Lecture 26.

Introduction to Relativistic Classical and Quantum Mechanics

(Ch. 2-5 of Unit 2   4.03.12)

Group vs. phase velocity and tangent contacts   *(Includes Lecture 25 review)*

Reviewing "Sin-Tan Rosetta" geometry

How optical CW group and phase properties give relativistic mechanics

Three kinds of mass (Einstein rest mass, Galilean momentum mass, Newtonian inertial mass)

What's the matter with light?

Bohr-Schrodinger (BS) approximation throws out Mc^2

Deriving relativistic quantum Lagrangian-Hamiltonian relations

Feynman's flying clock and phase minimization

Geometry of relativistic mechanics

Relativistic Classical and Quantum Mechanics

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Introducing the "Sin-Tan Rosetta Stone" *NOTE: Angle ϕ is now called stellar aberration angle σ*

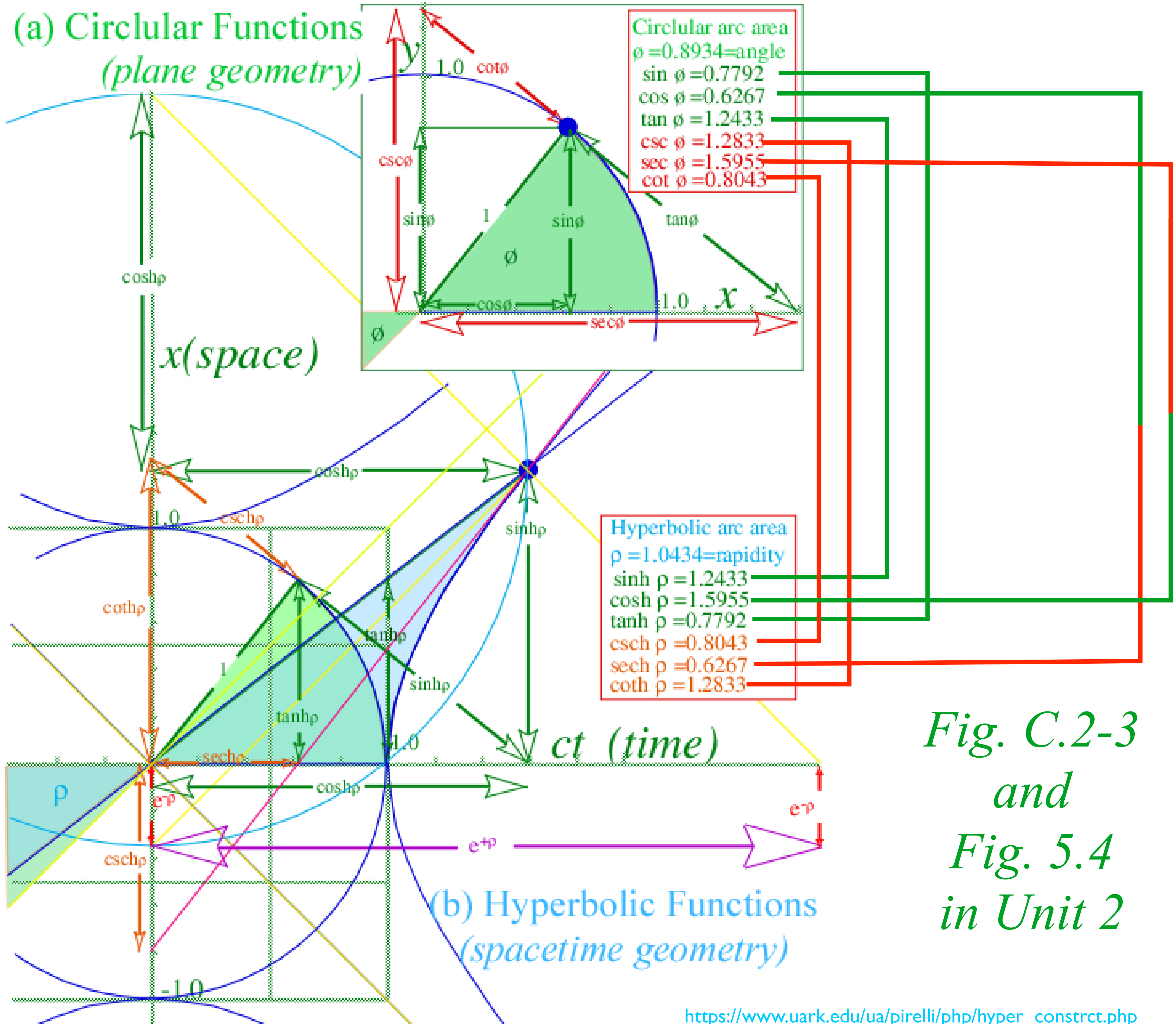
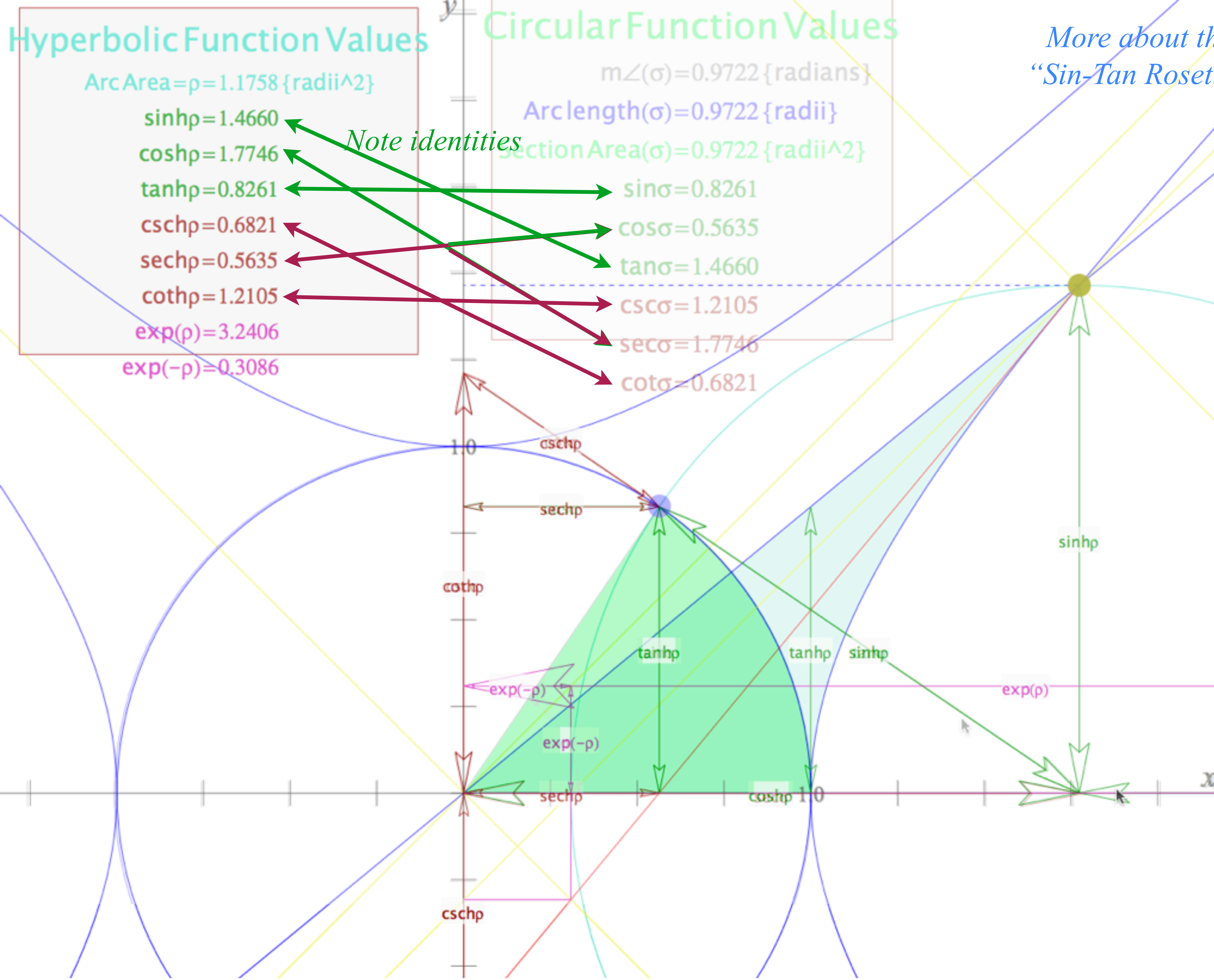


Fig. C.2-3
and
Fig. 5.4
in Unit 2

https://www.uark.edu/ua/pirelli/php/hyper_constrct.php

More about the "Sin-Tan Rosetta"



Relativistic Classical and Quantum Mechanics

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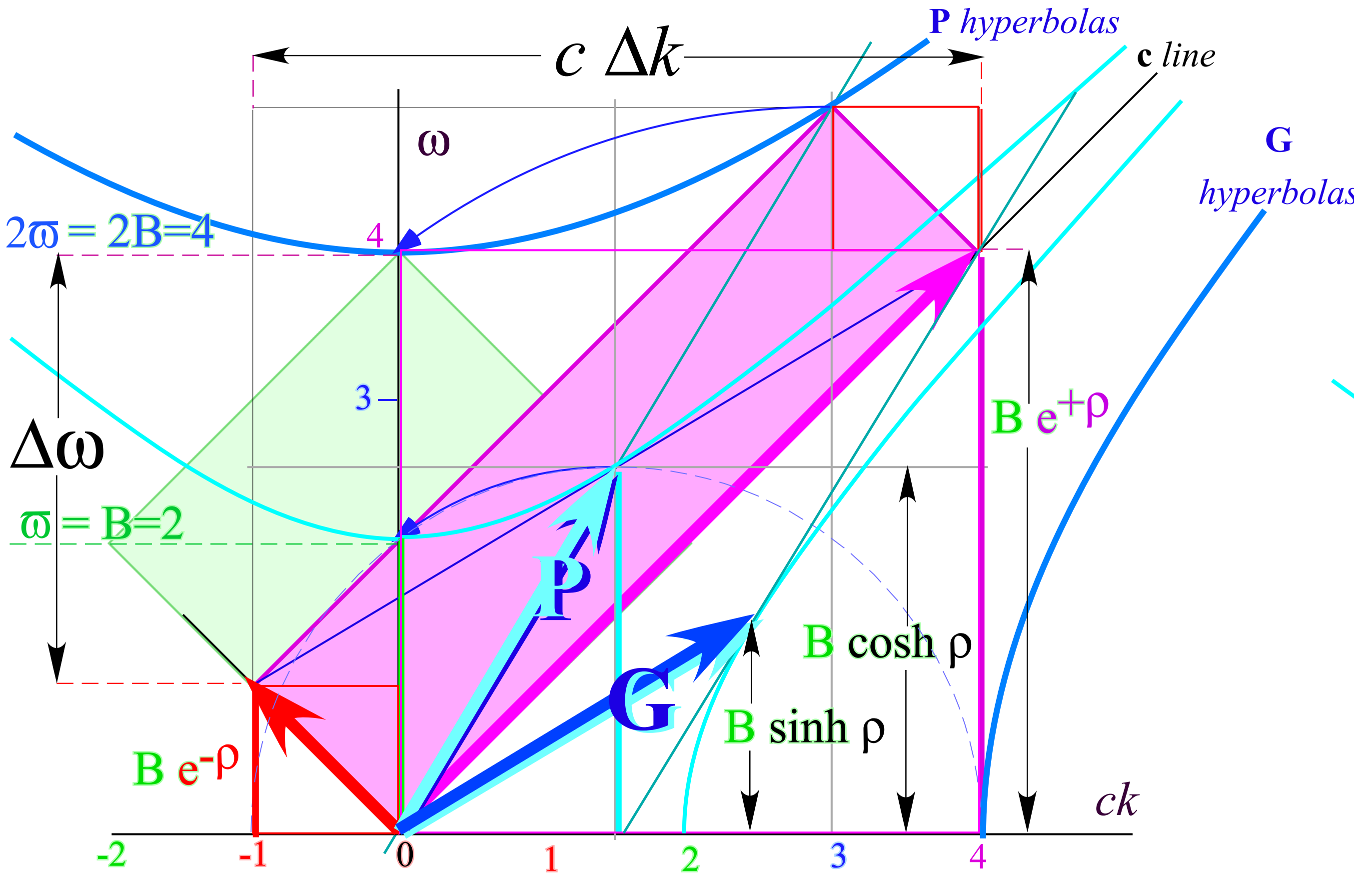
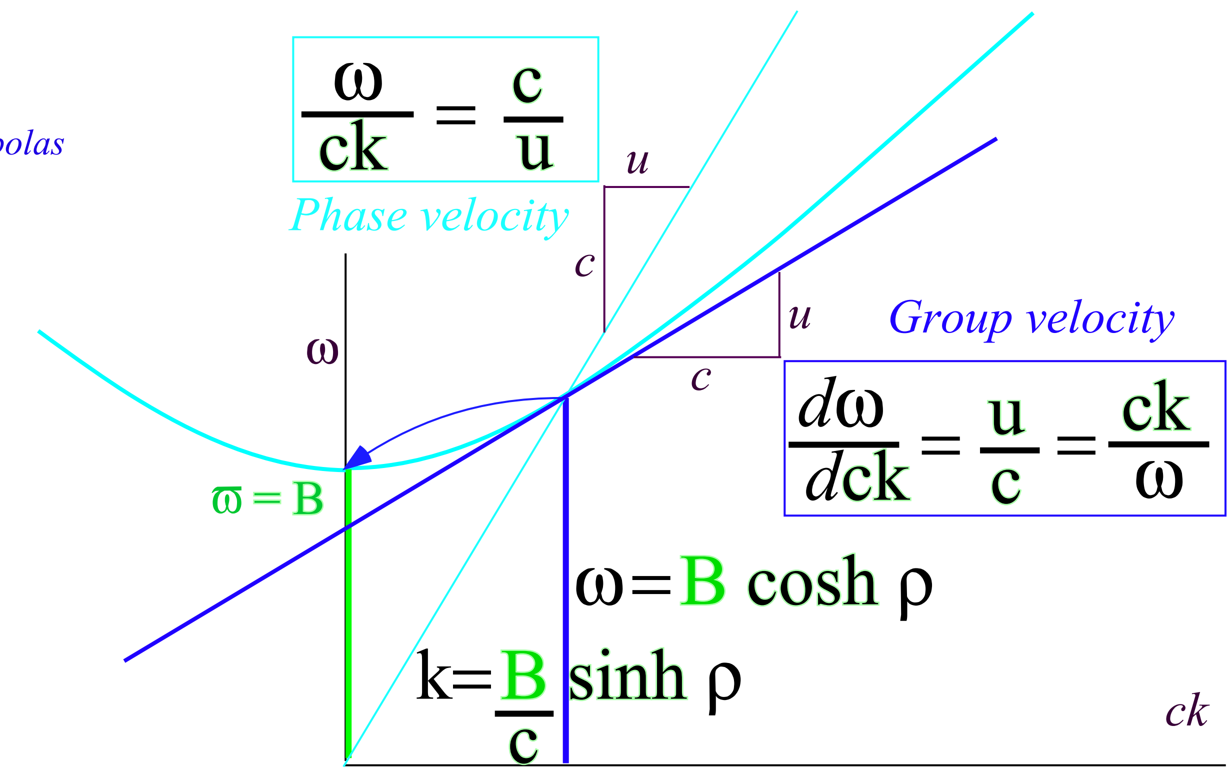
Group velocity u *and phase velocity* c^2/u *are hyperbolic tangent slopes*

(From Fig. 2.3.4)



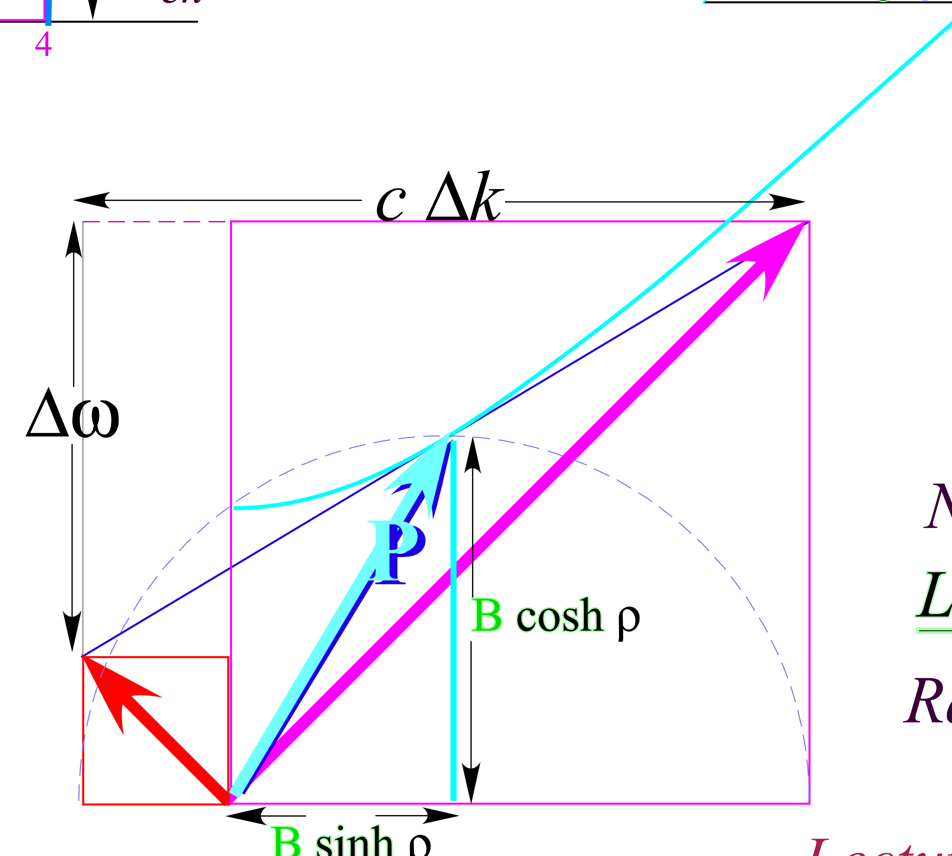


Rare but important case where

$$\frac{d\omega}{dk} = \frac{\Delta\omega}{\Delta k}$$

with LARGE Δk
(not infinitesimal)

Relativistic group wave speed $u=c \tanh \rho$

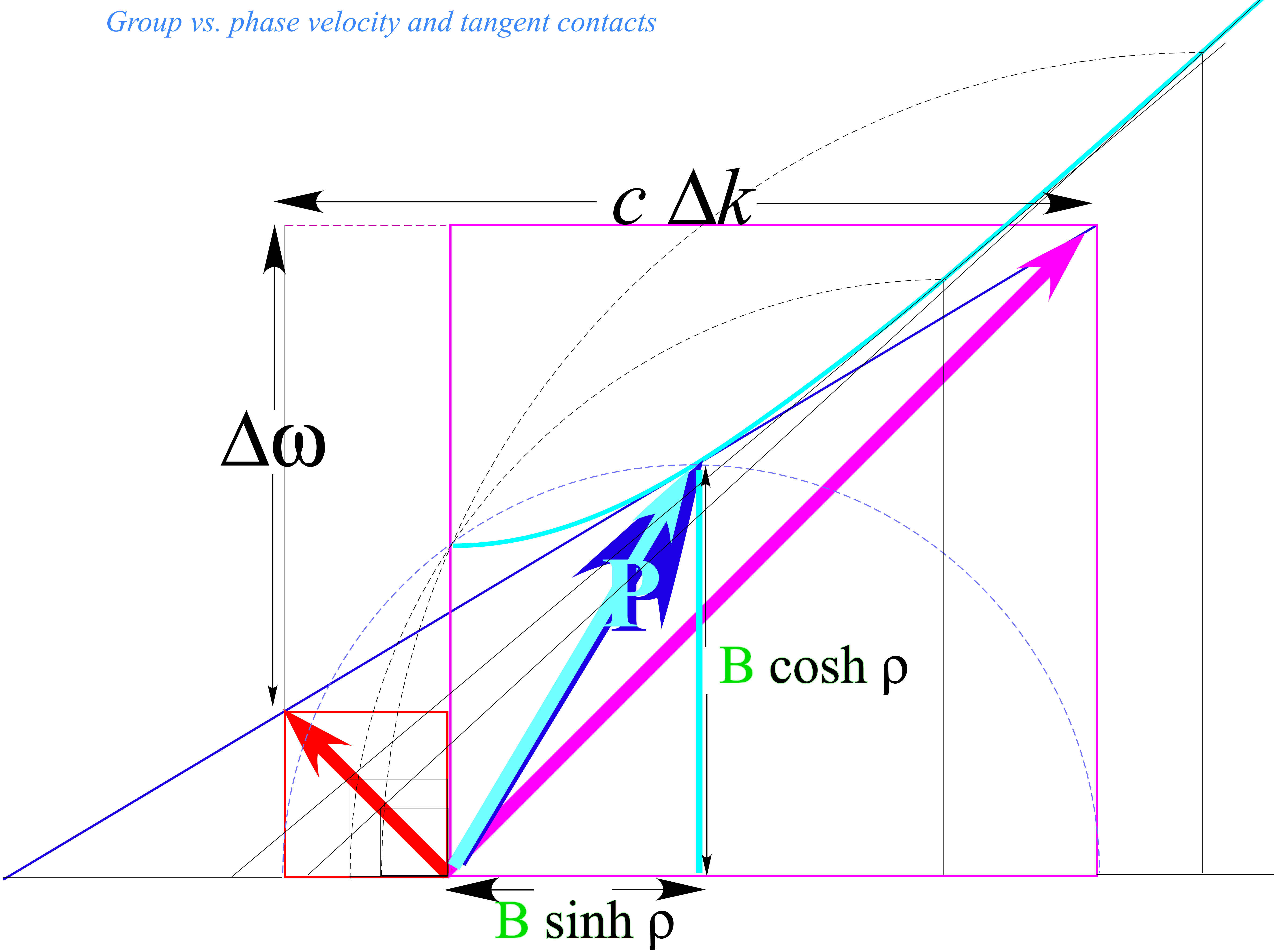


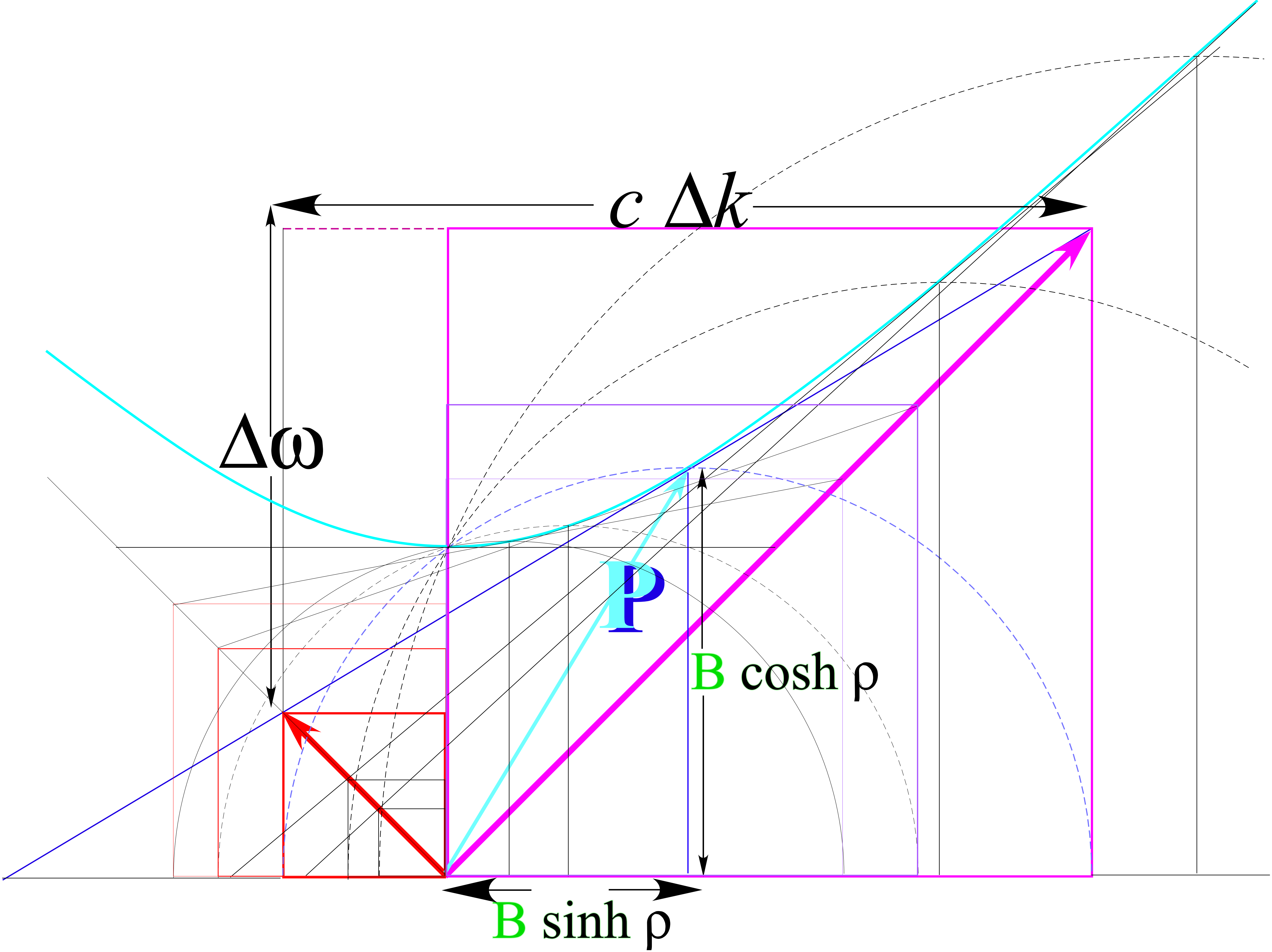
Newtonian speed $u \sim c\rho$

Low speed approximation

Rapidity ρ *approaches* u/c

Lecture 25 ended here


c Δk
Δω
ρ
B cosh ρ
B sinh ρ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Start with low speed approximations : $\omega = B\cosh\rho = B(1 + \frac{1}{2}\rho^2 + ...)$ where: $\rho \simeq \frac{u}{c}$

CW Axioms (*"All colors go c." and "r=1/b"*) imply hyperbolic dispersion then mechanics of matter

$$\omega = B\cosh\rho \cong B + \frac{1}{2}\frac{B}{c^2}u^2$$

These follow from CW axioms

$$k = \frac{B}{c}\sinh\rho \cong \frac{B}{c^2}u$$

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$$\omega = B\cosh\rho \cong B + \frac{1}{2}\frac{B}{c^2}u^2 \qquad k = \frac{B}{c}\sinh\rho \cong \frac{B}{c^2}u$$

$$E = \text{constant} + \frac{1}{2}Mu^2 \qquad p = Mu$$

(Newton's energy) *(Galileo's momentum)*

So *2-CW*-light *frequency* ω is like *energy* *E* while *k-number* is like *momentum p*, *Start with low speed approximations :* $\omega = B\cosh\rho = B(1+\frac{1}{2}\rho^2+...)$ where: $\rho \simeq \frac{u}{c}$

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So *2-CW*-light *frequency* ω is like *energy* *E* while *k-number* is like *momentum p*, implies *Planck's E=s·ω* scaling with factors: *s=ħ=s equal* to *DeBroglie's p=s·k*.

$$E = s\omega = sB\cosh\rho \cong sB + \frac{1}{2}\frac{sB}{c^2}u^2$$

$$p = sk = \frac{sB}{c}\sinh\rho \cong \frac{sB}{c^2}u$$

Start with low speed approximations: $\omega = B\cosh\rho = B(1+\tfrac{1}{2}\rho^2+\ldots)$ where: $\rho \simeq \dfrac{u}{c}$

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Both relations imply: $M = \dfrac{sB}{c^2}$ giving a (famous) *rest energy constant.* : $sB = Mc^2$

This then gives the famous *Einstein energy E* and also the *Einstein momentum p*

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(Newton's energy) *(Galileo's momentum)*

So *2-CW*-light *frequency* ω is like *energy* E while *k-number* is like *momentum p*, implies *Planck's* $E=s\cdot\omega$ scaling with factors: $s=\hbar=s$ *equal* to *DeBroglie's* $p=s\cdot k$.

$$E = s\omega = sB\cosh\rho \cong sB + \frac{1}{2}\frac{sB}{c^2}u^2 \qquad p = sk = \frac{sB}{c}\sinh\rho \cong \frac{sB}{c^2}u$$

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$$E = s\omega = Mc^2\cosh\rho \cong Mc^2 + \frac{1}{2}Mu^2 \qquad p = sk = Mc\sinh\rho \cong Mu$$

$$= \frac{Mc^2}{\sqrt{1-u^2/c^2}} \qquad = \frac{Mu}{\sqrt{1-u^2/c^2}}$$

Rest energy$(u=0)$: $\hbar B = Mc^2$

Scale factors determined by experiment

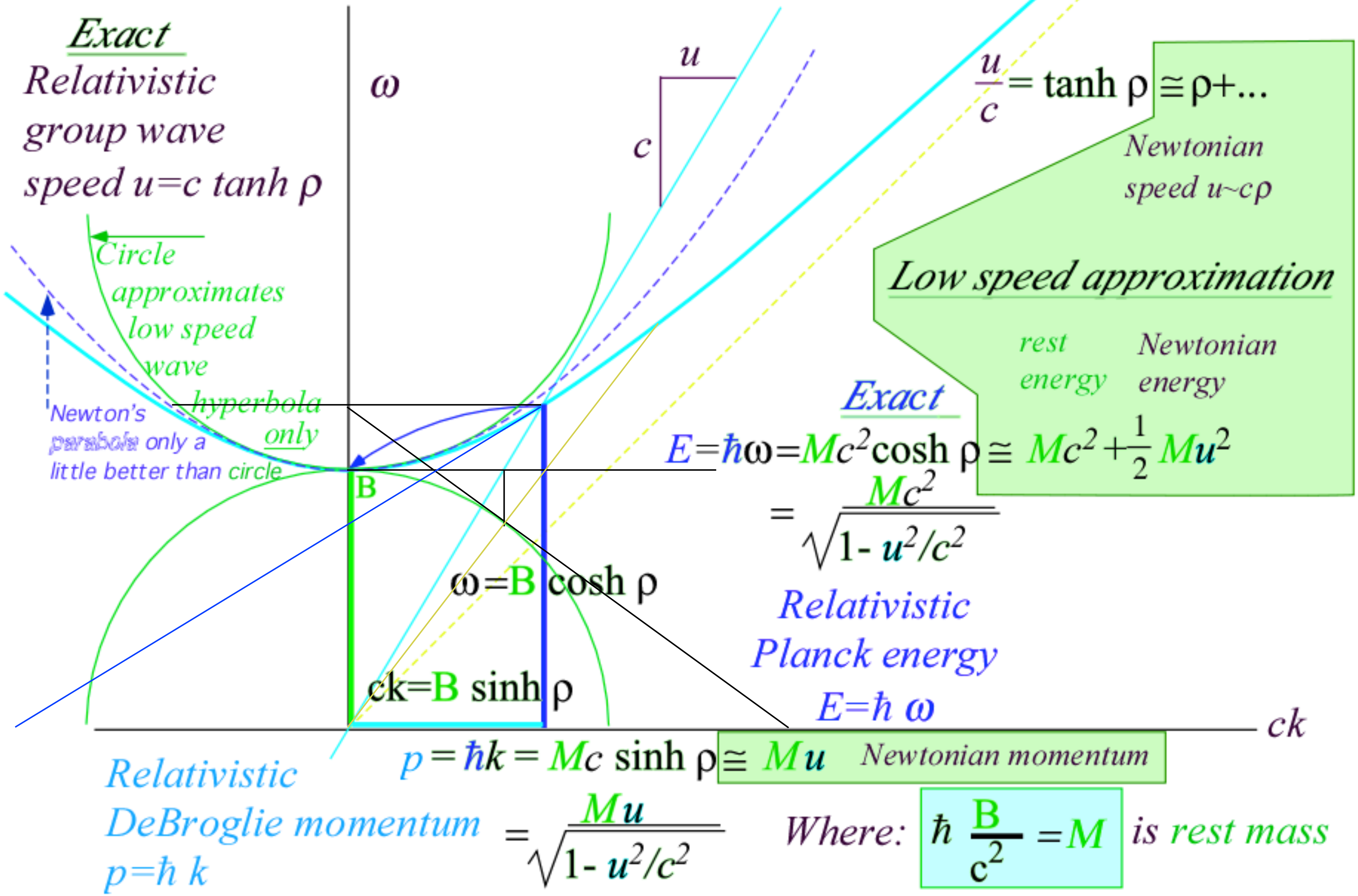
Planck's constant

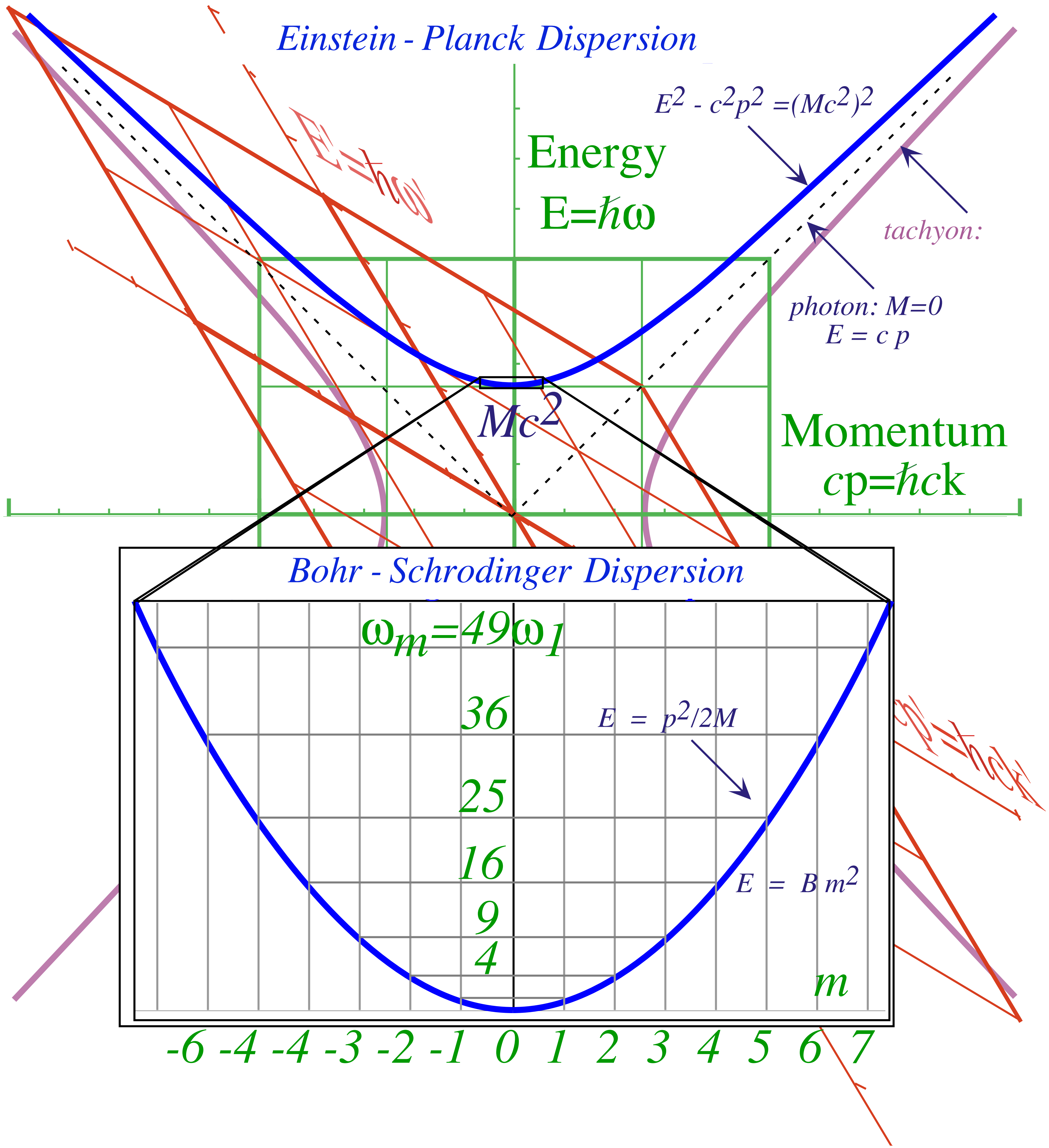
$s=\hbar=1.054572\cdot 10^{-34}$ Joule$\cdot$s

$h=6.626069\cdot 10^{-34}$ J$\cdot$s $=2\pi\hbar$

Rest momentum$(u=0)$: $p=0$

Summary of geometry ω-vs-ck or E-vs-cp relations with velocity u or rapidity ρ





Einstein - Planck Dispersion
Energy
E=ℏω
$E^2 - c^2p^2 = (Mc^2)^2$
tachyon:
photon: M=0
E = c p
Mc^2
Momentum
cp=ℏck
E′=ℏω′
cp′=ℏck′
Bohr - Schrodinger Dispersion
$\omega_m = 49\omega_1$
36
25
16
9
4
$E = p^2/2M$
$E = B m^2$
m
-6 -4 -4 -3 -2 -1 0 1 2 3 4 5 6 7

Relativistic Classical and Quantum Mechanics

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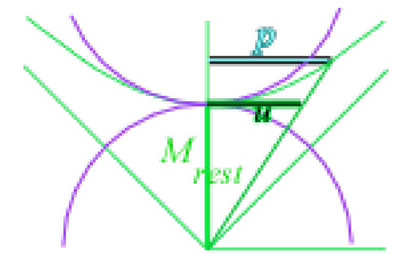
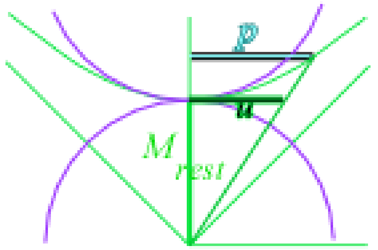
What's the Matter With Light? *Three definitions of optical mass*



1. *Rest mass* $M_N = h\upsilon_N / c^2$ based on Planck's law $E = h\upsilon_N = Nh\upsilon_1$

Rest mass: $M_{rest} = E/c^2 = h\upsilon_N / c^2$ *(Is invariant)*

What's the Matter With Light? *Three definitions of optical mass*



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Rest mass: $M_{rest} = E/c^2 = h\upsilon_N/c^2$

(Is invariant)

2. *Momentum mass* is defined by Galileo's old formula $p=Mu$ with newer forms for momentum $p=M_{rest}u\cdot\cosh\rho = M_{rest}u\cdot/(1-u^2/c^2)^{1/2}$ and group velocity $u = d\omega/dk$. It is the ratio p/u of *momentum* to *velocity*.

$$\text{Momentum mass: } M_{momentum} = p/u = M_{rest}\cosh\rho = M_{rest}/(1-u^2/c^2)^{1/2}$$

(Not invariant)

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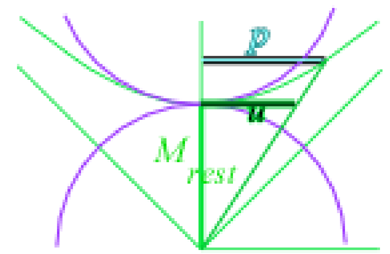

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$$\text{Momentum mass: } M_{momentum} = p/u = M_{rest}\cosh\rho = M_{rest}/(1-u^2/c^2)^{1/2}$$

(Not invariant)

3. *Effective mass* is defined by Newton's old formula $F = Ma$ with newer forms for $F = dp/dt = \hbar dk/dt$ *and* $a = du/dt =$ to give $F/a = (\hbar dk/dt)(dt/du) = \hbar dk/du = \hbar/(du/dk)$. It is the ratio F/a of *change of momentum* to the *change of velocity*,

$$\text{Effective mass: } M_{effective} = \hbar/(du/dk) = \hbar/(d^2\omega/dk^2) = M_{rest}\cosh^3\rho = M_{rest}/(1-u^2/c^2)^{3/2}$$

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Three kinds of mass for photon γ in CW relativistic theory

What's the matter with light?

(1)Einstein rest mass

$$M_{rest}=\frac{\hbar\omega_{proper}}{c^2}$$

(2) Galilean momentum mass

$$M_{mom}=p/u=\frac{\hbar k}{\frac{d\omega}{dk}}$$

(3) Newtonian inertial mass

$$M_{mom}=F/a=\frac{\hbar}{\frac{d^2\omega}{dk^2}}$$

Three kinds of mass for photon γ in CW relativistic theory

What's the matter with light?

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$$M_{rest} = \frac{\hbar\omega_{proper}}{c^2}$$

$$M_{rest}(\gamma) = 0$$

(2) Galilean momentum mass

$$M_{mom} = p/u = \frac{\hbar k}{\frac{d\omega}{dk}}$$

$$M_{mom}(\gamma) = p/c = \hbar k/c = \hbar\omega/c^2$$

(3) Newtonian inertial mass

$$M_{eff} = F/a = \frac{\hbar}{\frac{d^2\omega}{dk^2}}$$

$$M_{eff}(\gamma) = \infty$$

Equations (4.11) in Unit 2

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Equations (4.11) in Unit 2

A 2-CW *600THz* cavity has zero total momentum p, but each photon adds a tiny mass M_γ to it.

$$M_\gamma = \hbar\omega/c^2 = \omega\,(1.2\cdot 10^{-51})kg\cdot s = 4.5\cdot 10^{-36}kg \qquad \textit{(for: } \omega = 2\pi\cdot 600\text{THz}\textit{)}$$

Three kinds of mass for photon γ in CW relativistic theory
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$M_{rest}(\gamma)=0$

$M_{mom}(\gamma)=p/c=\hbar k/c=\hbar\omega/c^2$

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Equations (4.11) in Unit 2

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$M_\gamma=\hbar\omega/c^2=\omega\,(1.2\cdot10^{-51})kg\cdot s= 4.5\cdot10^{-36}kg$ *(for:* $\omega=2\pi\cdot600$THz *)*

A 1-CW state has no rest mass, but 1-photon momentum is a non-zero value $p_\gamma=M_\gamma c$. *(Galilean revemge II.)*

$p_\gamma=\hbar k=\hbar\omega/c=\omega\,(4.5\cdot10^{-43})kg\cdot m=1.7\cdot10^{-27}kg\cdot m\cdot s^{-1}$ *(for:* $\omega=2\pi\cdot600$THz *)*

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Bohr-Schrodinger (BS) approximation throws out Mc^2

$$E = \frac{Mc^2}{\sqrt{1-u^2/c^2}} = Mc^2\cosh\rho = Mc^2\sqrt{1+\sinh^2\rho} = \sqrt{\left(Mc^2\right)^2 + \left(cp\right)^2}$$

$$E = \left[\left(Mc^2\right)^2 + \left(cp\right)^2\right]^{1/2} \approx Mc^2 + \frac{1}{2M}p^2 \xrightarrow[BS-approx]{} \frac{1}{2M}p^2$$

ft.

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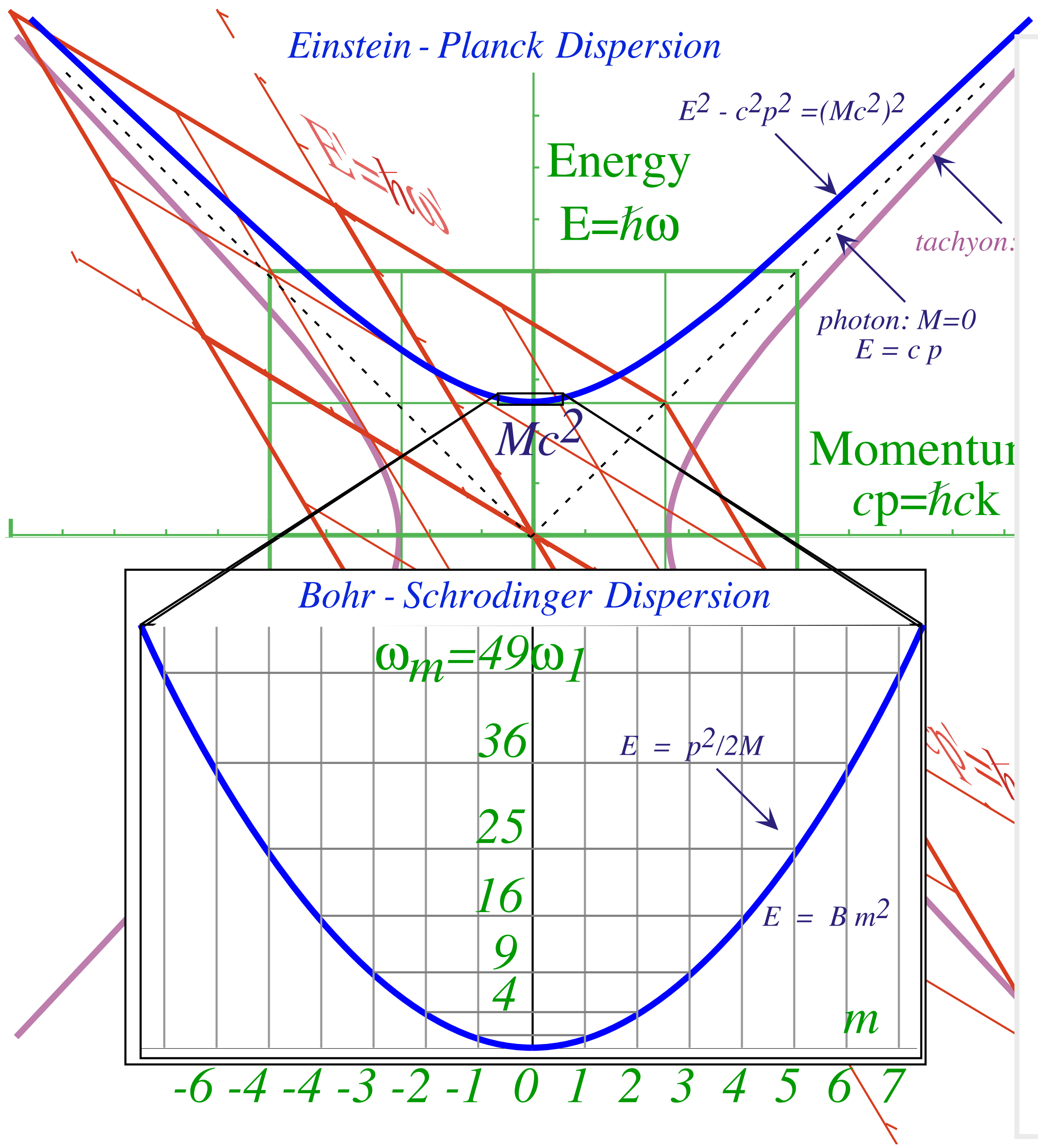
The BS claim: may shift energy origin *(E=Mc², cp=0)* to *(E=0, cp=0)*. (*Frequency is relative!*)



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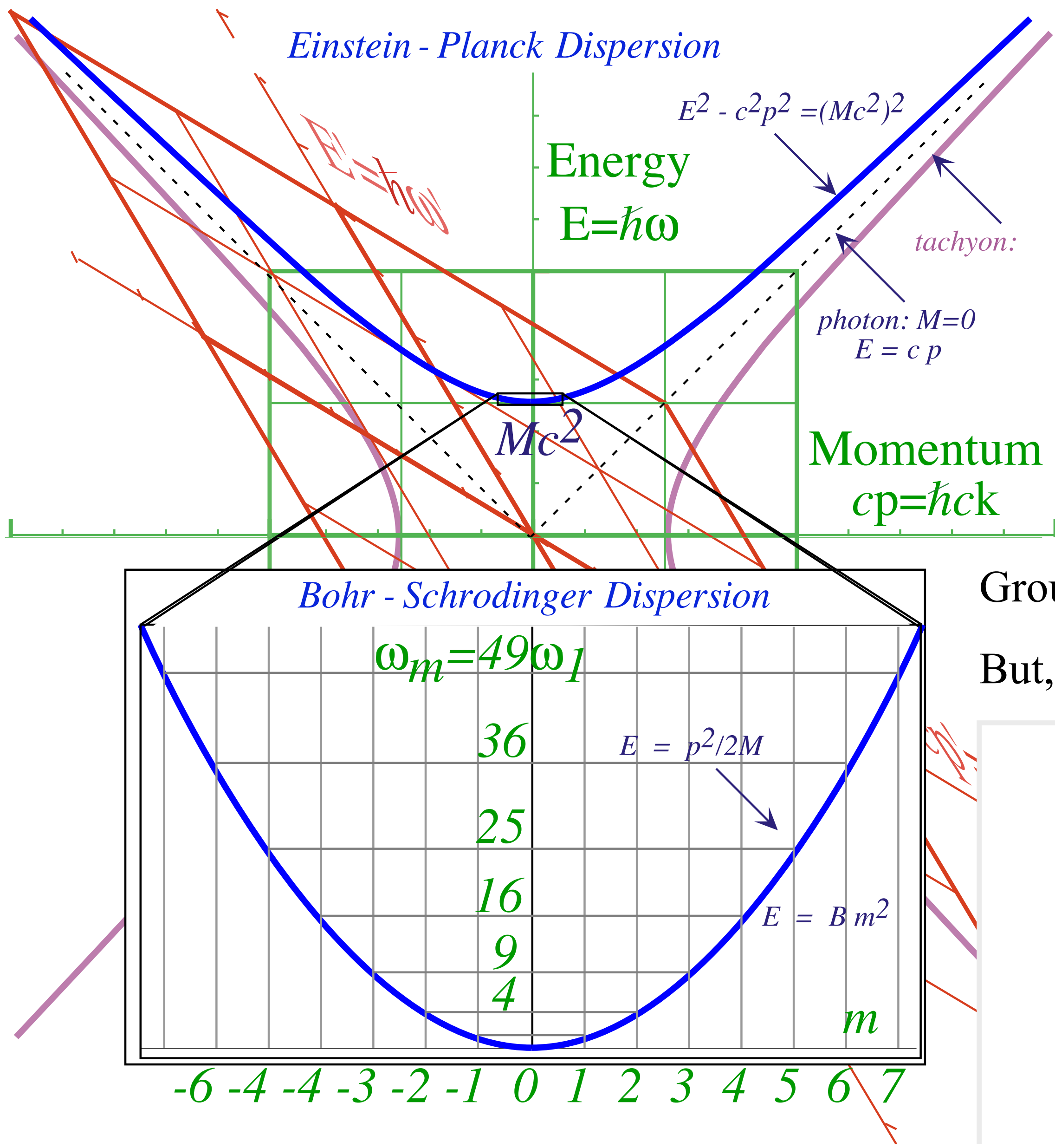

Group velocity $u=V_{group}=\frac{d\omega}{dk}$ is a differential quantity unaffected by origin shift.

But, Phase velocity $\frac{\omega}{k}=V_{phase}$ is greatly reduced by deleting Mc^2 from $E=\hbar\omega$.

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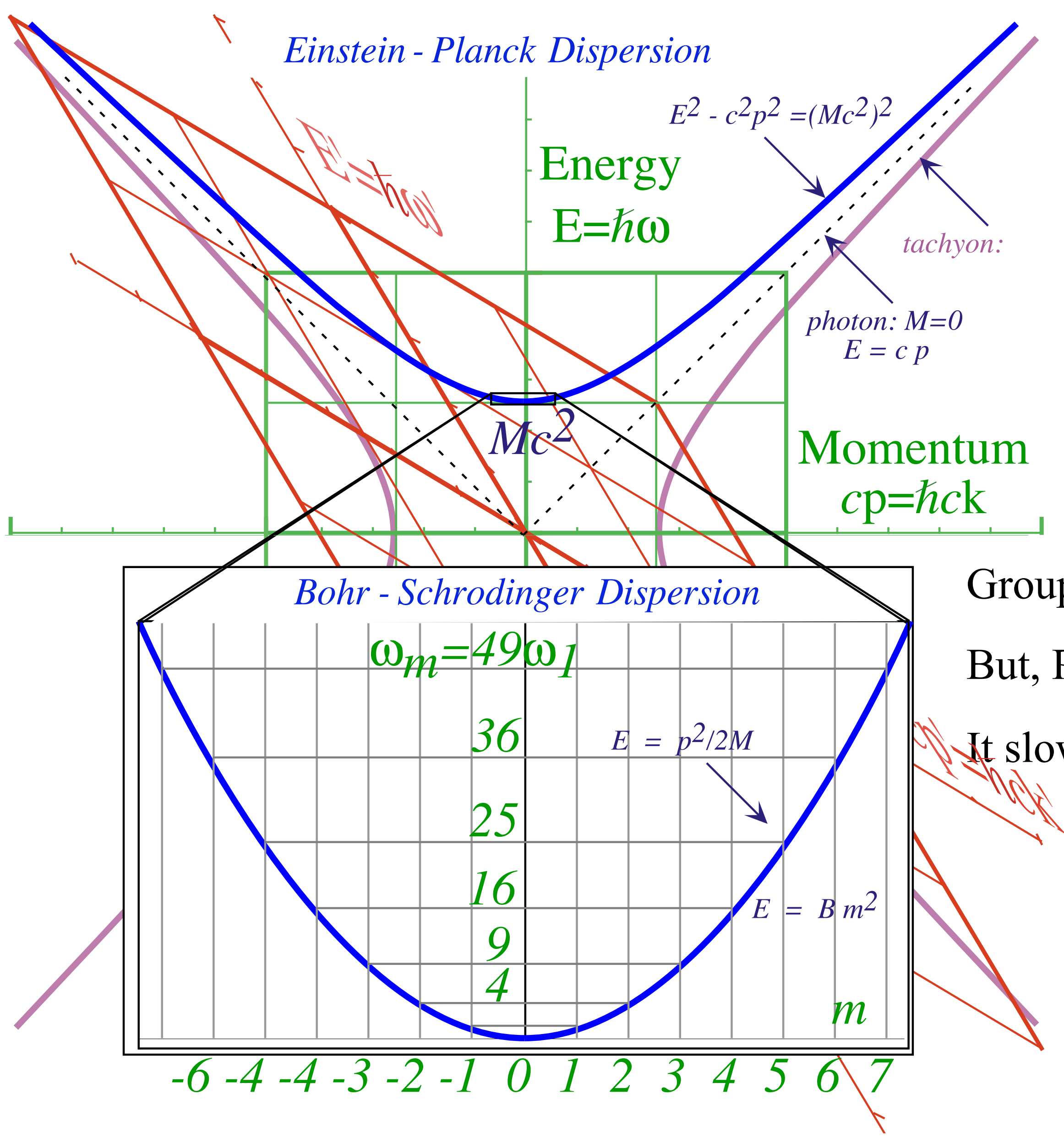

Group velocity $u=V_{group}=\frac{d\omega}{dk}$ is a differential quantity unaffected by origin shift.

But, Phase velocity $\frac{\omega}{k}=V_{phase}$ is greatly reduced by deleting Mc^2 from $E=\hbar\omega$.

It slows from $V_{phase}=c^2/u$ to a sedate sub-luminal speed of $V_{group}/2$.

$$\omega_{BS}(k) = \frac{k^2}{2M} \quad \text{gives:} \quad V_{phase} = \frac{\omega_{BS}}{k} = \frac{k}{2M}$$

$$\text{and:} \quad V_{group} = \frac{d\omega_{BS}}{dk} = \frac{k}{M}$$

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Deriving relativistic quantum Lagrangian-Hamiltonian relations

Start with phase Φ *and set* $k=0$ *to get product of proper frequency* $\mu = Mc^2/\hbar$ *and proper time* τ

$$d\Phi = k\,dx - \omega\,dt = -\mu\;d\tau = -(Mc^2/\hbar)\;d\tau. \qquad d\tau = dt\,\sqrt{(1-u^2/c^2)} = dt\;\mathrm{sech}\,\rho$$

Deriving relativistic quantum Lagrangian-Hamiltonian relations

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Differential action: $dS = L dt = p \cdot dx - H \cdot dt = \hbar k \cdot dx - \hbar\omega \cdot dt = \hbar d\Phi$

is Planck scale $\hbar$ times differential phase: $dS = \hbar d\Phi$

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For constant u the Lagrangian is: $L = -\hbar\mu\tau\ = -Mc^2\sqrt{(1-u^2/c^2)} = -Mc^2\mathrm{sech}\,\rho = -Mc^2\cos\sigma$

Deriving relativistic quantum Lagrangian-Hamiltonian relations

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For constant u the Lagrangian is: $L = -\hbar\mu\tau = -Mc^2\sqrt{(1-u^2/c^2)} = -Mc^2 sech\;\rho = -Mc^2 \cos\sigma$

...with Poincare invariant: $L = p\cdot\dot{x} - H = p\cdot u - H$

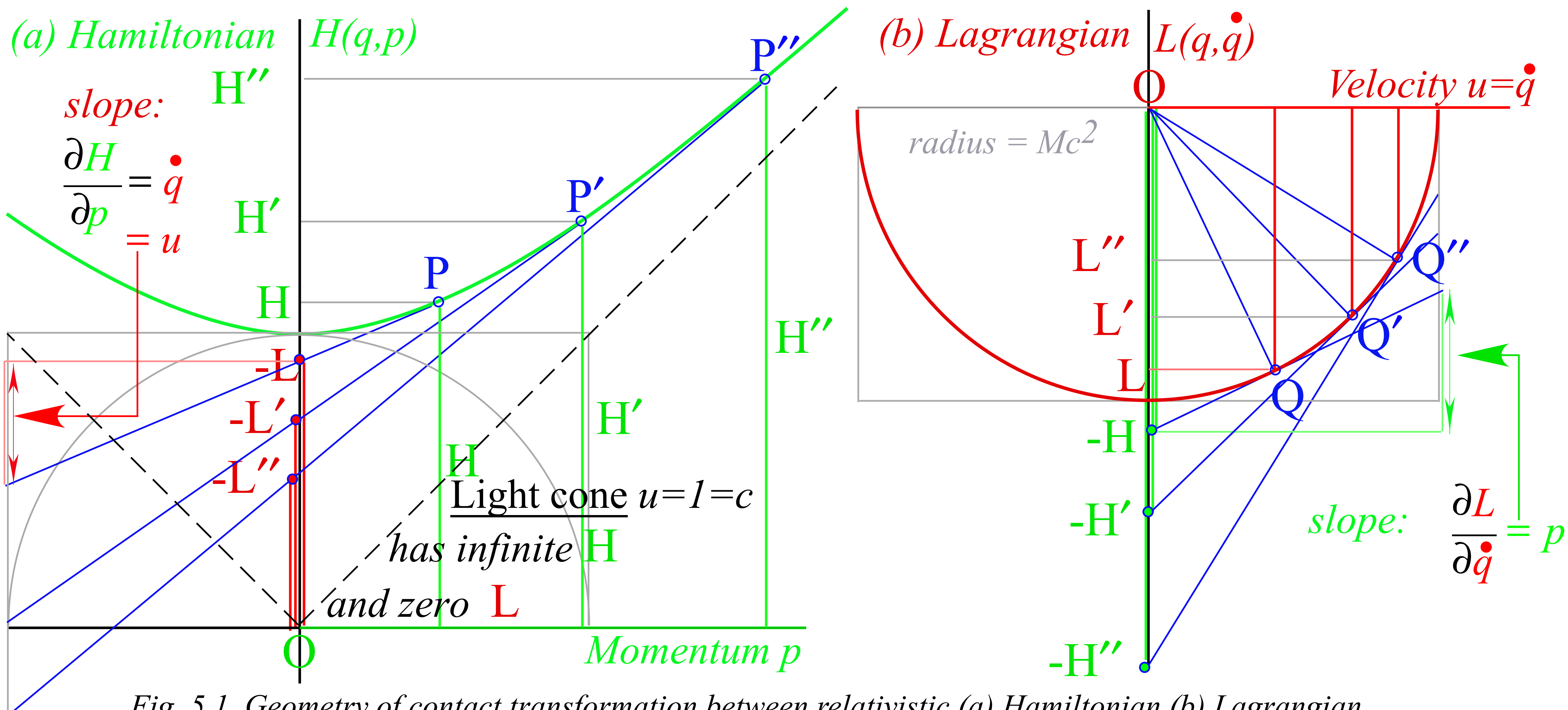

Fig. 5.1. Geometry of contact transformation between relativistic (a) Hamiltonian (b) Lagrangian

Relativistic Classical and Quantum Mechanics

Group vs. phase velocity and tangent contacts
Reviewing "Sin-Tan Rosetta" geometry
How optical CW group and phase properties give relativistic mechanics
Three kinds of mass (Einstein rest mass, Galilean momentum mass, Newtonian inertial mass)
What's the matter with light?
Bohr-Schrodinger (BS) approximation throws out Mc^2
Deriving relativistic quantum Lagrangian-Hamiltonian relations
Feynman's flying clock and phase minimization
Geometry of relativistic mechanics

Feynman's flying clock and phase minimization

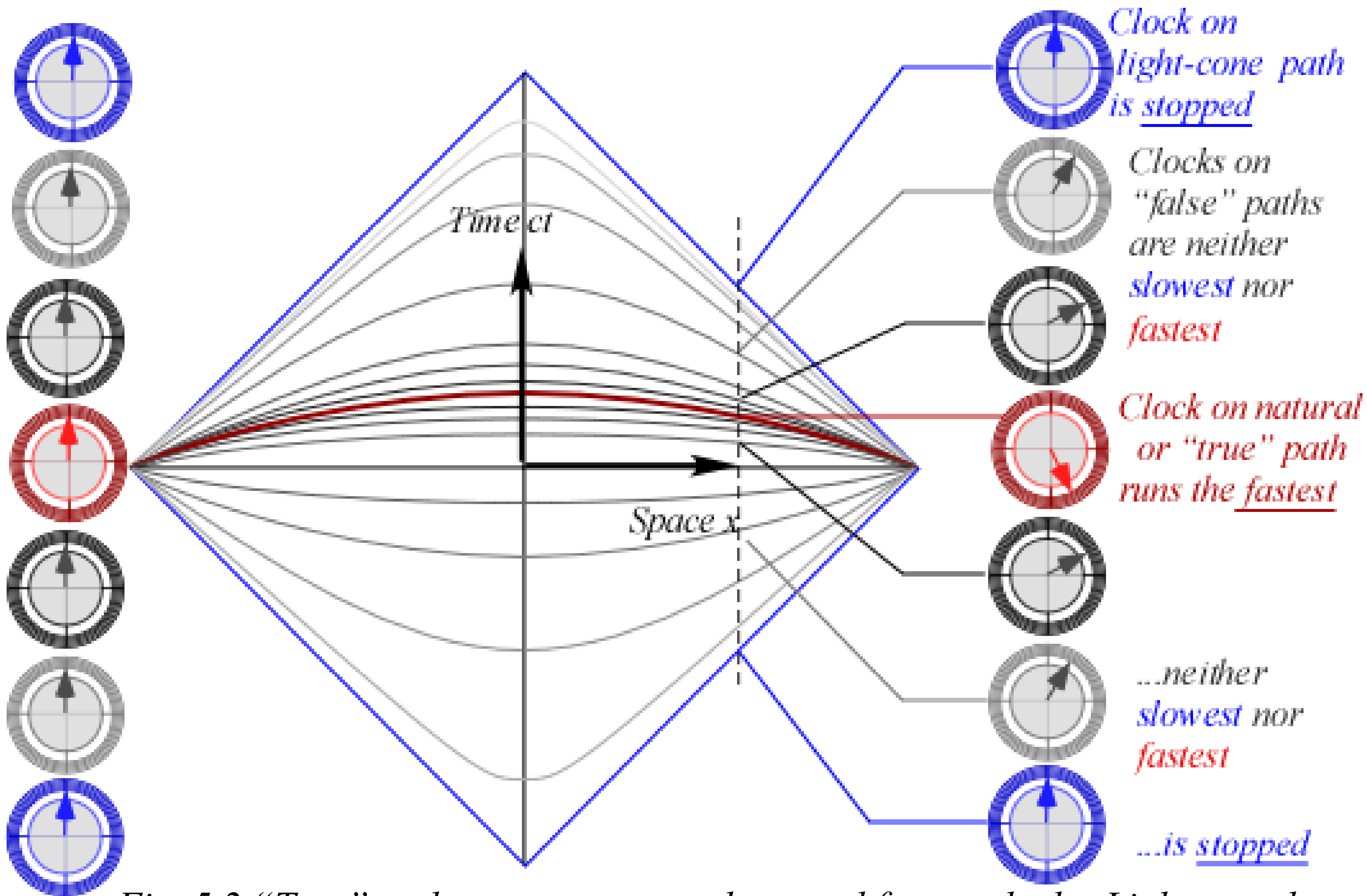

Fig. 5.2 "True" paths carry extreme phase and fastest clocks. Light-cone has only stopped clocks.

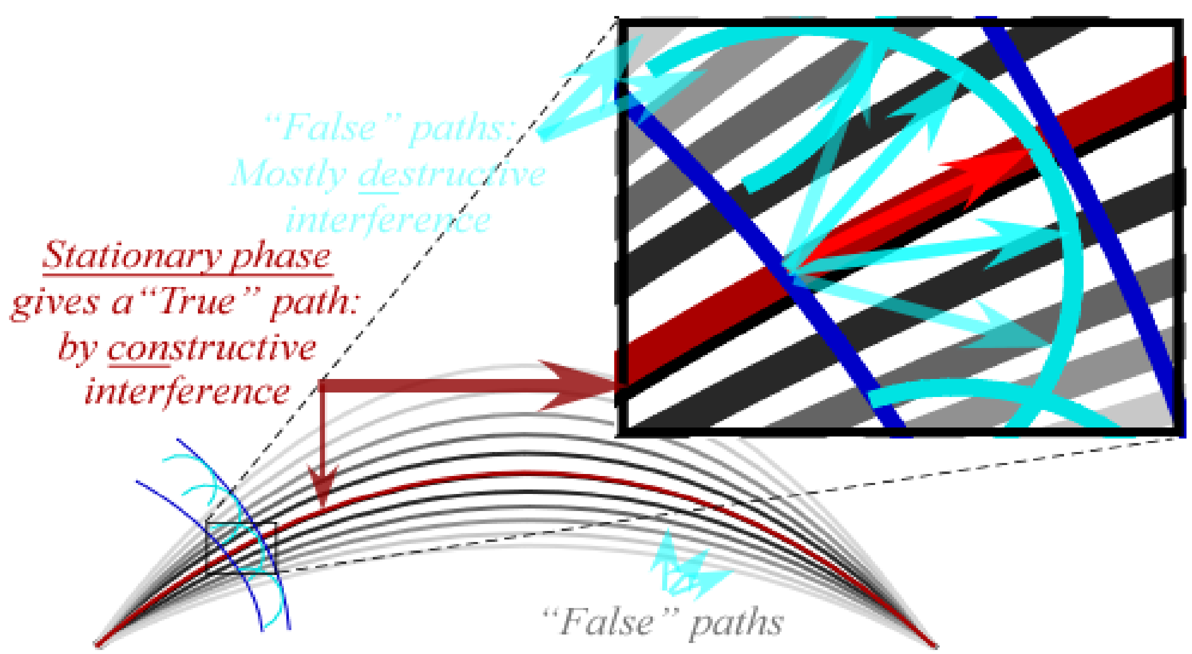

Fig. 5.3 Quantum waves interfere constructively on "True" path but mostly cancel elsewhere.

Relativistic Classical and Quantum Mechanics

Group vs. phase velocity and tangent contacts
- *Reviewing "Sin-Tan Rosetta" geometry*

How optical CW group and phase properties give relativistic mechanics
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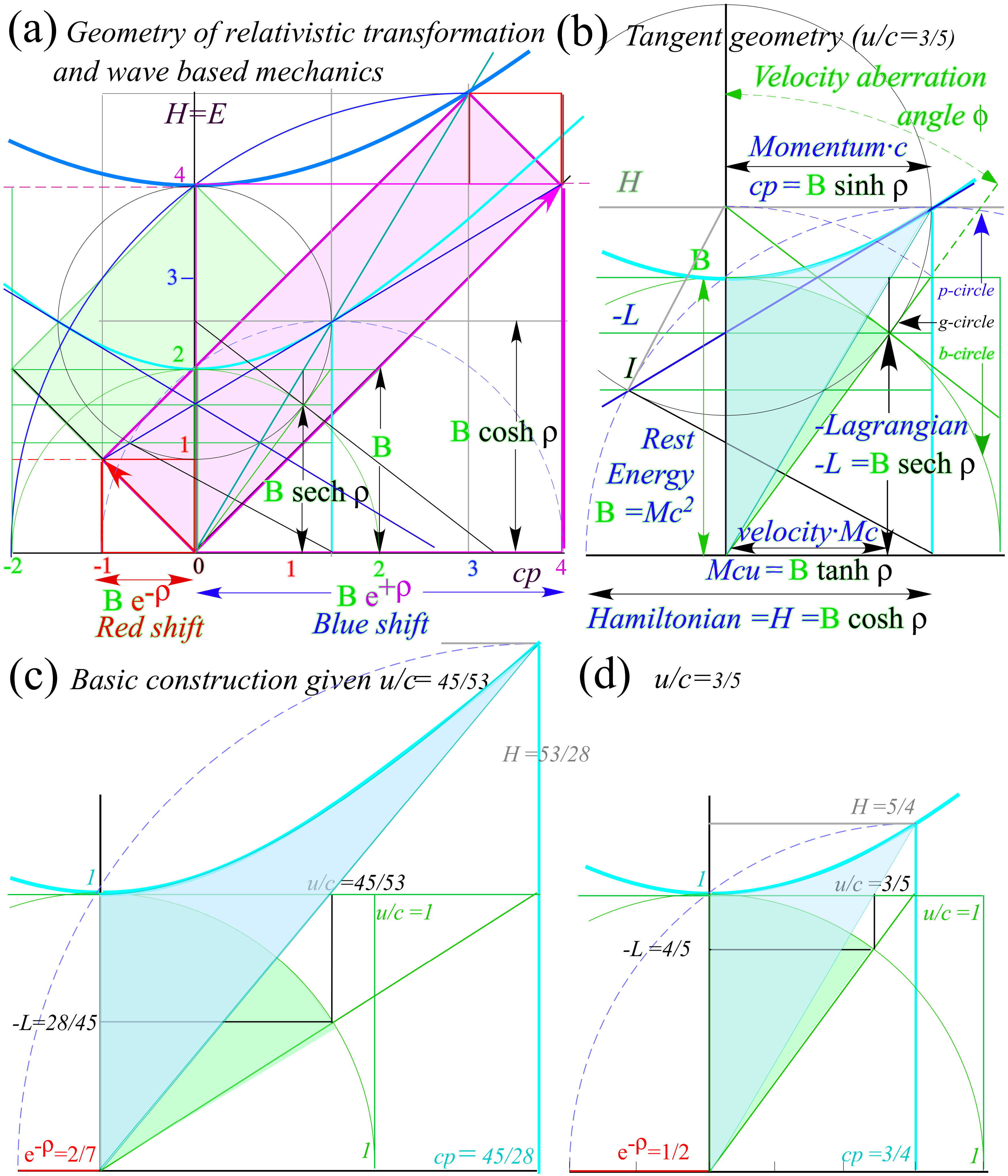

Fig. 5.5

Relativistic wave mechanics geometry.

(a) Overview.

(b-d) Details of contacting tangents.