

これから の大型 観測計画

Structure Formation in the Universe:

Remaining Issues

1. The Dark Ages

- When and where did the first stars form ?
- What are the sources of reionization ?
- How was the IGM enriched with metals ?
- What role did dark matter play in the first object formation ?

Structure Formation in the Universe:

Remaining Issues

2. Super-Massive Black Holes

- What seeded the formation of SMBHs ?
- How did BHs grow to become SMBHs ?
- Why is there almost always only one massive BH at the center of a large galaxy ?
- How did they co-evolve with galaxies ?

Structure Formation in the Universe:

Remaining Issues

3. The Nature of Dark Matter

- What are the particle properties of DM ?
- Are there primordial black holes ?
- Did DM cause dynamical effects other than gravity ? - annihilation, decay
- How is DM distributed in Milky Way ?

Structure Formation in the Universe:

Remaining Issues

4. Galaxies

- What shapes disks and ellipticals ?
 - Why are thin disks stable ?
 - Are ellipticals remnants of mergers ?
 - How faint are the faintest galaxies ?
- (- and what is a galaxy ?)

Structure Formation in the Universe:

Remaining Issues

5. Stars

- What shapes the initial mass function ?
- How are very massive stars formed ?
- Why aren't there super-massive stars ?
- Is IMF universal across cosmic time ?
- What drives turbulence in molecular clouds ?
- How is star-formation regulated in galaxies ?

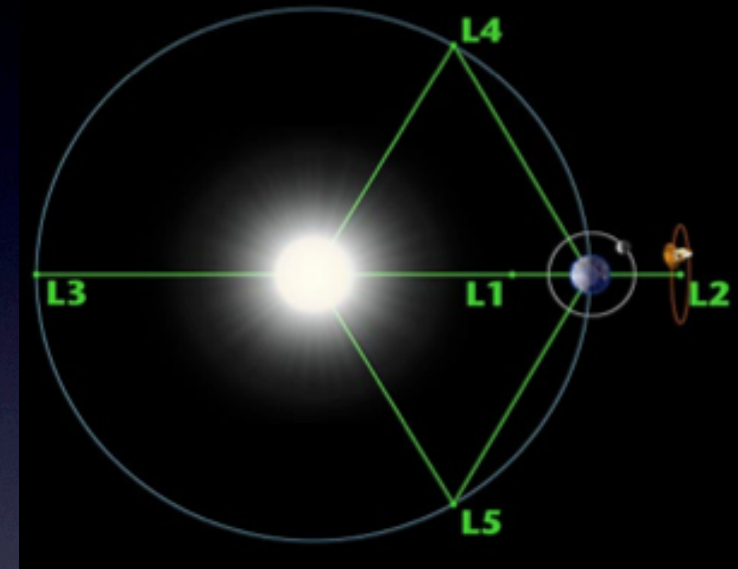
Structure Formation in the Universe:

Remaining Issues

6. Baryons

- Where are the baryons now ?
- Where are the baryons at high- z ?
- Why weren't baryons all converted into stars ?
- Does the distribution trace that of dark matter ?

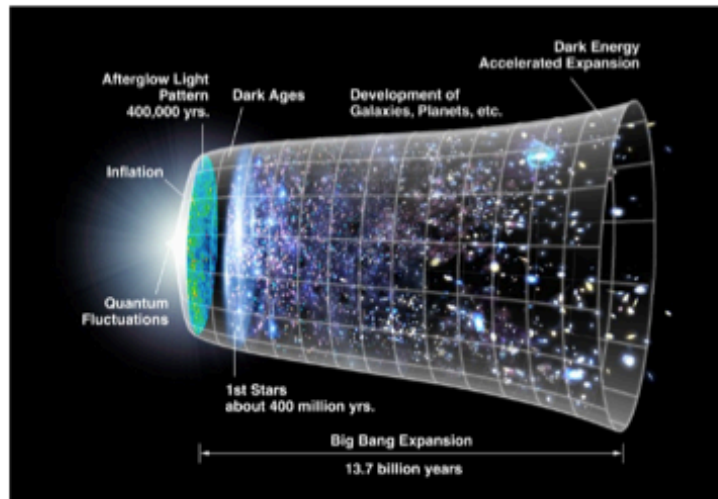
James Webb Space Telescope



2018年 打ち上げ予定

主鏡6.5メートル, 4つの観測装置 (主に赤外)

JWST science



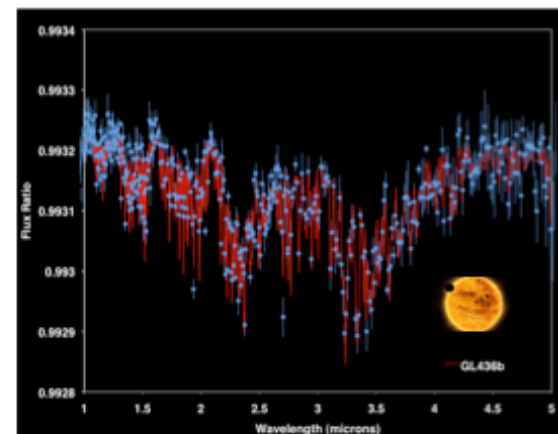
First Light and Reionization



Assembly of Galaxies

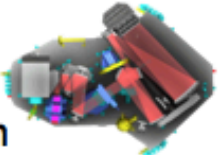
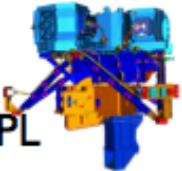
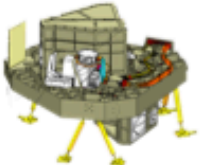


**Birth of stars and
proto-planetary systems**



**Planetary systems and the
origin of life**

JWST instruments

Instrument	Science Requirement	Capability
NIRCam Univ.Az/LMATC 	Wide field, deep imaging $>0.6\ \mu\text{m} - 2.3\ \mu\text{m}$ (SW) $>2.4\ \mu\text{m} - 5.0\ \mu\text{m}$ (LW)	Two $2.2' \times 2.2'$ SW Two $2.2' \times 2.2'$ LW Coronagraph
NIRSpec ESA/Astrum 	Multi-object spectroscopy $>0.6\ \mu\text{m} - 5.0\ \mu\text{m}$	$9.7\ \text{Sq arcmin } \Omega + \text{IFU} + \text{slits}$ MSA: 100 selectable targets $R=100, 1000, 3000$
MIRI ESA/UKATC/JPL 	Mid-infrared imaging $>5\ \mu\text{m} - 27\ \mu\text{m}$ Mid-infrared spectroscopy $>4.9\ \mu\text{m} - 28.8\ \mu\text{m}$	$1.9' \times 1.4'$ with coronagraph $3.7'' \times 3.7'' - 7.1'' \times 7.7''$ IFU $R=3000 - 2250$
FGS/TFI CSA 	Fine Guidance Sensor $0.8\ \mu\text{m} - 5.0\ \mu\text{m}$ Tunable Filter Imager $>1.6\ \mu\text{m} - 4.9\ \mu\text{m}$	Two $2.3' \times 2.3'$ $2.2' \times 2.2'$ $R=100$ with coronagraph

Slides from J. Mather, Austin meeting

Detectability

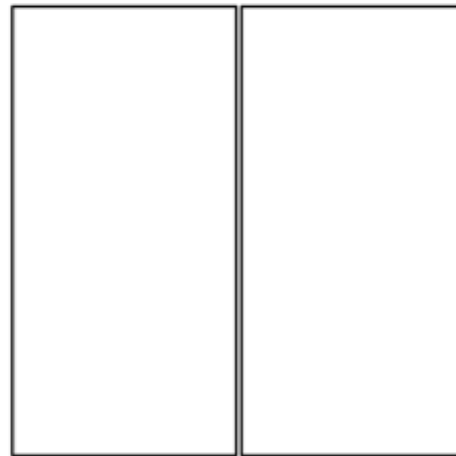
Redshift z	AB mag.	F _v (nJy)	Lyman Break wavelength
10	30.3	2.8	1.34 μm
15	30.9	1.6	1.95 μm
20	31.3	1.1	2.55 μm

Observation	Primary Instrument	Depth, Mode	Target Density
Ultra-deep survey (UDS)	NIRCam	1.4 nJy @ 2 μm	10 arcmin ²
In depth source study	NIRSpec MIRI	23 nJy, R=100 23 nJy @ 5.6 μm	Galaxies in UDS area
Lyman α forest diagnostics	NIRSpec	2x10 ⁻¹⁹ erg cm ⁻² s ⁻¹ , R~1000	Bright z>7 QSO or galaxy
Survey for Lyman α sources	FGS-TF	2x10 ⁻¹⁹ erg cm ⁻² s ⁻¹ , R~100	4 arcmin ² (containing known high-z object)
Transition in Ly α/Balmer	NIRSpec	2x10 ⁻¹⁹ erg cm ⁻² s ⁻¹ , R~1000	UDS or wider survey area
Measure ionizing continuum	NIRSpec	2x10 ⁻¹⁹ erg cm ⁻² s ⁻¹ , R~1000	UDS or wider survey area
Ionization source nature	NIRSpec MIRI	2x10 ⁻¹⁹ erg cm ⁻² s ⁻¹ , R~1000 23 nJy@ 5.6 μm	UDS or wider survey area
Luminosity Function of dwarf galaxies	NIRCam	1.4 nJy @ 2 μm	UDS data

Comparison with HST



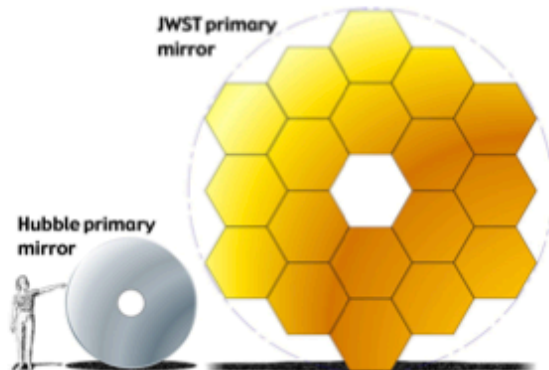
WFC3/IR
1014×1014
0.13"/pix
123"×137"



ACS/WFC
2×2048×4096
0.05"/pix
202"×202"



NIRC2 2 x 4 x 2048 x 2048
0.034"/pix
139" x 139"



Instrument	A Ω (sq arcsec; HST A=1)
WFC3/IR	16851
ACS WF2	40804
NIRC2	34848 * 7.3 = 282,000

Comparison with HST

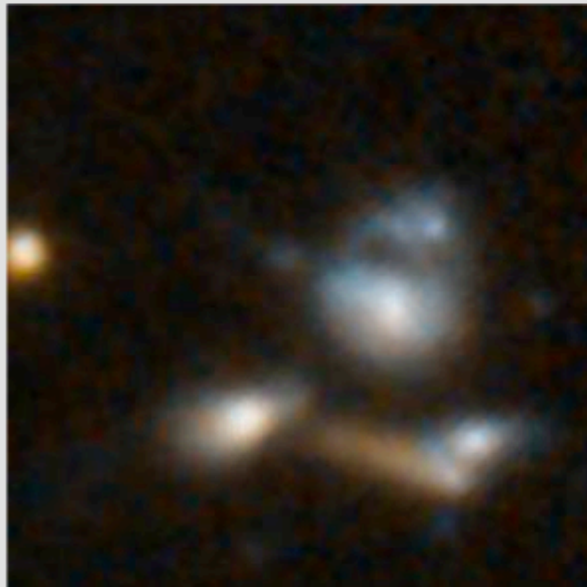
HST/ACS
Viz



JWST/NIRCam
Viz



HST/NICMOS
J H



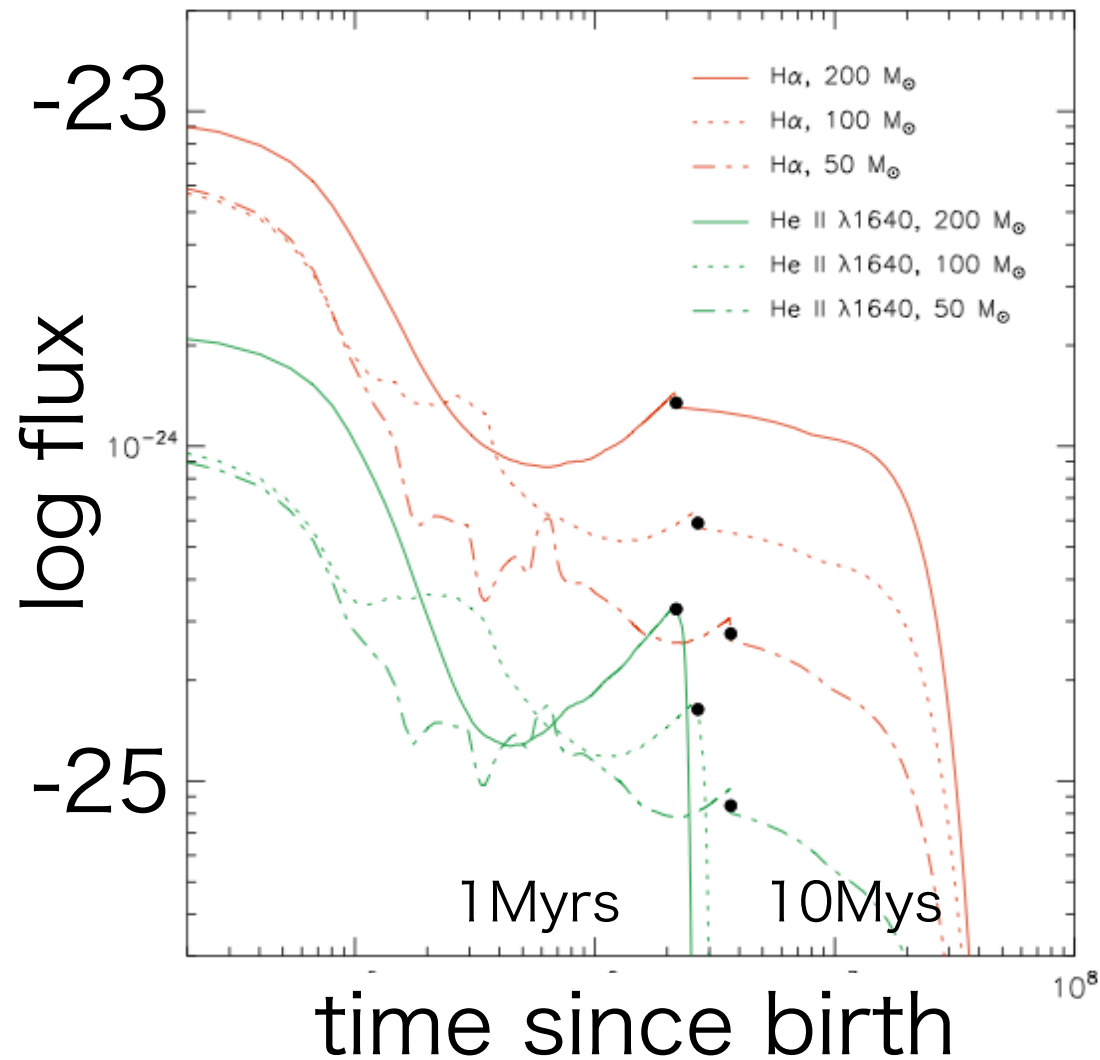
JWST/NIRCam
J H



Massimo Stiavelli

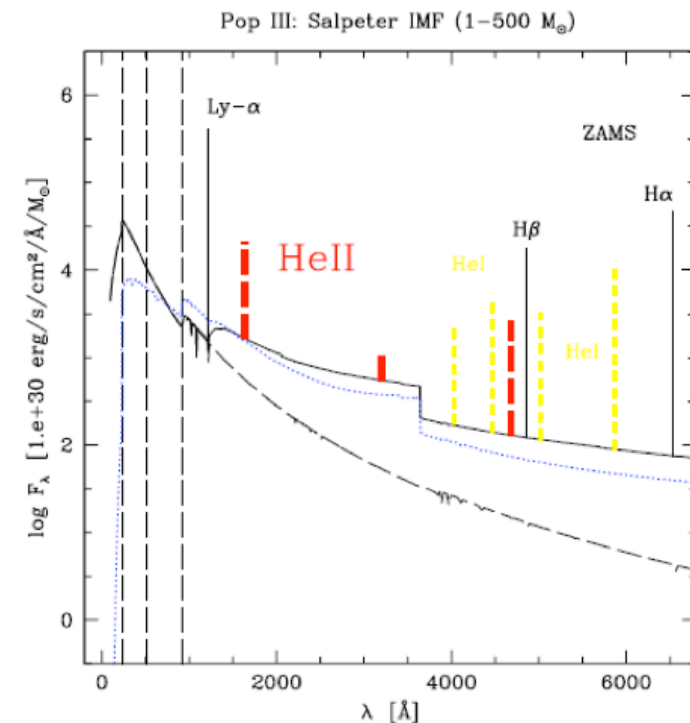
Even JWST cannot...

Greif et al. 2009



Recom. lines

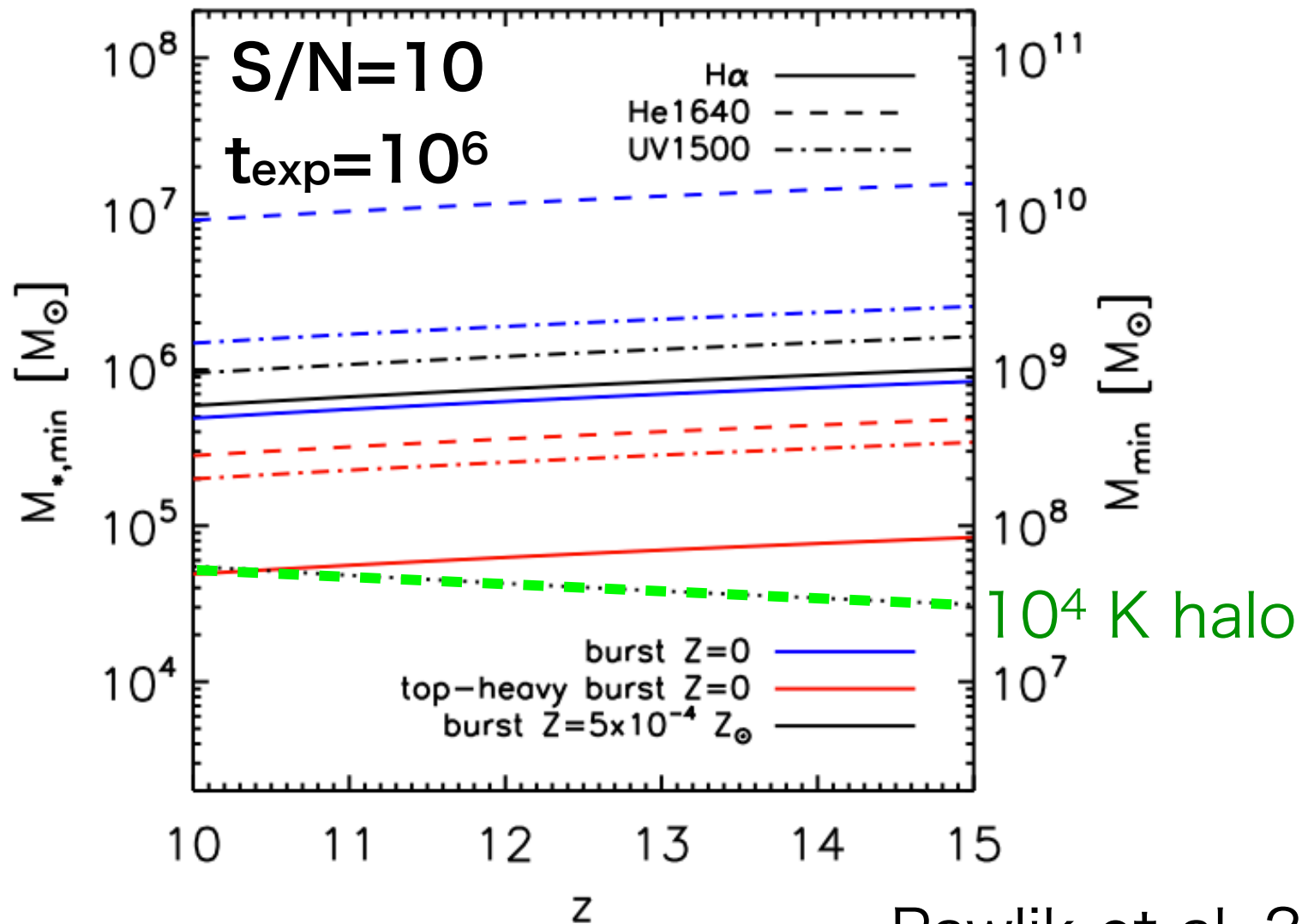
H α , He II $\lambda 1640$ flux



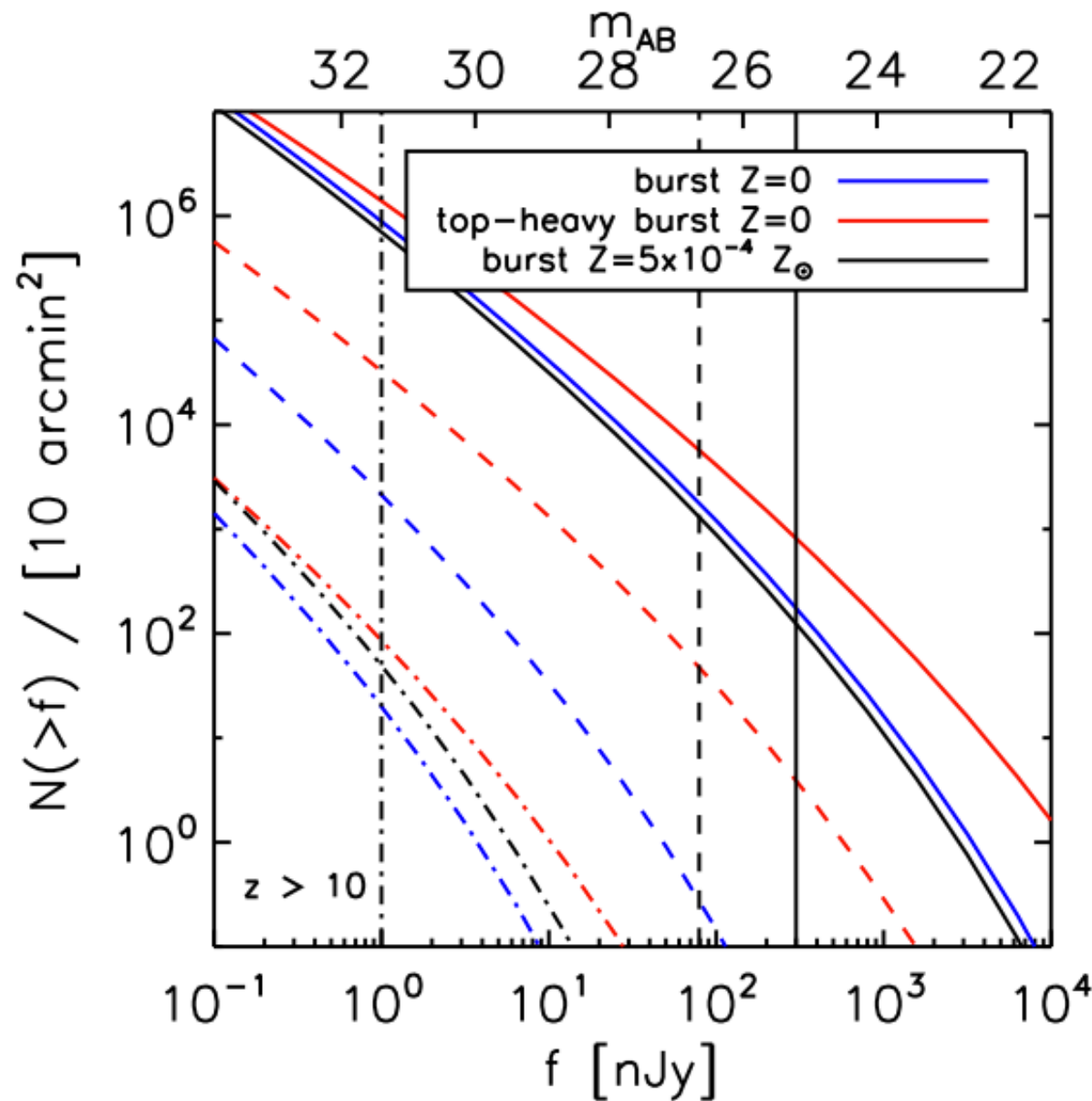
Sometimes the object or effect was predicted earlier, but considered too faint or difficult to be seen. This was the case with both neutron stars and black holes which are so tiny that it seemed reasonable to assume that they would be unobservable. What was required was for the emission to be stimulated (as in a laser) for the pulsar or highly beamed by relativistic outflow for the GRB. Any scientific paper written predicting their observational detection well before they were discovered would rightly have been rejected!

A. C. Fabian, "Serendipity in Astronomy"

$$M_{\star} \sim 10^5 M_{\odot} \left(\frac{f_{\star}}{0.1} \right) \left(\frac{f_{\text{cool}}}{0.01} \right) \left(\frac{M_{\text{vir}}}{10^8 M_{\odot}} \right)$$



$$\frac{dN}{d\Omega}(> z) = \int_z^\infty dz' \frac{dV}{dz' d\Omega} \frac{\tau_{\text{sb}}}{t_{\text{H}}(z')} \int_{M_{\text{min}}(z')}^\infty dM n(M, z'),$$

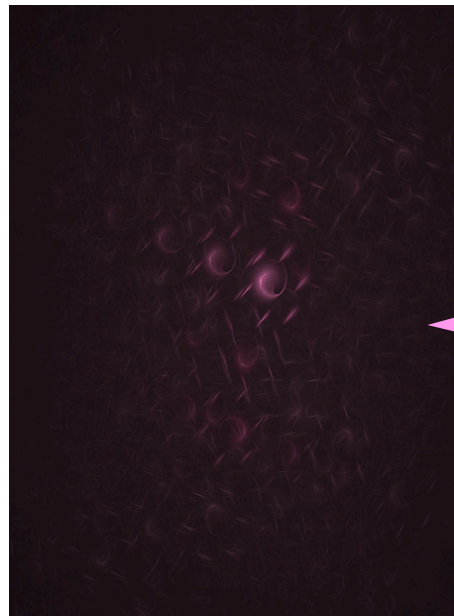


JWST source
counts

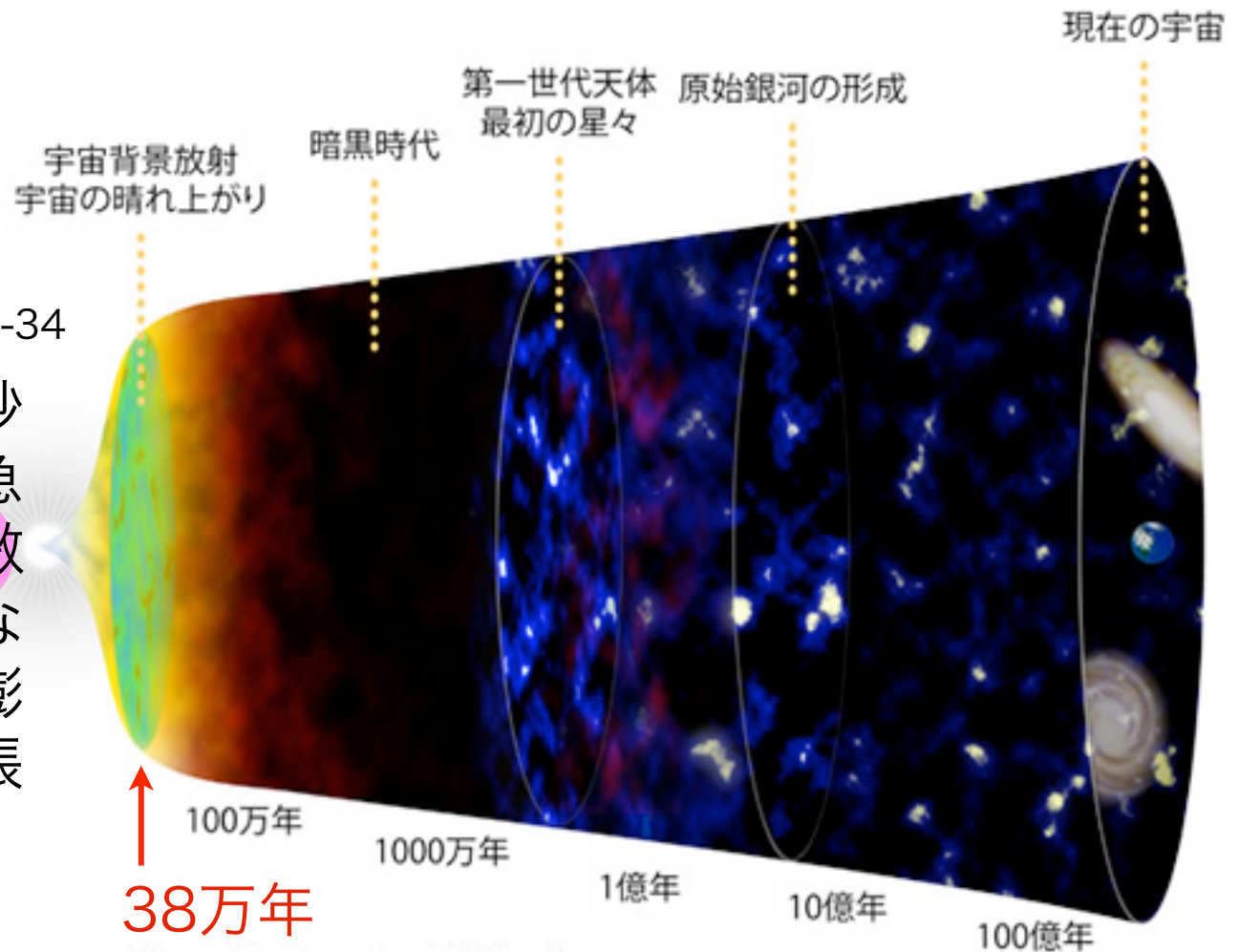
宇宙創生期を探る

インフレーション宇宙と原始重力波

真空の揺らぎ



10^{-34}
秒
急激な膨張

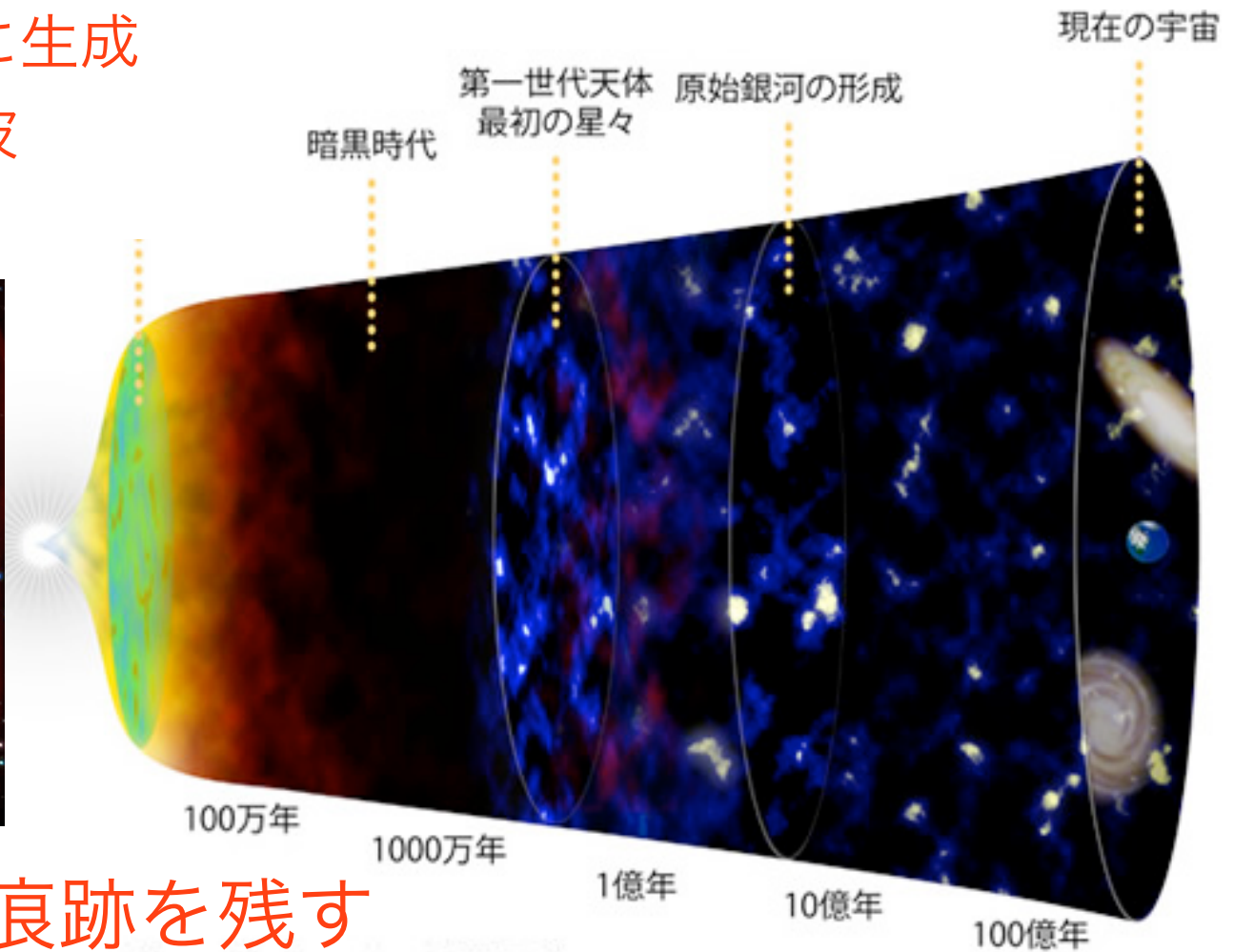
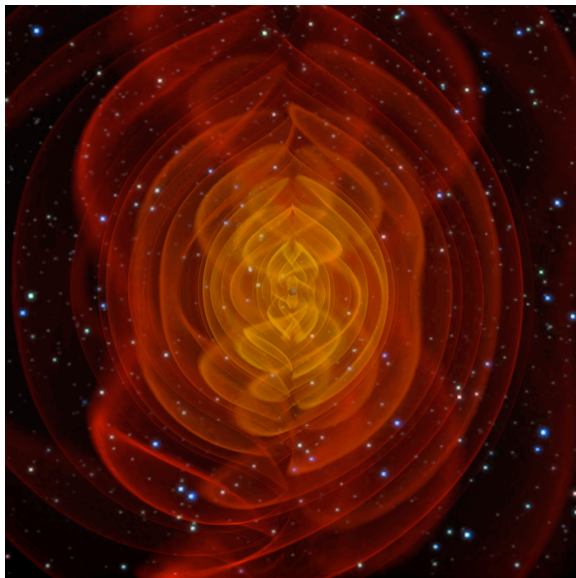


電磁波の観測で遡れる限界

宇宙創生期を探る

インフレーション宇宙と原始重力波

インフレーション中に生成
された原始重力波
(時空の揺らぎ)

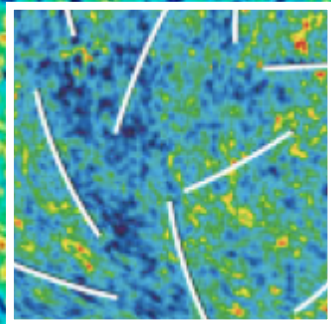


宇宙背景放射に痕跡を残す

マイクロ波背景放射

わずかだが偏光している

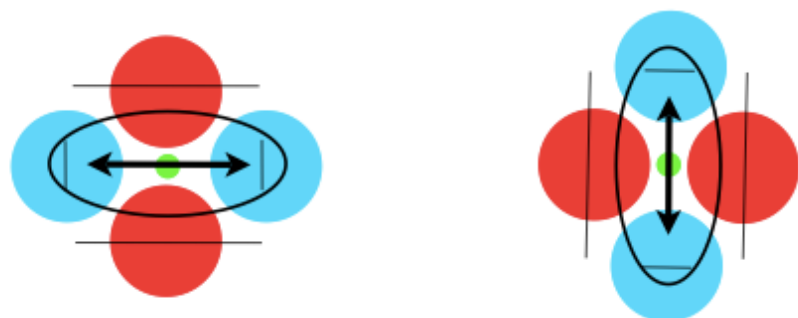
(Eモード)



全天から来る電波: 生まれたての宇宙の様子

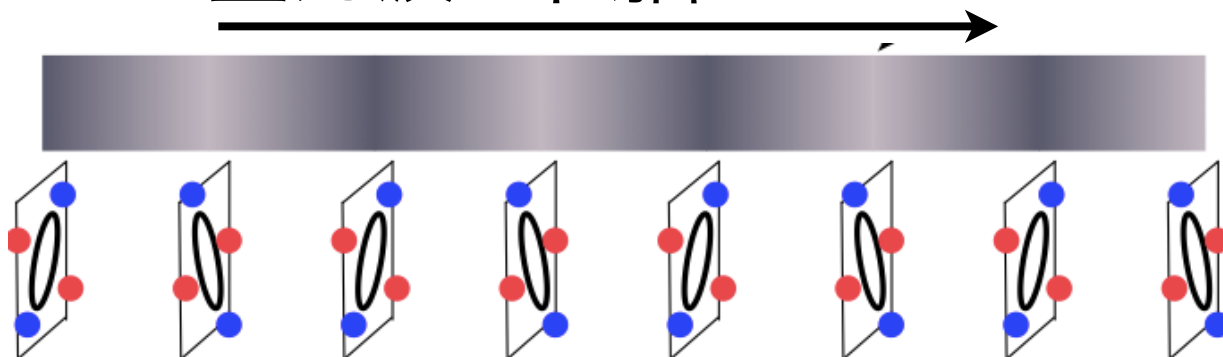
原始重力波の痕跡

空間の伸び縮み → 輻射温度の変化(熱冷)



↓
偏光の生成

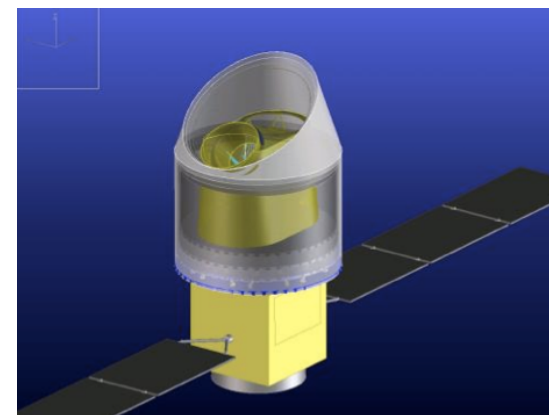
重力波の伝播



特徴的な偏光の方向

小松英一郎氏スライドより

LiteBIRD 衛星
(高エネ研他)

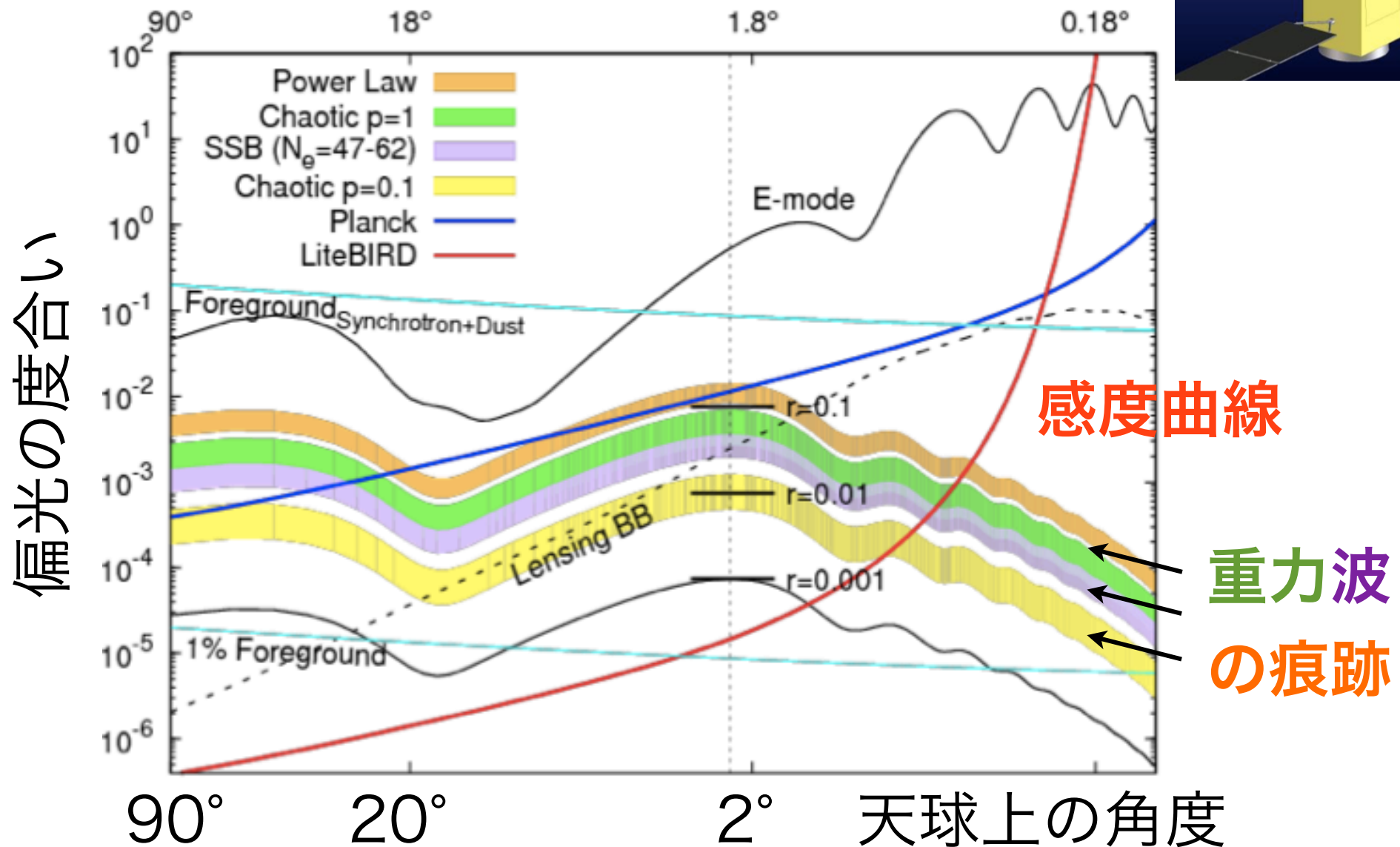
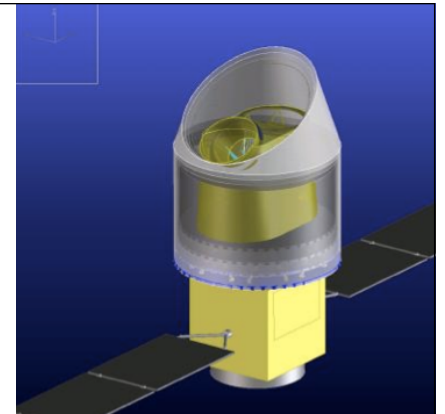


背景放射の

Bモード偏光を検出

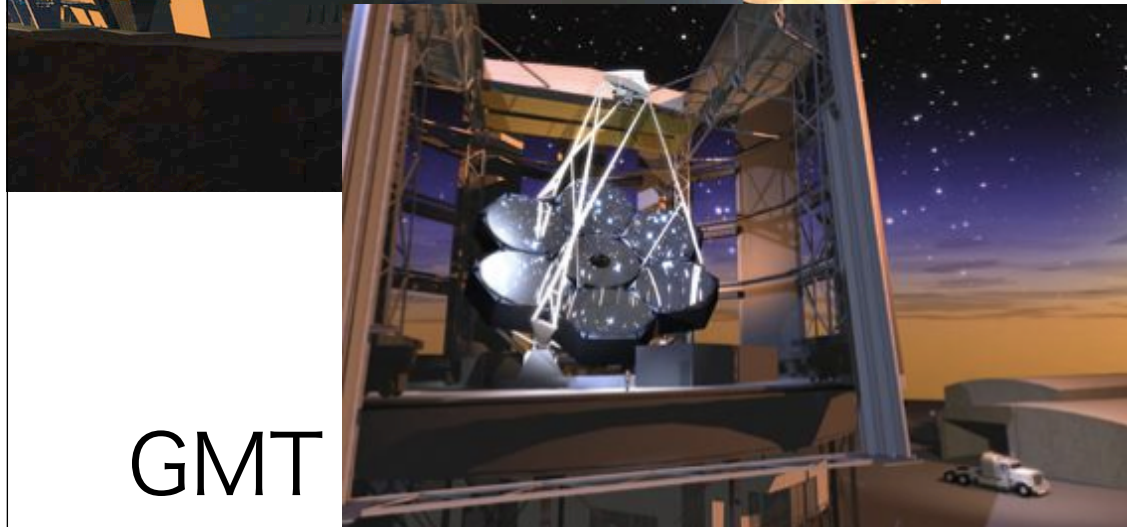
インフレーション理論の検証

原始重力波の痕跡



次世代大口径望遠鏡

30メートル望遠鏡
(米国、カナダ、日本)
ハワイ マウナケア山頂

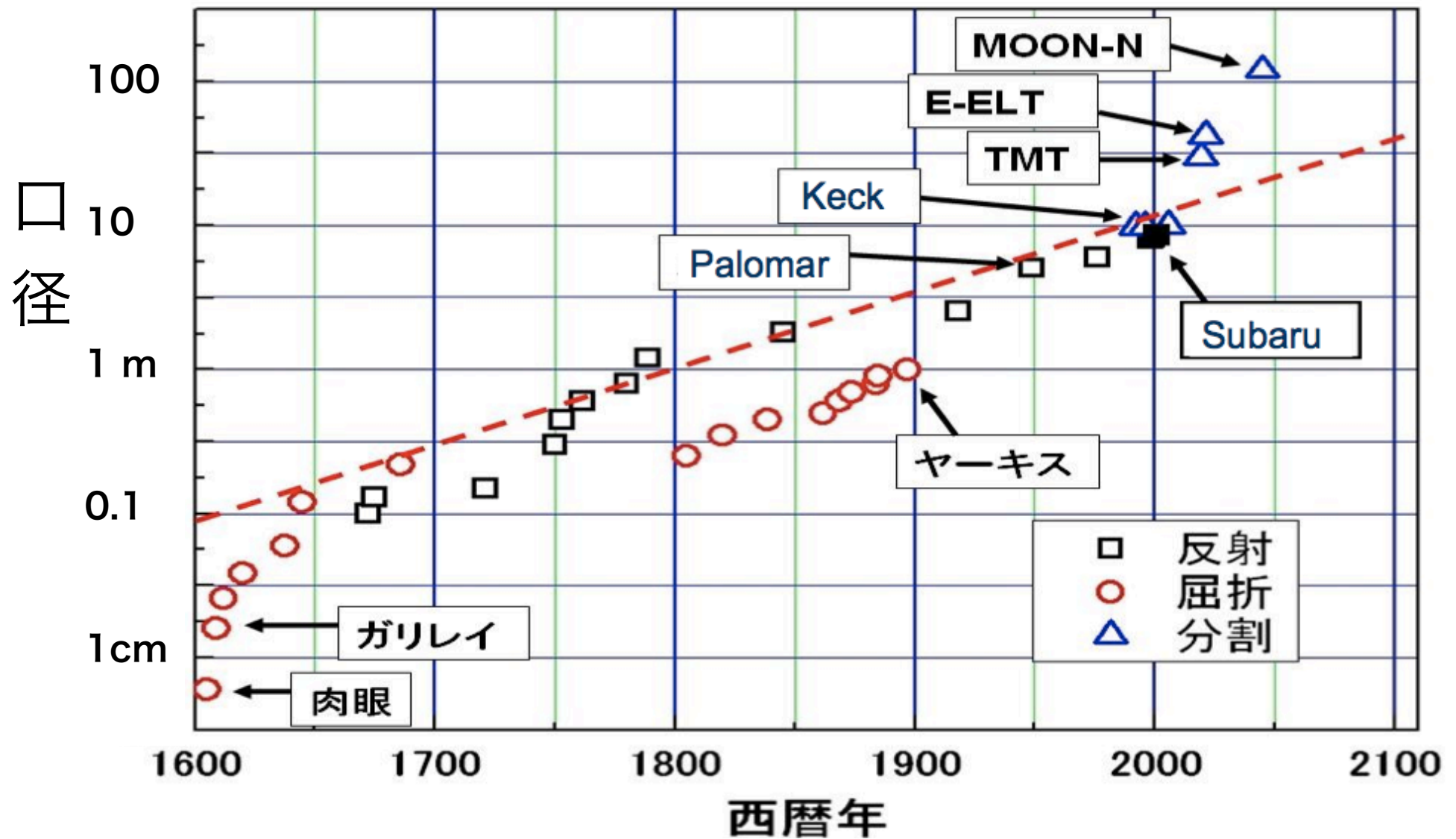


GMT

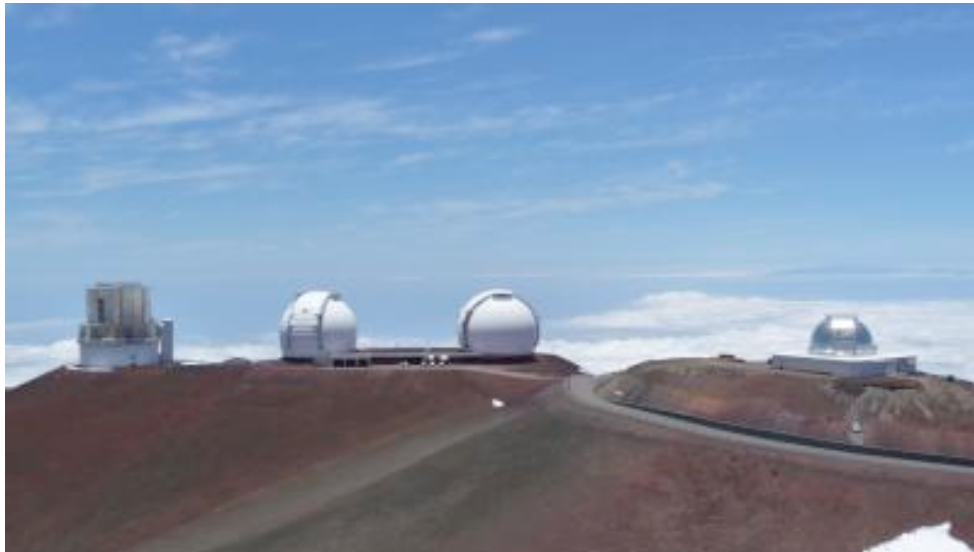


European-ELT

400 years

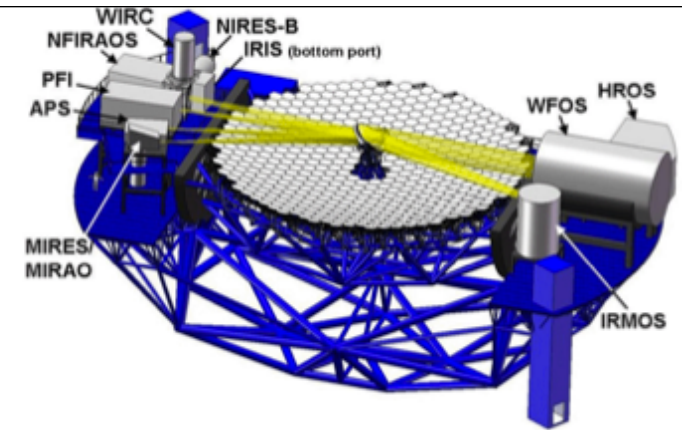






Thirty Meter Telescope

Instruments



Instrument	Spec.Res.	Science C
Near-IR DL Spectrometer & Imager (IRIS)	≤ 4000	- Assembly of galaxies at large redshift - Black holes/AGN/Galactic Center - Resolved stellar populations in crowded fields
Wide-field Optical Spectrometer (MOBIE)	300 - 5000	- IGM structure and composition $2 < z < 6$ - High-quality spectra of $z > 1.5$ galaxies suitable for measuring stellar pops, chemistry, energetics
Multi-slit near-DL near-IR Spectrometer (IRMS)	2000 - 10000	- Near-IR spectroscopic diagnostics of the faintest objects - JWST followup
Mid-IR Echelle Spectrometer & Imager (MIRES)	5000 - 100000	- Physical structure and kinematics of protostellar envelopes - Physical diagnostics of circumstellar/protoplanetary disks: where and when planets form during the accretion phase
ExAO I (PFI)	50 - 300	Direct detection and spectroscopic characterization of extra-solar planets
High Resolution Optical Spectrograph (HROS)	30000 - 50000	- Stellar abundance studies throughout the Local Group - ISM abundances/kinematics, IGM characterization to $z \sim 6$ - Extra-solar planets!
MCAO imager (WIRC)	5 - 100	- Galactic center astrometry - Stellar populations to 10Mpc
Near-IR, DL Echelle (NIRES)	5000 - 30000	- Precision radial velocities of M-stars and detection of low-mass planets - IGM characterizations for $z > 5.5$

TMTの威力： 大集光力と高解像力 (1)



Hubble Ultra Deep Field



TMT30mの解像度＝**すばるの4倍**
0.015秒角@近赤外線

TMT 30m の感度＝**すばる14台分**
シーイングリミットでの観測、集光力～口径²
回折限界での点源での効率 (**AO使用**)～口径⁴
=>**すばる200台分！**

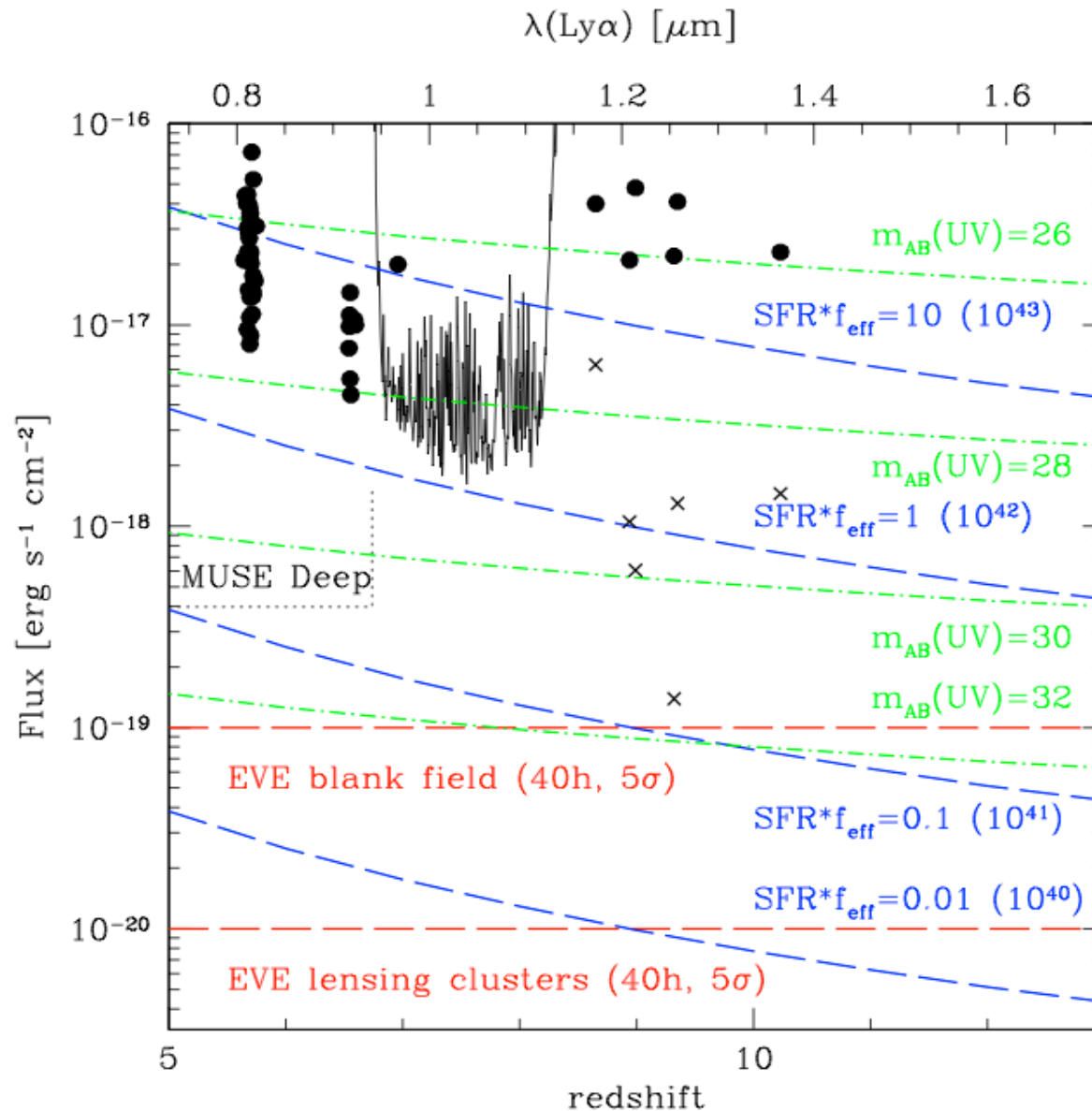
Currently in the design phase, the Thirty Meter Telescope (TMT) project is a collaboration between the University of California, the Associated Universities for Research in Astronomy, and the Association of Canadian Universities for Research in Astronomy and Caltech.

TMTの解像度

10 mas @	5 AU	36 km	Jovian's and moons
	5 pc	0.05 AU	Nearby stars - companions
	100 pc	1 AU	Nearest star forming regions
	1 kpc	10 AU	Typical Galactic Objects
	8.5 kpc	85 AU	Galactic Center or Bulge
	1 Mpc	0.05 pc	Nearest galaxies
	20 Mpc	1 pc	Virgo Cluster
	$z=0.5$	0.07 kpc	galaxies at solar formation epoch
	$z=1.0$	0.09 kpc	disk evolution, drop in SFR
	$z=2.5$	0.09 kpc	QSO epoch, Ha in K band
	$z=5.0$	0.07 kpc	protogalaxies, QSOs, reionization

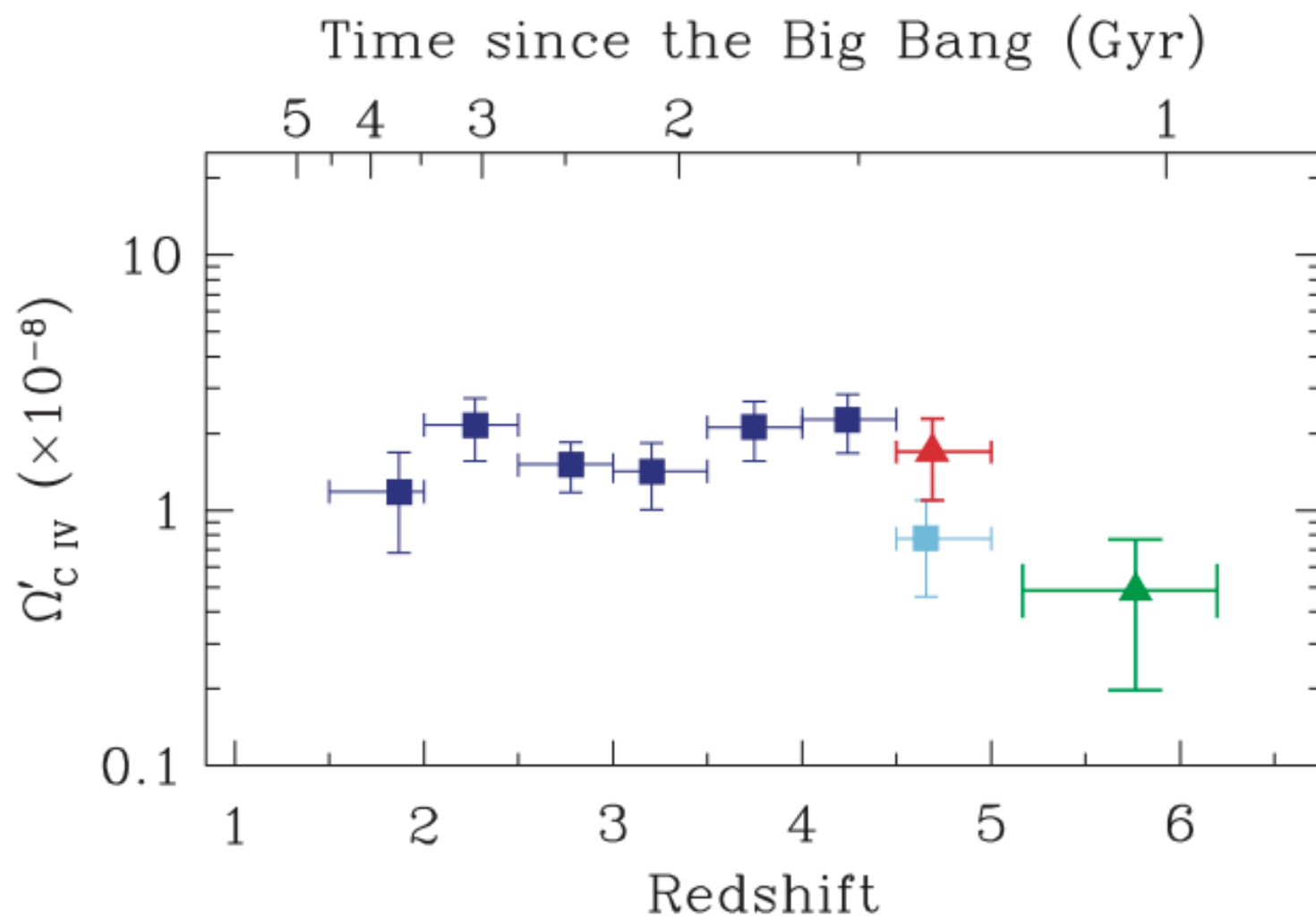
表 1.2: 地球からの各距離における、10 mas に対応する実距離

Lyman-a from PopIII clusters



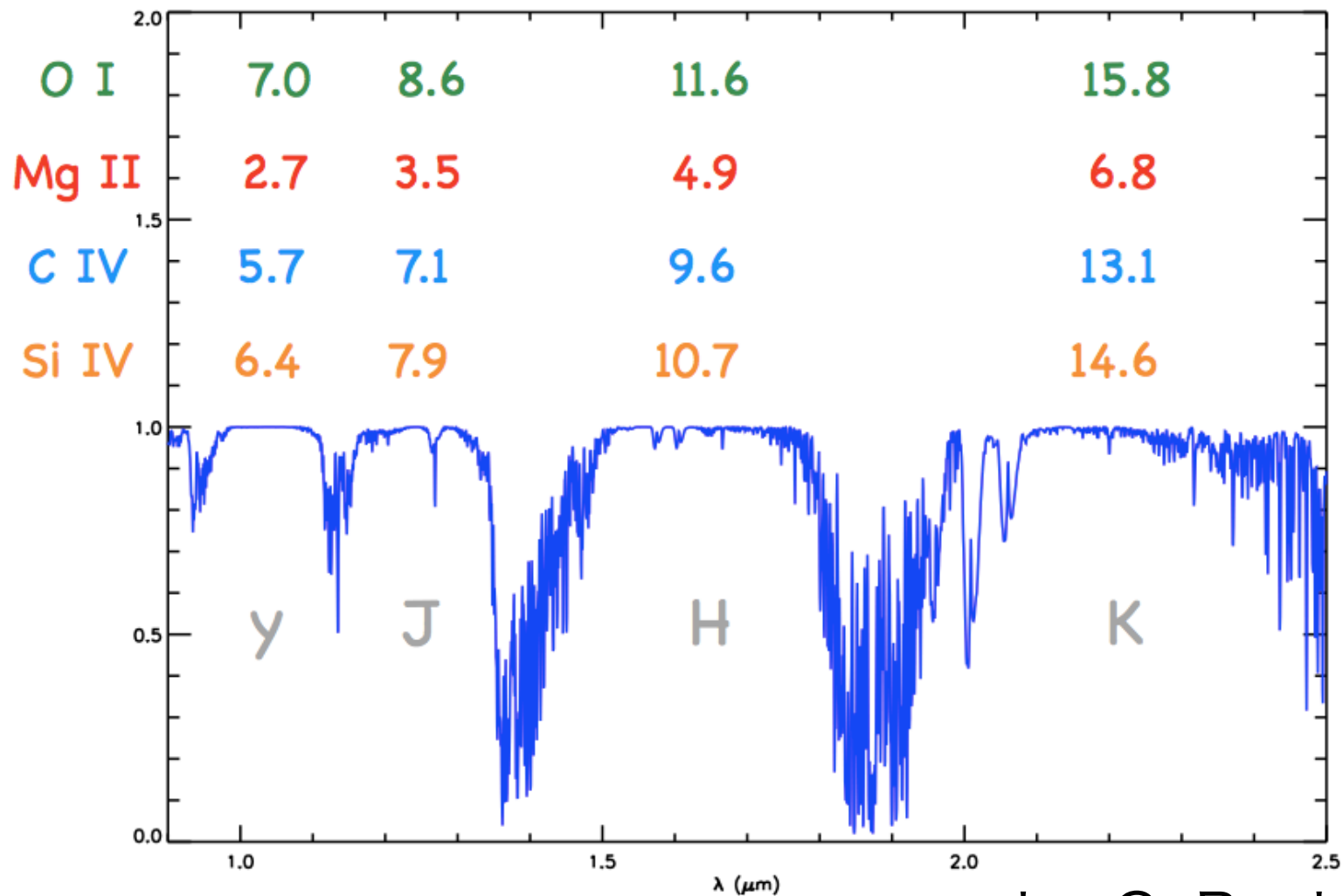
Schaerer 2009

IGM enrichment



Ryan-Weber+ 09

Metal lines@high-z

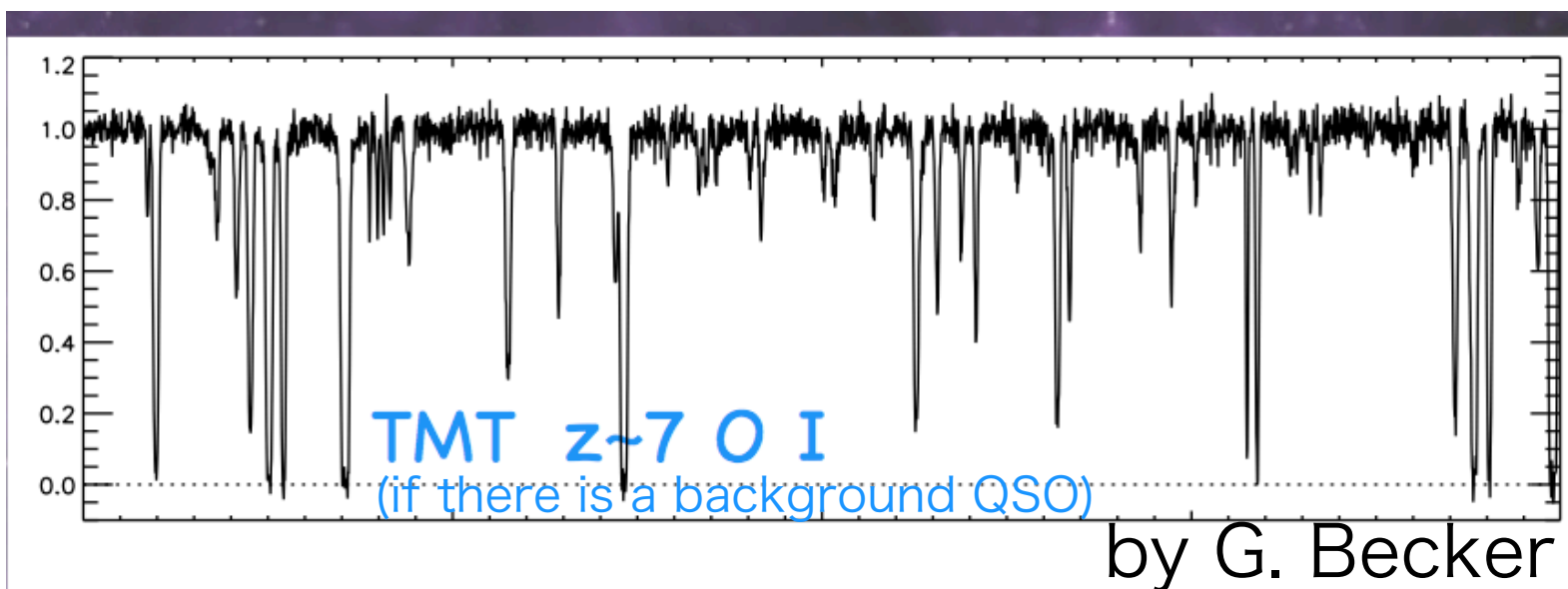


by G. Becker

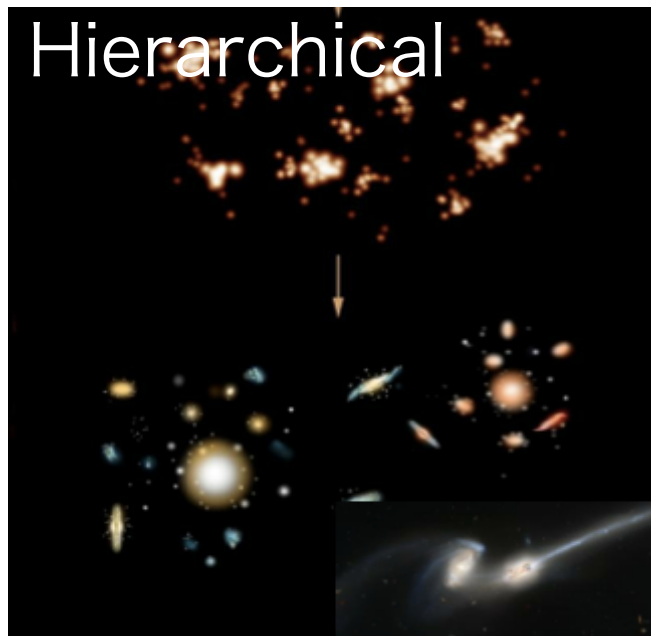
O I “forest”

O I and H I (close IP) are in charge exchange equilibrium.

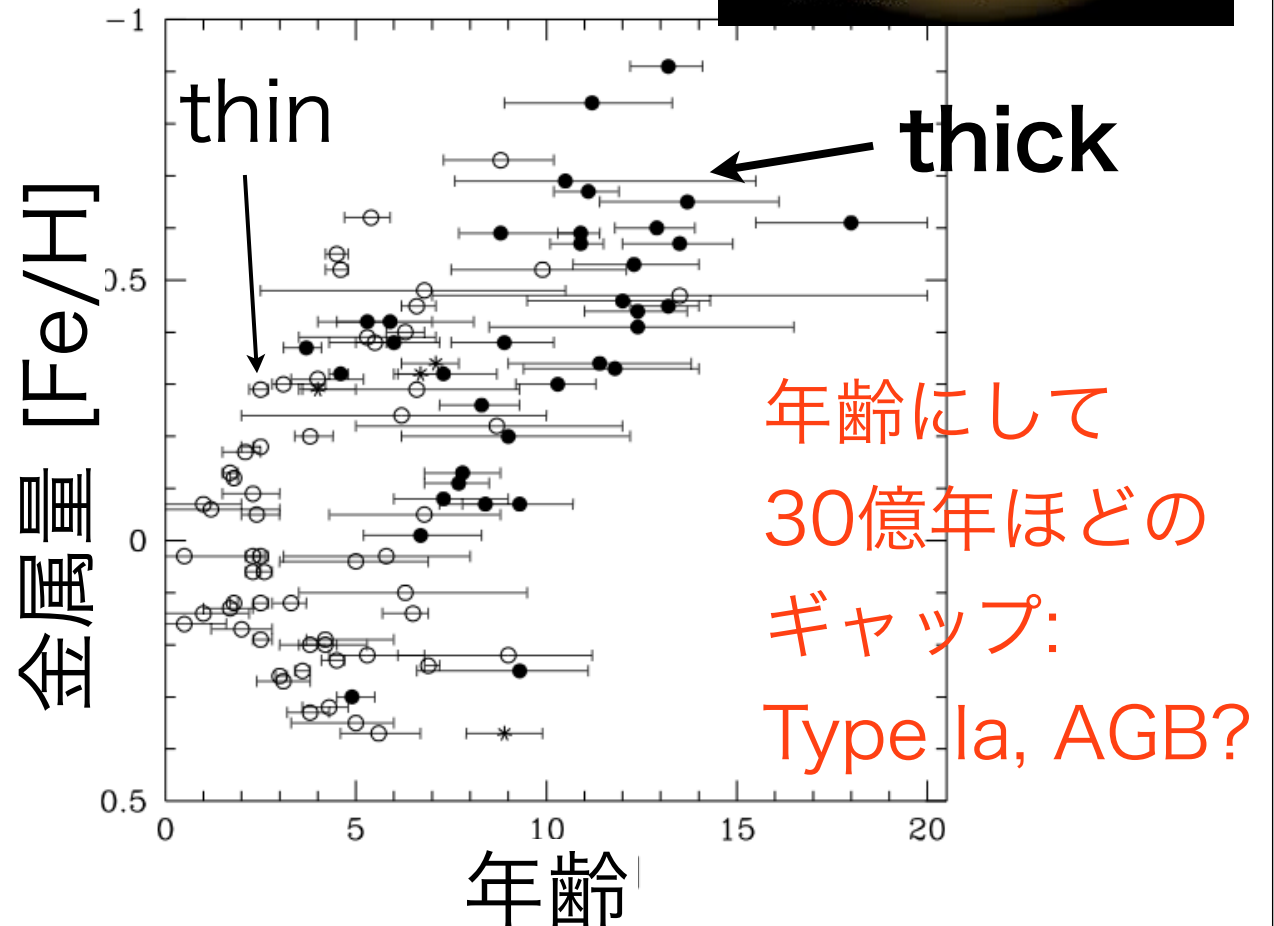
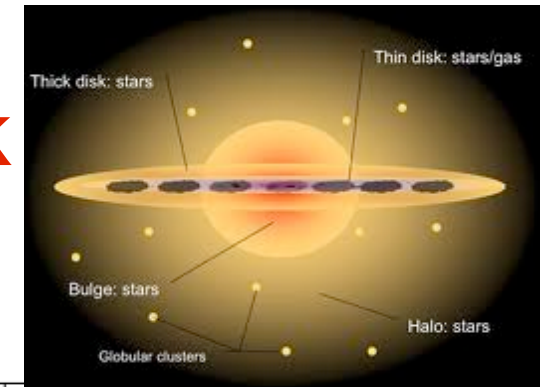
O I fluctuation probes a combination of reionization topology and metal enrichment.



天の川銀河の形成



The Thick Disk の起源

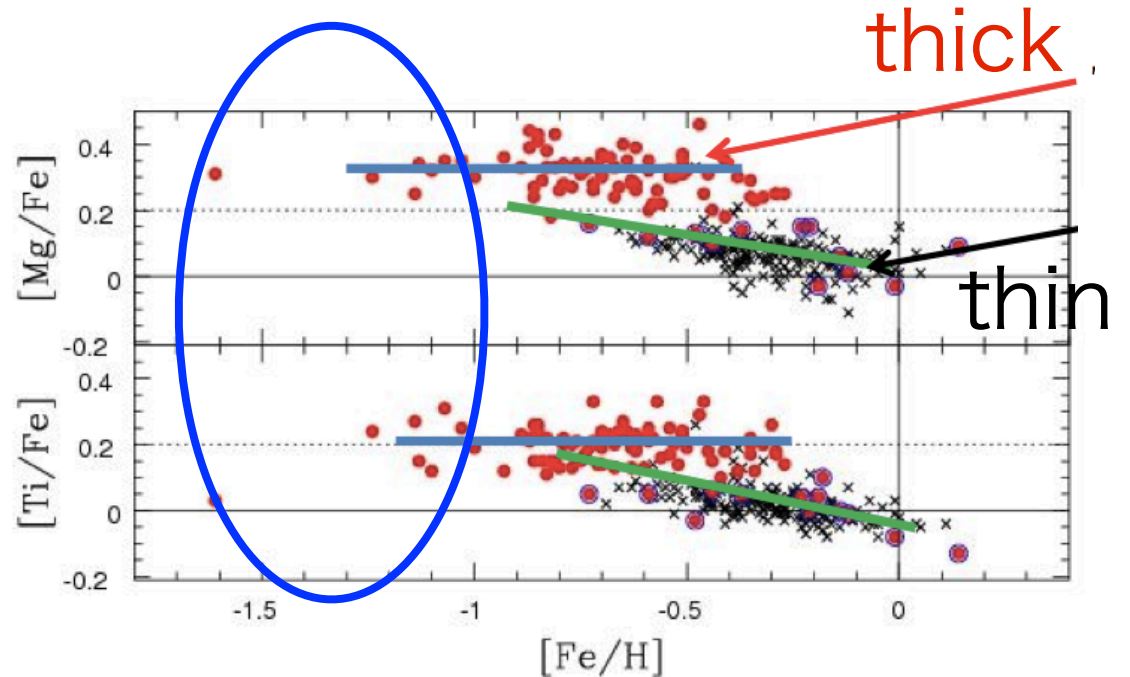


位置測定+化学進化

GAIA + TMT



GAIAは
15等までの星2600万個
18等まで2億個以上
太陽系から > 10kpc



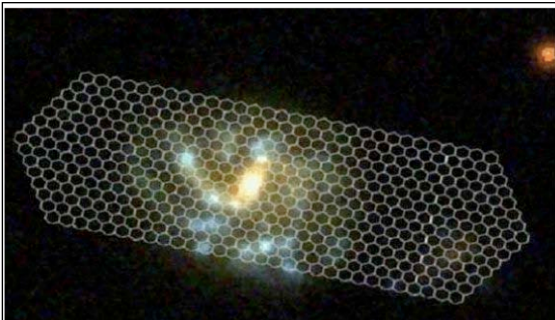
10m クラスだと分光($R \sim 6000$)に

1kpc: $m_v=14.8$ requires ~ 2 hours

2kpc: $m_v=16.3$ requires ~ 9 hours

5kpc: $m_v=18.3$ requires $\sim >50$ hours

30mによる統計で円盤力学構造解明



遠方銀河の構造

遠方銀河を解像し $z = 0$

・星形成率

・金属量

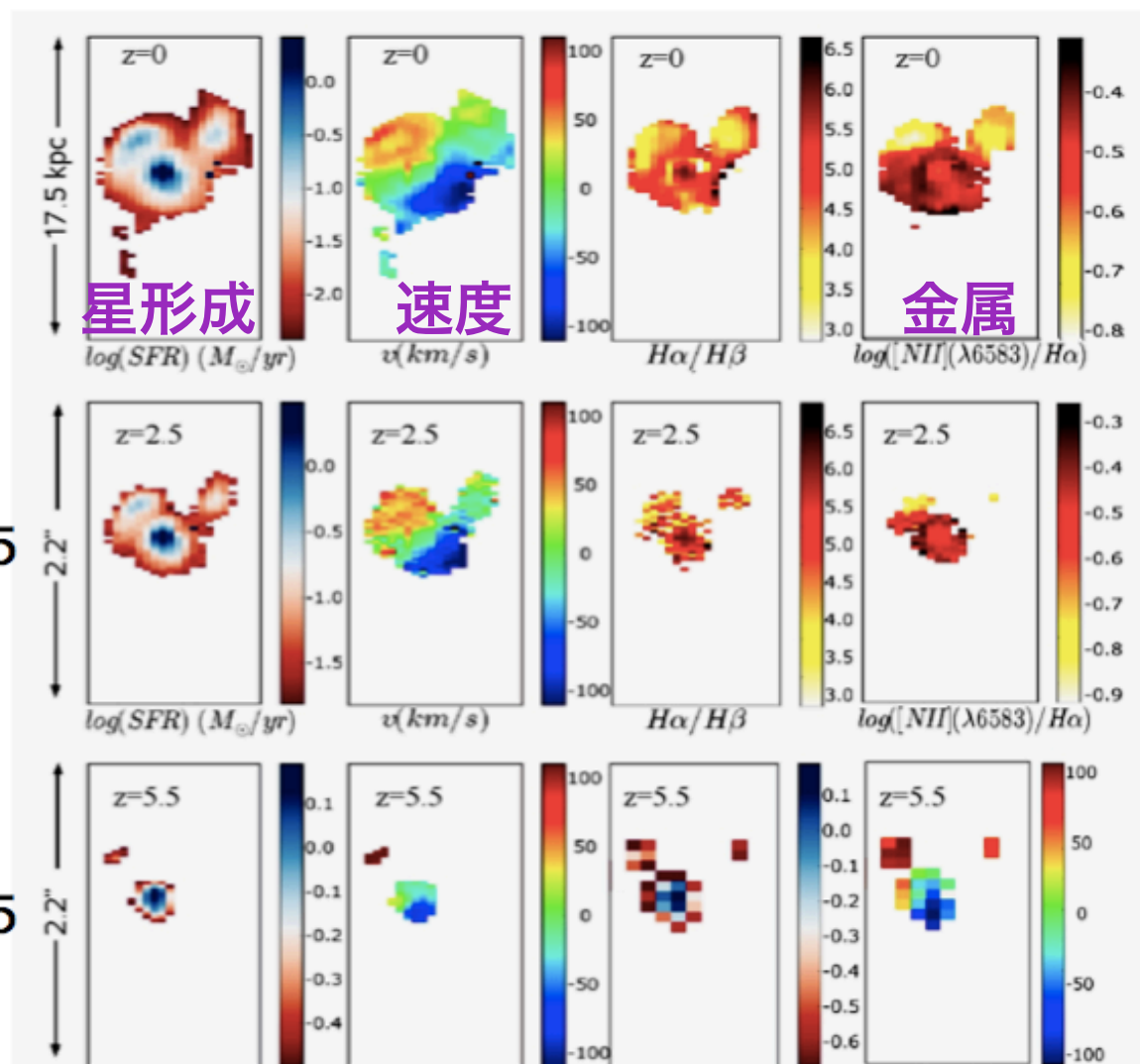
・運動速度

・減光

のマップを得る

$z = 2.5$

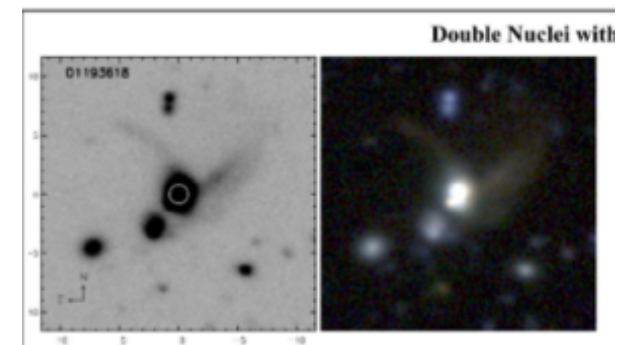
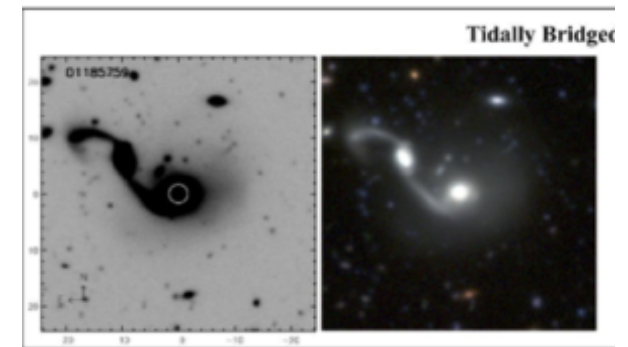
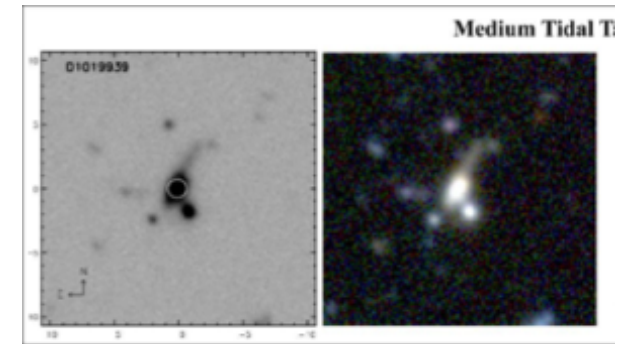
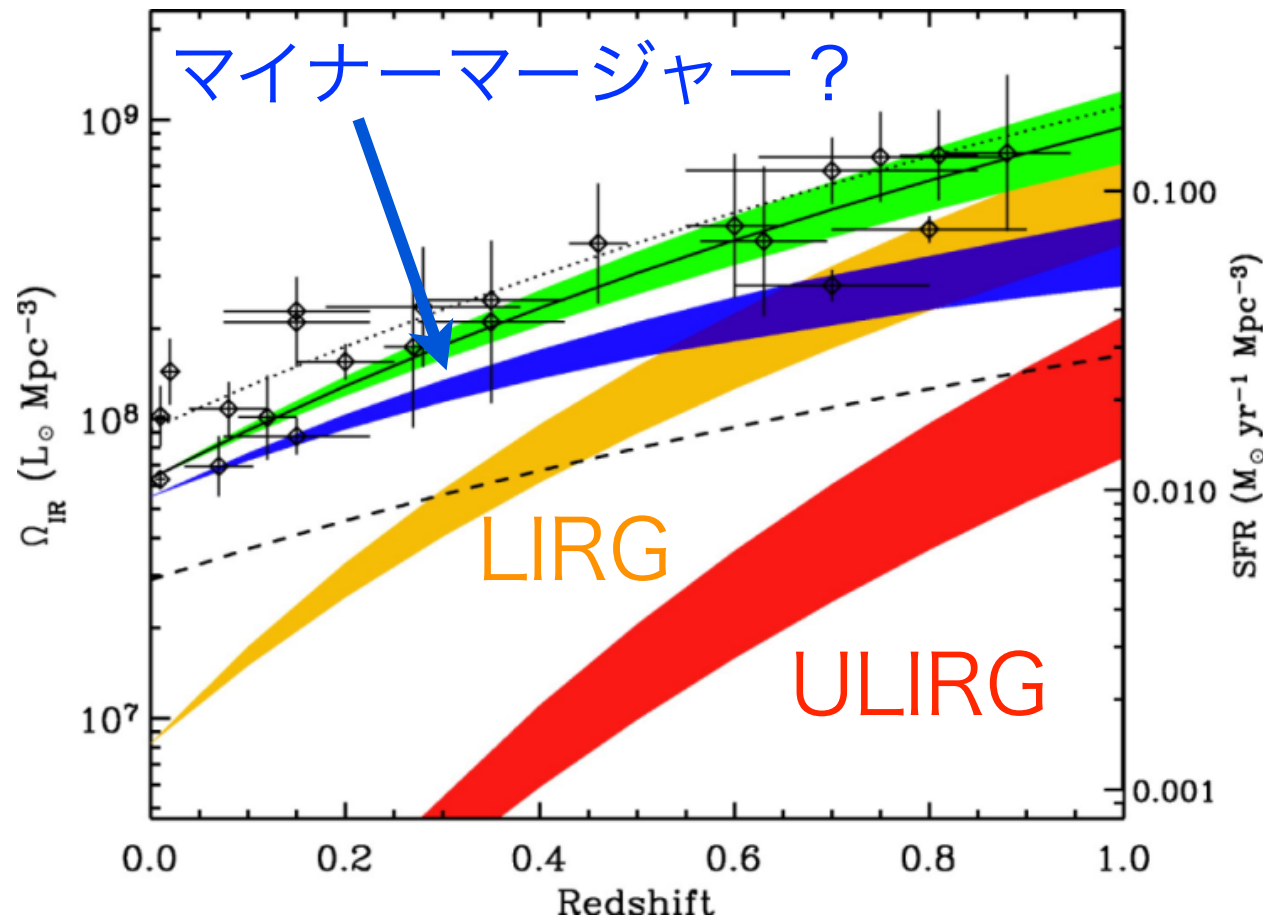
$z = 5.5$



ALMAとのコラボ!

銀河間相互作用

赤外エネルギー密度の進化

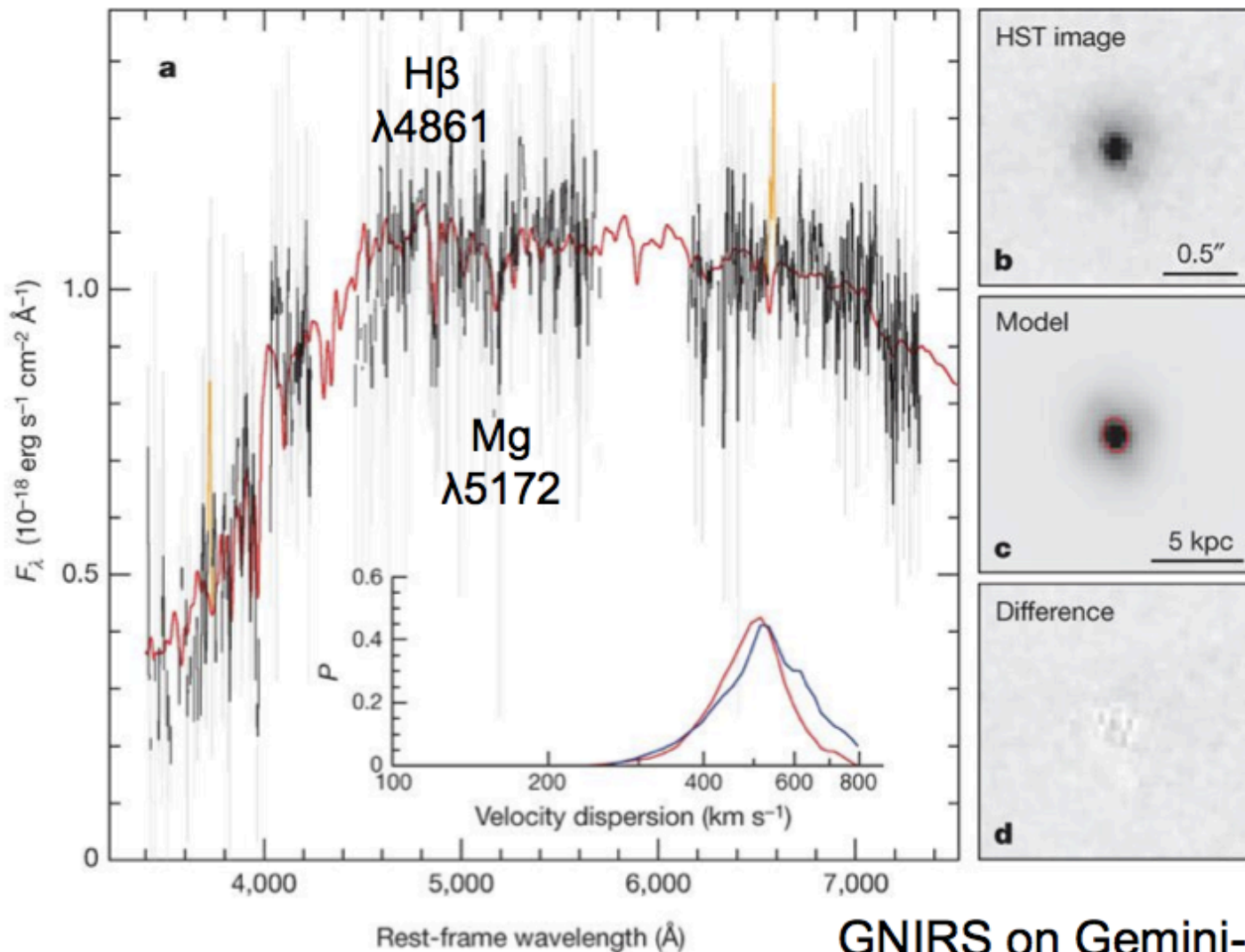


江上さん
スライドより

70pc@z=0.5の解像度で、
マイナーマージャーを同定

CFHTLS深撮像探査

遠方銀河とサイズ進化



Spectrum and HST images of 1255-0 at $z = 2.186$.
van Dokkum *et al.* *Nature* **460**, 717-719 (2009)

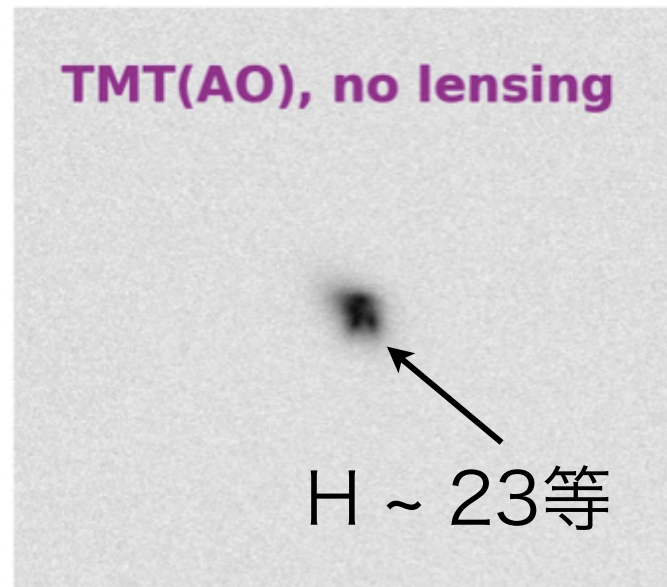
GNIRS on Gemini-S, 29 hrs

K=19.26 (Vega)

$M^* = 2 \times 10^{11} M_\odot$

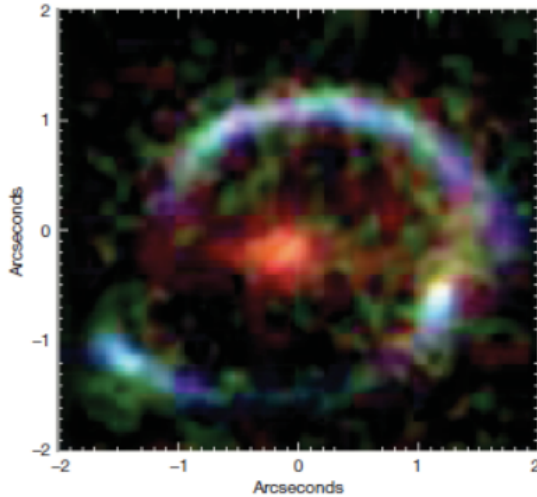
→ 2hrs exposure with TMT !

重力レンズ+AOで銀河構造



大栗さん
スライドより

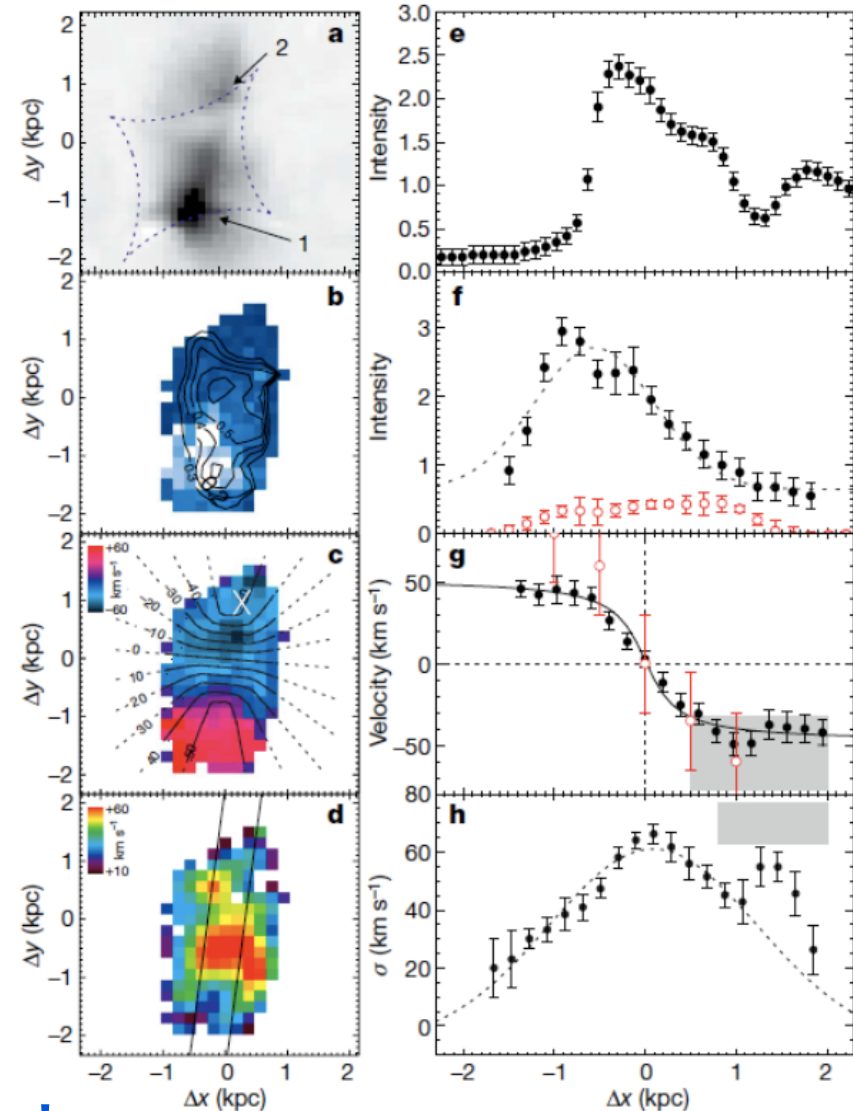
重力レンズ活用例



z~3 銀河の回転曲線
Keck/OSIRISの観測

レンズモデルにより
ソース天体の形状再構築

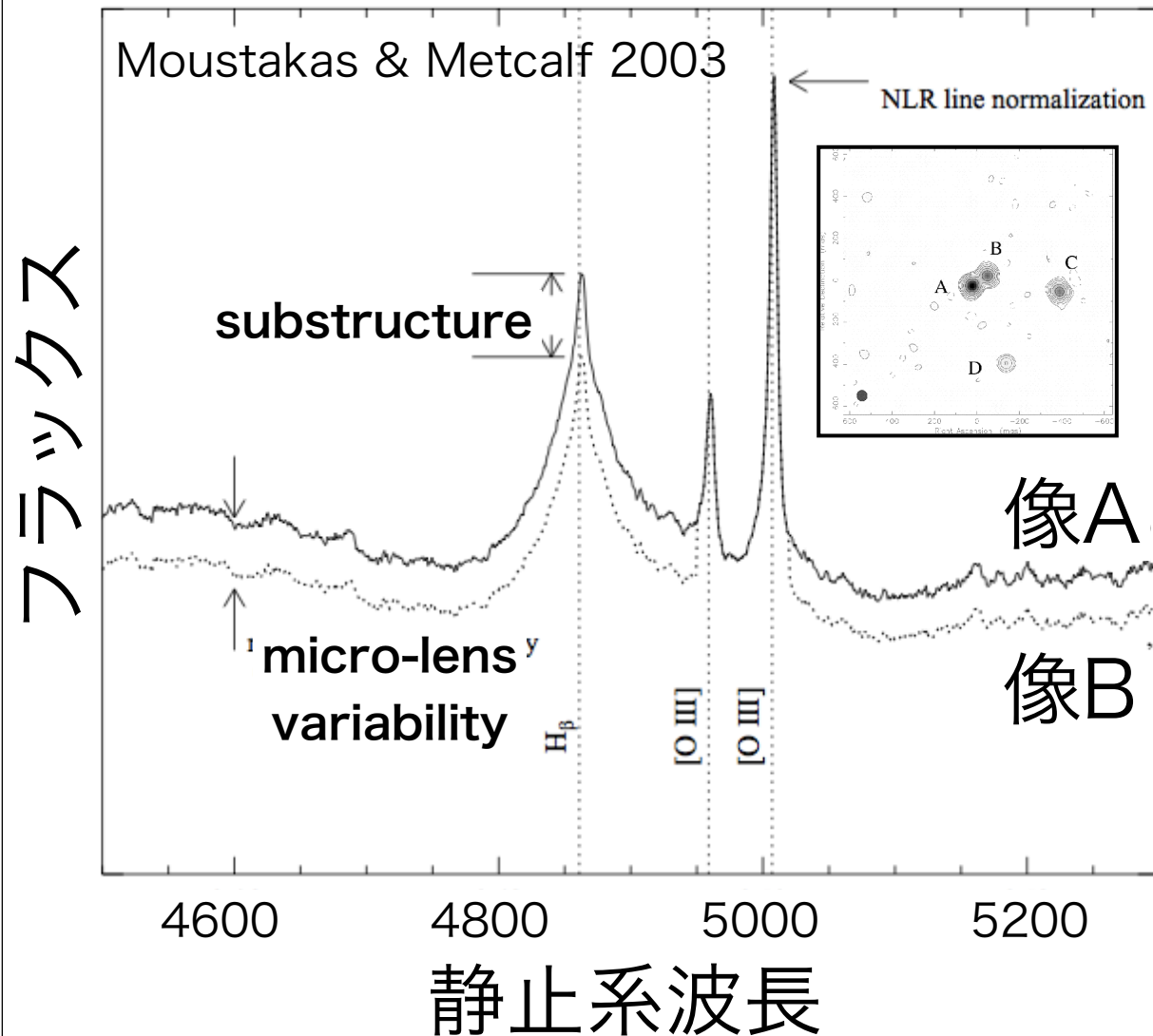
TMTでさらにhigh-z へ！



Stark+08

近赤分光で暗黒物質塊検出

広帯域フラックス比よりも正確



- Narrow Line Regions

~ 100pc

はサブハローにレンズ
されるが星による

マイクロレンズはない

- Broad Line Regions

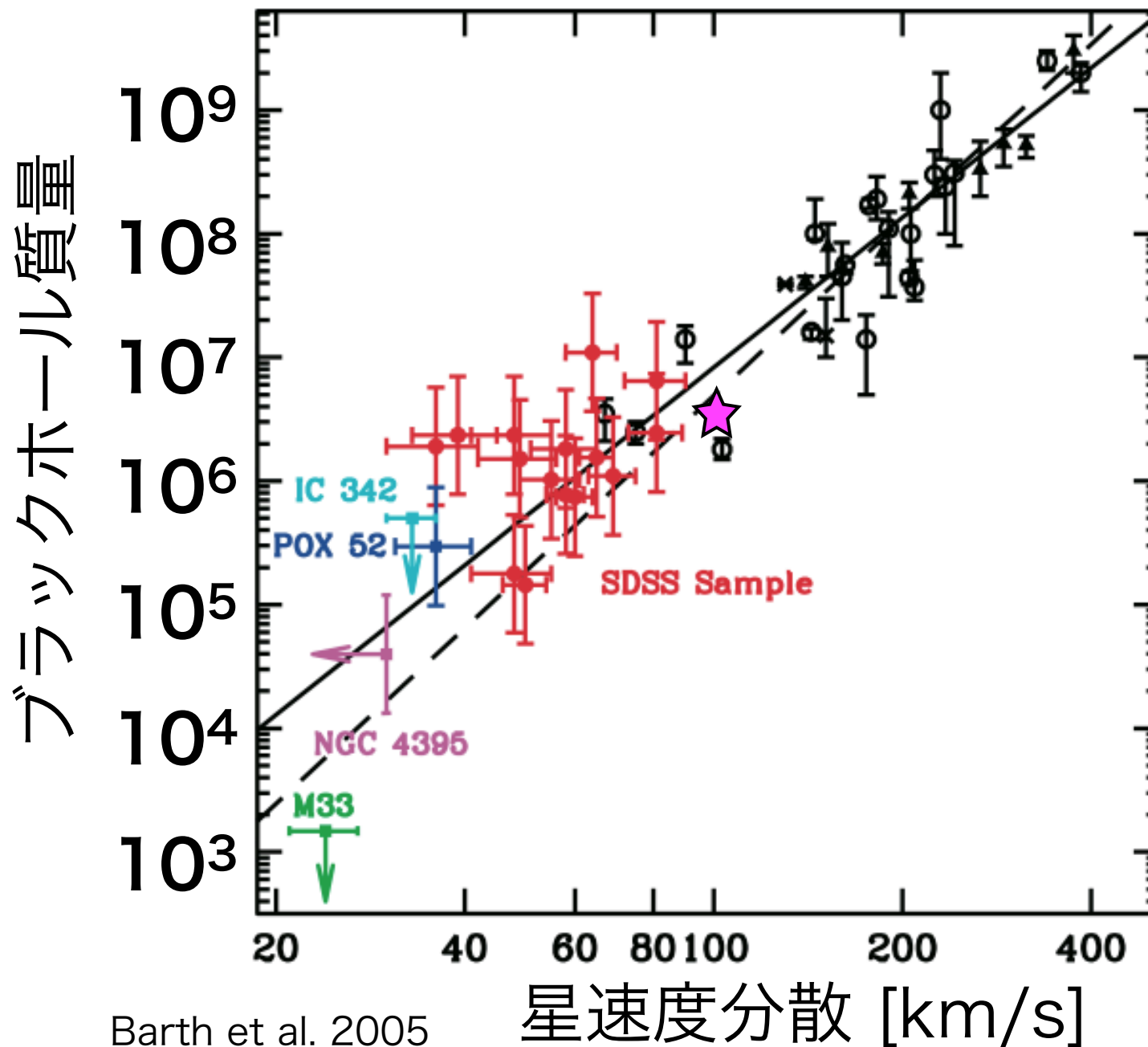
~ 1pc

は両方の影響を受ける

- Continuumは

星によるマイクロレンズ
で激変

ブラックホール-銀河共進化



共進化と言われても...

質量が M のブラックホールのシュワルツシルト半径は $r = 2GM / c^2$:

1 太陽質量なら $r \sim 3 \text{ km}$

1 億太陽質量でも $r \ll 1 \text{ pc}$

ブラックホールの重力による影響が及ぶのは

$$r_{\text{BH}} = GM/\sigma^2 = \underline{10.8 \text{ pc}} (M/10^8) (\sigma/200 \text{ km/sec})^{-2}$$

TMTあるいは電波で分解可能

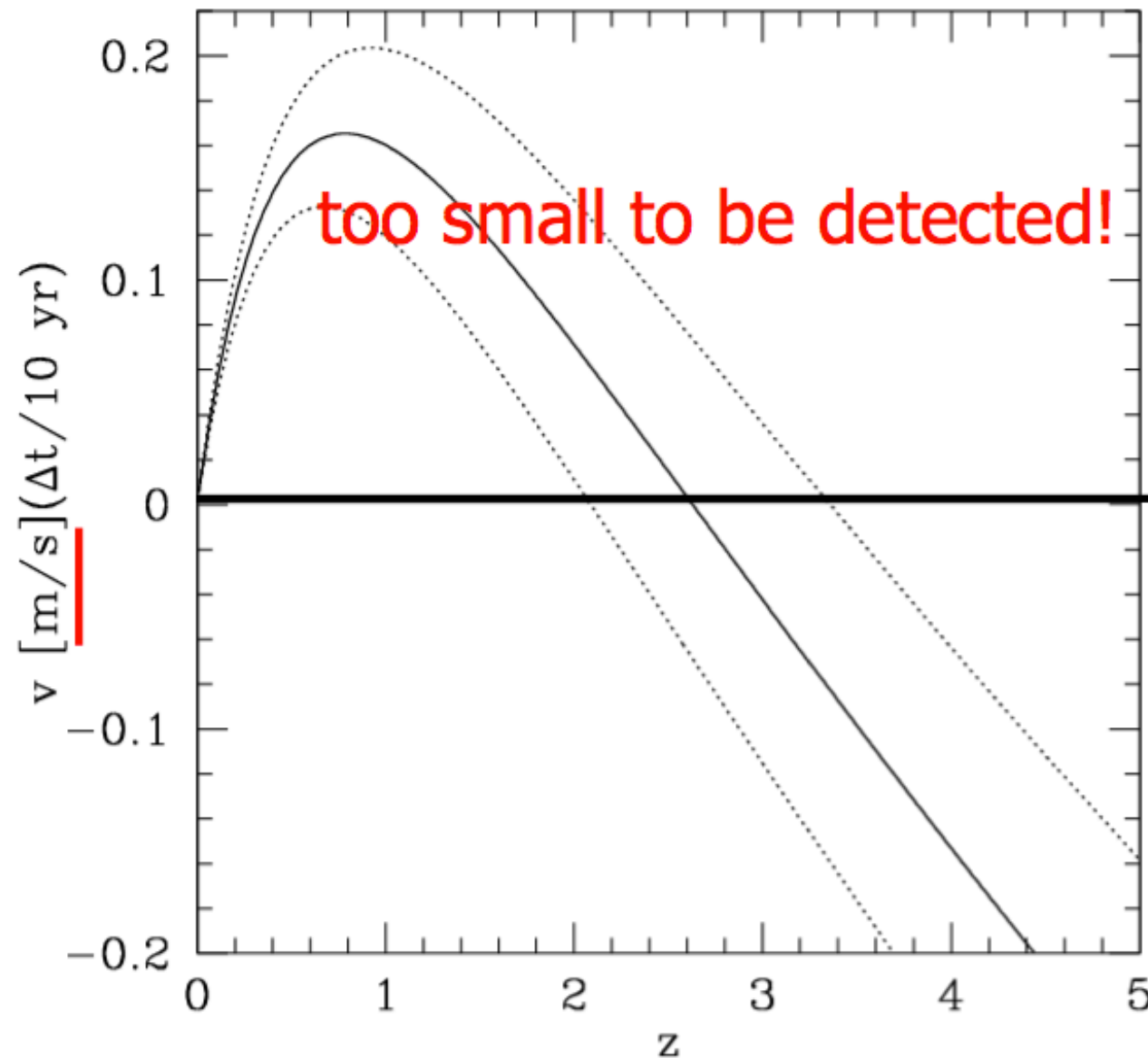
TMTの解像度

10 mas @	5 AU	36 km	Jovian's and moons
	5 pc	0.05 AU	Nearby stars - companions
	100 pc	1 AU	Nearest star forming regions
	1 kpc	10 AU	Typical Galactic Objects
	8.5 kpc	85 AU	Galactic Center or Bulge
	1 Mpc	0.05 pc	Nearest galaxies
	20 Mpc	1 pc	Virgo Cluster
	$z=0.5$	0.07 kpc	galaxies at solar formation epoch
	$z=1.0$	0.09 kpc	disk evolution, drop in SFR
	$z=2.5$	0.09 kpc	QSO epoch, Ha in K band
	$z=5.0$	0.07 kpc	protogalaxies, QSOs, reionization

表 1.2: 地球からの各距離における、10 mas に対応する実距離

宇宙の加速膨張の直接検出 by TMT, E-ELT

velocity shift over $\Delta t_0=10$ years



$$v = c\Delta z / (1 + z_e)$$

$$\Delta z > 0 \text{ for } 0 < z < 3$$

$$\Omega_{\Lambda} = 0.74 \pm 0.04$$

$$\Omega_m = 1 - \Omega_{\Lambda}$$

$$h = 0.71$$

$\text{Ly}\alpha$ forest as a target (Loeb)

10 yrs $\rightarrow$ 0.1 m/s

100 yrs $\rightarrow$ 1 m/s

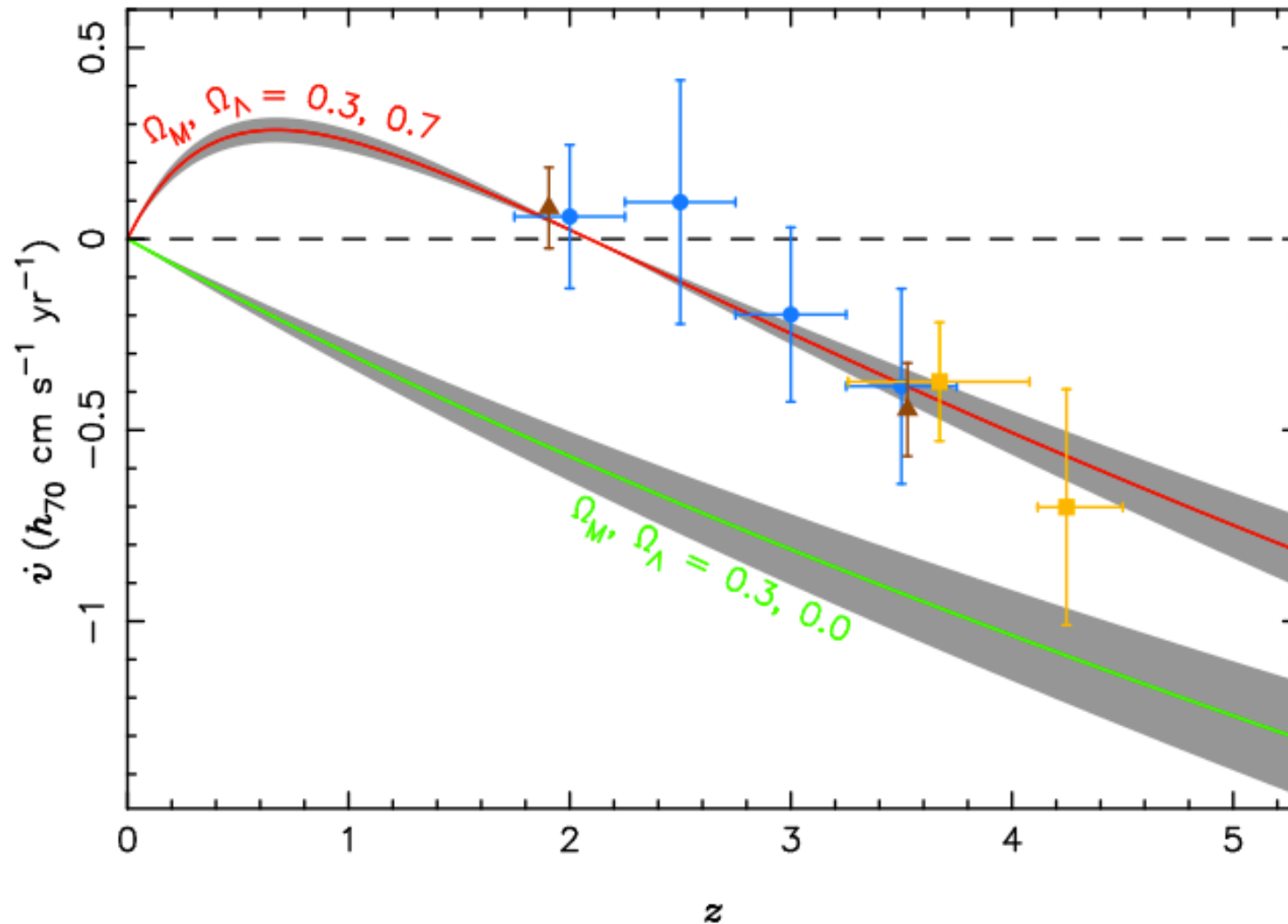
$\Leftrightarrow$ 1km/s pixel width in Keck HIRES (10^{-3} signal)

If $\text{Ly}\alpha$ forest flux varies 10% $\rightarrow$ 10^{-4} signal

With $S/N=100$, need $(100 \times 10^{-4})^{-2} = 10^4$ pixels

With 100 quasars, we can detect the signal over 10 yrs
(The same technique used to detect planet by Doppler shift of absorption lines)

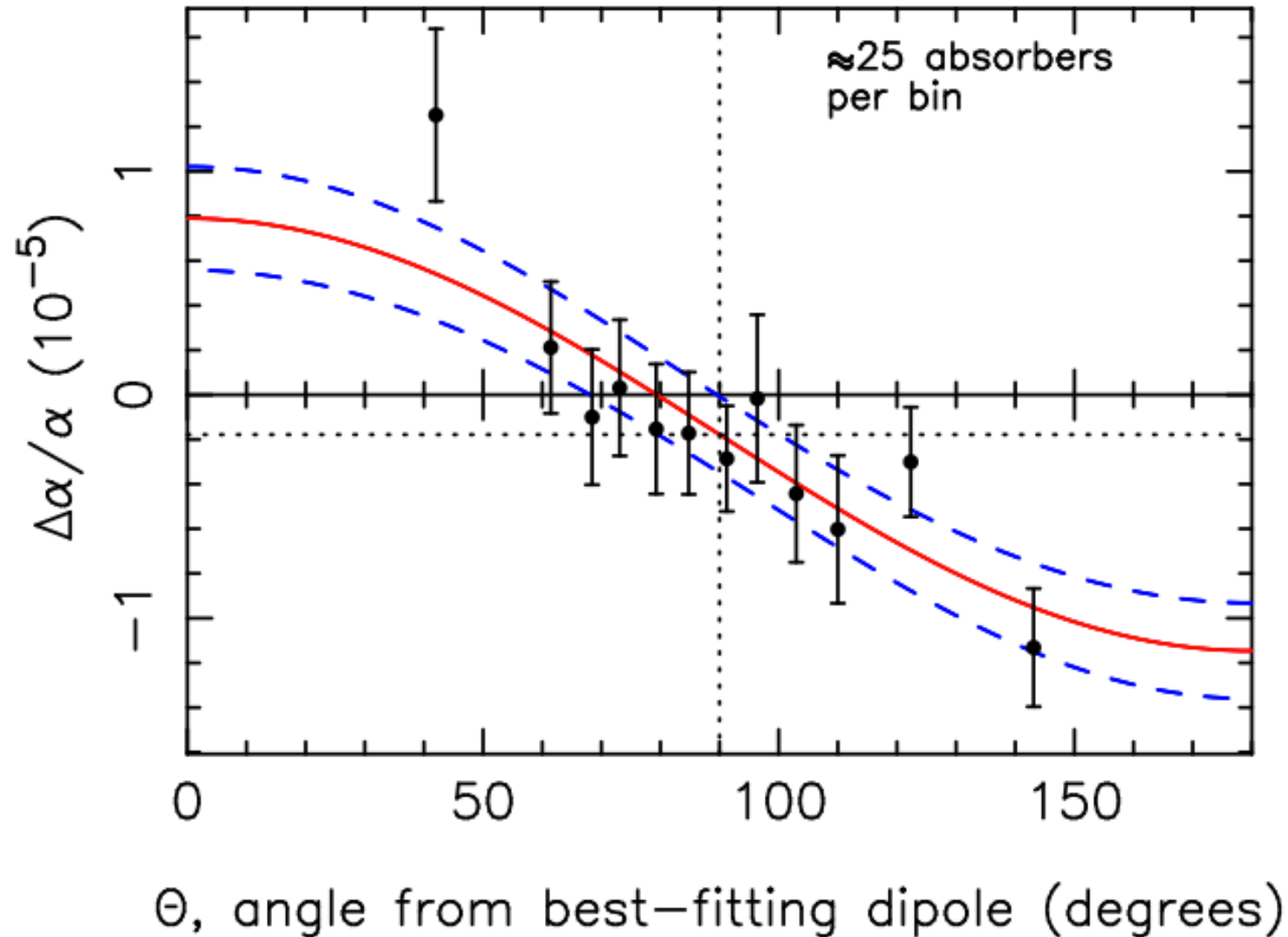
CODEX 20yrs



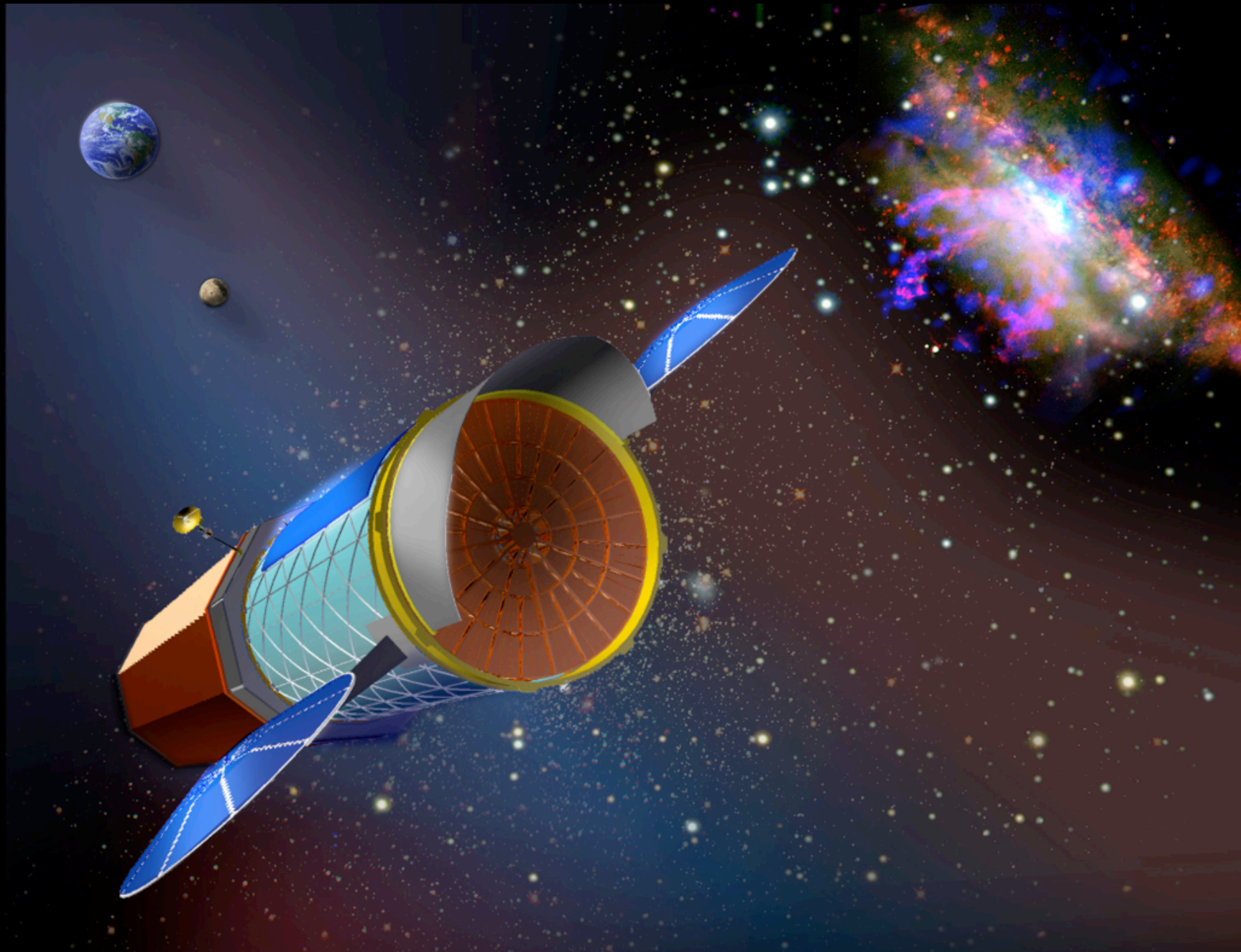
Liske et al. 2009

微細構造係数変化の方向性

Webb et al. 2009; Murphy et al. 2009



International X-ray Observatory



Atacama Large Millimeter Array



~0.01 秒角の分解能

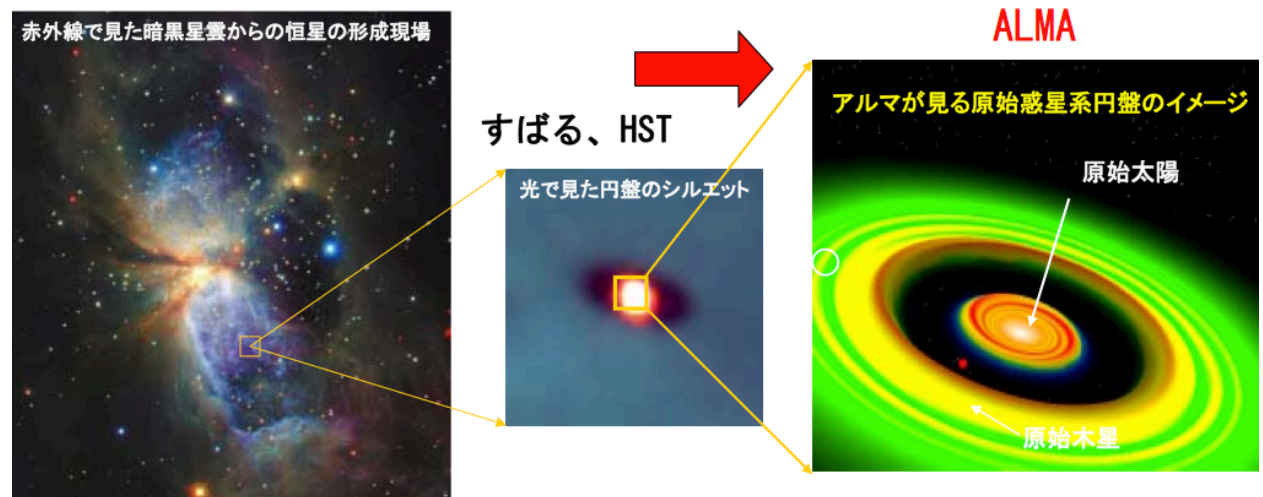
クイズ:角分解能

0.01秒角の分解能とはどれくらいだろうか？

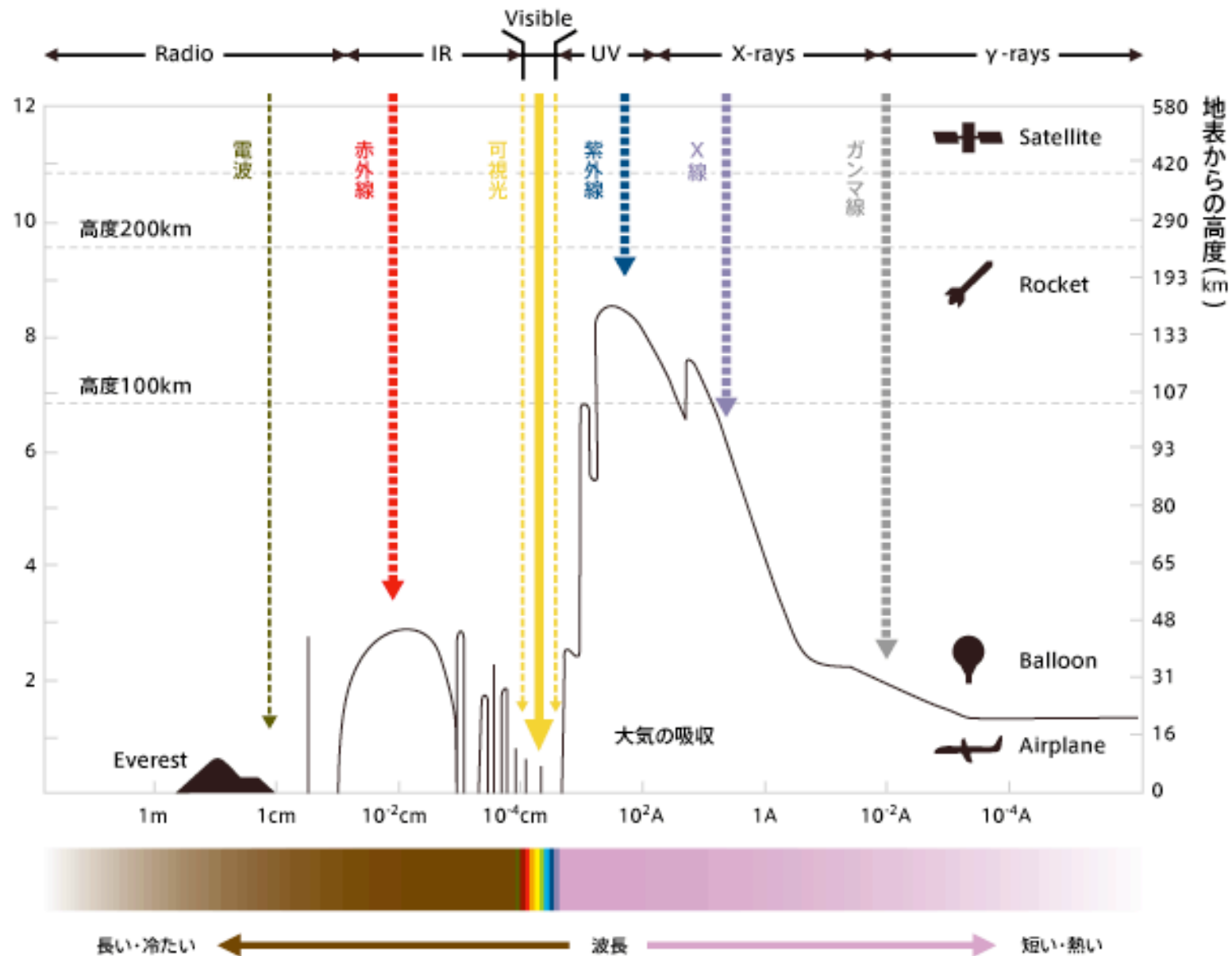
直径2センチの一円玉  をどれくらい

離れた場所から観測すると 0.01"に相当する

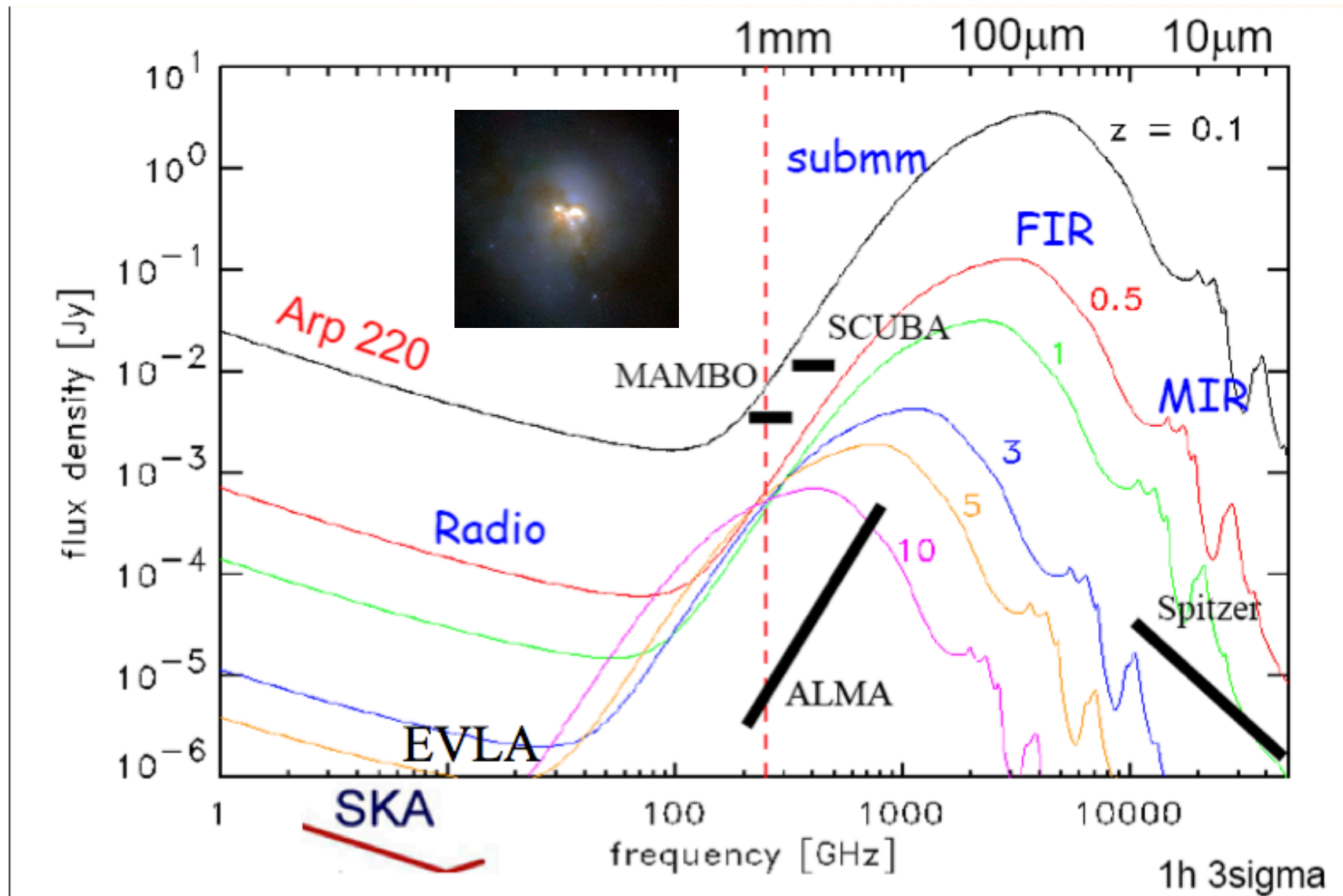
か計算しよう？



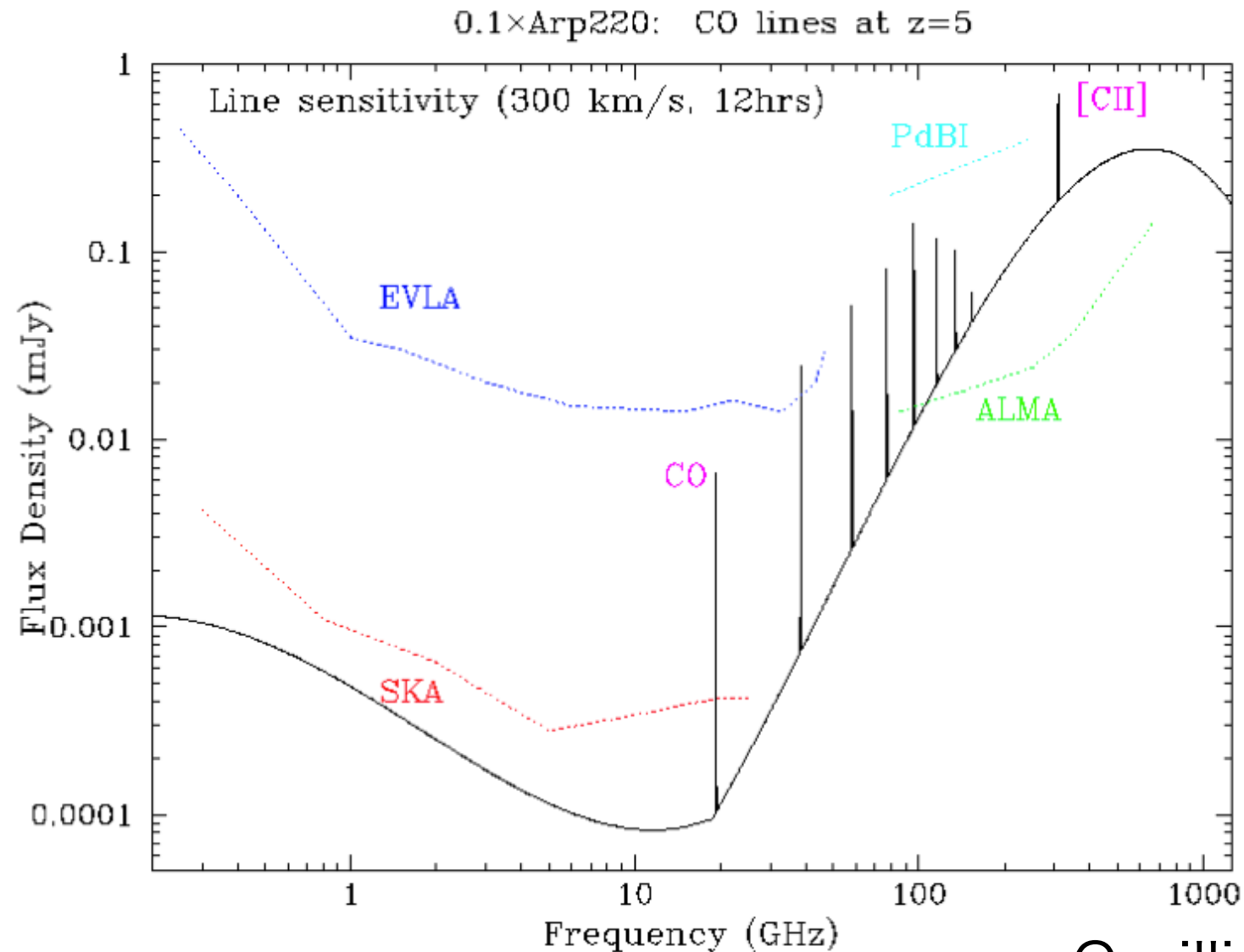
Why at a desert ?



Redshifted Arp220



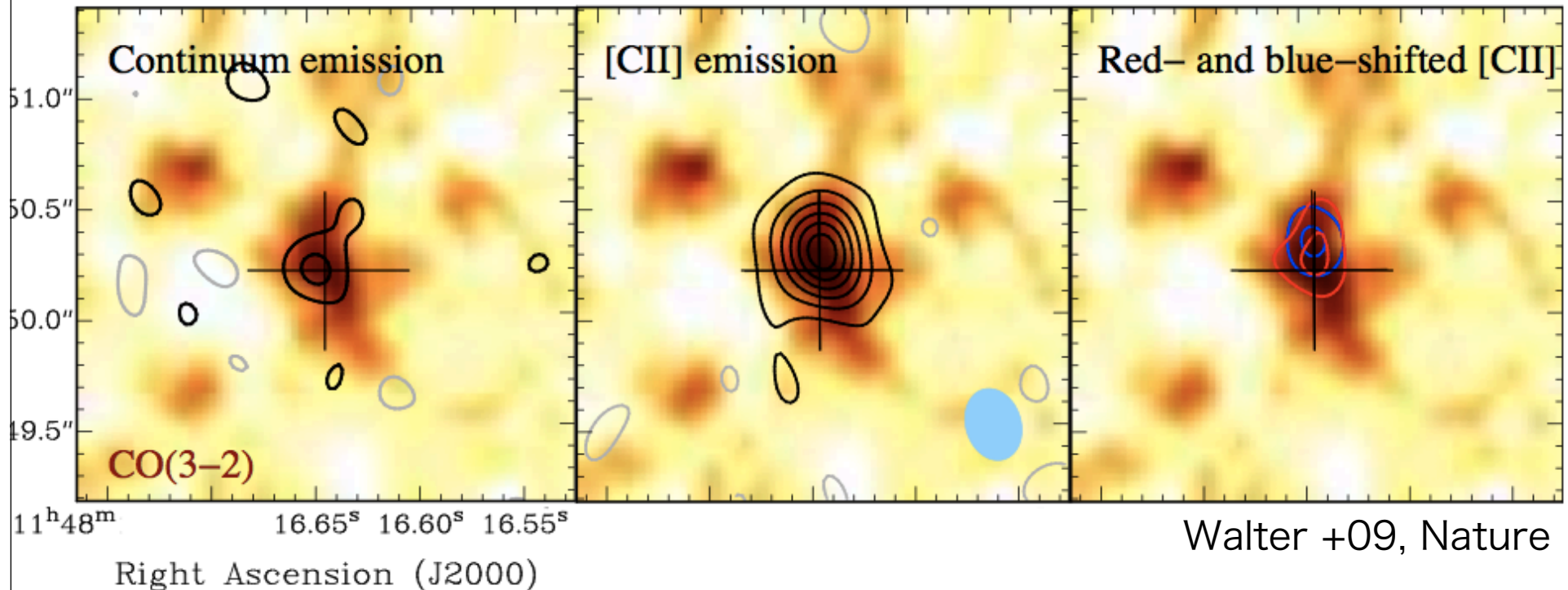
ALMA line sensitivity



Carilli 2006

[CII] emission from high-z

SDSS J1148 @ $z=6.42$

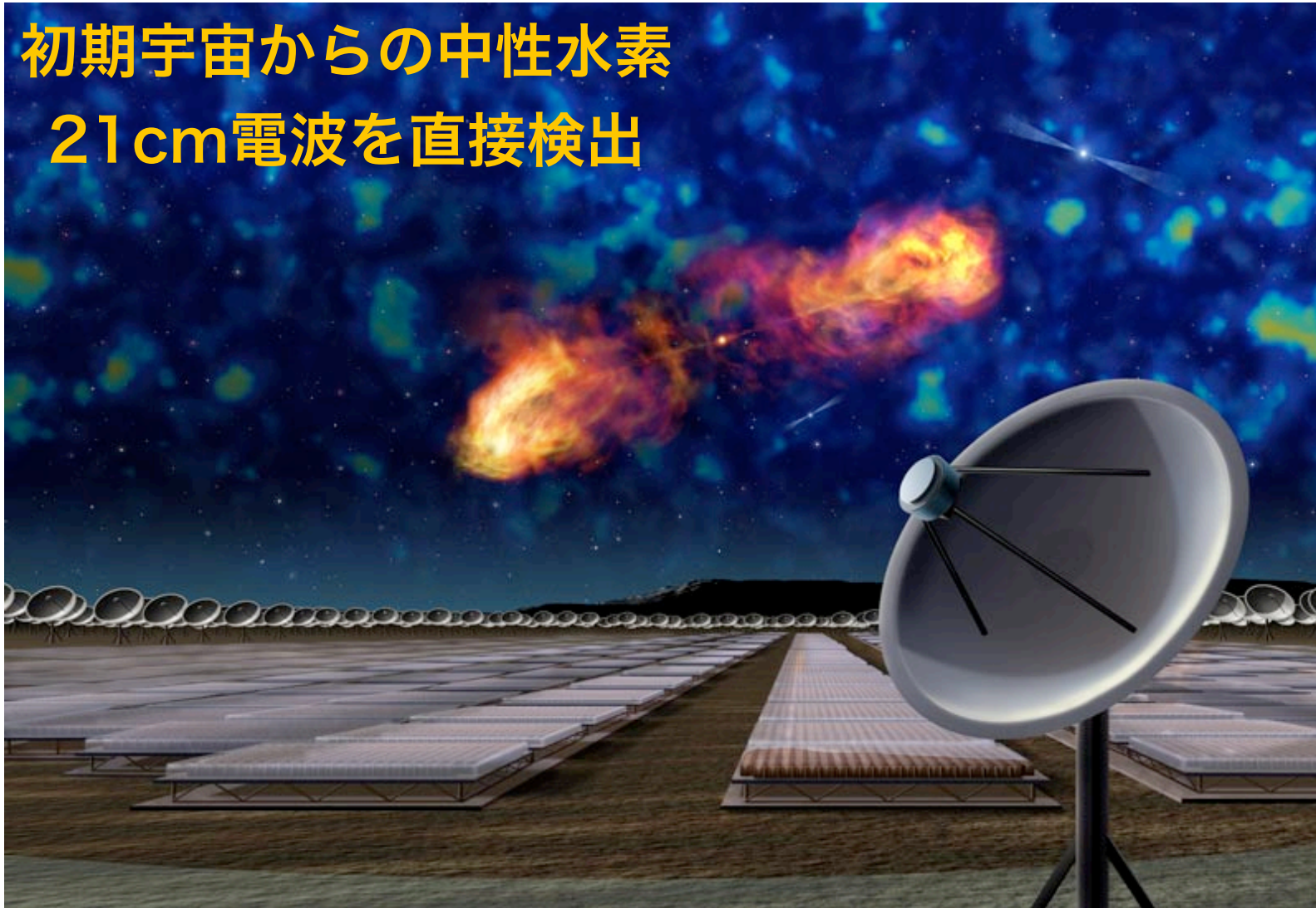


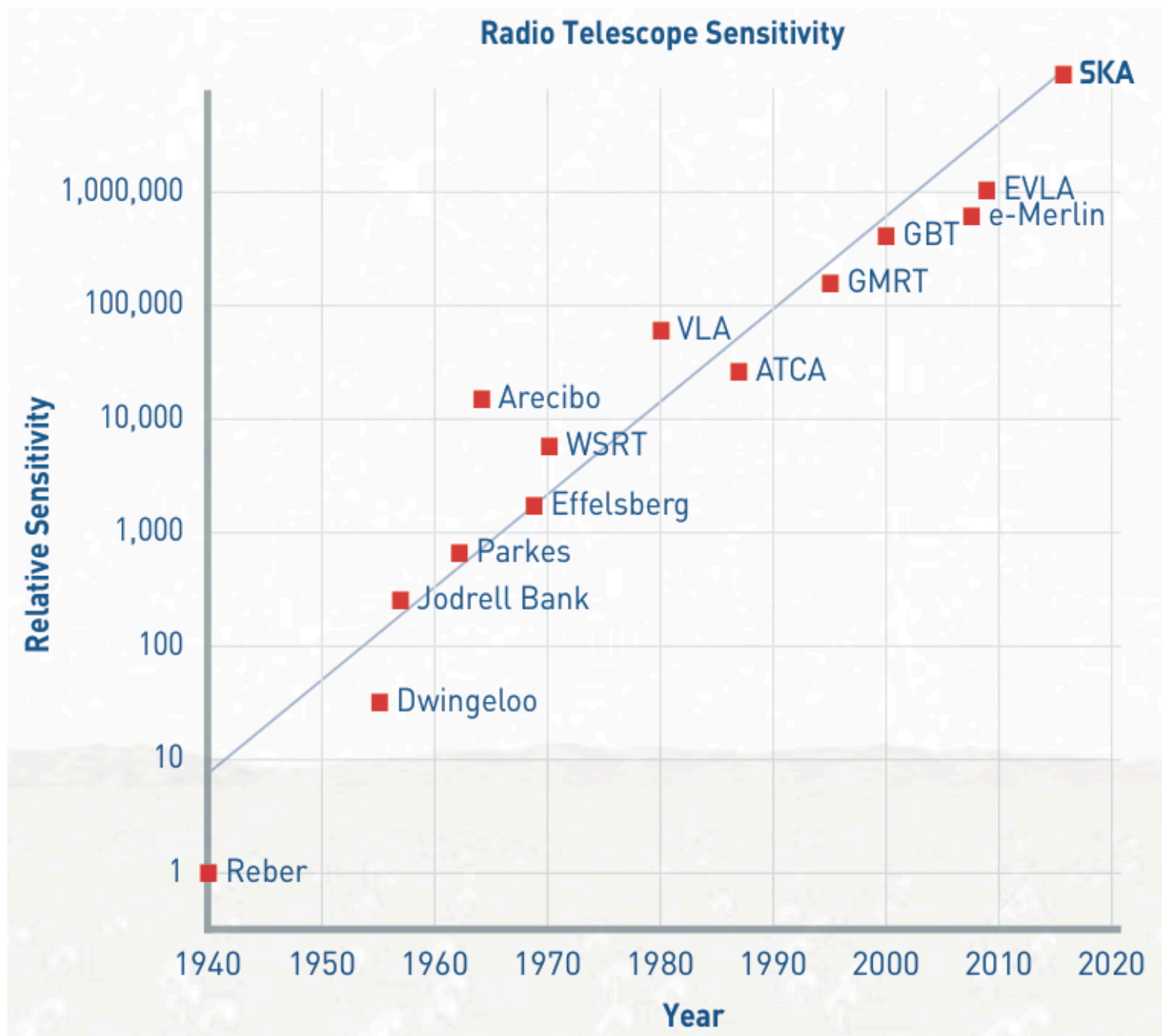
SFR $2000 M_{\odot}/\text{yr}$, $L_{\text{FIR}} > 10^{13} L_{\odot}$

158 microns $\times$ ($z \sim 6-10$) $\Rightarrow$ **ALMA** band 5

Square Kilometer Array

初期宇宙からの中性水素
21cm電波を直接検出

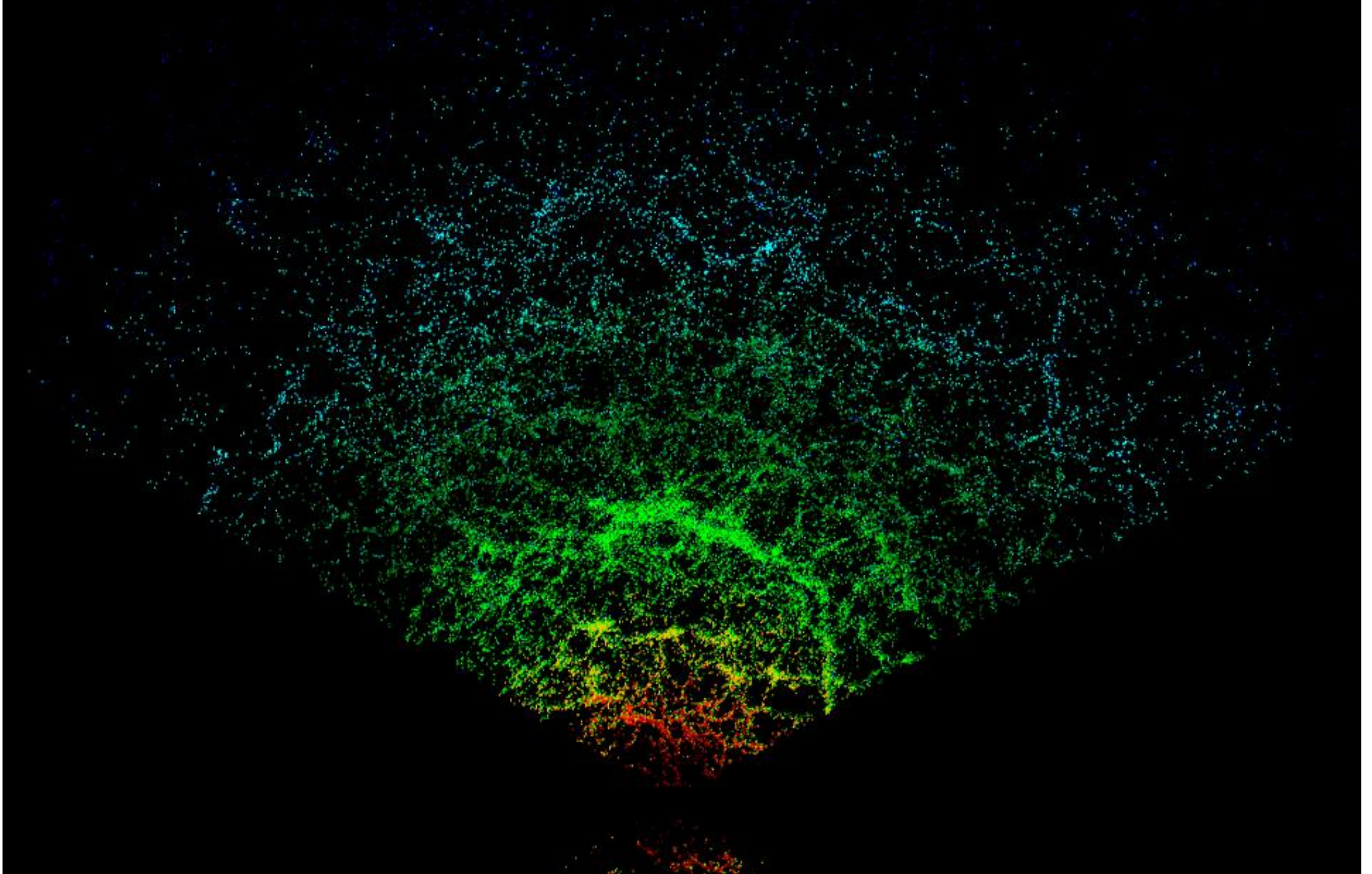




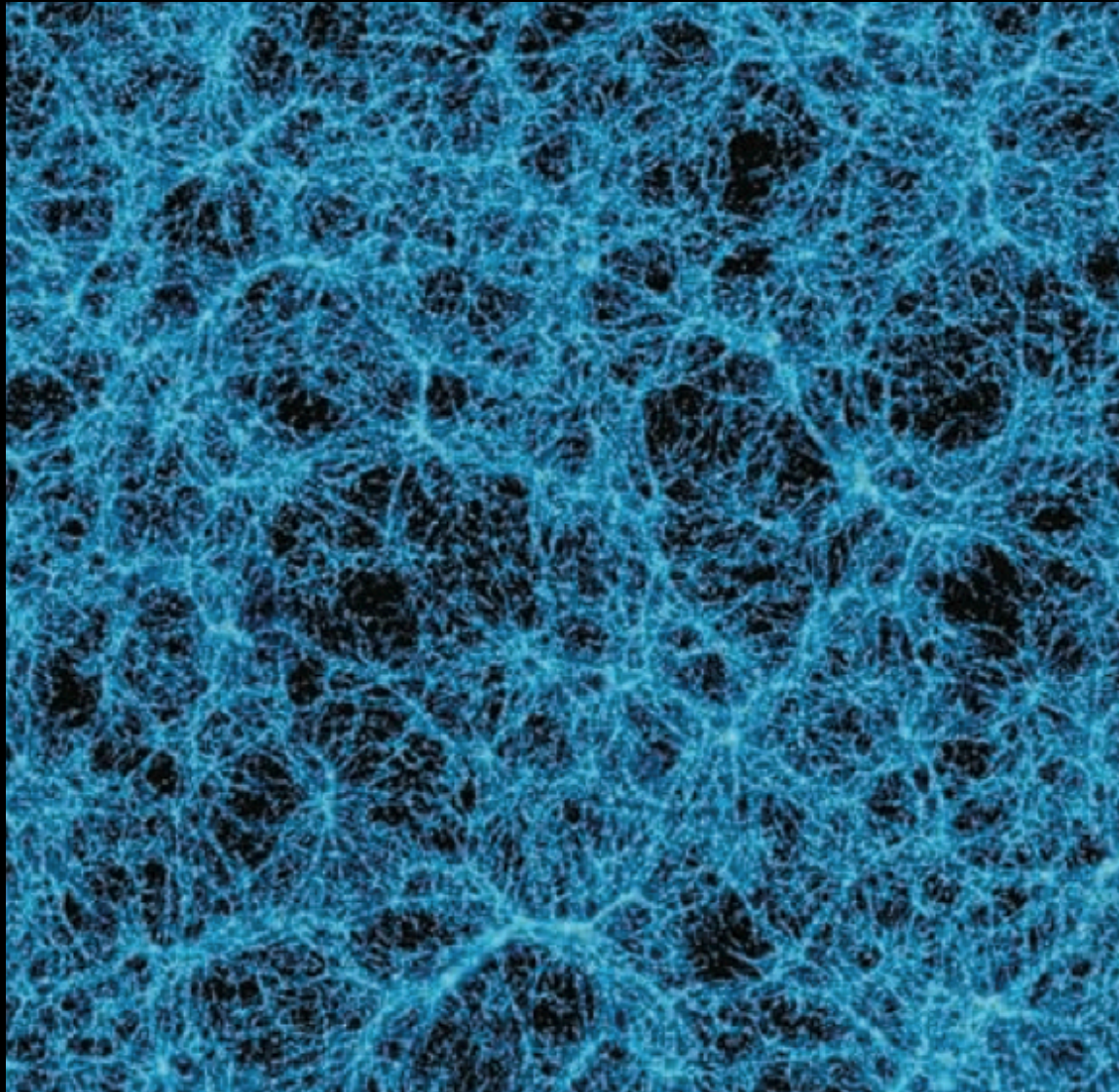
SKA science

- Cradle of life
- Probing the dark ages
- Galaxy evolution, cosmology and dark energy
- The origin of cosmic magnetism
- Extreme tests of gravity

LSS traced by galaxies

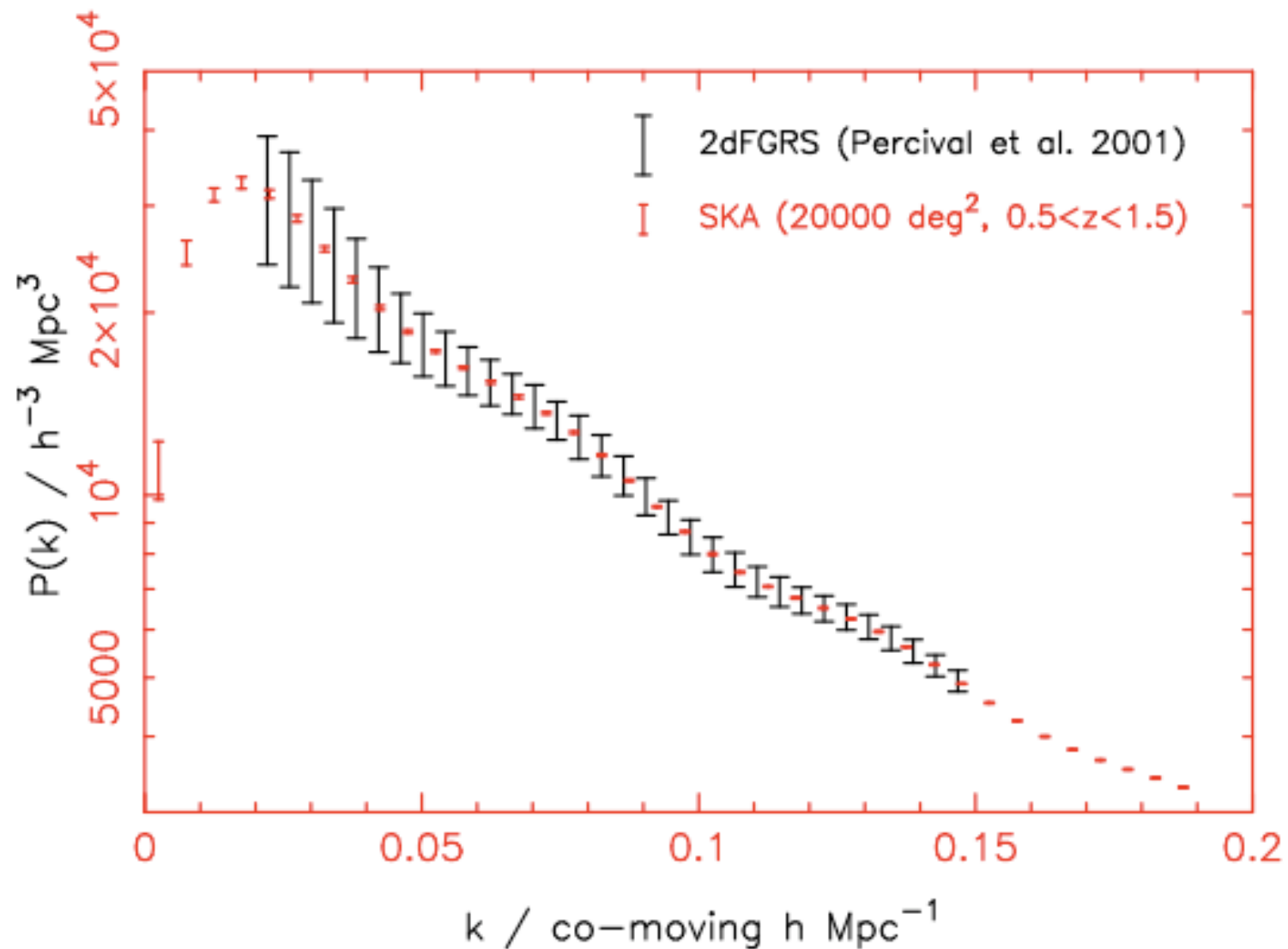


LSS traced by gas

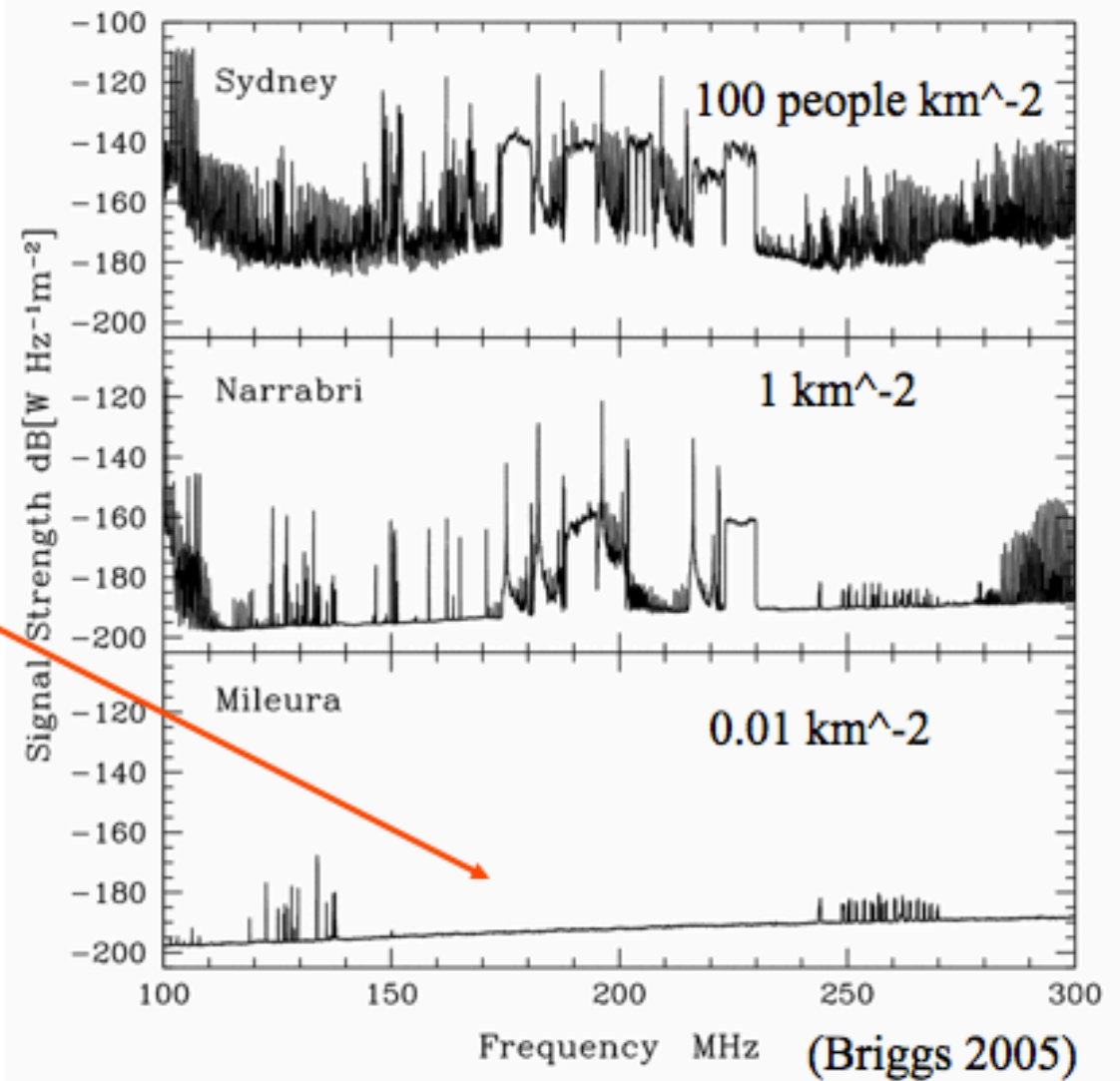
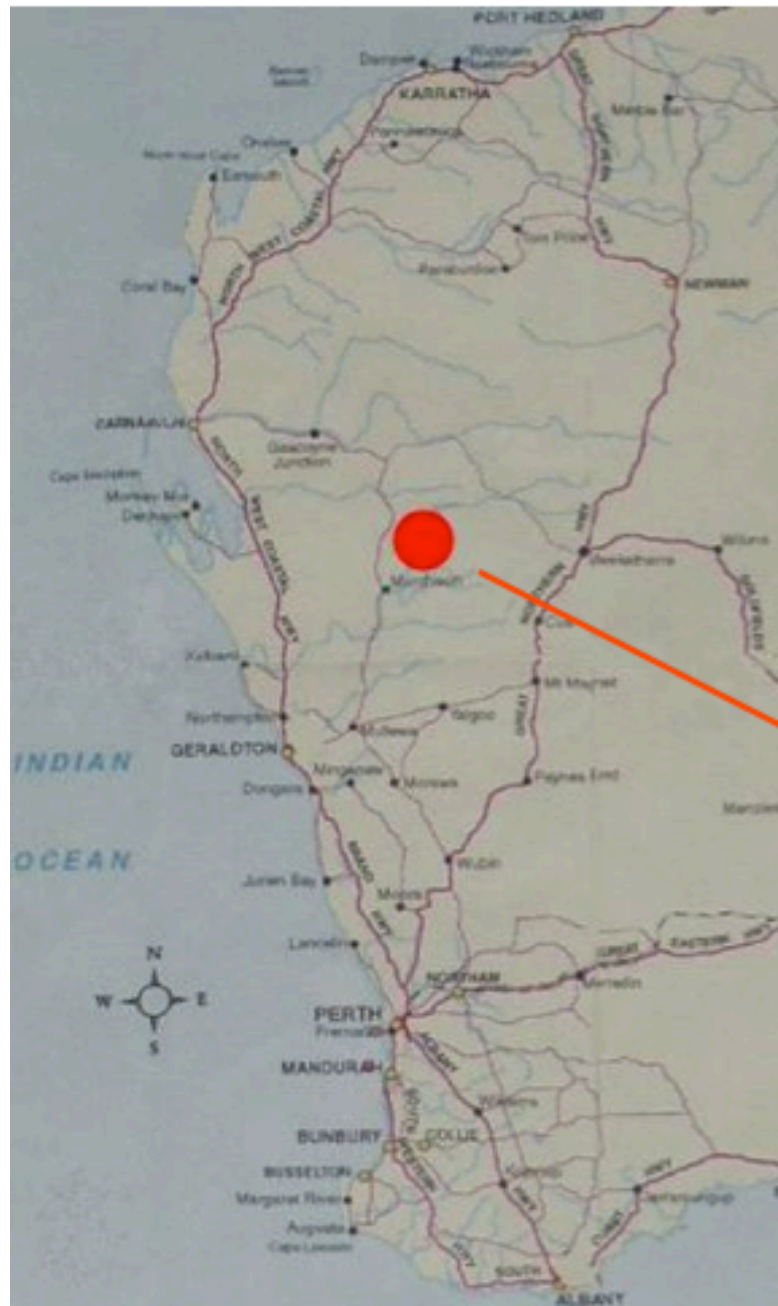


Numerical simulation

HI power spectrum



Australia ?



Probing the dark ages from the dark side of the Moon

C. Carilli (NRAO), Sackler Cosmology
Conf, Cambridge, MA, 2008



Moon?

