WBS update & how to move for its implementation

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RECAP ON MAIN CONCEPTS

Work Breakdown Structure – scope & main features

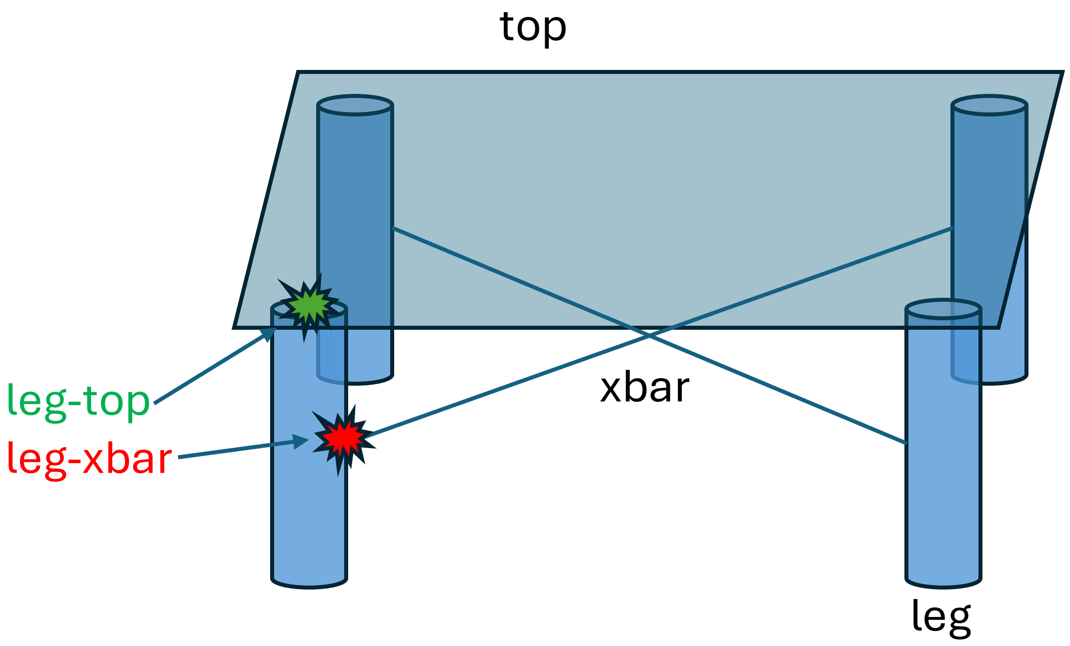
- Define hierarchical structure of activities to design, build, and operate ET
- Identify main systems
  - integrated systems
  - distributed functions
- Decompose systems into subsystems
- Decompose subsystems into tasks
- Decomposition should be suited for
  - proper **matching with PBS** elements
  - **scheduling**: identification of **causal dependencies** between **tasks** and **deliverables**
- For each system and for each subsystem identify:
  - required expertise
  - **one** coordinator (OBS)
  - a working team
    - people **in charge** for individual **tasks**

Work Breakdown Structure – project phases

- Specific activities will depend on project phase, but structure should be possibly kept throughout the project - **already needed to properly build TDR**
  - E.g. in wavefront sensing and control, task on ETM ring heaters
    - During preliminary design -> conceptual design & requirements definition of ring heaters
    - During technical design -> technical design of ring heaters
    - During construction –> RH parts procurement, RH assembly, RH installation
    - During commissioning –> RH tuning
    - During operations -> RH tuning, support for RH repair/replacement
    - During upgrades -> repeat cycle

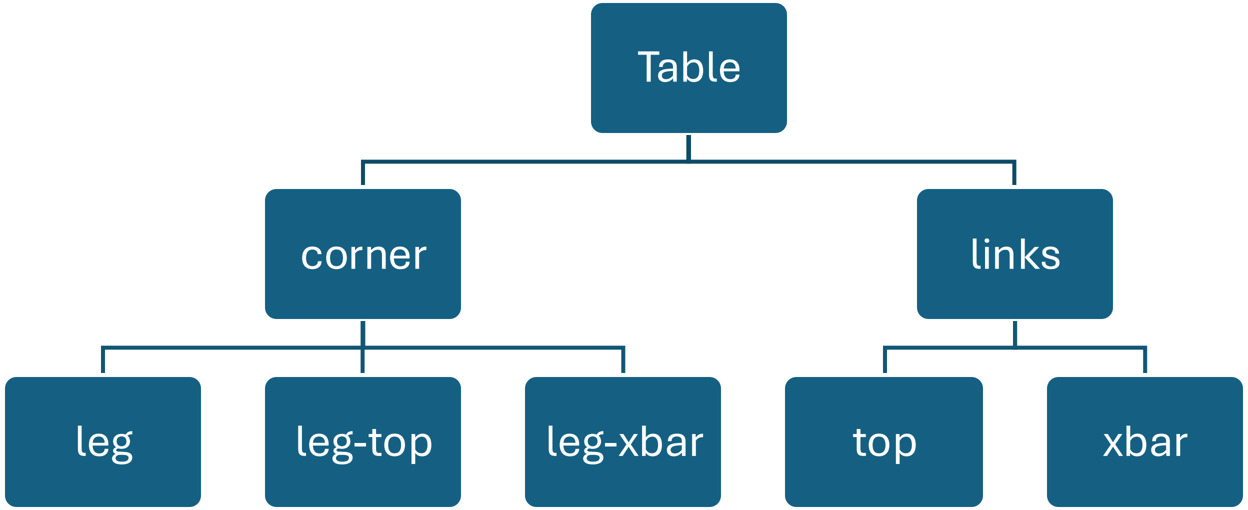
Functions vs system integration

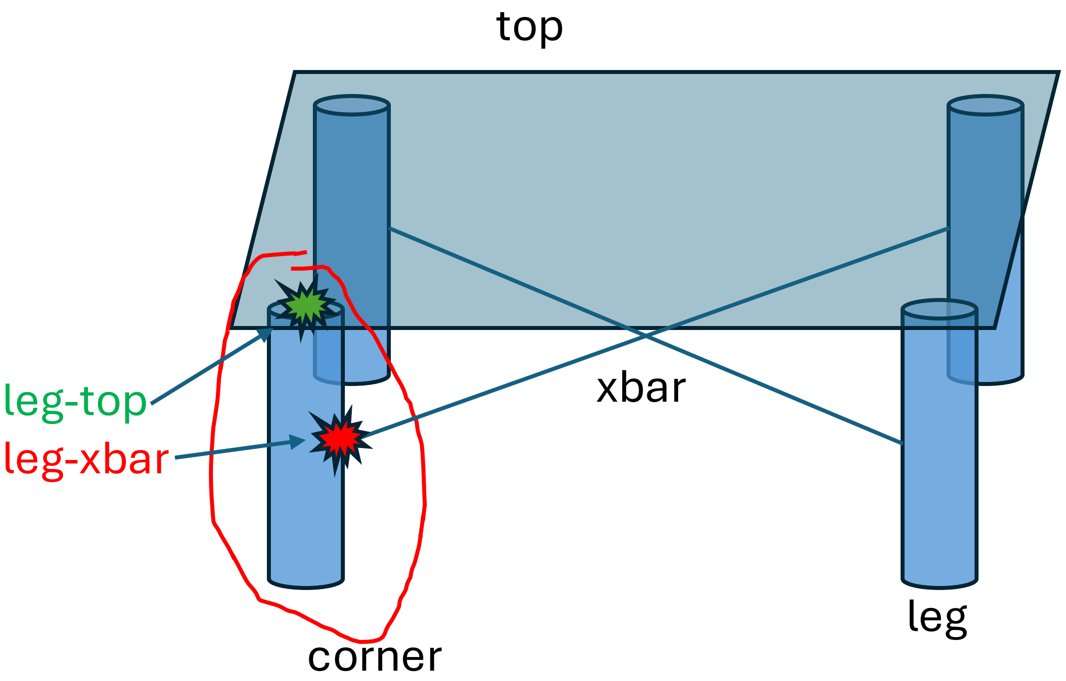
- Global functions require homogeneous and coherent design
  - planarity (legs relative height)
  - shape (top & xbar)
  - mechanics
    - legs position
    - top & xbar stiffnes
  - design top-> legs -> xbar & iterate
- Integration of several functions implies interfaces
  - leg-top
  - leg-xbar



Functions vs system integration

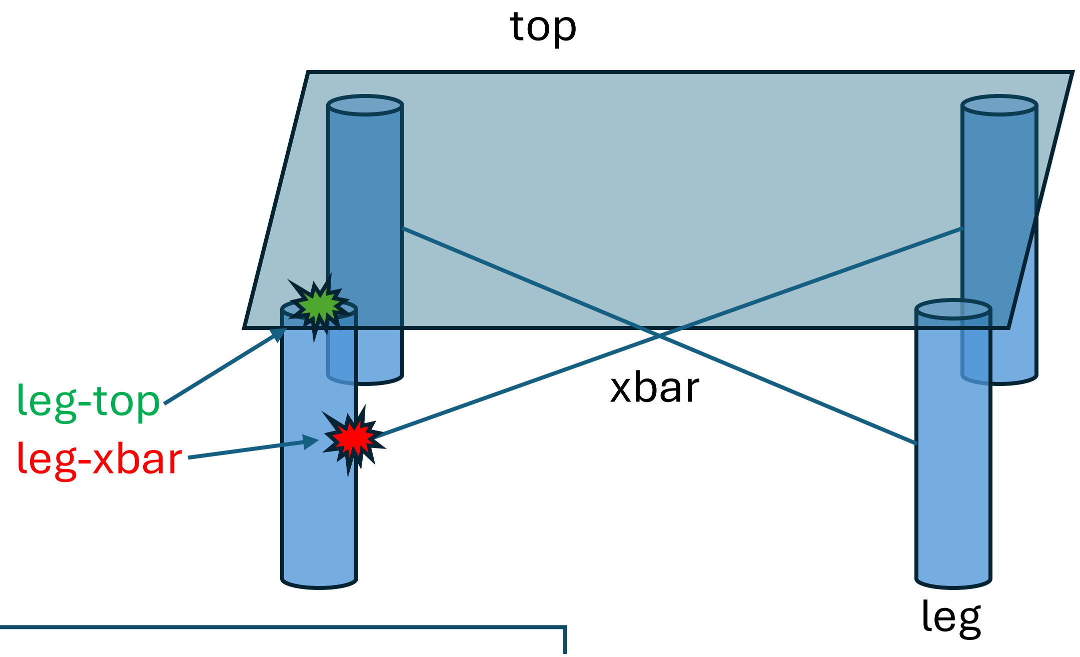
- Integration-oriented WBS
  - corner: integrated system
  - top & xbar: links
  - pros: integrator handles all interfaces
  - cons: less control on global functions

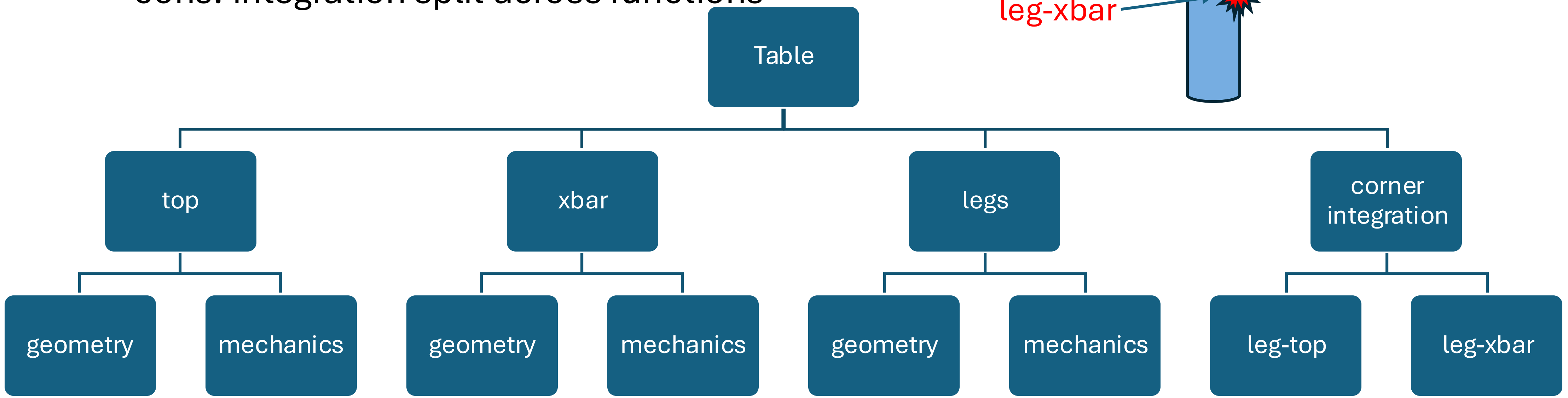




Functions vs system integration

- Function-oriented WBS
  - design driven by main functions
    - top shape and mechanical properties
  - integration in dedicated WBS branch
  - pros: control on global functions
  - cons: integration split across functions





WBS elements

- WBS elements represent **activities**, e.g.
  - Global system integration (interferometer, civil infrastructure, …)
    - coordination by high level scientific expert
  - Local system integration (core optics tower, suspended bench tower)
    - coordination by system engineer
  - Global function (stray light control, seismic isolation, wavefront sensing & control…)
    - coordination by technology expert
  - Design and requirements definition (optical design, optical simulation, sensing and control, noise budget)
    - coordination by scientist

Classes of subsystems: WBS functions

- Global integrated systems require coordination by high level scientific expertise to handle functional integration
  - Can be decomposed into integrated subsystems, requiring coordination by either high level scientific expertise or by system engineer, depending on the degree of functional integration
- Global integrated (sub)systems are decomposed into local integrated systems, requiring coordination by system engineering expertise to handle physical integration interfaces
- Global functions, either localised or distributed, are spread across the whole instrument and require coordination by specific technical expertise to handle either frontier technologies, mass production, standardisation, global functional integration, or a combination of these.
- Activities that are not related to physical deliverables generate requirements, simulation, and design

WBS functions

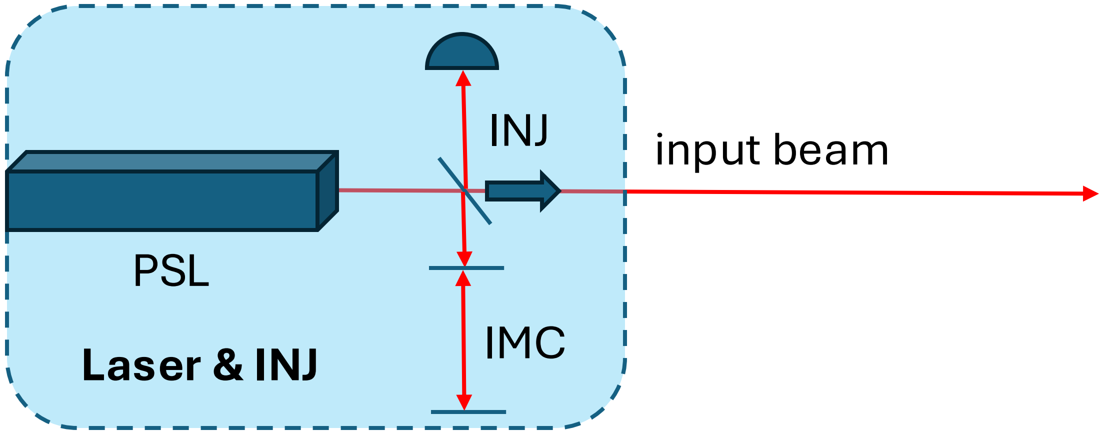
- Global (sub)system integration (GSI)
  - design, integrate, commission & operate the main integrated (sub)systems
  - requiring high level scientific expertise i.e. **coordination by high level scientific expert**
    - Laser injection, interferometer, quantum noise reduction, detection, underground civil infrastructure
- Local system integration (LSI)
  - interface management on instrument or infrastructure node
  - requiring system engineering expertise i.e. **coordination by system engineer**
    - tower, pipe, cavern, tunnel
- Global distributed functions (GDF)
  - design, develop, install & commission distributed functions
  - requiring inter-node integration & highly specialised expertise i.e. **coordination by technology expert**
    - stray light control, wavefront sensing & control, real-time control, vacuum, technical infrastructure for instrument functions, e-infrastructure
- Global localized functions (GLF)
  - design, develop, install & commission distributed functions
  - recurring at several locations, requiring standardisation, mass production & highly specialised expertise i.e. **coordination by technology expert**
    - seismic isolation, payload, optics, detectors & readout electronics, calibration, environmental monitoring
- Design, simulation & requirements generation (DRG)
  - pure WBS activities (no HW output) requiring **coordination by scientist**
    - optical design, simulation and characterisation, interferometer sensing & control, noise evaluation

WBS & PBS: configuration nodes

- Instrument nodes
  - integrated systems where several global functions of the instrument are crossing
    - mirror towers, suspended bench towers, pipes
  - GW detectors require suspending critical elements in vacuum
  - -> most hardware is conveniently grouped into optical nodes with a seismic isolation inside vacuum vessel
- Underground infrastructure nodes
  - integrated systems where several instrument nodes and technical infrastructure functions are crossing
    - caverns, tunnels
- All nodes (instrument & infrastructure) show up at layer 4 in PBS.2

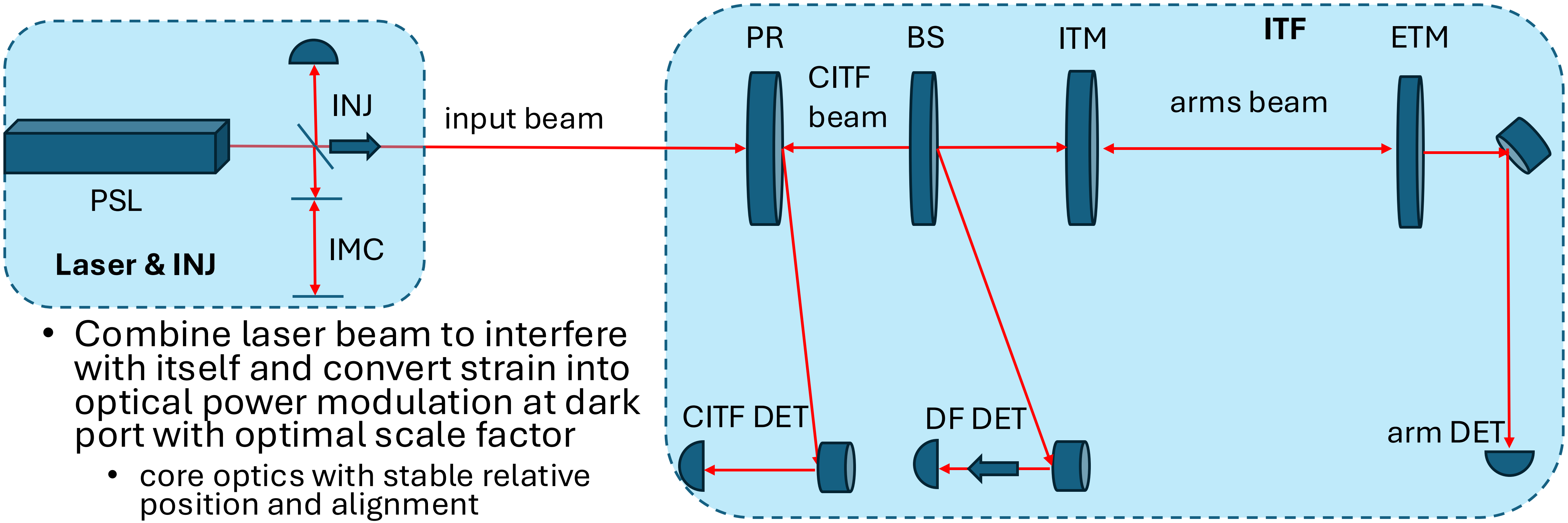
SYSTEM DECOMPOSITION - HF ITF

Global integrated systems – laser & injection



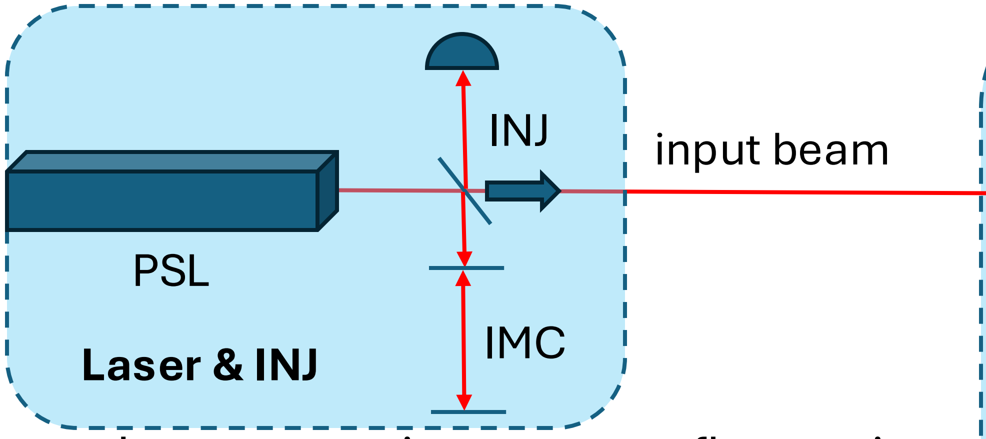
- Generate input laser beam to interferometer with suitable
  - spatial mode quality
  - alignment stability
  - phase/frequency stability
  - intensity stability
- Generate auxiliary laser beam for interferometer lock acquisition
- WBS functions: design, procure parts, integrate, commission, operate the system

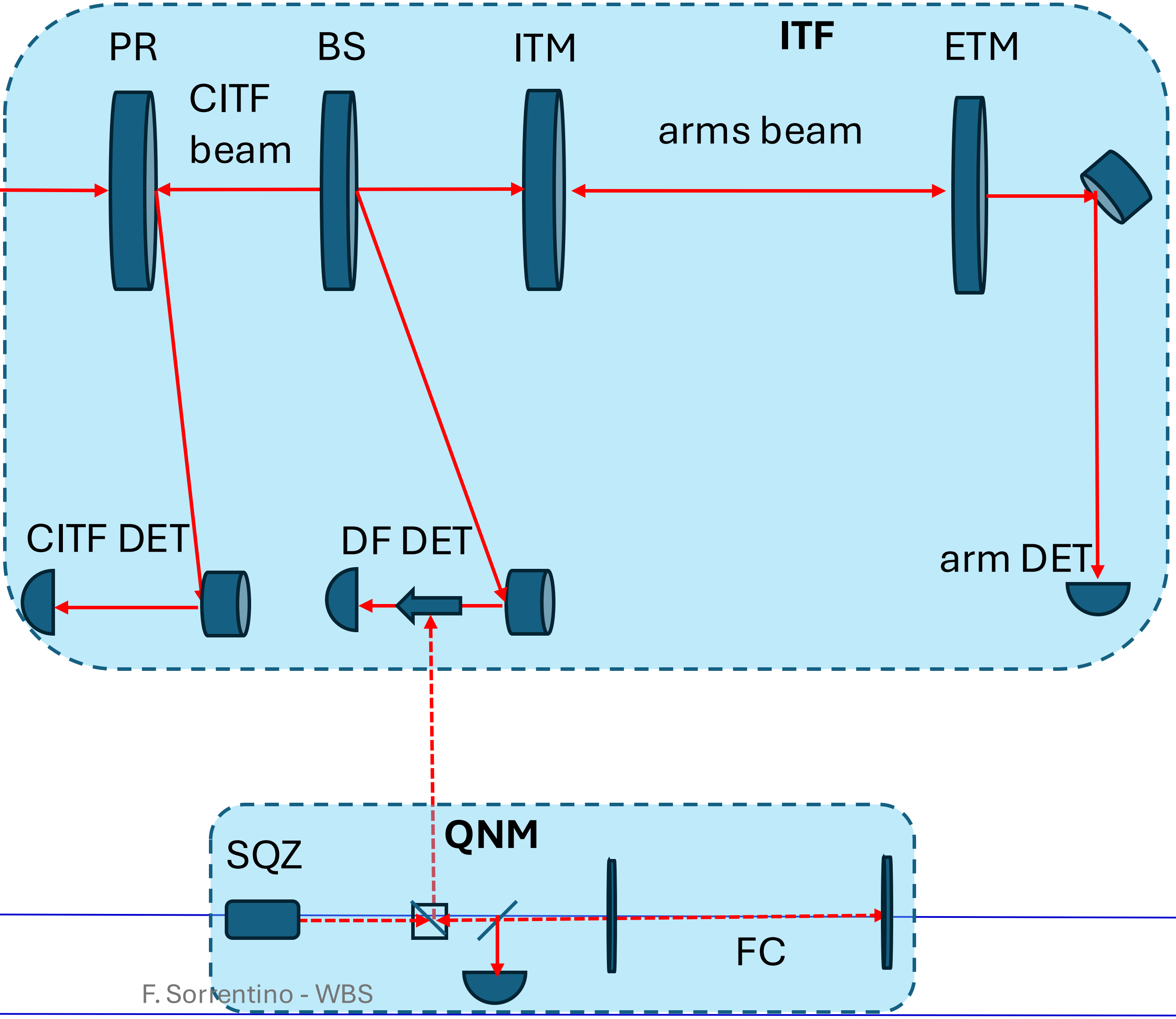
Global integrated systems - interferometer



- Combine laser beam to interfere with itself and convert strain into optical power modulation at dark port with optimal scale factor
    - core optics with stable relative position and alignment
    - optical benches for auxiliary beams
- WBS function: design, integrate, commission & operate the optical system

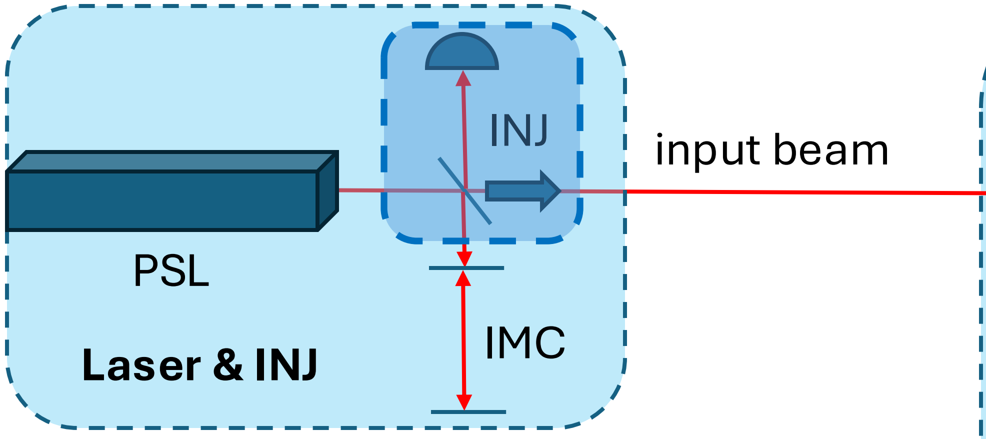
Global integrated systems – quantum noise mitigation

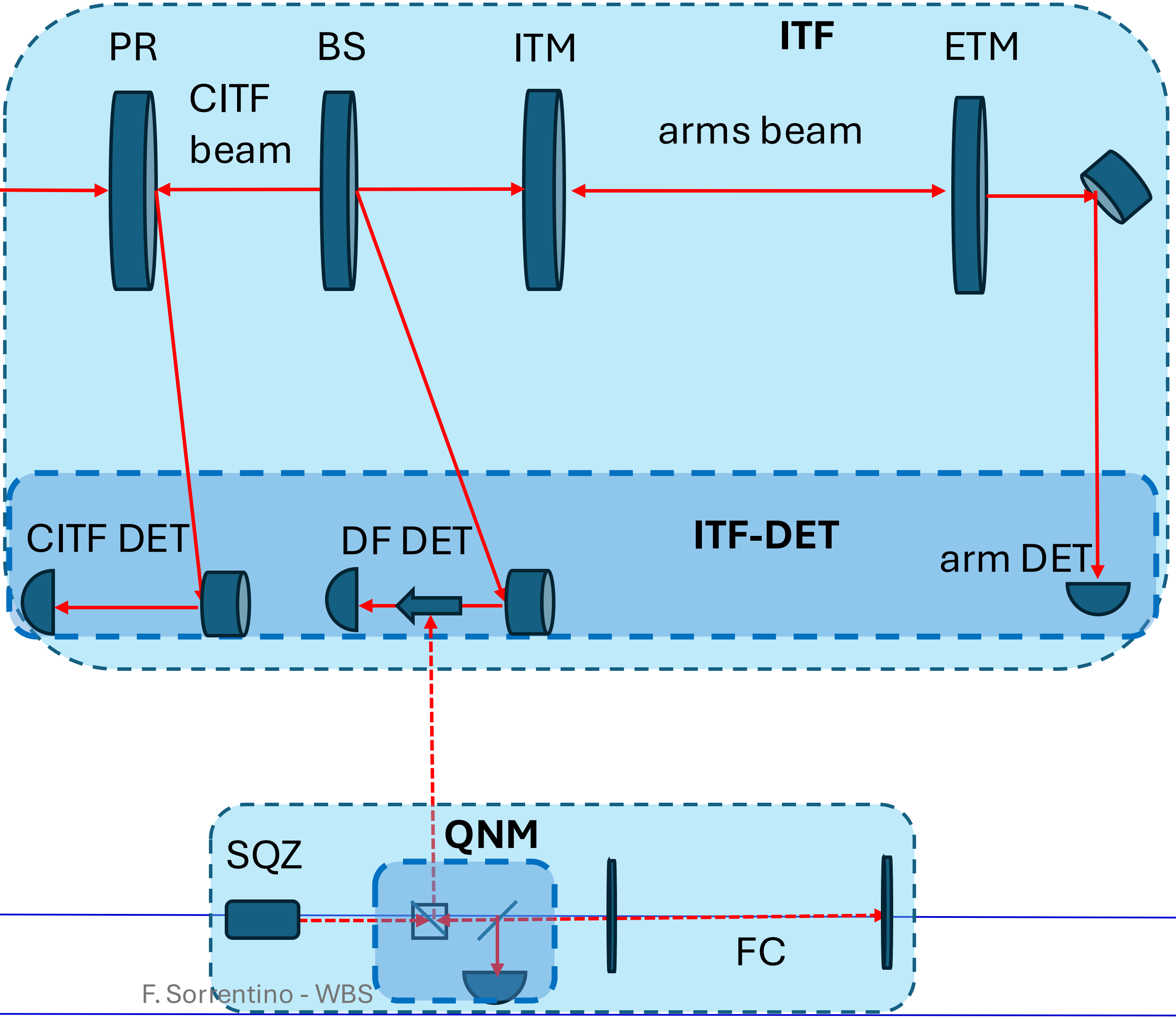




- reduce zero-point quantum fluctuations in the ITF mode
    - couple interferometer to an optical parametric oscillator
- Generate a frequency dependent shift
    - squeeze radiation pressure noise and shot noise in relevant bands
        - filter cavity
- WBS functions: design, procure, integrate, commission & operate the system

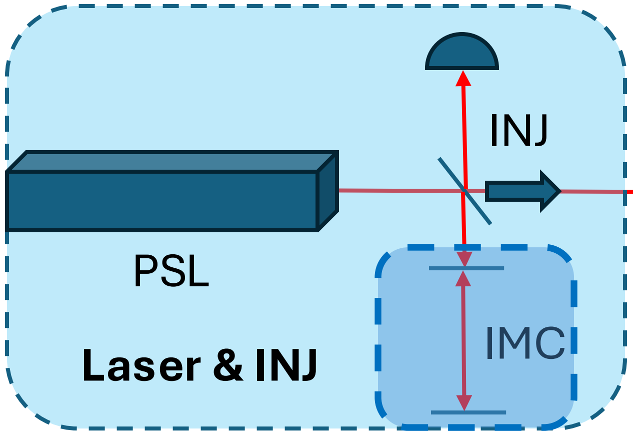
Global integrated subsystems - detection

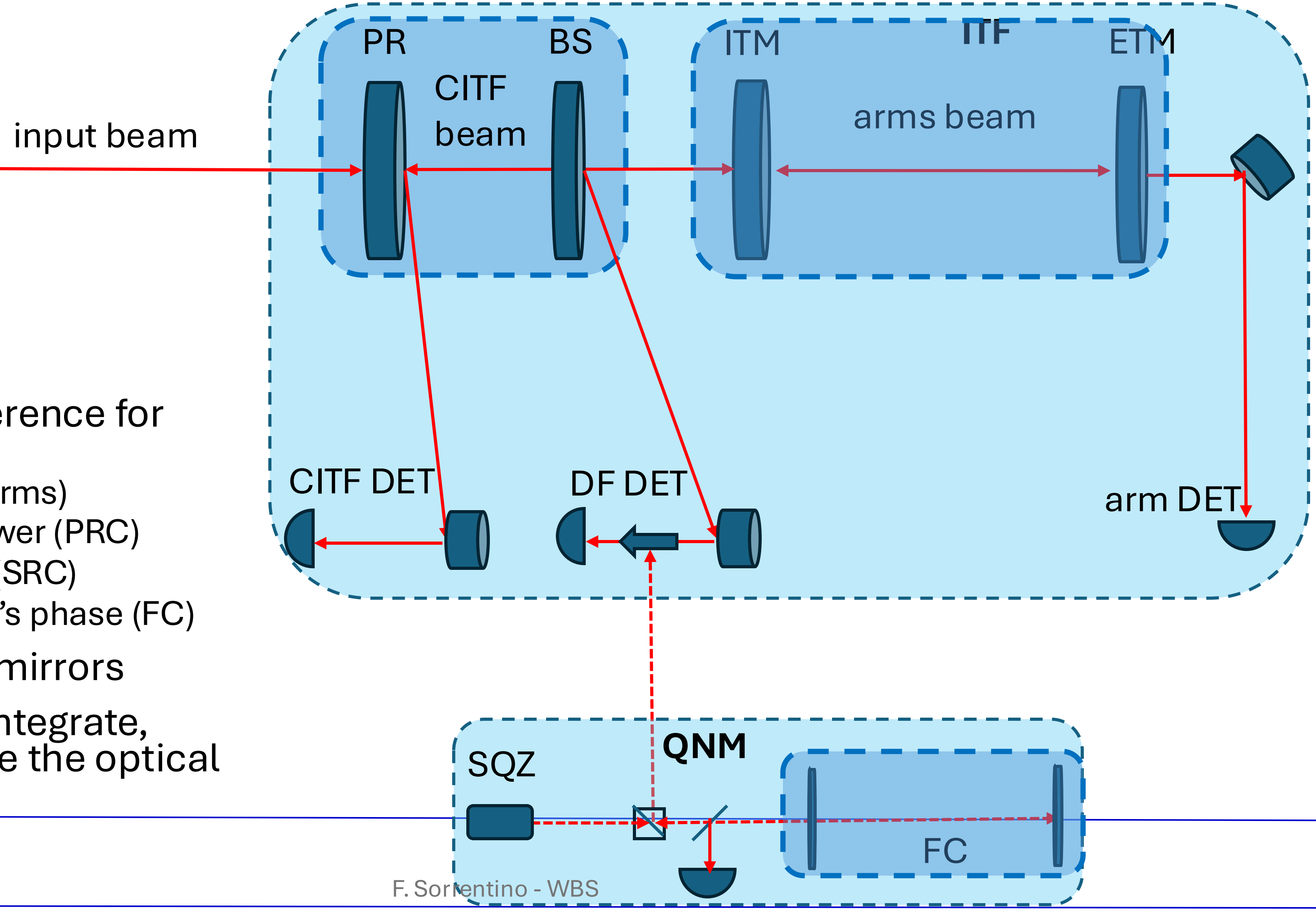




- Deliver main and auxiliary optical beams to photodetectors
  - Strain readout + control signal generation + optical monitoring & characterisation
- optical benches suspended in vacuum + few in-air benches
  - hosting DC & RF linear and quadrant photodiodes
  - hosting several elements for global functions (e.g. wavefront sensing & control, stray light control)
- WBS functions: design, integrate, commission & operate the optical benches

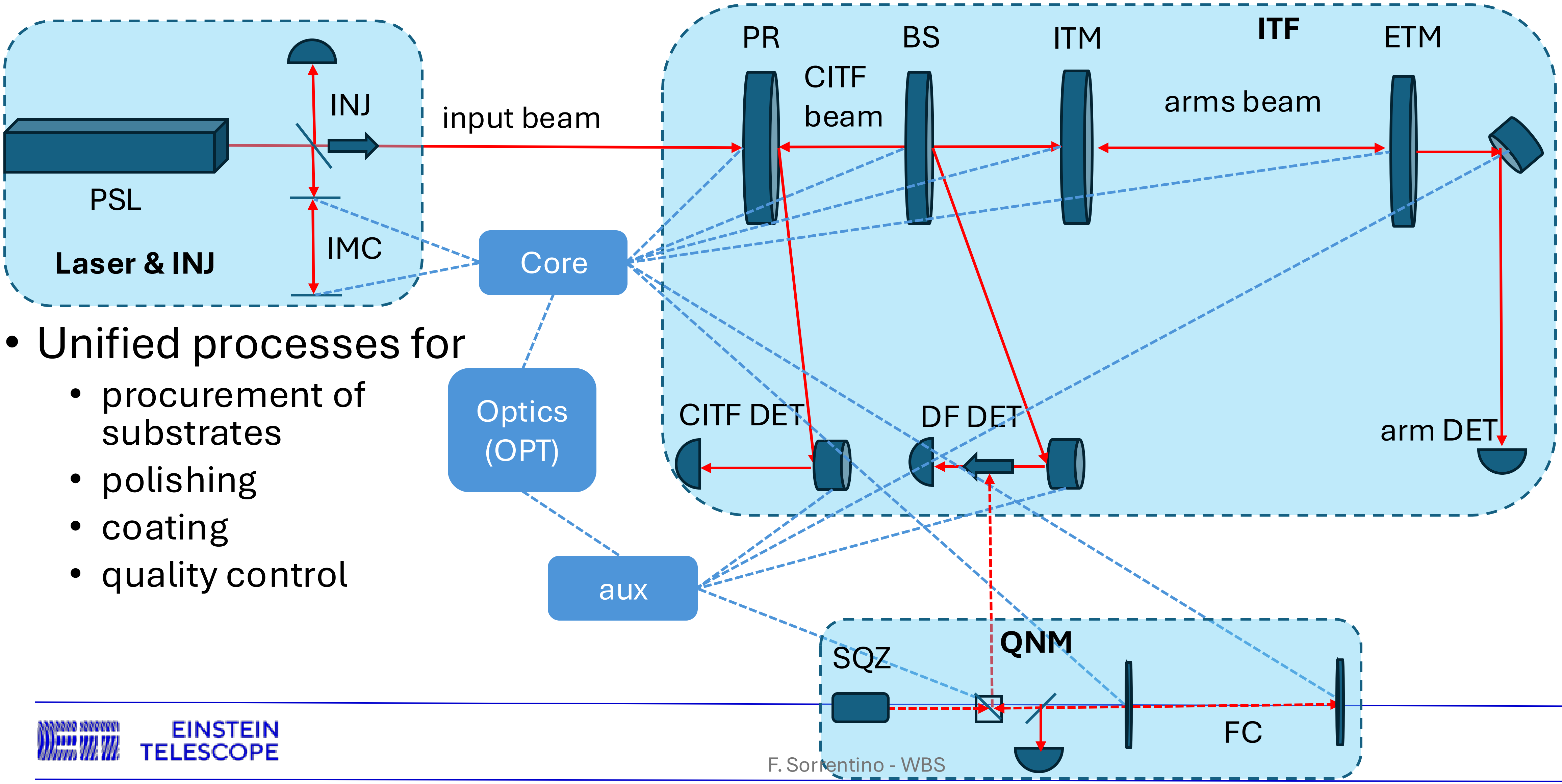
Global integrated subsystems - cavities





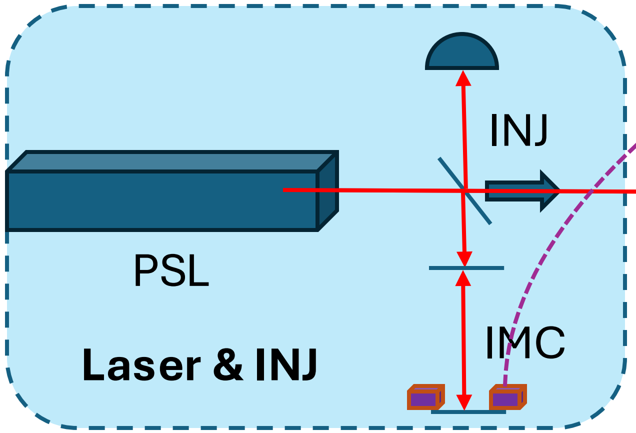
- Generate multiple interference for either:
  - maximize scale factor (arms)
  - maximize circulating power (PRC)
  - optimize detector band (SRC)
  - rotate quantum vacuum's phase (FC)
- suspended & controlled mirrors
- WBS functions: design, integrate, precommission & operate the optical cavities

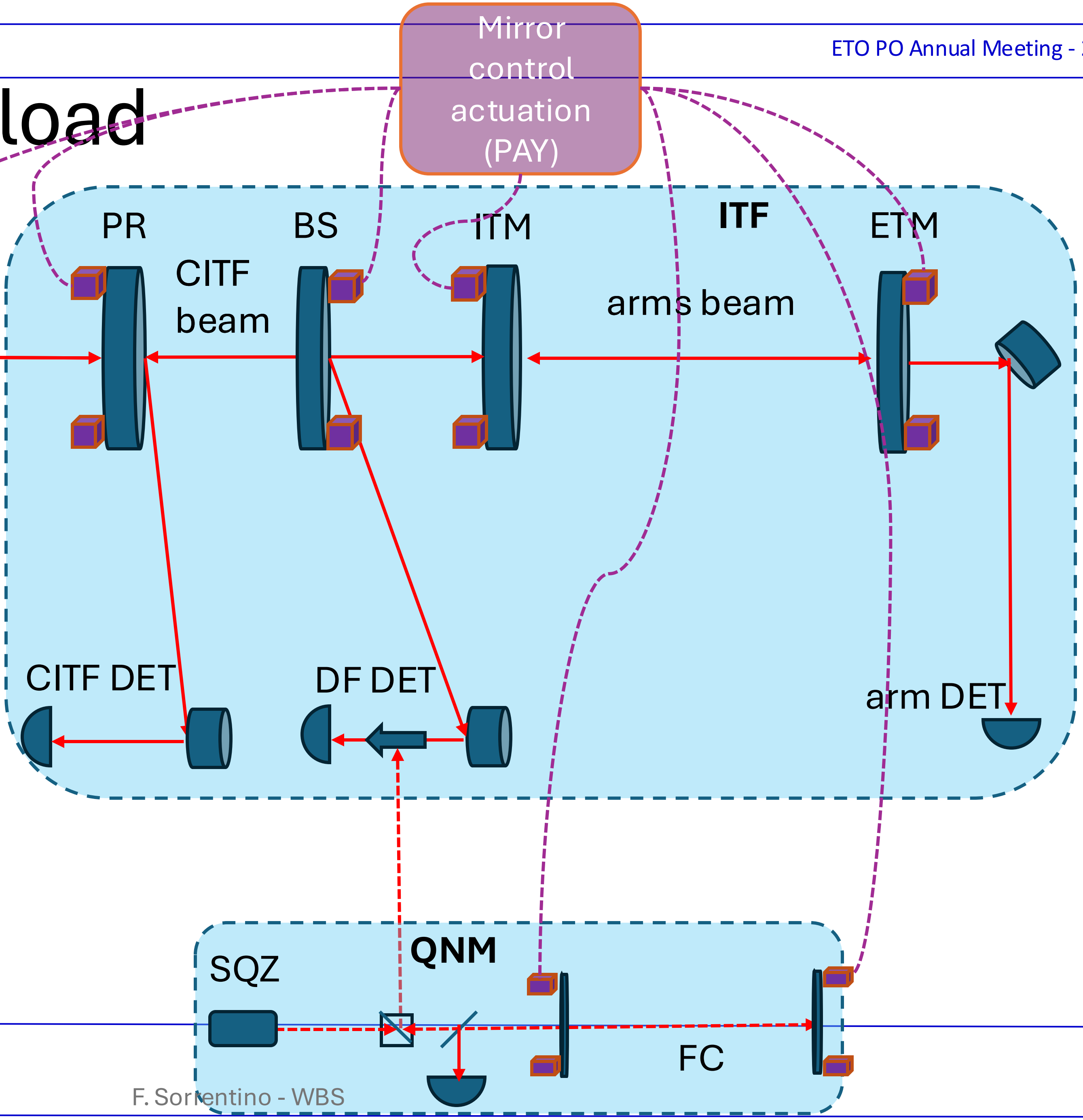
Global functions – optics



- Unified processes for
  - procurement of substrates
  - polishing
  - coating
  - quality control

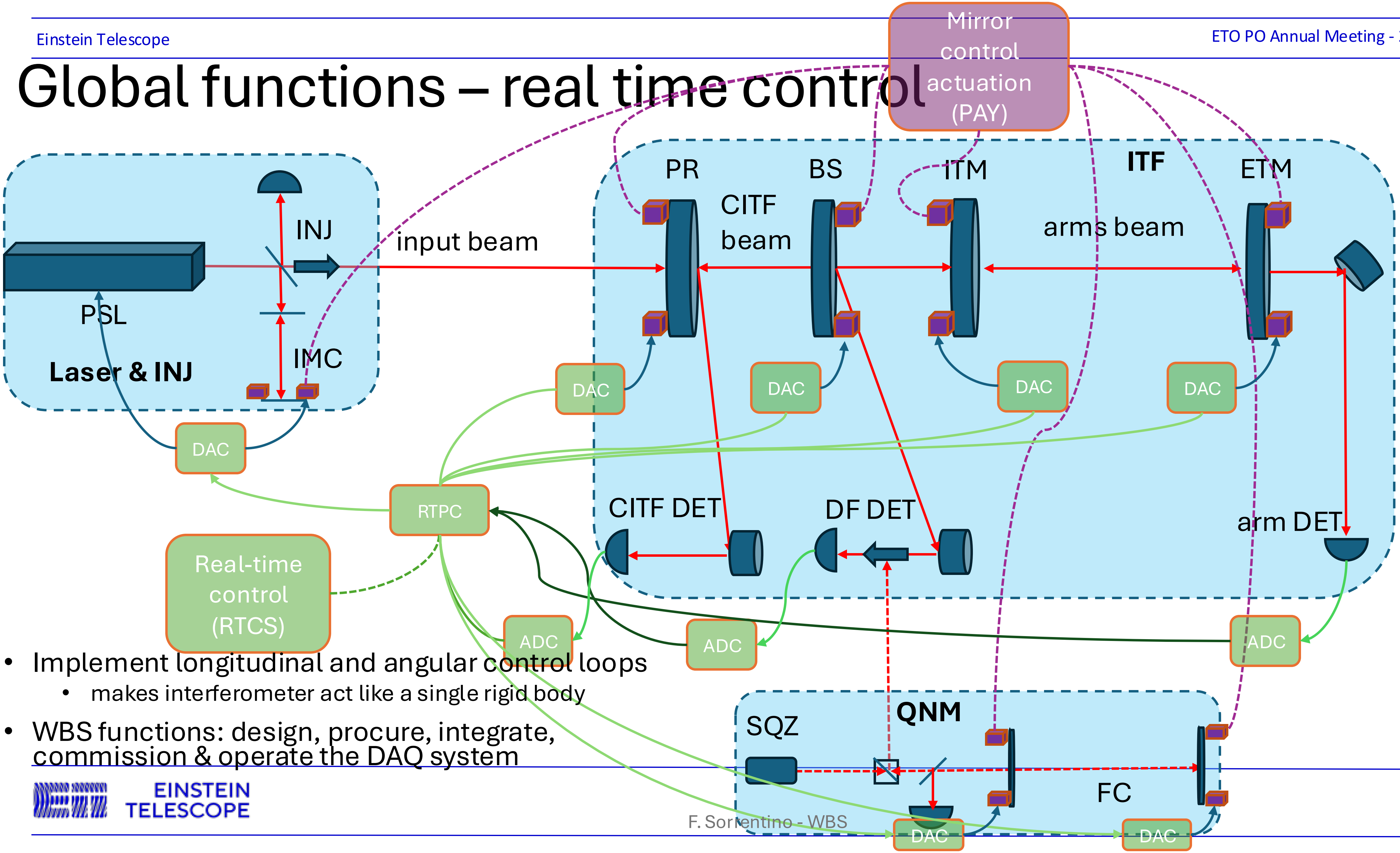
Global functions - payload





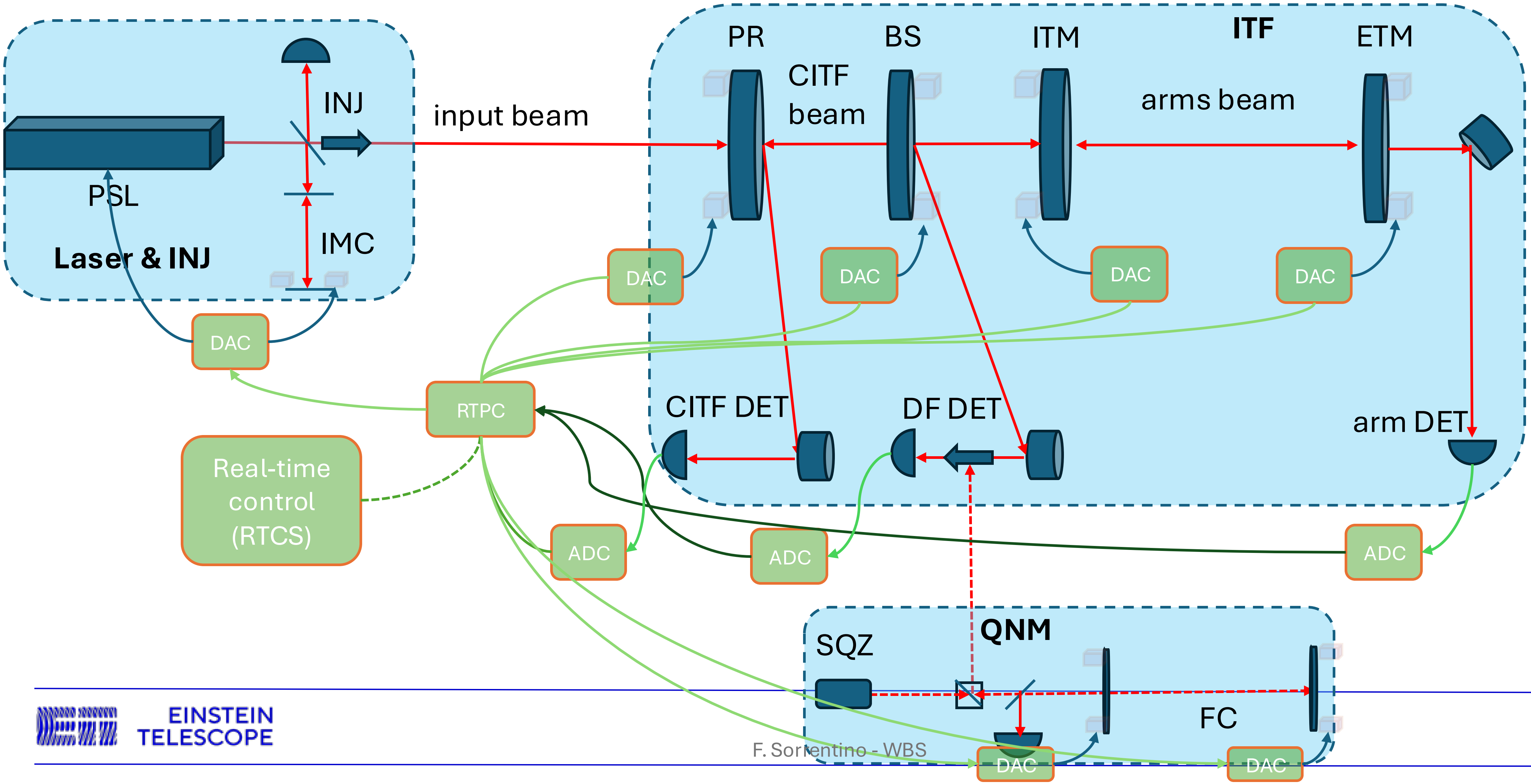
- Implementation of mechanical forces with minimal noise coupling
  - linear and angular positioning of core optics
  - including parts from global functions to move with mirrors
    - ring heaters, baffles
- WBS functions: integration
  - recurring at several locations
  - requires highly specialised expertise

Global functions – real time control

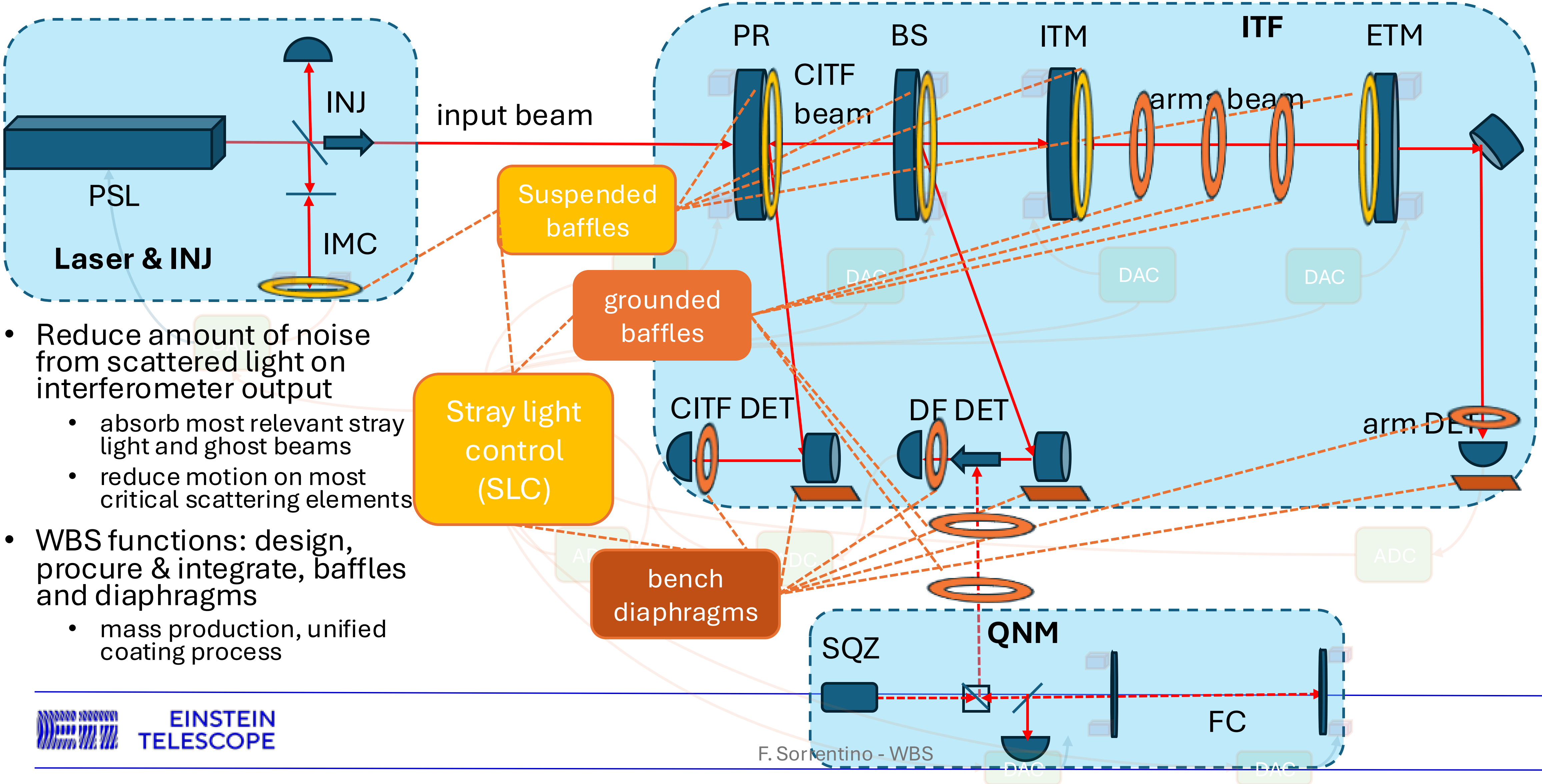


- Implement longitudinal and angular control loops
  - makes interferometer act like a single rigid body
- WBS functions: design, procure, integrate, commission & operate the DAQ system

Global functions – real time control

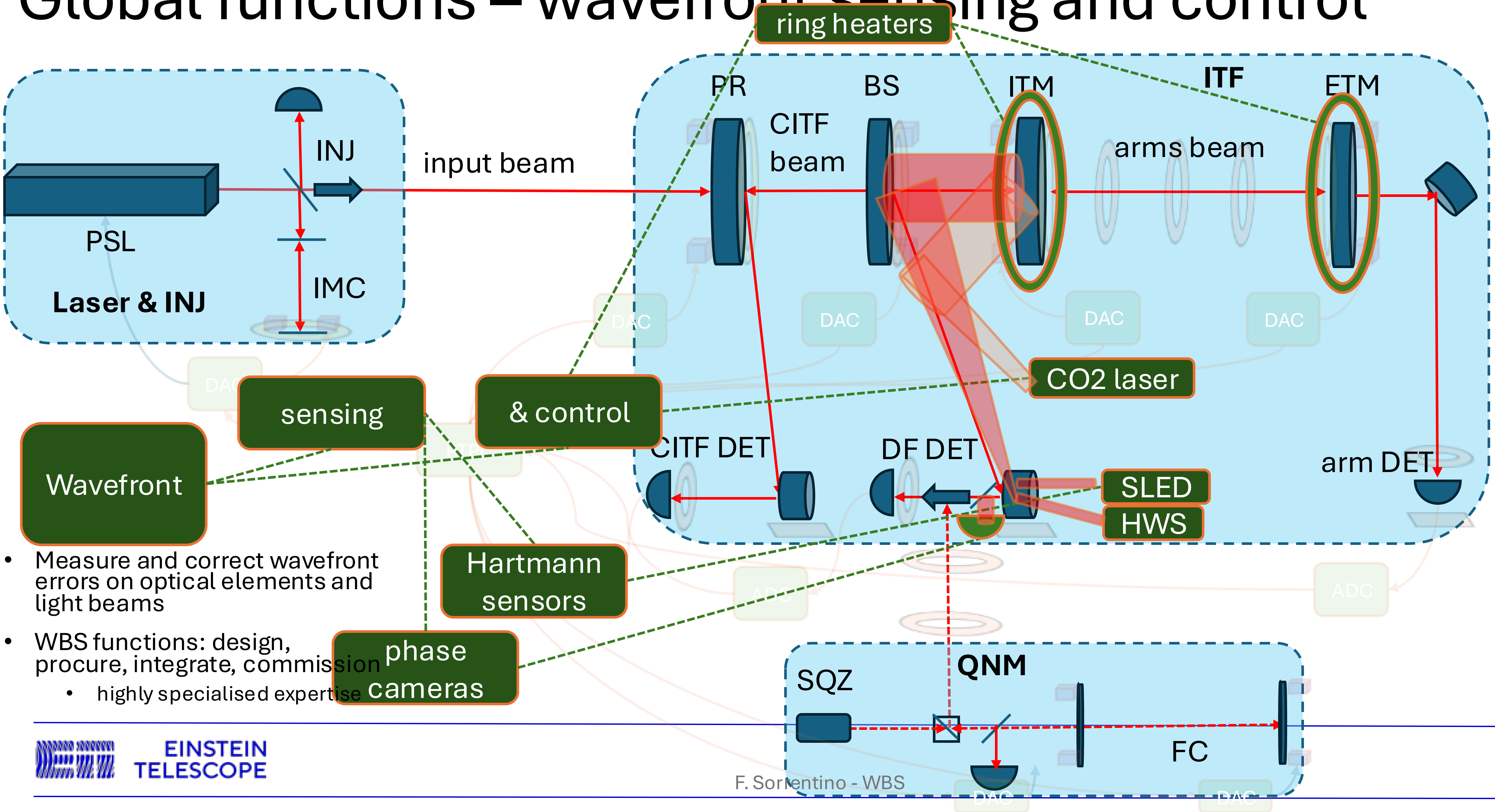


Global functions – stray light control



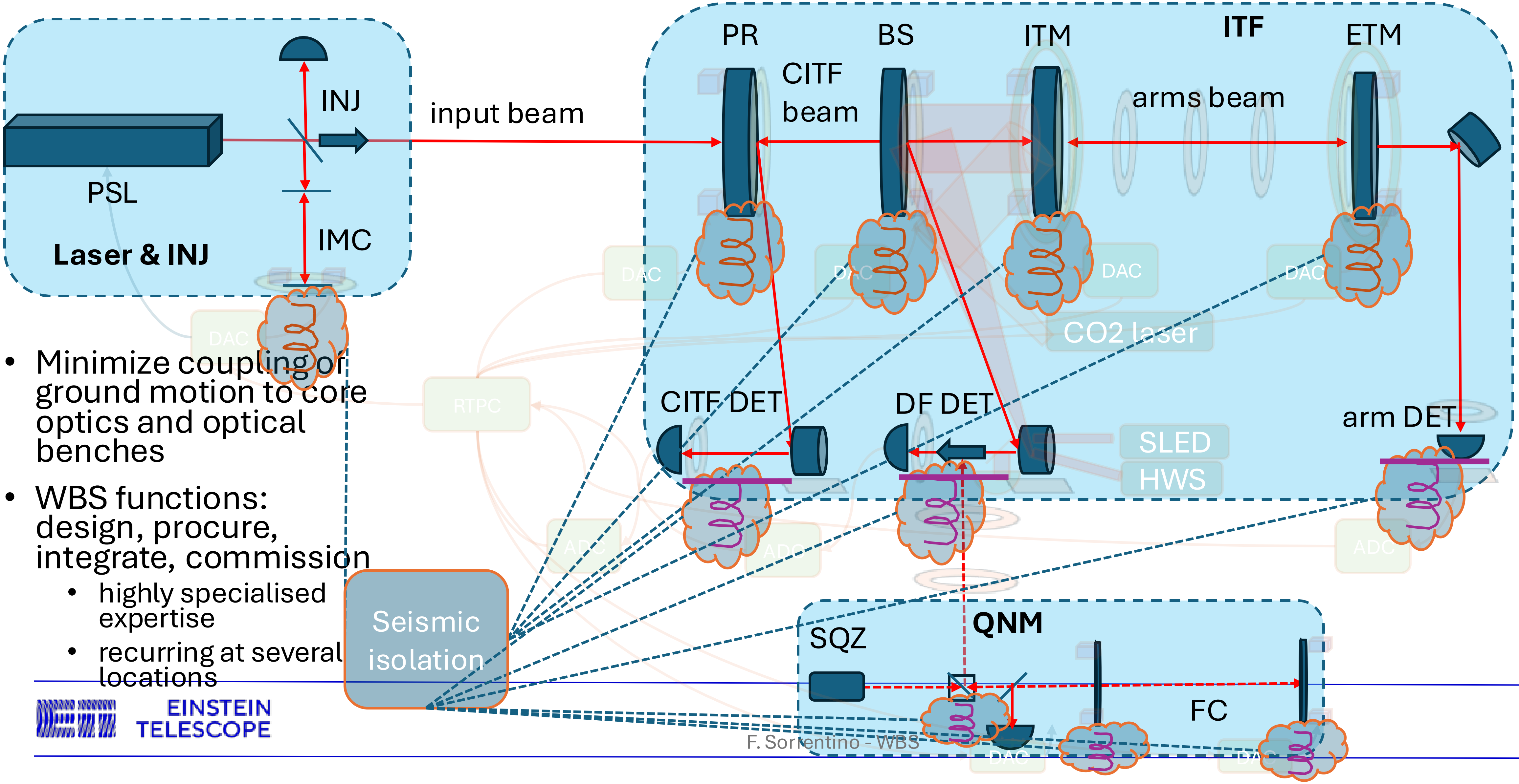
- Reduce amount of noise from scattered light on interferometer output
  - absorb most relevant stray light and ghost beams
  - reduce motion on most critical scattering elements
- WBS functions: design, procure & integrate, baffles and diaphragms
  - mass production, unified coating process

Global functions – wavefront sensing and control



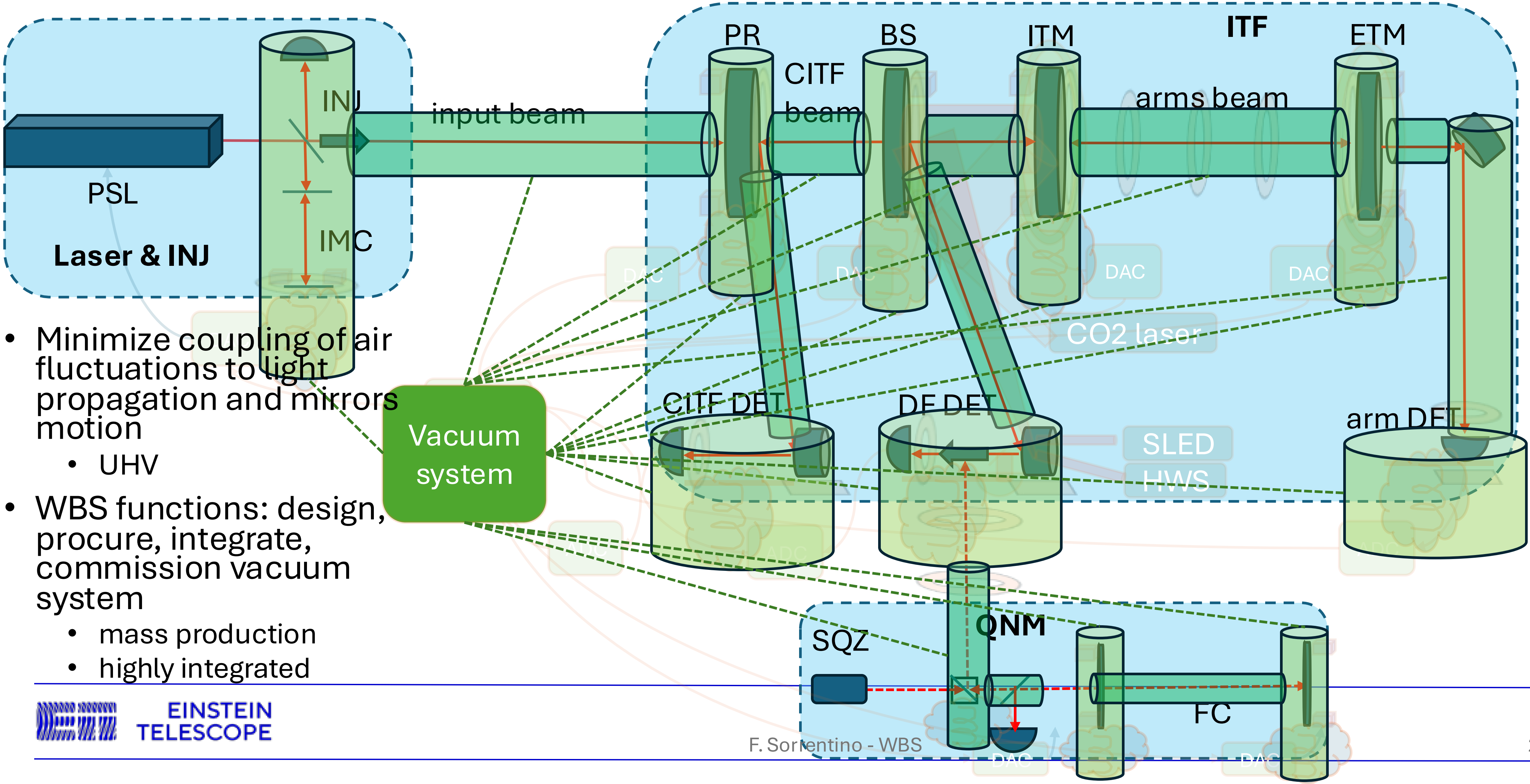
- Measure and correct wavefront errors on optical elements and light beams
- WBS functions: design, procure, integrate, commission
    - highly specialised expertise

Global functions – seismic isolation



- Minimize coupling of ground motion to core optics and optical benches
- WBS functions: design, procure, integrate, commission
  - highly specialised expertise
  - recurring at several locations

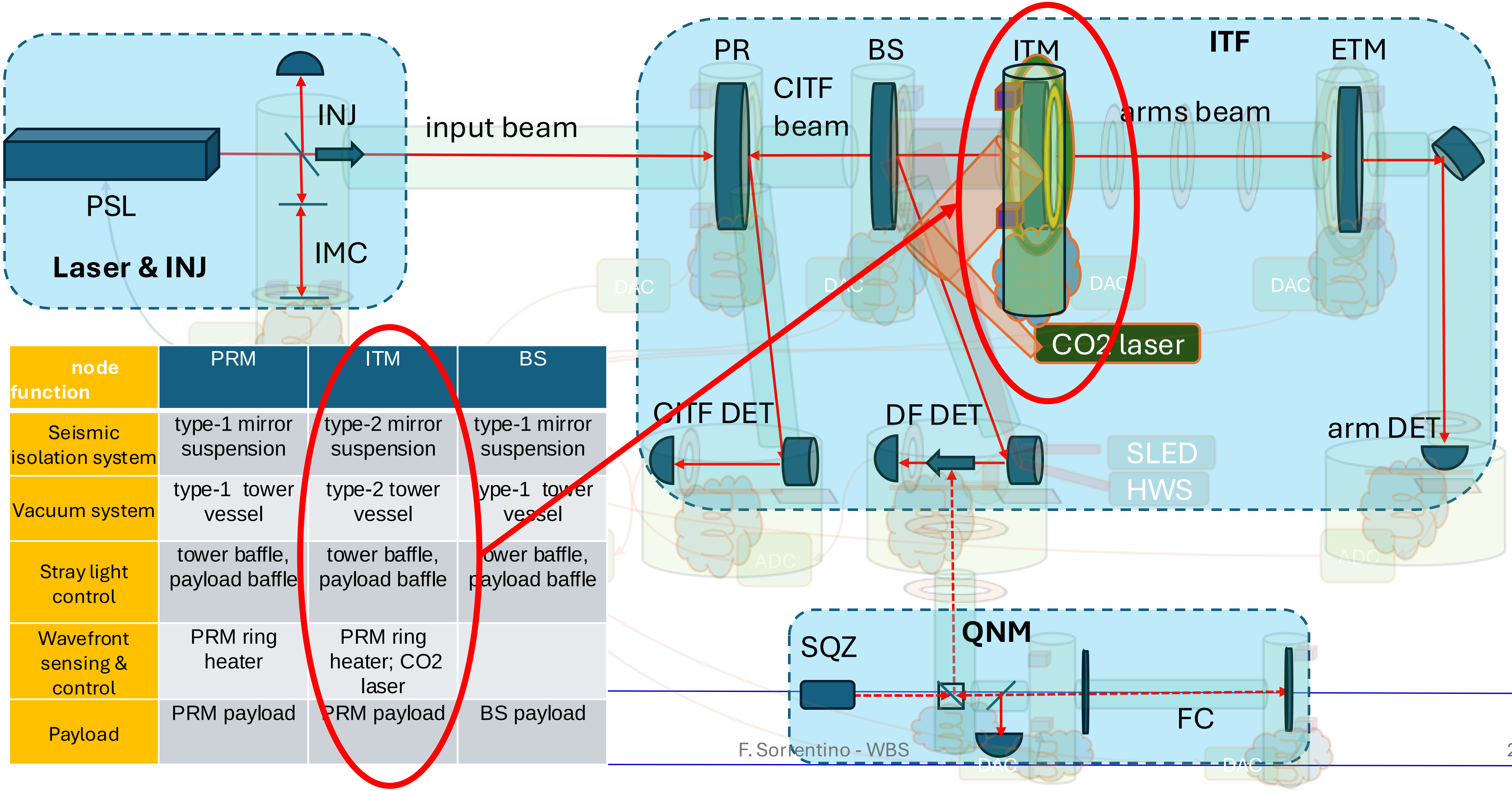
Global functions – vacuum



- Minimize coupling of air fluctuations to light propagation and mirrors motion
  - UHV
- WBS functions: design, procure, integrate, commission vacuum system
  - mass production
  - highly integrated

WBS & PBS

Global functions to node mapping



node function	PRM	ITM	BS
Seismic isolation system	type-1 mirror suspension	type-2 mirror suspension	type-1 mirror suspension
Vacuum system	type-1 tower vessel	type-2 tower vessel	type-1 tower vessel
Stray light control	tower baffle, payload baffle	tower baffle, payload baffle	tower baffle, payload baffle
Wavefront sensing & control	PRM ring heater	PRM ring heater; CO2 laser	
Payload	PRM payload	PRM payload	BS payload

Mapping global functions into PBS nodes - instruments

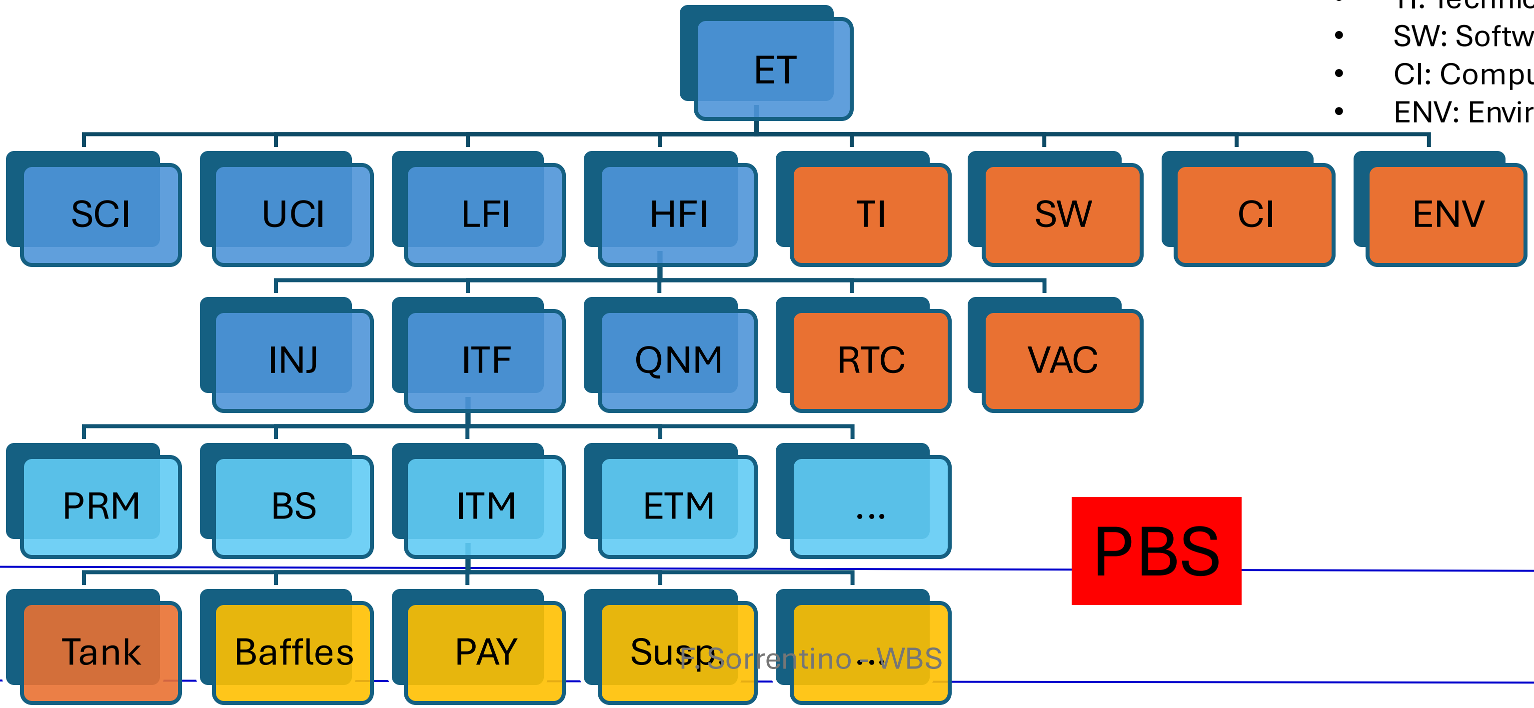
node / function	PSL	INJ optics	IOP	IMC-I	IMC-E	PRM	BS	SEM	ZM1	ZM2
Seismic isolation system		susp. bench	susp. bench	type-1 mirror suspension	type-1 mirror suspension	type-1 mirror suspension	type-1 mirror suspension	type-1 mirror suspension	type-1 mirror suspension	type-1 mirror suspension
Vacuum system		bench vessel	bench vessel	type-1 tower vessel	type-1 tower vessel	type-1 tower vessel	type-1 tower vessel	type-1 tower vessel	type-1 tower vessel	type-1 tower vessel
Stray light control		bench diaphragms	bench diaphragms	tower baffle, payload baffle	tower baffle, payload baffle	tower baffle, payload baffle	tower baffle, payload baffle	tower baffle, payload baffle	tower baffle, payload baffle	tower baffle, payload baffle
Wavefront sensing & control		HWS source and detector	HWS optics	IMC-I ring heater	IMC-E ring heater	PRM ringh heater		SEM ring heater		
Real-time control system	PSL DAQ	INJ DAQ			IMC-E DAQ					
Payload				IMC-I payload	IMC-E payload	PRM payload	BS payload	SEM payload	ZM1 payload	ZM2 payload
Optics	PSL optics	INJ optics	IOP optics	IMC-I mirror	IMC-E mirror					
Detectors & readout electronics	PLS photodiodes	IMC linear PD; IMC align. QPDs	Pstab PD		IMC-E linear PD					
Calibration										

Mapping global functions into PBS nodes - infrastructure

node function	Cavern A	Cavern B	Cavern C	Cavern D	Cavern E	Cavern F1	Cavern F2	Tunnel A	Tunnel B	Arm Tunnel
HFI		PSL, INJ, IOP, BS, PRM, SEM towers			ETM tower			ZRM-PRM pipe	HFI arm pipe	HFI arm pipe
LFI	PSL, INJ, IOP, BS, PRM, SEM towers		CAL towers	ETM tower		FC tower	IMC towers		LFI arm pipe	LFI arm pipe
HVAC	Cavern A HVAC	Cavern B HVAC	Cavern C HVAC	Cavern D HVAC	Cavern E HVAC	Cavern F1 HVAC	Cavern F2 HVAC	Tunnel A HVAC	Tunnel B HVAC	Arm tunnel HVAC
Electrical	supply LF vertex towers complex	supply HF vertex towers complex	supply LFI CAL	Supply LFI ETM	Supply HFI ETM	Supply LFI FC	Supply LFI IMC			
Lighting	Cavern A Lighting	Cavern B Lighting	Cavern C Lighting	Cavern D Lighting	Cavern E Lighting	Cavern F1 Lighting	Cavern F2 Lighting	Tunnel A HVAC Lighting	Tunnel B Lighting	Arm tunnel Lighting
Circulation	Cavern A stairs/elevators	Cavern B stairs/elevators	Cavern C stairs/elevators	Cavern D stairs/elevators	Cavern E stairs/elevators	Cavern F1 stairs/elevators	Cavern F2 stairs/elevators	Tunnel A stairs/elevators	Tunnel B stairs/elevators	Arm tunnel stairs/elevators
Dewatering	Cavern A dewatering	Cavern B dewatering	Cavern C dewatering	Cavern D dewatering	Cavern E dewatering	Cavern F1 dewatering	Cavern F2 dewatering	Tunnel A dewatering	Tunnel B dewatering	Arm tunnel dewatering
Plumbing										
Cryogenics	LF PRM and SEM cryopump	LF PRM and SEM cryopump		LF ETM cryopump	HF ETM cryopum					

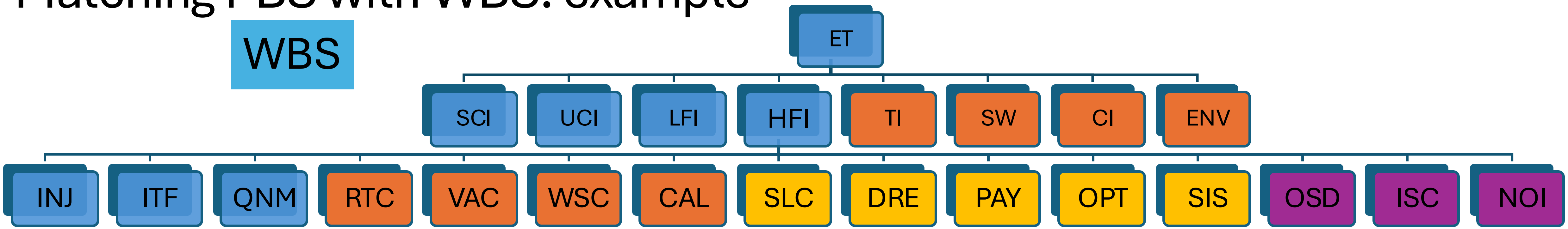
Matching PBS with WBS: example

Glossary:
- SCI: Surface Civil Infrastructure
- UCL: Underground Civil Infrastructure
- LFI: Low Frequency Instrument
- HFI: High Frequency Instrument
  - INJ: Laser & Injection system
  - ITF: Interferometer
    - PRM: Power Recycling Mirror Tower
    - BS: Beam Splitter Tower
    - ITM: Input Test Mass Tower
      - PAY: Payload
    - ETM: Terminal Test Mass Tower
  - QNM: Quantum Noise Mitigation system
  - RTC: Real-Time Control system
  - VAC: distributed Vacuum systems
- TI: Technical Infrastructure
- SW: Software & Data handling
- CI: Computing Infrastructure
- ENV: Environmental Monitoring



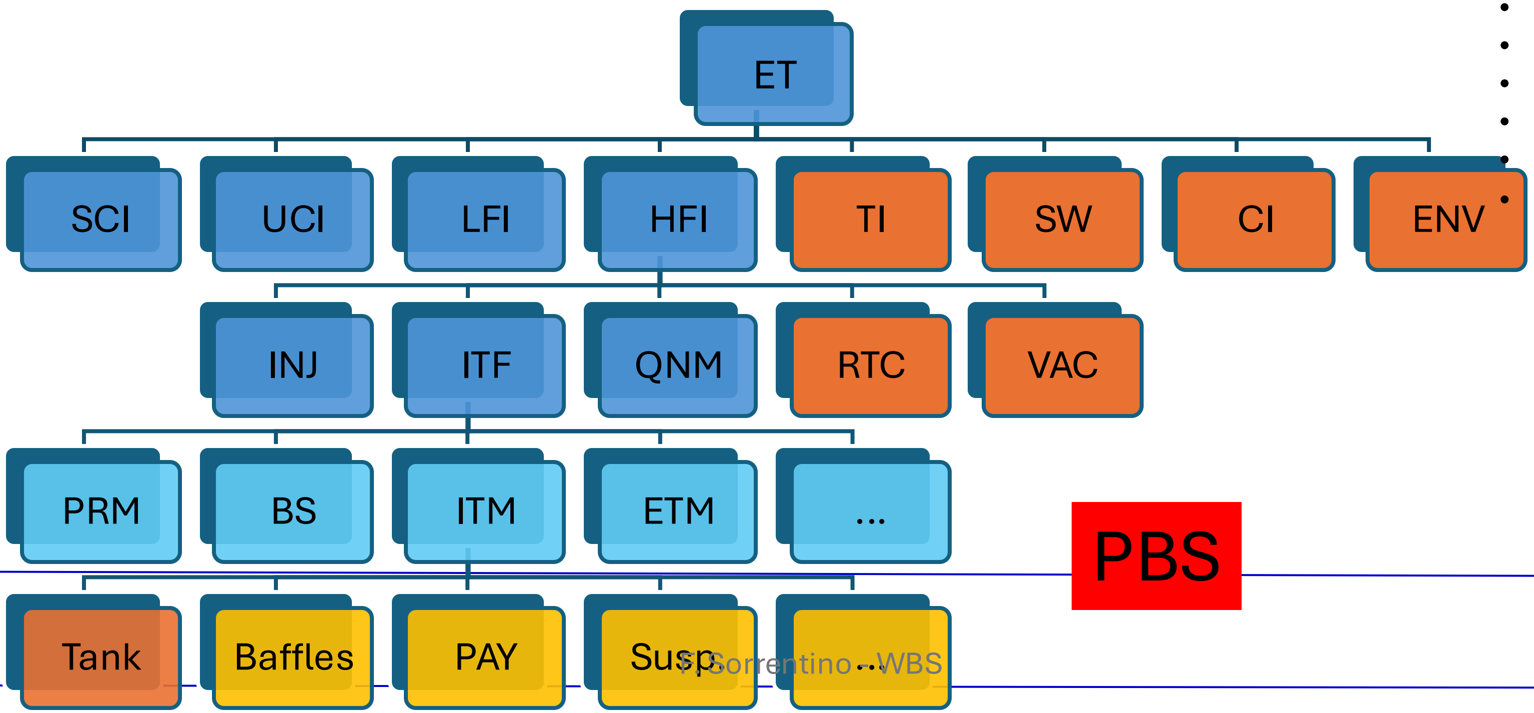
Matching PBS with WBS: example

WBS



Glossary:

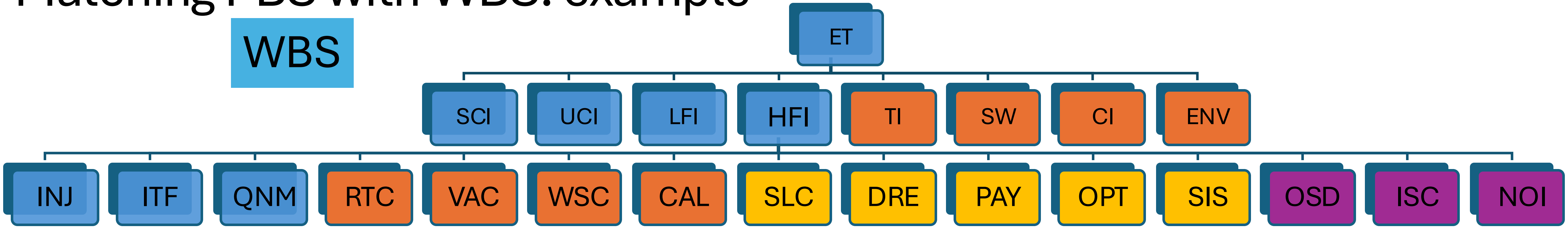
- WSC: Wavefront Sensing & Control
- CAL: Calibration
- SLC: Stray Light Control
- DRE: Detectors & Readout Electronics
- OPT: Optics
- SIS: Seismic Isolation System
- OSD: Optical Simulation & Design
- ISC: Interferometer Sensing & Control
- NOI: Noise Budget



PBS

Matching PBS with WBS: example

WBS

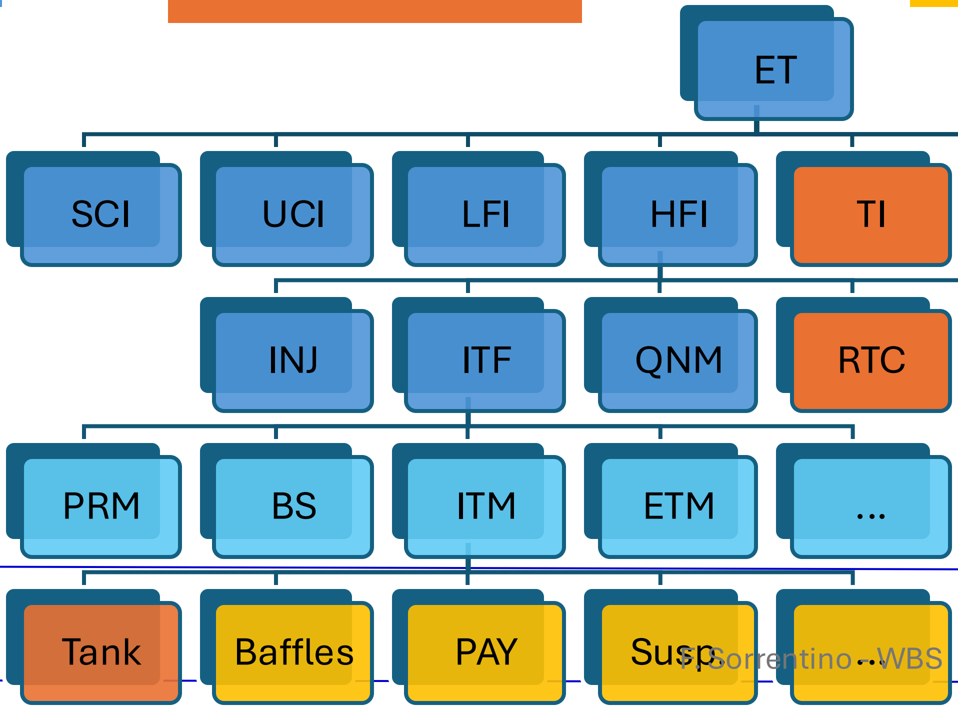


Global systems integration

Global distributed functions

Local distributed functions

Design & requirements generation



PBS

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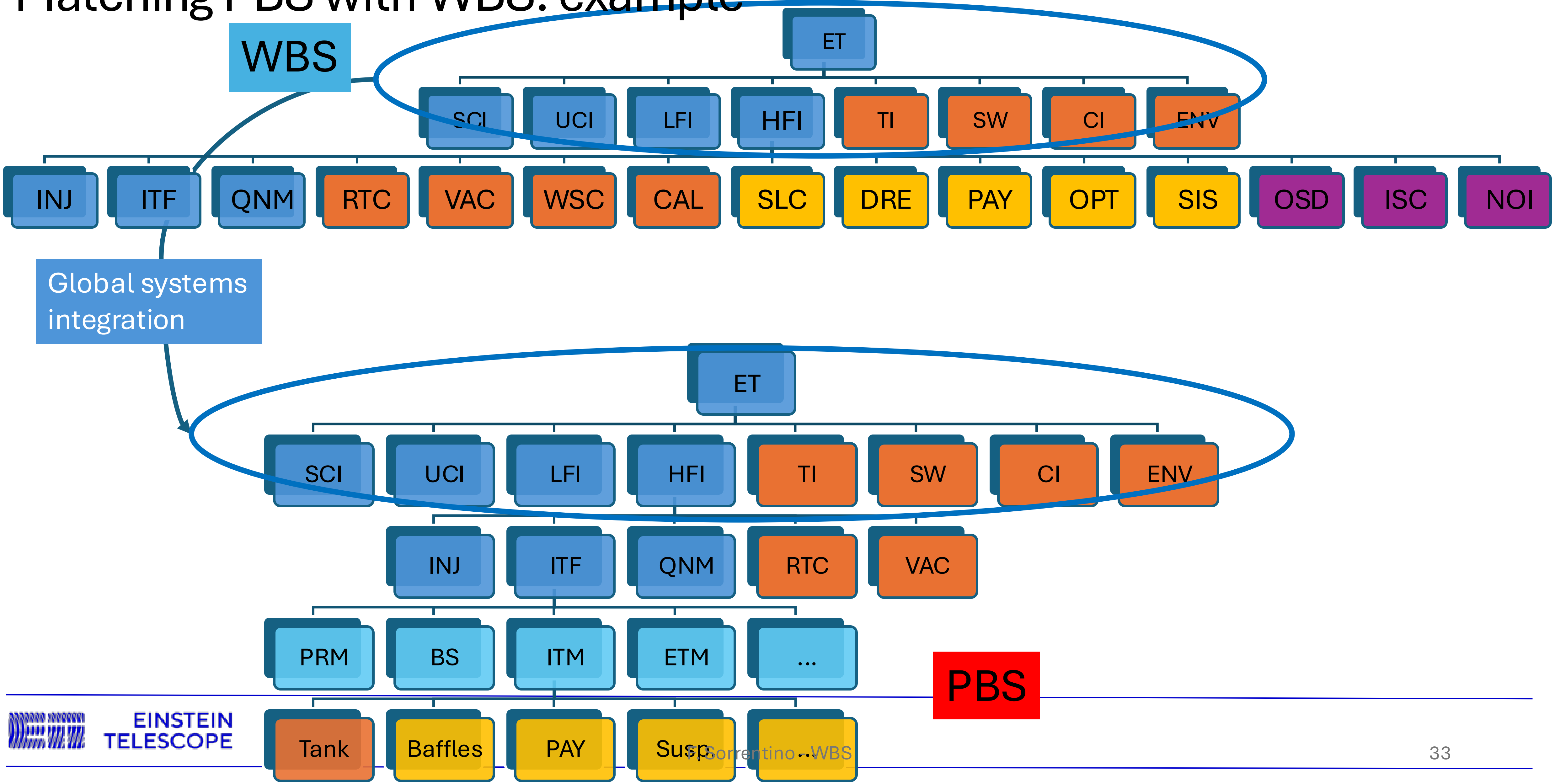

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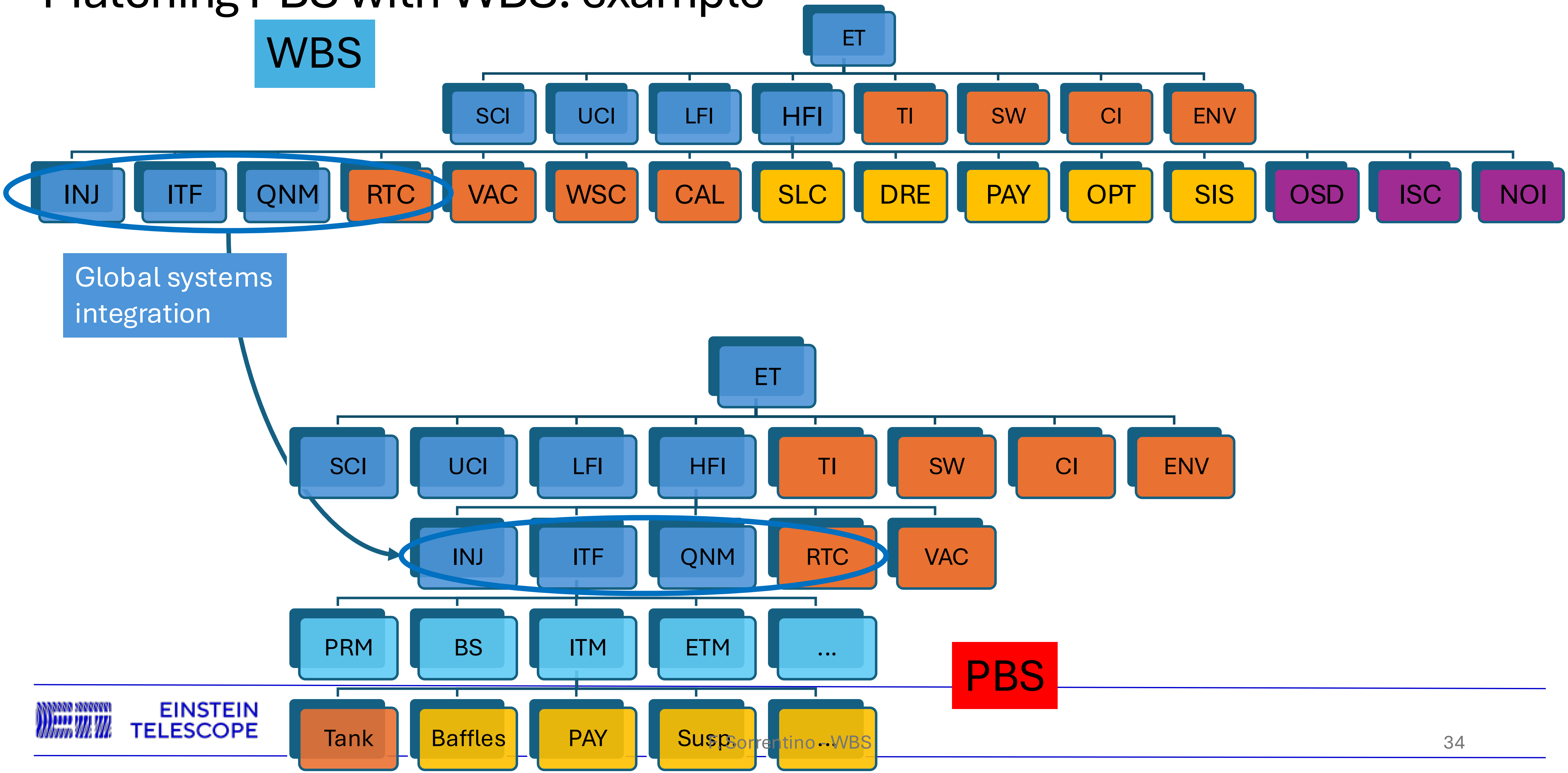

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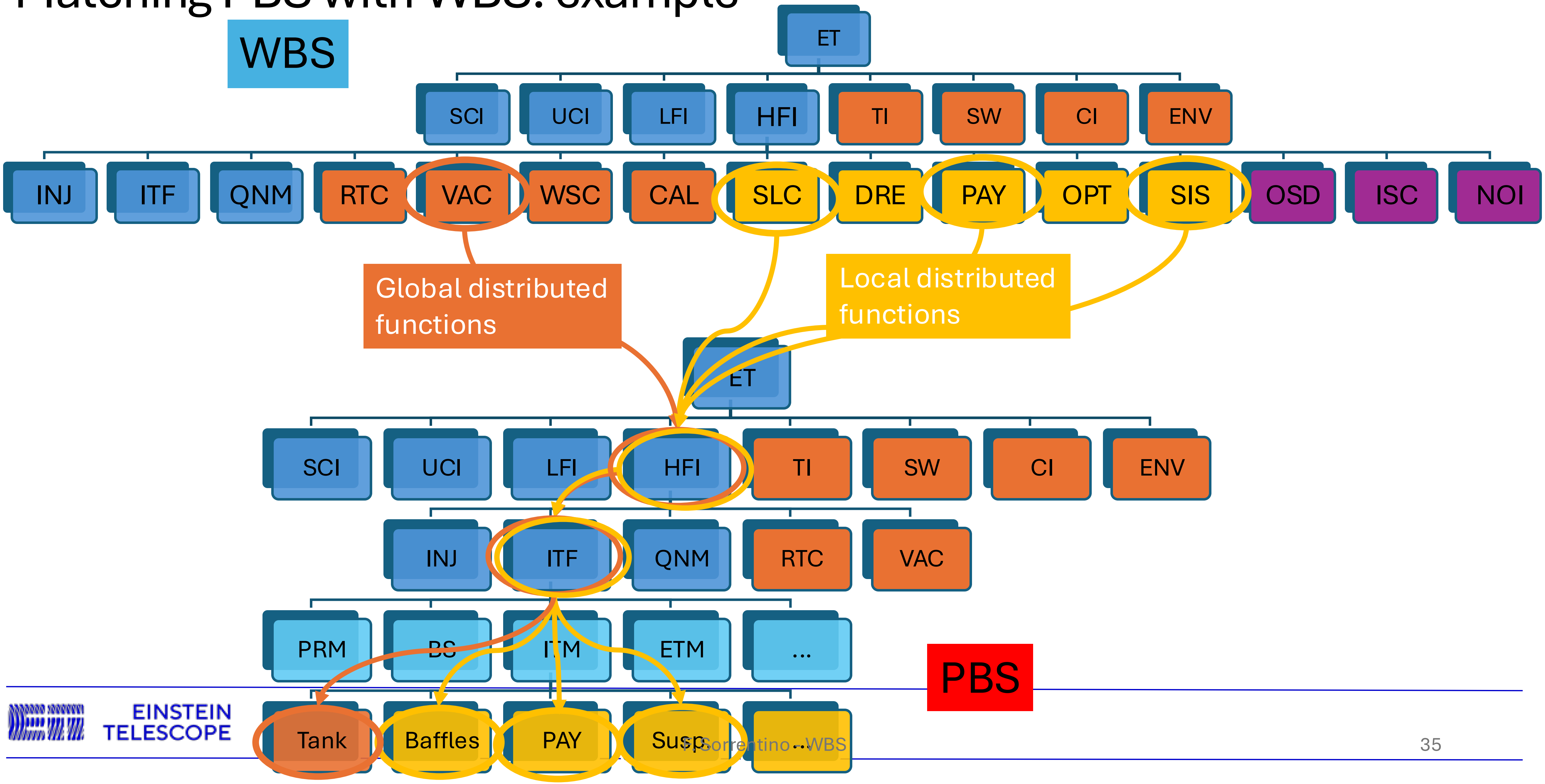

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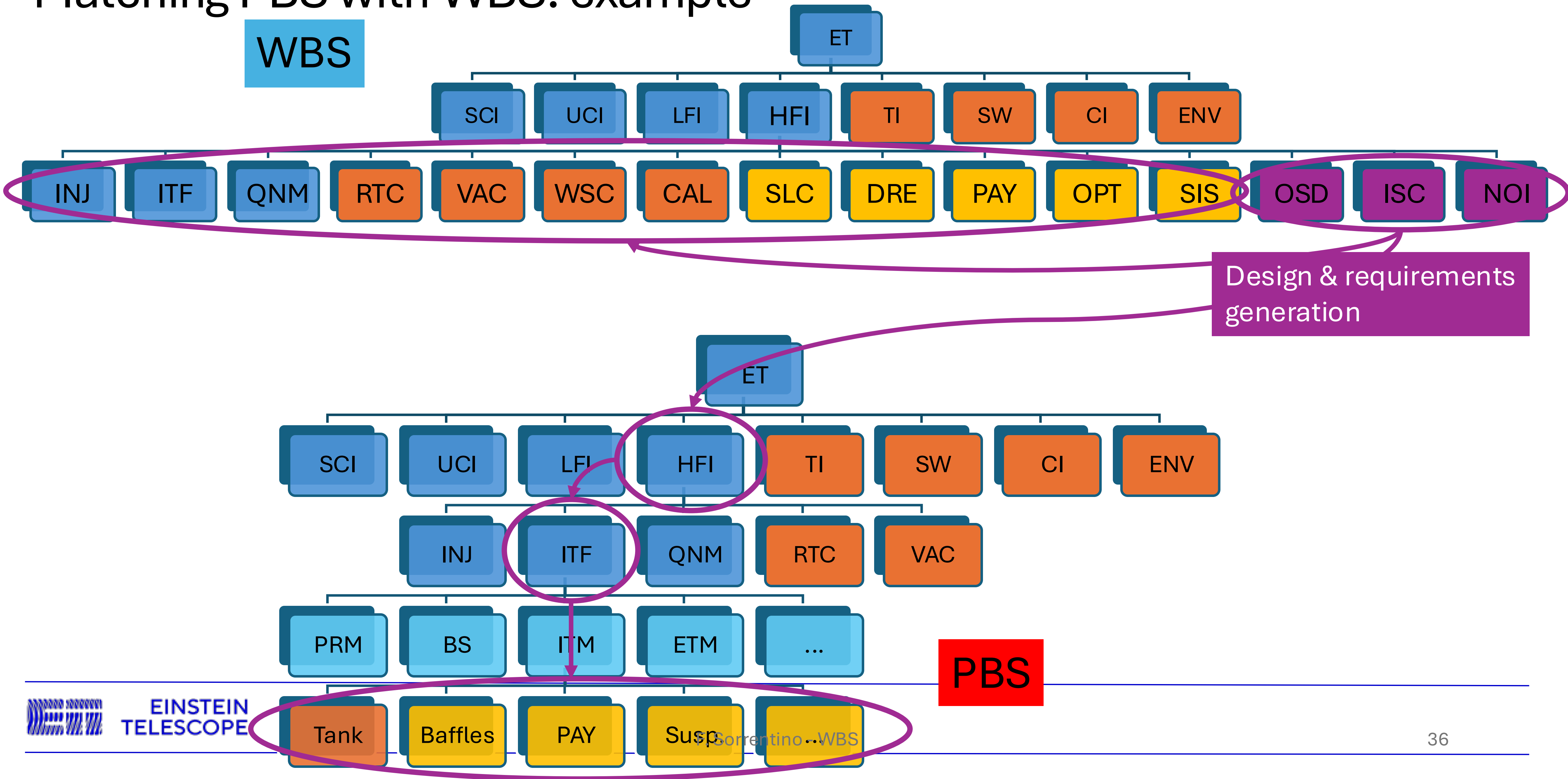

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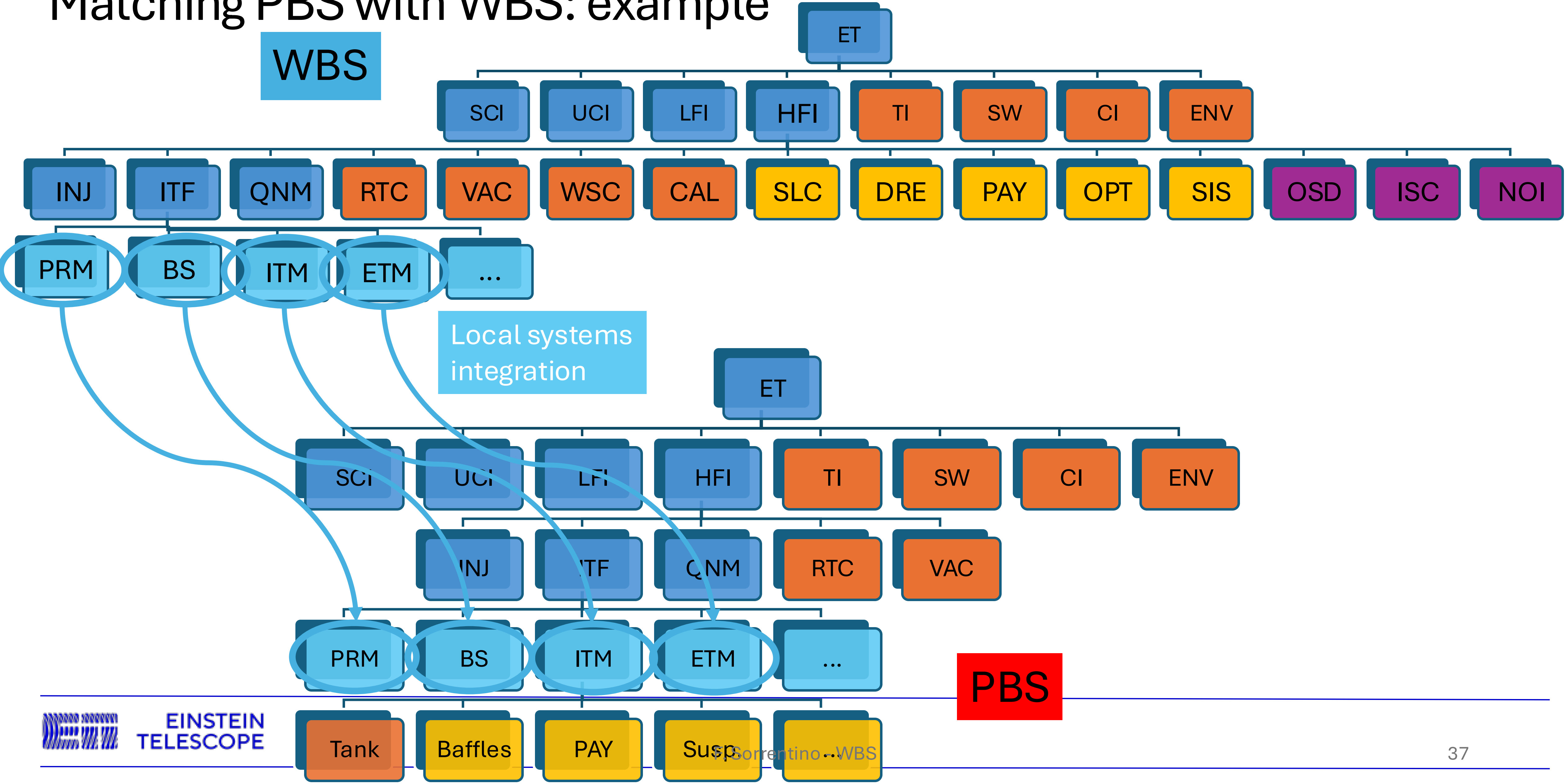


REQUIREMENTS TRACKING

Example of requirement tracking – SLC

- ITM mirror baffle
  - Functional requirements (through WBS)
    - inner diameter –> HFI_SCL –> HFI_OSD
    - Reflectivity –> HFI_SCL –> HFI_OSD
    - BSDF –> HFI_SCL –> HFI_OSD
  - Integration requirements (through PBS)
    - Outer diameter -> ITM_PAY-> ITM→ ITF
    - Mass -> ITM_PAY -> ITM_SIS –> ITM -> ITF
    - Outgassing rate –> ITM_VAC -> ITM -> ITF

STATUS, CONCLUSIONS & NEXT STEPS

Evolution after presentation @ ET annual meeting

- WBS.1 and PBS.2 tables available in shared spreasheet format

	A	Layer1 name	L1_type	L1_description	L2_ID	Layer2 name	L2_type	L2_description	L3_ID	Layer3 name	L3_type	L3_description	L4_ID	Layer4 name	L4_type
2	1	Einstein Telescope (ET)	GSI	Generation of top level requirements; integration of level 2 systems	11	Underground civil Infrastructure	GSI	Caverns and tunnels hosting instruments and technical infrastructure; functional and integration interfaces; design, construction and maintenance.	1101	Access	GLF		110101	Access Shaft	LSI
3													110102	Safety Shaft	LSI
4													110103	Access Tunnel	LSI
5													110104	Boreholes	LSI
6									1102	Caverns	GLF		110201	Cavern A	LSI
7													110202	Cavern A	LSI
8													110203	Cavern A	LSI
9													110204	Cavern A	LSI
10													110205	Cavern A	LSI
11													110206	Cavern A	LSI
12													110207	Cavern A	LSI
13													110208	Cavern A	LSI
14													110209	Cavern A	LSI
15													110210	Cavern B	LSI
16													110211	Cavern C	LSI
17													110212	Cavern D	LSI
18													110213	Cavern E	LSI
19													110214	Cavern F1	LSI
20													110215	Cavern F2	LSI
21													110216	Cavern F3	LSI
22													110217	Cavern G1	LSI
23													110218	Cavern G2	LSI
24													110219	Cavern G3	LSI

WBS_breakdown_1a | WBS_breakdown_1b | PBS_breakdown_2a | PBS_breakdown_2b | WBS level 4 dependency matrix | +

Evolution after presentation @ ET annual meeting

- WBS.1 and PBS.2 tables available in shared spreasheet format
- two versions: with and without integrated subsystems (i.e. arms)
  - more suitable for interface integration with underground civil infrastructure

L3_ID	Layer3 name	L3_type	L3_description	L4_ID	Layer4 name	L4_type	L4_description	L5_ID	Layer5 name	L5_type	L5_description
								17040502	E2)	LSI	
1705	Interferometer (HF-ITF)	GSI	Combine laser beam to interfere with itself and convert strain into optical power modulation at dark port with optimal scale factor; functional interfaces, active control of the system; design, integrate, commission & operate the optical system	170501	Interferometer arms (HFI-ARM)	GSI	Maximise interferometer scale factor by increasing effective arm length via Fabry-Pérot optical resonators; functional interfaces and integration interfaces with infrascructure; design, integrate, precommission the Fabry-Pérot arm cavities.	17050101	Arm 1 input test mass (HF-IM1)	LSI	Integration of payload, suspension, vacuum chamber and additional hardware in node; interfaces between VAC, SIS, optical elements, and with civil and technical infrastructure
								17050102	Arm 1 terminal test mass (HF-EM1)	LSI	Integration of payload, suspension, vacuum chamber and additional hardware in node; interfaces between VAC, SIS, optical elements, and with civil and technical infrastructure
											Integration of

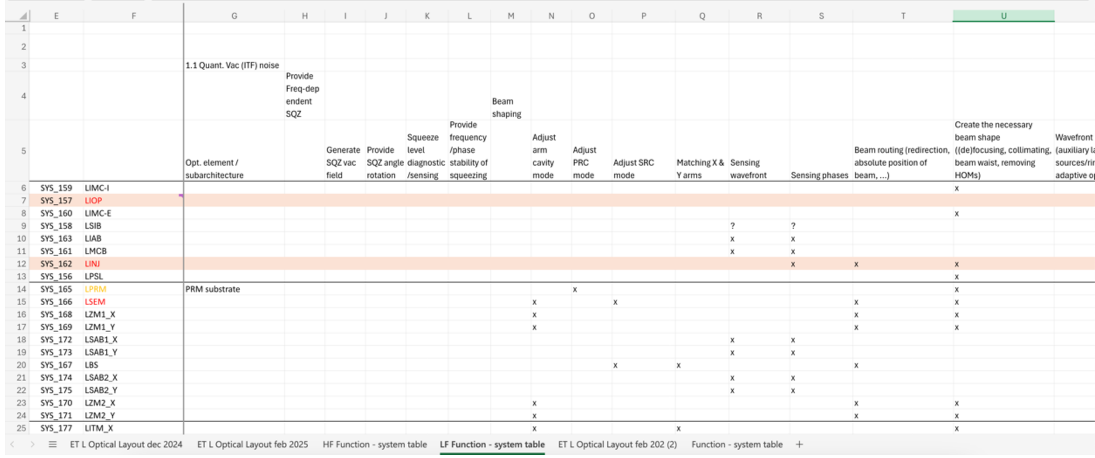
WBS_breakdown_1a | WBS_breakdown_1b | PBS_breakdown_2a | PBS_breakdown_2b | WBS level 4 dependency matrix | +

Evolution after presentation @ ET annual meeting

- WBS.1 and PBS.2 tables available in shared spreasheet format
- two versions: with and without integrated subsystems (i.e. arms)
  - more suitable for interface integration with underground civil infrastructure
- Start preparing integrated document on the structure of PBS.2 & WBS.1
  - Introduction
  - Product Breakdown structure: logic, decomposition, examples
  - Work Breakdown structure: logic, decomposition, examples
  - Mapping WBS functions into PBS nodes: logic and examples
  - Requirements flow: general logic, examples
  - WBS to OBS
  - WBS to scheduling: logic and examples
  - Conclusions

Evolution after presentation @ ET annual meeting

- WBS.1 and PBS.2 tables available in shared spreasheet format
- two versions: with and without integrated subsystems (i.e. arms)
  - more suitable for interface integration with underground civil infrastructure
- Start preparing integrated document on the structure of PBS.2 & WBS.1
- Examples of simplified structure from Task Force
  - system decomposition
  - functions -> node mapping
  - highlighting HFI/LFI-UCI integration functions



	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	
1																		
2																		
3			1.1 Quant. Vac (ITF) noise															
4				Provide Freq-dependent SQZ					Beam shaping									
5			Opt. element / subarchitecture		Generate SQZ vac field	Provide SQZ angle rotation	Squeeze level diagnostic /sensing	Provide frequency /phase stability of squeezing		Adjust arm cavity mode	Adjust PRC mode	Adjust SRC mode	Matching X & Y arms	Sensing wavefront	Sensing phases	Beam routing (redirection, absolute position of beam, ...)	Create the necessary beam shape ((de)focusing, collimating, beam waist, removing HOMs)	Wavefront (auxiliary la sources/ri adaptive o
6	SYS_159	LIMC-I															x	
7	SYS_157	LIOP																
8	SYS_160	LIMC-E															x	
9	SYS_158	LSIB												?	?			
10	SYS_163	LIAB												x	x			
11	SYS_161	LMCB												x	x			
12	SYS_162	LINJ													x	x	x	
13	SYS_156	LPSL															x	
14	SYS_165	LPRM	PRM substrate								x						x	
15	SYS_166	LSEM								x		x				x	x	
16	SYS_168	LZM1_X								x						x	x	
17	SYS_169	LZM1_Y								x						x	x	
18	SYS_172	LSAB1_X												x	x			
19	SYS_173	LSAB1_Y												x	x			
20	SYS_167	LBS										x	x			x		
21	SYS_174	LSAB2_X												x	x			
22	SYS_175	LSAB2_Y												x	x			
23	SYS_170	LZM2_X								x						x	x	
24	SYS_171	LZM2_Y								x						x	x	
25	SYS_177	LITM_X								x			x				x	

ET L Optical Layout dec 2024 | ET L Optical Layout feb 2025 | HF Function - system table | LF Function - system table | ET L Optical Layout feb 202 (2) | Function - system table

Next steps

- Finalize spreadsheet
  - solve details in the structure, e.g. include telescopes as subsystems? technical infrastructure etc.
  - complete description of main functions into spreadsheet
  - include tables to map functions into configuration nodes
- Prepare an integrated document describing the logic and structure PBS.2 and WBS.1
- Propagate WBS concept to ET-PP CDR system decomposition
- Share full proposal (document & spreadsheet) for PBS.2 + WBS.1 with stakeholders
  - ISB, PO, ED, end others (e.g. CERN)
  - ask for feedback and incorporate useful suggestions
  - implement & manage PBS.2 structure (involving ISB, ED, CERN, ...)
  - set up a proto-WBS for phase 1
    - synchronise with ETO directorate for timing
- test advanced management tools (involving relevant stakeholders to make use of such tools in the future: ISB, ED, CERN, ...)
    - WBS: scheduling tool
    - PBS: PLM/MBSE
    - configuration: database & requirements management tool