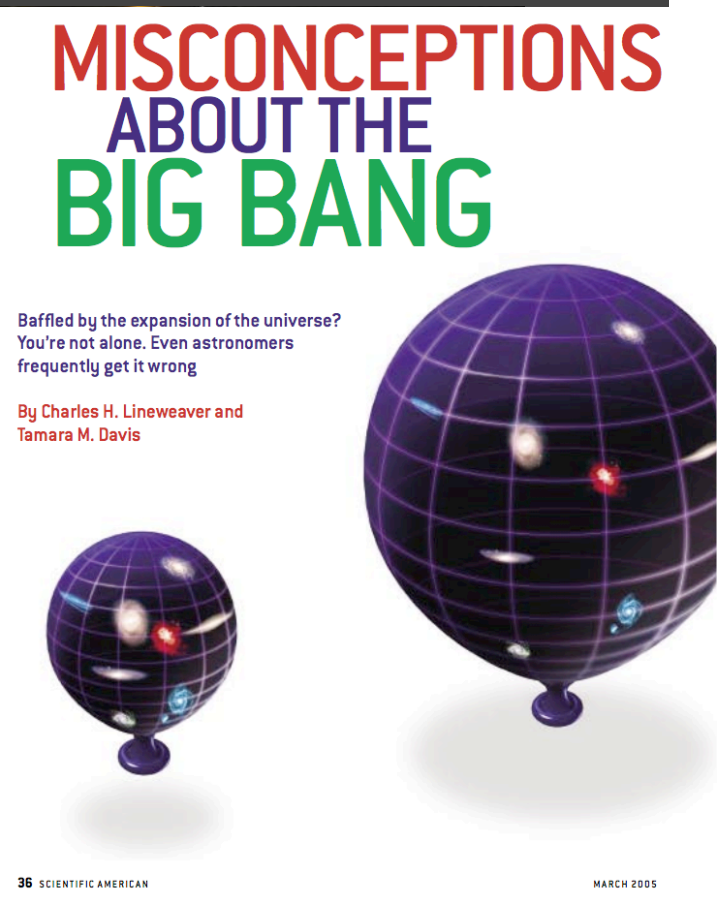
Cosmic Confusion

…common misconceptions about the big bang, the expansion of the universe and cosmic horizons.

What is the expansion of space?
Is there an edge to space?
What is the universe expanding into?
What came before the big bang?
What causes the expansion?
What expands?
Is there a limit to how far we can see?
What is an event horizon?


MISCONCEPTIONS
ABOUT THE
BIG BANG

Baffled by the expansion of the universe? You're not alone. Even astronomers frequently get it wrong

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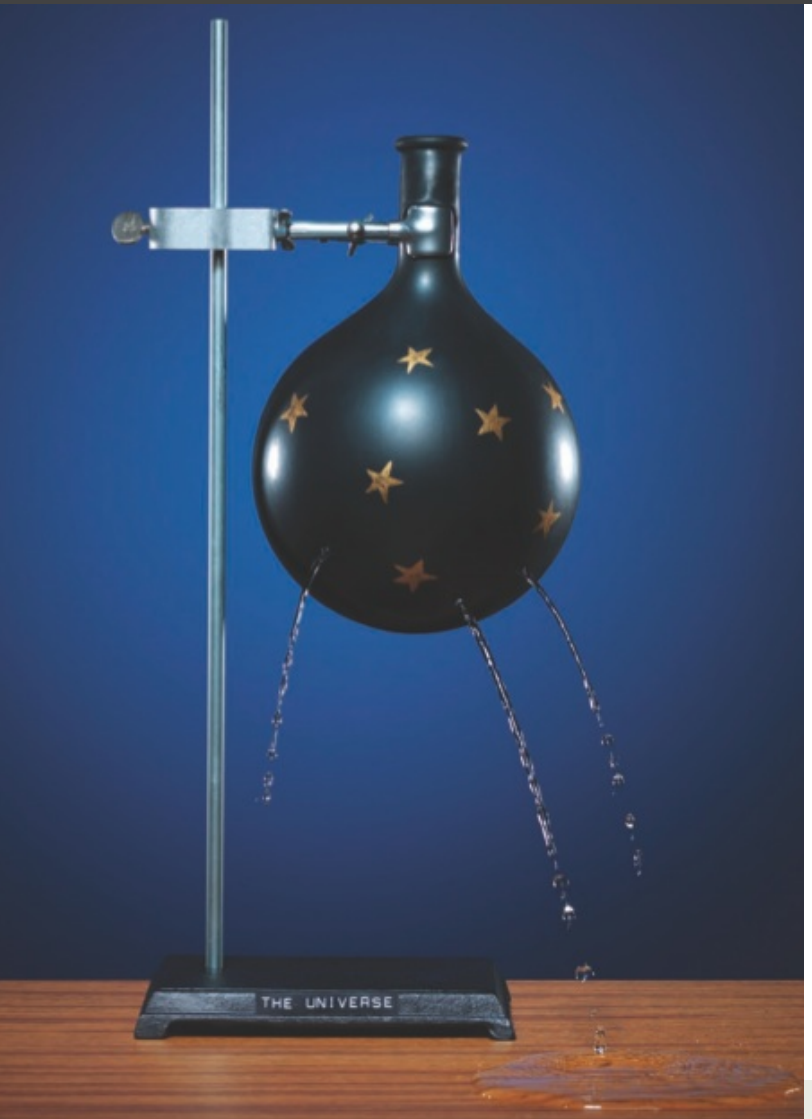
Outline



- The basics – coordinates and velocities
- Horizons – limits of knowledge
- Can space expand faster than the speed of light?
- Stretching space – What is expanding space? What expands when space expands? Are galaxies dragged along by the expansion?
- Where does the energy go in the cosmological redshift?

Can the laws of physics change with time?

Metric and equation of motion

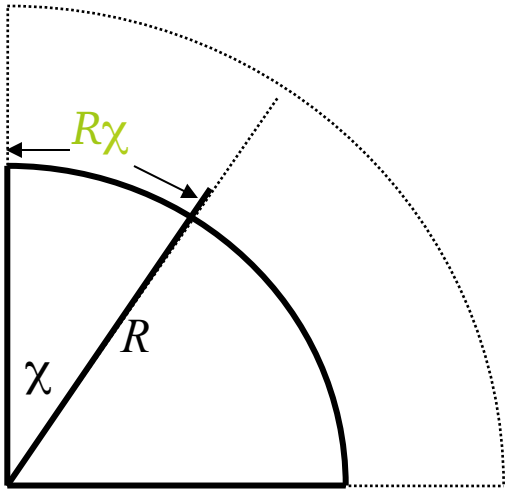
Friedmann-Robertson-Walker metric

$$ds^2 = -c^2dt^2 + R^2(t)\,[\,d\chi^2 + S_k^2(\chi)(d\theta^2+\sin^2\theta\, d\phi^2)\,]$$

Radially: $ds^2 = -c^2dt^2 + R^2(t)d\chi^2$

Photon: $ds=0 \Rightarrow c = R\, d\chi/dt$

Time slice: $dt=0 \Rightarrow D = R\chi$



Velocity: $v= dD/dt = (dR/dt)\chi + R(d\chi/dt)$

Metric and equations of motion

- Geodesic equations

$$\frac{d^2x^\gamma}{d\tau^2} + \Gamma^\gamma_{\alpha\beta}\frac{dx^\alpha}{d\tau}\frac{dx^\beta}{d\tau} = 0.$$

- Only non-vanishing Christoffel symbols

$$\Gamma^1_{01} = \Gamma^1_{10} = \frac{\dot{R}}{R}, \qquad \Gamma^0_{11} = \frac{R\dot{R}}{c^2}.$$

- Friedmann equations

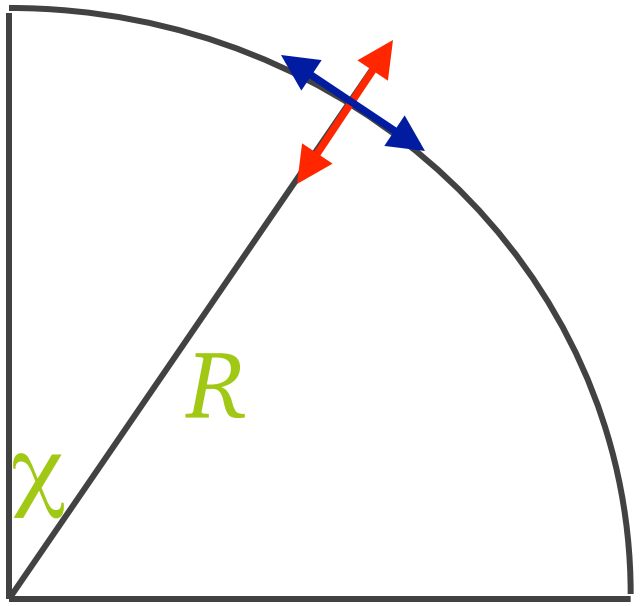
$$\frac{H^2}{H_0^2} = \frac{\Omega_m}{a^3} + \frac{\Omega_k}{a^2} + \frac{\Omega_x}{a^{3(1+w)}}$$

Two types of velocity

- Velocity

$$v = \frac{dR}{dt}\chi + R\frac{d\chi}{dt}$$

$$= v_{recession} + v_{peculiar}$$



VIOLATES SPECIAL RELATIVITY ??

Recession velocity

$$v_{recession} = \dot{R}\chi = \frac{\dot{R}}{R}D$$

$$v_{recession} = HD$$

$$\Rightarrow H = \frac{\dot{R}}{R}$$

Peculiar velocity (incl photons)

$$v_{peculiar} = R\dot{\chi} \qquad c = R\dot{\chi}$$

The universe itself keeps on
expanding and expanding,
In all of the directions it can whizz,
As fast as it can go,
That's the speed of light you know,
Twelve million miles a minute
and that's the fastest speed there is

Monty Python, The Galaxy Song

Other metrics, other velocities

- **Velocity** is a *coordinate dependent* property
- **Redshift** is measurable and *coordinate independent*
- Usual coordinates: Friedman-Robertson-Walker
  - it describes an **homogeneous** and **isotropic** universe
  - **time** is the proper time of comoving observers
  - **synchronicity** can be measured by the CMB temperature
  - it makes calculations **simple**
- Other metrics are equally valid,
  - conformal: $ds^2 = R^2(t)\ [\ -c^2dt^2 + d\chi^2 + S_k^2(\chi)(d\theta^2+\sin^2\theta\ d\phi^2)\ ]$

We need to understand the implications of our coordinate choice

Superluminal recession

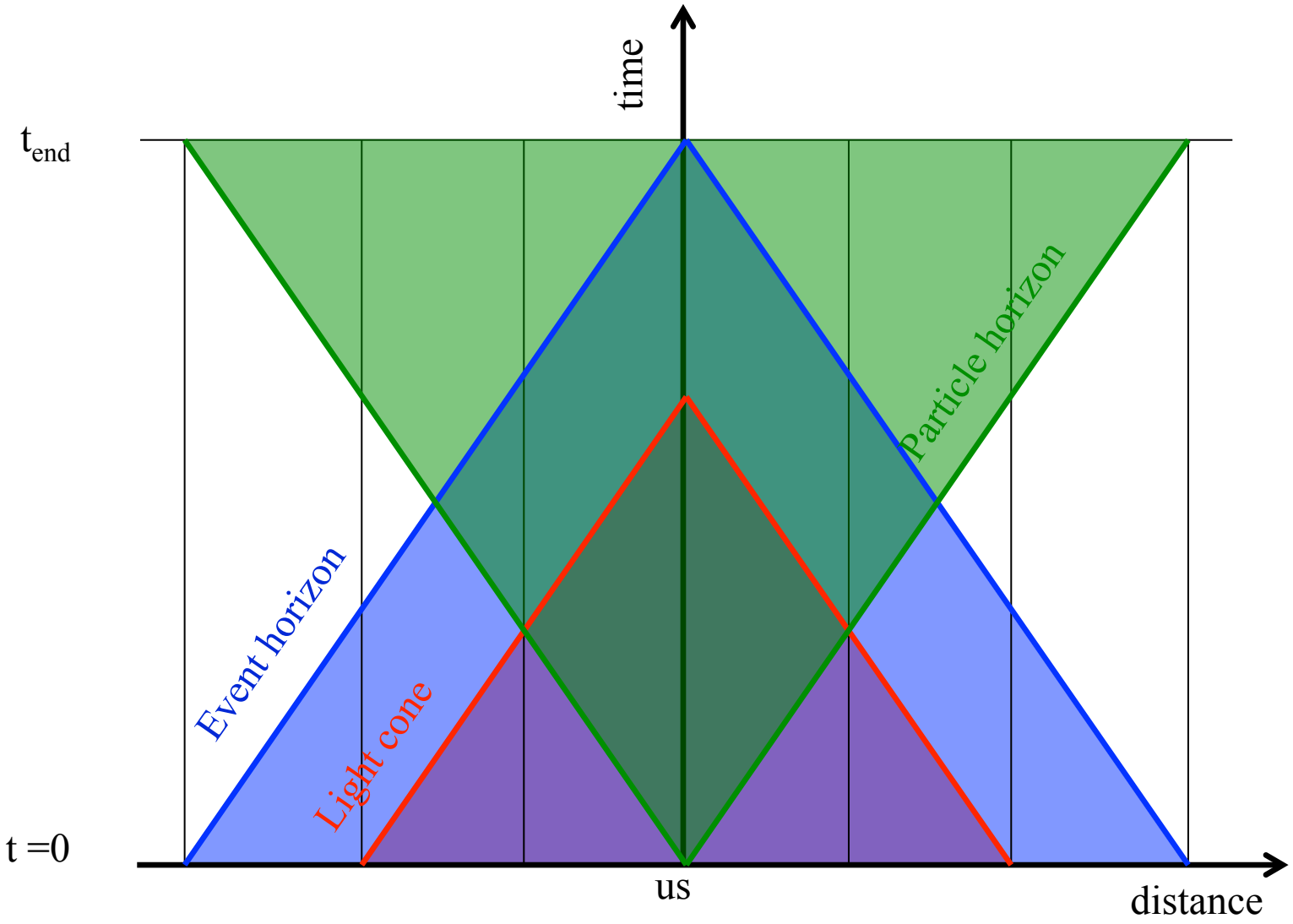
- Yes, recession velocities can exceed the speed of light.
- This DOES NOT violate special relativity
  - Nothing ever overtakes a photon
  - Photons always travel at c

Nothing recedes faster than the speed of light in any inertial frame.

- There exist metrics that do not have superluminal recession.

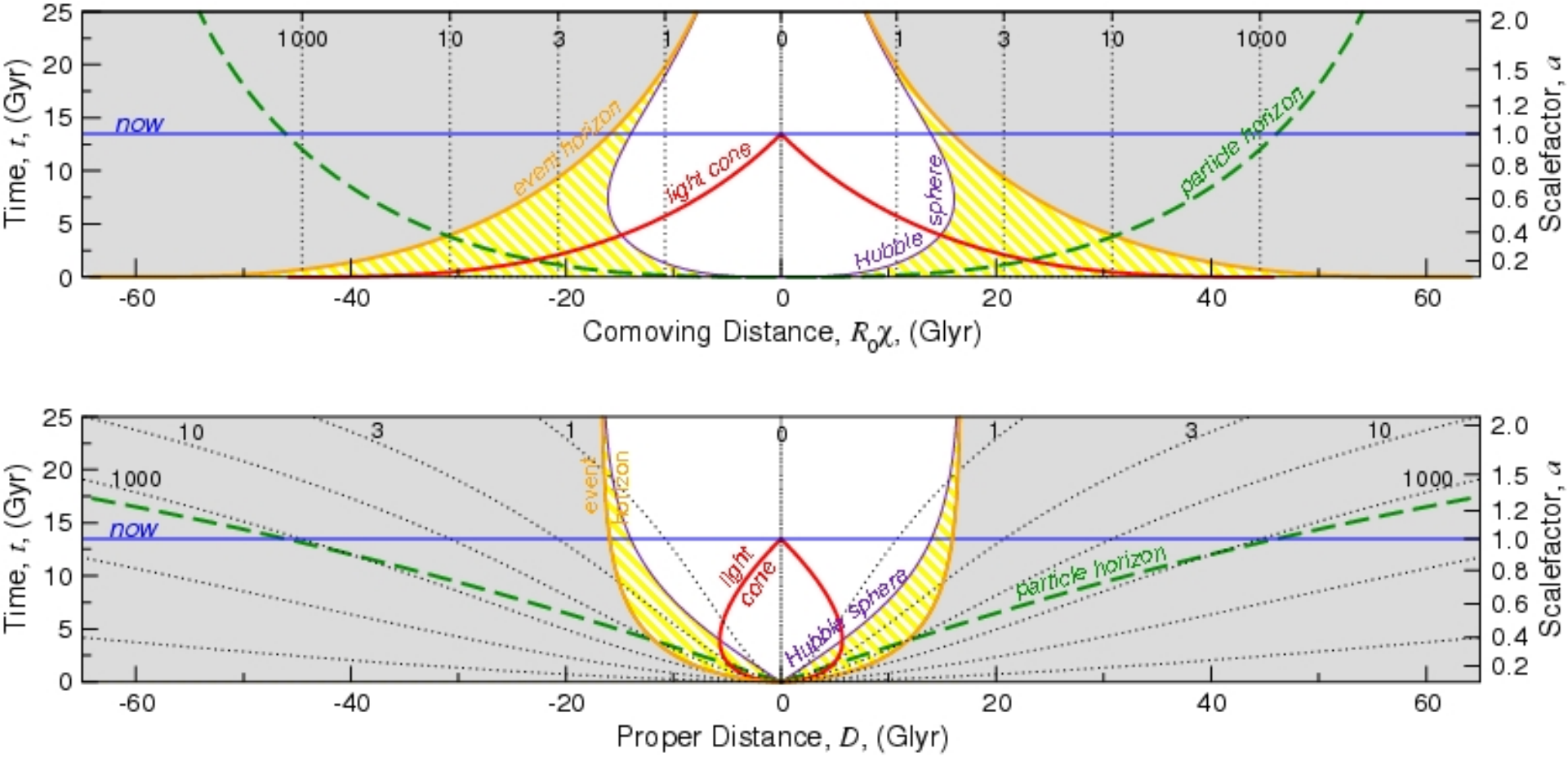
Shine a torch

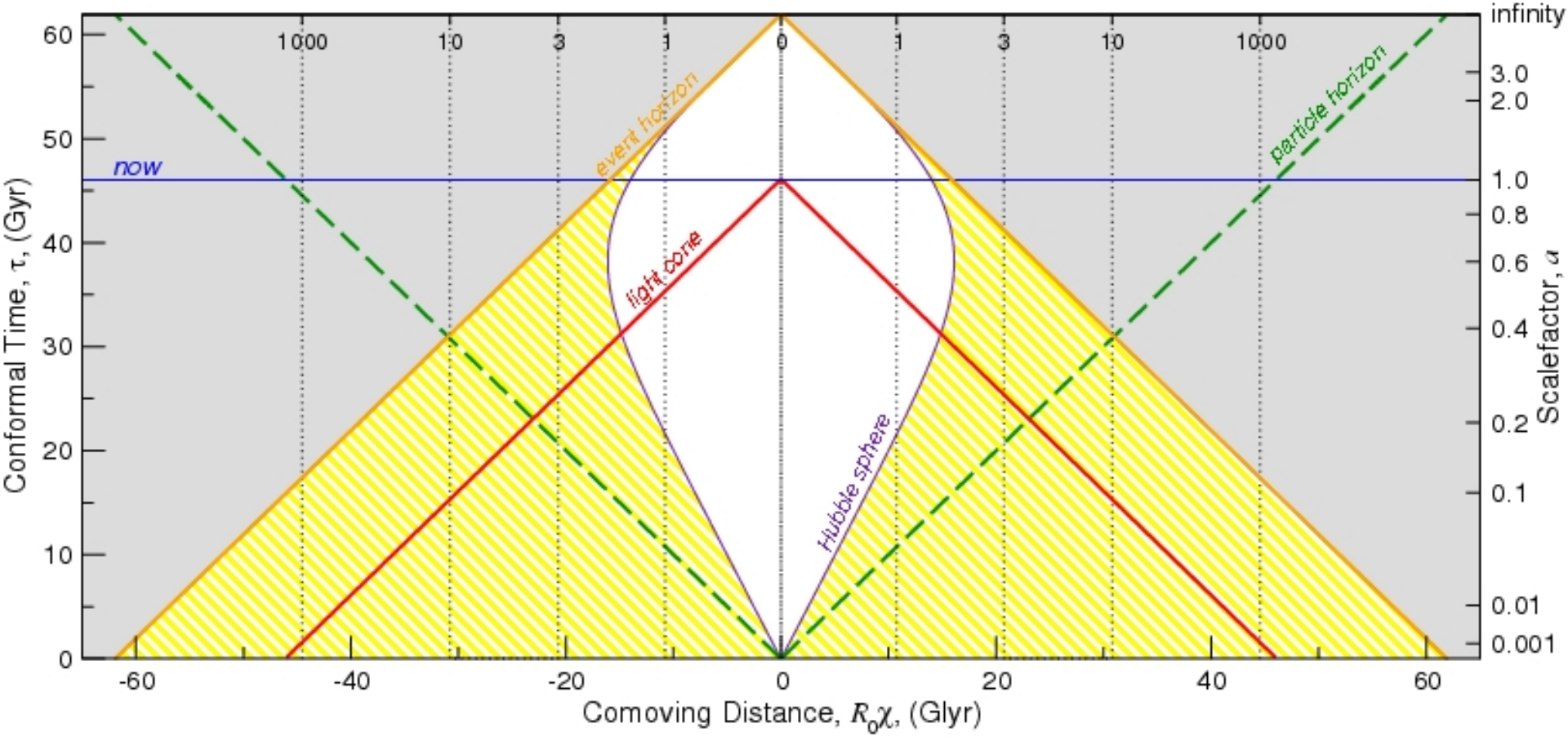
- How far will the light reach?



Objects we can see at a particular time

Event we can see at a particular time


Time, t, (Gyr)
Scalefactor, a
Comoving Distance, $R_0\chi$, (Glyr)
now
event horizon
light cone
Hubble sphere
particle horizon
1000
10
3
1
0
1
3
10
1000
Proper Distance, D, (Glyr)



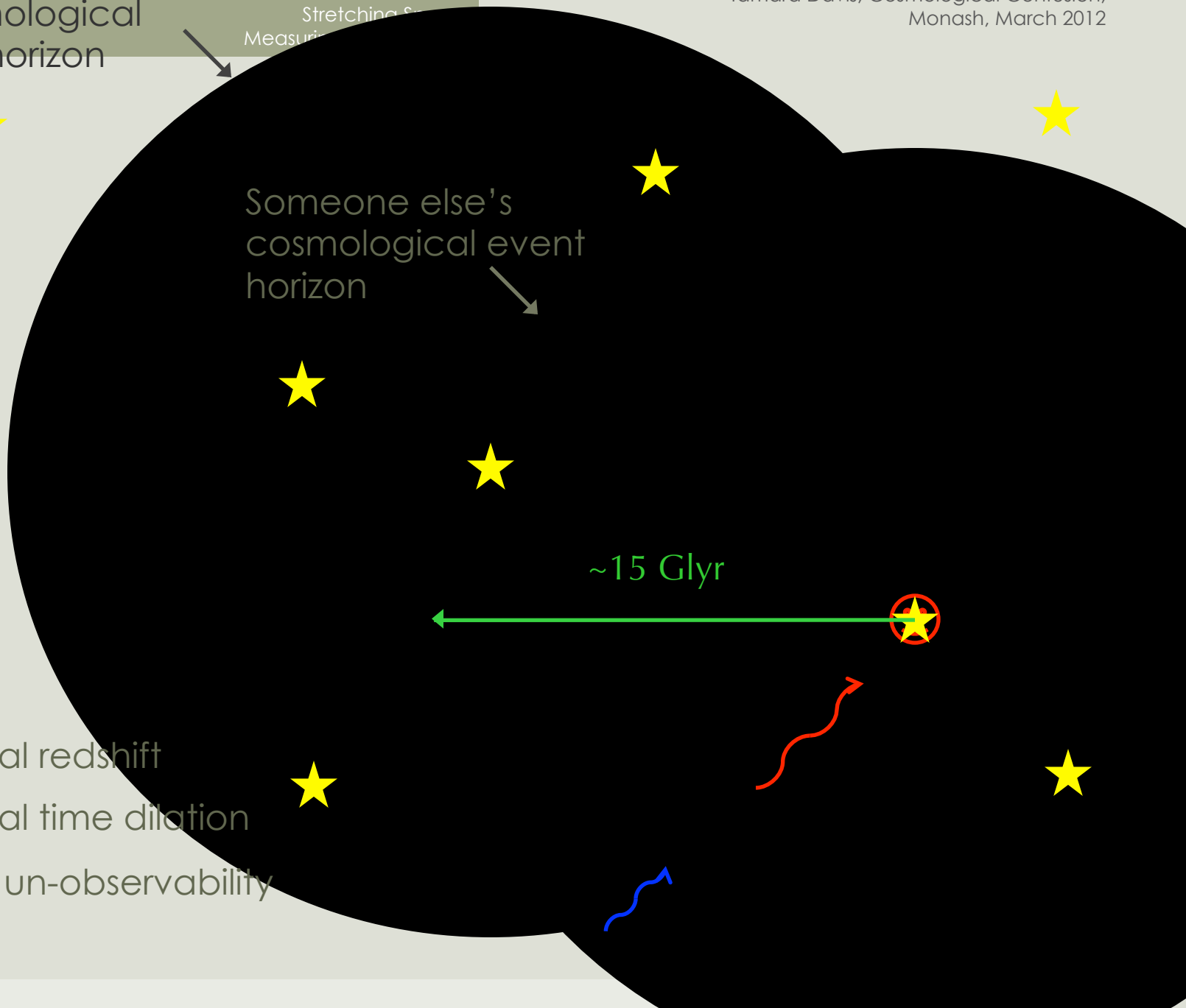
$$ds^2 = R^2(t)\ [\ -c^2dt^2 + d\chi^2 + S_k^2(\chi)(d\theta^2+\sin^2\theta\ d\phi^2)\ ]$$

gravitational redshift

gravitational time dilation

redshift into un-observability

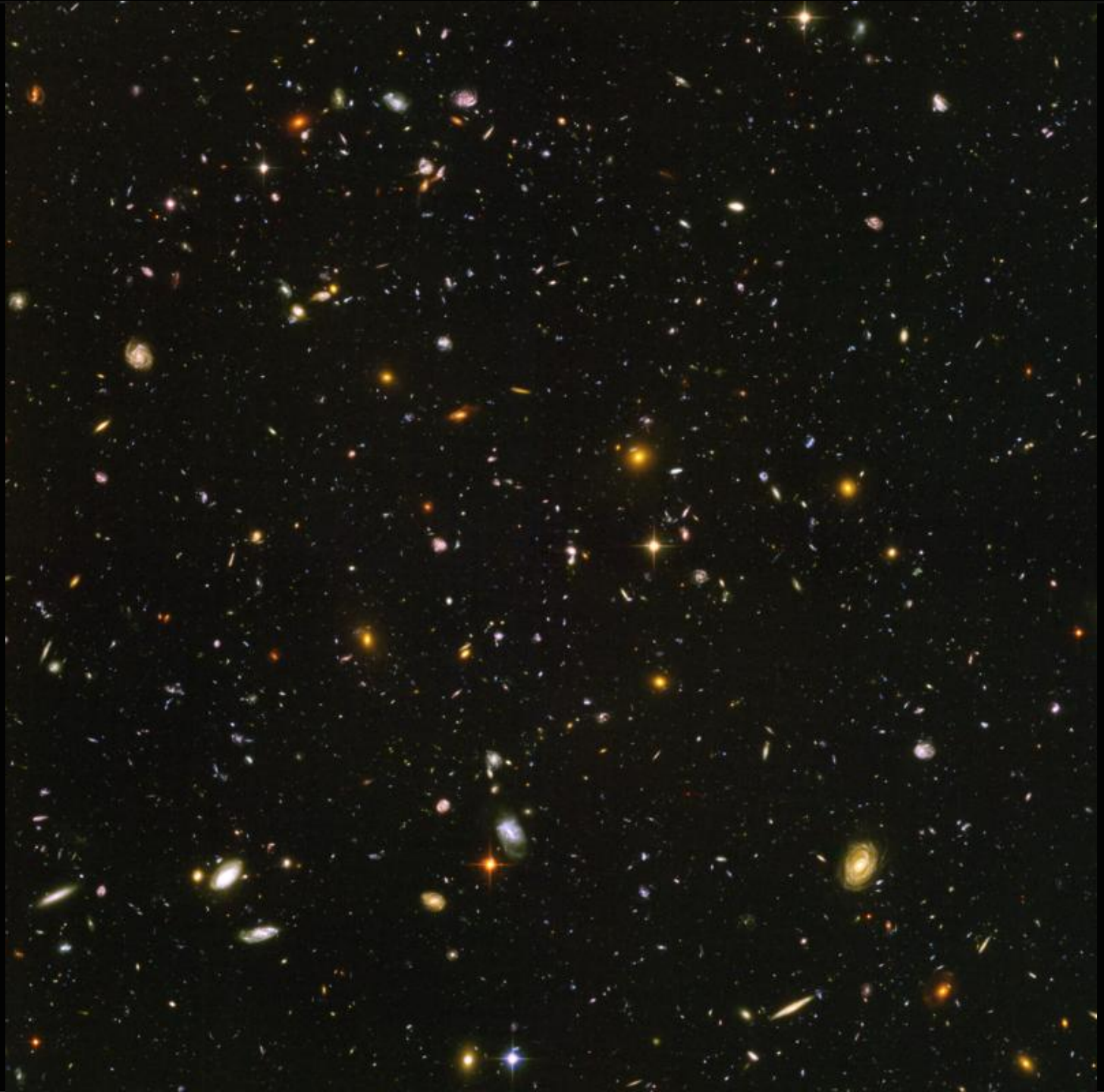
Our cosmological event horizon



cosmological redshift

cosmological time dilation

redshift into un-observability



Do all universes have event horizons?

- No.
- Only eternally expanding and accelerating universes

$$\frac{H^2}{H_0^2} = \frac{\Omega_m}{a^3} + \frac{\Omega_k}{a^2} + \frac{\Omega_x}{a^{3(1+w)}}$$