東京女子大セミナー

電磁波で探る”暗い宇宙”

遠方の銀河の冷たい分子ガスからアクシオン探査まで

成田 佳奈香

東京大学理学系研究科天文学専攻　博士課程2年

自己紹介

画像：劇場版『名探偵コナン 隻眼の残像』公式サイトより）

はじめまして

- 名前：成田佳奈香
- 専門：電波天文学
- 出身：東京都
- 所属：東京大学大学院理学系研究科天文学専攻
- 趣味：美味しいものを食べること！

野辺山観測所公開日にて

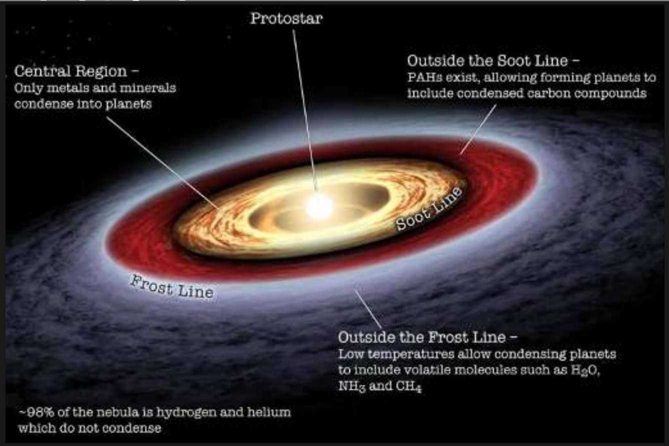
本日のお品書き

宇宙の電磁波のシグナルから”暗い宇宙”を探る

- ミリ波・サブミリ波でみる、遠方銀河と隠された星形成
  - さまざまな銀河
  - 星の形成と銀河の進化
  - サブミリ波銀河とALMA望遠鏡
- 銀河団の重力によって曲げられて増光することで遠くの銀河のガスをALMA望遠鏡で観測
- 暗黒物質により原始惑星系円盤の偏光面が振動する現象を観測

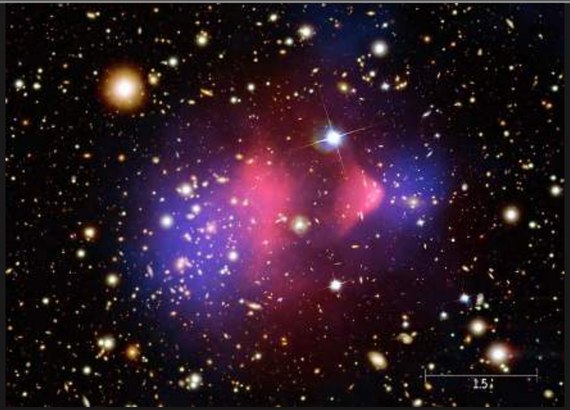
本日のお品書き

暗黒物質探査
Talk3



NASA/JPL-Caltech/Invader Xan

恒星系（惑星）



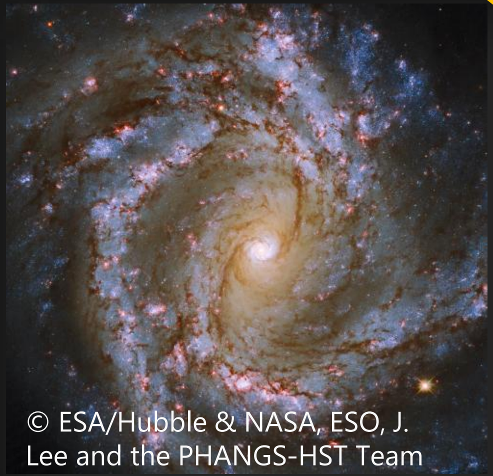
X-ray: NASA/CXC/CfA/M.Markevit

銀河団

天然の望遠鏡
Talk2

画像:アストロアーツ

惑星



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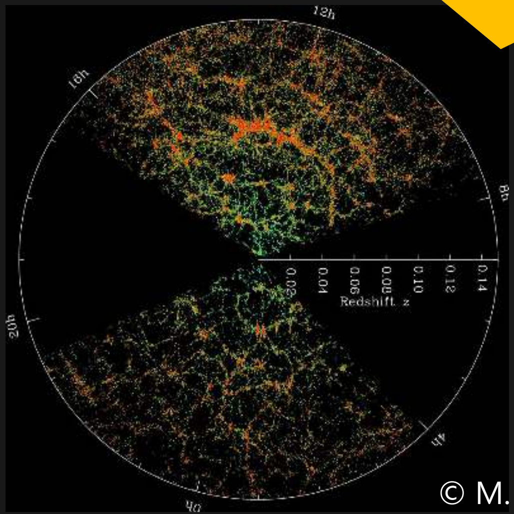
今日の主役
Talk1 & Talk2

銀河



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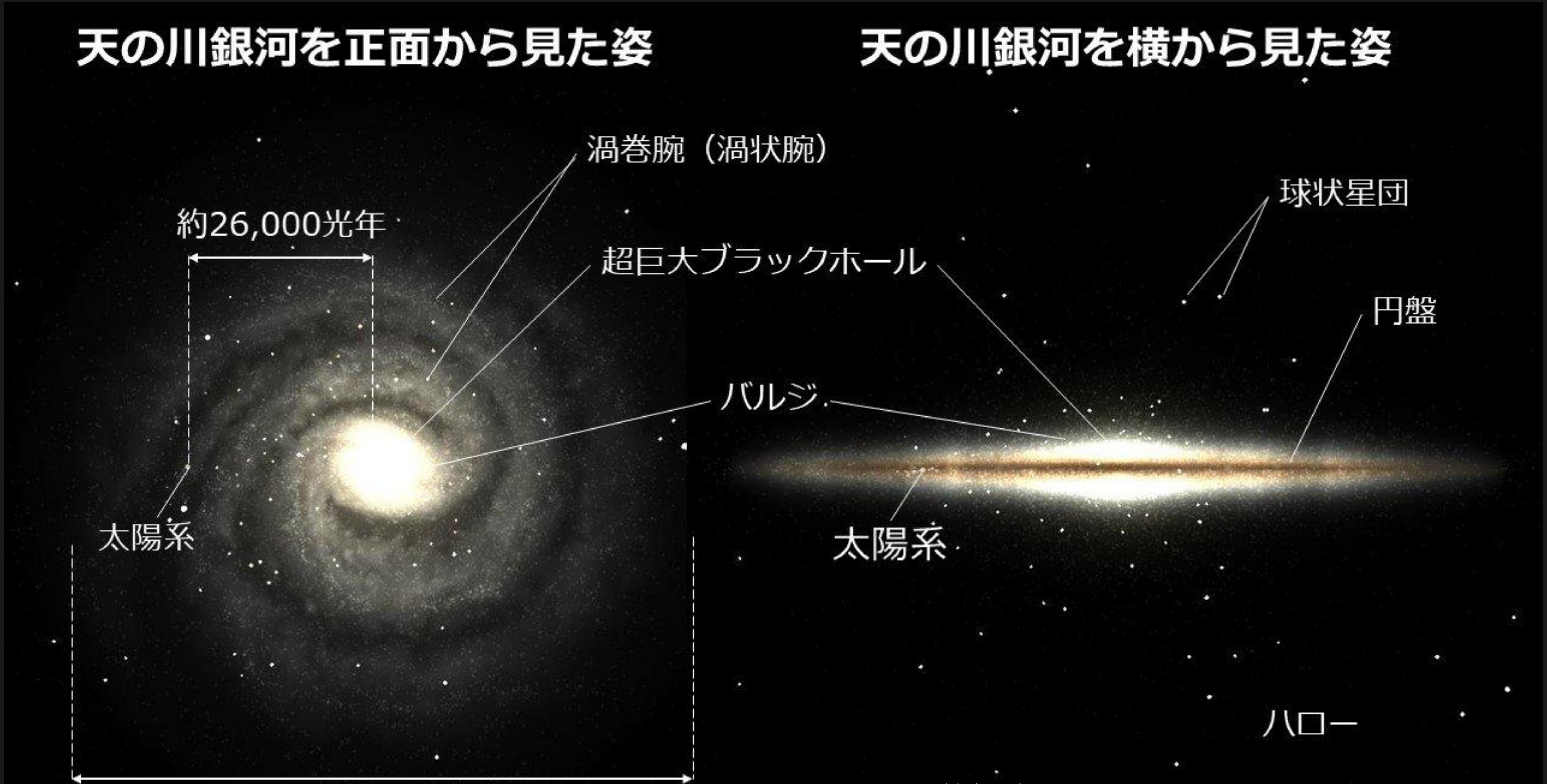
宇宙大規模構造

天の川銀河(銀河系)



Credit: 加藤恒彦, 4D2U Project, NAOJ, ALMA (ESO/NAOJ/NARO)

さまざまな銀河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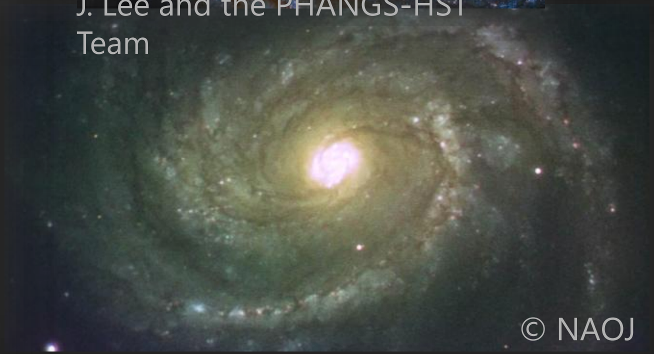
© NAOJ


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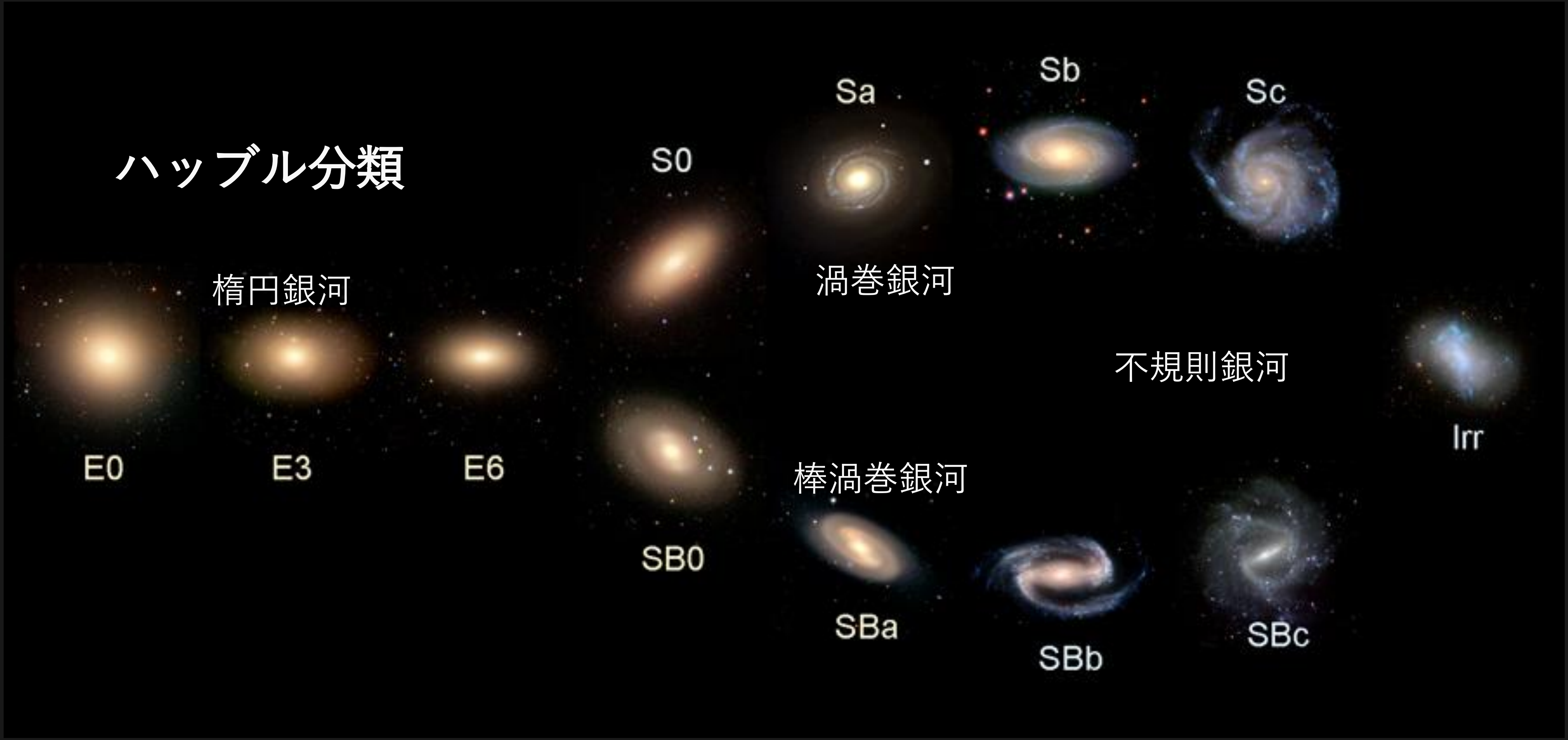
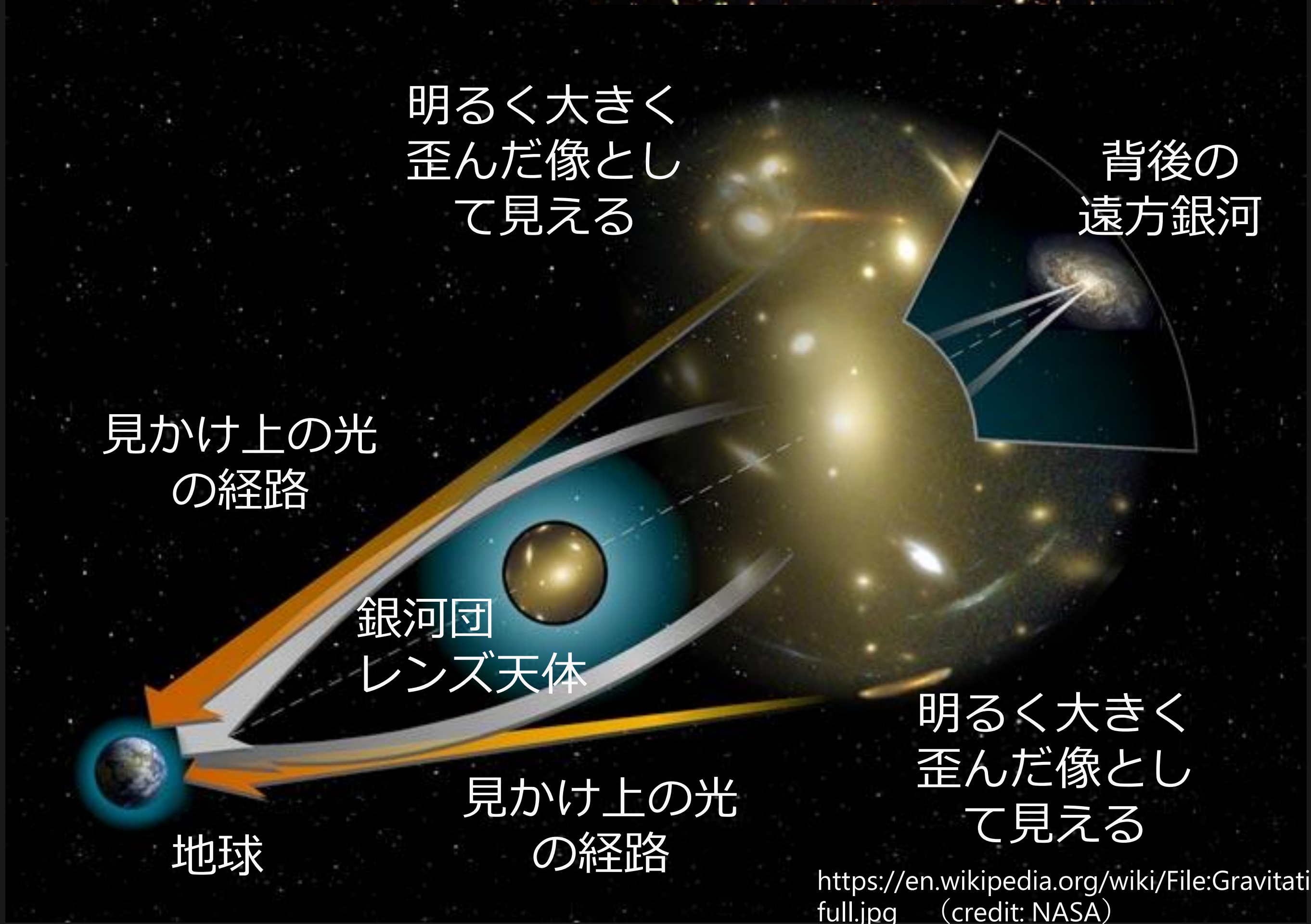
銀河の形態分類


ハッブル分類
楕円銀河
E0
E3
E6
S0
SB0
Sa
Sb
Sc
渦巻銀河
不規則銀河
Irr
棒渦巻銀河
SBa
SBb
SBc

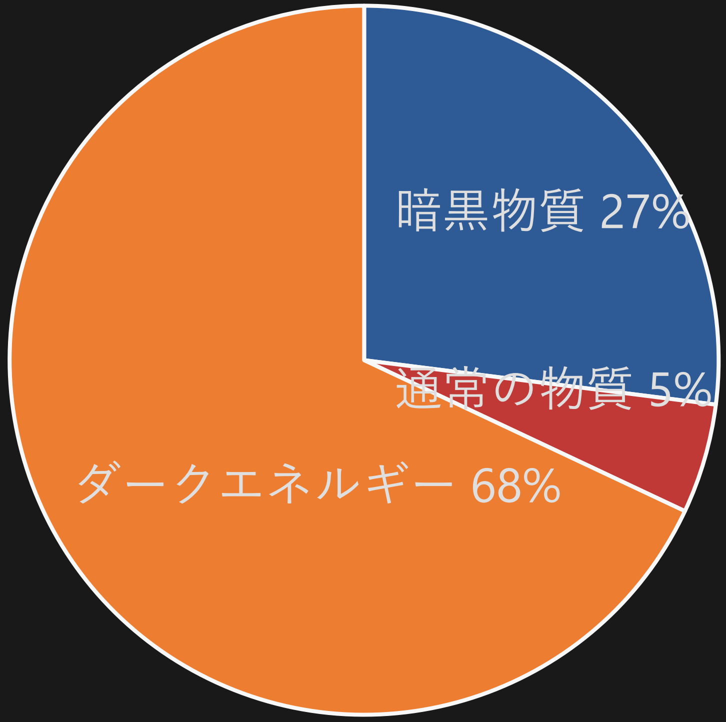
銀河団

X-ray: NASA/CXC/CfA/M.Markevit

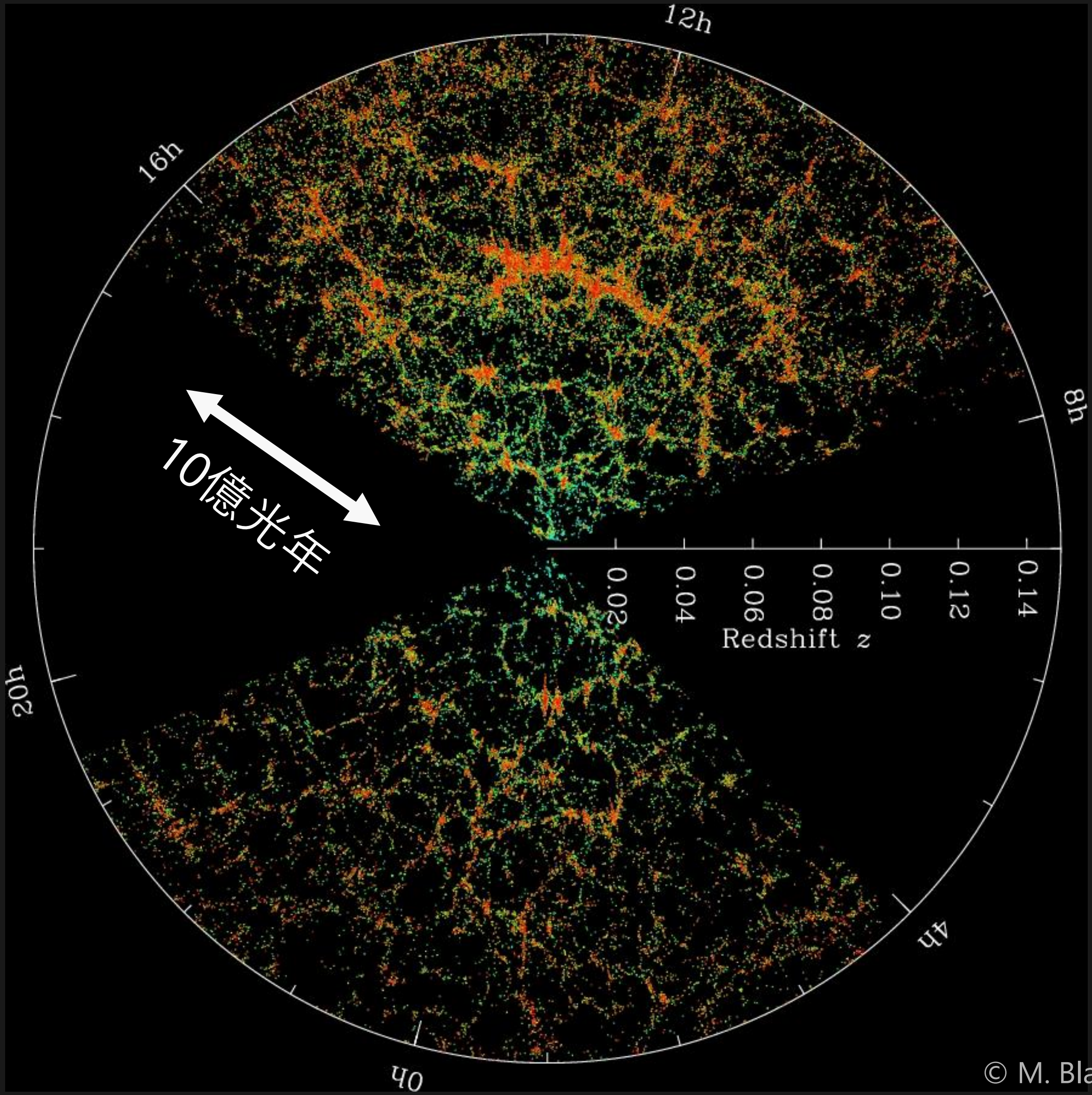
- 数百個から数千個の銀河から構成
- 銀河に付随するX線を放射する高温ガス、質量の大半を占める暗黒物質(ダークマター)から構成
- 銀河団の全質量は10^{14}～10^{15}太陽質量



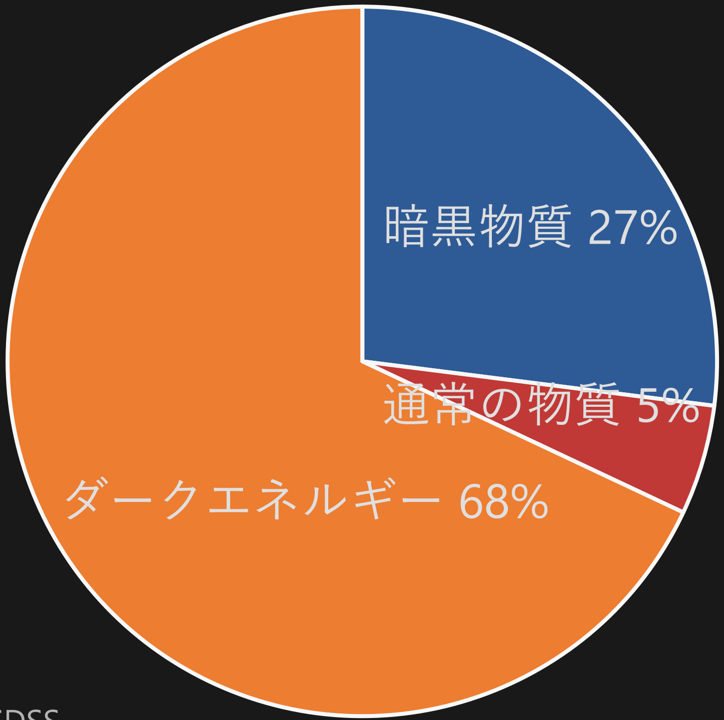
https://en.wikipedia.org/wiki/File:Gravitational_lens-full.jpg　（credit: NASA）



宇宙の大規模構造



大規模構造を支えているのは暗黒物質

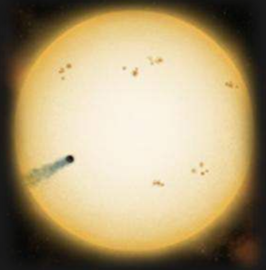


遠くの宇宙」＝「過去の宇宙」

アンドロメダ銀河

約250万光年

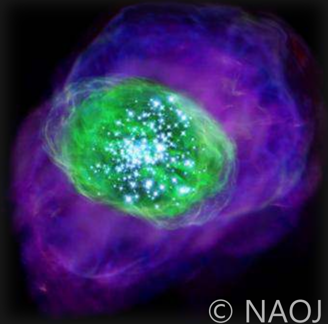
太陽



約8分20秒

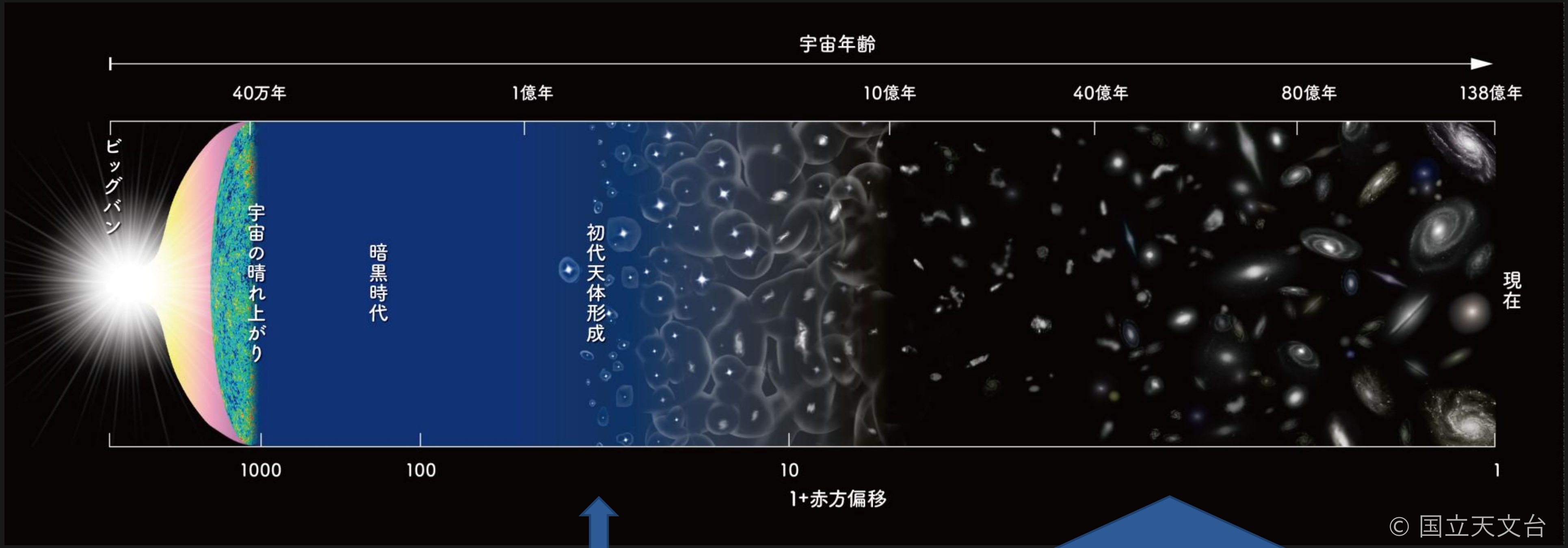
1.5億km

初期宇宙の銀河



約130億光年

宇宙の歴史



初代星・初代銀河？

宇宙にはいくつ銀河があるでしょうか？

① 1億個

② 100億個

③ 1兆個以上

宇宙にはいくつ銀河があるでしょうか？

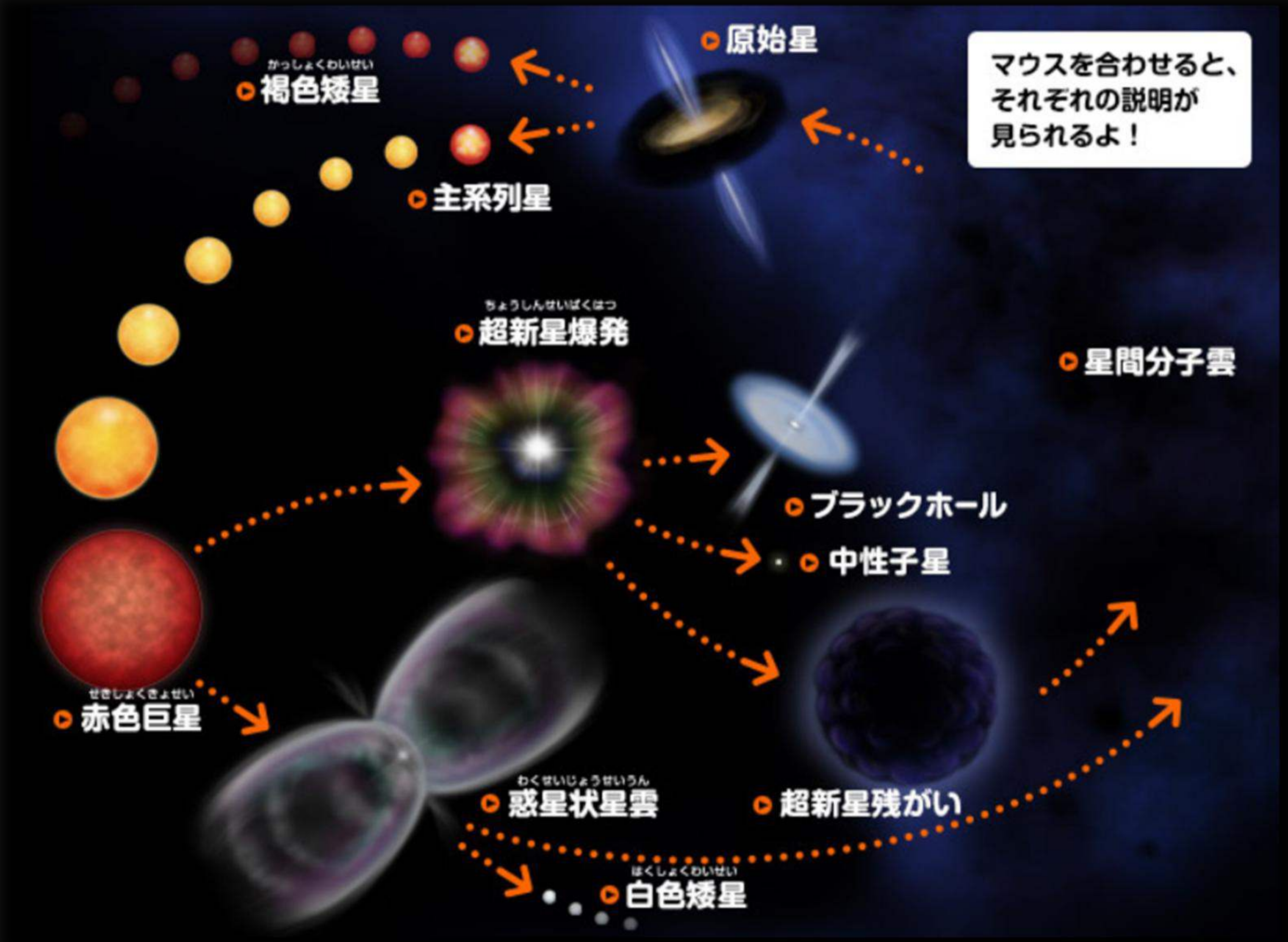
① 1億個

② 100億個

③ 1兆個以上

星の形成と銀河の進化

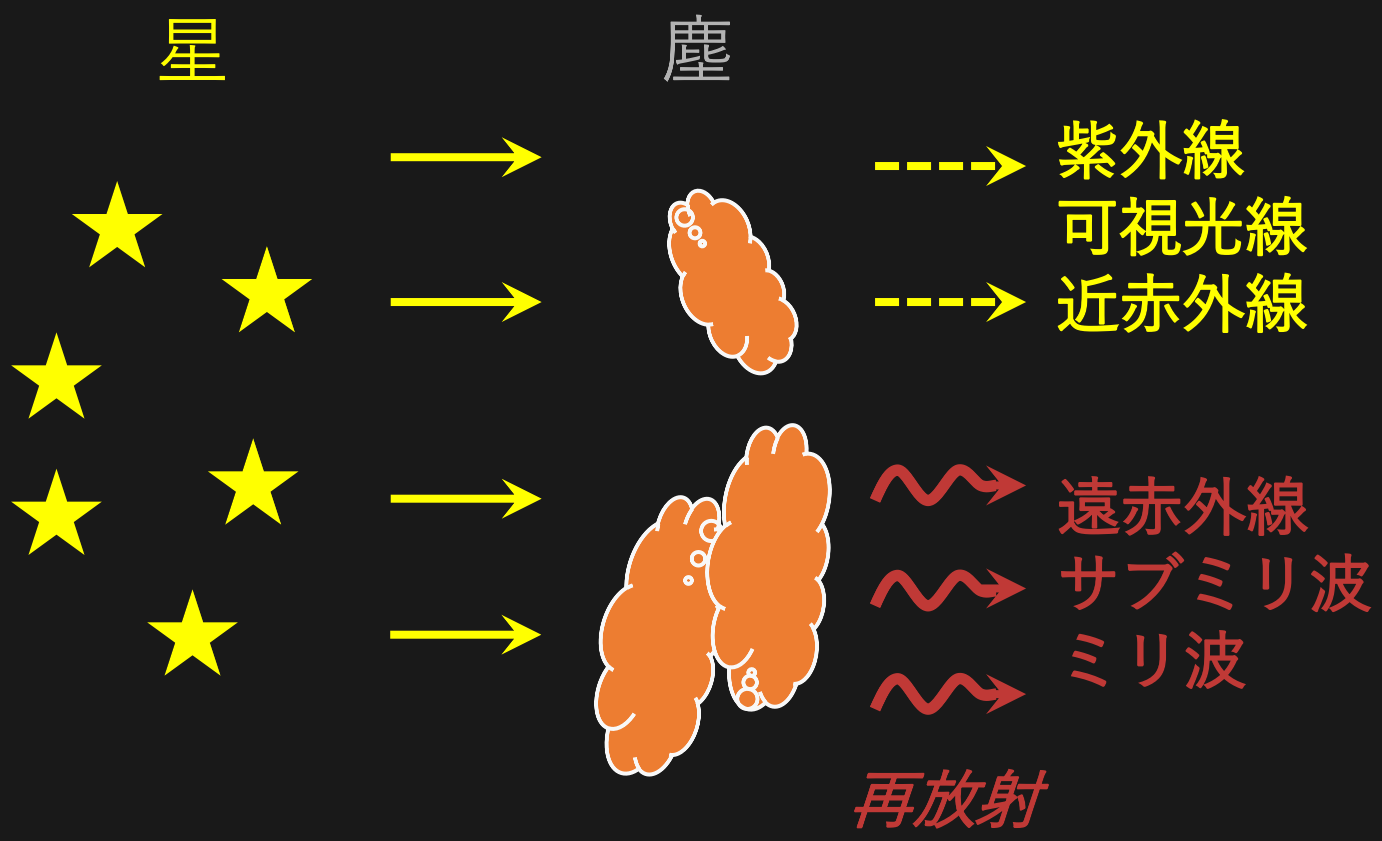
星の誕生と死

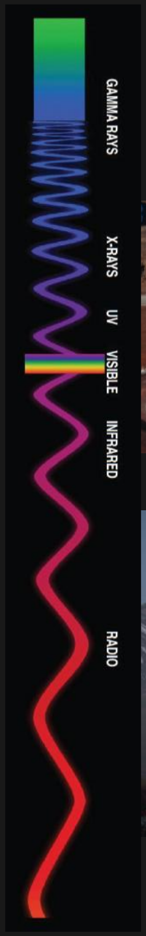

原始星
マウスを合わせると、
それぞれの説明が
見られるよ！
褐色矮星
主系列星
超新星爆発
星間分子雲
ブラックホール
中性子星
赤色巨星
惑星状星雲
超新星残がい
白色矮星

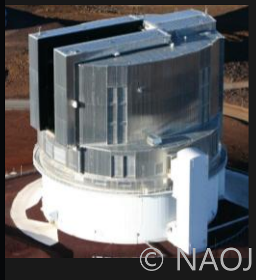
銀河の形成・進化


大量のガスの集まり
ガスから星が誕生
ガスが消費されていく
年老いた星が増える
星形成の材料が枯渇
年老いた星の集団
© ESA/Hubble & NASA,
Acknowledgement: Judy
Schmidt
© NAOJ

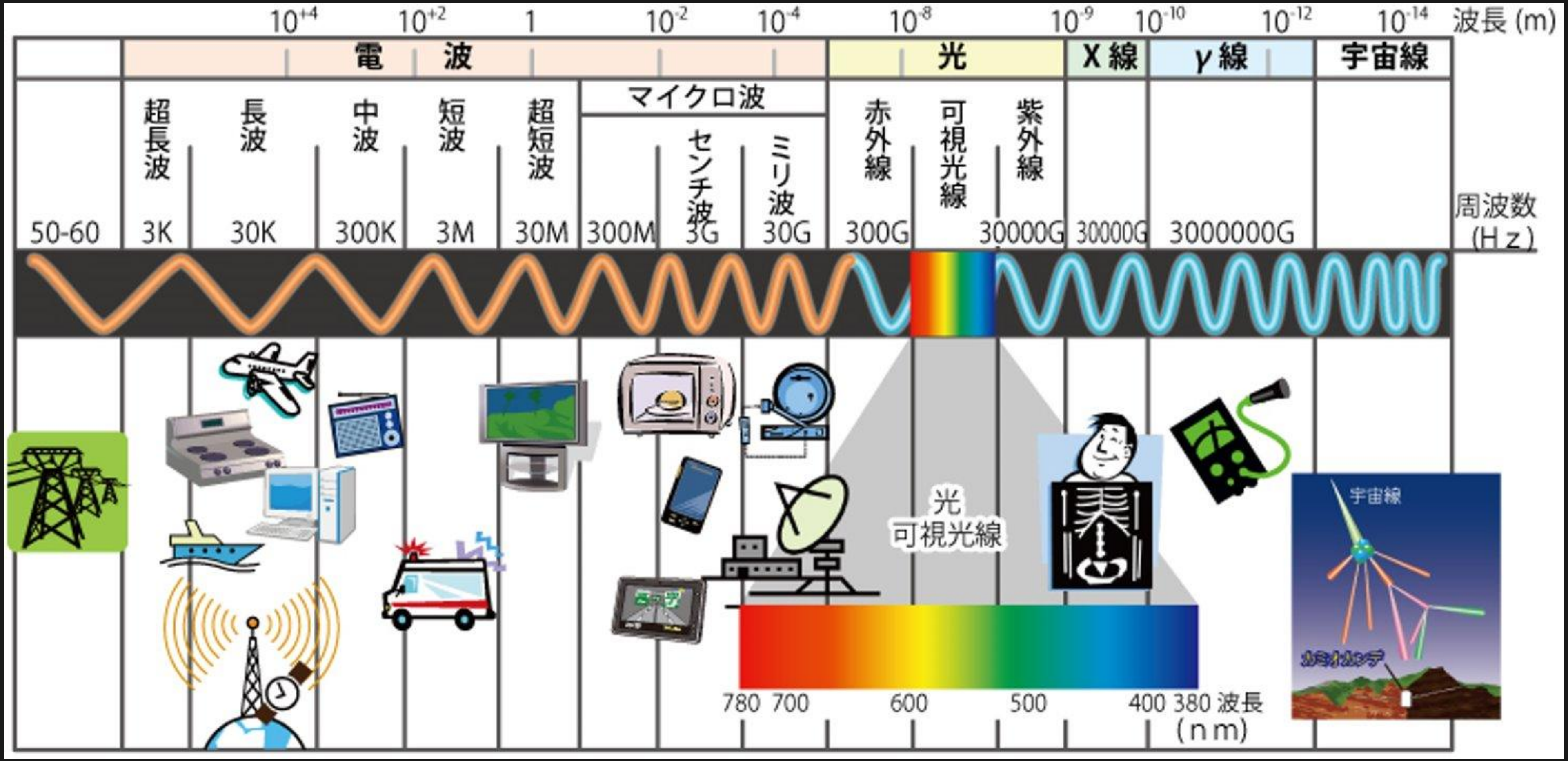
星形成の活動をとらえる



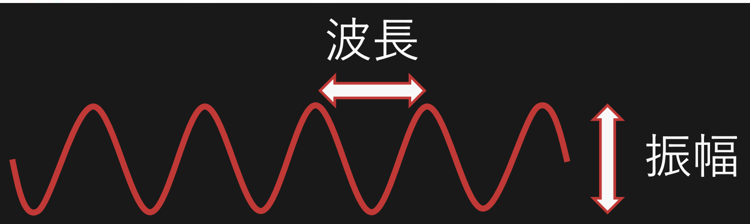




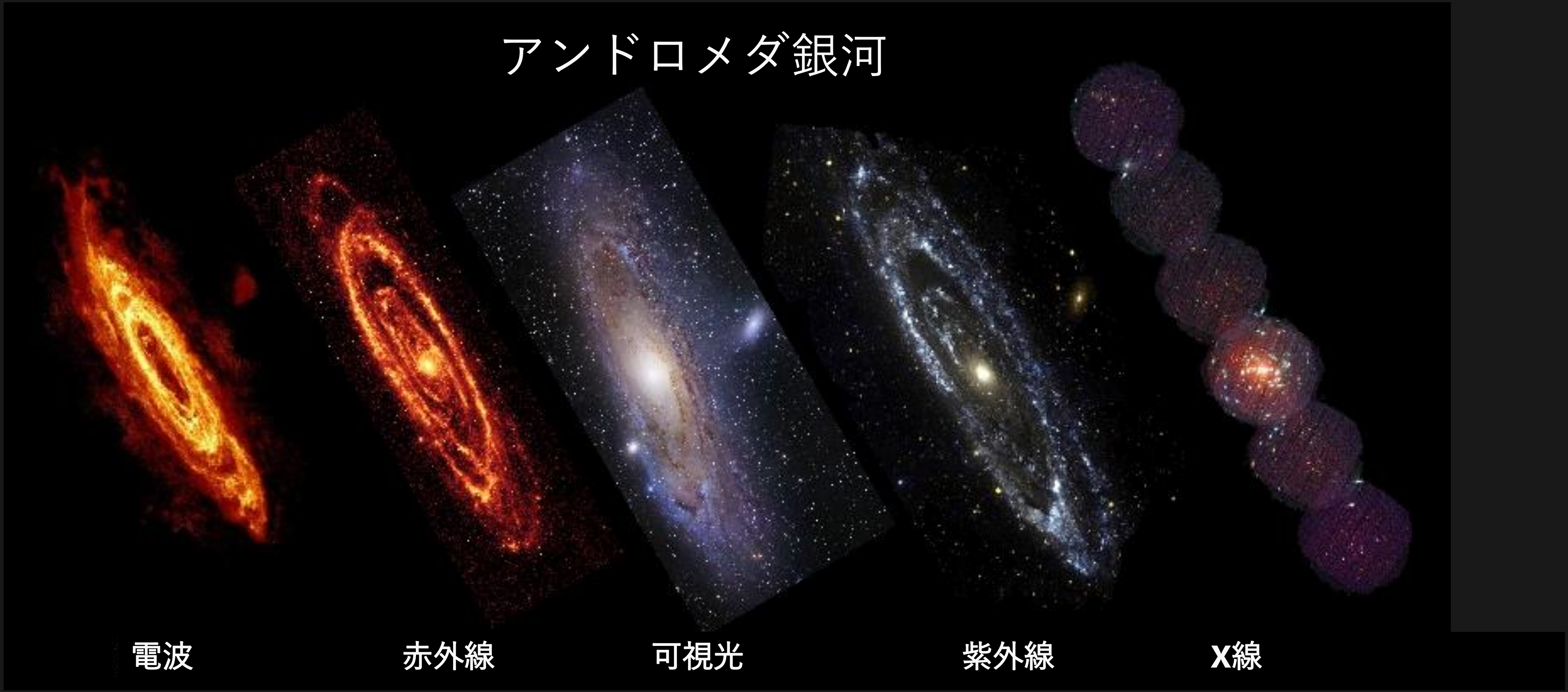
電磁波


10+4
10+2
1
10-2
10-4
10-8
10-9
10-10
10-12
10-14
波長 (m)
電波
光
X線
γ線
宇宙線
超長波
長波
中波
短波
超短波
マイクロ波
センチ波
ミリ波
赤外線
可視光線
紫外線
周波数 (Hz)
50-60
3K
30K
300K
3M
30M
300M
3G
30G
300G
30000G
300000G
3000000G
光
可視光線
780 700 600 500 400 380 波長 (nm)
宇宙線
カミオカンデ

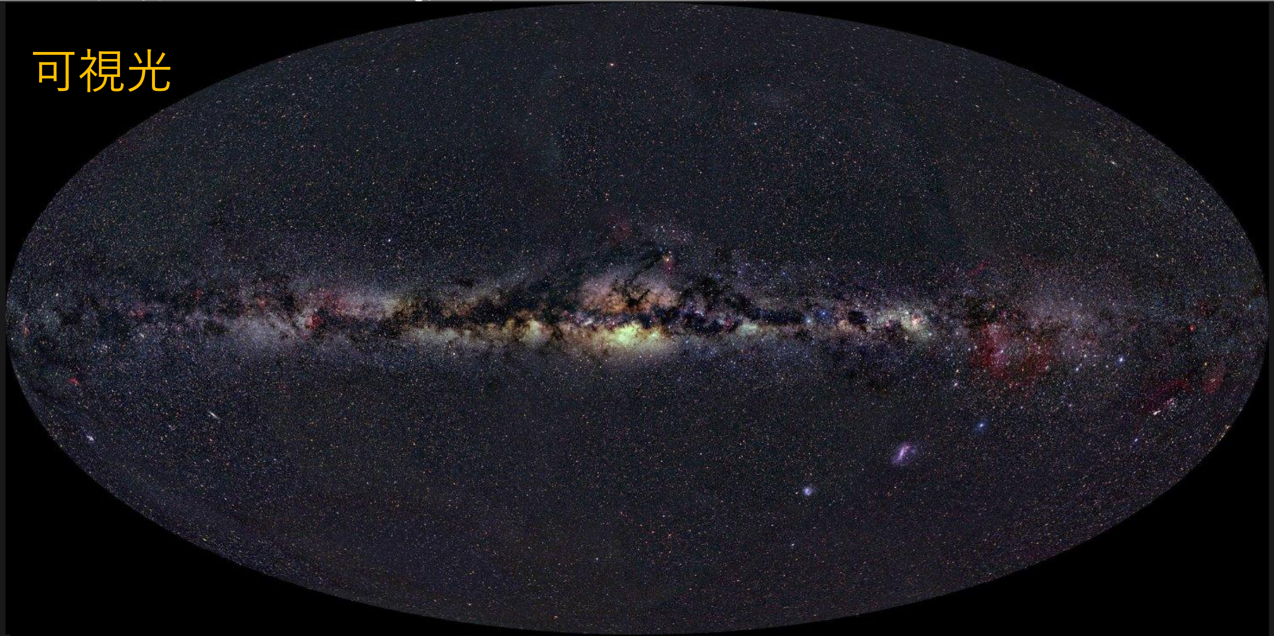
@NICT

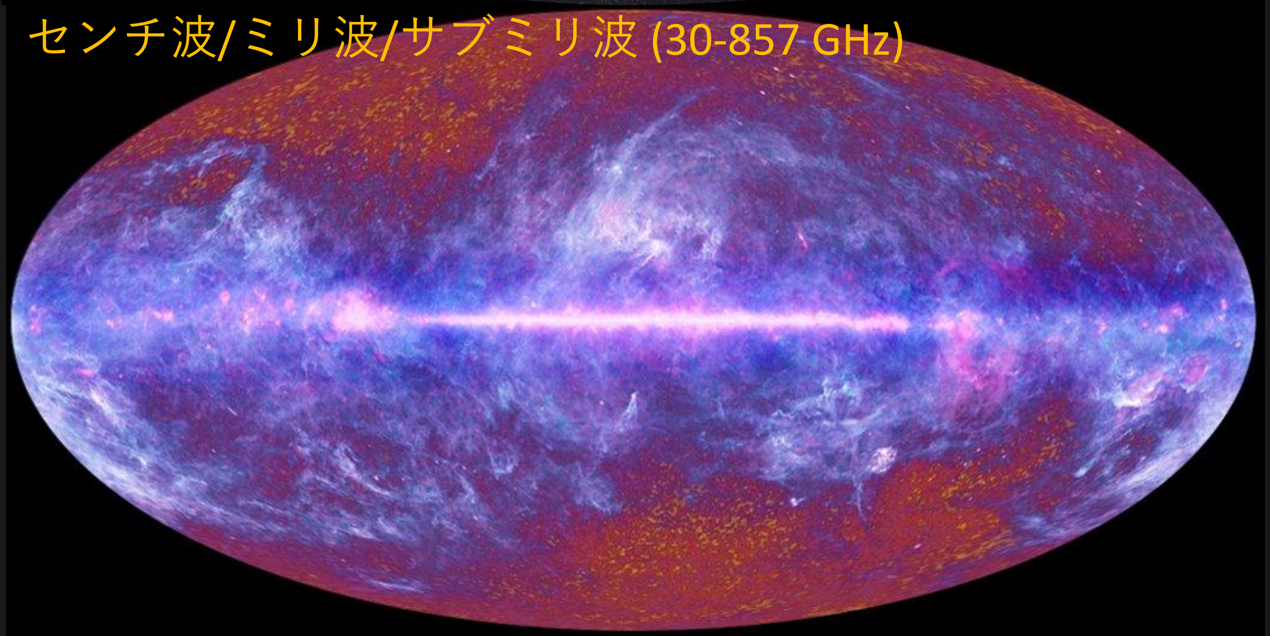

波長
振幅

色々な波長で見た銀河の姿



天の川銀河を可視光と電波で比べてみたら…

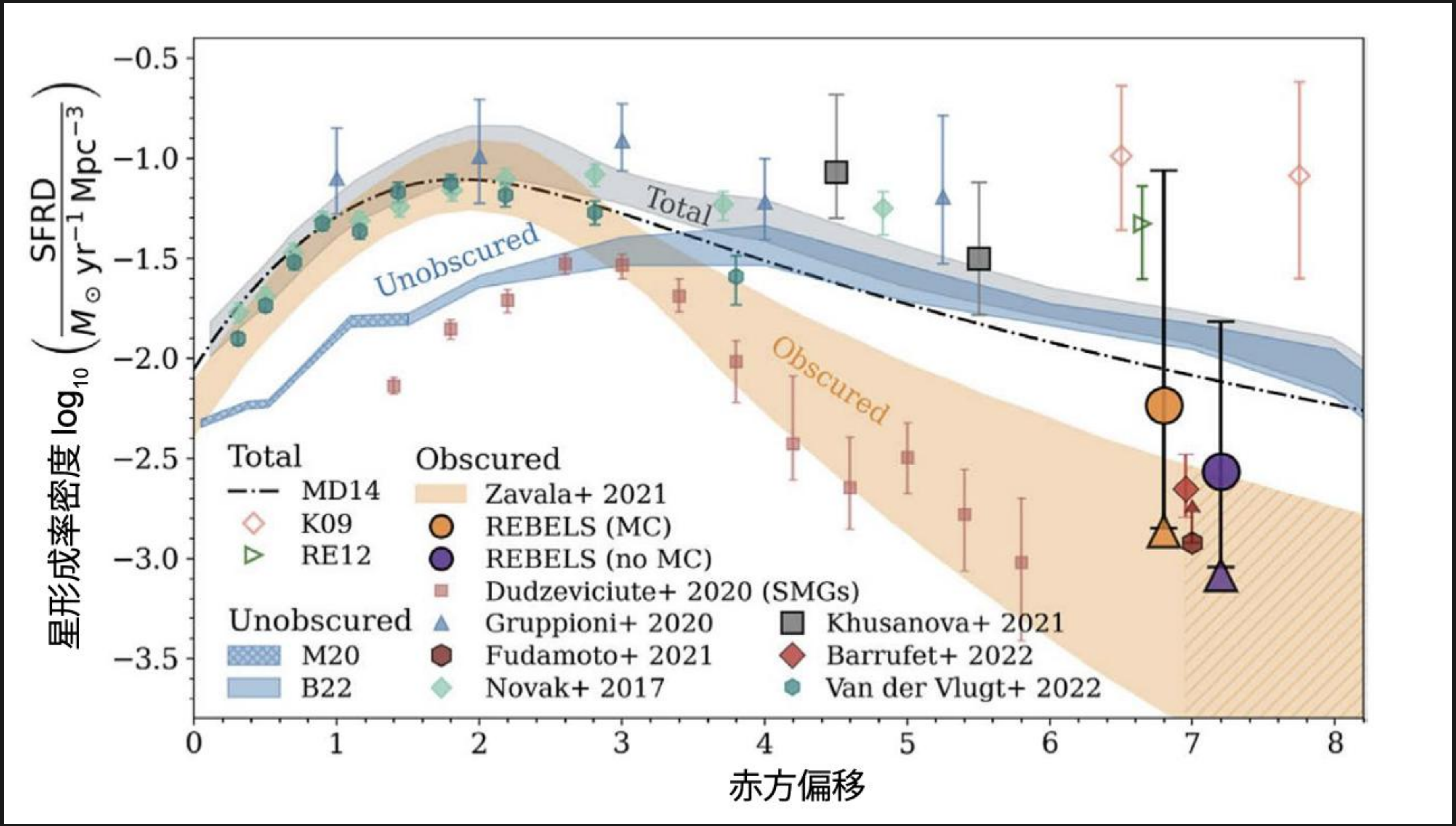




塵が星の光を覆い隠している！

隠された銀河の星形成活動を見る鍵がミリ波・サブミリ波！

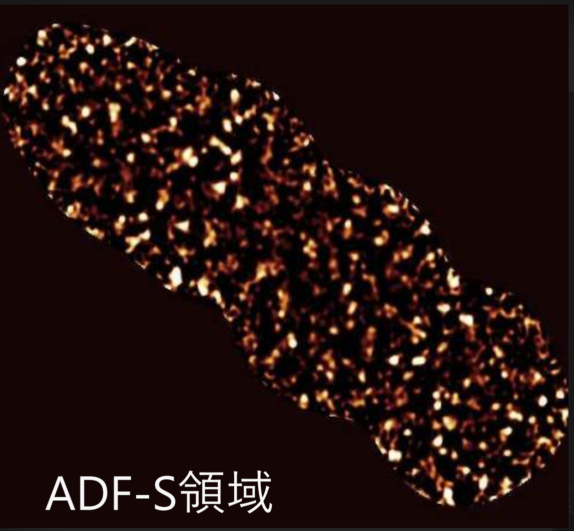
宇宙の星形成史

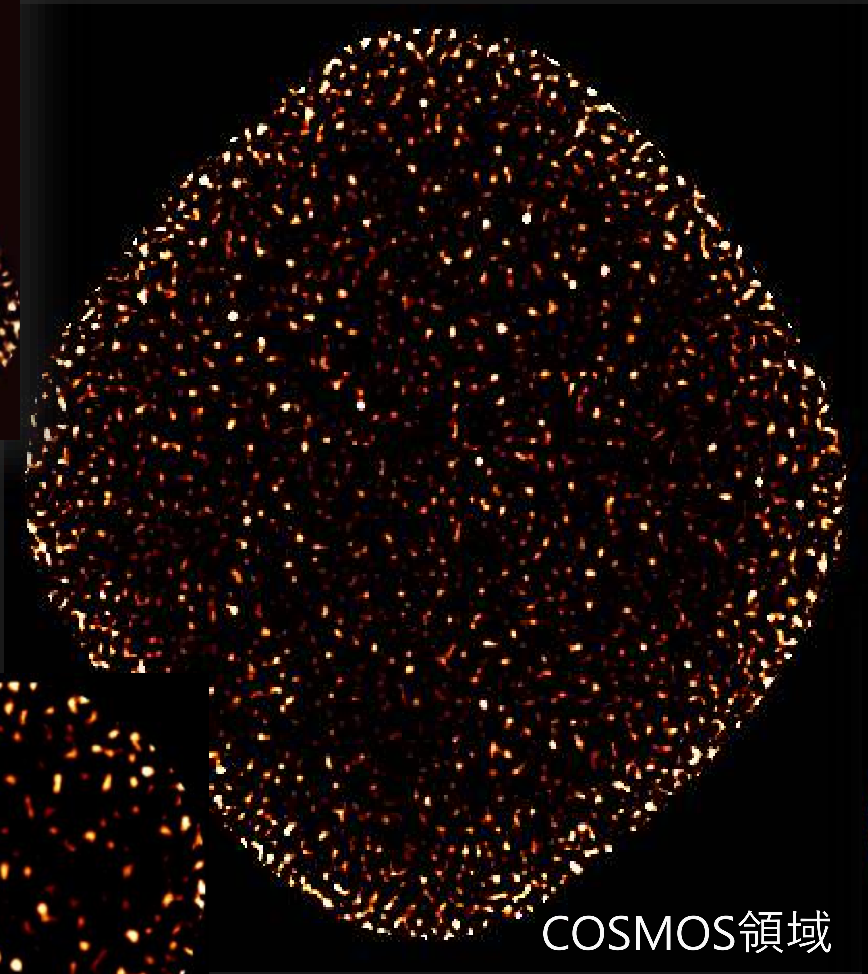


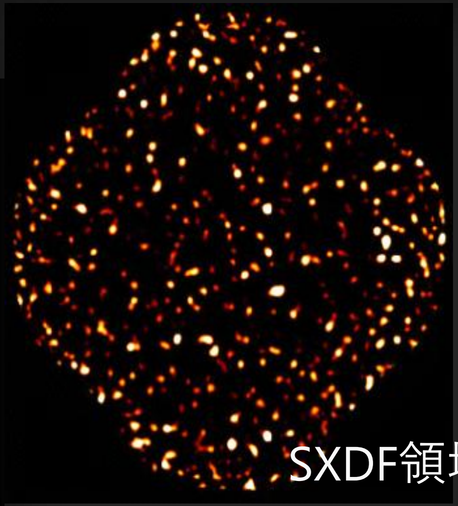
天文月報2024年4月号

サブミリ波銀河とALMA望遠鏡

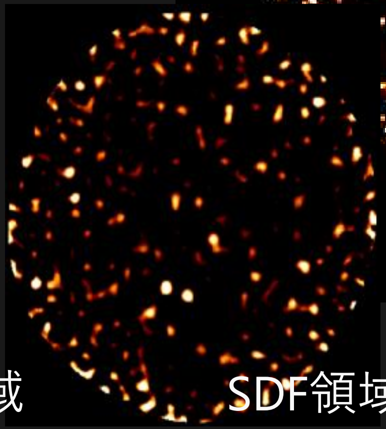
塵に埋もれた銀河の探査

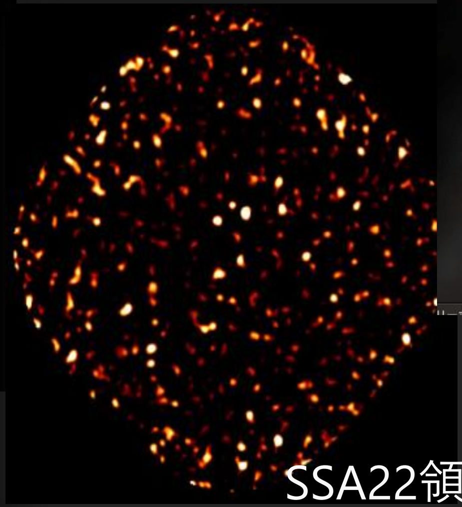

ADF-S領域

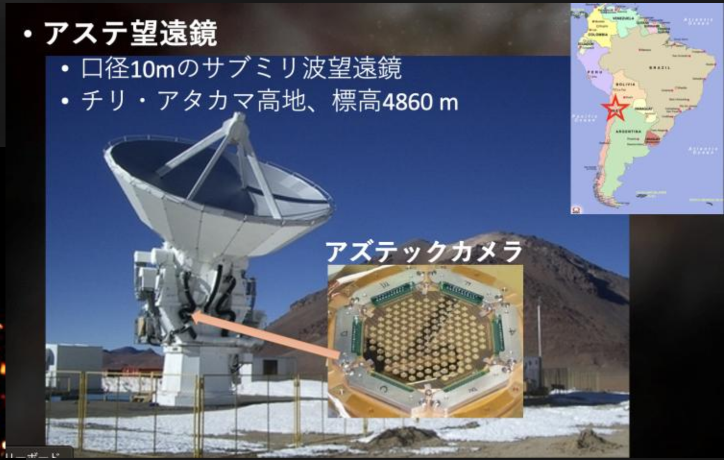

COSMOS領域


SXDF領域

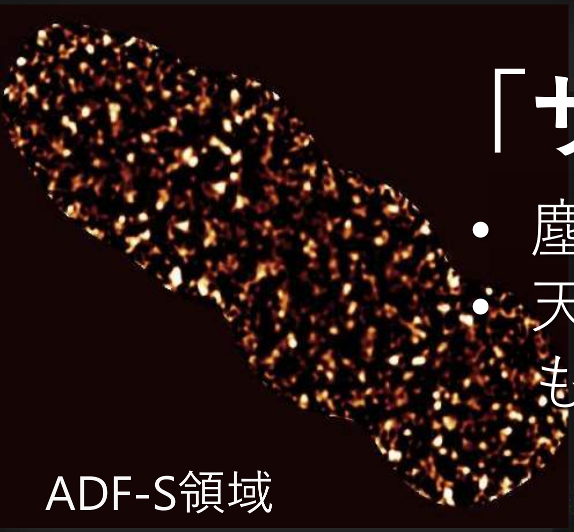

GOODS-S領域


SDF領域


SSA22領域



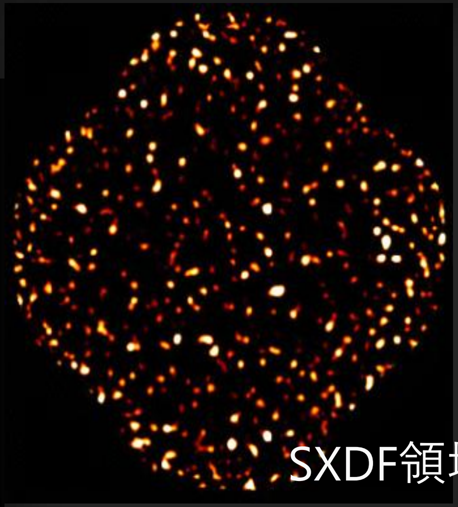
サブミリ波銀河

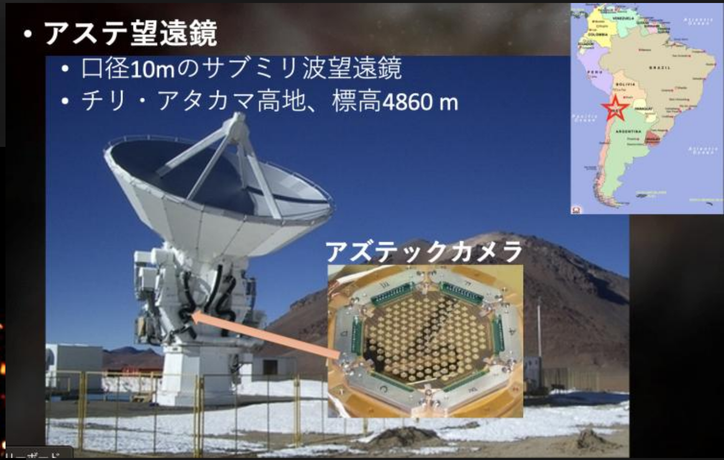


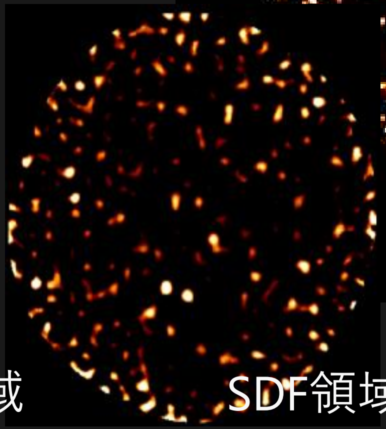
「サブミリ波銀河」

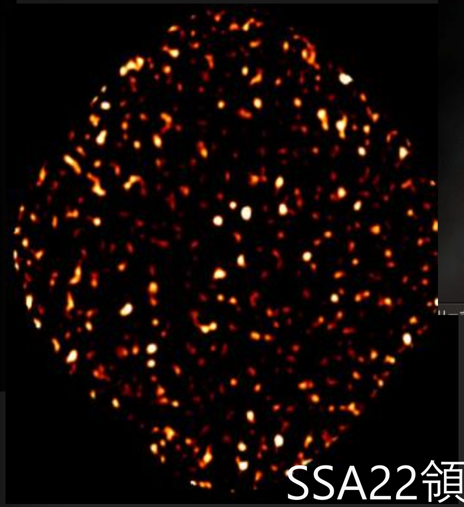
- 塵に厚く覆われた銀河
- 天の川銀河の100～1000倍もの勢いで星を生み出す

モンスター級⁉



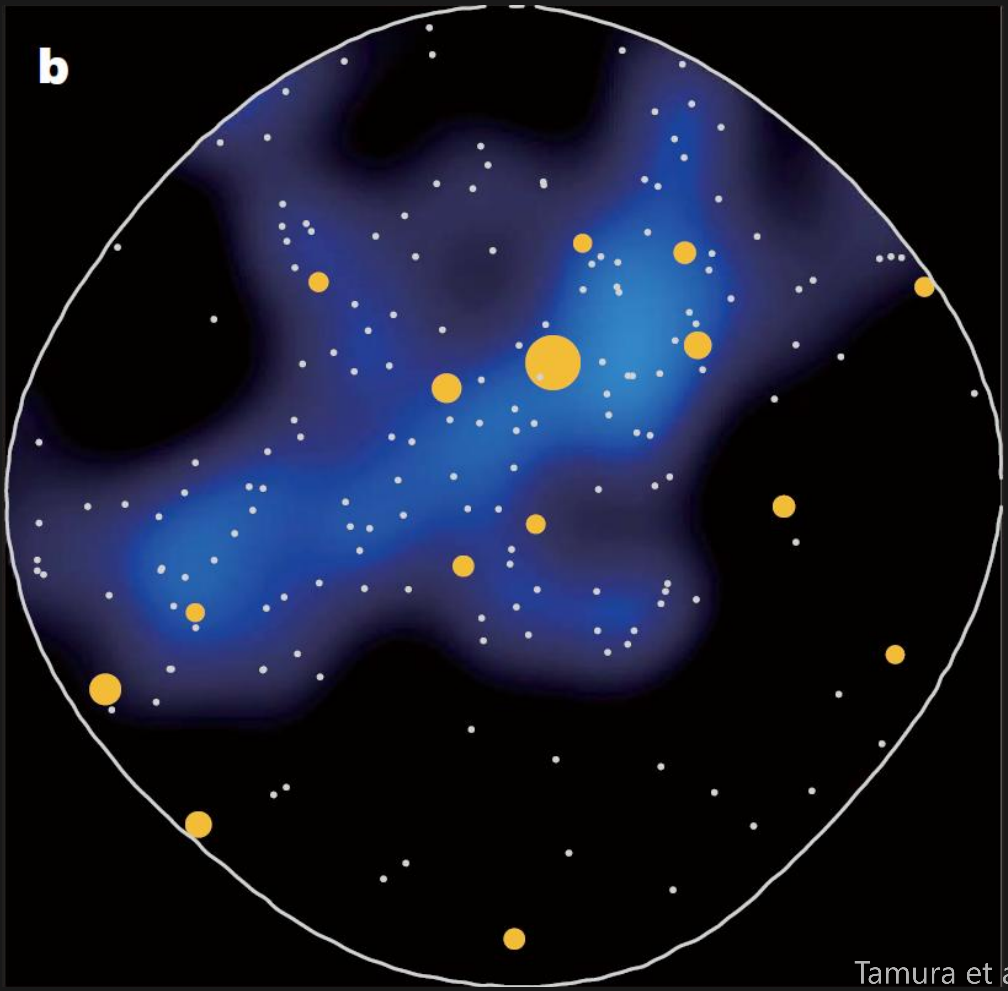






銀河の群れの中心に存在

重たいサブミリ波銀河（黄色）と軽い銀河の分布



Tamura et al. 2009, Nature 459, 61

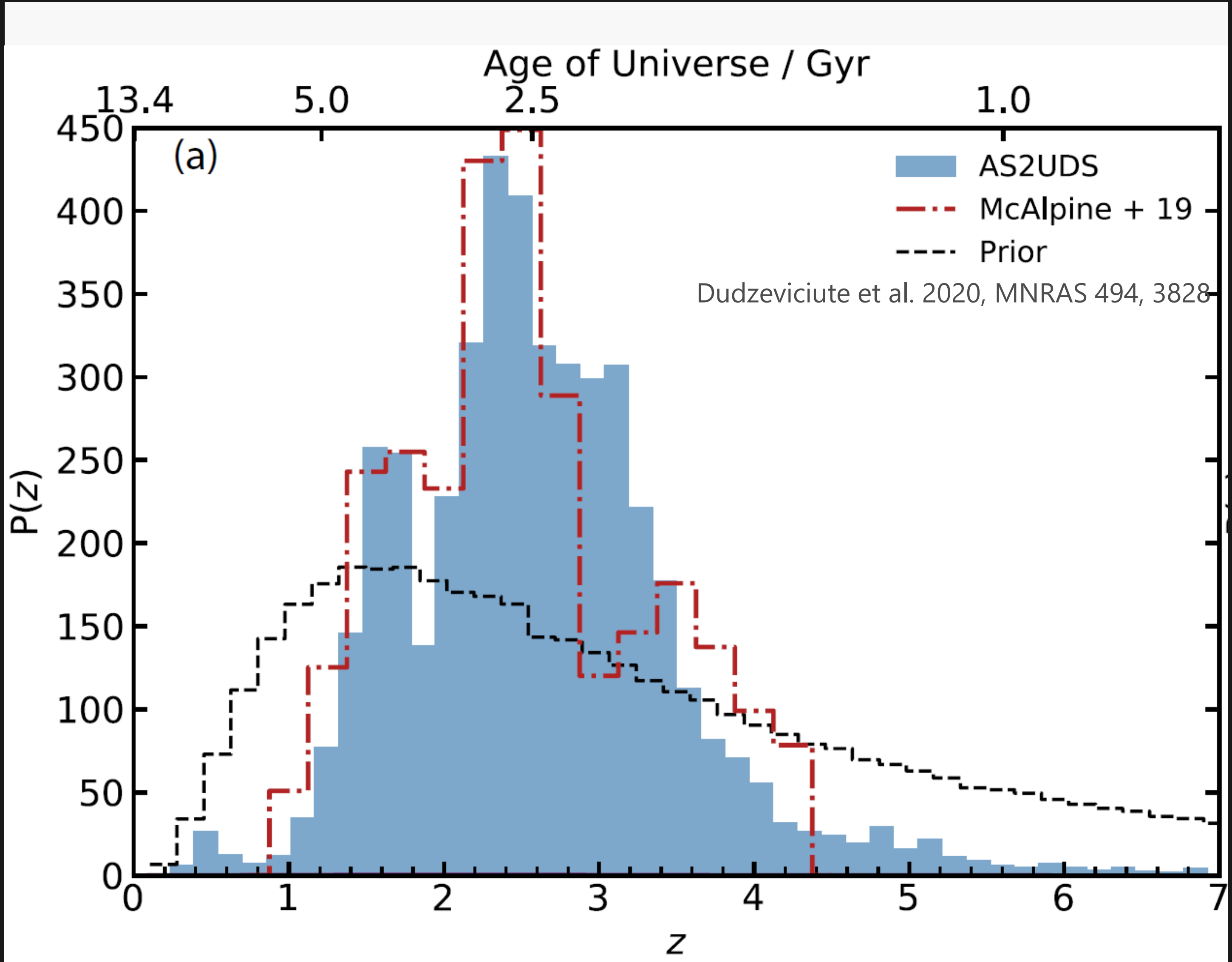
銀河の群れの中心に存在

ALMA望遠鏡 (Atacama Large Millimeter/submillimeter Array; ALMA)

南米チリ、標高5000 mのアタカマ砂漠に建設された電波望遠鏡
日本を含む東アジア、北米、欧州南天天文台加盟国とチリの22の国と地域が協力
66台のアンテナ（口径12 m x 54台、口径7 m x 12台）を結合させて1つの巨大な望遠鏡として機能させる「干渉計」
アンテナを直径16 kmの範囲内に配置することで巨大な望遠鏡に匹敵する視力を実現

Credit: ESO, ALMA (ESO/NAOJ/NRAO), C. Malin (christophmalin.com), P. Horálek, Liam Young, B. Tafreshi (twanight.org), J.J. Tobin (University of Oklahoma/Leiden University), M. Kaufman, Theofanis N. Matsopoulos, H.H.Heyer, S. Argandoña and H. Zodet.

サブミリ波銀河の時代ごとの分類

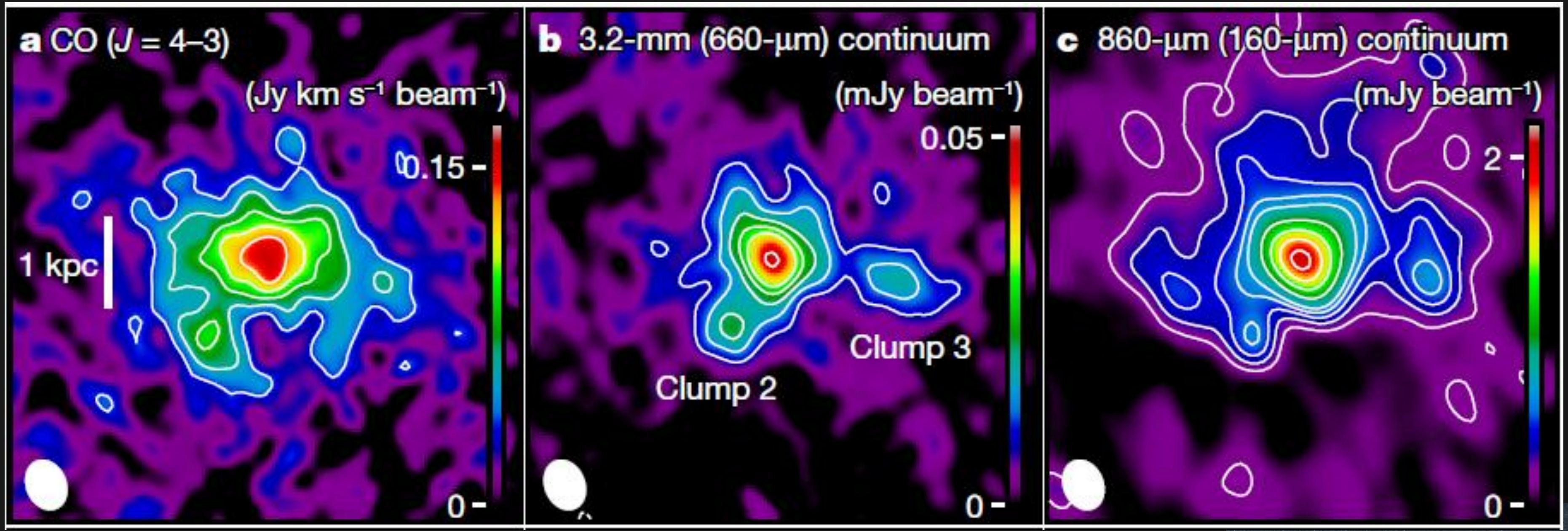


Dudzeviciute et al. 2020, MNRAS 494, 3828

大量の星の材料

120億光年かなたのサブミリ波銀河

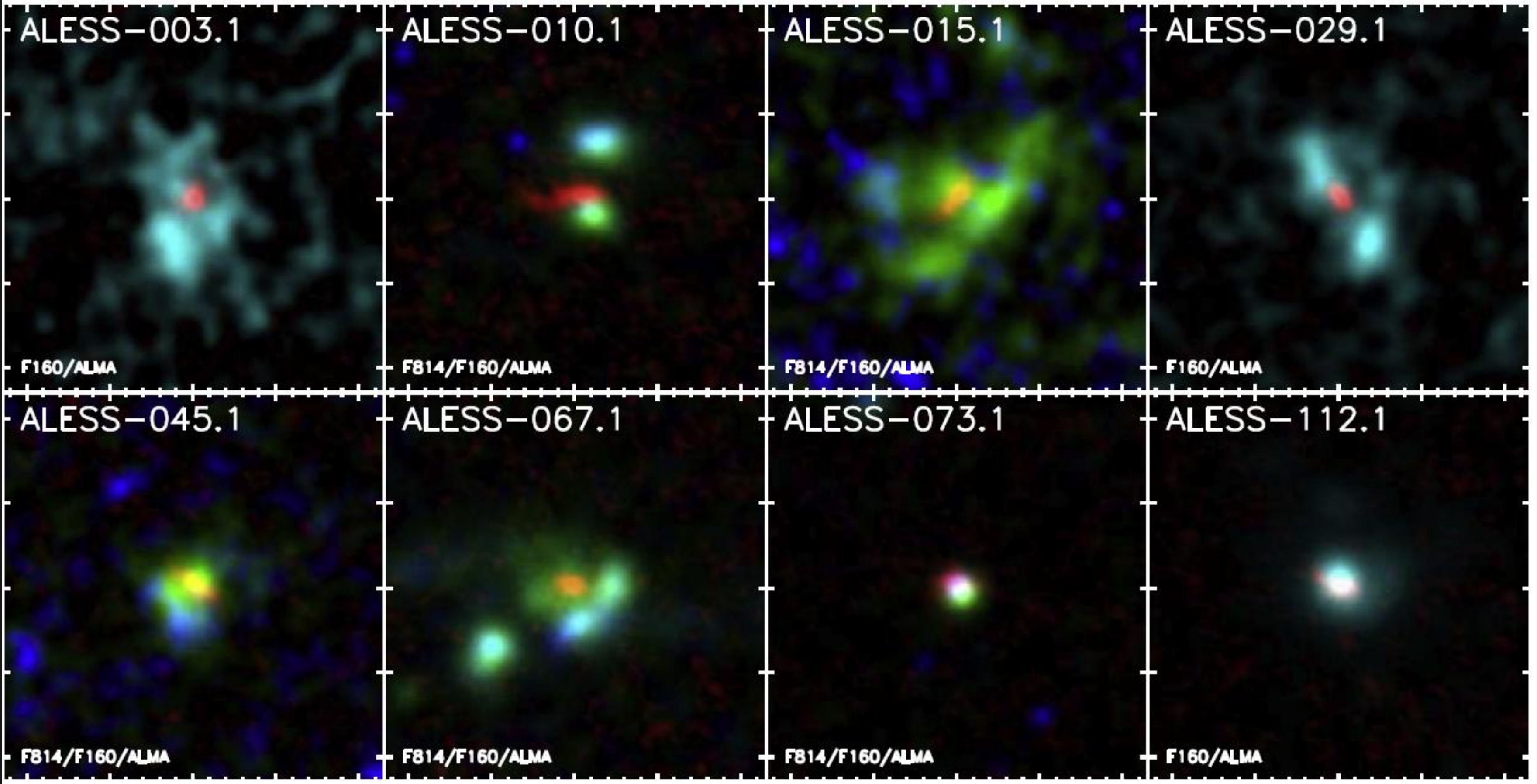
分子ガスの分布　　　　　塵（星形成活動）の分布



Tadaki et al. 2018, Nature 560, 613

衝突、合体によって星形成が駆動？

110億年かなたのサブミリ波銀河の可視光・近赤外線画像



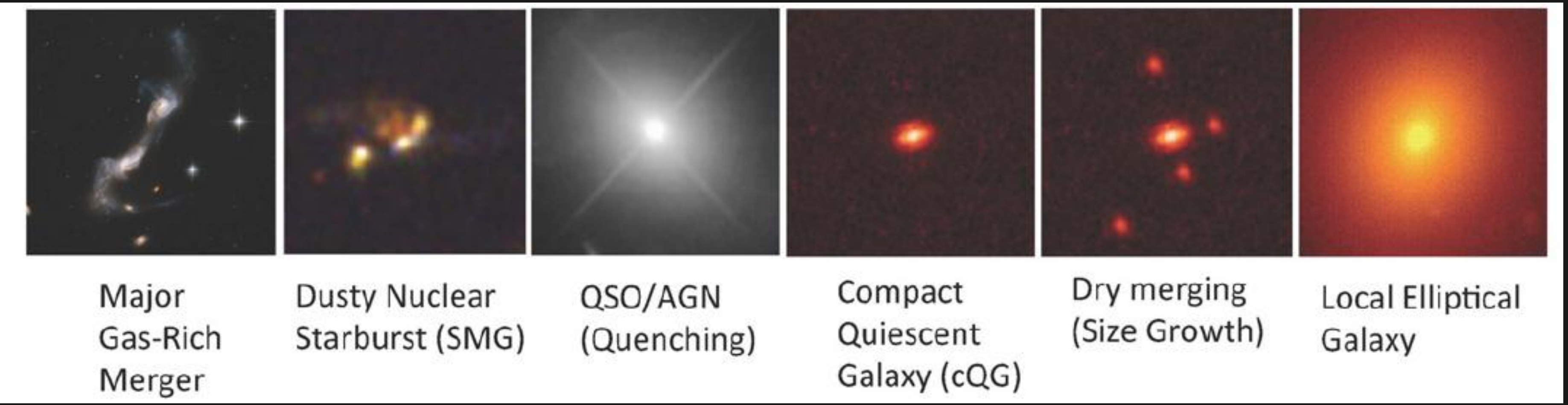
Hodge et al. 2016, ApJ 833, 1

大量のガス流入？

サブミリ波銀河は現在の楕円銀河の祖先かも？

銀河進化のシナリオ

Toft et al. 2014, ApJ 782, 68



衝突・合体 ➔ **サブミリ波銀河** ➔ 活動銀河核 ➔ 活動を終えた銀河 ➔ 現在の**楕円銀河**

ALMA Lensing Cluster Survey: Molecular Gas Properties of Line-Emitting Galaxies from a Blind Survey and Discovery of CH Emission at z~ 1

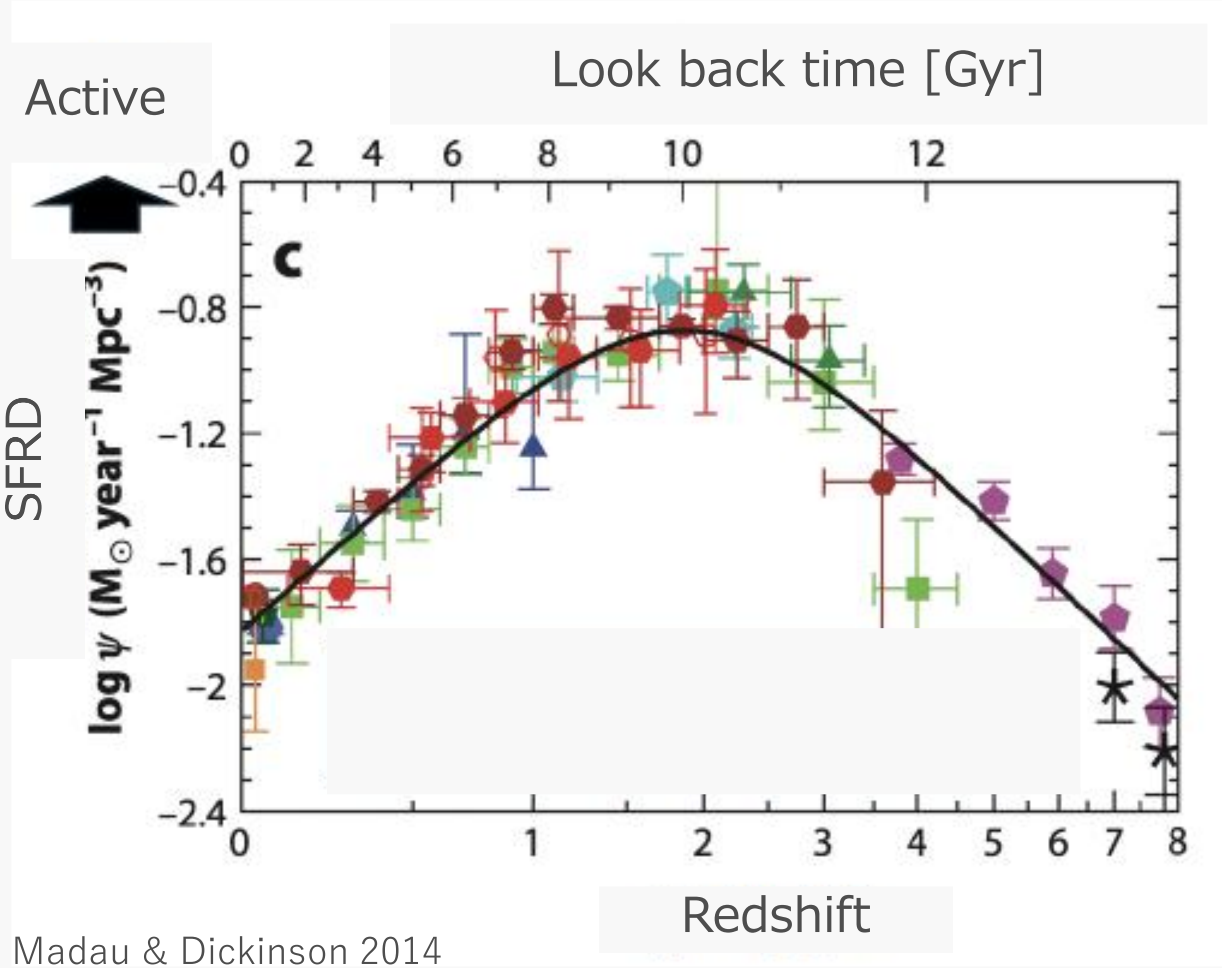
Kanako Narita (The University of Tokyo)

Bunyo Hatsukade, Seiji Fujimoto, Jorge Gonzalez Lopez, Kotaro Kohno and ALCS collaboration

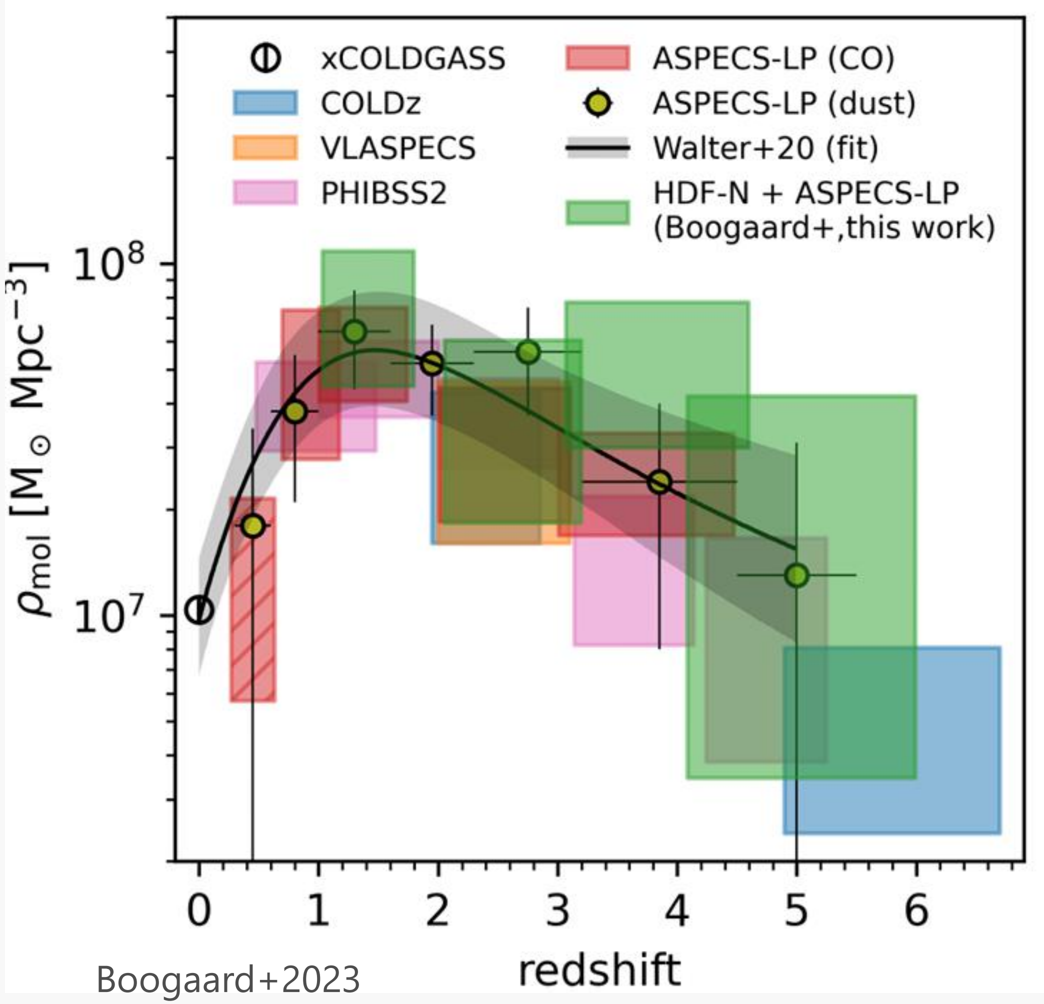
Submitted to ApJ (2025)

Importance of cosmic evolution of molecular gas mass density

- **The evolution of molecular gas mass density is key to understanding the drivers of cosmic star formation history.**



Madau & Dickinson 2014



Boogaard+2023

Current Challenges in Cosmic Molecular Gas Studies

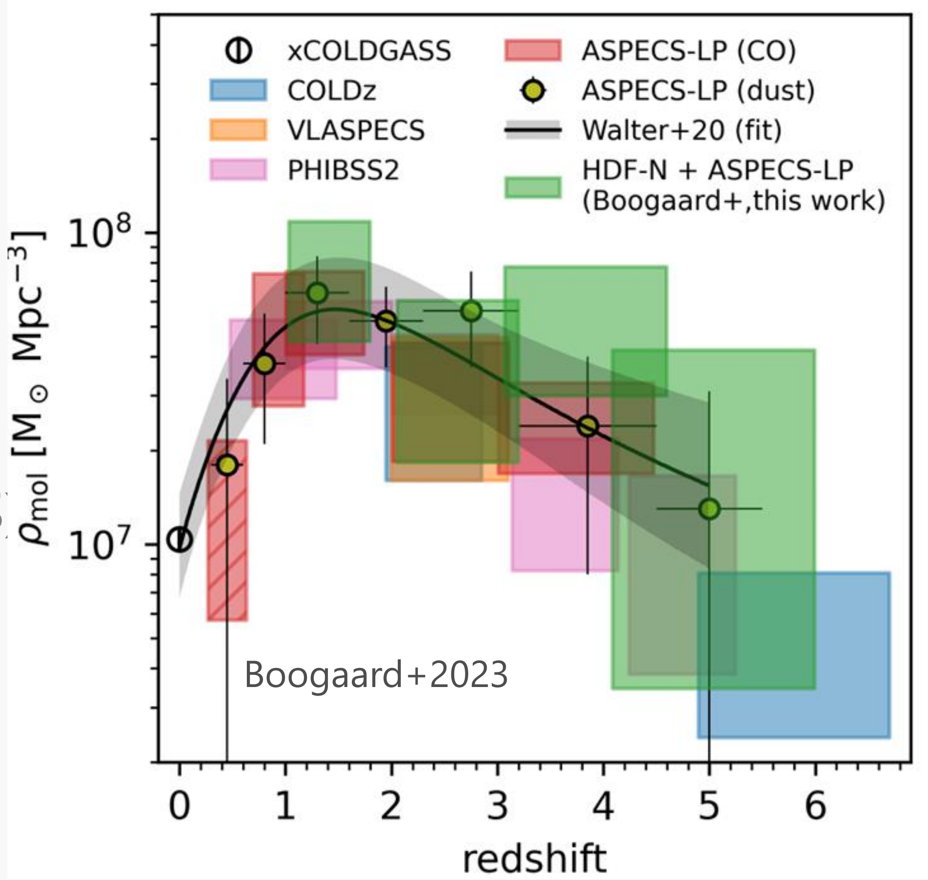
- **Follow-up observations of galaxies selected at other wavelengths**
  - UV/optical/NIR bright galaxies

- **ALMA Discovery of JWST-Dark Galaxies**

  (Sun et al. 2025)

→ **Bias regarding stellar mass, SFR**

- Blind search!
  - e.g., ALMA Spectroscopic Survey in HUDF (ASPECS)
  - Small field ~a few arcmin^2
  - Small sample size ~a few tens of
  - Missing Low–Molecular-Gas Galaxies



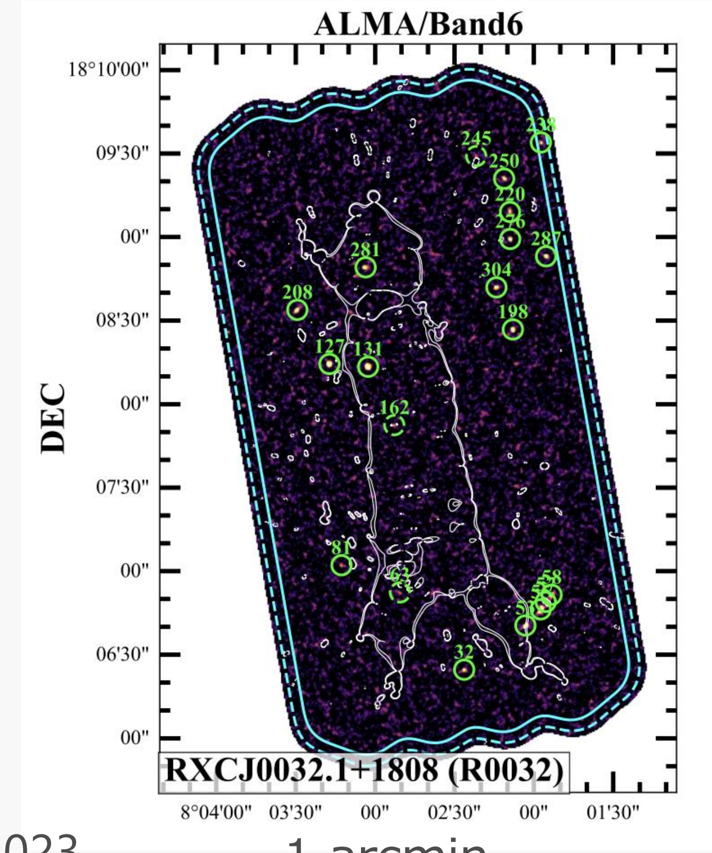
Our Approach

- **Blind survey toward lensing clusters**

Strong lensing effect enables us to probe faint and rare molecular/atomic line emitters

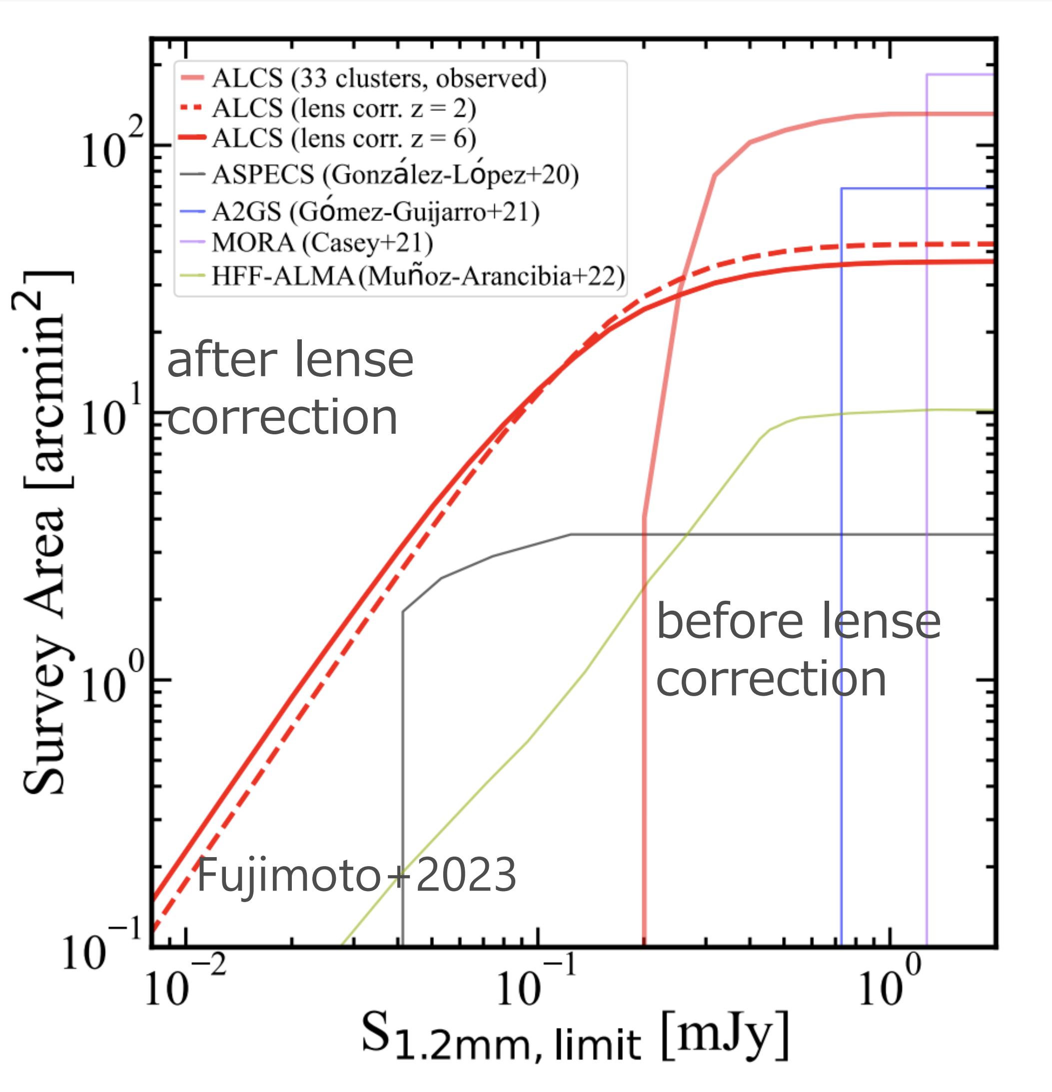
ALMA Lensing Cluster Survey (ALCS)

- ALMA Large Program in Cycle 6 (PI: K. Kohno)
- Frequency ranges:250.0-257.5 GHz and 265.0-272.5 GHz (Band 6)
- Survey Area: 133 arcmin2, Typical beam size: 1 arcsec
- rms noise level: 46.9-91.6 μJy/beam for continuum
  848.1-1706.4 μJy/beam for 60 km/s for cube



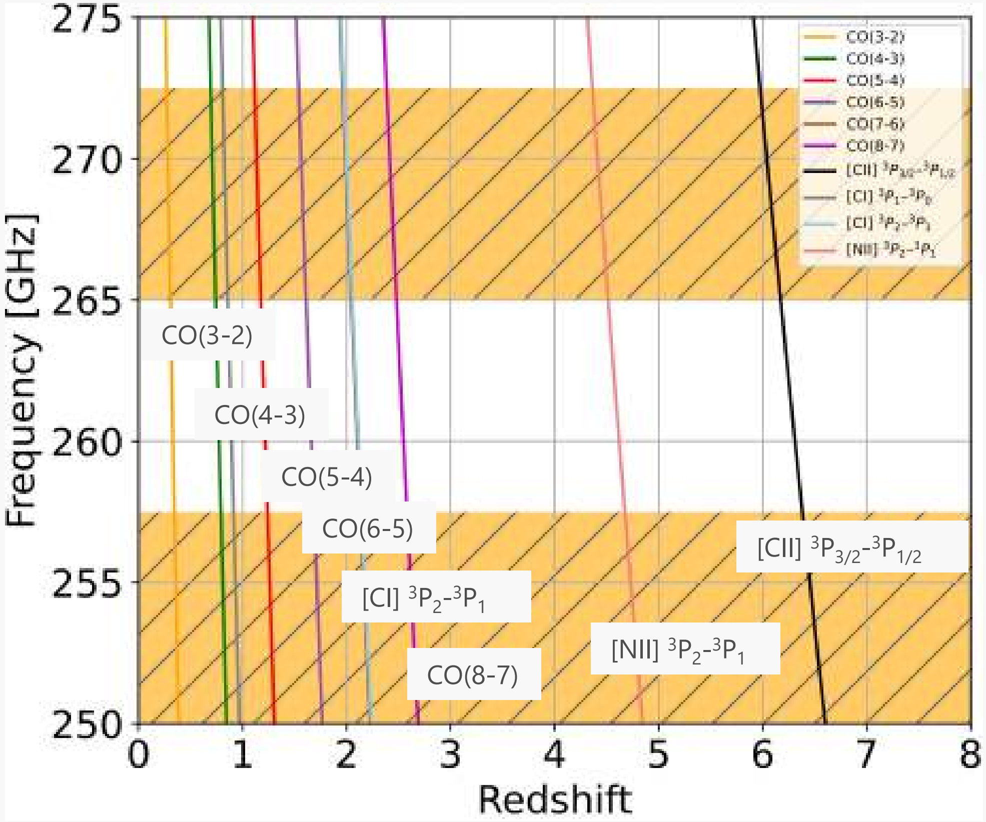
Fujimoto+2023

1 arcmin



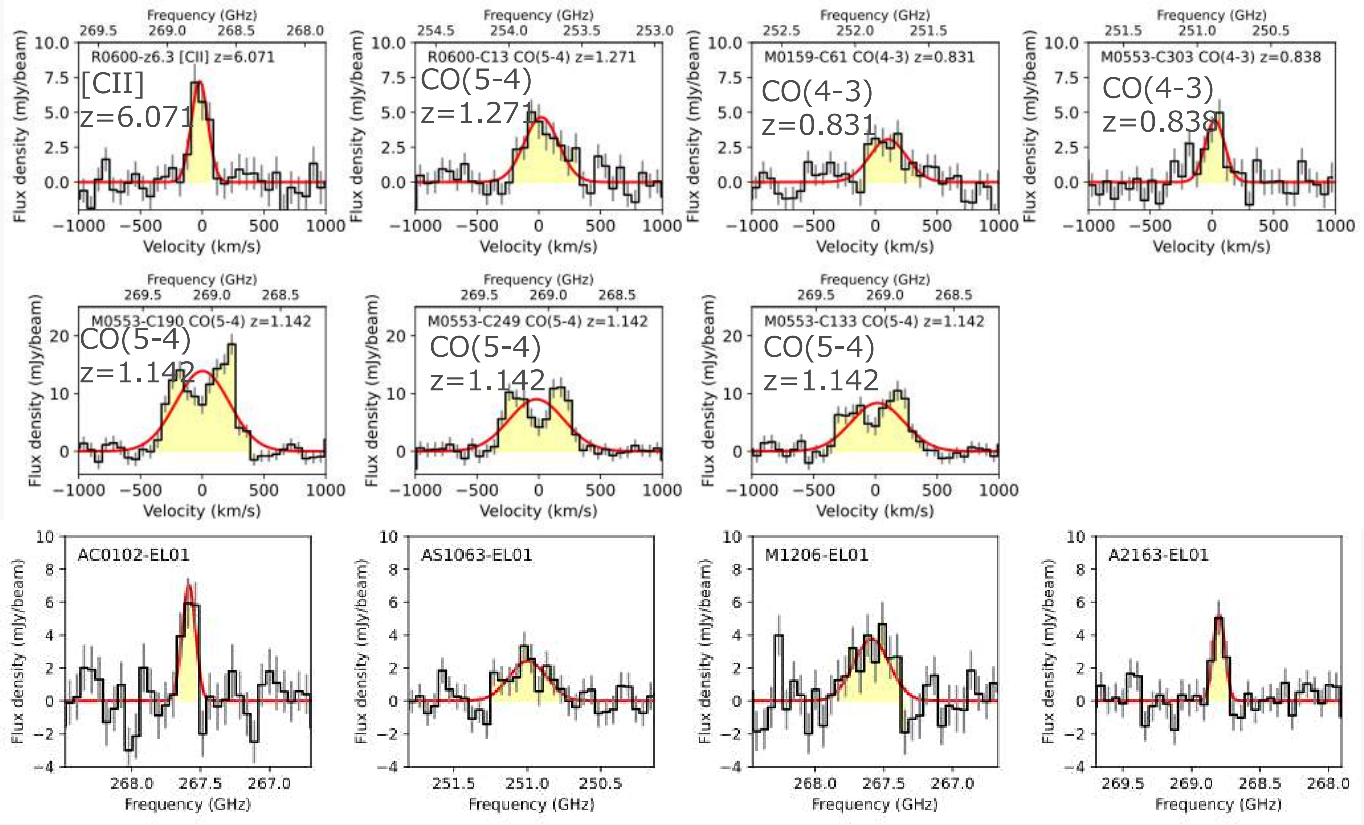
Line Emitter Search

- LineSeeker (Gonzalez-Lopez+2017)
  - Data cubes of 60 km/s and 150 km/s binning
  - Emission line candidates with S/N > 5
- Counterpart ID
  - HST, Spitzer, Herschel
- Photo-z with EAZY, MAGPHYS
  - optical–NIR SED fitting Kokorev+2022
  - FIR SED fitting Sun+2022
- Selected the most likely line within the photo-z range.



Identification of lines

- **6 CO lines, 1 [CII] line and 4 optical-dark emitter candidates are detected**
  - of which 3 CO lines are from multiple images of the same source
  - * cluster members are excluded



Identified sources with the redshift and line assignment

ID	redshift	line
R0600-z6.3	6.071	[CII]
R0600-C13	1.271	CO(5-4)
M0159-C61	0.831	CO(4-3)
M0553-C303	0.838	CO(4-3)
M0553-C190	1.142	CO(5-4)
M0553-C249	1.142	CO(5-4)
M0553-C133	1.142	CO(5-4)

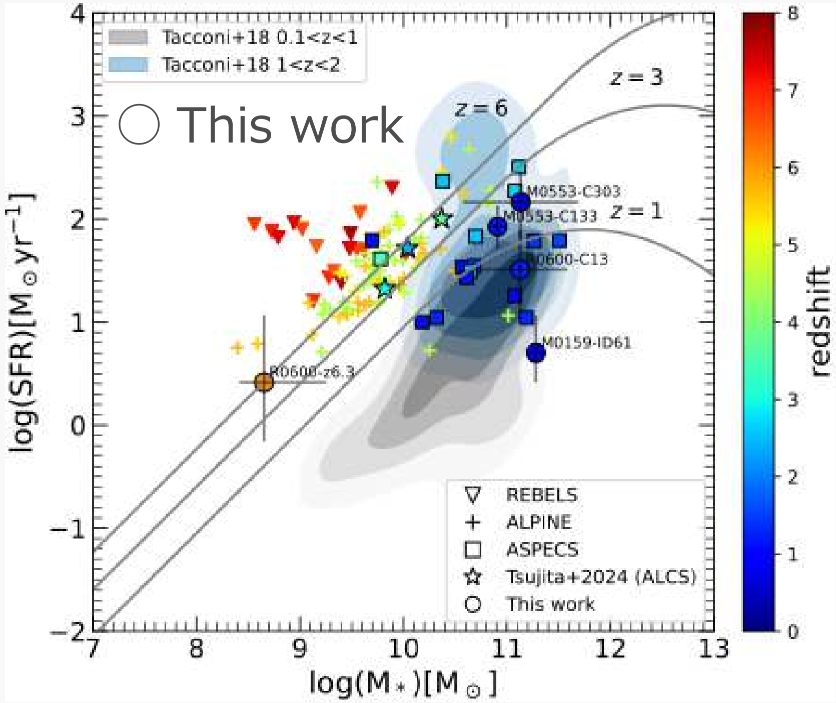
Molecular gas mass vs stellar mass/SFR

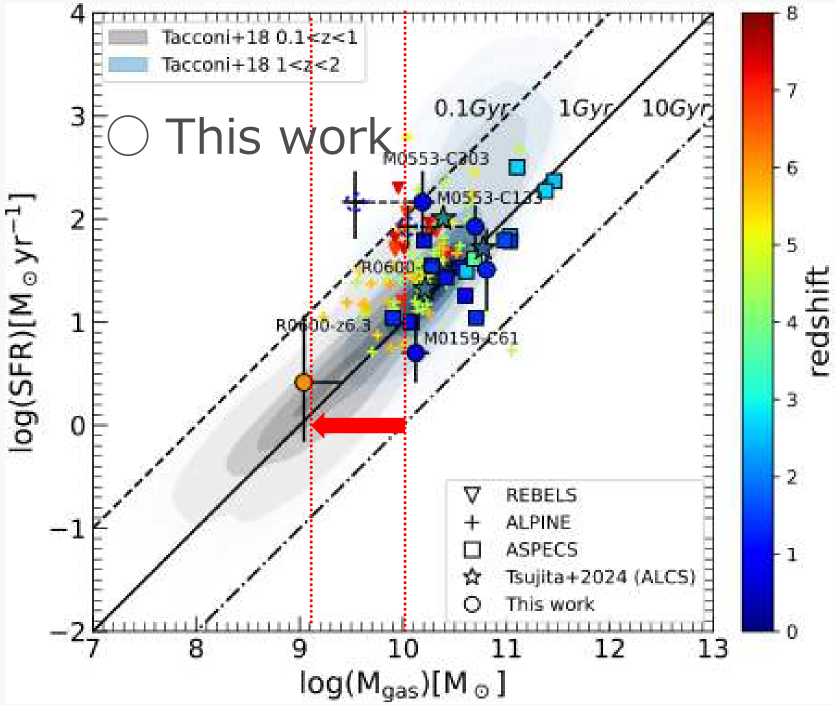
- **Detected molecular gas mass ~1 dex below lower bound of previous blind search.**

Line ratios derived for massive MS galaxies (Daddi+2015), αCO = 3.6 M⊙ (K km s^{-1} pc^{2})$^{-1}$ and α[CII] = 31 M⊙/ L⊙

αCO = 0.8 M⊙ (K km s^{-1} pc^{2})$^{-1}$ for log(ΔMS)>0.4 (dashed circle)

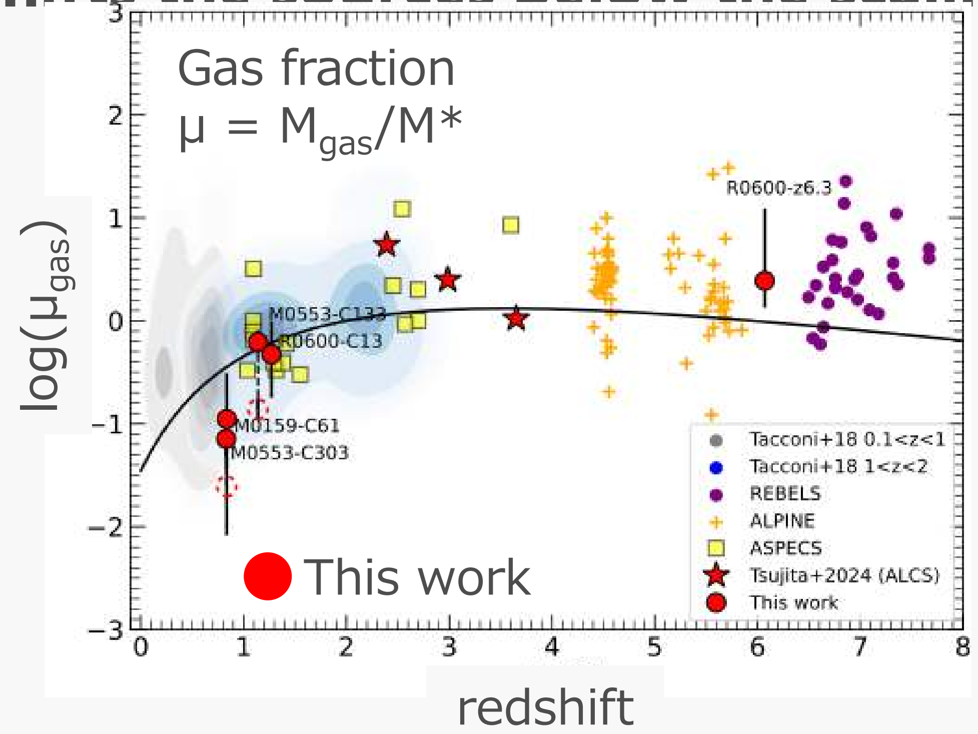
SFR/Steller Mass (MAGPYHS; Uematsu+24)

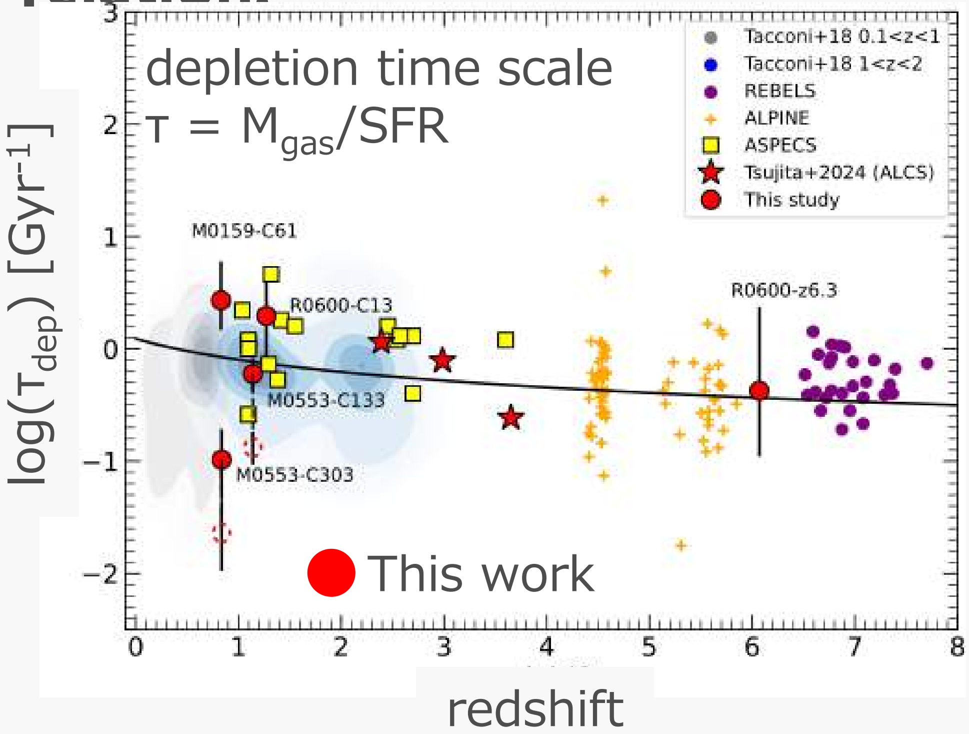




Redshift evolution

- **Consistent within the range of scatter with those from follow-up observations of pre-selected galaxies.**
- **Assuming the starburst conversion factor of αCO (red dashed circle) shifts the sources below the scaling relation.**

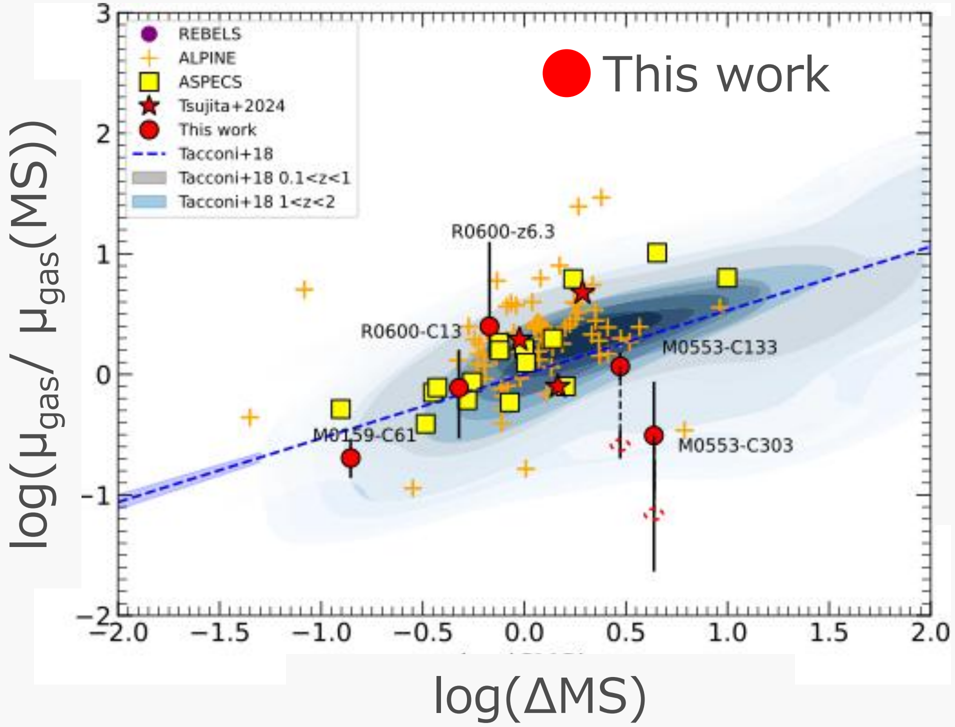


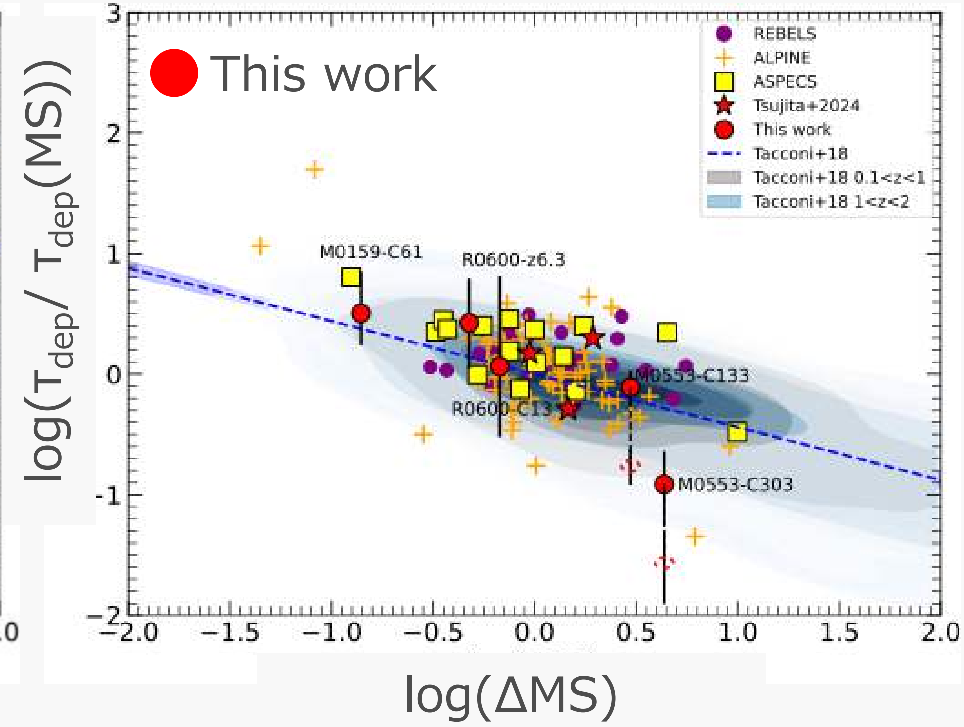


Scaling relation breakdown?

- **Most of the sources follow the scaling relations within the scatter once the dependencies on ΔMS (offset from the main sequence), stellar mass, and redshift are considered.**

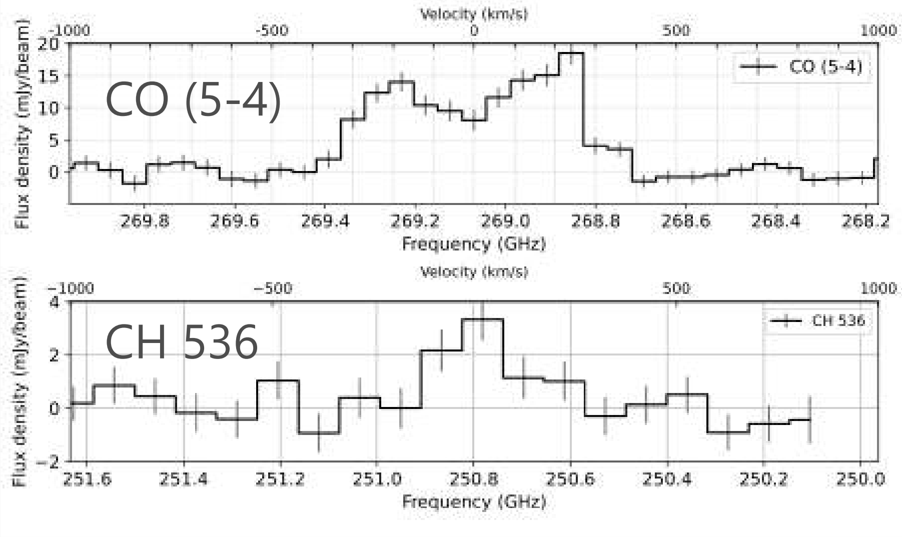
- **Assuming the starburst value of αCO shifts the sources below the scaling relation.**

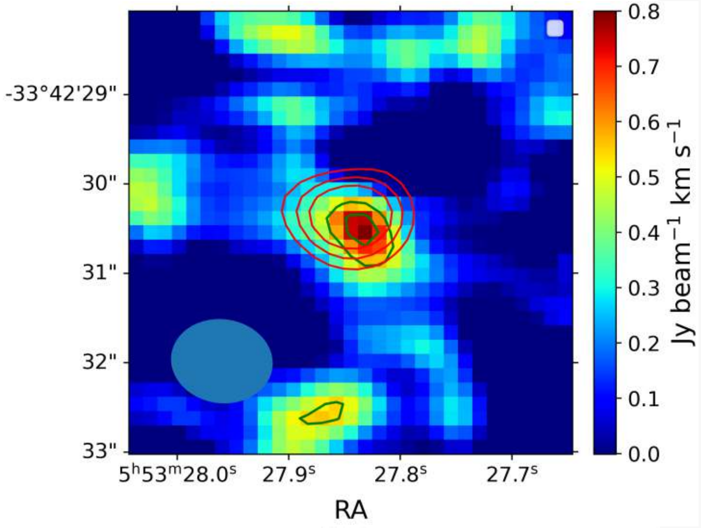


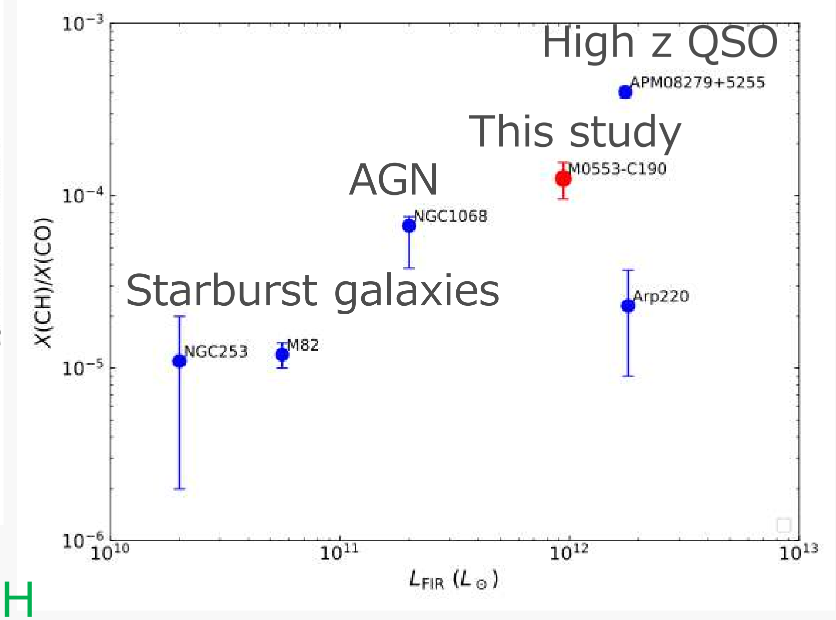


CH Emission Suggests AGN presence？

- **First CH (N = 1, J = 3/2 → 1/2 Λ-doublet transition) detection at cosmological distance (z=1.142) through blind survey**
- **N(CH)/N(CO)~10^{-4} : consistent with AGN/XDR models; comparable to local AGN (NGC 1068).**
- **CH/CO abundance ratio might be a tracer of distant obscured AGN.**







image/green contour：CH
red contour：CO

Conclusions & Future Work

- **ALCS blind survey detected 6 CO emitters, 1 [C II] emitter, and 4 unidentified candidates**
- **Gravitational lensing allows probing ~1 dex fainter galaxies than blank-field surveys**
- **Most sources are consistent with scaling relations when ΔMS, stellar mass, and redshift are taken into account**
- **First CH detection at cosmological distance (z = 1.14, M0553-C190)**
- **Elevated CH/CO ratio suggests CH as a potential tracer of obscured AGN at high redshift**
- **Future Work: Follow-up with NOEMA/ALMA will test the AGN nature of CH emitters**

Axions in Japan
Kavli IPMU

Probing Axion-like Particle Dark Matter via Time-Variable Polarization in Protoplanetary Disks

Kanako Narita[1], Tomohiro Fujita[2,3], Ryo Tazaki

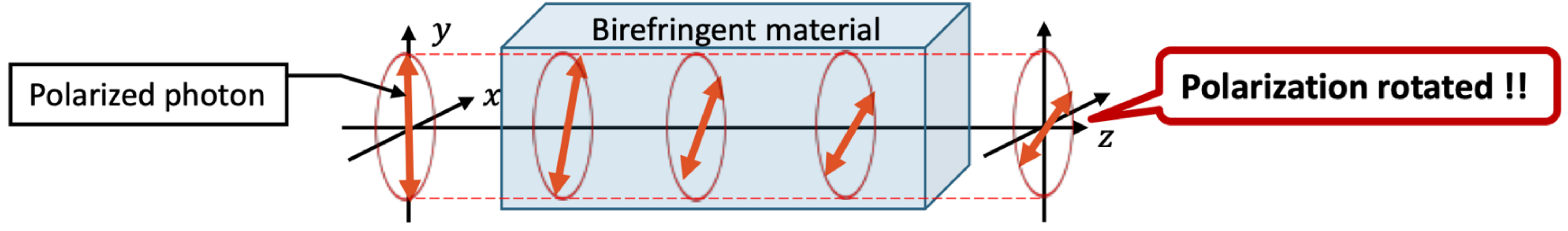
UTokyo (Science)[1], Ochanomizu University[2], UTokyo ipmu[3],

(Ultralight) Axion like particle (ALP) Dark matter

- Arises from compactification in string theory.
- A leading solution to small-scale issues (e.g., the core–cusp problem).
  - Acts as CDM on large scales; wave-like on small scales, suppressing structures.

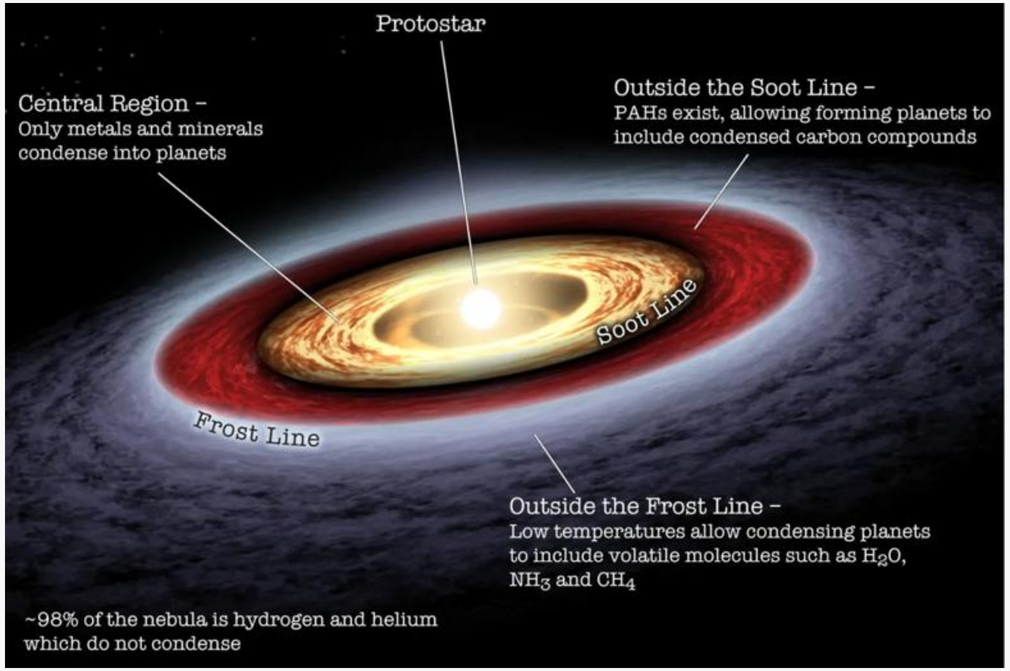
- Properties of ALPs
  - ALP DM can be very light (10^{-22}eV $\lesssim$ m)
  - Coupled to photon $\mathcal{L}_{\rm int} = g_{a\gamma} a \vec{E} \cdot \vec{B}$
  - Parity violation

- ALP dark matter oscillates at a frequency corresponding to its mass.
- The axion field acts as a birefringent medium, rotating the polarization plane.
- Detecting ALP-induced polarization requires linearly polarized light sources.



Proto Planetary Disks (PPDs)

- A thin disk of gas and dust surrounding a young star.
- In the optical and near-infrared, stellar light is scattered and linearly polarized.



NASA/JPL-Caltech/Invader Xan

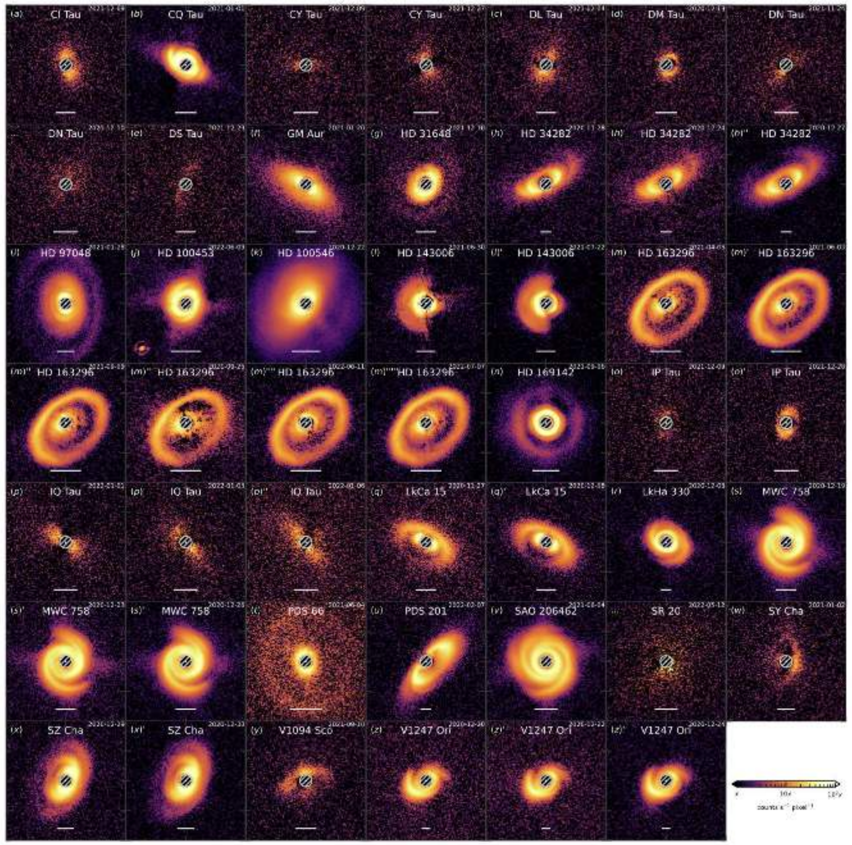


Fig. 1. K_s-band Q_ϕ maps with dimensions of 2″×2″ with different color bars in log scale. The letter identifiers are from Table 1. The rulers correspond to 50 au. The regions interior to 0.″1 are not accessible with coronagraph usage. We note that the data used to create this figure are available at the CDS.

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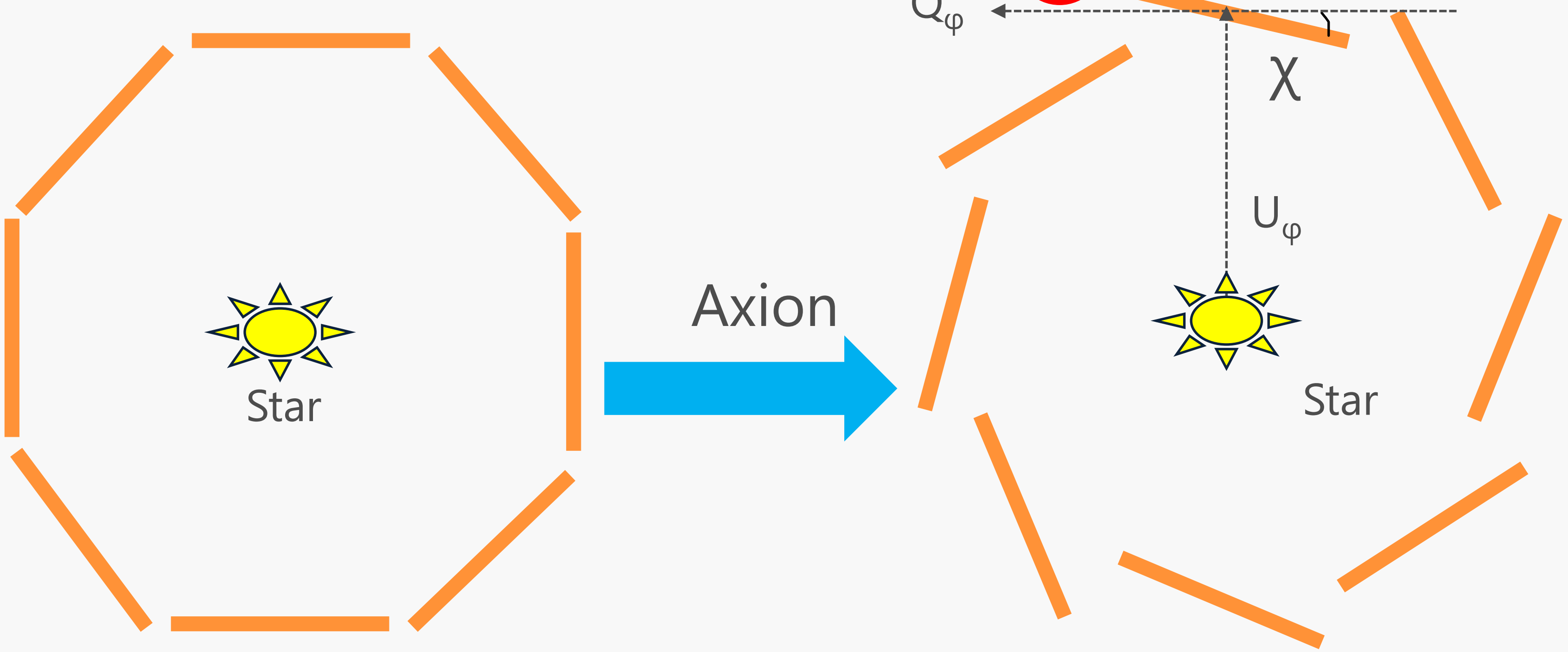
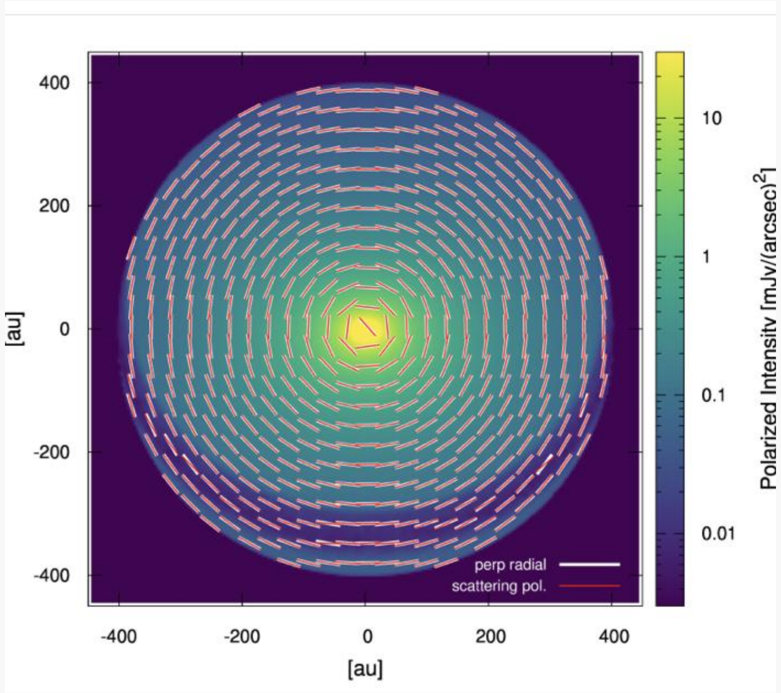
Birefringence Induced by ALP Dark Matter

- Without axions, a concentric polarization pattern is expected.
- Temporal oscillation of the ALP field causes periodic rotation of the polarization plane (Fujita, Toma & Tazaki, PRL 2019).

$$\chi(t,T) \propto \sin(mt + const)\, g m^{-1}$$

mass, constant, coupling, mass





Fujita, Toma & Tazaki, PRL2019

- **Previous work: single-snapshot limits (Fujita, Toma & Tazaki 2019)**
- **This work: time-series analysis using VLT/SPHERE archival data**
  - Focused on the most frequently observed target, HD 163296.

Analysis Procedure

- Mask the central region around the star.
- Measure the RMS in an emission-free region of the U-Stokes image.
- Select pixels with polarized intensity ≥ 5σ.
- Average over a beam-sized 3×3-pixel box and compute the representative polarization angle for each region.

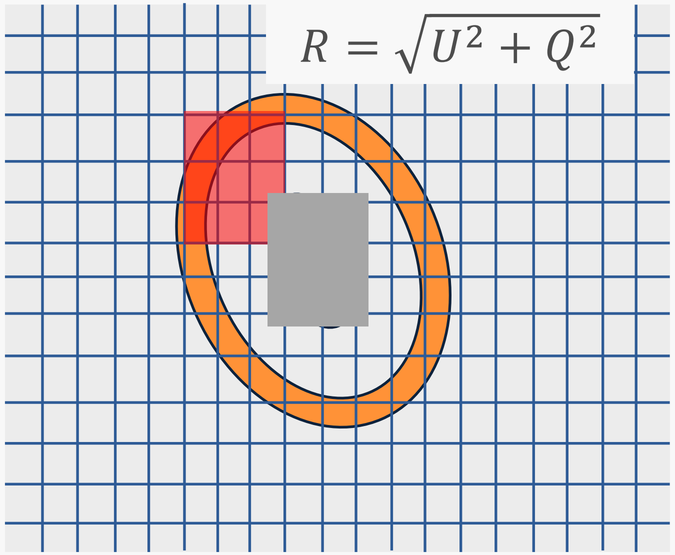
$$\chi = 0.5\,\arctan(U/Q)$$

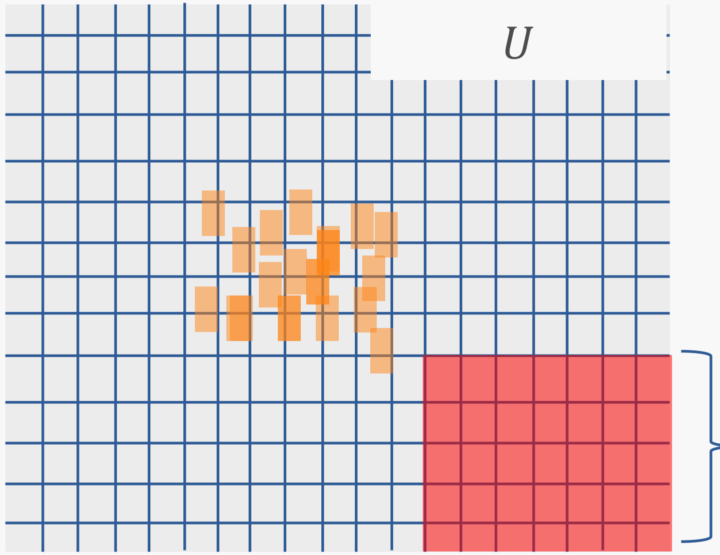
- Weight the polarization angle samples by their measurement uncertainties and compute the weighted mean angle and its uncertainty.

Weight $$w_i = \frac{1}{\sigma_{\chi,i}^2}$$

Weighted Average $$\chi_{\mathrm{mean}} = \frac{1}{2}\arctan\left(\frac{\sum_i w_i \sin(2\chi_i)}{\sum_i w_i \cos(2\chi_i)}\right)$$

Weighted Uncertainty $$\sigma_{\chi,\,\mathrm{mean}} = \left(\sum 1/\sigma_{\chi,i}^2\right)^{-1/2}$$

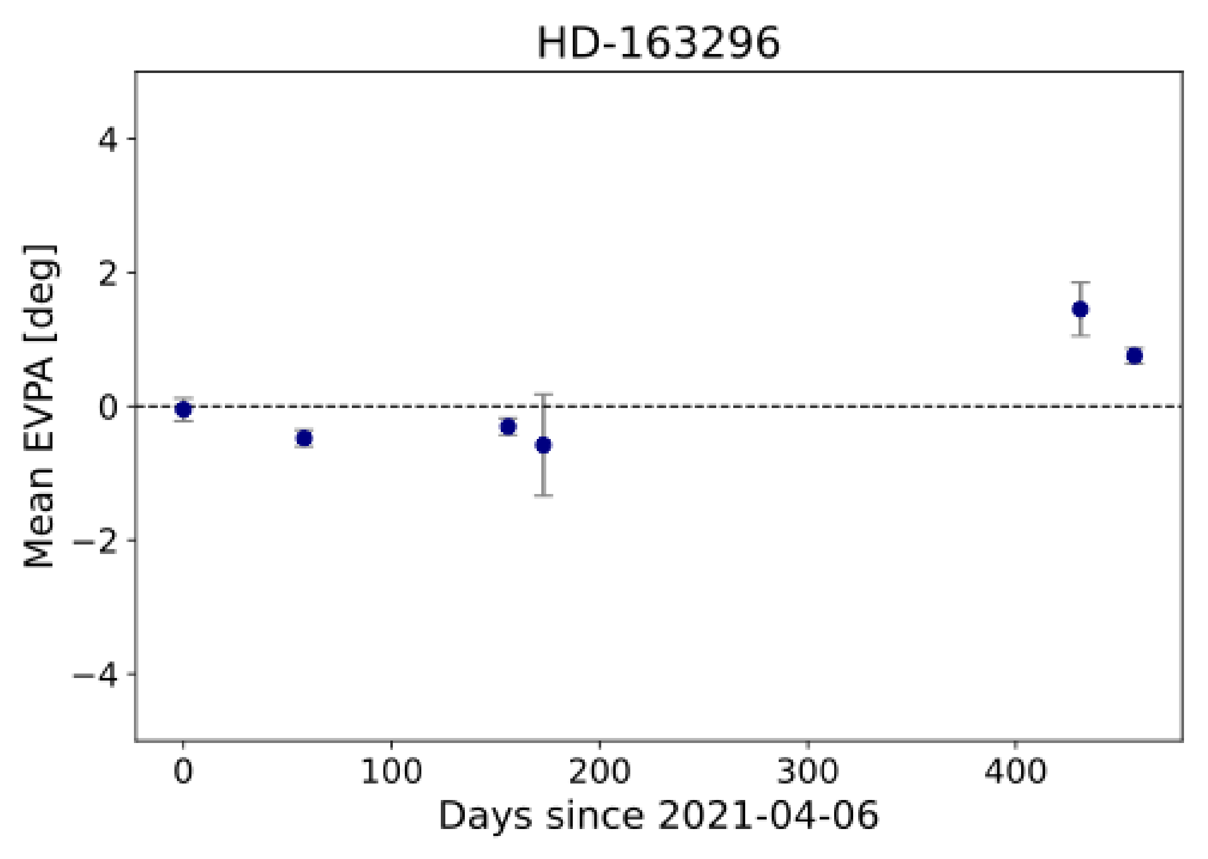




Emission– free region

Time Series of Polarization Angles

- Data Summary
  - Number of data points: 6
  - Observation intervals: 17–457 days
- Positional uncertainty: ~0.1° –0.8°
- Possible variations at ~400 days ?



Future Prospect – Improving Positional Uncertainty

- **The polarization angle uncertainty per pixel can be expressed as a function of the signal-to-noise ratio (SNR).**

$$\sigma_\chi \approx \frac{1}{2}\frac{\sigma}{R}, \quad (R/\sigma = \mathrm{SNR})$$

$$R = \sqrt{U^2 + Q^2}$$

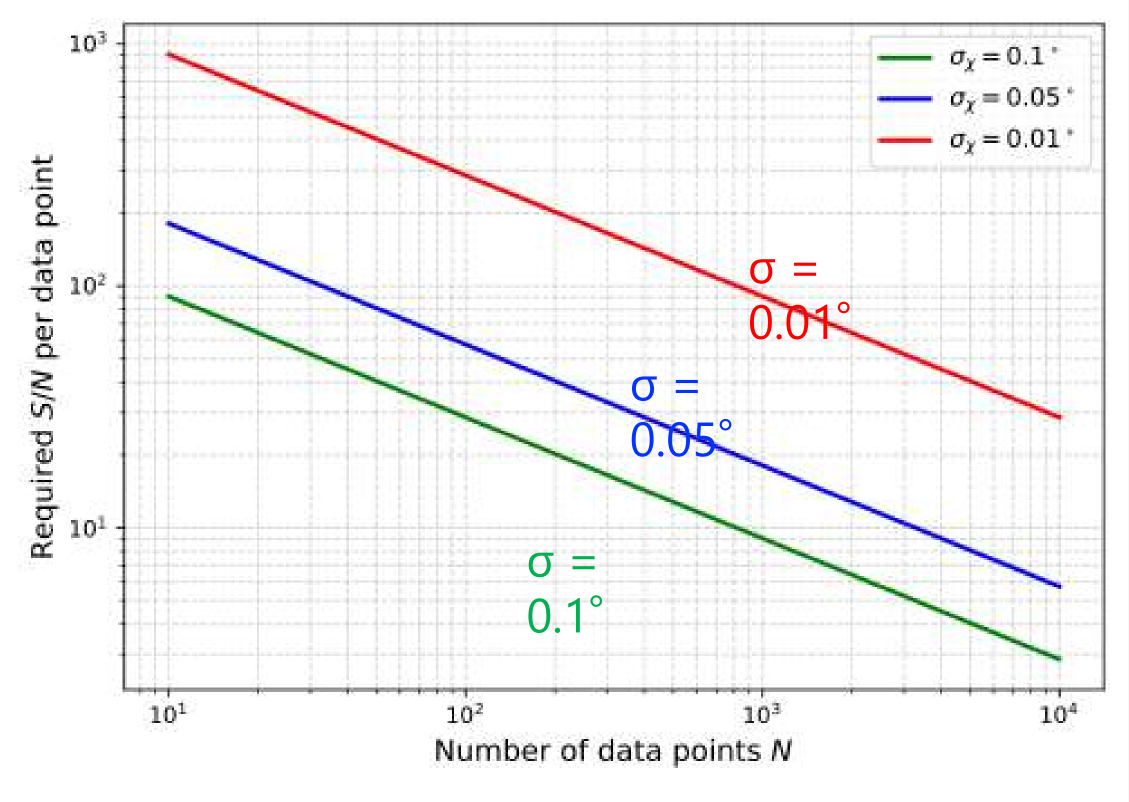
- **The mean polarization angle uncertainty is expected to improve statistically with the number of pixels.**

$$\sigma_{\chi,\mathrm{mean}} \approx \frac{\sigma_\chi}{\sqrt{N}}$$

- **The uncertainty is mainly set by SNR**

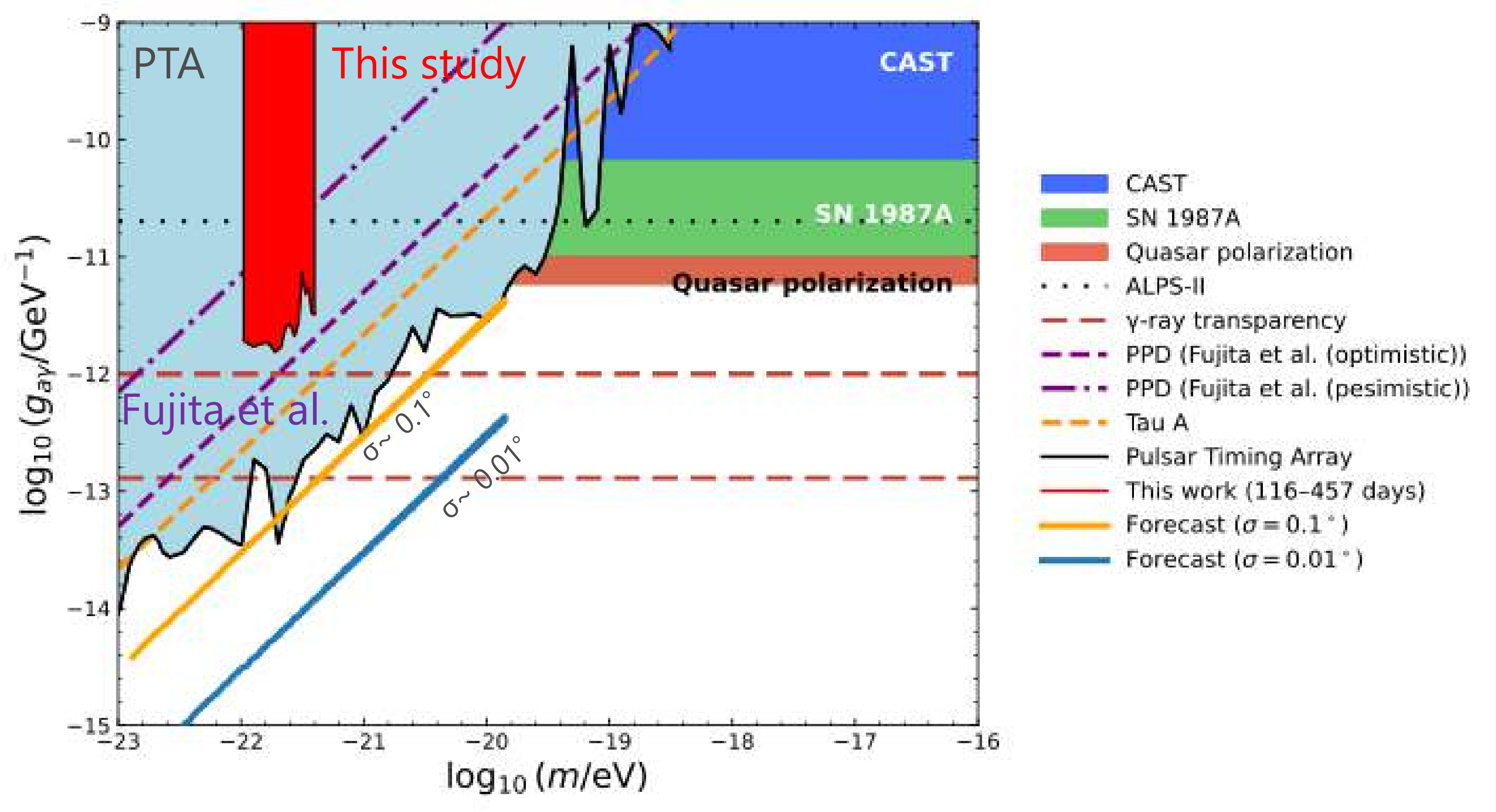
and the number of pixels/data points.

  - With SNR ≈ 10 and ~1000 data points, the uncertainty can reach ~0.1° .



Constraints and Future Sensitivity Forecast

- Fitted noise simulations by frequency to derive 95% CL upper limits.
  - Generated noise simulations based on positional uncertainties from six HD 163296 observations.
  - For the forecast, assumed 150 observing days per year over a 10-year monitoring period.
- Achieves world-leading sensitivity for ALP masses of 10^{-23}–10^{-20} eV with $\sigma \approx 0.1°$.



Summary and Future Prospects

- **Searched for ALP dark matter–induced polarization angle variations using polarimetric observations of protoplanetary disks (PPDs).**
- **Analyzed archival VLT/SPHERE data of HD 163296 to extract and evaluate the polarized angles with consistent error estimation.**
- **Detected significant variations on ~400 day timescales; its uncertainty typically 0.3°.**
- **Future high-precision monitoring (e.g., S/N ≈ 10 and 1000 data points per image) could reach ~0.1° accuracy.**
- **Continuous 10-year monitoring (150 days yr^{-1}, $\sigma \approx 0.1°$) can probe ALP masses of 10^{-23}–10^{-20} eV with world-leading sensitivity.**
- **Next steps: high-cadence monitoring of multiple PPDs and careful assessment of intrinsic variability.**