HUMINANITY

Series of PowerPoint Presentations by J. W. Gardner

- **Misbeliefs – Acquisition & Probable Examples**
- **Big Picture Science – Observable Universe**
- **Big Picture Science – Planet Earth**
- **Big Picture Science – Life on Earth**
- **Basic Science Sampler – Quantum Physics, Relativistic Physics and Thermodynamics**

Quantum Physics

Double-slit experiment

Entanglement

Periodic Table

Standard Model

Special Relativity

General Relativity

Relativity of time interval -- Hafele-Keating -- Slowing of time by gravity

Relativity of length

Nonlinear speed addition

Relativity of simultaneity

Relativistic dynamics

Bending of light

Black holes

Gravitoelectromagnetism

Gravitational waves

Thermodynamics

First and second laws

Entropy generation

Shortcuts to topics underlined

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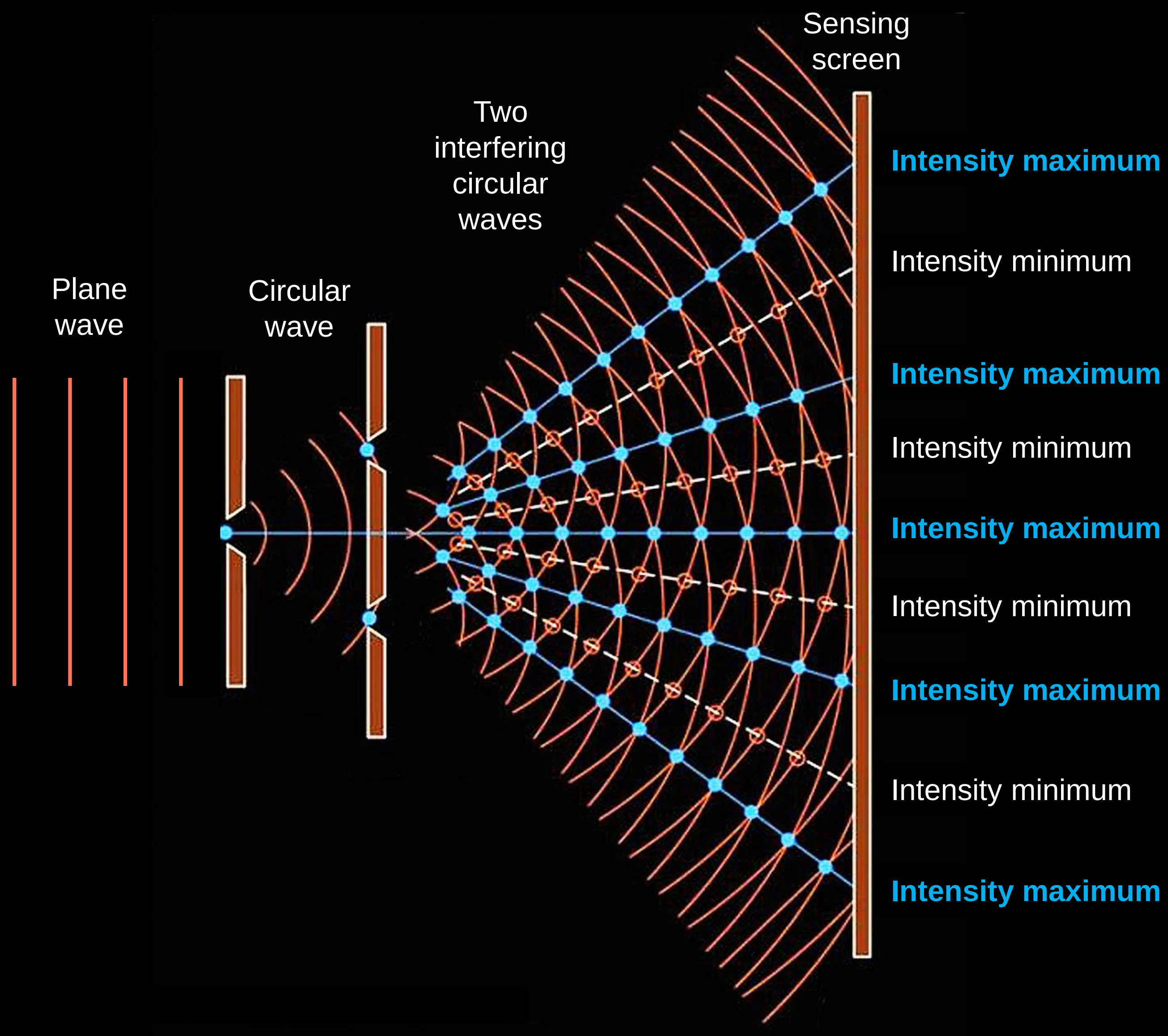
Double-Slit Experiment

Experiment with Light

Oldest type demonstrates wave nature of light in form of interference bands

Light also can exhibit particle-like behavior, as in photoelectric effect

Double-Slit Experiment with Light



Light intensity maximums and minimums resulting from constructive and destructive wave interference. Similar experiment first done by Thomas Young in 1803. Same behavior exhibited by water waves in pan

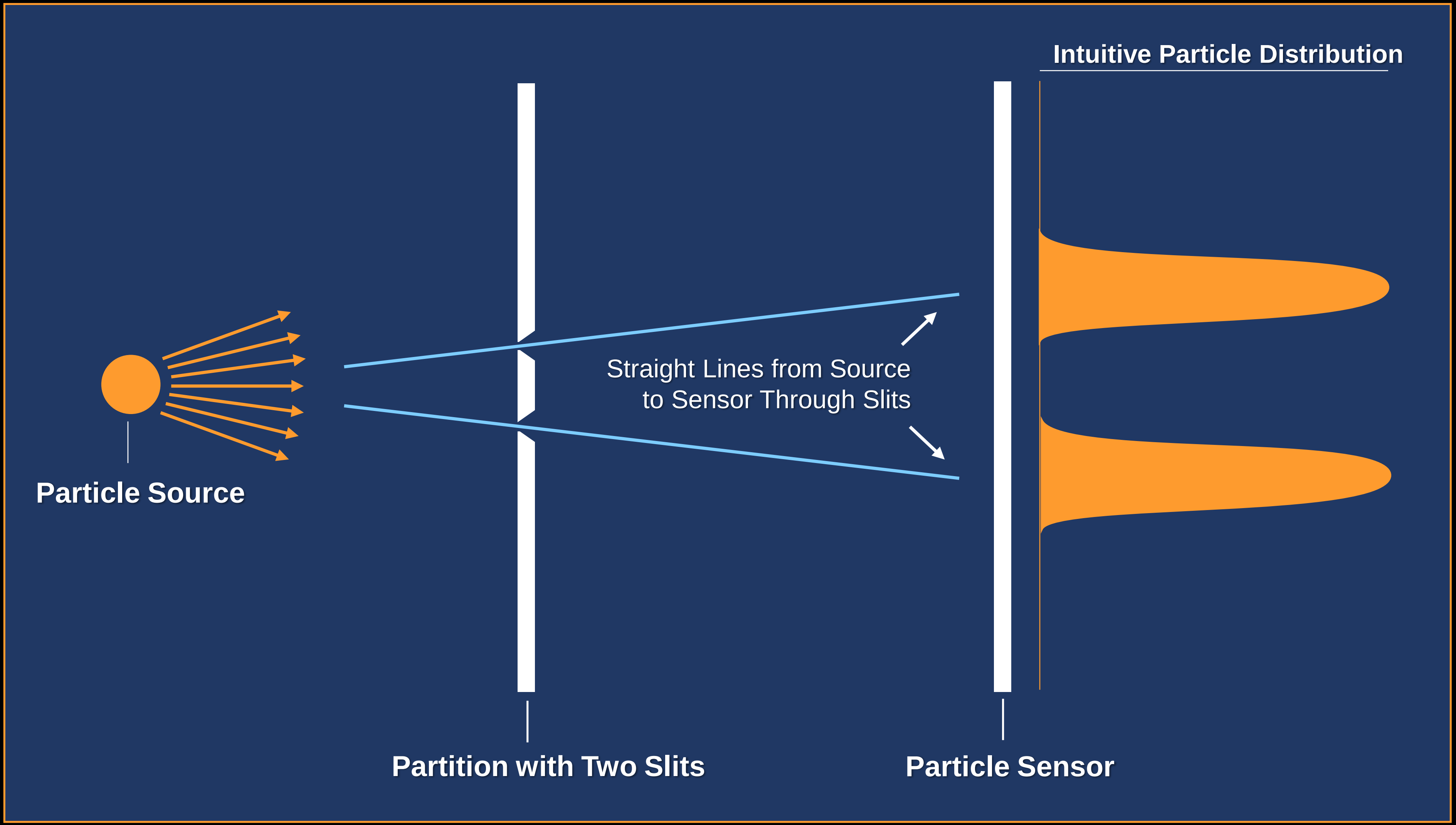
Double-Slit Experiment

Experiment with Massive Particles

Counterintuitively, experiment with massive particles also reveals interference bands

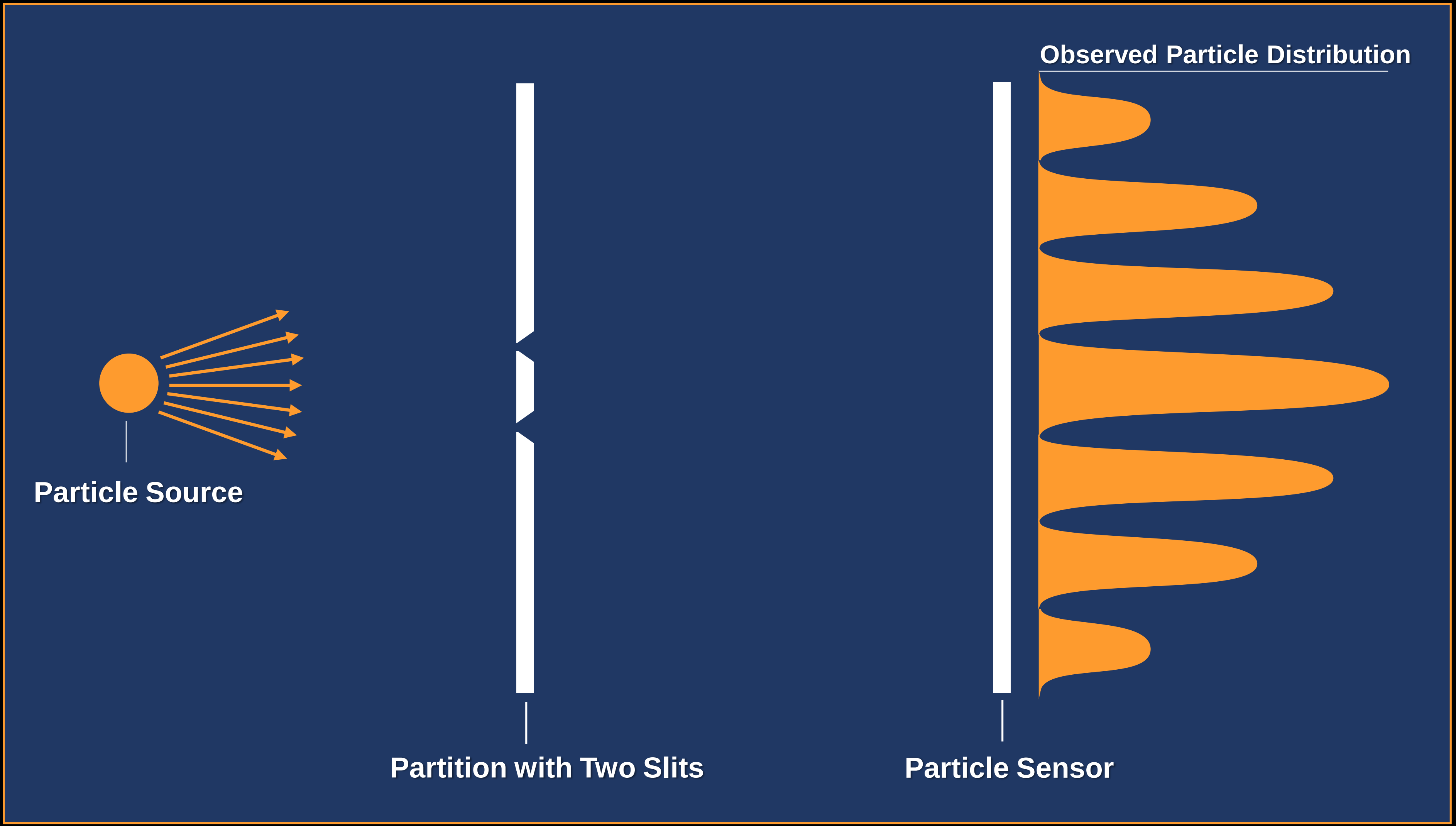
Double Slit Experiment with Massive Particles

Intuitive (Classical) Expectation for Particles Is No Interference



Double Slit Experiment with Massive Particles

Actual Result = Quantum Mechanical Prediction (Wave Interference Pattern)



Observed with electrons and with molecules containing as many 70 carbon atoms (perhaps more)

Double-Slit Experiment

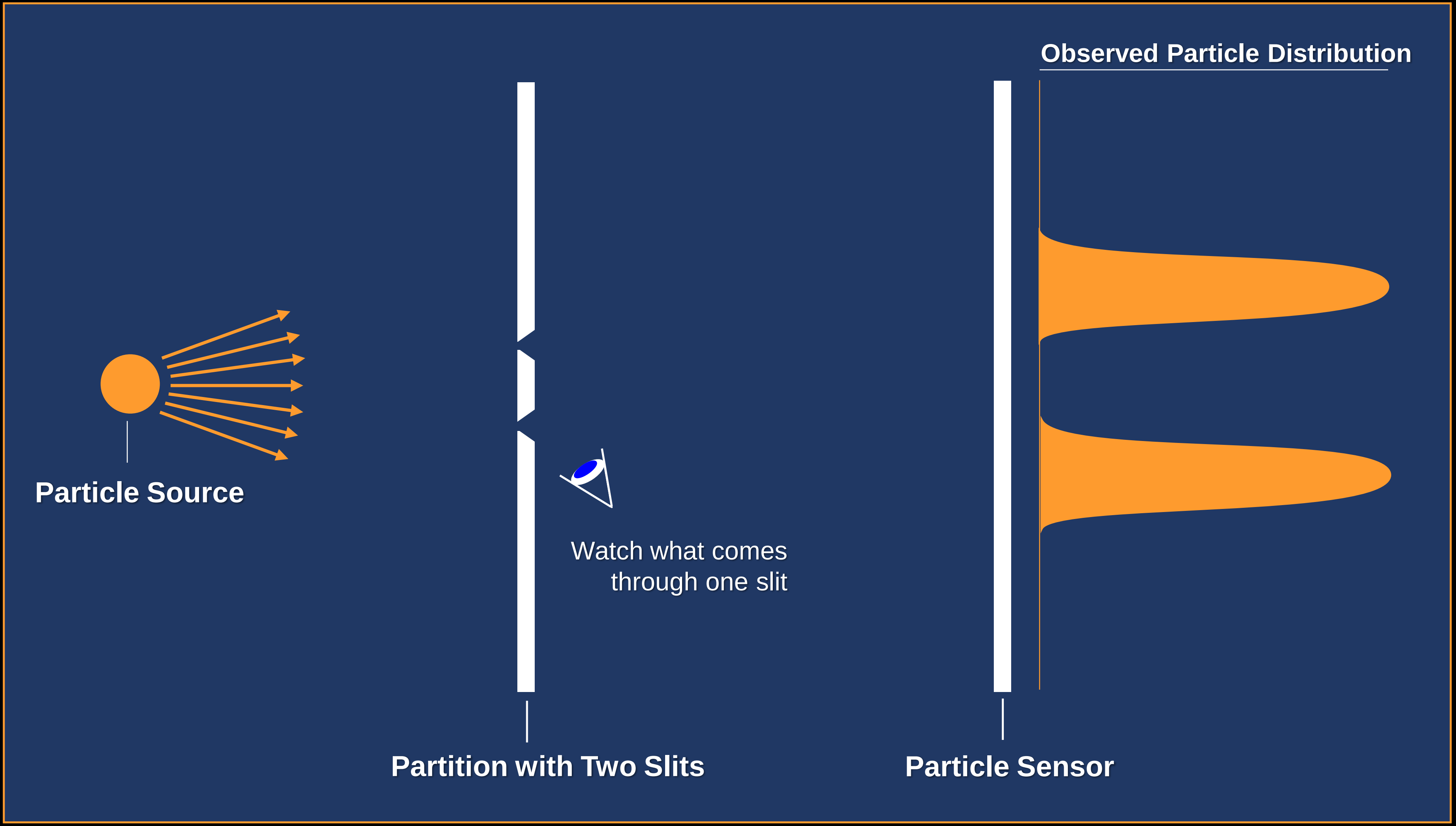
Monitor Particles Exiting One Slit

Not surprisingly, perhaps, monitoring particles exiting one slit eliminates interference pattern

Not surprising because act of observation alters system

Double Slit Experiment with Massive Particles

Watch What Comes Though One Slit



If what comes through either slit is observed then classical result is obtained

Double-Slit Experiment

One Particle at a Time

More counterintuitive is what happens if the experiment is done one particle at a time

Tonomura Double-Slit Experiment with Individual Electrons

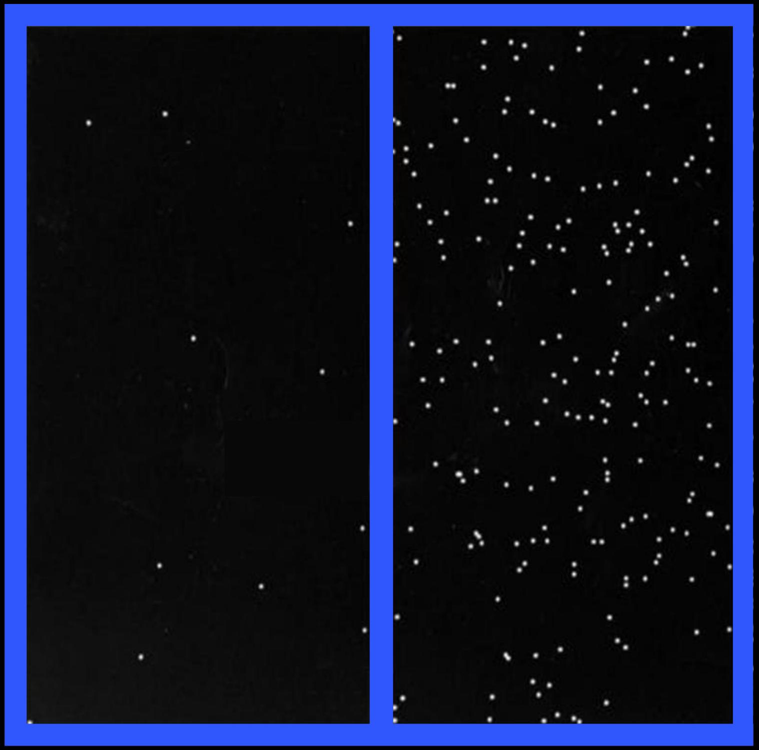
Screen now in plane of slide. Each electron hit recorded before next fired

Increasing Time

"Demonstration of single-electron buildup of an interference pattern," Tonomura, et al, *Am. J. Phys*. 57, 117 (1989)

Tonomura Double-Slit Experiment with Individual Electrons

Screen now in plane of slide. Each electron hit recorded before next fired



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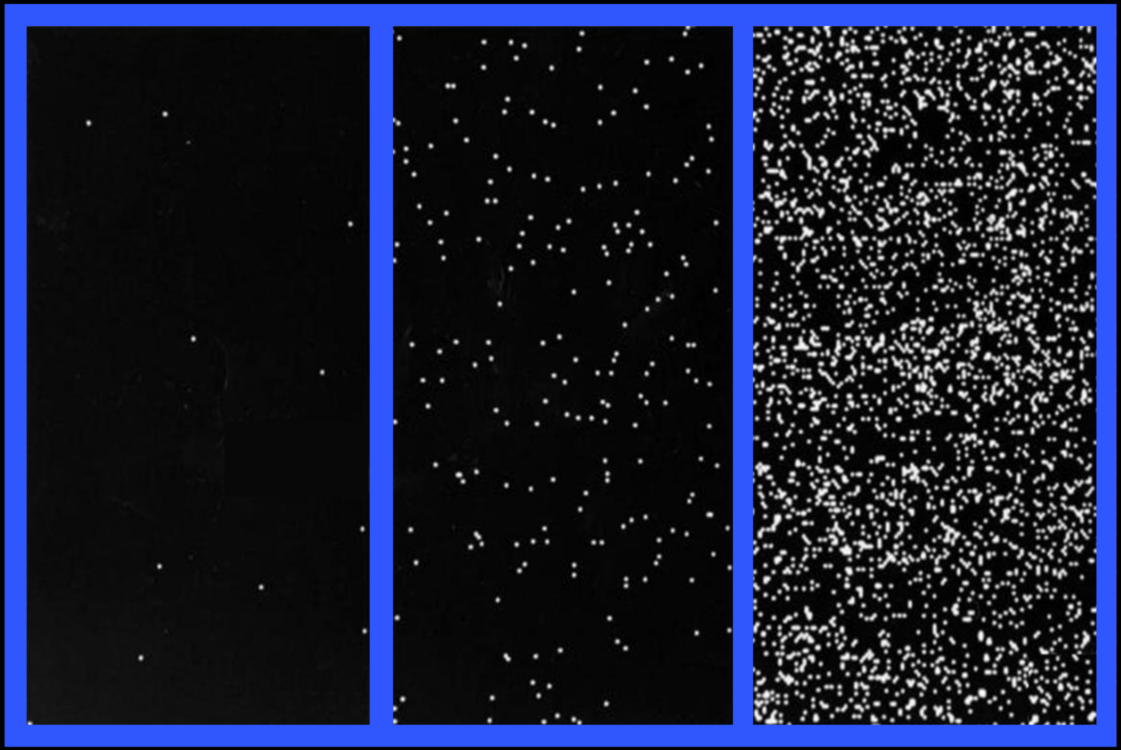

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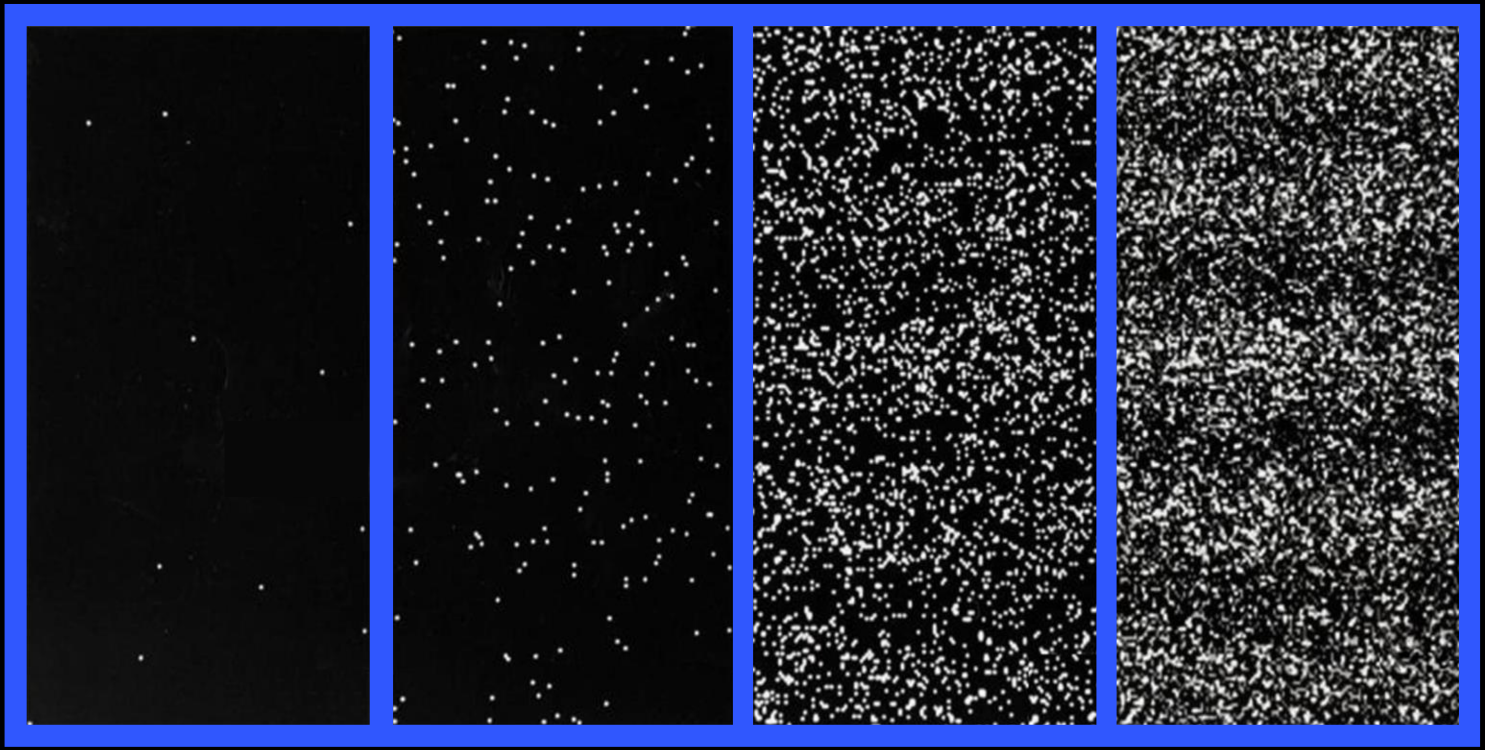

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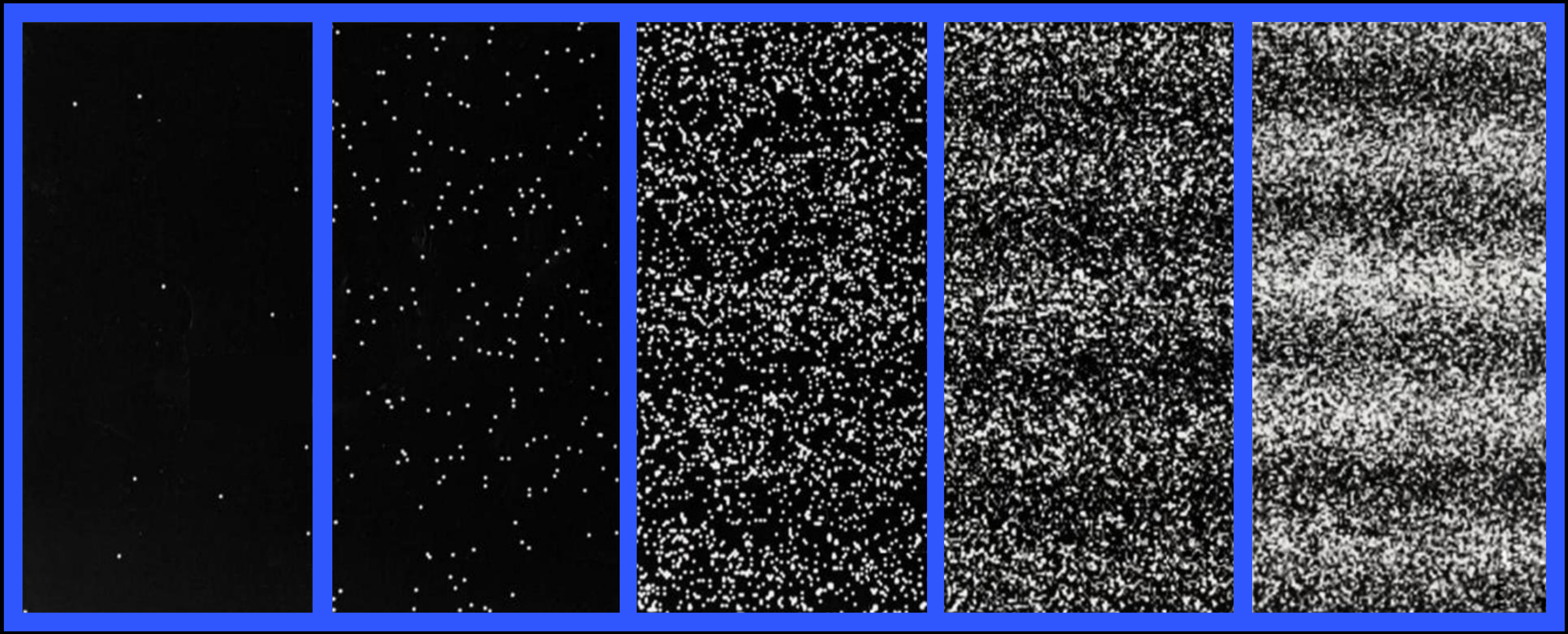

Increasing Time →

"Demonstration of single-electron buildup of an interference pattern," Tonomura, et al, *Am. J. Phys*. 57, 117 (1989)

Last experiment emphasizes the probabilistic nature of quantum mechanics

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Quantum Entanglement

- Limbo-like state in which two particles are linked over arbitrary distances and property values are undetermined
- Measuring a property value of one particle breaks entanglement, whence other particle manifests complimentary value
- Quantum mechanics places no limit on rate of manifestation

Laser pulses, for example, have been used to entangle photons of different polarity and electrons of different spin

Quantum Entanglement

- Limbo-like state in which two particles are linked over arbitrary distances and property values are undetermined
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- Quantum mechanics places no limit on rate of manifestation

That required to satisfy some conservation principle

Quantum Entanglement

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- Measuring a property value of one particle breaks entanglement, whence other particle manifests complimentary value
- Quantum mechanics places no limit on rate of manifestation

Manifestation times less than 1/10,000 of light transit time between particles have been observed

Experiments of Yin, et al (2013) arXiv:1303.0614v1 [quant-ph] 4 Mar 2013. Probably instantaneous. Conflicts with special relativity

Quantum Entanglement: Einstein's "Spooky Action at a Distance"

It has now been shown that either causal influences propagate faster than light, or a common-sense notion about what the word "cause" signifies is wrong

– Howard Wiseman (2015)*

*Writing in reference to experiments by Henson, et al (2015) "Experimental loophole-free violation of a Bell inequality using entangled electron spins separated by 1.3 km" arXiv:1508.05949

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Periodic Table of Elements

- Table organizing 118 discovered elements. The standard version is based on atomic number, electron configuration & recurring chemical properties
- One alternative is based solely on quantum numbers associated with the solution of the Schrödinger equation for a single electron orbiting a nucleus

Standard Periodic Table

Found on Walls of Chemistry Classrooms & Labs

1 H Hydrogen																	2 He Helium
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium											13 Al Aluminium	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	57–71 La–Lu Lanthanides	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	89–103 Ac–Lr Actinides	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovium	116 Lv Livermorium	117 Ts Tennessine	118 Og Oganesson

57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium
89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium

Numbers in boxes are atomic numbers (numbers of protons in nucleus). Columns consist of elements with similar properties. From Scientific Gems - WordPress.com

Periodic Table of Elements

- Table organizing 118 discovered elements. The standard version is based on atomic number, electron configuration & recurring chemical properties
- One alternative is based solely on quantum numbers associated with the solution of the Schrödinger equation for a single electron orbiting a nucleus

The particular such alternative considered here is the left-step table of Charles Janet

Quantum Mechanics of Hydrogen Atom

Time-independent Schrödinger equation for electron

$$E\psi = \left[\frac{-\hbar^2}{2\mu} \nabla^2 - \frac{e^2}{4\pi\varepsilon_0 r} \right] \psi$$

Solution in spherical coordinates

$$\psi_{n\ell m}(r,\theta,\phi) = \sqrt{\left(\frac{\rho}{r}\right)^3 \frac{(n-\ell-1)!}{2n(n+\ell)!}}\, e^{-\rho/2} \rho^{\ell} L_{n-\ell-1}^{2\ell+1}(\rho) Y_{\ell}^{m}(\theta,\phi)$$

E = energy, ψ = wave function, $\hbar$ = reduced Planck constant, μ = reduced mass = $m_e m_p/(m_e + m_p)$
m_e = electron mass, m_p = proton mass, e = charge magnitude of electron and proton,
ε_0 = dielectric constant, r = distance from center of proton, n = principal quantum number,
ℓ = azimuthal quantum number, m = magnetic quantum number, $\rho = 2r/(na_0)$,
a_0 = Bohr radius = $4\pi\varepsilon_0\hbar^2/m_e e^2$, $L_{n-\ell-1}^{2\ell+1}(\rho)$ = Laguerre polynomial, $Y_{\ell}^{m}(\theta,\phi)$ = spherical harmonic

Meaning of Quantum Numbers

- **Principal quantum number n linked to energy level of electron orbital, with values** 1, 2, 3 **. . .**
- **Azimuthal quantum number ℓ linked to orbital angular momentum of electron, with values** 0, 1, 2 **. . .** $n - 1$,
- **Magnetic quantum number m linked to magnetic moment of electron, with values** $-\ell, -(\ell - 1)$ **. . .** $-1, 0, 1$ **. . .** $\ell - 1, \ell$
- **Spin quantum number m_s linked to "orientation" of electron spin, with values** $+\frac{1}{2}$ **or** $-\frac{1}{2}$

Note that the wave function ψ is not dimensionless, but has units of length$^{-3/2}$

Consequently, the probability density (next slide) has units of reciprocal volmue

Hydrogen Atom Orbitals

Electron Probability Densities

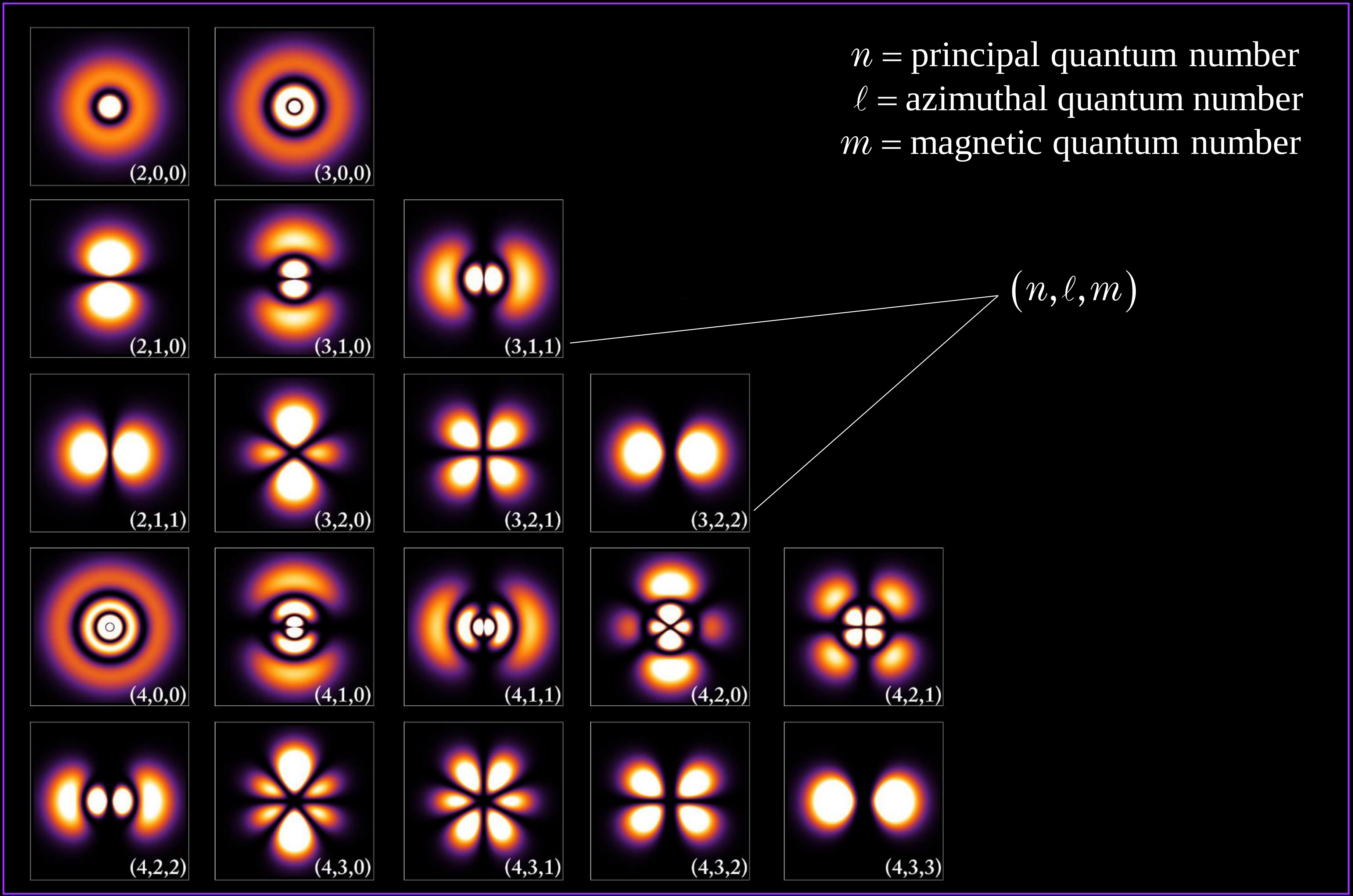
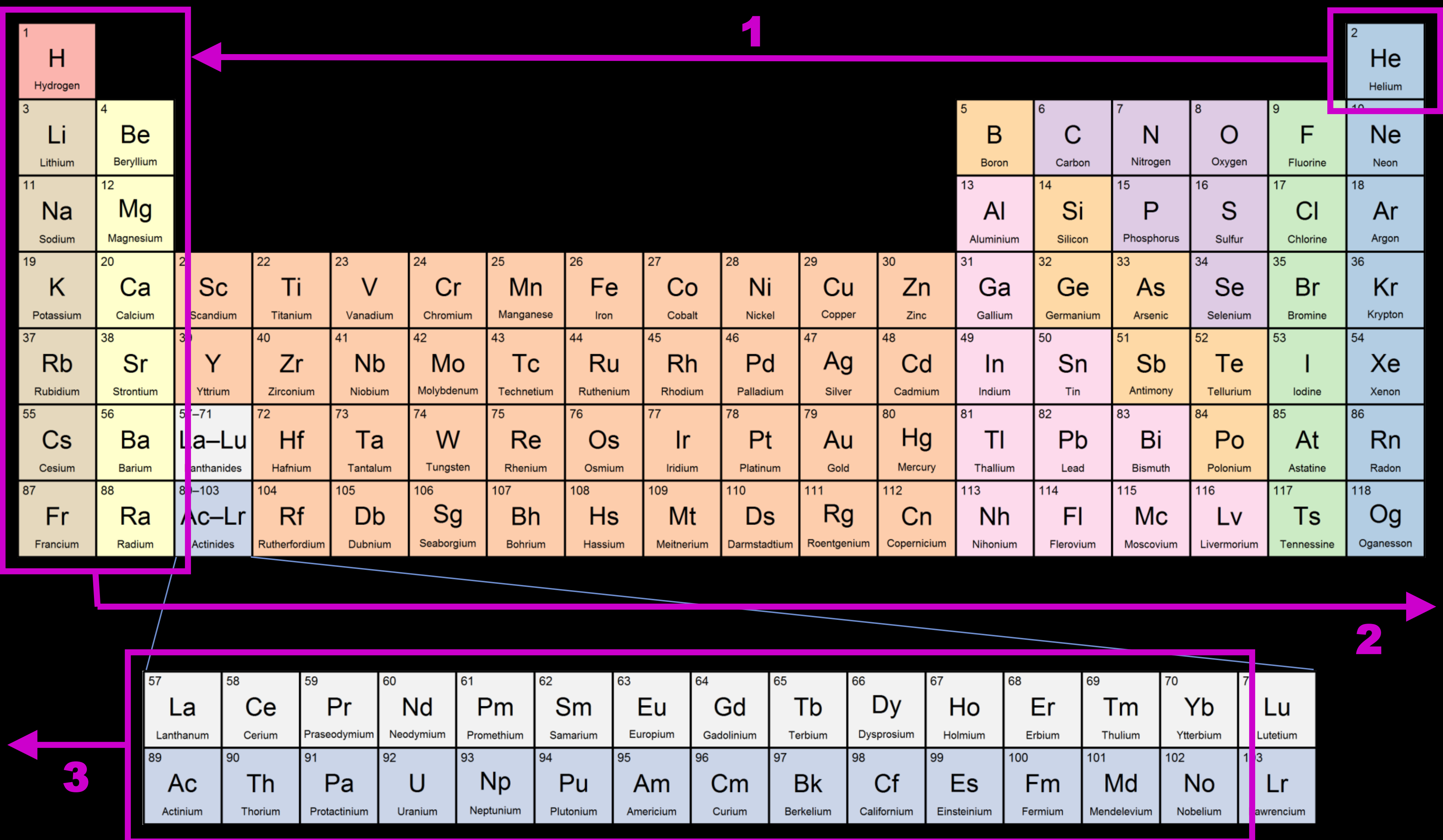


Image from Wikipedia "Quantum mechanics" article

Note also that atoms are mostly empty space. If the entire atom were the size of a baseball stadium, the nucleus, where essentially all the mass is concentrated, would be the size of a peanut

Conversion of Standard Table to Janet Table



Charles Janet Left-Step Periodic Table (1929)

$\ell = 3$ $\ell = 2$ $\ell = 1$ $\ell = 0$

Block letters f, d, p and s correspond to values of azimuthal quantum number ℓ

Magnetic quantum number m varies along each row of a block

f														d										p						s	
																														1 H	2 He
																														3 Li	4 Be
																								5 B	6 C	7 N	8 O	9 F	10 Ne	11 Na	12 Mg
																								13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	19 K	20 Ca
														21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	37 Rb	38 Sr
														39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	55 Cs	56 Ba
57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	72 Hf	73 Ta	74 W	75 Rc	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	87 Fr	88 Ra
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og	119	120

Block row number. Equal to value of principal quantum number n

4f
5f

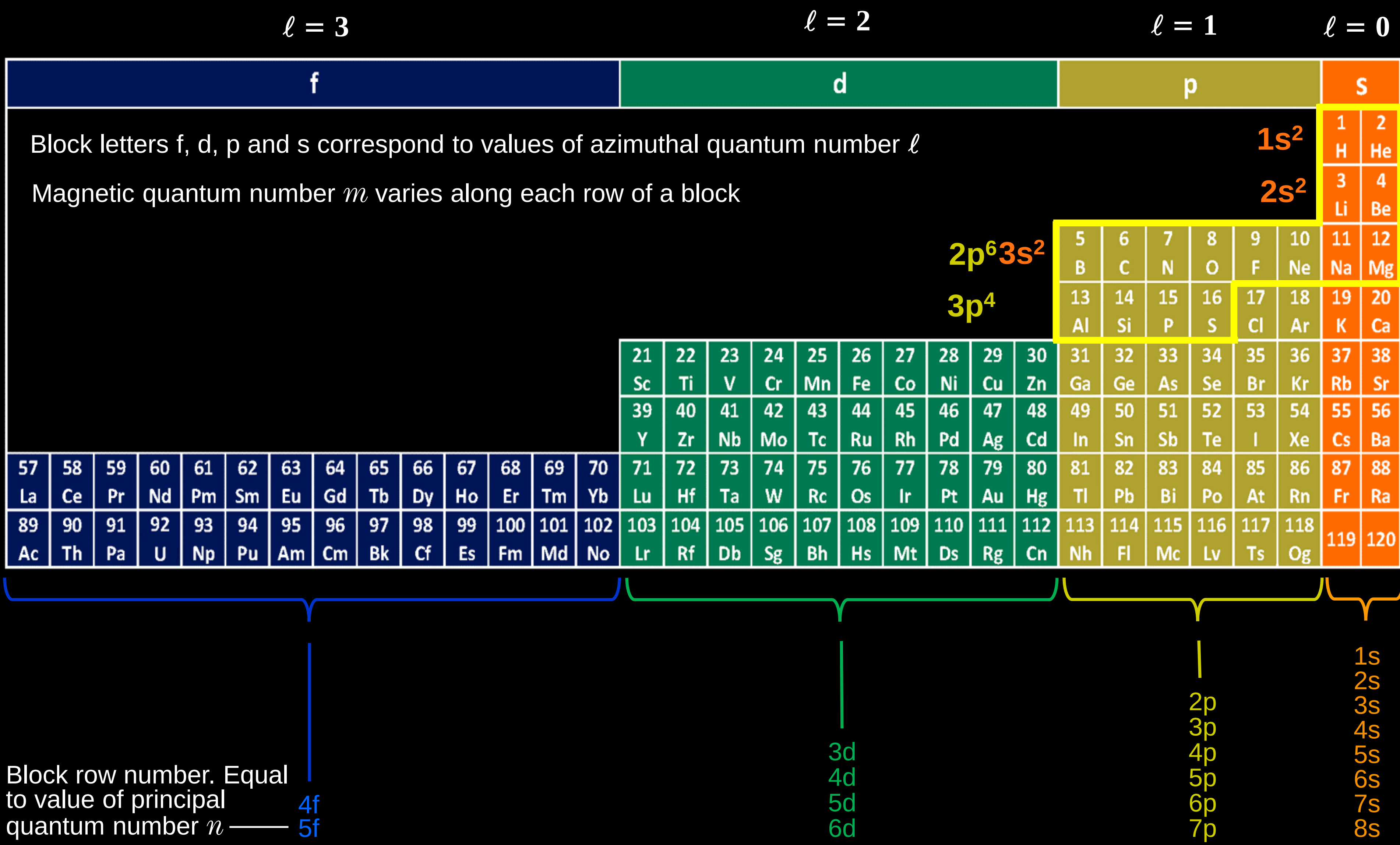
3d
4d
5d
6d

2p
3p
4p
5p
6p
7p

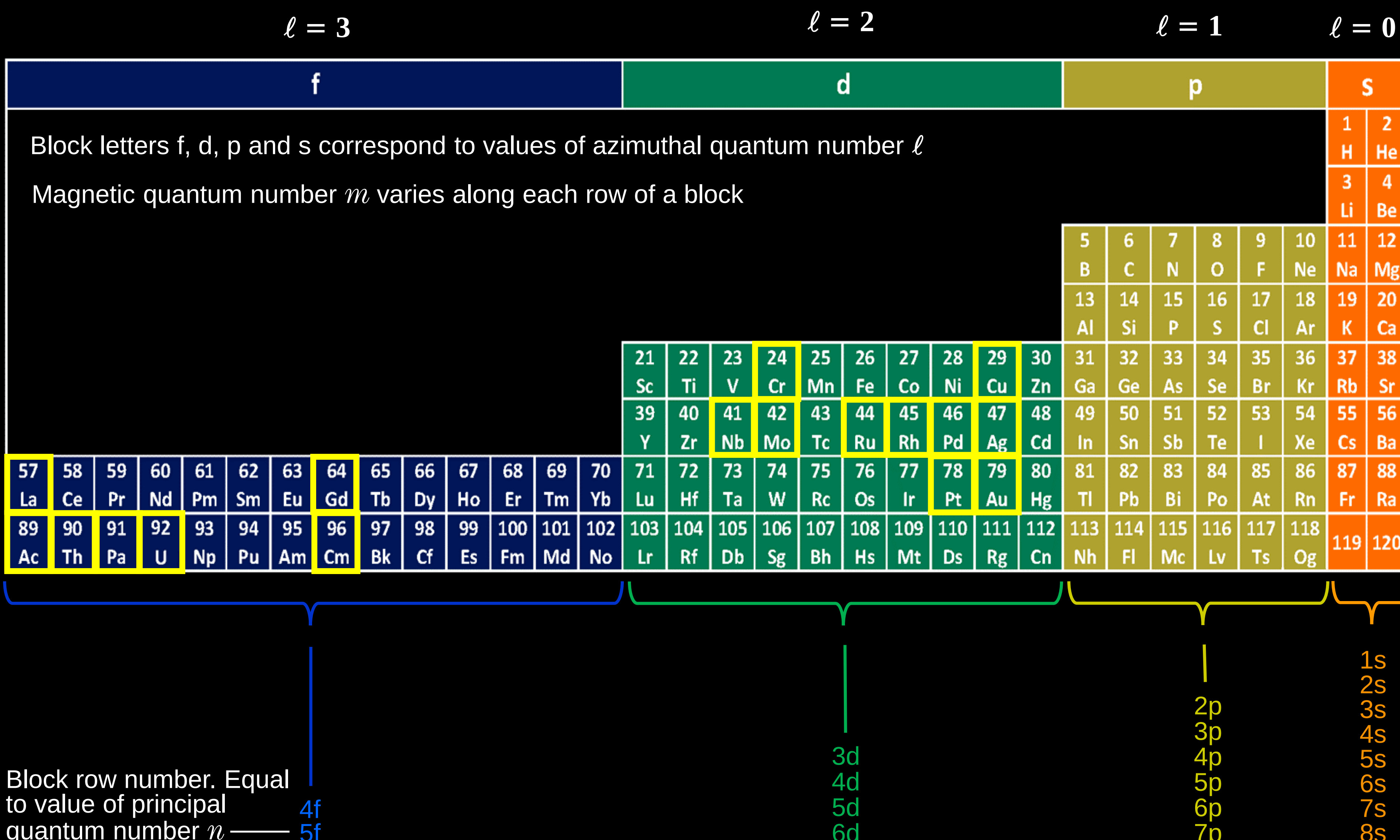
1s
2s
3s
4s
5s
6s
7s
8s

Quantum numbers here apply to the outermost or valence electron of each element

For most elements, the electron configuration can be read directly from the Janet Table. In the case of **sulfur**, for example, the configuration is $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^4$ (read left to right, row by row, starting with hydrogen)



Because some energy levels are quite close, reading the electron configuration directly from the Janet table does not always work, as with Cr, Cu, Nb, Mo, Ru, Rh, Pd, Ag, La, Gd, Pt, Au, Ac, Th, Pa, U and Cm (highlighted by yellow borders below)*



*From "The Periodic Table of the Elements" on Albert Tarantola's web page

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Standard Model of Particle Physics

- Currently most fundamental and comprehensive theory of the world supported by laboratory experiments
- Describes three of the four known fundamental forces of nature (electromagnetic, weak and strong nuclear, but <u>not</u> gravity) as exchanges of mediating particles (bosons) between matter particles (quarks and leptons, known collectively as fermions)
- Loose combination of two quantum field theories: electroweak theory and quantum chromodynamics
- As a quantum field theory, adopts the flat spacetime of special relativity
- Also excludes dark matter and dark energy, which are important in cosmology, but have yet to be linked to observable particles

Inside Molecules

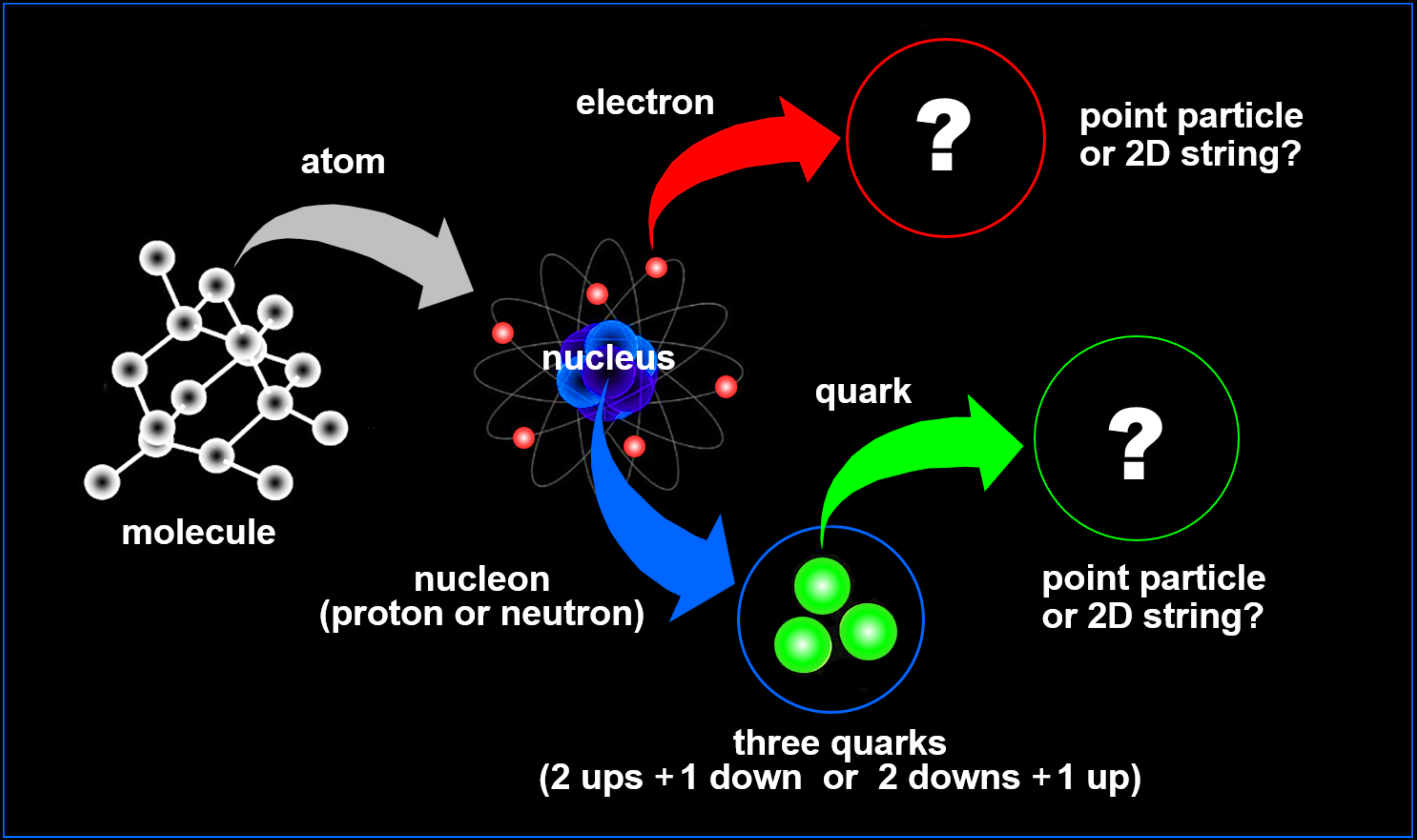


Image concept from Wikipedia "String Theory" article (modified)

More fundamental particles than electrons and up/down quarks have been observed in particle colliders

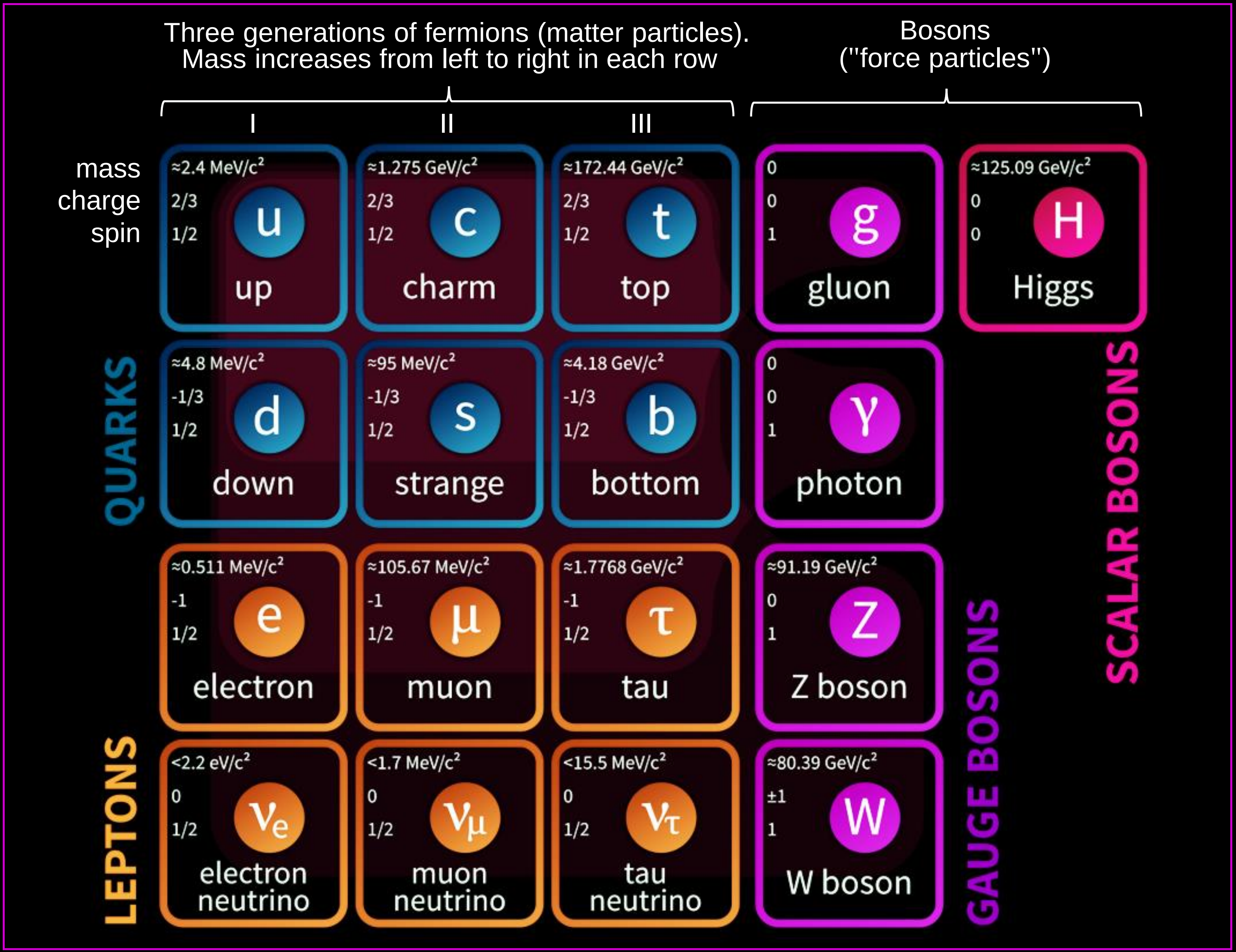
Fundamental Particles

- Fermions – Matter particles
- Bosons – "Force particles"

Fermions are spin 1/2 particles (masses and charges vary). Gauge bosons are spin 0 particles (masses and charges vary). The other boson is the Higgs (massive; spin and charge both 0)

Standard Model of Particle Physics

Fundamental Particles and Properties



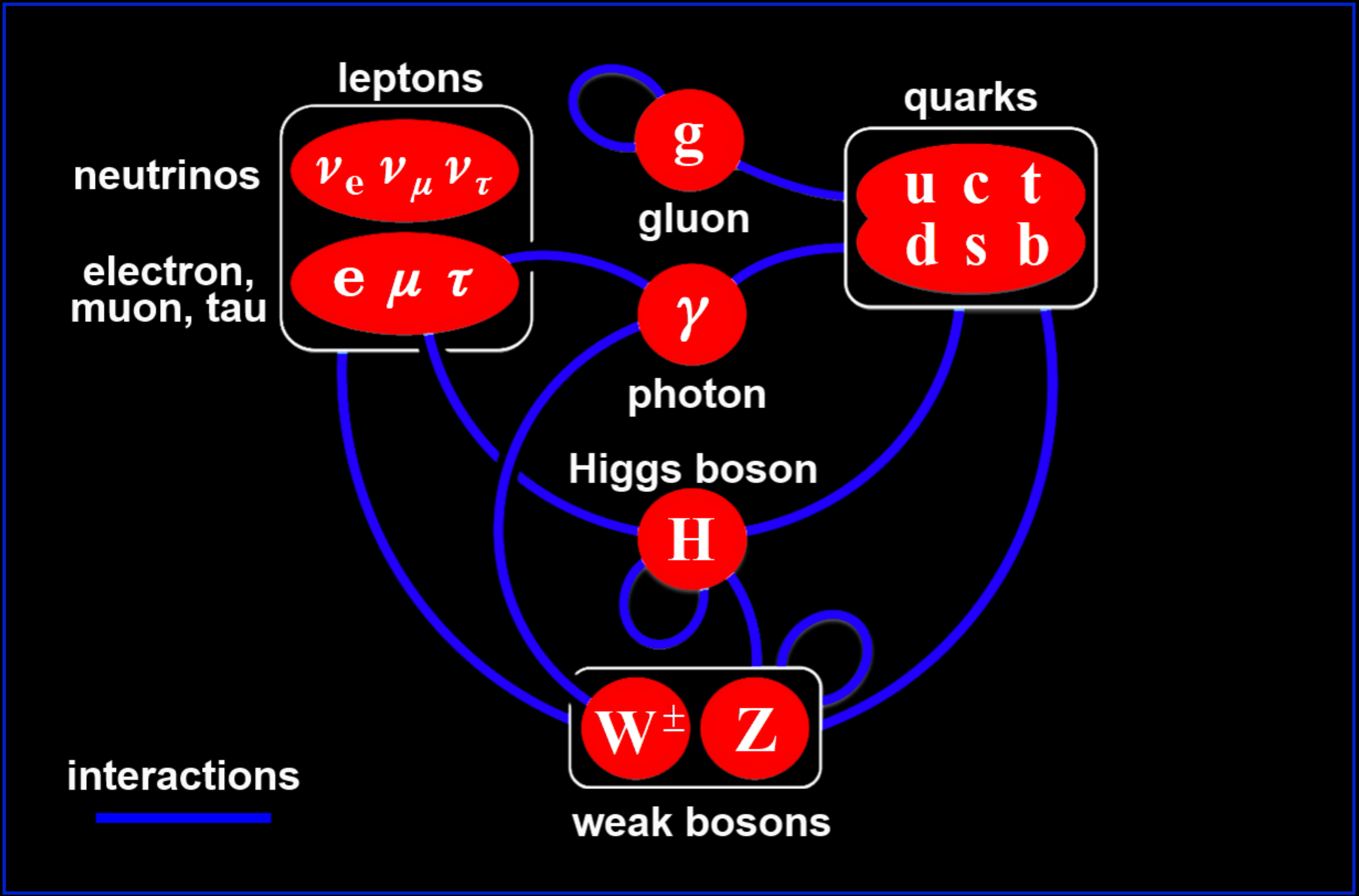
Whether standard model particles are points, 2D strings or something else is unknown. Image: Wikipedia "Standard Model" article (modified slightly)

Fundamental Bosons

- Gluon – Carrier of strong force
- Photon – Carrier of electromagnetic force
- W and Z bosons – Mediators of weak force
- Higgs boson – Gives mass to W, Z & other particles via Higgs mechanism

Standard Model of Particle Physics

Fundamental Particles and Interactions



Standard model is loose combination of two quantum field theories: electroweak theory and quantum chromodynamics. Image from Wikipedia "Standard Model" article (recolored)

Standard Model of Particle Physics

Action Principle Formulation in Lagrangian Density

Lagrangian density $\mathscr{L}$ =

$-\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$	U(1), SU(2), SU(3) gauge terms
$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}\nu_L \\ e_L\end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu\nu_R +$ H.C.	lepton dynamical terms
$-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi}\begin{pmatrix}\nu_L \\ e_L\end{pmatrix}\right]$	electron, muon, tauon mass terms
$-\frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu\nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T\begin{pmatrix}-e_L \\ \nu_L\end{pmatrix}\right]$	neutrino mass terms
$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}u_L \\ d_L\end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R +$ H.C.	quark dynamical terms
$-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi}\begin{pmatrix}u_L \\ d_L\end{pmatrix}\right]$	down, strange, bottom mass terms
$-\frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T\begin{pmatrix}-d_L \\ u_L\end{pmatrix}\right]$	up, charmed, top mass terms
$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2$	Higgs dynamical and mass terms

Major achievement of mankind. From *An Introduction to the Standard Model of Particle Physics, 2nd Ed.* W.N. Cottingham and D.A. Greenwood, Cambridge University Press, Cambridge, 2007, Extracted by J.A. Shifflett, updated from PDG tables at pdg.lbl.gov, 2 Feb 2015. H.C.= Hermitian conjugate of prior terms

Standard Model of Particle Physics

Derivative Operations

$$D_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = \left[\partial_\mu - \frac{ig_1}{2} B_\mu + \frac{ig_2}{2} \mathbf{W}_\mu\right] \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

$$D_\mu \nu_R = \partial_\mu \nu_R, \quad D_\mu e_R = [\partial_\mu - ig_1 B_\mu]\, e_R$$

$$D_\mu \phi = \left[\partial_\mu + \frac{ig_1}{2} B_\mu + \frac{ig_2}{2} \mathbf{W}_\mu\right] \phi$$

$$D_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} = \left[\partial_\mu + \frac{ig_1}{6} B_\mu + \frac{ig_2}{2} \mathbf{W}_\mu + ig\mathbf{G}_\mu\right] \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

$$D_\mu u_R = \left[\partial_\mu + \frac{i2g_1}{3} B_\mu + ig\mathbf{G}_\mu\right] u_R$$

$$D_\mu d_R = \left[\partial_\mu - \frac{ig_1}{3} B_\mu + ig\mathbf{G}_\mu\right] d_R$$

Action Principle Example – Classical EM Field

Lagrangian density → Maxwell Equations

Action Principle Example – Classical EM Field

Lagrangian density

$$\mathscr{L} = -\frac{1}{4\mu_0} F_{\mu\nu} F^{\mu\nu} + A_\nu J^\nu$$

where $F_{\mu\nu} = \nabla_\mu A_\nu - \nabla_\nu A_\mu = \partial_\mu A_\nu - \partial_\nu A_\mu =$ EM field 4-tensor, $A_\nu =$ EM field 4-vector and $J^\nu =$ 4-current density

Action

$$S\left[A_\mu\right] = \int \mathscr{L} \sqrt{-g}\, d^4x$$

Variation of action

$$\delta S = \int \left[\frac{\partial\left(\sqrt{-g}\,\mathscr{L}\right)}{\partial A_\beta} \delta A_\beta + \frac{\partial\left(\sqrt{-g}\,\mathscr{L}\right)}{\partial\left(\partial_\alpha A_\beta\right)} \delta\left(\partial_\alpha A_\beta\right) \right] d^4x$$

Stationary action

$\delta S = 0$ which can be shown to be satisfied by

Heterogeneous Maxwell equations

$$-\nabla_\alpha F^{\alpha\beta} = \mu_0 J^\beta$$

Homogeneous Maxwell equations

$\nabla_\alpha F^{*\alpha\beta} = 0$ (follows from antisymmetry of $F^{\alpha\beta}$)

where $F^{*\alpha\beta} =$ dual of $F^{\alpha\beta}$

Maxwell Equations

Heterogeneous

$$-\nabla_\alpha F^{\alpha\beta} = \mu_0 J^\beta \quad \begin{cases} \boldsymbol{\nabla}\cdot\mathbf{E} = \rho_C/\varepsilon_0 \\ \boldsymbol{\nabla}\times\mathbf{B} - \partial_t\mathbf{E}/c^2 = \mu_0\mathbf{J}_C \end{cases}$$

Gauss Law

Extended Ampere law

Homogeneous

$$\nabla_\alpha F^{*\alpha\beta} = 0 \quad \begin{cases} \boldsymbol{\nabla}\cdot\mathbf{B} = 0 \\ \boldsymbol{\nabla}\times\mathbf{E} + \partial_t\mathbf{B} = \mathbf{0} \end{cases}$$

Gauss Law of Magnetism

Faraday Law

In each pair of blue 3-vector equations the top one is the time component ($\beta = 0$) and the bottom one is the space component

Symmetry and Conservation

- Much of quantum field theory has to do with symmetries that exist in nature
- First examples deduced by Emmy Noether in 1915
- A number of others discovered since then
- Concept heavily exploited in standard model

Symmetry and Conservation

Lorentz Symmetry

Invariance	Conserved Quantity
Translation in time	Electric charge
Translation in space	Lepton generation number
Rotation in space	Hypercharge

Discrete Symmetry

Invariance	Conserved Quantity
Coordinate inversion (P)	Spatial parity
Charge conjugation (C)	Charge parity
Time reversal (T)	Time parity
CPT	Product of parities

From Wikipedia "Symmetry (physics)" article

Symmetry and Conservation

Internal Symmetry

Invariance	Conserved Quantity
U(1) gauge transformation	Electric charge
U(1) gauge transformation	Lepton generation number
U(1) gauge transformation	Hypercharge
$U(1)_Y$ gauge transformation	Weak hypercharge
U(2) [U(1) x SU(2)]	Electroweak force
SU(2) gauge transformation	Isospin
$SU(2)_L$ gauge transformation	Weak isospin
P x SU(2)	G-parity
SU(3) "winding number"	Baryon number
SU(3) gauge transformation	Quark color
SU(3) (approximate)	Quark flavor
S(U(2) x U(3)) [U(1) x SU(2) x SU(3)]	Standard Model

From Wikipedia "Symmetry (physics)" article. An internal symmetry acts on the space of fields (i.e. space-time functions) and not on the space-time manifold

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Special Relativity

- Based in part on empirical observation that speed of light c is the same in all inertial frames
- More generally, takes the 4D spacetime interval as the fundamental kinematic invariant, whereby time, distance and simultaneity become relative
- Relativistic dynamics includes the famous $E = mc^2$
- Spacetime foundation of quantum field theory and thereby of the standard model of particle physics

Key Kinematic Phenomena of Special Relativity

Twins Tale

- Nonaccelerated twin A observes, with instrumentation, his identical twin B moving at constant speed V relative to himself. A finds that B's clocks tick slower than his own by the factor $1/\gamma$ and that B (and everything at rest around B) is foreshortened in the direction of motion by that same factor. B, with his instrumentation, draws the same conclusions about A and A's surroundings
- A's instrumentation, stationary in his rest frame, includes an array of synchronized clocks. B has similar equipment in his rest frame. A finds that B's clocks are out of synchronization in the direction of relative motion. B draws the same conclusion about A's clocks
- As A approaches B at speed V he fires a projectile at B (never really liked him anyway). The projectile travels at speed v relative to A's rest frame. No matter how close V and v are to c, the speed at which B perceives the projectile approaching is always less than c
- B dodges the projectile, and avoids further assault by traveling to a distant star and back at a significant fraction of c. Still young upon his return, he is pleased to find that A has died of old age

$$1/\gamma = \sqrt{1-(V/c)^2} \qquad c = \text{speed of light}$$

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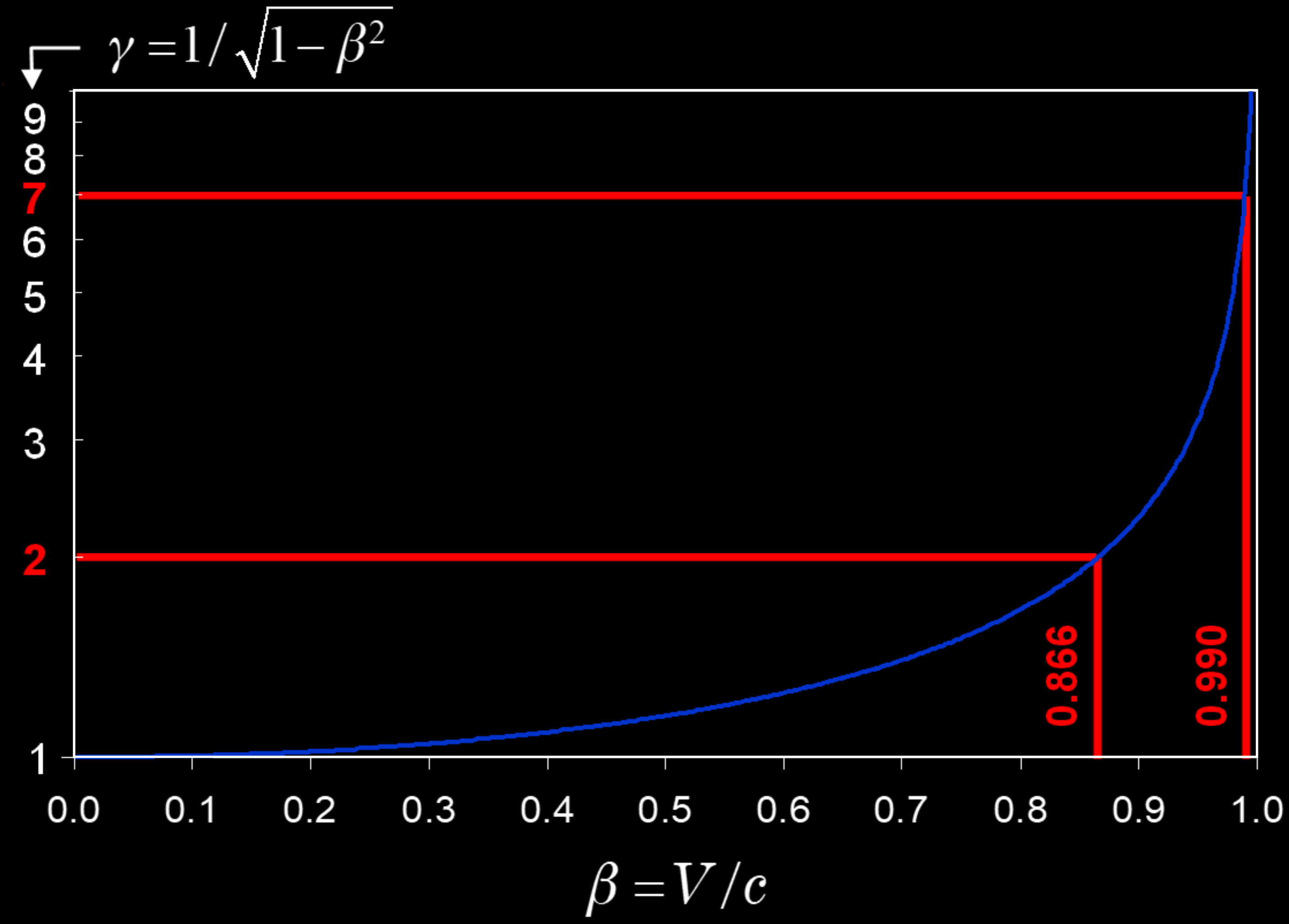
Stretch Factor



Relativistic Kinematics in Direction of Motion

Based on Invariance of $\Delta\mathbf{x} \cdot \Delta\mathbf{x}$

$$\bar{t}_2 - \bar{t}_1 = (t_2 - t_1)/\gamma$$

Relativity of time interval

$$\bar{L} = L/\gamma$$

Relativity of length

$$\bar{v} = \frac{V + v}{1 + Vv/c^2}$$

Non-linear speed addition

$$\bar{t}_2 - \bar{t}_1 = -\gamma V (x_2 - x_1)/c^2$$

Relativity of simultaneity*

$\Delta\mathbf{x}$ = 4D displacement vector. c = light speed (invariant among inertial frames). V= relative speed of frames.

*Assumes events of interest are simultaneous in unbarred frame (last equation only)

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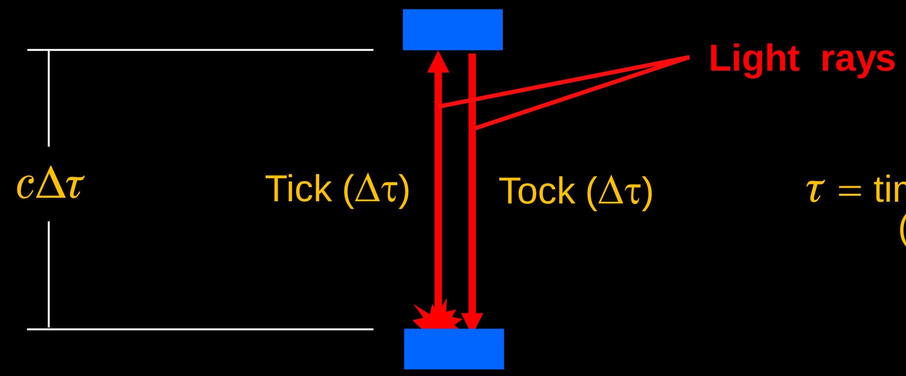
Relativity of Time Interval – Derivation

Based on invariance of light speed across inertial frames

Two ticks of light clock in clock rest frame

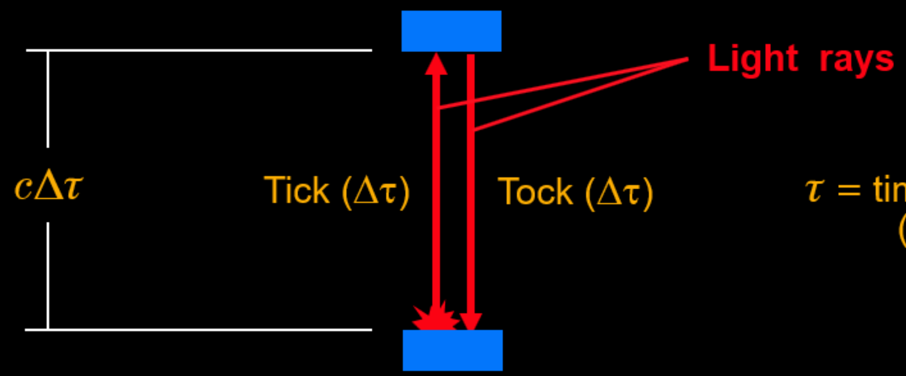


τ = time in clock rest frame (proper clock time)

Relativity of Time Interval – Derivation

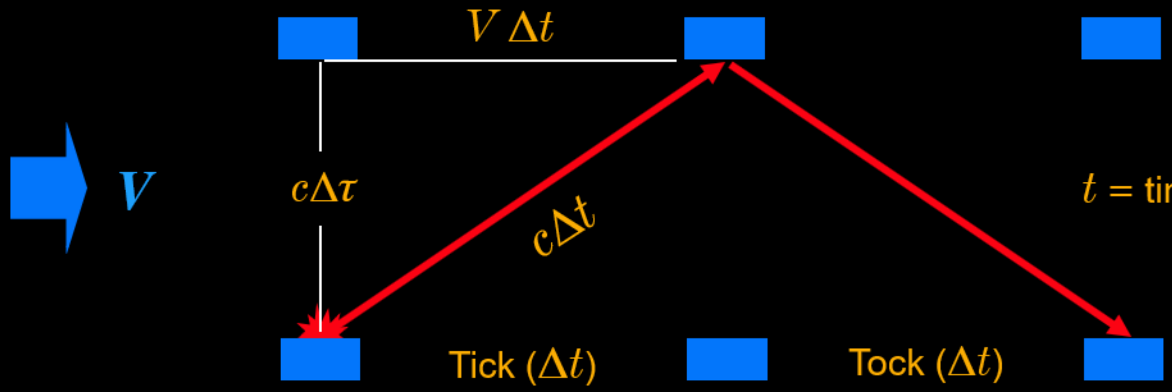
Based on invariance of light speed across inertial frames

Two ticks of light clock in clock rest frame



τ = time in clock rest frame (proper clock time)

Two ticks of light clock moving rightward at speed V in slide rest frame



t = time in page rest frame

Also, blue blocks foreshortened in direction of motion

Pythagorean theorem $(c\Delta t)^2 = (c\Delta\tau)^2 + (V\Delta t)^2 \Rightarrow \Delta\tau = \Delta t/\gamma$

Situations Where Relativity of Time of Practical Importance

- The slowing of time at high speeds is significant in each particle collision in the Large Hadron Collider. Particles are brought together at near-light speeds. Highly unstable particles created in collisions also travel at high speeds – high enough to survive long enough to be detected in frame of experiment
- The GPS system provides another example. Speeds of the GPS satellites are not particularly high, but the time-keeping precision needed for accurate results requires that both special and general relativistic effects be accounted for

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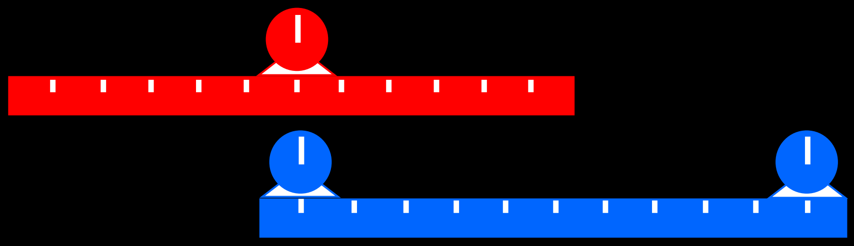
Relativity of Length (and Time Interval)

Size Foreshortened (and Time Slowed) in Direction of Motion

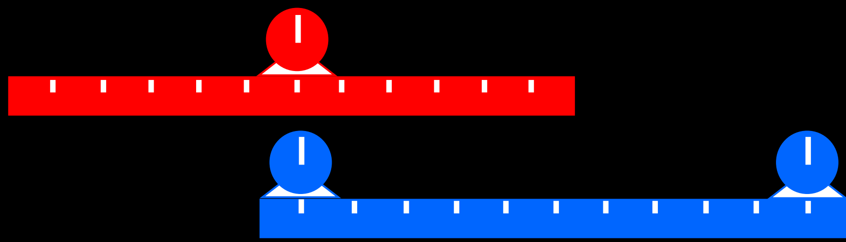
Synchronized clocks and ruled platforms in shared inertial rest frame



Relativity of Length (and Time Interval)

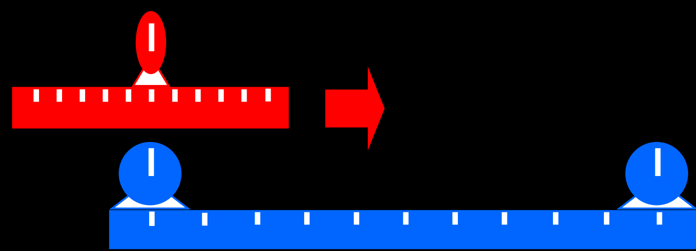
Size Foreshortened (and Time Slowed) in Direction of Motion

Synchronized clocks and ruled platforms in shared inertial rest frame



Red system moves rightward at high speed (0.866c ⇒ γ = 2)

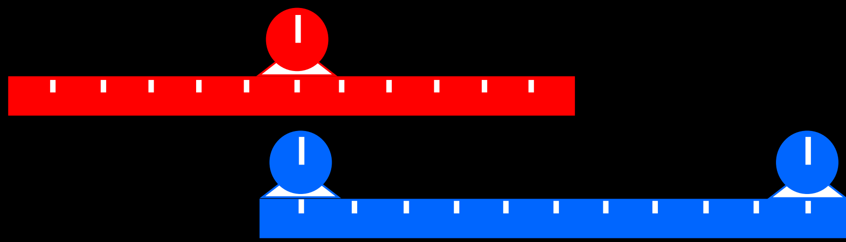
Shorter length
(1/2 blue value)



Relativity of Length (and Time Interval)

Size Foreshortened (and Time Slowed) in Direction of Motion

Synchronized clocks and ruled platforms in shared inertial rest frame



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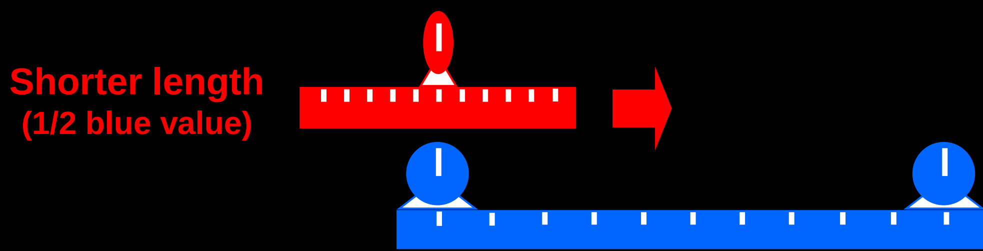
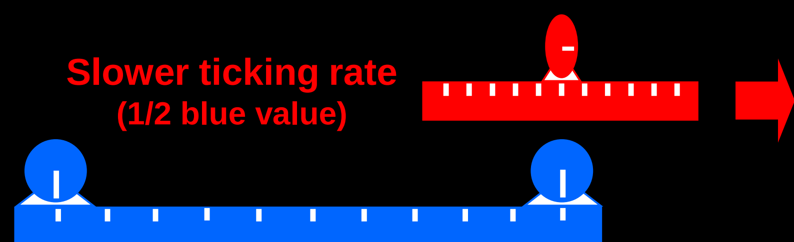


One-half revolution of blue clock hands later



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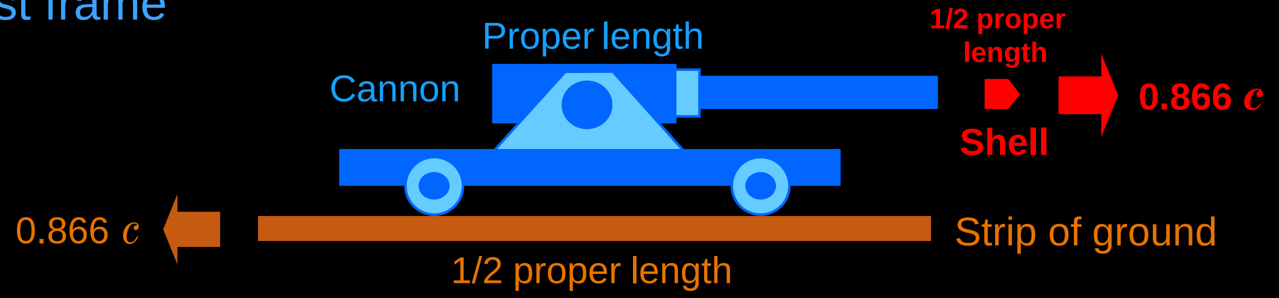
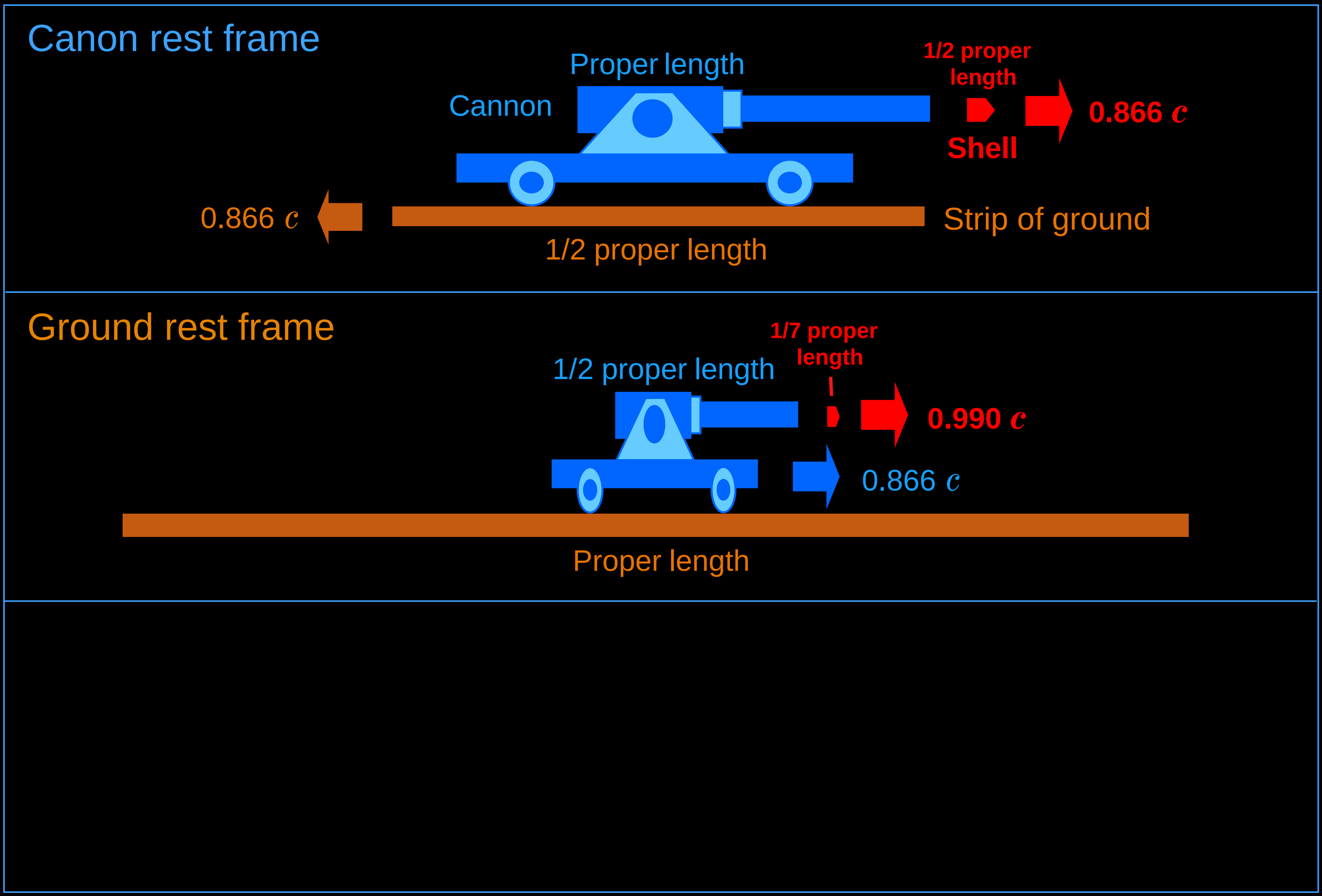
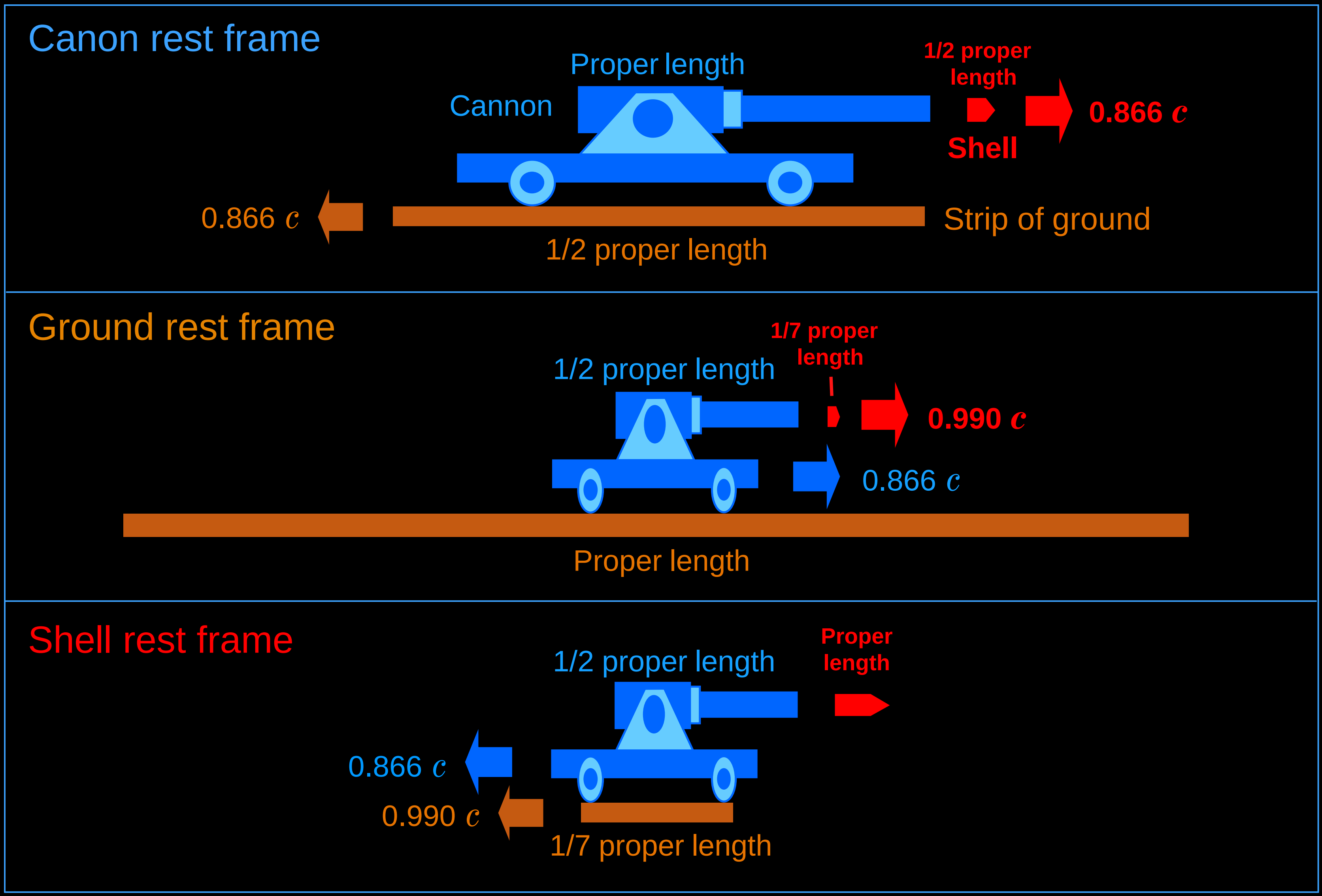
Canon rest frame



Non-Linear Speed Addition



Non-Linear Speed Addition



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Different Event Orderings for Different Observers

- Recall from above that spatially separated events which occur simultaneously in one frame cannot occur simultaneously in a second frame moving parallel to the direction of separation
- As a consequence, multiple events can occur in different sequences in different frames

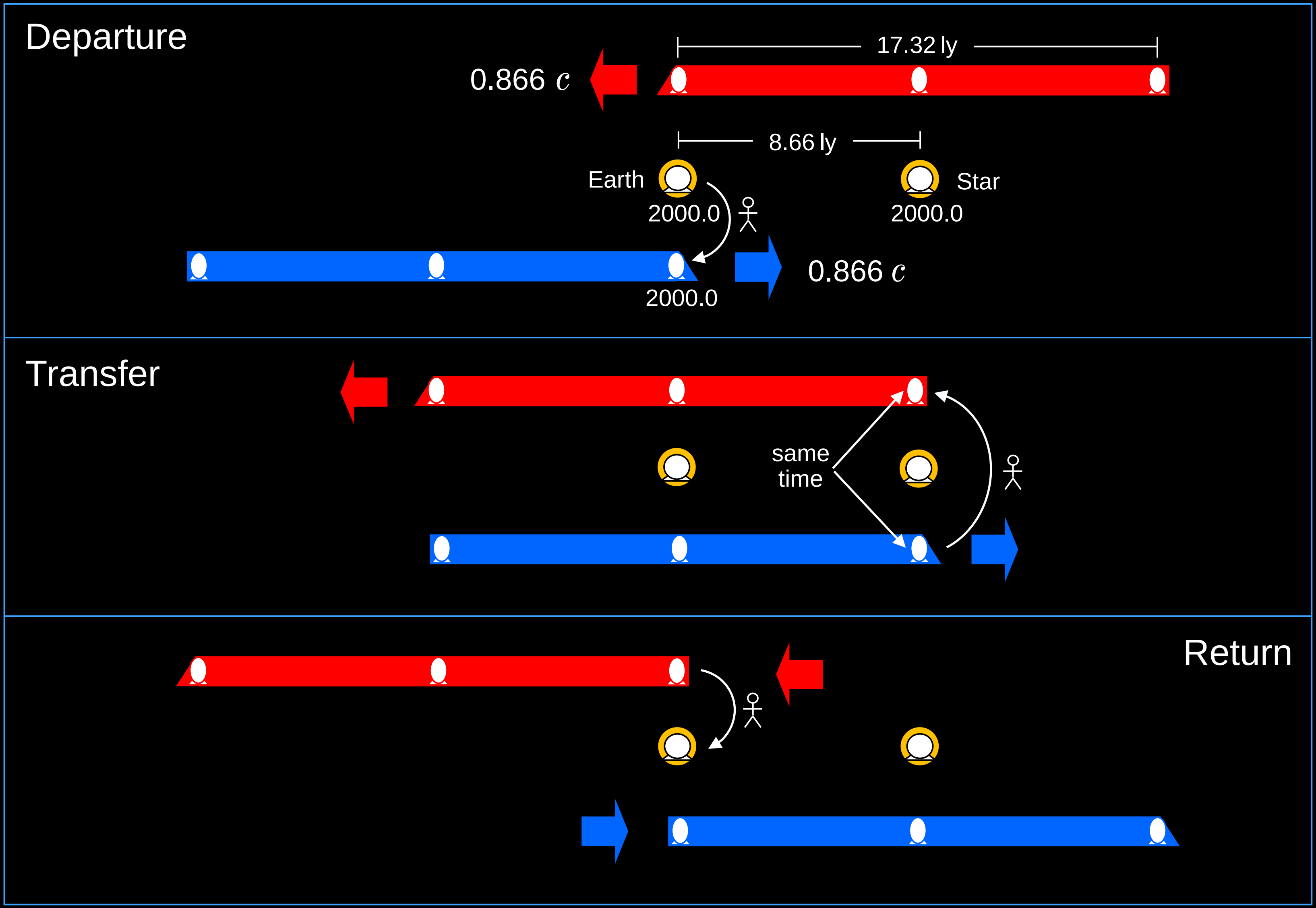
Different Event Orderings in Twin Paradox Problem

- The twin paradox problem can provide examples of event orderings that differ from one frame to another
- One of two Earth-born twins travels to a distant star and back by hitching rides on outbound and inbound astrotrains*
- Consider the trip in each of three reference frames: (1) Earth-star (2) outbound train (3) inbound train

*Such fanciful trains also can be found in *Spacetime Physics* (1992) by Taylor and Wheeler

Twin Paradox

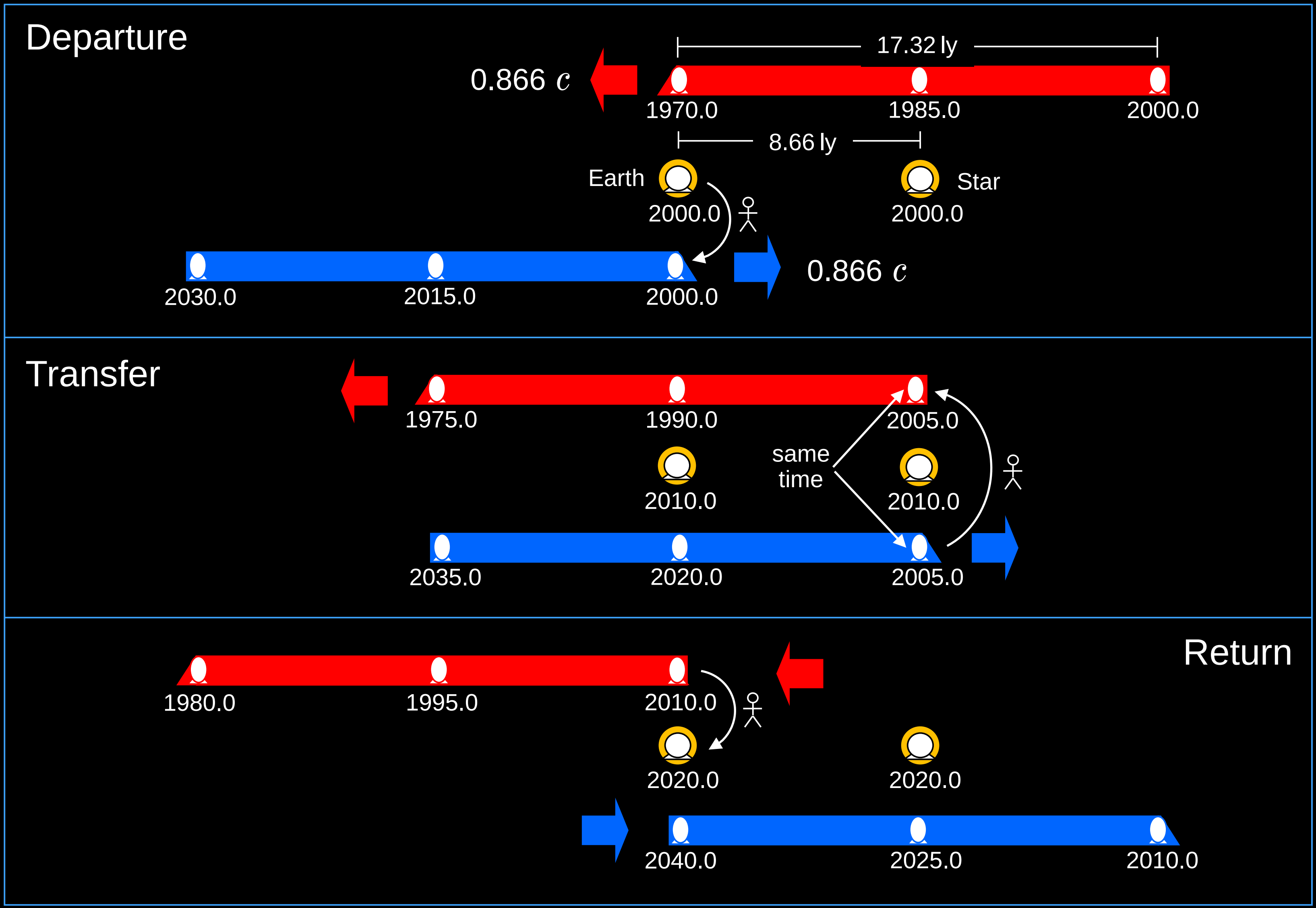
Trip in Earth-Star Rest Frame: Givens



Note that Earth and star clock faces are circular but train clock faces are foreshortened in direction of motion

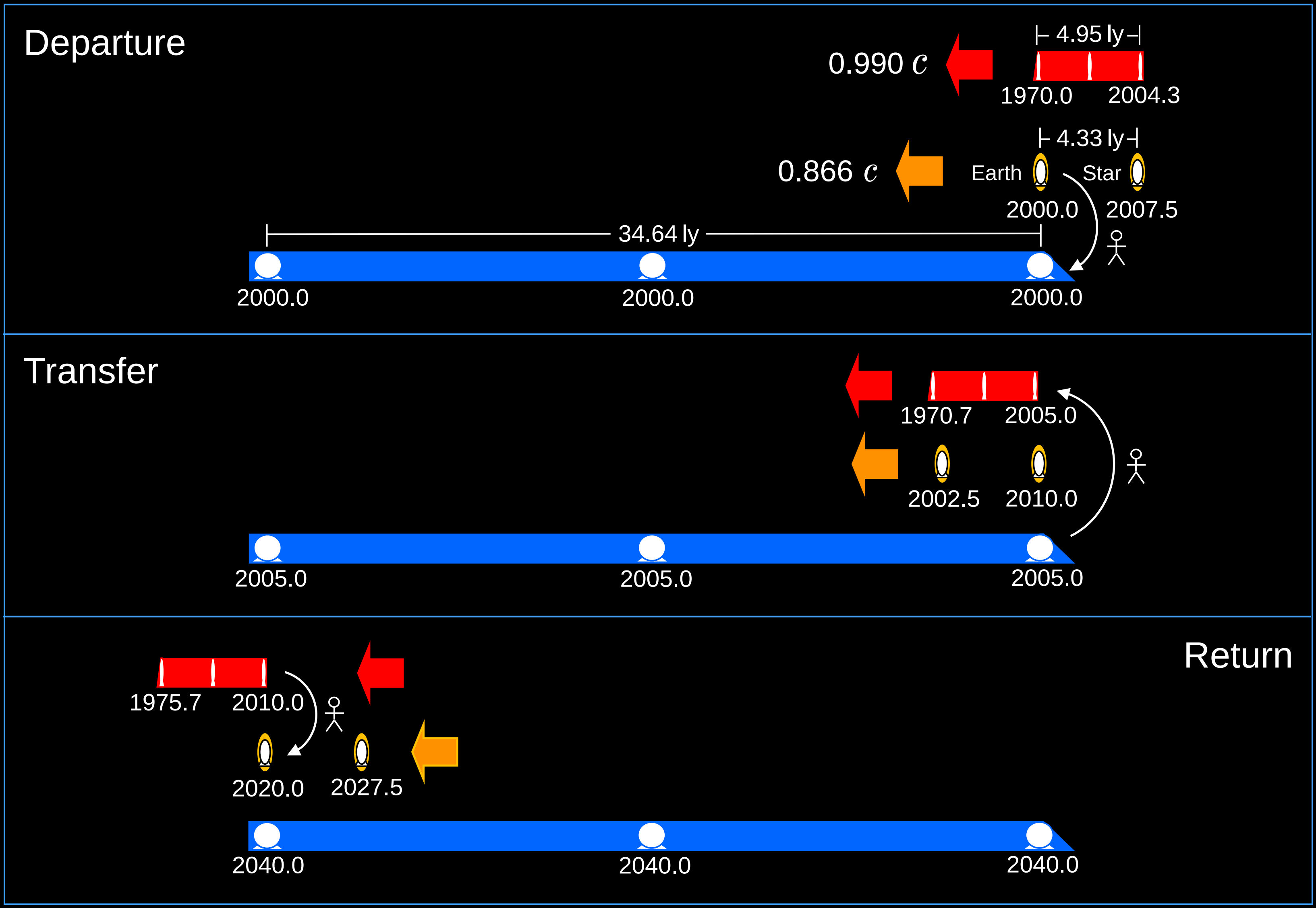
Twin Paradox

Trip in Earth-Star Rest Frame: All Clock Times



Twin Paradox

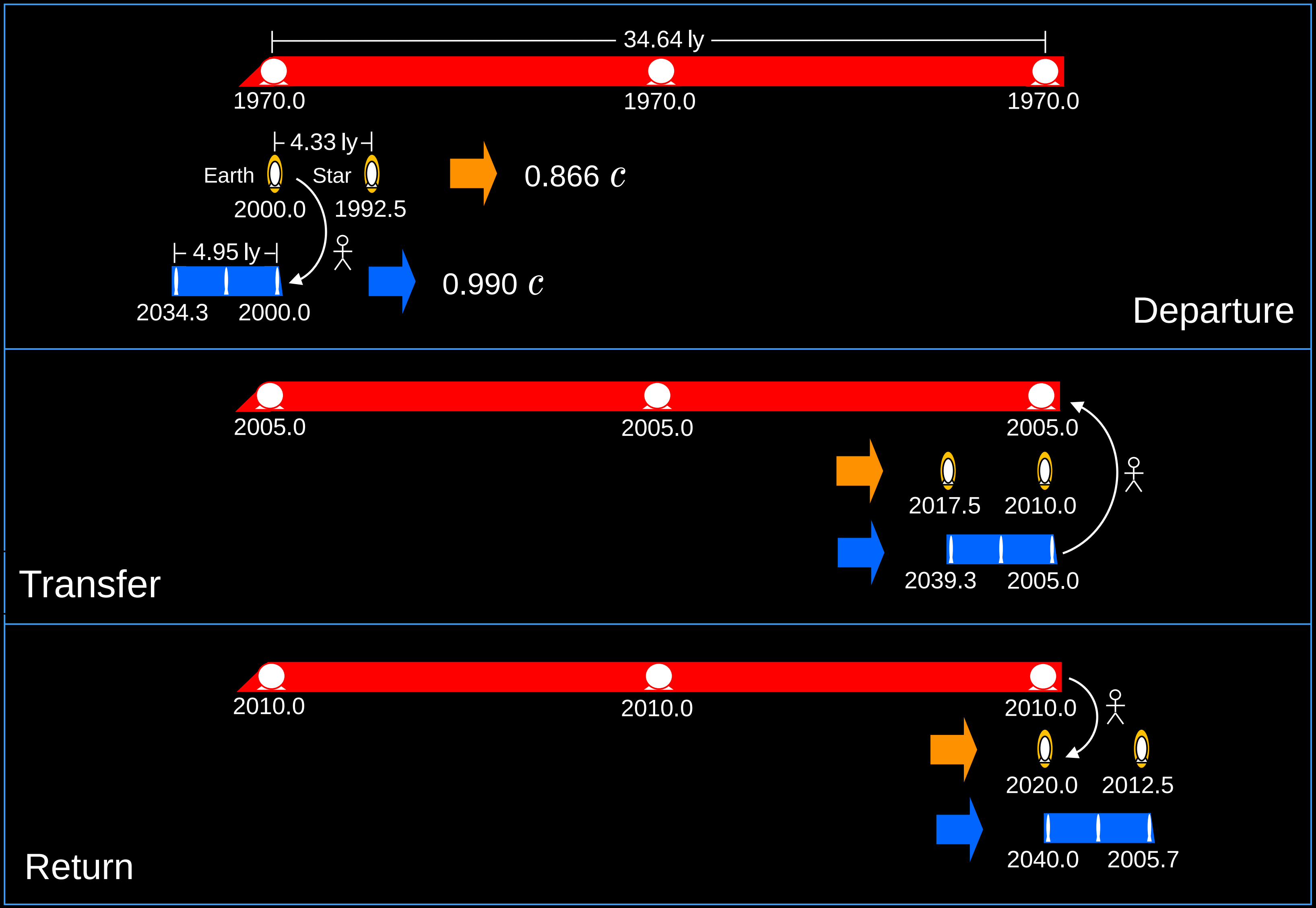
Trip in Outbound Train Rest Frame



Outbound train at true length. Severe foreshortening of inbound train (including clock faces)

Twin Paradox

Trip in Inbound Train Rest Frame



Inbound train at true length. Severe foreshortening of outbound train (including clock faces)

Twin Paradox

Frame-Dependent Ordering of Train Clock Passings

Earth-star rest frame

Front OB – Front IB

→ (Front OB – Middle IB; Middle OB – Front IB)

→ (Front OB – Rear IB; Middle OB – Middle IB; Rear OB – Front IB)

→ (Middle OB – Rear IB; Rear OB – Middle IB)

→ Rear OB – Rear IB

Outbound train rest frame

Front OB – Front IB

→ Front OB – Middle IB

→ Front OB – Rear IB

→ Middle OB – Front IB

→ Middle OB – Middle IB

→ Middle OB – Rear IB

→ Rear OB – Front IB

→ Rear OB – Middle IB

→ Rear OB – Rear IB

Inbound train rest frame

Front OB – Front IB

→ Middle OB – Front IB

→ Rear OB – Front IB

→ Front OB – Middle IB

→ Middle OB – Middle IB

→ Rear OB – Middle IB

→ Front OB – Rear IB

→ Middle OB – Rear IB

→ Rear OB – Rear IB

Bracketed events are simultaneous. No passings are simultaneous in either train rest frame

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Special Relativistic Dynamics

4-Momentum & Components, Including Mass-Equivalent Energy

$$\mathbf{p} = m\mathbf{u}$$

$$\mathbf{u} = \mathrm{d}\mathbf{x}/\mathrm{d}\tau \qquad \mathrm{d}\mathbf{x} = \boldsymbol{\eta}_0 c\mathrm{d}t + \mathrm{d}\mathbf{x} \qquad \mathrm{d}t = \gamma\mathrm{d}\tau \qquad \mathrm{d}\mathbf{x} = \mathbf{v}\mathrm{d}t$$

$$\mathbf{p} = \boldsymbol{\eta}_0 \gamma m c + \gamma m \mathbf{v} = \boldsymbol{\eta}_0 p^0 + \mathbf{p}$$

$$p^\mu = (p^0, \mathbf{p}) = (E/c, \mathbf{p})$$

$$E = p^0 c = \gamma m c^2 = E' + K$$

$$E' = mc^2 \qquad K = (\gamma - 1) mc^2 = \tfrac{1}{2} m v^2 \left(1 + \tfrac{3}{4}\beta^2 + \tfrac{5}{8}\beta^4 + \ldots\right)$$

$\mathbf{p}$ = 4-momentum, m = mass, $\mathbf{u}$ = 4-velocity, d$\mathbf{x}$ = 4-displacement, dτ = proper time interval, $\boldsymbol{\eta}_0$ = temporal base vector, c = speed of light, dt = inertial time interval, d$\mathbf{x}$ = displacement (orthogonal to $\boldsymbol{\eta}_0$), γ = stretch factor, $\mathbf{v}$ = velocity, $\mathbf{p}$ = momentum, p^0 = 4–momentum time component, p^μ = 4–momentum components, E = energy, E' = rest (mass-equivalent) energy, K = relativistic kinetic energy, $\beta = v/c$

Special Relativistic Dynamics

Single Particle Equation of Motion & Components

4-vector (invariant) equation of motion

$$\mathsf{a} = \hat{\mathsf{K}}$$

$v << c$ | $v < c$

3-vector low-speed equations

$$\mathbf{a} = \hat{\mathbf{F}}$$

$$\mathrm{d}\tfrac{1}{2}v^2 = \hat{\mathbf{F}} \cdot \mathrm{d}\mathbf{x}$$

space component

time component

3-vector high-speed equations

$$\mathbf{a} = (\mathbf{1} - \boldsymbol{\beta}\boldsymbol{\beta}) \cdot \hat{\mathbf{F}} / \gamma$$

$$\mathrm{d}\hat{K} = \hat{\mathbf{F}} \cdot \mathrm{d}\mathbf{x}$$

a = 4-acceleration, $\hat{\mathsf{K}}$ = 4-force per unit mass, v = speed, c = light speed, $\mathbf{a}$ = acceleration, $\hat{\mathbf{F}}$ = force per unit mass, $\mathrm{d}\mathbf{x}$ = displacement, $\mathbf{1}$ = identity tensor, $\boldsymbol{\beta} = \mathbf{v}/c$, $\gamma = 1/\sqrt{1-\beta^2}$, $\beta = v/c$, $\hat{K} = (\gamma - 1)c^2 = \frac{1}{2}v^2\left(1 + \frac{3}{4}\beta^2 + \frac{5}{8}\beta^4 + \ldots\right)$ = relativistic KE per unit mass

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*Cosmological applications covered in Big Picture Science presentation on Observable Universe

General Relativity

- Treats gravity as local curvature of spacetime, said curvature caused by presence of energy and/or momentum
- Successful predictions include slower clock rates in stronger gravitational fields, black holes, gravito-electromagnetism and gravity waves, among others
- Underlying theory of Big Bang Cosmology in form of ΛCDM model*

*Λ = Einstein cosmological constant. CDM = Cold Dark Matter

General Relativity

Spacetime tells matter how to move; matter tells spacetime how to curve

– John Archibald Wheeler

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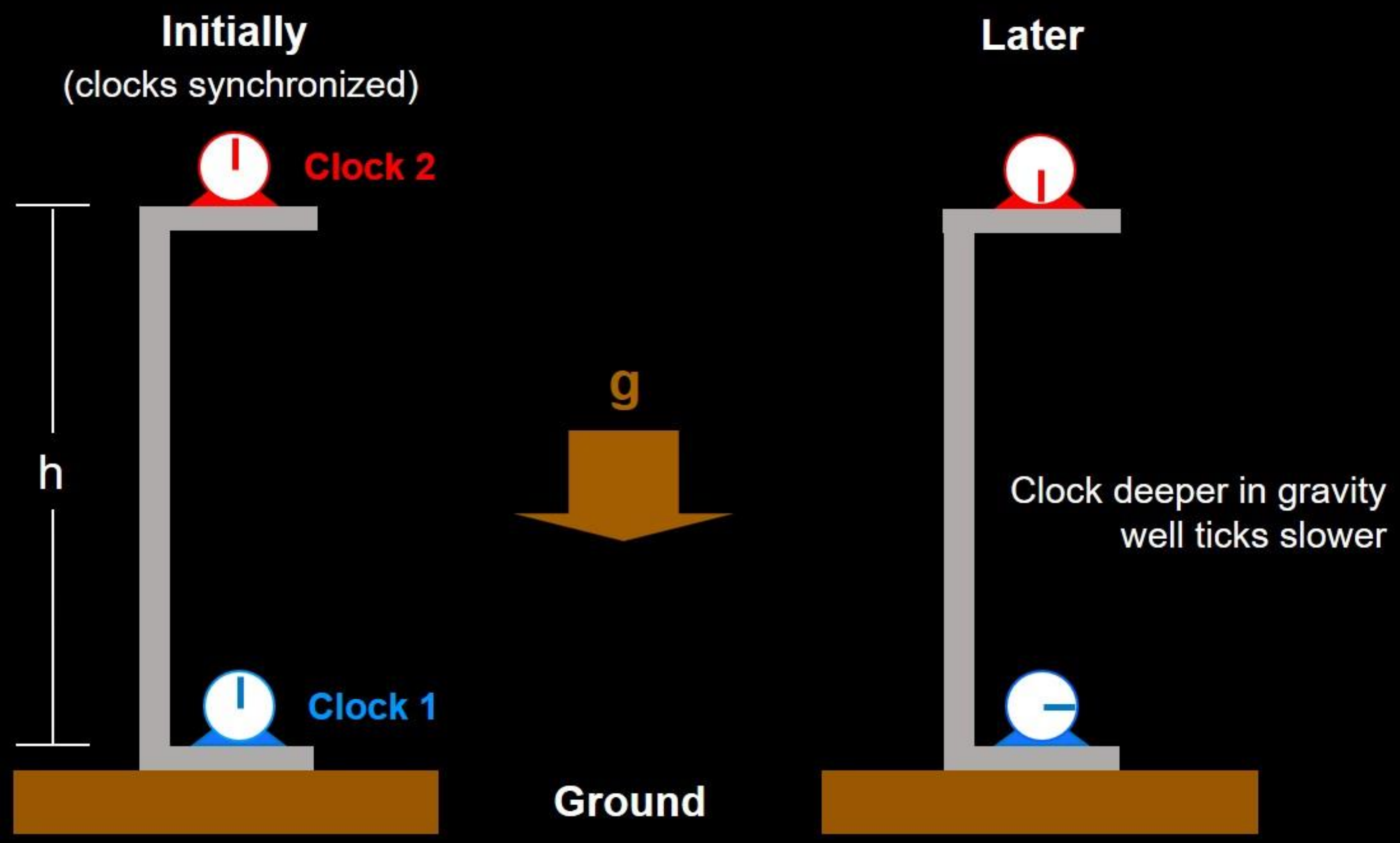
Slowing of Time by Gravity

Weak Gravitational Field (e.g., that of Earth)



$$\frac{\Delta\tau_2}{\Delta\tau_1} = 1 + \frac{gh}{c^2}$$

First experimental confirmation of effect: Pound, R. V.; Rebka Jr. G. A. (November 1, 1959). "Gravitational Red-Shift in Nuclear Resonance". *Physical Review Letters*. 3 (9): 439–441

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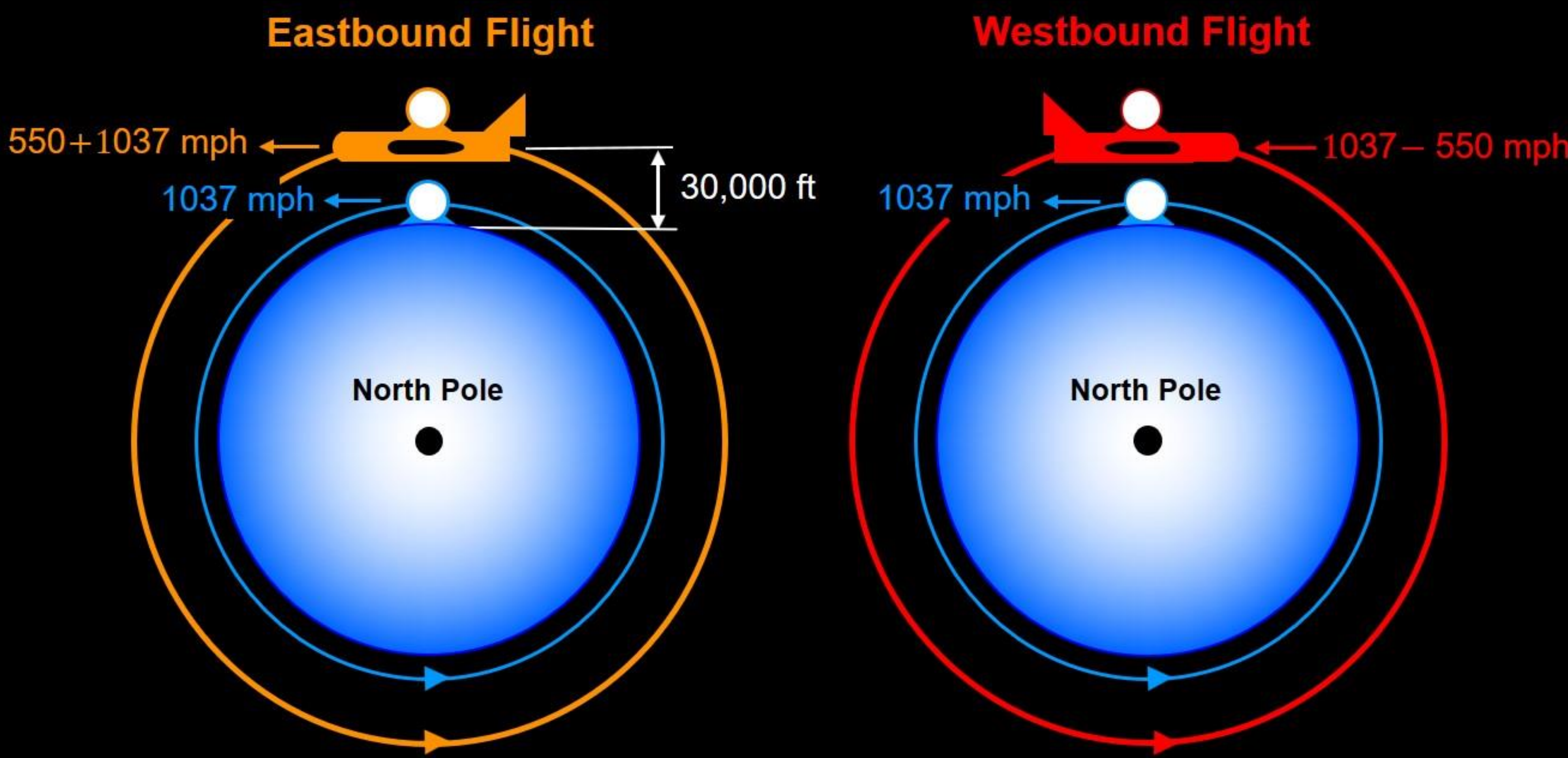
Hafele-Keating Experiment

- Demonstrates impact of special and general relativistic effects on ticking rates of clocks flown around the world in east-bound and west-bound directions
- First version carried out in 1971 by Hafele and Keating.* Repeated multiple times with increasing precision
- Effects involved have implications for the GPS system
- Only idealized version of the experiment considered here

*Hafele, J. C.; Keating, R. E. (July 14, 1972). "Around-the-World Atomic Clocks: Predicted Relativistic Time Gains". *Science*. 177 (4044): 166–168

Idealized Hafele-Keating Experiment



Two clocks are flown around the equator – one eastward, one westward. A third clock sits on the equator. Which of the three clocks ticks fastest and which ticks slowest? Evaluate in a nonrotating reference frame with origin at the center of the Earth

Idealized Hafele-Keating Experiment

Qualitative Analysis

- **General relativistic effect** Gravity slows time. Both flying clocks therefore gain time on the ground clock (GC), which, at a lower elevation, experiences a stronger gravitational field
- **Special relativistic effect** Motion slows time. The slowest moving, west-bound flying clock (WBFC) therefore gains time on both the GC and the eastbound flying clock (EBFC)
- **Net effect** The WBFC clearly ticks fastest, as it gains time on both of the other clocks. Which clock ticks slowest cannot be determined from qualitative analysis

Quantitative Analysis

- Quantitative analysis (or an actual experiment) will reveal that the EBFC loses more time to the GC from its higher speed than it gains from its higher elevation. The EBFC therefore ticks the slowest of the three clocks, with the parameter values of this particular problem

The net times gained and lost here involve tens of nanoseconds. Such relativistic effects must be accounted for in the GPS system, otherwise the system would quickly become useless as a navigational aid

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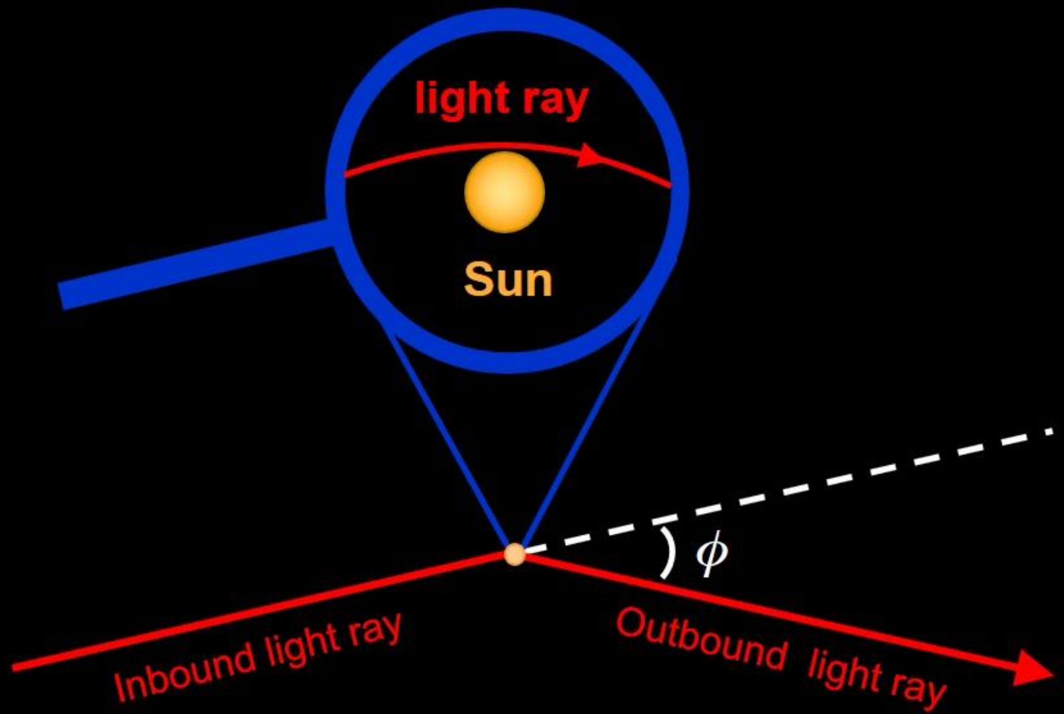
Bending of Light by Gravity



$$\phi = \frac{4GM_\odot}{r_\odot c^2} = 1.75 \text{ arcsec}$$

Bending exaggerated in image. Confirmation of above phenomena during a solar eclipse [Eddington et al (1919)] brought Einstein's general theory to attention of general public

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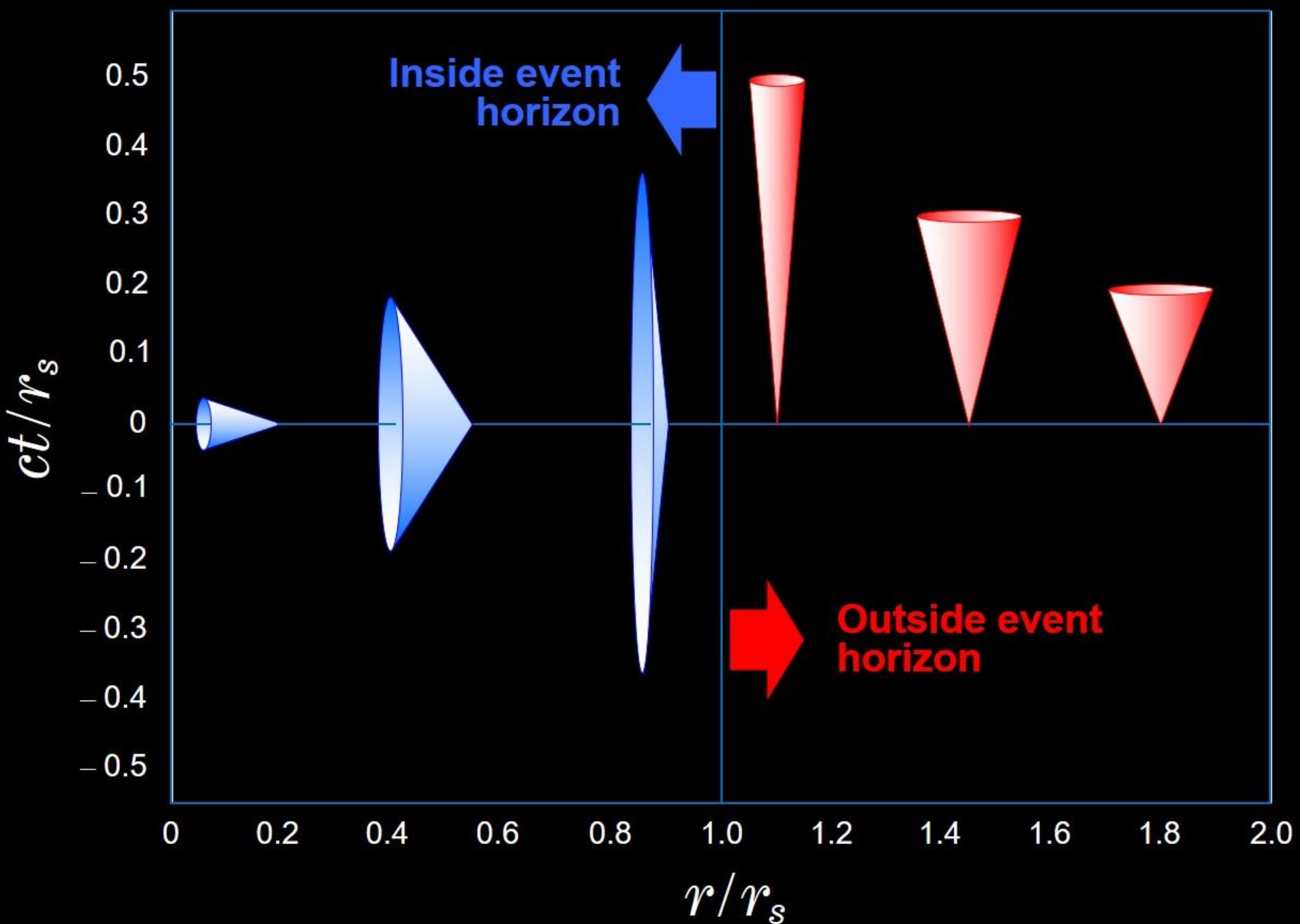
Black Holes

- Remnants of supermassive stars, so dense and massive that even light cannot escape once inside the bounding event horizon
- Once formed, black holes can continue to grow by absorbing more nearby matter
- Such absorption has led to the presence of supermassive black holes at the centers of most galaxies, where matter is concentrated

Trapping of Light in Black Hole



$r_S = 2MG/c^2$ is the Schwarzschild radius (also event horizon for a black hole). Coordinates r and t swap signs inside event horizon. Once inside the event horizon light cannot escape

Black Holes

- Remnants of supermassive stars, so dense and massive that even light cannot escape once inside the bounding event horizon
- Once formed, black holes can continue to grow by absorbing more nearby matter
- Such absorption has led to the presence of supermassive black holes at the centers of most galaxies, where matter is concentrated

Black Holes

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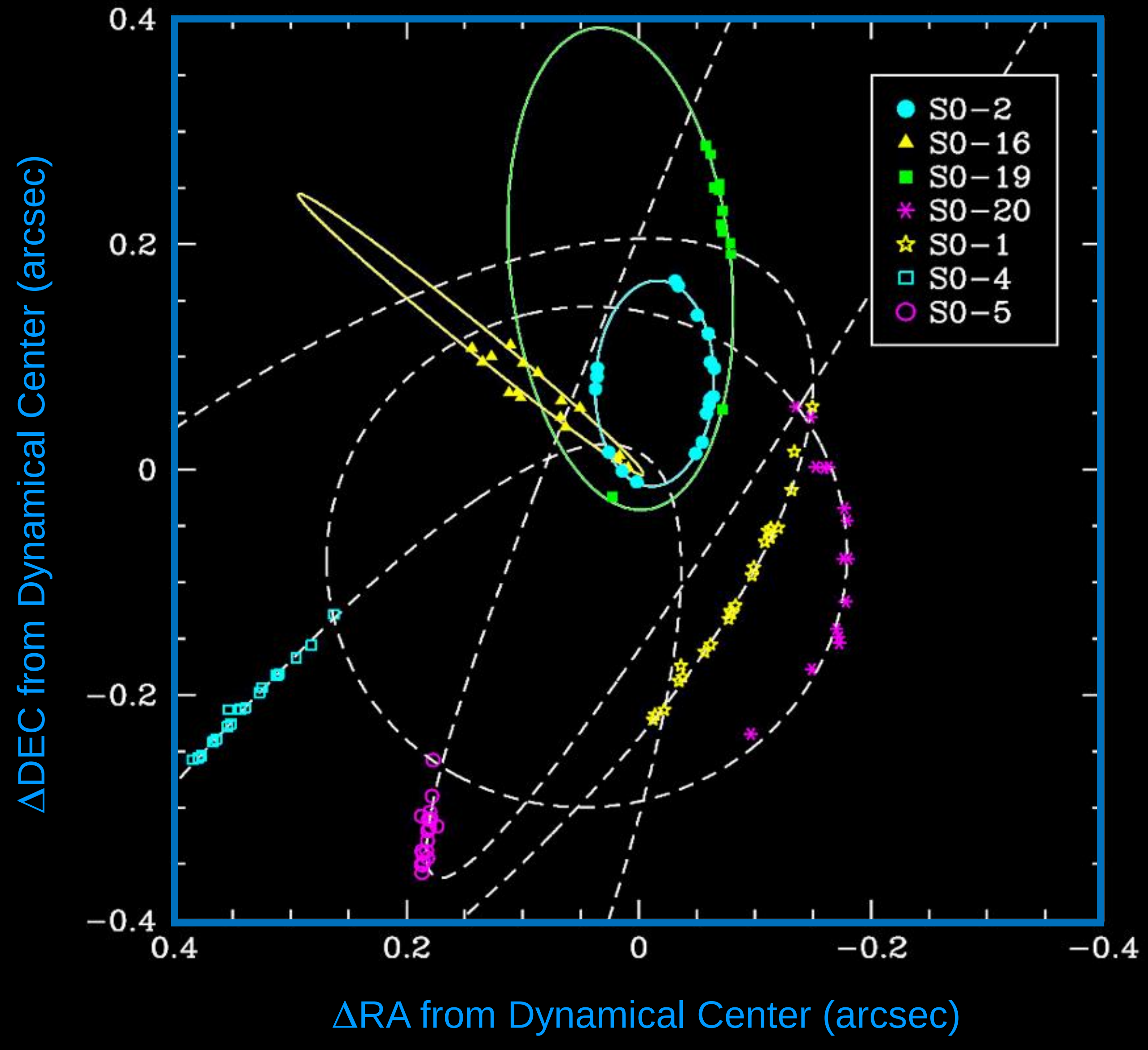
Sagittarius A*

Supermassive Black Hole at Milky Way Center



Stars orbiting unseen Sagittarius A*. Mass roughly 4 million times that of Sun. Ghez et al (2004)], "Stellar Orbits Around the Galactic Center Black Hole", 620:744–757, 2005 February 20, *Astrophysical Journal*

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Entropy generation

Gravitoelectromagnetism

- Under weak-field, slow-motion conditions, the central equation of general relativity, the Einstein field equation, yields four partial differential equations mathematically equivalent to the Maxwell equations of electromagnetism
- Predictions extracted from these gravitoelectromagnetic equations are claimed to agree with data collected by an orbiting satellite

Electromagnetism and Gravitoelectromagnetism

Analogous Field Equations

4D EM Field Equation	**4D Gravitational Field Eqn**
$-\nabla\cdot\mathbf{F} = \mu_0 \mathbf{J}_\mathrm{C}$	$\mathbf{G} = \kappa\mathbf{T}$

Maxwell Equations	**GEM Equations**
$\nabla\cdot\mathbf{E} = \rho_\mathrm{C}/\varepsilon_0$	$\nabla\cdot\mathbf{g} = \rho/\alpha$
$\nabla\times\mathbf{B} - \partial_t\mathbf{E}/c^2 = \mathbf{J}_\mathrm{C}/(\varepsilon_0 c^2)$	$\nabla\times\frac{1}{2}\mathbf{h} - \partial_t\mathbf{g}/c = \mathbf{J}_\mathrm{M}/(\alpha c)$
$\nabla\cdot\mathbf{B} = 0$	$\nabla\cdot\mathbf{h} = 0$
$\nabla\times\mathbf{E} + \partial_t\mathbf{B} = \mathbf{0}$	$\nabla\times\mathbf{g} + \partial_t\frac{1}{2}\mathbf{h}/c = \mathbf{0}$

The invariant electromagnetic and gravitational field equations are written in 4-vectors and 4-tensors. The Maxwell (electromagnetic) and GEM (gravitoelectromagnetic) equations are written in 3-vectors. The GEM equations come from the linearized (weak-field) form of the Einstein field equation $\mathbf{G} = \kappa\mathbf{T}$

Gravitoelectromagnetism

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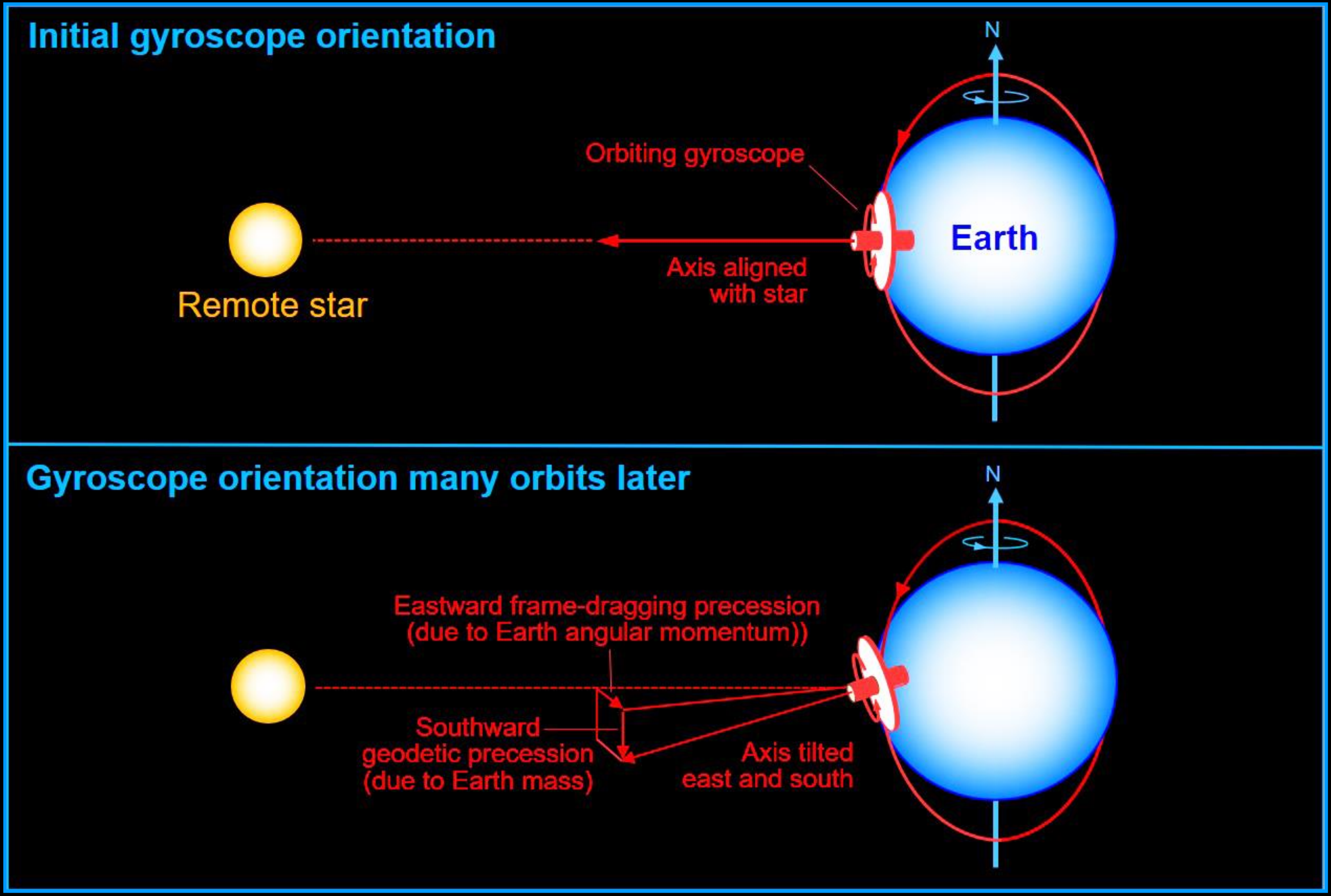
Gravitoelectromagnetism

Precession of Orbiting Gyroscope



Not to scale. Geodetic precession much greater than frame-dragging precession. Confirmation claimed by Everitt et al, PRL 106, 221101 (2011) via the Gravity Probe B experiment (longest continuously funded science project in NASA history, begun in 1963). Actual gyroscope consisted of four spinning spheres, two of which malfunctioned during experiment, which greatly complicated data analysis

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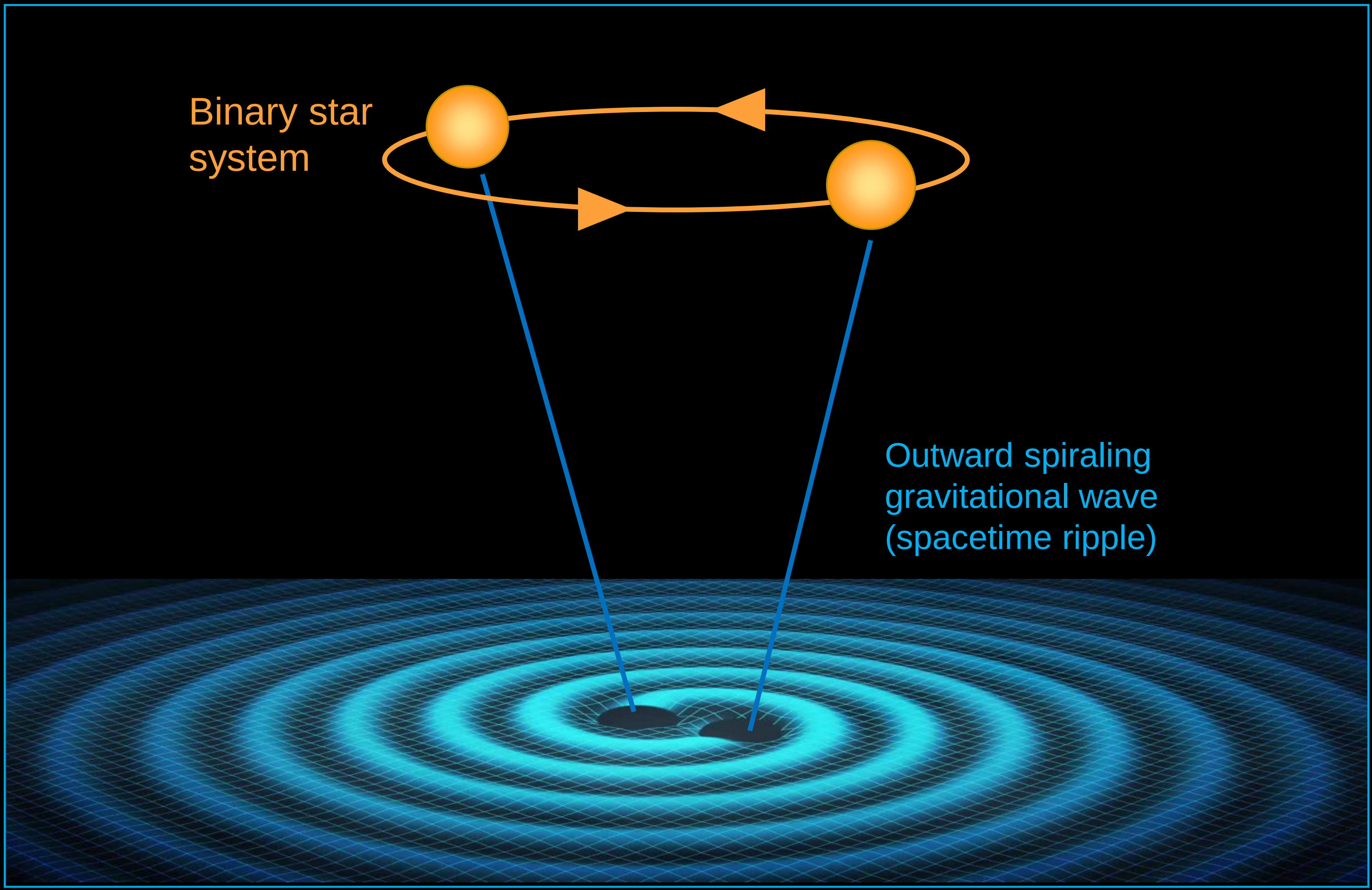
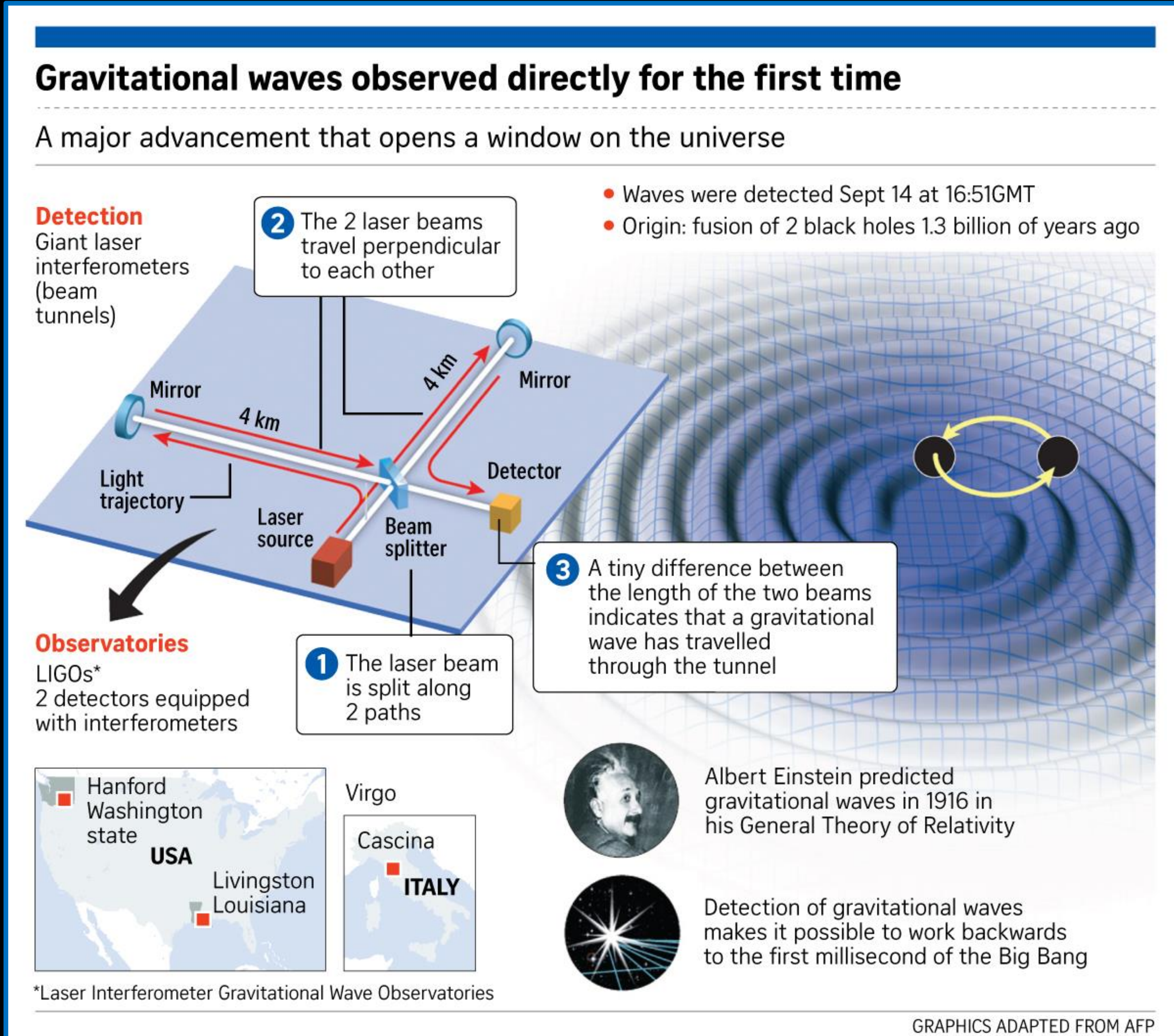
Gravitational Waves



Einstein predicted such ripples in 1916. Detection (extremely difficult) took 100 years (next two slides)


Gravitational waves observed directly for the first time
A major advancement that opens a window on the universe
Detection
Giant laser interferometers (beam tunnels)
2 The 2 laser beams travel perpendicular to each other
Waves were detected Sept 14 at 16:51GMT
Origin: fusion of 2 black holes 1.3 billion of years ago
Mirror
4 km
4 km
Mirror
Light trajectory
Laser source
Beam splitter
Detector
3 A tiny difference between the length of the two beams indicates that a gravitational wave has travelled through the tunnel
Observatories
LIGOs*
2 detectors equipped with interferometers
1 The laser beam is split along 2 paths
Hanford Washington state
USA
Livingston Louisiana
Virgo
Cascina
ITALY
Albert Einstein predicted gravitational waves in 1916 in his General Theory of Relativity
Detection of gravitational waves makes it possible to work backwards to the first millisecond of the Big Bang
*Laser Interferometer Gravitational Wave Observatories
GRAPHICS ADAPTED FROM AFP

Observation of Gravitational Waves from a Binary Black Hole Merger

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203,000 years. The source lies at a luminosity distance of 410 Mpc corresponding to a redshift $z = 0.09$. In the source frame, the initial black hole masses are 36 $M_\odot$ and 29 $M_\odot$, and the final black hole mass is 62 $M_\odot$, with 3.0 $M_\odot c^2$ radiated in gravitational waves. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger

Title and abstract verbatim from Abbott et al, *Physical Review Letters* **116**, 061102 (2016), except for omission of standard deviations to reduce clutter. $M_\odot$ = Sun mass. 2017 Nobel Prize awarded to Rainer Weiss, Kip Thorne and Barry C. Barish

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Thermodynamics

- Science of energy and entropy
- First law for isolated system: Energy is a constant (conserved)
- Second law for isolated system: Entropy cannot decrease
- Uniqueness of thermodynamics lies in the second law, which provides an "arrow of time." Isolated macroscopic systems "run down" and eventually experience a "heat death"
- Thermodynamics precludes existence of perpetual motion machines*

*Claims of such machines are automatically dismissed by the US Patent and Trademark Office

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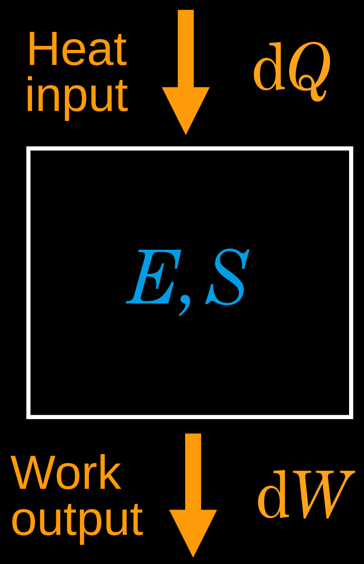
Thermodynamics – First & Second Laws

Exclude External Time-Varying Gravitational / Electromagnetic Fields

Closed System



E = energy
S = entropy

1st Law $\mathrm{d}E = \mathrm{d}Q - \mathrm{d}W$

2nd Law $\mathrm{d}S \geq \mathrm{d}Q/T$ T = system temperature where heat enters

Equal sign in reversible case

"Closed" means no
mass in/out of system

Thermodynamics – First & Second Laws

Exclude External Time-Varying Gravitational / Electromagnetic Fields

Closed System	Isolated System
Heat input ↓ $\mathrm{d}Q$	$\mathrm{d}Q = 0$
E, S	E, S
Work output ↓ $\mathrm{d}W$	$\mathrm{d}W = 0$

1st Law: $\mathrm{d}E = \mathrm{d}Q - \mathrm{d}W$ (closed); $E = \mathrm{Const}$ (isolated)

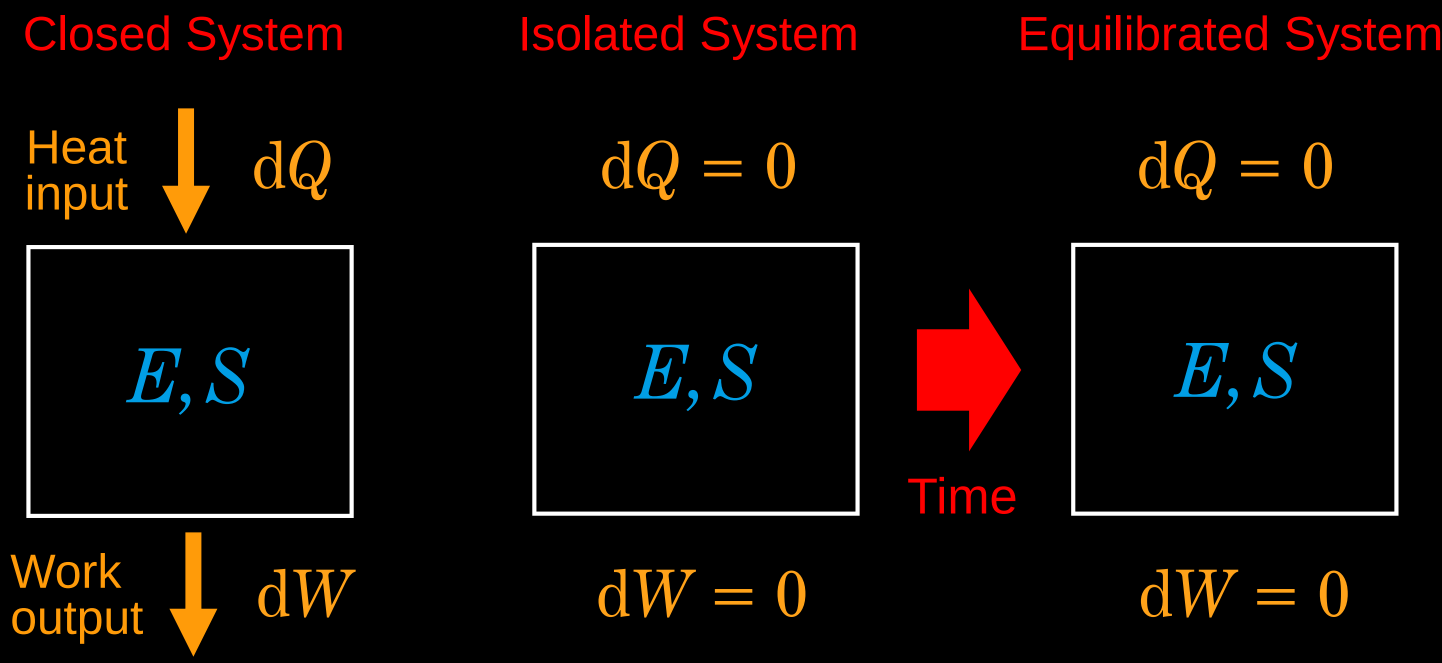
2nd Law: $\mathrm{d}S \geq \mathrm{d}Q/T$ (closed); $\mathrm{d}S \geq 0$ (isolated)

"Closed" means no mass in/out of system

"Isolated" means no input/output of any kind

Thermodynamics – First & Second Laws

Exclude External Time-Varying Gravitational / Electromagnetic Fields



	Closed System	Isolated System	Equilibrated System
1st Law	$\mathrm{d}E = \mathrm{d}Q - \mathrm{d}W$	$E = \mathrm{Const}$	$E = \mathrm{Const}$
2nd Law	$\mathrm{d}S \geq \mathrm{d}Q/T$	$\mathrm{d}S \geq 0$	$S = \mathrm{Const} = \mathrm{Max}$

"Closed" means no mass in/out of system

"Isolated" means no input/output of any kind

"Equilibrated" means no longer changing

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What kinds of internal changes cause the entropy of a system to rise?

Thermodynamics – Entropy Generation Density

Entropy generation-rate density for simple fluid at local equilibrium

$$\sigma = \frac{\overbrace{-\mathbf{q}\cdot\nabla\frac{1}{T}}^{\text{thermal conduction}} \overbrace{-\sum_i \mathbf{j}_i\cdot T\nabla\frac{\mu_i}{T}}^{\text{mass diffusion}} \overbrace{+\mathbf{j}\cdot(\mathbf{E}+\mathbf{v}\times\mathbf{B})}^{\text{electric current}} \overbrace{-\boldsymbol{\tau}:\boldsymbol{\varepsilon}}^{\text{friction}} \overbrace{-\sum_r R_r A_r}^{\text{reactions}}}{T}$$

Each term in the numerator consists of a thermodynamic flux-force product. Each thermodynamic flux (left) is driven by a thermodynamic force (right). Each product provides a positive contribution to the entropy generation rate density σ resulting from thermalization of energy

At overall equilibrium, when the fluxes have been driven to zero and all energy that can be thermalized has been thermalized, the entropy of the system is maximized

$\mathbf{q}$ = internal energy diffusion flux density, ∇ = gradient operator, T = absolute temperature, $\mathbf{j}_i$ = chemical species i diffusion flux density, μ_i = species i chemical potential, $\mathbf{j}$ = conduction current density, $\mathbf{E}$ = electric field, $\mathbf{v}$ = fluid velocity, $\mathbf{B}$ = magnetic field, $\boldsymbol{\tau}$ = shear stress tensor, $\boldsymbol{\varepsilon}$ = strain rate tensor, R_r = rate of chemical reaction r, A_r = affinity of chemical reaction r

The End