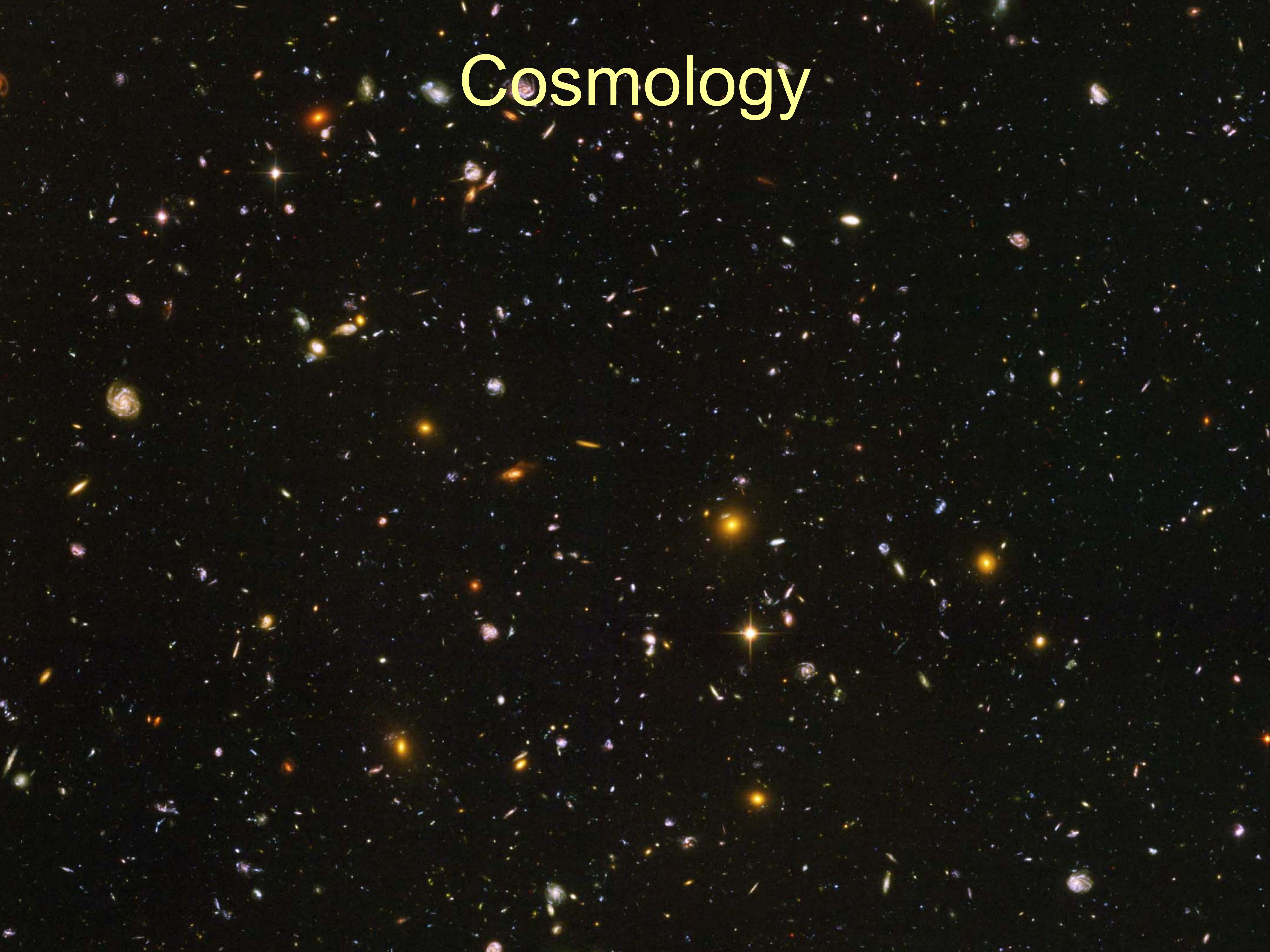
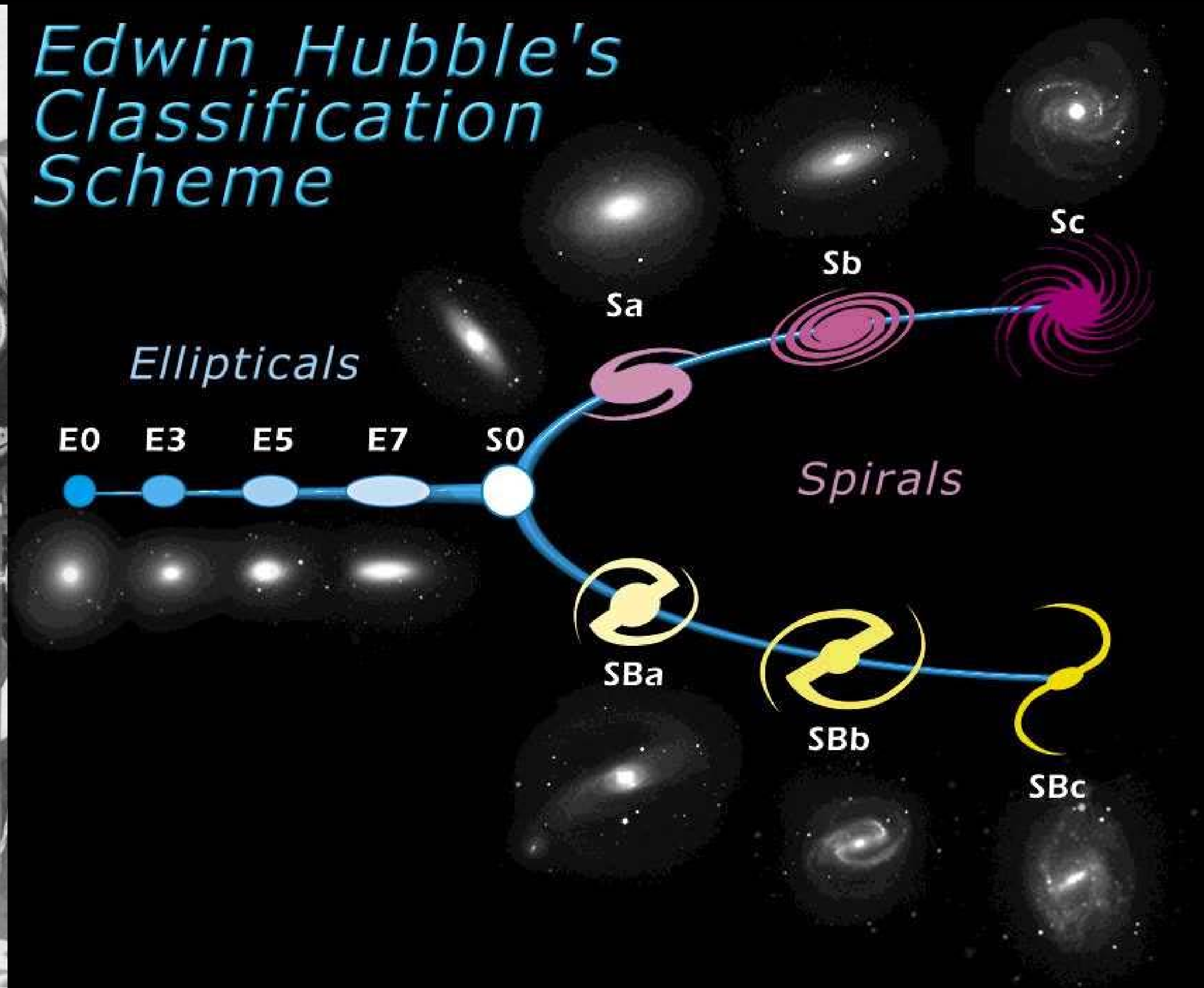
Rostock University, founded 1419

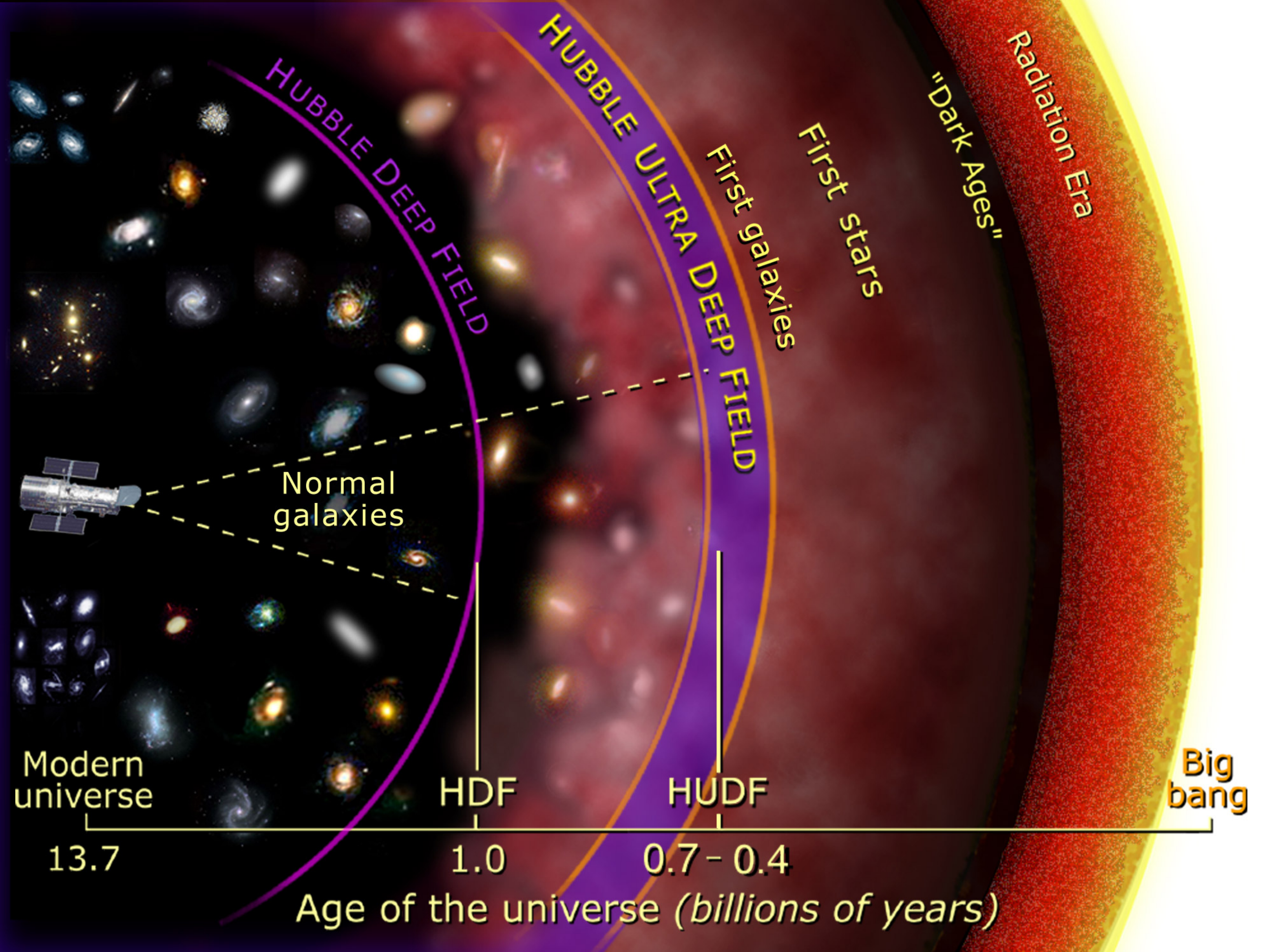
Hanse-Sail in August

Cosmology

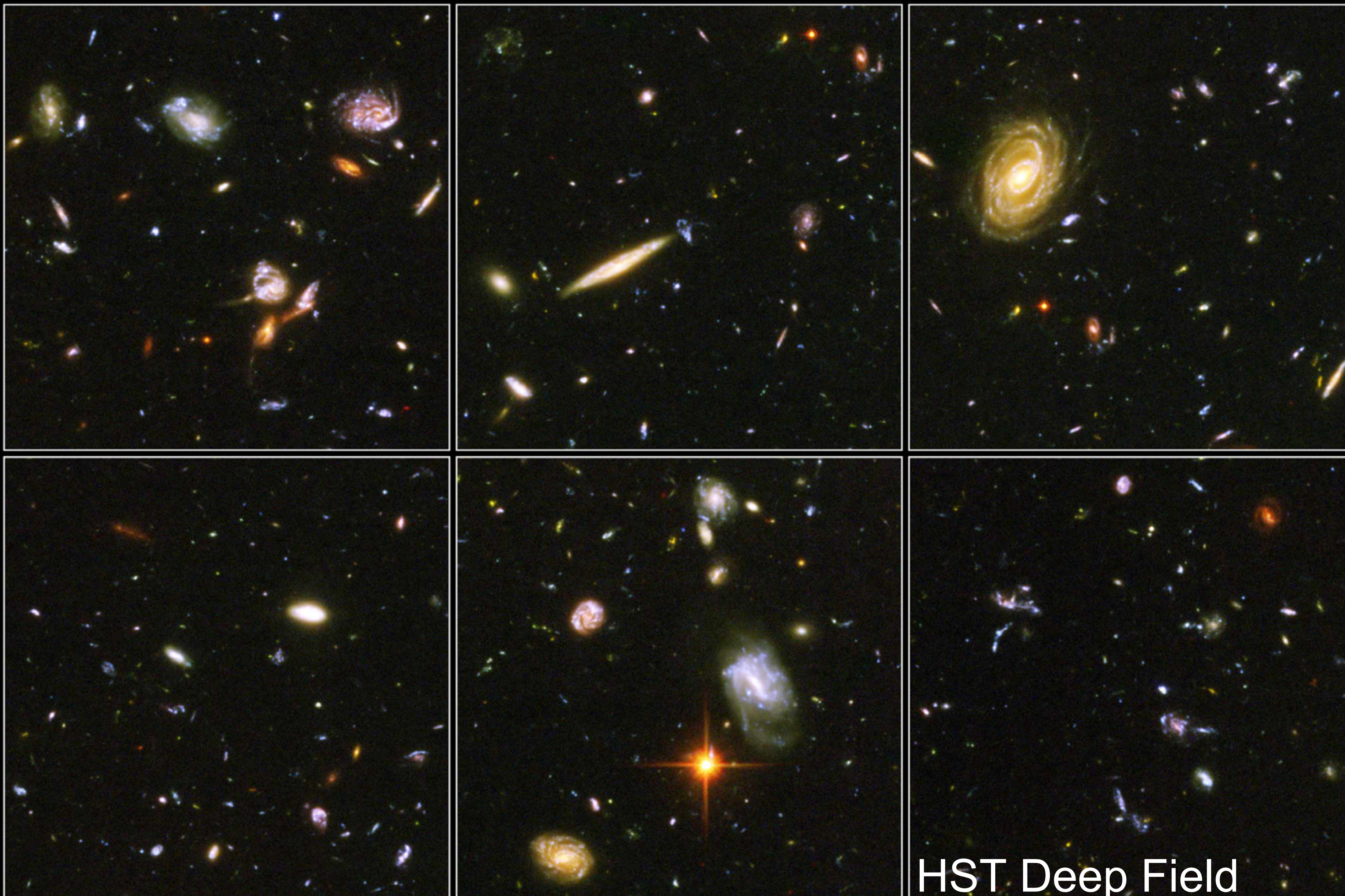


Edwin Hubble 1929



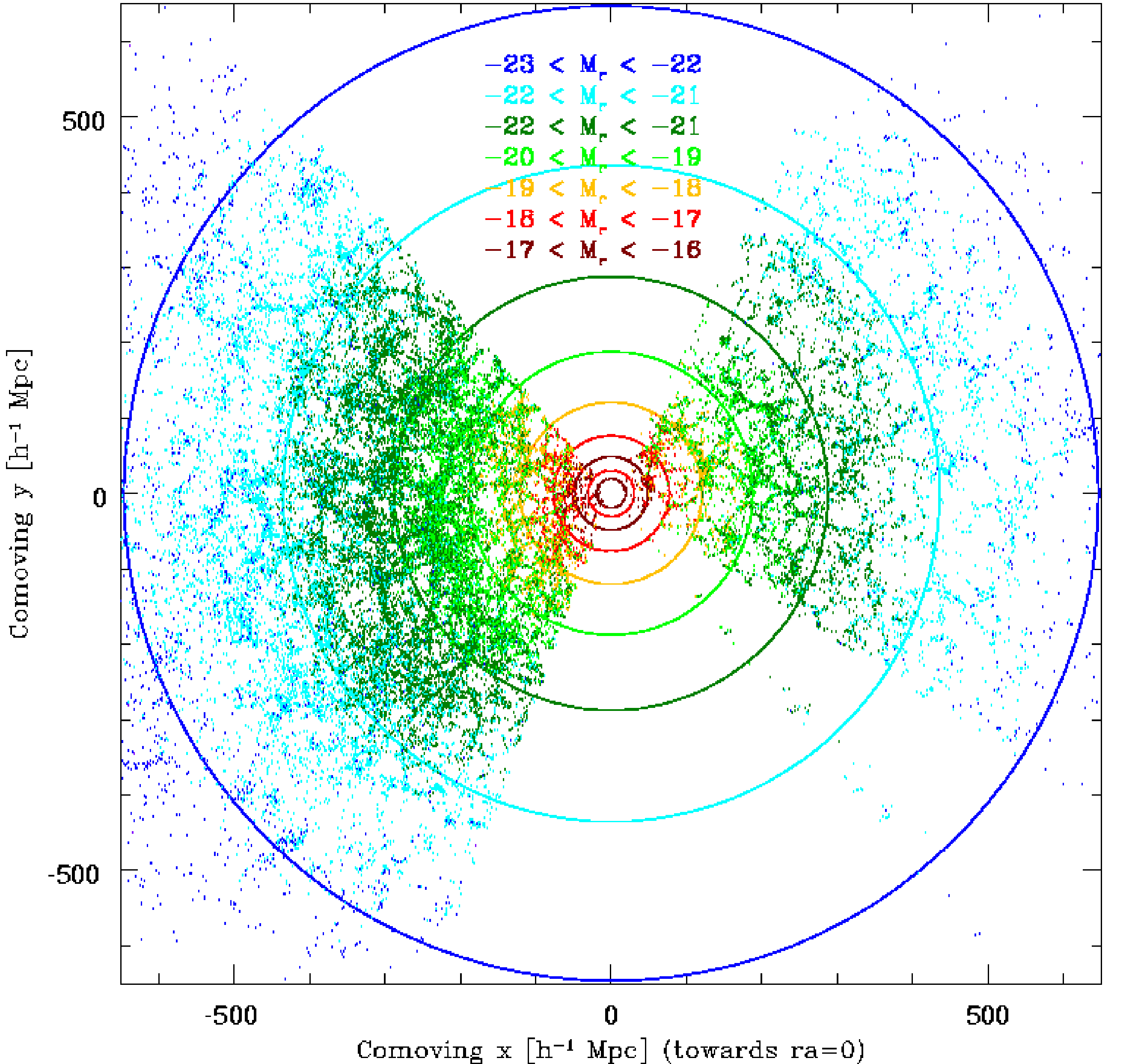

HUBBLE DEEP FIELD
HUBBLE ULTRA DEEP FIELD
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe *(billions of years)*

Visible Matter Distribution

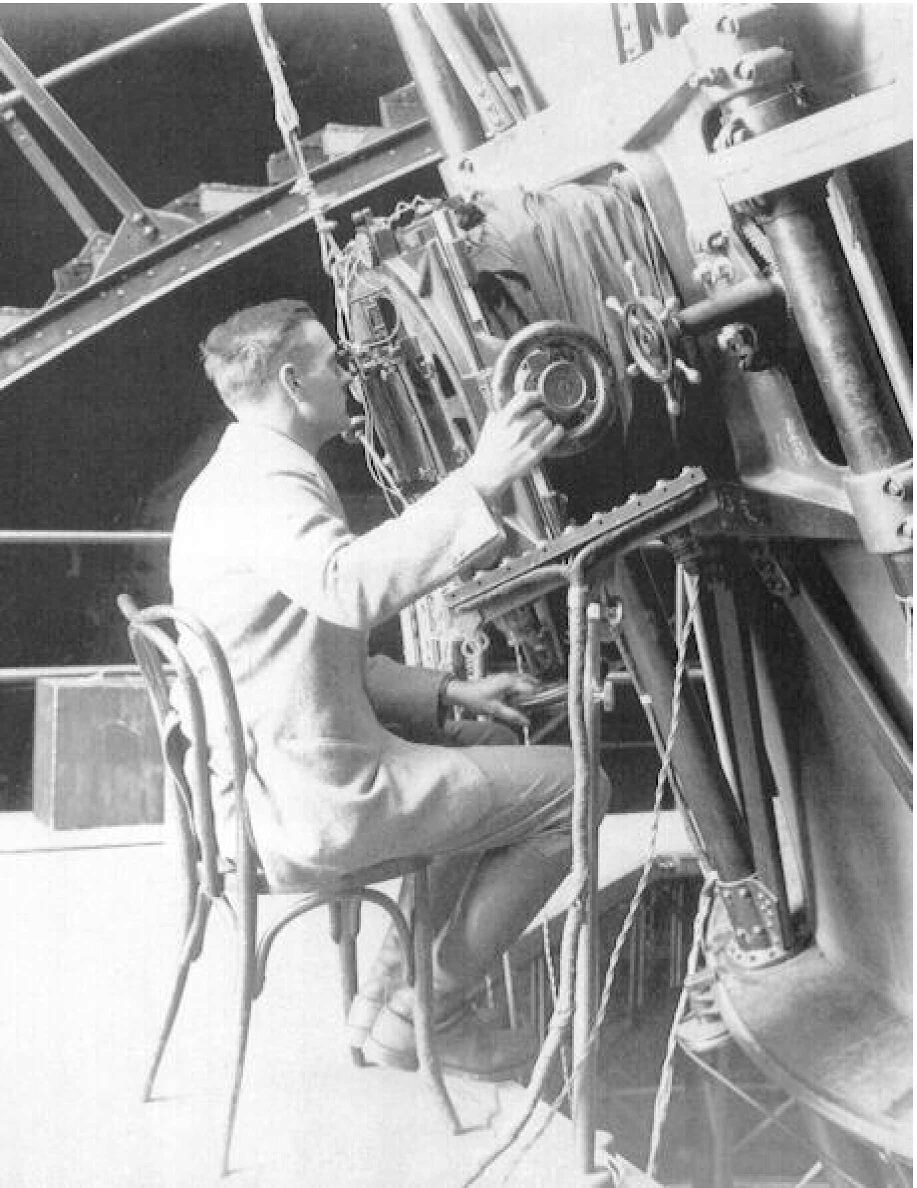


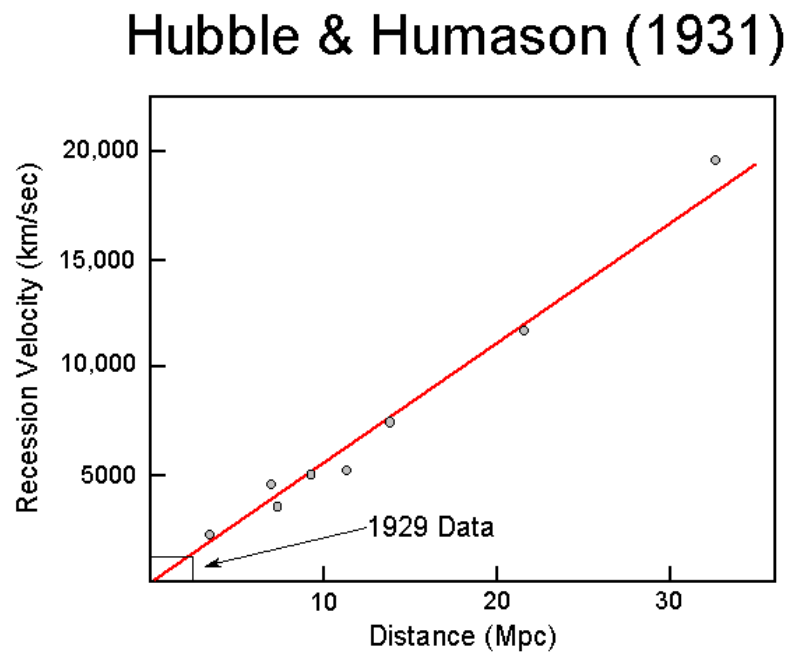
HST Deep Field

Sloan Digital Sky Survey (SDSS) – (1998-2006)



Edwin Hubble 1929





today: $H_0 \approx 70$ km/s/Mpc

Doppler Effect

$$\begin{aligned} \lambda_{Obs} &= \lambda_{Src} \cdot \gamma(1+\beta\cos\vartheta) \\ &= \lambda_{Src} \cdot (1+z) \\ &= \lambda_{Src} \cdot \sqrt{\frac{1+\beta}{1-\beta}} \quad \text{for} \quad \vartheta = 0° \end{aligned}$$

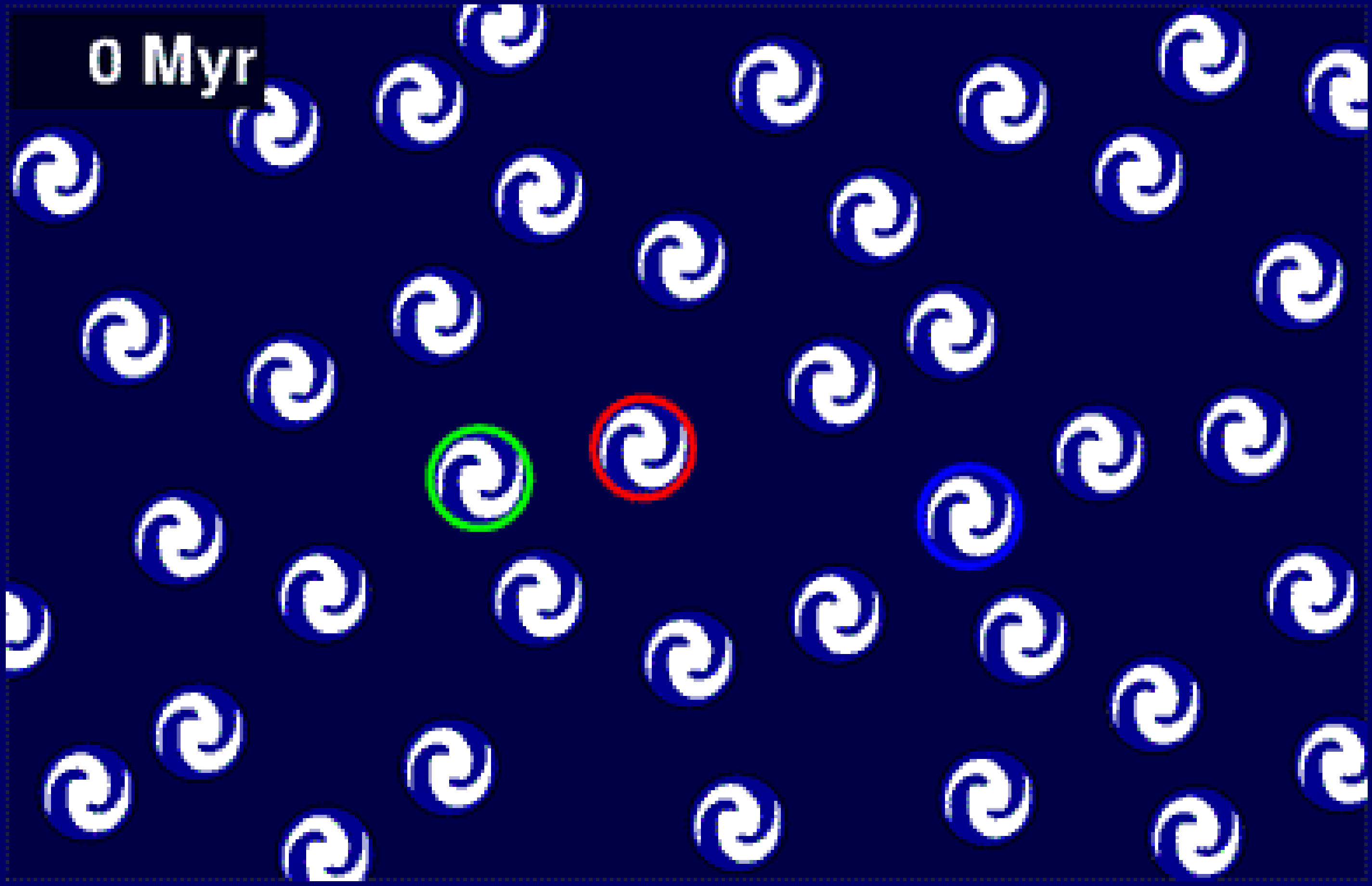
Redshift

$$z = \gamma - 1 + \beta\gamma\cos\vartheta$$

$$\beta = \mathrm{v}/c$$

$$\text{for } \vartheta = 0 \text{ and } \beta << 1: \quad z \approx \beta$$

Expansion of the whole Universe



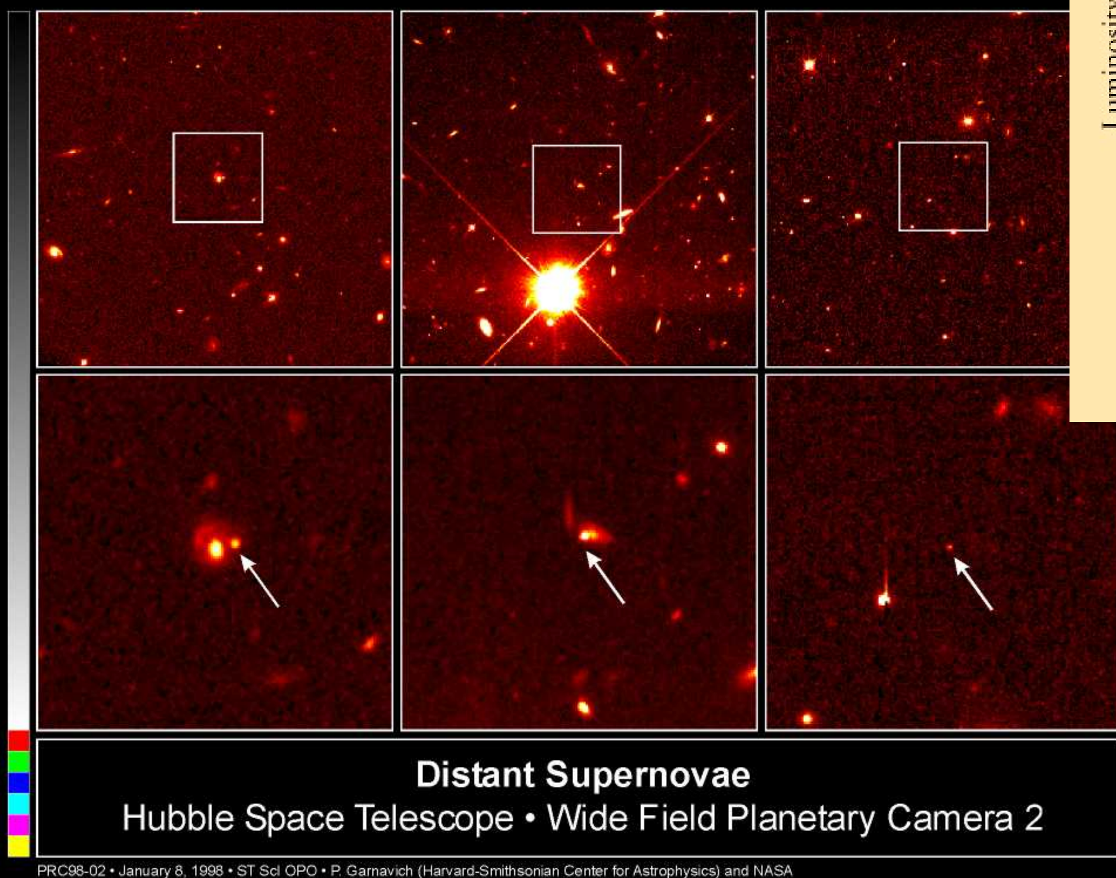
when expansion started = beginning of Universe (Big Bang)

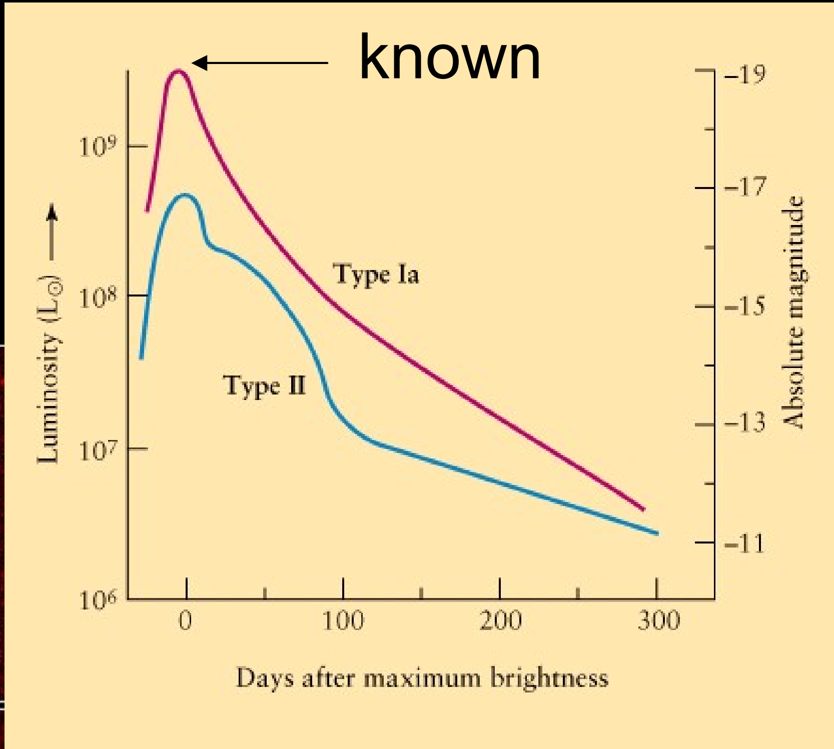
H_0 = 70 km/s/Mpc

$1/H_0 = 14 \cdot 10^9 a$

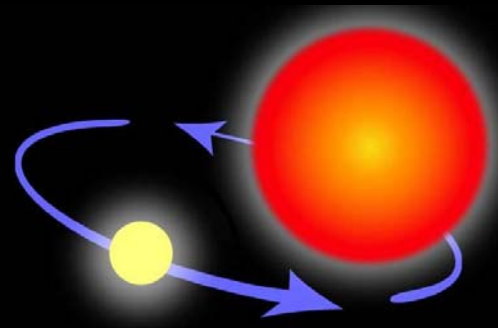
"Standard Candle"

known
absolute brightness (M_B=–19.6)
at maximum
of supernova type Ia

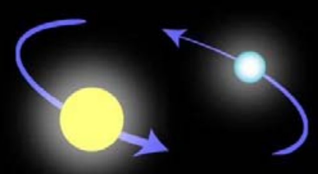




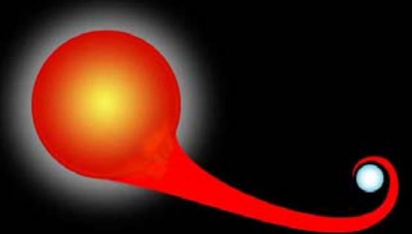
Supernova Ia



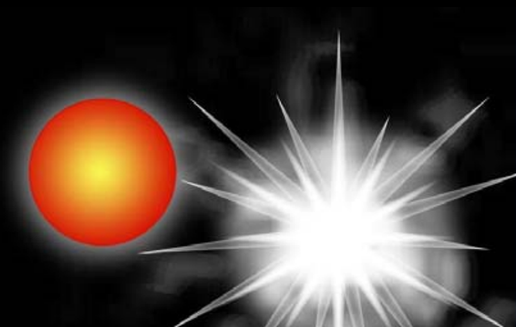
star 1: Red Giant
star 2: Main Sequence Star



star 1: White Dwarf
star 2: Main Sequence Star

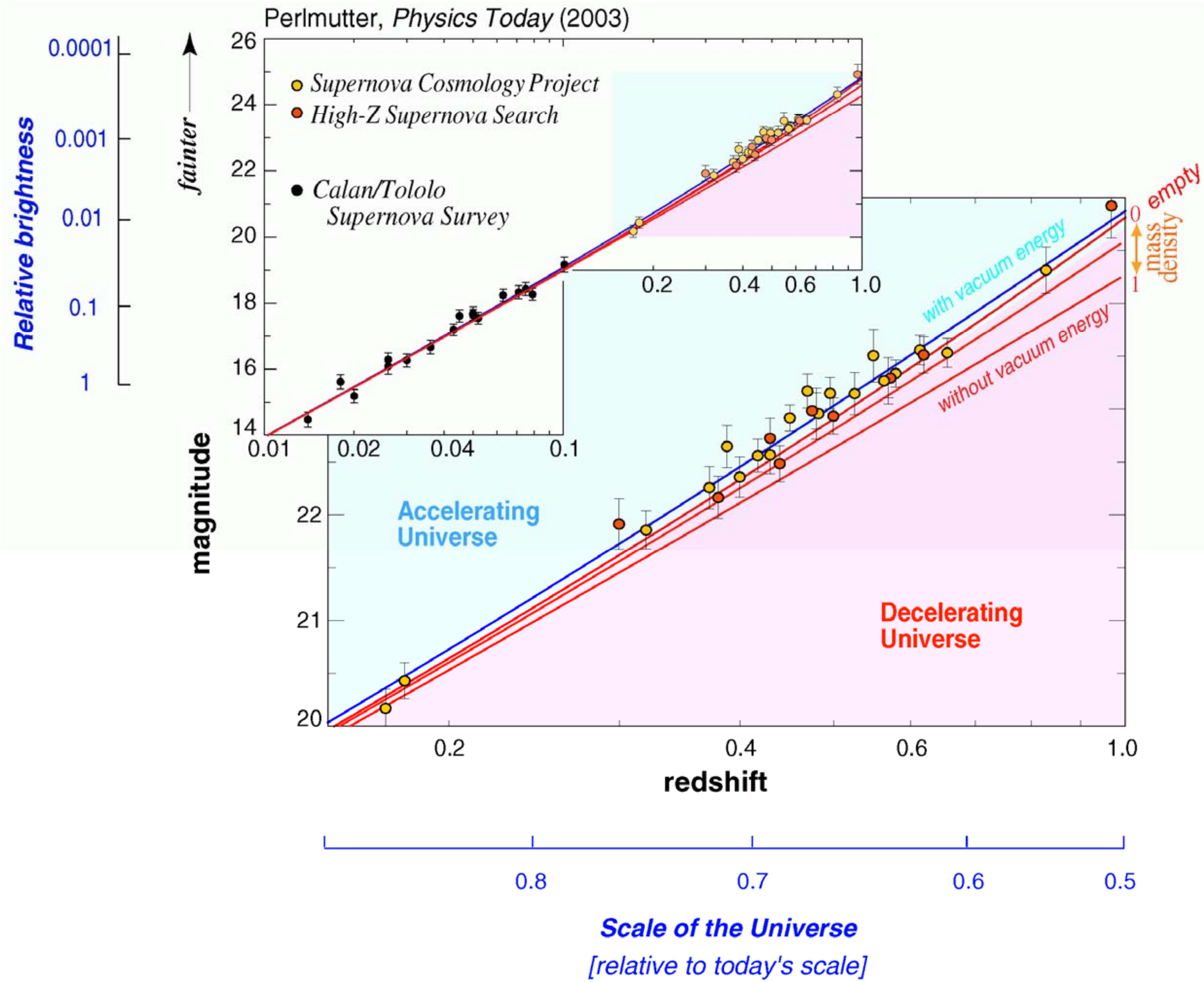


star 1: White Dwarf
mass increasing → Chandrasekhar-mass
star 2: Red Giant
mass flow to star 1



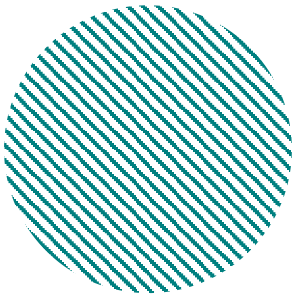
star 1: Supernova Ia

Distance Scale: Supernovae Type Ia



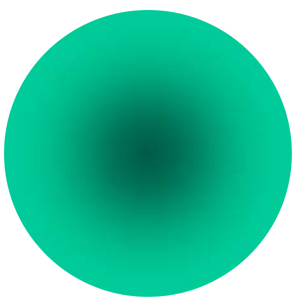
Universe is…

(on large scales > 100 Mpc)

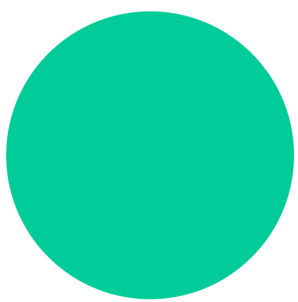


homogenous (translational invariant)

and



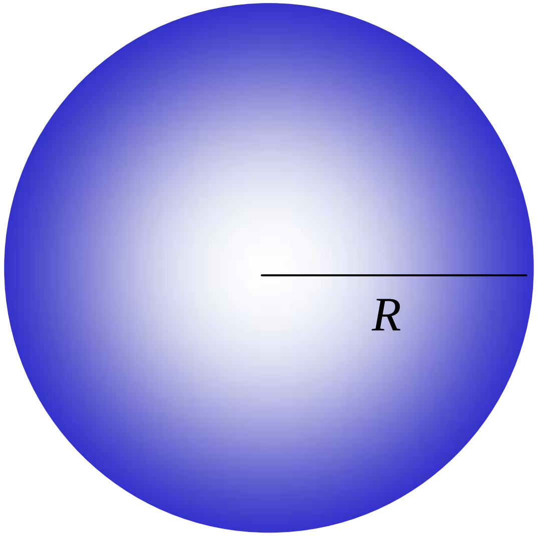
isotropic (rotational invariant)

=  looks the same everywhere

The Classical Friedmann Equation

Sphere of mass *M*, radius *R*, density ρ

expanding or contracting under gravity



force $$\ddot{R} = -\frac{GM}{R^2} = -\frac{4\pi G\rho}{3} R$$

$$\frac{\ddot{R}}{R} = -\tfrac{4}{3}\pi G\rho(t)$$

energy $$\tfrac{1}{2}\dot{R}^2 = \frac{GM}{R} + \frac{E}{m} = \frac{4\pi G\rho}{3} R^2 + \frac{E}{m}$$

$$\left(\frac{\dot{R}(t)}{R(t)}\right)^2 = \tfrac{8}{3}\pi G\rho(t) + \frac{2E/m}{R(t)^2}$$

(Newtonian Mechanics)

The Friedmann Equation

$$\left(\frac{\dot{R}(t)}{R(t)}\right)^2 = \tfrac{8}{3}\pi G\rho(t) + \frac{2E/m}{R(t)^2} = \frac{2GM}{R^3} + \frac{2E/m}{R^2}$$

- If E > 0
  - right-hand side always positive
  - universe expands forever
- If E = 0
  - RHS $\rightarrow$ 0 as $t \rightarrow \infty$
  - universe expands at ever-decreasing rate
- If E < 0
  - $\rho(t) \propto R^{-3}$
  - E-term $\propto R^{-2}$
  - at $R = GM/(-E/m)$ expansion reverses
  - universe headed for a Big Crunch

The fluid equation

- Friedmann equation has two unknowns: ρ and R
  - need another equation
  - try thermodynamics: $dQ = dE + P\,dV$
    - energy in volume V is
      $E / c^2 = \rho V$; $dE / c^2 = V d\rho + \rho dV$
    - $V \propto R^3$ so $dV / V = 3dR / R$
    - $dQ = 0$ for expansion of universe

$$\dot{\rho} + 3\frac{\dot{R}}{R}\left(\rho + \frac{P}{c^2}\right) = 0$$

the fluid equation

$$\dot{\rho}R = -3\dot{R}\left(\rho + \frac{P}{c^2}\right)$$

The acceleration equation

- Friedmann eqn. multiplied by R^2

$$\dot{R}(t)^2 = \tfrac{8}{3}\pi G\rho(t)R(t)^2 - kc^2, \qquad k = E/m$$

- differentiate:

$$2\ddot{R}\dot{R} = \frac{8\pi G}{3}\left(2R\dot{R}\rho + \dot{\rho}R^2\right) = \frac{8\pi G\dot{R}R}{3}\left(2\rho - 3\left(\rho + \frac{P}{c^2}\right)\right)$$

- using fluid equation:

$$\dot{\rho}R = -3\dot{R}\left(\rho + \frac{P}{c^2}\right)$$

- simplify:

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}\left(\rho + \frac{3P}{c^2}\right)$$

Always deceleration unless pressure is negative!

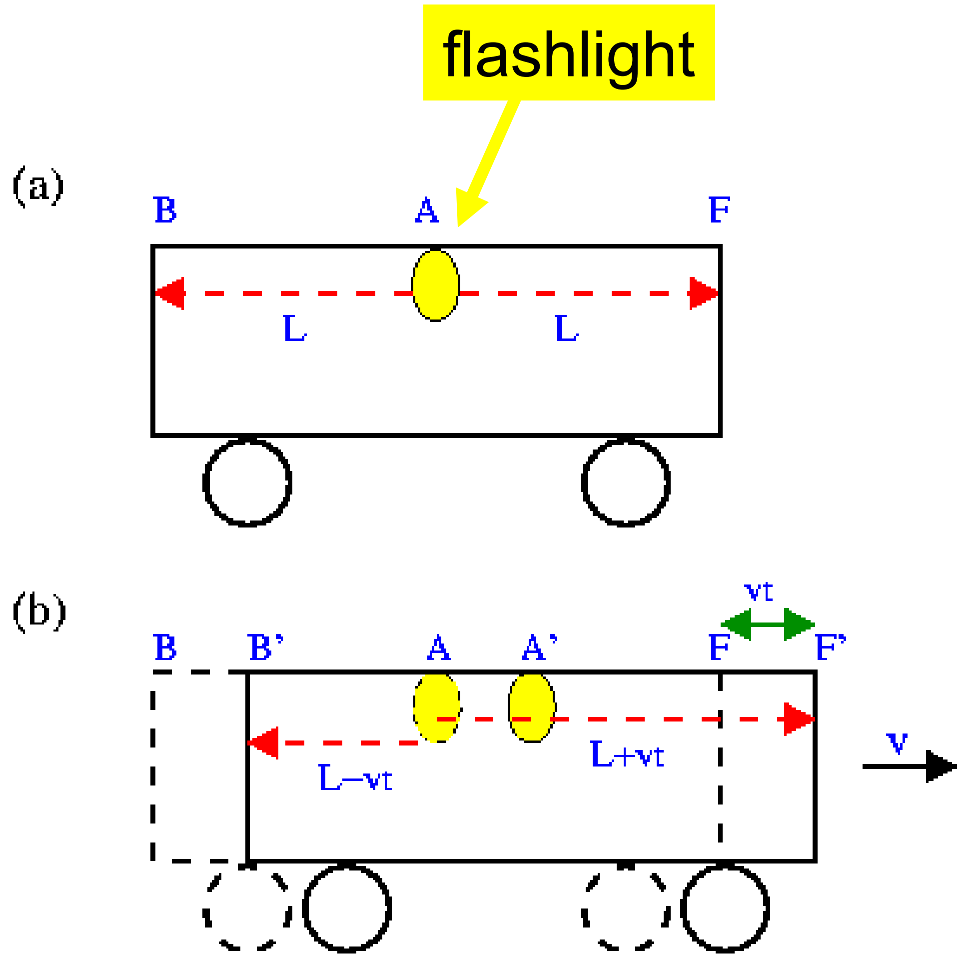
Special Relativity

- c = constant
  independent of (relative) motion
  all (inertial = not accelerated) systems are equivalent
- transformation between systems in relative motion conserves linearity of distance and time

Lost of Simultaneousness

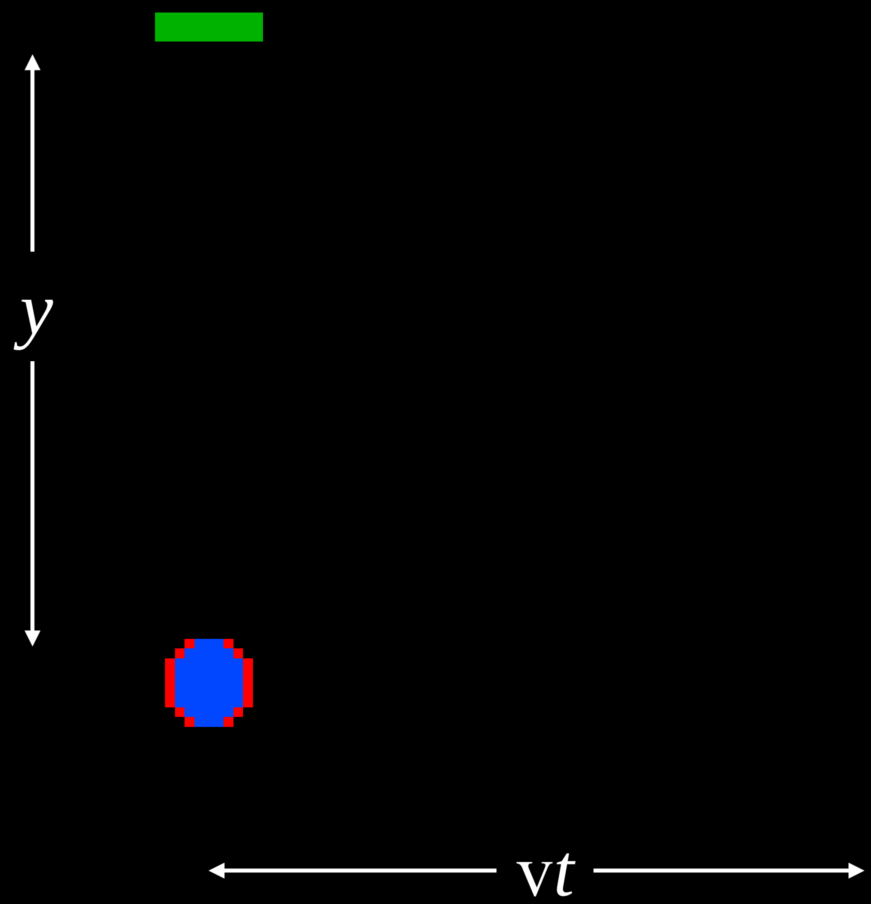
(a) inside moving car:
    t(B) = t(F)

(b) outside observer:
    t(B′) < t(F′)



Photon-Clock (pendulum = photon)

time dilation



$$t' = \frac{2y}{c}$$

$$t = \frac{\sqrt{(2y)^2 + \mathrm{v}^2 t^2}}{c}$$

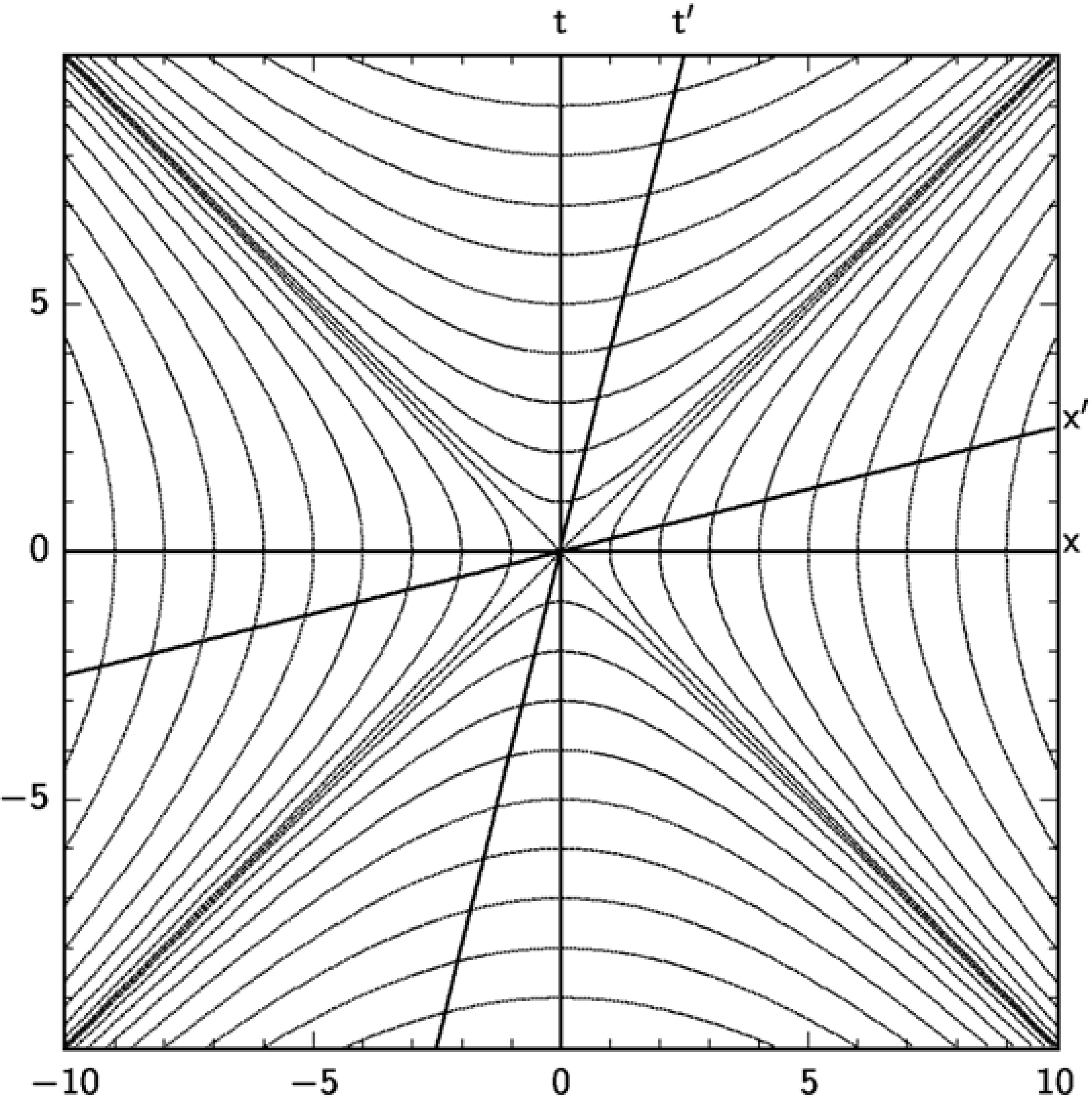
$$t^2\left(1 - \frac{\mathrm{v}^2}{c^2}\right) = \frac{(2y)^2}{c^2} = t'^2$$

Lorentz contraction

length = difference in coordinate at the same time

if simultaneousness is lost, this is the distance
of different spacetime-points

Special Relativity: Lorentz transformation = hyperbolic rotation

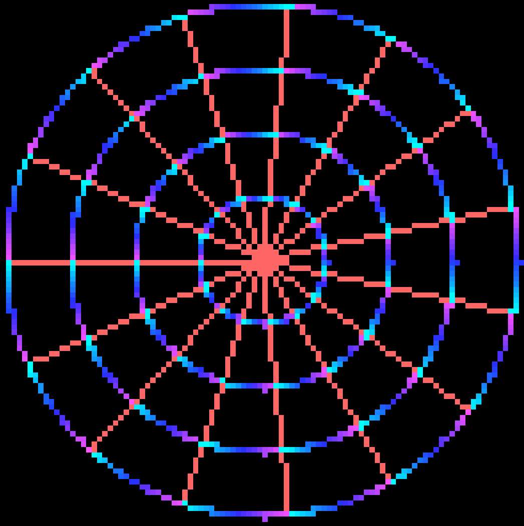


$$x' \quad = \cosh y \cdot x - \sinh y \cdot (ct)$$
$$(ct') = -\sinh y \cdot x + \cosh y \cdot (ct)$$

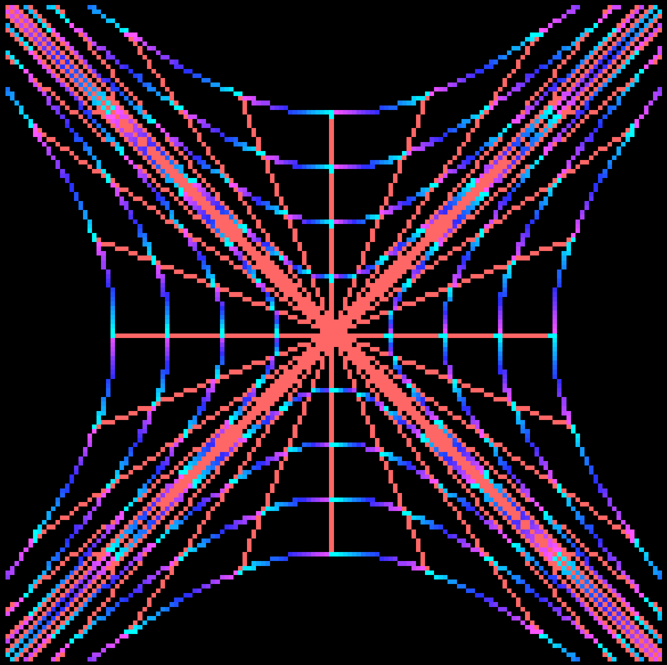
$$\beta = \frac{\mathrm{v}}{\mathrm{c}} = \tanh y$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \cosh y$$

Minkowski-Rotation vs. Euklidian Rotation

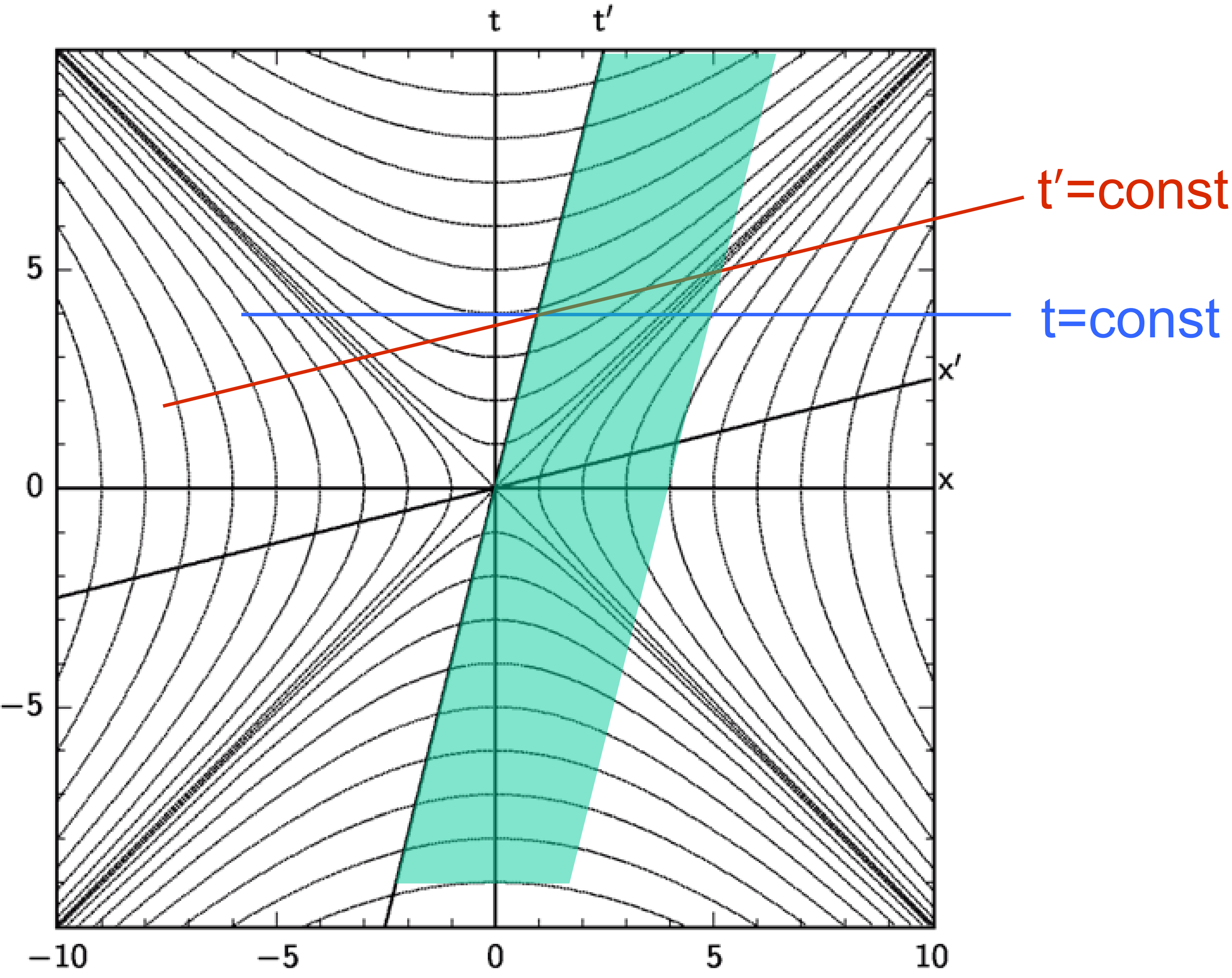


Euklidean Rotation

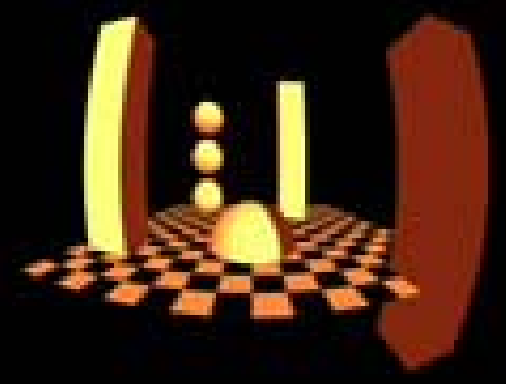


Hyperbolic “Rotation” in Minkowski spacetime

Special Relativity: Lorentz transformation = hyperbolic rotation

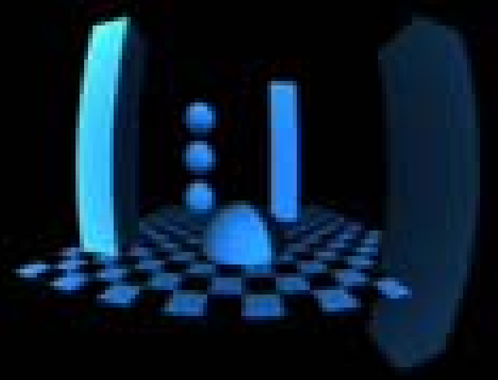


Relativistic Flight at β=0.90



scene illuminated by Planck radiation (2800K)
geometrical effects (Lorentz-contraction, aberration geometry)

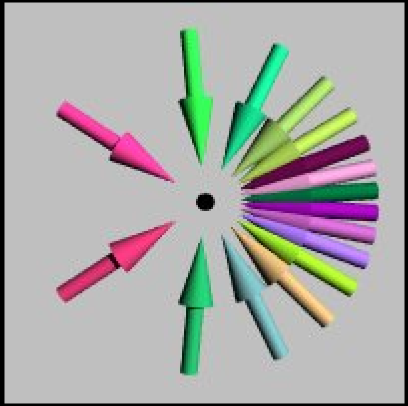
Relativistic Flight at β=0.90



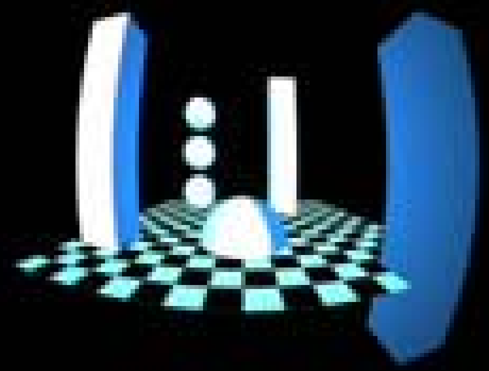
…plus Doppler effect (blue shift)

Relativistic Flight at β=0.90

…plus flux change from aberration

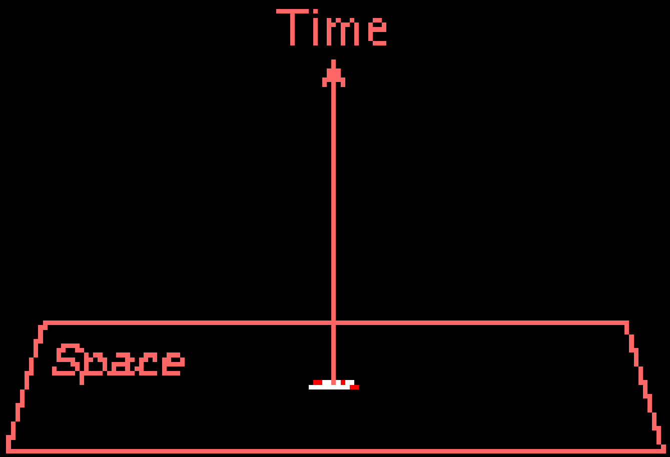


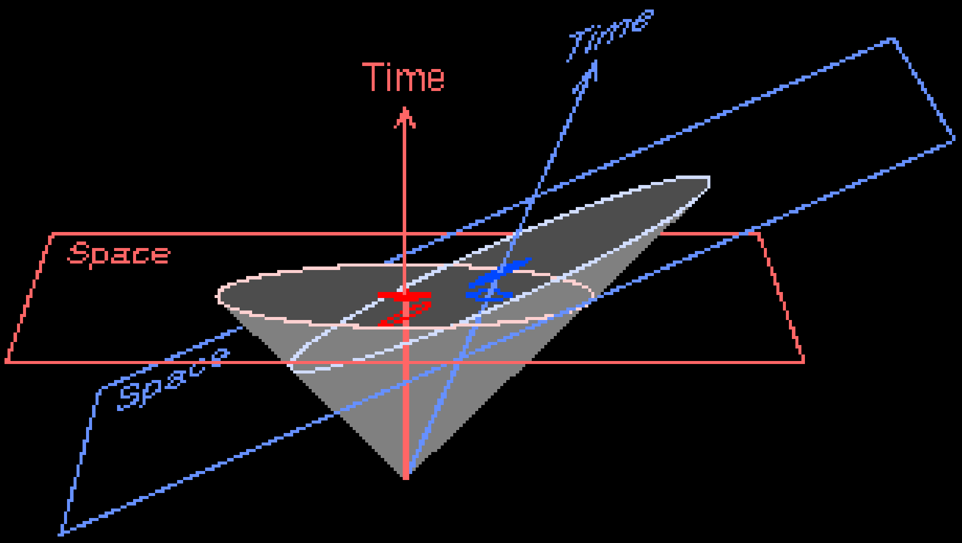
Relativistic Flight at β=0.90



…plus flux change from aberration

The Lightcone





General Principle of Relativity

physical laws are independent of the system of reference (coordinate system)

special relativity: in inertial systems, with constant relative velocity

general relativity: also with relative acceleration

for mathematical description of physical laws:
use local Cartesian systems
but may be (sometimes must be) globally curved!

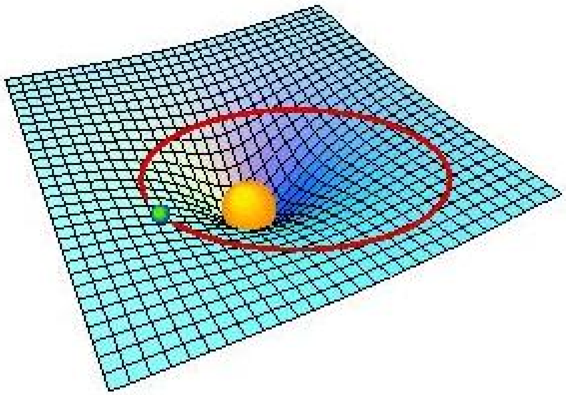
Equivalence Principle

gravitational mass = inert mass

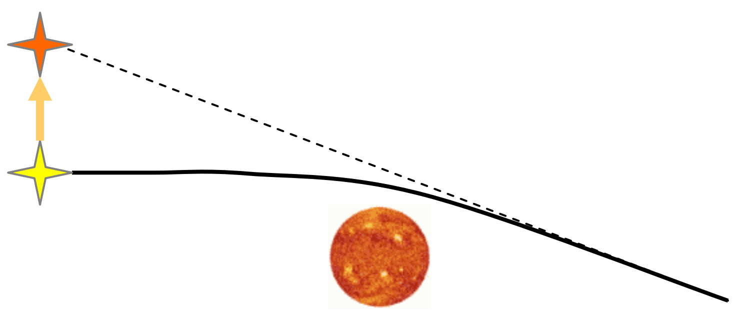
→ cannot distinguish acceleration $m \cdot a$ from gravity $m \cdot g$ locally!

time dilation, Lorentz contraction
→ distortion of space-time by gravitation

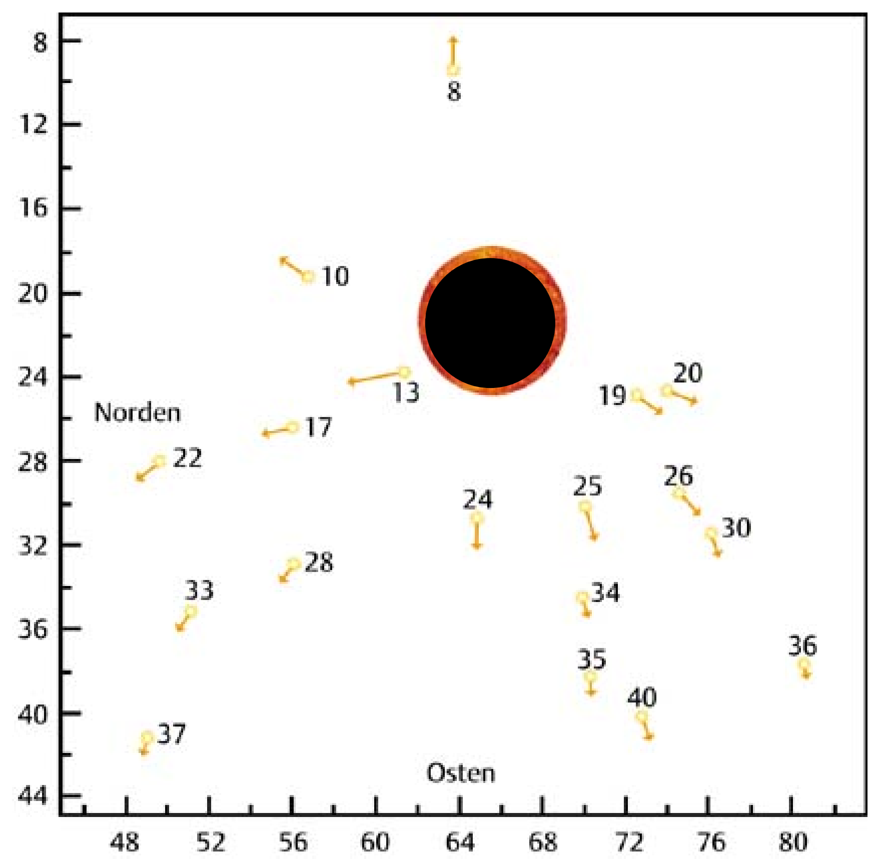
curved space!



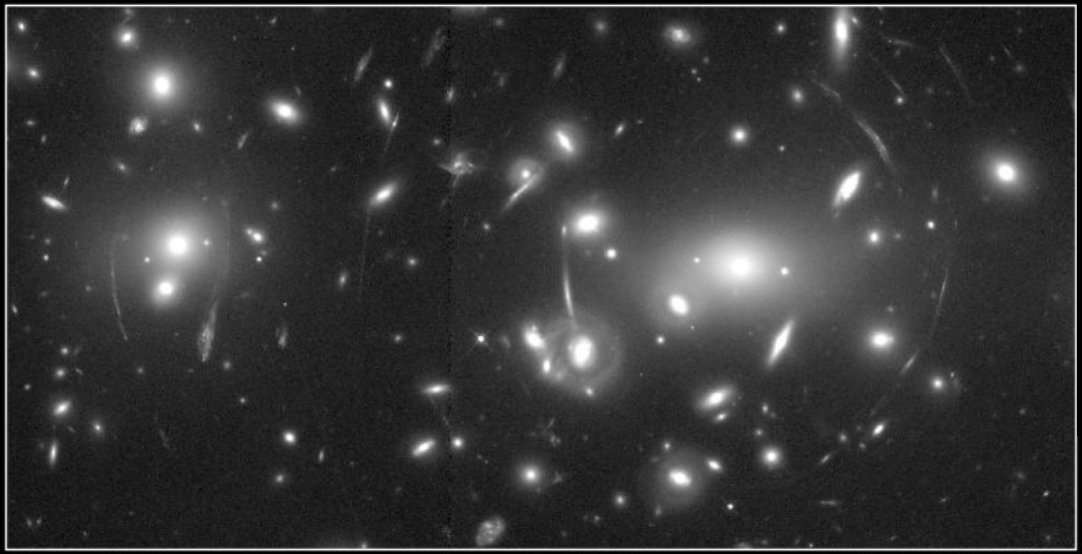
Light Deflection at the Sun



solar eclipse 1919

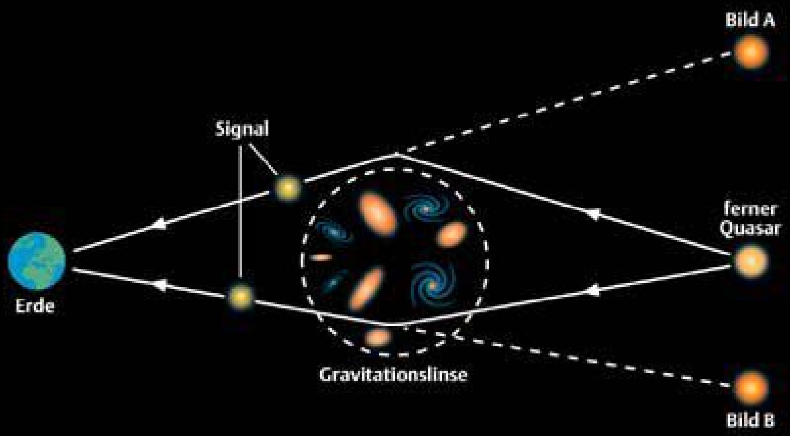


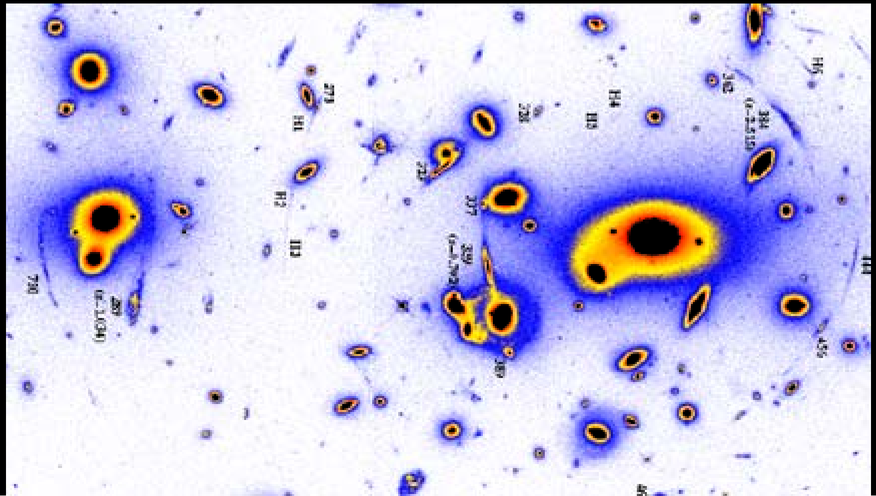
Gravitational Lensing



Gravitational Lens in Abell 2218 HST • WFPC2

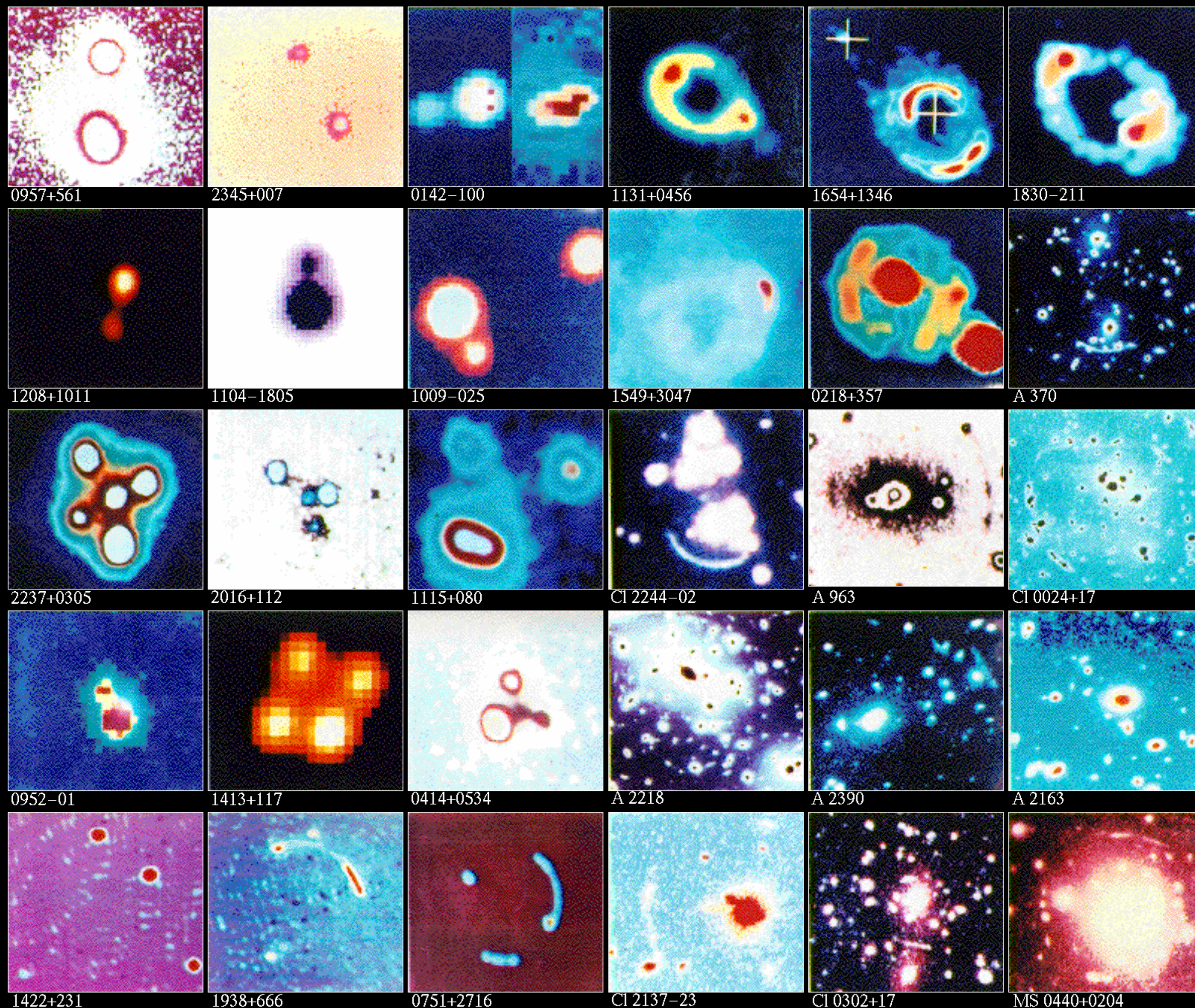
PF95-14 • ST ScI OPO • April 5, 1995 • W. Couch (UNSW), NASA





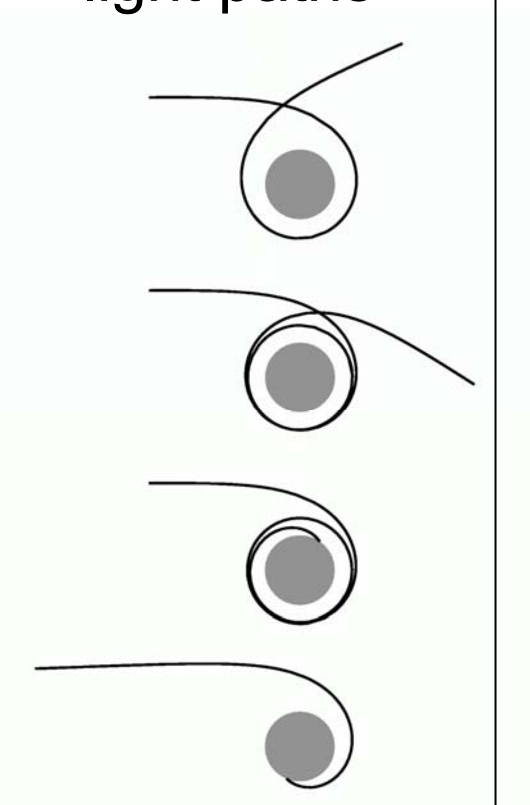
B1938+666
HST 1998

Gravitational Lensing Images

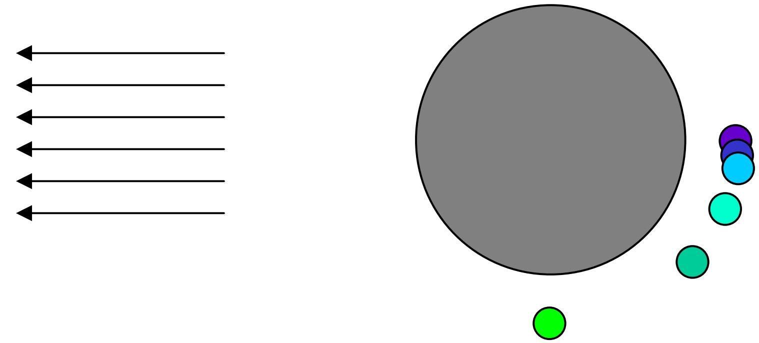


Light deflection near massive objects

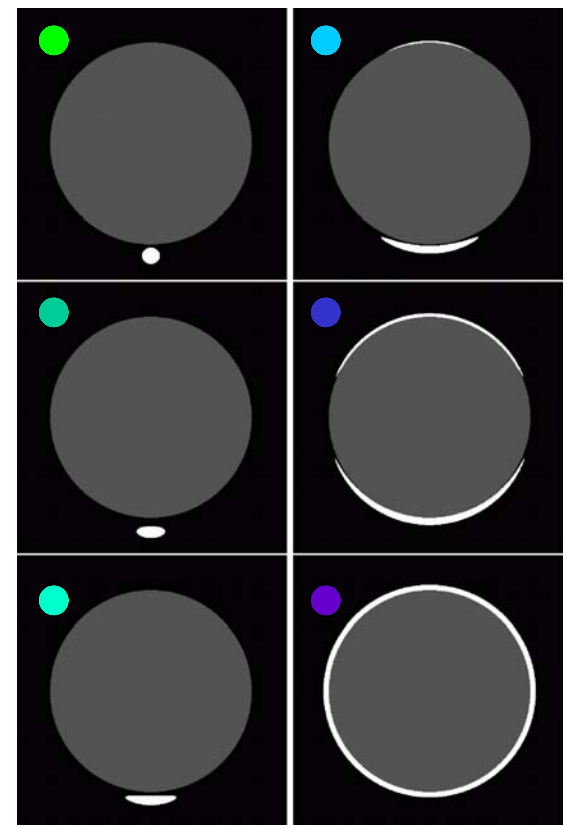
light paths



Observer



$r = 2.5\ r_S$



graphics: Uni Tübingen