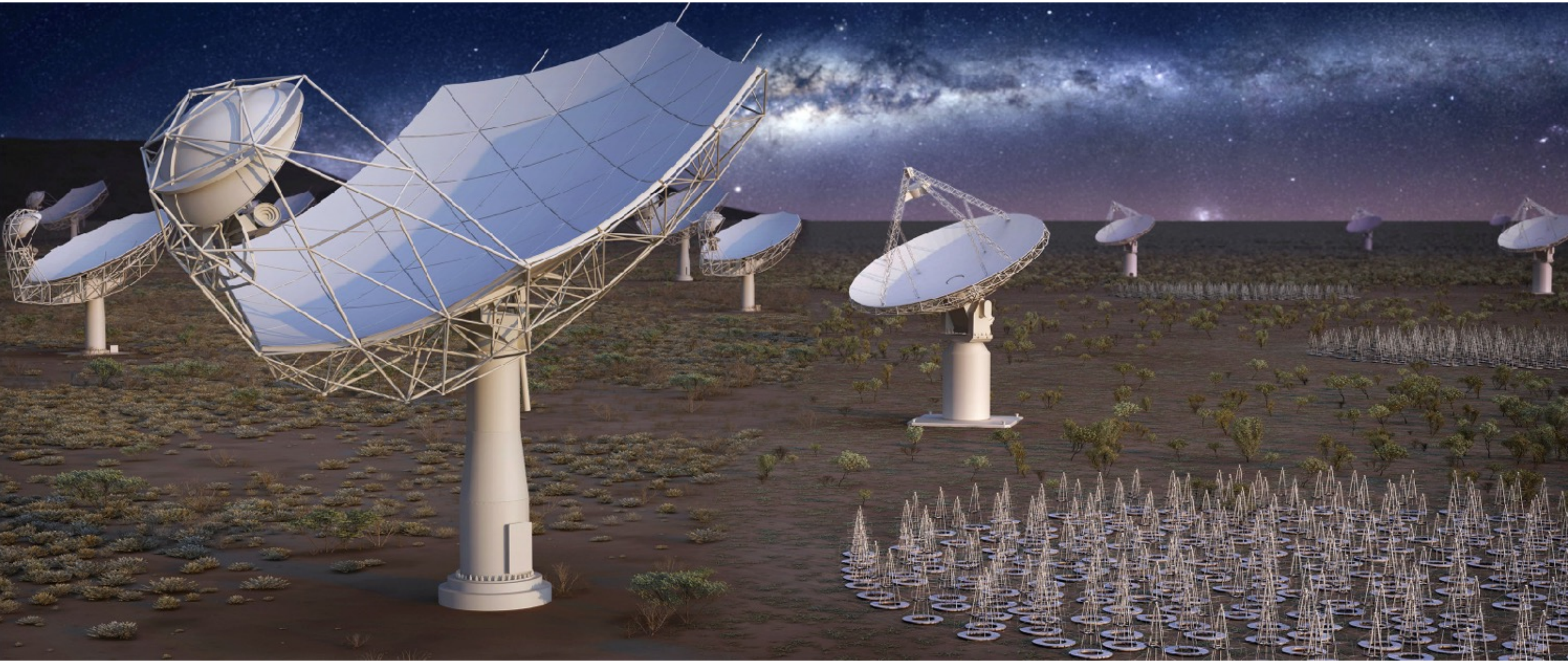
Low Frequency Radio Observation (SKA) of Transient High-Energy Phenomena



NAOJ SKA1 STUDY GROUP
国立天文台SKA1検討グループ

Takuya Akahori

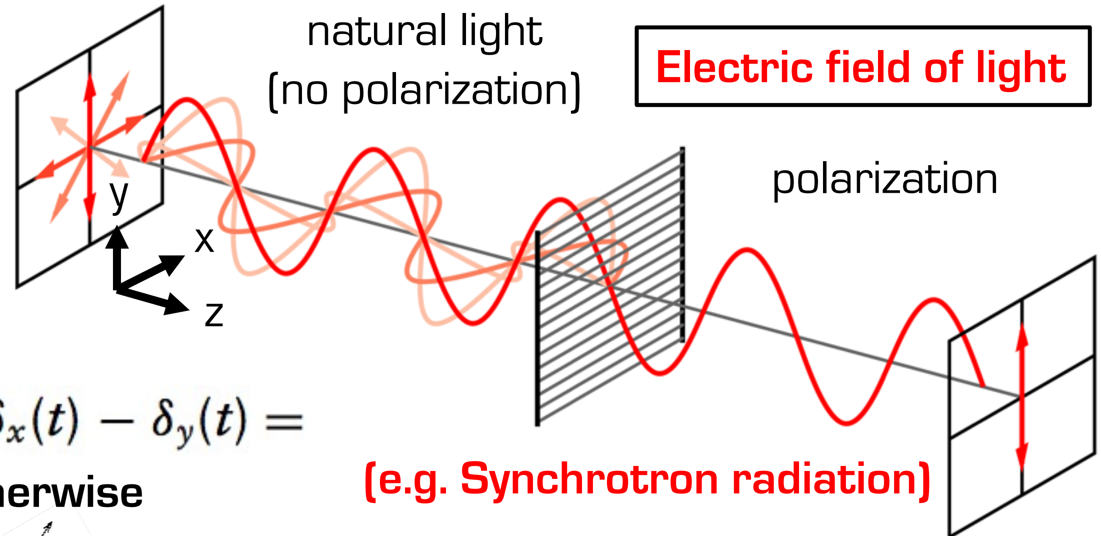
Group Scientist & Manager

Polarization and Stokes parameter

■**The function of the electric field of light:**

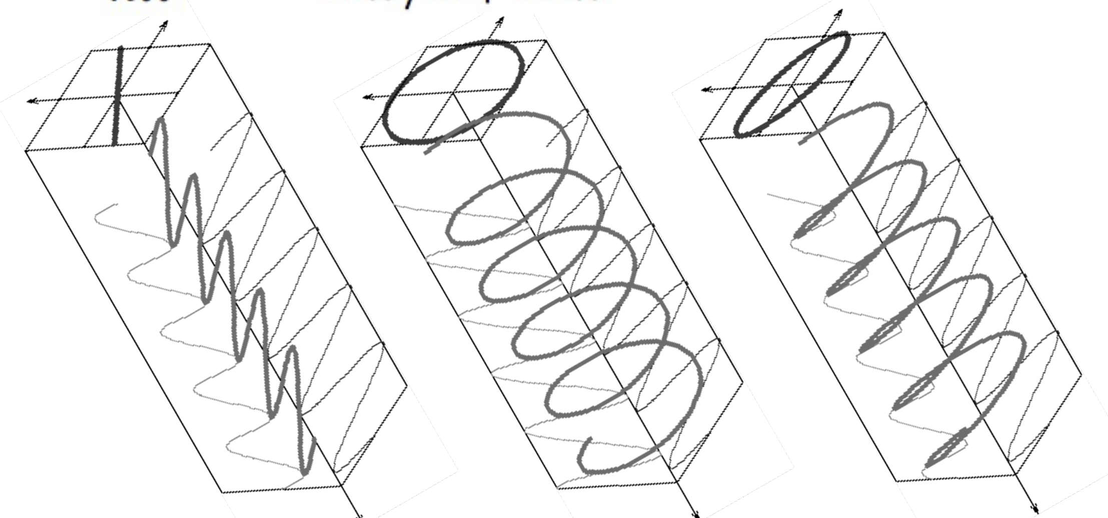
$$E_x(t) = E_{x0}(t)e^{i\{2\pi\nu t+\delta_x(t)\}}$$
$$E_y(t) = E_{y0}(t)e^{i\{2\pi\nu t+\delta_y(t)\}}$$

ν: frequency [Hz], t: time [s]



■**The phase difference:** $\delta_x(t) - \delta_y(t) =$

$n\pi$ | $\pm\pi/2 + 2n\pi$ | otherwise



Linear Polarization | Circular Polarization | Elliptical Polarization

The Stokes parameters

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 0 & -i & i & 0 \end{pmatrix} \begin{pmatrix} \langle E_x E_x^* \rangle \\ \langle E_x E_y^* \rangle \\ \langle E_y E_x^* \rangle \\ \langle E_y E_y^* \rangle \end{pmatrix}$$

I: the total intensity of radiation

P=sqrt(Q²+U²): the polarized intensity

P/I: the linear-polarization fraction

ψ=arctan(U/Q)/2: the polarization angle

V/I: the circular-polarization fraction

 Figures from wikipedia

Faraday Rotation and RM

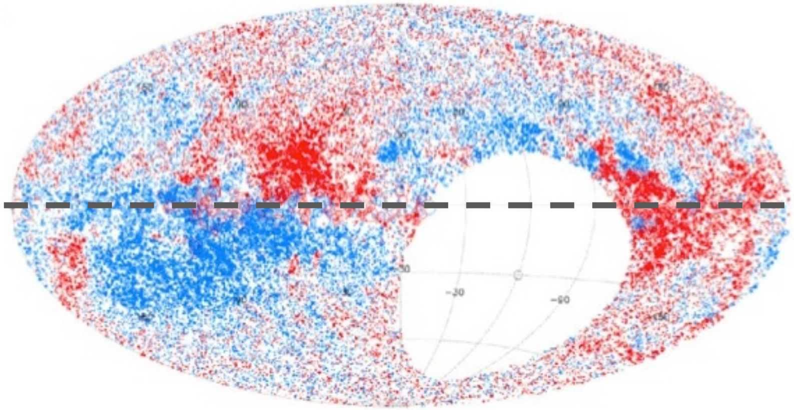
- When a linearly-polarized light passes through a magneto-ionic medium, the polarization angle rotates as:

$$\psi(\lambda) = RM\lambda^2 + \psi_0$$

- The coefficient (RM) is the Faraday rotation measure

$$RM\,(\mathrm{rad\,m^{-2}}) \approx 811.9 \int \left(\frac{n_e}{\mathrm{cm^{-3}}}\right)\left(\frac{B_{||}}{\mu\mathrm{G}}\right)\left(\frac{dr}{\mathrm{kpc}}\right)$$

$$\mathrm{RM_{obs}} \equiv \frac{\Psi(\lambda_1) - \Psi(\lambda_2)}{\lambda_1^2 - \lambda_2^2}$$



Taylor+09 [NVSS1365+1435]

●positive ●negative

Contents of My Talk

（お題）高エネルギー天体現象の電波観測やマルチメッセンジャー天文学に関わるトピックについて

→低周波の電波観測とSKA計画

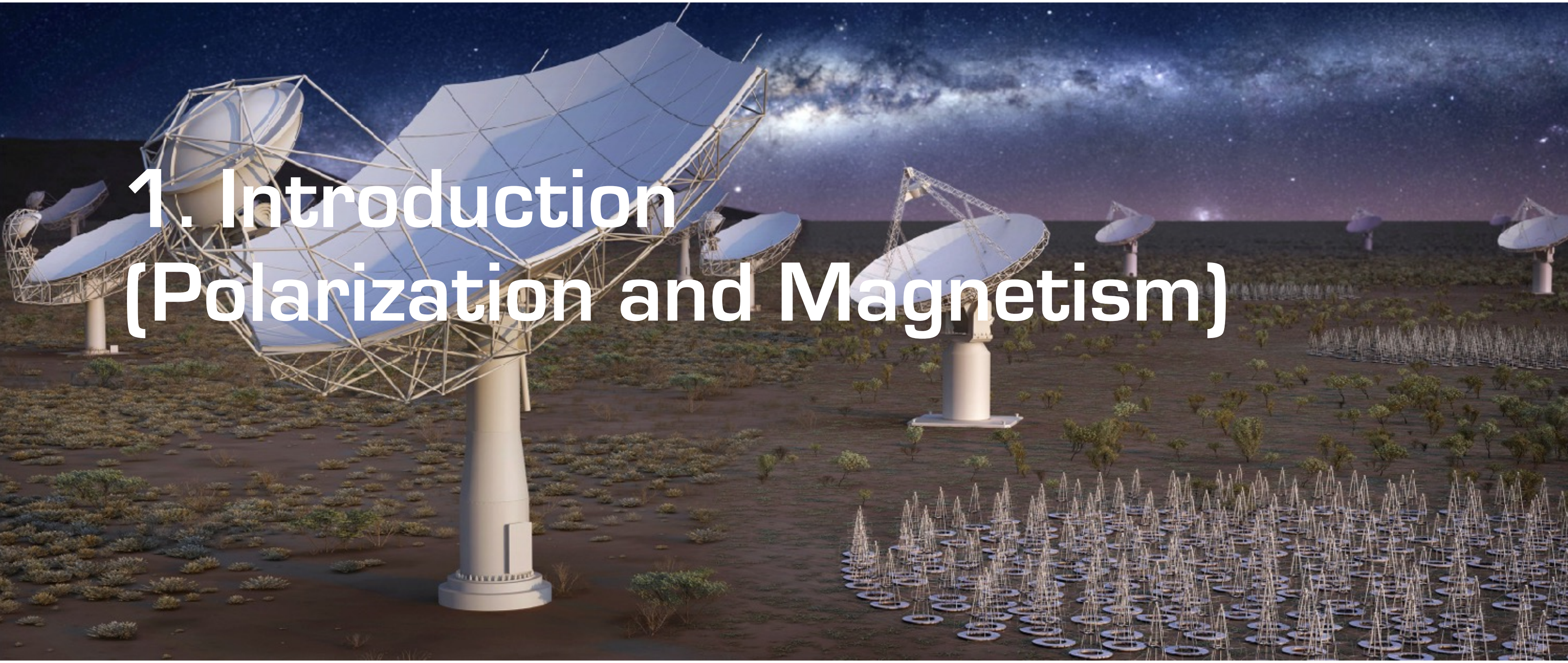
（希望）可能ならば観測の基礎や実際の観測からデータの公開までには何があるのかなどの**裏話**も

（内容）4トピック話します

1. 導入（偏波観測と宇宙磁場）
2. 瞬発電波バースト(FRB)
3. マグネターアウトバースト(MRO)
4. SKA計画はここがすごい(裏話も)

（2.・3.について）発生源・放射機構は樫山さん講演！

1. Introduction (Polarization and Magnetism)



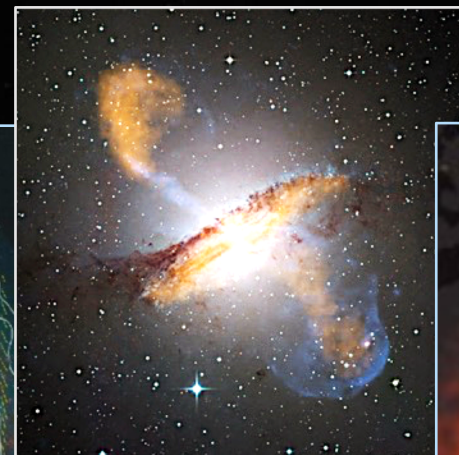
1. Polarization and Magnetism

We Live in Magnetized Universe

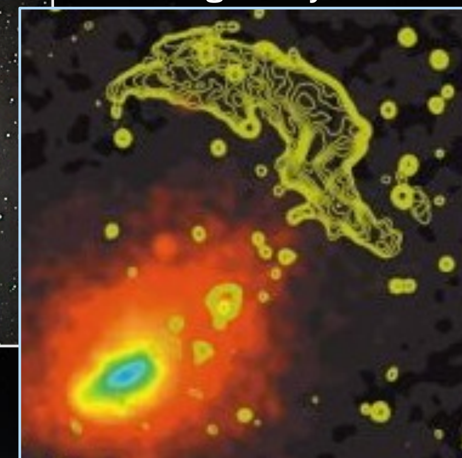
✓Make Universe's Diversity and Universality

Star Formation,
Supernova

Instability,
Morphology



Accretion disk,
Jet, Feedback



Particle acceleration
Missing baryon

✓Influence Outstanding Problems

- 21cm Line
  Epoch of Reionization
- CMB Polarization
  Prove of Inflation
- High Energy CRs
  The Origin

TA+ (2018a)

Publ. Astron. Soc. Japan (2018) 70 (1), R2 (1–44)
doi: 10.1093/pasj/psx123
Advance Access Publication Date: 2017 December 21
Invited Review

Invited Review

Cosmic magnetism in centimeter- and meter-wavelength radio astronomy

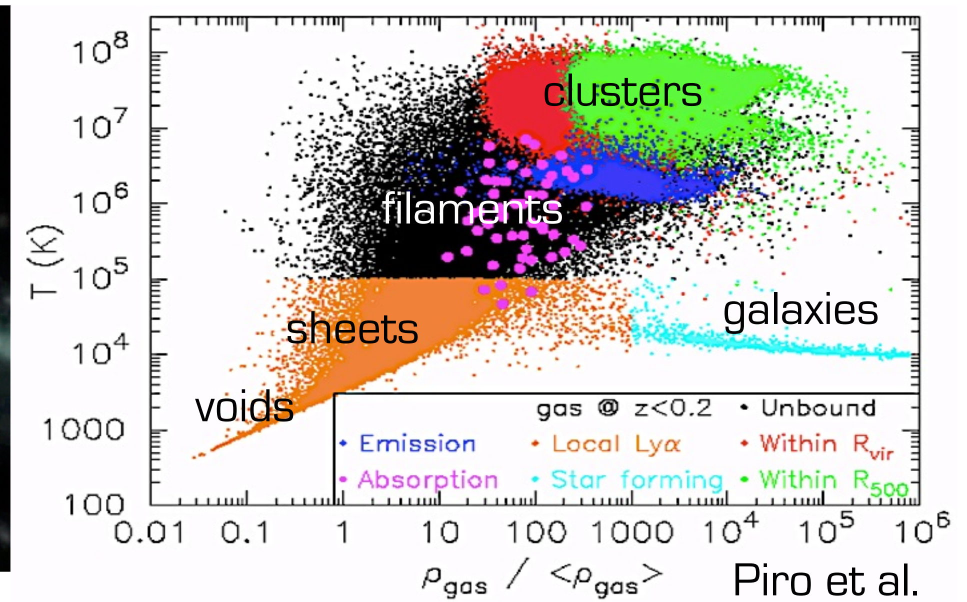
Takuya Akahori,[1,6,*] Hiroyuki Nakanishi,[1] Yoshiaki Sofue,[2] Yutaka Fujita,[3] Kiyotomo Ichiki,[4] Shinsuke Ideguchi,[5] Osamu Kameya,[6] Takahiro Kudoh,[7] Yuki Kudoh,[8] Mami Machida,[9] Yoshimitsu Miyashita,[10] Hiroshi Ohno,[11] Takeaki Ozawa,[12] Keitaro Takahashi,[10] Motokazu Takizawa,[13] and Dai G. Yamazaki[12,14]

NASA & http://kajipon.sakura.ne.jp/kt/kt81b.html

1. Polarization and Magnetism
The Missing Baryon Problem

Big-Bang Cosmolgy	Total baryon content in the Universe
Observations	galaxies・clusters・H_I・Lyα・O_{VI} — Matter in filaments? — MOND?

See Fukugita, Hogan, Peebles (1998); recent constraint by Nicastro et al. (2018)



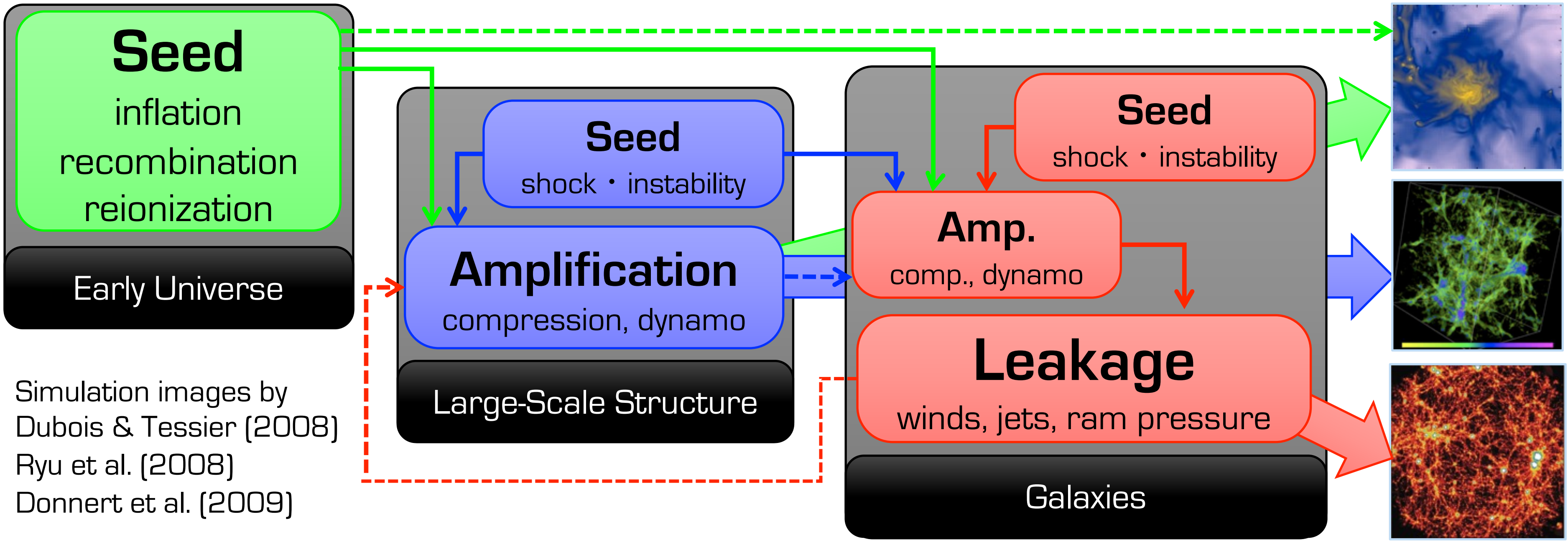
Piro et al. (2007)

■Warm-Hot Intergalactic Medium (WHIM)

- Exists in galaxy filaments, T~$10^{5\text{-}7}$ [K], n~10^{-6} – 10^{-4} [cm^{-3}]
- The last major ***yet-unproven*** piece of the cosmology

1. Polarization and Magnetism

The IGMF in the WHIM



Simulation images by
Dubois & Tessier (2008)
Ryu et al. (2008)
Donnert et al. (2009)

See reviews: Ryu et al. (2012) & Widrow et al. (2012)

■The Inter-Galactic Magnetic Field (IGMF)

- Various possibilities of field generation & amplification → the WHIM should be most likely magnetized
- If μG in clusters of galaxies → ***1-100 nG in filaments***

1. Polarization and Magnetism

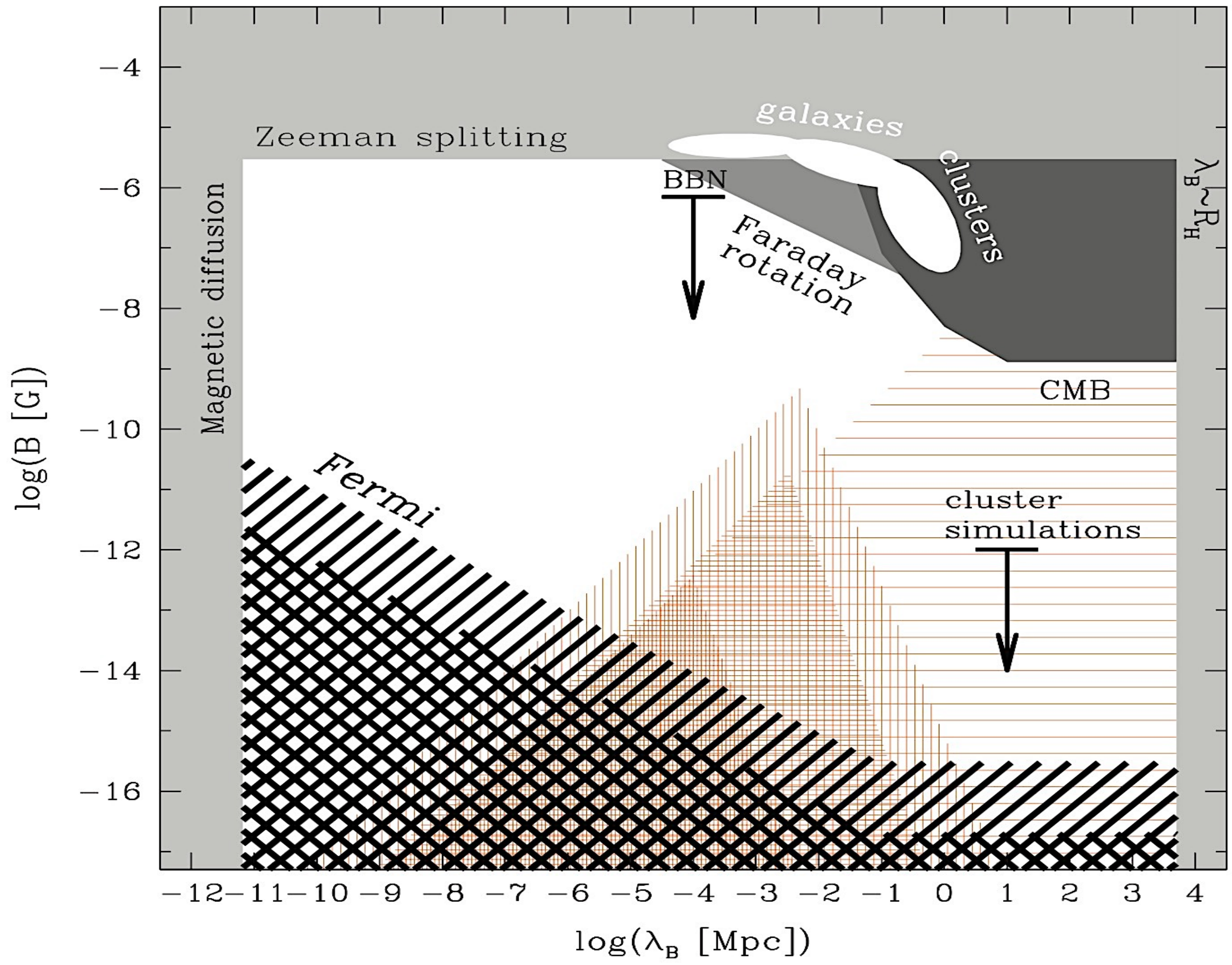
Constraint on IGMF by Transients

■Pair halo/echo of γ-rays

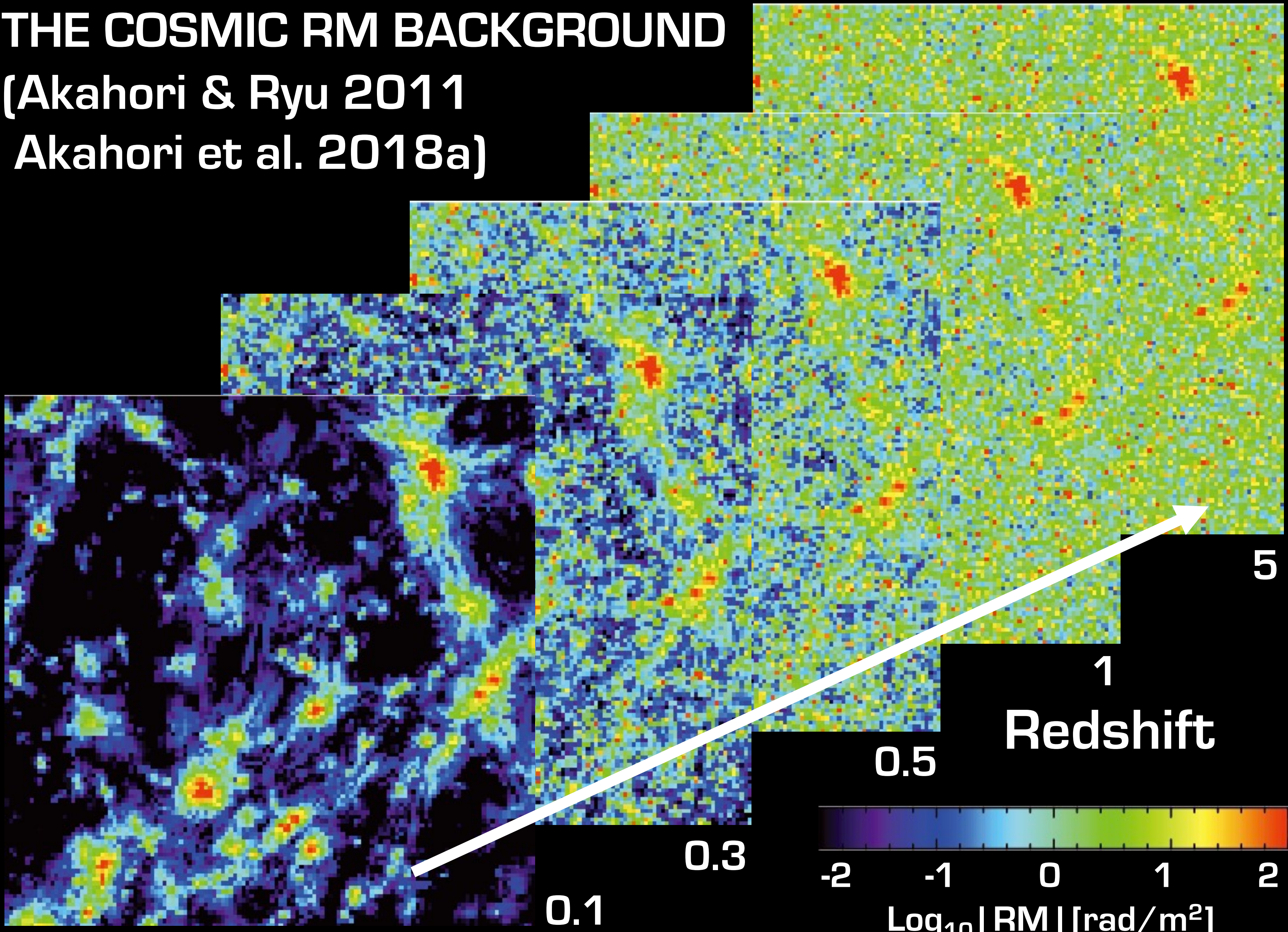
- Blazar at z~1
- $B > 3\times10^{-7}$ nG (Neronov & Vovk 2010, Science)
- Mostly IGMF of voids

■Linearly-polarized FRB

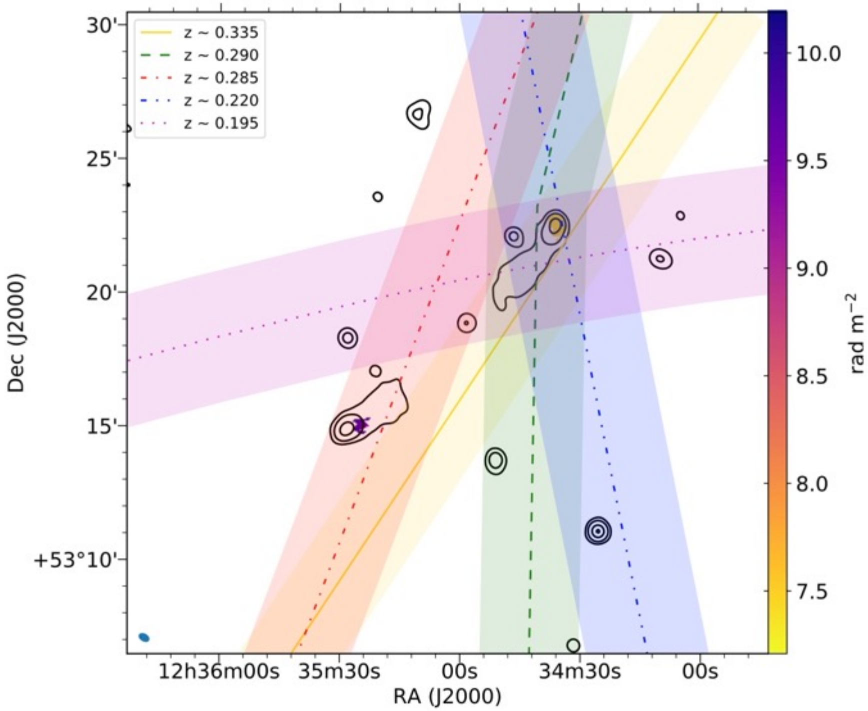
- See later
- Mostly IGMF of filaments

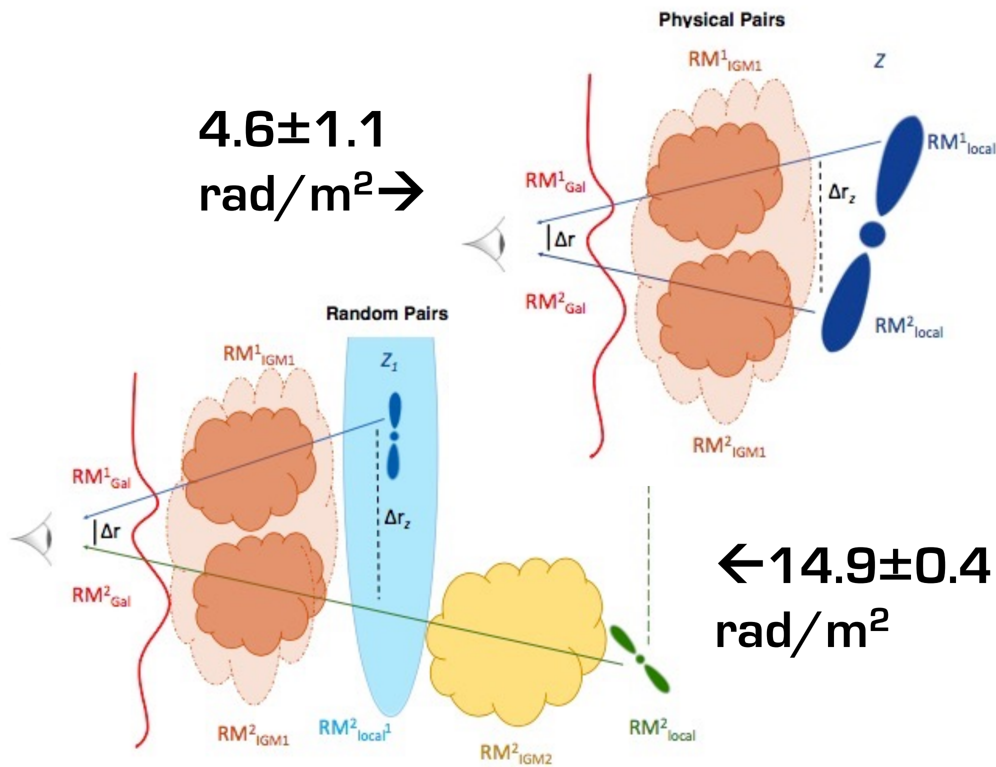


THE COSMIC RM BACKGROUND
(Akahori & Ryu 2011 Akahori et al. 2018a)



Differential RM of filament IGMF





4.6±1.1 rad/m²→

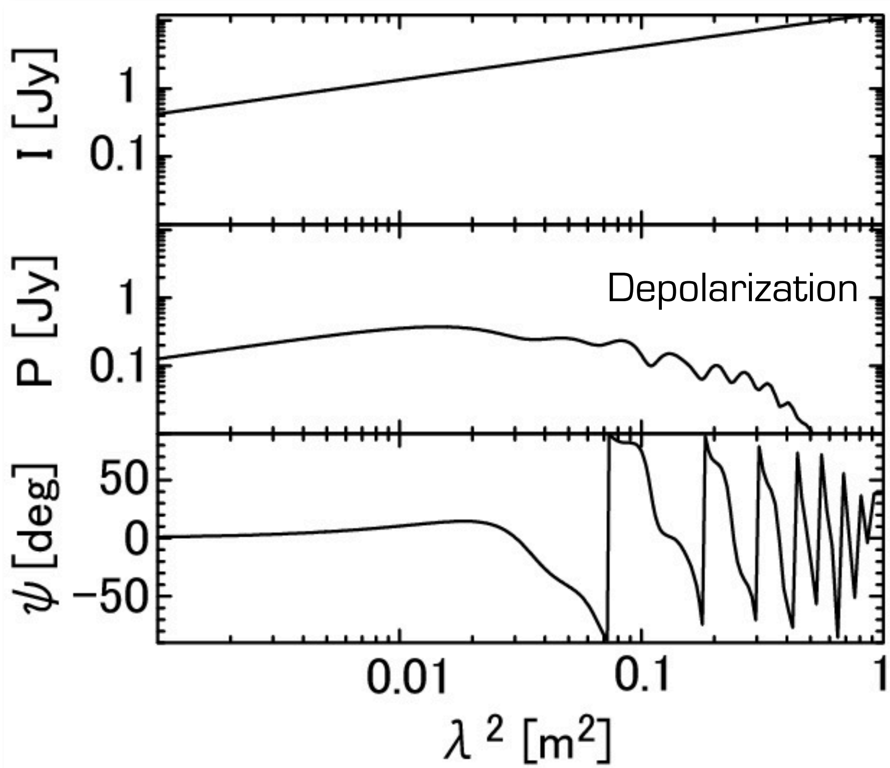
←14.9±0.4 rad/m²

- ■The diff. RM (2.5rad/m²) for radio lobes → 10-50 nG [O'Sullivan+18]
- ■The diff. RM (10 rad/m²) for pair sources → 40 nG [Vernstrom+19]

See also Akahori et al. (2014a)

1. Polarization and Magnetism

Problem of RM measurement



$$\mathrm{RM_{obs}} \equiv \frac{\Psi(\lambda_1) - \Psi(\lambda_2)}{\lambda_1^2 - \lambda_2^2}$$

Narrow band fit

RM=50 rad/m^2

Wideband fit

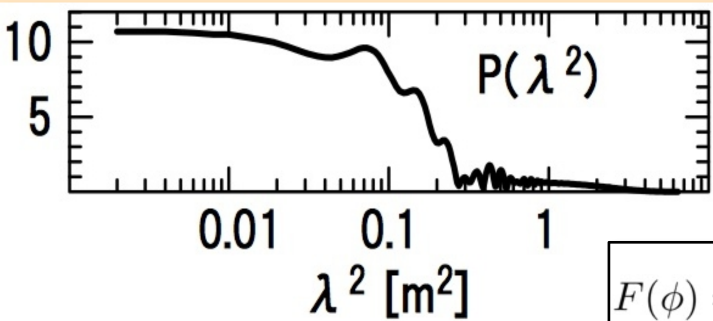
RM=30 rad/m^2

+ σ_{RM}=30 rad/m^2

- **The best-fit depends on wavelength coverage. A fit with narrow-band data may mislead you.**
- **A classical linear-fit cannot quantify the broad-band properties which contain valuable LoS information.**

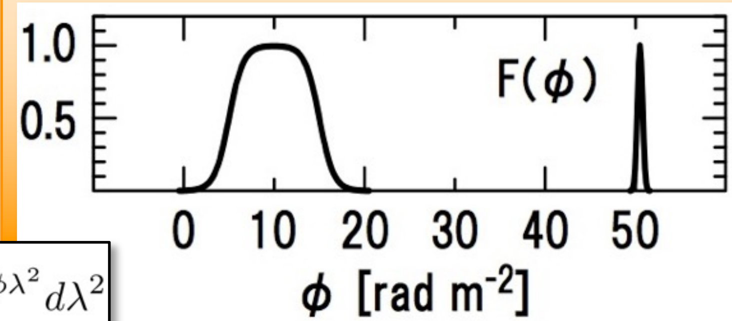
Overview of Faraday Tomography

Pol. Intensity $P(\lambda^2)=Q(\lambda^2)+iU(\lambda^2)$



FT

Faraday Spectrum F(ϕ)

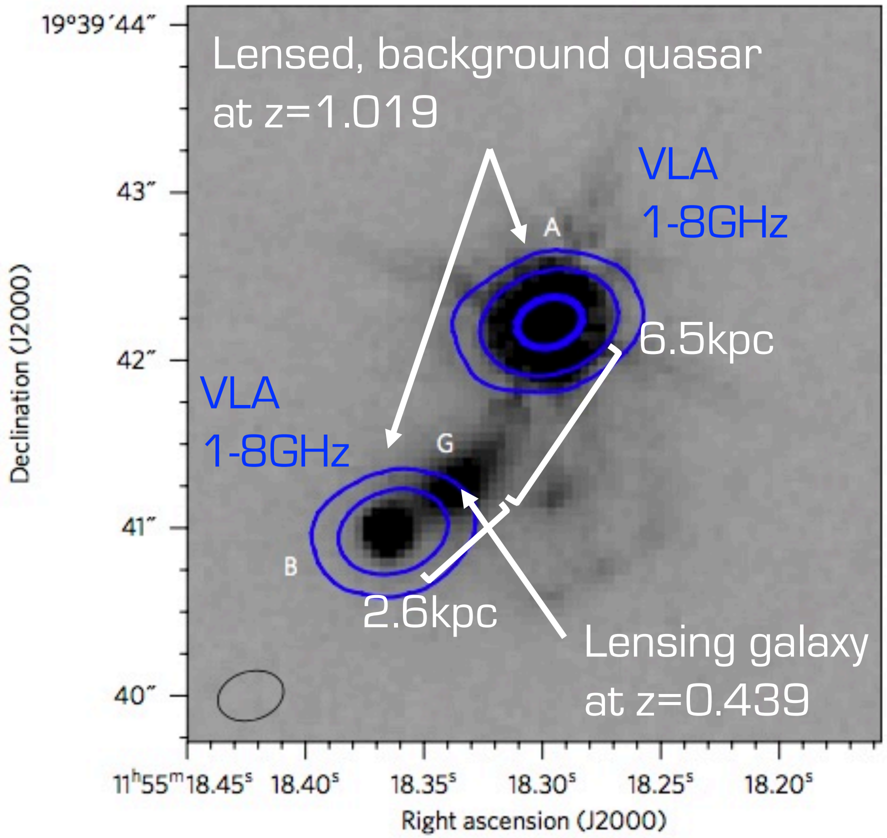


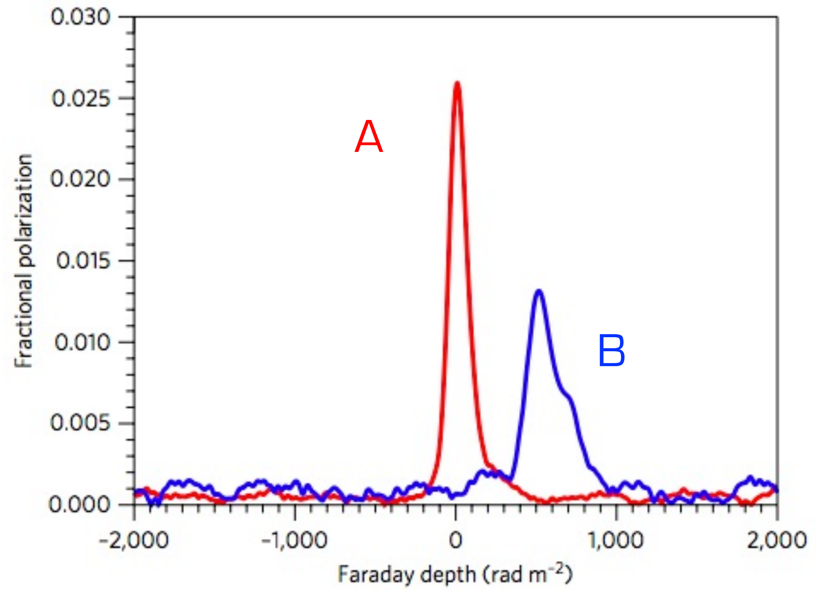
$$F(\phi) = \int_{-\infty}^{+\infty} P(\lambda^2) e^{-2i\phi\lambda^2} d\lambda^2$$

Faraday Tomography

■**Faraday tomography reveals LoS properties of polarization**

CLASS B1152+199





Mao+18, Nature Astronomy

	p_0 (%)	θ_0 (°)	RM (rad m^{-2})	σ_{RM} (rad m^{-2})	χ_ν^2
Image A					1.18
Component 1	2.89 (7)	+32 (1)	0 (1)	13.2 (8)	
Component 2	1.1 (1)	−38 (4)	+160 (20)	61 (9)	
Image B					1.02
Component 1	1.9 (7)	+30 (10)	+500 (30)	50 (10)	
Component 2	1.0 (8)	−20 (20)	+710 (80)	70 (40)	

- **A lensing galaxy at z=0.439 has a coherent B-field 8-11 μG and a random B-field 2-6 μG**

λ^2 coverage: RMSF

$$F(\phi) = \frac{1}{\pi}\int_{-\infty}^{\infty} P(\lambda^2) e^{-2i\phi\lambda^2} d\lambda^2$$

$$\tilde{F}(\phi) = \frac{1}{\pi}\int_{-\infty}^{\infty} W(\lambda^2) P(\lambda^2) e^{-2i\phi\lambda^2} d\lambda^2$$

$$\tilde{F}(\phi) = K^{-1} R(\phi) * F(\phi)$$

R is the RM spread function

$$R(\phi) = K \int_{-\infty}^{\infty} W(\lambda^2) e^{-2i\phi\lambda^2} d\lambda^2$$

$$K = \left[\int_{-\infty}^{\infty} W(\lambda^2) d\lambda^2\right]^{-1}$$

$W(\lambda^2) = 1$ for $\lambda^2_{\rm min} \le \lambda^2 \le \lambda^2_{\rm max}$

otherwise $W(\lambda^2) = 0$

$$\mathrm{FWHM}\,(\mathrm{rad\,m^{-2}}) = \frac{2\sqrt{3}}{\Delta\lambda^2(\mathrm{m}^2)}$$

$$\Delta\lambda^2 = \lambda^2_{\rm max} - \lambda^2_{\rm min}$$

ϕ space λ² space

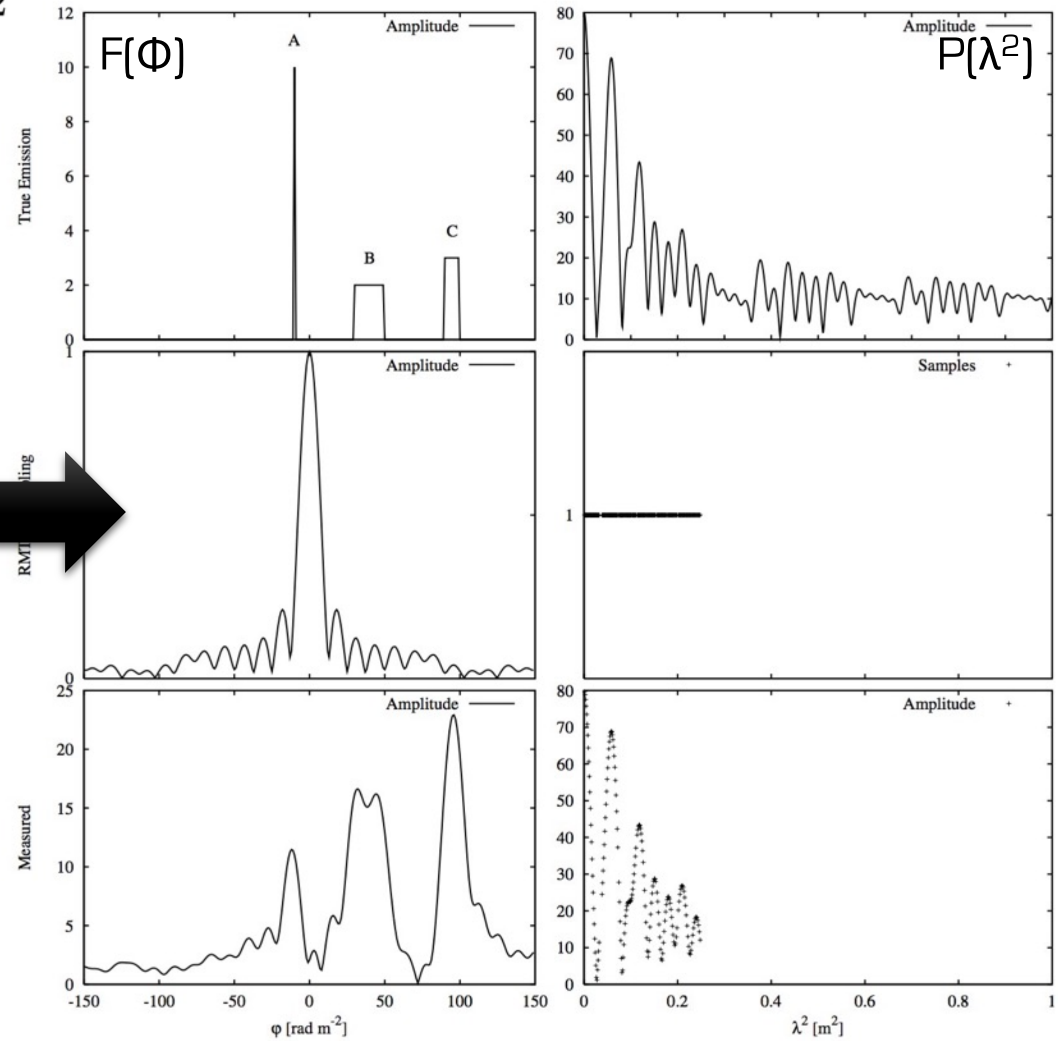
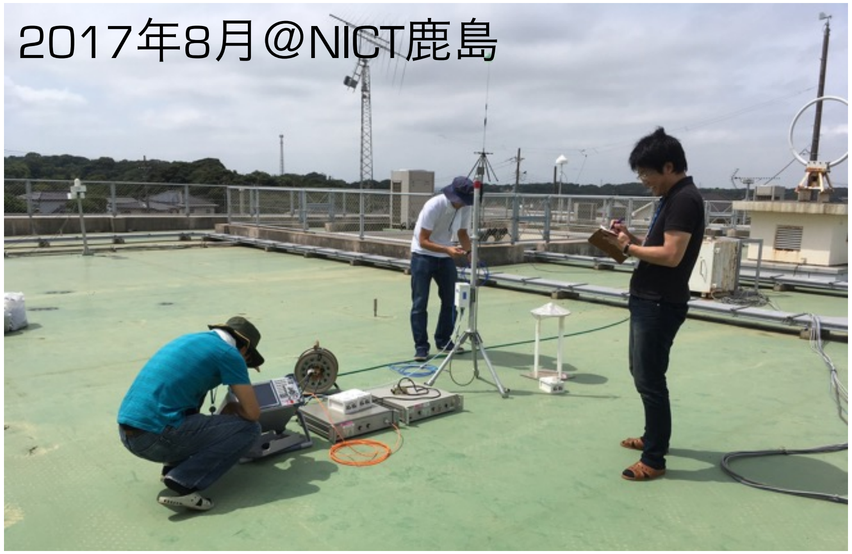


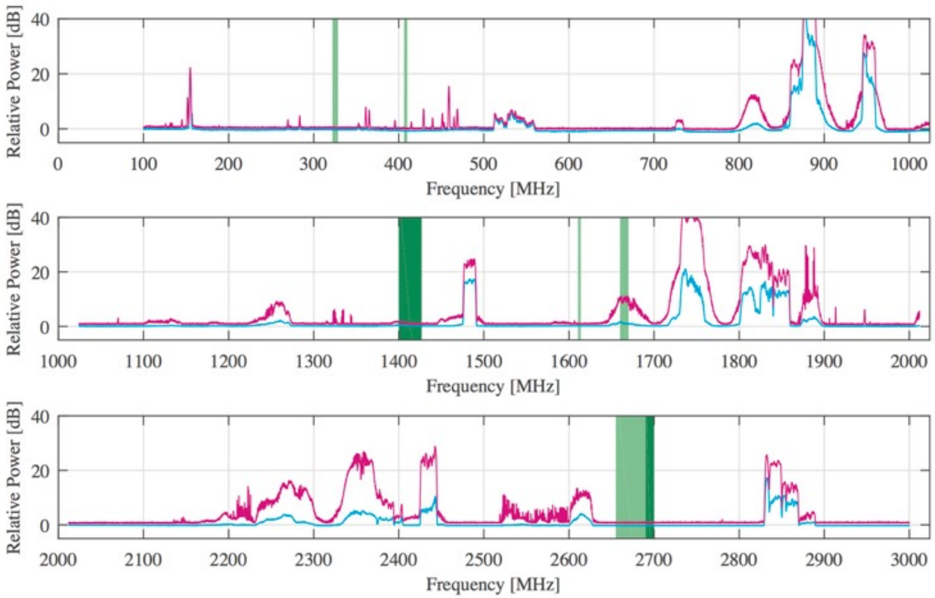
Fig. B.1. Wavelength range: 3.6–50 cm.

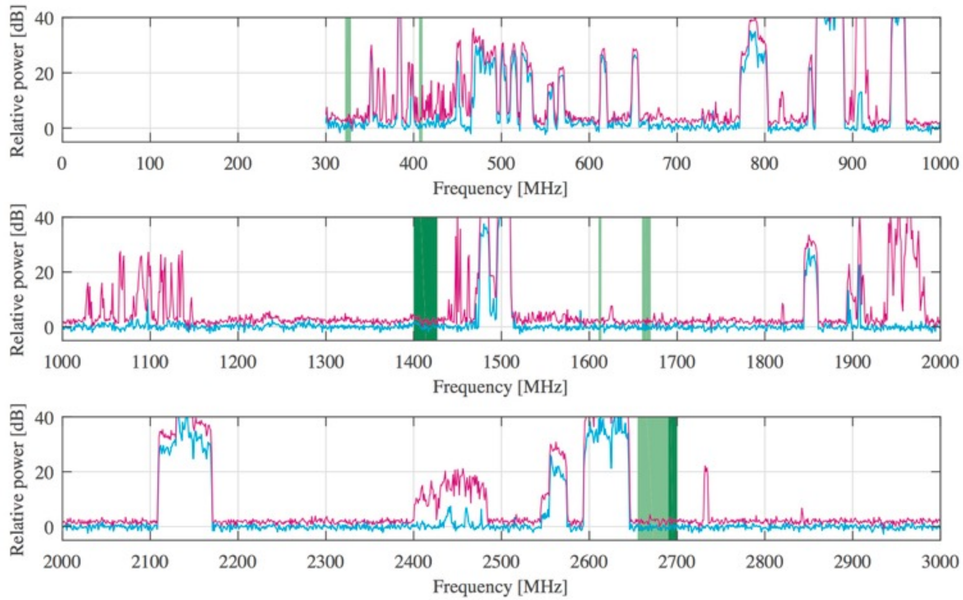
See e.g., Brentjens & de Bryun 05; TA+18a

1. Polarization and Magnetism

Radio Frequency Interference







Radio Frequency Interference

■Mobile Phone is a fatal RFI for radio astronomy

周波数(MHz)	バンド	docomo	au	SoftBank
700	28	●	●	●
800	8			●プラチナ
800	18		●プラチナ	
800	19	●プラチナ		
800	26			
1500	11		●	●
1500	21	●		
1700-1800	1	●東名阪限定		●Ymobile
2000-2100	3	●主力	●主力	●主力
2500	41		●WiMAX系	●停波予定
3500	42	●CA	●CA	●CA

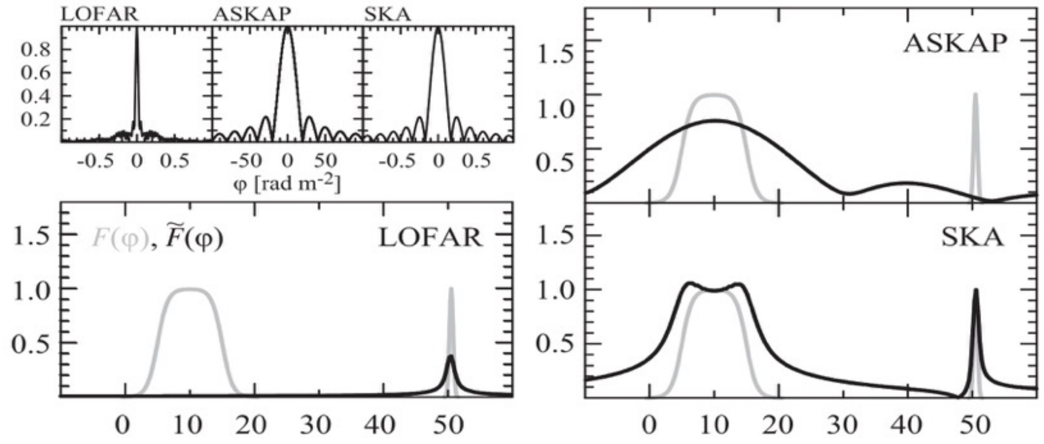
→ Carrier Aggregation (LTE-Advanced Release 10)

https://telektlist.com/career-bands/

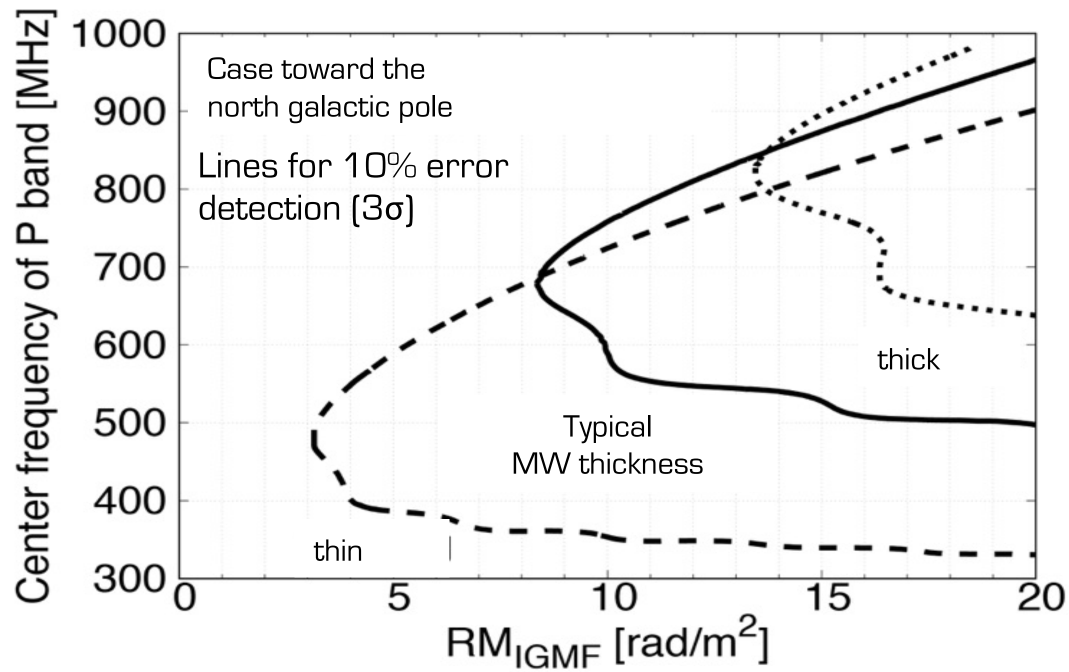
1. Polarization and Magnetism

Similarity to interferometer imaging

- **Quality of Faraday tomography primarily depends on λ² coverage**
  - Low frequency is sensitive to fine structure
  - High frequency is sensitive to diffuse structure
- **Is there the optimum frequency coverage**
  - Yes. 0.7+1.4 (+2.3) GHz for the IGMF search
- **I recommend a Band 1 follow-up observation for the notional Magnetism KSP (Band 2 all-sky)**



TA+14b;18a



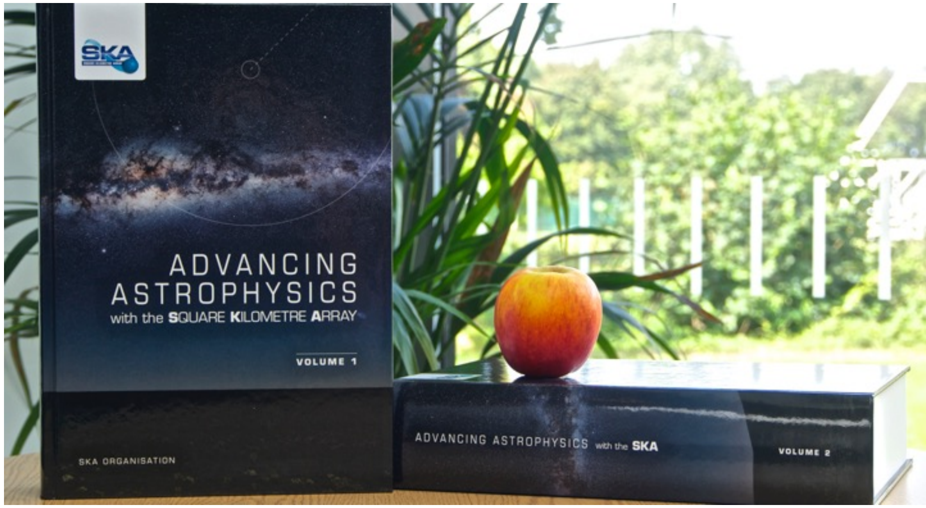
TA+18c;TA18d

2. Fast Radio Burst

2. Fast Radio Burst

What are Radio Transients?

■ **SKA Science Book (2015)** https://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=215



Session 4: The Transient Universe

The Transient Universe with the Square Kilometre Array
PoS(AASKA14)051 pdf *R. Fender, A. Stewart, J.P. Macquart, I. Donnarumma, T. Murphy, A. Deller, Z. Paragi and S. Chatterjee*

The SKA View of Gamma-Ray Bursts
PoS(AASKA14)052 pdf *D. Burlon, G. Ghirlanda, A. van der Horst, T. Murphy, R.A.M.J. Wijers, B. Gaensler, G. Ghisellini and I. Prandoni*

Incoherent transient radio emission from stellar-mass compact objects in the SKA era
PoS(AASKA14)053 pdf *S. Corbel, J.C.A. Miller-Jones, R. Fender, E. Gallo, T. Maccarone, T. O'Brien, Z. Paragi, M. Rupen, A. Rushton, S. Sabatini, G. Sivakoff, J. Strader and P.A. Woudt*

SKA as a powerful hunter of jetted Tidal Disruption Events
PoS(AASKA14)054 pdf *I. Donnarumma, E.M. Rossi, R. Fender, S. Komossa, Z. Paragi, S. Van Velzen and I. Prandoni*

Fast Transients at Cosmological Distances with the SKA
PoS(AASKA14)055 pdf *J.P. Macquart, E. Keane, K. Grainge, M. McQuinn, R. Fender, J. Hessels, A. Deller, R. Bhat, R. Breton, S. Chatterjee, C. Law, D. Lorimer, E.O. Ofek, M. Pietka, L. Spitler, B. Stappers and C. Trott*

The SKA contribution to GRB cosmology
PoS(AASKA14)056 pdf *L. Amati, S. Capozziello, A.C. Ruggeri, M. De Laurentis, M. Della Valle, O. Luongo and G. Stratta*

Time domain studies of Active Galactic Nuclei with the Square Kilometre Array
PoS(AASKA14)058 pdf *H.E. Bignall, S.D. Croft, T. Hovatta, J.Y. Koay, J. Lazio, J.P. Macquart and C. Reynolds*

Core-collapse and Type Ia supernovae with the SKA
PoS(AASKA14)060 pdf *M. Pérez-Torres, A. Alberdi, R.J. Beswick, P. Lundqvist, R. Herrero-Illana, C. Romero-Canizales, S. Ryder, M. Della Valle, J. Conway, J.M. Marcaide, S. Mattila, T. Murphy and E. Ros*

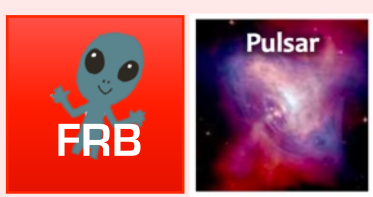
Thermal radio emission from novae & symbiotics with the Square Kilometre Array
PoS(AASKA14)062 pdf *T. O'Brien, M. Rupen, L. Chomiuk, V.A.R.M. Ribeiro, M. Bode, J. Sokoloski and P.A. Woudt*

Investigations of supernovae and supernova remnants in the era of SKA
PoS(AASKA14)064 pdf *L. Wang, X. Cui, H. Zhu and W. Tian*

The SKA and the Unknown Unknowns
PoS(AASKA14)065 pdf *P. Wilkinson*

Early Phase Detection and Coverage of Extragalactic and Galactic Black Hole X-ray Transients with SKA
PoS(AASKA14)066 pdf *W. Yu, H. Zhang, Z. Yan and W. Zhang*

12 papers

	Fast Transients (<1 sec)	Slow Transients (> 1 sec)
Galactic	 Pulsar, Magnetar	 CV, Magnetar, SN Ia, XRB, CCSN
Extra-Galactic	 FRB, Pulsar	 CCSN, TDE, AGN, Merger

Figures taken by Dr. Aoki's slides

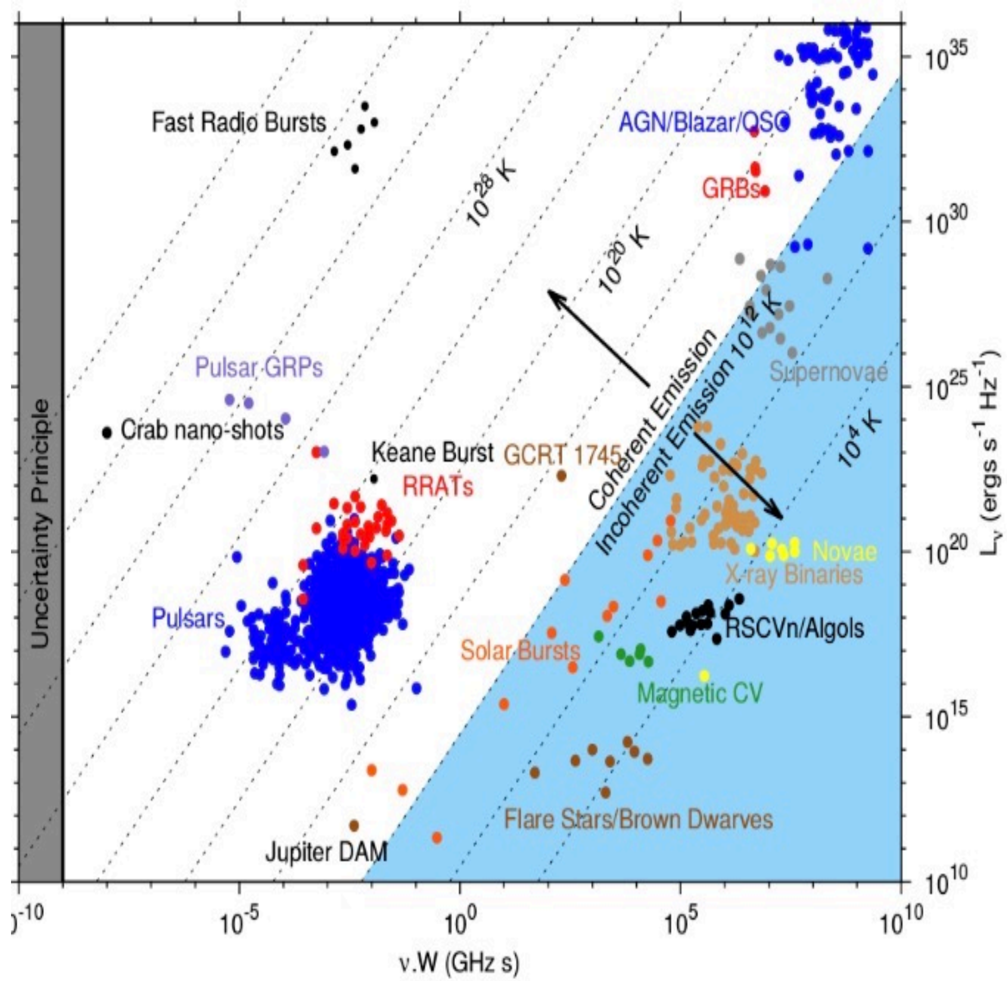
What are Radio Transients?

■Incoherent Events

- Synchrotron, thermal, etc → Radiation mechanism known
- Brightness limited by inverse Compton limit → $T_b < 10^{12}$ K
- Luminous ≒ larger ≒ slower transient → fould in image

■Coherent Events

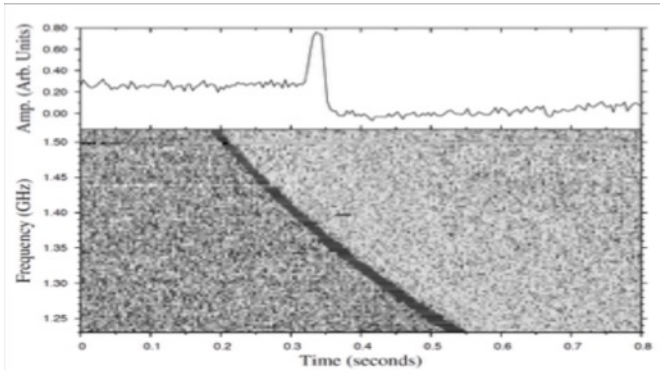
- Maser, curvature radiation → Mechanism (largely) unknown
- High brightness, $T_b > 10^{20}$ K (PSR) and $> 10^{30}$ K (FRB)
- Dispersion timescale → fast transient → found in voltage



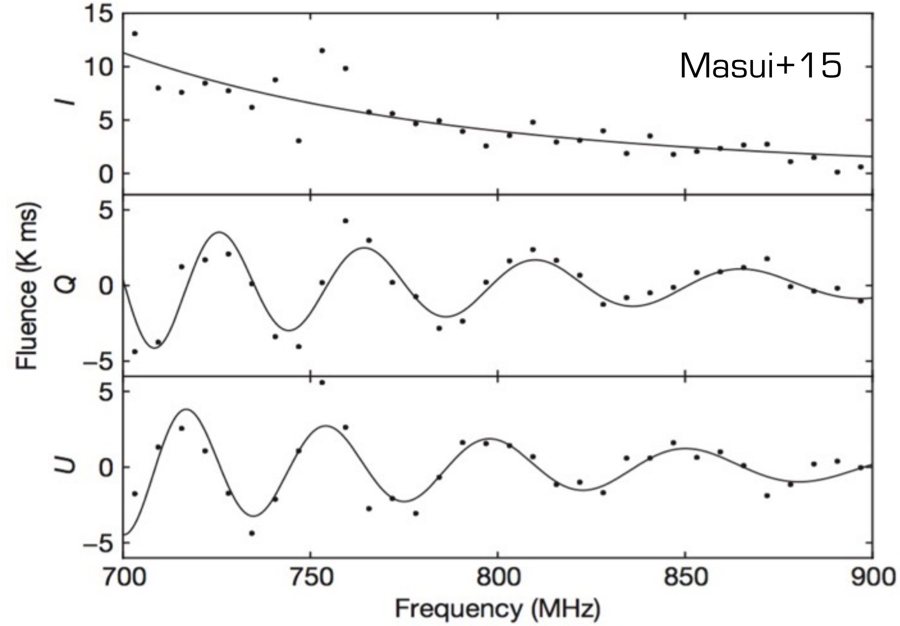
Fender+2015

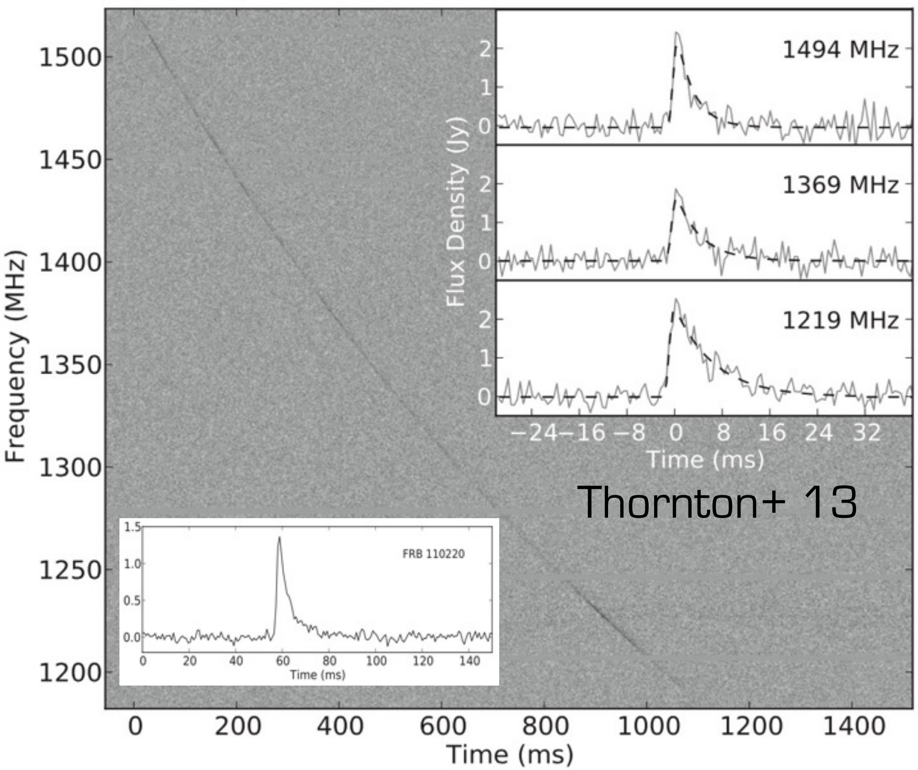
2. Fast Radio Burst

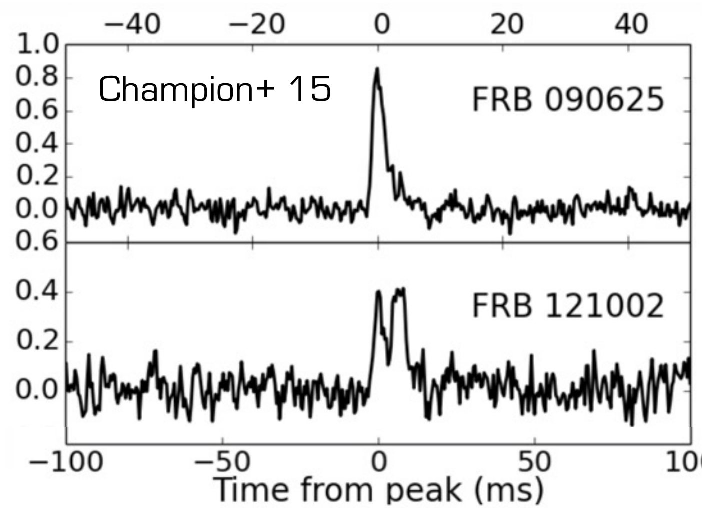
Radio Burst with Millisecond Duration



FRB010724
Lorimer+07







2. Fast Radio Burst

A Brief History of the Discoveries

- First report [Lorimer+07), Second report (4 events, Thornton+13)
- Realtime (no counterpart), circular pol.~21±7% (FRB140514, Petroff+15)
- Linear polarization, RM=-186 rad/m^2 (FRB110532: Masui+15)
- Double-peak FRB (FRB121001: Champion+15)
- First repeating FRB (FRB121102: Spitler+16)
- Localization(?), z~0.49, Ω_{IGM} ~4.9±1.3% (FRB150418: Keane+16)
- Brilliant FRB, 120Jy, B_{LSS} < 21(1+z) nG (FRB150807: Ravi+16)
- Localization, SF region at dwarf galaxy (FRB121102: Chatterjee+17;Bassa+17)
- First 8 GHz, Very large RM~+140k rad/m^2 (FRB121102: Michilli+18)
- ASKAP 20 FRBs, two populations (the repeater and the others) (Shannon+18)
- CHIME 13 FRBs, first 400-800 MHz, DM~109 pc/cm^3 (CHIME+19)
- Second repeating FRB (FRB180814.J0422+73, CHIME+19)
- Localization, MW-like galaxies (FRB180924 Bannistar+19; FRB190523 Ravi+19)

SQUARE KILOMETRE ARRAY
NAOJ SKA1 STUDY GROUP

2. Fast Radio Burst

The Era of Early Statistics: DM

■Dispersion Measure

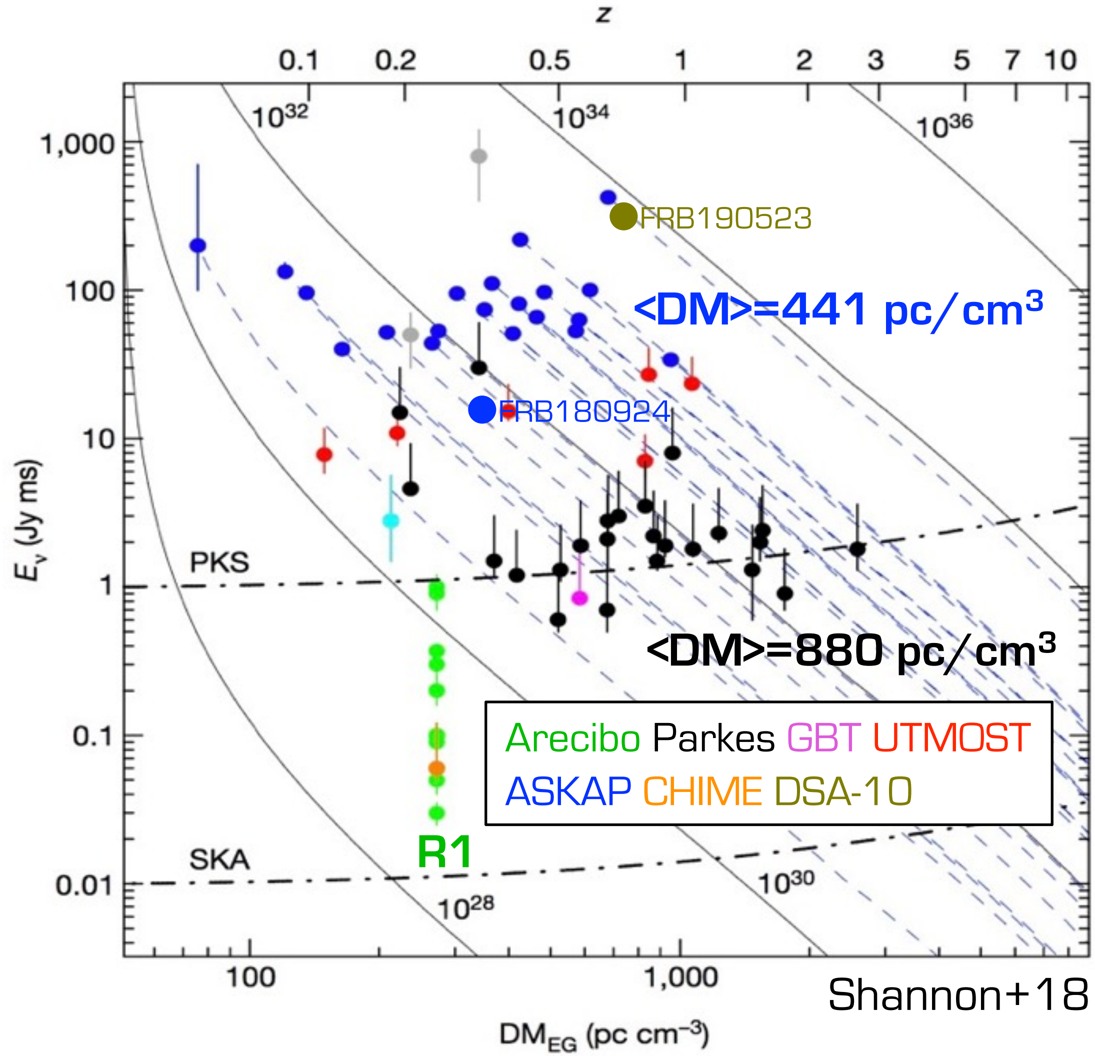
- DM=100-3000 pc/cm^3
- >> Milky Way contribution

■Event rate

- 1.5-3.8/deg^2/month above 2Jy msec (Champion+16; Keane & Petroff 2015)
- Populations in energy and in redshift under discussion

■A new messenger of cosmology

- With redshift of the host galaxy and DM → Ω_{IGM} ~4.9±1.3% (Keane+16)



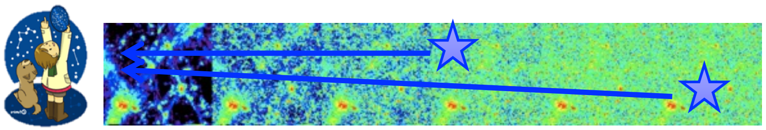
Shannon+18

2. Fast Radio Burst

Linearly-Polarized FRB

	ID	Facility	P (%)	RM (rad/m^2)	Reference
1	110523	Parkes	44±3	-186.1±1.4	Masui+15

- **Q: Can we derive LSS's IGMF strength from LSS's DM & RM, if extracted from observed ones?**
- **A: Yes. But $B_{||}^{\dagger} \sim RM/DM$ is not!**

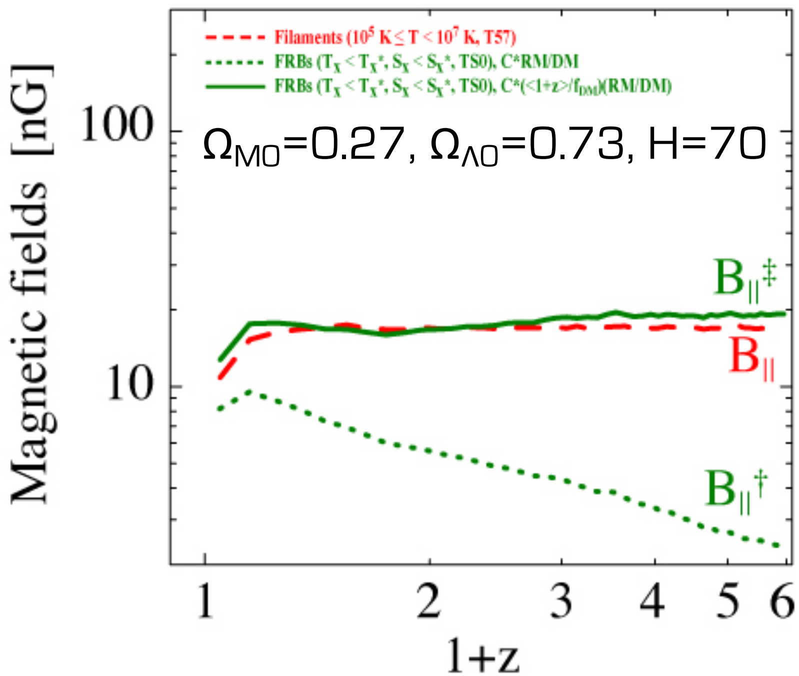


$$DM = C_{\rm D} \int_0^{z_i} \frac{n_{\rm e}(z)}{(1+z)} \frac{dl(z)}{dz} dz \quad {\rm pc\ cm^{-3}}$$

$$RM = C_{\rm R} \int_{z_i}^{0} \frac{n_{\rm e}(z) B_{||}(z)}{(1+z)^2} \frac{dl(z)}{dz} dz \quad {\rm rad\ m^{-2}}$$

$$B_{||}^{\dagger} = \frac{C_{\rm D} RM}{C_{\rm R} DM} = 12.3 \left(\frac{RM}{10\ {\rm rad\ m^{-2}}} \right) \left(\frac{DM}{10^3\ {\rm pc\ cm^{-3}}} \right)^{-1} {\rm nG}$$

$$B_{||}^{\ddagger} = \frac{\langle 1+z \rangle}{f_{DM}} B_{||}^{\dagger} = \frac{\langle 1+z \rangle}{f_{DM}} \frac{C_{\rm D} RM}{C_{\rm R} DM}$$



TA, Ryu, Gaensler (2016)

2. Fast Radio Burst

Linearly-Polarized FRBs

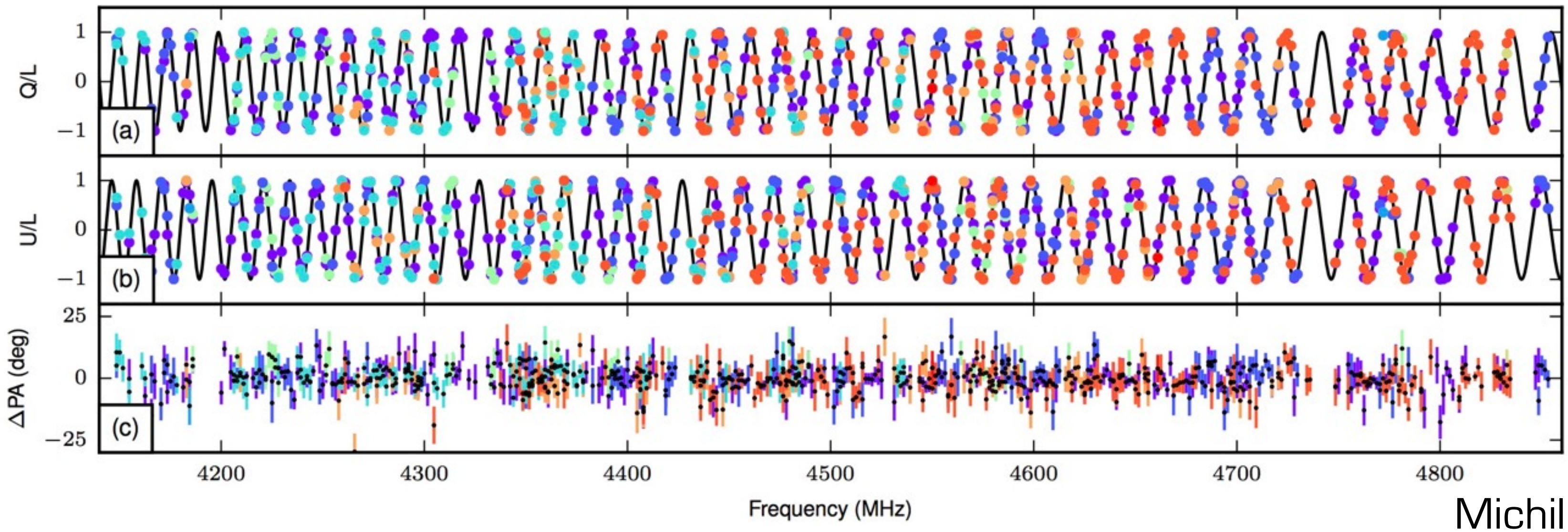
	ID	Facility	P (%)	RM (rad/m^2)	Reference
1	110523	Parkes	44±3	-186.1±1.4	Masui+15
2	150807	Parkes	80±1	12.0±7	Ravi+16
3	150215	Parkes	43±5	1.6±10	Petroff+17
4	150418	Parkes	9±2	36±52	Keane+16
5	151230	Parkes	35±13	0	Caleb+18
6	160102	Parkes	84±15	-221±6	Caleb+18
7	121102	Arecibo/GBT	~100	1x10^5	Michilli+18
8	180924	ASKAP	80	14±1	Bannistar+19
9	181226	CHIME	~100	-114.6±0.6	CHIME/FRB+19

■ **Upper limit of extragalactic magnetic field:**

- **B < 21 nG (Ravi+16), B < 30 nG (Bannistar+19)**
- Faraday RM synthesis (tomography) is a key technique to derive RM

Faraday Rotation of FRB121102

	ID	Facility	P (%)	RM (rad/m^2)	Reference
7	121102	Arecibo/GBT	~100	1×10^5	Michilli+18



Michilli+18

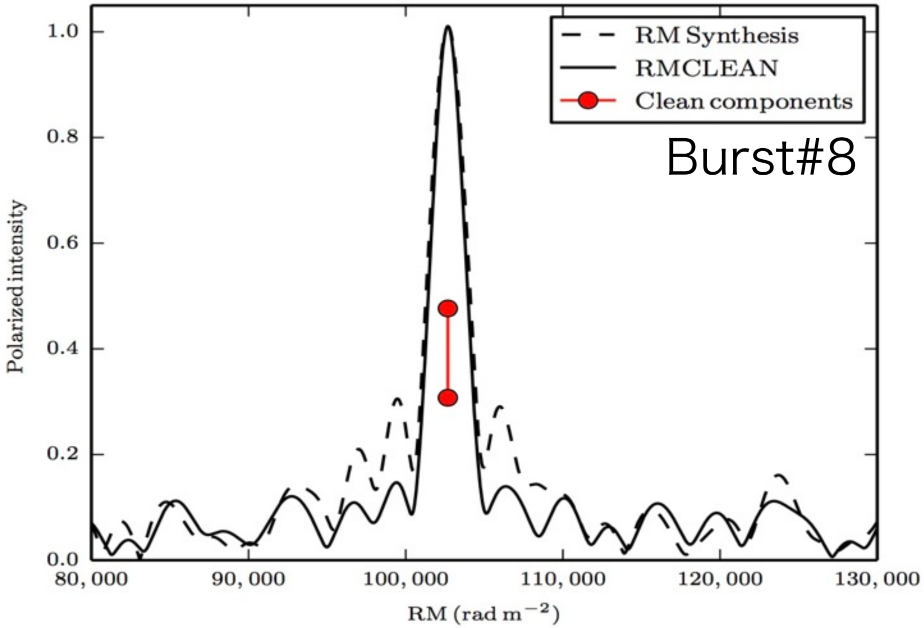
- **No depolarization → Coherent (regular) magnetic field**
  - P/I >98% → Sightline ΔRM < 20 rad/m^2 and in-beam σ_{RM} < 25 rad/m^2
- **Faraday tomography → Single screen in front of the source**
  - RM~10^5 rad/m^2 is likely from the source environment with $B_{||}$ > 0.6-2.4 mG
- **Extreme RM & 10% RM variation in 7 months**
  - An SMBH environment?

2. Fast Radio Burst

RM screen of FRB121102

- **Faraday tomography → Single Faraday screen in front of the source**
- **Possible contributions**
  - RM_{MW} ~ -25±80 rad/m² (Opperman, TA+15)
  - RM_{IGM} < 100 rad/m² (TA, Ryu 10;11)
  - RM_{Earth} ~O(1) rad/m²

→RM~10^5 rad/m² is most likely from the source environment

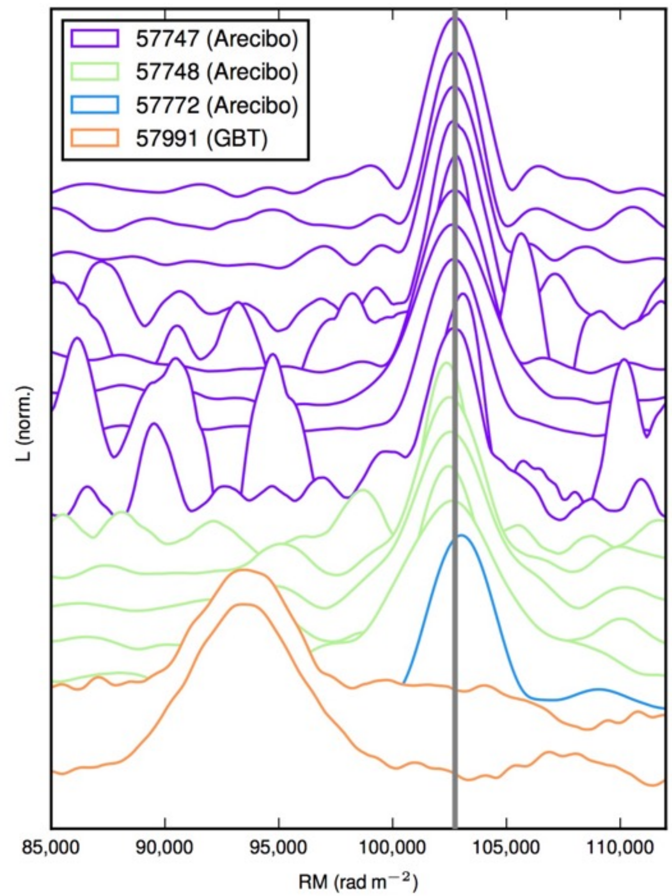


- **RM gives $B_{||}$ > 0.6-2.4 mG**
  - DM_{host} = 70-270 pc cm^{-3}
  - $B_{||}$ ~RM_{src}/DM_{host}
  - c.f. ~ 5μG for interstellar magnetic-field of Our Galaxy

Variability of the Screen

- 10% variation of RM just in 7 months (and strong B)
  →an environment near a SMBH?

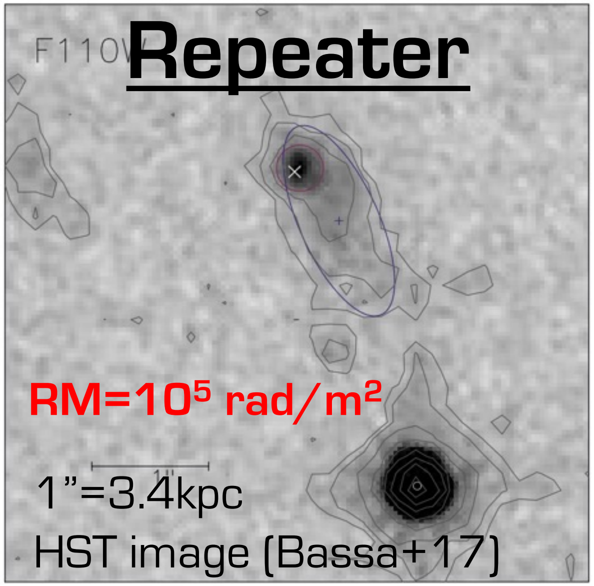
Burst	MJD	Width (ms)	S (Jy)	F (Jy ms)	RM_{obs} (rad m^{-2})	PA_{∞} (deg)	RM_{global} (rad m^{-2})	PA_{∞}^{global} (deg)
1	57747.1295649013	0.80	0.9	0.7	$+102741 \pm 9$	49 ± 2		
2	57747.1371866766	0.85	0.3	0.2	$+102732 \pm 34$	55 ± 9		
3	57747.1462710273	0.22	0.8	0.2	$+102689 \pm 18$	64 ± 5		
4	57747.1515739398	0.55	0.2	0.09	–	–		
5	57747.1544674919	0.76	0.2	0.1	–	–	$+102708 \pm 4$	
6	57747.1602892954	0.03	1.8	0.05	$+102739 \pm 35$	49 ± 9		
7	57747.1603436945	0.31	0.6	0.2	$+102663 \pm 33$	71 ± 9		
8	57747.1658277033	1.36	0.4	0.5	$+102668 \pm 18$	67 ± 4		
9	57747.1663749941	1.92	0.2	0.3	–	–		58 ± 1
10	57747.1759674338	0.98	0.2	0.2	–	–		
11	57748.1256436428	0.95	0.1	0.1	–	–		
12	57748.1535244366	0.42	0.4	0.2	$+102508 \pm 35$	63 ± 10		
13	57748.1552149312	0.78	0.8	0.6	$+102522 \pm 17$	59 ± 4	$+102521 \pm 4$	
14	57748.1576076618	0.15	1.2	0.2	$+102489 \pm 18$	67 ± 5		
15	57748.1756968287	0.54	0.4	0.4	$+102492 \pm 37$	64 ± 10		
16	57772.1290302972	0.74	0.8	0.6	$+103020 \pm 12$	64 ± 3	$+103039 \pm 4$	
GBT-1	57991.5801286366	0.59	0.4	0.2	$+93526 \pm 72$	73 ± 8	$+93573 \pm 24$	68 ± 2
GBT-2	57991.5833032369	0.27	0.9	0.2	$+93533 \pm 42$	71 ± 4		



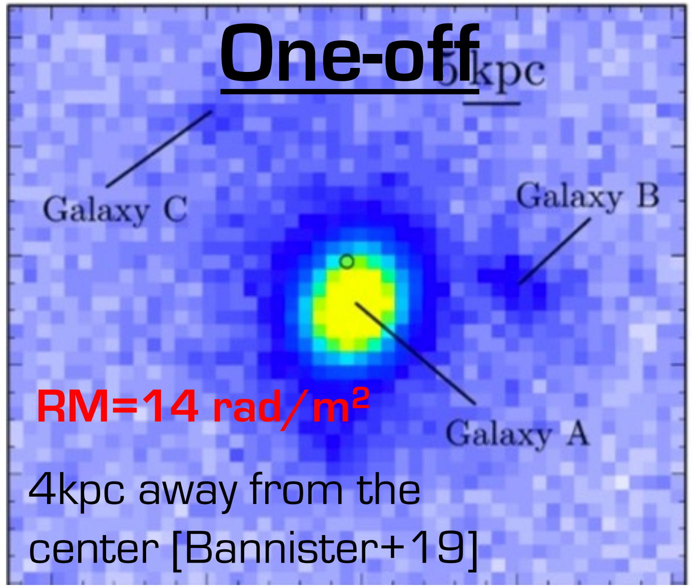
Michilli+18

2. Fast Radio Burst

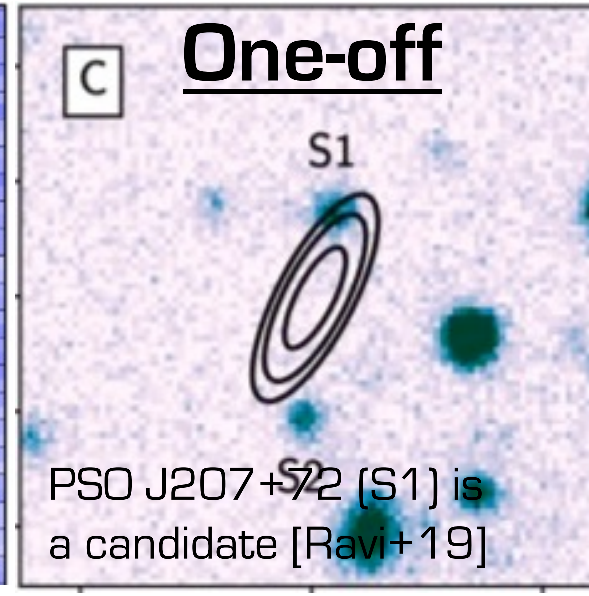
Host Galaxies



An low-M, low-Z, star-forming dwarf irregular galaxy



An early-type, MW-sized, low-star-forming galaxy



An early-type, MW-sized, low-star-forming galaxy

Events related to stellar activities?

- Flare of massive stars (Loeb+13)
- Young magnetars (Thornton+13)?

Events related to aged stars?

- NS-NS merger (Totani+13)
- WD-WD merger (Kashiyama+13)

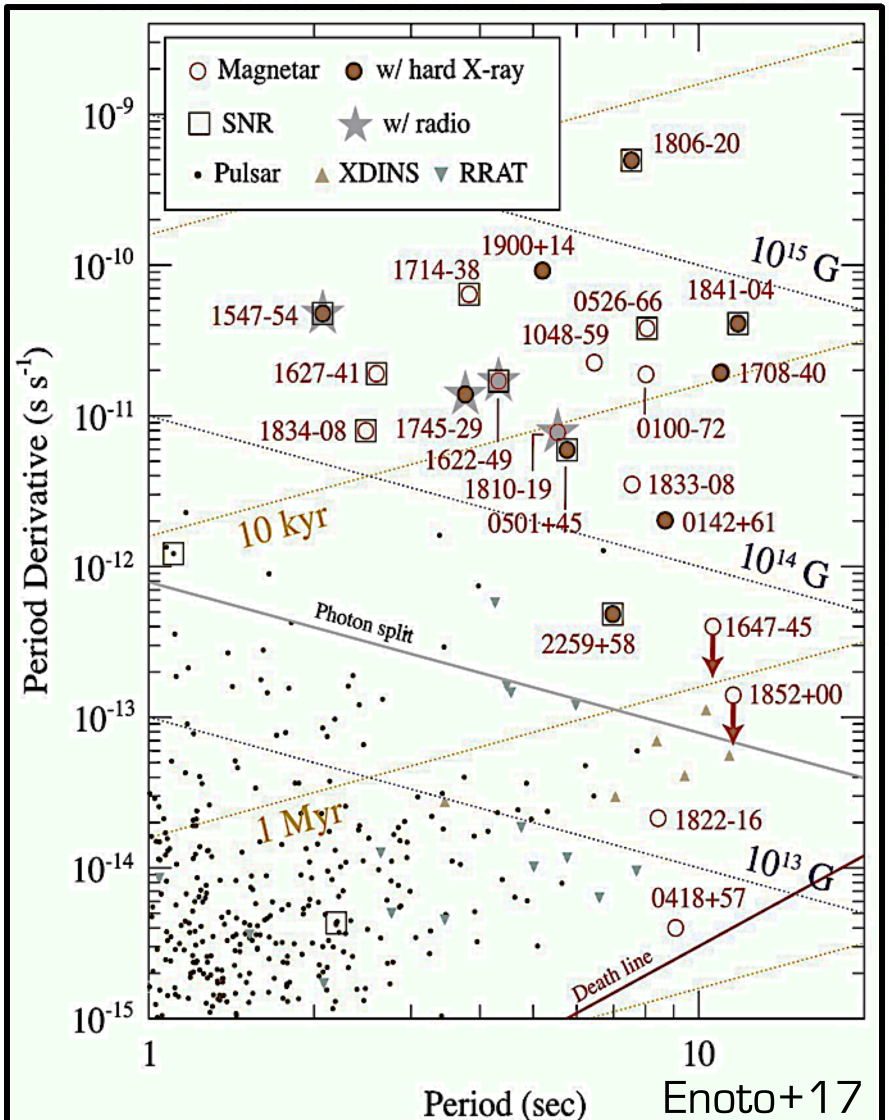
Or, anything else: Core Collapse SN (Falcke+13), Evaporation of BH (Keane+12), Superconductive strings (Cai+12), etc etc…

3. Magnetar Radio Outburst

SQUARE KILOMETRE ARRAY
NAOJ SKA1 STUDY GROUP

3. Magnetar Radio Outburst

Pulsar and Magnetar



■**A slow-rotating (>2 sec), fast spin-down [>1 ms/yr] NSs**

- X-ray/γ-ray emission → **Strong magnetic field** (>10^{14} G dipole field)
- Even stronger that the quantum critical field (=4.4×10^{13} G, r_g~λ_e)

■**Magnetar is radio-quiet**

- Too-slow spin to emit?
- Obscured?
- Off-beam?
- Not dipole-B?
- Suppressed by B?

■**Exception = Radio Outburst!**

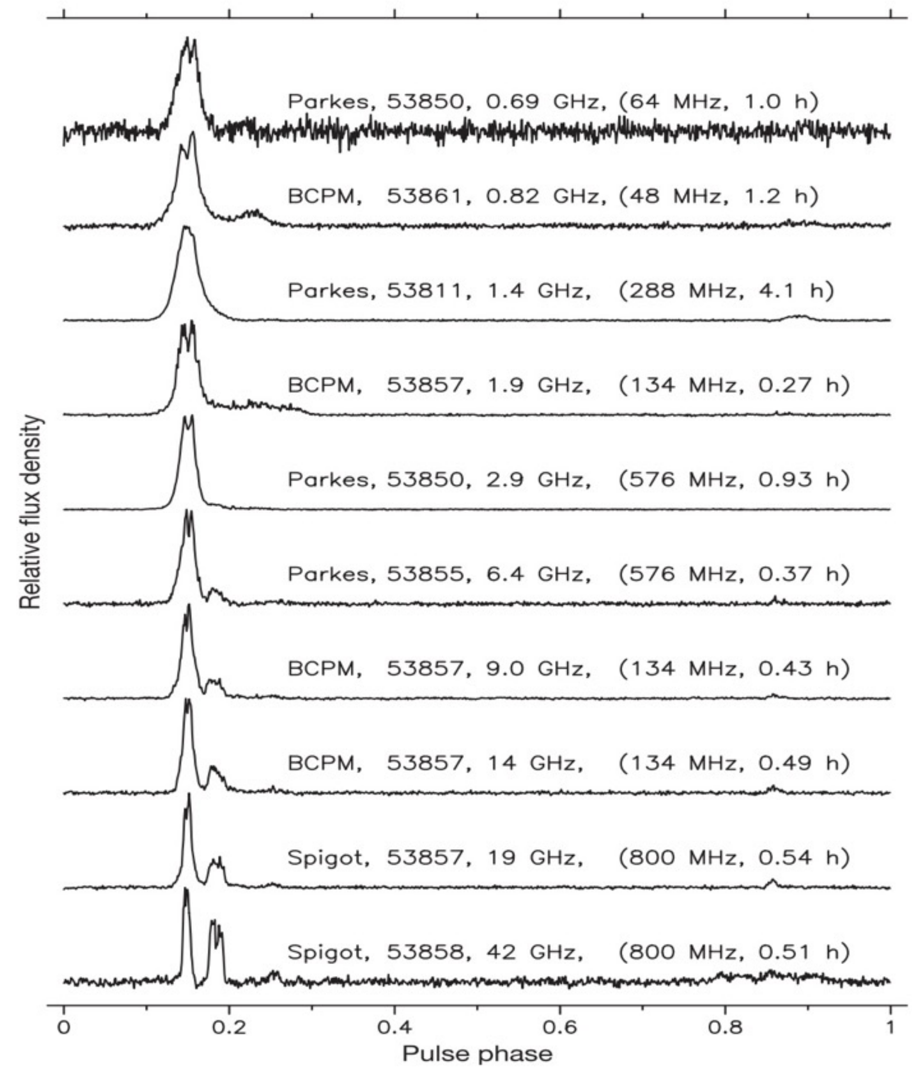
3. Magnetar Radio Outburst

Radio Outburst from Magnetars

Name	P [s]	B [10^{14}G]	T [kyr]	D [kpc]
XTE J1810-197	5.54	2.1	11	3.5?
1E 1547.1-5408	2.07	3.0	0.69	4.5?
PSR J 1622-4950	4.33	2.7	4.0	9??
SGR J 1745-2900	3.76	2.3	4.3	8.3?

XTE J1810-197

- Discovered in 2003 as an X-ray pulsar with P = 5.54s, B_d = 3 x 10^{14} G (Ibrahim+04)
- In 2004, radio emission was found at 1.4 GHz (Halpern+05).
- In 2006, radio pulsation was found [Camilo+06]. A flat (α≒0) and variable spectrum (Kramer+07; Lazaridis+08] → similar to FRB and Crab Giant Radio Pulse (GRP)
- Radio disappeared in 2008



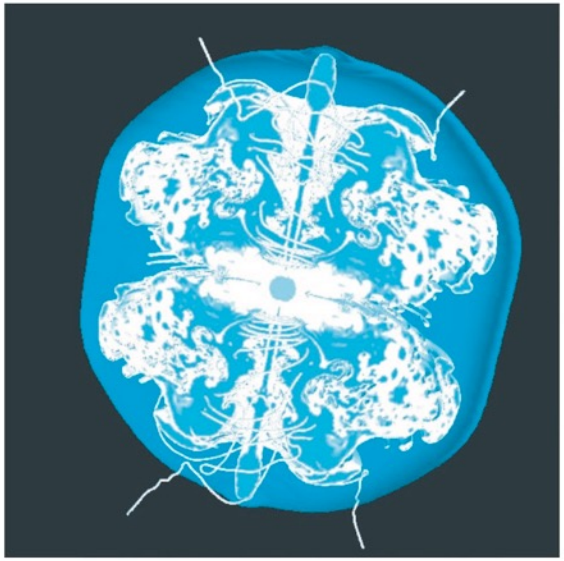
XTE J1810-197: Camilo+06

Issues on Magnetar Hypothesis

■The magnetar hypothesis explains AXP and SGR well, but…

1. What is the origin of strong B?

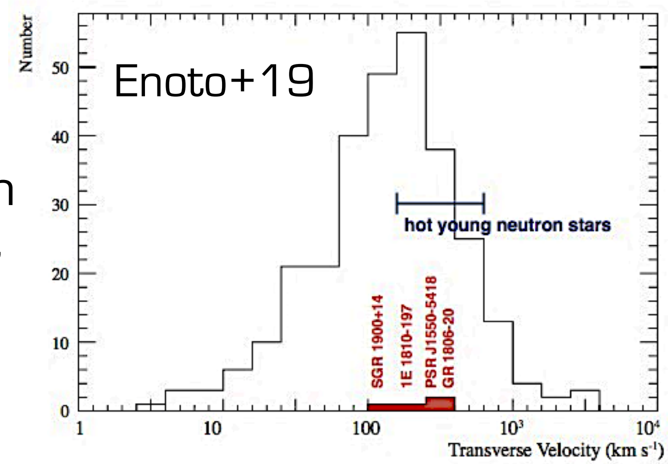
- The standing accretion shock instability (SASI) can induce **dynamo** at a supernova explosion
- Hypothesis: SNR has a **peculiar morphology**?
- Method: Identify the progenitor SNR → Measure the magnetar's location and velocity



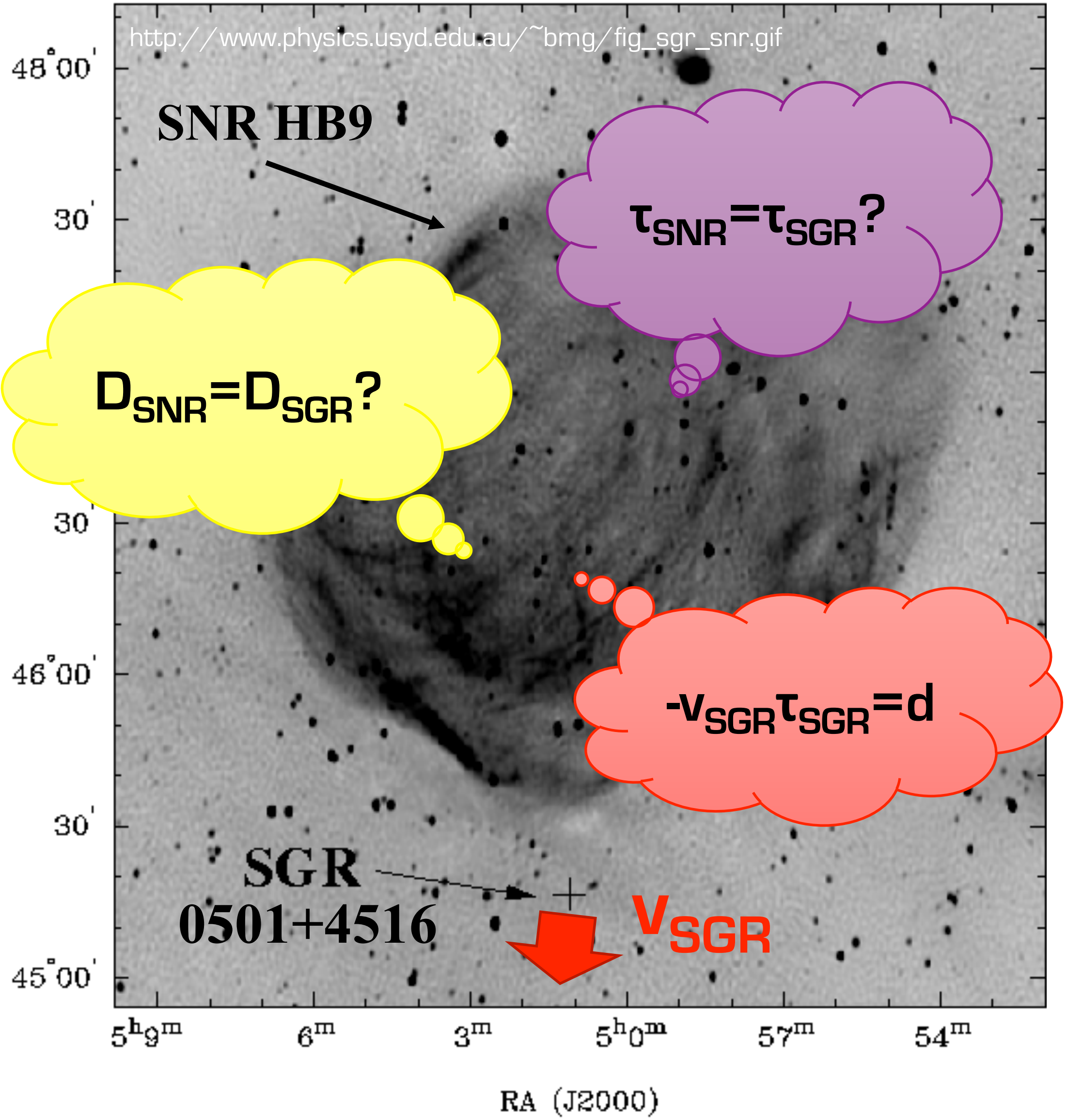
Takiwaki-san's Geppou

2. What is the trigger of outburst?

- Supernovae "kick" neutron stars
- Violent (v = several x 100km/s) interaction with the ISM may induce **Alfvenic waves** and impact onto the magnetosphere
- Hypothesis: Magnetars have **higher velocity**?
- Method: Measure the magnetar's velocity



Quiz



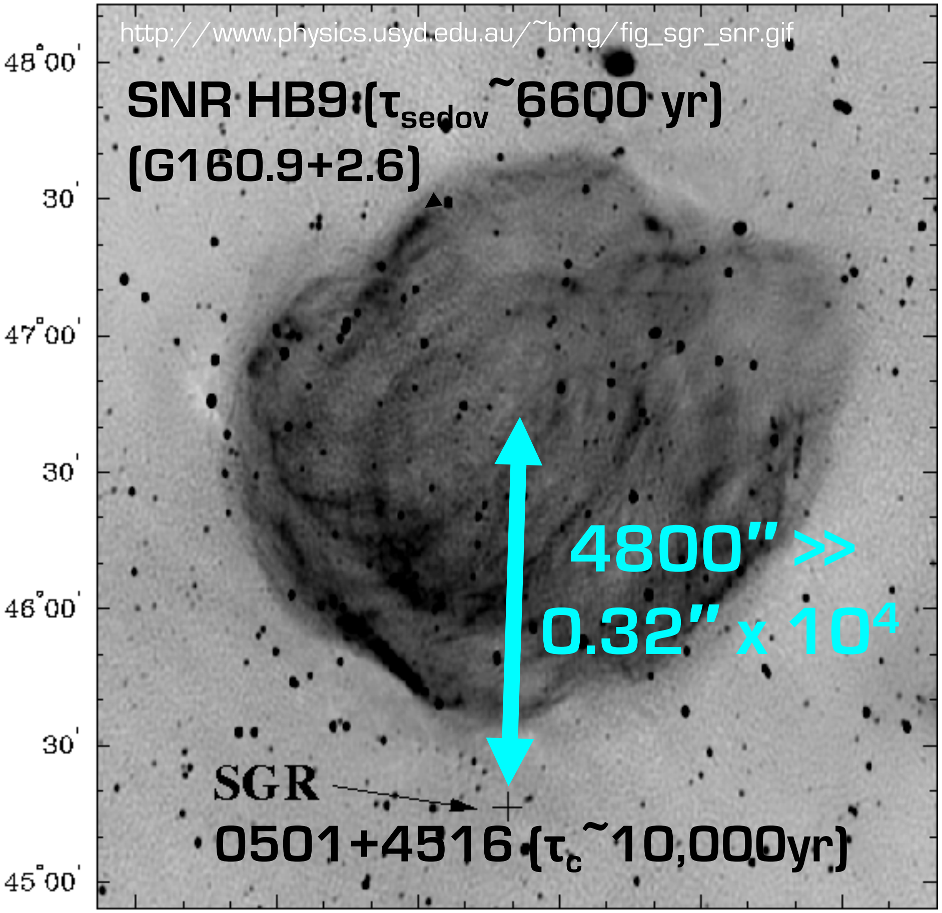
Q: Is HB9 the progenitor of SGR0501?

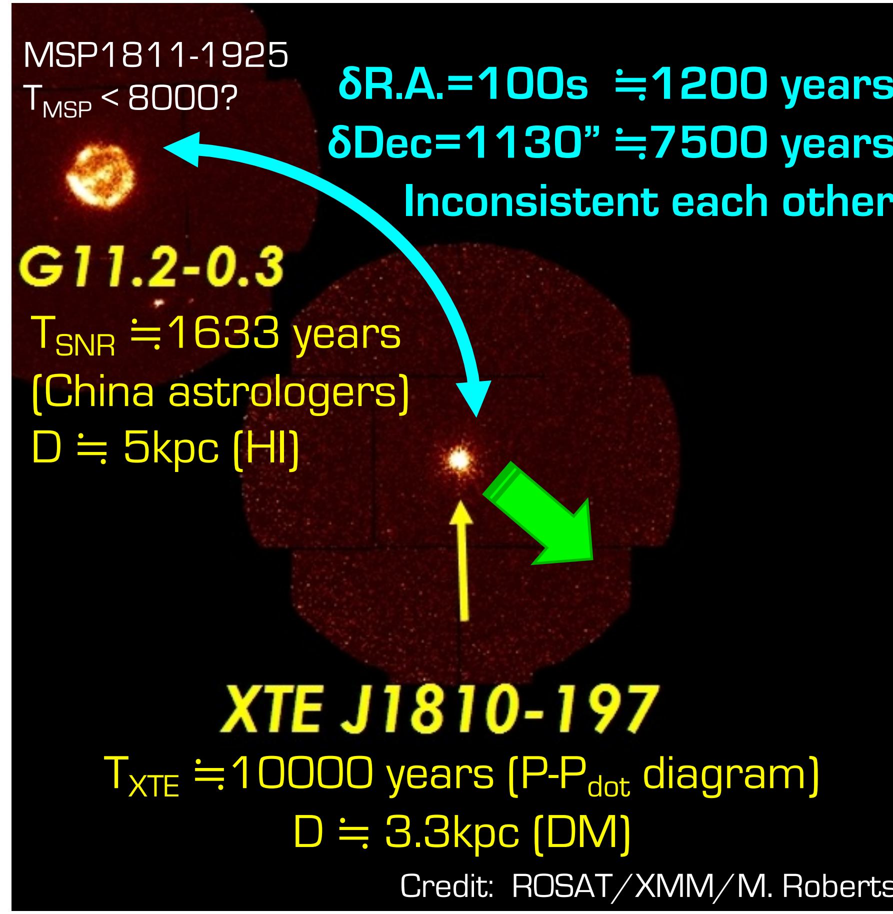
1. Yes
2. No
3. Uncertain

Which physical parameters are needed to conclude?

3. Magnetar Radio Outburst

Missing Link: Magnetar and SNR





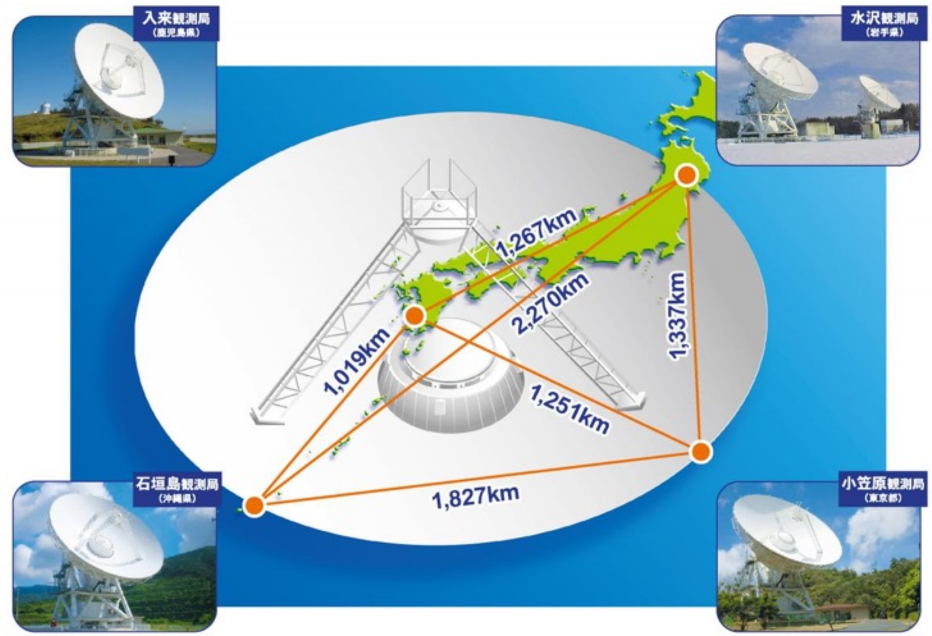
Chandra upper limit of **0.32"/yr** may **reject** this progenitor (Mong & Ng 18, assuming D=5kpc)

VLBA astrometry of v= **212 km/s** toward **SW** may **reject** this progenitor (Helfand+07)

Observing Strategy with VERA

Why VERA 22 GHz?

1. **Resolution = 1.2 mas!**
   - Can capture 1.7 mas/month for 200 km/s @ 2 kpc
2. **Sensitivity = 0.2mJy!**
   - per 8hr per 128MHz (open use)
   - Note: 2048MHz for SWG



Target selection criteria

1. At anti-galactic center to meet low DM & low time pressure.
2. With phase calibrators
   - Ideal: d < 2°, S > 300mJy
   - OK: d < 3°, S > 60mJy

■Exception = outburst (ToO) →

Name	P (sec)	D (kpc)	Flux (mJy)	SNR
SGR0501+452	5.76	1-5?	300?	HB9?
4U 0142+61	8.69	3.6?	???	?
1E 2259+586	6.98	3.2?	???	CTB 109?
XTE1810-197	5.54	3-5?	10?	G11.2 -0.3?

3. Magnetar Radio Outburst

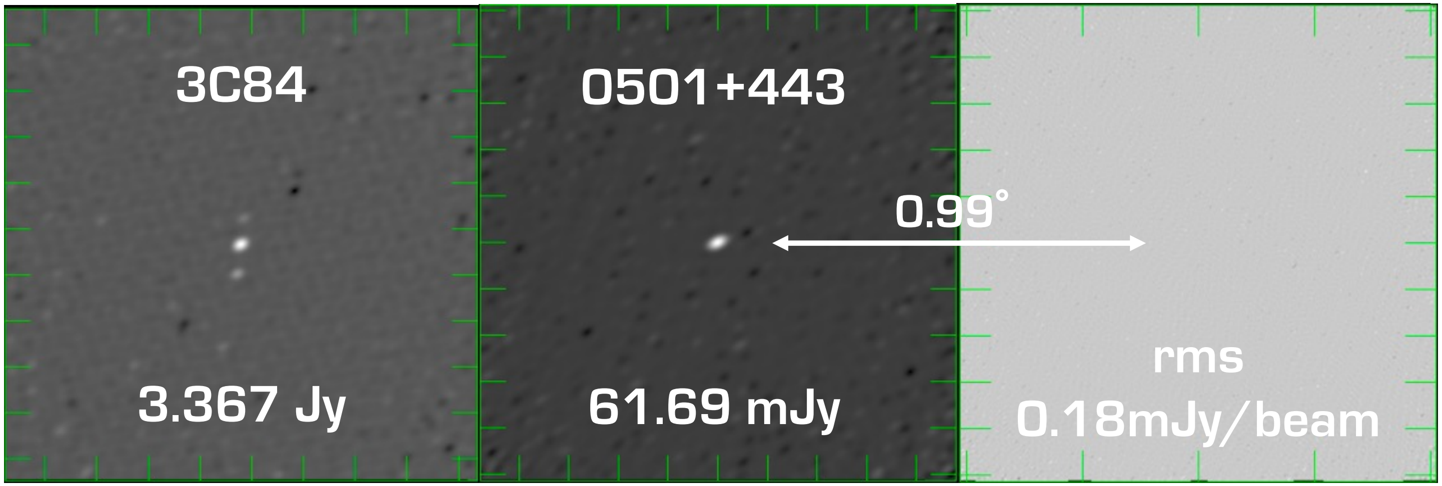
Result of SGR0501 VLBI Imaging

Sta	τ_0	T_{rx}	T_{sys}
MIZ	0.12	83	121
IRK	0.09	93	135
OGA	0.11	86	131
ISG	0.20	97	186

10hr

End	τ_0	T_{rx}	T_{sys}
MIZ	0.14	85	142
IRK	0.08	96	142
OGA	0.10	89	135
ISG	0.18	110	189

R18093A(2018/4/3)

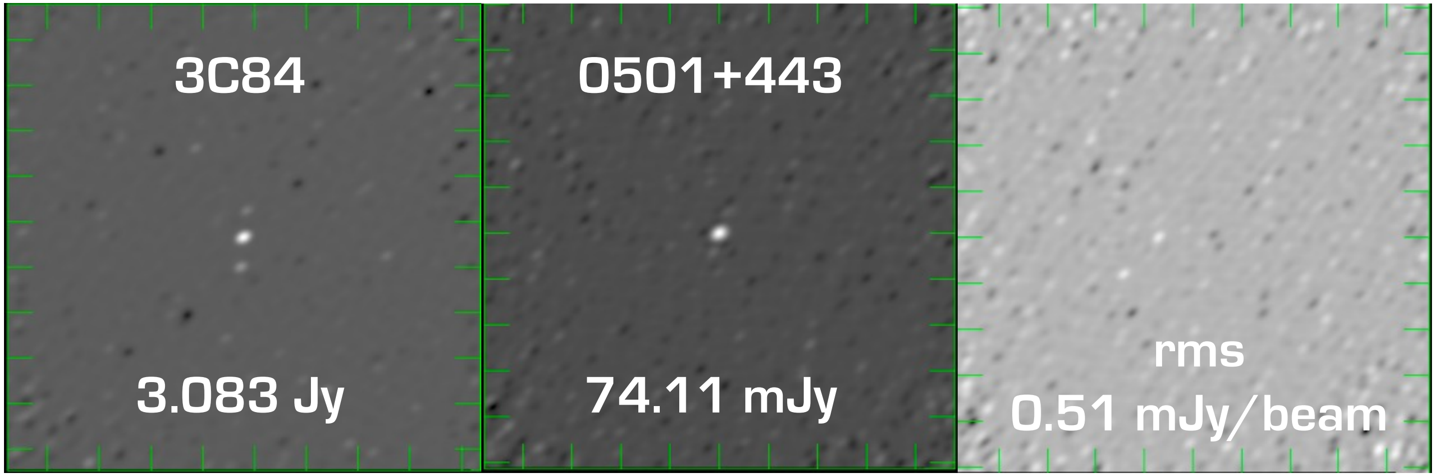


Sta	τ_0	T_{rx}	T_{sys}
MIZ	0.15	71	132
IRK	0.25	119	232
OGA	0.19	117	203
ISG	0.26	176	310

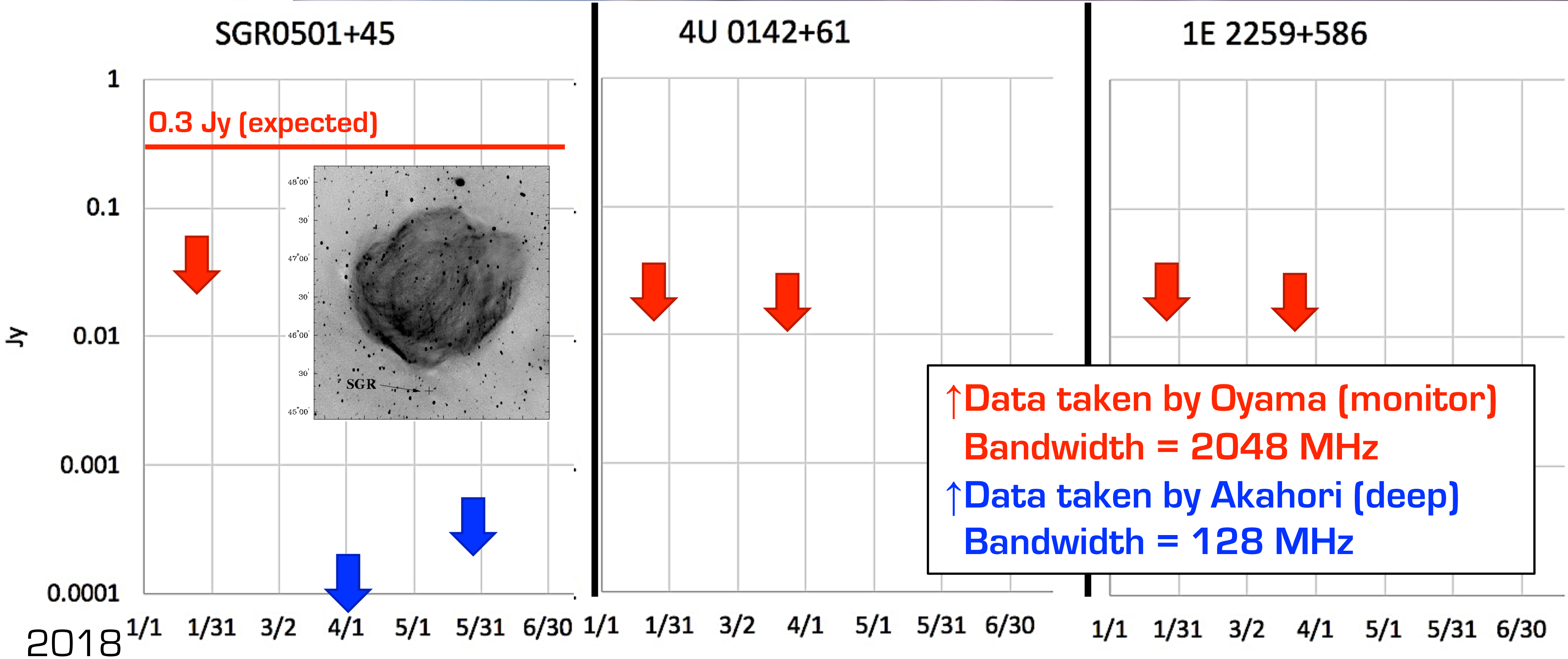
10hr

End	τ_0	T_{rx}	T_{sys}
MIZ	0.17	88	157
IRK	0.21	124	229
OGA	0.29	143	278
ISG	0.23	114	216

R18148B(2018/5/29, 55days)



Result of SGR0501 VLBI Imaging

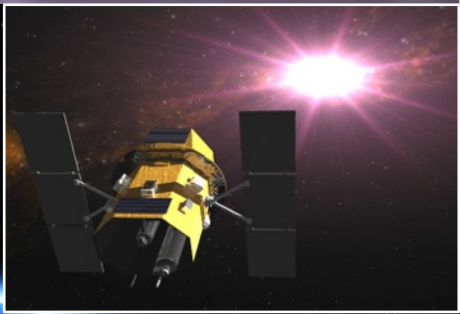


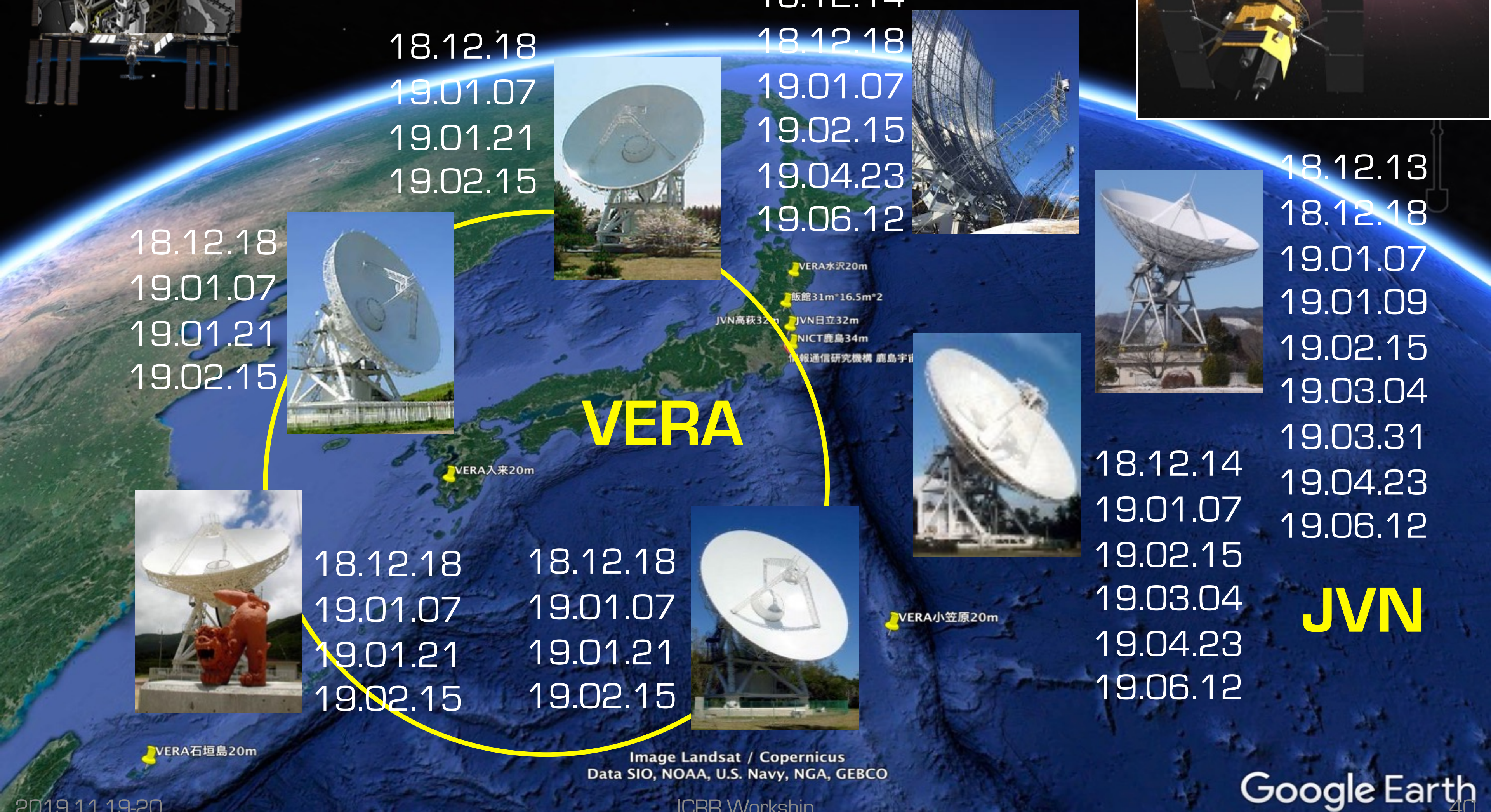
- No radio emission was detected
- An upper limit of 0.2-0.5 mJy → top 20% of known normal radio pulsars are excluded

3. Magnetar Radio Outburst

Revival of XTE1810 Radio Outburst

Iitate 31m (0.3 GHz), Kashima 34-m (2 GHz), Hitachi 32-m (7/8 GHz), four VERA 20m (22 GHz), and NICER and Swift

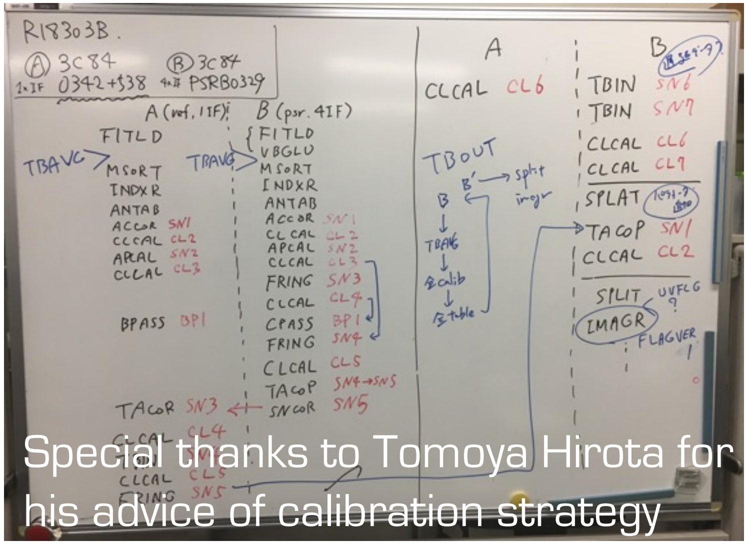




VLBI for 2019 Outburst

■VLBI is a tough work…

- Shipping data (2weeks)
- Correlation (2 weeks)
- Fringe search (# of trials)
- Small FoV → many imaging to explore a moving source!

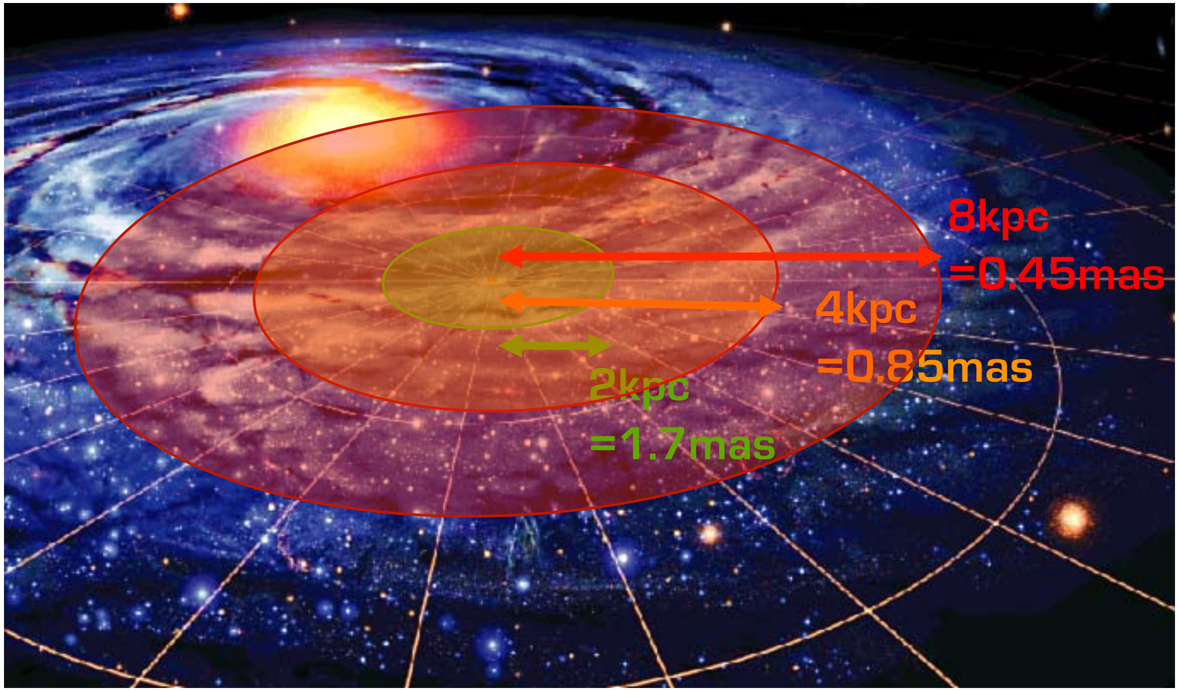


Special thanks to Tomoya Hirota for his advice of calibration strategy

Work in progress…

3. Magnetar Radio Outburst

K-band VLBI of Magnetars (ToO)



■ Resolving the proper motion of 200 km/s in a month

MOT-VERA

Magnetar Observation Team of VERA

Local arm, Perseus arm

VERA 3000 km = 1.2 mas

MUAY-THAI (2023-)

Magnetar Unprecedented Astrometry Yielded by Thailand

MOT-VERA + inter-arm, halo

Super EAVN 6000km = 0.6 mas

KAIRAKUEN (2030-)

Key Alliance of International Radio Astrometry at K-band for Ultimate Exploration of NSs

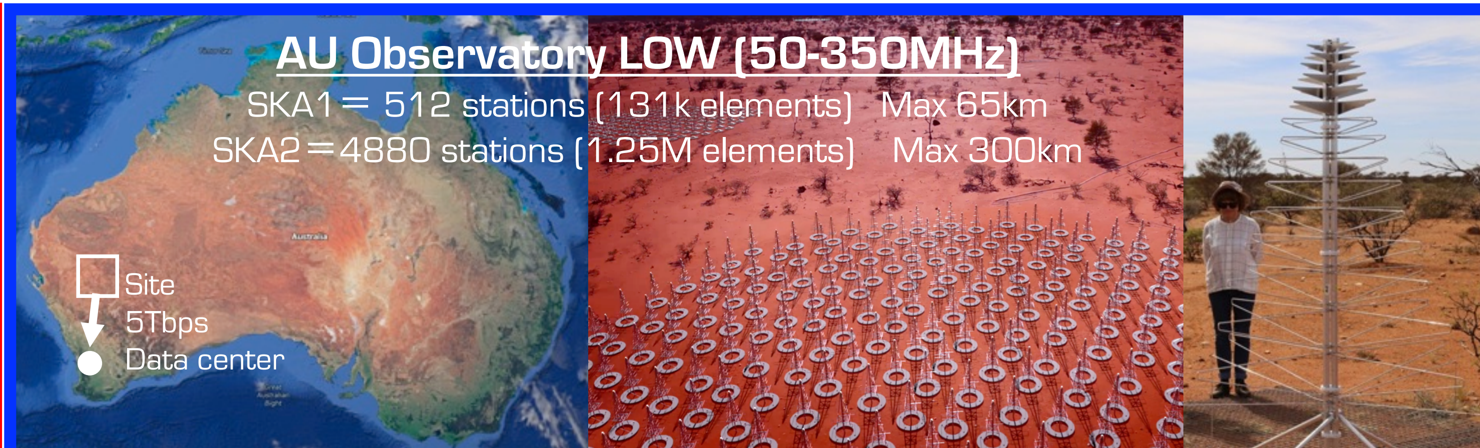
MUAY-THAI + arms + galactic center

SKA-VLBI with EAVN 12000 km = 0.3 mas

4. Square Kilometre Array (SKA)

Square Kilometre Array (SKA)

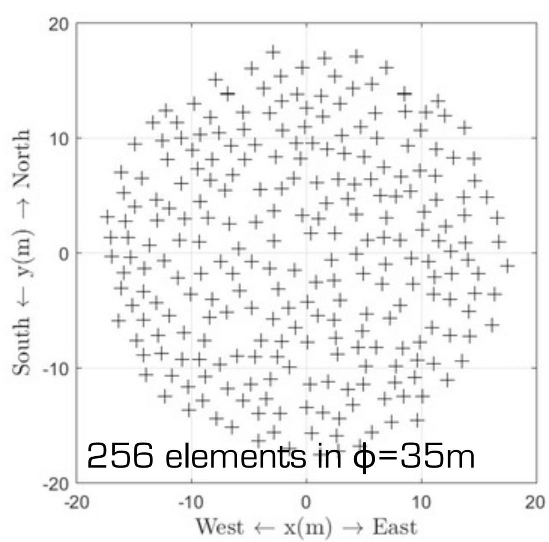
■SKA is a project to construct the world-largest radio telescopes at Australia and South Africa from 2021, and to operate it in 30 years with investments of ~1B€ by >13 countries.

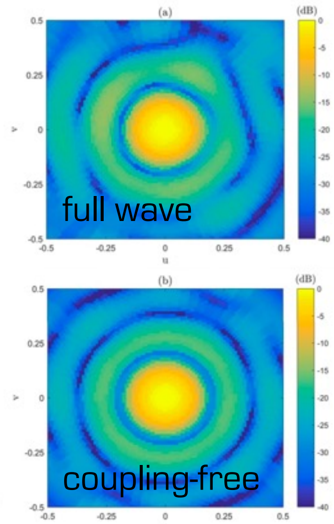


4. SKA

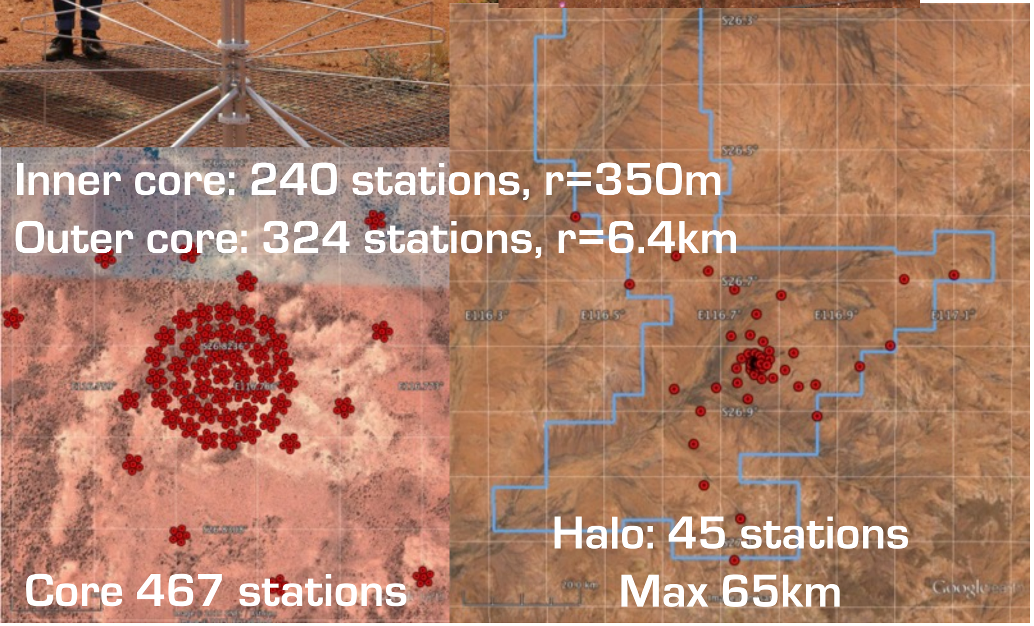
LFAA: 50MHz – 350 MHz

"Element"
Log periodic dipole

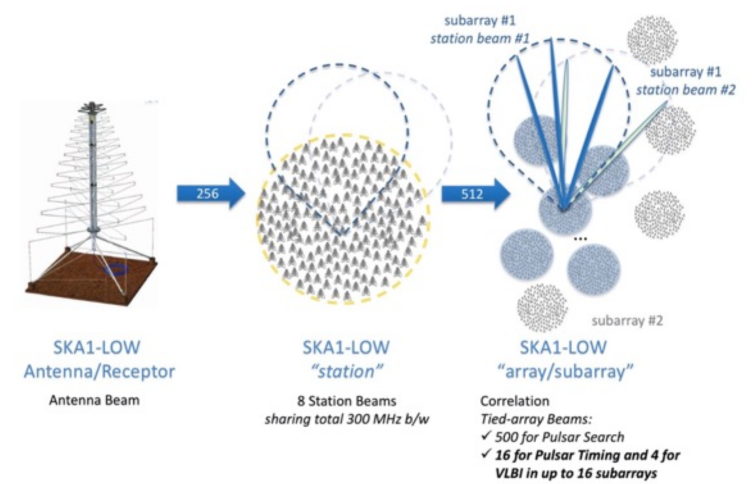




Ninni+19 IEEE, 8739902



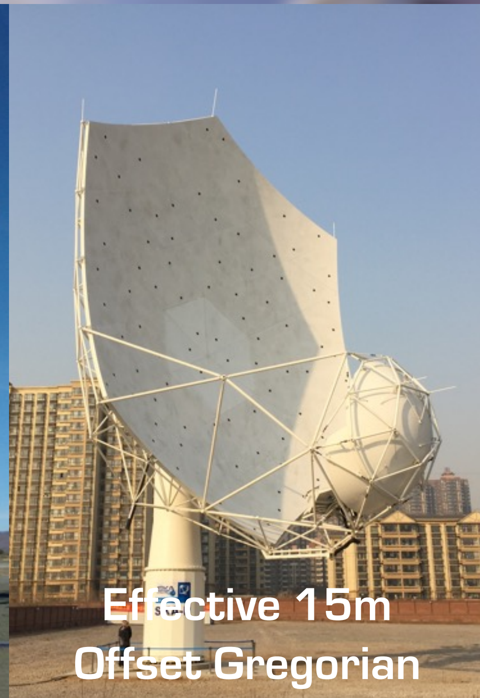
Inner core: 240 stations, r=350m
Outer core: 324 stations, r=6.4km
Core 467 stations
Halo: 45 stations
Max 65km

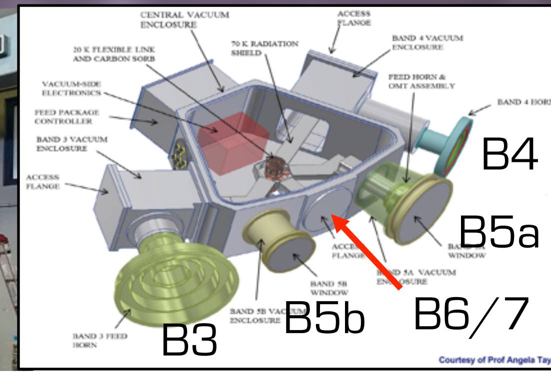


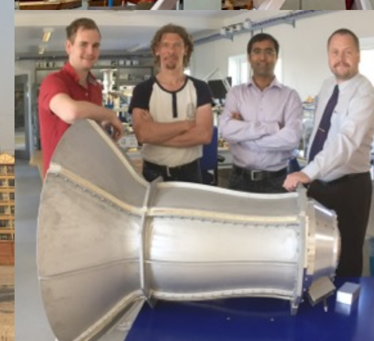
Garcia-Miro+ 1903.08627

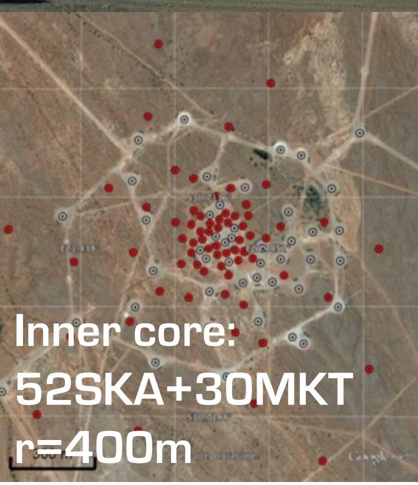
4. SKA

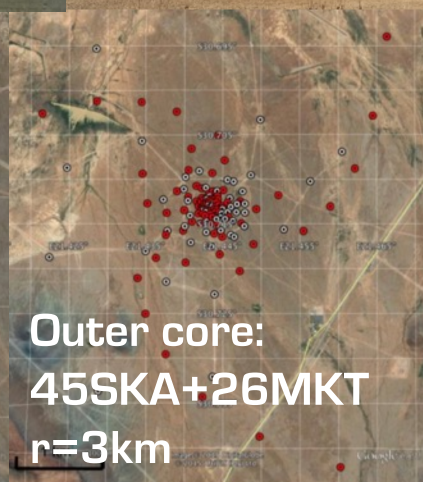
DISH: 0.35 GHz – 15 (50) GHz

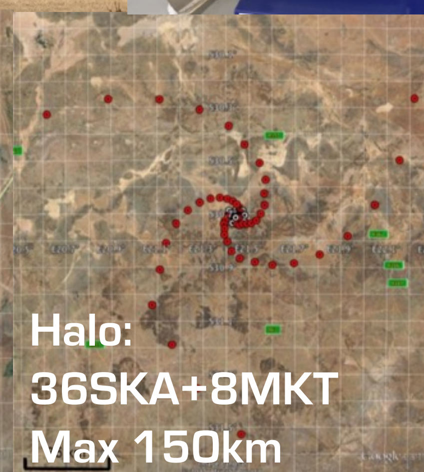




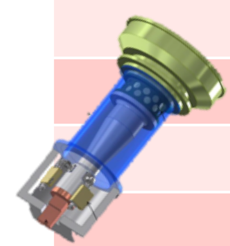








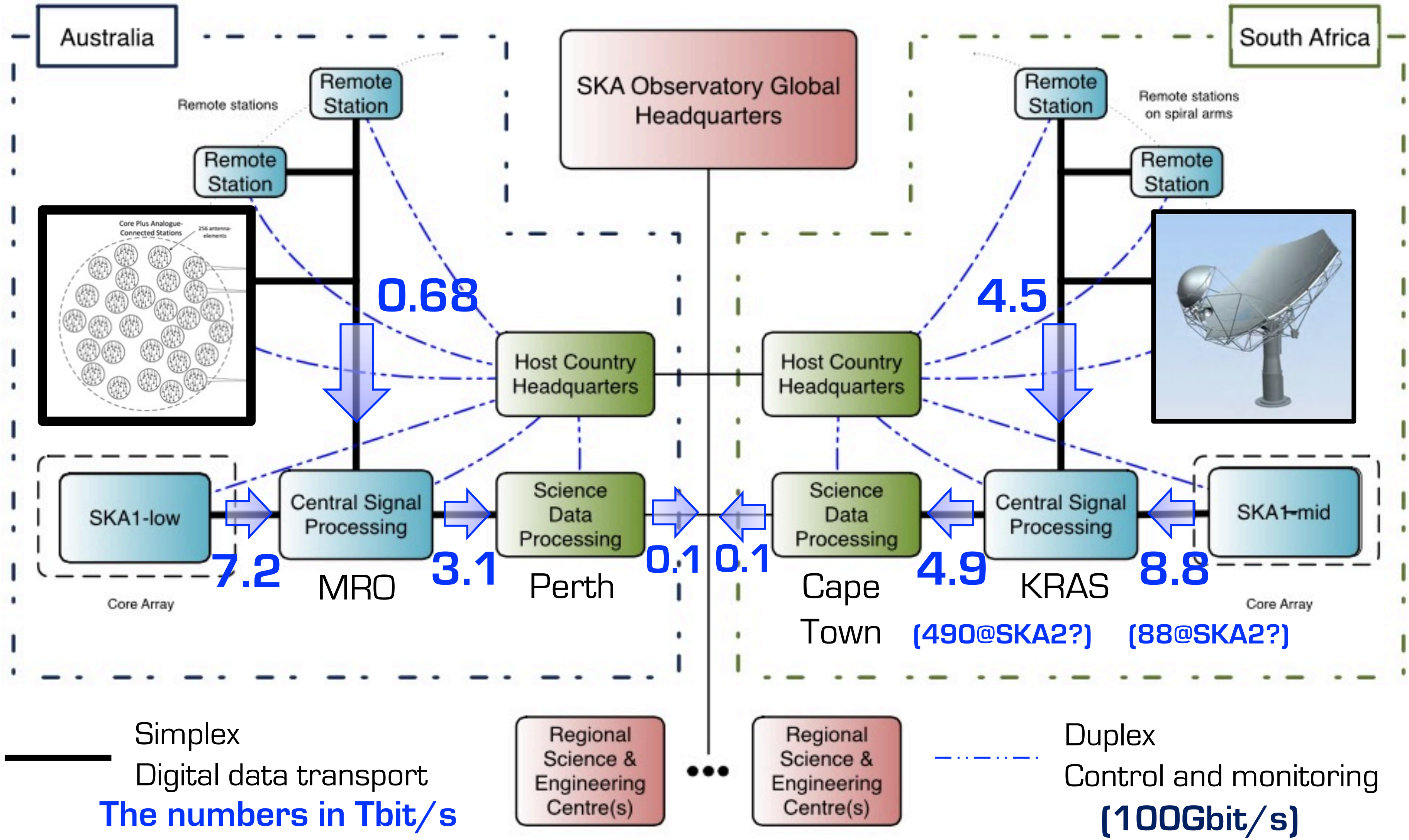
Telescope		Freq. (GHz)
LOW		0.05-0.35
MID	1	0.35-1.05
	2	0.95-1.76
	3	1.65-3.05
	4	2.80-5.18
	5a	4.60-8.50
	5b	8.00-15.3
	6	15-25
	7	25-50



Or wideband 6+7

1. SKA Status Report

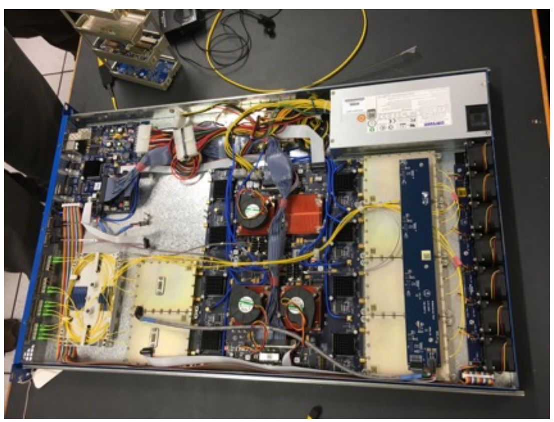
SKA Data Transport



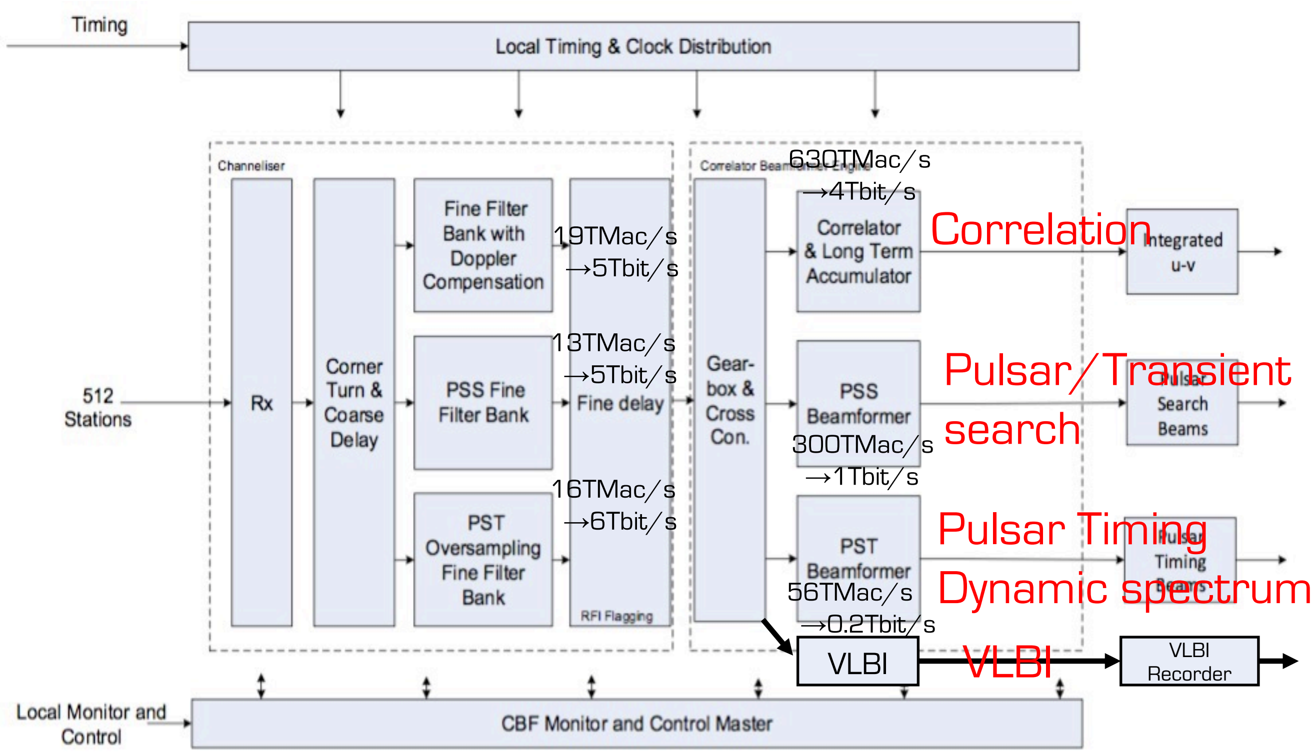
CSP: Central Signal Processor

- Realtime, simultaneous operation with any combination of imaging, pulsar/transient search, pulsar timing/dynamic spectrum, VLBI
- The switching time between telescope observing modes shall take less than 30 seconds (not including dish slewing time)

Gemini FPGA LRU
by G. Hampson



ASKAP/MWA's
CSP system



COR: Max 323,776 BLs, PSS: Max 1500 beams, PST: Max 16 beams

26 Frequency Slice Processors

***Example #1:** Band 5 full-bandwidth imaging: One sub-array performing full-bandwidth Band 5 imaging:*

Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams
1	5	5000.0	0	0	0.0	0		

- *In this case, ~324k channels/pp³/baseline are available, which can be pruned with post-correlation channel averaging and/or channel selection prior to transport to the SDP. Each FSP processes a 200 MHz Frequency Slice, so 13 are required to process each of the 2.5 GHz data streams, for a total of 26 FSPs.*

***Example #2:** Band 2 + Band 5: Two sub-arrays with (1) central array core for Band 2 (L-band) imaging, pulsar search, pulsar timing, concurrent with (2) long-baseline (out of core) Band 5 imaging:*

Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams
1	2	810.0	8	1500	810.0	16		
2	5	2500.0						

- *In this case, in Band 2 ~60k channels/pp/baseline are available. The correlator produces ~15k channels for each zoom window. The tuning and bandwidth of each zoom window is independent, with bandwidths anywhere from 100 MHz to 3 MHz in octave steps.*
- *In Band 5, 162k channels/pp/baseline are available, which can be pruned with post-correlation channel averaging and/or channel selection prior to transport to the SDP.*
- *The IMAG function requires one FSP per 200 MHz Frequency Slice, so covering 2500 MHz in Band 5 requires 13 FSPs. Five of those same FSPs are required to handle the full 810 MHz of Band 2 in the other subarray, leaving 13-5= 8 free to provide zoom windows in that subarray. The 1500 PSS beams require 1500/192 (rounded up)= 8 further FSPs, and another 5 are required to cover the 810 MHz bandwidth of PST beams in that subarray. The total number of FSPs is then 13 IMAG + 8 PSS-BF + 5 PST-BF= 26 FSPs.*

***Example #3:** Targeting multiple spectral lines in Band 5: Entire array in Band 5 with 26 zoom windows, each one tunable within any 200 MHz frequency slice and each with bandwidths from 200 MHz to 3 MHz. Total number of channels is 26 x ~15k = 390k/pp/baseline; similar channel pruning as above can be performed or channels can be integrated longer to reduce the data rate to the SDP:*

Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams
1	5	0.0	26					

- *With one FSP required for each zoom window, the 26 zoom windows here require 26 FSPs. Note that one could for instance position all 26 such windows within a single 200 MHz frequency slice.*
- *Similar use of zoom windows can occur in any Band. For example, in Band 2 with 20 zoom windows, ~300k channels/pp/baseline are available.*

***Example #4:** VLBI beamforming and concurrent imaging, pulsar search, and pulsar timing in Band 2:*

Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams
1	2	810.0	3	1500	810.0	16	810.0	2

- *One FSP is required for each 200 MHz of continuum BW, so 5 FSPs are required to cover the 810 MHz of BW. Each zoom window requires one FSP, so an additional 3 are required for that function. 1500/192 (rounded up)=8 FSPs are needed to produce the PSS beams, and 810/200 (rounded up)= 5 more are required for PST beamforming. Finally, the VLBI beams also require 810/200 (rounded up)= 5 FSPs. The total then is 5+3 IMAG plus 8 PSS-BF plus 5 PST-BF plus 5 VLBI= 26 FSPs.*

***Example #5:** Full Band 5 continuum bandwidth, with other sub-arrays full continuum as well as with zoom windows since all 26 FSPs are in IMAG function mode and the processing resources are available anyway:*

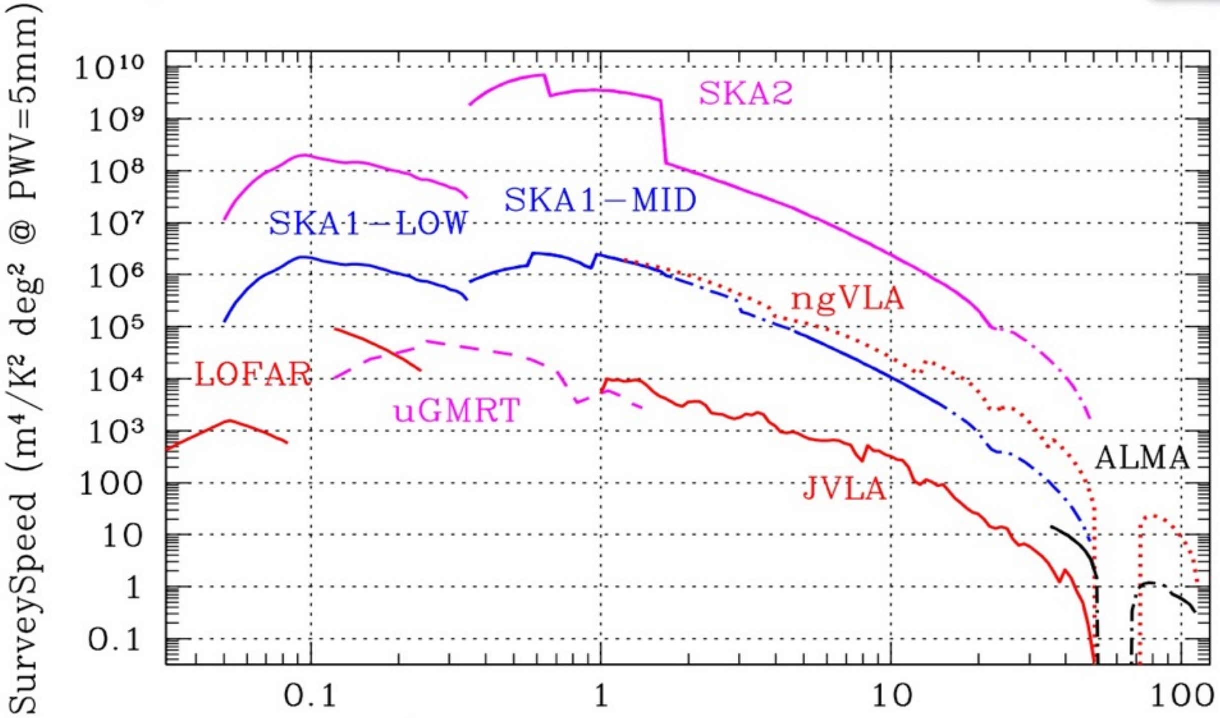
Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams
1	5	5000.0						
2	1	700.0	22					
3	2	810.0	21					
4	3	1400.0	19					
5	4	2380.0	14					

***Example #6:** On the following page is a CBF setup showing 16 sub-arrays, each with different observing goals, indicating the allocation of FSPs to the various functions (e.g. "N_PSS_FSPs" is the number of FSPs allocated to PSS beamforming, etc.).*

Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams	Subarray N_imag_FSPs	Subarray N_PSS_FSPs	Subarray N_PST_FSPs	Subarray N_VLBI_FSPs
1	1	700.0	5	500	700.0	4	600.0	2	9	2.604	4	3
2	2	810.0	5	1000	810.0	4	600.0	2	10	5.208	5	3
3	3	1400.0	3						10	0.000	0	0
4	5	2000.0			1000.0	4			10	0.000	5	0
5	5	2000.0			1000.0	4			10	0.000	5	0
6	5	2000.0					600.0	2	10	0.000	0	3
7	5	2000.0					600.0	2	10	0.000	0	3
8	5	1000.0	5						10	0.000	0	0
9	4	2000.0							10	0.000	0	0
10	4	2000.0							10	0.000	0	0
11	4	2000.0							10	0.000	0	0
12	3		10				600.0	2	10	0.000	0	3
13	3		10				600.0	2	10	0.000	0	3
14	3		10				600.0	2	10	0.000	0	3
15	2		10						10	0.000	0	0
16	2		10						10	0.000	0	0

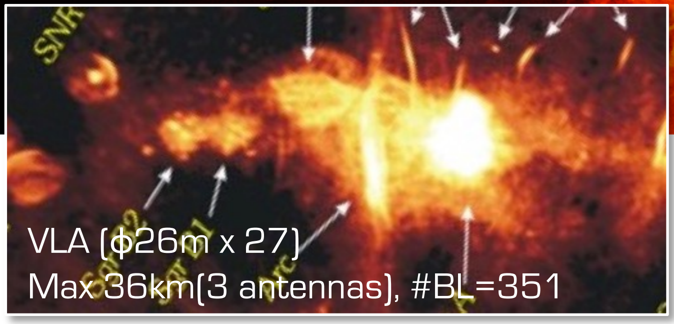
Leaps: Survey Speed and Image Quality

- Figure of merit S = FOV x Sensitivity
- S(SKA1) ~ S(ngVLA) >> x100 S(JVLA) around 1-10 GHz
- SKA1's uv coverage > JVLA's A^{+}+A+B+C+D+E



Frequency [GHz]

4. SKA
The Power of Image Quality



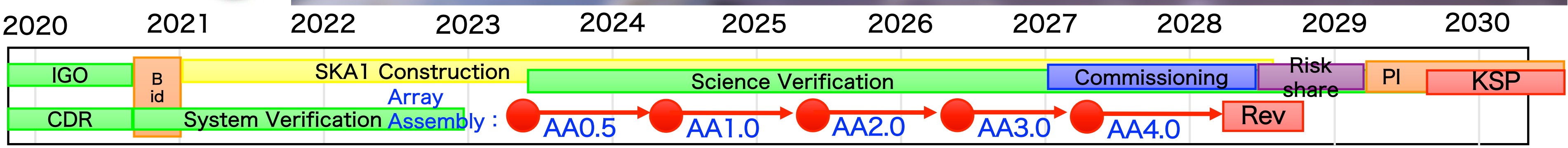
MeerKAT(ϕ13.5m x 64)
Max 8km(8 antennas), #BL=2016

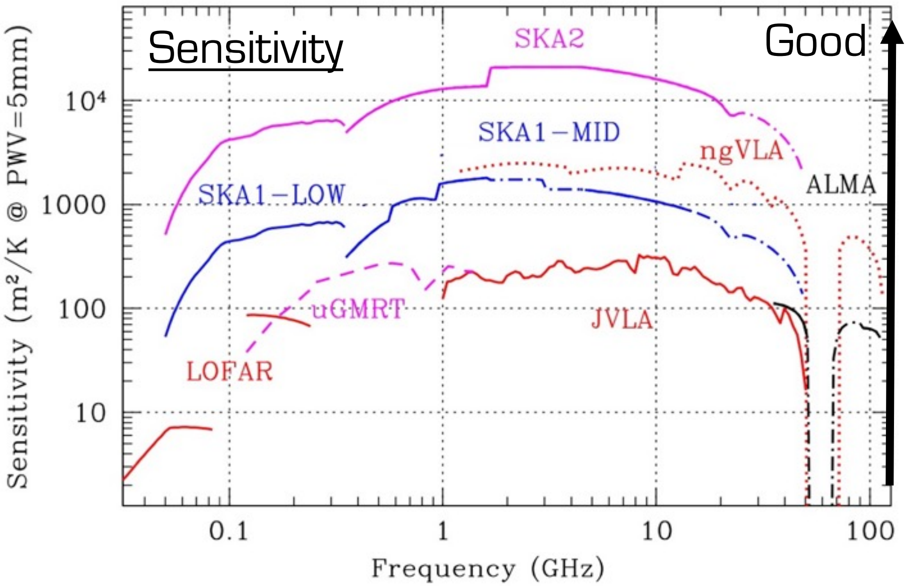
4. SKA

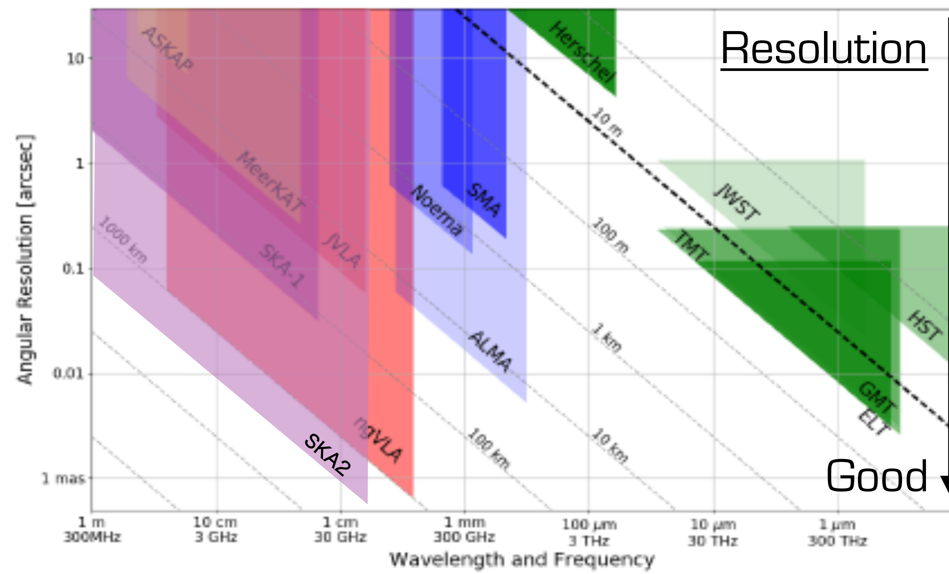
MeerLICHT

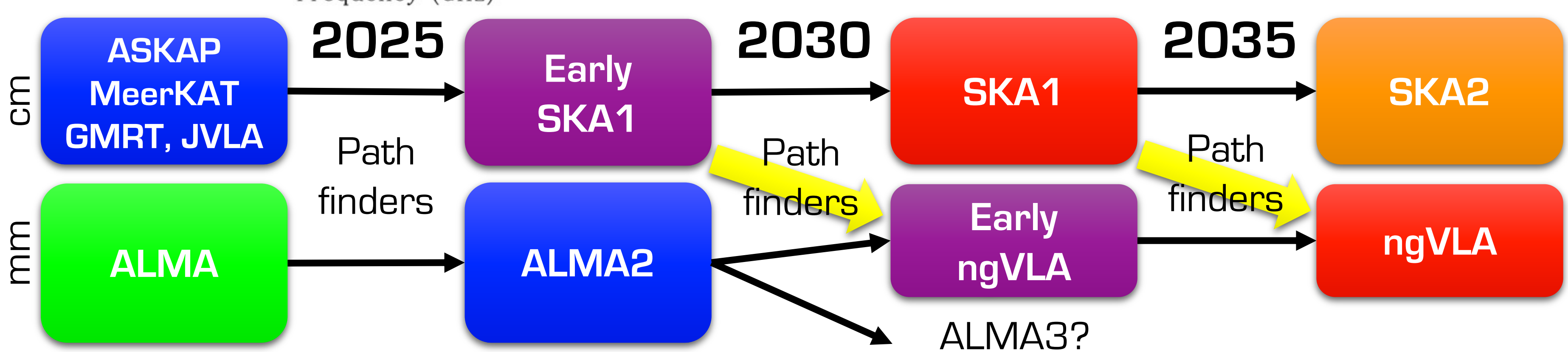
- A fully robotic 0.65m telescope at the Sutherland of the South African Astronomical Observatory
- The largest 100-megapixel CCD provided by STA, giving a FoV of MeerKAT (2.7 square degrees).
- The science is strongly linked to the ThunderKAT and TRAPUM MeerKAT Large Survey Projects and covers a broad range of astrophysical transients.
- We will, for the first time ever, provide optical multi-band observations of every night-time observation conducted by a radio telescope, ensuring that every transient in the field of view will be simultaneously covered in the radio and the optical.
- Opens up the regime of simultaneous, short time-scale radio-optical correlations in dwarf novae, novae, X-ray binaries, pulsars, fast radio bursts, supernovae, gamma-ray bursts, active galactic nuclei, gravitational wave events and sources yet unknown

4. SKA
The Era of SKA1/SKA2 and ngVLA









4. SKA

Science Keywords of SKA

Cosmic plasma Magnetism Galaxies AGN

Stars Neutron stars FRB Black hole

Hot Universe

LOW	Band 1	Band 2	3/4	Band 5ab	6	7

0.05 0.3 1.0 1.4 1.6 6.7 15 22 43 Freq. (GHz)

MWA/LOFAR	ASKAP/MeerKAT/Parkes	JVN	VERA/KaVA

SETI ?? GHz

HI (EoR)

HI (ext. galaxies)

HI (Milky Way)

OH*

CH_3OH*

HCN

Amino acid

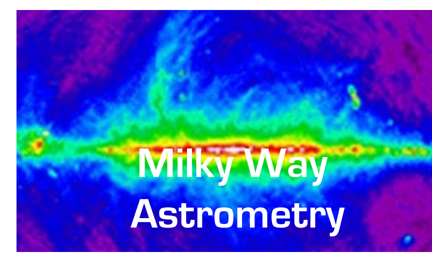
H_2CO

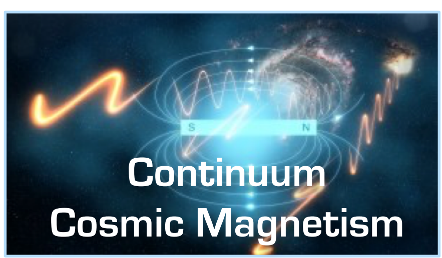
H_2O*

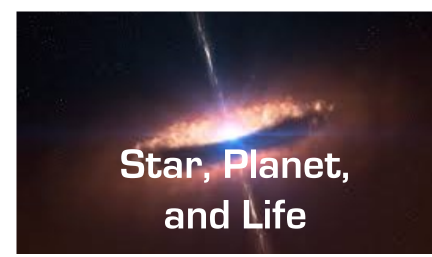
NH_3

SiO*

Cold Universe

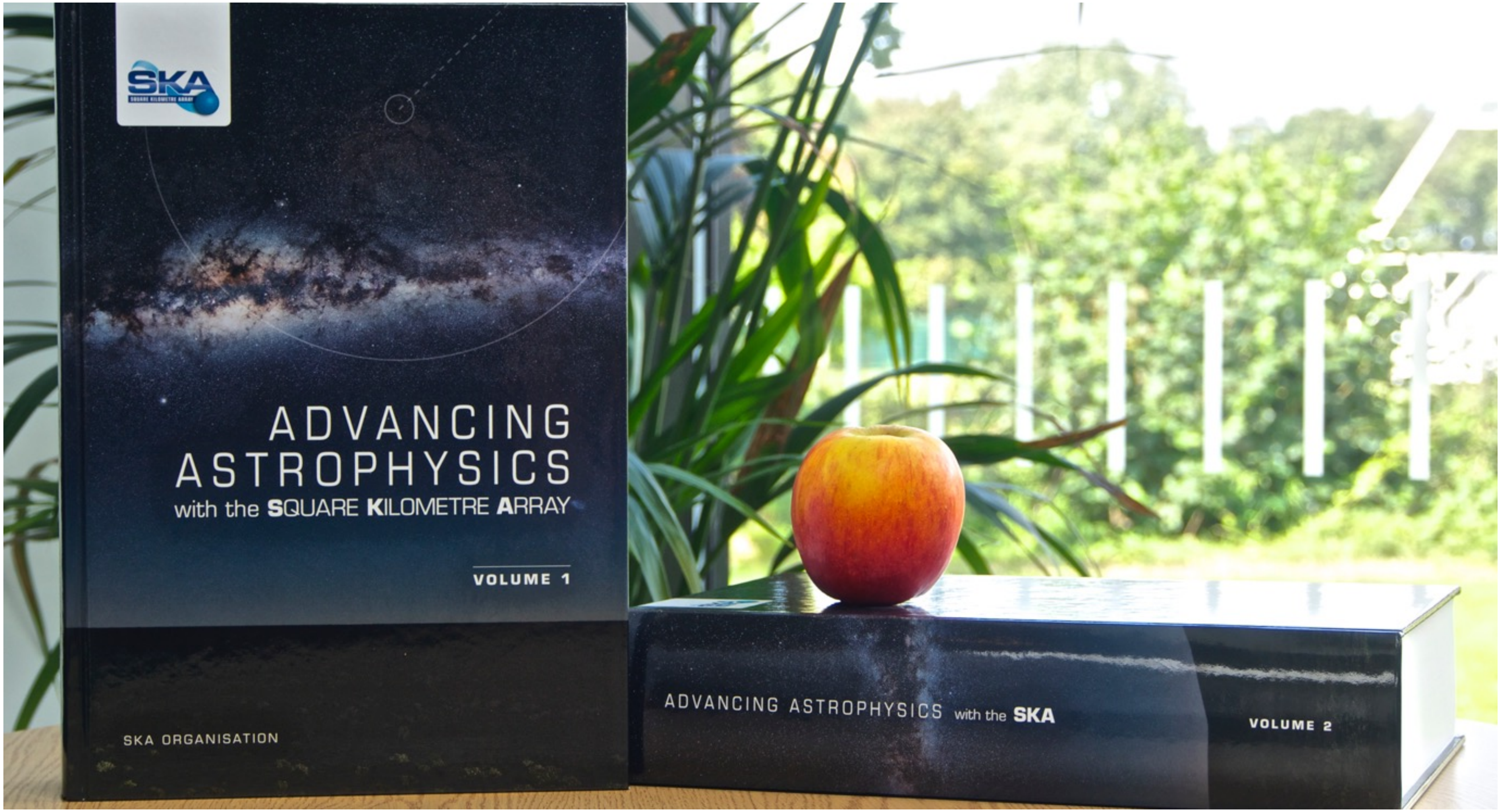






SKA Science Book 2015

■http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=215



SQUARE KILOMETRE ARRAY
NAOJ SKA1 STUDY GROUP

4. SKA
Highest Priority Science Objectives

SWG (AASKA ID)	Measurement objectives	Measurement requirements		Instruments	Instrument Requirements			Data Products			
		Frequency Low-High MHz	Sensitivity RMS Noise Min:Max @ Beam @ Bandwidth		Spec. DR (Imx/Imn) dB	Brigh. DR (Imx/Imn) dB	Polari. DR (Imx/Pmn) dB	Total Area deg²	Res. arc sec	Total time hour	Time per pointing hour
EOR (001)	EoR images	50-200	1.4:100 mK @ 300" @ 1 MHz	LOW	50	50	45	100	10	5000	2000
EOR (001)	EoR deep power spectra	50-200	4.6:330 mK @ 300" @ 1 MHz	LOW	50	50	40	1000	10	5000	200
	EoR wide power spectra	50-200	14:1000 mK @300" @ 1 MHz	LOW	50	50	35	10k	10	5000	20
PSR (040)	Search pulsars	150-350	20uJy/bm @ 145" @ cont	LOW	30	30	25	30k	320	13k	40min
	Search pulsars	650-950	20 uJy/bm @ 65" @ cont	B1	30	30	25	2400	105	800	10min
	Search pulsars	1250-1550	7 uJy/bm @ 45" @ cont	B2	30	30	25	2400	60	2400	10min
PSR (037)	Measure timing	150-350	10 uJy/bm @ 8" @ cont	LOW	30	30	40	-	8	4300	40min
	Measure timing	950-1760	3 uJy/bm @ 7" @ cont	B2	30	30	40	-	7	1600	15min
HI (128)	Measure high z HI	790-950	16 uJy/bm @ 2-10" @ line	B1	30	50	35	5.4	3.5	5000	1000
HI (129)	Measure low z HI	1300-1400	14 uJy/bm @ 2-10" @ line	B2	30	50	30	3.8	3.5	2000	200
HI (130)	Measure Galactic HI	1415-1425	75 uJy/bm @ 2-10" @ line	B2	30	45	30	1080	5	13k	4.4
Trans (055)	Search/Measure FRB	650-950	7 mJy/bm @ 65" @ cont	B1	30	30	25	30k	105	10k	2msec
CoL (117)	Planet formation	8000-12000	80 nJy/bm @ 0.04" @ cont	B5	30	40	25	0.05	0.04	6000	600
Mag (092)	Get RM grids	1000-1700	7 uJy/bm @ 2" @ cont	B2	30	45	30	31k	2	10k	7.4min
Cos (019)	High z intensity mapping	350-1050	3.3 mJy.bm @ 1.7 deg @ line	B1	45	40	40	30k	-	10k	2.2
Cos (032)	Measure ISW and Dipole	1000-1700	7 uJy/bm @ 2" @ cont	B2	30	45	30	31k	2	10k	7.4min
Cont (067)	SFR wide	1000-1700	1.3 uJy/bm @ 0.5" @ cont	B2	30	60	30	1000	0.5	10k	3.8
	SFR deep	1000-1700	0.25 uJy/bm @ 0.5" @ cont	B2	30	60	30	7.8	0.5	2000	95
	SFR ultra deep	1000-1700	65 nJy/bm @ 0.5" @ cont	B2	30	60	30	0.38	0.5	2000	2000
	SFR wide	7000-11000	400 nJy/bm @ 0.05 @ cont	B5	25	45	30	0.5	0.05	1000	16.4
	SFR ultra deep	7000-11000	50 nJy/bm @ 0.05 @ cont	B5	25	45	30	025	0.05	1000	1000

4. SKA

Operation

■How can we access to the data?

① Propose **Key Science Projects (70%)**
② Propose **PI-led Programs (25%)**
③ Propose PI-led Open-sky (5%)
④ Wait for public release (1-2 years after the delivery of the data)

Need cash/in-kind contributions to the construction (for ① and ②)
NAOJ would provide the opportunity of access to Japanese community
Japan's target = 1-3% (<40億円)

■Proposal type for transient observation

- **Target of Opportunity (ToO)**
  - ✓ Submit your proposal during the regular call for proposal. Write clear triggering criteria to perform the observation. Telescopes will join on the best effort basis
- **Director's Discretionary Time (DDT)**
  - ✓ Unexpected or urgent ToO can be submitted as DDT proposals anytime. If the observatory director approves DDT, telescopes will join on the best effort basis

■SKAO staffs operate the SKA telescope instead of users

- Community/Board are considering "**Open Alert System**" like Atel (Astronomer's Telegram), GCN (Gamma-ray Coordination Network), etc

■Data is delivered to the SKA Regional Centers (SRCs)

- China SRC in East Asia. Japan may join it or have our owns
- CASA-like? Fits. IVOA (international virtual observatory alliance)

Japan SKA Consortium

#211 (2018.4)

Chair
N. Sugiyama (Nagoya)

Advisors
H. Kobayashi, M. Honma (NAOJ)

Vice Chairs
K. Takahashi (Kumamoto), H. Nakanishi (Kagoshima)

NAOJ liaison
T. Akahori (NAOJ) → NAOJ HQ, Government

Outreach
T. Handa (Kagoshima)

Outreach
K. Hasegawa (Nagoya)

Funding
H. Imai (Kagoshima)

Engineering WG
T. Aoki (Yamaguchi) → VLBI

Industry Forum
T. Kumazawa (TOYO Co.) → Industry

- **UHF receiver** – T. Akahori (NAOJ)
- **Backend** – Y. Kono (NAOJ)
- **Tomography** – S. Ideguchi (NAOJ)

Science WG
K. Ichiki (Nagoya) → Physics

- **High-z** – H. Hirashita (ASIAA)
- **Epoch of Reionization** – K. Hasegawa (Nagoya)
- **Cosmology** – D. Yamauchi (Kanagawa)
- **Galaxy Evolution** – T. Takeuchi (Nagoya)
- **Magnetism** – S. Ideguchi (NAOJ)
- **Transients** – K. Niinuma (Yamaguchi)
- **Pulsar** – K. Takahashi (Kumamoto)
- **Astrometry** – H. Imai (Kagoshima)
- **ISM** – M. Machida (Kyushu)
- **Star & Planet Form.** – Y. Tsukamoto (Kagoshima)
- **Plants (new!)** – TBD

AUS ← **MWA-Japan**
Tashiro, Ouchi
Yajima, et al.
#13

Int'l SWG ← **Int'l SWG**
S. Inoue
et al.
#22

4. SKA
Transients SWG

■Chair: K. Niinuma

- Theorists
- Radio astronomers
- Others

■Monthly Zoom telecon

- Review recent papers
- Share transients info.
- Study science use cases
- Write a white paper
- Co-proposal

■Please join us!

http://ska-jp.org/ws2015/SKA-JP/talks/SKAJP_Science_Book_2015.pdf

名前	所属
青木 貴弘	山口大学
赤堀 卓也	国立天文台
廣田 朋也	国立天文台
小山 友明	国立天文台
新沼 浩太郎	山口大学
端山 和大	福岡大学
高橋 慶太郎	熊本大学
亀谷 收	国立天文台
寺澤 敏夫	東京大学
Eie Sujin	東京大学/国立天文台
榎戸 輝揚	京都大学
木坂 将大	東北大学
井上 進	理化学研究所
長瀧 重博	理化学研究所
前田 啓一	京都大学
浦田裕次	国立中央大学 (台湾)
伊藤裕貴	理化学研究所
岩井一正	名古屋大学
Lee Shiu-Hang (Herman)	JAXA
柴田一成	京都大学
戸谷友則	東京大学
本間希樹	国立天文台
宇野友理	東京大学
山崎翔太郎	東京大学

Summary: Low Frequency Radio Observation of Transient High-Energy Phenomena

■Polarization and Magnetism

- Magnetic field in the cosmic web
- RM measurement and Faraday Tomography

■Fast Radio Burst

- A new extragalactic messenger
- Two types (Repeaters=dwarf-SFG/One-offs=MWtype-G)?

■Magnetar Radio Outburst

- Analogy to FRB
- VLBI astrometry to understand the origins of strong-B & MRO

■SKA Project

- Construction from 2021, full operation in 2028
- Multi-mode, widefield observation