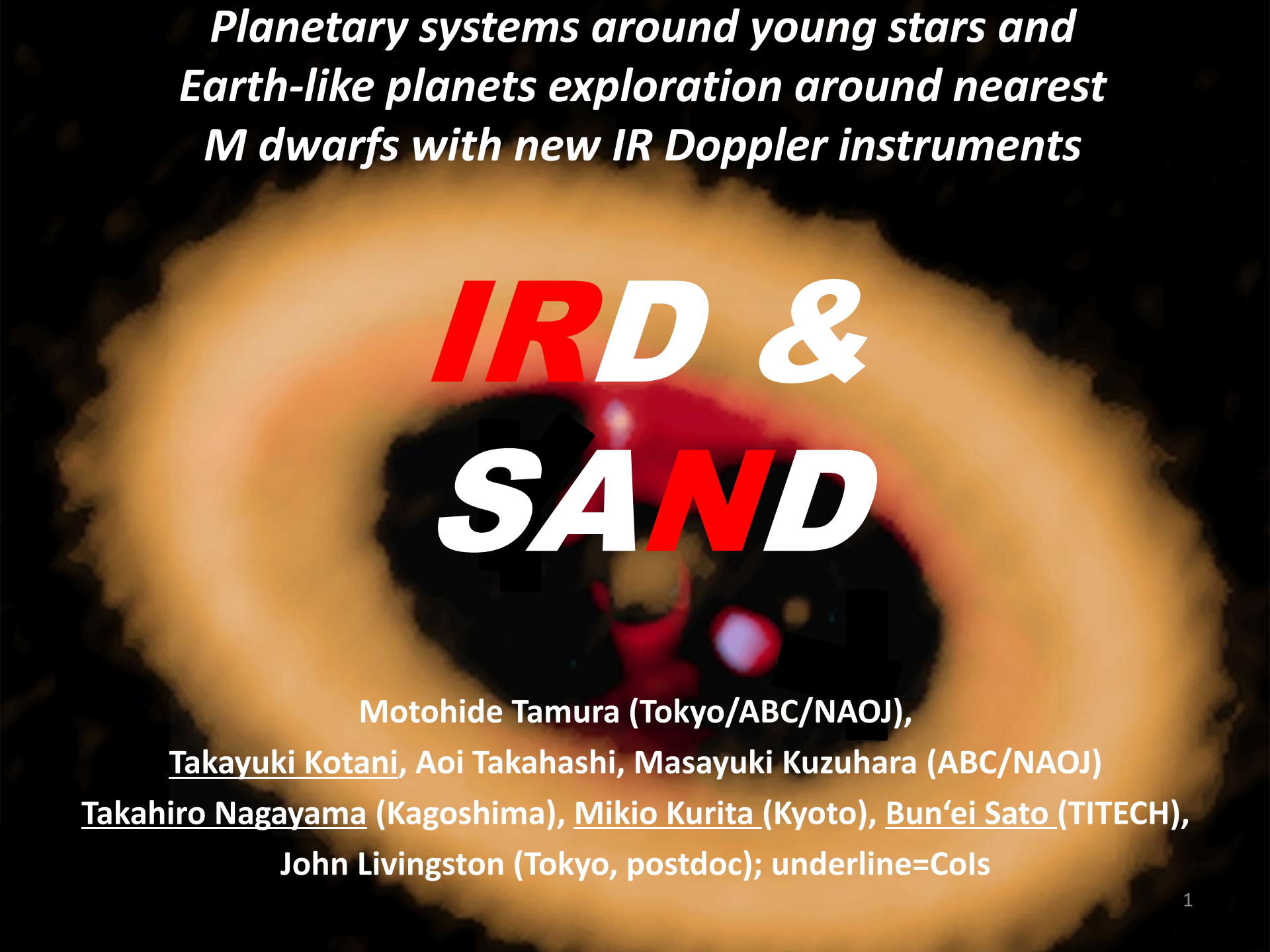
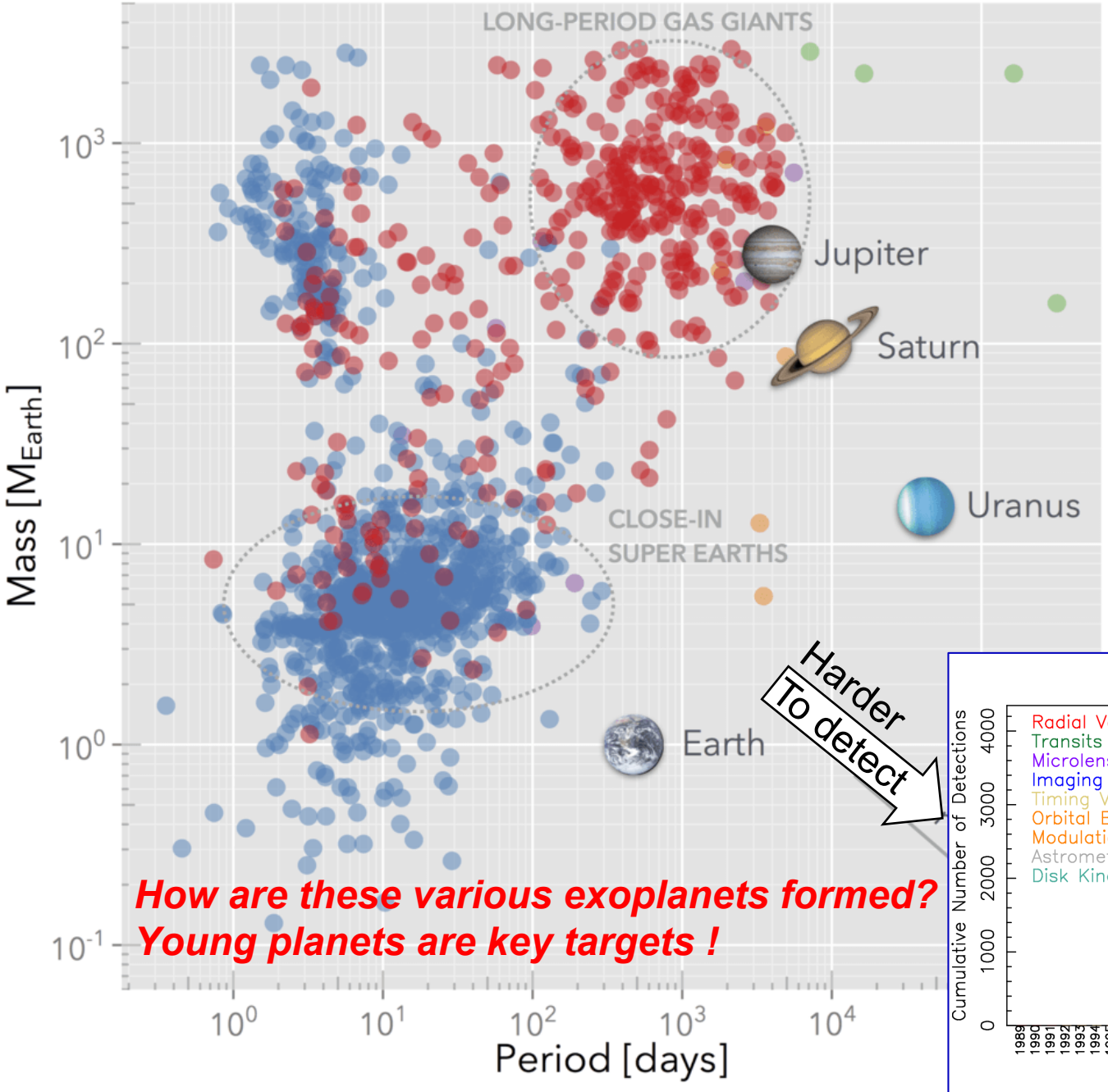
Planetary systems around young stars and Earth-like planets exploration around nearest M dwarfs with new IR Doppler instruments



Motohide Tamura (Tokyo/ABC/NAOJ),
Takayuki Kotani, Aoi Takahashi, Masayuki Kuzuhara (ABC/NAOJ)
Takahiro Nagayama (Kagoshima), Mikio Kurita (Kyoto), Bun'ei Sato (TITECH),
John Livingston (Tokyo, postdoc); underline=CoIs

Various Planets detected by Various Techniques

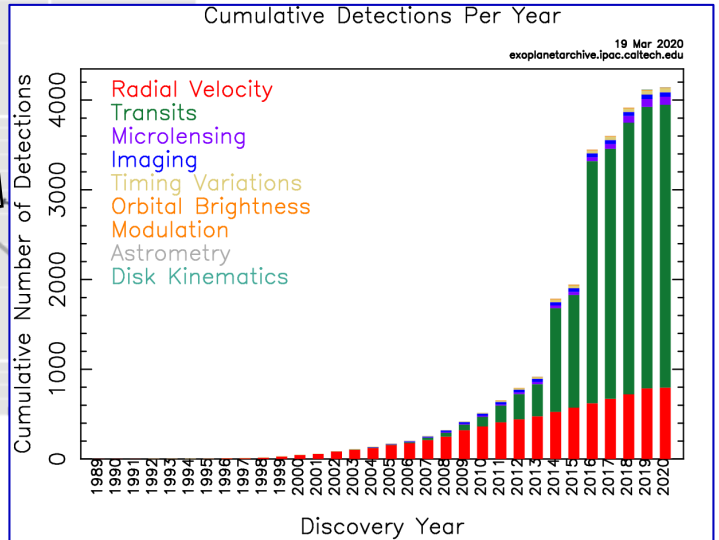


>4100 confirmed
of which
57% by Kepler
10% by K2
~1% by TESS so far

Discovery method

- RV
- Transit
- Imaging
- Timing
- Microlensing

Harder
To detect



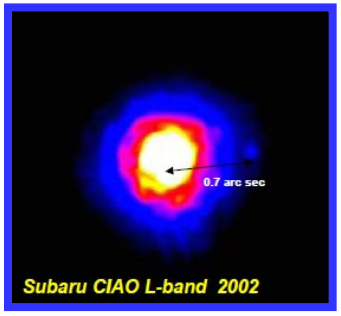
How are these various exoplanets formed?
Young planets are key targets !

Planets around YSOs have been unexplored

- YSOs have high stellar activity
  - Large radial velocity (RV) jitter
  - Large photometric jitter
  - Problematic for Doppler, Transit at least at optical
  - Much less problematic for Direct Imaging and Infrared-RV/Transit
- YSOs are faint at optical (but bright at IR)
  - Problematic for Doppler, Transit at least at optical
  - Much less problematic for Direct Imaging and RV at NIR
- YSOs are far away (typically 100pc, nearest 50pc)
  - Apparently very close to central star
  - Problematic for Direct Imaging
- **InfraRed-RV advantage**
  - Targets are bright at IR
  - Targets have less jitter by factors 2-3 at IR (spot-to-photosphere temperature contrasts are lower)
  - Direct Imaging have been successful at IR (e.g., **SEEDS**)

SEEDS –Strategic Explorations of Exoplanets and Disks with Subaru

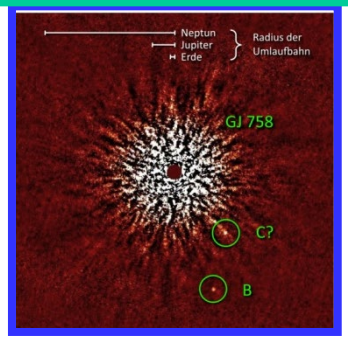
- The first “Subaru Strategic Program (SSP)” – An open-use category
- 120 nights from 2009, **61 refereed papers so far**, **now post-SEEDS**
- NIR direct imaging and census of **giant planets in the outer regions** (10-100AU) around **~500 solar-type and massive stars**
- Exploring **protoplanetary disks** and debris disks for the origin of their diversity and evolution at the same radial (10-100AU) regions
- **Direct linking** between planets and protoplanetary disks



Resolution
=0.1-0.2”

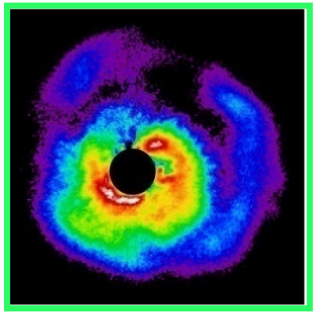
>100AU scale
w/ CIAO

⇒



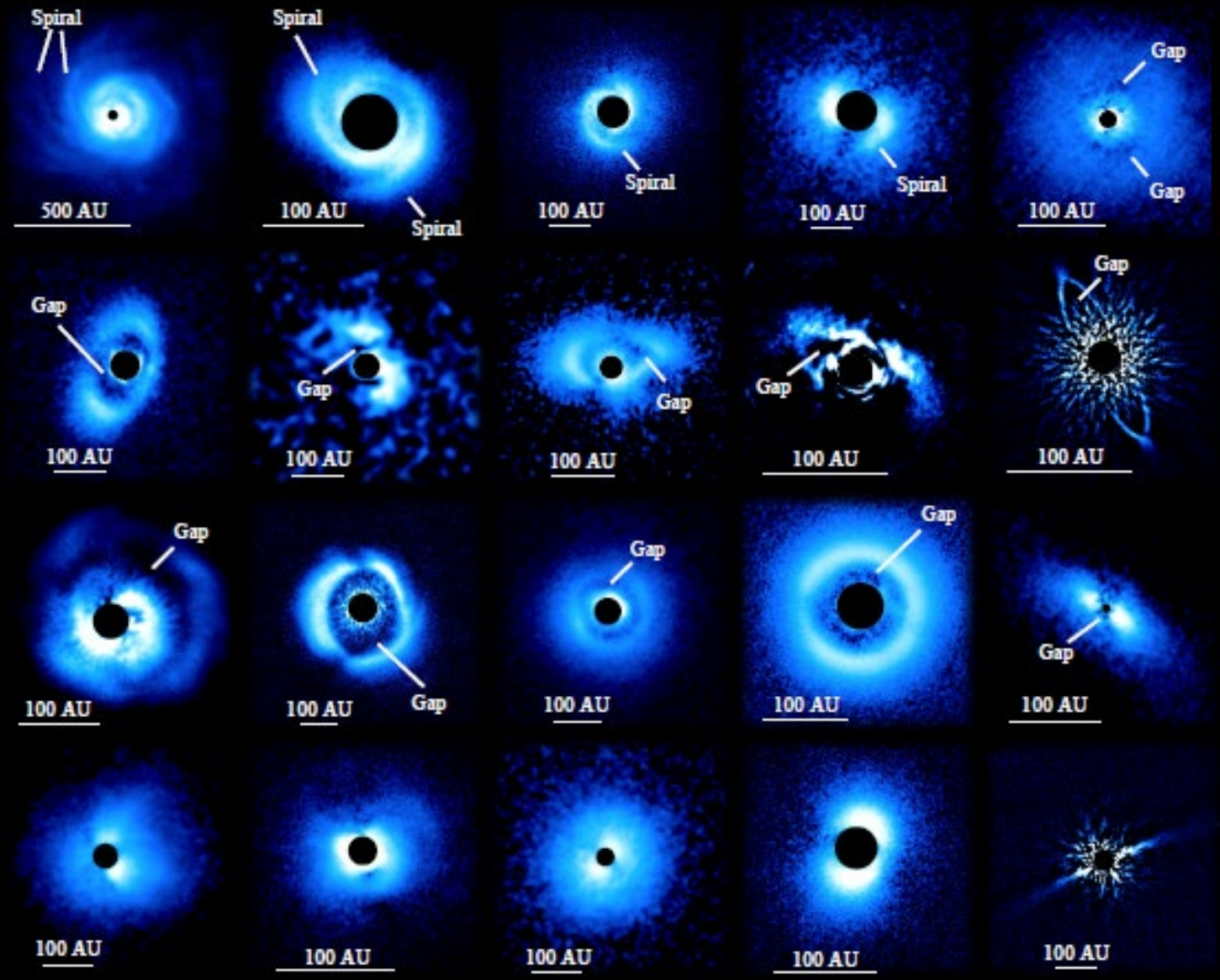
Solar-System Scale (<100AU) w/ HiCIAO

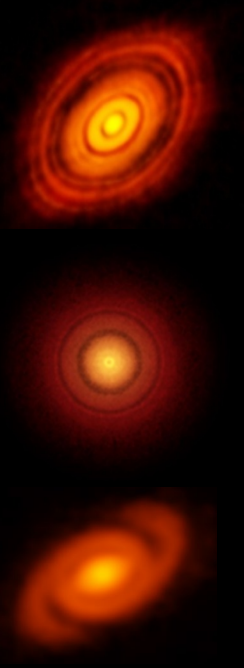
Resolution =0.05-0.1”
Contrast Improved by ~10



SEEDS has revealed gaps & rings of <100AU scale in many disks by polarimetric imaging (Res.~0.06", IWA~0.1") in 2009-2017

Note that ALMA images (>2015) is thermal emission .





ALMA

HL Tau
TW Hya
EL2-27

POST-SEEDS is SCExAO and CHARIS:

Next Generation High-Contrast Im & Sp

Publication rush now.

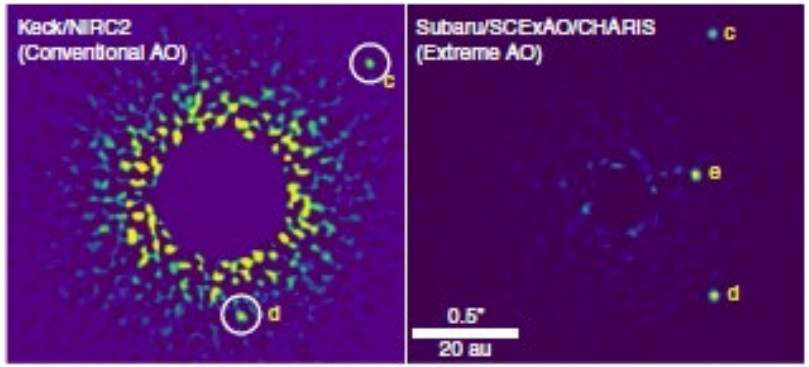
8 science papers and 15 technical papers

Several new imaged planets candidates, too!

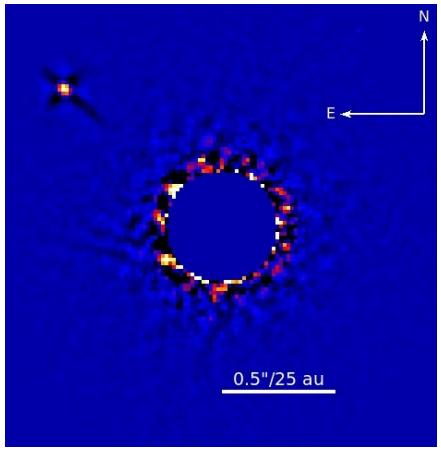
Lyot 2019 at Odaiba, 2019 October; 200 attendants

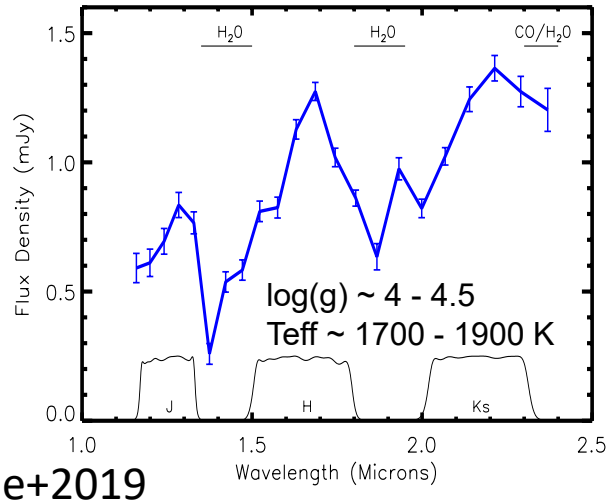
HR 8799 c,d,e Keck NIRC2 vs. SCExAO

No new inner planets detected

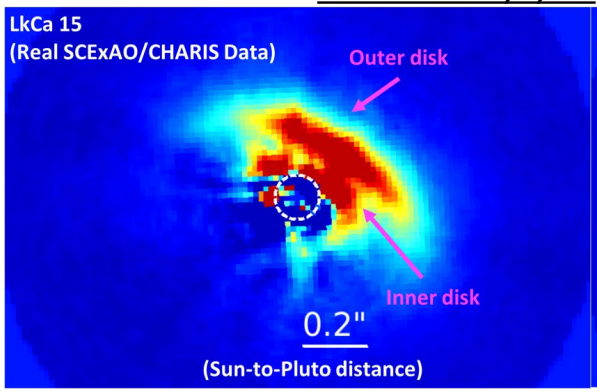


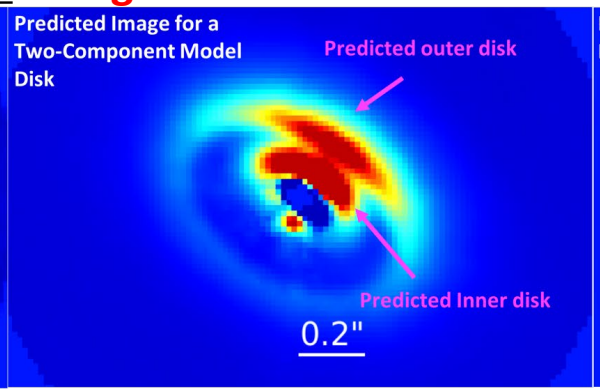
kappa And b, Currie+2018, Uyama+2019

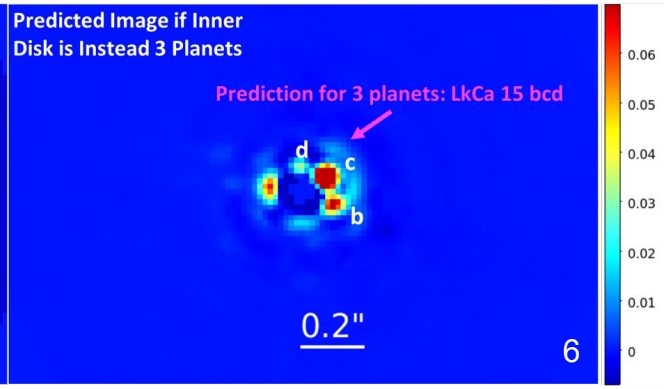




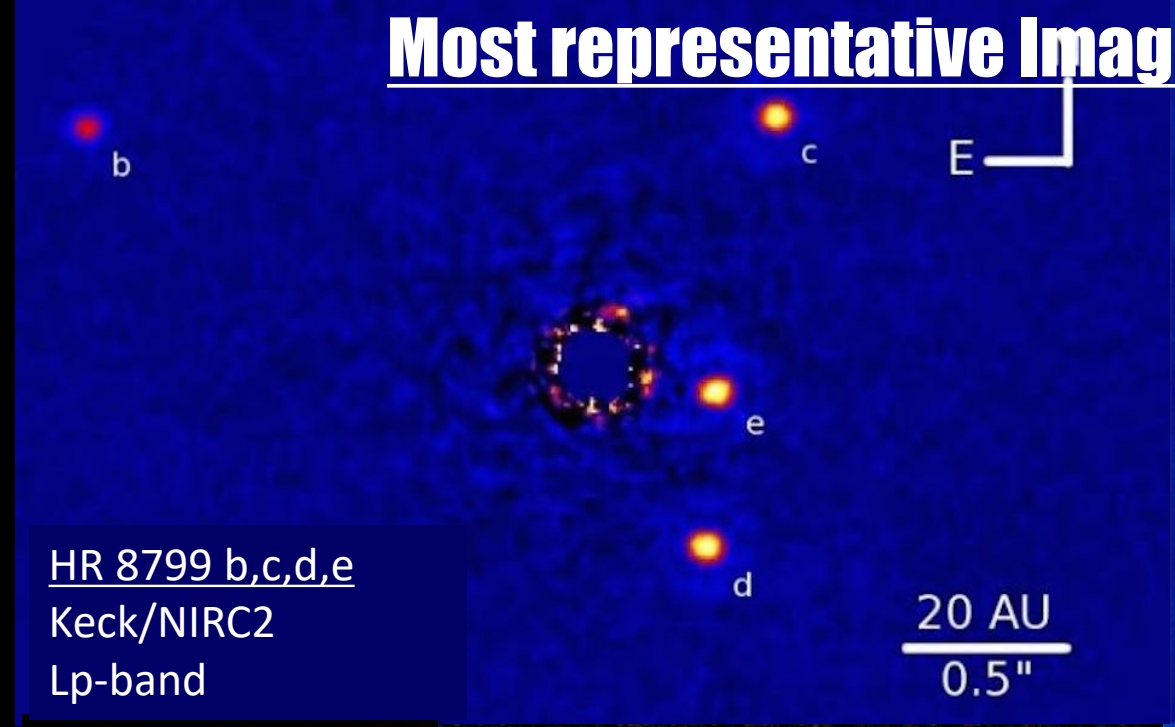
LkCa 15 b,c,d **Young Planets are Illusive!!** Currie+2019



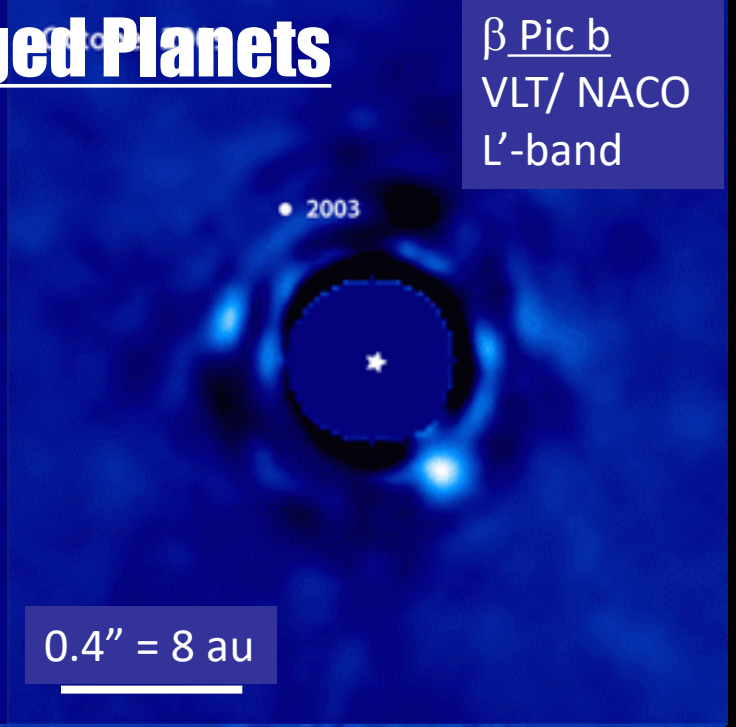




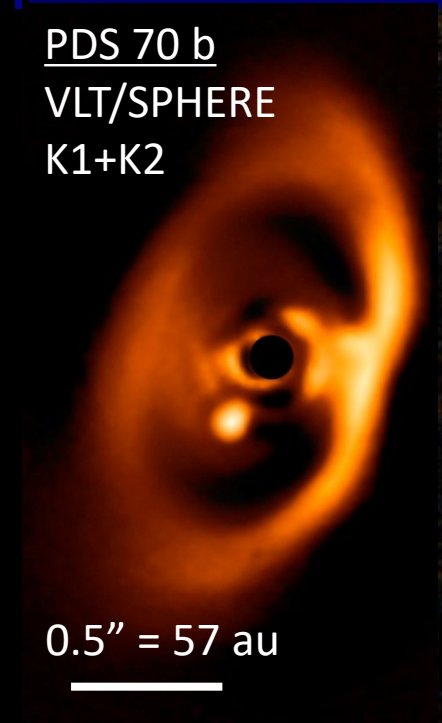
Most representative Imaged Planets



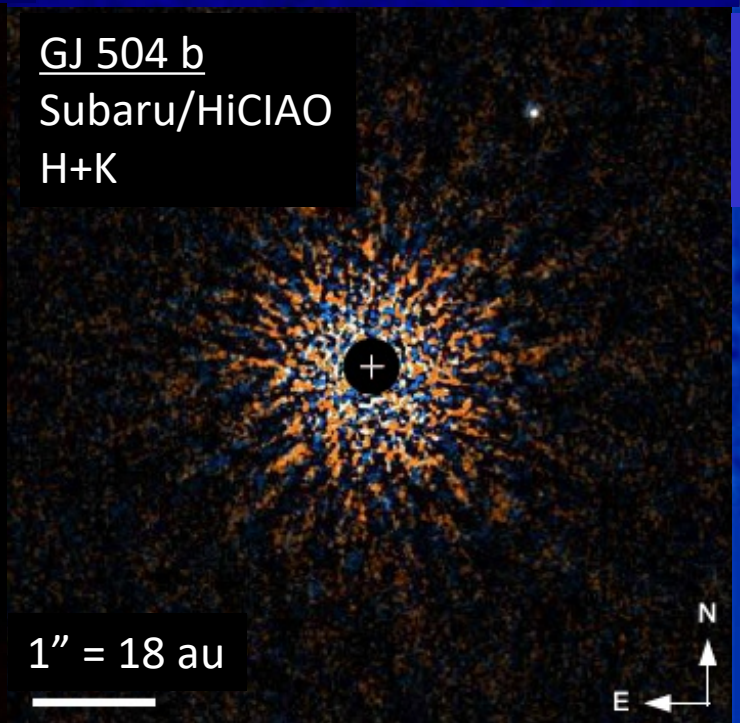
HR 8799 b,c,d,e
Keck/NIRC2
Lp-band



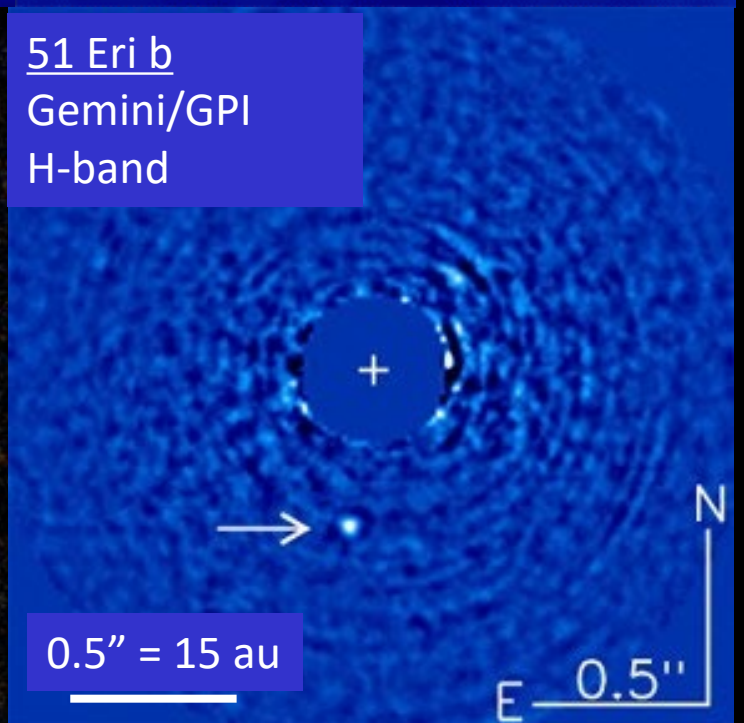
β Pic b
VLT/ NACO
L’-band



PDS 70 b
VLT/SPHERE
K1+K2

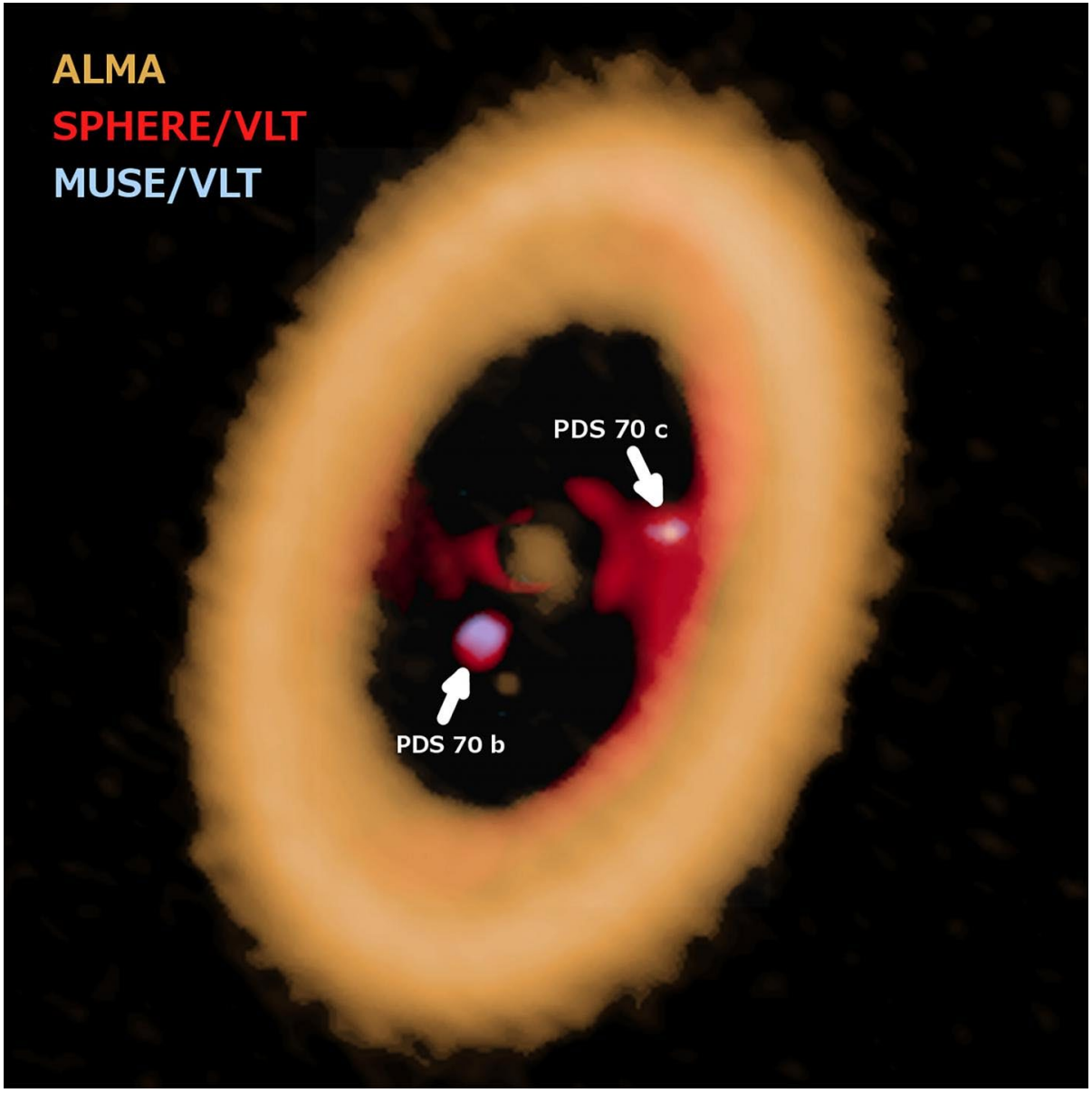


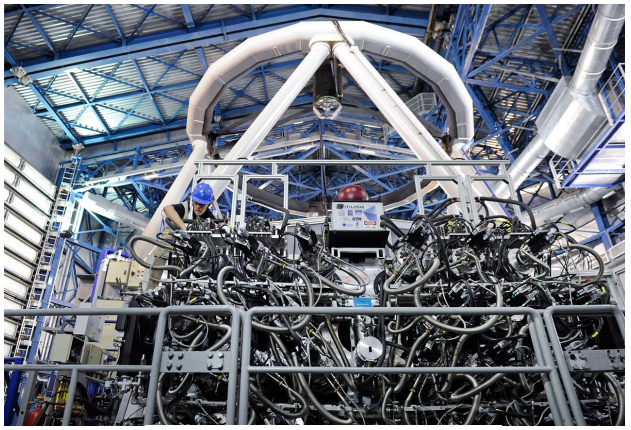
GJ 504 b
Subaru/HiCIAO
H+K



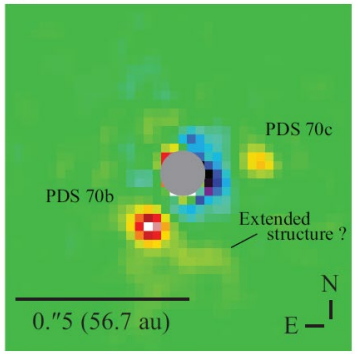
51 Eri b
Gemini/GPI
H-band

Unique Young Accreting Planets PDS 70 b,c

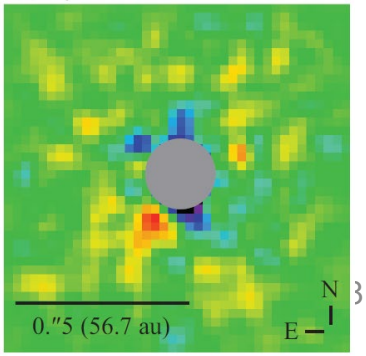




(a) Hα



(b) Hβ



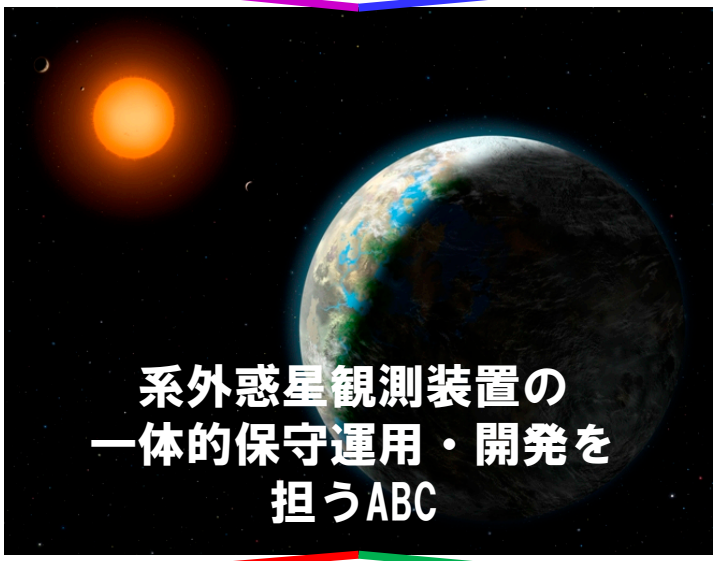
すばる他による2019年度の科学的成果

① 速度変化検出 - すばるIRD

- 世界最高の速度決定精度を持つ赤外分光器
- 戦略枠による集中観測（順調に進行）
- 共同利用は高い競争率（夜数で約10倍）

② 光度変化検出 - MuSCAT

- カナリア諸島に専用望遠鏡確保
- 可視光４色同時測光
- TESS惑星候補の集中観測



③ 系外惑星直接観測 - すばるSCExAO

- 巨大惑星と円盤を直接画像として捉える
- 極限補償光学系と面分光器
- 査読論文＋装置論文多数

④ 30m鏡等用の将来装置開発

- TMTの2装置で国際協力開始
- MODHIS分光器とPSI直接観測装置

計画研究B03

赤外線による若い惑星とハビタブル惑星の観測の新機軸

- **PRIMEおよびIRSF望遠鏡とファイバーリンクした高分散赤外線分光器**
  - **本学術研究の最重要目的のひとつである「系外惑星の多様性の起源」を解明するための観測データを与えるのが本計画班の観測の使命、もちろん、すばるIRDも活用**
  - **若い恒星周りの巨大ガス惑星探索**
    - 恒星活動の影響が小さい近赤外域が有利
  - **近傍M型星周りのハビタブル惑星探索**
    - 恒星光強度がピークとなる近赤外域が有利

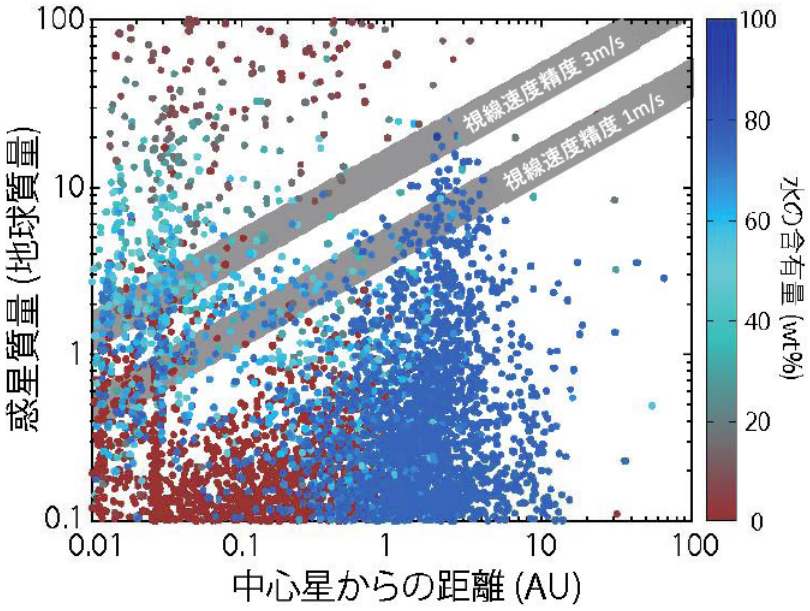
本班で答えるべき課題

A) **分光器（SAND, South Africa Near-Infrared Doppler）**

- 波長範囲：z, Y-band (0.83 - 1.13 um)
- 波長分解能：55,000 max
- 検出器：H2RG 1基
- 波長校正：ファブリペローフィルター
- 視線速度測定安定性: 1～3 m/s
- 冷却系：検出器 80K、光学系 180K
- 目標ピーク効率（望遠鏡も含む）20%

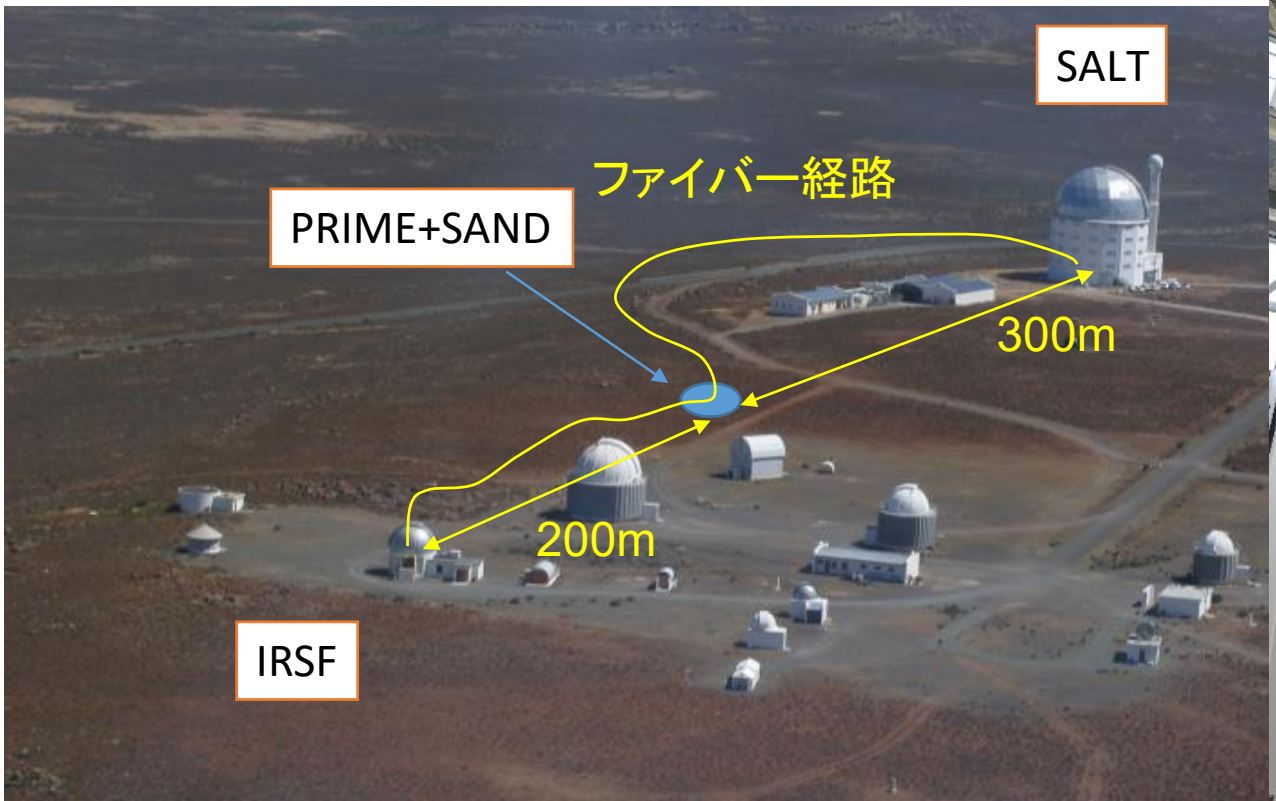
B) **長期モニター観測用望遠鏡**

- PRIME：1.8m、主焦点ファイバー導入
- IRSF：1.4m、カセ焦点ファイバー導入
- 専用なので各恒星を高頻度で観測可能
- SALT 11mとも結合を検討中



PRIME望遠鏡

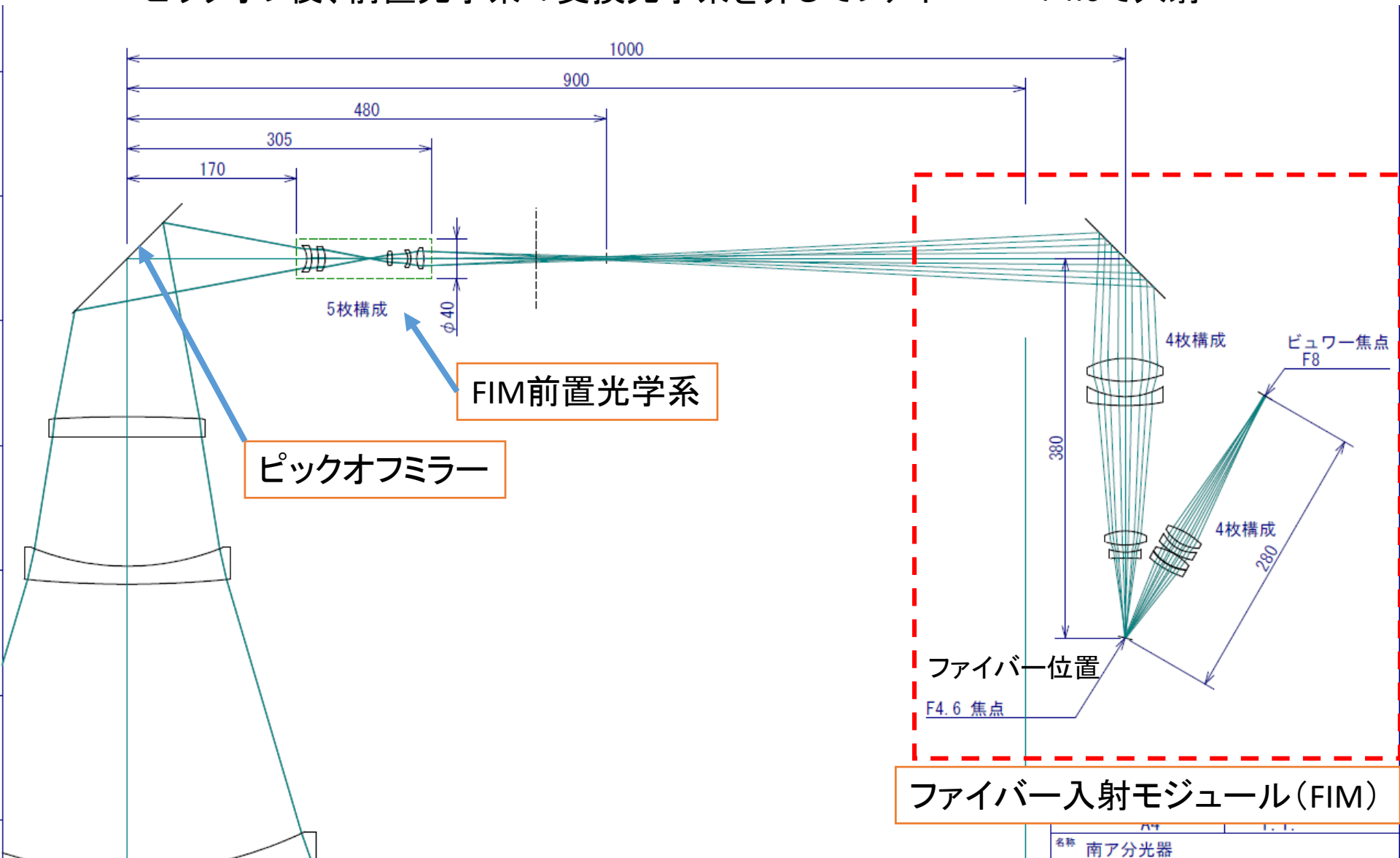
- 阪大が南アフリカ天文台に建設中の1.8m望遠鏡+赤外主焦点カメラ。重力レンズによる銀河中心方向の系外惑星探査が主目的
- 銀河中心が見えない間は、視線速度・分光観測に使用
- 主焦点カメラの途中にピックオフミラーを入れ、トップリング上のファイバー入射モジュールに光を送る
- 分光器はPRIMEドーム隣接の建物に設置

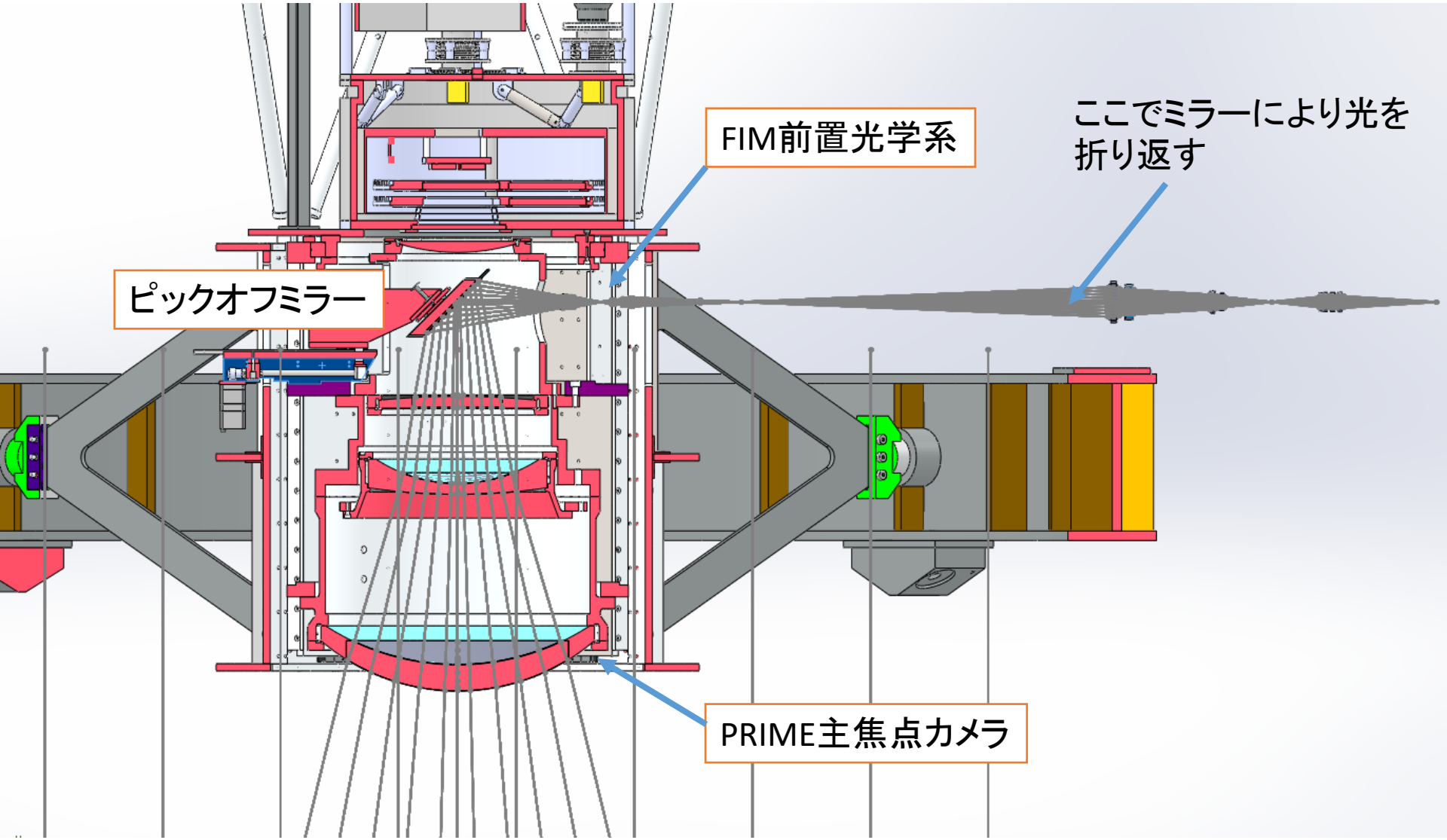


西村製作所で製作中のPRIME望遠鏡

ピックオフミラー＆FIM前置光学系

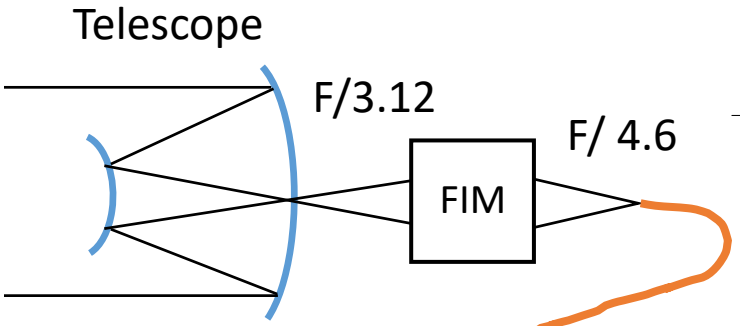
- PRIME主焦点カメラ内で光をピックオフし、SANDファイバーへと入射させるミラー
- ピックオフ後、前置光学系・F変換光学系を介してファイバーへF4.6で入射

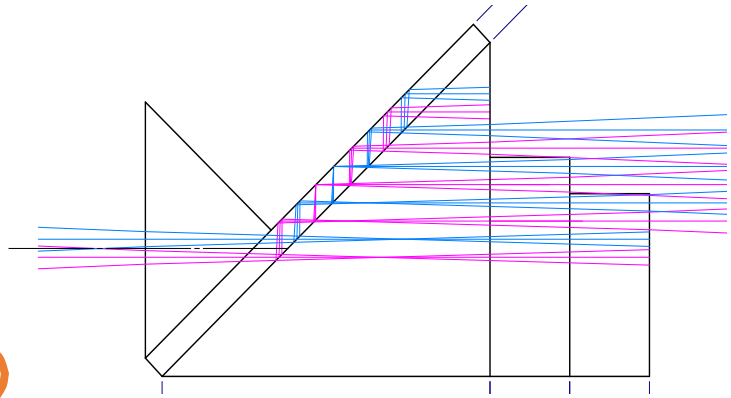



FIM前置光学系
ここでミラーにより光を
折り返す
ピックオフミラー
PRIME主焦点カメラ

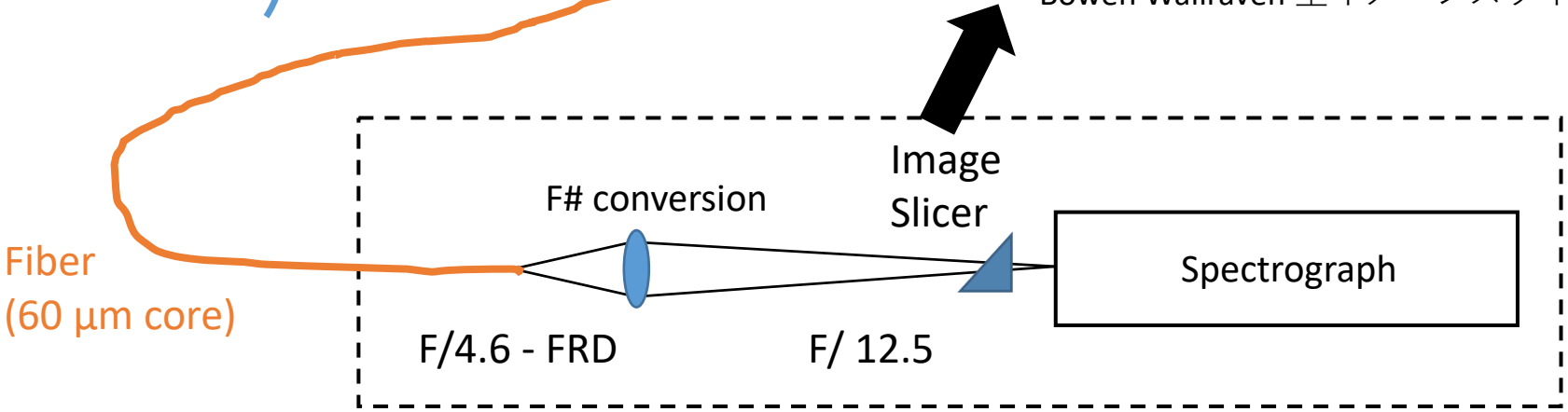
南アフリカ近赤外高分散分光器
South Africa Near-infrared Doppler (SAND)

光学系全体の概要





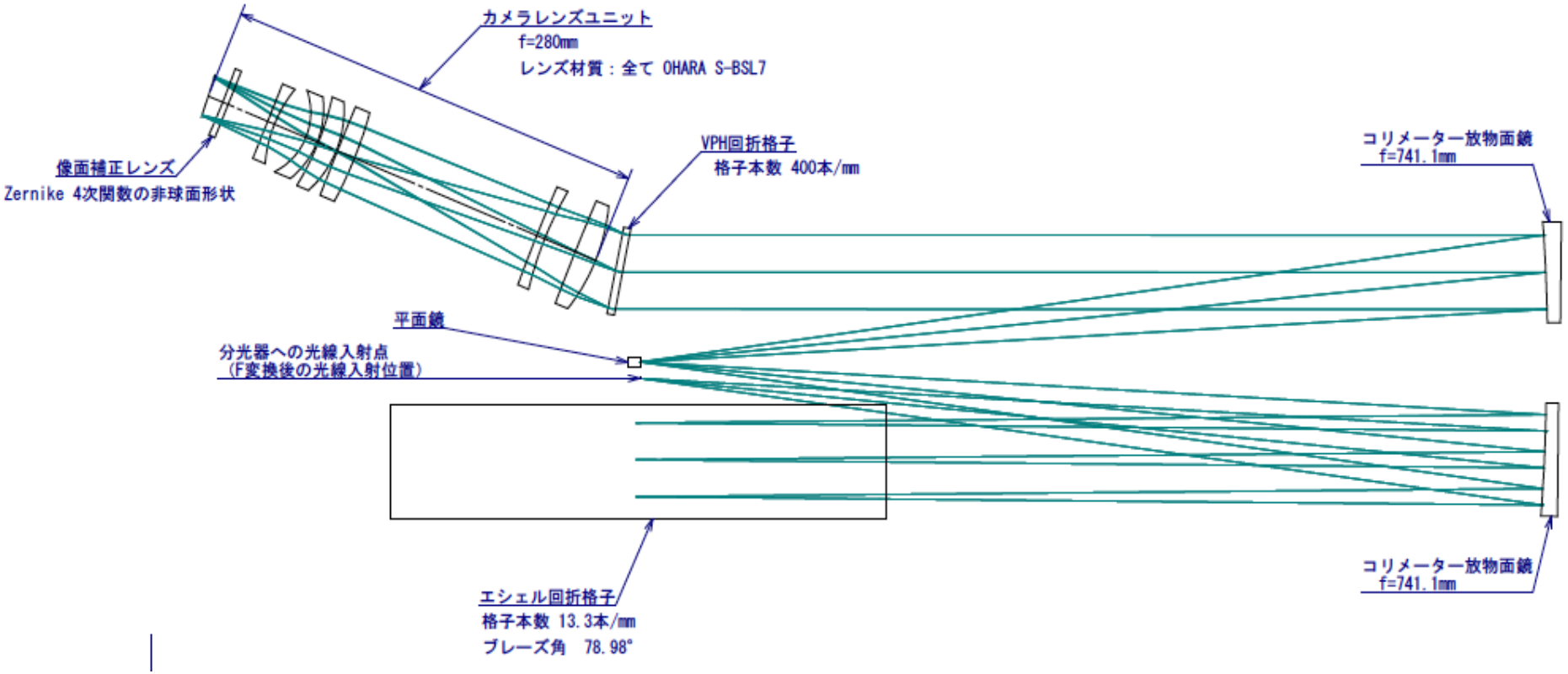
Bowen Wallraven 型イメージスライサー



真空チャンバー（光学系全体を 180K, カメラ光学系は 60K に冷却）

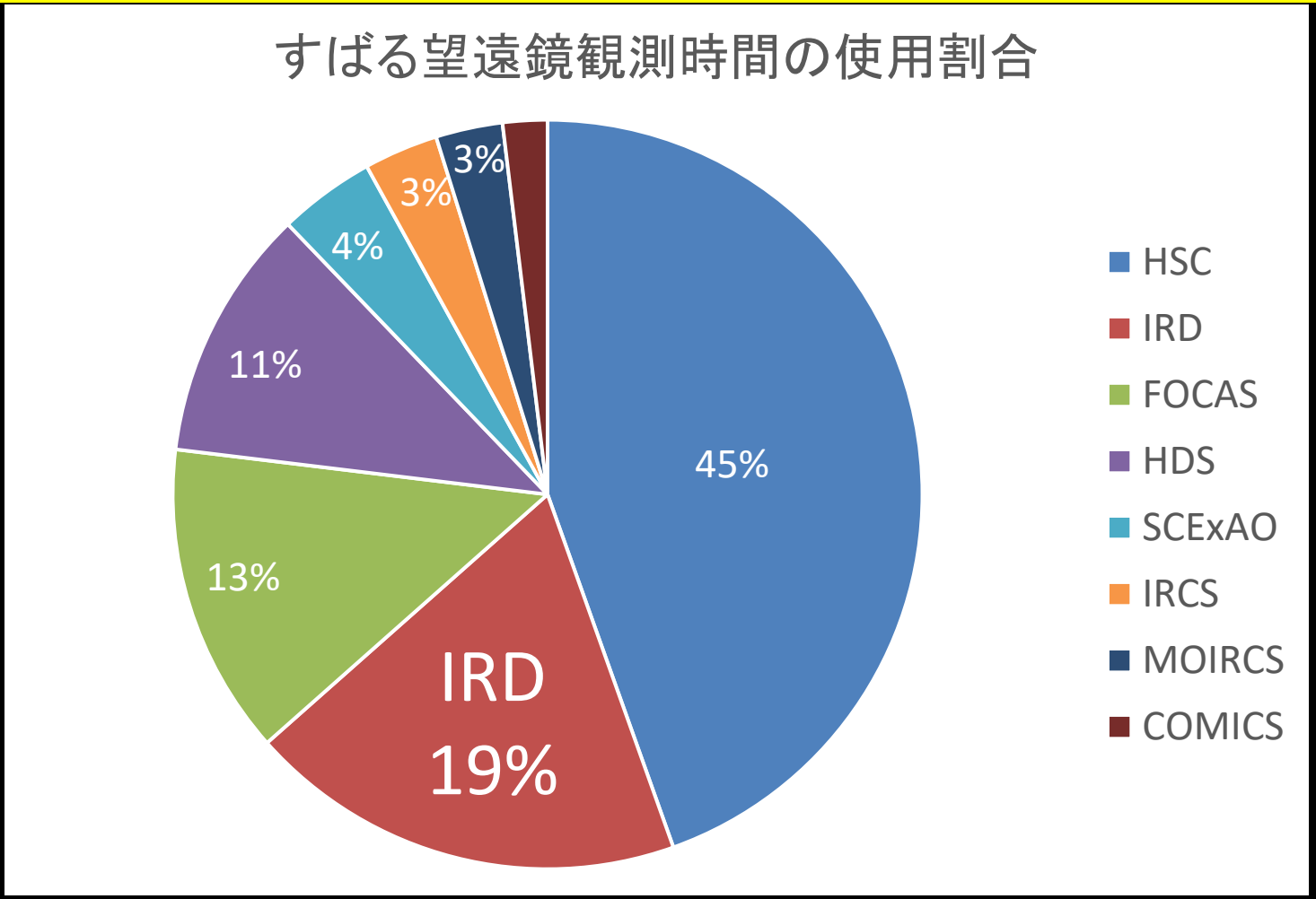
南アフリカ近赤外高分散分光器
South Africa Near-infrared Doppler (SAND)

分光器概念設計



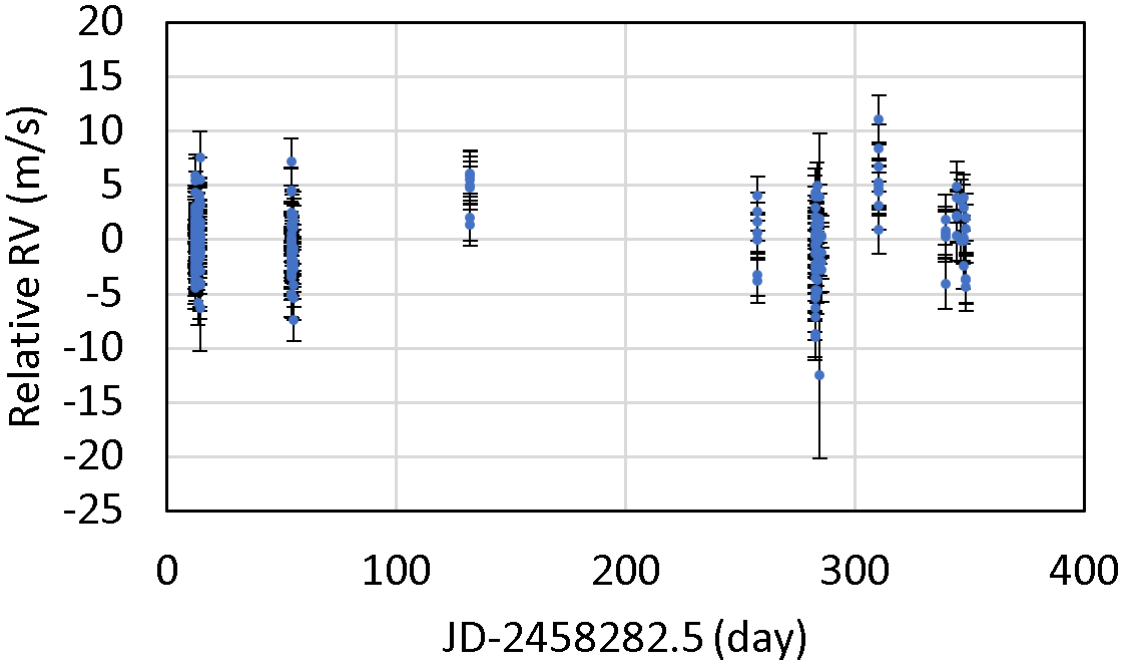
地球型惑星観測装置 IRD

2019年2月より、すばる望遠鏡戦略枠観測開始
2019年度は59夜観測（戦略枠30＋共同利用観測29）
すばる望遠鏡観測装置の中で2番目に多い観測数

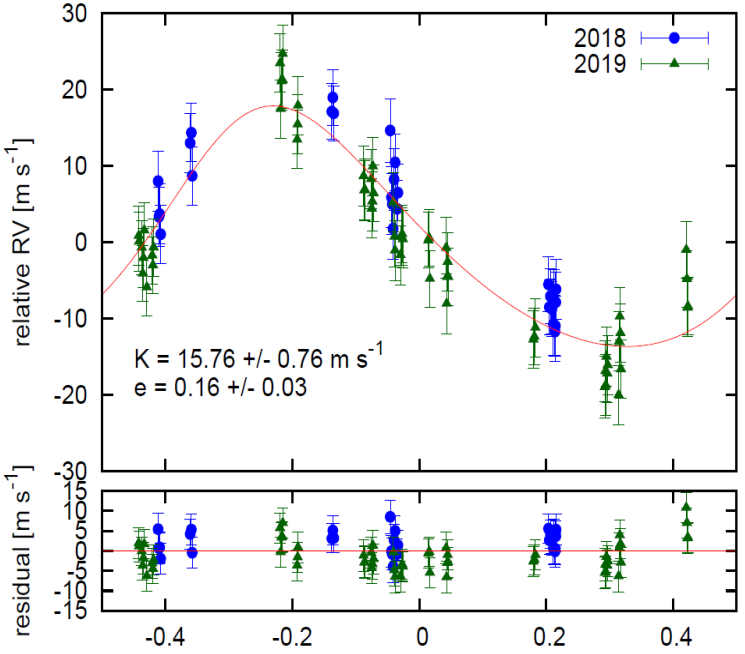


IRD Performance and Very Early Science

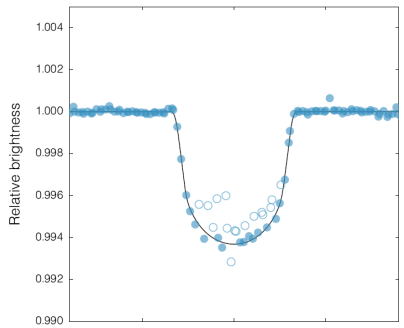
Long (~1 year) Term Stability Confirmed

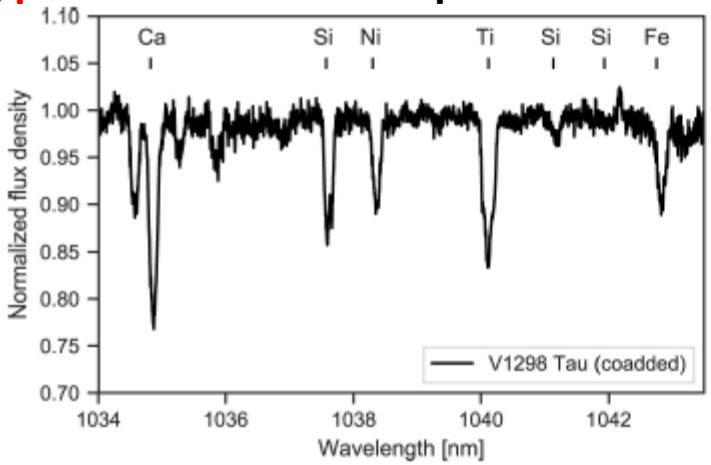


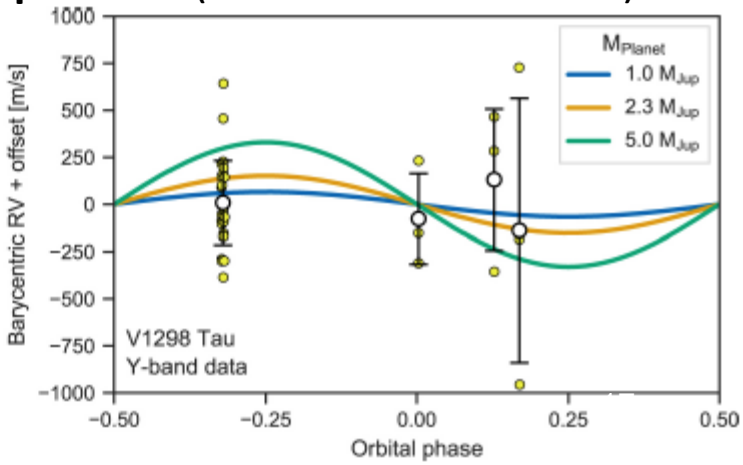
Known M star planet GJ 436 b



Young transiting planet V1298 Tau b: planet mass upper limit (Beichman&IRD+2019)

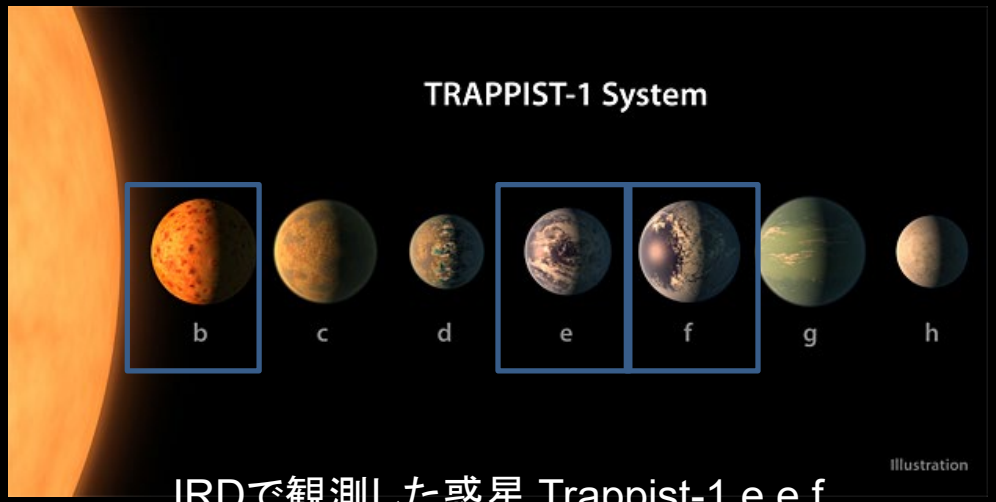




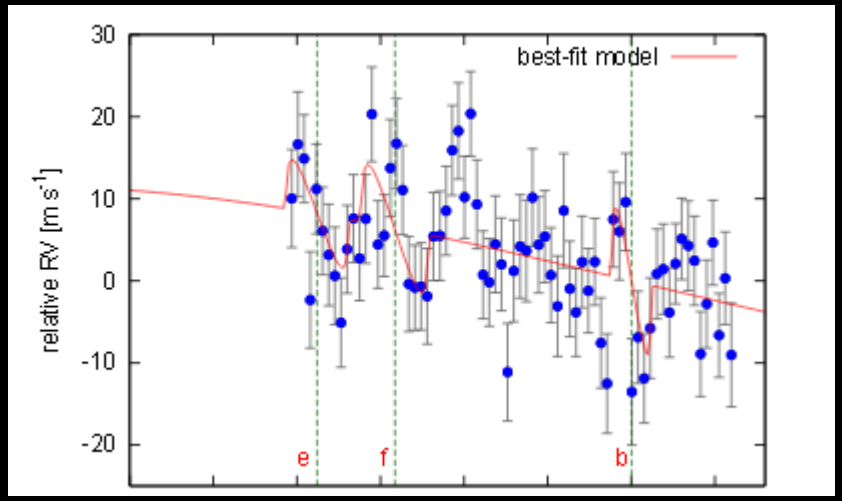


地球型惑星観測装置 IRD（続）

Trappist-1地球型惑星の自転軸と公転軸は大きく傾いていないことを初めて発見 (Hirano et al. 2020)



IRDで観測した惑星 Trappist-1 e,e,f



観測された視線速度変動

- **惑星軌道を大きく乱すような擾乱を受けていないことが示唆される ⇒ ハビタビリティの議論には重要**

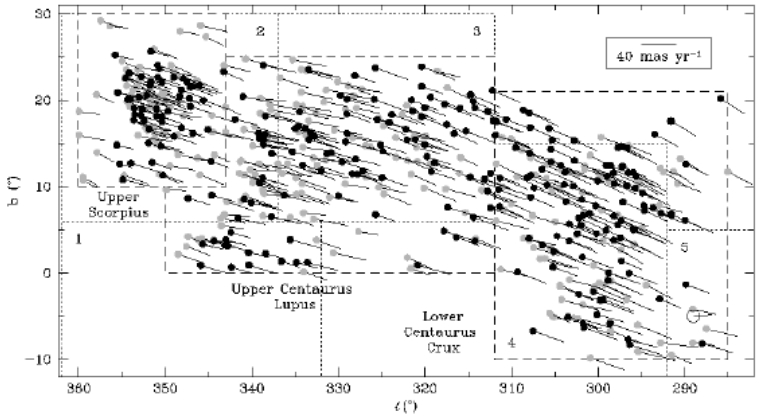
2020年3月にプレスリリース予定

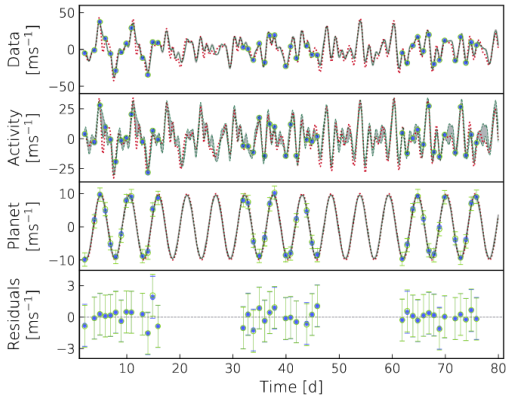
2019年度IRD査読論文4編出版

その他投稿済み1編、投稿予定3編

Planets around YSOs: upper Sco

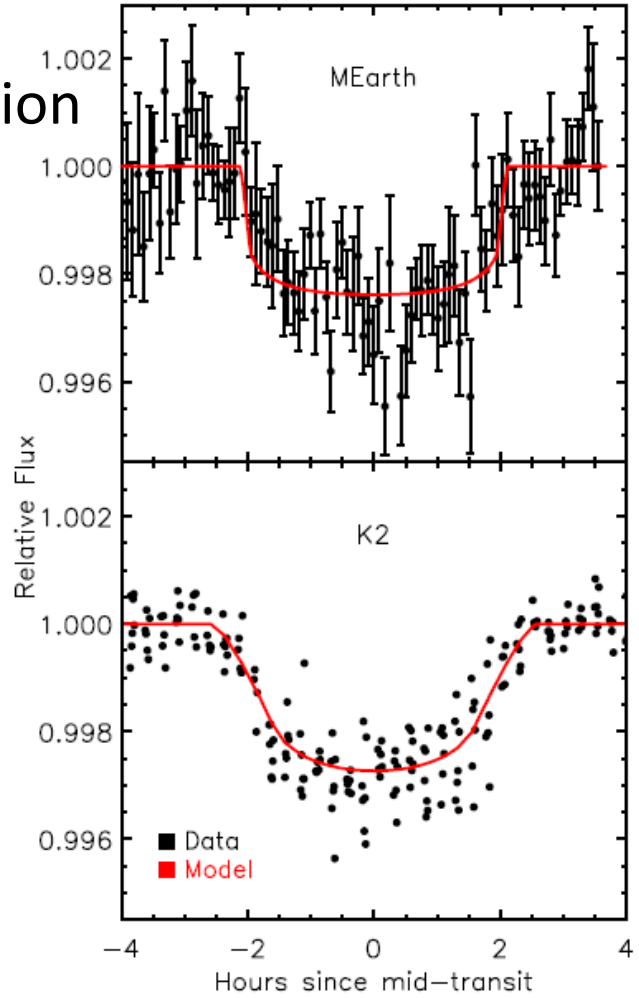
- Planet: K2-33, A close-in super-Neptune size planet (5 R_J)
- Host: M3 pre-main sequence (11 Myr), a member of the Upper Scorpius OB association
- Mann+2016, Klein+2020; RV simulation





若い星のロシター効果はA01の研究ともリンク

もちろん、A03のトランジット観測とも連携可能



Summary

1. Searches for **planets around YSOs** are important and promising because in that (1) they are unexplored, (2) they can be well studied at IR planet detection techniques such as IR-RV.
2. Search for **planets around low-mass stars** are promising in that (1) Earth-like planets in the HZ produce larger signals, (2) the planet occurrence rate rises towards lower stellar-mass regime (but little is known for late M dwarfs).
3. High precision InfraRed-RV instruments (**IRD & SAND**) will be invaluable for the exoplanet community in Japan for both short and long term RV searches.