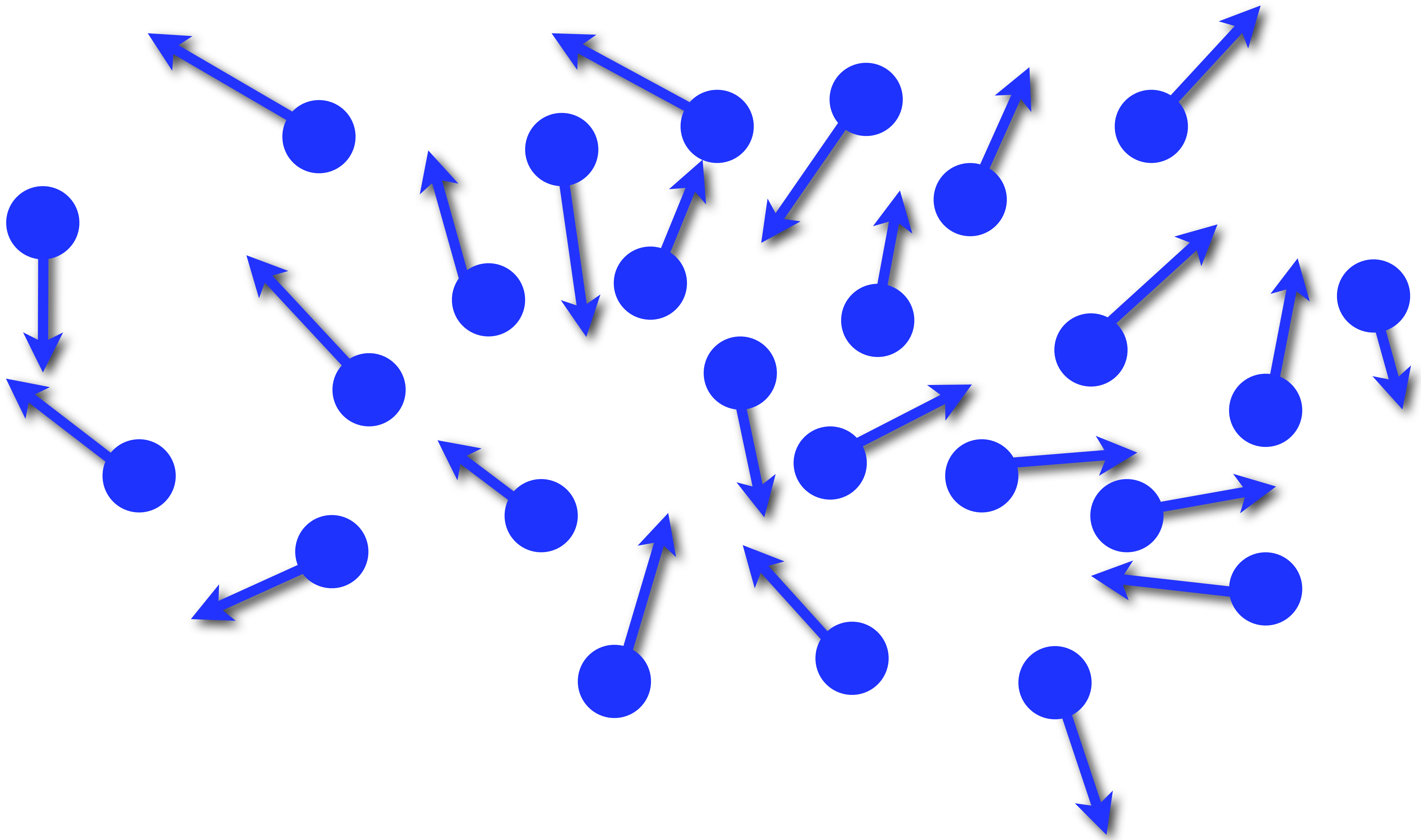
eRHIC Parameters

	e	p	He	Au	U
Energy (GeV)	20	325	215	130	130
Current (mA)	50	420	420	420	420
Polarization, %	80	70	70	none	none
Beta, cm	5	5	5	5	5
Luminosity	1.46×10^{34} cm $^{-2}$ sec $^{-1}$				

Intra-Beam Scattering



Intra-Beam Scattering



Intra-beam Scattering

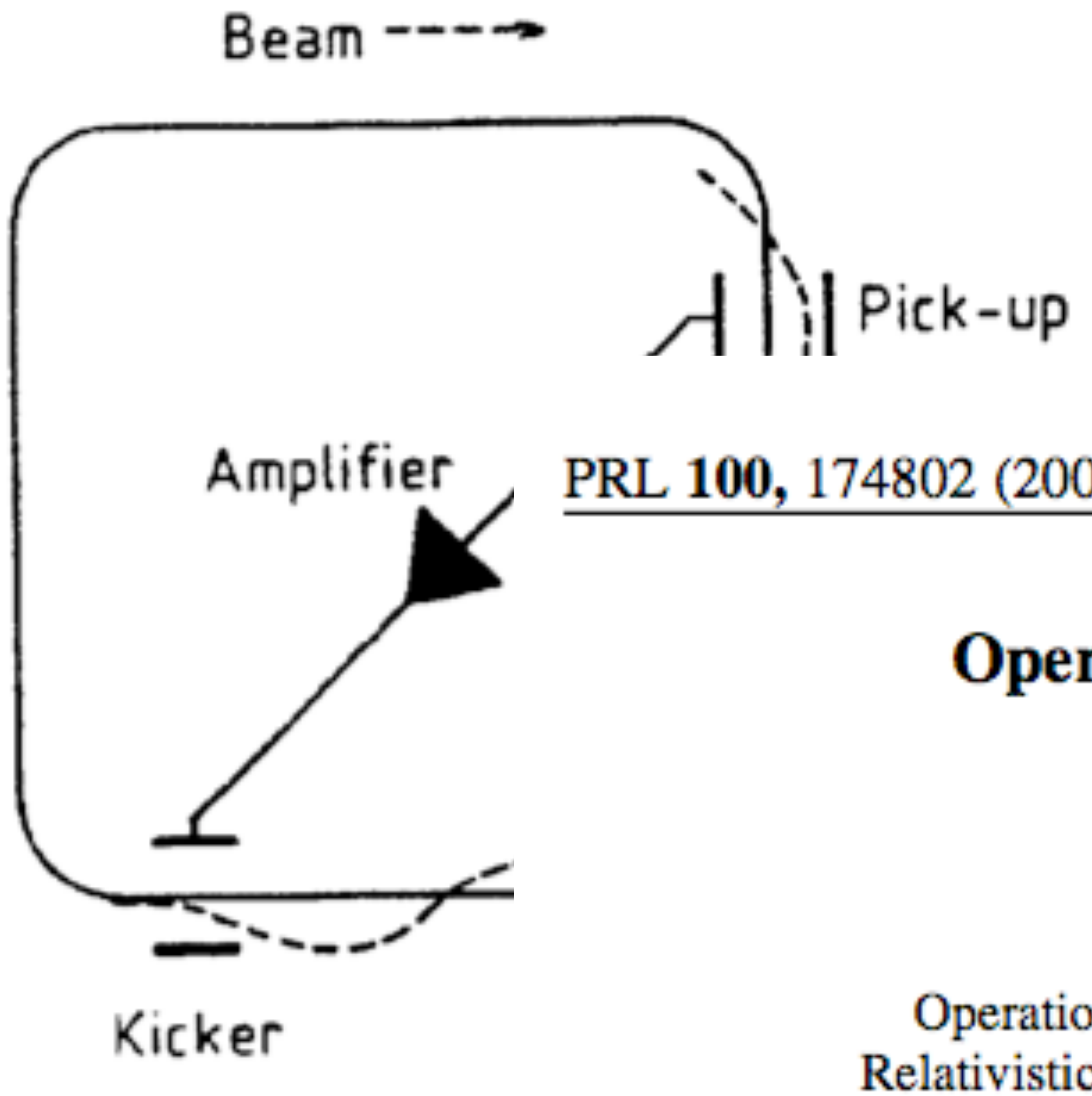
Dispersion

$$x_\beta = x - D\frac{\Delta p}{p}$$

Coulomb Scatter

$$\Delta(\epsilon_{x,1} + \epsilon_{x,2}) = 2\frac{\pi}{\beta_x}\frac{p_x}{p}^2[(D\gamma)^2 - \beta_x^2]$$

Intra-beam Scattering



$$\frac{1}{\ } \propto \frac{2W}{\ }$$

PRL **100**, 174802 (2008) PHYSICAL REVIEW LETTERS week ending 2 MAY 2008

Operational Stochastic Cooling in the Relativistic Heavy-Ion Collider

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(Received 2 October 2007; published 2 May 2008)

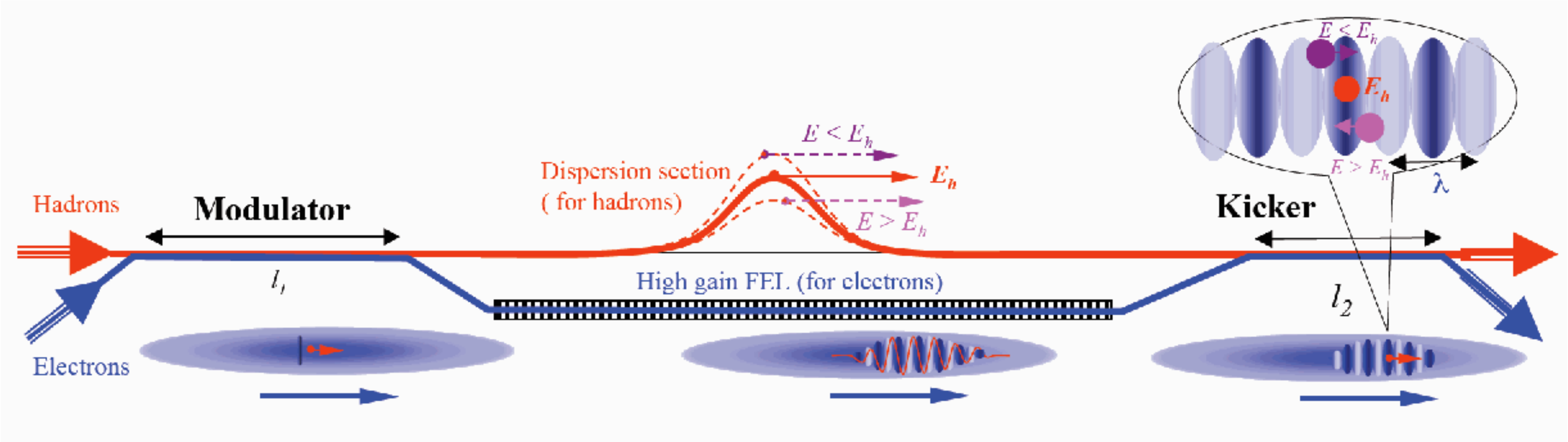
Operational stochastic cooling of 100 GeV/nucleon gold beams has been achieved in the BNL Relativistic Heavy-Ion Collider. We discuss the physics and technology of the longitudinal cooling system and present results with the beams. A simulation algorithm is described and shown to accurately model the system.

Shamelessly lifted from D. Mohl "Stochastic Cooling"

Coherent Electron Cooling

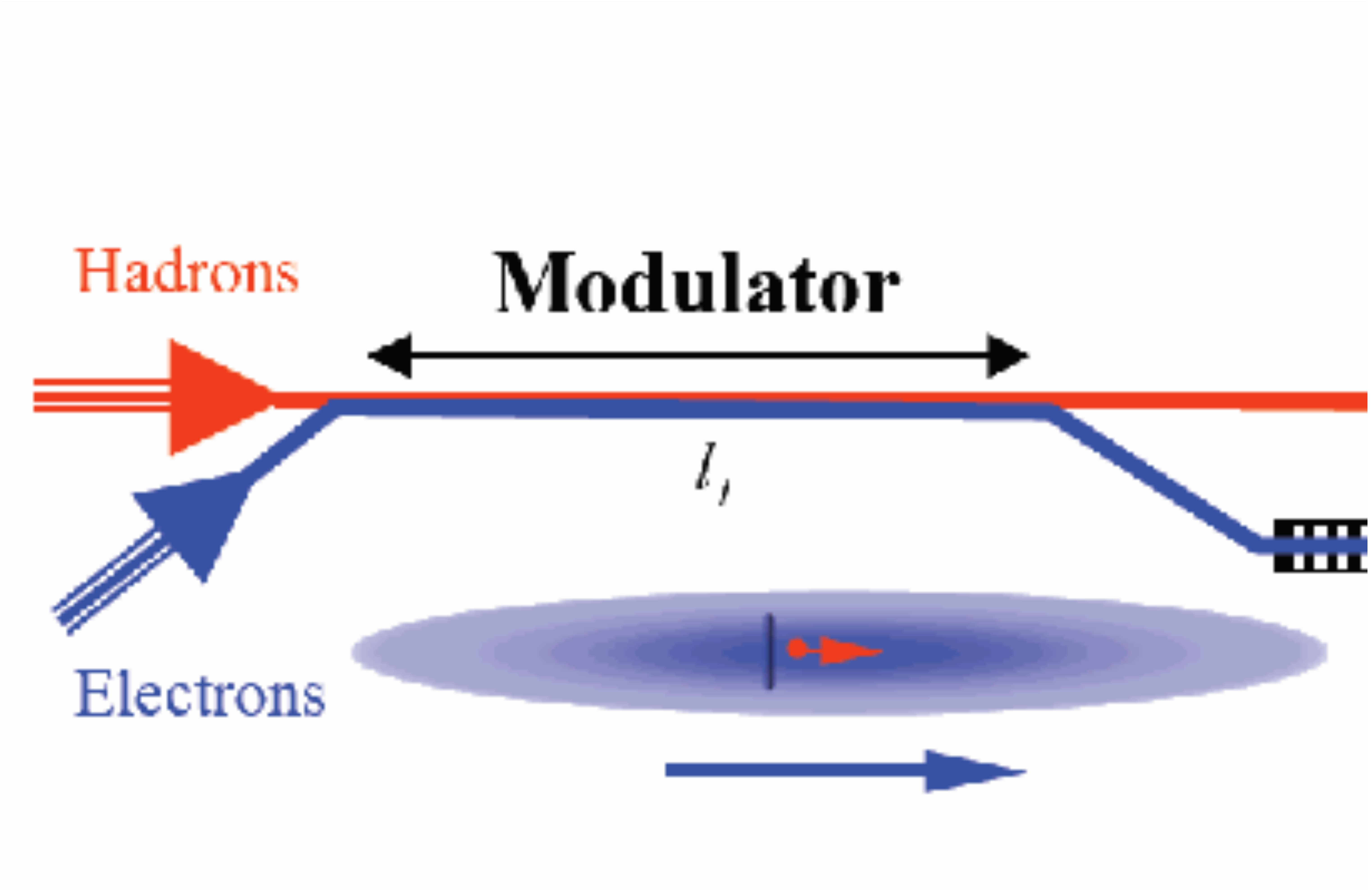
- Schematic of CeC
- Theoretical Description (FELs & plasmas)
- Current status

CeC Schematic

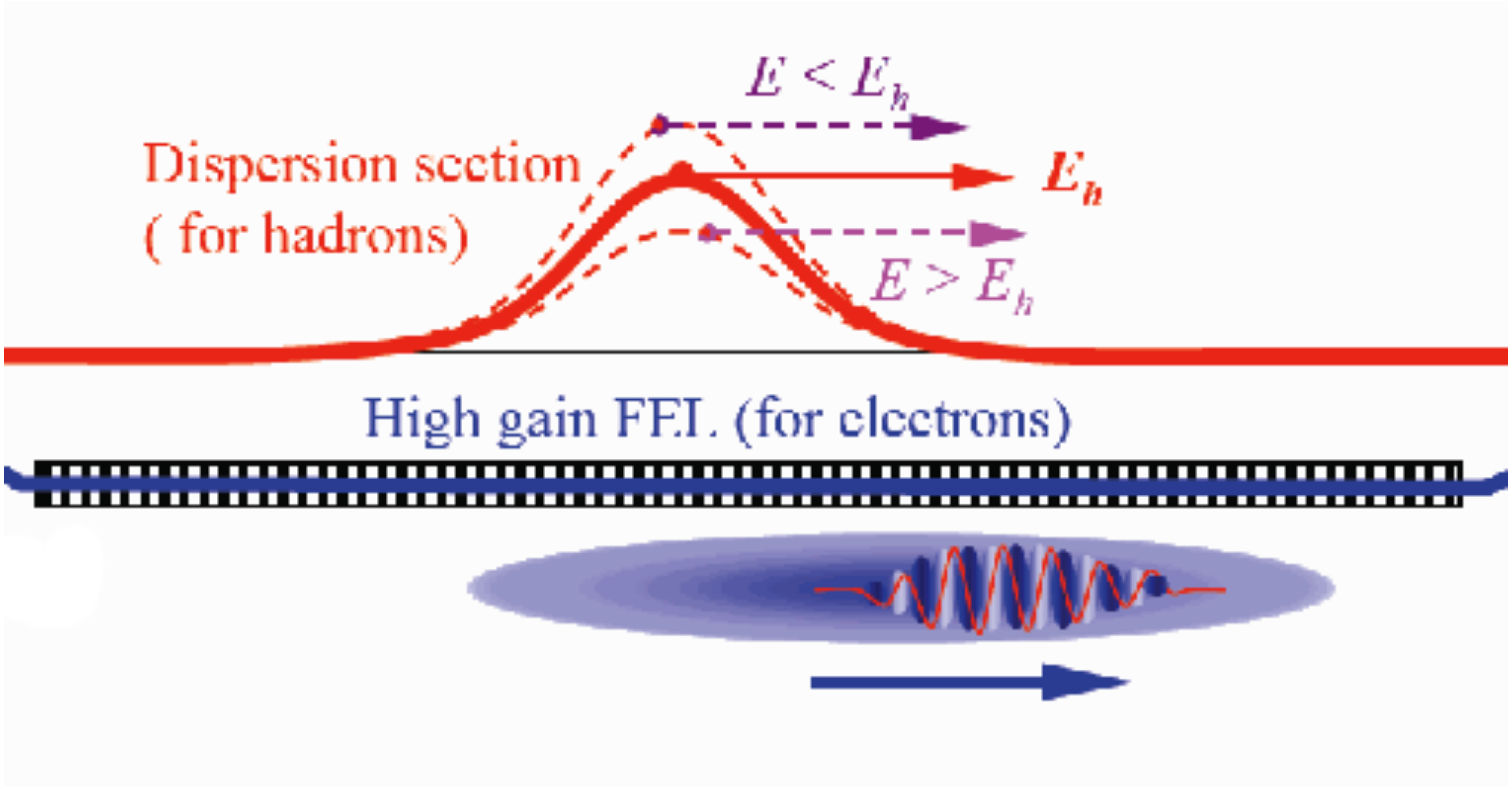


Shamelessly lifted from http://www.bnl.gov/cad/ecooling/CoherentEcooling.asp

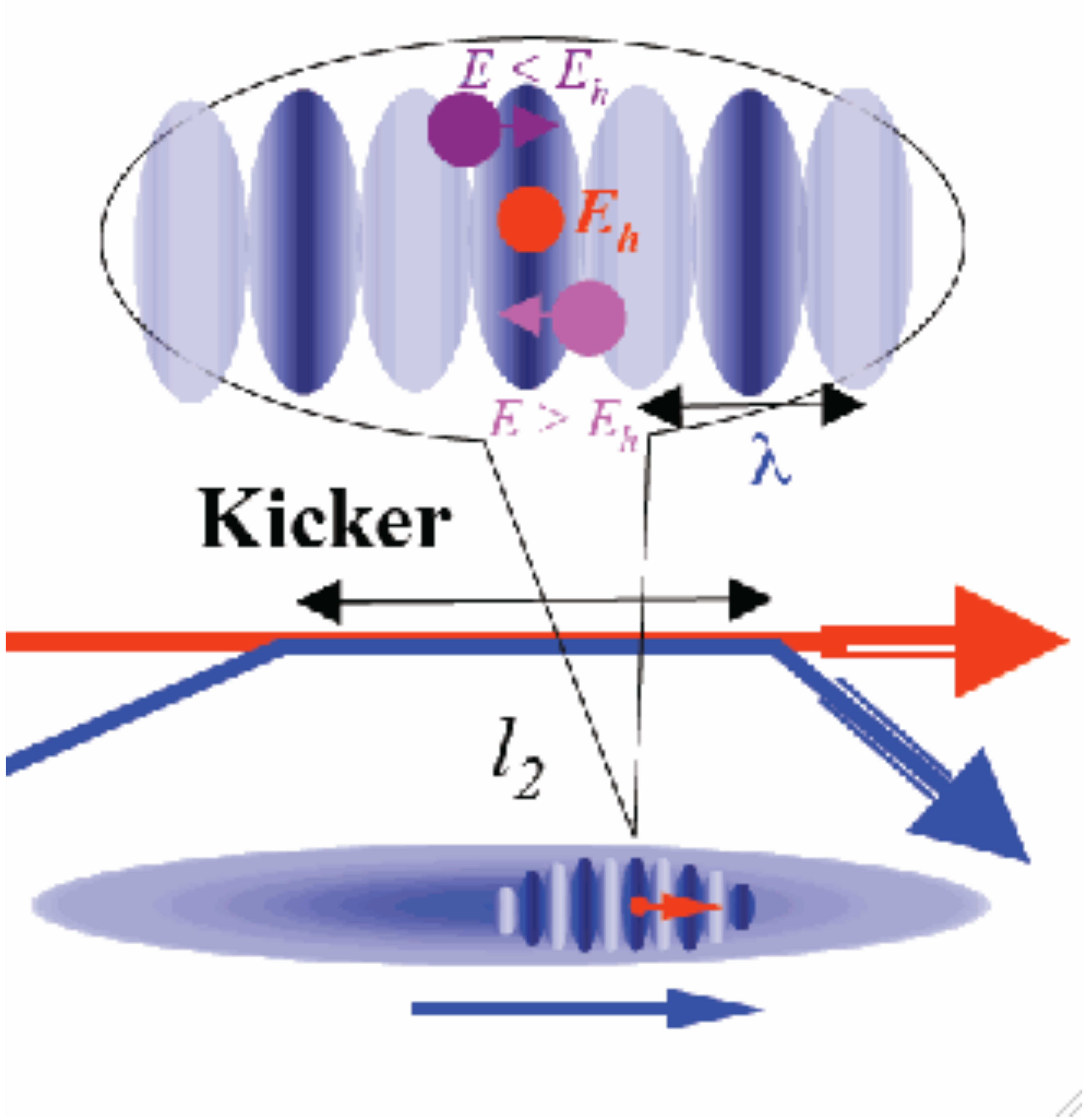
CeC Schematic



CeC Schematic



CeC Schematic



$$g \propto G_0 \frac{Z^2}{A} \frac{1}{\epsilon_\perp}$$

Theoretical Description

- [x] Debye screening of hadron in pick-up (Wang, Blaskiewicz PR E 2008)
- [ ] 3D FEL description of phase space density
- [ ] Dynamics in the kicker
- [ ] Other (???)

Theoretical Description

- [x] Debye screening of hadron in pick-up (Wang, Blaskiewicz PR E 2008)
- [x] 3D FEL description of phase space density (Webb, Wang, Litvinenko)
- [ ] Dynamics in the kicker (work in progress)
- [ ] Other (???)

1D FEL Theory

Detuning

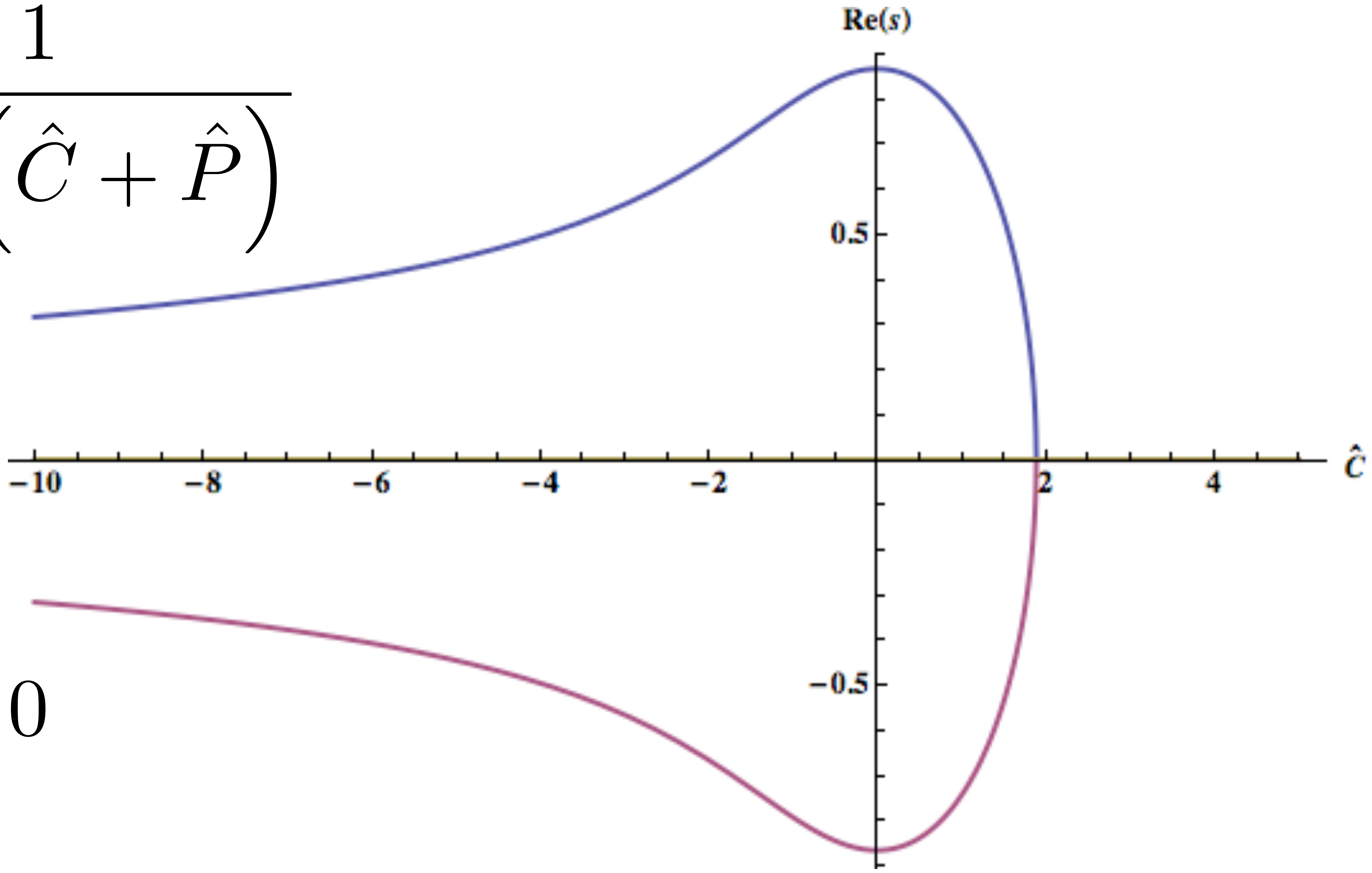
$$\hat{C} = \Gamma^{-1}\left(k_w + \frac{\omega}{c} - \frac{\omega}{v_z(\mathcal{E}_0)}\right)$$

Normalized
Energy

$$\hat{P} = \frac{\mathcal{E} - \mathcal{E}_0}{\rho \mathcal{E}_0}$$

1D FEL Theory

$$s - \int d\hat{P}\ \frac{d\hat{F}}{d\hat{P}} \frac{1}{s + \imath\left(\hat{C} + \hat{P}\right)}$$



$$s\left(s + \imath\hat{C}\right)^2 - \imath = 0$$

3D FEL Theory

Detuning

$$\hat{C} = \Gamma^{-1} \left(k_w + \frac{\omega}{c} - \frac{\omega}{v_z(\mathcal{E}_0)} \right)$$

Diffraction Length

$$d = \sqrt{\frac{c\Gamma^{-1}}{2\omega_r}}$$

Normalized Energy

$$\hat{P} = \frac{\mathcal{E} - \mathcal{E}_0}{\rho \mathcal{E}_0}$$

3D FEL Theory

$$\tilde{f}_1(\hat{C},\hat{P},\hat{z}) = \int d\hat{P}_0\; d^2\hat{r}_\perp\; dt_0$$

$$\underbrace{\mathcal{G}_{FEL}(\hat{C},\hat{P},\hat{k}_\perp,\hat{z};t_0,\hat{P}_0,\hat{r}_\perp)}_{\text{FEL Green function}} \times f_1(t_0,\hat{P}_0,\hat{r}_\perp)$$

3D FEL Theory

- Assume:
  - No betatron oscillations
  - Zero transverse momentum spread
- Reduces to simple analytical form

3D FEL Theory

$$\mathcal{G}_{\mathrm{FEL}}(\hat{k}_\perp, \hat{C}, \hat{P}; \hat{r}_{\perp 0}, t_0, \hat{P}_0 | \hat{z}) = e^{\imath(\hat{C}+\hat{P}+\hat{k}_\perp^2)\hat{z}} +$$

$$\sum_\jmath \frac{1}{1 - \hat{D}'_\jmath + \imath\hat{\Lambda}_p^2\left(\hat{D}_j + s_\jmath \hat{D}'_\jmath\right)} \left(\frac{1}{s_\jmath + \imath(\hat{C} + \hat{P}_0 + \hat{k}_\perp^2)}\right)^2 \times$$

$$\left\{(1 + \imath\hat{\Lambda}_p^2 s_\jmath)\left[\left(e^{s_\jmath \hat{z}} - e^{-\imath(\hat{C}+\hat{P}_0+\hat{k}_\perp^2)\hat{z}}\right) - \left(1 - e^{-\imath(\hat{C}+\hat{P}_0+\hat{k}_\perp^2)\hat{z}}\right)\right]\right\} \frac{d\hat{F}}{d\hat{P}_0}$$

$$\times e^{-\imath\hat{k}_\perp \cdot \hat{r}_{\perp 0}} e^{\imath(1-\rho\hat{C})\omega_r t_0} \delta(\hat{P} - \hat{P}_0)$$

3D FEL Theory

1D Theory

$$s\left(s+\imath\hat{C}\right)^2-\imath=0$$

3D Theory (infinite beam)

$$s\left(s+\imath(\hat{C}+\hat{k}_\perp^2)\right)^2-\imath=0$$

$$\hat{C}_{3D}=\hat{C}+\hat{k}_\perp^2$$

What's Next?

- Coherent Electron Cooling Dynamics
- Quantum Free-Electron Lasers

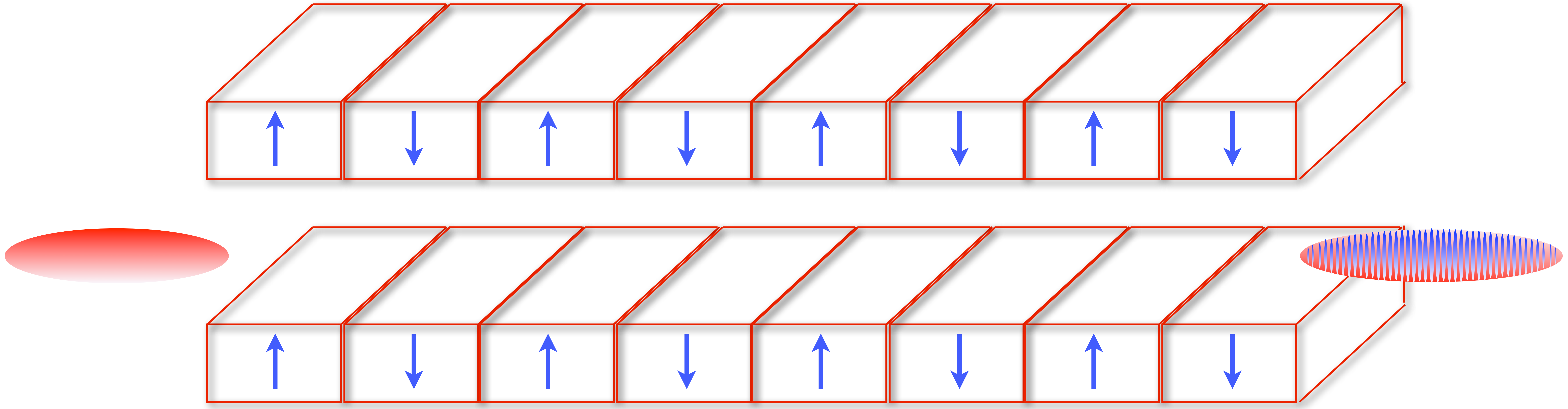
Numerical Benchmarking

- Analytical models of
  - Finite beam size Debye screening
  - Kicker dynamics
- CeC Kinetic Equation

qFELs

- What is a classical FEL?
- What is a quantum FEL?
- Mean field theory and beyond

Free-electron Laser



$$\vec{B}(z) = B_w \sin(k_w z)\hat{y}$$

Free-electron Laser

Resonance Wavelength

$$\lambda_r = \frac{\lambda_w}{2\gamma_0^2}(1 + K^2)$$

Gain Length

$$\Gamma^{-1} \sim \text{meters}$$

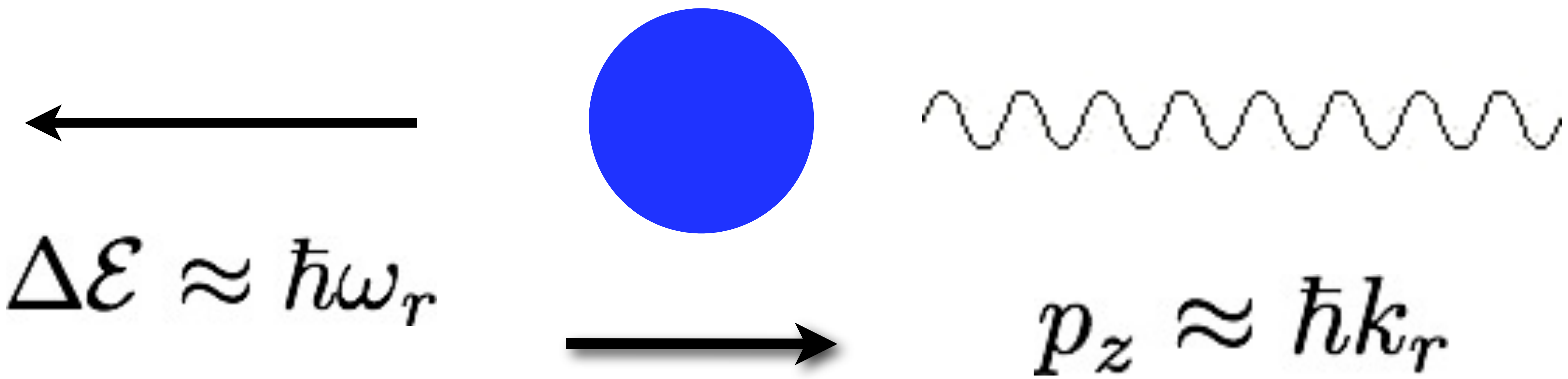
Pierce Parameter

$$\rho = (\Gamma^{-1} k_w)^{-1} \sim 10^{-3}$$

Bandwidth

$$\frac{\delta\omega}{\omega_r} = \frac{\Delta\mathcal{E}}{\mathcal{E}_0} \sim \rho$$

qFELs



$$\Delta\mathcal{E} \approx \hbar\omega_r$$

$$p_z \approx \hbar k_r$$

$$v \approx c$$

Synchrotron Radiation Contributes
Strongly to Heating

$$\frac{\Delta\mathcal{E}}{\mathcal{E}_0} \sim \rho$$

Pierce Parameter

$$\rho = (k_w L_g)^{-1}$$

qFELs

Conventional FEL design?

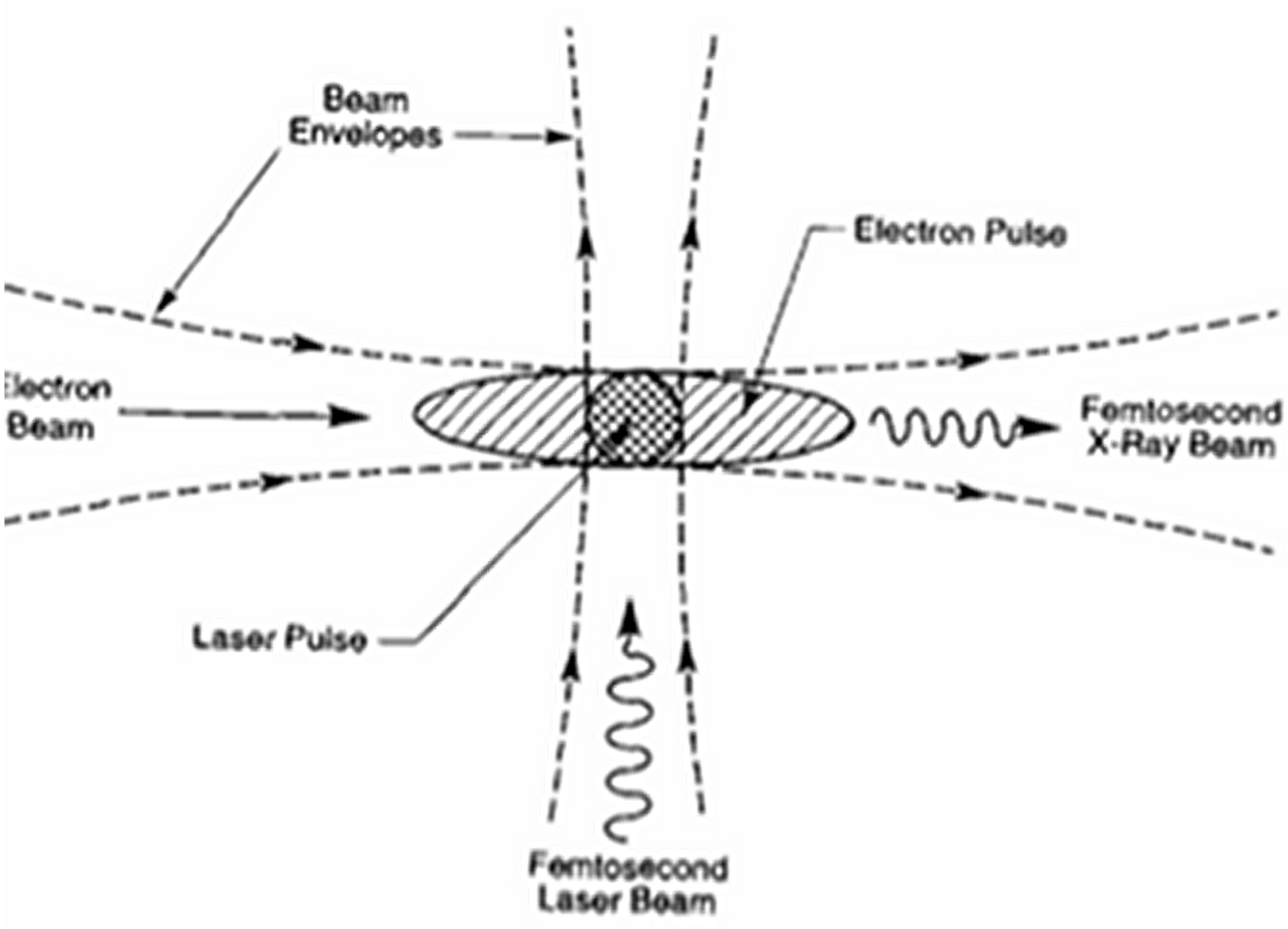
For conventional FEL:

$$\lambda_w \sim 4 \text{ cm} \qquad \rho \sim 10^{-3} \longrightarrow \gamma_0 \sim 10^7$$

NO

Unconventional FEL designs relax this restriction

90° Thomson scattering



Shamelessly lifted from K.-J. Kim et al. NIM A 341 (1994)

90° Thomson scattering

Femtosecond X-ray Pulses at 0.4 Å
Generated by 90° Thon
for Probing the Structur

R. W. Schoenlein,* W. P. Leer
T. E. Glover, P. Balling,
S. Chattopadhy

Pulses of x-rays 300 femtoseconds in durati
electron volts) have been generated by 90°
watt laser pulses and highly relativistic elec
scattering geometry, the duration of the x-r
the laser pulse across the ~90-micromete
x-rays are highly directed (~0.6° divergenc
of femtosecond x-rays will make it possible
time resolution to investigate structural dyr

PHYSICS OF PLASMAS VOLUME 11, NUMBER 5 MAY 2004

PLEIADES: A picosecond Compton scattering x-ray source for advanced backlighting and time-resolved material studies[a)]

David J. Gibson,[c)] Scott G. Anderson, Christopher P. J. Barty, Shawn M. Betts,
Rex Booth, Winthrop J. Brown, John K. Crane, Robert R. Cross, David N. Fittinghoff,[b)]
Fred V. Hartemann, Jaroslav Kuba, Gregory P. Le Sage, Dennis R. Slaughter,
Aaron M. Tremaine, Alan J. Wootton, Edward P. Hartouni,
and Paul T. Springer
Lawrence Livermore National Laboratory, L-280, P.O. Box 808, Livermore, California 94551-0808

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(Received 31 October 2003; accepted 9 December 2003; published online 23 April 2004)

The PLEIADES (Picosecond Laser-Electron Inter-Action for the Dynamical Evaluation of Structures) facility has produced first light at 70 keV. This milestone offers a new opportunity to develop laser-driven, compact, tunable x-ray sources for critical applications such as diagnostics for the National Ignition Facility and time-resolved material studies. The electron beam was focused to

Bonifacio Equations

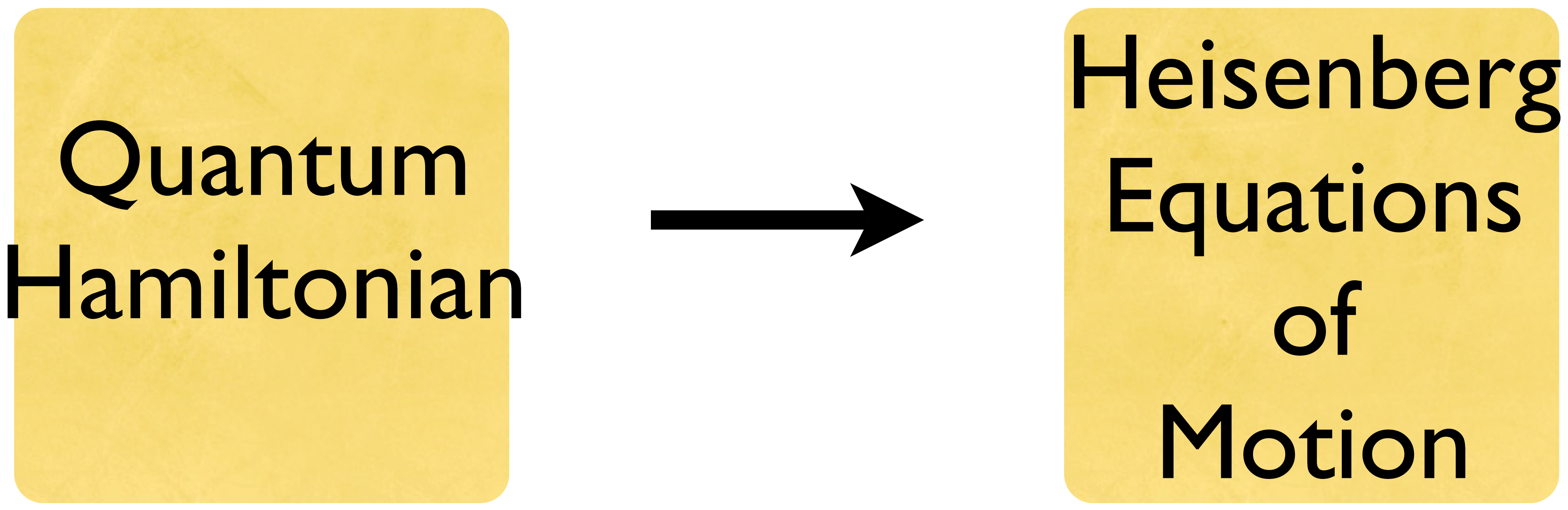
Quantum
Hamiltonian

Bonifacio Equations

$$\hat{\mathcal{H}} = \sum_{\imath} \hbar\omega_{\imath} \left(a_{\imath}^{\dagger} a_{\imath} + \frac{1}{2} \right) + \sum_{\jmath} \hbar\Omega \frac{p_j^2}{2}$$

$$+ \sum_{\imath} \hbar g_{\imath} \left(a_{\imath}^{\dagger} a_u \sum_{j} e^{-\imath\theta_{\imath\jmath}} + h.c. \right)$$

Bonifacio Equations



Bonifacio Equations

$$\theta'_{\imath\jmath} = \frac{\overline{k}_\imath}{\overline{k}_r}\Omega p_\jmath$$

$$p'_\jmath = \imath \sum_\imath \frac{\overline{k}_\imath}{\overline{k}_r} g_\imath (a_\imath^\dagger a_u e^{-\imath\theta_{\imath\jmath}} - h.c.)$$

$$a'_\imath = -\imath\omega_\imath a_\imath - \imath g_\imath a_u \sum_\jmath e^{-\imath\theta_{\imath\jmath}}$$

Bonifacio Equations

Quantum Hamiltonian → Heisenberg Equations of Motion → Collective Variable

Bonifacio Equations

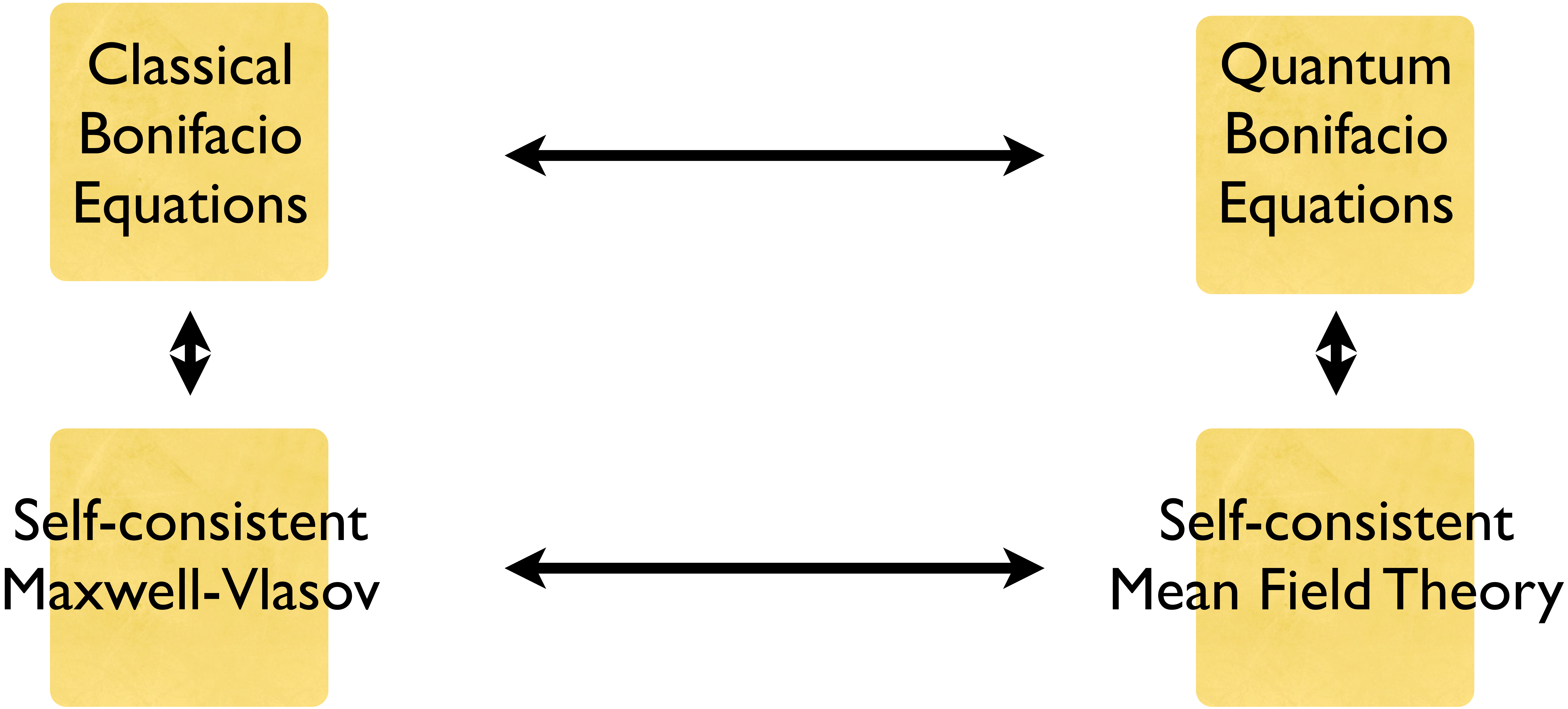
$$b_\imath = \frac{1}{N_e} \sum_\jmath e^{\imath\theta_{\imath\jmath}}$$

$$\pi_\imath = \frac{1}{N_e} \sum_\jmath e^{-\imath\theta_{\imath\jmath}} \frac{p_\jmath}{\hbar \bar{k}_\jmath}$$

What’s missing?

- Electrons are fermions
- Many-body effects and beyond
- Analytical treatment of saturation

Mean Field Theory



Acknowledgements

I would like to thank:

- Vladimir Litvinenko
- Mike Blaskiewicz
- Gang Wang
- Abhay Deshpande
- Ilan Ben-Zvi
- Erdong Wang
- The rest of the eRHIC collaboration

Thank you

Super Bonus Slides!!

RHIC vs. eRHIC

	RHIC	eRHIC
Energy/nucleon	100 GeV (Au)	130 GeV (Au)
Current	4.2 mA	420 mA
Emittance (Au)	17-20 mm mrad	1.2 mm mrad
Luminosity	20×10^{26} cm^{-2} sec^{-1}	1.46×10^{34} cm^{-2} sec^{-1}
Betatron wavelength	0.75 m	0.05 m

Main Accelerator Challenges

ENC at FAIR	ELIC at JLaB	eRHIC at BNL	LHeC at CERN Ring-Ring	LHeC at CERN Linac-Ring
	β*=0.5 cm 50x reduction	Polarized electron gun – 50x increase	Depolarization at the top energy	Polarized e$^-$ source
8 MV, 3 A magnetized electrostatic (Voltage*2, Current*6)	HE Electron Cooling – 100x increase in the rate of cooling	Coherent Electron Cooling – New concept	Energy reach beyond 70 GeV for leptons	Potential 10x gains from cooling, but need special CeC
Investigation of large beam-beam tune shift in space charge dominated regimes	High current recirculating ring with ERL-injector New concept	Multi-pass SRF ERL 5x increase in current 30x increase in energy	Synchrotron radiation losses in the arcs	Multi-pass SRF ERL 5x increase in current 30x increase in energy
Crab crossing (compliance with acceptance of PANDA)	Crab crossing 5x the angle New for hadrons	Crab crossing New for hadrons	Crab crossing New for hadrons	Crab crossing New for hadrons
	Polarized ^{3}He production		By-passes	Totally new tunnel
Limited space for electron ring	Never explored beam-beam parameter range 3-4x in ξ	Understanding of beam-beam affects New type of collider	Complexity of the sharing tunnel with LHC	Very challenging to have e+ source
Polarization life time in electron ring (lattice considerations)	Dispersive crab crossing Traveling focus New concepts	β*=5 cm 5x reduction		Using crossing angle to avoid SR in IR
Space charge limits beam dynamics, Bunching (1→200)	Sub-nsec kicker with MHz rep-rate 50x shorter pulses	Multi-pass SRF ERL 3-4x in # of passes	Need new injector	
	Figure-8 ring spin dynamics New concept	Feedback for kink instability suppression Novel concept	Synchrotron radiation in the IR	

Major IEC Accelerator R&D in the US

Common R&D activities for eRHIC and ELIC

• Polarized 3He production and acceleration (BNL)	[5 FTE-yrs; M&S: $ 1.0 M Total: $2M]
• Coherent Electron Cooling (BNL)	[15 FTE-yrs; M&S: $ 5.0 M Total: $8M]
• Energy recovery technology for 100 MeV level electron beam. (JLab)	[20 FTE-yrs; M&S: $4.5 M Total: $8.5M]
• Crab cavities	[8 FTE-yrs; M&S: $1.2M Total: $2.8M]

R&D activities specific to eRHIC

• High current polarized electron source (MIT)	[7.5 FTE-yrs; M&S: $ 2.0 M Total: $3.5M]
• Energy recovery technology for high energy and high current beams (BNL)	[10 FTE-yrs; M&S: $ 3.0 M Total: $5M]
• Development of eRHIC-type SRF cavity (BNL)	[10 FTE-yrs; M&S: $ 2.0 M Total: $4M]

R&D activities specific to ELIC

• Ion space charge sim. (JLab in collab. with SNS)	[2 FTE-yrs; M&S: $0.5M Total: $0.9M]
• Spin track studies for ELIC (JLab)	[8 FTE-yrs; Total: $1.6M]
• Studies traveling focus scheme (JLab)	[3 FTE-yrs; Total: $0.6M]
• Simulation studies supporting ELIC project (JLab)	[5 FTE-yrs; Total: $1.0M]