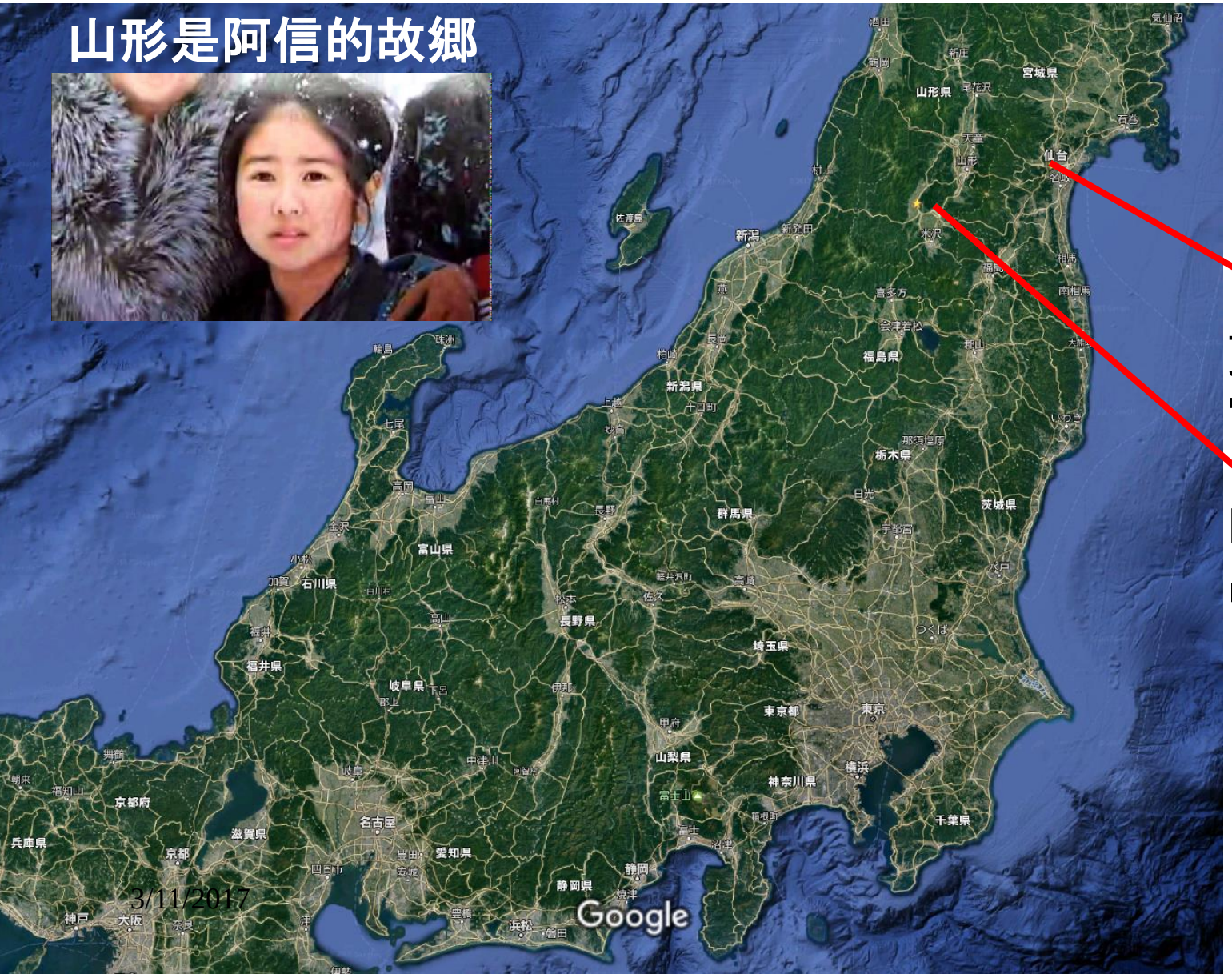
# Gravitational Lensing in the Universe
# 宇宙重力透鏡

梅津 (Umetsu) 敬一 (Keiichi)

中研院天文所 研究員

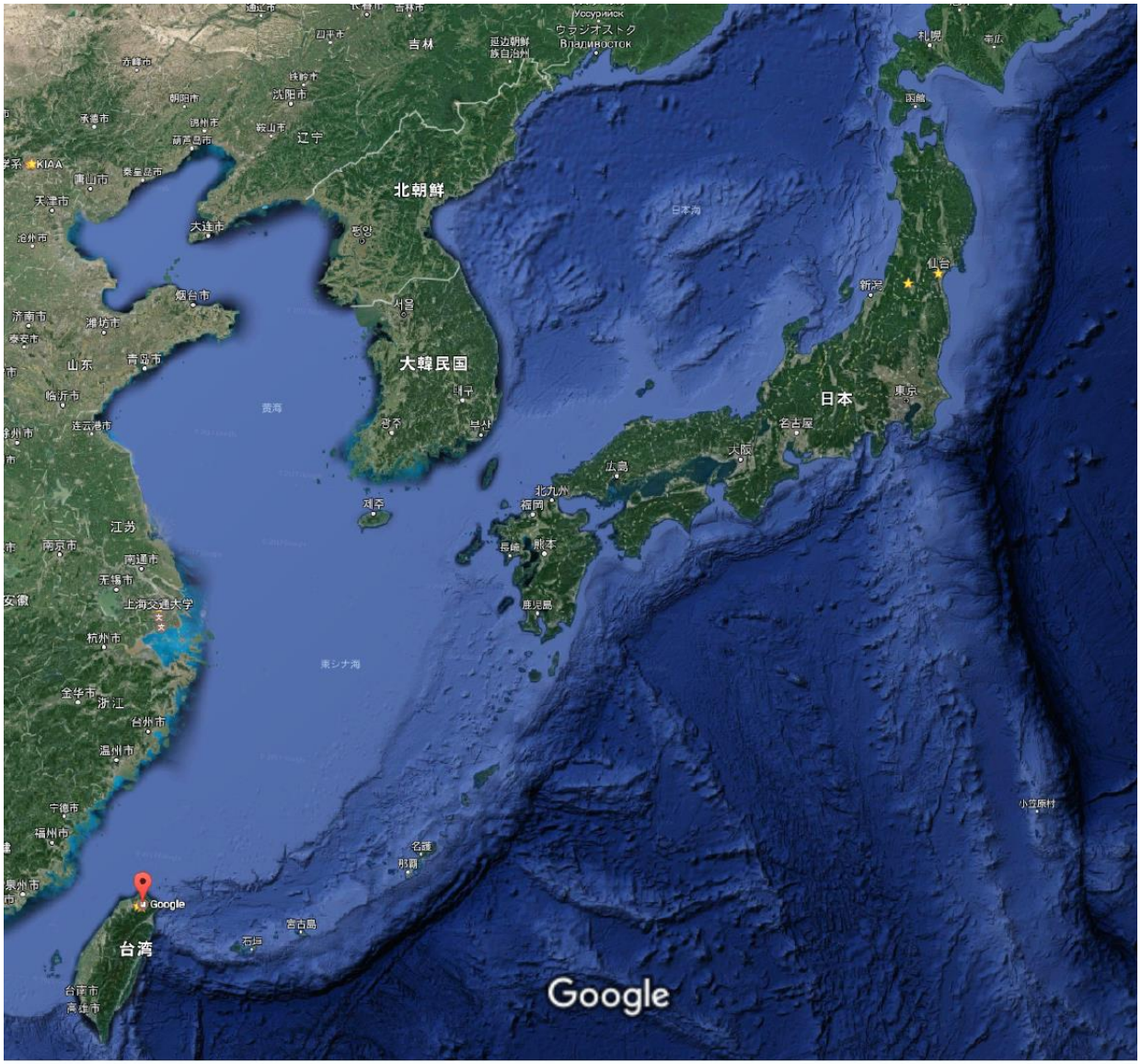
# *Who am I?*

# Where am I from?



# Where am I from?

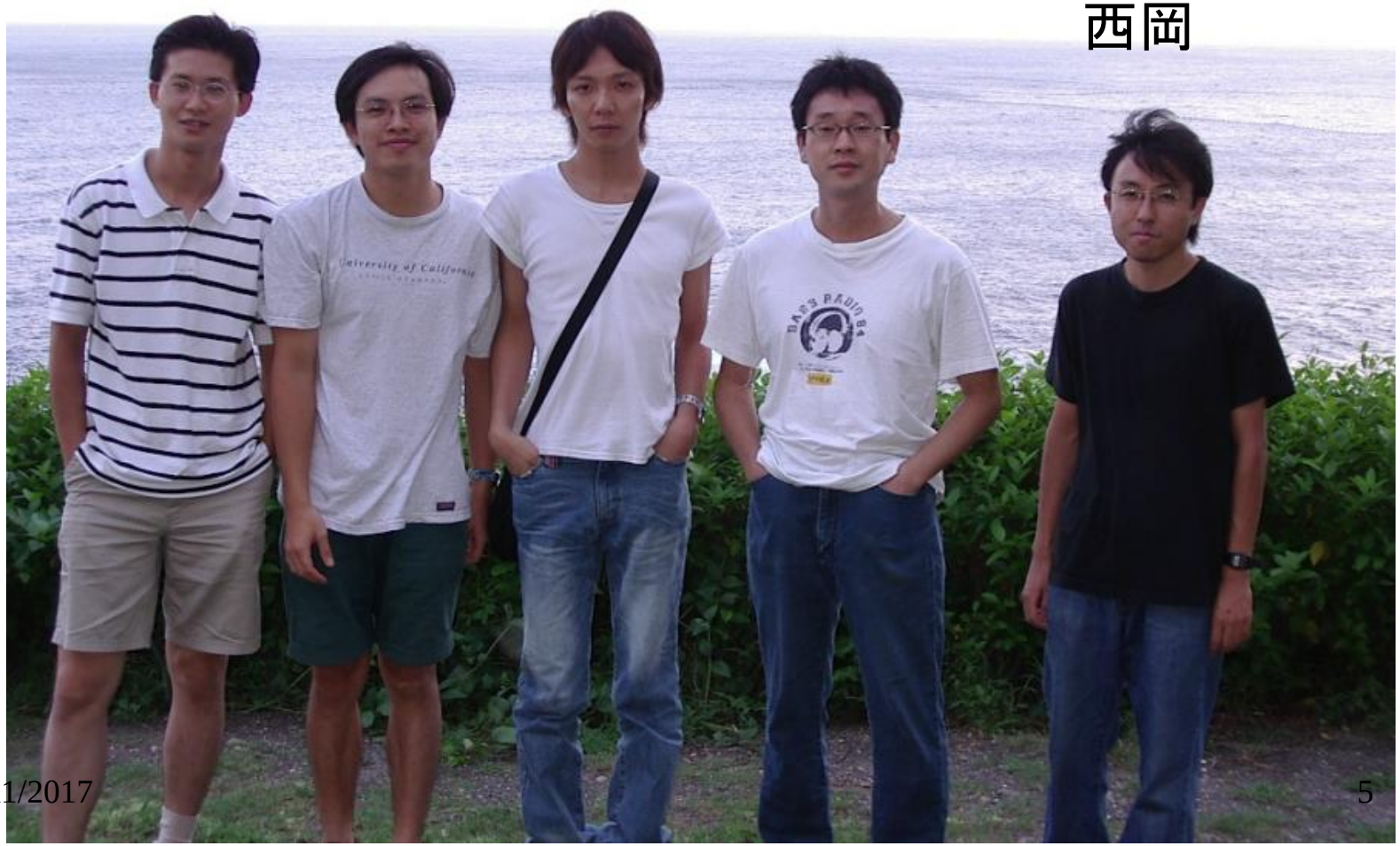
2001年6月、我移到台湾来



# Looking back to 2003 (14年前)..

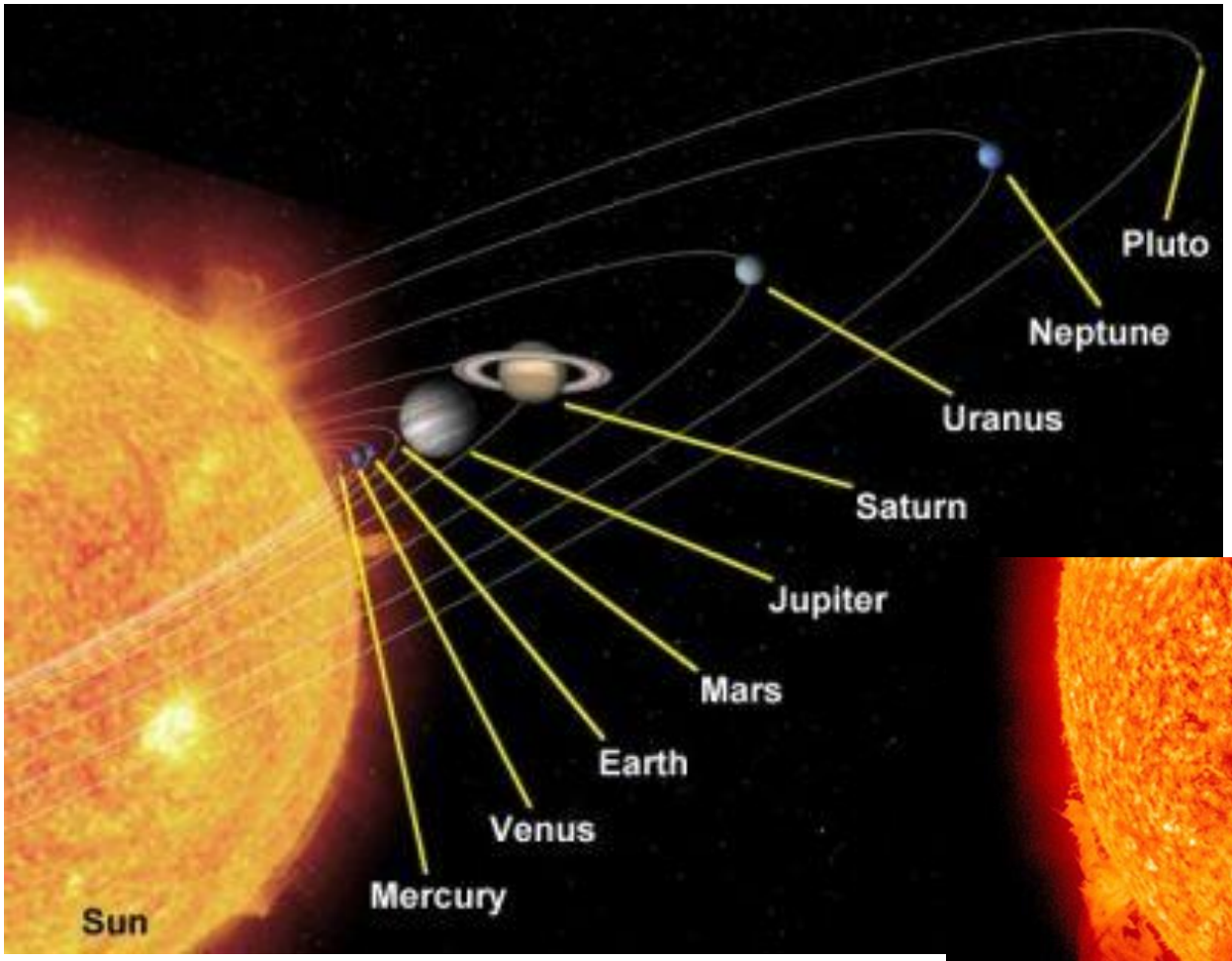
副所長

西岡

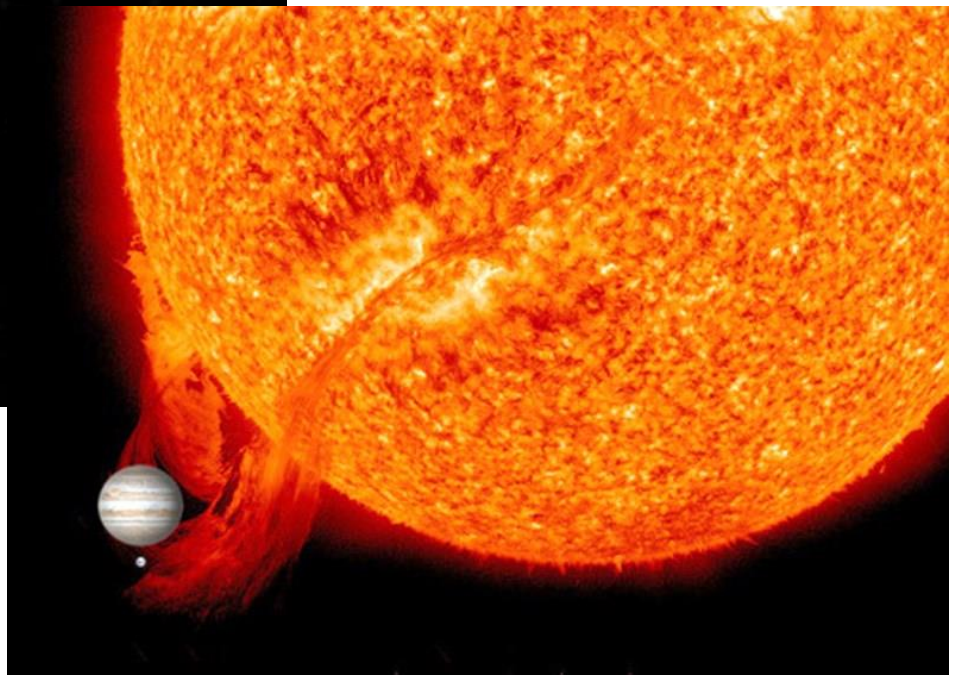


***Where are we?***

# Where are we? – Solar system (太陽系)

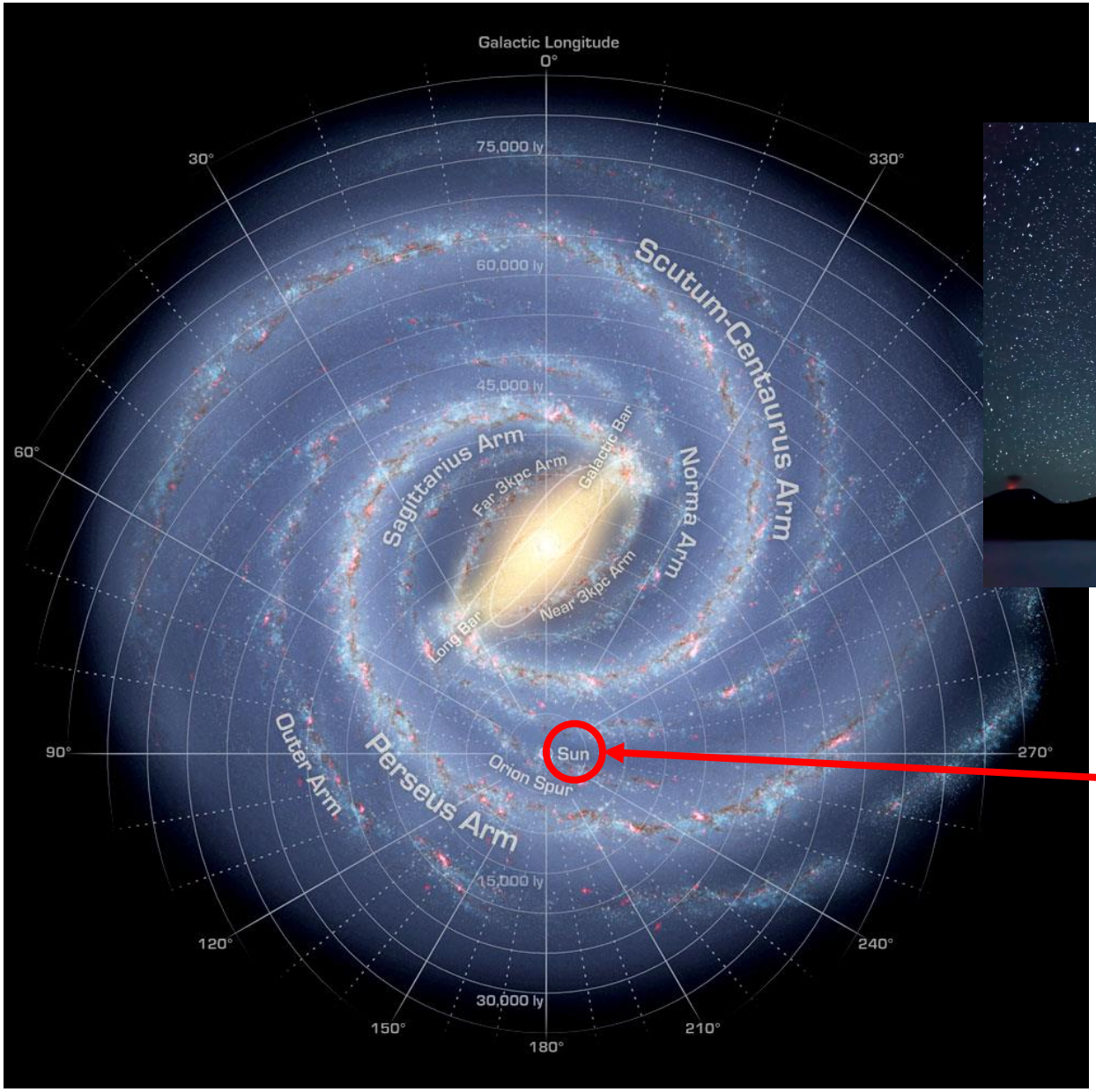



太陽>>木星>>地球



光速度是有限的: 30万km/h
光由太陽到地球的時間: 8分20秒

# Where is the solar system? – Milky Way




Milky Way (銀河系)

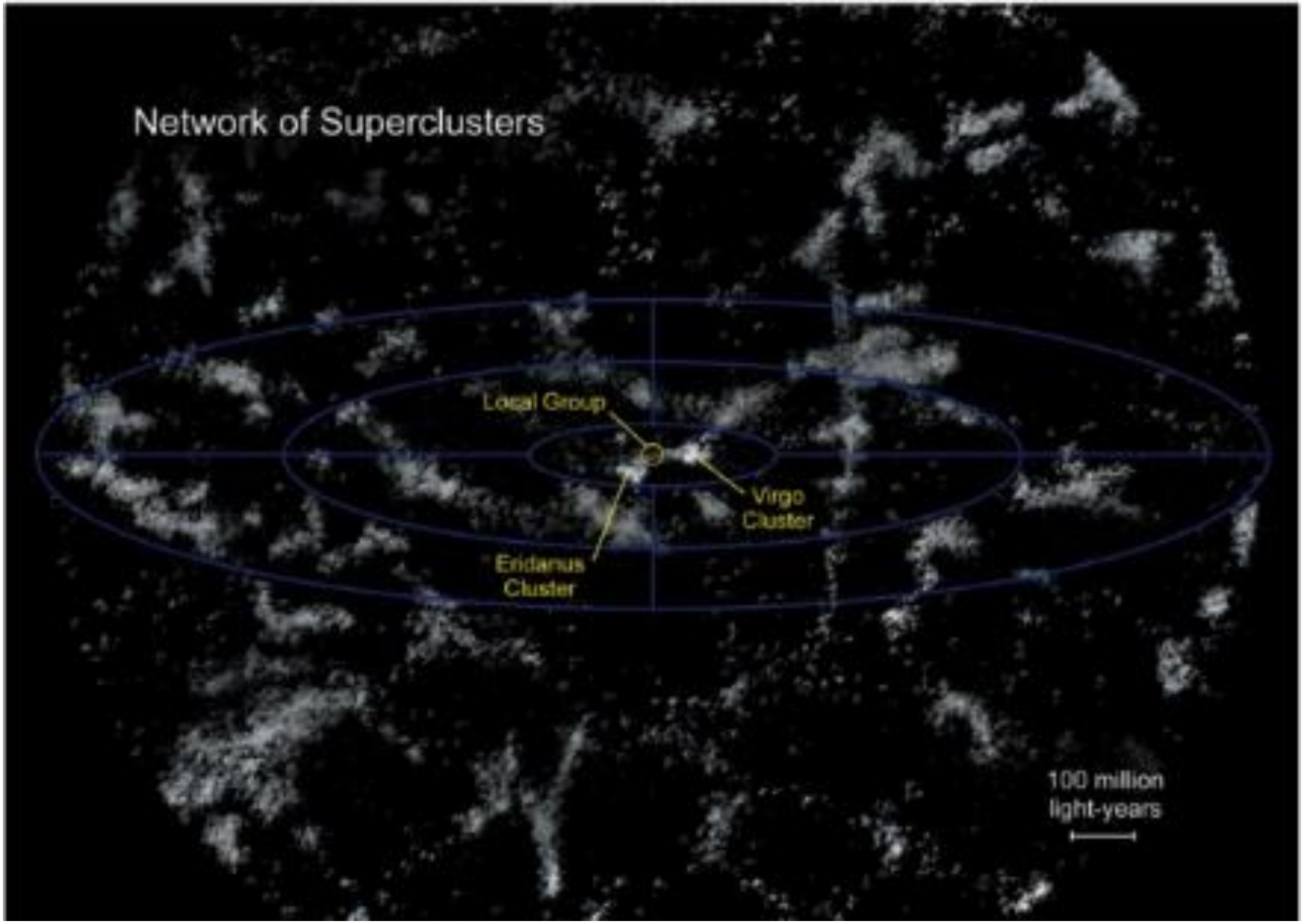
太陽系

由銀河中心到太陽系:
2.5万光年的距離

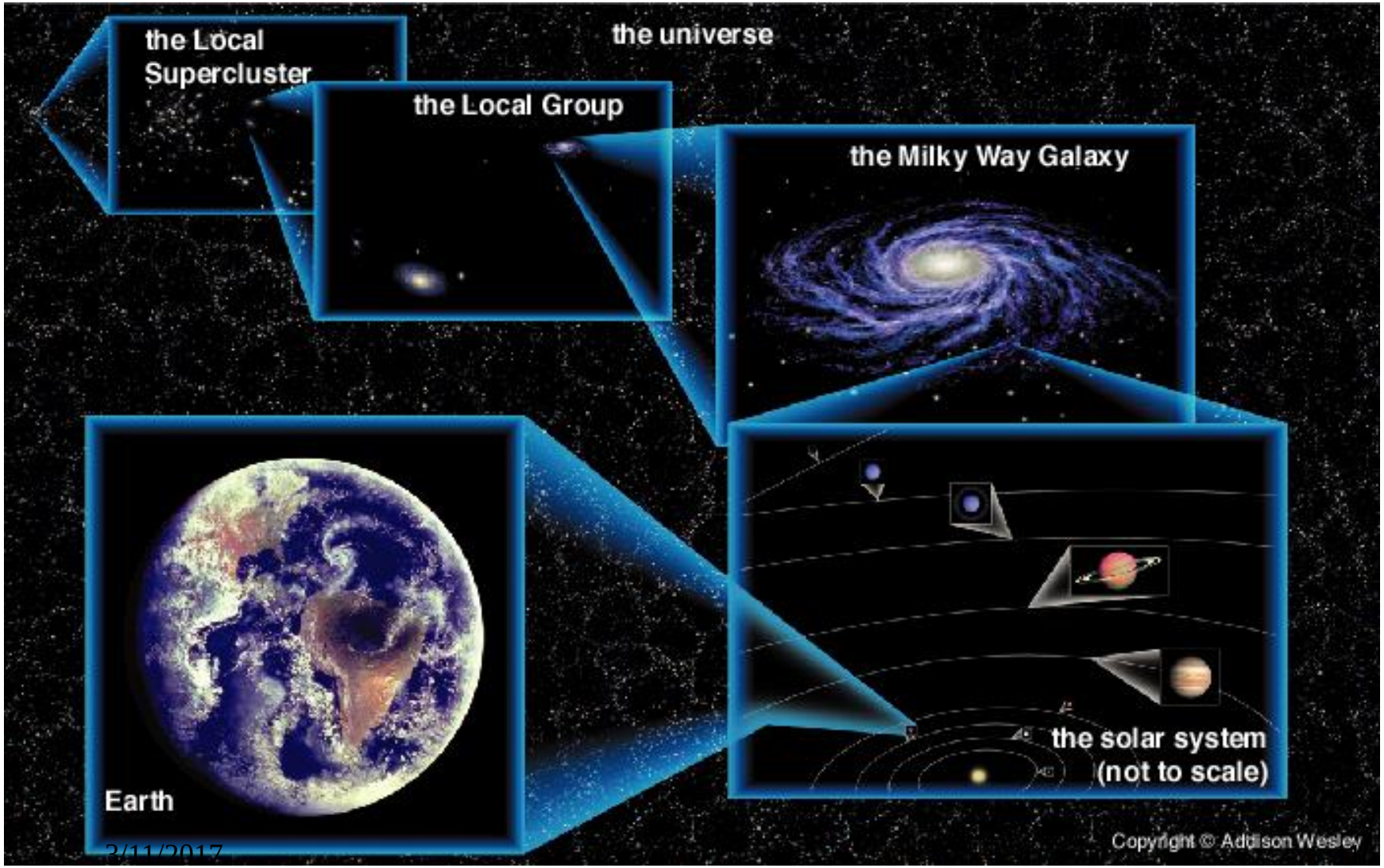
# Where is our Galaxy? – Local Group

Local Group (星系群): our 隣居

# Local superclusters (超星系団)

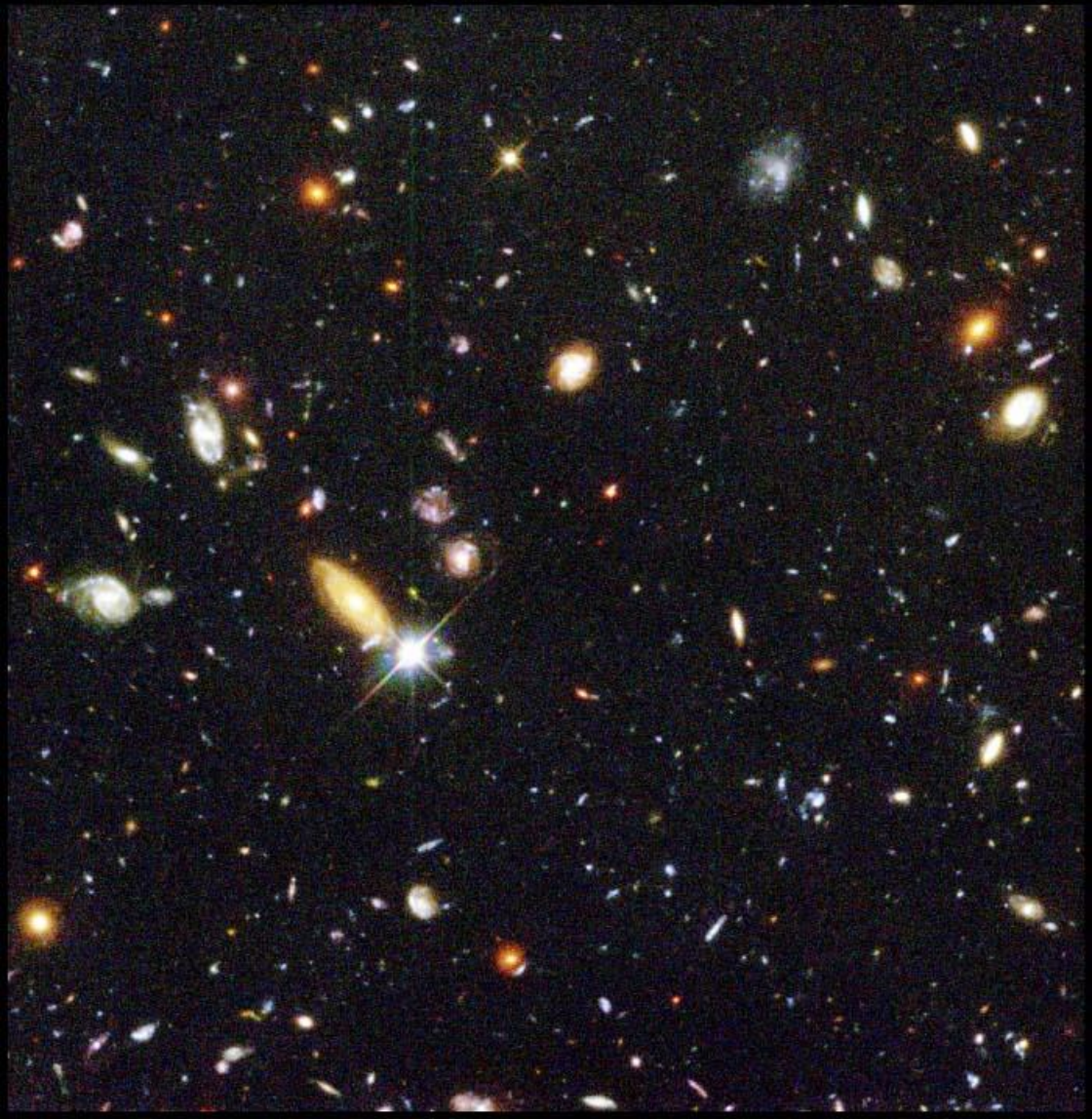


# 宇宙階層結構


the universe
the Local Supercluster
the Local Group
the Milky Way Galaxy
the solar system (not to scale)
Earth
Copyright © Addison Wesley

*Now looking into the sky*

# Many² Distant Galaxies (遠星系)




Hubble Space Telescope (HST)

# *Clusters of Galaxies* (星系团)

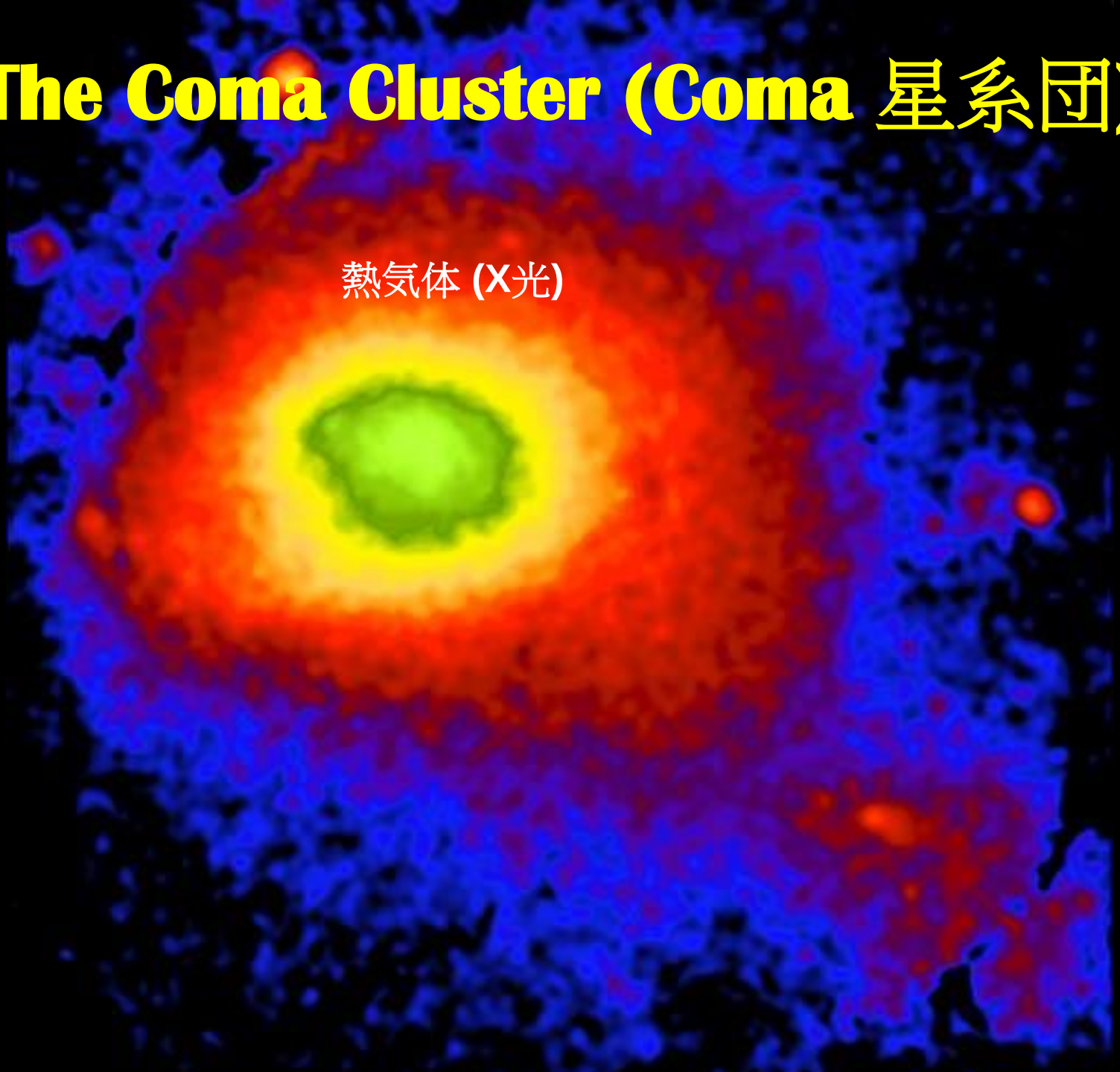

Cluster A1689

# Clusters of Galaxies (星系团)


Cluster A2744: Massive merging cluster

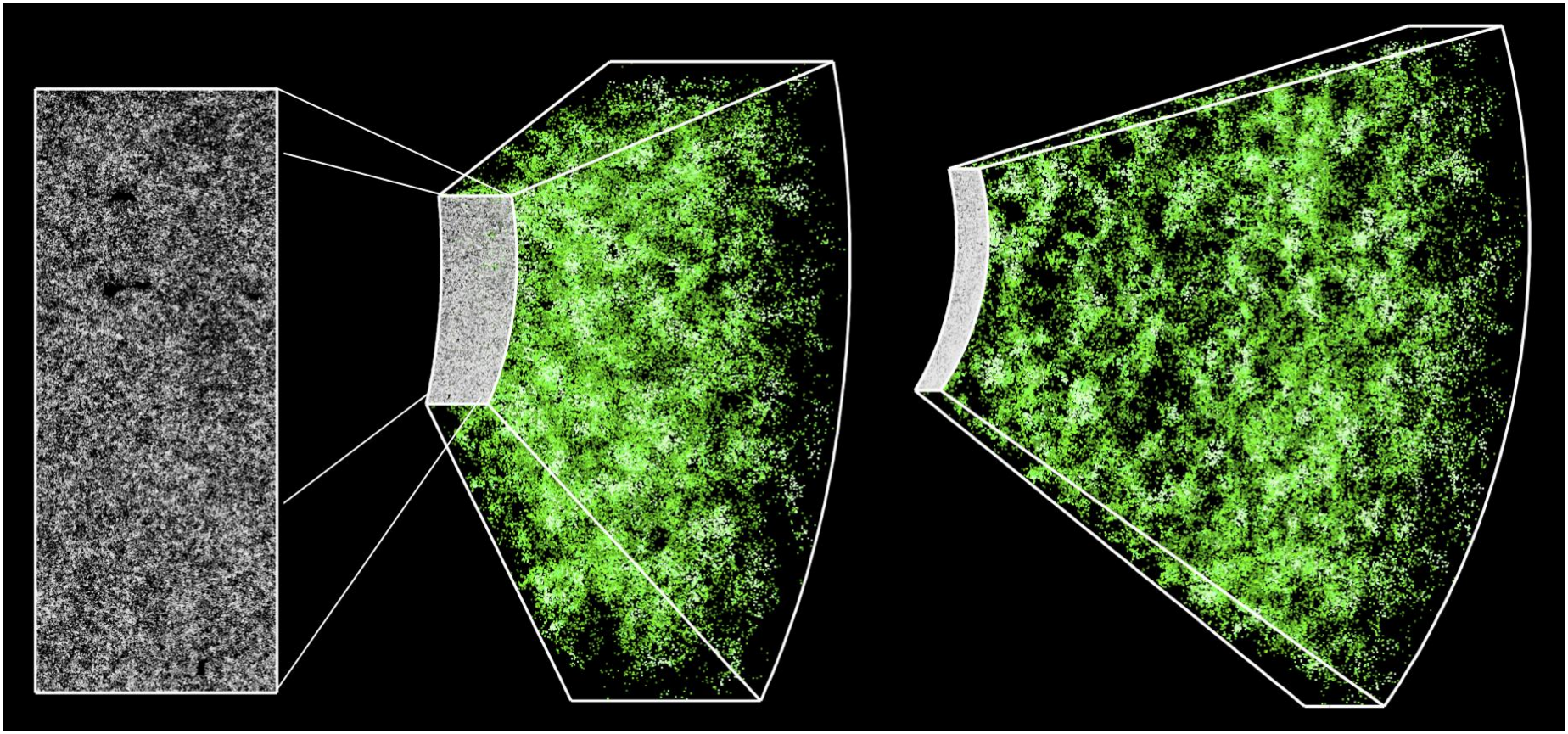
# The Coma Cluster (Coma 星系团)

# The Coma Cluster (Coma 星系団)



# 3D星系分布地図: 大尺度結構

12万星系在1000平方度内(SDSS/BOSS観測計画)



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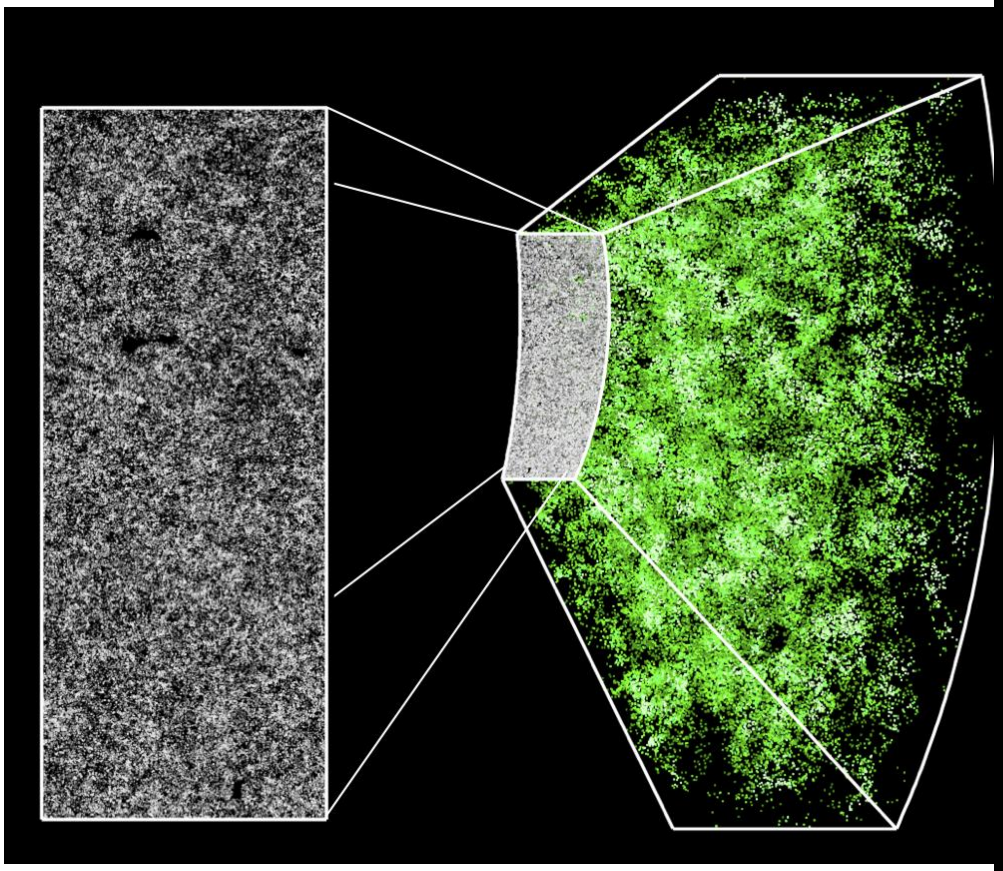
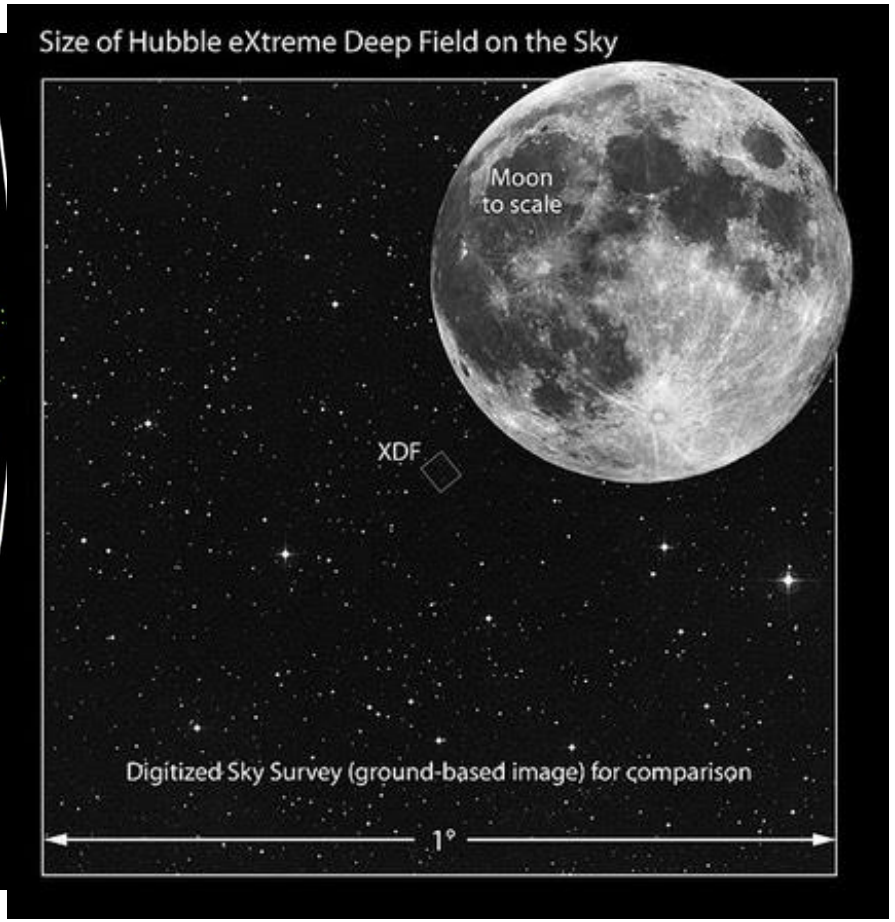
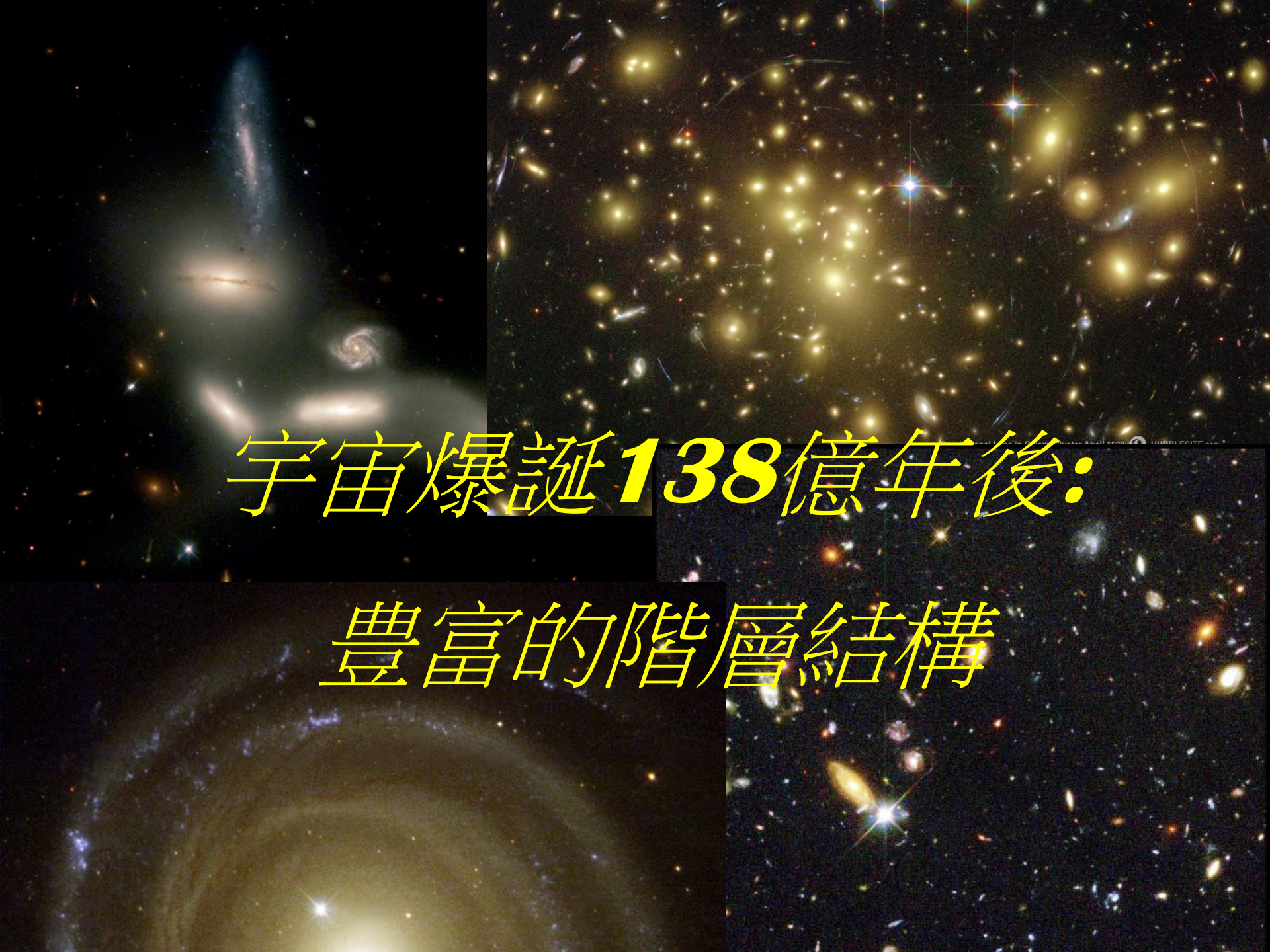


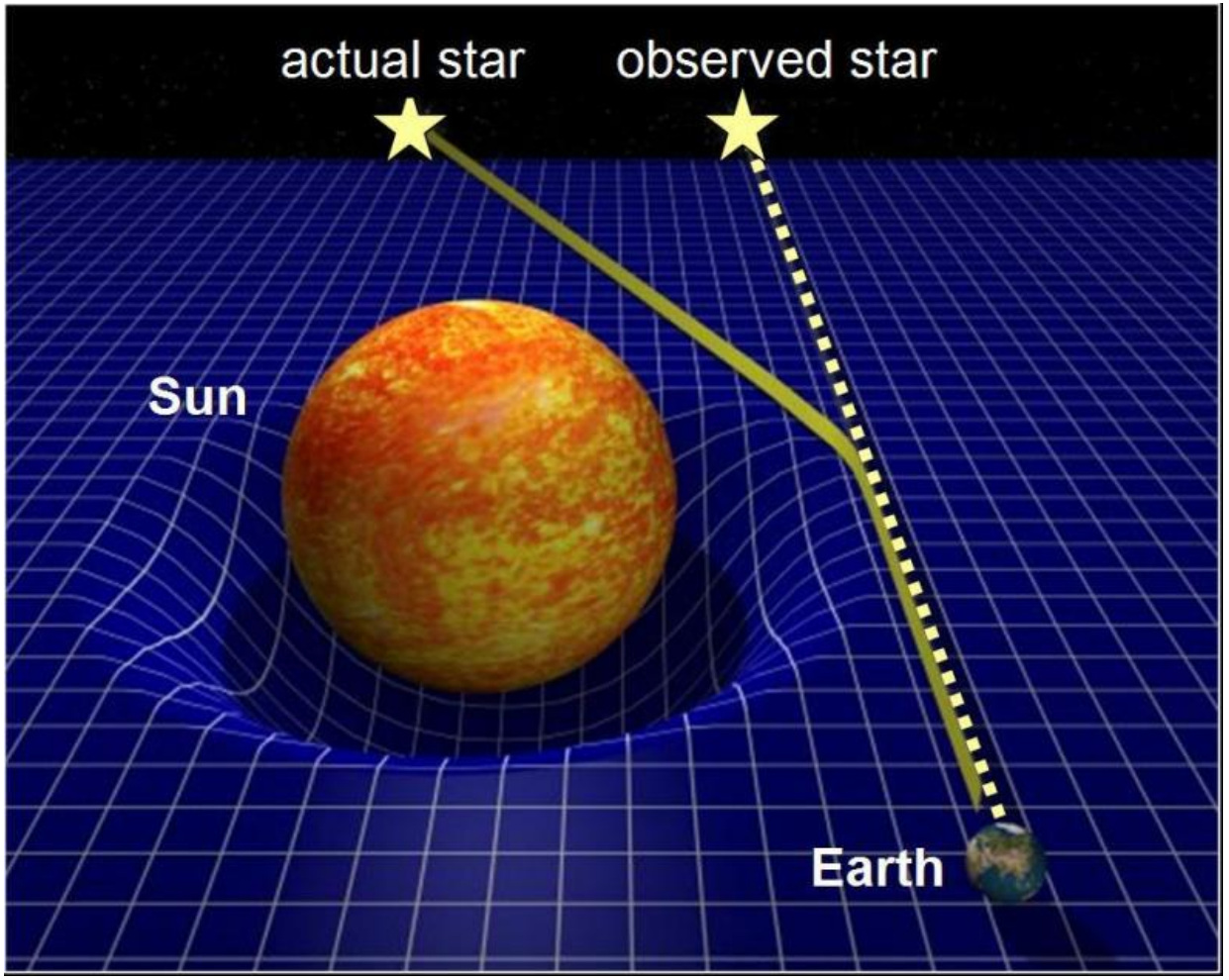



宇宙爆誕138億年後:
豊富的階層結構

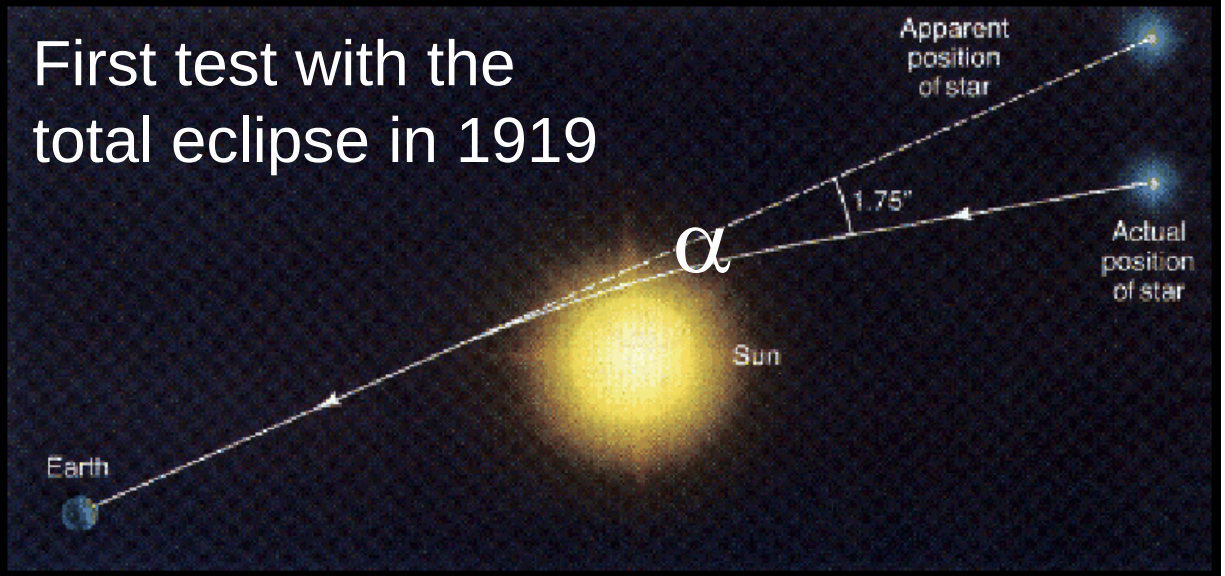
# 重力透鏡現象

# Gravitational Bending of Light

Einstein's 重力理論 (相対論): Mass distorts space-time (時空), and light follows a curved path (geodesic).



# The Bending of Light

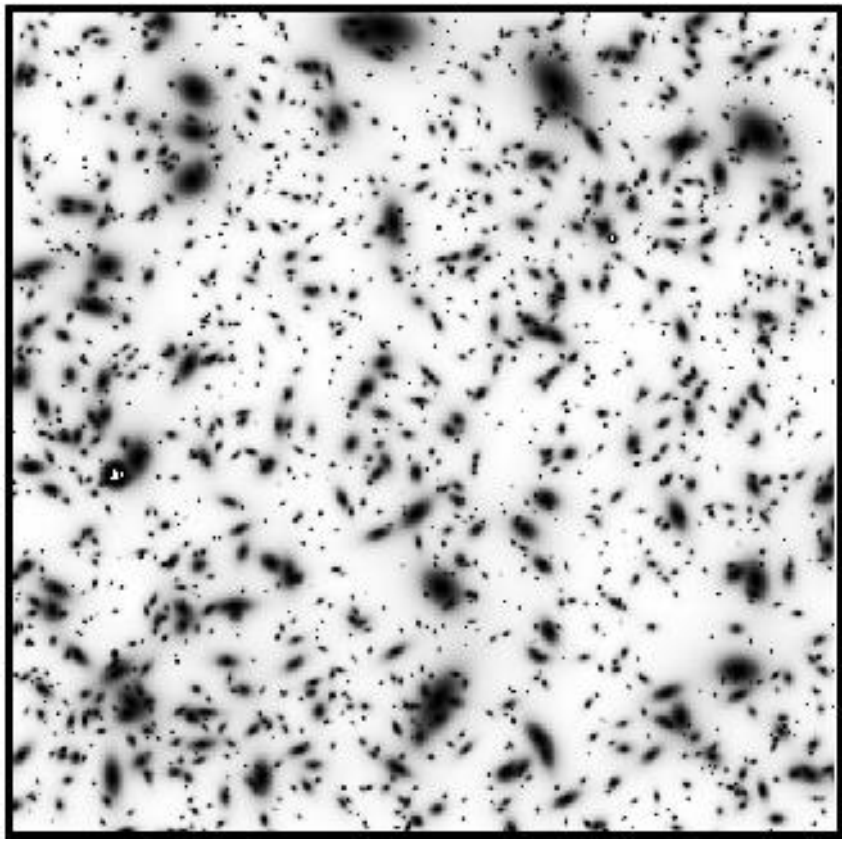



$$\alpha^{\mathrm{GR}} = 2\alpha^{\mathrm{Newton}} \approx \frac{4GM}{c^2 r} = 1.''75\left(\frac{M}{M_{sun}}\right)\left(\frac{r}{R_{sun}}\right)^{-1}$$

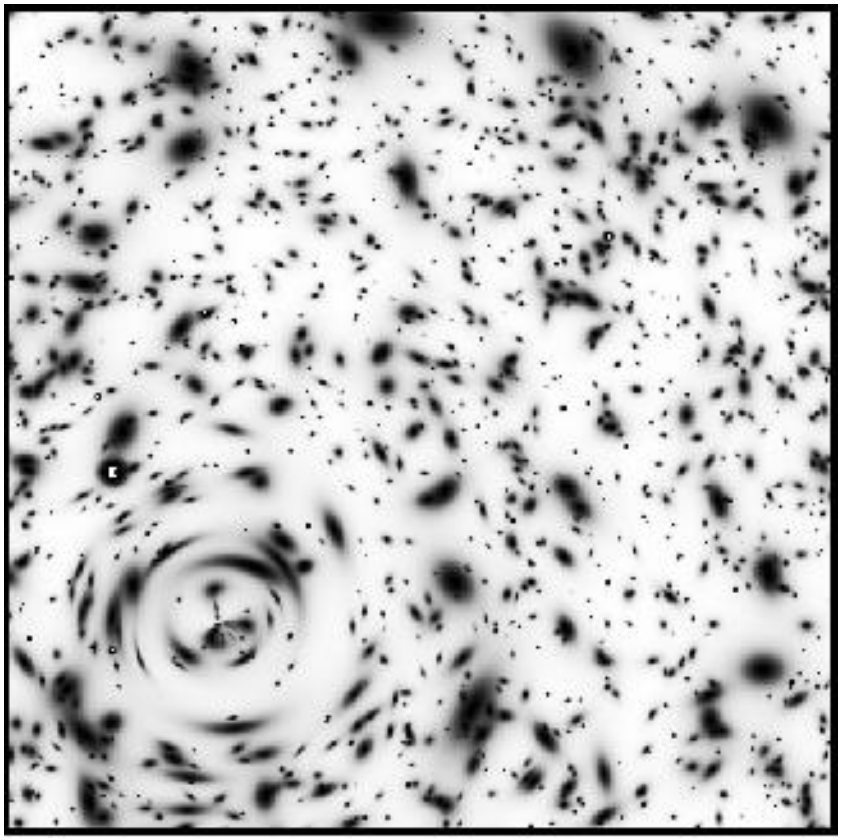
$$1'' = 1/3600\,\mathrm{deg}$$

# 重力透鏡 電腦模擬

**没有重力透鏡**

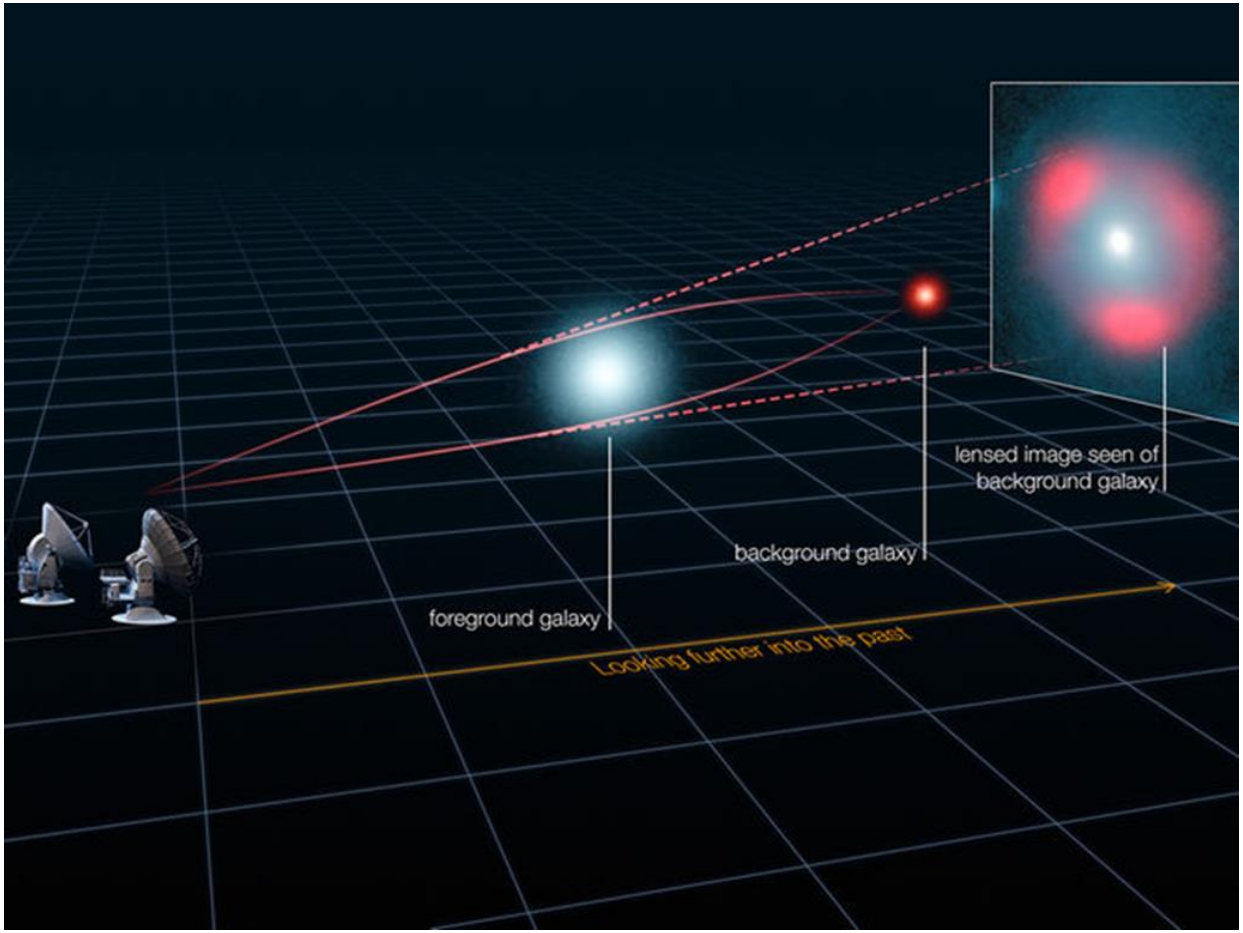


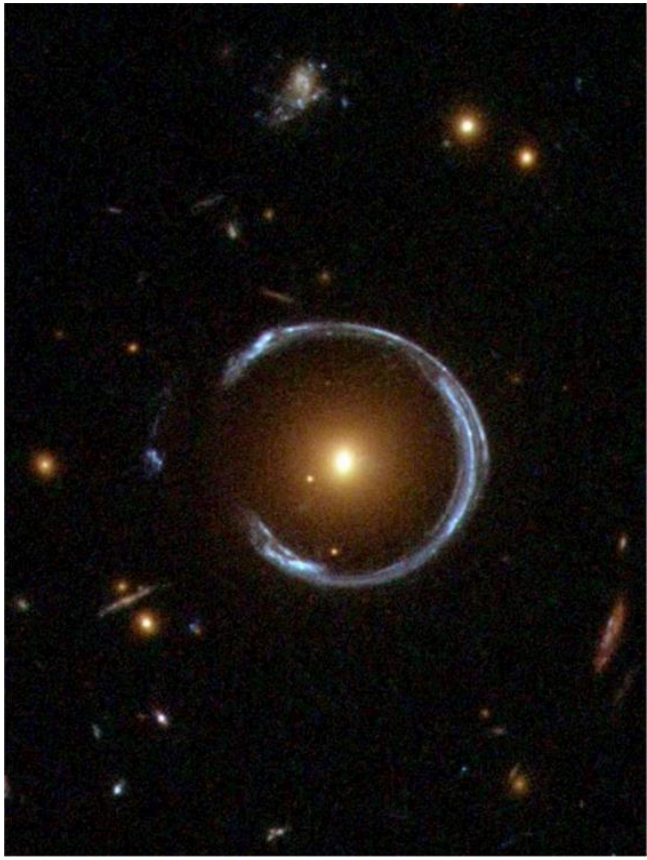
**有重力透鏡**



Computer simulation

# Einstein Ring by 重力透鏡



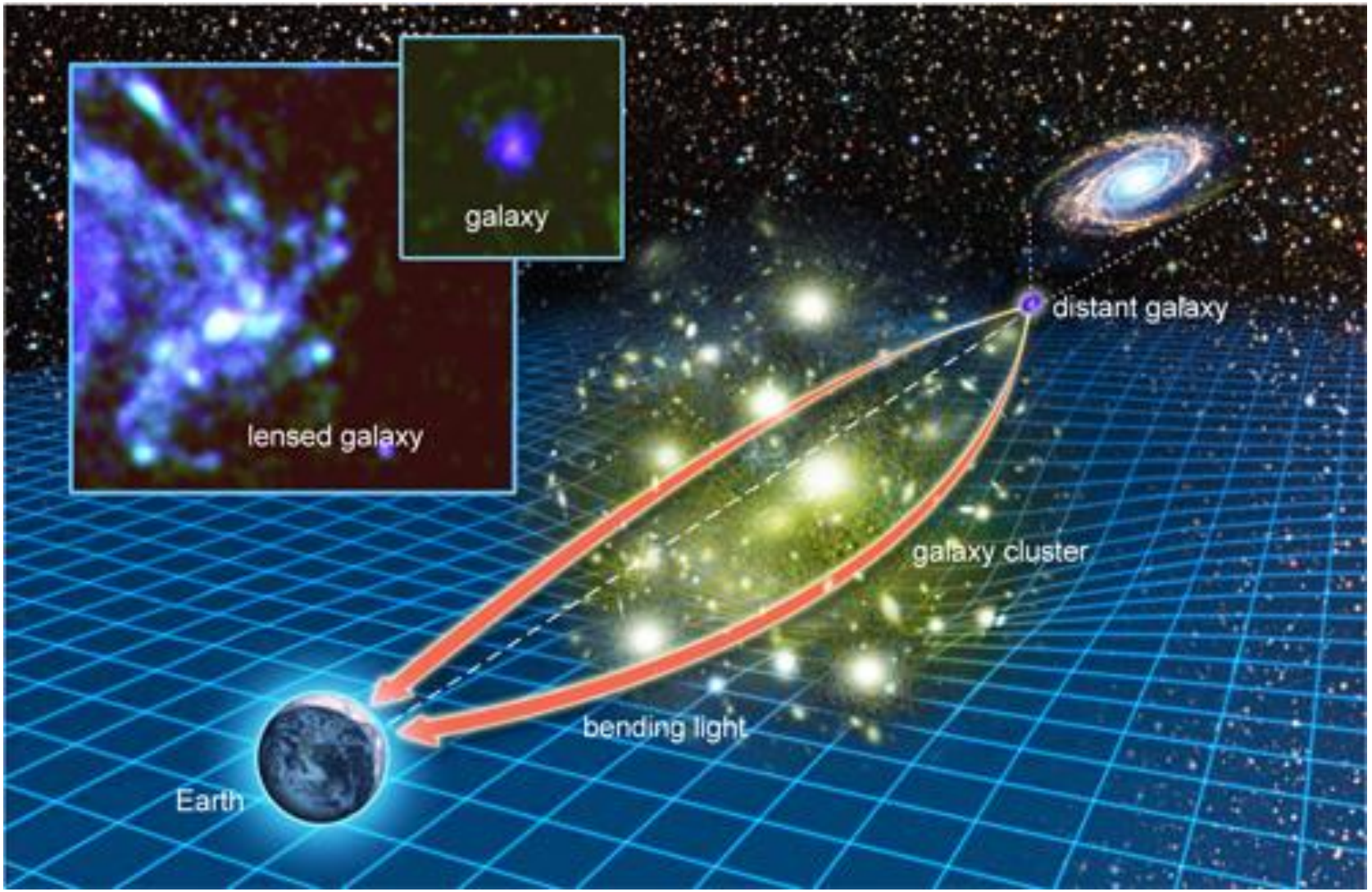



Hubble Space Telescope

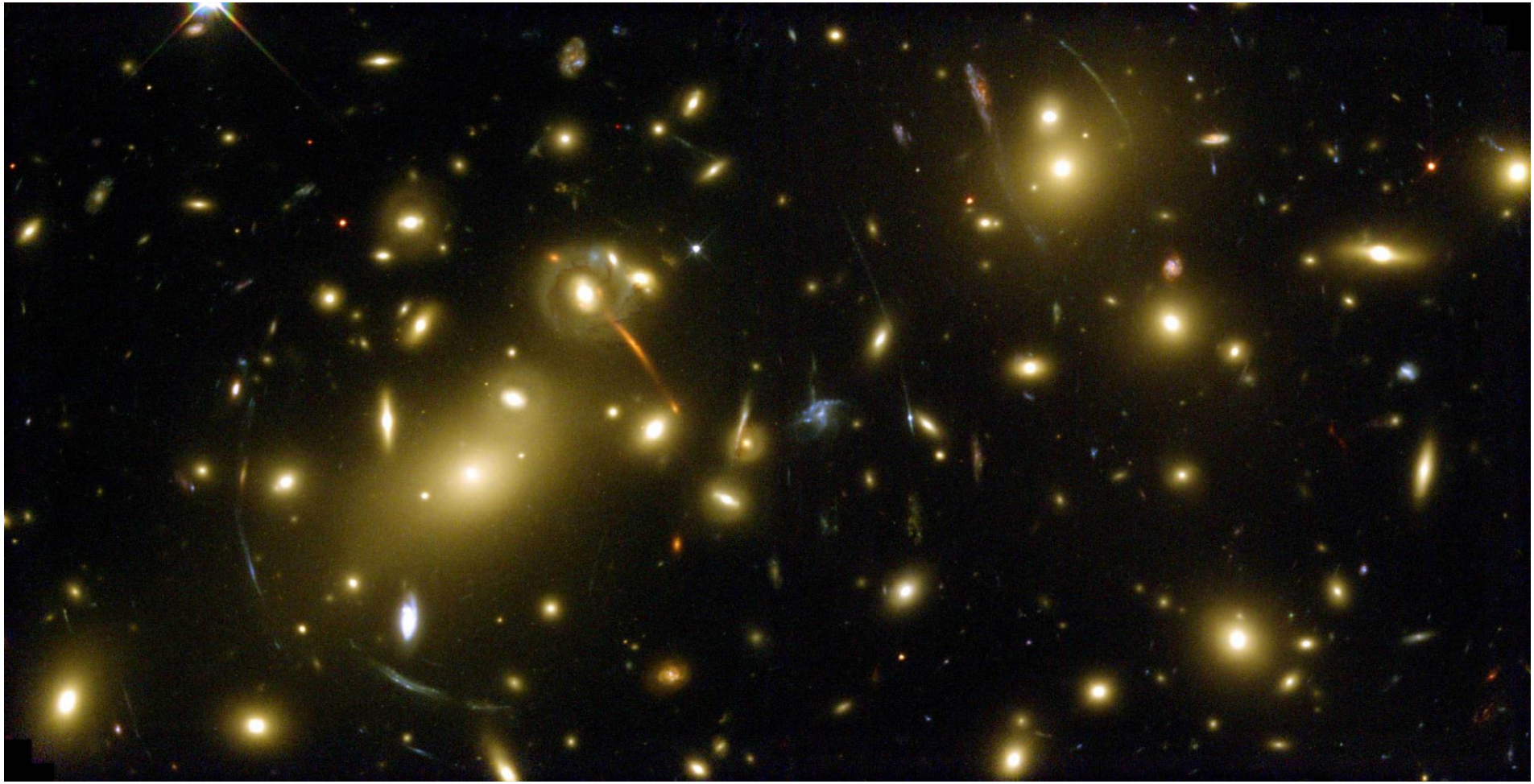
# Einstein Ring Examples

Hubble Space Telescope

# 重力透鏡 by 星系団


galaxy
lensed galaxy
distant galaxy
galaxy cluster
bending light
Earth

# 星系団重力透鏡: Arcs

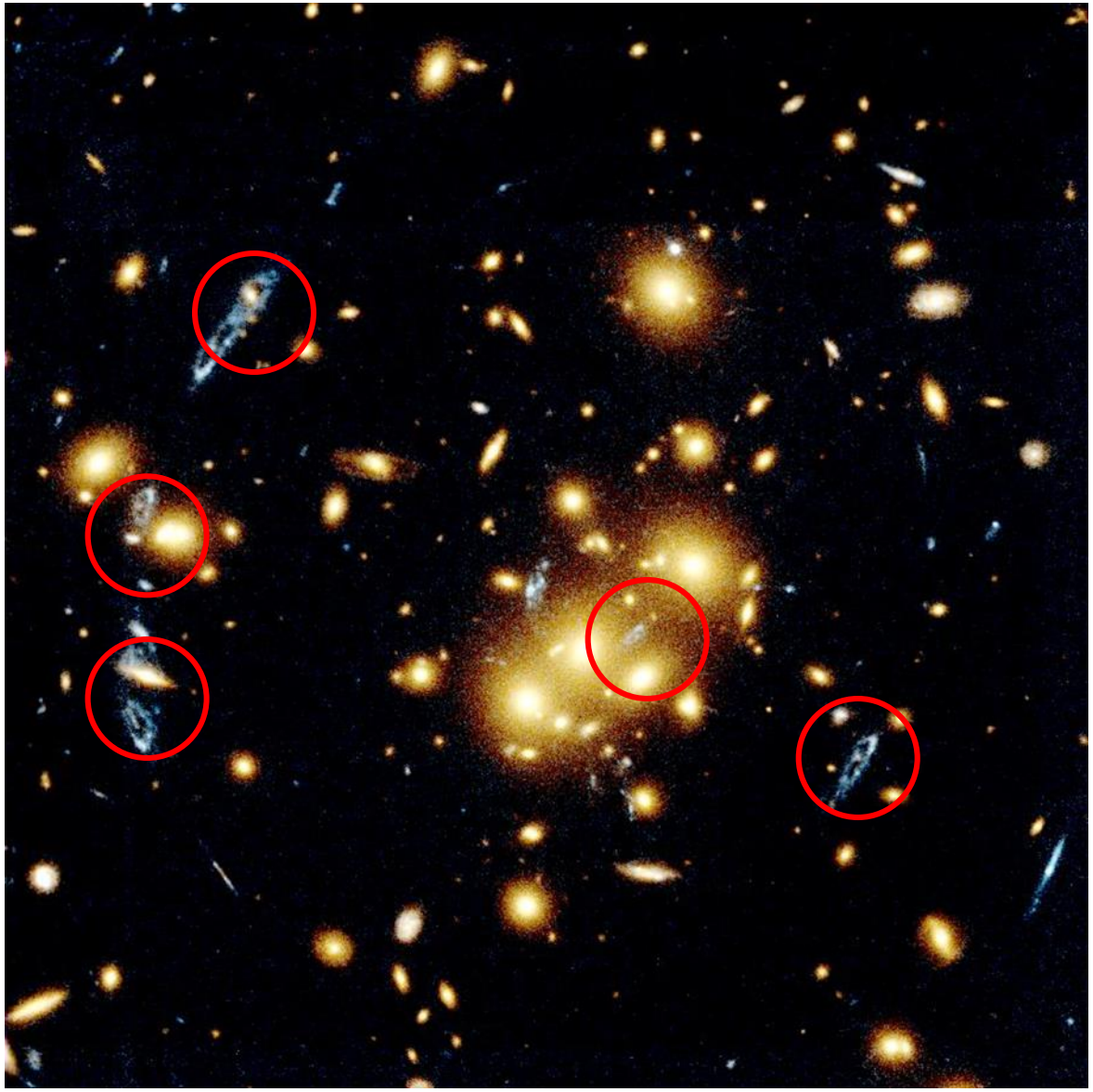


Cluster A2218

# 星系団重力透鏡:多重像

Cluster CL0024+1654

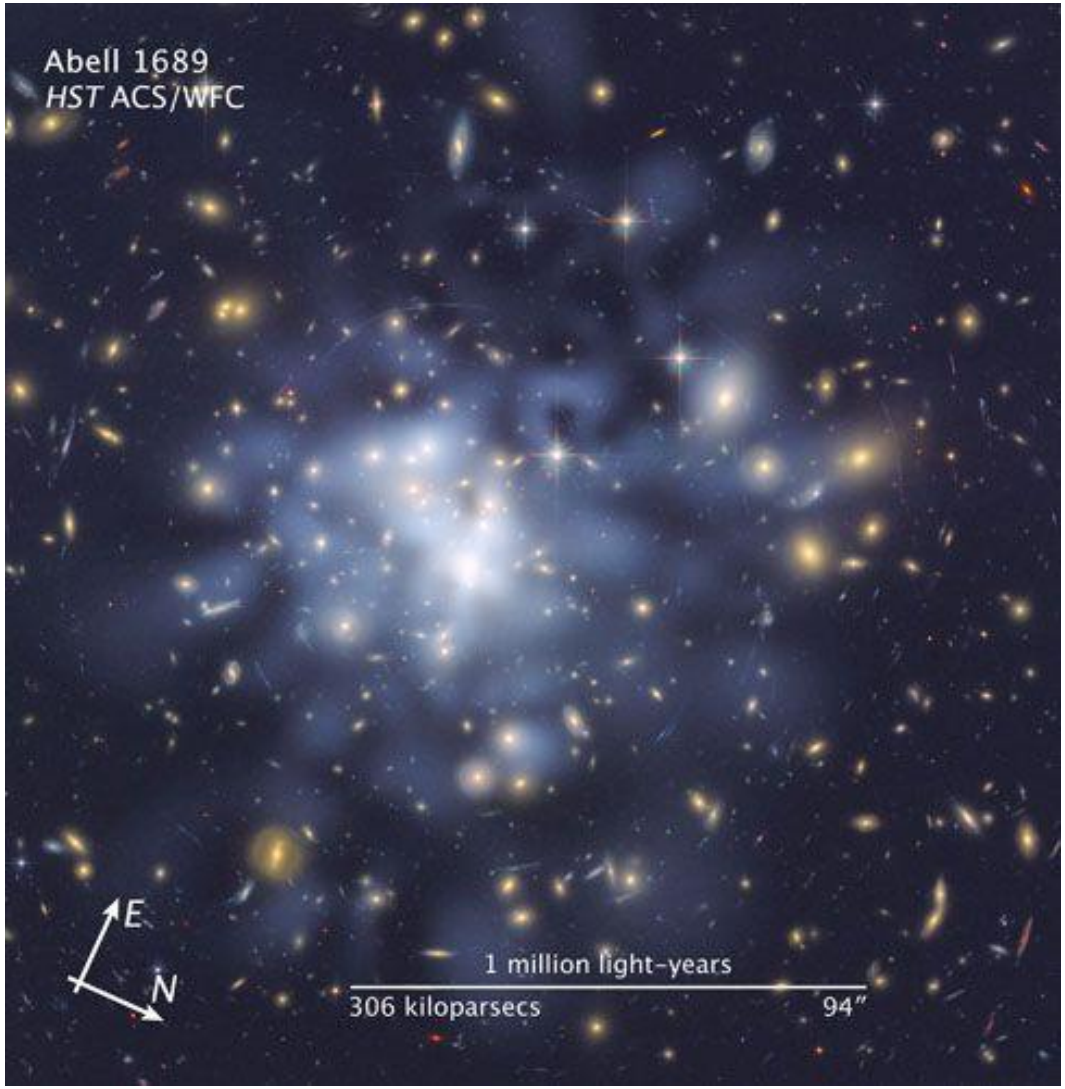
# 星系団重力透鏡: 多重像

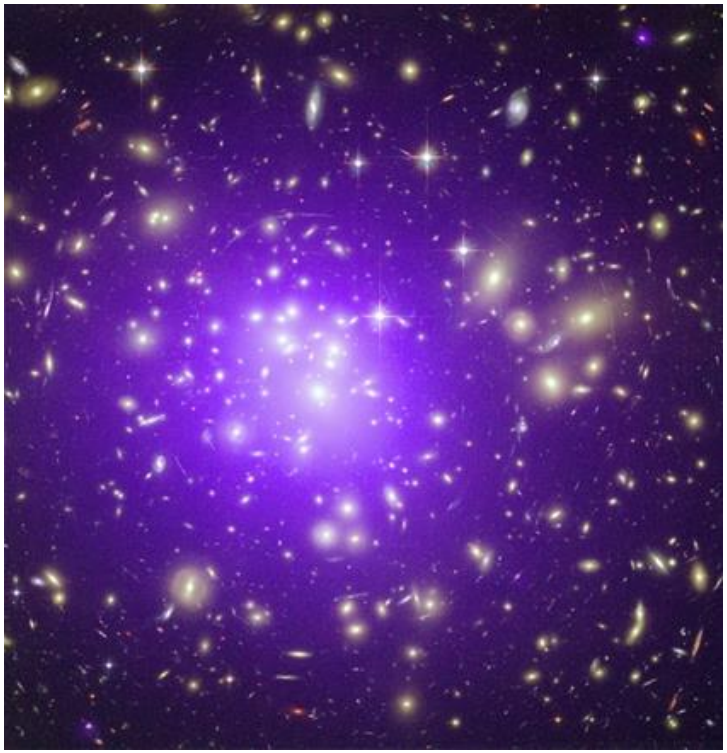


Cluster CL0024+1654

# 星系団重力透鏡: Magnification (増光)

# Seeing the unseen: 暗物質



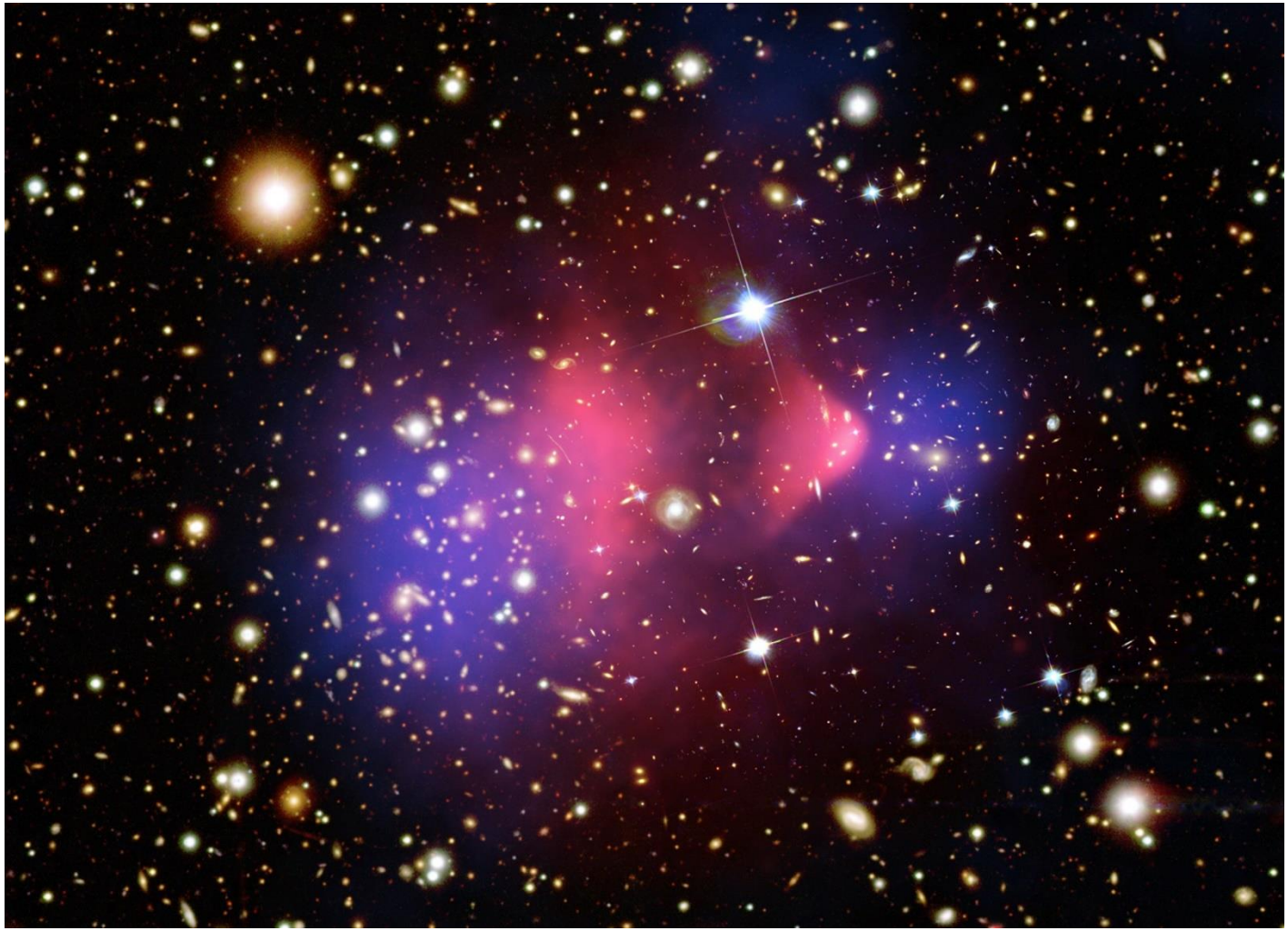



**青**: 熱気体 (X光)

**白**: 暗物質 (重力透鏡)

# Seeing the unseen: 暗物質

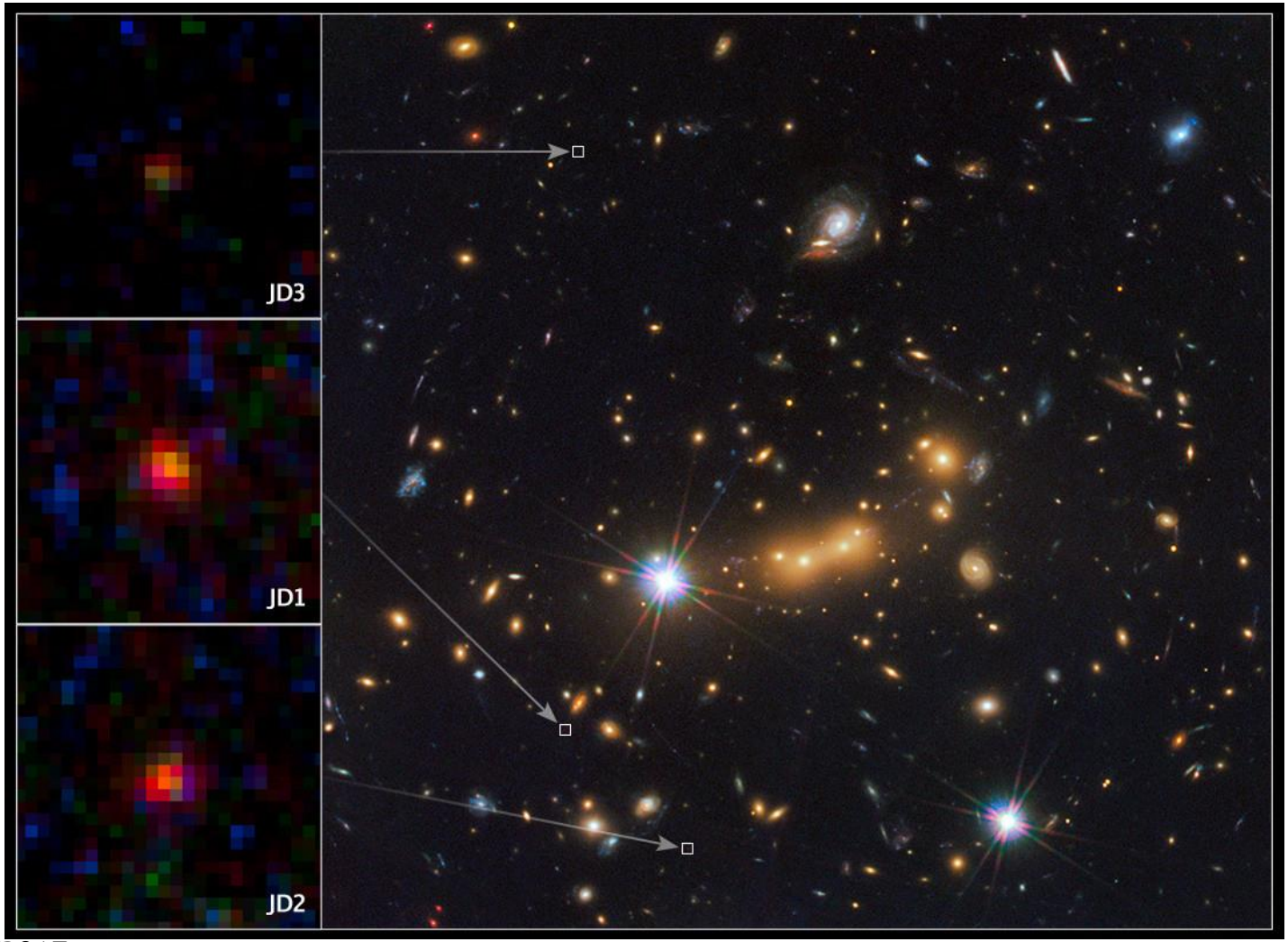
## 子弾星系団 (Bullet cluster)



**青**: 暗物質
**赤**: 熱気体

# Hunting the first galaxies with lensing

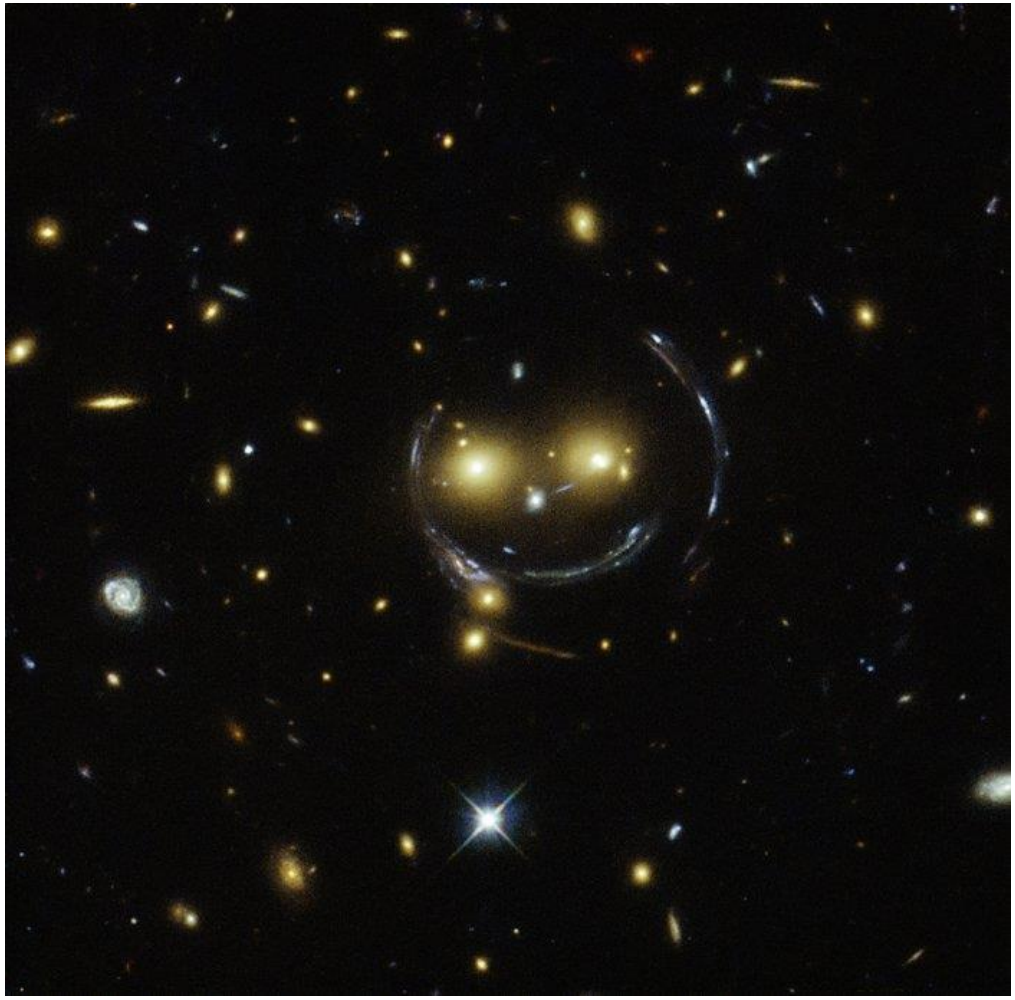
Highly magnified distant galaxy: 宇宙4億歳時候的年軽星系



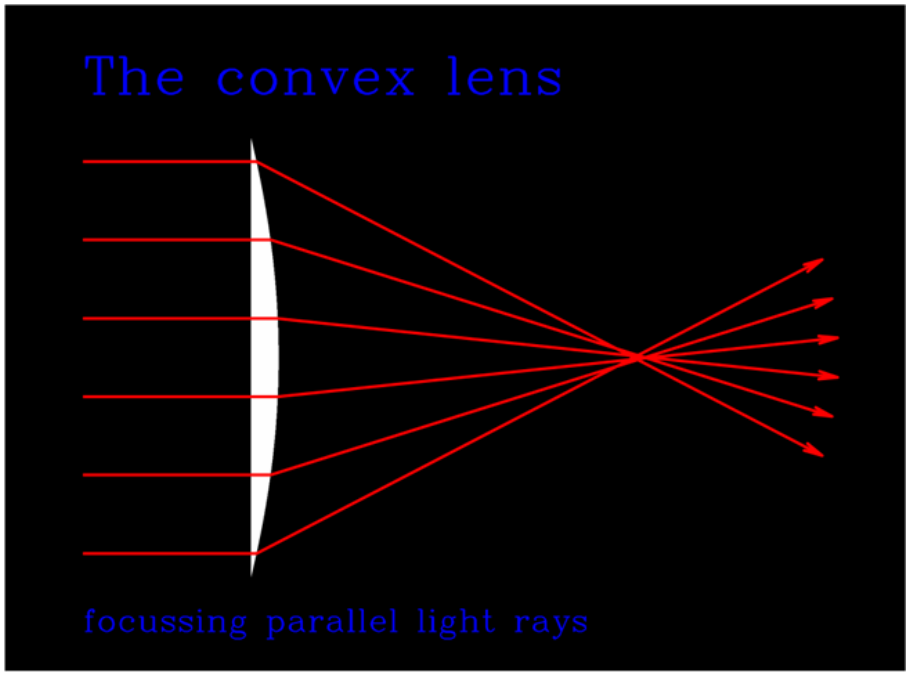

Cluster MACS064

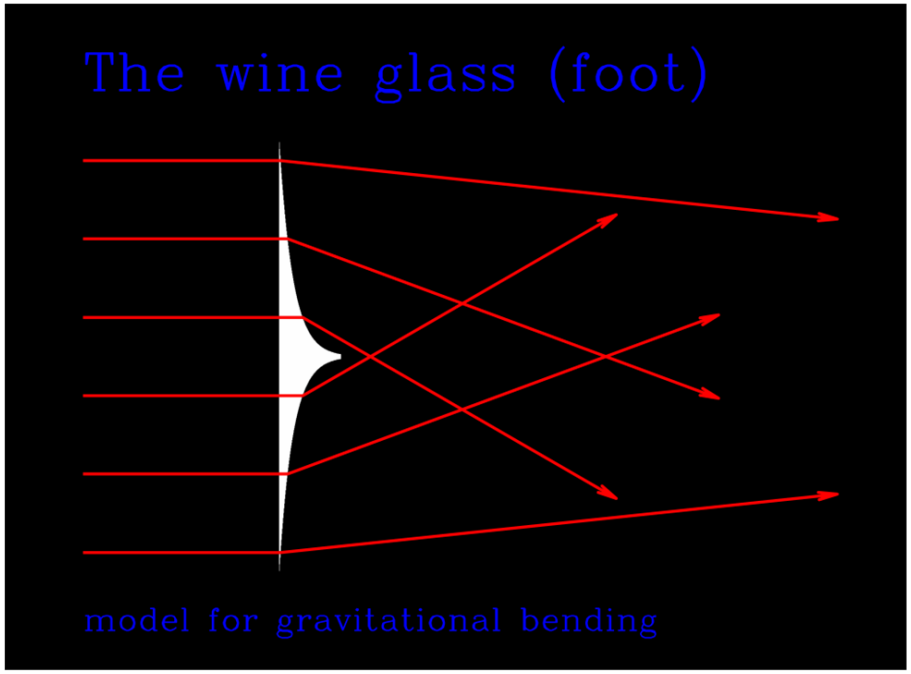
# Summary

Gravitational lensing is exciting!!!

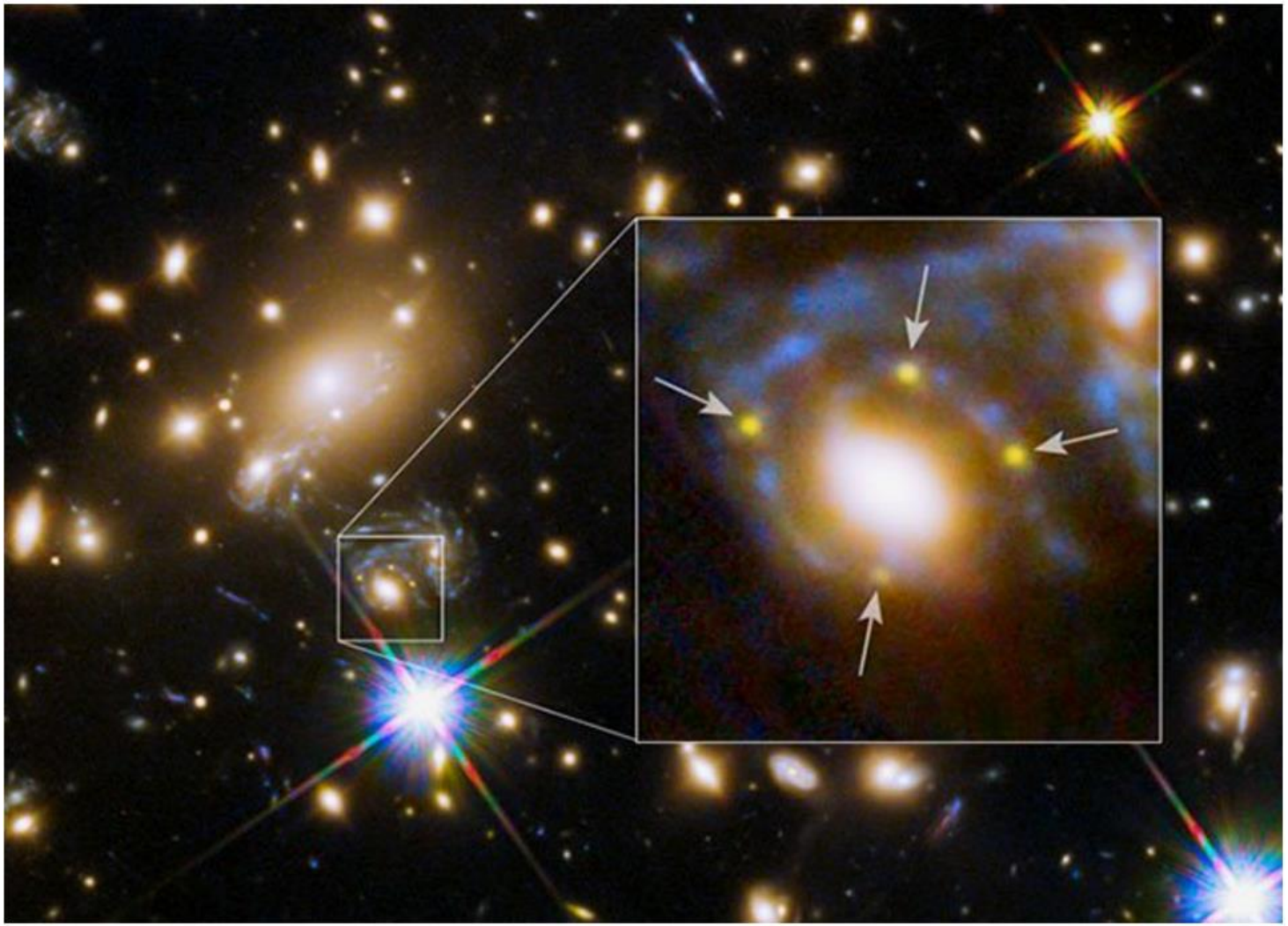


# 凸面 vs. 重力透鏡


The convex lens
focussing parallel light rays

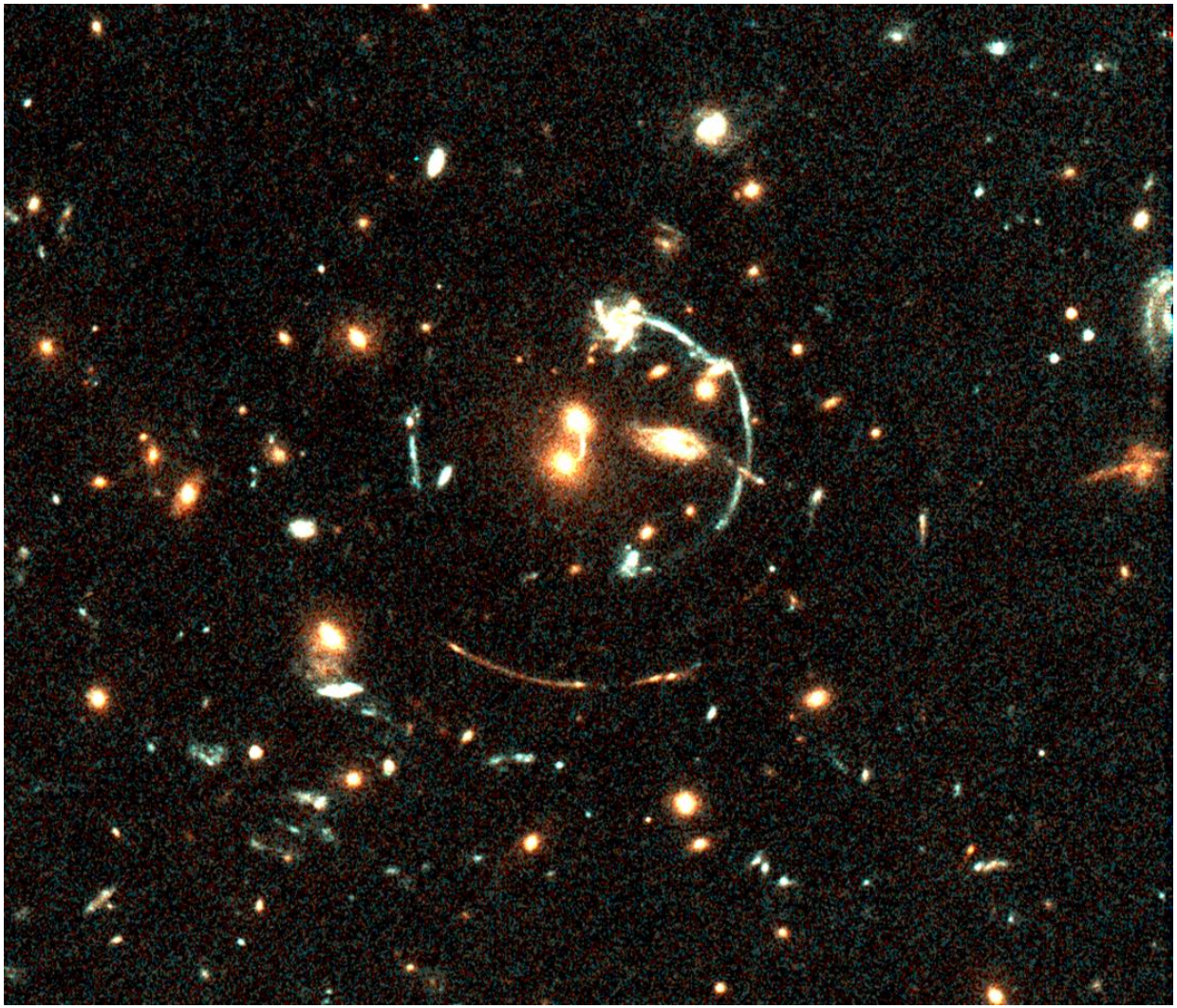

The wine glass (foot)
model for gravitational bending

# Multiple images of 超新星



Cluster
MACS1149

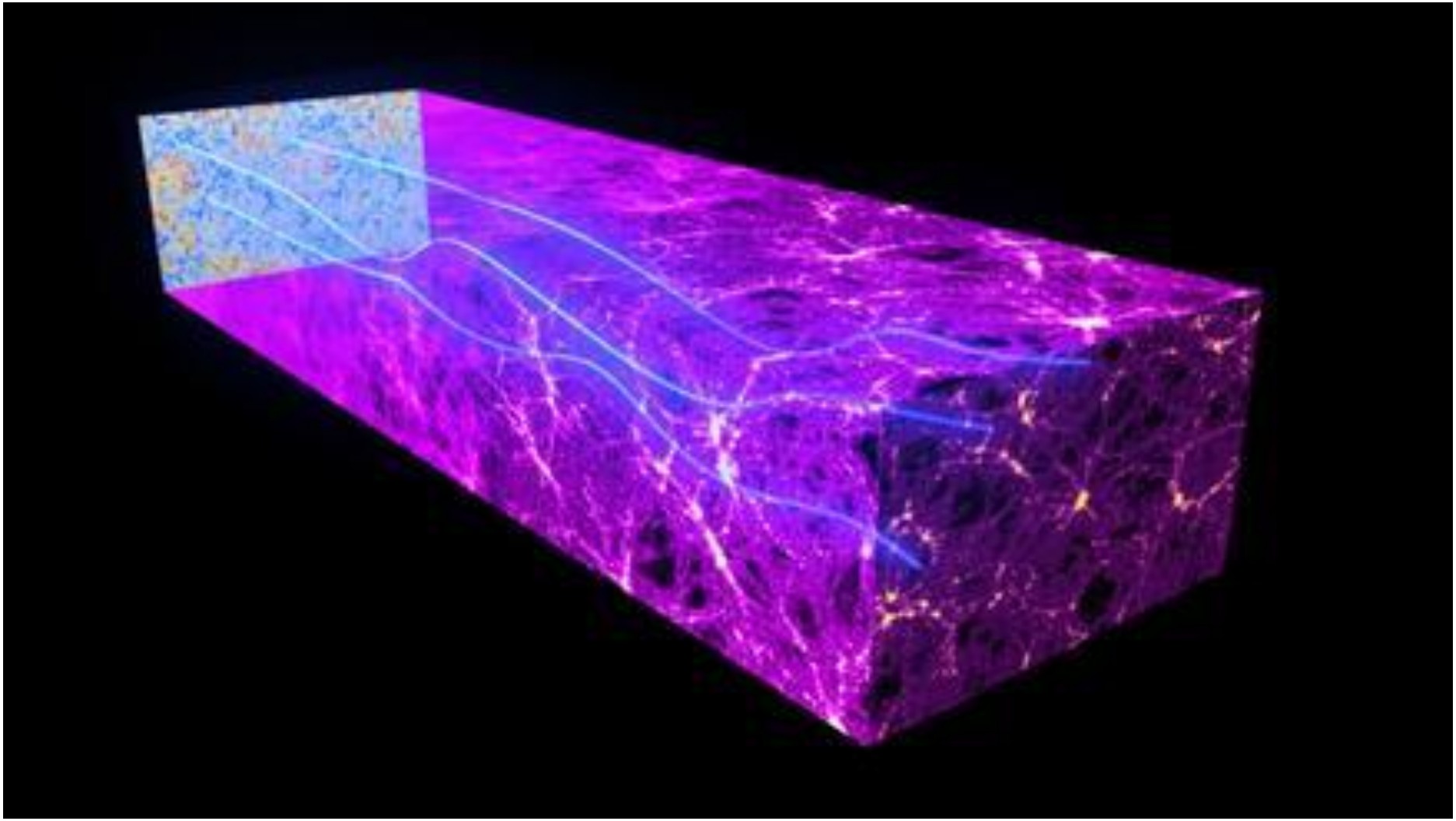
# 星系団重力透鏡: Giant arcs



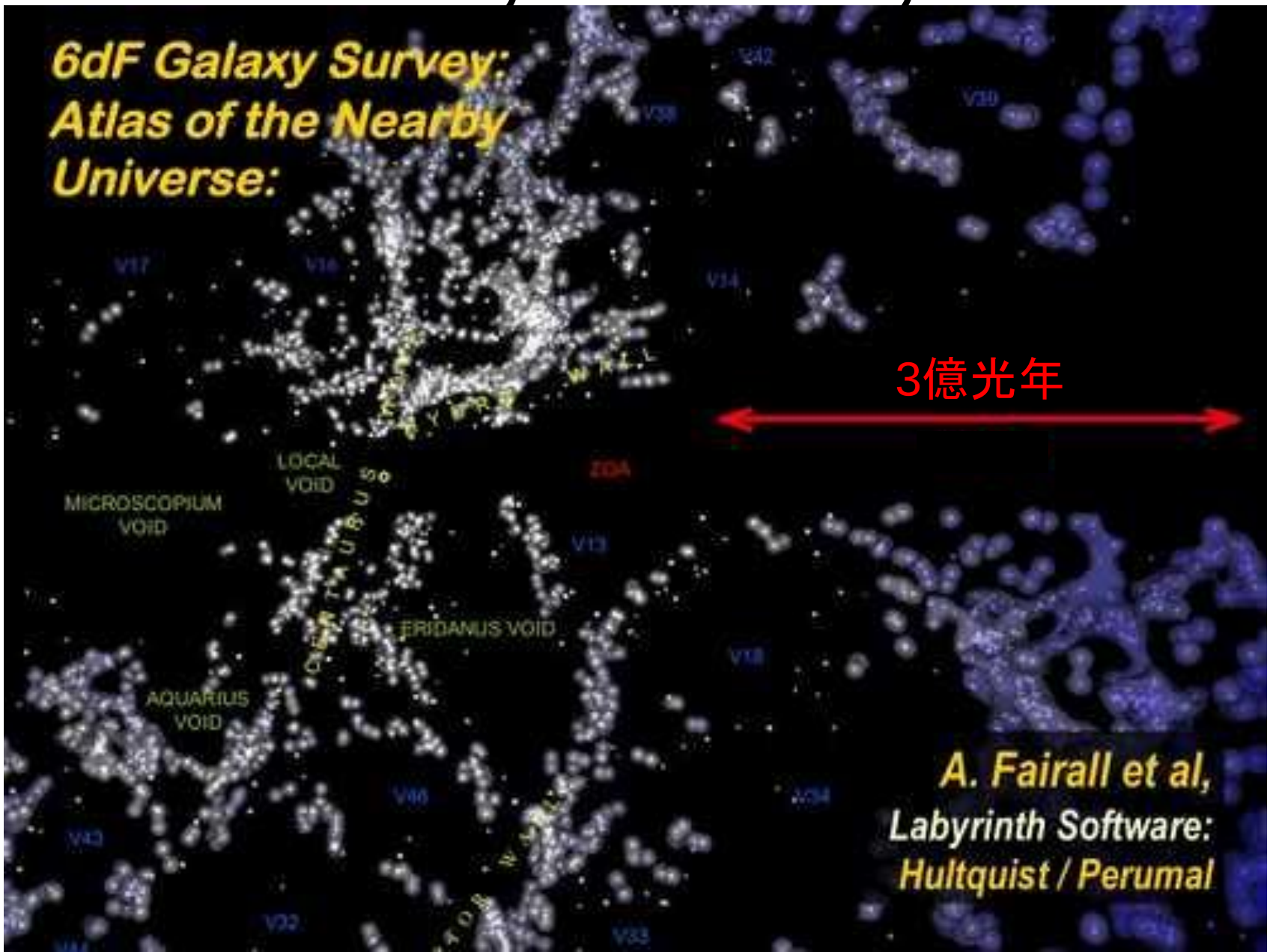
# Supplementary material

# Photons (光子): travelers in the cosmos

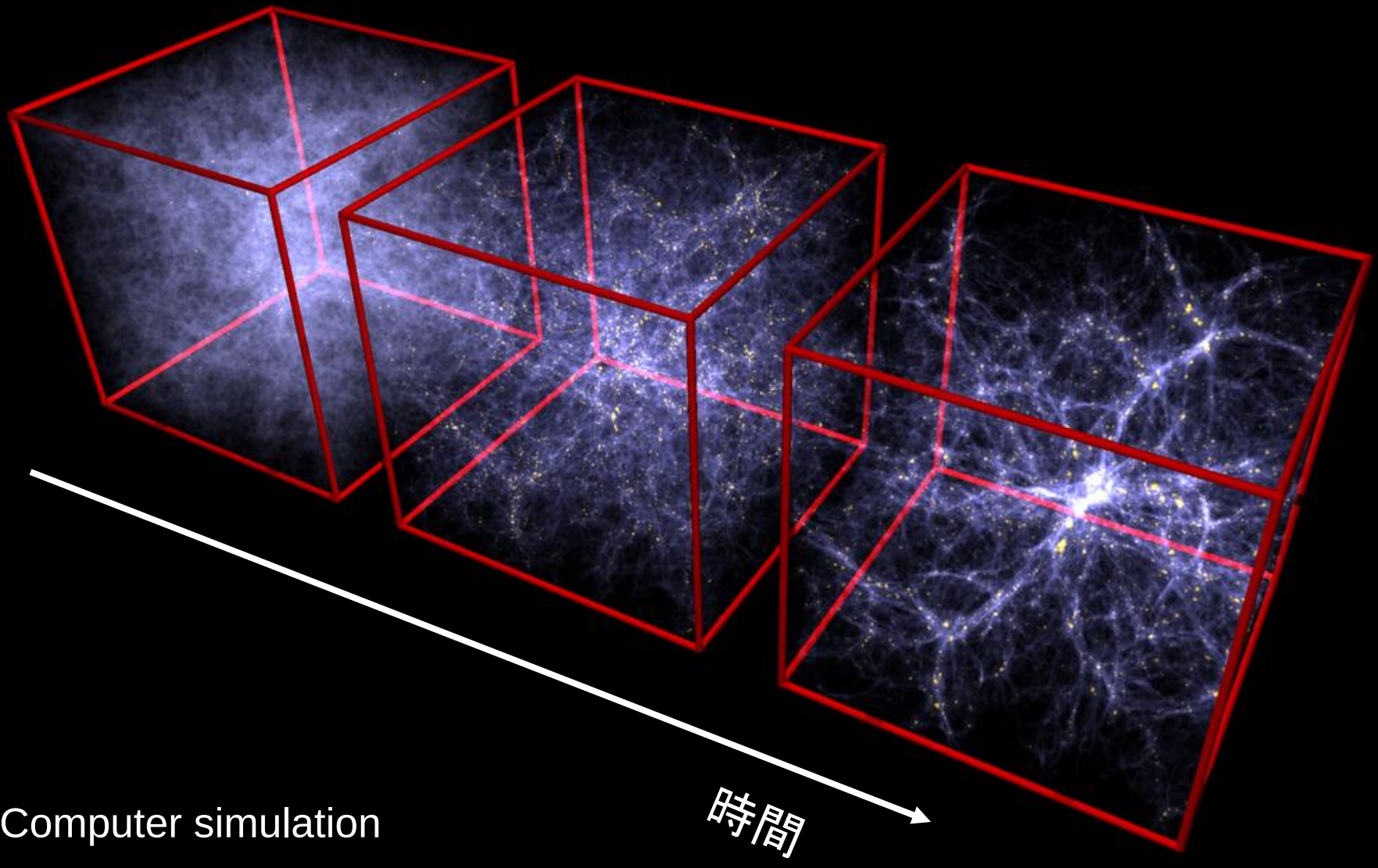
Photons are traveling through the clumpy universe.



# Great walls, filaments, voids

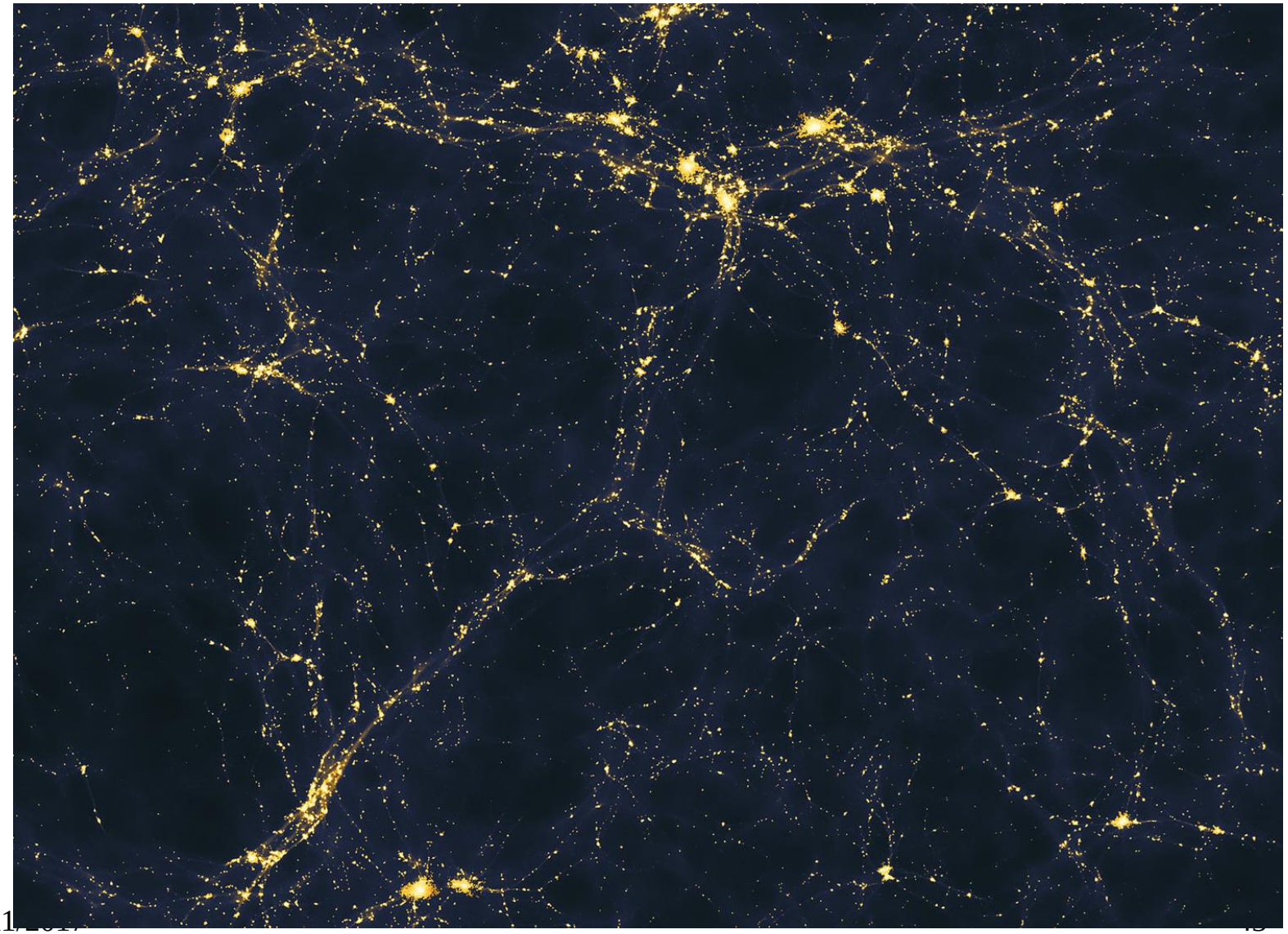


# Gravitational Growth of Structure



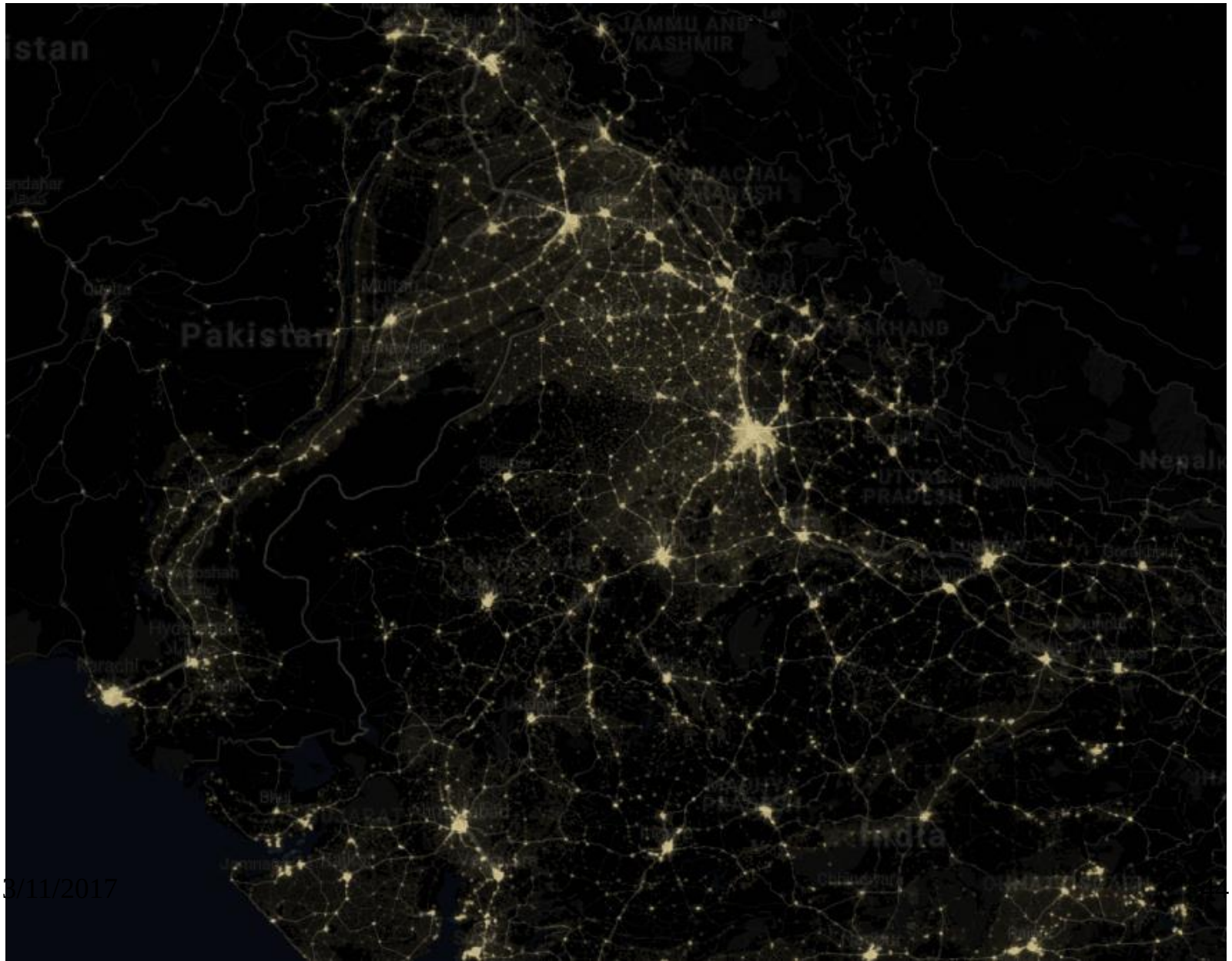

Computer simulation

# 大尺度結構系統之模擬

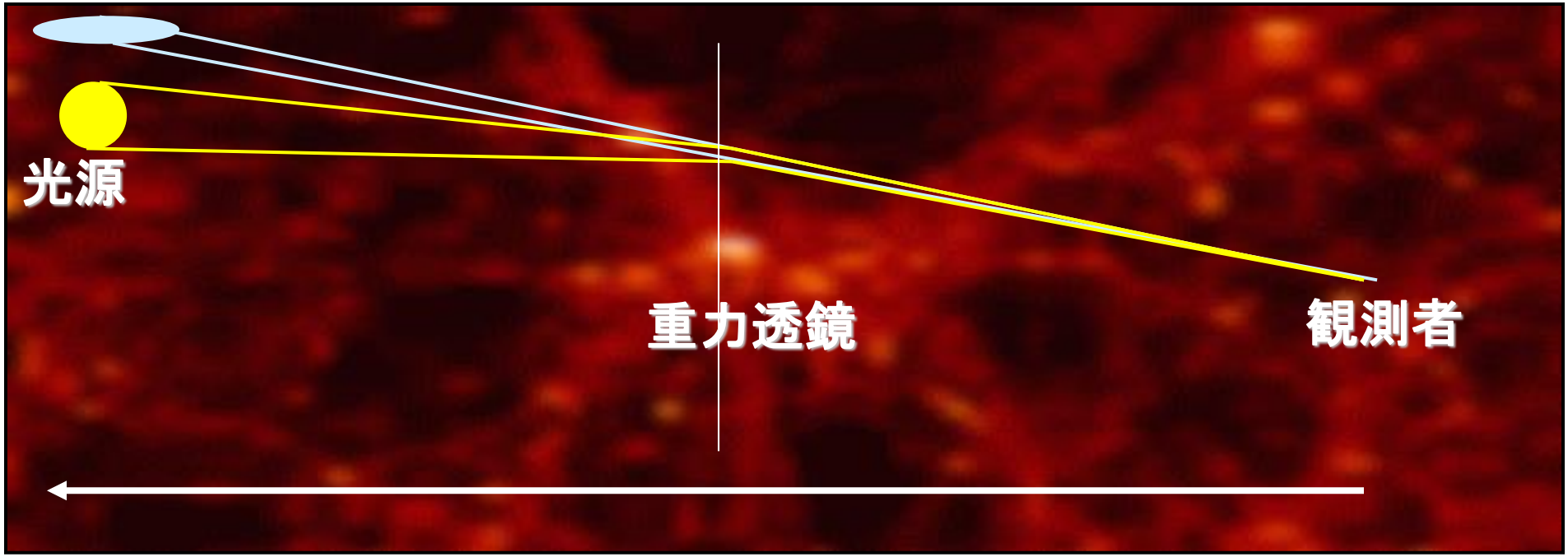


5000万光年

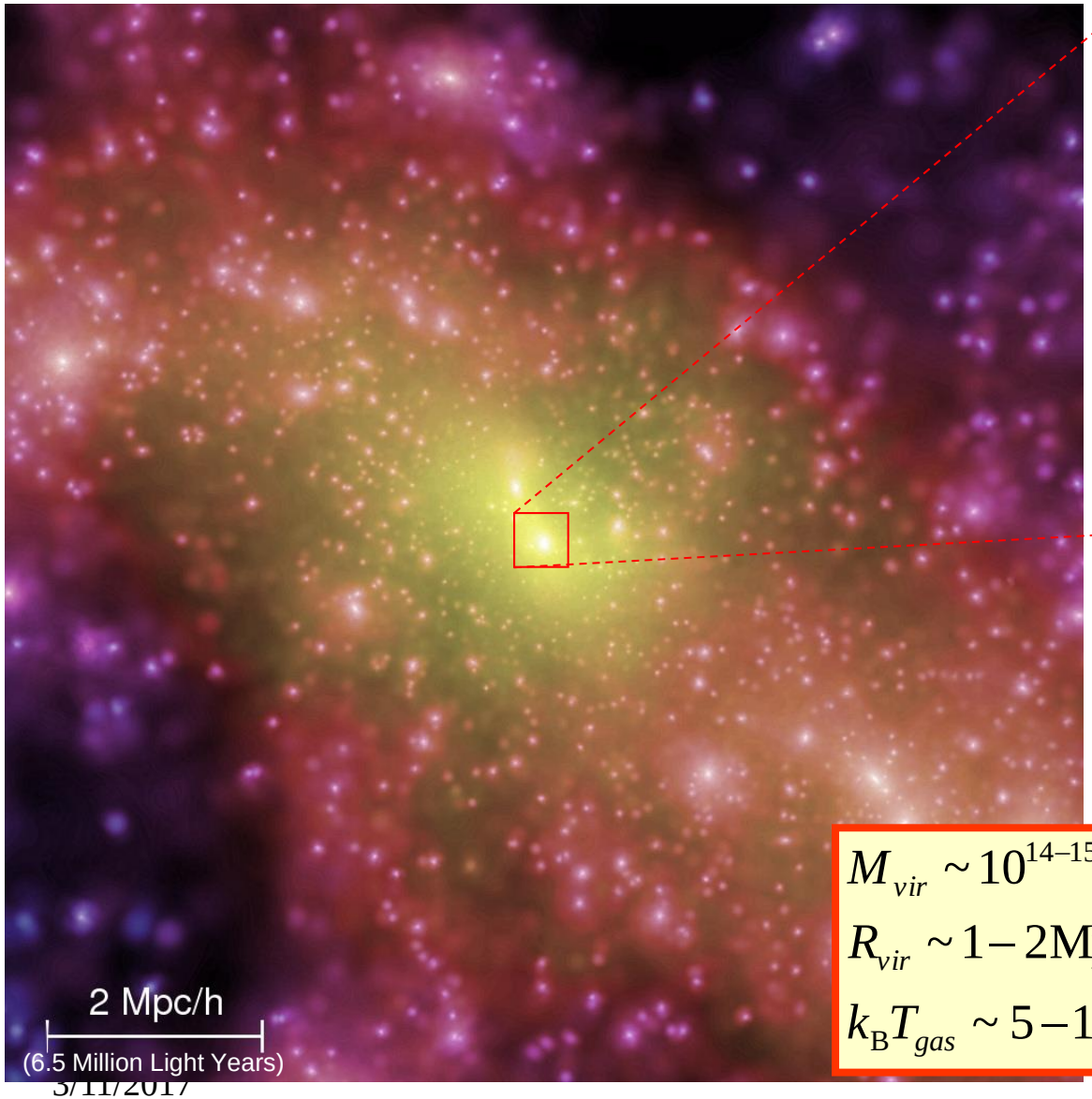
# Night Light Map

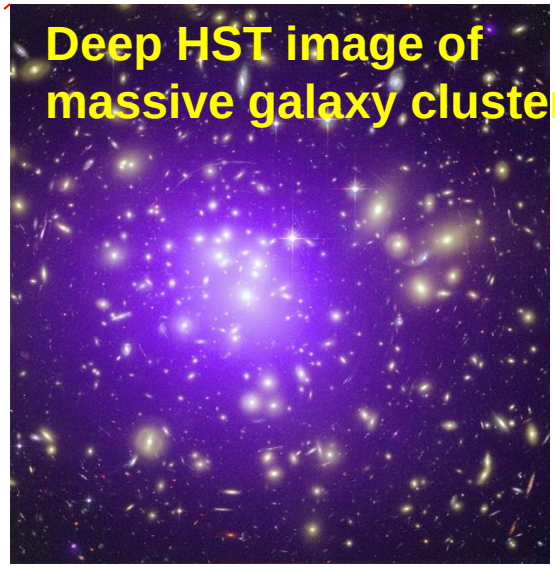


# Gravitational Lensing



# Clusters of Galaxies




Clusters of galaxies: largest self-gravitating systems (aka, DM halos) with $\delta$>>1, composed of $10^{2\text{-}3}$ galaxies

$$M_{vir} \sim 10^{14-15} M_{\rm sun}/h$$

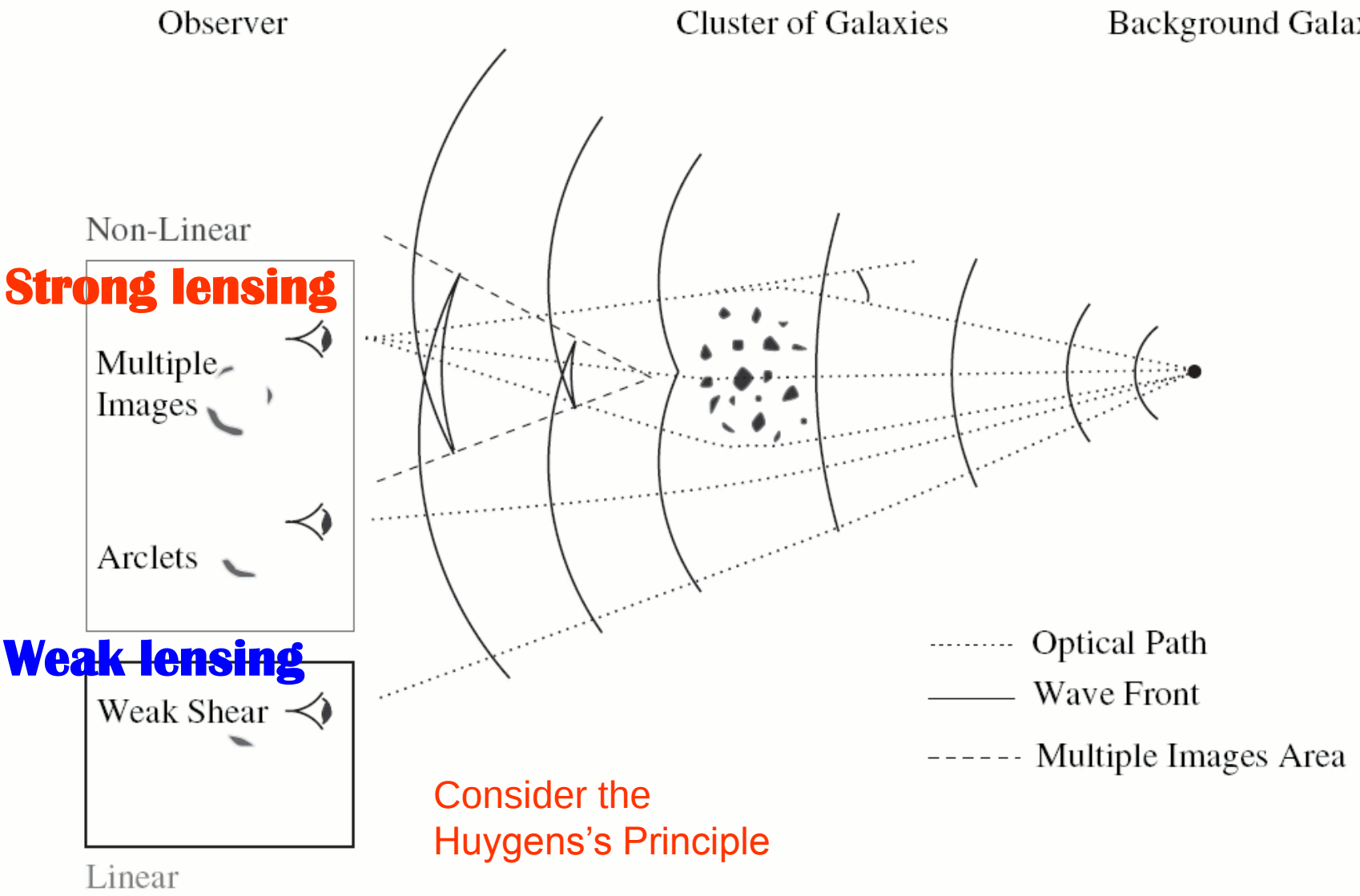
$$R_{vir} \sim 1-2{\rm Mpc}/h \Rightarrow t_{dyn} = 3-5{\rm Gyr} < {\rm t_H}$$

$$k_{\rm B}T_{gas} \sim 5-10{\rm keV}$$



Simulation of dark matter around a forming cluster (Springel et al. 2005)

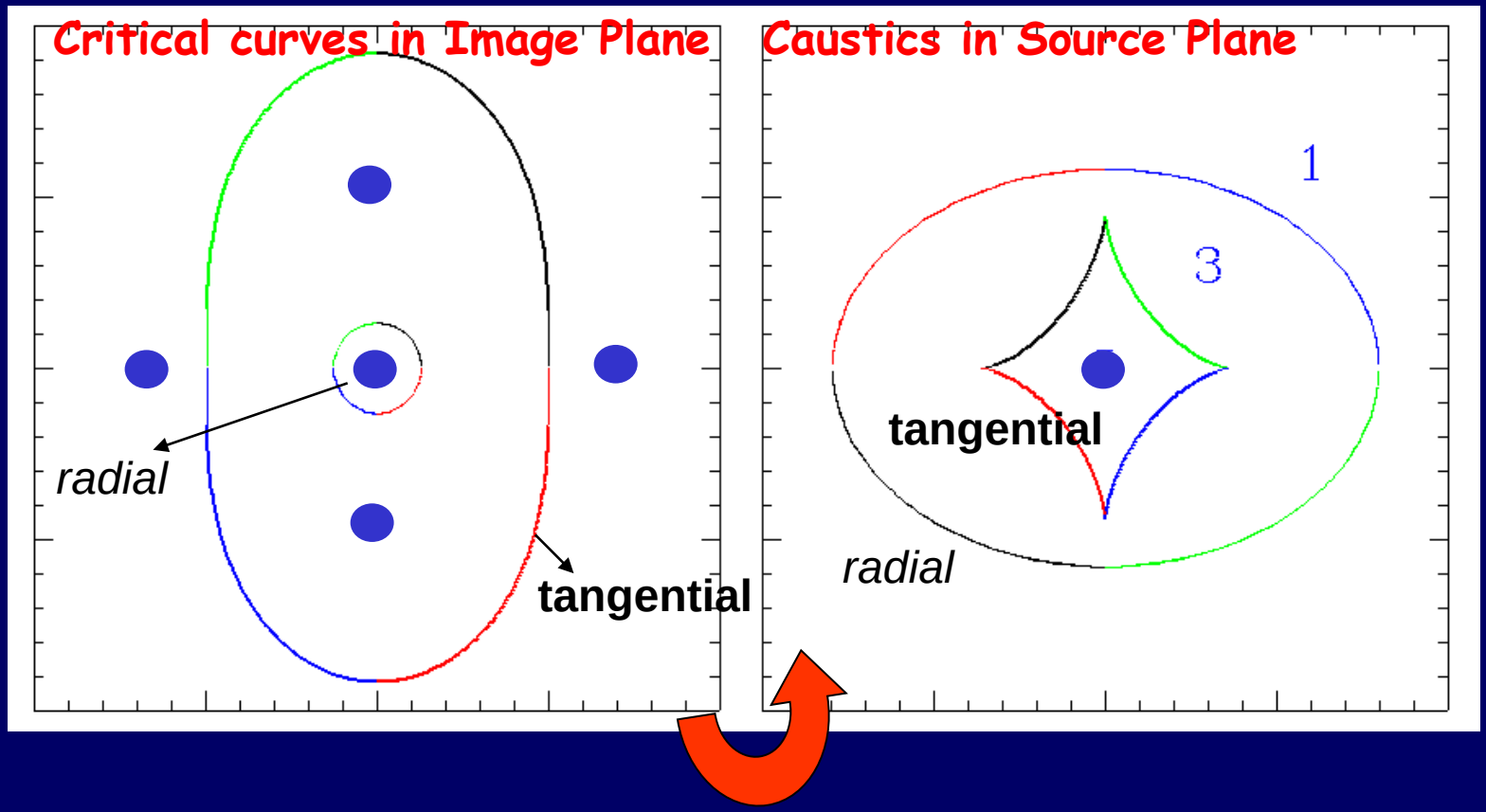
# Strong and Weak Lensing in Clusters




Consider the Huygens's Principle

# Strong Lensing: Critical Curves and Caustics

**Elliptical lens potential** (non-circularly symmetric case)




$$\boldsymbol{\beta} - \boldsymbol{\theta} = -\nabla \psi(\boldsymbol{\theta})$$