EUROPEAN ARC
ALMA Regional Centre || Allegro

Radboud Universiteit Nijmegen

EventHorizonTelescope

Event Horizon Telescope Technical Implementation & Spring 2015 mmVLBI Campaign

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Allegro, ALMA ARC node, Leiden Observatory, Netherlands

European Affiliations through BHC + MIT/Haystack

MAX-PLANCK-GESELLSCHAFT

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

JIVE JOINT INSTITUTE FOR VLBI IN EUROPE

ESO

MIT HAYSTACK OBSERVATORY

erc

EHT Technical Working Group

EventHorizonTelescope

ETWG was convened in the summer of 2013

Objectives:

1. Survey the capabilities at all EHT facilities
2. Establish a set of specifications for future EHT observations
3. Outline a technical developments needed to reach these goals
4. Based on prioritized science objectives, formulate a project roadmap for the EHT that is grounded in technical feasibility with the resources available

Remo Tilanus (chair), *IMAPP, Radboud University**

Geoff Crew, *MIT Haystack*

Yusuke Kono, *NOAJ*

Dan Marrone, *Univ. of Arizona*

Satoki Matsushita, *ASIAA*

Vincent Piétu, *IRAM*

Dick Plambeck, *CARMA*

Alan Roy, *MPIfR*

Jonathan Weintroub, *SAO*

and

Shep Doeleman, *PI EHT*

(expert & advisory role)

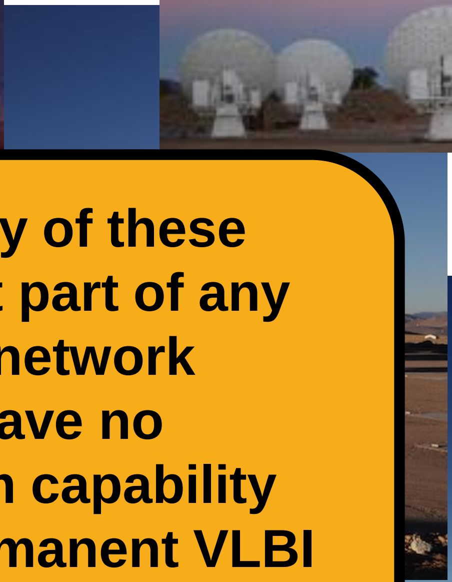
* *Project Manager ERC Synergy Project BlackHoleCam*

EHT Stations

+ GLT, Llama, …?

EHT Stations



Note: Majority of these telescopes not part of any (mm)VLBI network & many have no 7mm and 3mm capability (nor, so far, permanent VLBI equipment)



+ GLT, Llama, …?

EHT Specifications

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1. VLBI single-dish signal-chain:
   - ***64 Gbps***
   - *Downconverter + R2DBE or DBBC3 + Mark 6 recorders*
2. IF Range for sideband-separating VLBI (64 Gbps):
   - *1.3 mm: 5-9 GHz*
   - *0.8 mm: 4-8 GHz*
3. LO frequency for observations :
   - *1.3 mm: 221.1 GHz*
   - *0.8 mm: 342.3 GHz*
4. Dual-polarization observations standard
5. Polarization products formed at correlator
   - *desirable long term, but default for ALMA and functionality being added to DiFX*
6. Optimization: Semi-turnkey systems, **'flexible scheduling'**, eVLBI, VLBI reduction pipeline

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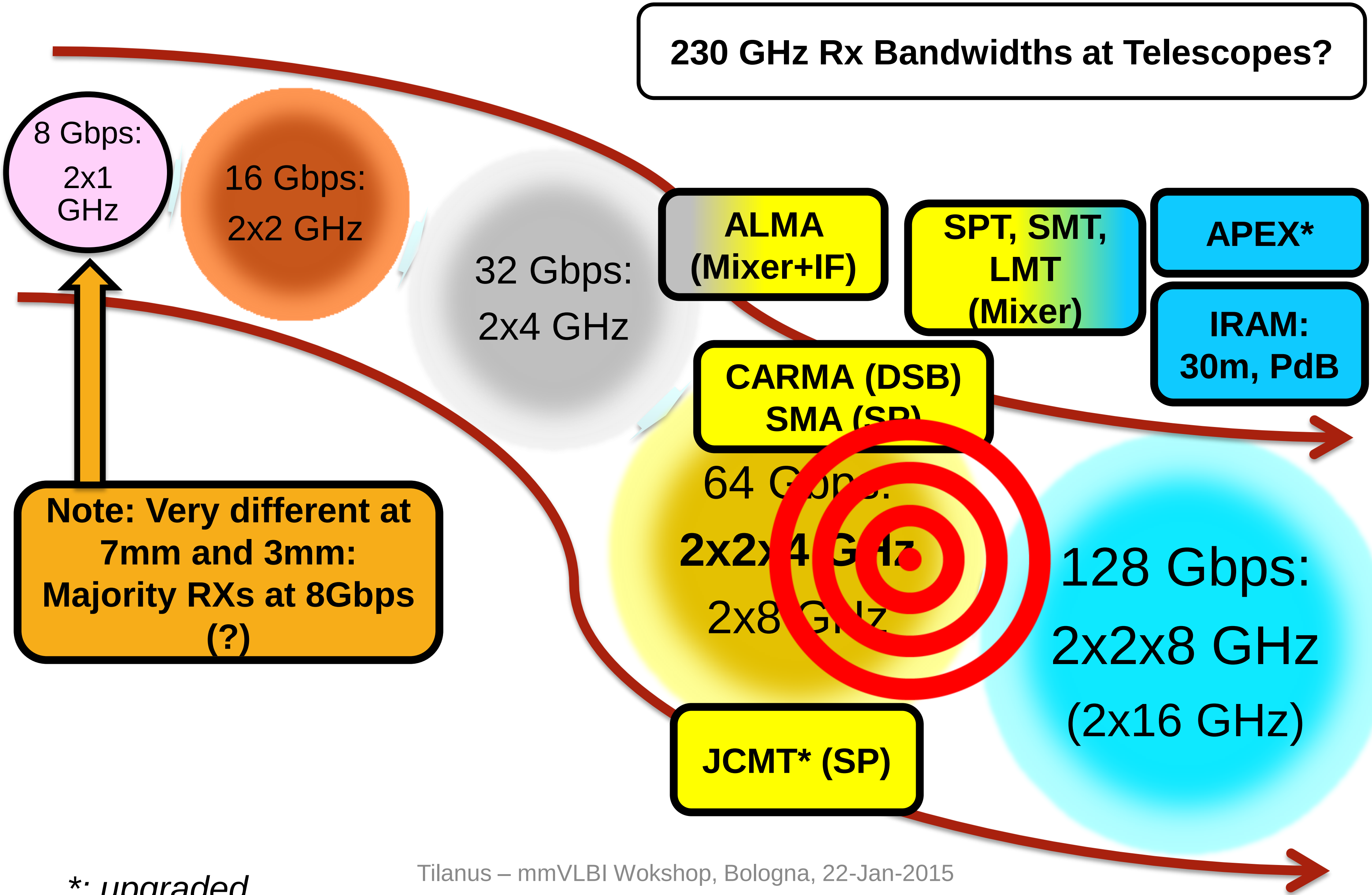
Note: unlike at 3mm, 'flexible scheduling' will be critical for 1.3mm and 0.87mm VLBI

Target mmVLBI bandwidth



*: upgraded

Next-Gen mmVLBI Equipment

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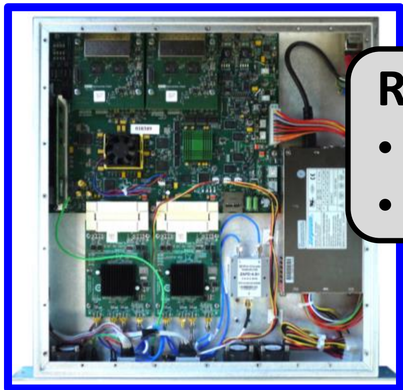
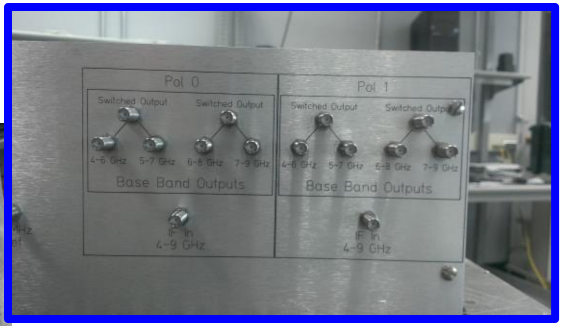



R2DBE (SAO)
- 16 Gbps
- 2 x 2 GHz


Mark-6 (Conduant)
- 16 Gbps
- 4 modules
- 32 disks (@6Tb =192 TB)

DBBC3 (INAF/MPIfR/OSO)
- 16 to 64 Gbps
- n x 4 GHz



Haystack-SRON/NOVA Block-Downconverter
- 2x2 GHz within 4-9 GHz

Next-Gen mmVLBI Equipment

Next Gen Equipment:
- **R2DBE**: n*16 Gbps or **DBBC3:** 16-64 Gbps
- **Mark-6**: 16 Gbps

8 Gbps: 2x1 GHz

16 Gbps: 2x2 GHz

32 Gbps: 2x4 GHz

64 Gbps:
2x2x4 GHz
2x8 GHz

128 Gbps:
2x2x8 GHz
(2x16 GHz)

1 Mark6/station + total 2.6 PB (440 6TB disks)

4 Mark6/station + total 10.5 PB (1750 6TB disks)

8 Mark6/station + total 21 PB (3500 6TB disks)

7-station VLBI run 5 “nights” of 16 hours @ 65% duty cycle

Next-Gen mmVLBI Equipment

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Next Gen Equipment:
- **R2DBE**: n*16 Gbps or **DBBC3:** 16-64 Gbps
- **Mark-6**: 16 Gbps

8 Gbps: 2x1 GHz

16 Gbps: 2x2 GHz

32 Gbps: 2x4 GHz

64 Gbps: **2x2x4 GHz** 2x8 GHz

128 Gbps: 2x2x8 GHz (2x16 GHz)

EHT Target:
64 Gbps

per station:
- 4 R2DBEs or DBBC3
- 4 Mark-6
- 32 disks modules

(256 6TB disks: 1.5 PB)

2x2x4 GHz

IF-range 230 GHz (2SB setup)

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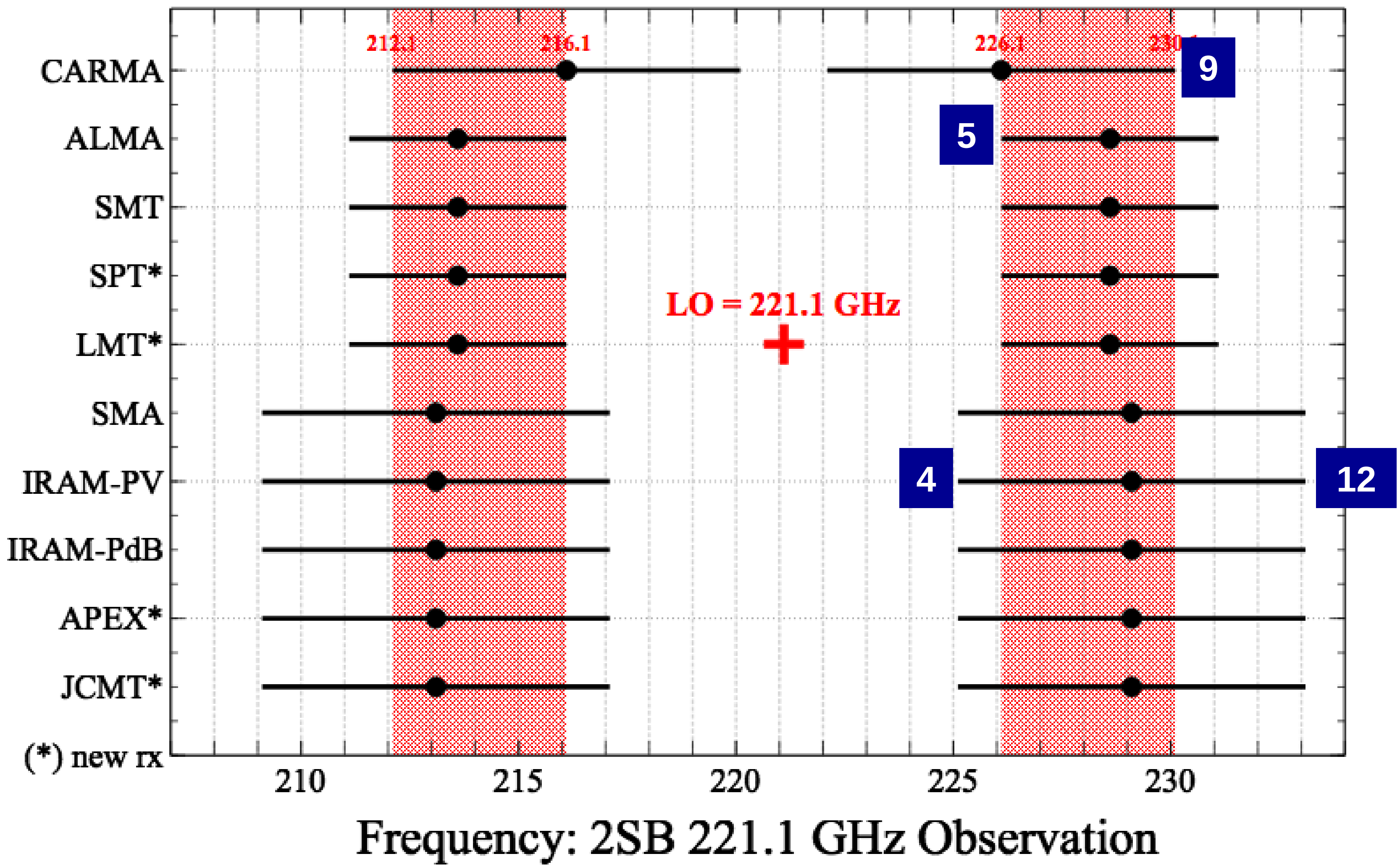
IF Range: 5-9 GHz Only!



Note: 0.87 mm will use IF Range 4-8 GHz

Next-Gen Downconverter

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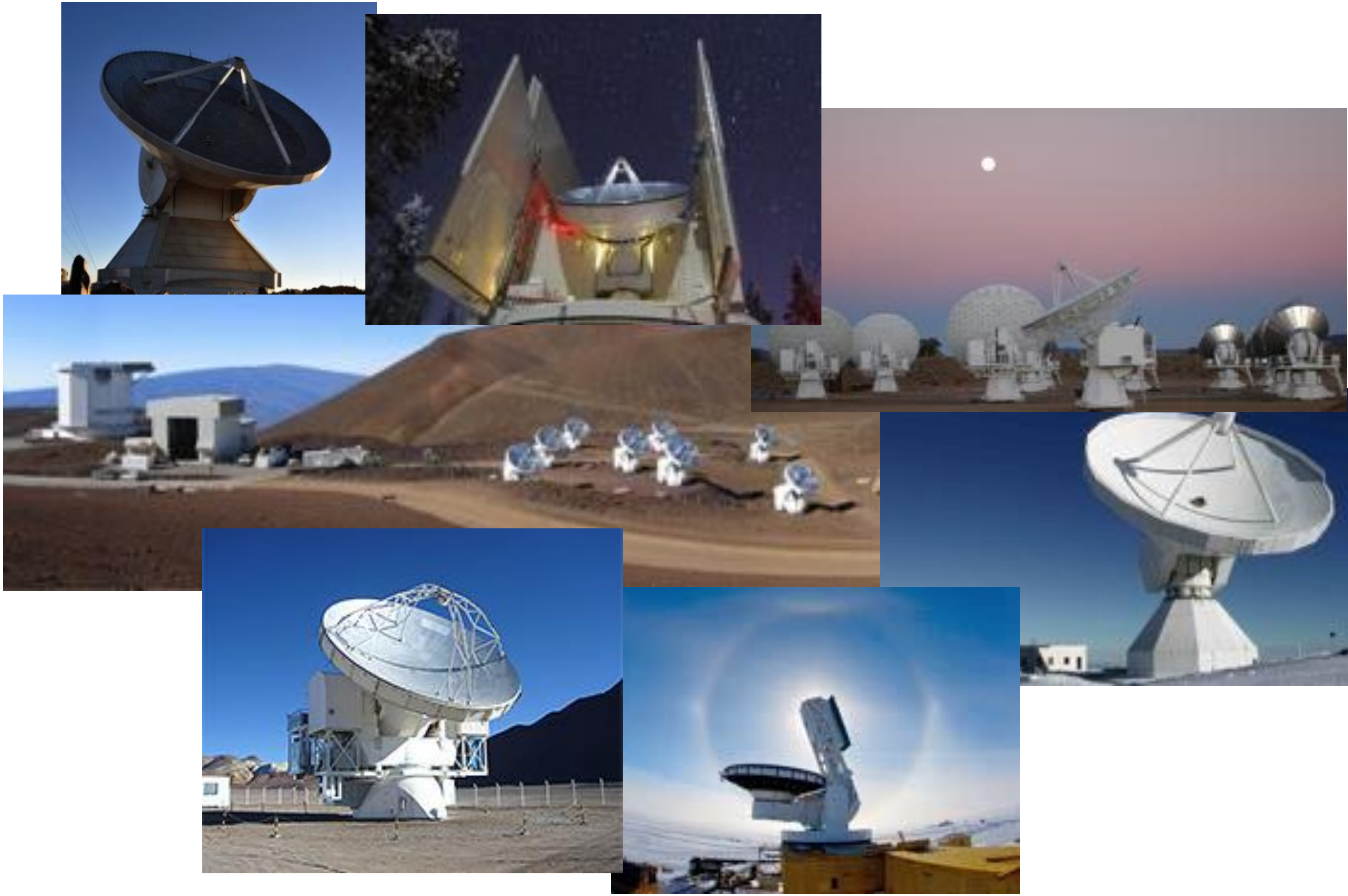
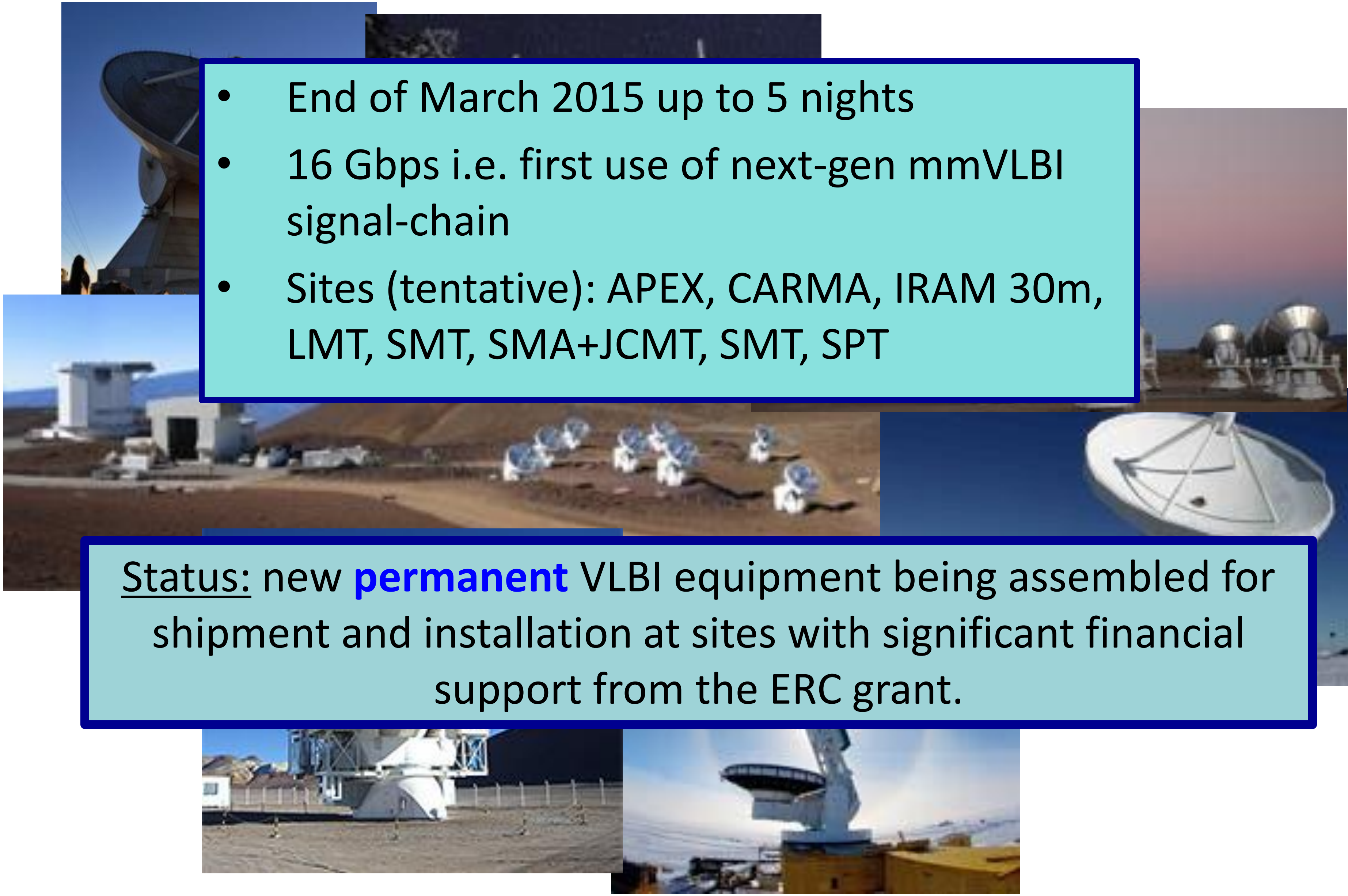
- For use with the R2DBE:
  - 2x4 GHz to 4x2 GHz in baseband (0-2 GHz)
  - Haystack design, assembly by SRON/NOVA
- DBBC3 will use integrated downconverter

2015 mmVLBI Campaign

EventHorizonTelescope



2015 mmVLBI Campaign



- End of March 2015 up to 5 nights
- 16 Gbps i.e. first use of next-gen mmVLBI signal-chain
- Sites (tentative): APEX, CARMA, IRAM 30m, LMT, SMT, SMA+JCMT, SMT, SPT

Status: new **permanent** VLBI equipment being assembled for shipment and installation at sites with significant financial support from the ERC grant.

EHT – 32 Gbps (2 x 4 GHz 1SB/DSB)

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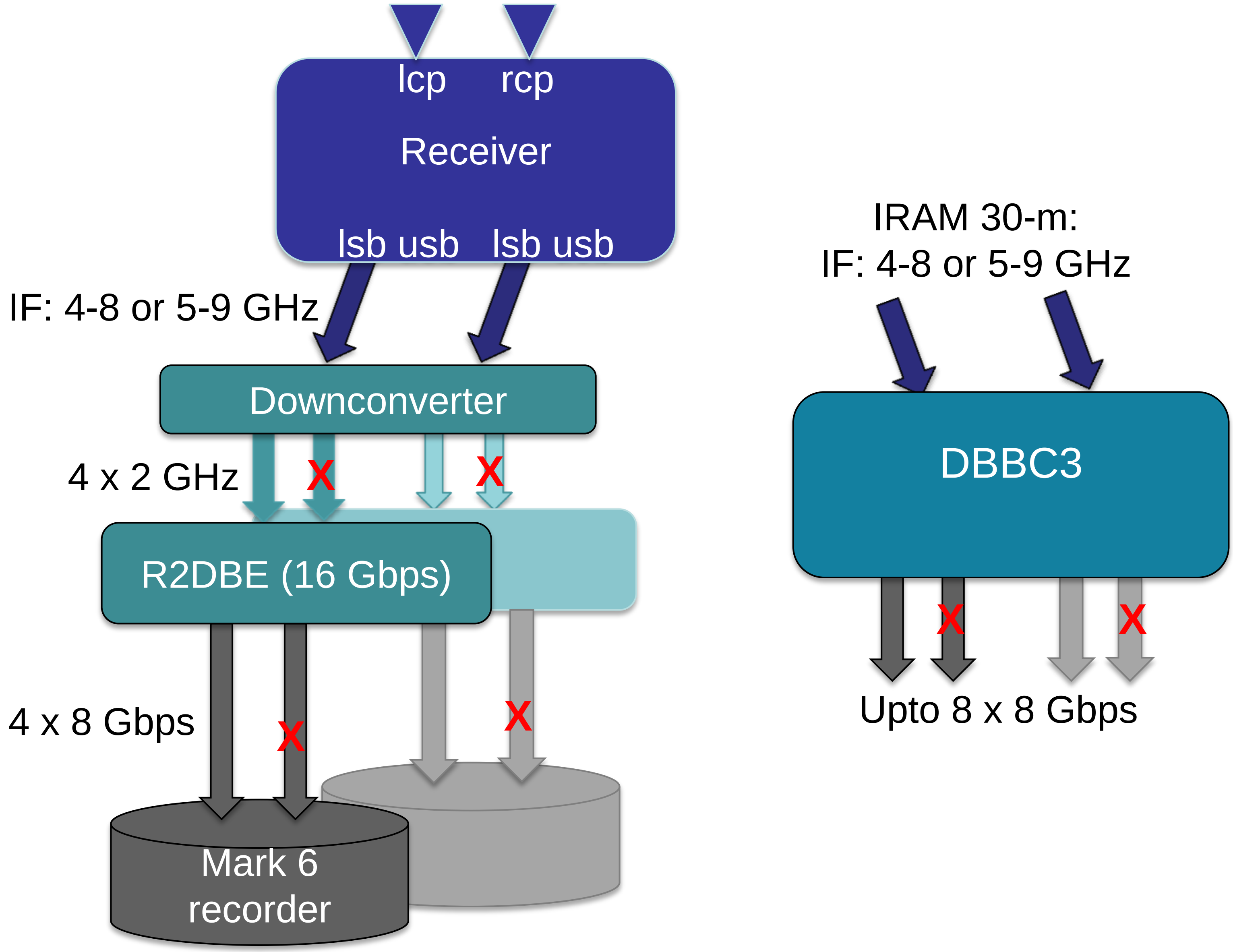
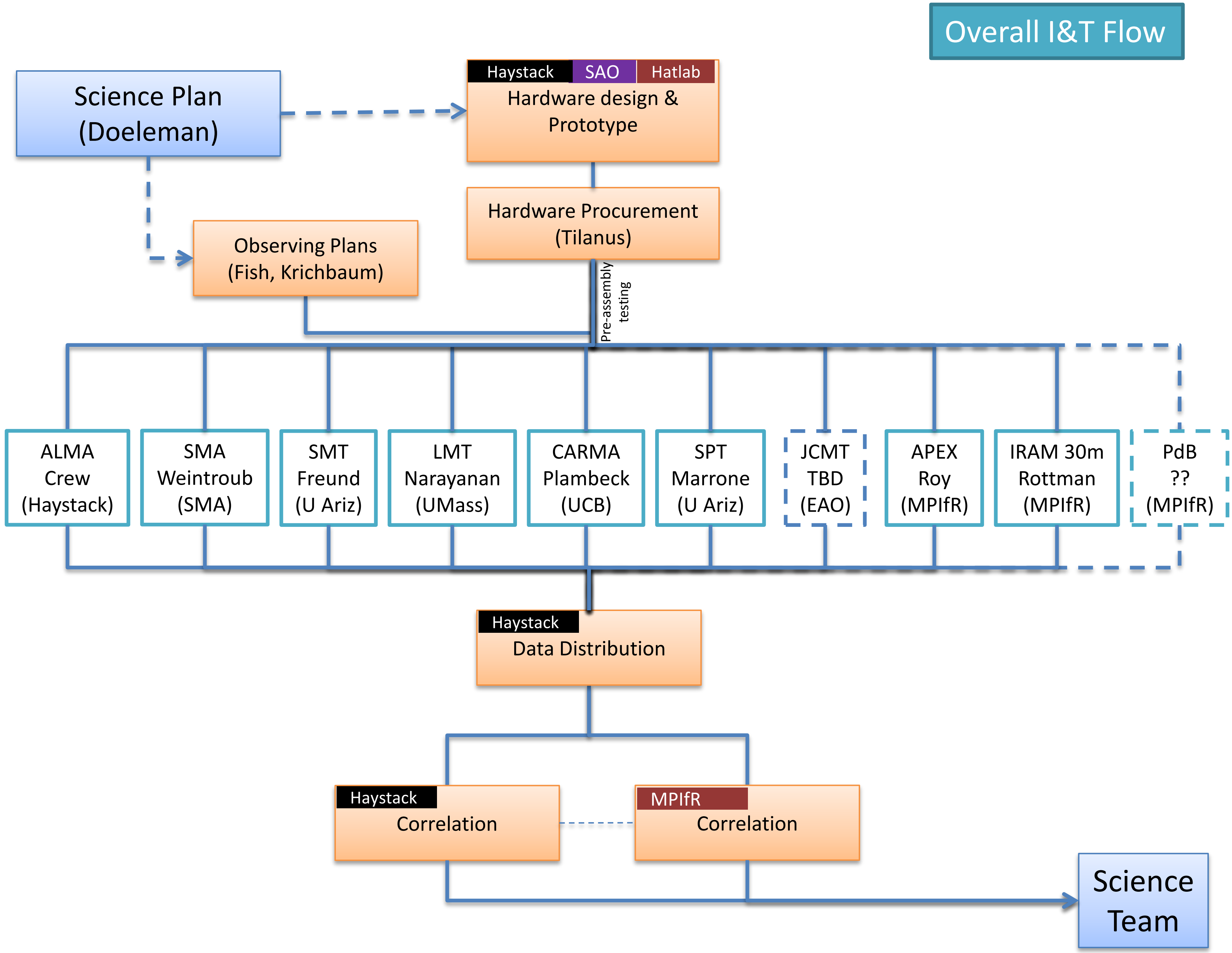
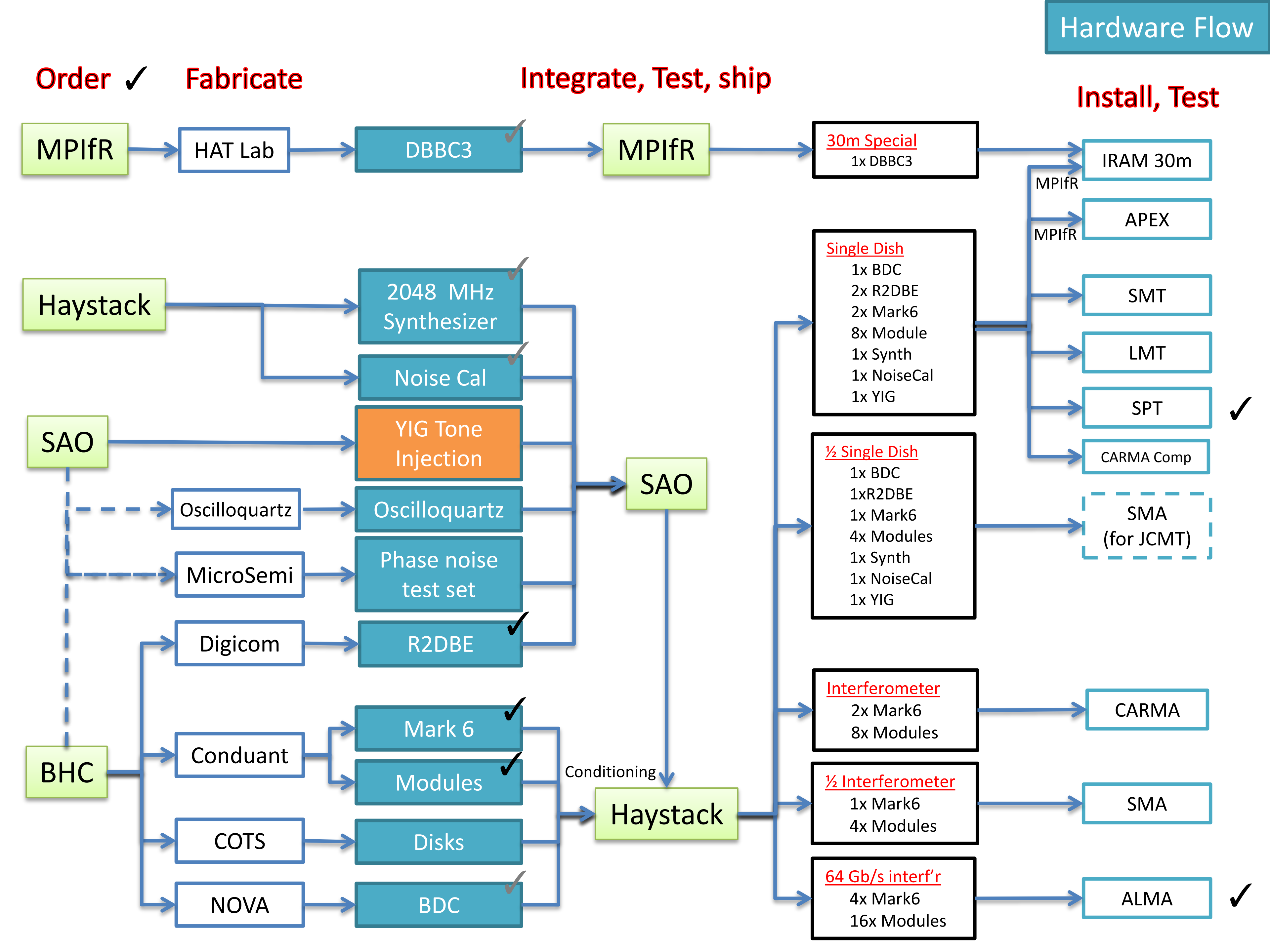


X: *spring 2015 will use two channels for 16 Gbps*


Overall I&T Flow
Science Plan (Doeleman)
Haystack
SAO
Hatlab
Hardware design & Prototype
Hardware Procurement (Tilanus)
Observing Plans (Fish, Krichbaum)
Pre-assembly testing
ALMA Crew (Haystack)
SMA Weintroub (SMA)
SMT Freund (U Ariz)
LMT Narayanan (UMass)
CARMA Plambeck (UCB)
SPT Marrone (U Ariz)
JCMT TBD (EAO)
APEX Roy (MPIfR)
IRAM 30m Rottman (MPIfR)
PdB ?? (MPIfR)
Haystack
Data Distribution
Haystack
Correlation
MPIfR
Correlation
Science Team


Hardware Flow
Order ✓
Fabricate
Integrate, Test, ship
Install, Test
MPIfR
HAT Lab
DBBC3
MPIfR
30m Special
1x DBBC3
IRAM 30m
MPIfR
APEX
MPIfR
Haystack
2048 MHz Synthesizer
Noise Cal
SAO
YIG Tone Injection
Oscilloquartz
Oscilloquartz
MicroSemi
Phase noise test set
Digicom
R2DBE
SAO
Single Dish
1x BDC
2x R2DBE
2x Mark6
8x Module
1x Synth
1x NoiseCal
1x YIG
SMT
LMT
SPT ✓
CARMA Comp
½ Single Dish
1x BDC
1xR2DBE
1x Mark6
4x Modules
1x Synth
1x NoiseCal
1x YIG
SMA
(for JCMT)
BHC
Conduant
Mark 6
Modules
Conditioning
Haystack
COTS
Disks
NOVA
BDC
Interferometer
2x Mark6
8x Modules
CARMA
½ Interferometer
1x Mark6
4x Modules
SMA
64 Gb/s interf'r
4x Mark6
16x Modules
ALMA ✓

Possible 2015 EHT Observations

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(mmVLBI)

Commissioning – Jan. 2015

- *Dates: January 8-17*
- *Band: 1.3 mm*
- *Capability goal:*
  - *Dual polarization (circ)*
  - *2 GHz bandwidth*
  - *16 Gb/s*
- *Targets:*
  - *TBD*
- *Participants:*
  - *ALMA (single dish)*
  - *APEX*
  - *SPT*
  - *(OSF?)*

Observation – March 2015

- ***Dates: March 20-30***
  - ***5 nights***
- ***Band: 1.3mm***
- ***Capability goal:***
  - ***Dual polarization (circ)***
  - ***2 GHz bandwidth***
  - ***16 Gb/s***
- ***Targets:***
  - ***Sgr A*, M87, Others***
- ***Participants:***
  - ***SMT***
  - ***LMT***
  - ***SMA***
  - ***JCMT?***
  - ***CARMA***
  - ***APEX (single pol)***
  - ***SPT? (If receiver present)***
  - ***IRAM 30m***
  - ***ALMA 1-dish (cal sources)?***

Commissioning – May 2015

- ***Dates: (GMVA session?)***
- ***Band: 3 mm***
- ***Capability goal:***
  - ***Dual polarization (circ)***
  - ***0.5 - 2 GHz bandwidth***
  - ***4 - 16 Gb/s***
- ***Targets:***
  - ***TBD***
- ***Participants:***
  - ***ALMA***
  - ***IRAM 30m***
  - ***PdeB***
  - ***Haystack?***
  - ***VLBA***
  - ***LMT***

Conclusions & Remarks

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- EHT well-underway to realize a 32 (64) Gbps array for mmVLBI at 1.3mm and poised to push ahead to 0.87mm. As such it is a ***pathfinder*** for but is not a common-user, open-access mmVLBI facility.
- The < 1.3mm array is mostly ***complementary*** to e.g. the GMVA at 3mm, rather than overlapping: extending existing networks to higher frequencies involves agreements with new observatories.
- EHT capabilities will maximally exploit capabilities at ALMA. That appears not the case for capabilities at most 7 and 3mm observatories (with notable exceptions such as IRAM, LMT). This suggests as a ***priority objective to expand capabilities at the longer wavelengths***.
- "Routine" high-frequency mmVLBI requires ***flexible scheduling i.e. semi-turnkey systems*** (and smooth integration with telescope operations). This appears less the case at lower frequencies where classical scheduling is adequate.
- To support wide range of general science mmVLBI observing modes will need to be expanded beyond those that support "event-horizon science".

Conclusions & Remarks

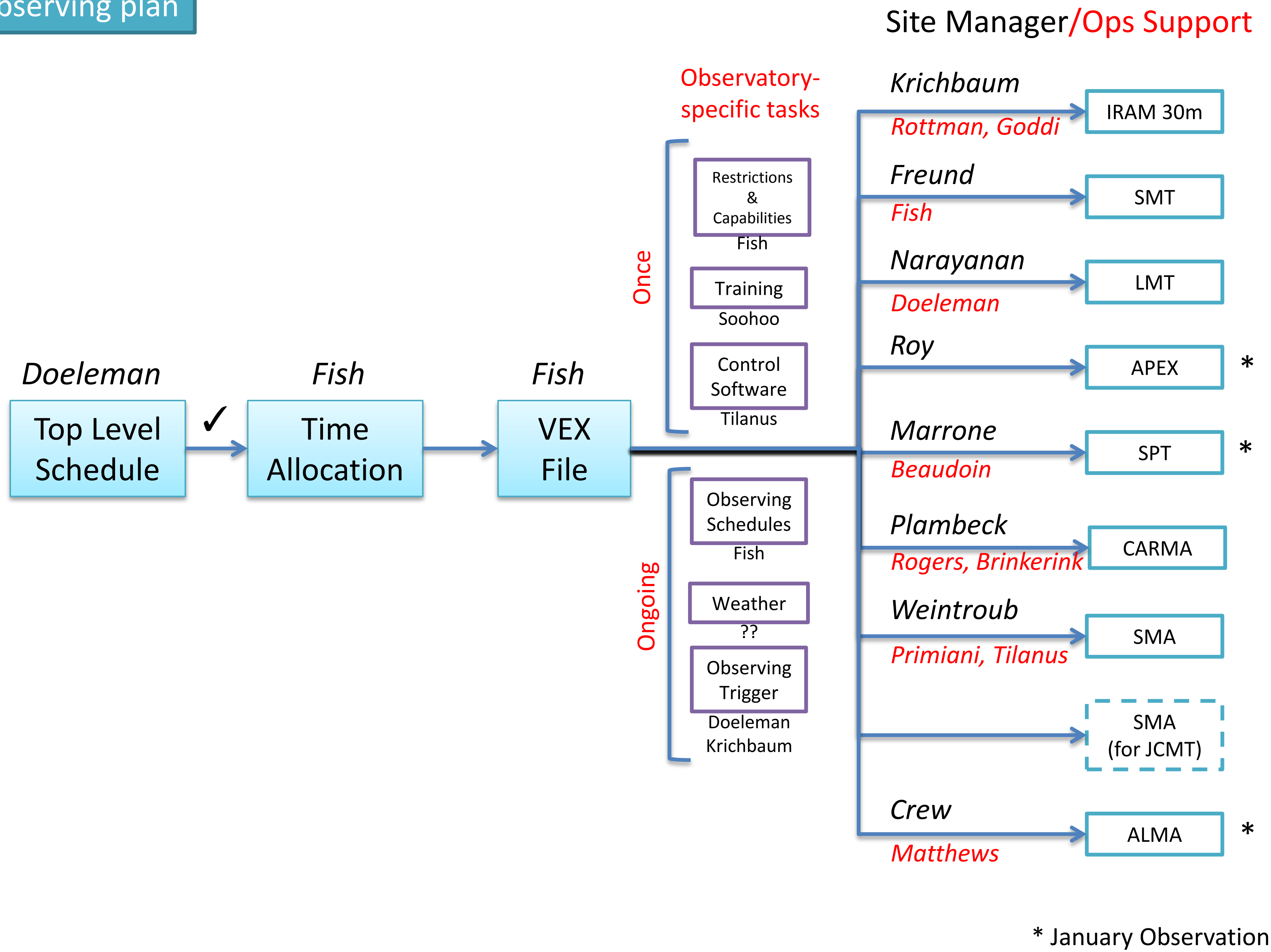
EventHorizonTelescope

My(!) assessment of road-map towards high-frequency mmVLBI with ALMA:

- Regarding open-access, common-user mmVLBI with ALMA, existing networks (e.g. GMVA) should (initially) concentrate on **3mm (and 7mm) mmVLBI**.
- 7 and 3mm facilities should actively pursue an **expansion of their capabilities** that allow to maximally exploit ALMA.
- Start discussions with high-frequency facilities on a **general mmVLBI network** that covers ALMA frequencies (whether as an expansion or successor of e.g. the GMVA)
- In the mean time and in close coordination with the above activities, **EHT** will continue as **pathfinder** to develop and implement necessary infra-structure at higher frequencies able to support general user access.
- At an appropriate time offer **< 2mm open-user mmVLBI** through the general mmVLBI network.

PAU

Observing plan



Optimization & Infra-structure

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- Correlation: data increase from 8Gbps & 3-5 stations to 64Gbps & 7+
  - Both correlators are being expanded
  - Based on commercial servers, DIFX software correlation
  - Already has to work in 2015, grow thereafter
- Flexibility and Remote Control
  - Current operation is manpower intensive, inflexible
  - Telescopes wish better integration with standard observing that can be supported by non-expert operators
  - Need remote monitoring and telescope control
- "Flexible scheduling" of VLBI i.e. no pre-determined fixed observing dates (but e.g. within encompassing VLBI blocks).
  - EHT also requires to benefit from best conditions at most sites.
  - New VLBI scheduling software

Optimization & Infra-structure

EventHorizonTelescope

- Quality assurance:
  - Near-time fringe verification on calibrators: e.g. port EVN Mark 5 eVLBI "snap-shot" mode to Mark 6
  - Standardize calibration practices
  - Remote monitoring
  - Special hardware (e.g., standardized tone injection, WVRs)

- Standard robust data products:
  - Pipeline reduction: port VLBI functionality to CASA?
  - Synthetic data:
    - *Key interface to science activities*
    - *Both theory and analysis*
  - Data management

(Software is focus of NSF ATI, NSF MSIP, ERC grants)

- New sites; general global mmVLBI facility
  - New sites: GLT, Llama, African submm telescope
  - GMVA successor for VLBI $\lambda < 7$mm

LO Freq at 0.8mm: 342.3 GHz

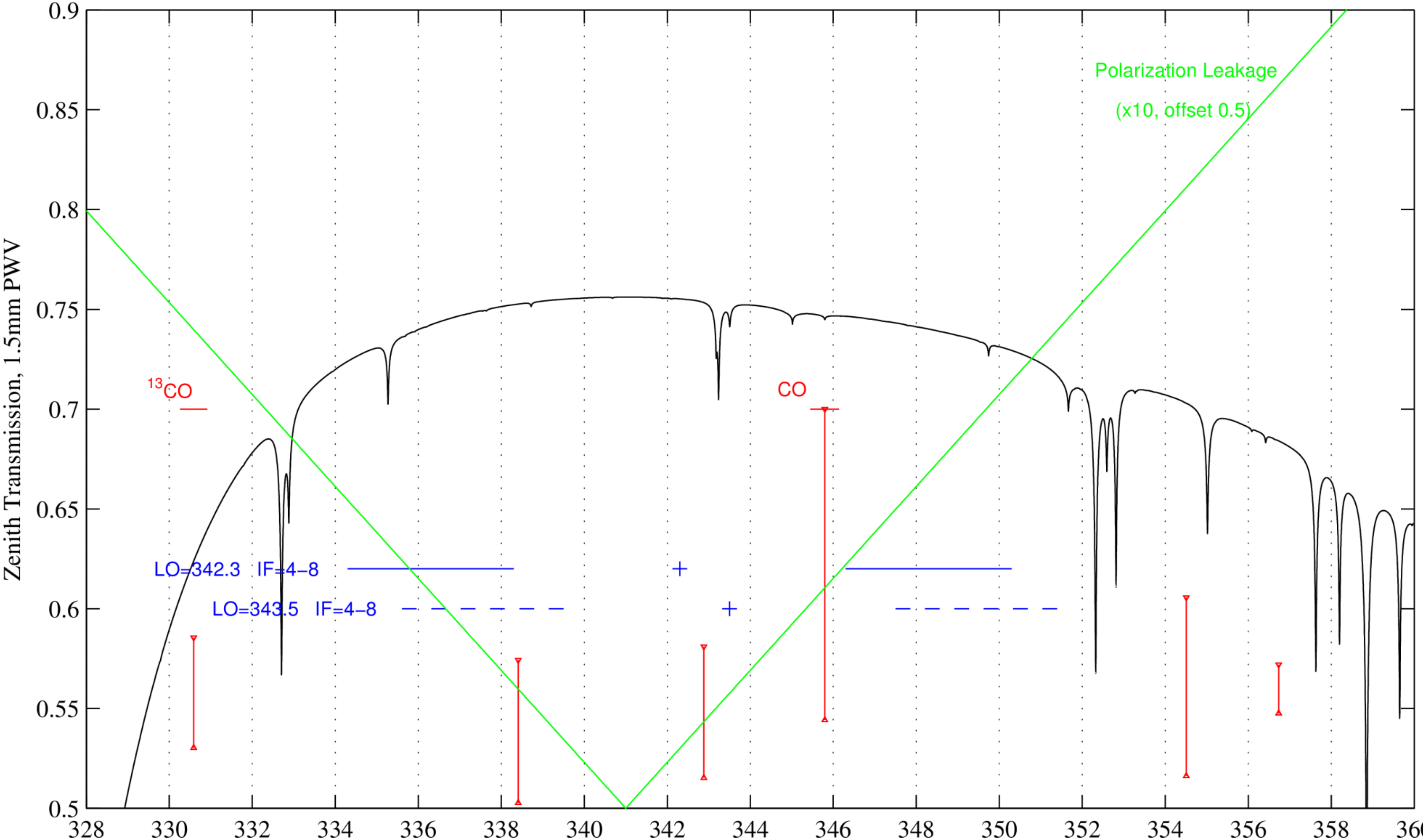

Figure courtesy Dan Marrone

Polarization

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In general: Polarizations at different telescopes do not automatically align

To-date: use polarimeter with 1/4-λ waveplates to convert to circular polarization.

Polarization will be discussed in talks by Dan Marrone and Ivan Marti-Vidal

	Circ Waveplate	Remote In/Out	Remote rotation
SMTO	y	n	n
SMA	y	y	y
CARMA	n/a	n/a	n/a
JCMT	y	n	y
APEX	y	n	n
LMT			
IRAM-PV	y	n	n
SPT	y	n/a	n
ALMA	n/a	n/a	n/a
IRAM-PdB	y	y	n

Polarization

EventHorizonTelescope

In general: Polarizations at different telescopes do not automatically align

(talk Ivan Marti-Vidal)

To-date: use 1/4-λ waveplates,

With dual-pol receivers: Switch to forming polarization products at correlator

➔Default at ALMA: being coded into DiFX.

Waveplate cons:

- Loss of sensitivity
- Insertion/setting not remotely controlled.
- Some existing systems require waveplate swaps between e.g. 1.3 and 0.8 mm.

➔Long-term, waveplates would require development suitable polarimeter

	Circ Waveplate	Remote In/Out	Remote rotation
SMTO	y	n	n
SMA	y	y	y
CARMA	n/a	n/a	n/a
JCMT	y	n	y
APEX	y	n	n
LMT			
IRAM-PV	y	n	n
SPT	y	n/a	n
ALMA	n/a	n/a	n/a
IRAM-PdB	y	y	n

Future mmVLBI bandwidths