Lectures 6 to 8

Tue. 2.9.16 to Thur 2.11.2016

Introducing Lightwave Fourier Analysis

(Comparing wave dynamics to classical behavior in Ch. 3 thru Ch. 5 of Unit 1)

Introducing lightwave Fourier analysis - Pulse Waves (PW) versus Continuous Waves (CW)

Simplest is CW (Continuous Wave, Cosine Wave, Colored Wave, Complex Wave,...)

CW parameters: Wavelength λ *and Wave period* τ

CW inverse parameters: Wavelnumber $\kappa=1/\lambda$ *and Wave frequency* $\upsilon=1/\tau$

CW angular parameters: Wavevector $k=2\pi\kappa=2\pi/\lambda$ *and angular frequency* $\omega=2\pi\upsilon=2\pi/\tau$

CW wavefunction : $\psi=A\exp[i(kx-\omega t)]=A\cos(kx-\omega t)+iA\sin(kx-\omega t)$

Wave phasors, phasor chain plots, dispersion functions $\omega(k)$*, and phase velocity* $V_{phase}=\omega(k)/k$

Special case: Lightwave linear dispersion:$V_{phase}=c$ *or:* $\omega(k)=ck$

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Building PW from CW components using "Fourier Control" app-panel

Fourier PW "box-car" geometric series summed

Animation of PW obeying lightwave linear dispersion $\omega(k)=ck$

Important Evenson axiom for relativity: "All colors go c"

Visualizing PW wave uncertainty relations for space: $\Delta x\cdot\Delta\kappa=1$ *and* time: $\Delta t\cdot\Delta\upsilon=1$

PW "wrinkles" go away if Fourier "boxcar" is tapered to a softer "Gaussian"

Opposite-pair CW (colliding $\pm m=\pm 2$*) Fourier components trace a Cartesian space-time grid*

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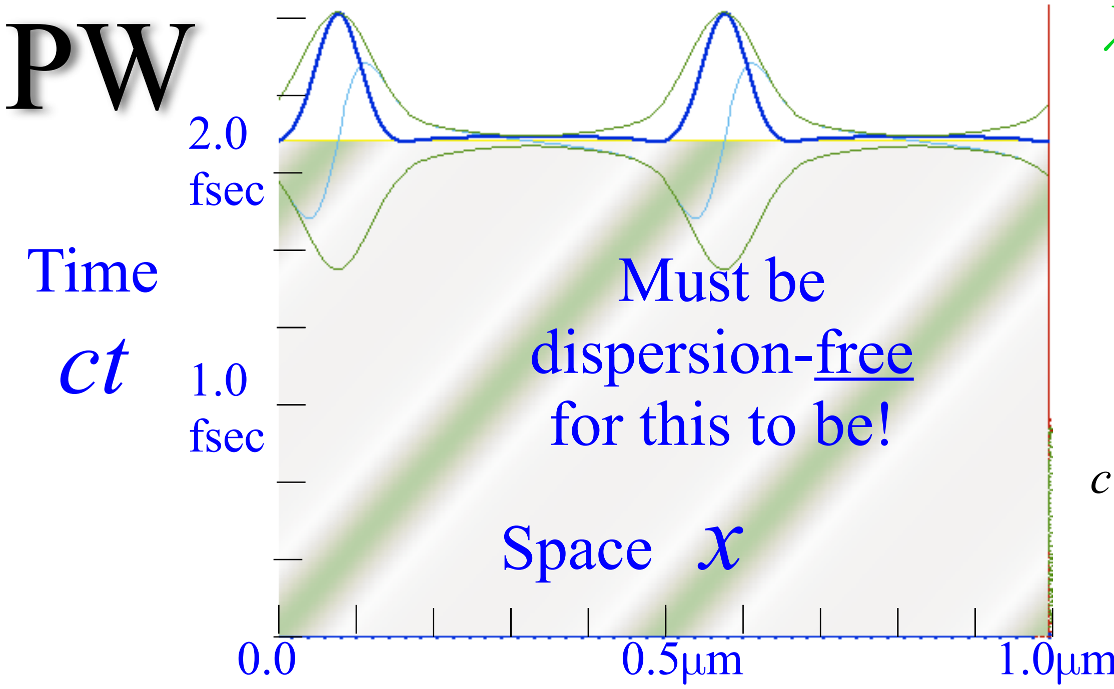
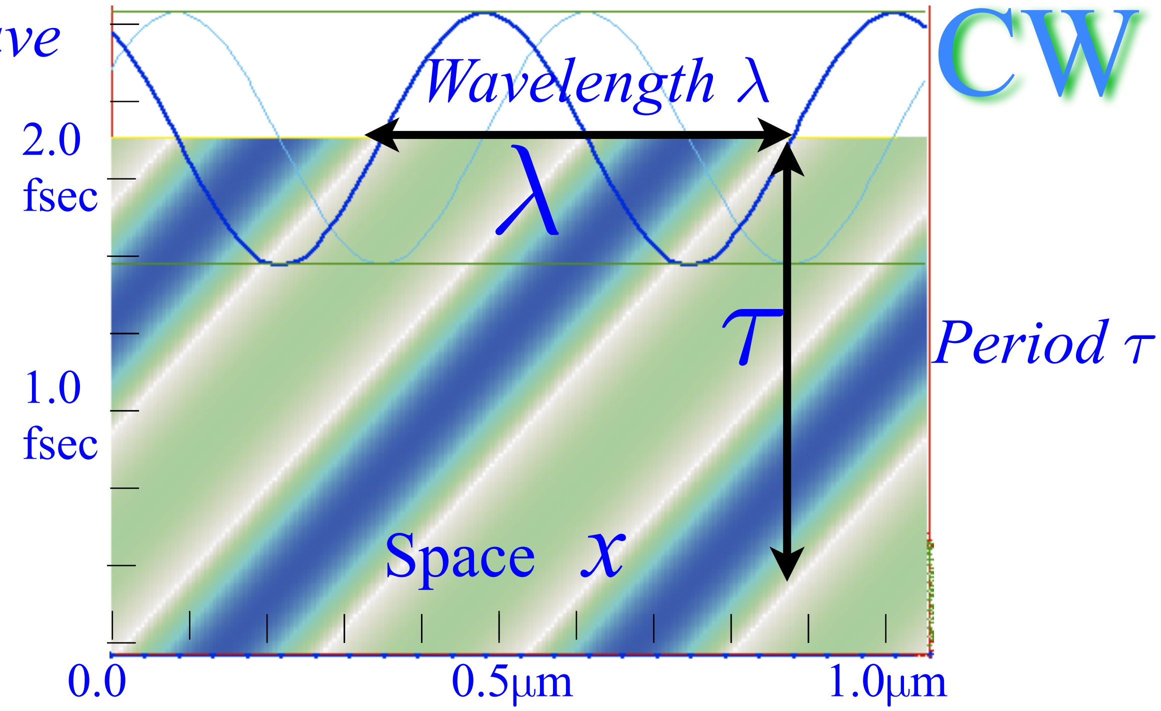


λ=0.5µm per wave

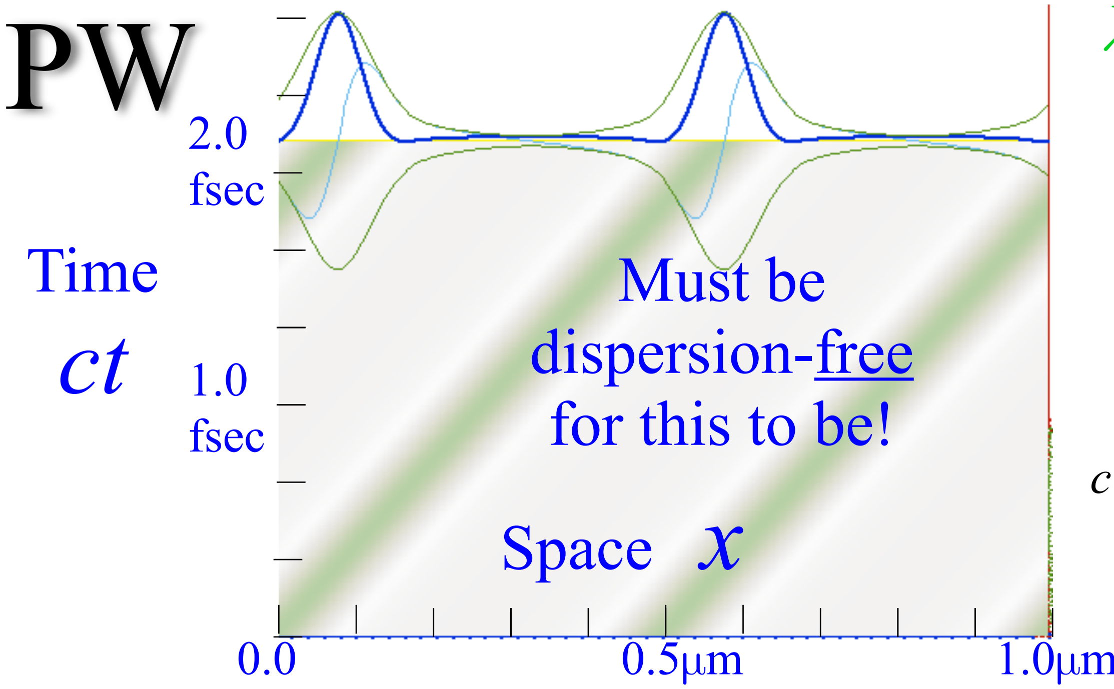
Time

ct

$c = 2.99792458 \cdot 10^8 m/s$
$\approx 3 \cdot 10^8 m/s$
$\approx 0.3\ \mu m/fs \approx 1\ ft/ns$



It helps to introduce two *archetypes* of light waves and contrast them.



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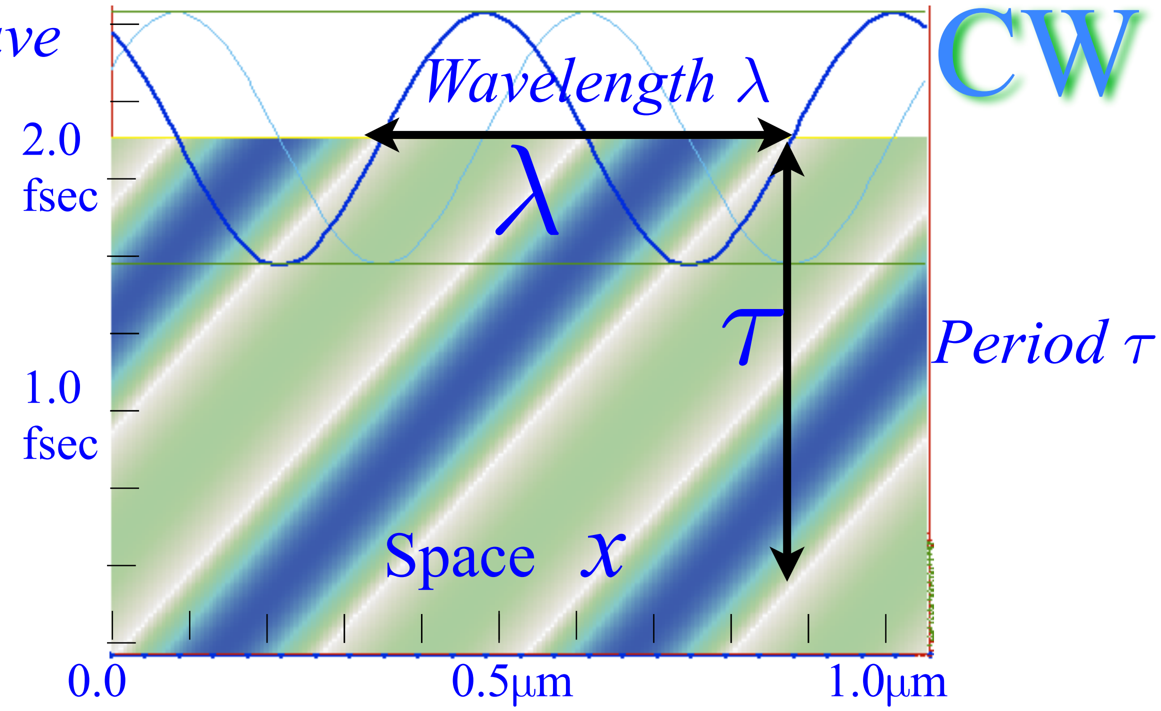

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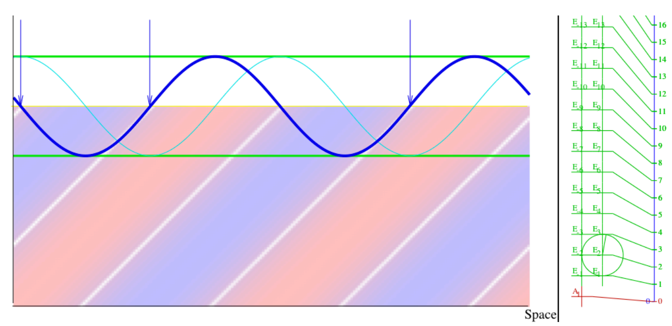

Single panel with k-phasors & Phase zero tracers in space-time
http://www.uark.edu/ua/modphys/markup/BohrItWeb.html?scenario=330002

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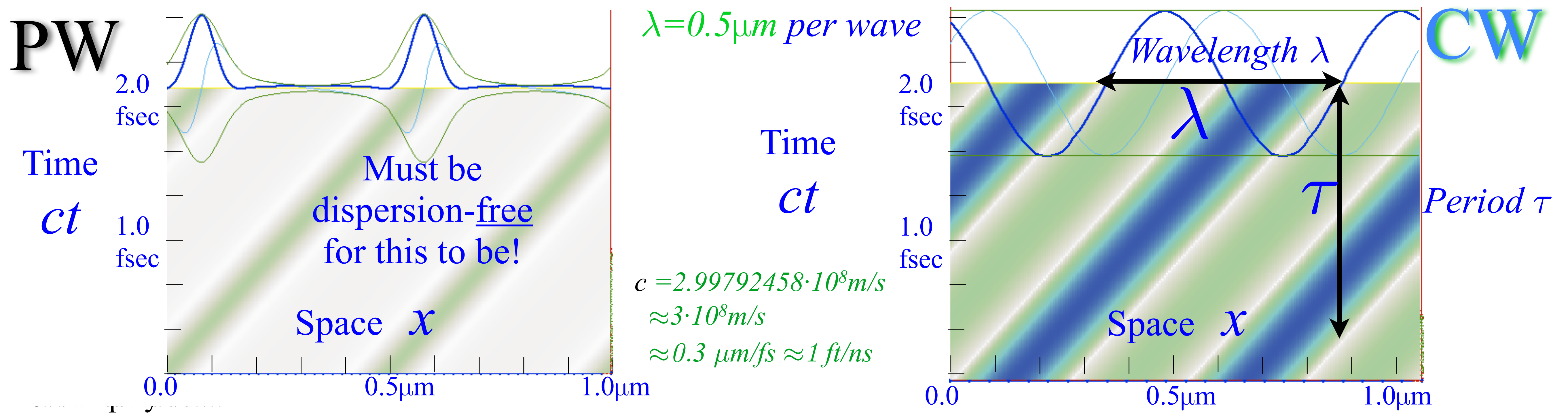

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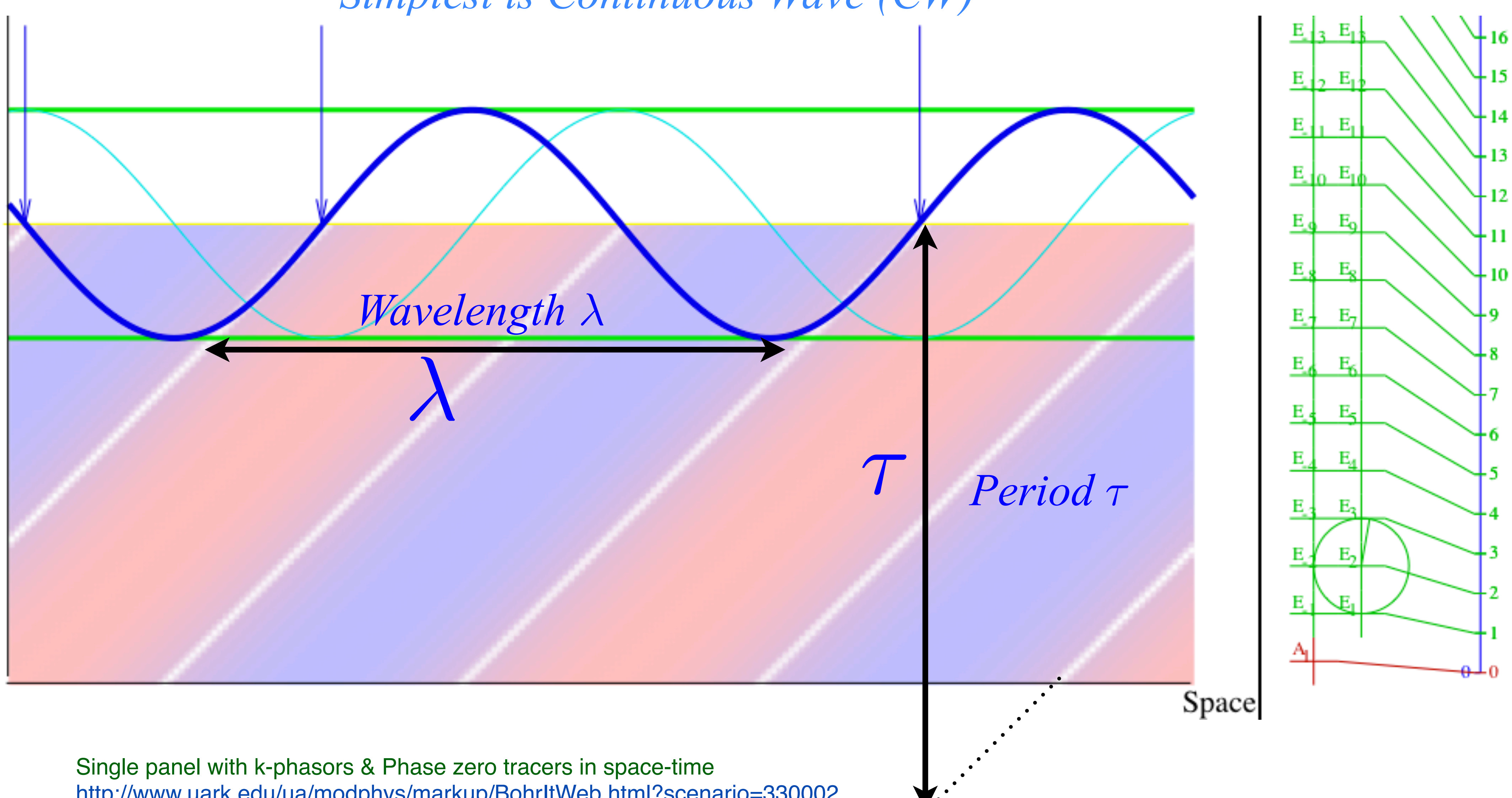

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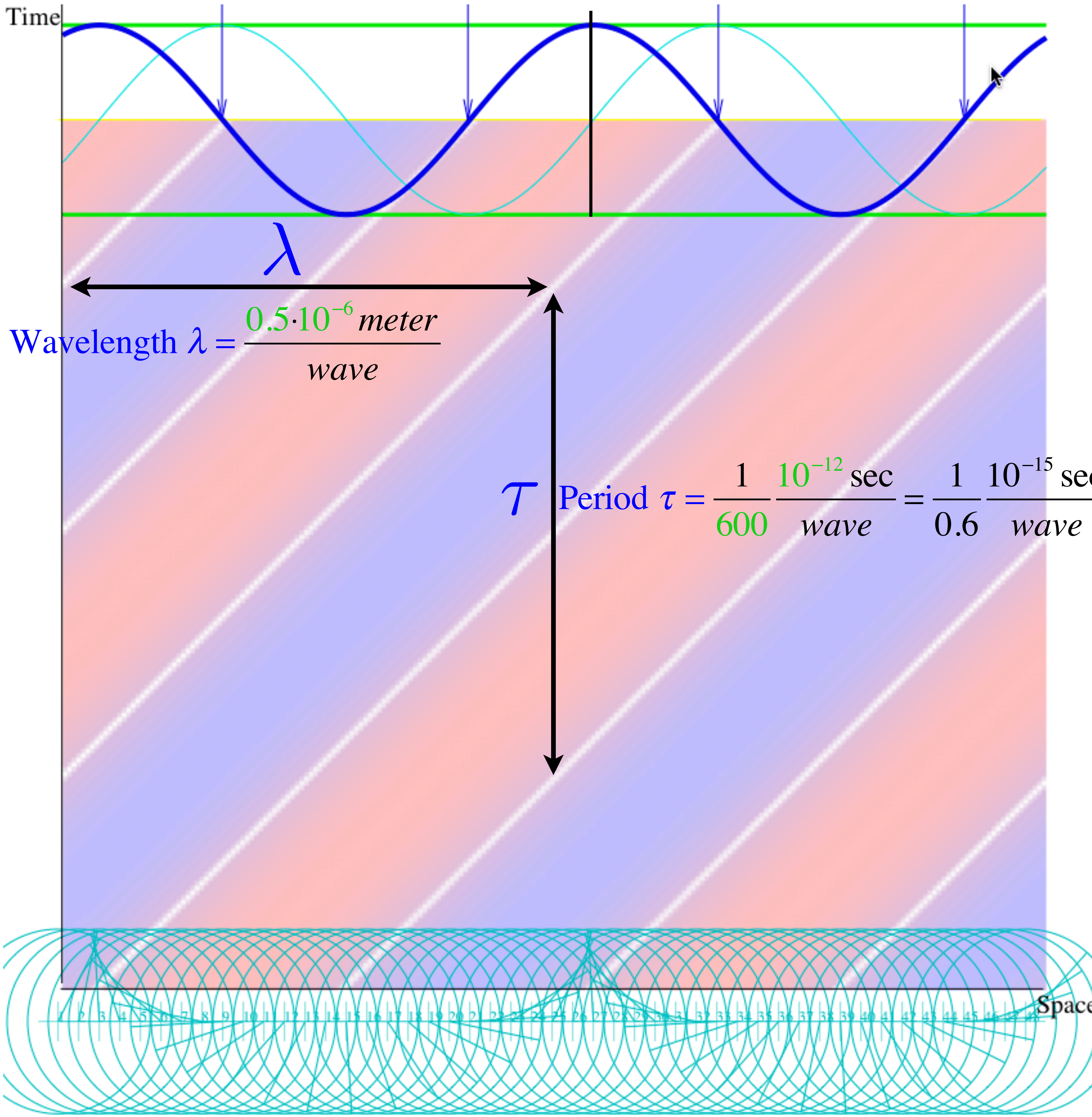

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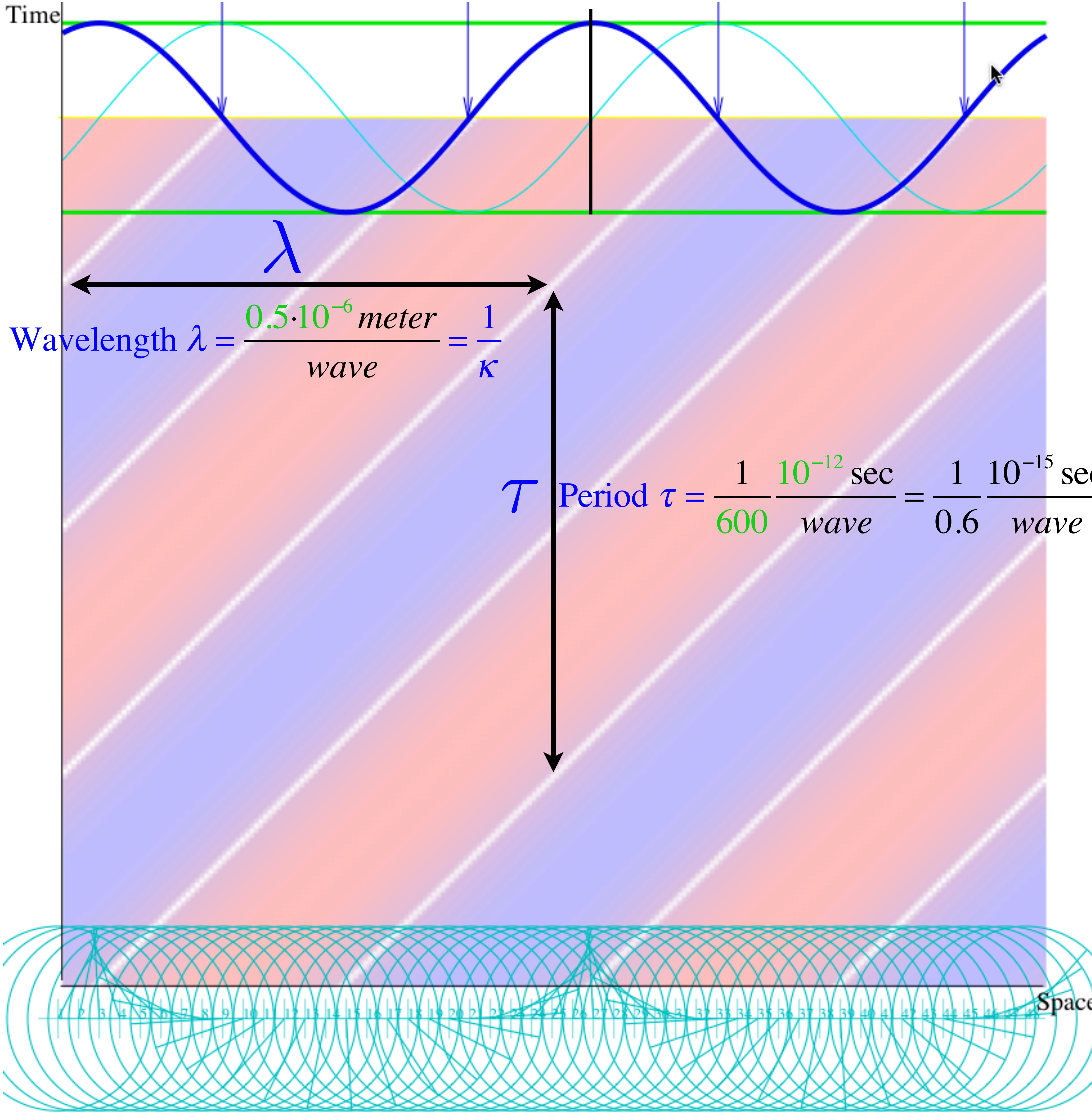

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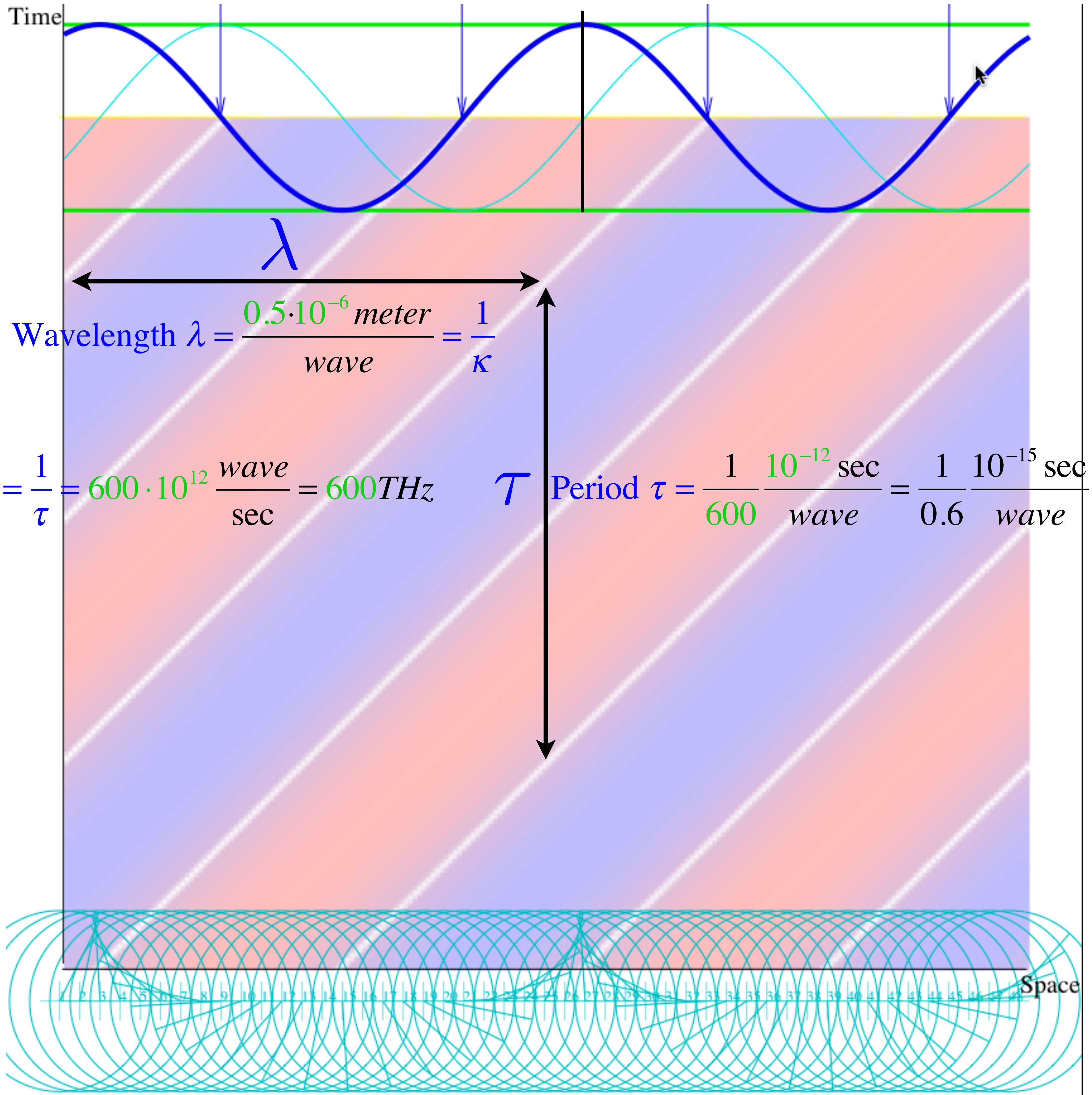

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Frequency $\upsilon = \frac{1}{\tau} = 600 \cdot 10^{12} \frac{wave}{\sec} = 600\, THz$

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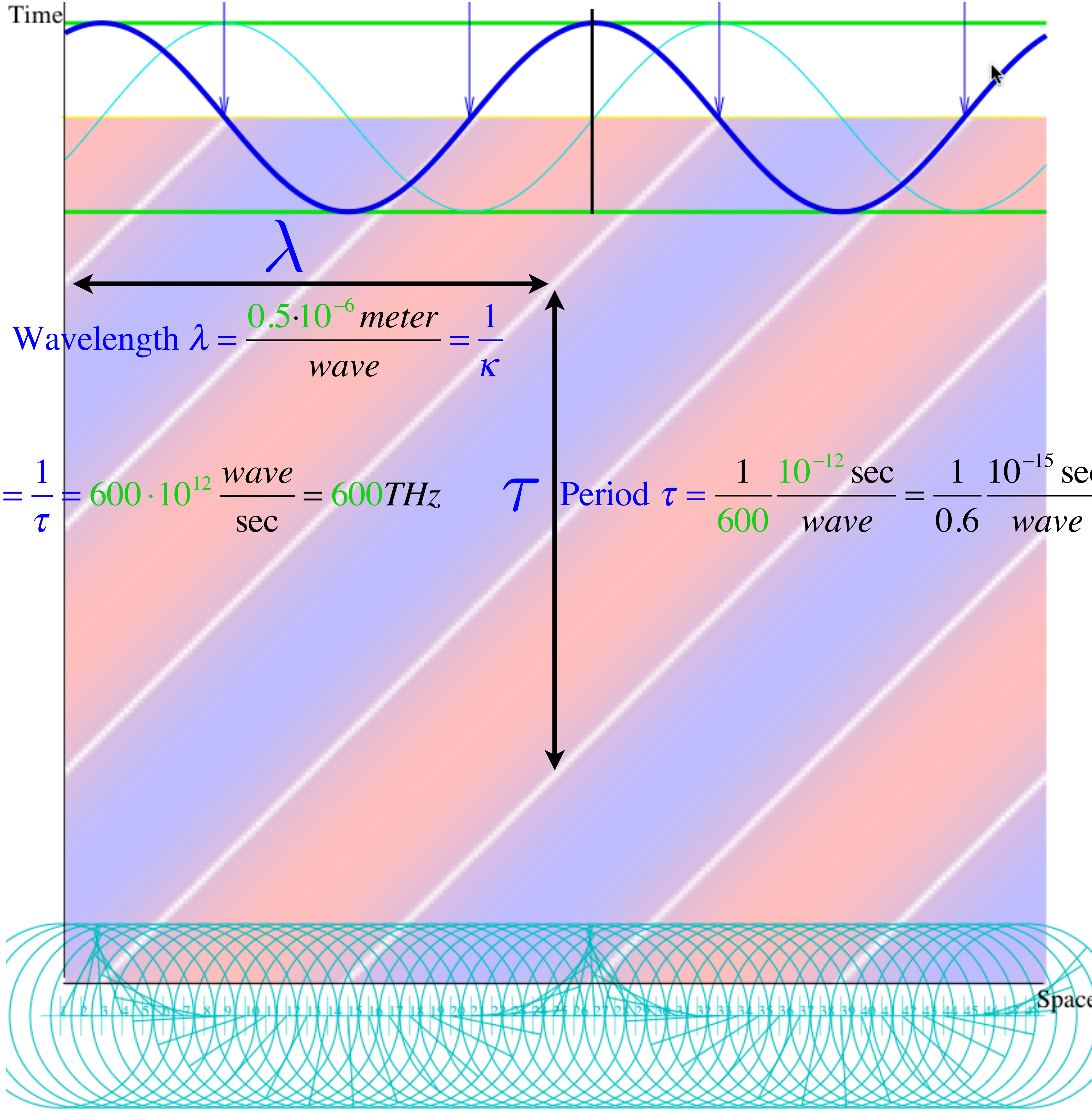

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Heinreich Hertz 1857-1894

$1Hz = 1sec^{-1}$

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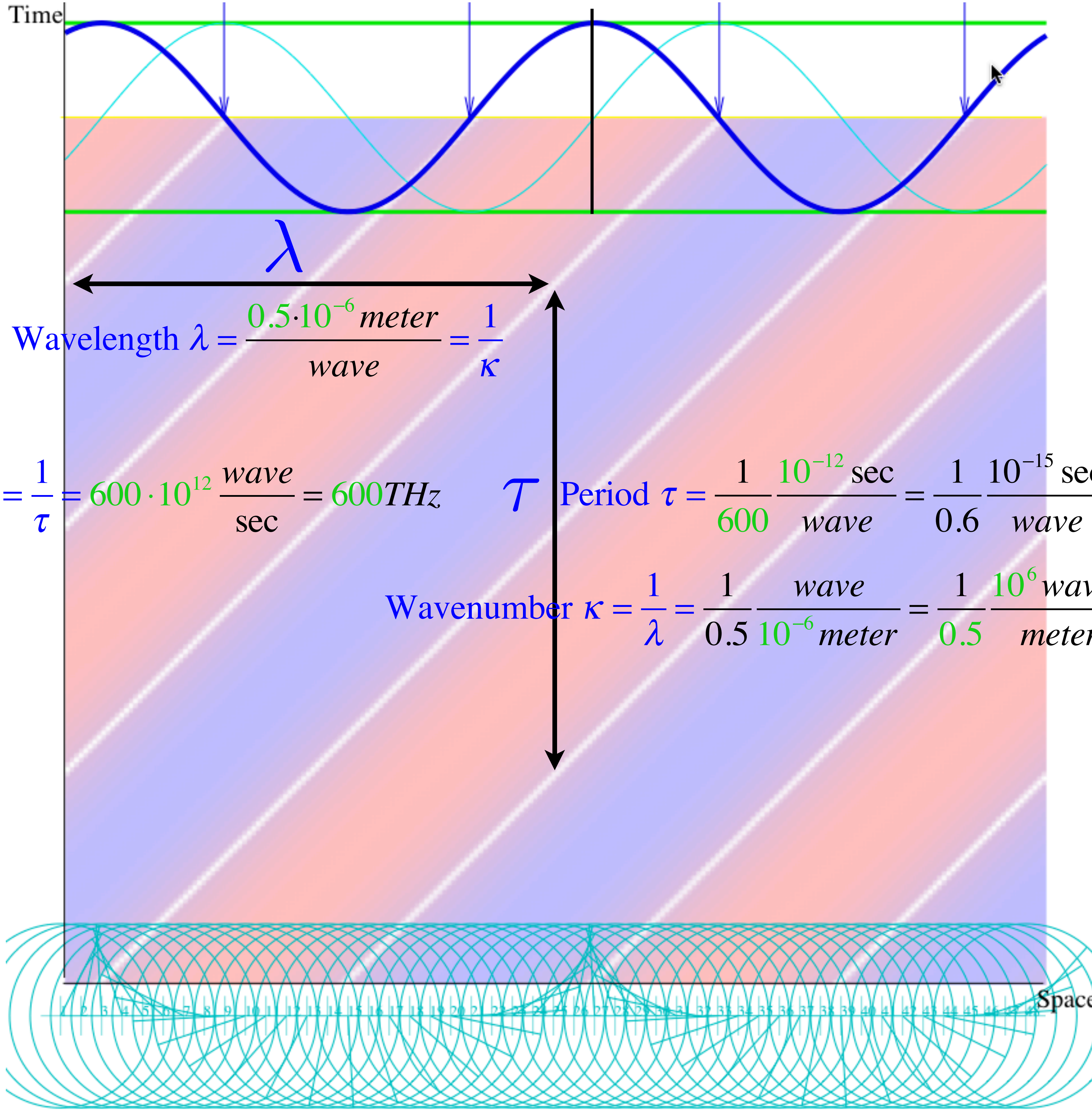

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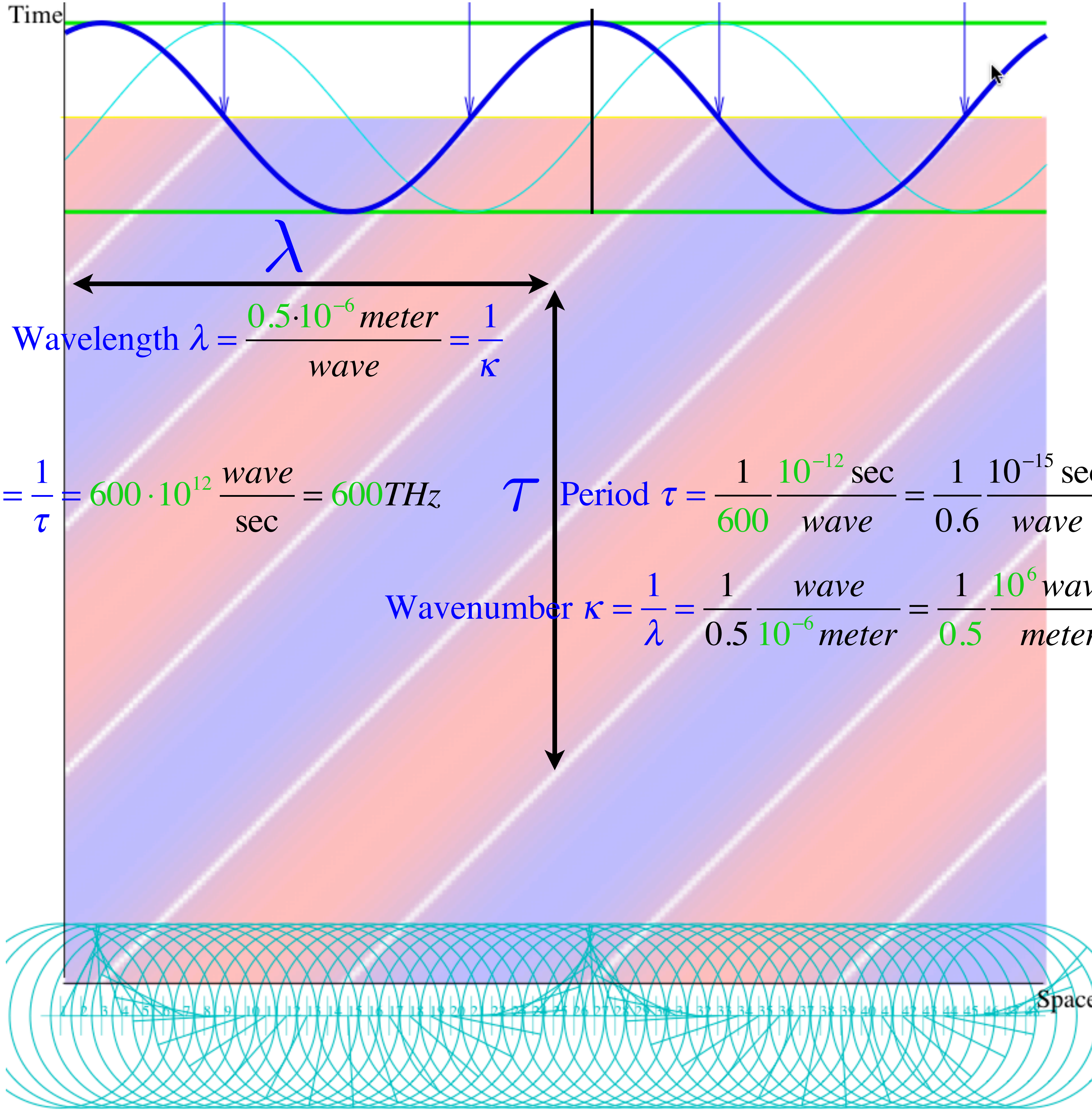

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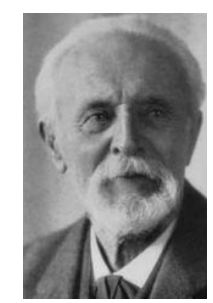

Heinreich Kayser 1853-1940

1Kayser=1cm^{-1}

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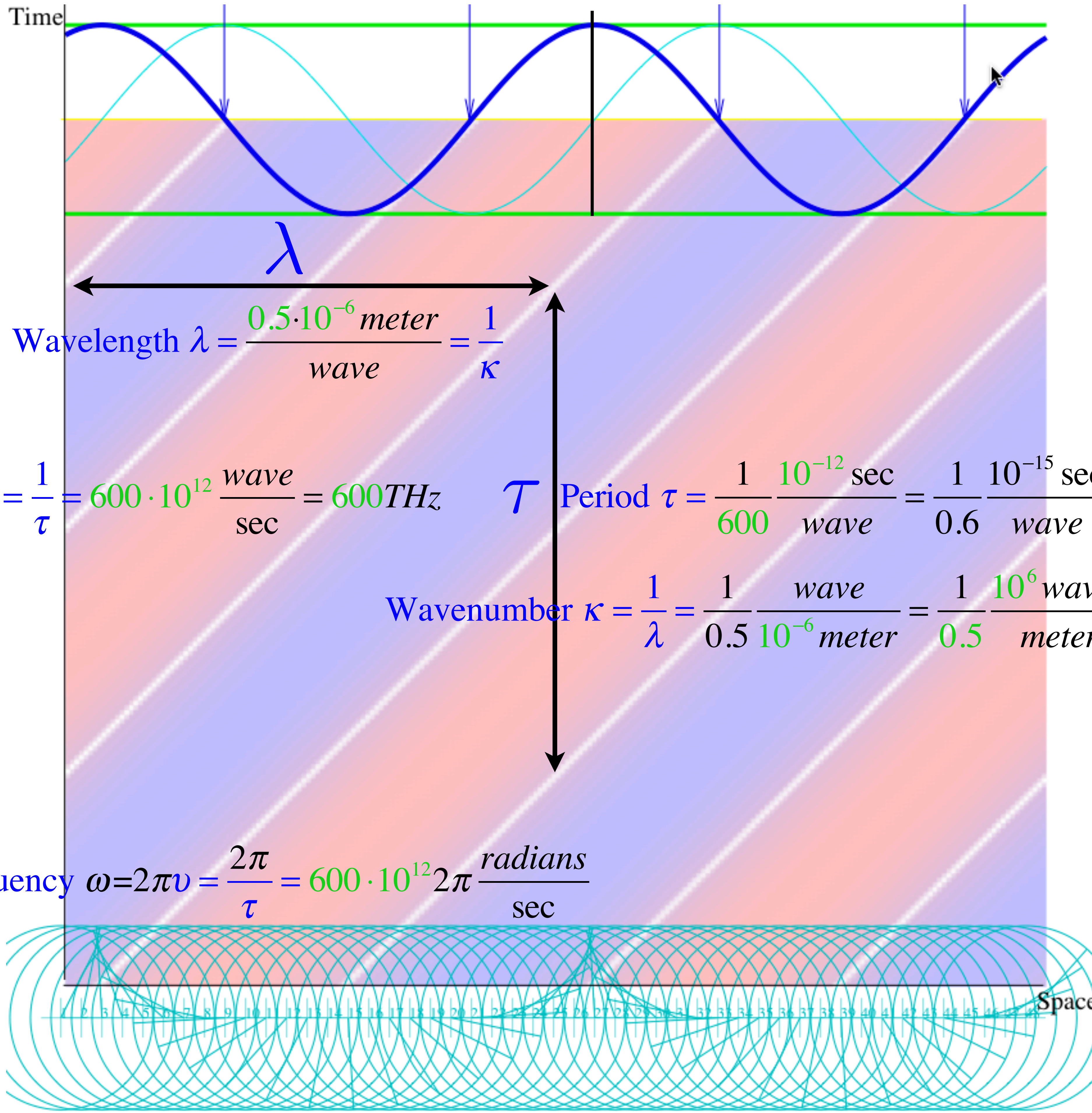

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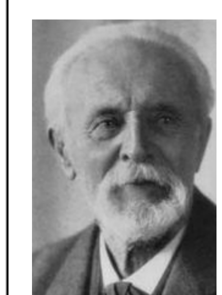

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Angular Frequency $\omega = 2\pi\upsilon = \frac{2\pi}{\tau} = 600 \cdot 10^{12} 2\pi \frac{radians}{\sec}$

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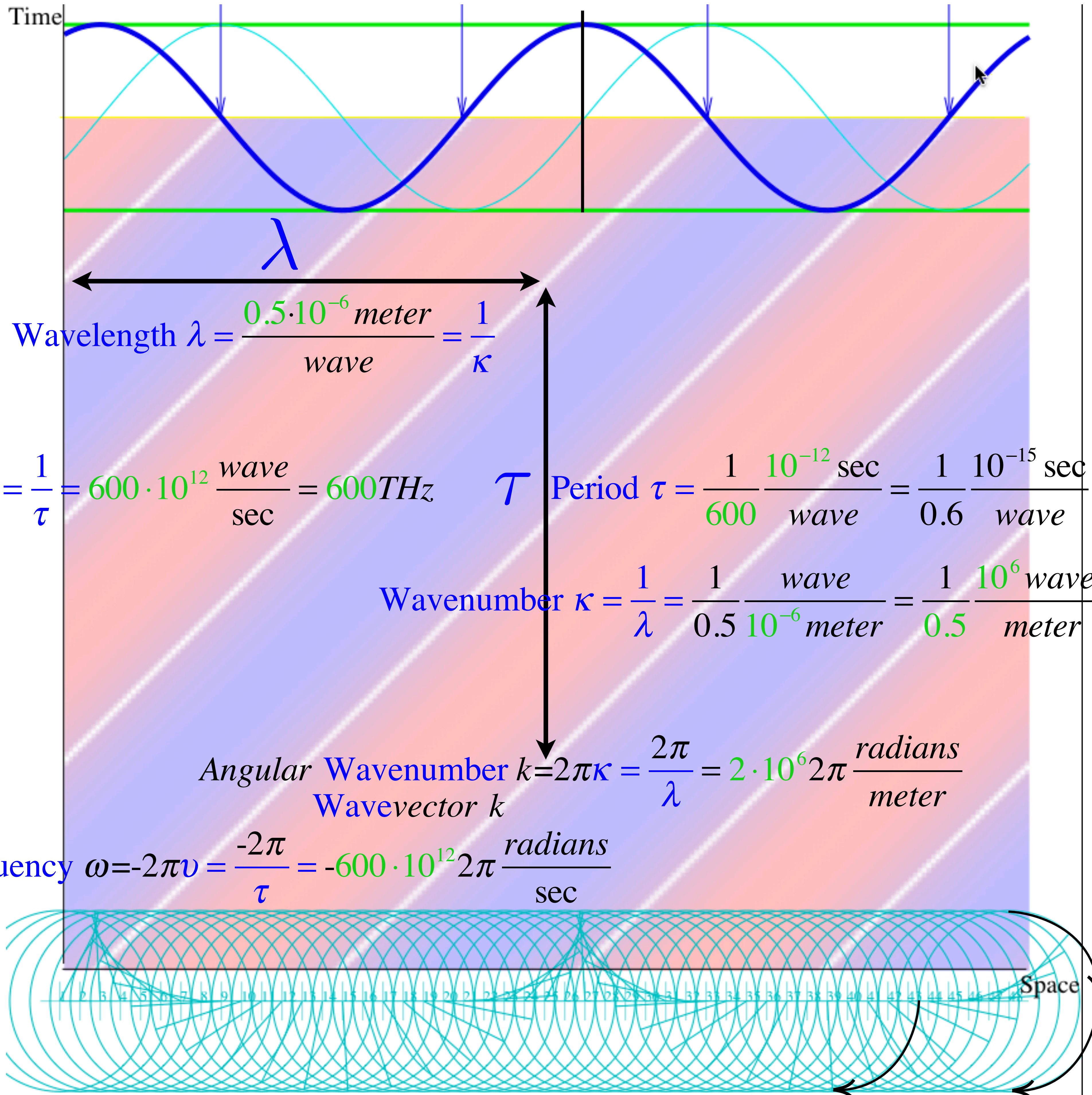
CW



$$\lambda$$

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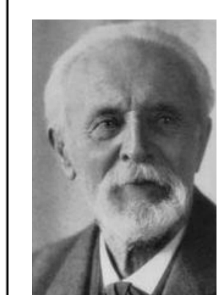

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Angular Wavenumber $k = 2\pi\kappa = \frac{2\pi}{\lambda} = 2\cdot 10^{6}\, 2\pi\,\frac{radians}{meter}$
Wavevector k

Angular Frequency $\omega = -2\pi\upsilon = \frac{-2\pi}{\tau} = -600\cdot 10^{12}\, 2\pi\,\frac{radians}{\sec}$

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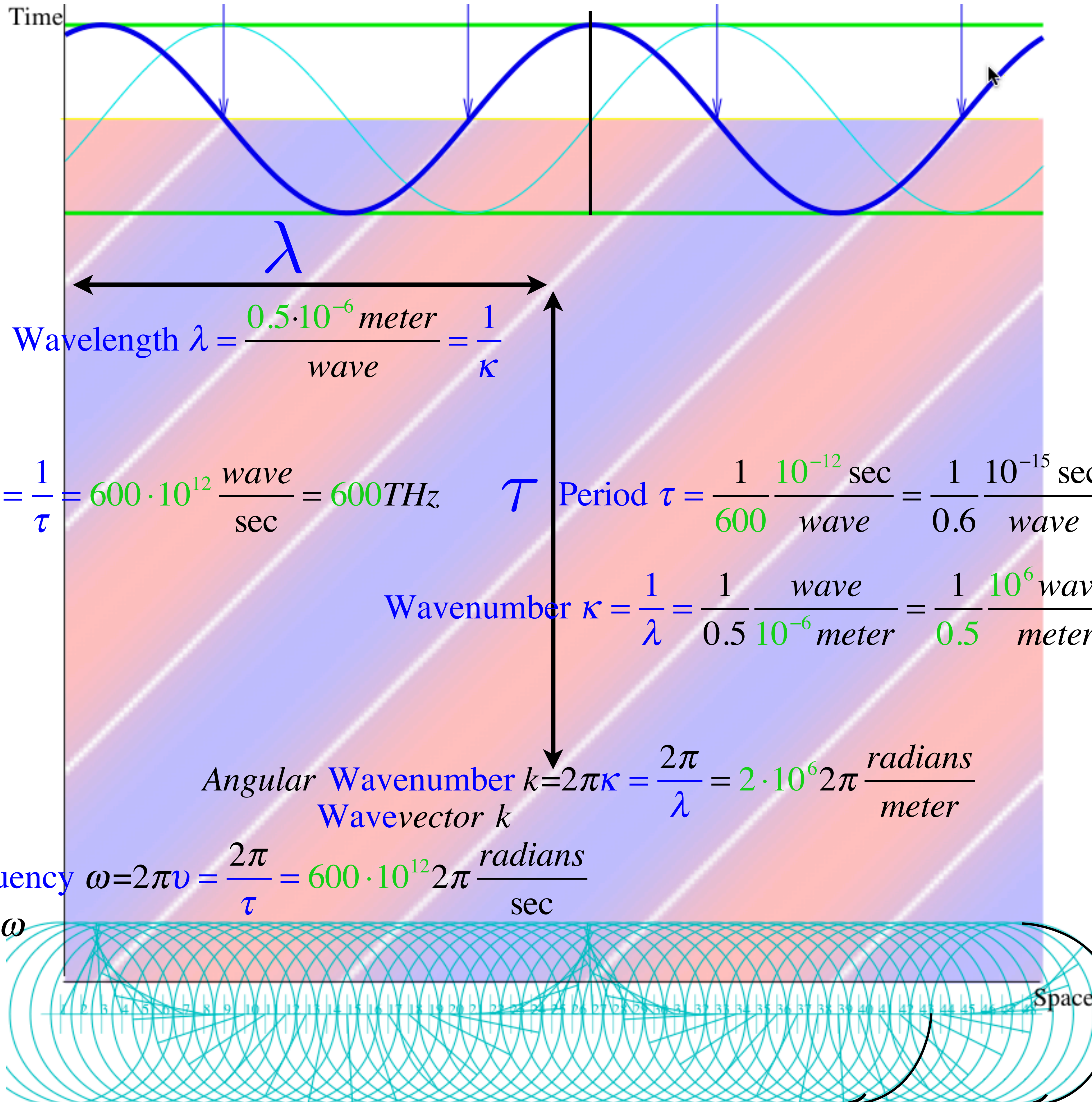

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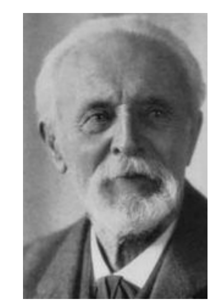

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Wavevector k

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Wavescalar ω

Not standard terminology (but should be)

Angular Frequency

$\omega = -2\pi\upsilon \frac{radians}{\sec}$

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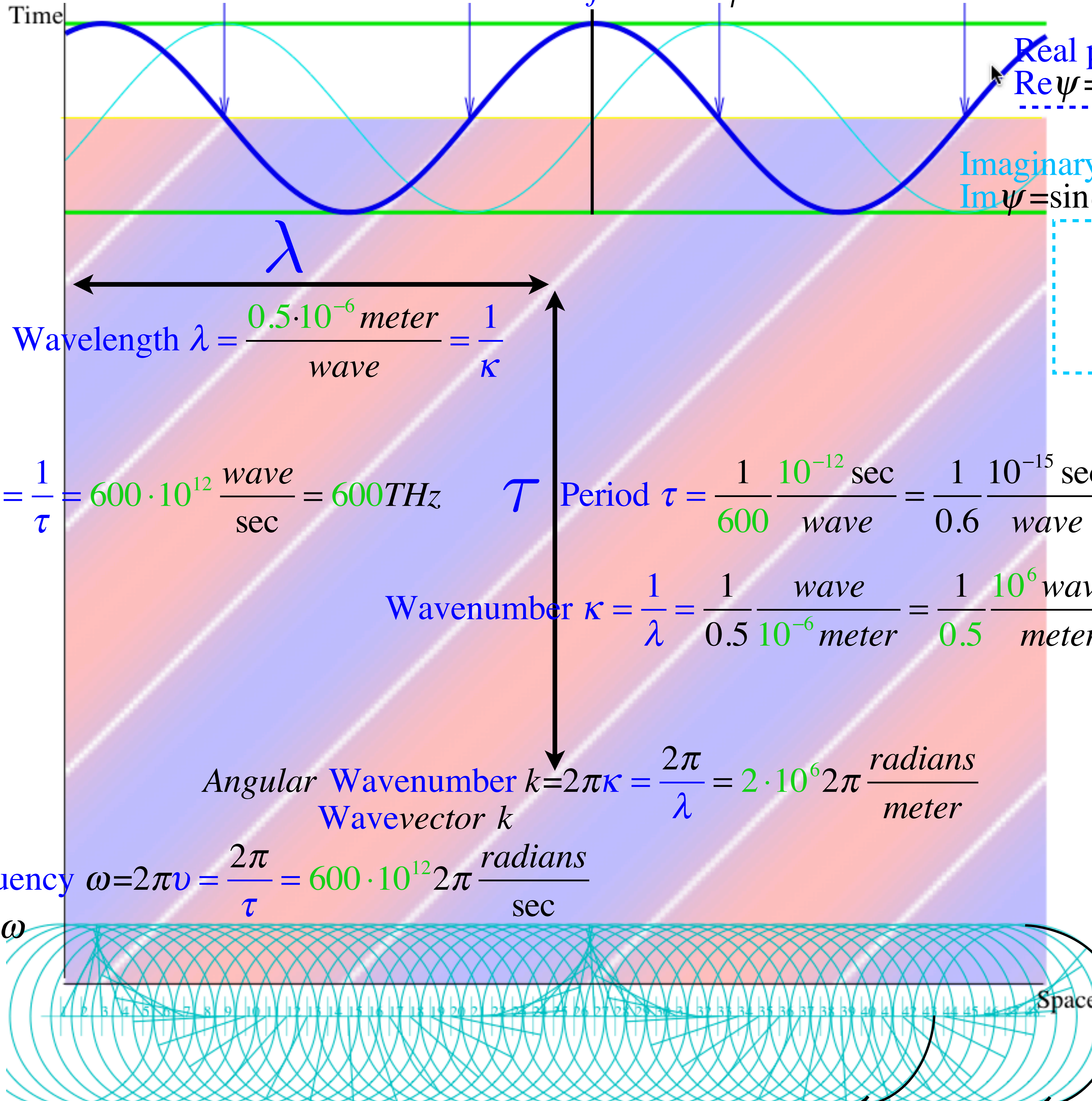

$$\text{Wavefunction}: \psi = e^{i\phi} = e^{i(kx-\omega t)}$$

Real part:
$$\mathrm{Re}\,\psi = \cos\phi = \cos(kx-\omega t)$$

Imaginary part:
$$\mathrm{Im}\,\psi = \sin\phi = \sin(kx-\omega t)$$

$$\phi = kx-\omega t$$

λ

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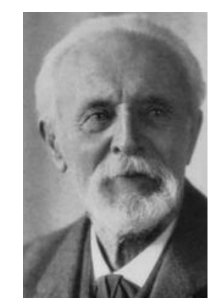
$$\text{Frequency } \upsilon = \frac{1}{\tau} = 600\cdot 10^{12}\frac{wave}{\sec} = 600THz$$

τ

$$\text{Period } \tau = \frac{1}{600}\frac{10^{-12}\sec}{wave} = \frac{1}{0.6}\frac{10^{-15}\sec}{wave} = \frac{5}{3}\frac{femto\sec}{wave} = \frac{1}{\upsilon}$$

Heinreich Hertz 1857-1894
1Hz=1sec^{-1}

$$\text{Wavenumber } \kappa = \frac{1}{\lambda} = \frac{1}{0.5}\frac{wave}{10^{-6}\,meter} = \frac{1}{0.5}\frac{10^{6}\,waves}{meter} = 2\cdot 10^{6}\frac{waves}{meter}$$



Heinreich Kayser 1853-1940
1Kayser=1cm^{-1}

$$\textit{Angular}\ \text{Wavenumber } k = 2\pi\kappa = \frac{2\pi}{\lambda} = 2\cdot 10^{6}\,2\pi\frac{radians}{meter}$$

Wavevector k

$$\textit{Angular}\ \text{Frequency } \omega = 2\pi\upsilon = \frac{2\pi}{\tau} = 600\cdot 10^{12}\,2\pi\frac{radians}{\sec}$$

Wavescalar ω

Not standard terminology (but should be)

Angular Frequency

$$\omega = -2\pi\upsilon\frac{radians}{\sec}$$

Single panel with k-phasors & Phase zero tracers in space-time
http://www.uark.edu/ua/modphys/markup/BohrItWeb.html?scenario=330002

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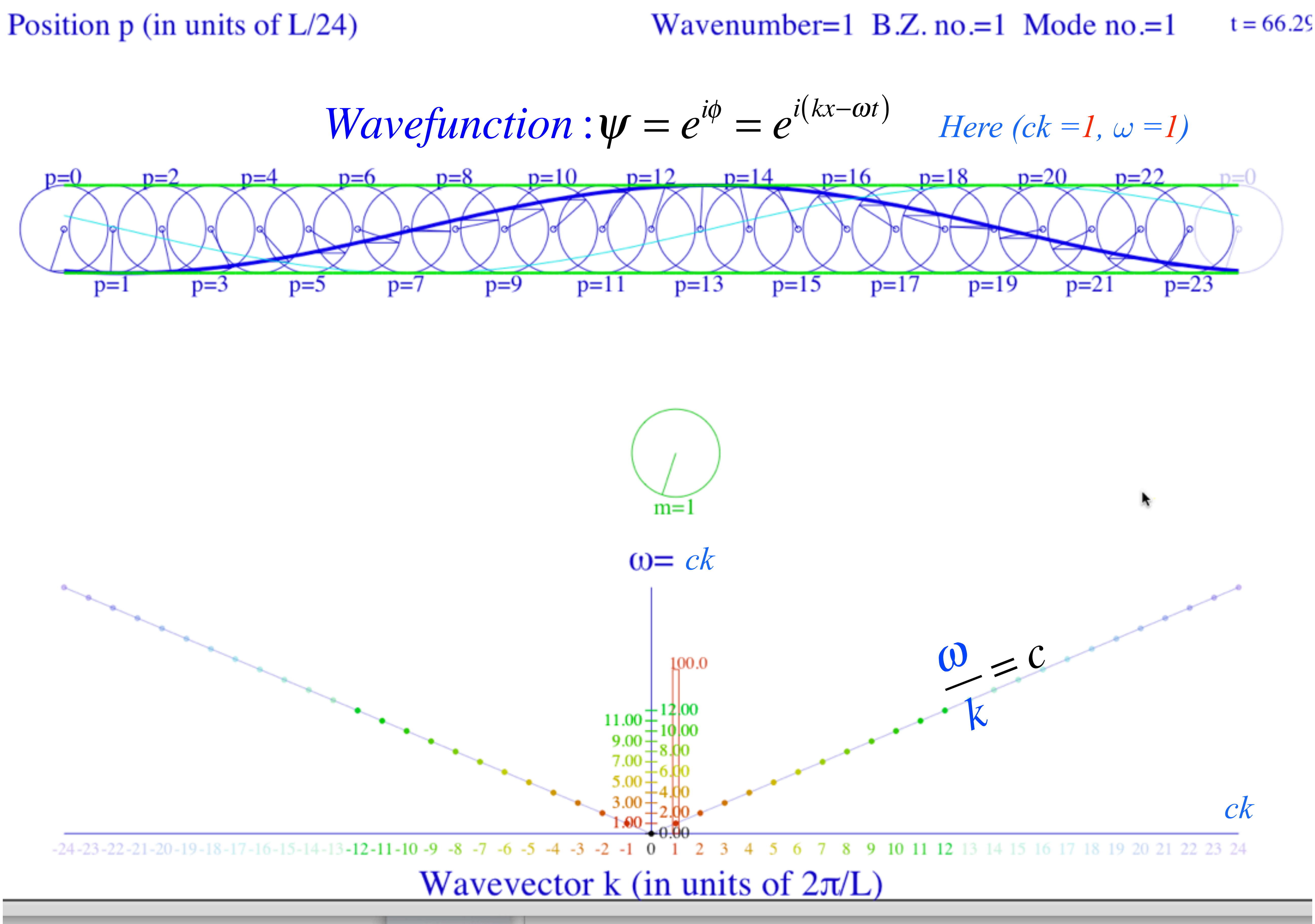
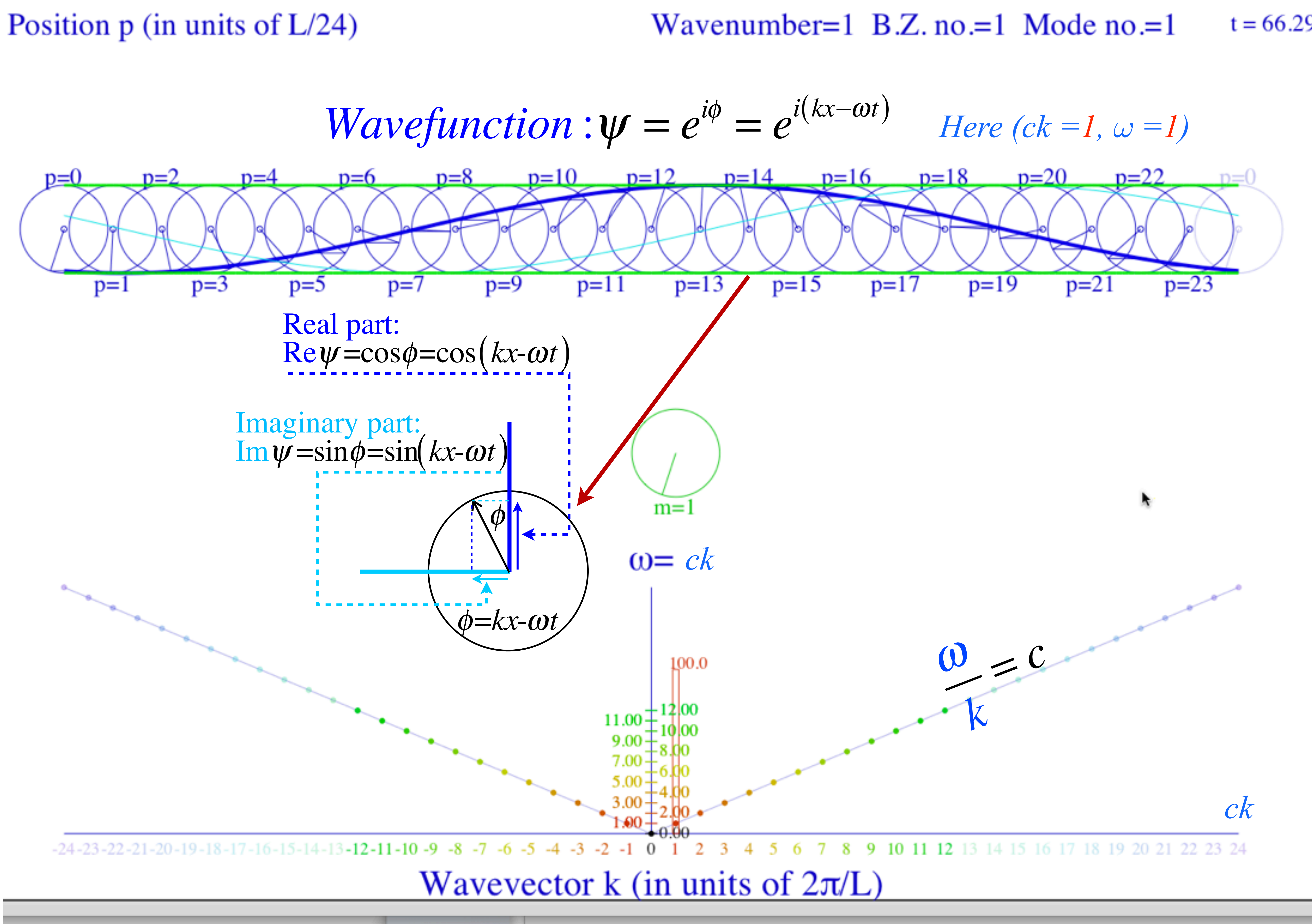


solo right 1-CW over linear dispersion + k-histogram
http://www.uark.edu/ua/modphys/markup/WaveItWeb.html?scenario=1CW_K+1_2016HP



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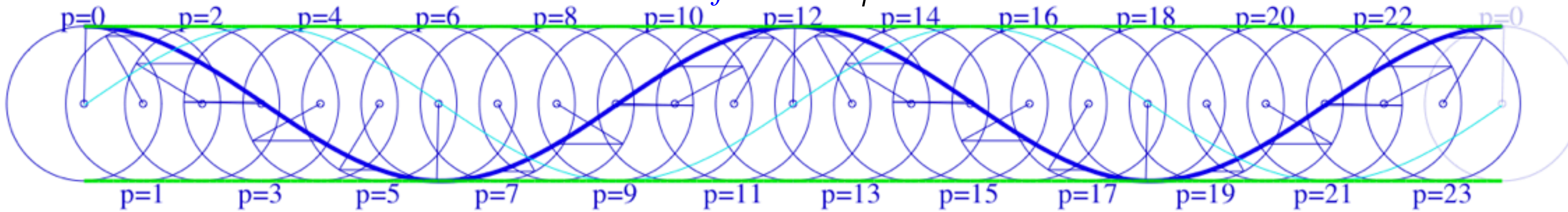
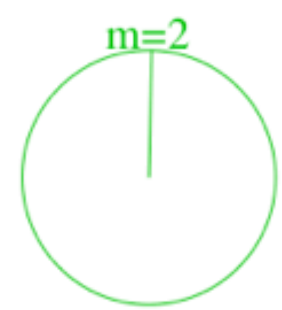
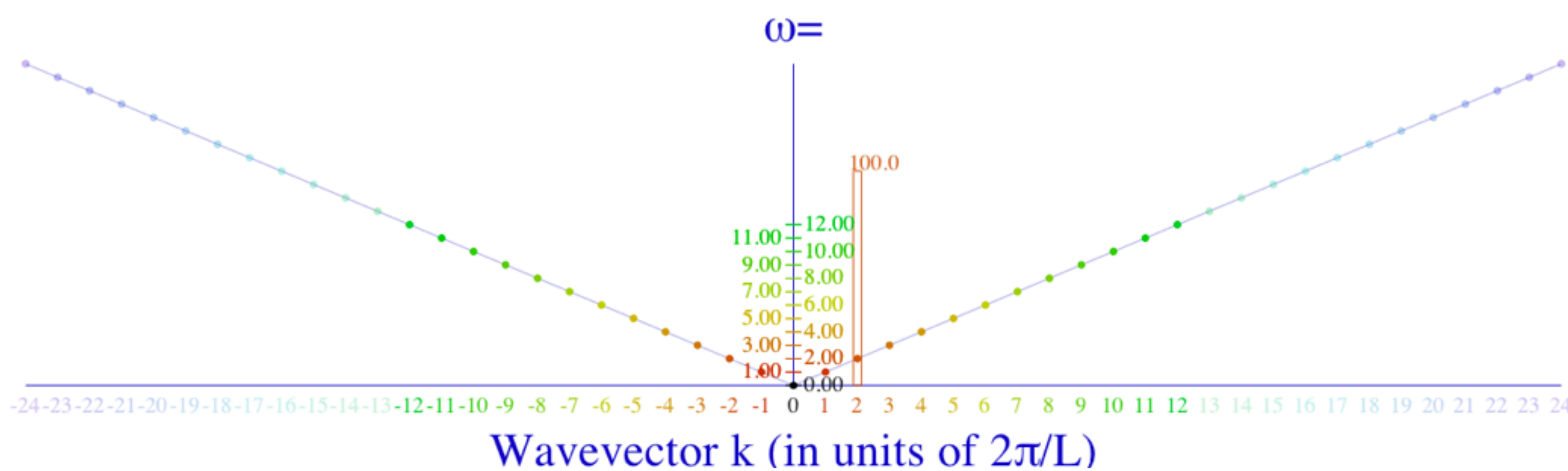
Position p (in units of L/24) Fourier Control On Mode No. 2 t = 3.08

$$\textit{Wavefunction}: \psi = e^{i\phi} = e^{i(kx-\omega t)}$$







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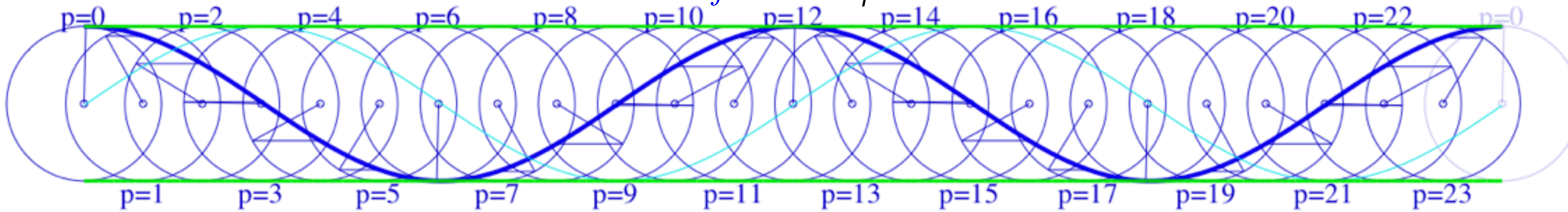
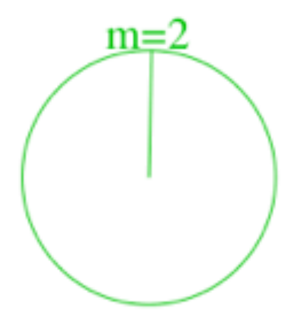
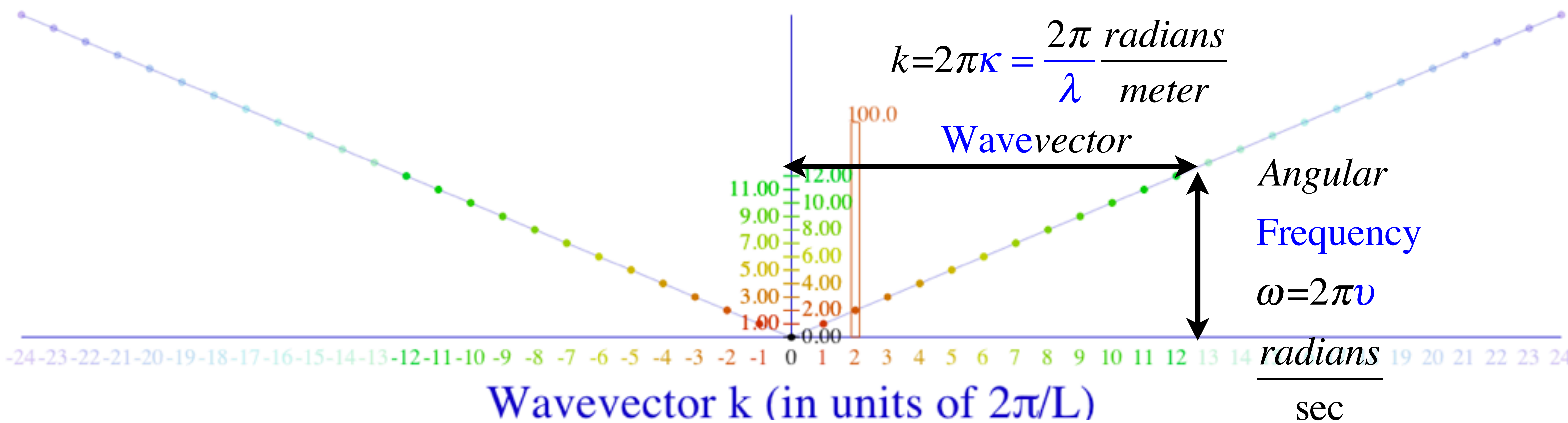


Q: How fast does phase ϕ=kx - ωt go?



$\omega = 2\pi\upsilon$



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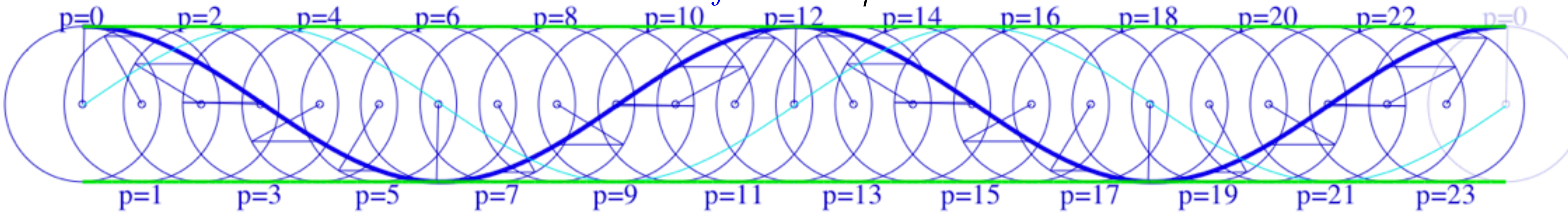


Q: How fast does phase $\phi = kx - \omega t$ *go?*

A: Solve $\phi = kx - \omega t$ *to get:* $kx = \omega t + \phi$

$$x = \frac{\omega}{k} t + \frac{\phi}{k}$$

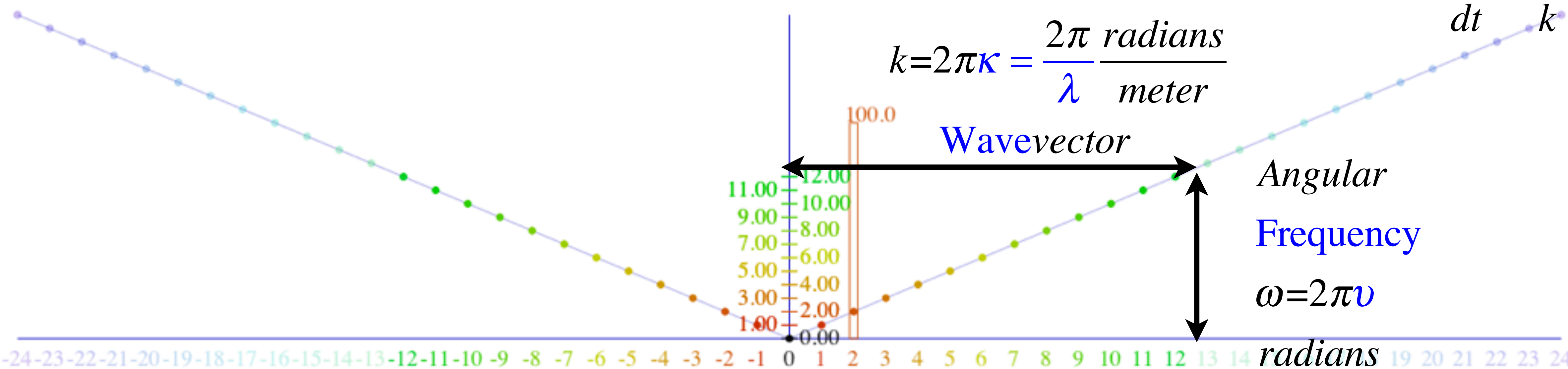
$$\frac{dx}{dt} = \frac{\omega}{k}$$

$\omega = 2\pi\upsilon$

$$k = 2\pi\kappa = \frac{2\pi}{\lambda} \frac{radians}{meter}$$

Wavevector

Angular Frequency $\omega = 2\pi\upsilon$ $\frac{radians}{sec}$



Wavevector k (in units of 2π/L)

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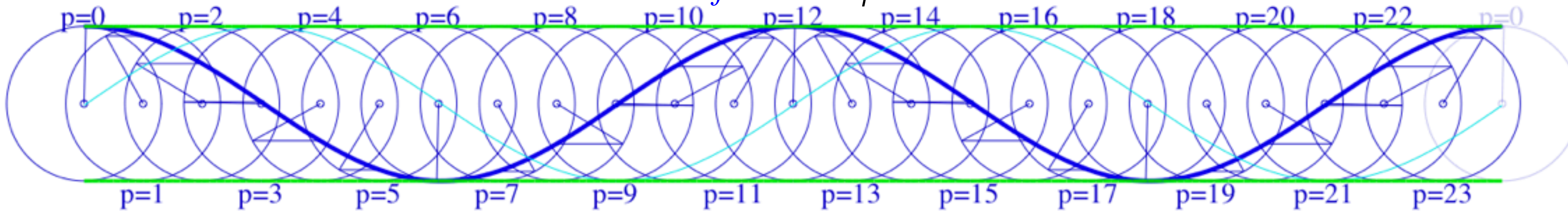

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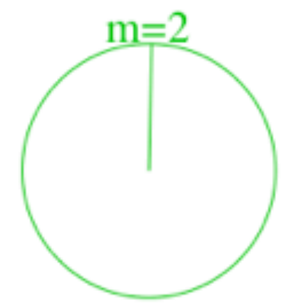

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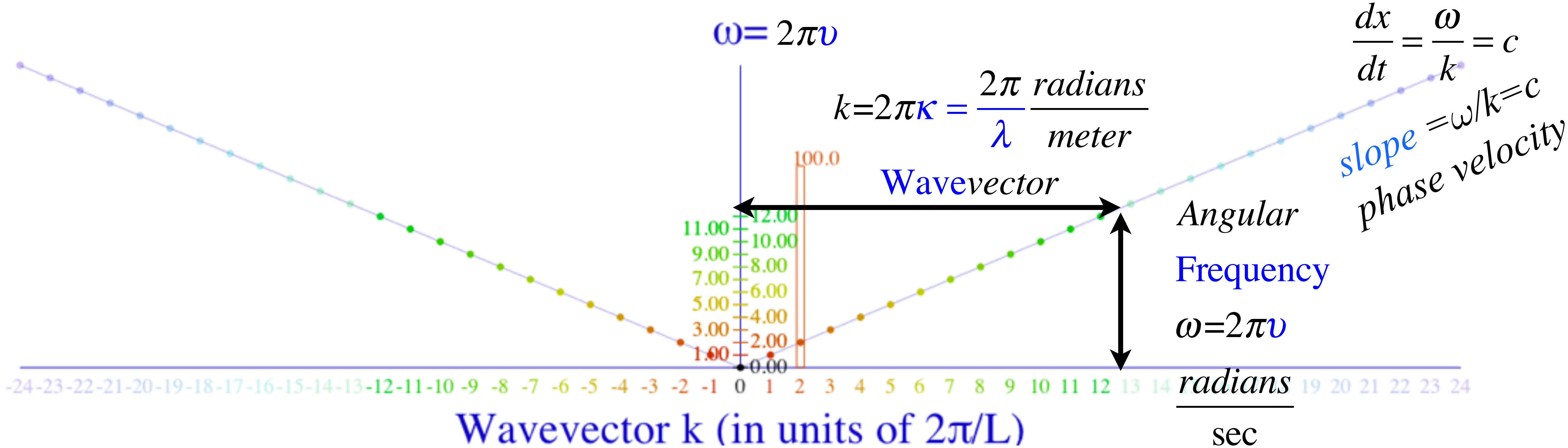

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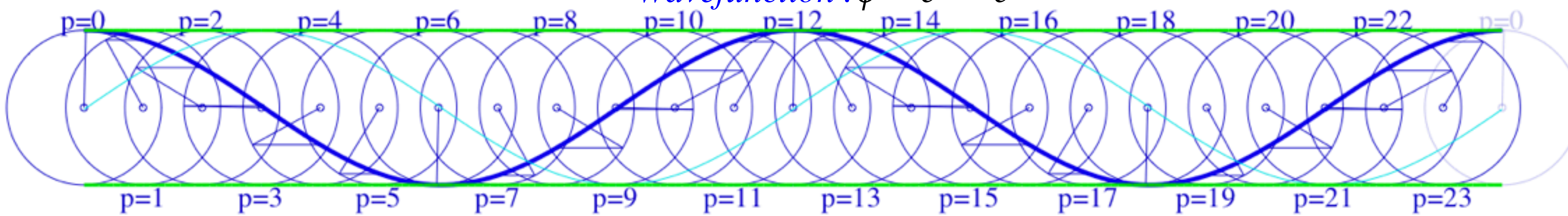

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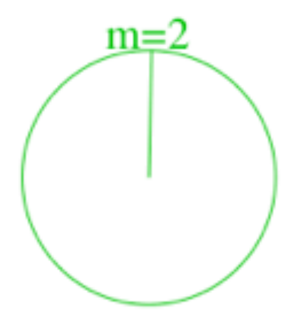

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slope $=\omega/k=c$ *phase velocity*

$\omega = 2\pi\upsilon$

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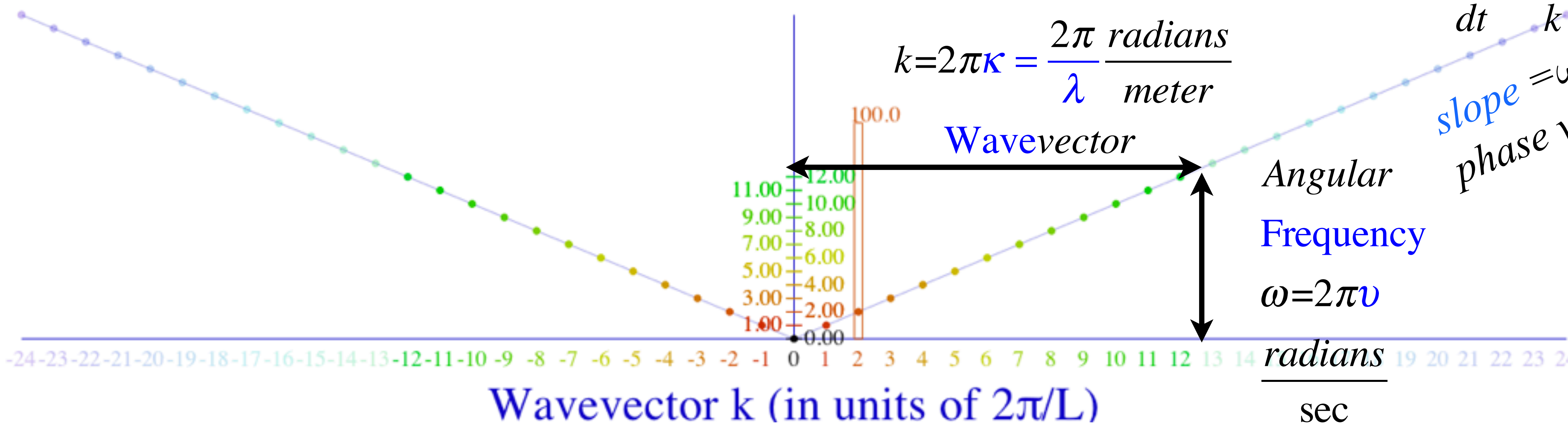
Wavevector

Angular Frequency $\omega = 2\pi\upsilon$ $\frac{radians}{\text{sec}}$



Usually we plot light waves unit slope $=\omega/ck=1$ *for phase velocity since "All colors go c"*

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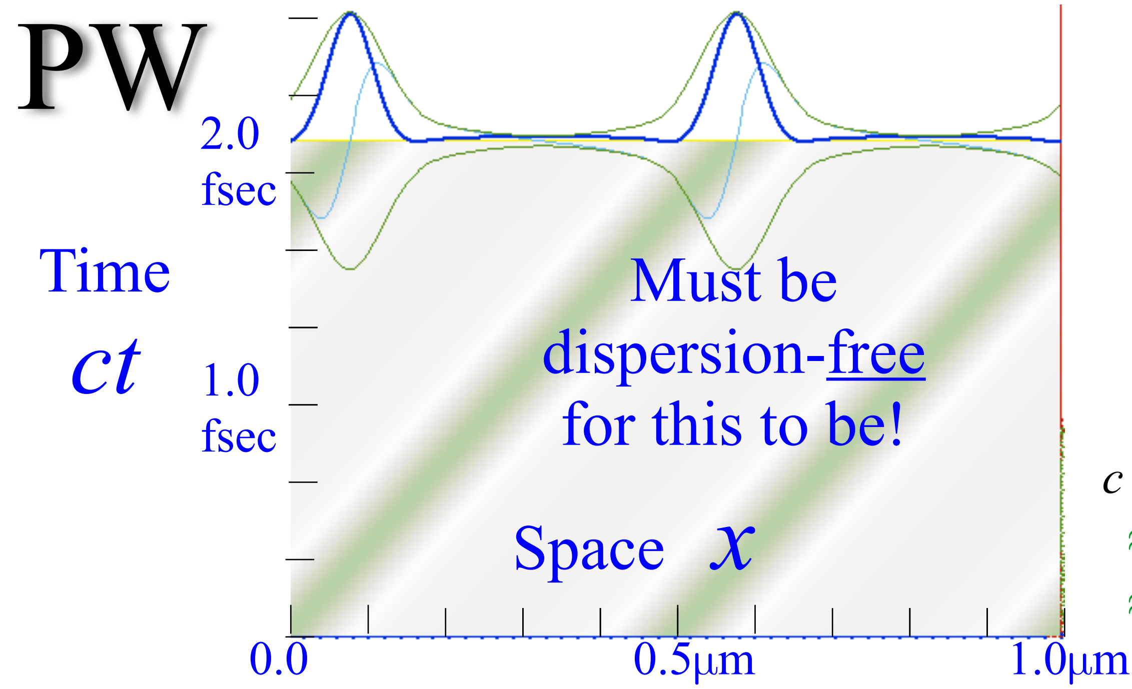
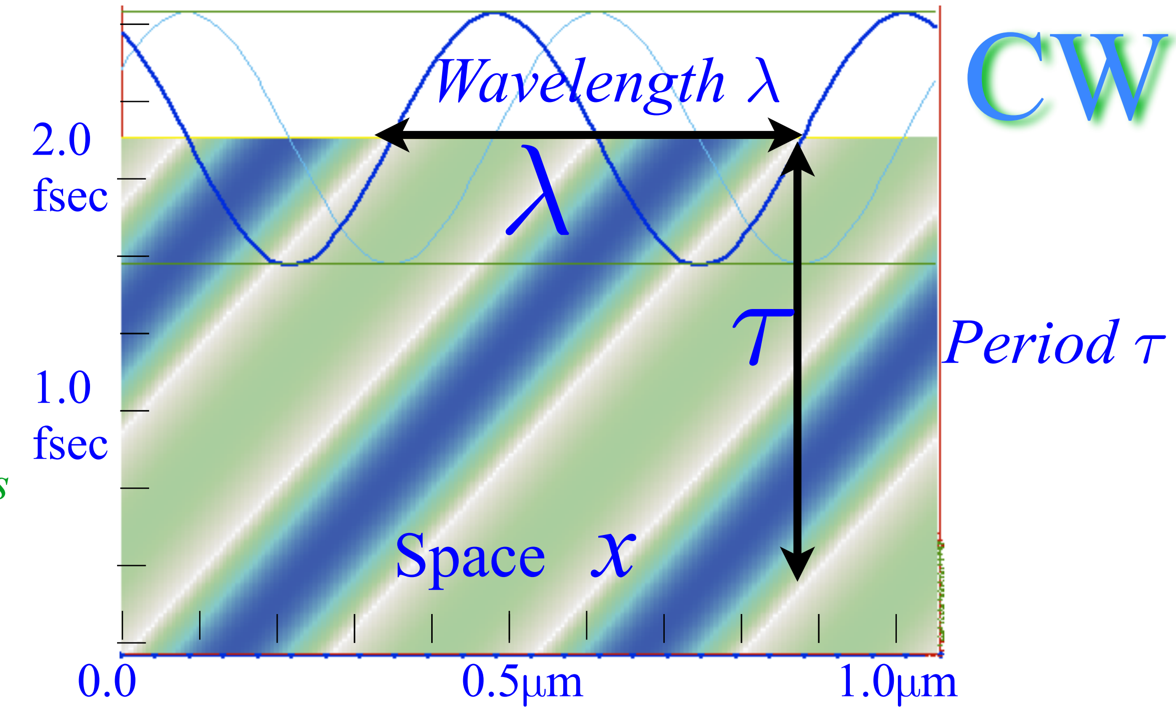


$c = 2.99792458 \cdot 10^8 m/s$

$\approx 3 \cdot 10^8 m/s$

$\approx 0.3\ \mu m/fs \approx 1\ ft/ns$



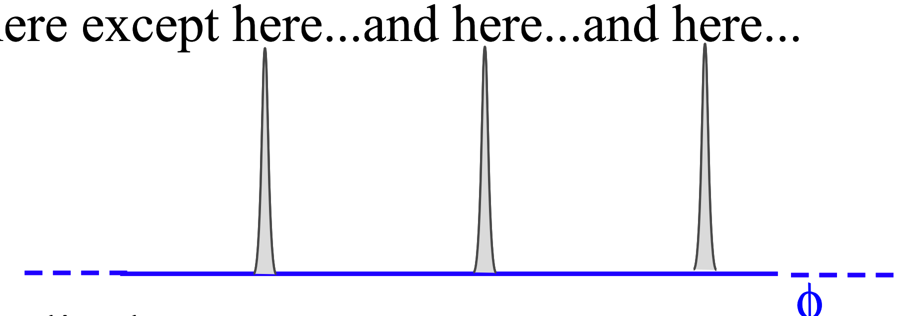
It helps to introduce two *archetypes* of light waves and contrast them.

The first *(PW)* is a *Particle-like Wave* or part of a *Pulse-Wave* train.
The second *(CW)* is a *Coherent Wave* or part of a *Continuous-Wave* train.

..or *Cosine Wave* ...or *Colored Wave*

(1) The PW archetype

PW amplitude is *ZERO* *(mostly...)*
everywhere except here...and here...and here...



PW amplitude...

ZEROS.

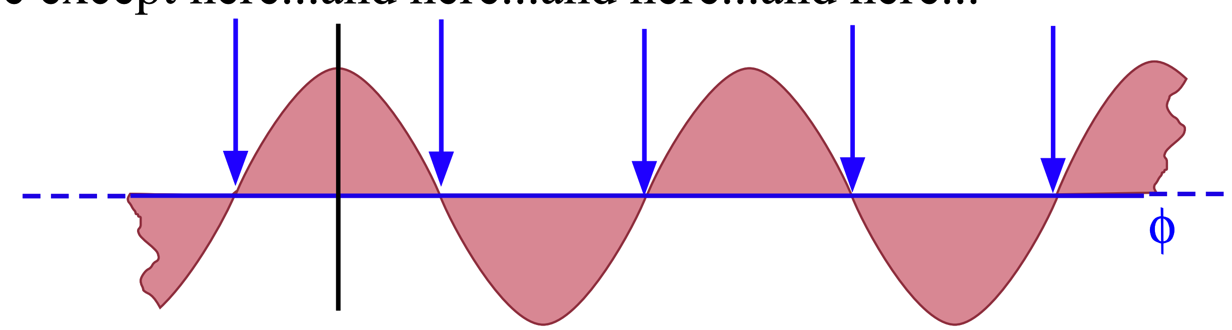
...but has sharp *PEAKS*.

...is best defined by where it *IS*.

Ideal *PW* shape is a *Dirac Delta function*.

(2) The CW archetype

CW amplitude is *NON-zero* *(exactly!)*
everywhere except here...and here...and here...and here...



...is mostly *NON-zero* with rounded crests and troughs.

...but has sharp *ZEROS*.

...is best defined by where it *IS NOT*.

Ideal *CW* shape is a *cosine wave (cos(ϕ))*

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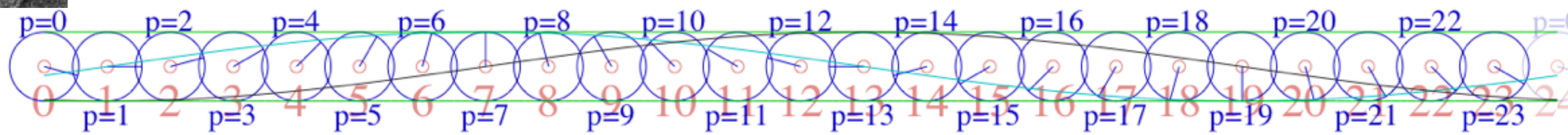
Jean-Baptiste Joseph Fourier 1768-1830

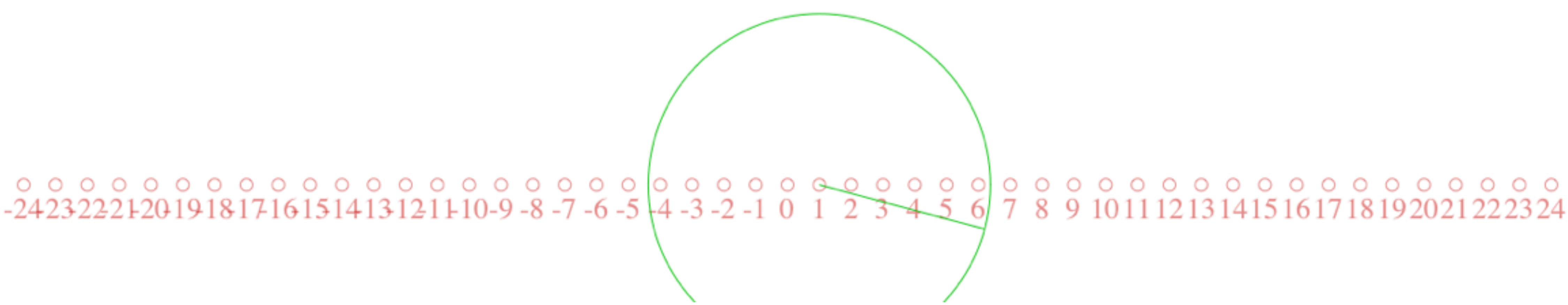
t =



Wave amplitudes vs. position p (p in units of L/24)

Click-Drag from dots to change amplitudes. Click here to zero all: ☐

Wave amplitude vs. wavevector m (m in units of 2π/L)



solo right 1-CW over linear dispersion + k-histogram
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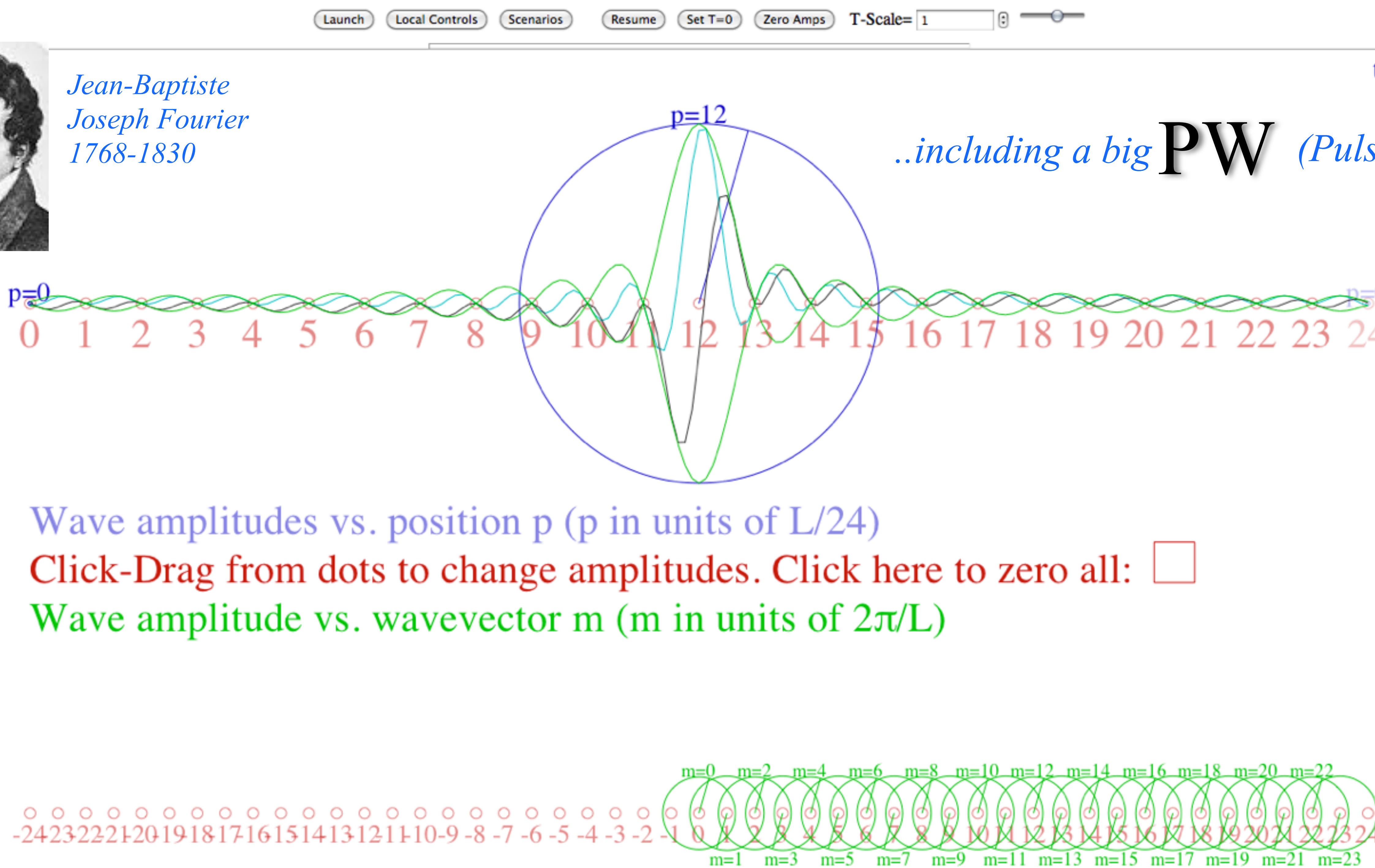
..including a big **PW** *(Pulse Wave)*



This is called a "Boxcar" spectrum when each Fourier component-m has same amplitude

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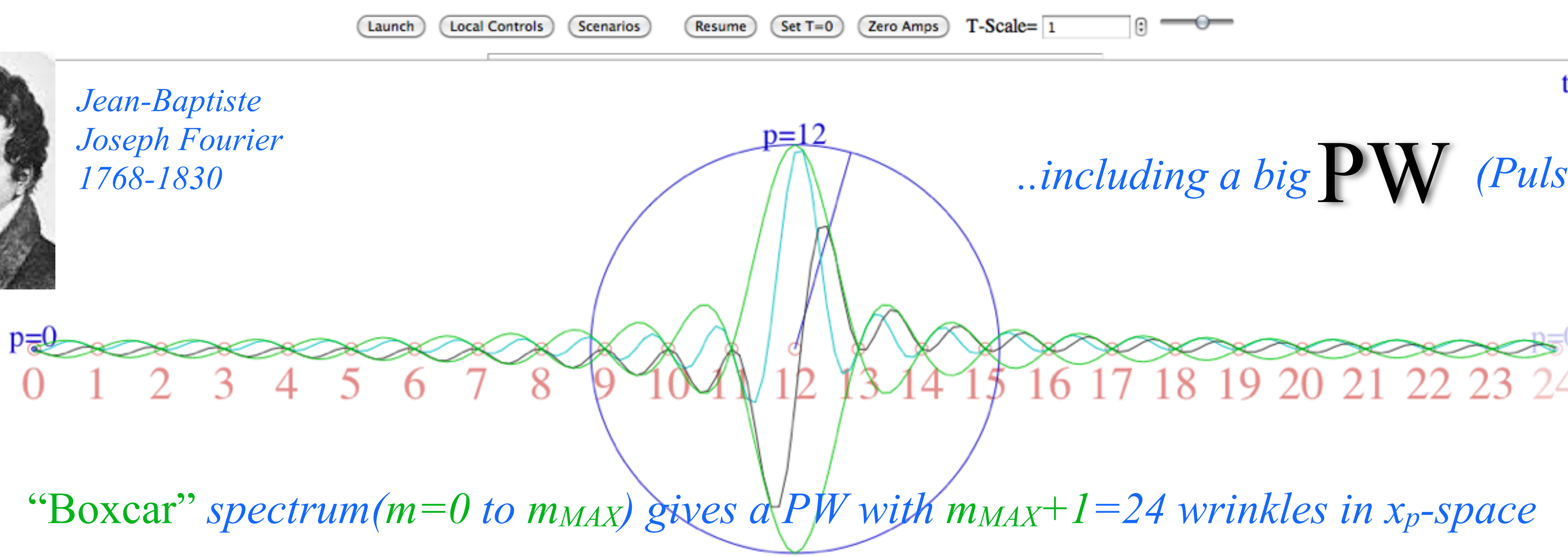

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"Boxcar" *spectrum($m=0$ to m_{MAX}) gives a PW with $m_{MAX}+1=24$ wrinkles in x_p-space*

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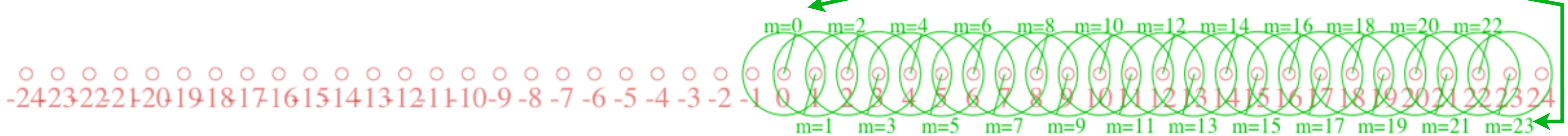
Wave amplitude vs. wavevector m (m in units of 2π/L)

$m=0$ to $m_{MAX}=23$



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(But alternating ± phases)

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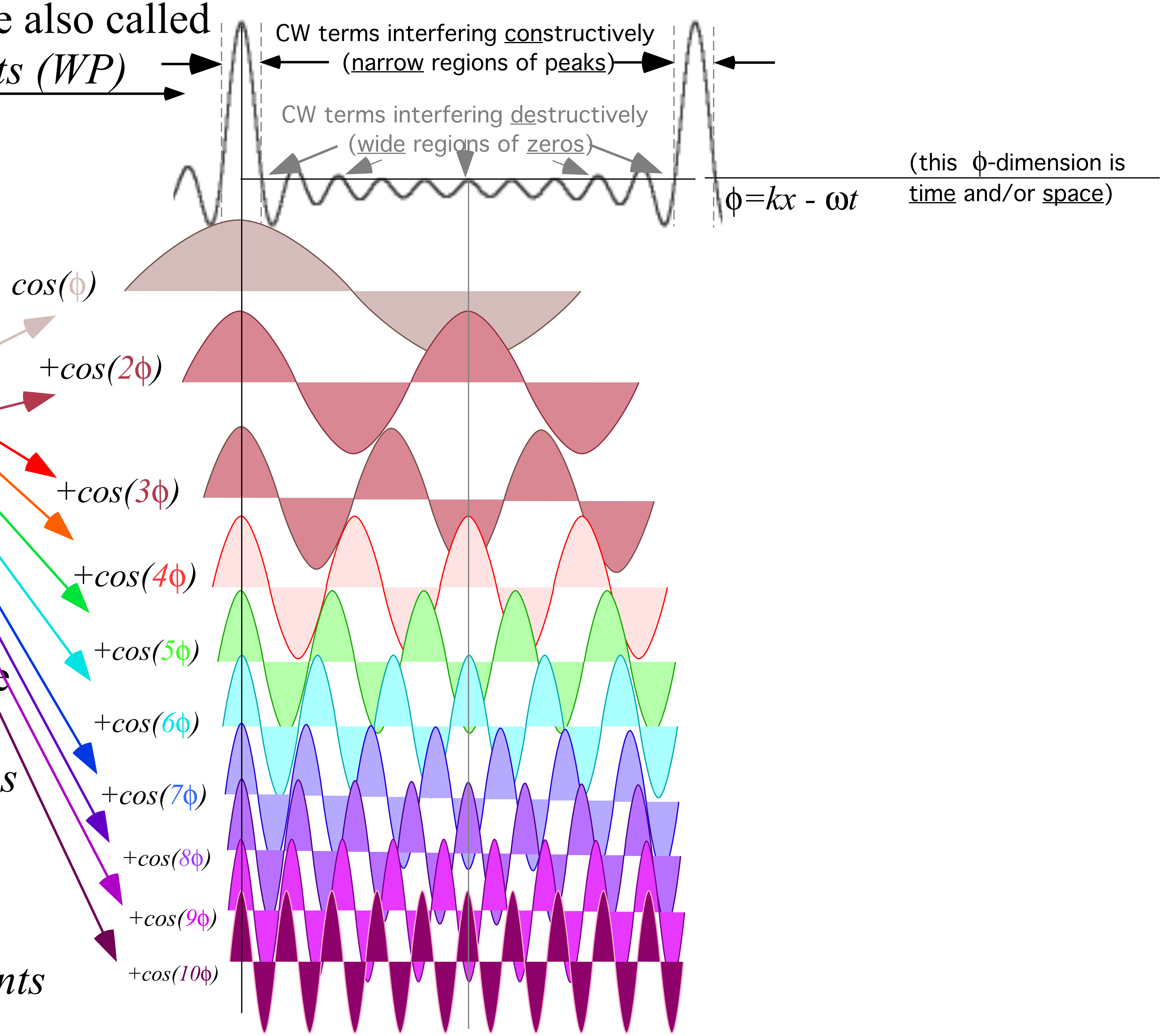
PW forms are also called *Wave Packets (WP)* since they are interfering sums of many *CW* terms (10-Cosine Waves make up this pulse)



CW terms are also called *Color Waves* or *Fourier Spectral Components*

[*WaveIt animation: 24 Spectral Components*]

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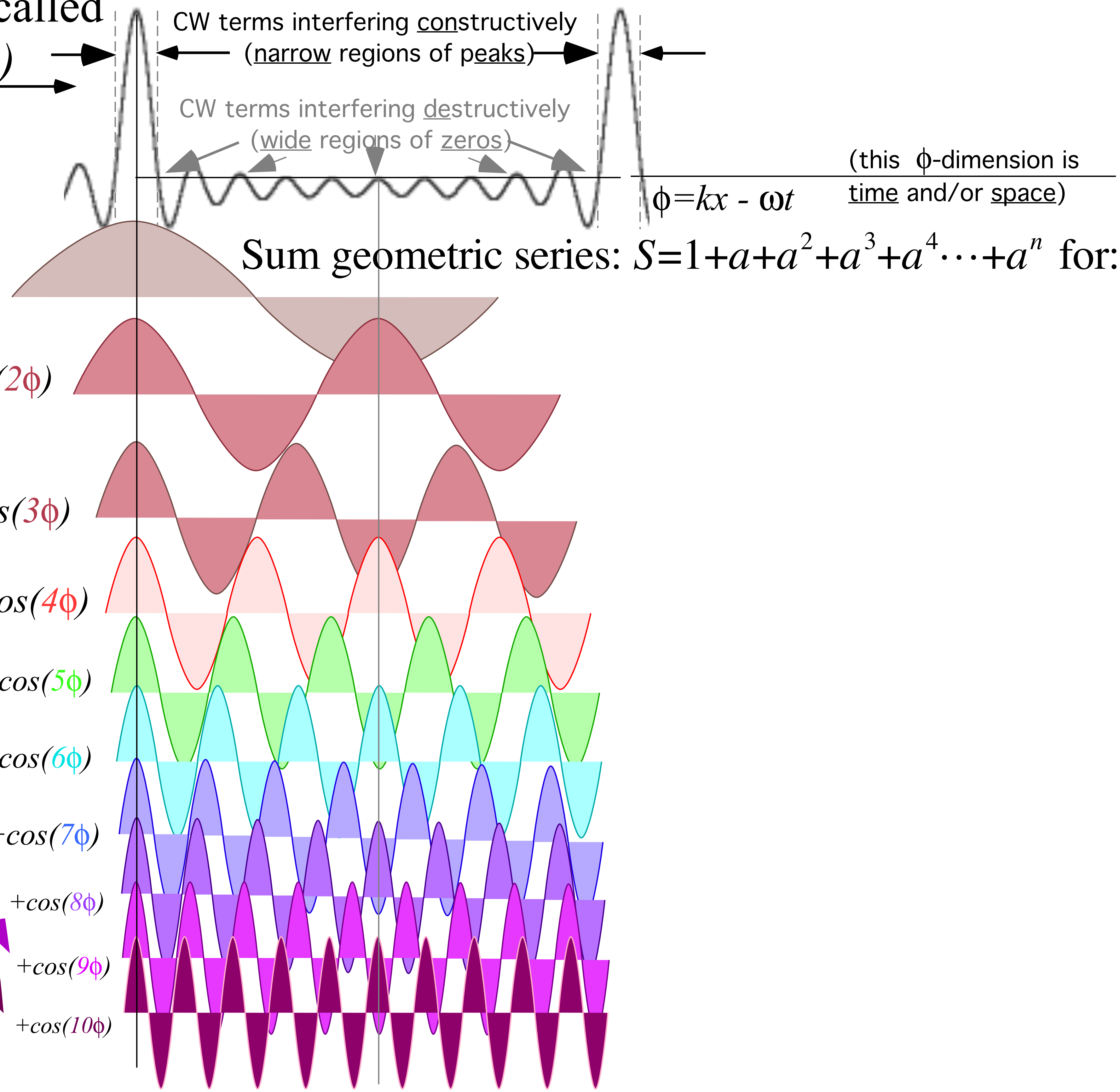

Sum geometric series: $S=1+a+a^2+a^3+a^4\cdots+a^n$ for: $a=e^{i\phi}$

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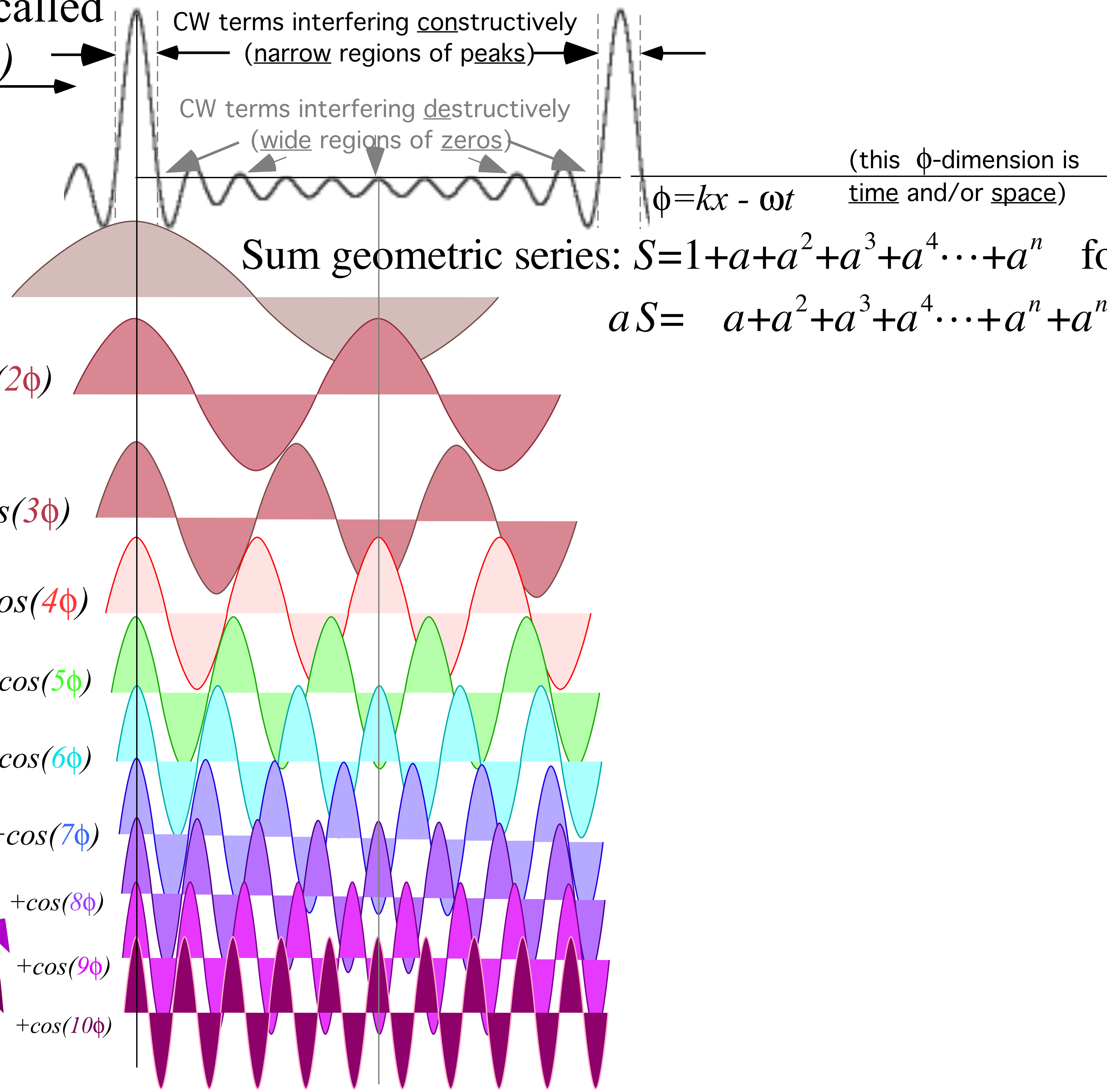

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$$aS = \quad a + a^2 + a^3 + a^4 \cdots + a^n + a^{n+1}$$

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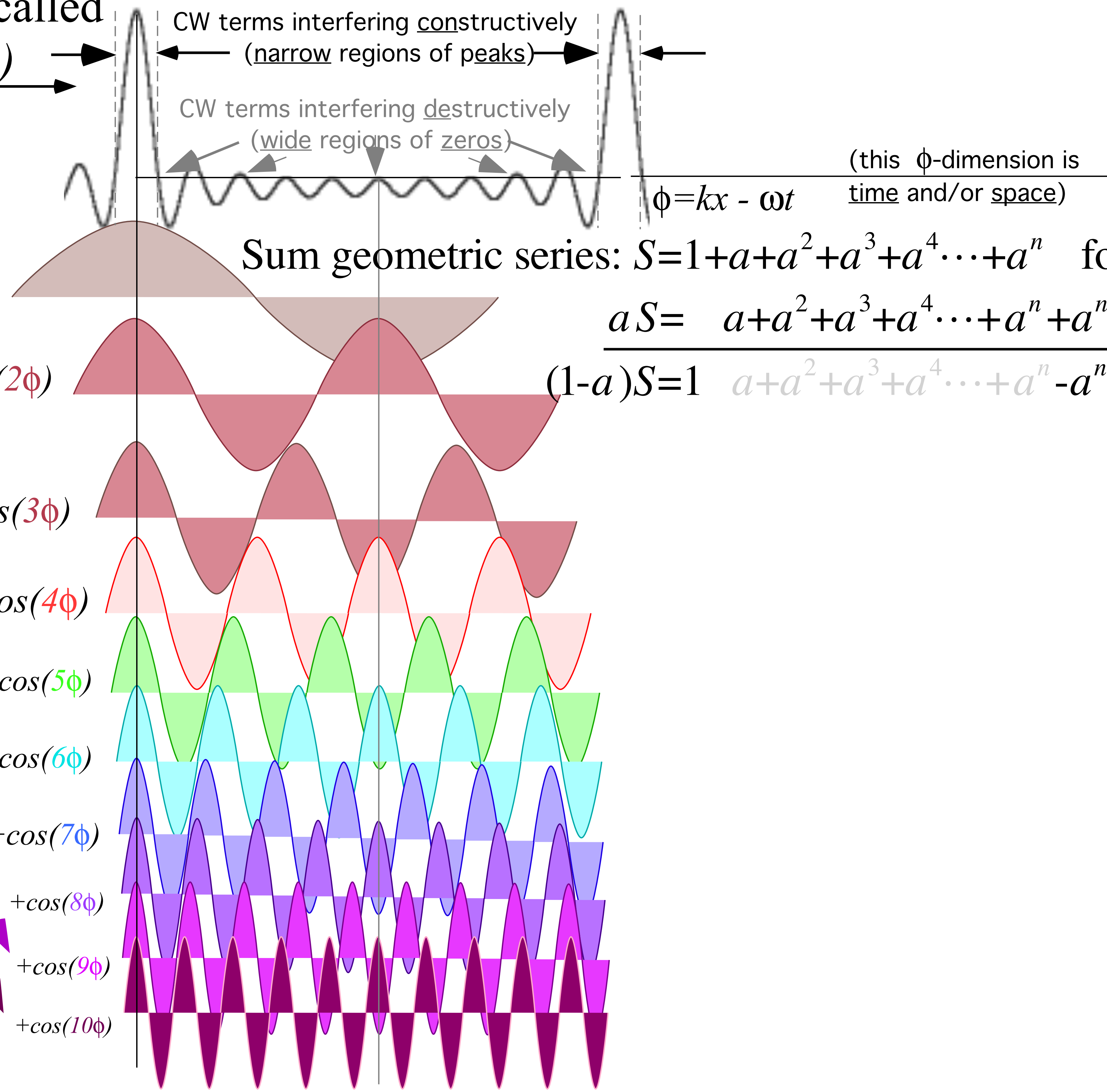
(10-Cosine Waves make up this pulse)



Sum geometric series: $S = 1 + a + a^2 + a^3 + a^4 \cdots + a^n$ for: $a = e^{i\phi}$

$$aS = \quad a + a^2 + a^3 + a^4 \cdots + a^n + a^{n+1}$$

$$(1-a)S = 1 \quad \cancel{a + a^2 + a^3 + a^4 \cdots + a^n} - a^{n+1}$$

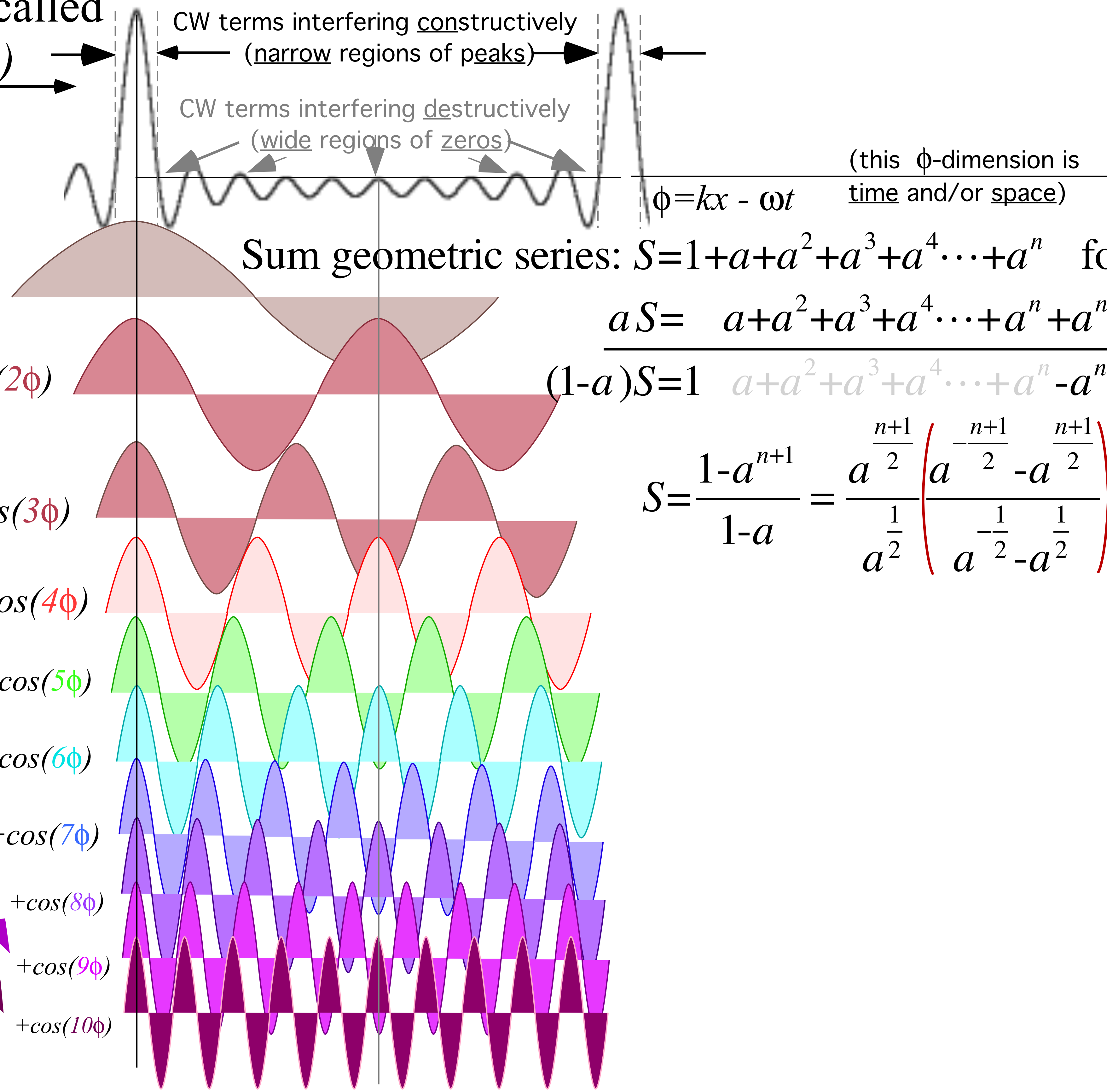
CW terms are also called *Color Waves* or *Fourier Spectral Components*

[*WaveIt animation: 24 Spectral Components*]

PW

PW forms are also called *Wave Packets (WP)* since they are interfering sums of many *CW* terms

(10-Cosine Waves make up this pulse)



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$$S = \frac{1-a^{n+1}}{1-a} = \frac{a^{\frac{n+1}{2}}}{a^{\frac{1}{2}}} \left(\frac{a^{-\frac{n+1}{2}} - a^{\frac{n+1}{2}}}{a^{-\frac{1}{2}} - a^{\frac{1}{2}}} \right)$$

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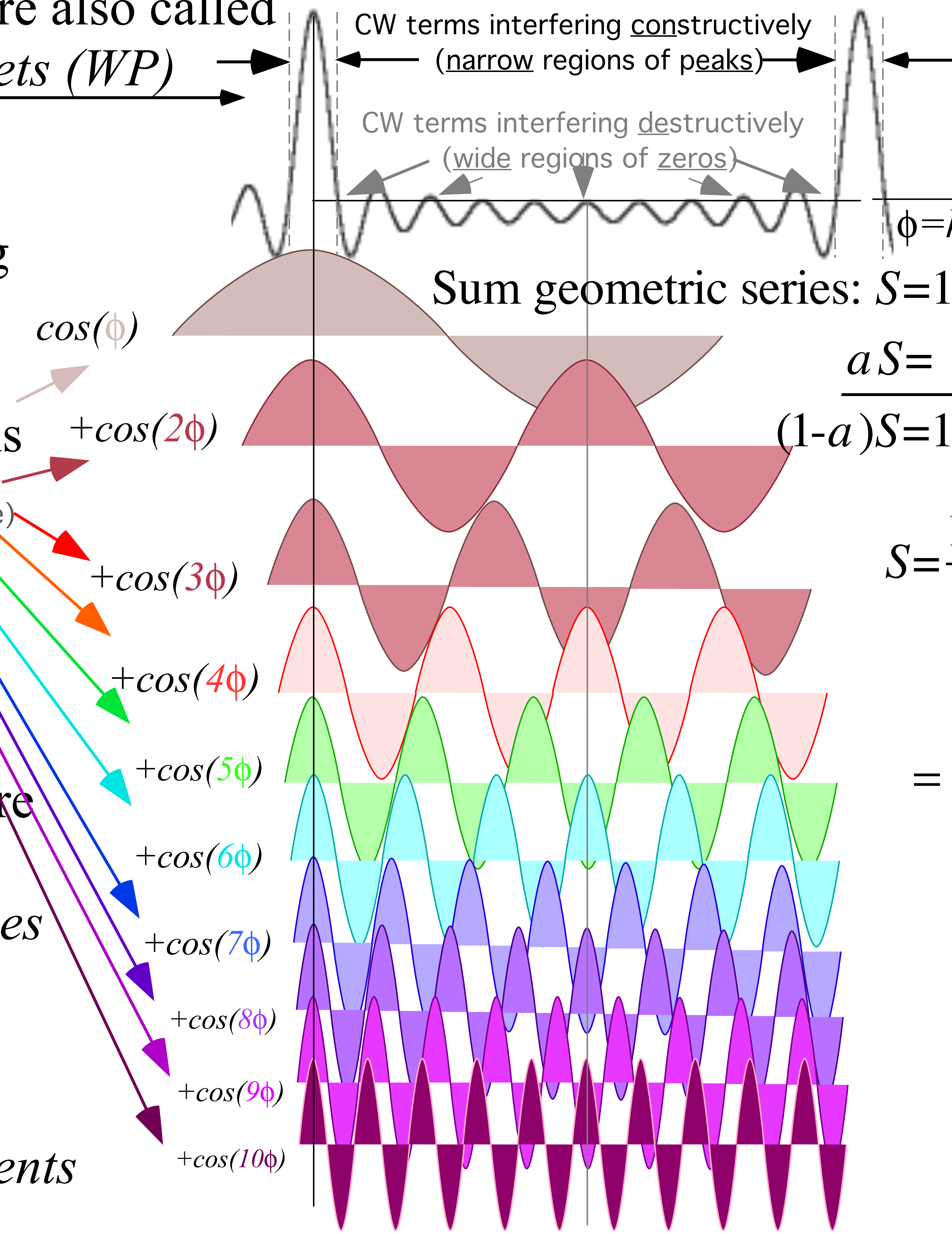

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$$=e^{i\phi\frac{n}{2}}\left(\frac{e^{-i\phi\frac{n+1}{2}}-e^{i\phi\frac{n+1}{2}}}{e^{-\frac{i\phi}{2}}-e^{\frac{i\phi}{2}}}\right)=e^{i\phi\frac{n}{2}}\frac{\sin\frac{n+1}{2}\phi}{\sin\frac{\phi}{2}}$$

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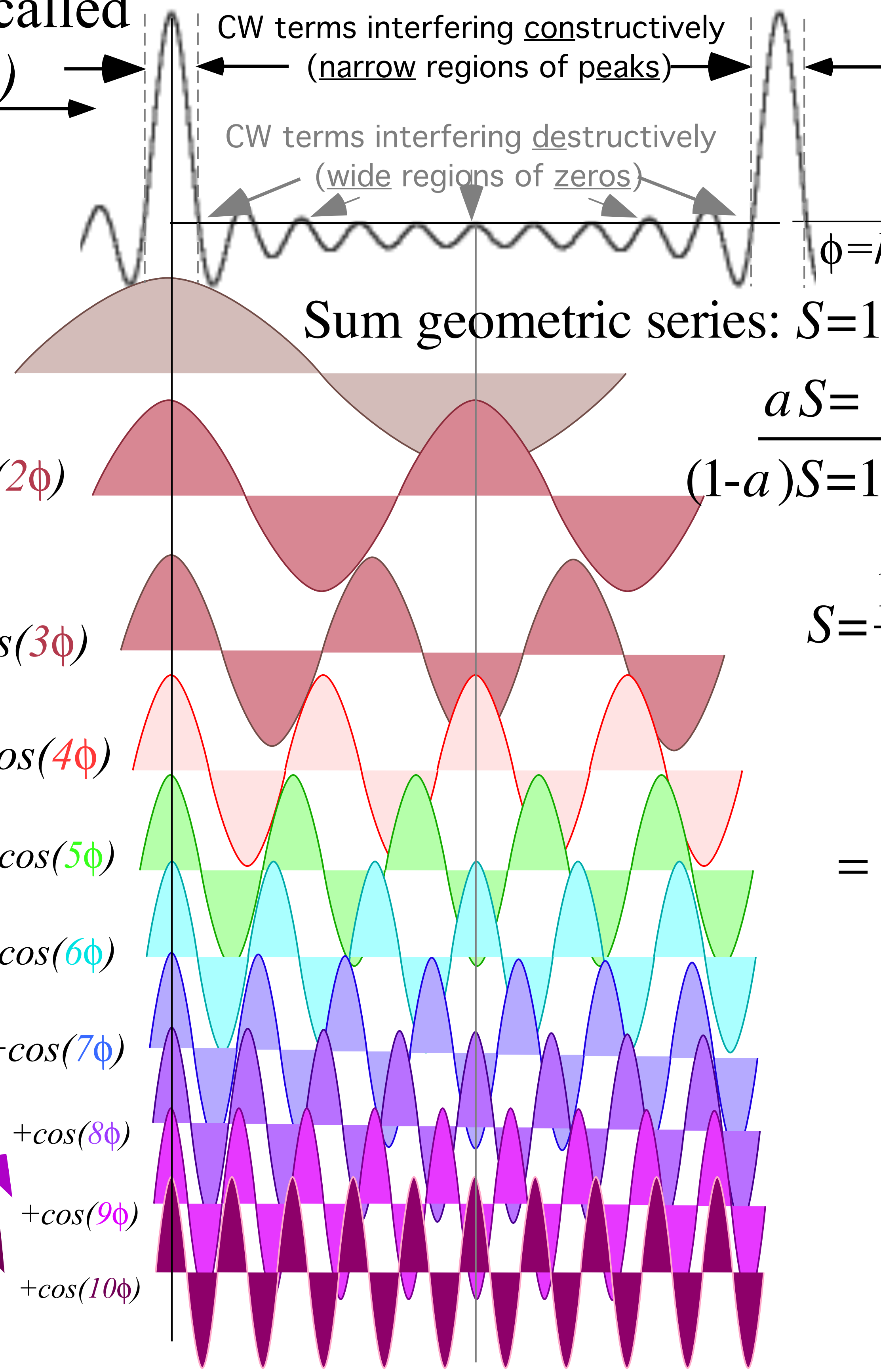

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$$\xrightarrow[as\,\phi\to 0]{} e^{i\phi\frac{n}{2}}\frac{\frac{n+1}{2}\phi}{\frac{\phi}{2}}\to n+1$$

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[*WaveIt animation: 24 Spectral Components*]

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→ *Animation of PW obeying lightwave linear dispersion $\omega(k)=ck$* ←

Important Evenson axiom for relativity: "All colors go c"

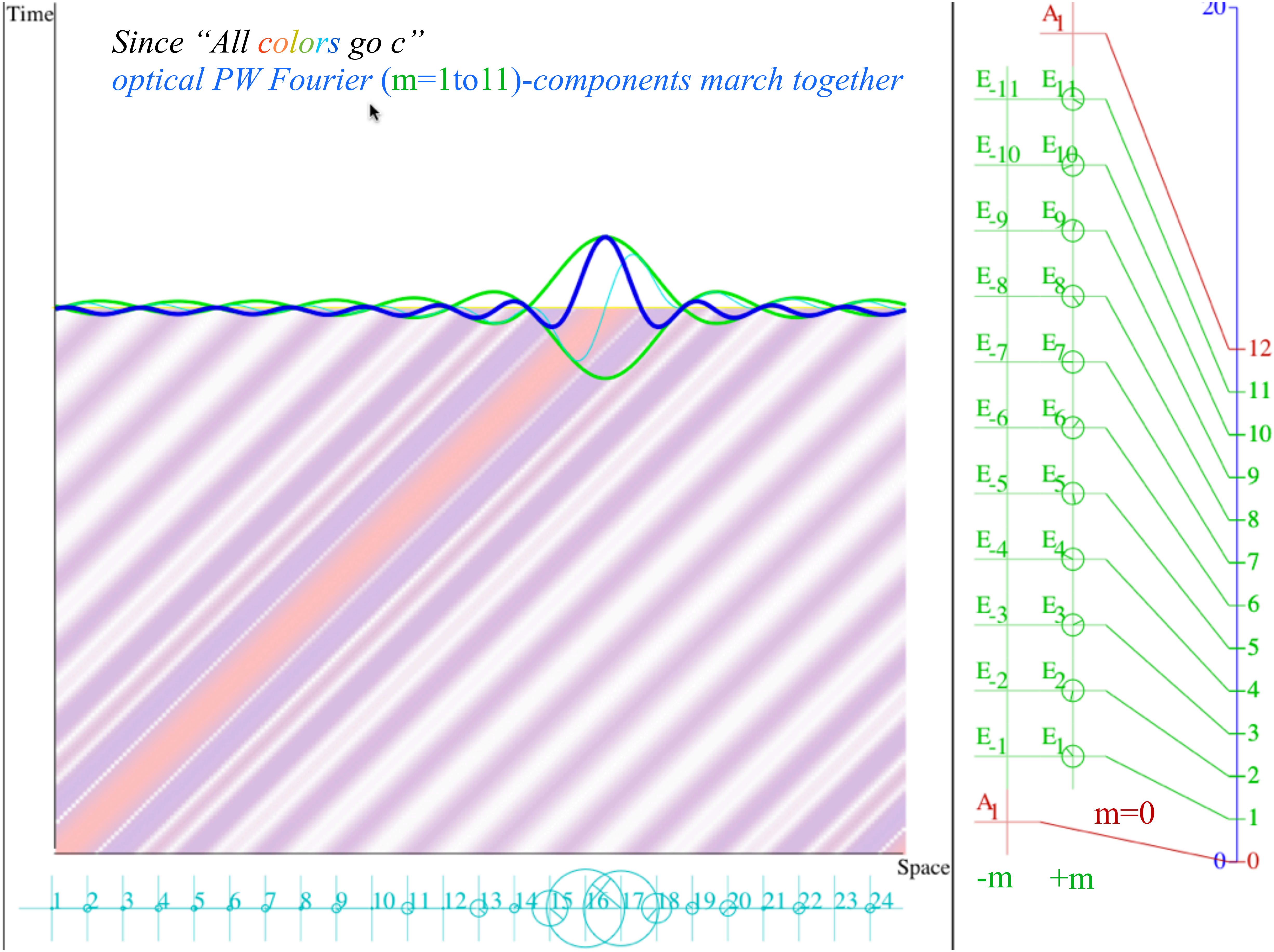
Visualizing PW wave uncertainty relations for space: $\Delta x\cdot\Delta\kappa=1$ *and* time: $\Delta t\cdot\Delta\upsilon=1$

PW "wrinkles" go away if Fourier "boxcar" is tapered to a softer "Gaussian"

Opposite-pair CW (colliding $\pm m=\pm 2$) Fourier components trace a Cartesian space-time grid

PW

Since "All colors go c"
optical PW Fourier (m=1to11)-components march together



1-Way Dirac Delta PW +1
http://www.uark.edu/ua/modphys/markup/BohrItWeb.html?scenario=4002

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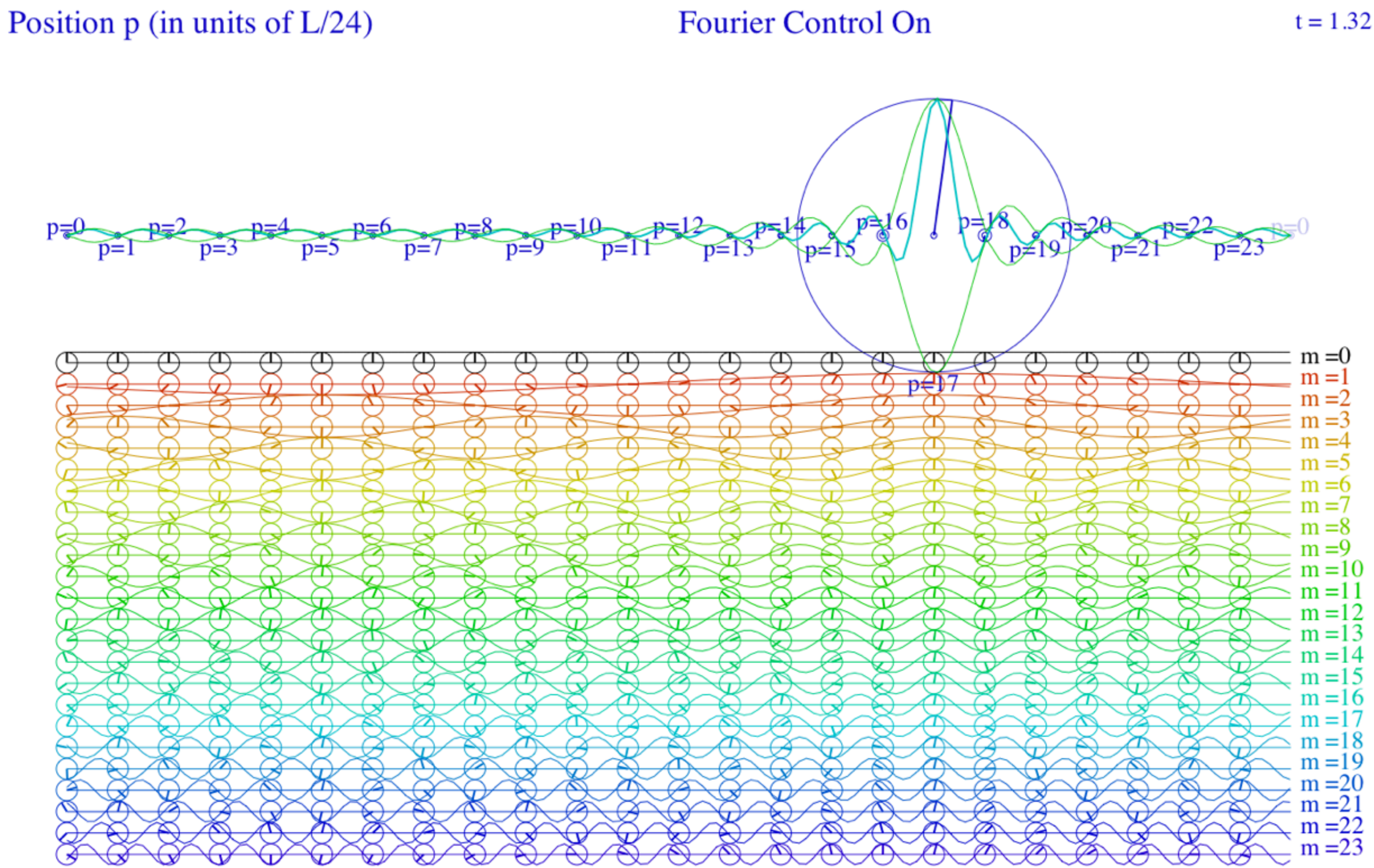
PW *Since "All colors go c" optical PW Fourier CW components march together in lock-step*



http://www.uark.edu/ua/modphys/markup/WaveItWeb.html?scenario=1PW_R_Stacked_2016HP

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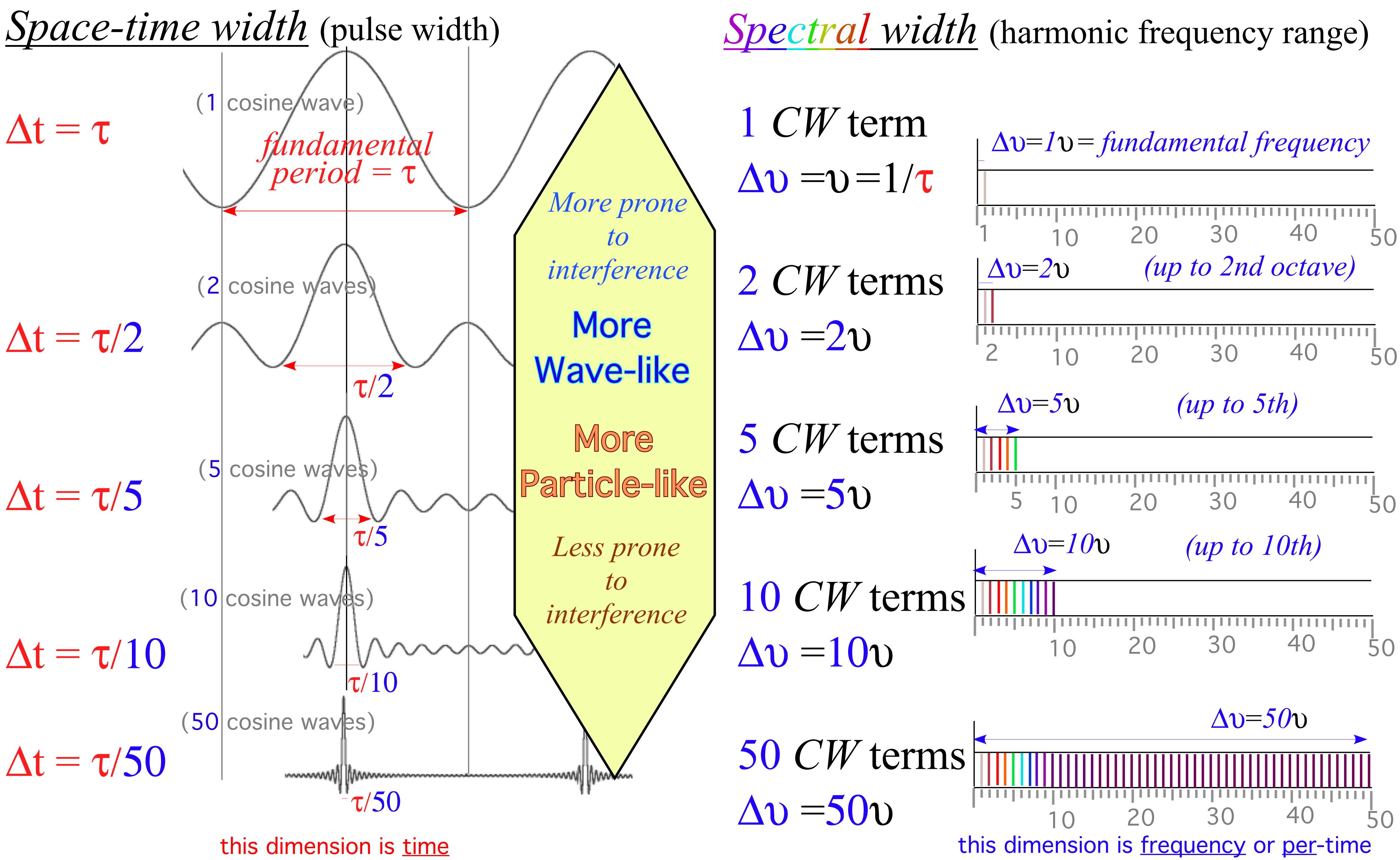
Comparing spacetime uncertainty (Δx or Δt) with per-spacetime bandwidth (Δκ or Δυ)

PW widths reduce proportionally with more *CW* terms (greater *Spectral* width)



Fourier-Heisenberg product: $\Delta t \cdot \Delta \upsilon = 1$ (time-frequency uncertainty relation)

PW widths reduce proportionally with more *CW* terms (greater *Spectral* width)

Space-time width (pulse width) | ***Spectral width*** (harmonic frequency range)

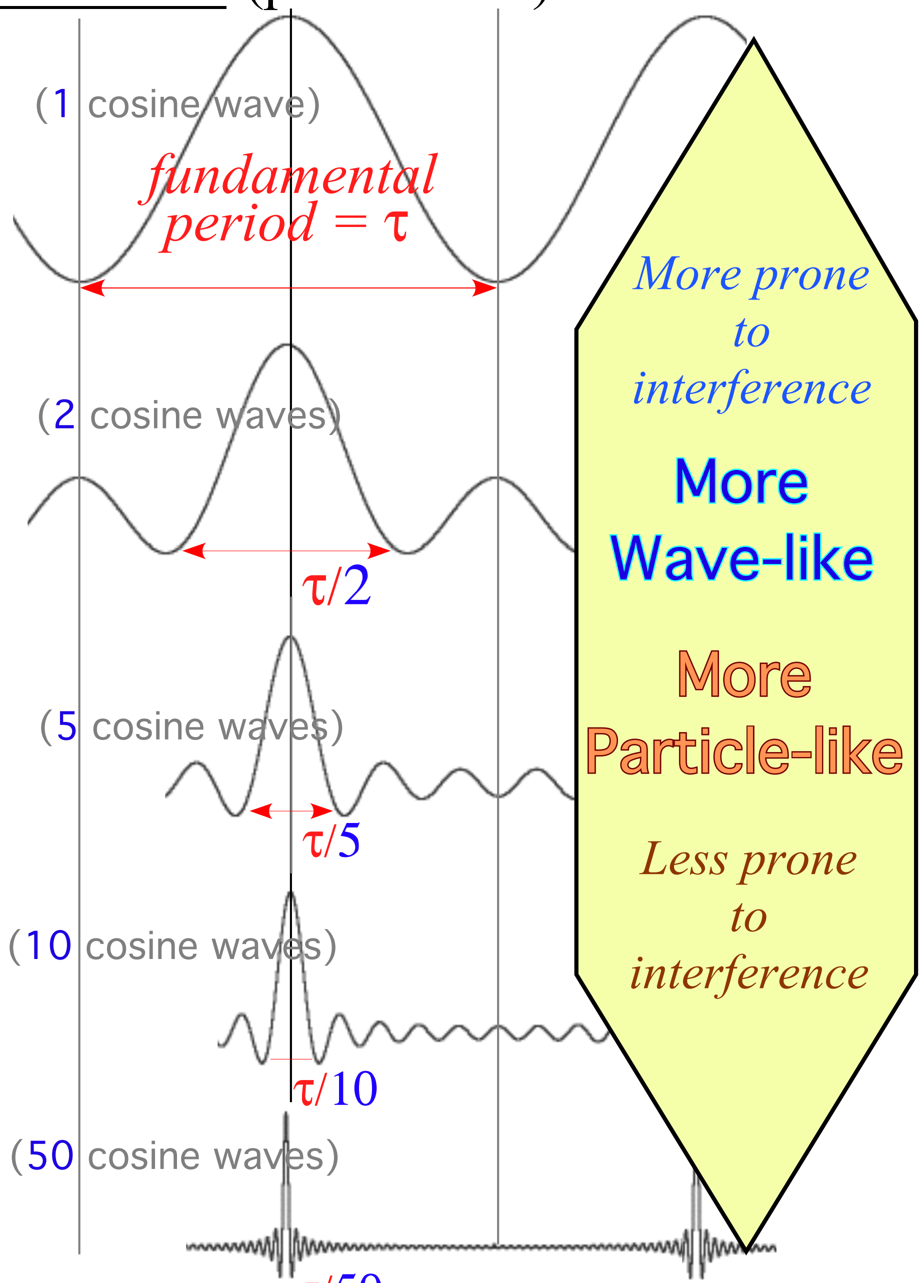
$\Delta t = \tau$ — 1 *CW* term, $\Delta\upsilon = \upsilon = 1/\tau$

$\Delta t = \tau/2$ — 2 *CW* terms, $\Delta\upsilon = 2\upsilon$

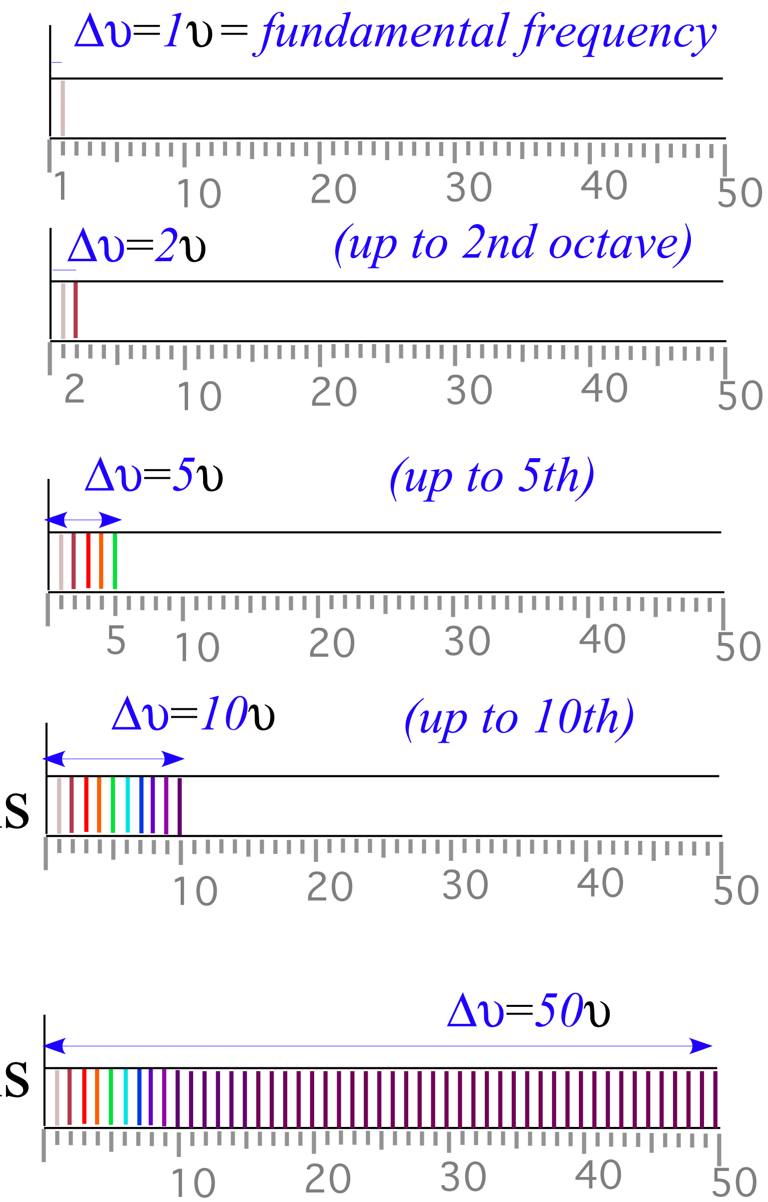
$\Delta t = \tau/5$ — 5 *CW* terms, $\Delta\upsilon = 5\upsilon$

$\Delta t = \tau/10$ — 10 *CW* terms, $\Delta\upsilon = 10\upsilon$

$\Delta t = \tau/50$ — 50 *CW* terms, $\Delta\upsilon = 50\upsilon$



this dimension is time



this dimension is frequency or per-time

Fourier-Heisenberg product: $\Delta t \cdot \Delta\upsilon = 1$ (time-frequency uncertainty relation)

or this dimension is space... $\Delta x \cdot \Delta\kappa = 1$ if this dimension is wavenumber or per-space...

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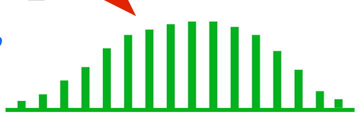
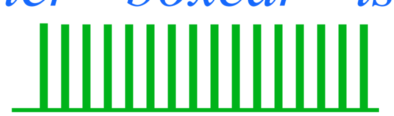
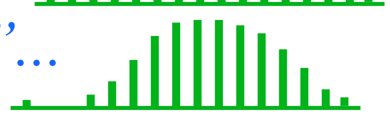




or "Poissonian"...



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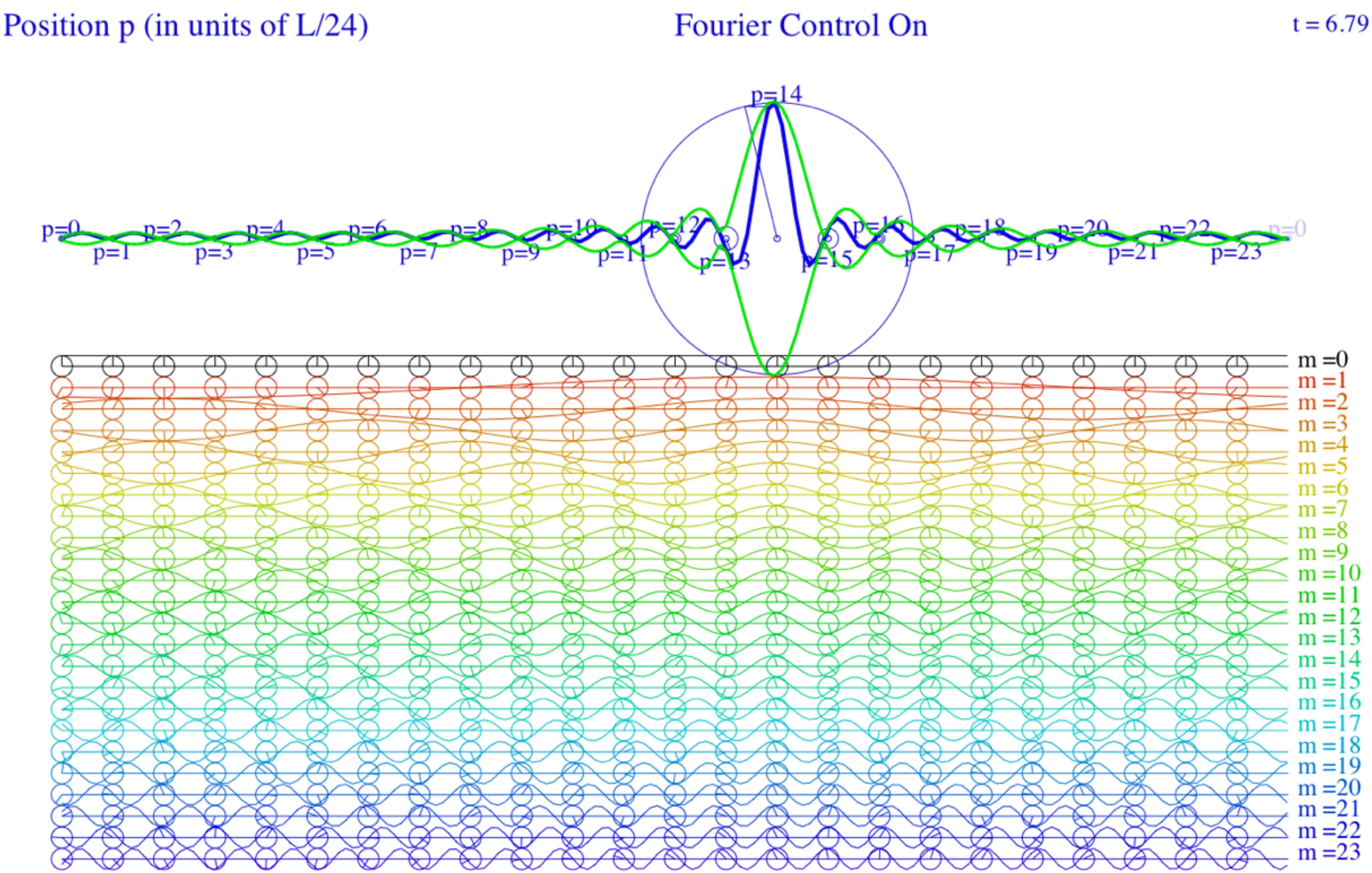

http://www.uark.edu/ua/modphys/markup/WaveItWeb.html?scenario=1PW_R_Stacked_2016HP

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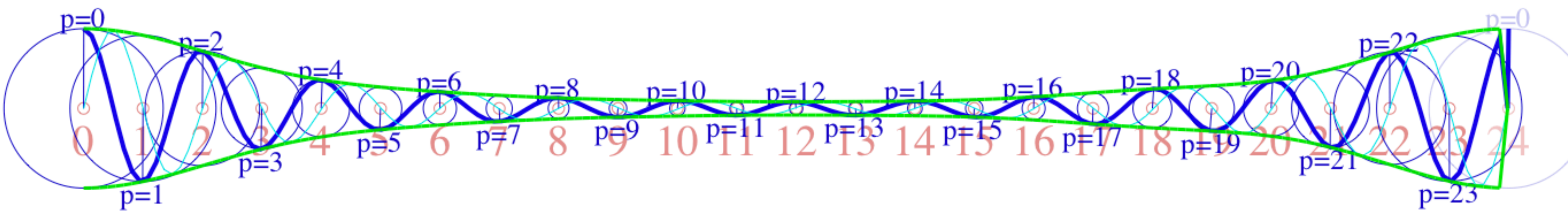

Wave amplitudes vs. position p (p in units of L/24)

Click-Drag from dots to change amplitudes. Click here to zero all:

Wave amplitude vs. wavevector m (m in units of 2π/L)

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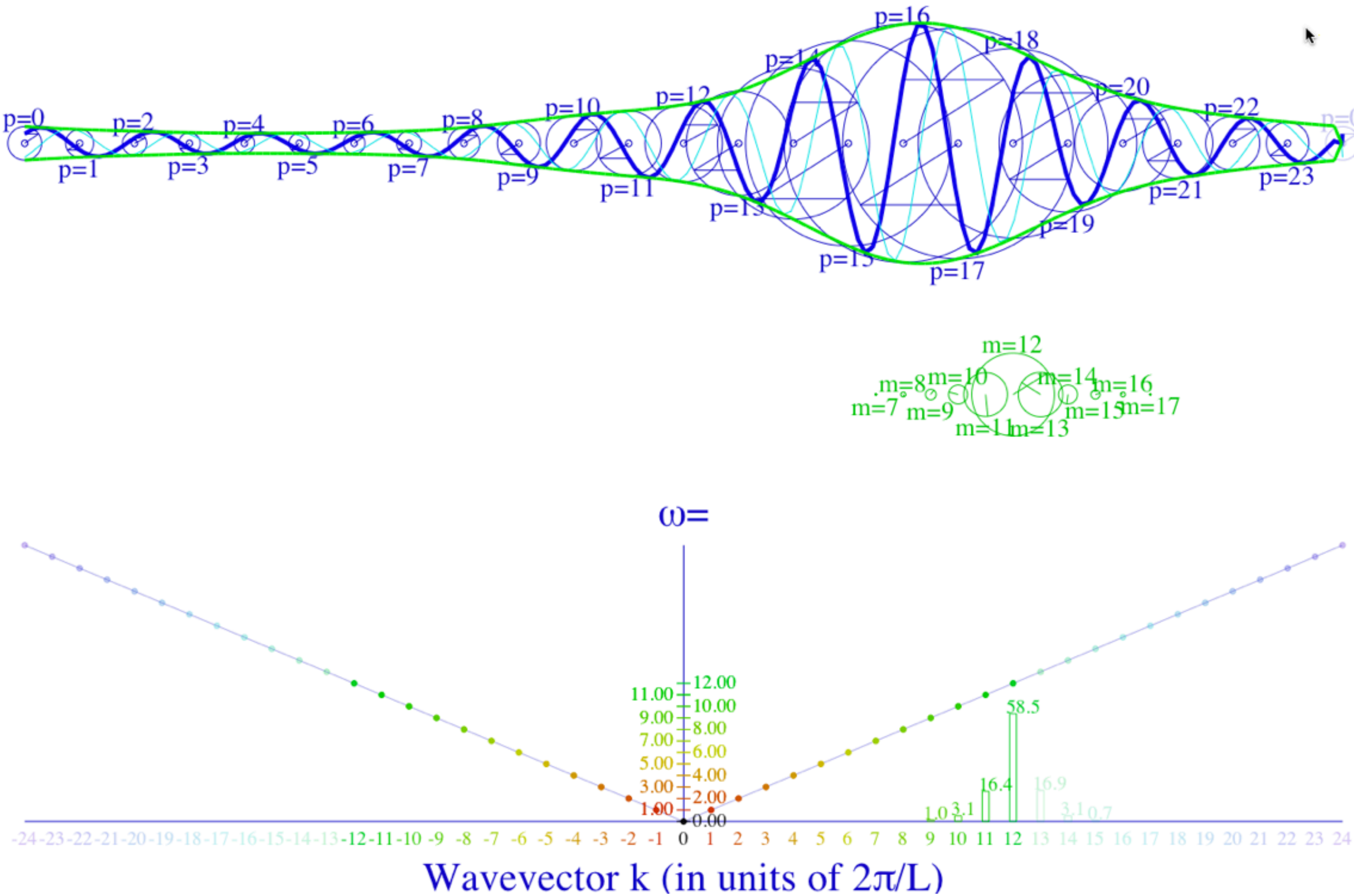

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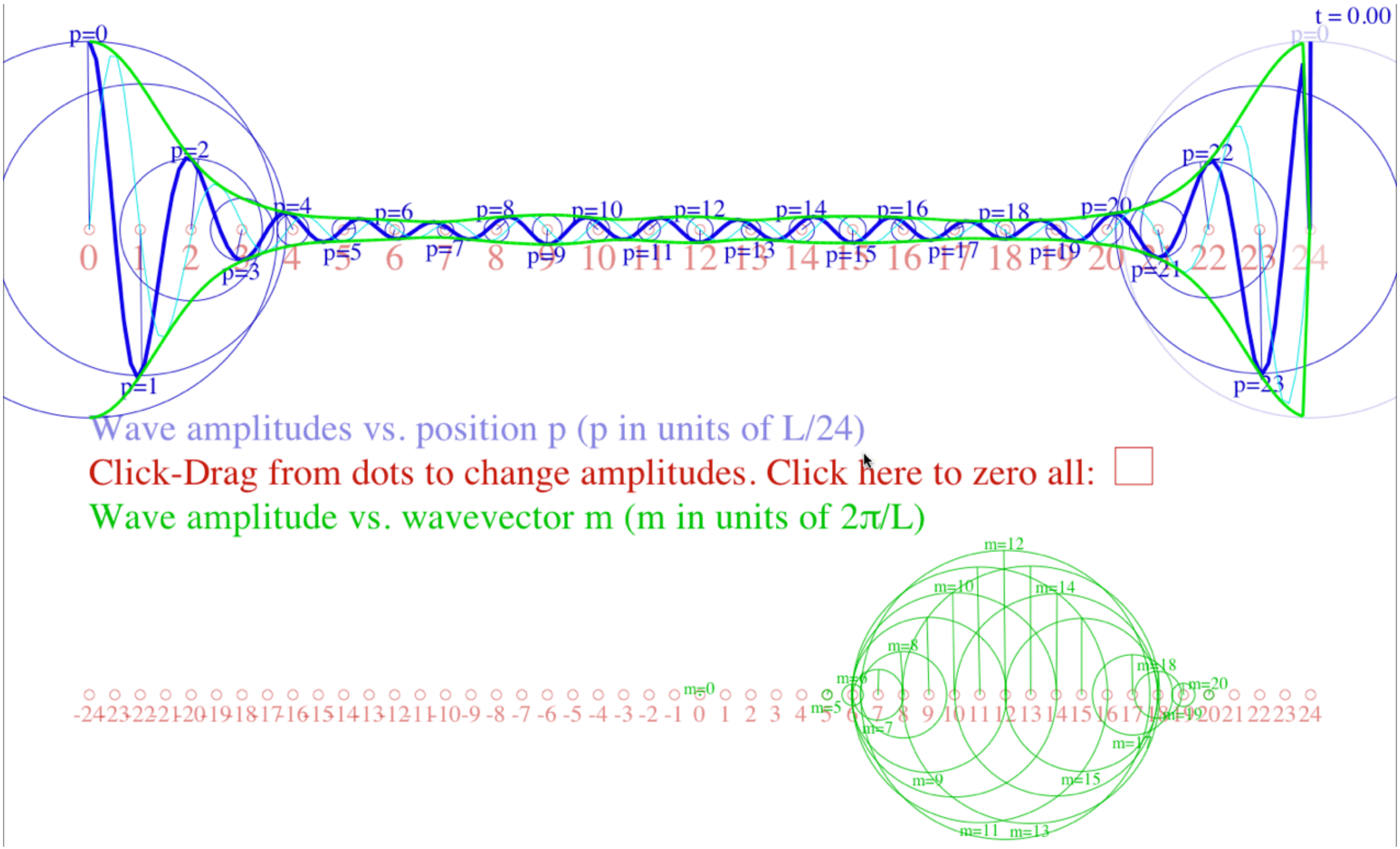
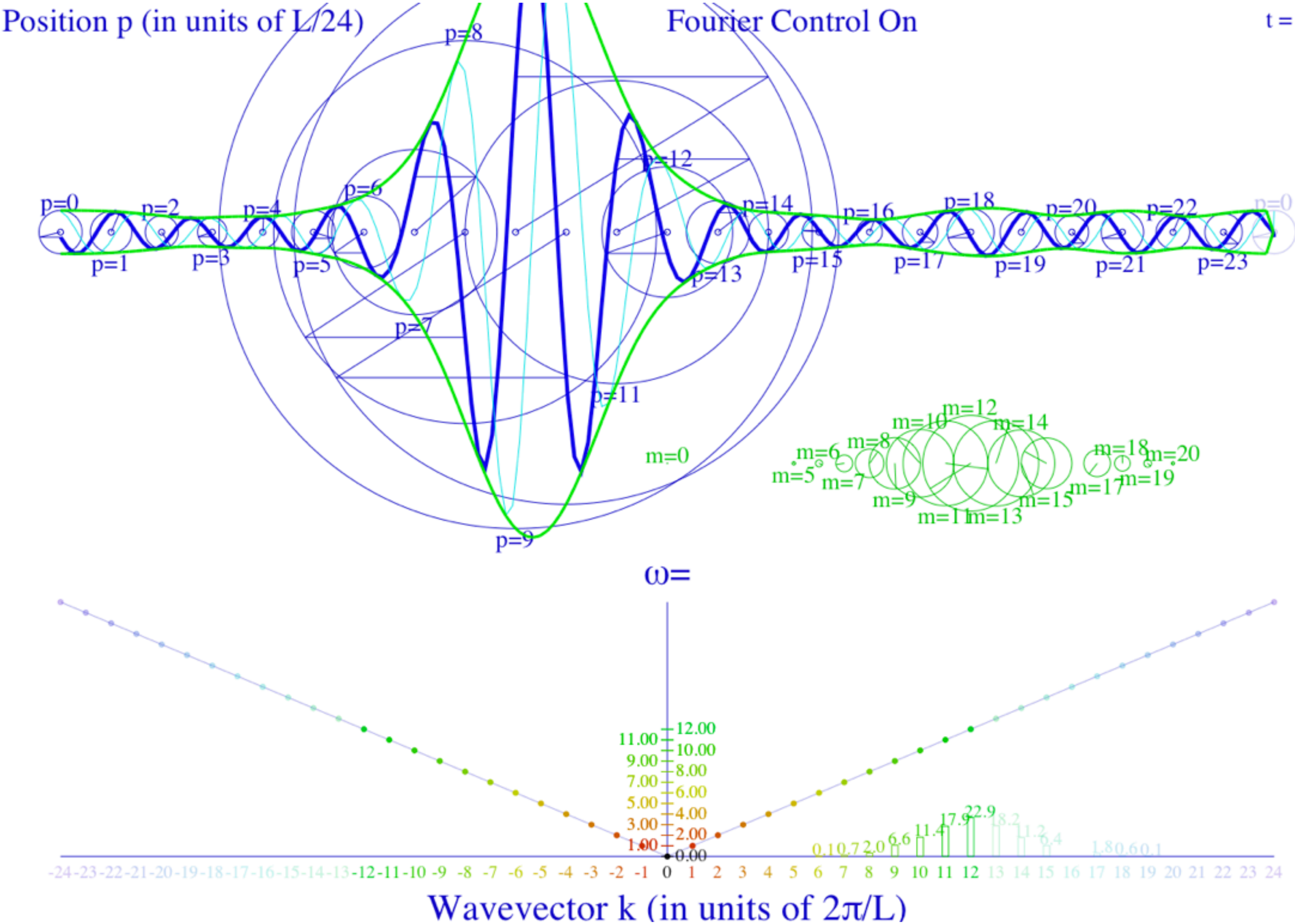
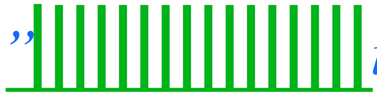
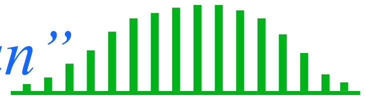
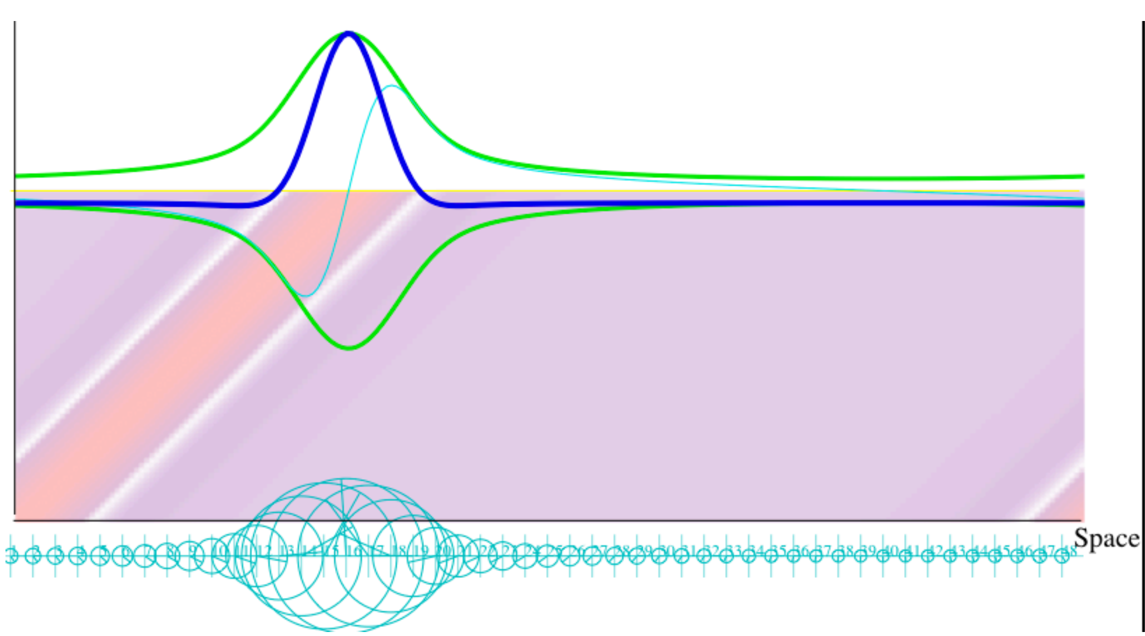
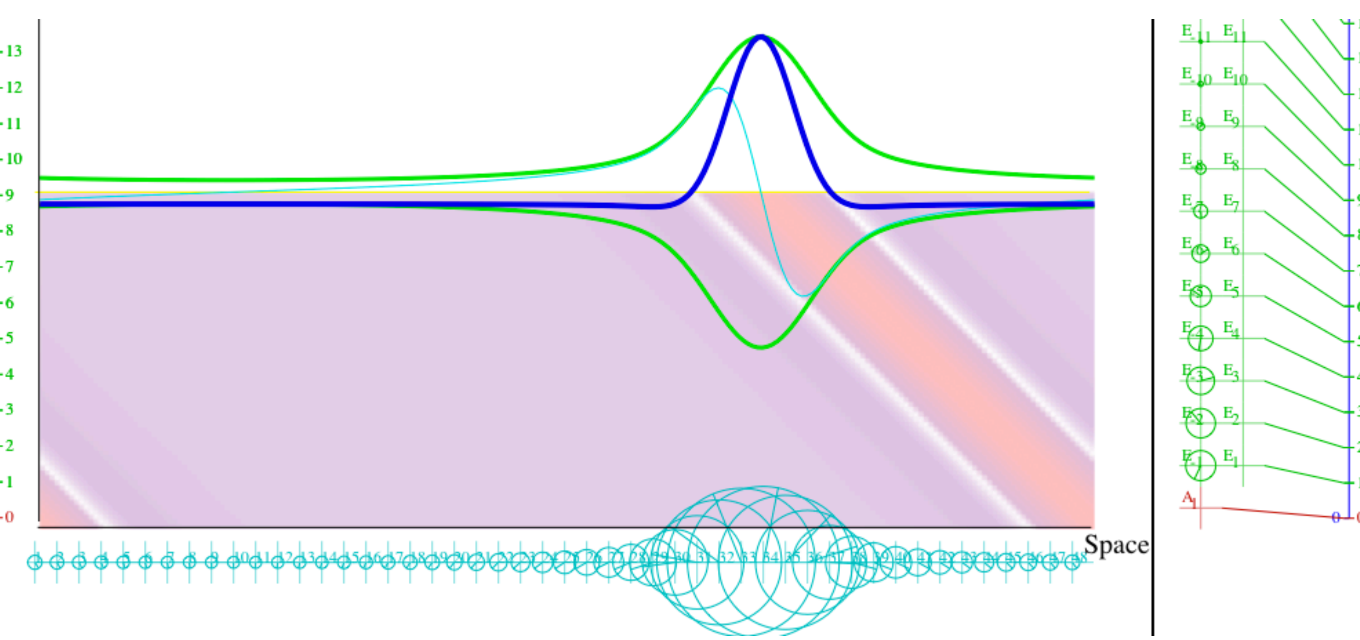



Position p (in units of L/24)
Fourier Control On
t = 1
p=0
p=1
p=2
p=3
p=4
p=5
p=6
p=7
p=8
p=9
p=11
p=12
p=13
p=14
p=15
p=16
p=17
p=18
p=19
p=20
p=21
p=22
p=23
m=0
m=5
m=6
m=7
m=8
m=9
m=10
m=11
m=12
m=13
m=14
m=15
m=17
m=18
m=19
m=20
ω=
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00
12.00
0.1 0.7 2.0 6.6 11.4 17.9 22.9 18.2 11.2 6.4 1.8 0.6 0.1
-24 -23 -22 -21 -20 -19 -18 -17 -16 -15 -14 -13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Wavevector k (in units of 2π/L)

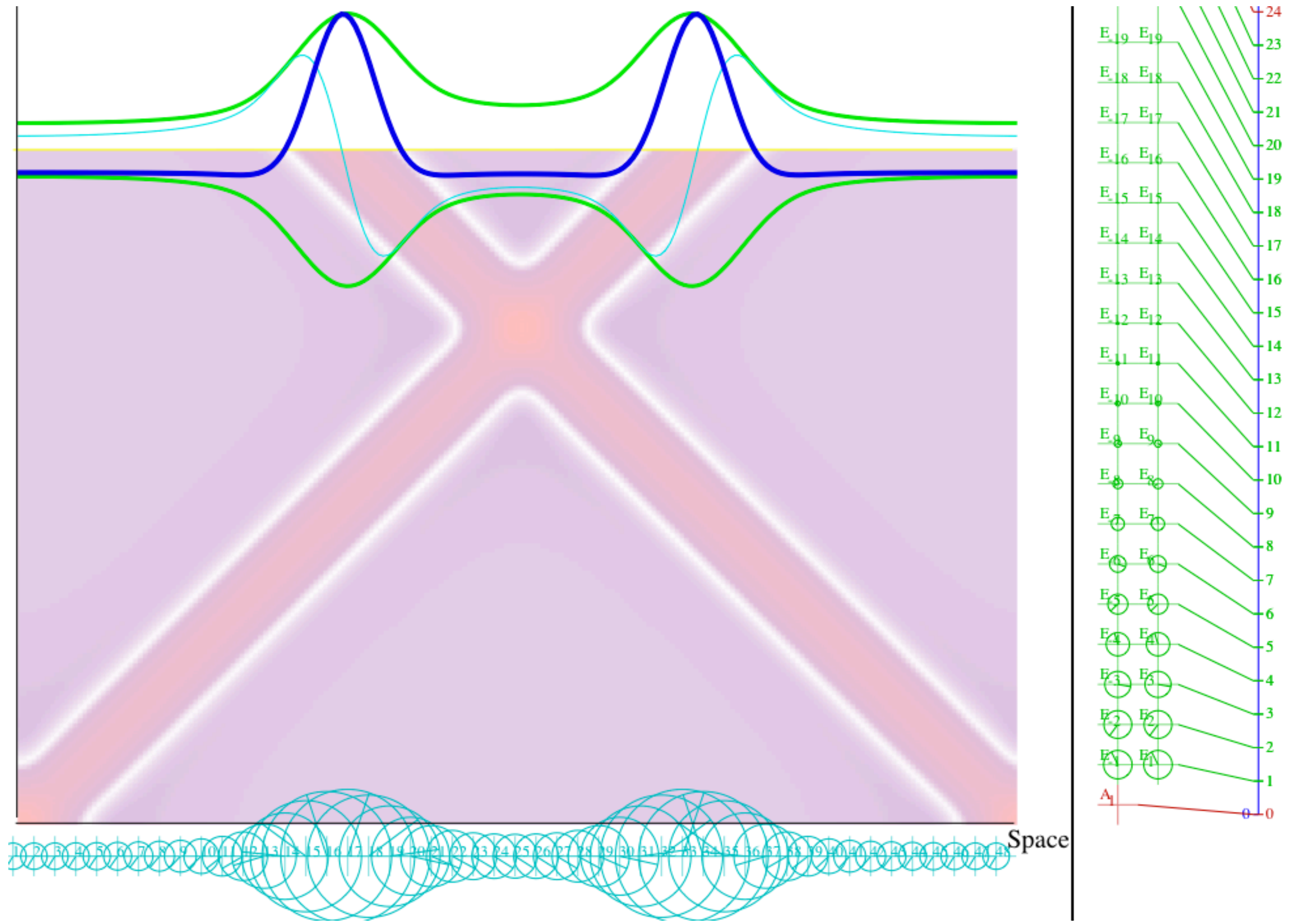
PW "wrinkles" go away if Fourier "boxcar"  *is tapered to a softer "Gaussian"* 

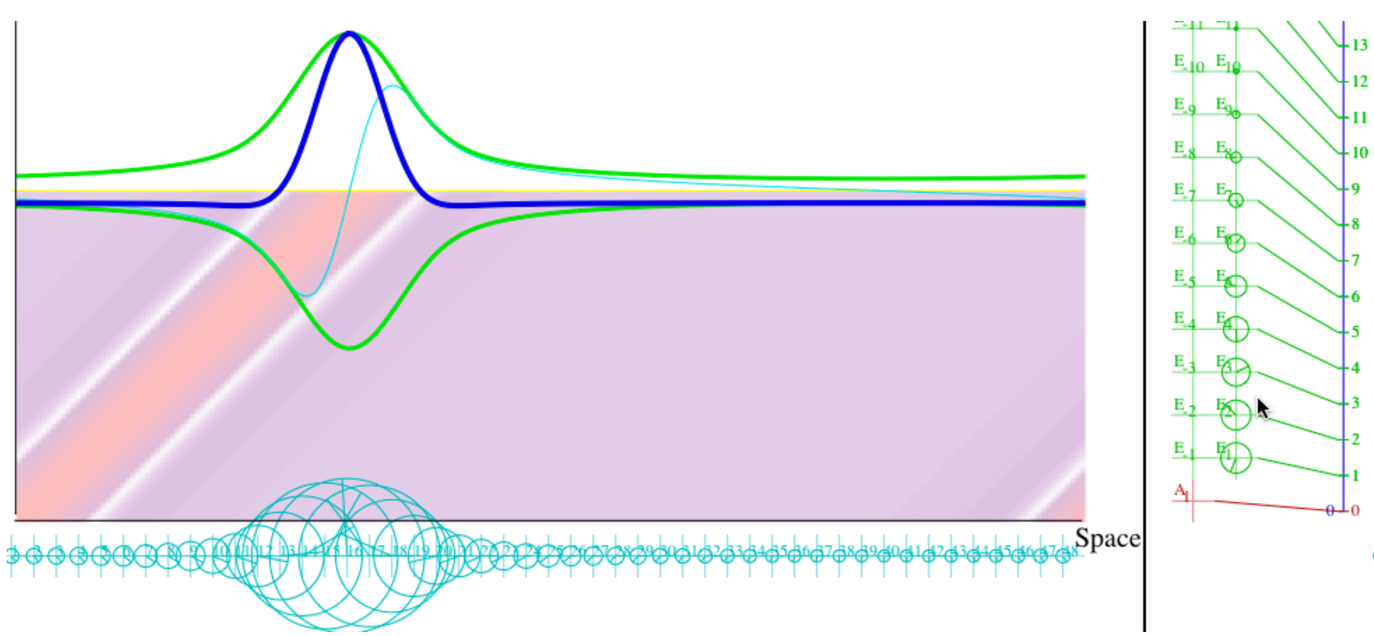


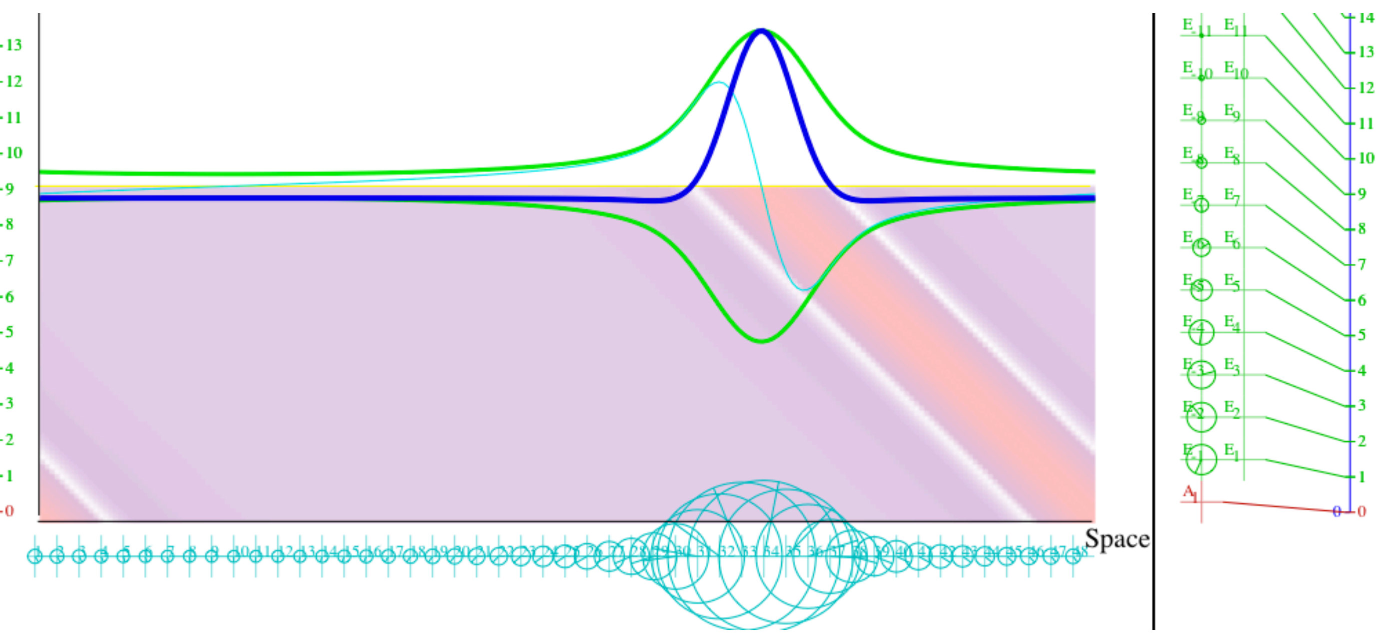
1-Way Gaussian PW -1
http://www.uark.edu/ua/modphys/markup/BohrItWeb.html?scenario=5001



1-Way Gaussian PW +1
http://www.uark.edu/ua/modphys/markup/BohrItWeb.html?scenario=5002







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1-Way Gaussian PW +1
http://www.uark.edu/ua/modphys/markup/BohrItWeb.html?scenario=5002

2-Way Gaussian PW ±1
http://www.uark.edu/ua/modphys/markup/BohrItWeb.html?scenario=5000

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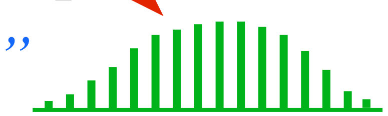

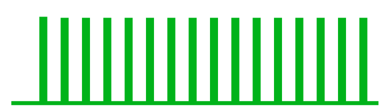

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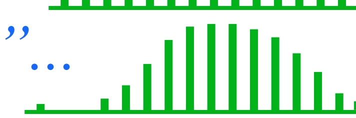
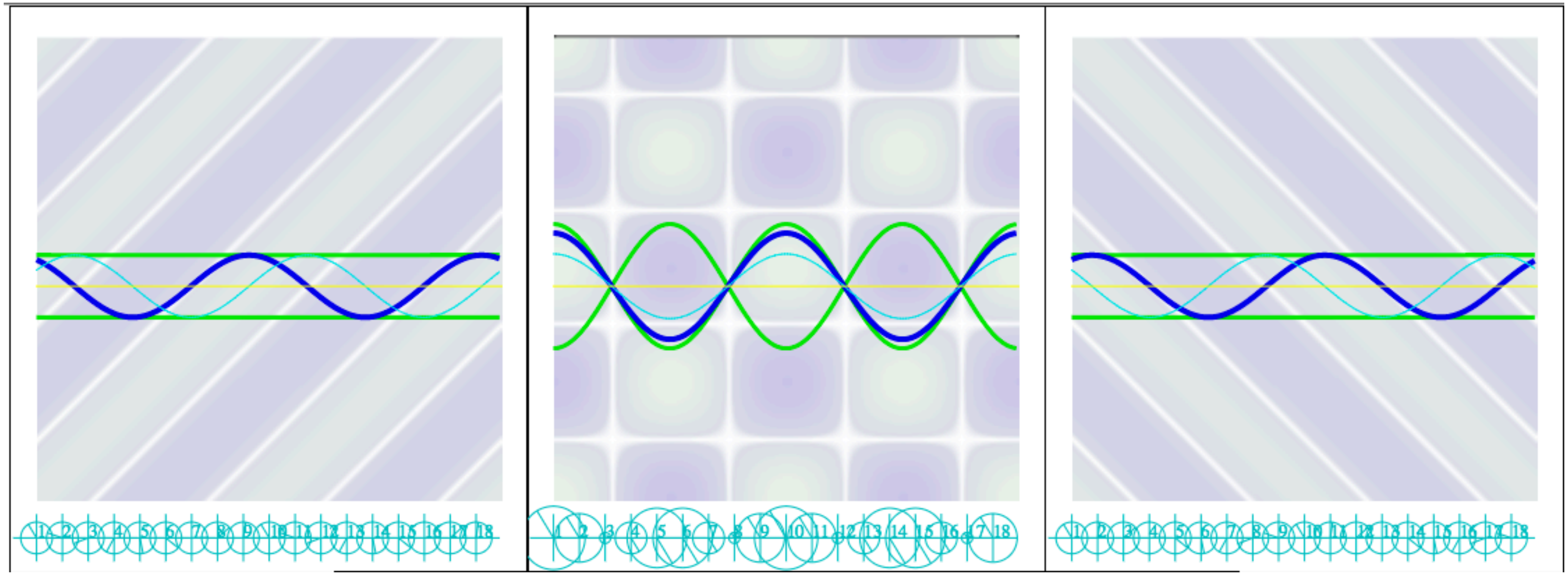


Opposite-pair CW (colliding $\pm m=\pm 2$) Fourier components trace a Cartesian space-time grid

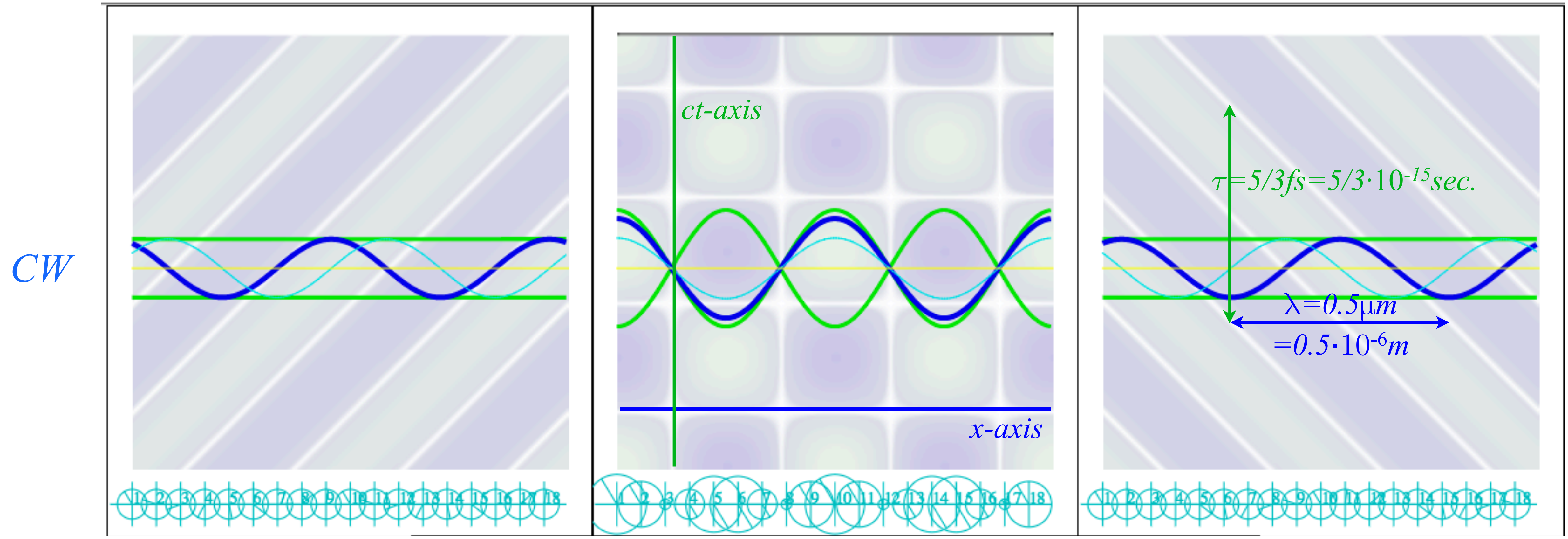
Spacetime animation of head-on collision of two υ=600THz CW modes of light

CW

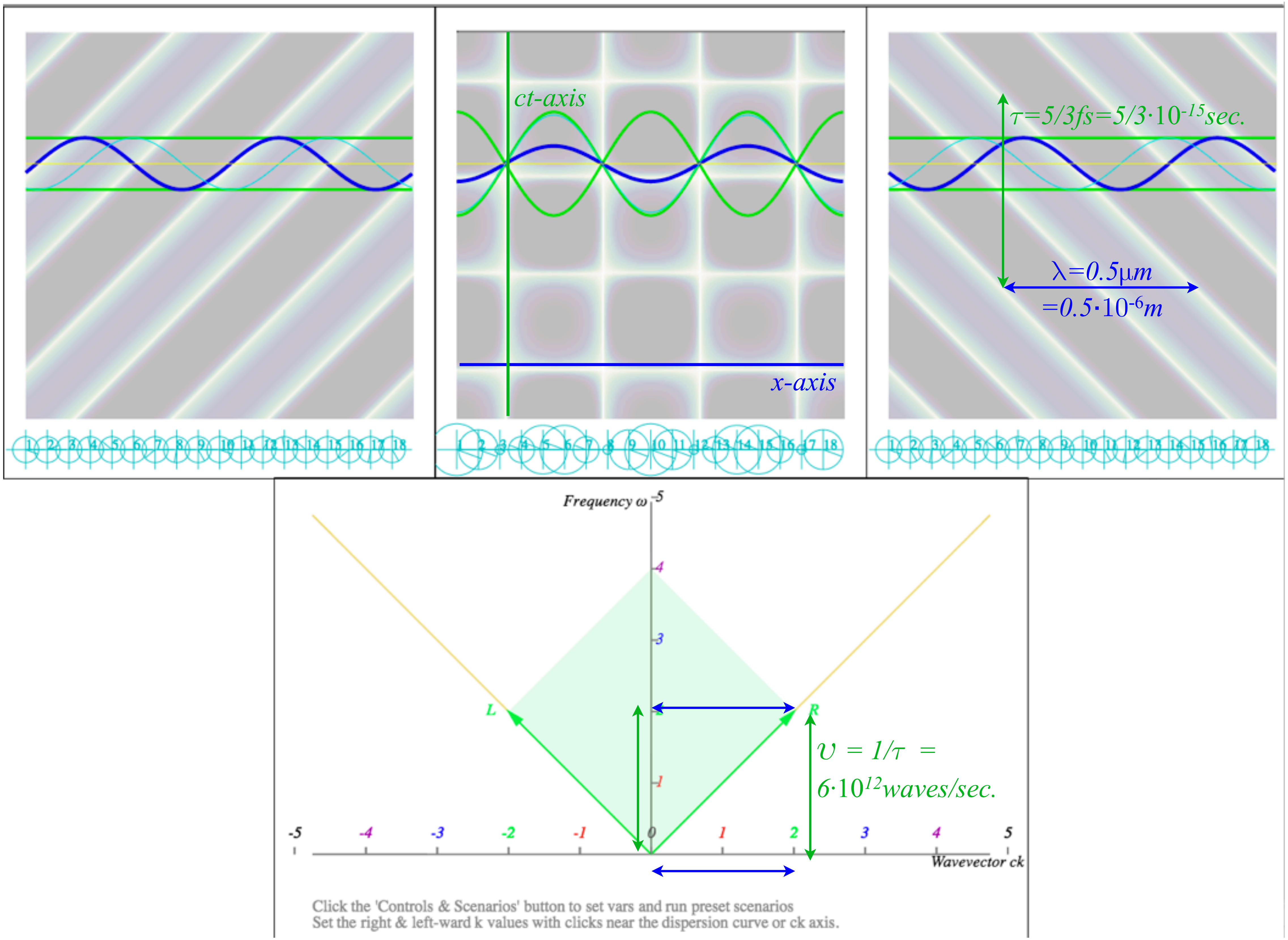


BohrIt Web Simulation
2 CW *ct vs x* Plot (ck = ±2)

Spacetime animation of head-on collision of two υ=600THz CW modes of light



[BohrIt Web Simulation](#)
[2 CW *ct vs x* Plot (ck = ±2)](#)



$\kappa = 1/\lambda =$

$2 \cdot 10^6$*waves/m*

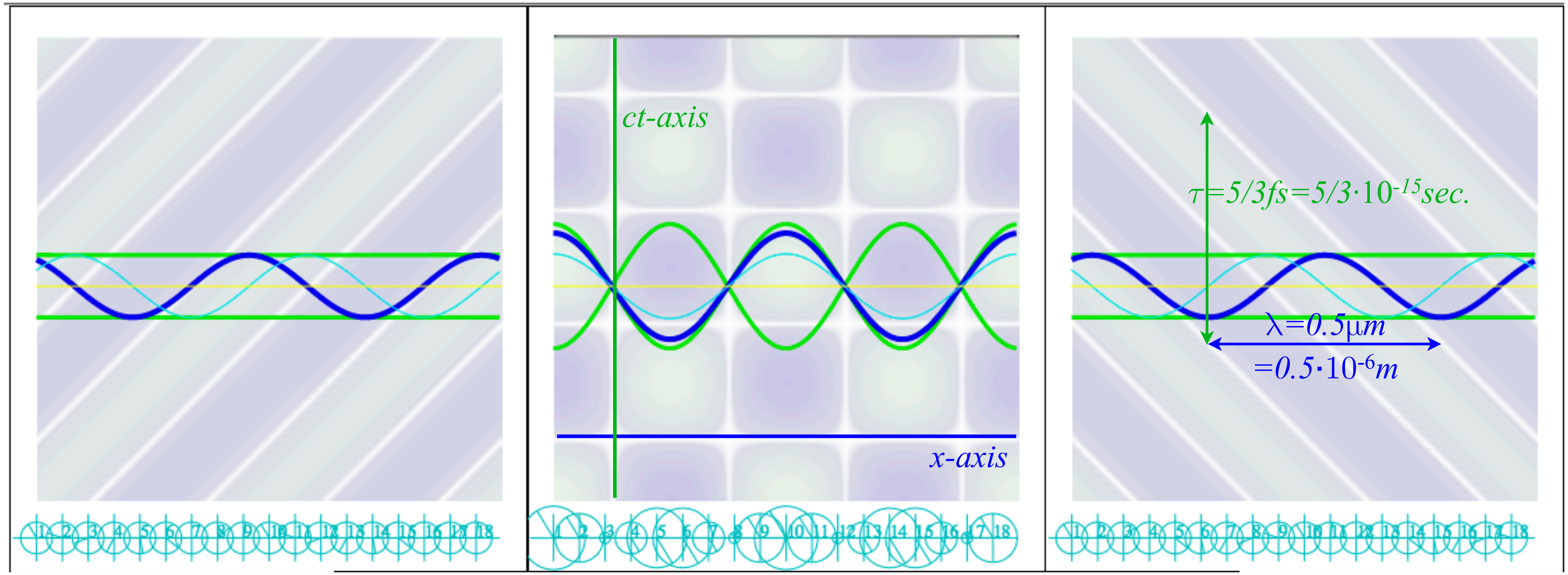
[BohrIt Web Simulation](#)
[2 CW *ct vs x* Plot (ck = ±2)](#)

Opposite-pair CW (colliding $\pm m = \pm 2$*) Fourier components trace a Cartesian space-time grid*

➔ *Colliding PW) Fourier components trace space-time "baseball diamonds"*

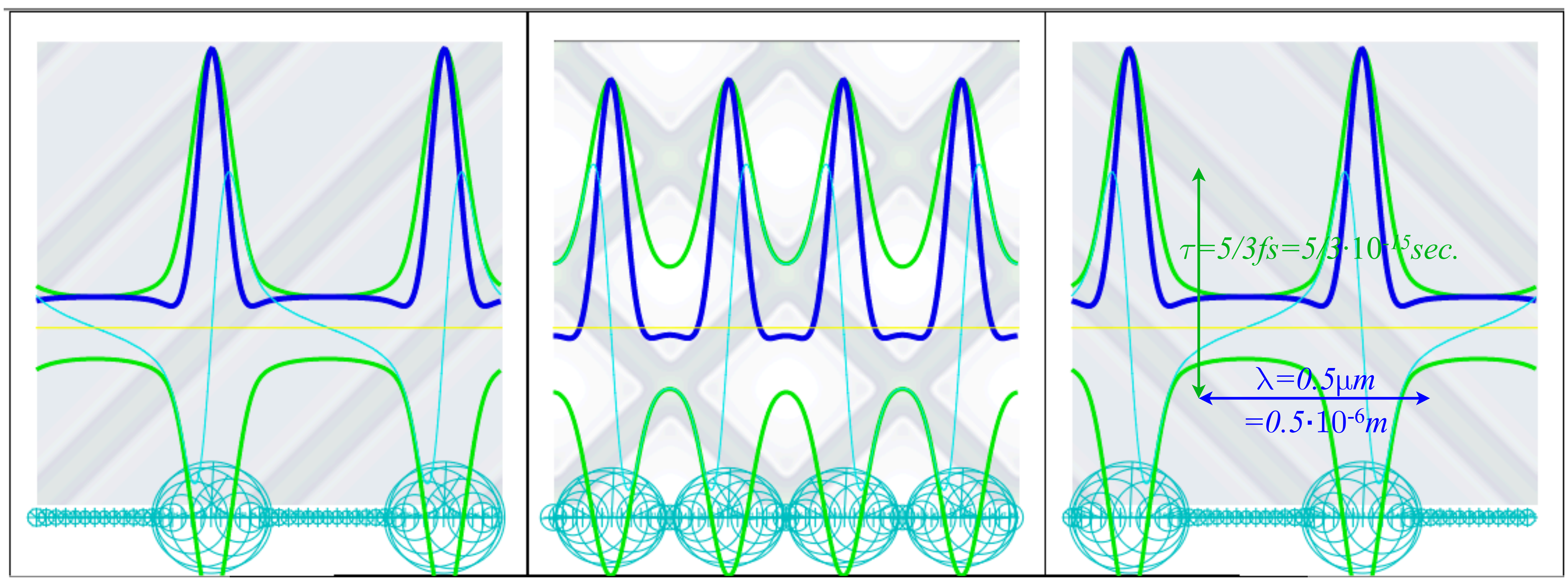
Spacetime animation of head-on collision of two υ=600THz CW modes of light

CW



Spacetime animation of head-on collision of two Nυ=600N THz PW modes of light

PW



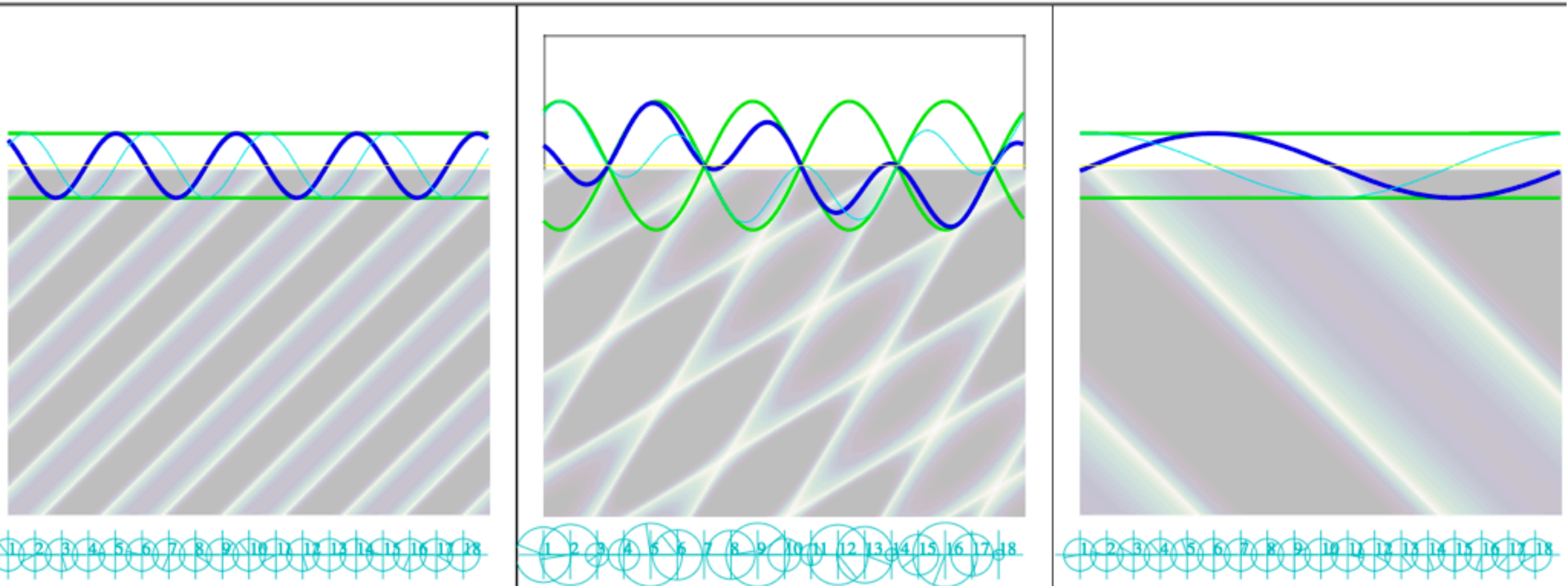
BohrIt Web Simulation
2 CW *ct vs x* Plot (ck = ±2)

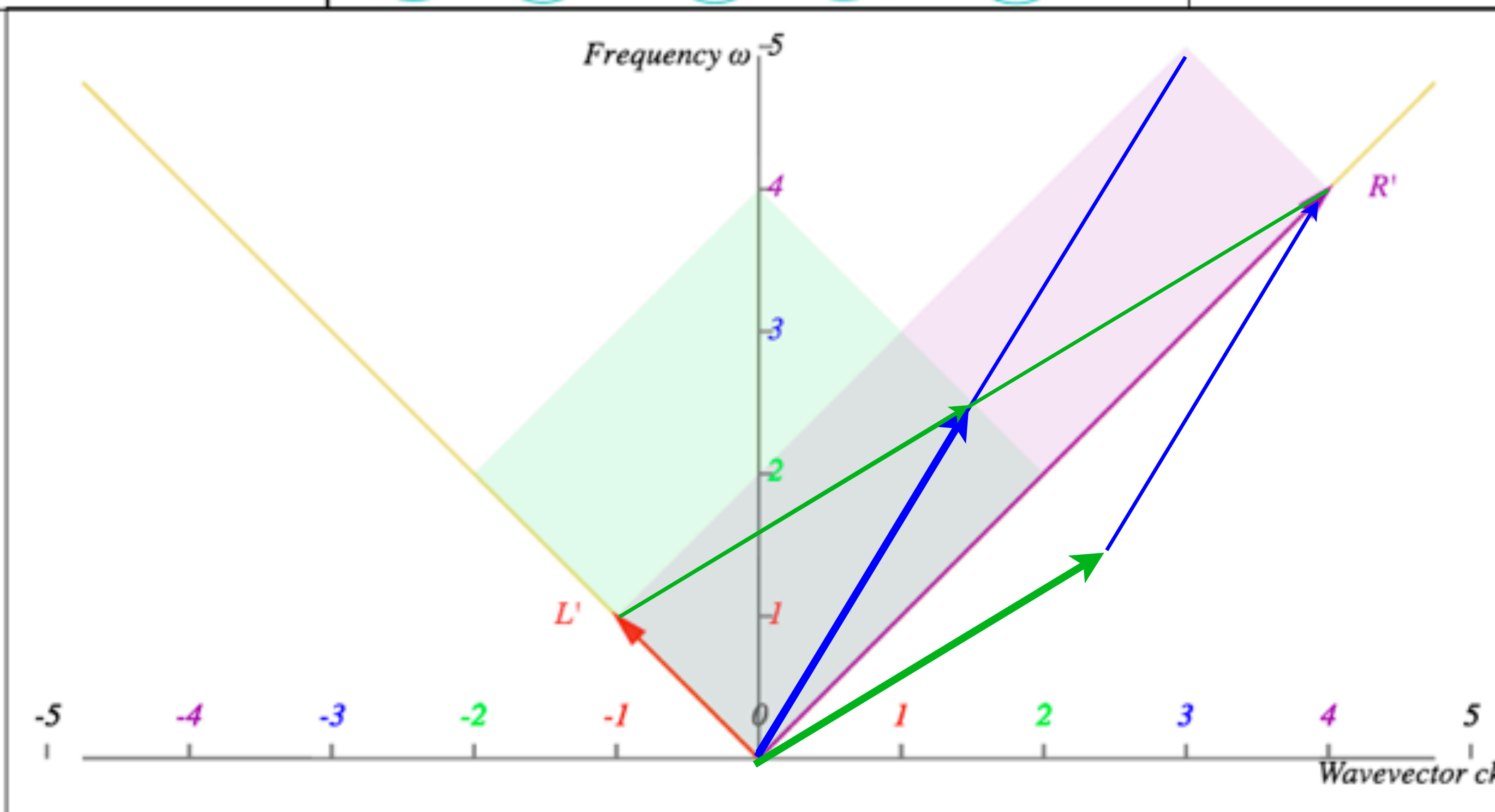
BohrIt Web Simulation
2 PW *ct vs x* Plot (ck mod 2 = 0)

Opposite-pair CW (colliding ±m=±2) Fourier components trace a Cartesian space-time grid

Colliding PW lightwaves trace space-time "baseball diamonds"

→ *Introducing CW (colliding ±m=±2) Doppler shifted to (m=-1 and m=+4)*





Click the 'Controls & Scenarios' button to set vars and run preset scenarios
Set the right & left-ward k values with clicks near the dispersion curve or ck axis.