International Radio-Telescope Project "ALMA" and Its Scientific Results

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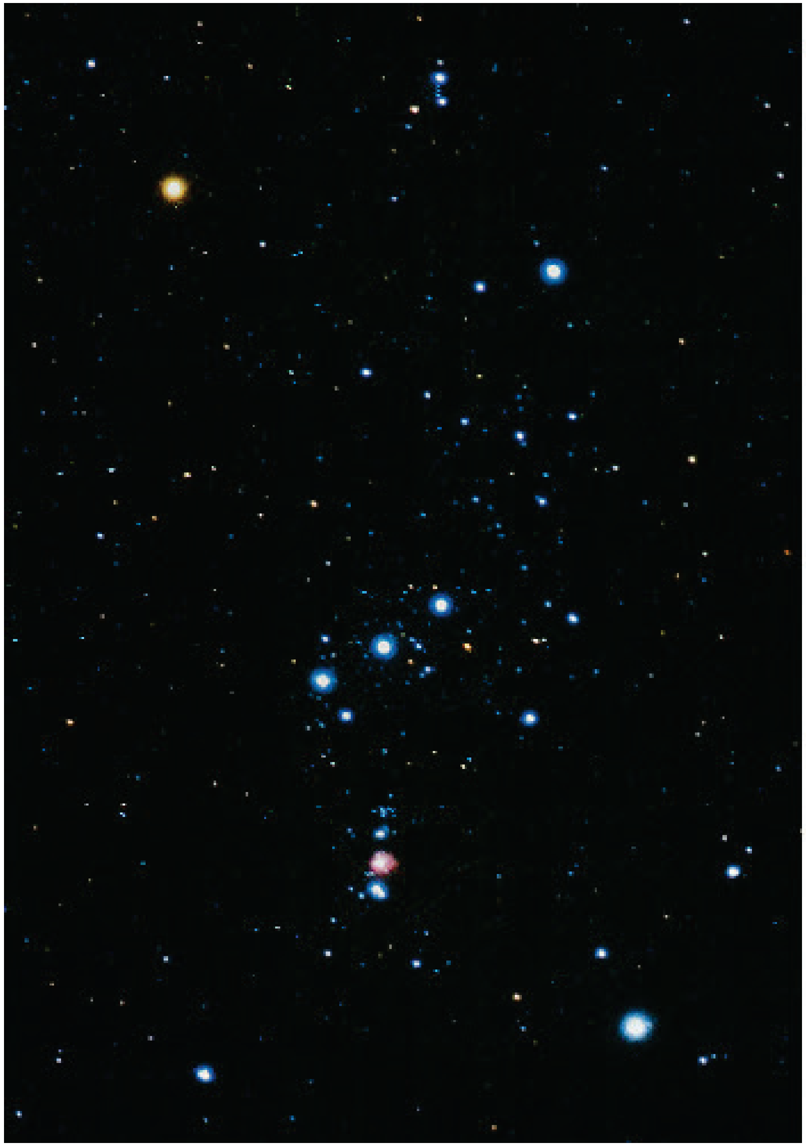
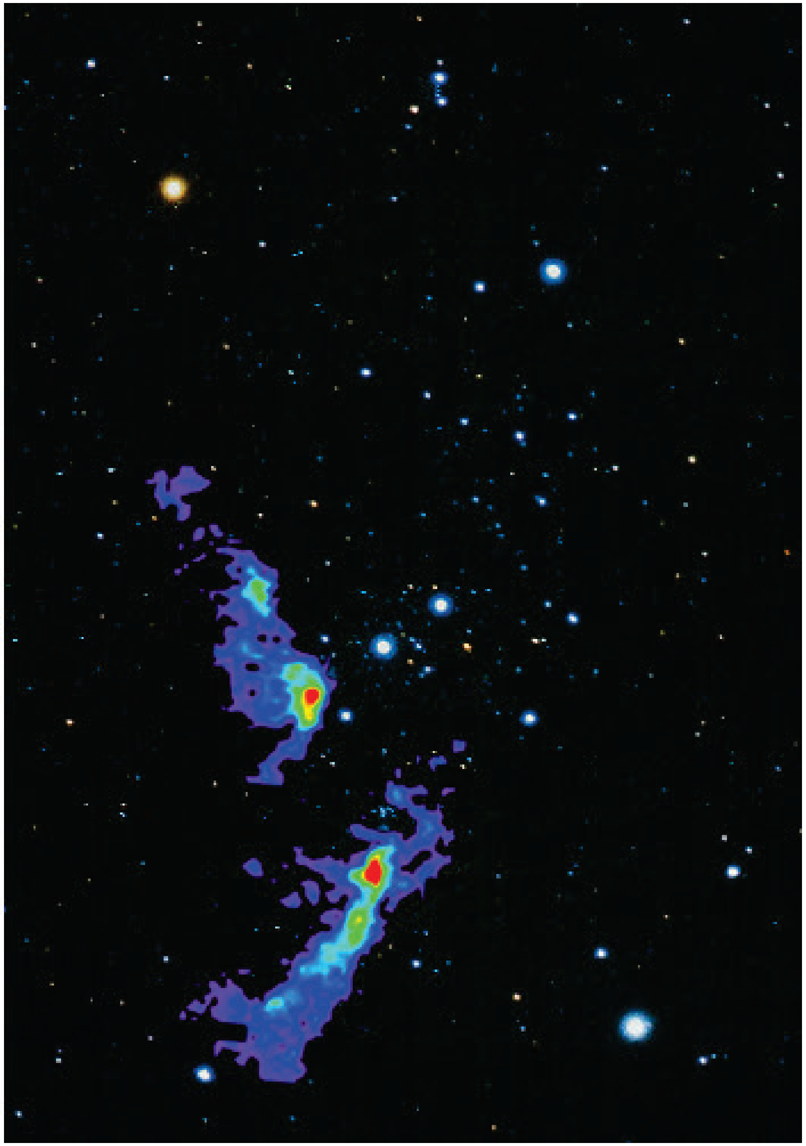
Toward nuclear fusion
核融合に向かって

- We, astronomers, are studying how stars form (starts nuclear fusion)

Orion at optical at radio wavelengths

Seiichi Sakamoto et al.

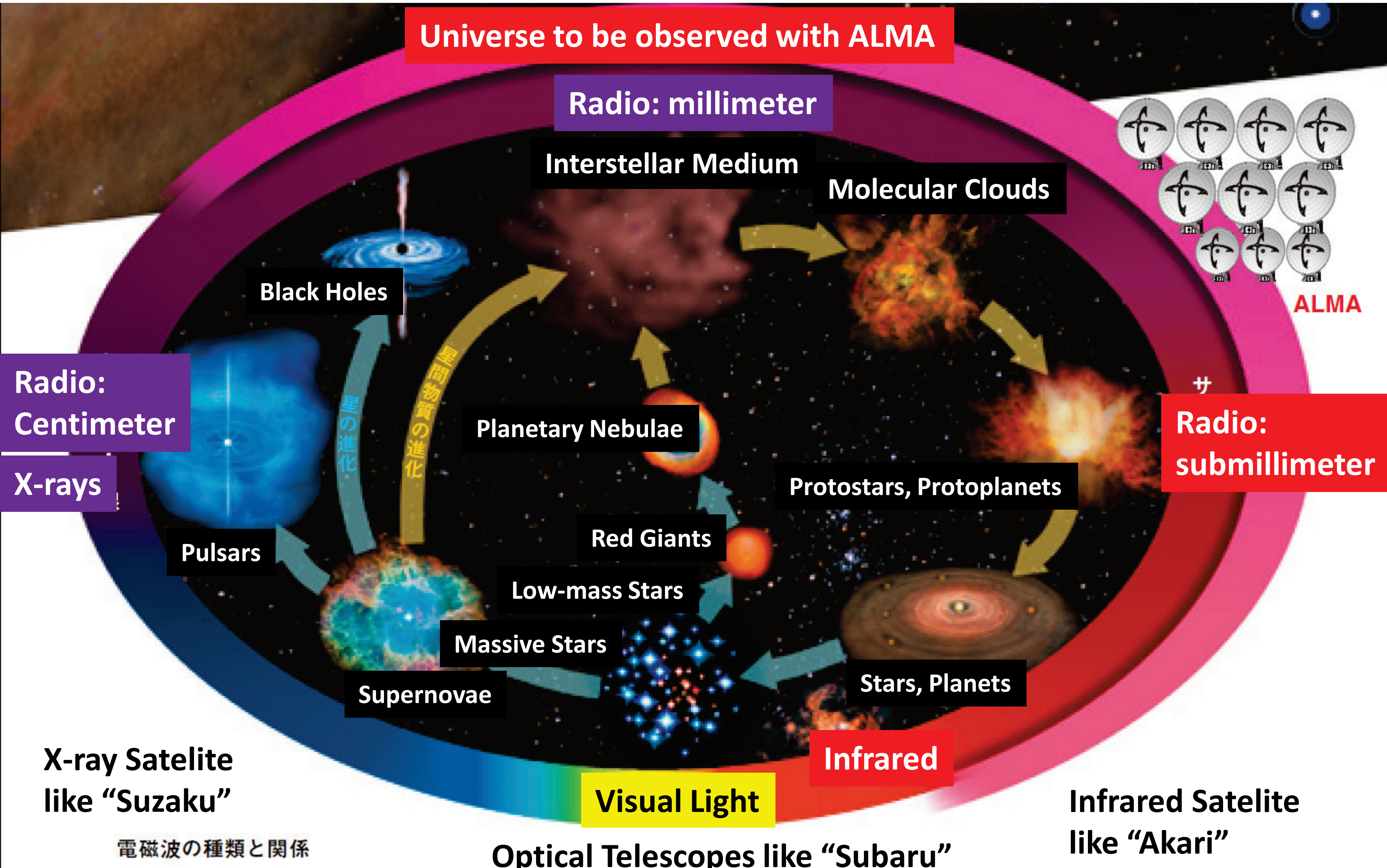




Visual Universe and Radio電波 Universe

- We can see “visible light可視光”（wavelength λ = 0.4-0.8 μm)
  - our eyes are designed to see light of the sun whose surface temperature is 6000K, (reflected by matters around us)
  - Therefore, in the night sky, we see adult stars having very hot surface temperature like our sun
- Radio signal of millimeterミリ波 (λ = 1-10 mm) and submillimeter wave サブミリ波(λ = 0.1-1 mm)
  - We can see “**Cold Universe**” of < -150 ℃ or 10-100 K

Life Cycle in the Universe –ecosystem-



Radio Telescope “ALMA”

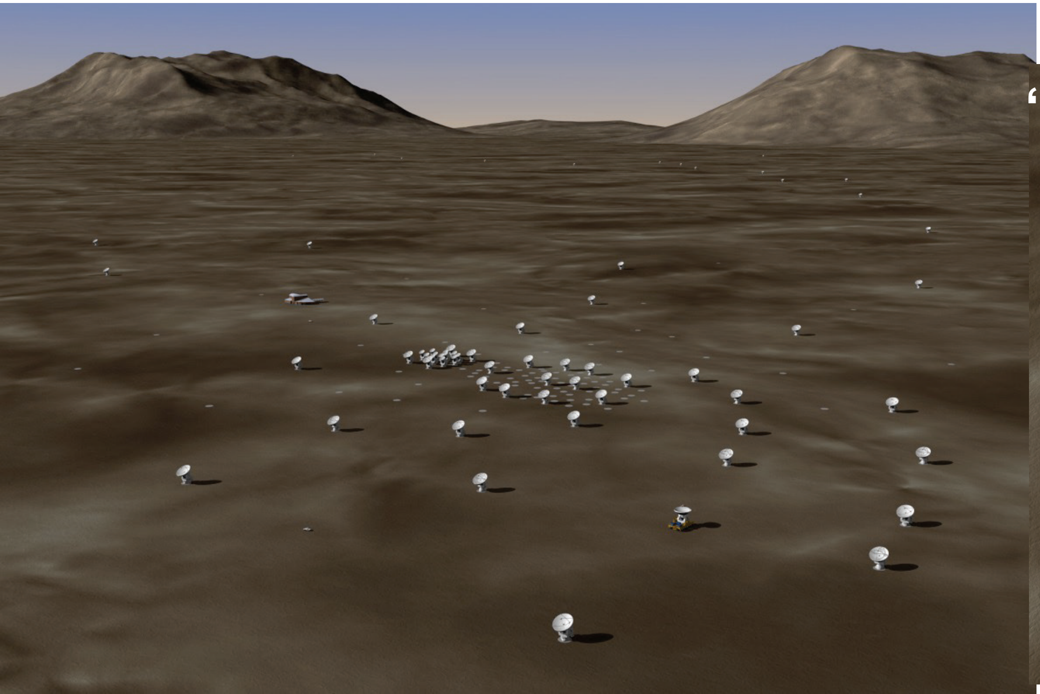
- International radio telescope project by 20 countries lead by NAOJ, NRAO and ESO to construct and operate the telescope in Chile
- Taiwan and Korea participate ALMA through collaboration with NAOJ
- Atacama Large Millimeter/submillimeter Array
- ALMA means “soul　魂” in Spanish used in Chile
- Construction started in 2002, Inauguration in 2013

Photo of the ALMA antennas “Morita Arrayモリタアレイ” built by Japan

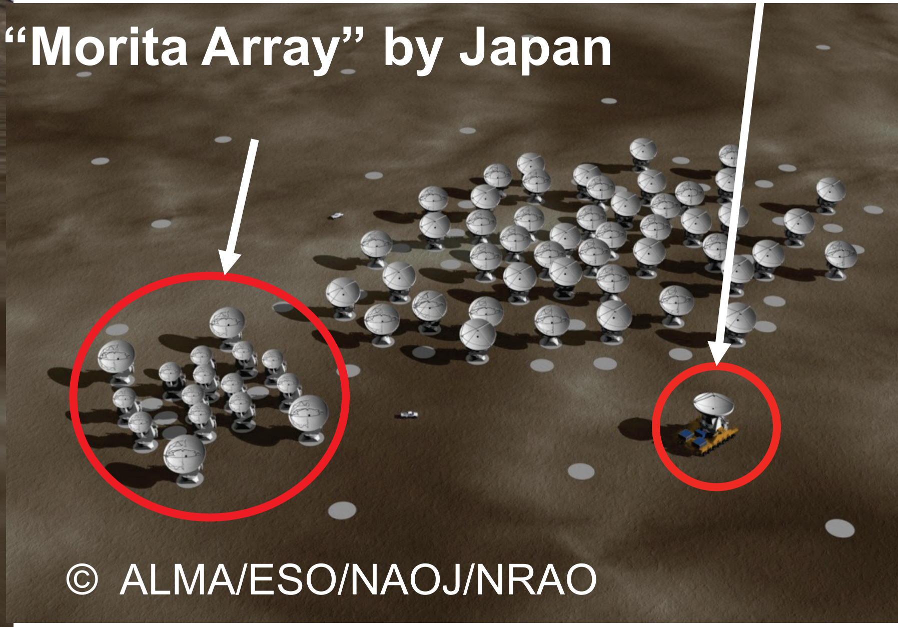
credit: ALMA (ESO/NAOJ/NRAO)

Atacama Large Millimeter/submillimeter Array

- 66 parabolas in **16 km diameter campus**
- Spatial Resolution ~ telescope size/wavelength
- **Vision　視力 of 6000**, which is 10 times better than Hubble (vision of 600)



Movable antennas with a transporter



Sciences with ALMA
Our promise for the government (e.g.MEXT文科省)
We cannot break it!!!

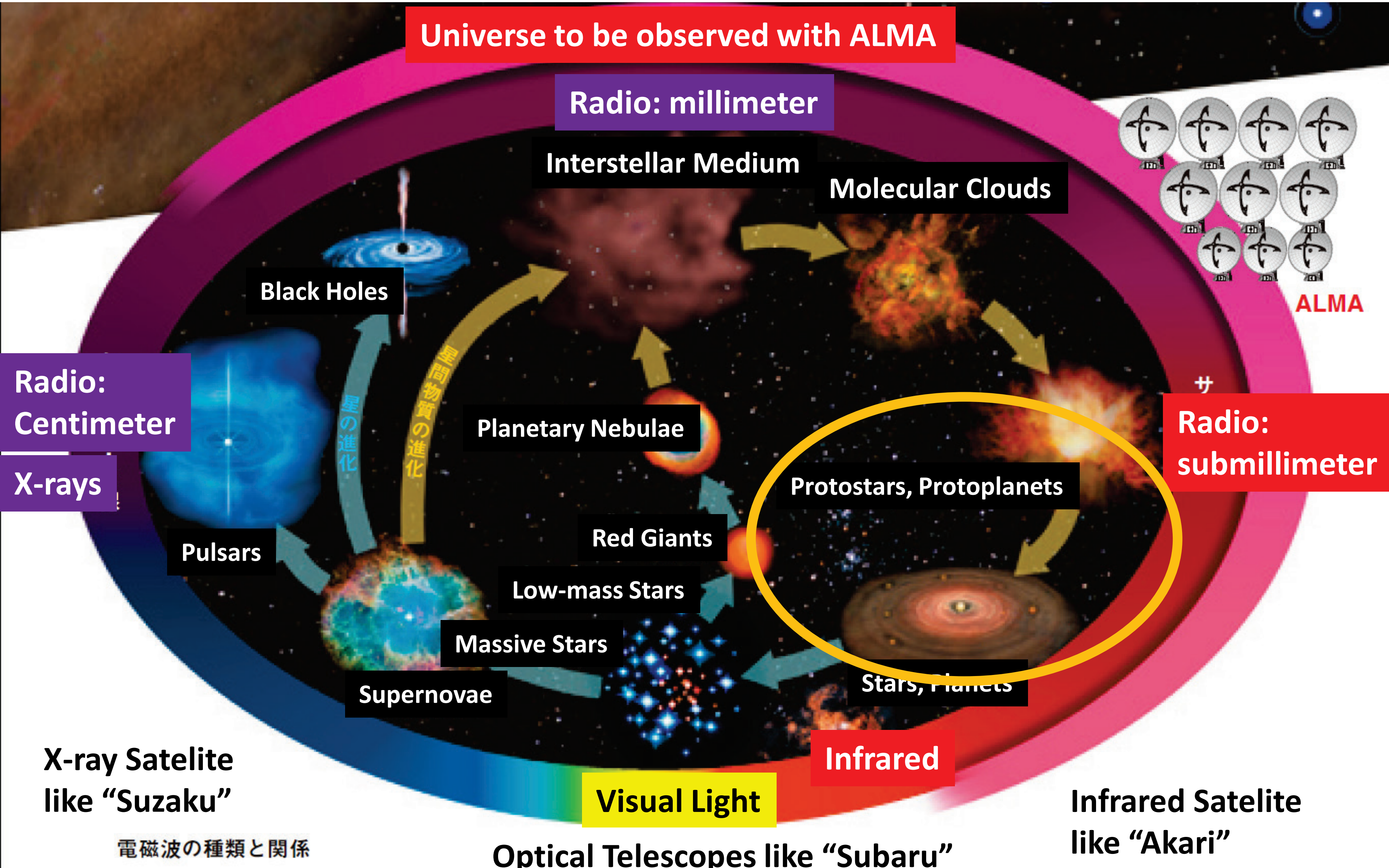
Target 1
Formation of Planets

Target 2
Formation and Evolution of Galaxies

Target 3
Evolution of matter in the Universe –
prebiotic molecules (e.g. amid acid)

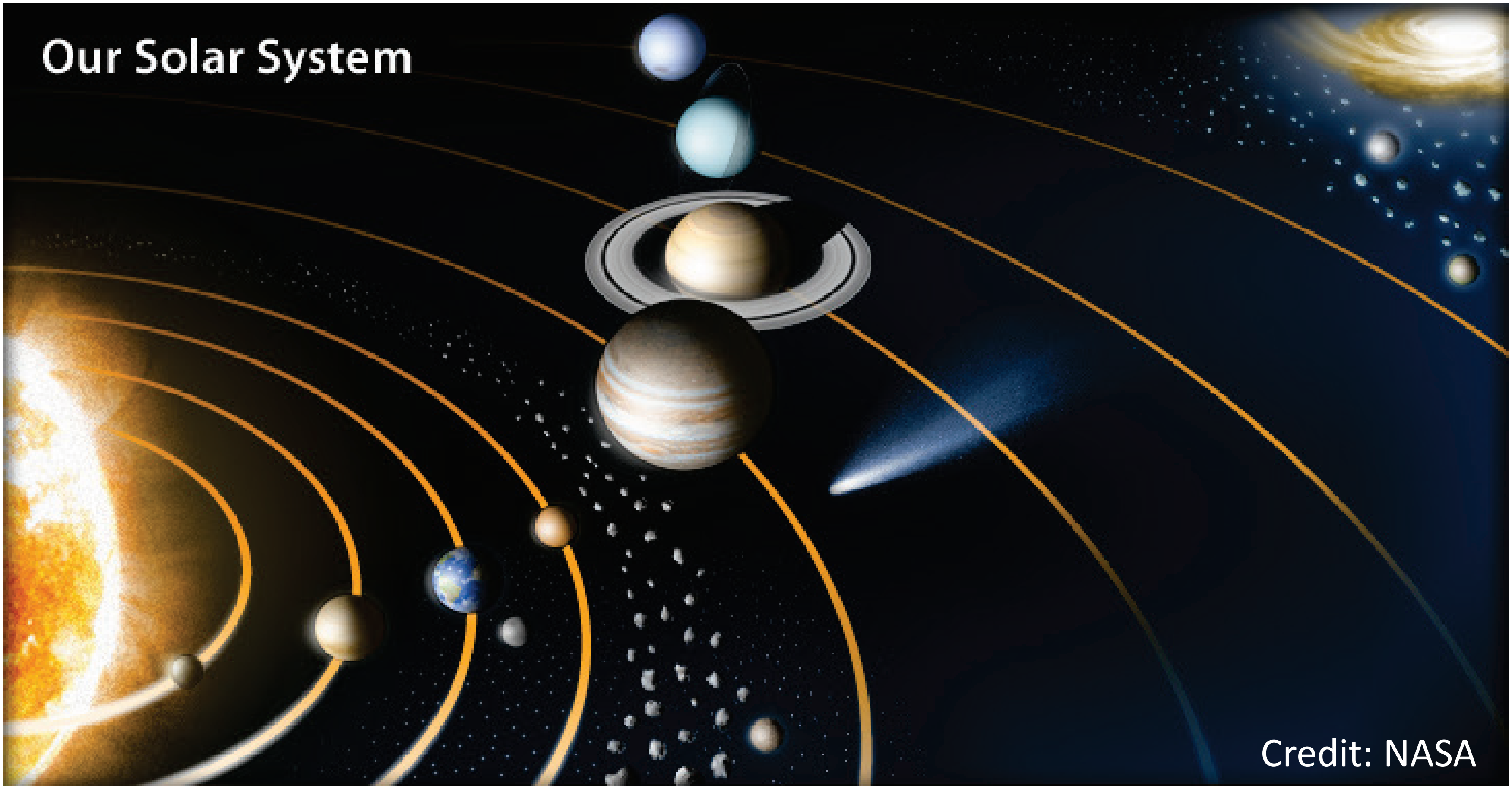
By utilizing ALMA's great spatial resolution and sensitivity

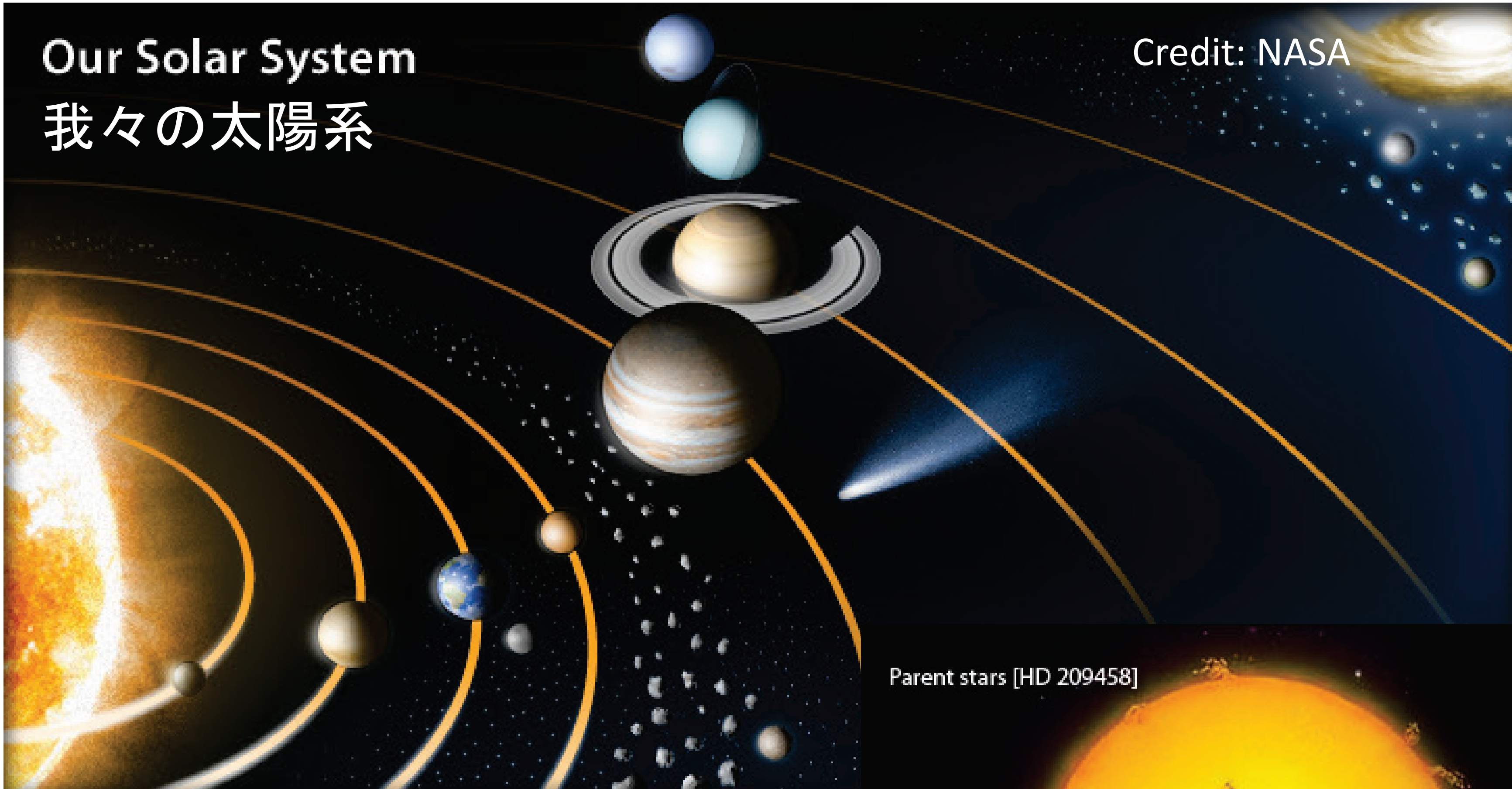
Formation of Planetart System

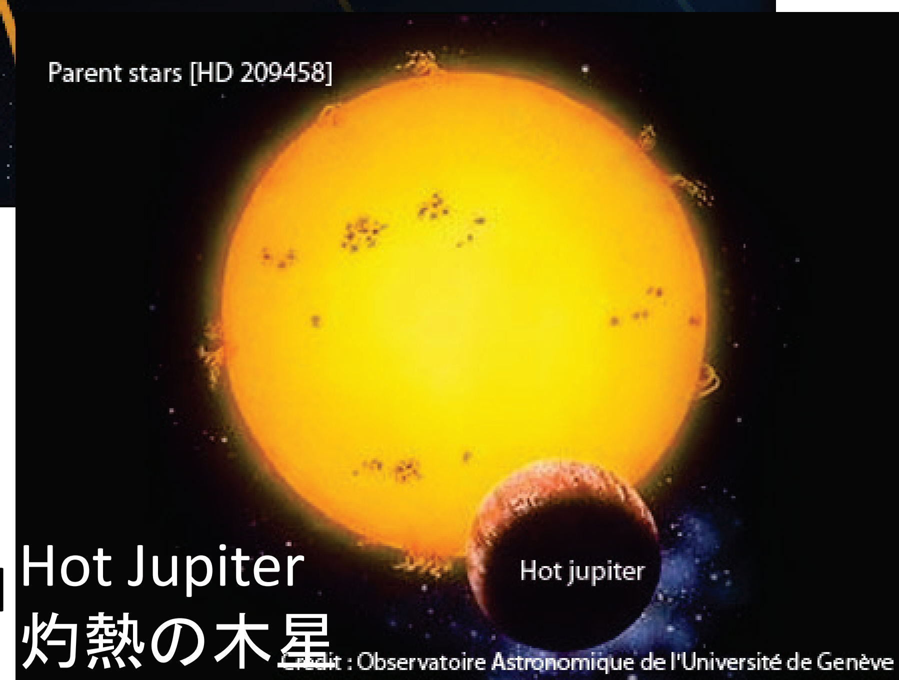


Our Solar System

Untill 1995, this has been the sole planetary system we knew

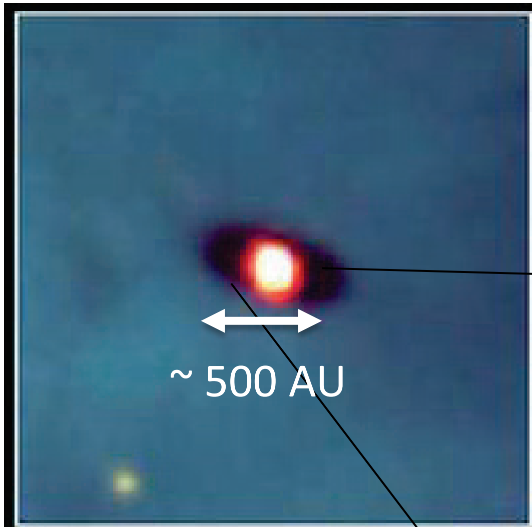




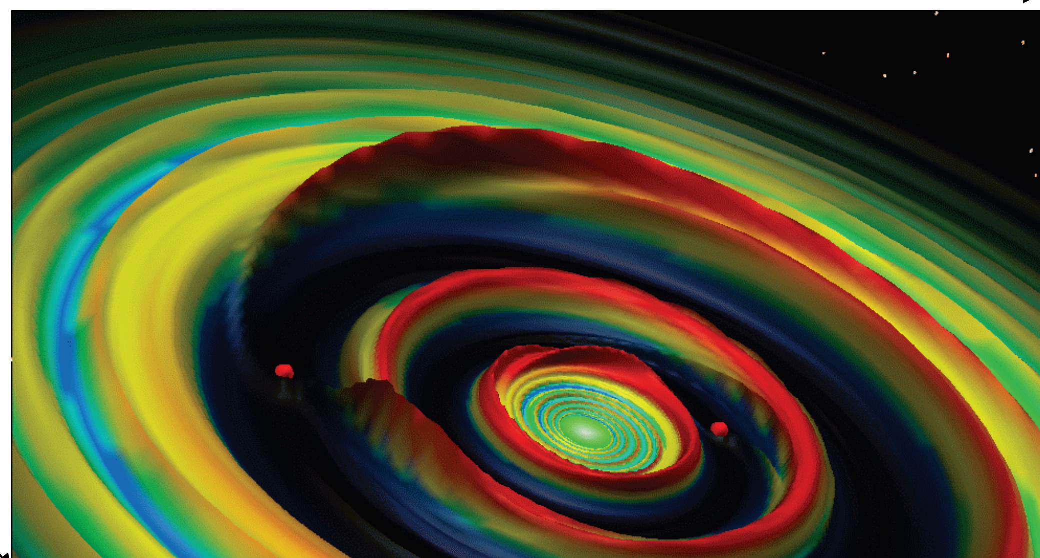


Discovery of thousands exoplanets
Variety of exoplanets
Our solar system may not be typical

ALMA was expected to be the first telescope to see platnet formation



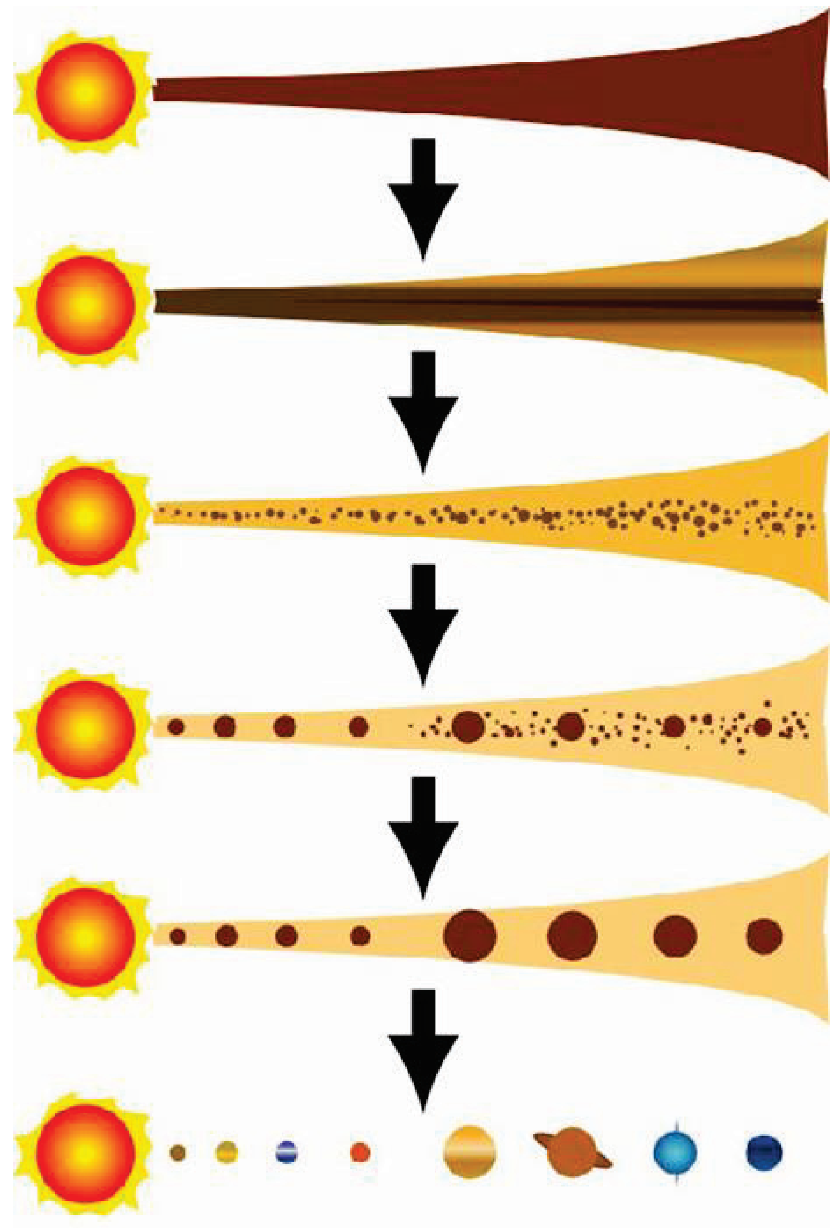
Obserevation with Hubble ©STScI
Silhouette disk (protoplanetary disk) against the Orion Nebula. Red star is a protostar.



Computer simulation (Bryden et al. 1999)
Protoplanets are formed by accreting gas. ALMA will be used to investigate which model is correct.

"Kyoto model" C. Hayashi et al.) planetesimal accretion

- Explained the formation of our solar system rather than "Cameron model" (gravitationa instability)
- However, exoplanets observations show variety of systems
- Some cases are hard to explain with Kyoto model. Cameron model?
- Planet migration? Planets move from the birth site.

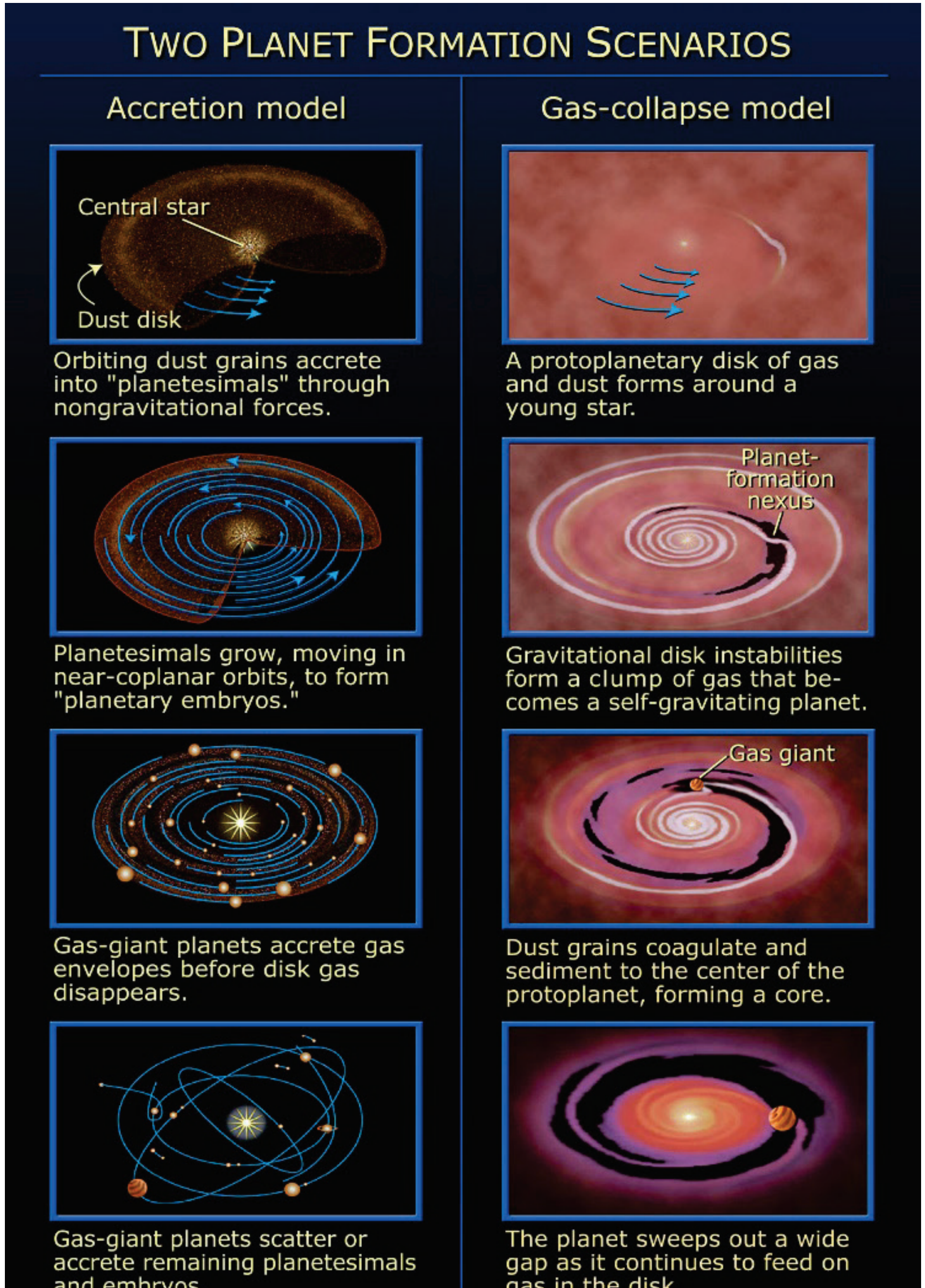


Kyoto model

Core Accretion

Planetesimals

C. Hayashi 1977 PASJ 29,163



Credit: NASA/ESA and A. Feild (STScI)

Cameron model

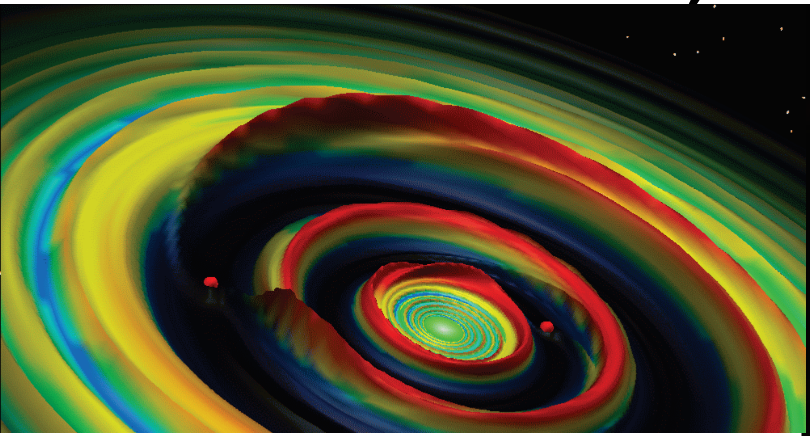
Gravitational Instability

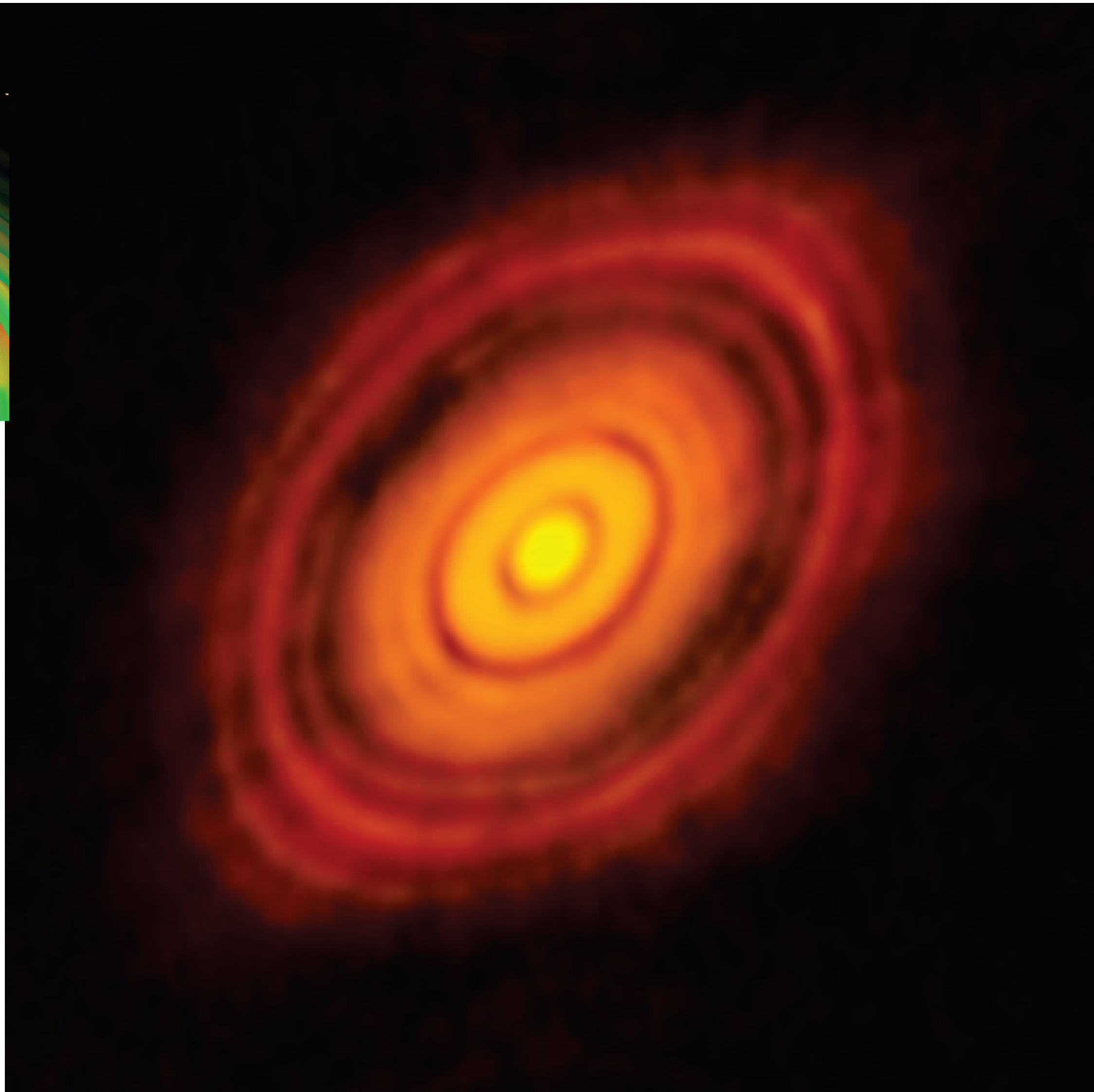
AGW Cameron 1973 Icar 16, 407

Protoplanetary Disk around HL Tau

T Tau star ~10^6 yr old

vision=2000; 0.035 arcsec resolution





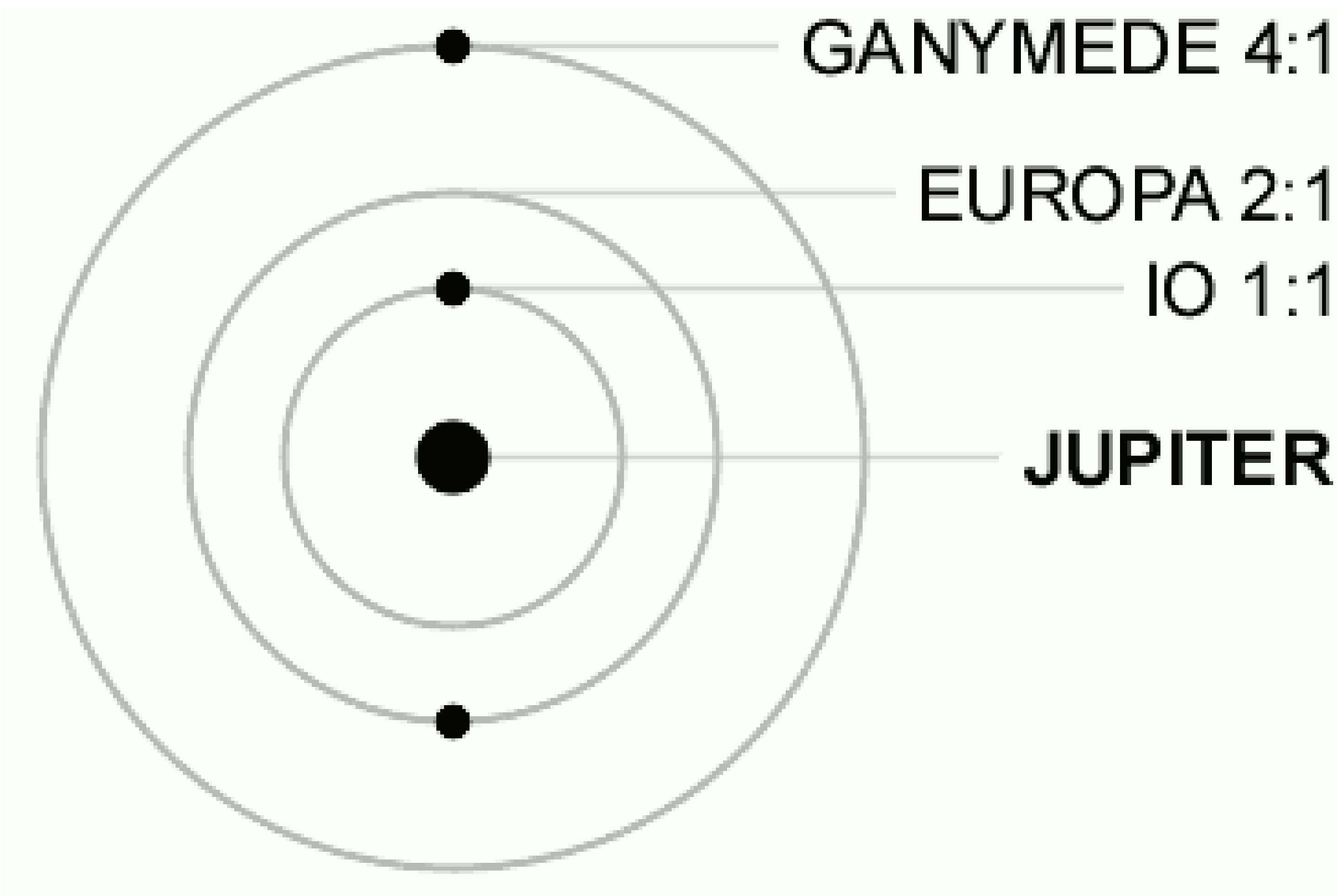
HL Tau (10^6 yr) formed planets so quickly!! (C. Hayashi+85, PPII)

1102 C. HAYASHI ET AL.

TABLE I
Chronological Table of Planetary Formation

Time (yr)	
-10^{6-5}	Collapse & fragmentation of a giant molecular cloud
-10^{5-4}	Collapse of a rotating presolar cloud
0	Formation of protosun and solar nebula
	⟨Growth & sedimentation of dust-grains⟩
10^4	Fragmentation of dust layer into planetesimals
10^5	⟨Accumulation of planetesimals⟩
10^6	
	Formation of the Earth
10^7	Formation of Jupiter's core & accretion of gas onto it
	Dissipation of nebular gas
10^8	Formation of Saturn's core & capture of remaining gas
	Formation of Asteroid Belt
10^9	Formation of Uranus(?)
	Formation of Neptune(?)
10^{10}	

Resonance between three satellites of Saturn Wikipedia



Dipierro et al. (2015) three planets with 0.2, 0.27, 0.55 x Jupiter mass

- Left: ALMA image; right: simulation

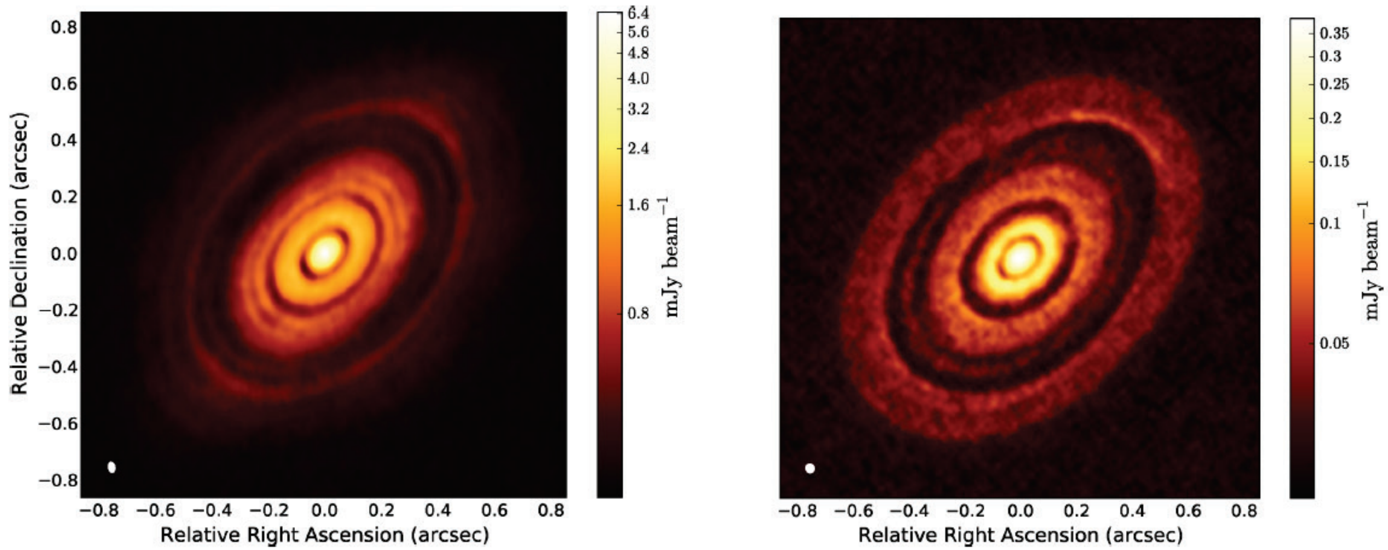


Figure 4. Comparison between the ALMA image of HL Tau (left) with simulated observations of our disc model (right) at band 6 (continuum emission at 233 GHz). Note that the colour bars are different. The white colour in the filled ellipse in the lower left corner indicates the size of the half-power contour of the synthesized beam: (left) 0.035 arcsec × 0.022 arcsec, P.A. 11°; (right) 0.032 arcsec × 0.027 arcsec, P.A. 12°.

~~氷結~~モデル
焼結

- Sintering (焼結) model

氷結®グレープフルーツ

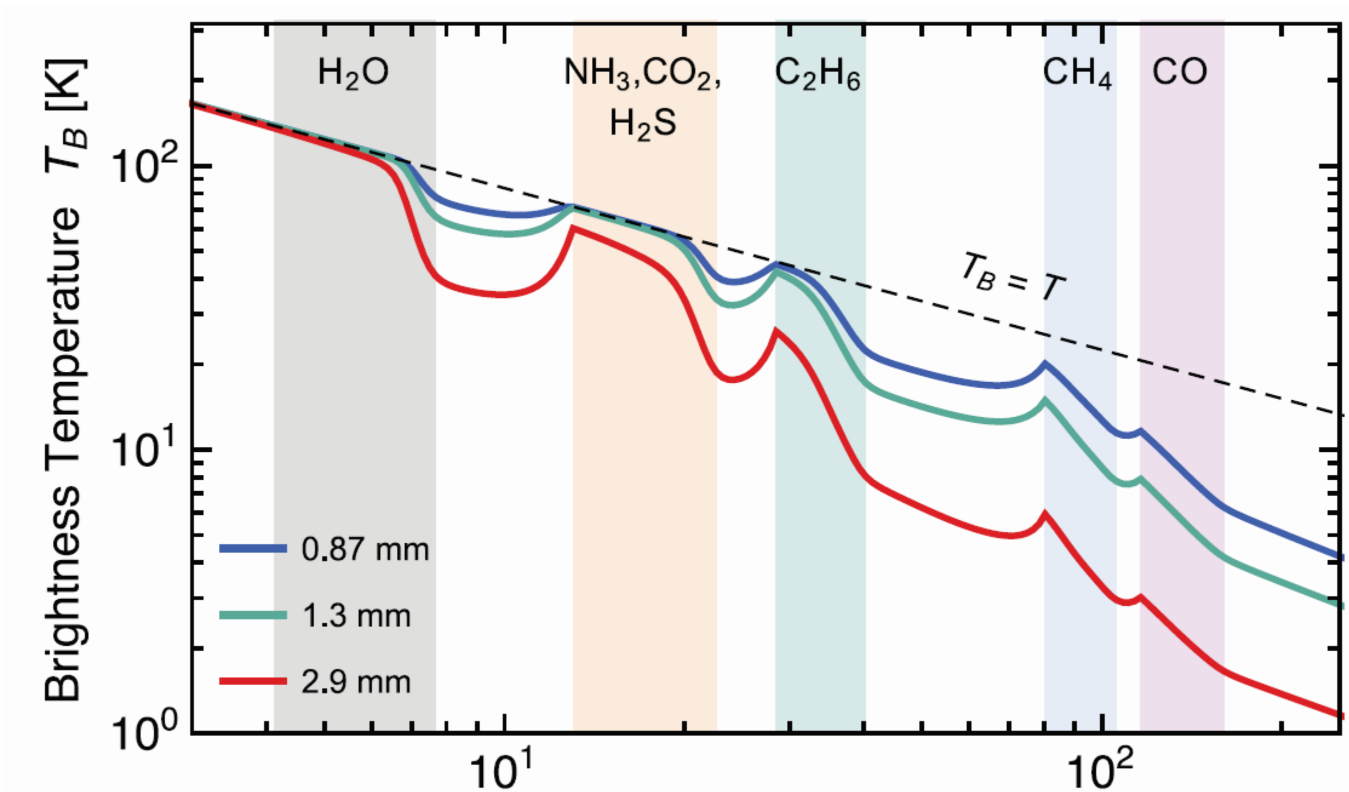
Alternative explanation（Okuzumi+ Titech）

- Gap is not evidence of planet formation
- However, it is evidence that small solid grains are forming from gas???

Sintering 焼結 model
Okuzumi (Titech)+2015

- More packing of fluffy snow at slightly lower temperature of sublimation temperature (fluffy snow to more solid snow)

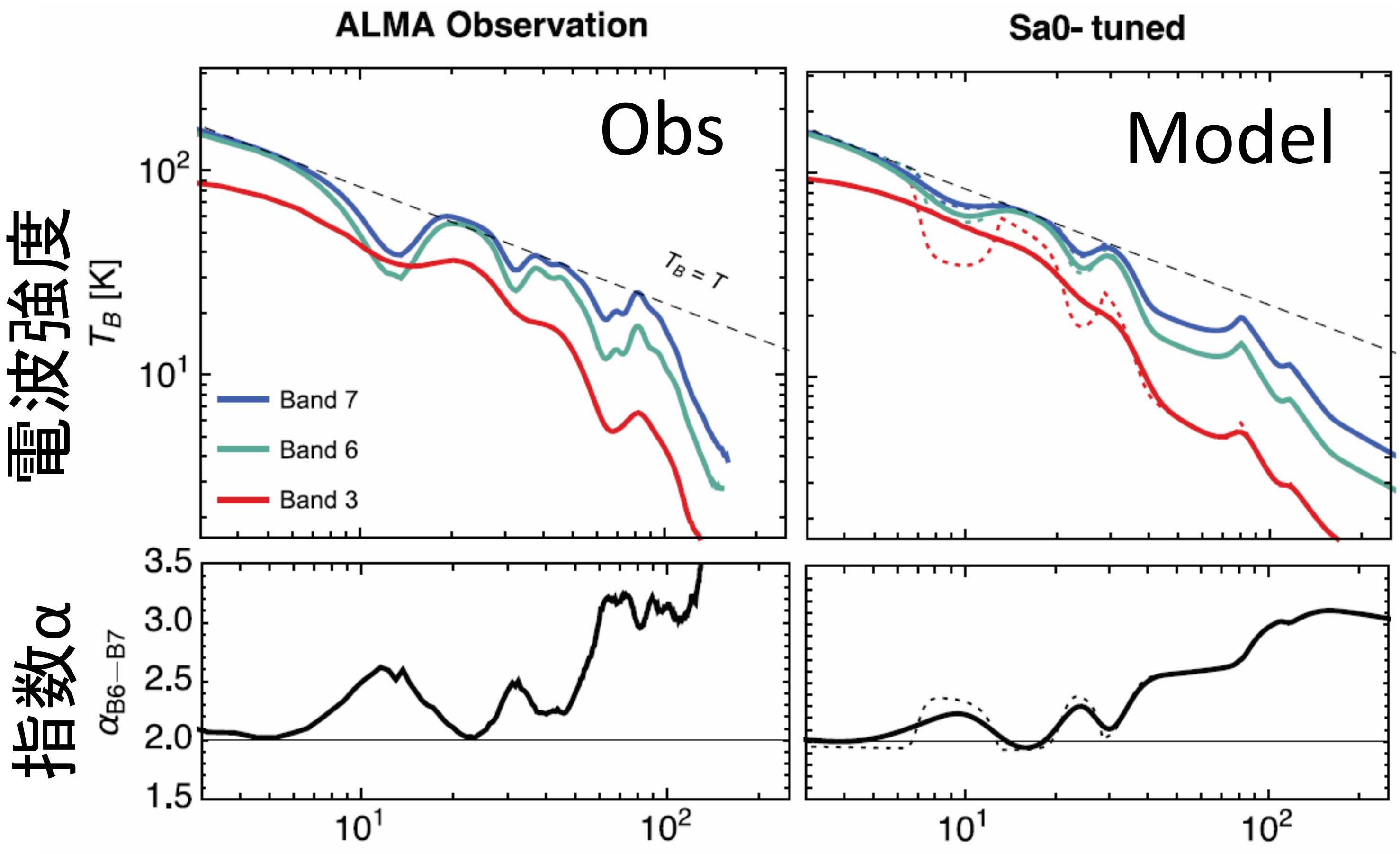
Radio intensity



Raduis from the star (Astronomical Unit)

Okuzumi+2015

Gap due to sintering will disappear in 2 Myr



中心星からの距離（天文単位）

HL Tau (100万歳) では惑星が早く形成!! 太陽系の木星は1000万年で形成。

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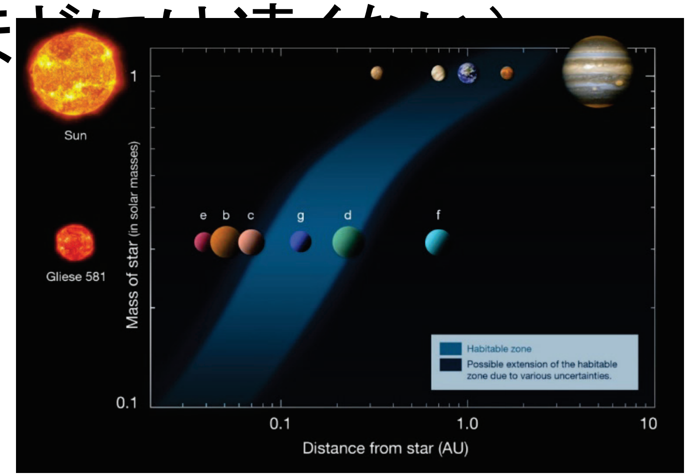
Time (yr)	
10^6	
	Formation of the Earth
10^7	Formation of Jupiter's core & accretion
	Dissipation of nebular gas
10^8	Formation of Saturn's core & capture of remaining gas
	Formation of Asteroid Belt
10^9	Formation of Uranus(?)
	Formation of Neptune(?)
10^{10}	

Habitable planets
生命居住可能惑星

- Planets suitable for life
  - Terrestrial planets地球型惑星（having the ground）
  - Existence of liquid water液体の水が存在
  - Greenhouse effect温室効果（二酸化炭素が凍ってドライアイスになってしまうほ
  - 右の図
    - Top: Solar system
    - Bottom: exo-planets with low mass star
    - Light blue: habitable zone

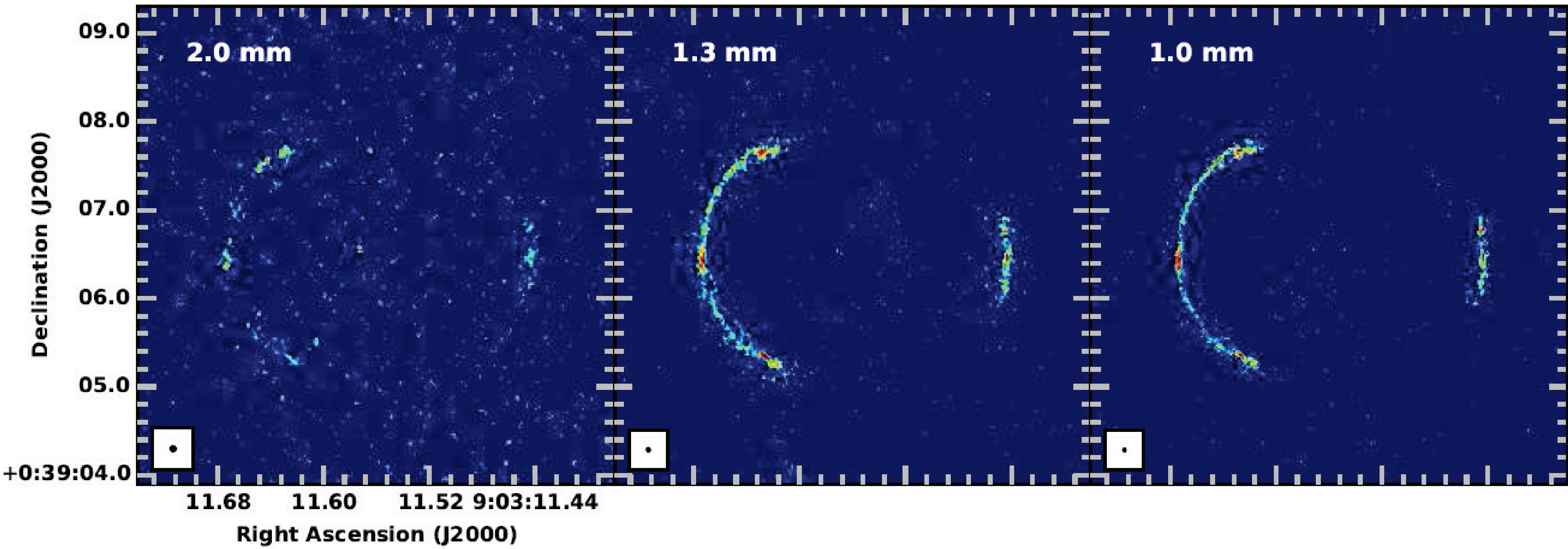


Credit: ESO

Importance of the snow line

- Paper by Okuzumi may indicate snow line-sintering line

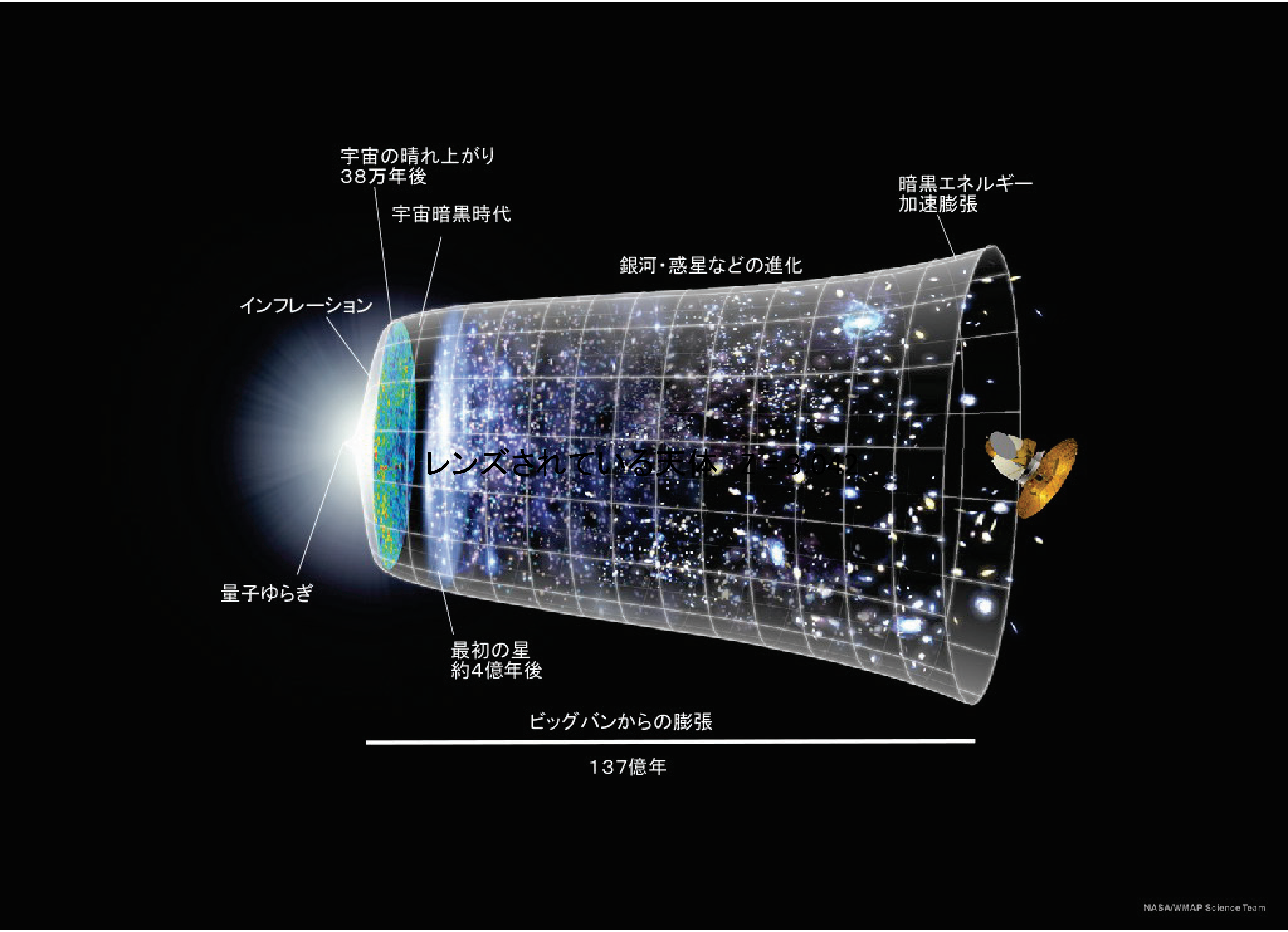
Gravitational lens SDP.81(z~3.04) with vision 2000



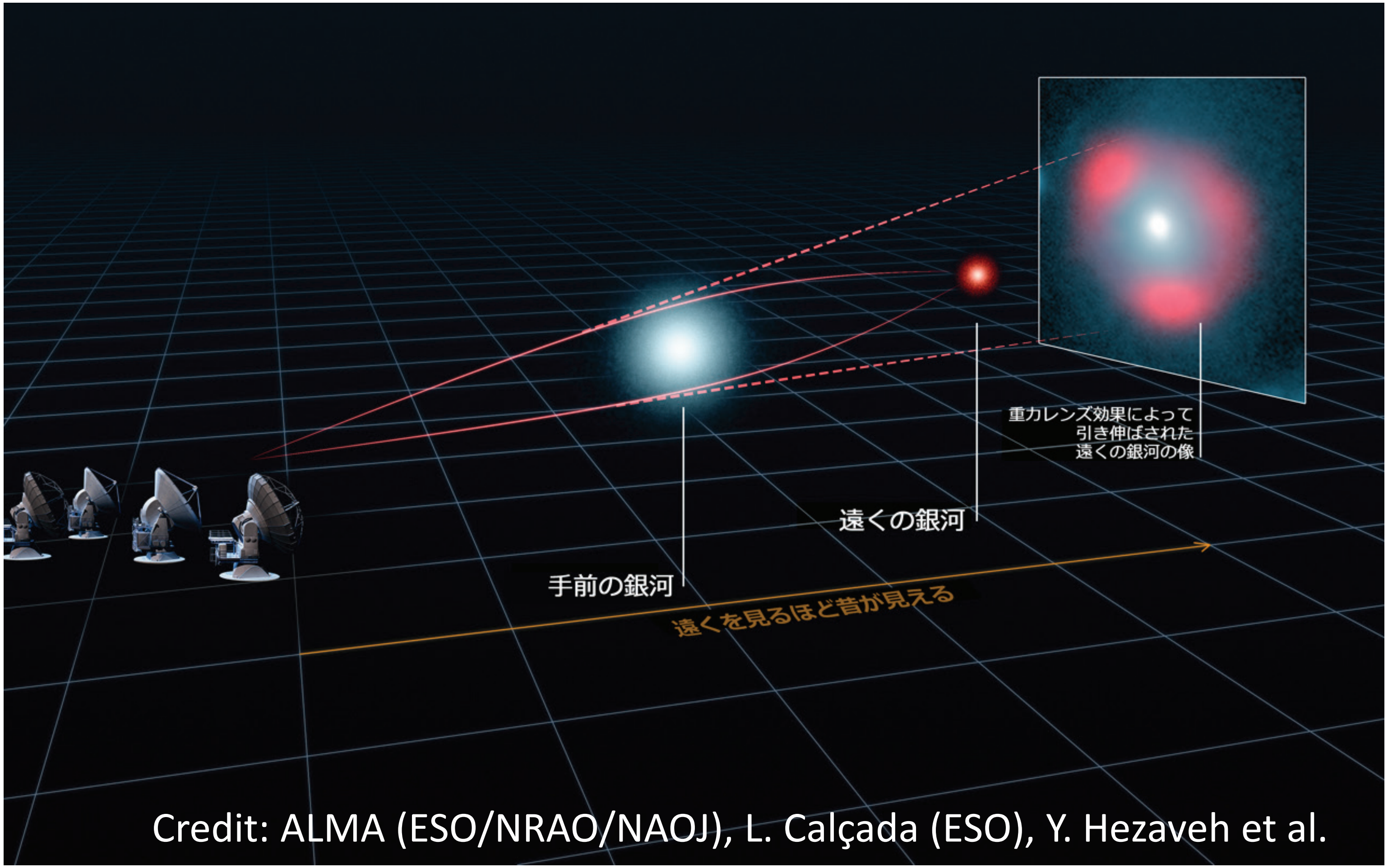
- Mass of lensing point source is > $3x10^8$ $M_{\odot}$

Lensed galaxy Z = 3.042
Redshift and age (after Big Bang)

- $z = (\lambda obs-\lambda_0)/\lambda_0$ λ_0 = rest wavelength
- $1+z= \lambda obs/\lambda_0$
- $z = ((1+v/c)/(1-v/c))^{1/2} -1 \sim v/c$ (if $v<<c$)
- z = 0→age 13.8 Gyr (present)
- z = 1→age 5.8Gyr
- z = 3→age 2.14Gyr
- z = 6→age 0.9 Gyr
- z = 10→age 0.5 Gyr
- z = 1000→age 380 kyr


宇宙の晴れ上がり
38万年後
宇宙暗黒時代
暗黒エネルギー
加速膨張
銀河・惑星などの進化
インフレーション
レンズされている天体 z = 3.042
量子ゆらぎ
最初の星
約4億年後
ビッグバンからの膨張
137億年
NASA/WMAP Science Team

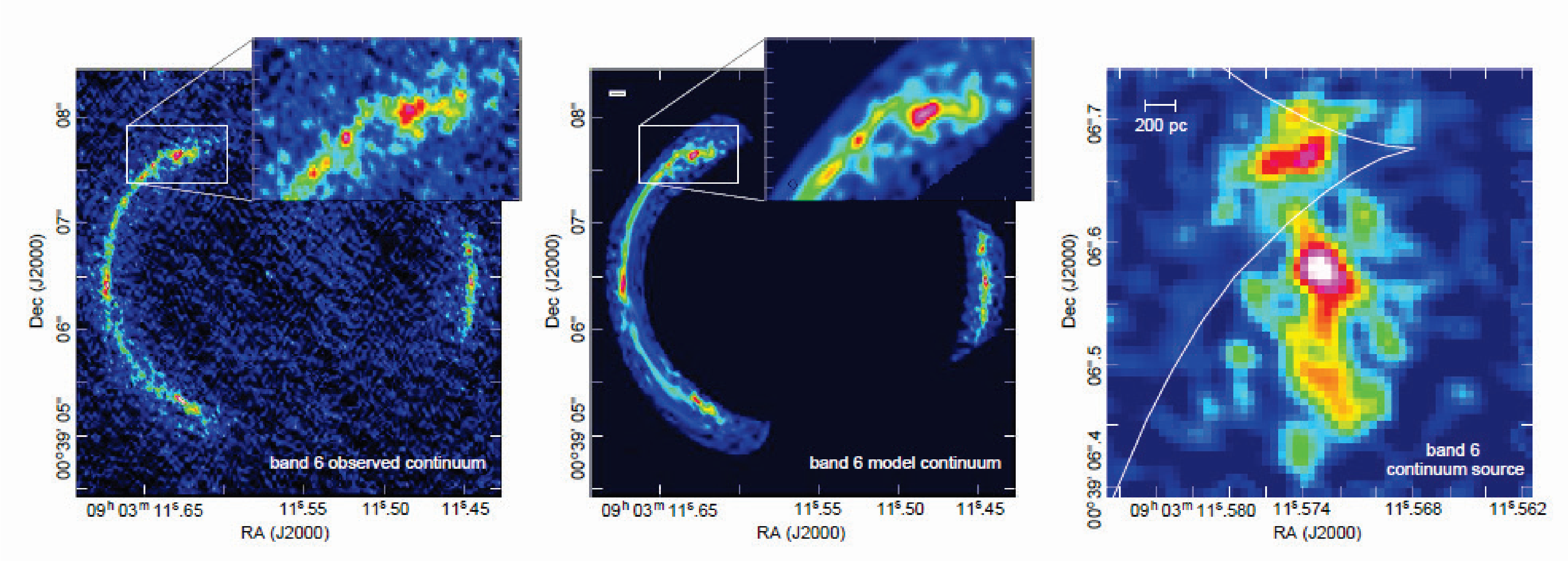
Gravitational lens



Credit: ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al.

SDP.81 ALMA CO emission
Dye et al. (2015)

- Left: observed Einstein ring
- Middle: best-fit model
- Reght: restored CO original distribution



SDP.81 radio and near infrared
ALMA(white contour) vs Hubble(color)

Dye et al. (2015)

- Left: obs, Middle: restored distribution, Right: enlarged. cloud seen in radio is located next to star system seen in near infrared. Interacting

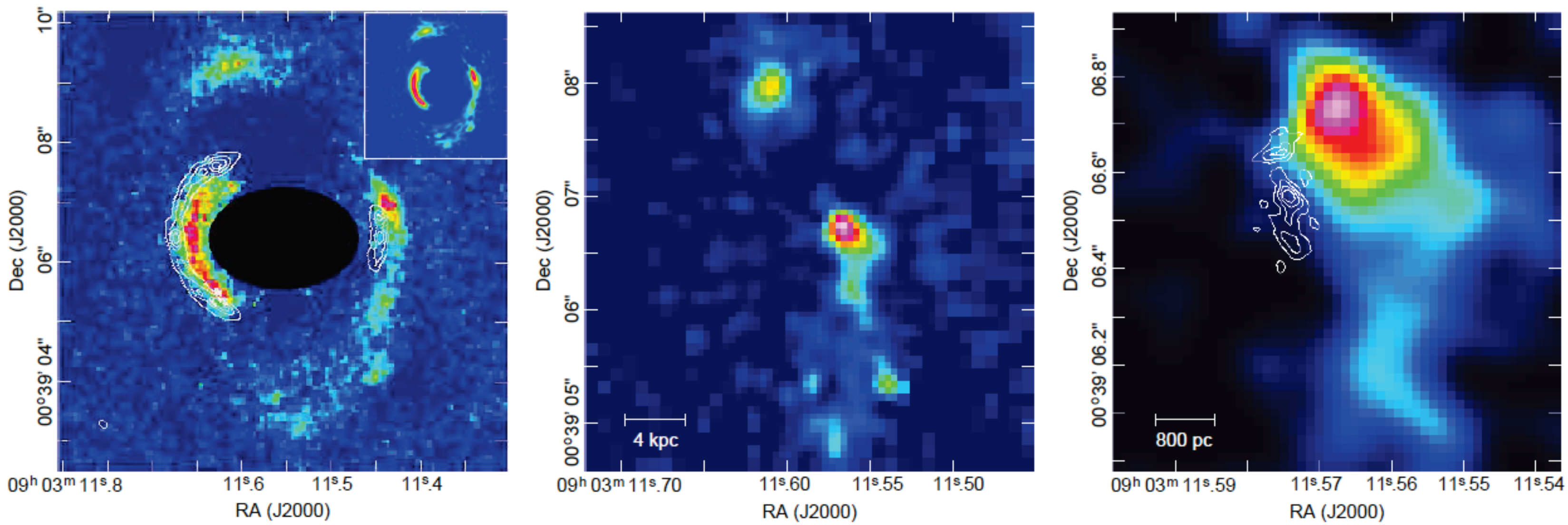
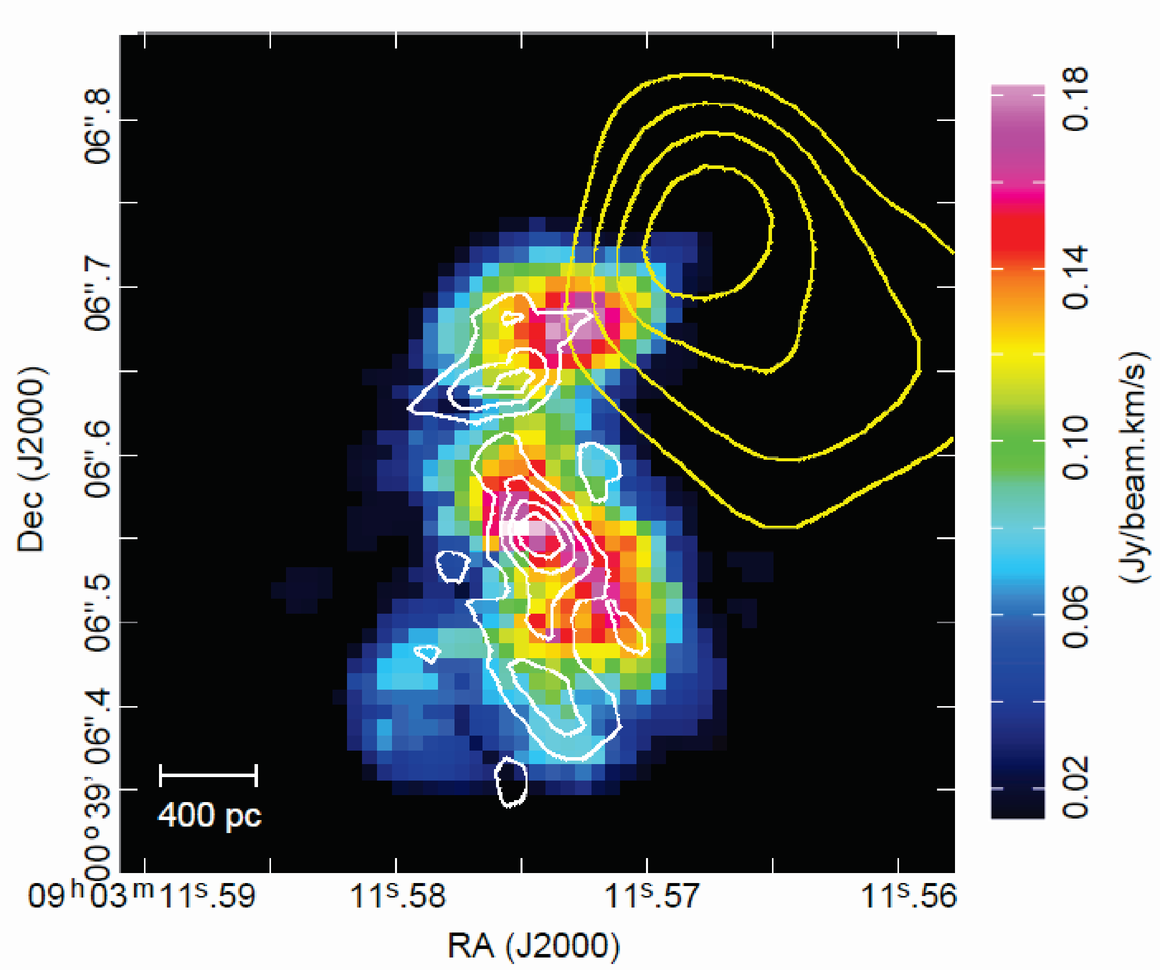


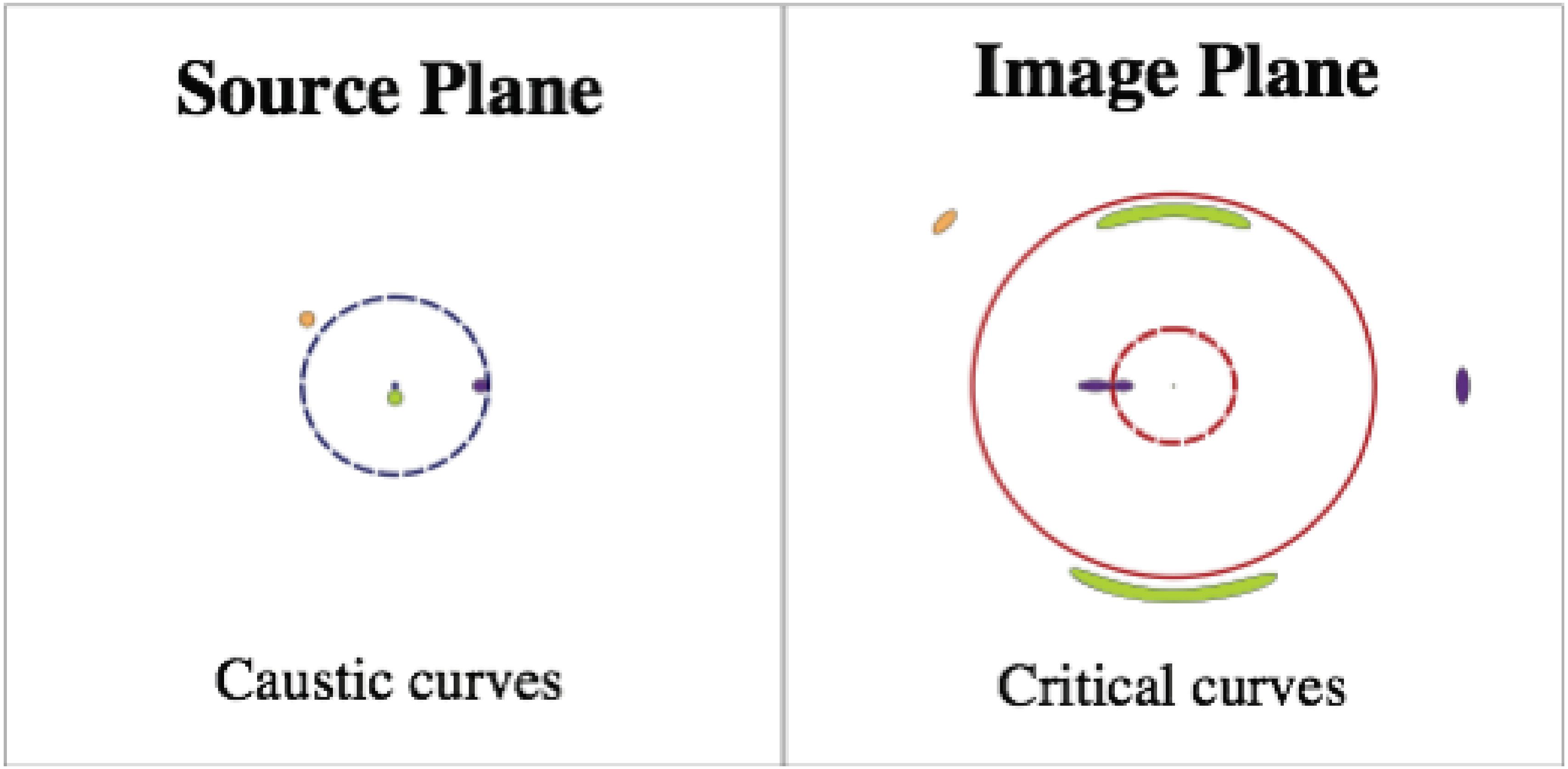
Figure 2. Source reconstruction of the HST F160W data. Panels show the observed image (left; black ellipse masks out residual noise left from lens galaxy light subtraction and the inset panel shows the lensed image of the reconstructed source), the full scale of the reconstructed source that fits the tidal debris-like emission seen in the observed image (middle) and a zoomed-in section of the source overlaid with band 6 continuum contours (right).

SDP.81: restored image
Dye et al. (2015)

- Color: ALMA, CO
- White: ALMA, dust
- Yellow: Hubble



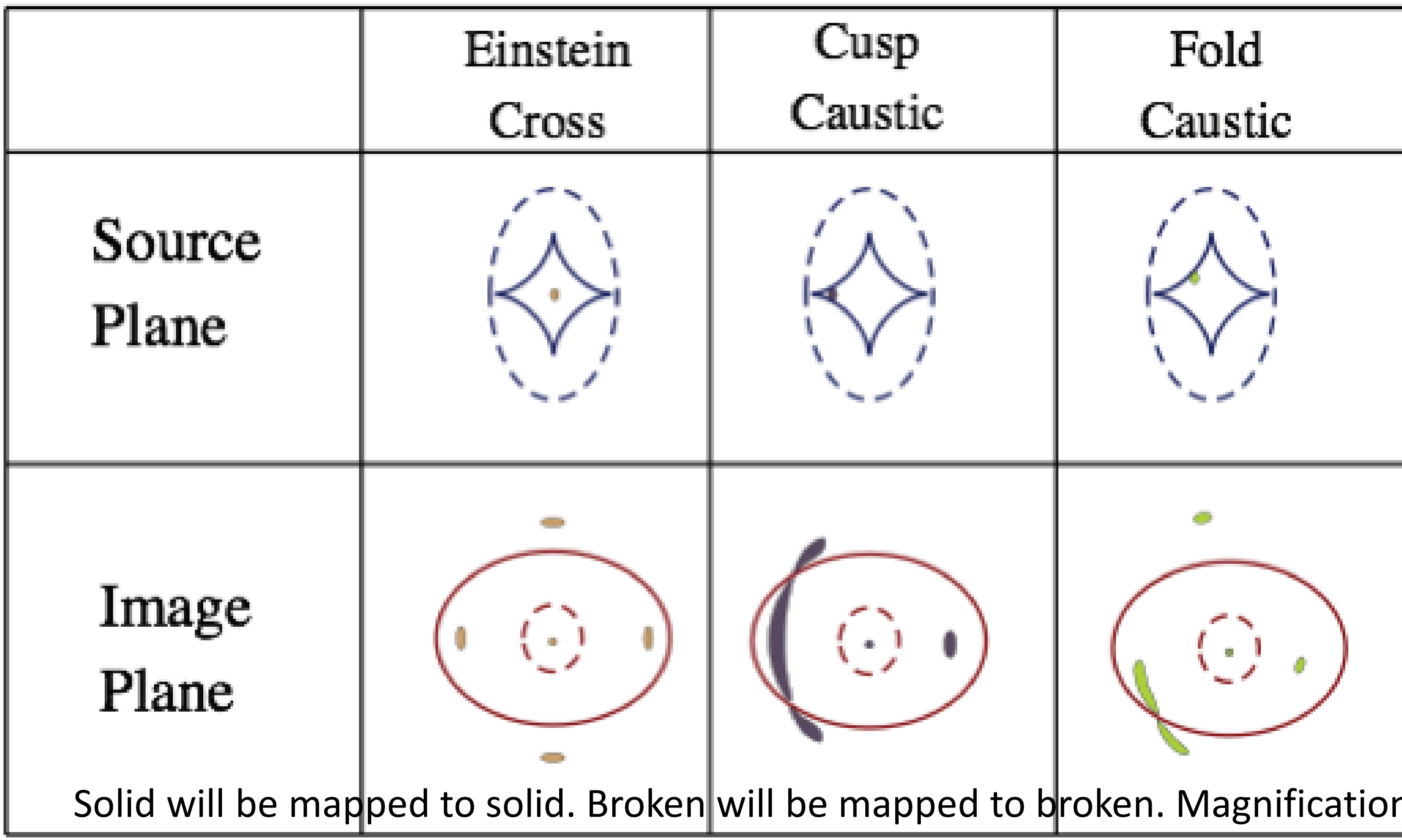
Case that lensing gal is point-symmetric



http://gravitationallensing.pbworks.com/

Gravitational lens（lensing gal: elliptical）

caustic 焦線（blue）、critical curve臨界線（red）

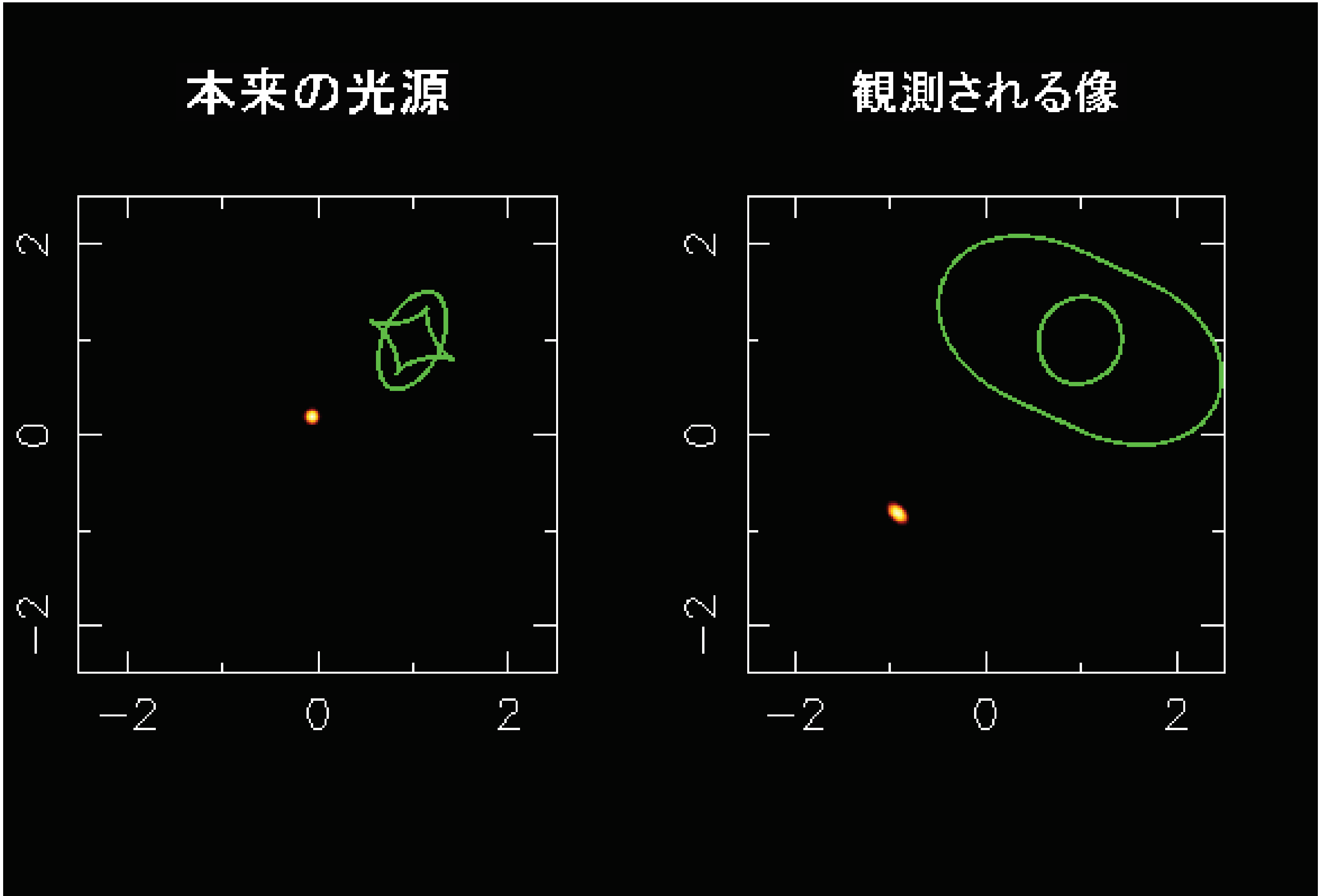


Solid will be mapped to solid. Broken will be mapped to broken. Magnification becom

http://gravitationallensing.pbworks.com/

Gravitational lense PG1115+080

（裳華房のページより） 資料提供：米原厚憲（筑波大学）

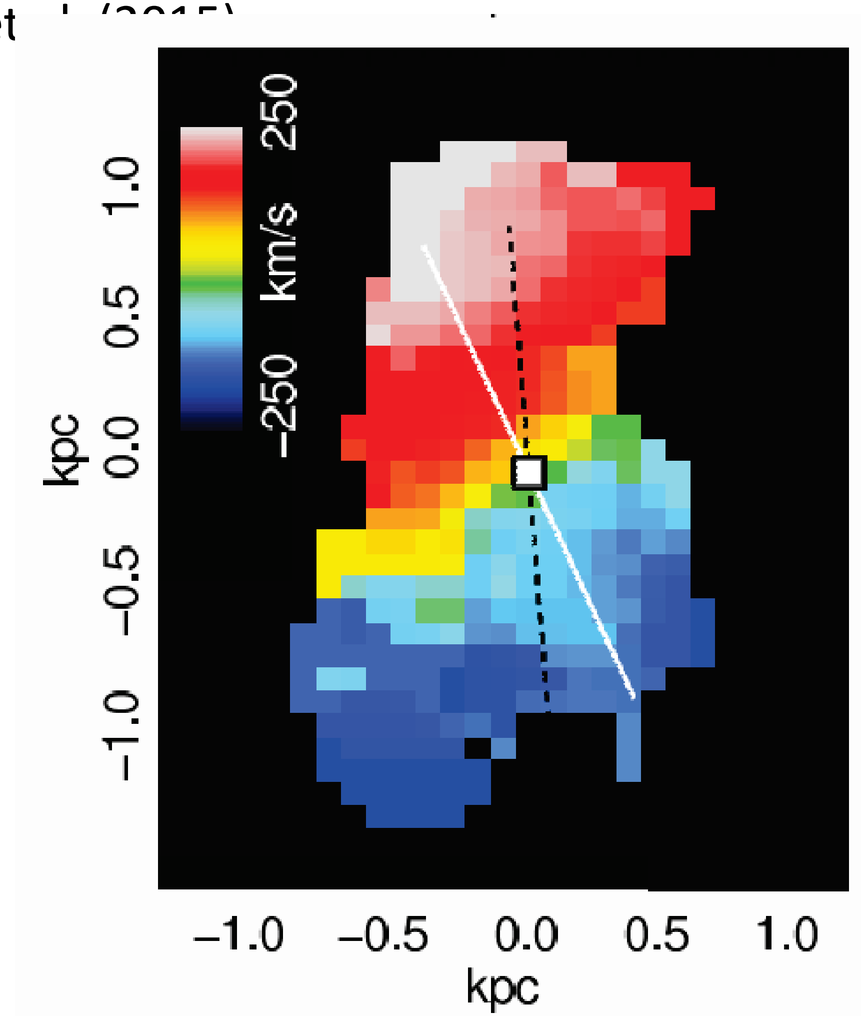


SDP.81 ALMA CO (5-4) Velocity field

Measure kinematics by using Doppler effect.

Dye et al. (2015)

- Rotating disk



Toomre's Q

- $$Q = \frac{\kappa c_s}{\pi G \Sigma_0},$$
- Cs: sound speed（∝ √temperature ）
- κ：epicyclic frequency =angular speed（Kepler rotation）
- G:gravitational constant
- Σ：surface density
- If Q>1, disk is stable if Q<1, disk is unstable

Gravitational lensSDP.81

- Q=0.2 from CO observation
- Molecular gas disk is unstable
- Star forming rate = 500 Mo/y

（cf. 3 Mo/yr in our Milky Way Galaxy)

Lensed galaxy is forming stars very actively
(hundred times more than our Galaxy)

Conclusion

- We have achieved two of three promises we made for the Government
- However, one model claims that the gaps do not represent planet formation!!!
- Very high resolution image by using gravitational lenses
- We should like to achieve the third promise (amid acid detection beyond the solar system)

Thank you for your attention！