"Mind the Gap" session
243rd AAS Meeting, 9 January 2024

UV CMOS Detectors for CASTOR and Beyond

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Thanks to Pat Côté (NRCC, CASTOR science PI) for slide contributions

CASTOR Mission Overview

Acronym!

The Cosmological Advanced Survey Telescope for Optical and uv Research

- Light-weighted Zerodur 1m primary mirror

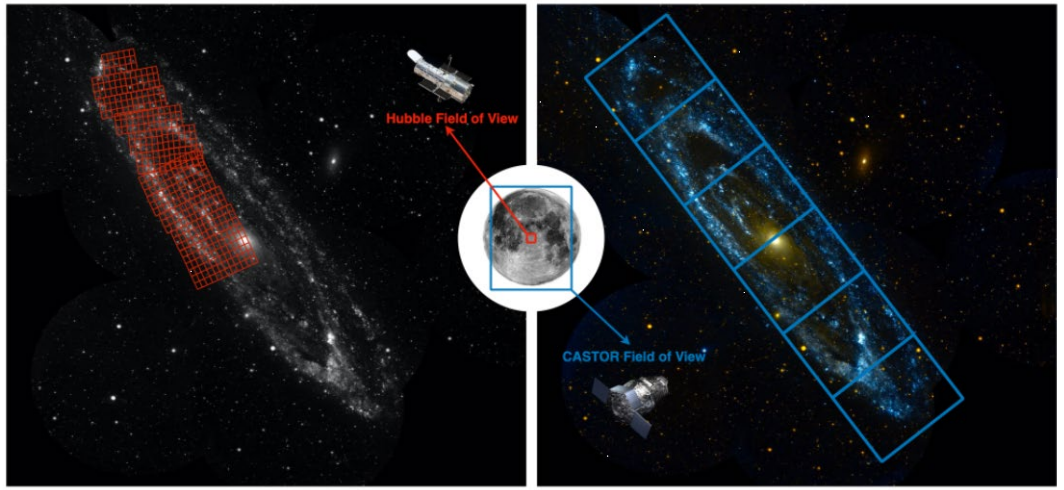
  Three Mirror Anastigmat with 0.25 deg^2 FoV
- Active M2 for WFE compensation
- Fine steering mirror for image stabilization
- 1063 kg spacecraft and 10 Gbps optical downlink
  - MAC200-small-SAT bus

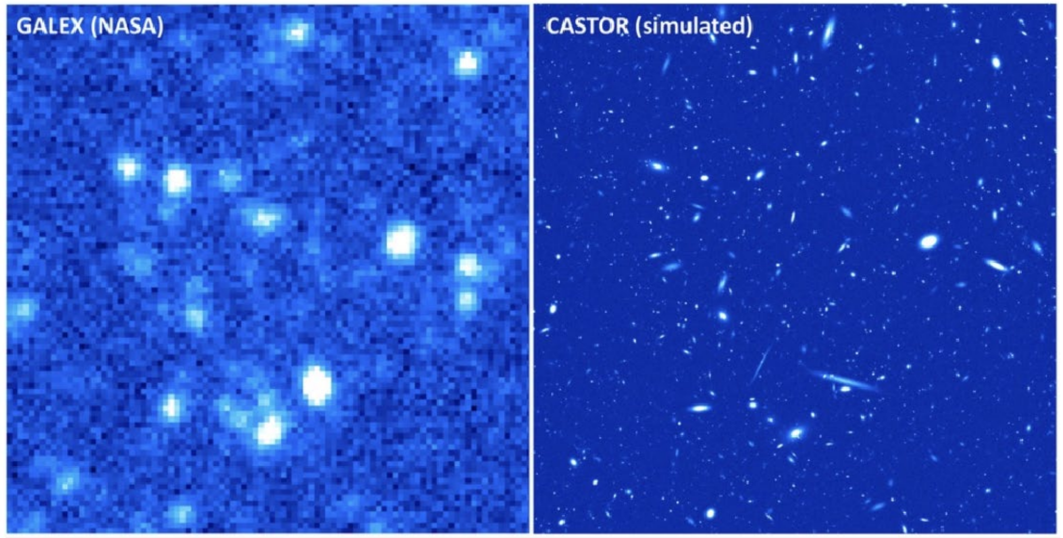
  800 km polar SSO for efficient surveys
- Dichroic separation of wavebands
- Optical coatings on all mirrors for red leak control

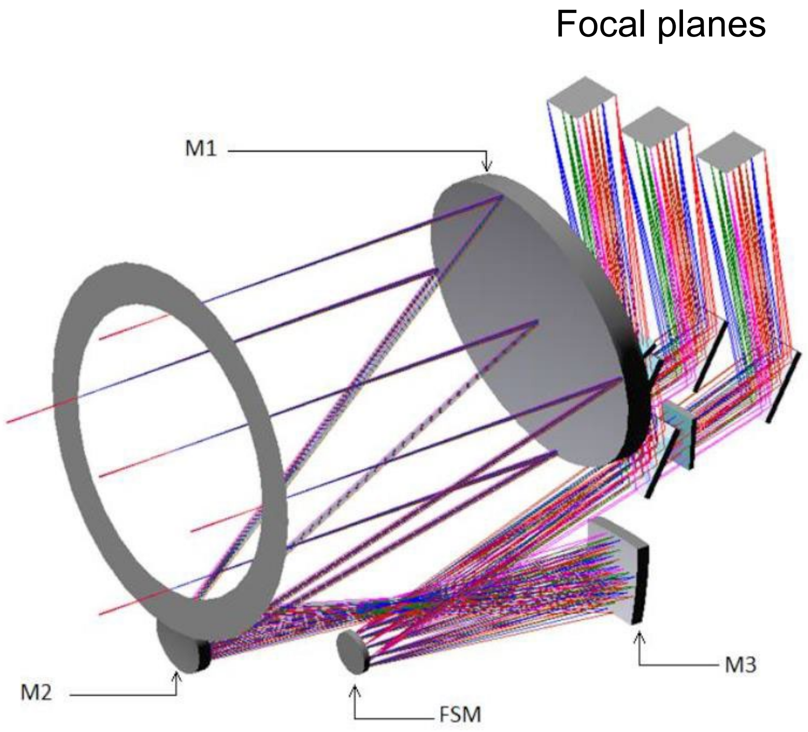
  Minimum 5 year mission (Goal:10 years)

  Combination of Legacy Surveys (64%), Guest Observer programs (25%), Target-of-Opportunity programs (8%), and calibration time (3%)

  14 candidate Legacy Surveys advanced to SRL4 during Phase 0
  - To be revisited once the partnership is finalized







> *"Our highest recommendation at the very large investments scale is for CASTOR, an exciting mission with a broad and compelling science case, and which would be Canada's first marquee space astronomy mission."*
>
> ***— Canadian Astronomy Long-Range Plan 2020***

Imaging and UV Spectroscopy

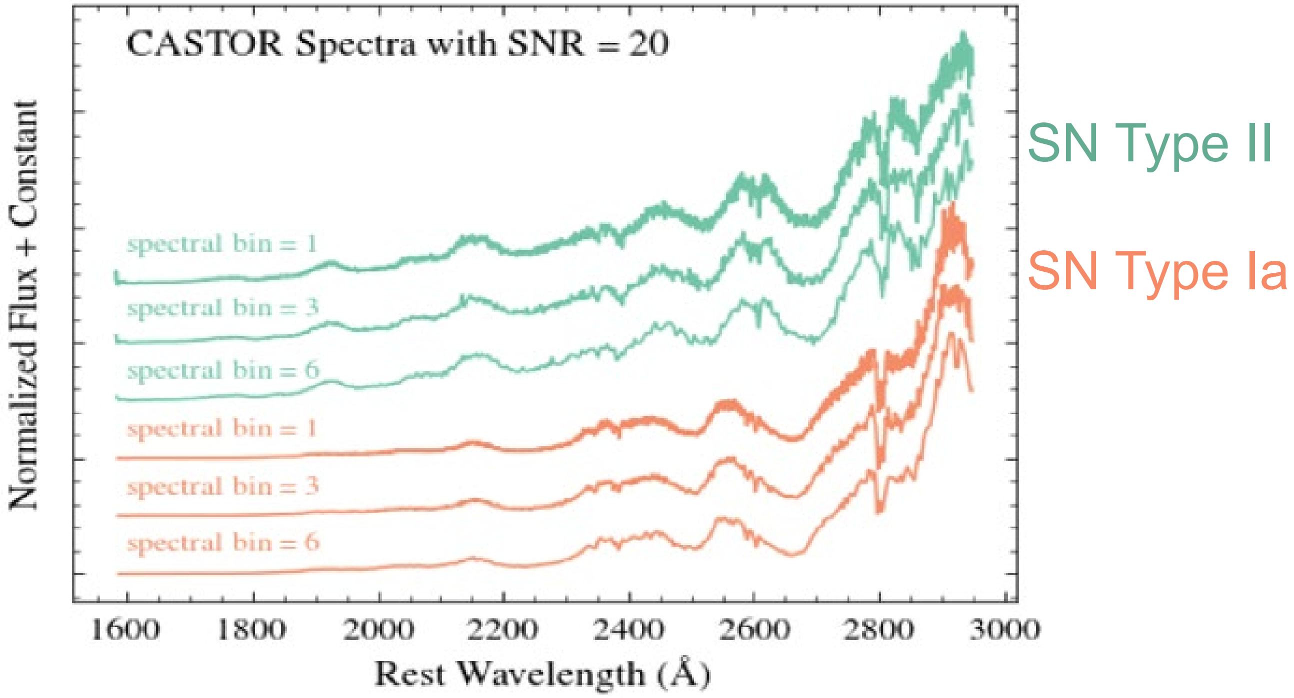
Wide-field UV/blue-optical imaging

- 3 x 310 Megapixel arrays sampled at 0.1”/pixel
- Simultaneous imaging in three channels

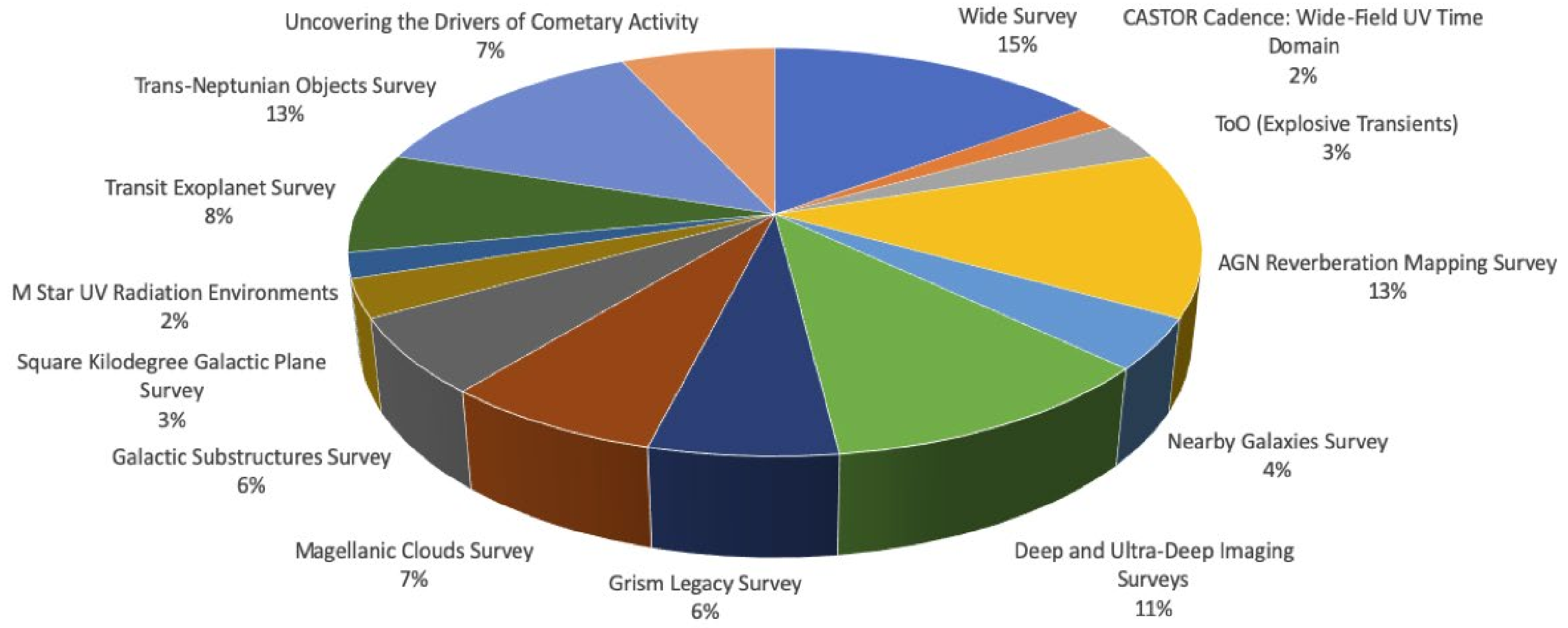
Back-illuminated large-format CMOS detectors with ALD AR coatings and 2D-doping

Two spectroscopic modes

- Deployable grism (150-400nm, R~350) over full FOV
- UVMOS with DMD selector (150-300nm, R~1000-2000) over 207” x 117” (offset from FOV)



TIME REQUEST BY SURVEY (Spectroscopic)



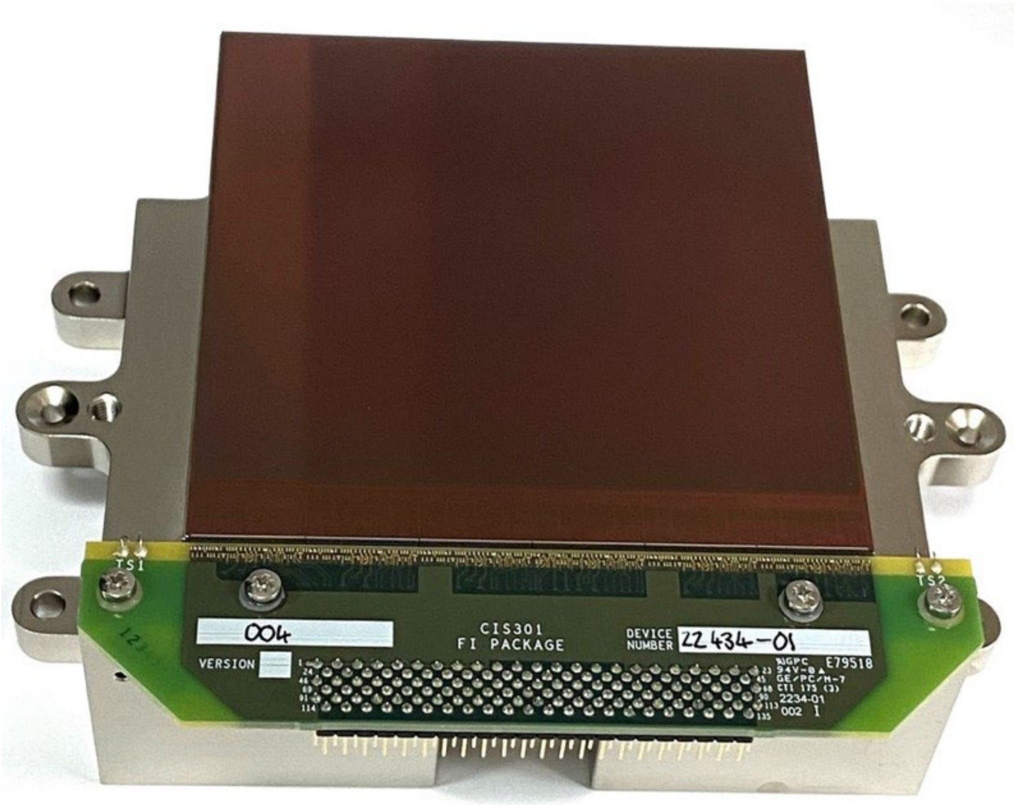
- ❑ Grism and UVMOS instruments make up roughly one third of the time requested for legacy surveys
  - Grism spectroscopy is used in 6/14 surveys
  - UVMOS spectroscopy is used in 7/14 surveys
- ❑ Spectroscopic science drivers include the progenitors of kilonovae, the evolution of the cosmic web, AGN reverberation mapping, flare rates in M dwarfs, the surface chemistry of Trans Neptunian Objects, and more

CASTOR detector requirements

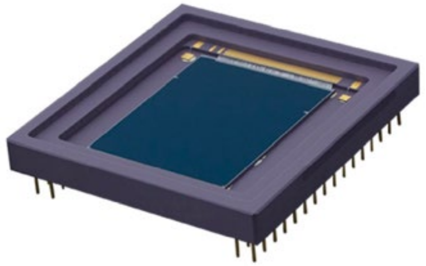
- Low dark current < 0.01 e-/px/s
- Low read noise < 6 e- rms
- Low power dissipation
- Pixel pitch <= 10 µm
- Ability to do 10 Hz fine guiding on main array without disrupting science integrations
- Large, buttable arrays to reduce chip gaps and number of detectors
- Radiation hard

→ **CMOS solution**

- High UV QE → **2D doping and AR-coating**



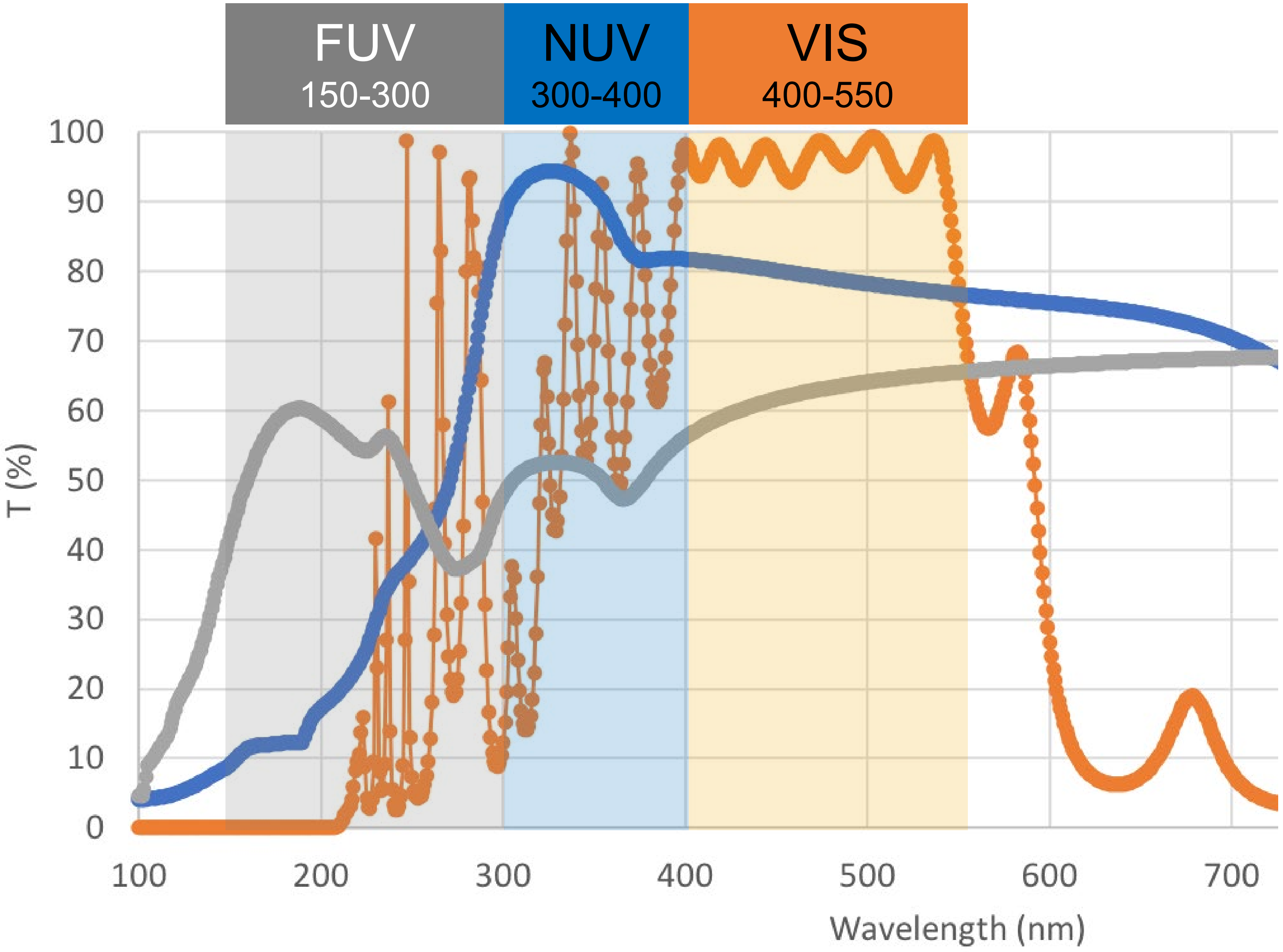
Teledyne-e2v CIS301
9K x 8.6K pixels ; 10µm pitch

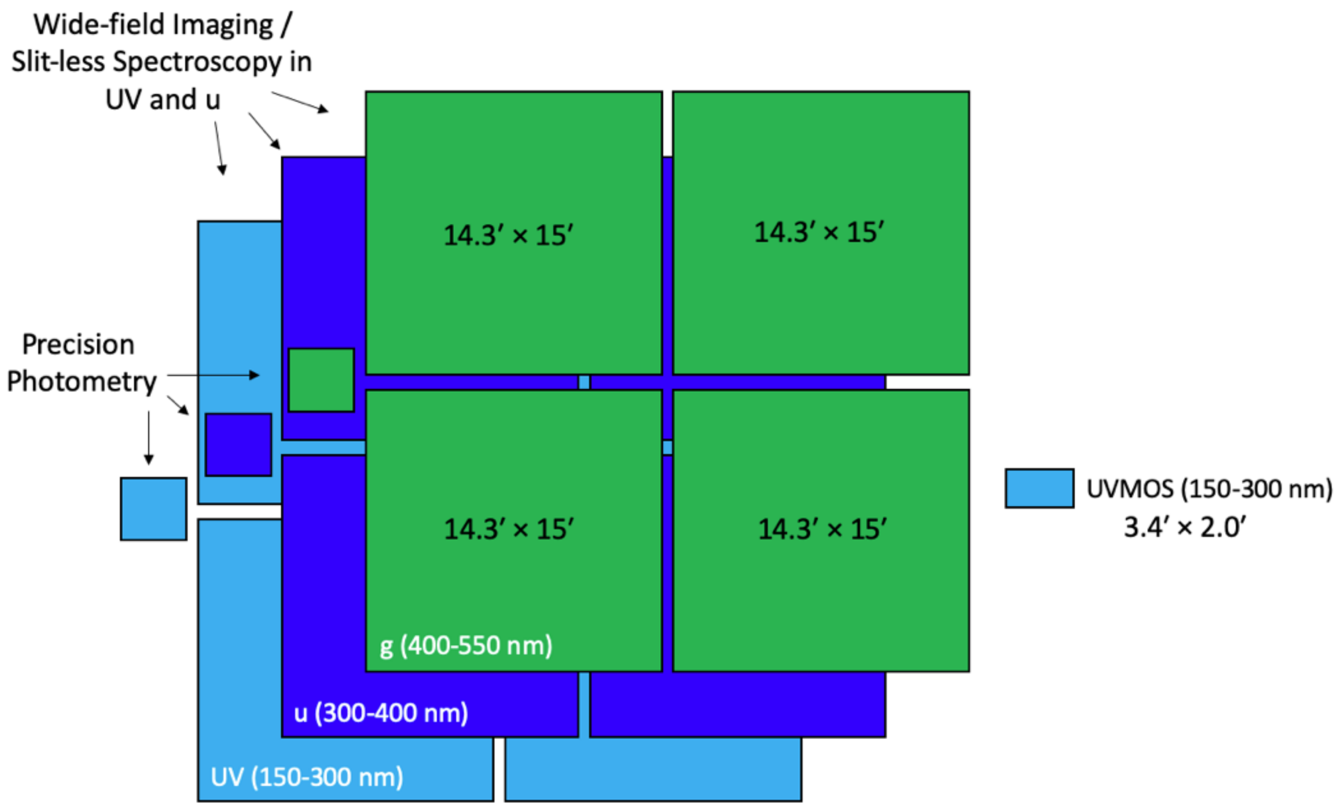


Teledyne-e2v CIS120
2K x 2K pixels ; 10µm pitch

~1 Gpx focal plane divided into 3 channels/bands

Nominal bands with detector AR coatings





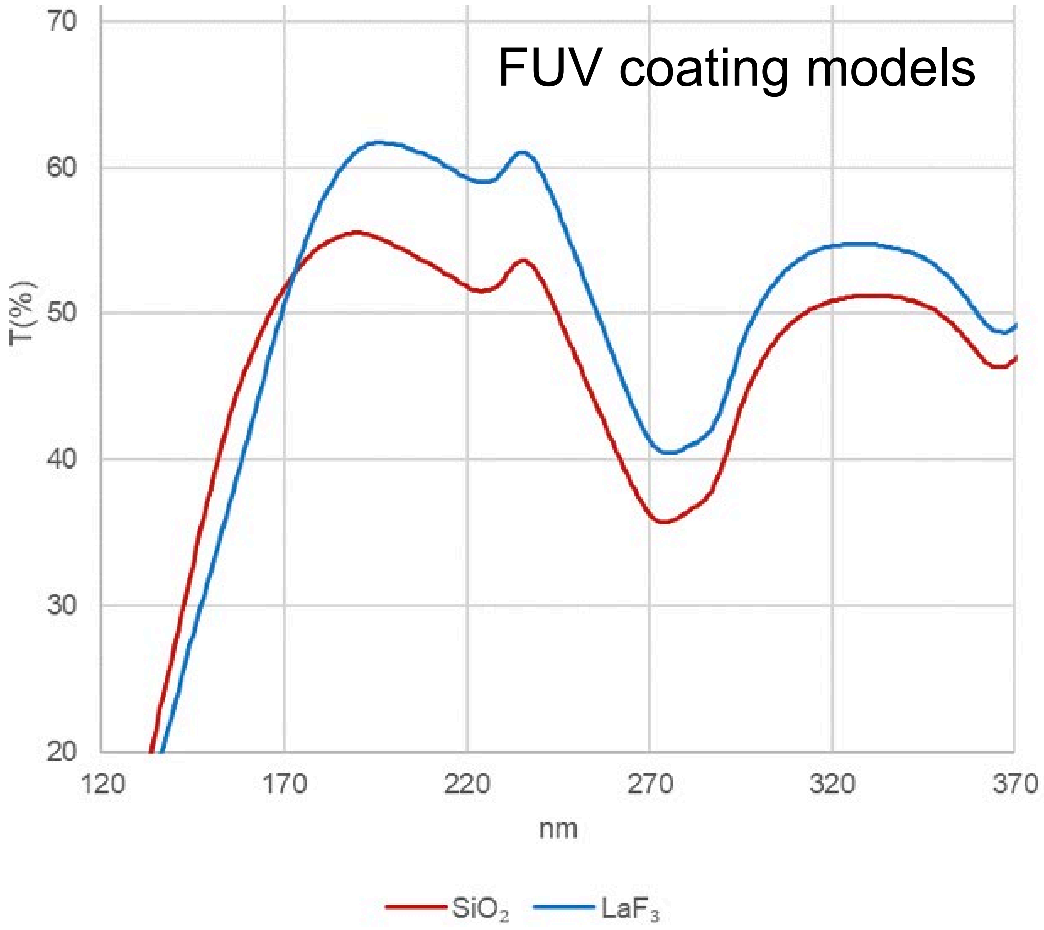
- Detector coatings chosen by CASTOR to maximize in-band QE for each channel
- Out-of-band light rejected by dichroics and mirror coatings

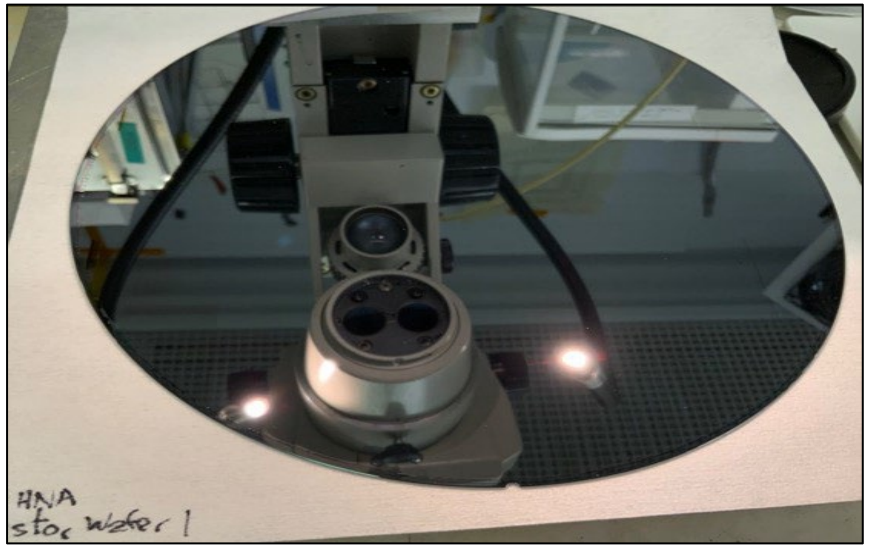
JPL Engagement in CASTOR

- CASTOR partners (NRCC, Honeywell, ABB) have been working closely with JPL since 2017, with the ultimate goal of securing a NASA partnership.

- **Science** JPL/IPAC scientists made key contributions to the 2019 CASTOR Science Maturation study, serving as co-leads on 7 of 8 science working groups for the Phase 0 study. (POC: Jason Rhodes)

- **Technology** JPL’s Advanced Detector group and Teledyne-e2v have delivered 2D doped and AR coated CIS120 prototypes to CSA as part of their Space Technologies Development Program (POC: Chaz Shapiro)


FUV coating models



CIS120 wafer inspection

2D-Doping: Expanding design space for UV missions of all sizes

- Detectors are the heart of an instrument, driving major mission design trades: mass, power, optical configuration, observing strategy, cost
- Solid state detectors continue to grow in scale, sensitivity, and capability. Choose from: CCD (incl. Skipper, EMCCD), CMOS, APD, SPAD...
- …but they are *not* natively UV-sensitive

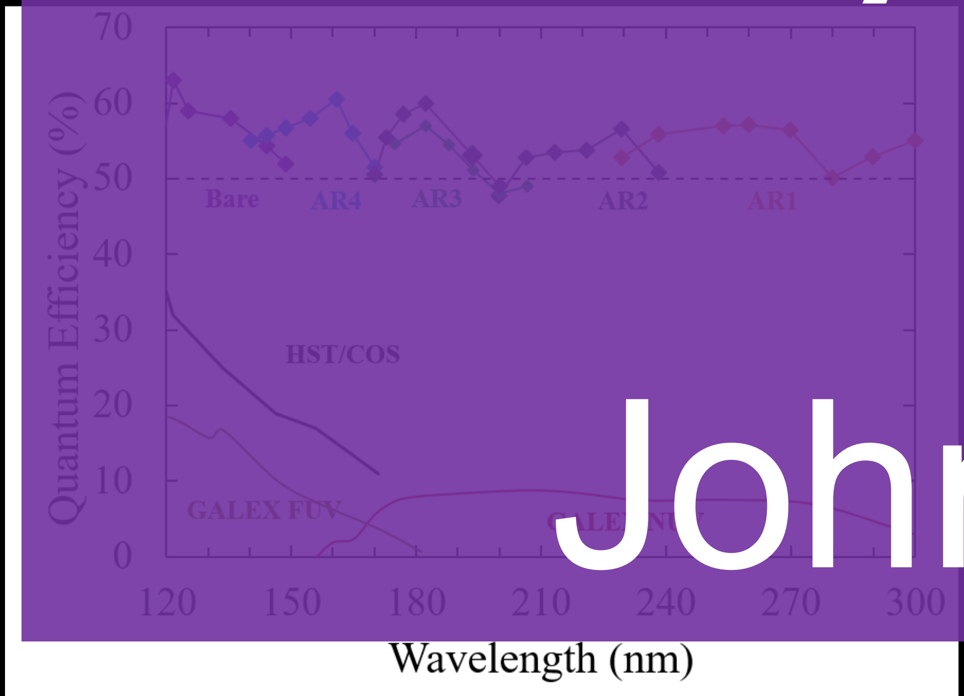
- JPL's 2D-doping process converts Si-based devices into UV detectors, allowing UV missions to take full advantage of latest technologies. 2D-doping and subsequent coatings:
  - provide high, stable QE in UV
  - are agnostic to device architecture – process on backside doesn't "see" frontside
  - allow QE to be tailored to required wavelength bands
  - are radiation tolerant (Hoenk et al. 2014)

Antireflection (AR) Coatings and Metal Dielectric Filters (MDF) optimize QE

- Precision coatings via Atomic Layer Deposition
- Single and Multilayer coatings can tailor response to band out of the desired band.
- Coatings deposited on detector eliminate standalone filters and reduce optical complexity.

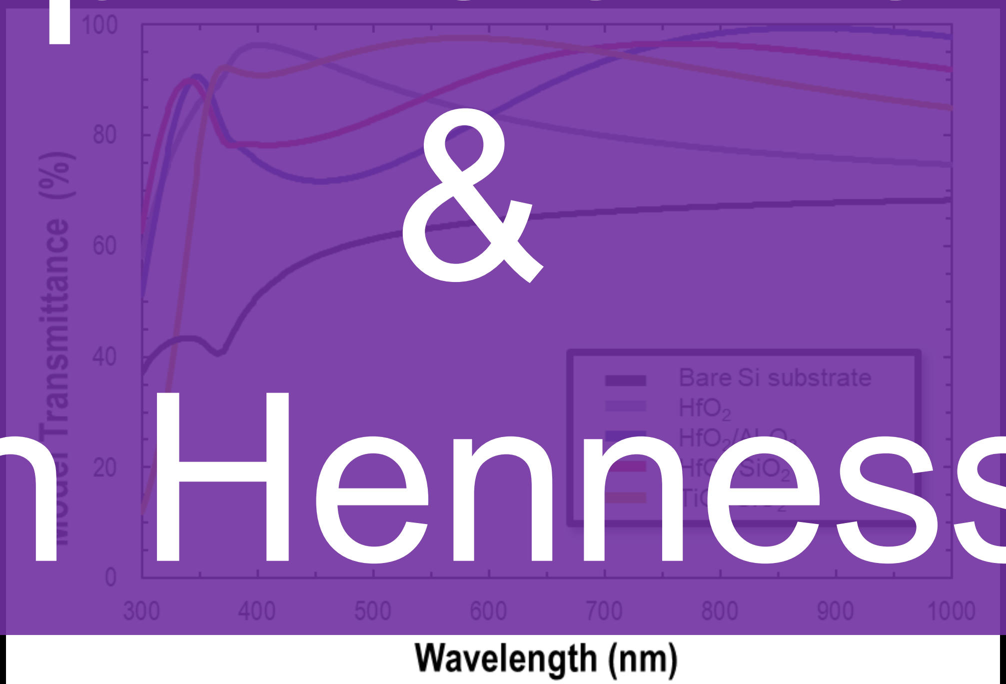
See talks by
April Jewell
&
John Hennessey!

Narrow band AR



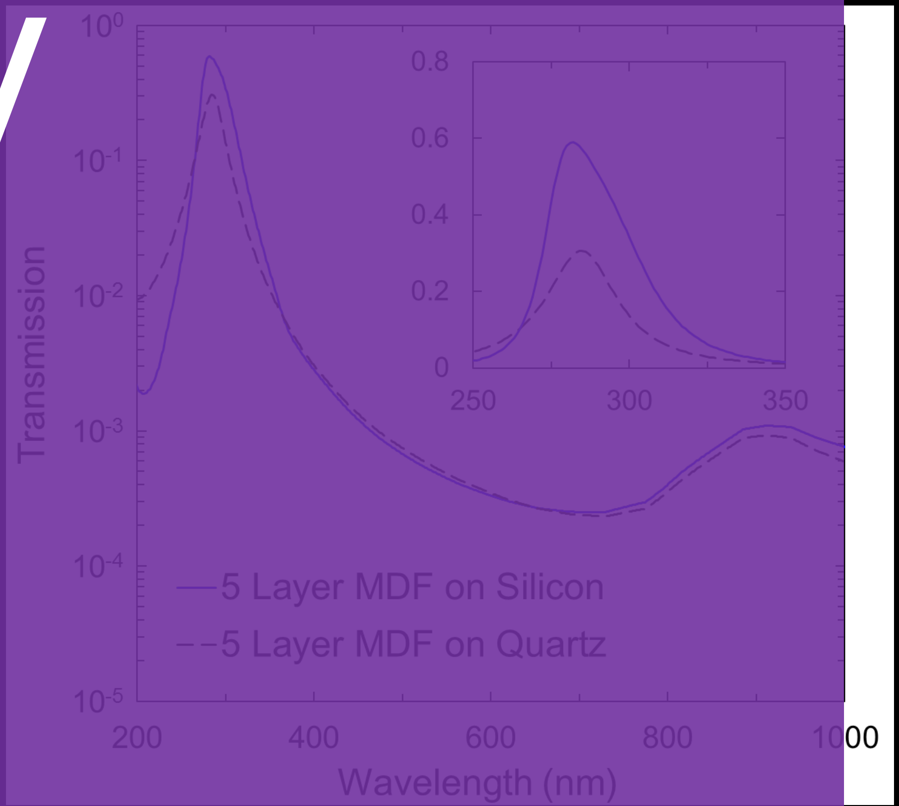
Nikzad, *et al.*, *Applied Optics*, **51**, (2012) 365

Broadband AR



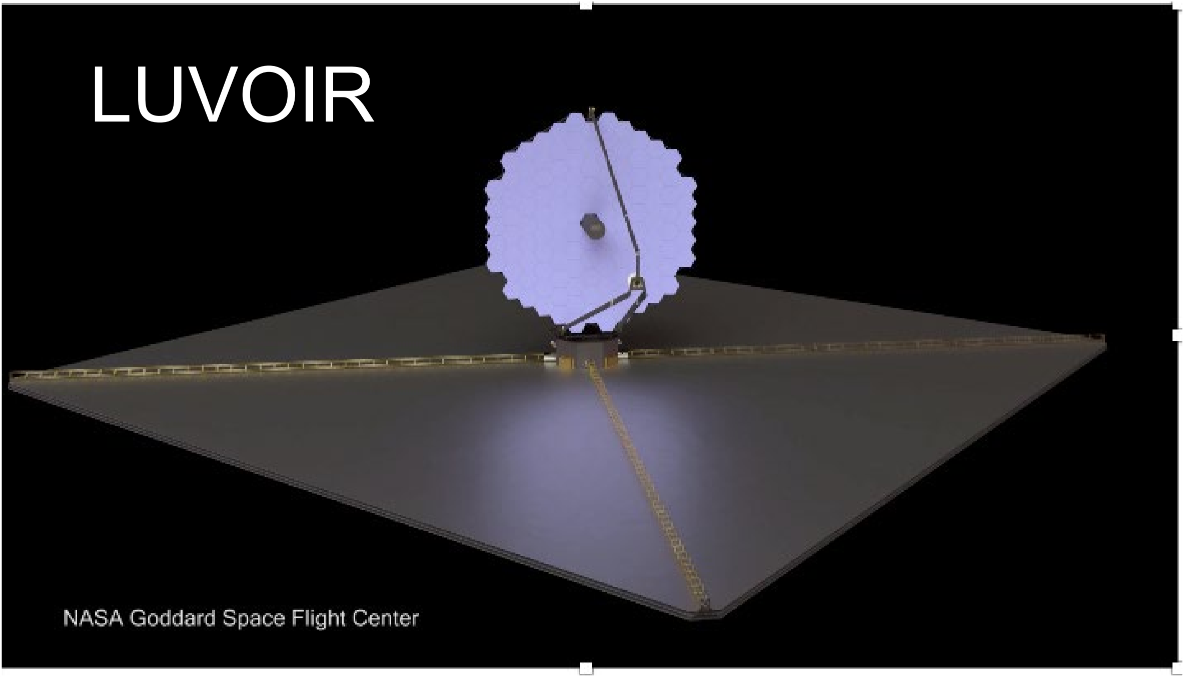
Jewell, *et al.*, *Proc. SPIE* **8820** (2013) 88200Z

Solar blind MDF

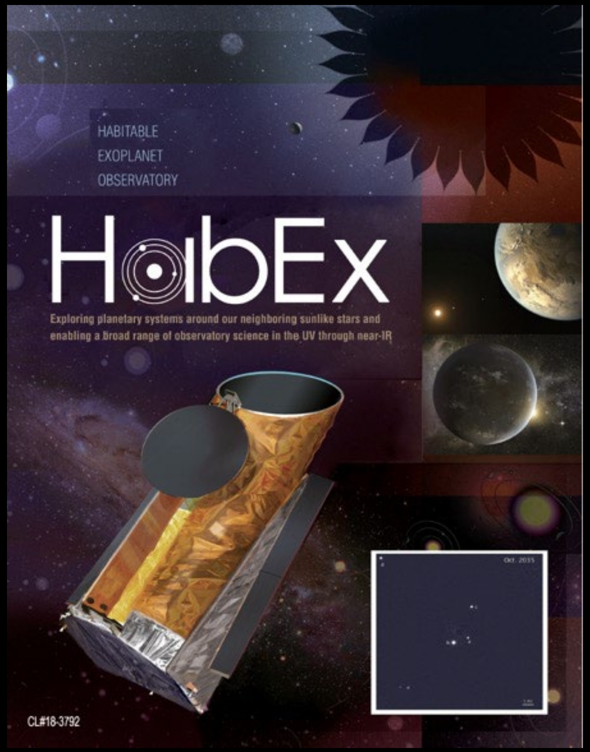


The Future: Explorers and Flagships

~~LUVOIR & HabEx~~
Habitable Worlds Observatory!



- 2D-doped detectors are baselined or backups for several instruments
- Working with industry to develop devices that meet challenging requirements
- E.g. LUVOIR needs large, buttable arrays with <7µm pixels and fast, low noise readout.


HABITABLE
EXOPLANET
OBSERVATORY

HabEx

Exploring planetary systems around our neighboring sunlike stars and enabling a broad range of observatory science in the UV through near-IR

CL#18-3792

Instrument	Baseline Detector
High Definition Imager (HDI)	Delta-doped CMOS array; 200-1100nm
Ultraviolet Multi-Object Spectrograph (LUMOS)	Delta-doped CMOS array; 200-400nm (MCP 100-200)
Pollux (European Contribution)	Delta-doped CCDs; 97-390nm
ECLIPS (Coronograph)	Delta-doped EMCCD; 200-525nm

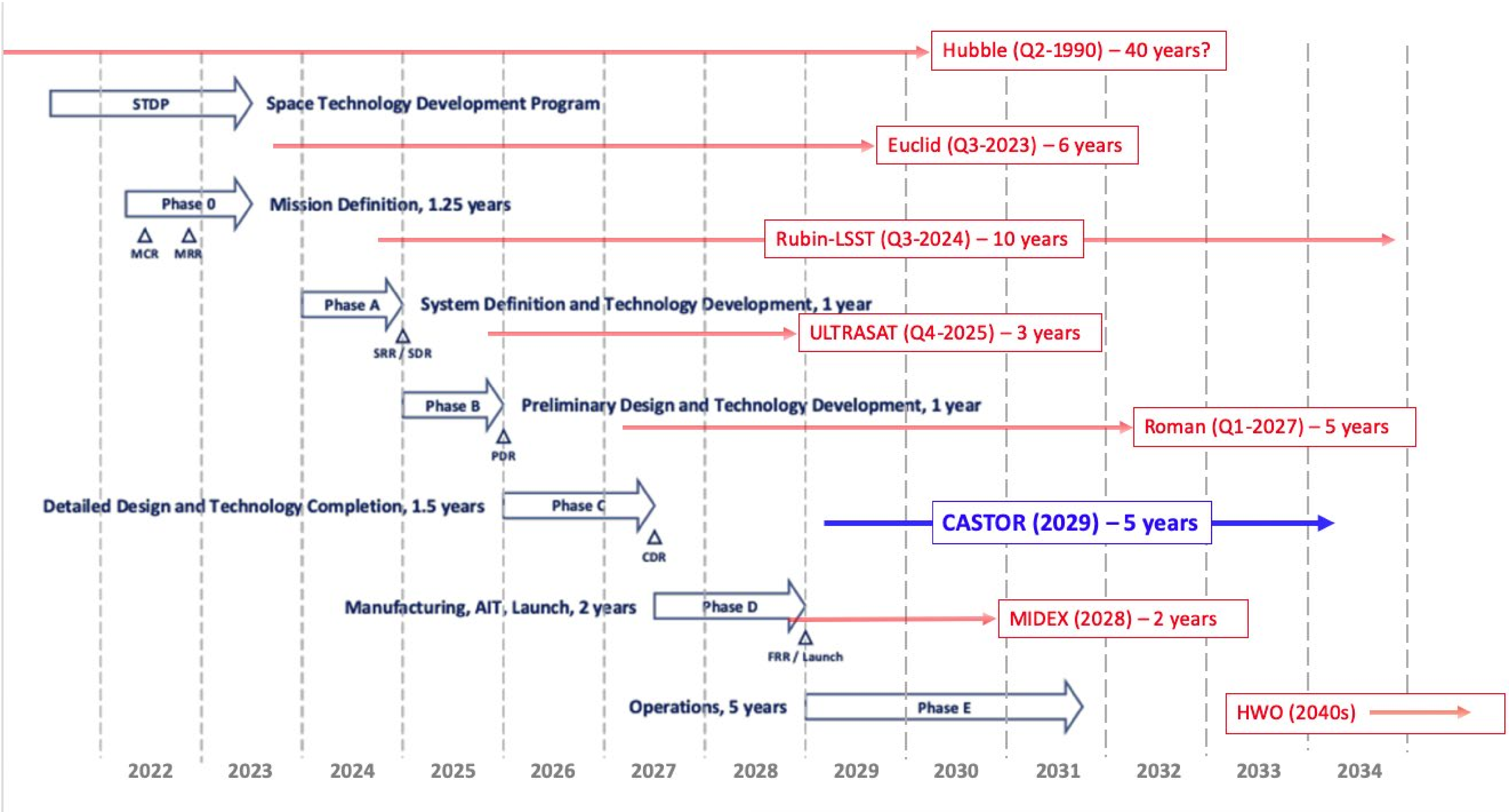
(Some wavelength ranges shown span multiple channels)

Instrument	Baseline Detector
Workhorse Camera (HWC)	Delta-doped CCD/CMOS; 150-950nm
UV Spectrometer	Delta-doped EMCCD (backup); 115-300nm
Coronograph	Delta-doped EMCCD; 450-670nm
Starshade	Delta-doped EMCCD; 200-450nm

Backup

Notional Schedule

Canadian Space Agency
Agence spatiale canadienne



Hubble (Q2-1990) – 40 years?

STDP Space Technology Development Program

Euclid (Q3-2023) – 6 years

Phase 0 Mission Definition, 1.25 years

MCR MRR

Rubin-LSST (Q3-2024) – 10 years

Phase A System Definition and Technology Development, 1 year

SRR / SDR

ULTRASAT (Q4-2025) – 3 years

Phase B Preliminary Design and Technology Development, 1 year

PDR

Roman (Q1-2027) – 5 years

Detailed Design and Technology Completion, 1.5 years Phase C

CDR

CASTOR (2029) – 5 years

Manufacturing, AIT, Launch, 2 years Phase D

FRR / Launch

MIDEX (2028) – 2 years

Operations, 5 years Phase E

HWO (2040s)

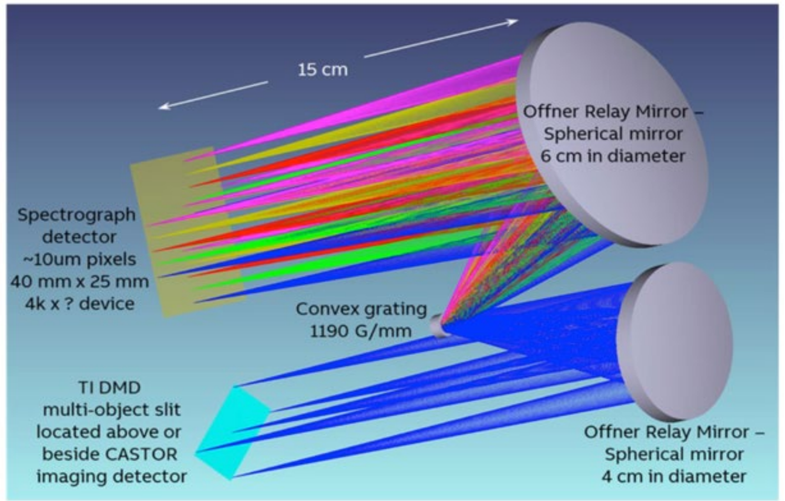
TDAMM Science with CASTOR UVMOS

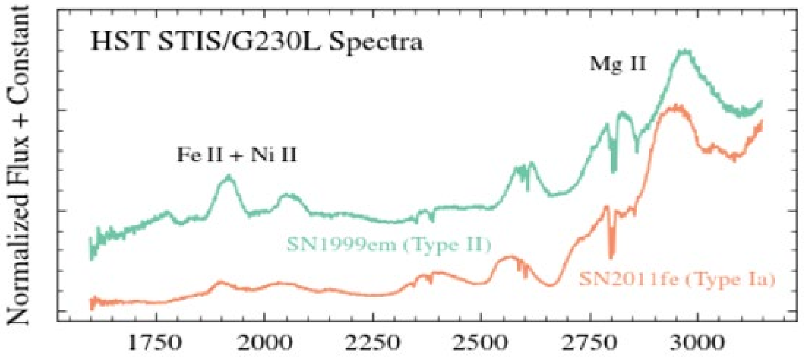
CASTOR

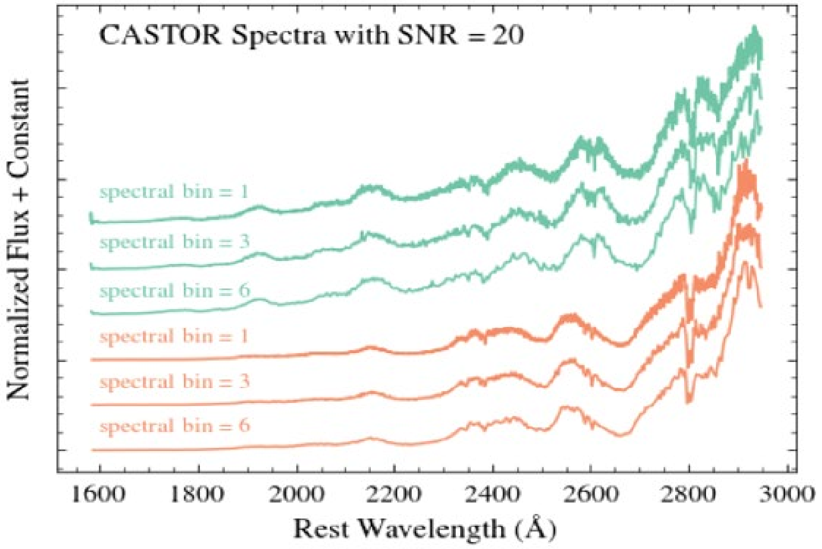
Applications of intermediate-resolution UVMOS spectroscopy for TDAMM science

- Supernovae spectra: characterization of CSM and progenitor stars from Fe II, Ni II and Mg II absorption depths, plus the height and slope of the UV continuum
- Spectroscopic follow up of kilonovae and other transients out to distances of 500 Mpc
- UV emission-line observations of tidal disruption events
- Characterization of super-luminous and infant supernovae from UV continuum measurements and equivalent widths for lines of ionized Si, C, Mg and Ti between 220 and 270 nm

Trigger Type	Response Time Required	Key CASTOR Capabilities
Prompt Localization and Follow-up	fast (~hours)	field of view sensitivity & resolution
Late-time follow-up and Environment	slow (weeks to years)	sensitivity & resolution
Spectroscopic	moderate (days to weeks)	UV spectroscopy



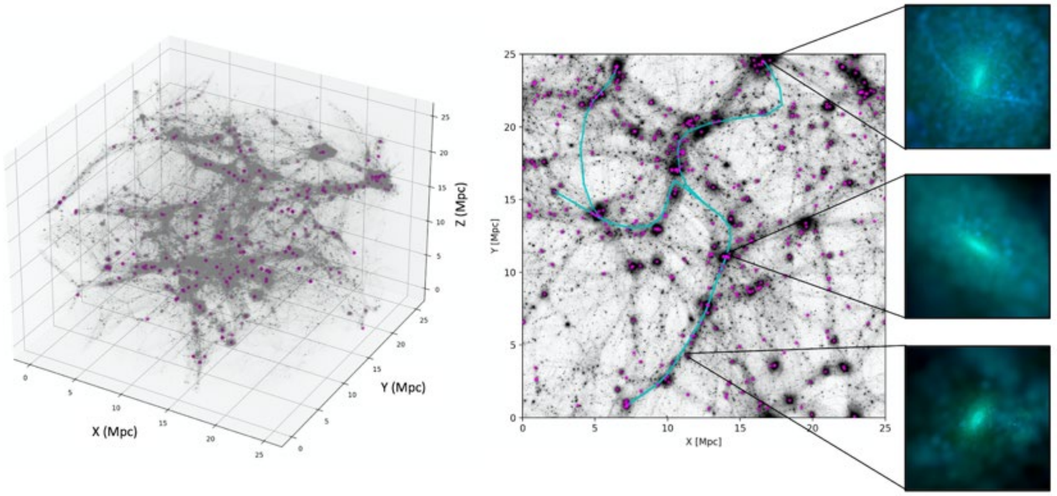




Galaxies in the Cosmic Web with CASTOR

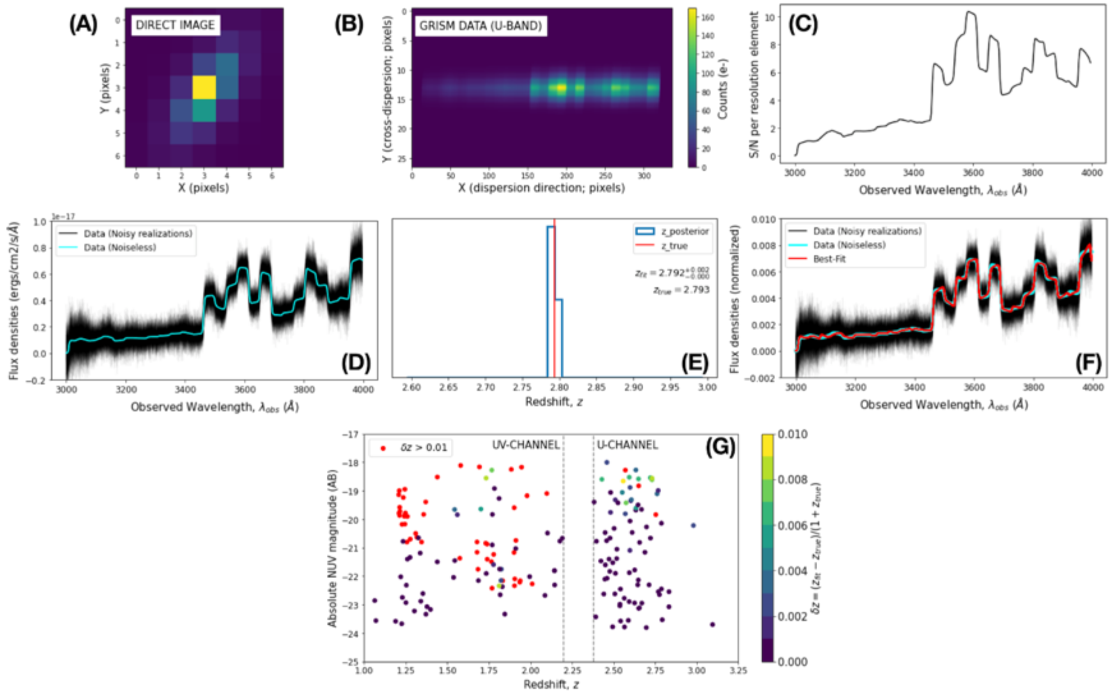
The Cosmological Advanced Survey Telescope for Optical and uv Research

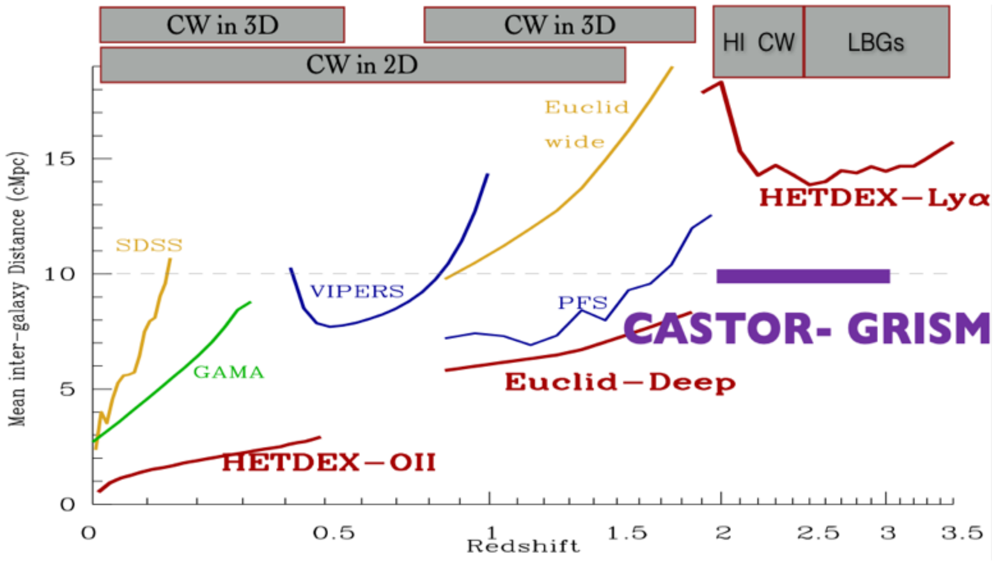
- ❑ Grism and UVMOS slit-less grism spectra will capture redshifts for 1000s of Lyman-α emitters (LAEs) and Lyman Break Galaxies (LBGs) per pointing
- ❑ CASTOR grism redshifts will trace the cosmic web to z~3
- ❑ This will allow us to study galaxy evolution in the full range of cosmic environments to 11 Gyr before the present



CASTOR

EAGLE simulation: McAlpine et al. (2016)





Partnerships and Collaborations

- **NASA** Desired contribution: CASTOR’s three WFI cameras (see below). Additional contributions are possible and welcome

- **UKSA** Participation approved in Jan. 2023 through a new bilaterals program in space science
  - Contributions under discussion with CSA, including detector qualification, testing, electronics; cryo-cooler; filters; coatings; secondary; data flows
  - Detector procurement discussions are ongoing, focusing on a separate UKSA funding stream

- **India/ISRO** In December 2021, ISRO had expressed strong interest in a partnership
  - Expected contributions: launch, UVMOS, ground stations
  - A timely agreement could not be reached. CASTOR is now seeking other partners to provide these items

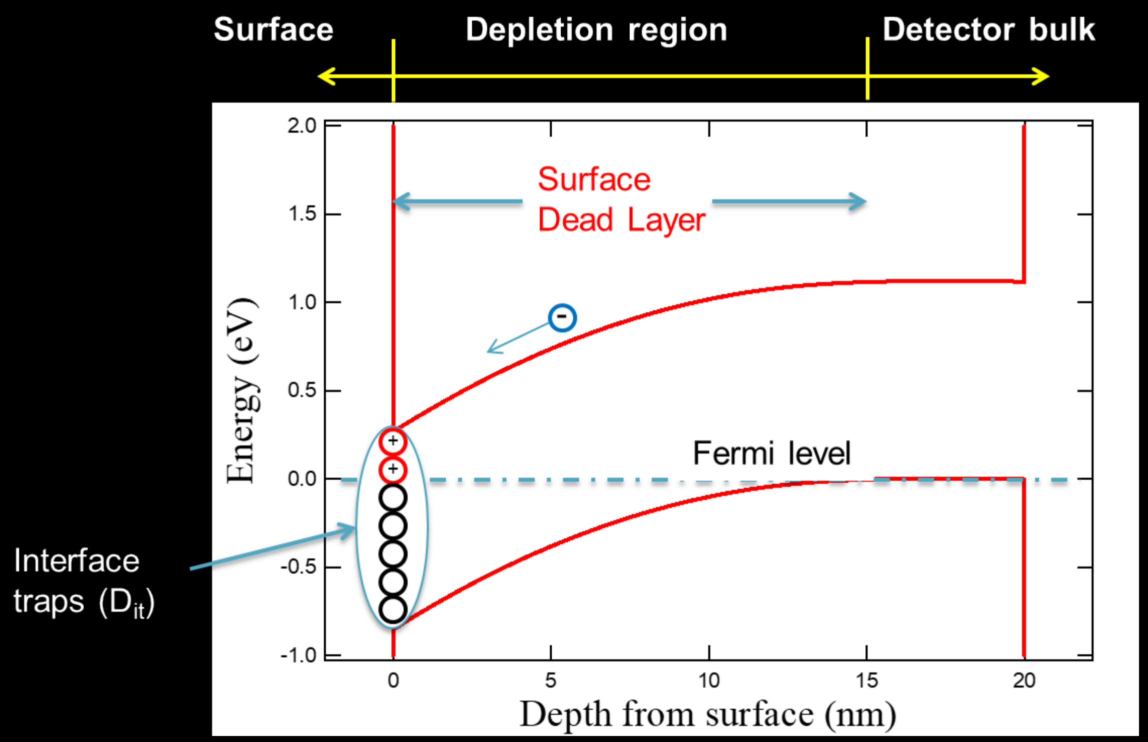
- **Spain/France** Strong interest in the UVMOS (formerly an Indian contribution).

- **South Korea** Discussions underway

The Silicon UV Problem

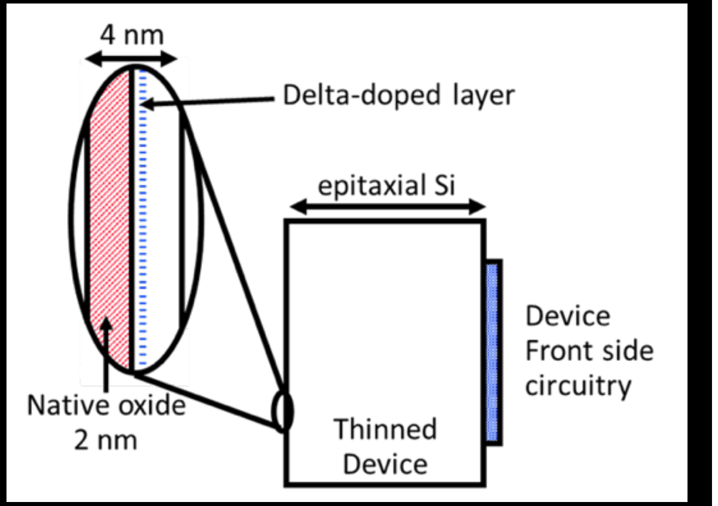
Dead layer
+
shallow absorption

= poor QE

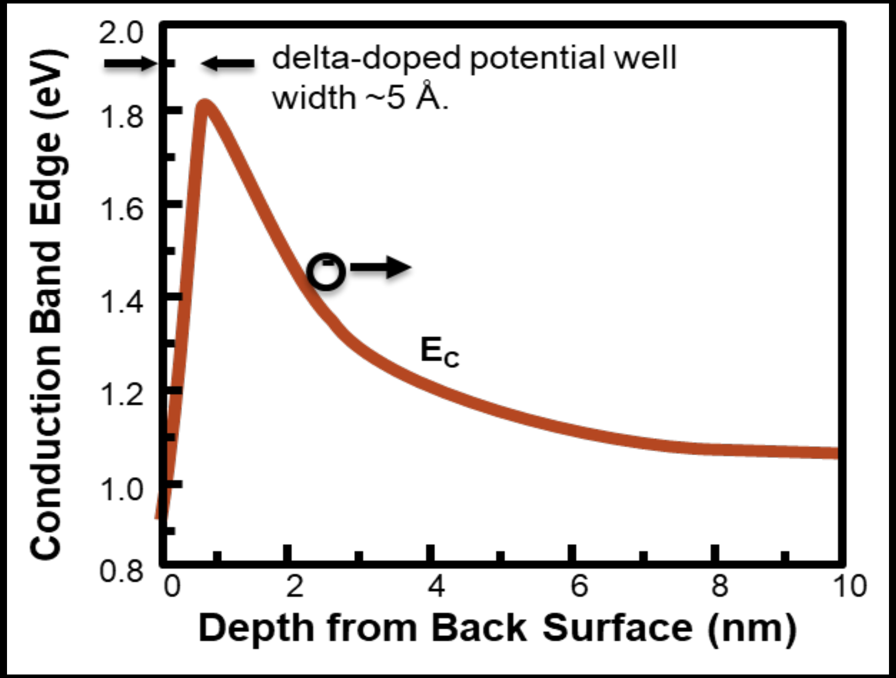


Passivation by 2D-Doping shrinks the dead layer

2D-doping provides the maximum possible QE, limited only by photon transmission into the silicon.



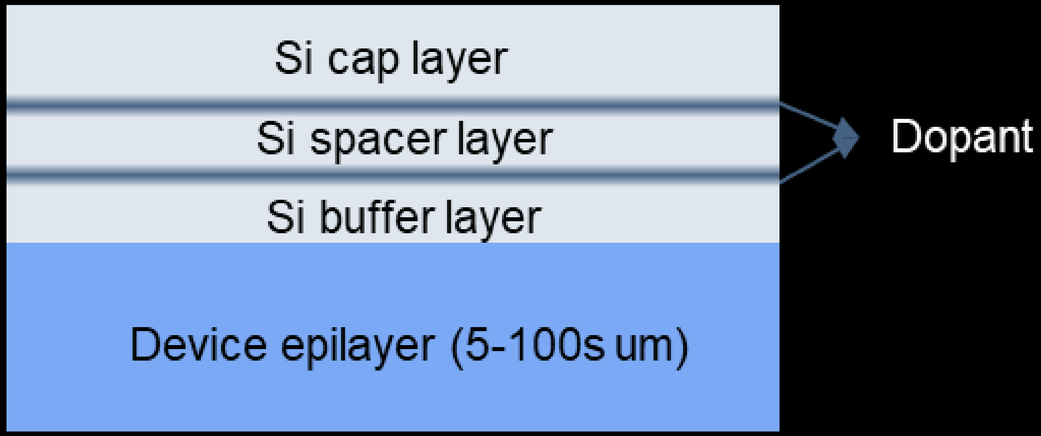
"delta" doping =
Delta function profile

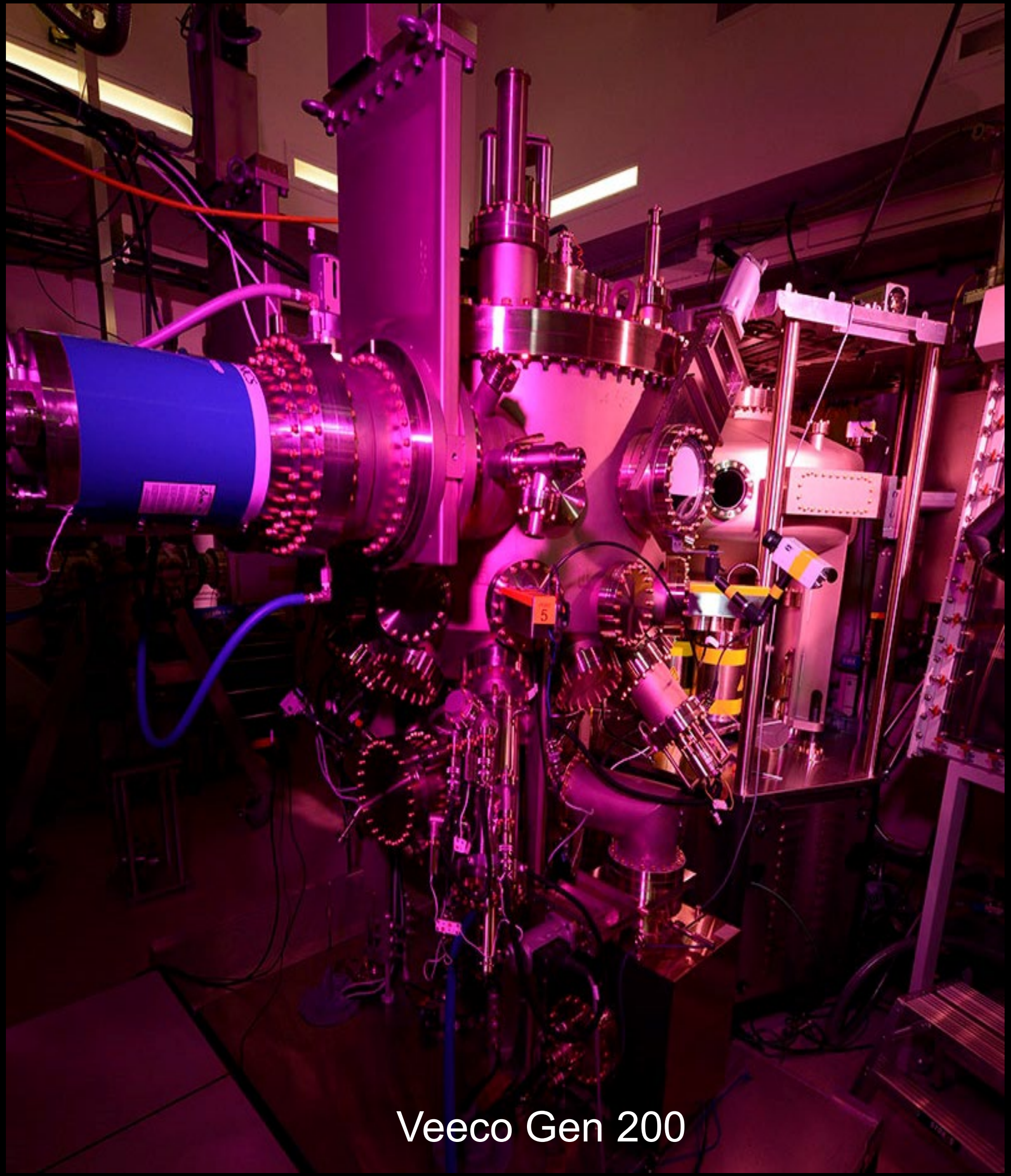


Hoenk et al., *APL*, **61** (1992) 1084
Nikzad et al., *Proc. SPIE* **4139** (2000) 250

2D-doping Process: Molecular Beam Epitaxy (MBE)

- Device wafer (up to 8”) bonded to handle wafer to protect frontside structures and add stability
- Backside surface is thinned to epitaxial Si layer
- New Si deposited by e-beam evaporation
- “Delta” layer of dopant added: P-type doping (B) or N-type (Sb)
- Additional Si cap added
  - OR repeat for “superlattice” doping for extra stability
- Deposited silicon layers typically 1-3 nm
- Wafer is diced, devices are completed with packaging




Veeco Gen 200

Wafer in MBE