SUBARU Strategic Exploration of Exoplanets and Disks with HiCIAO/AO188 (SEEDS Project)

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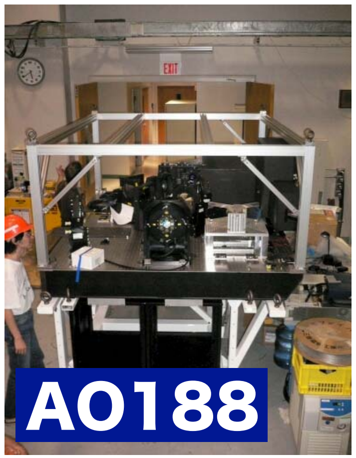
on behalf of Motohide Tamura [NAOJ, PI of SEEDS]
and SEEDS/HiCIAO/AO team



2010 Sep 27 "Dust in Planetary Systems" workshop
Univ. of Jena, Germany

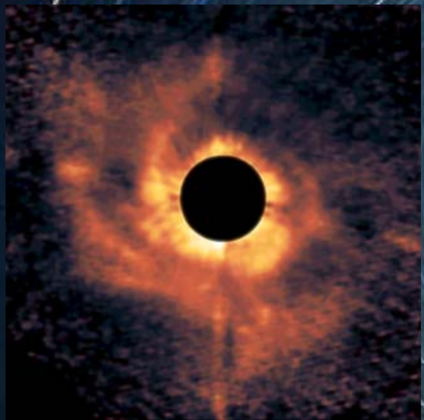
Talk Outline

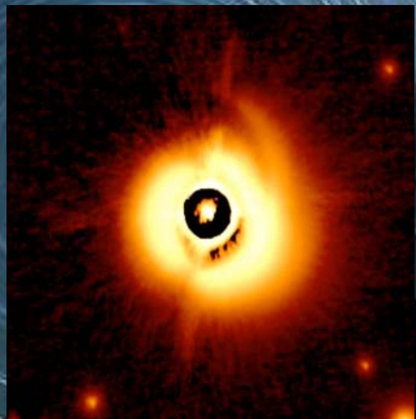
- **HiCIAO status in brief**
- **SEEDS status**
  - Project objective/goal, targets, observations, and current progress (mainly for exoplanet studies)
  - Research organization in SEEDS project
- **Early scientific results from SEEDS/ HiCIAO**
  - Some exoplanet/companion candidates
  - "Fine structures" of protoplanetary disks
- **Schedule, future instrumentation**
- **Summary**

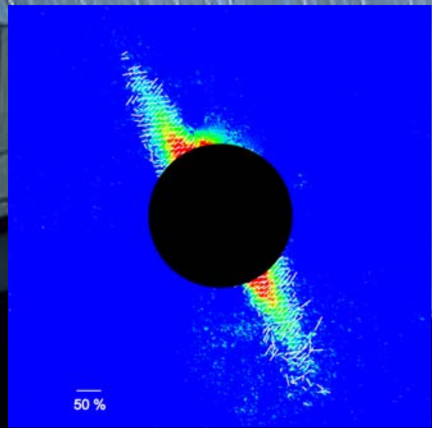
Subaru has an AO Coronagraph since 2001

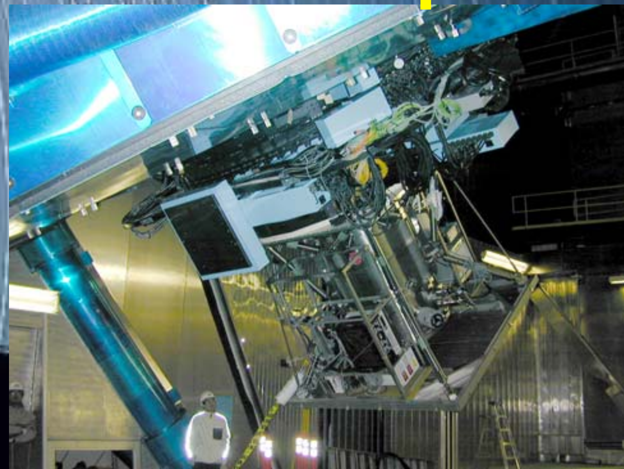
◆CIAO + 36-actuator AO at Cass.

★First dedicated cold coronagraph on 8-m telescopes





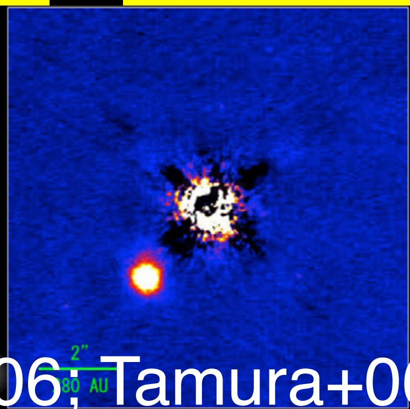


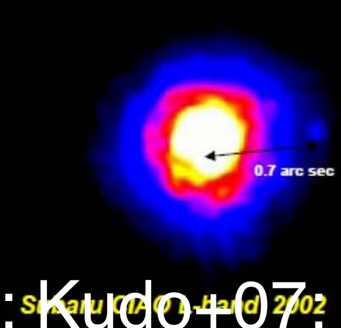


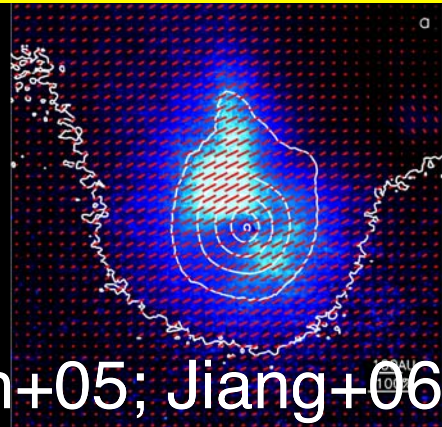
Diversity of proto-Planetary disks

Young very low-mass Companion

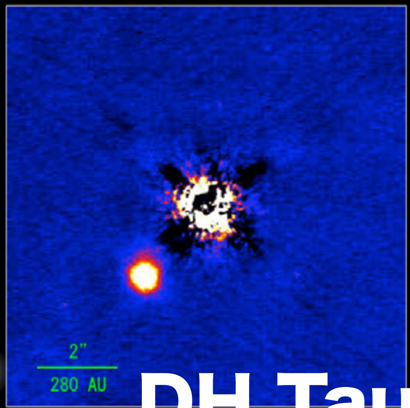
Compact disk around massive YSOs

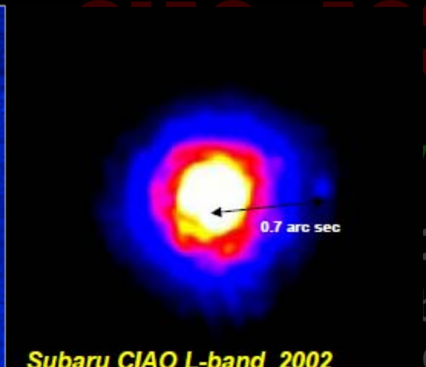






Fukagawa+04,+06; Tamura+06; Kudo+07; Itoh+05; Jiang+06; +

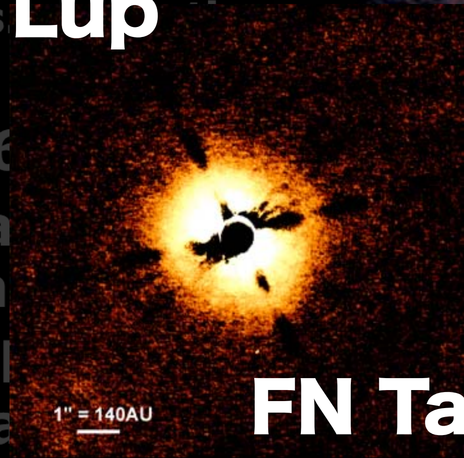




★ HD142527: new-type … hology discovered (Fukagawa et al. 2006 …

★ FN Tau: first PP disk a… ass (0.1 Mo) star directly discovered (Kudo et a…

★ Beta Pic: First NIR pol… oronagraph revealed nature of debris disk dust (Ta…).



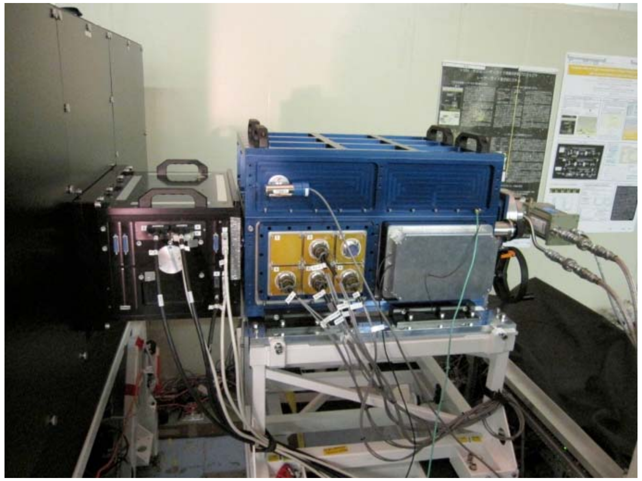
Improvement after 2007-2008

- low order adaptive optics (AO36->**AO188+Subaru**),
- lack of differential capabilities (CIAO->**HiCIAO**),
- limited upgrade flexibilities accepting various coronagraph ideas and AO upgrades.

Subaru/HiCIAO

- HiCIAO: High Contrast Instrument for next generation Adaptive Optics
  - For Subaru 8.2m telescope
  - Based on a previous Japan/MEXT grant (Tokutei)
  - PI & CoPIs: Motohide Tamura (NAOJ), Klaus Hodapp (UH), Ryuji Suzuki (NAOJ; now TMT)
- Combined with the curvature-sensing AO with 188 elements (Hayano, Takami et al.) and SCExAO1024 upgrade (Guyon, Martinache et al.)
- Commissioned in 2009 (including Princeton/MPIA teams for angular differential imaging and commissioning)

- Specifications and Performance
  - 2048x2048 HgCdTe and ASIC readout
  - Wavelengths: 1 – 2.5 microns (NIR)
  - Observing modes: DI, PDI (dual beam), SDI (quad beam), & ADI; w/wo occulting masks (>=0.1"φ)
  - Contrasts: 10^-6 at 1", 10^-4 at 0.15" (SDI)



HiCIAO Instrument

Nasmyth platform

Telescope → **Warm:** Common Optics + **AO Module** → **Coronagraph Module** → **High Contrast Optics Module** → **Cold:** **IR Camera Module**

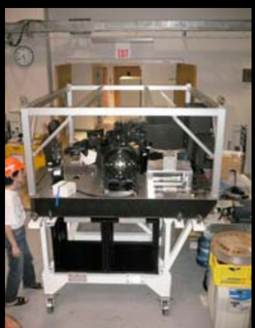
188 actuators AO
Future:
Complementary MEM DM (32×32)

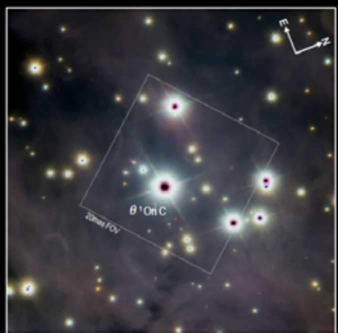
Coronagraph
Focal masks
Pupil stops

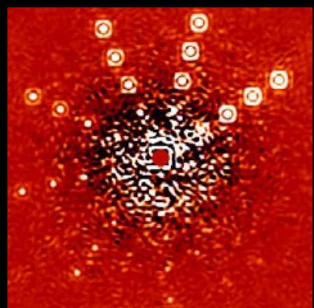
Differential optics
(Wollaston prisms)

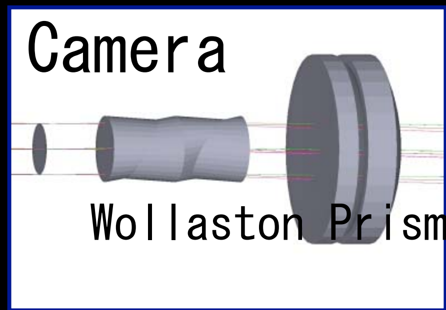
Hawaii 2-RG
2k × 2k array
ASICS Sidecar Controller

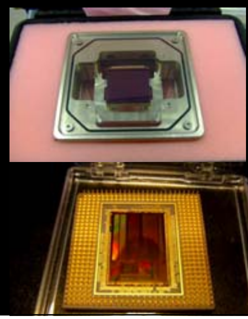
Filters
Common+Differential

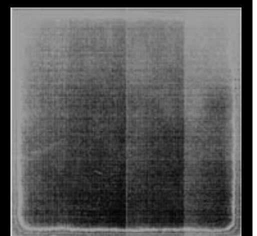












HiCIAO Instrument

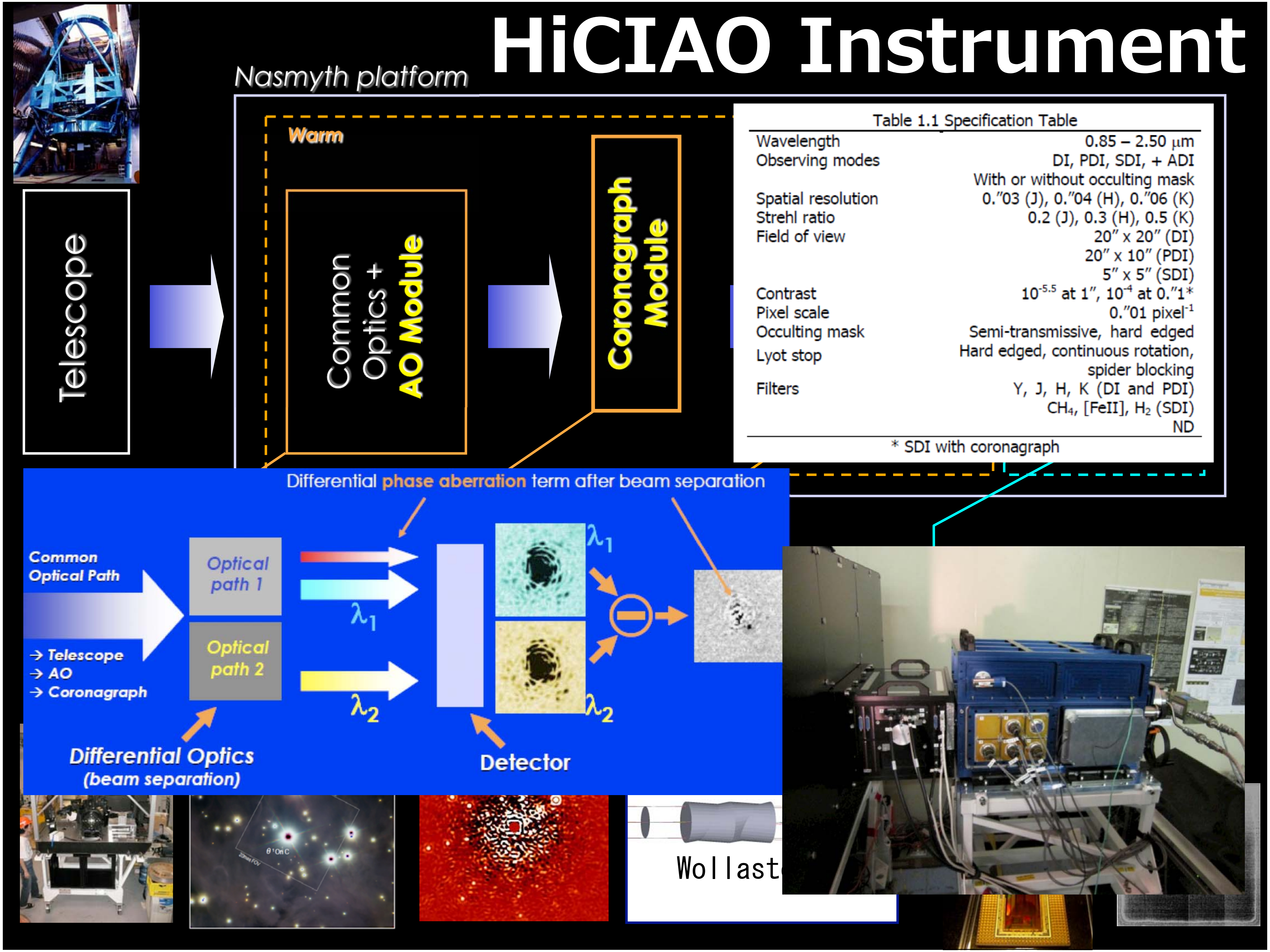


Table 1.1 Specification Table

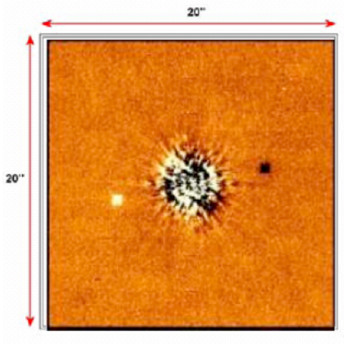
Wavelength	0.85 – 2.50 μm
Observing modes	DI, PDI, SDI, + ADI With or without occulting mask
Spatial resolution	0."03 (J), 0."04 (H), 0."06 (K)
Strehl ratio	0.2 (J), 0.3 (H), 0.5 (K)
Field of view	20" x 20" (DI) 20" x 10" (PDI) 5" x 5" (SDI)
Contrast	$10^{-5.5}$ at 1", 10^{-4} at 0."1*
Pixel scale	0."01 $pixel^{-1}$
Occulting mask	Semi-transmissive, hard edged
Lyot stop	Hard edged, continuous rotation, spider blocking
Filters	Y, J, H, K (DI and PDI) CH_4, [FeII], H_2 (SDI) ND

* SDI with coronagraph

Obs Modes

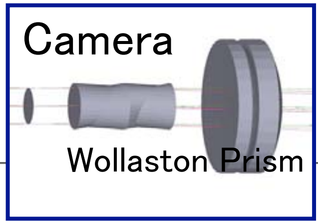
DI

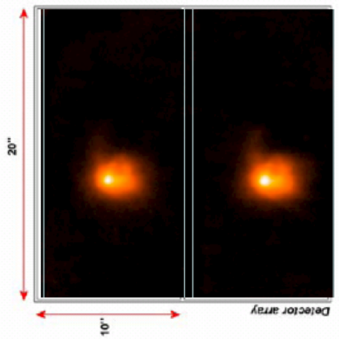
(1) FOV for the **Direct Imaging mode** (the cross marks the center of the field)



PDI

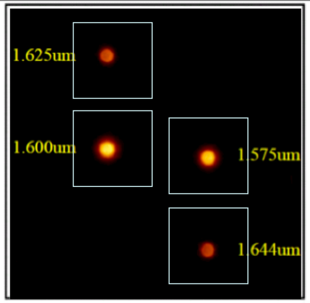
(2) Layout and FOV for the two images in single Wollaston **PDI mode**.





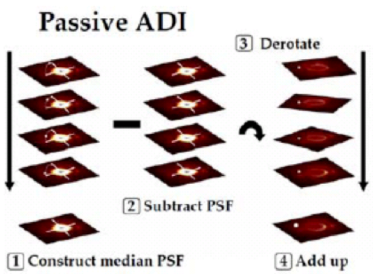
SDI

(3) Layout and FOV for the four images in dual Wollaston **SDI mode.** Wavelength in each channel can be selectable in each run, if necessary.



ADI

(4) Concept of (passive) **ADI mode**.



DI (Direct Imaging) mode
- FoV: 20”x20”

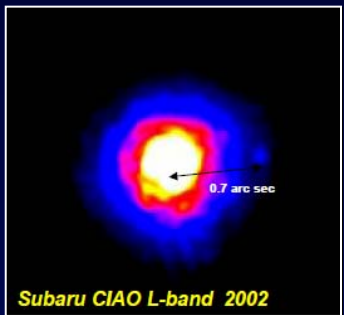
PDI (Polarization Differential) mode
- Single Wollaston
- FoV: 10”x20” (x2, simultaneous)

SDI (Spectral Differential) mode
- Double Wollaston
- FoV: 5”x5” (x4, simultaneous)

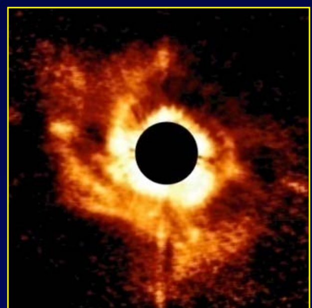
ADI (Angular Differential) mode
- Obs in "Pupil-stable" mode
- Combination with DI, PDI, SDI

SEEDS –Strategic Exploration of Exoplanets and Disks with Subaru

- First "Subaru Strategic Observations"
- 120 nights in 5 years on Subaru with HiCIAO and AO
- Direct imaging and census of giant planets around ~500 solar-type and massive stars in the outer regions (a few - 40 AU)
- Exploring protoplanetary disks and debris disks for origin of their diversity and evolution at the same radial regions
- Direct linking between planets and protoplanetary disks



>100AU scale



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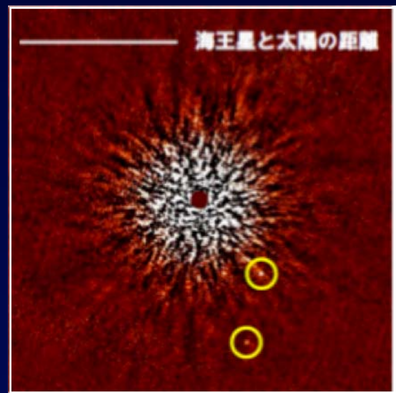


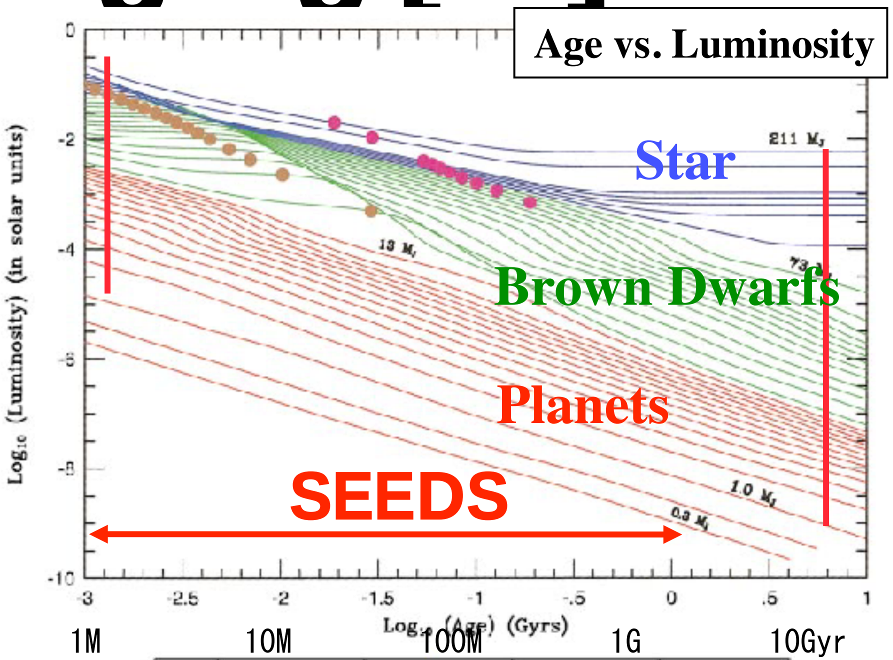
Solar-System Scale (<50AU)

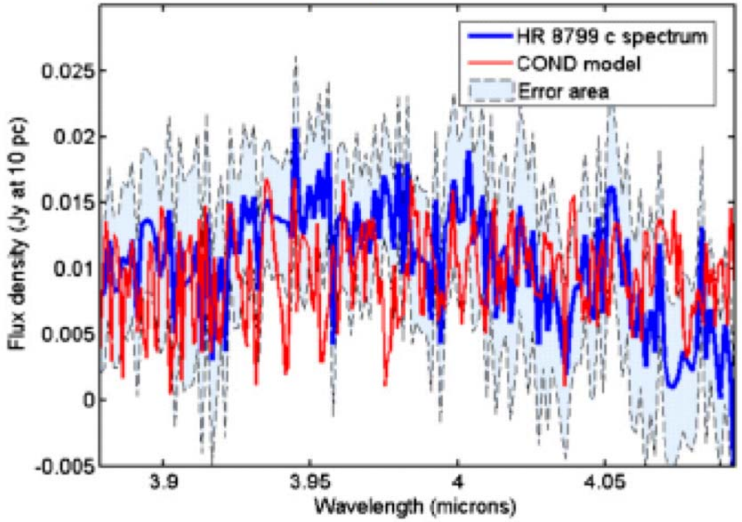
?

disk data shown later

Why direct imaging [DI] ?

- Exoplanets detection
  - –Direct methods to explore beyond a few AU
  - –Spectroscopy of exoplanet atmosphere
  - –DI is the best way to investigate Jupiter-mass planets around young stars in the outer regions where they form
    - RV & Transit studies: confined to the inner region (<6 AU for 15 yr) around less active star (complementary with DI)
- Circumstellar disks
  - –Protoplanetary / Debris disks
  - –Planet signatures



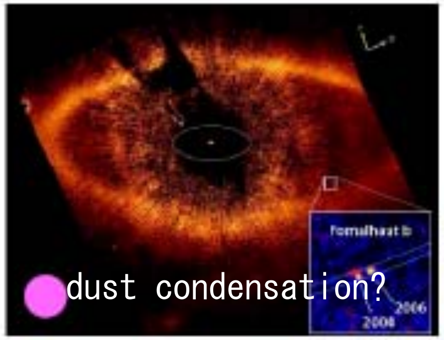


Spatially resolved VLT/NACO 3.88–4.10 μm spectroscopy of HR 8799 c (Janson et al. 2010)

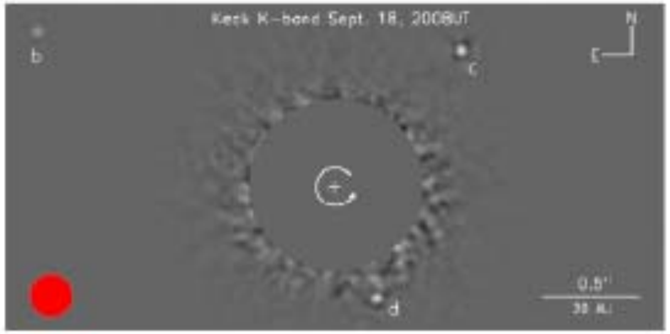
SEEDS – Where should we study by direct imaging technique?

confirmed in 2010 June!

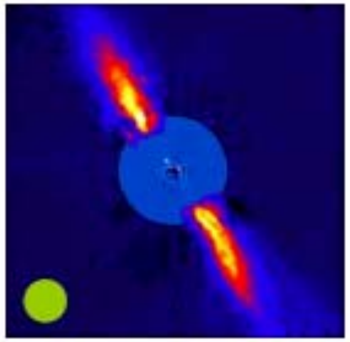
Fomalhaut



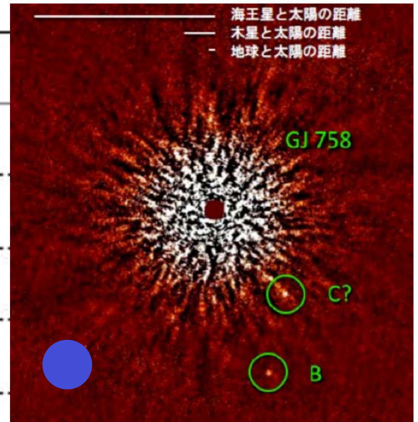
HR8799

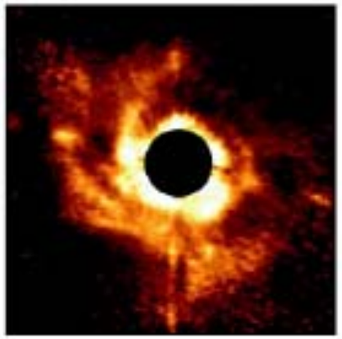


beta Pic

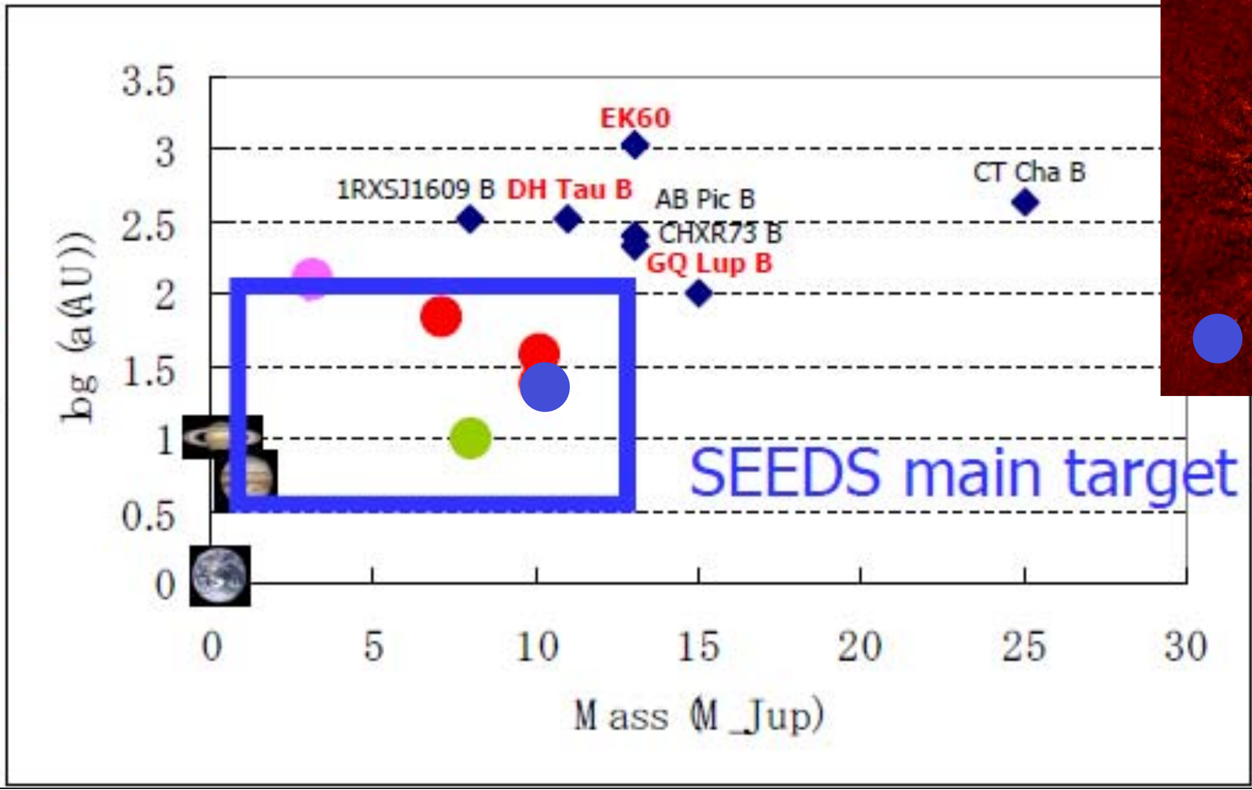


GJ 758





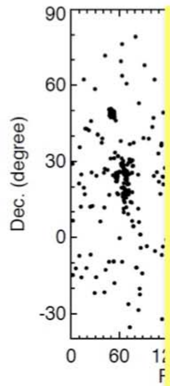
A star PP disk forming such "planets"?

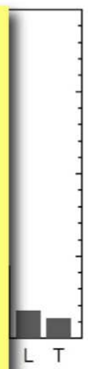


SEEDS main target space

Target Category

Category	Planet searches (in methane SDI/ADI mode)			Disk Searches (in PDI mode)		Total number
	(a)	(b)	(c)	(d)	(e)	
	SFR YSOs	Open cluster & Moving Group	Nearby stars	Protoplanetary disks	Debris disks	
Number	90	100	140+37	130	70	567
Distance	~140 pc	<125 pc	<30 pc	~140 pc	<130 pc	
Age	1-10 Myr	10~100 Myr	100 Myr - 1 Gyr	1-10 Myr	5 Myr - 6 Gyr	
Comment	Tau/Sco	UPleiades/ several MGs	subcategory	TTS/HAeBE/ polarized sources	SST/AKARI sample	



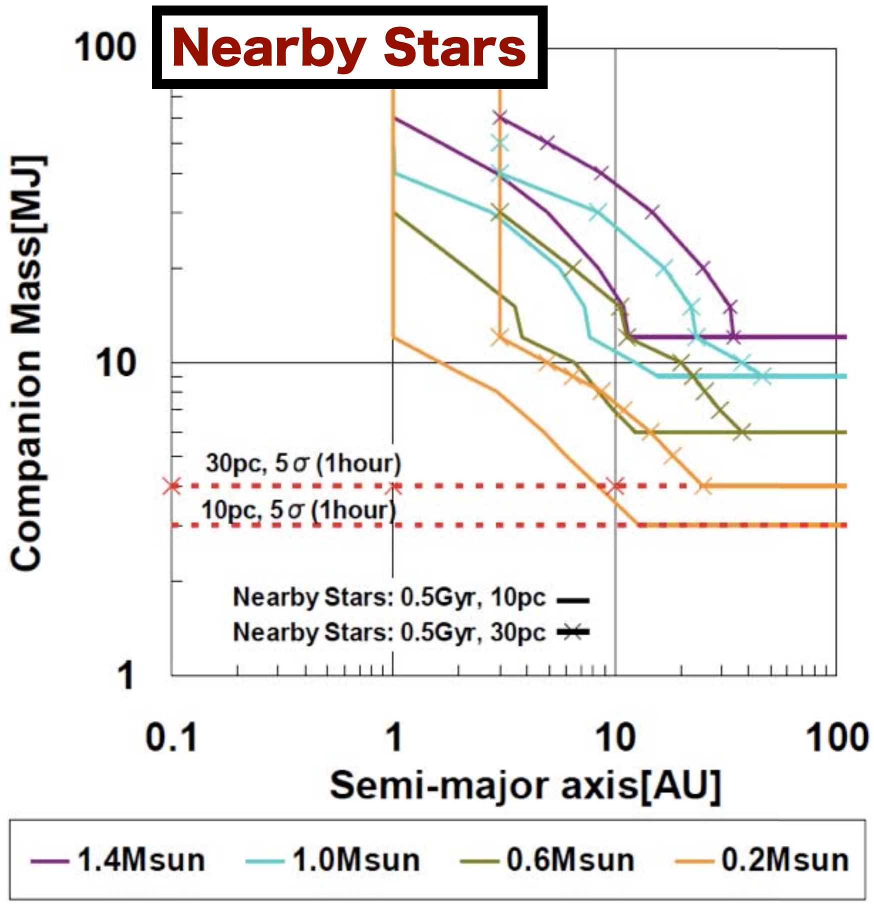


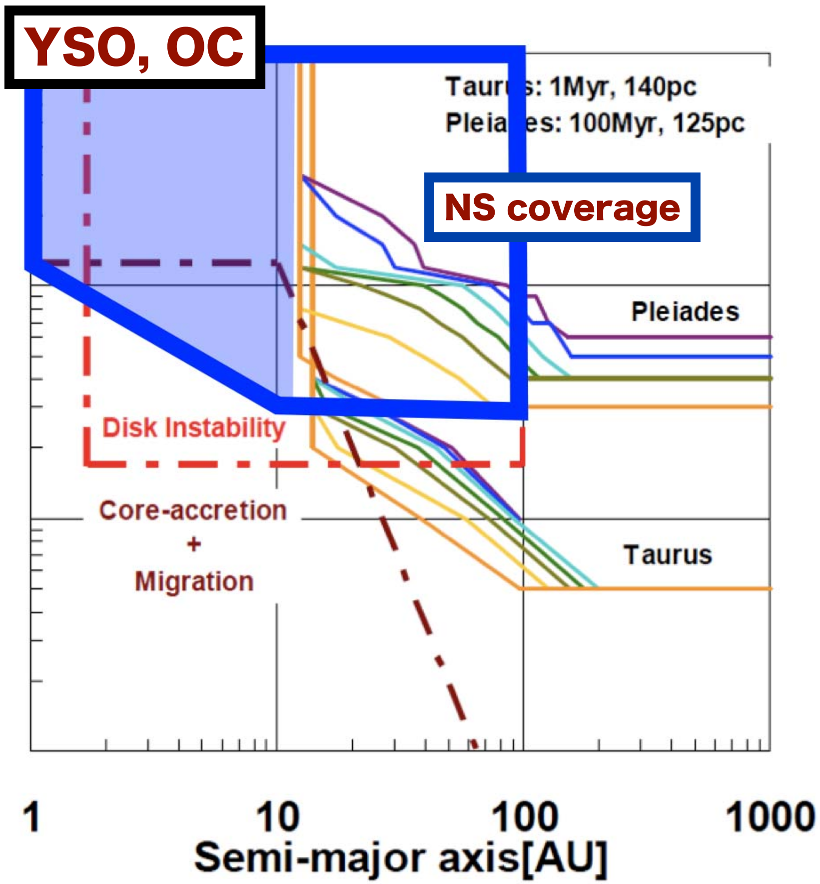
- **Giant gas planets (~1-13 M_J) in the outer region (> a few AU) around nearby (< 140 pc), young (self-luminous), solar-type stars.**

RA-DEC H-mag R-mag Sp-Type

Feasibility

Category	Expected Planet Detection Performance	
YSOs	>2 M_J for >15 AU	>0.5 M_J for >100 AU
Open Clusters	>5 M_J for >12 AU	>3 M_J for >30 AU
Nearby Stars	>10 M_J for a few AU	>1 M_J for >25 AU





- **Planetary-mass detection is available in all the category (based on simulated contrast performance of HiCIAO) .**

Performance Verification

MASKS/ MODES	0.15"	0.3"	0.5"	1"	1.2"	1.5"
DI(H)	---	(-4.14)	(-4.51)	(-5.46)	(-5.7)	(-6.09)
DI(K)	---	(-4.45)	(-4.62)	(-5.60)	(-5.7)	(-6.09)
SDI(H)	-3.94	-4.26	-4.65	-5.32	-5.42	---
ADI(H)	---	-3.7	-4.3	-5.4	-5.6	-6.0
ADI(K)	---	-4.3	-4.7	-5.5	-5.7	-6.0
PDI(H)	-4.0	-4.6	-4.8	-5.8	-6.0	-6.1
CS(H)	-3.70	-4.0	-4.5	-5.2	-5.4	~-5.7
CIAO(K)	---	---	---	---	-4.3	~-4.7

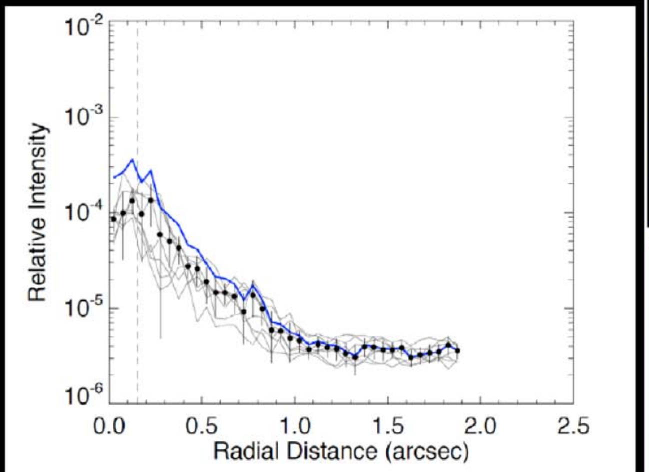
HiCIAO PV report (09 Sep)

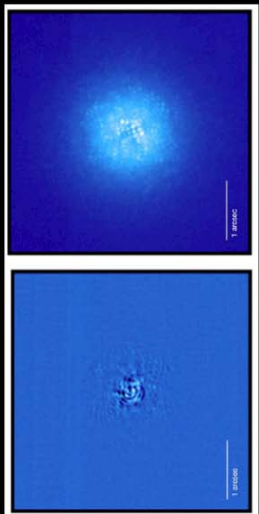
Observed contrast in each mode

Expected contrast (computer simulation)

Spectral Differential Imaging (SDI)

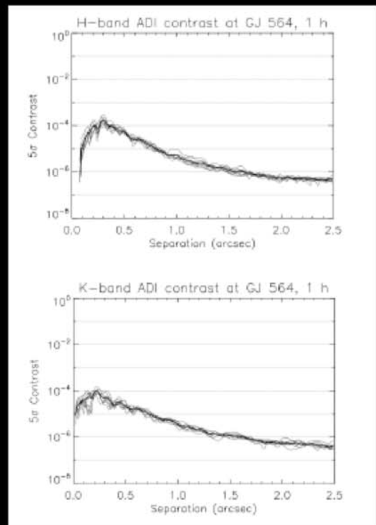
- Suitable subtraction among channels is crucial.
- Highest contrast at closest distance achieved.

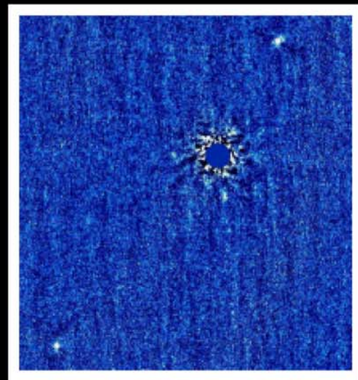




Angular Differential Imaging (ADI)

- Can apply with DI, SDI, and PDI.
- LOCI reduction technique.





Center of the final image from H band ADI observations of 1RXS1609. The bright spot on the upper right is the 8 MJ planet discovered by Lafrenière et al. (2008). The similarly bright spot on the lower left is a background star.

Performance Verification

MASKS/ MODES	0.15"	0.3"	0.5"	1"	1.2"	1.5"
DI(H)	---	(-4.14)	(-4.51)	(-5.46)	(-5.7)	(-6.09)
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CS(H)	-3.70	-4.0	-4.5	-5.2	-5.4	~-5.7
CIAO(K)	---	---	---	---	-4.3	~-4.7

HiCIAO PV report (09 Sep)

Observed contrast in each mode

Expected contrast (computer simulation)

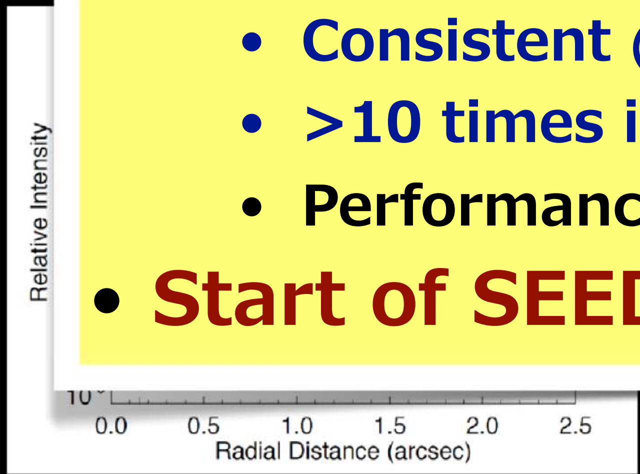
Spectral Differential Imaging (SDI)

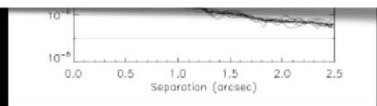
Angular Differential Imaging (ADI)

◆ S

◆ H

- **Confirmation of contrast performance**
  - **Consistent** (even better) **value with simulation**
  - **>10 times improvement than CIAO** ($10^{-5\sim-6}$)
  - **Performance verification report approved by SAC**
- **Start of SEEDS Science Run (2009 Oct 30)**

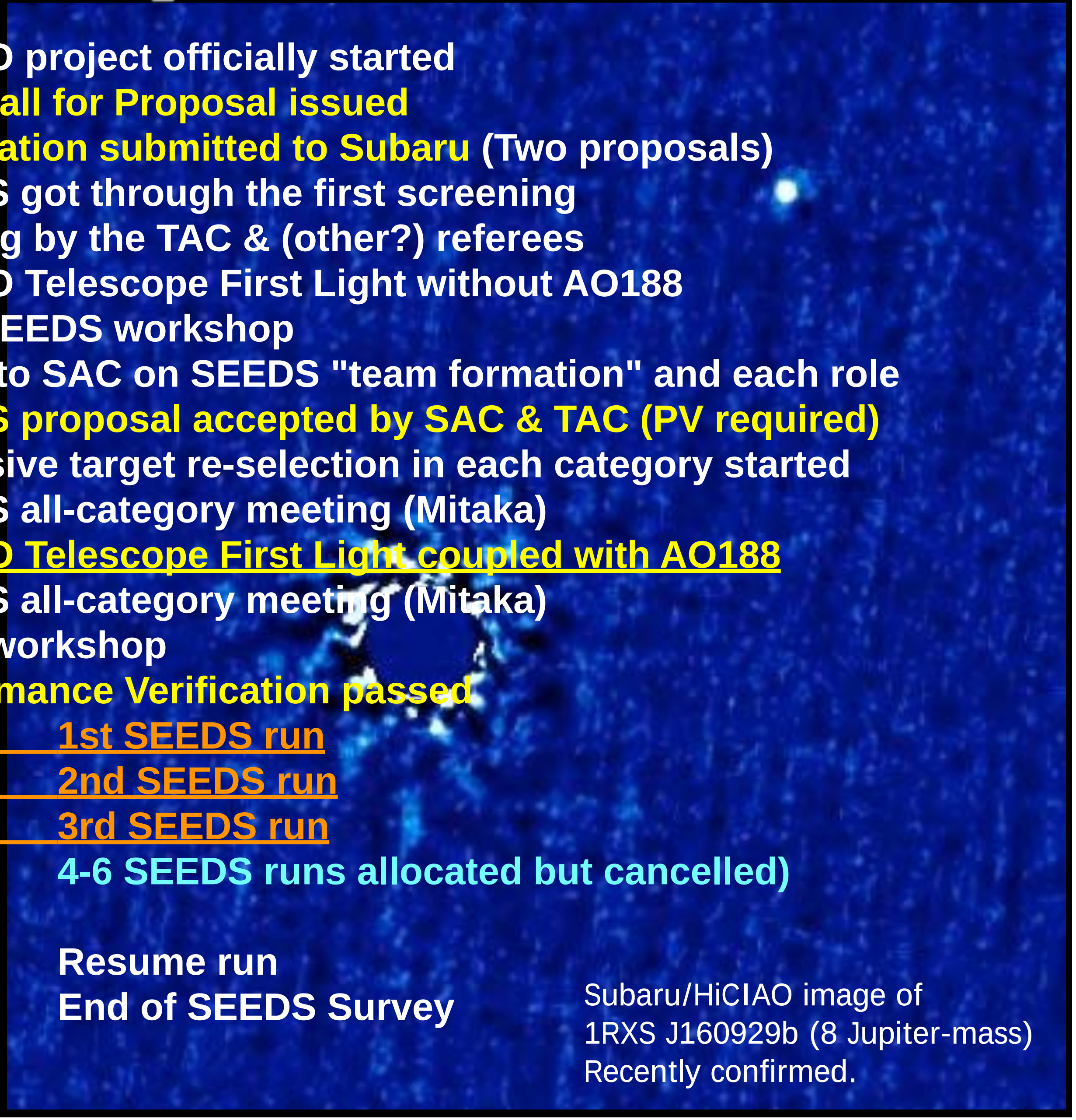




... on the upper right is the 8 MJ planet discovered by Lafrenière et al. (2008). The similarly bright spot on the lower left is a background star.

SEEDS History

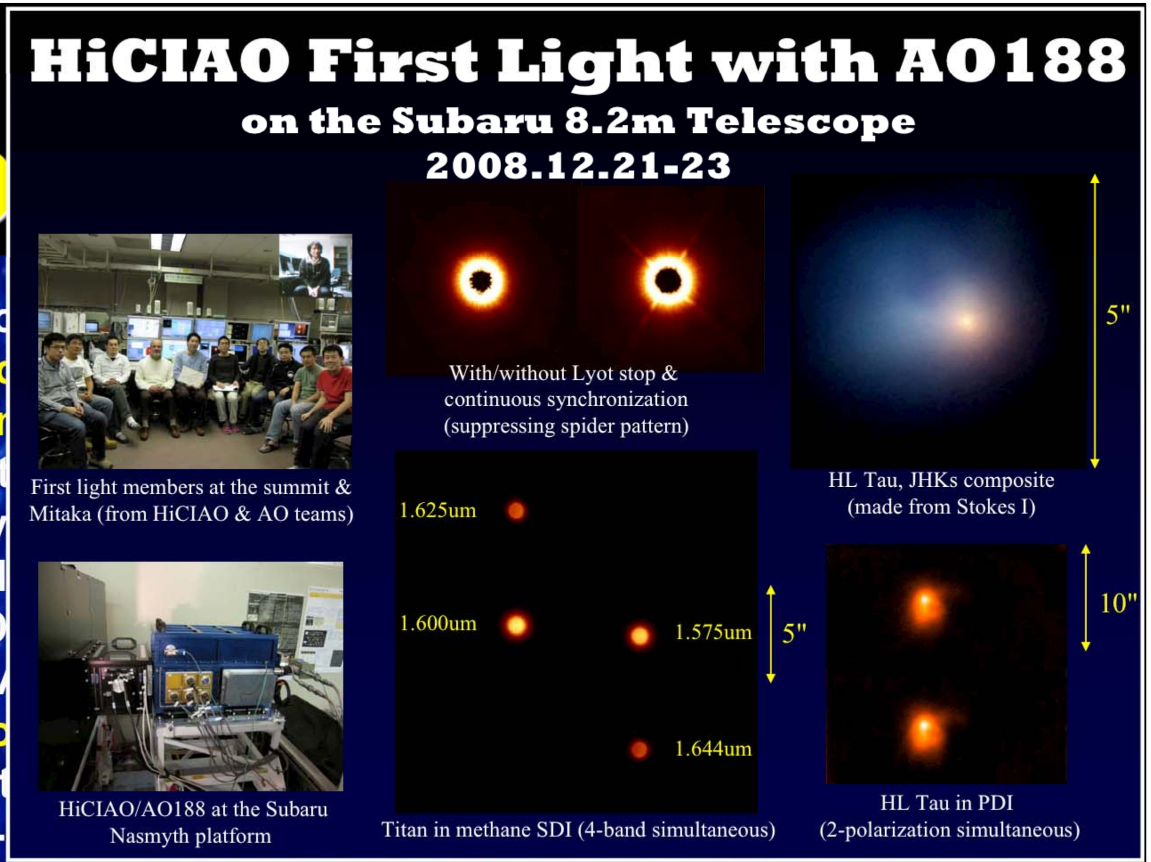
(2004)	Sep	HiCIAO project officially started
(2007)	Mar 27	SSO Call for Proposal issued
	Jul 31	Application submitted to Subaru (Two proposals)
	Aug 8	SEEDS got through the first screening
	Nov 14	Hearing by the TAC & (other?) referees
	Dec 3	HiCIAO Telescope First Light without AO188
(2008)	Feb 1	First SEEDS workshop
	Feb 12	Reply to SAC on SEEDS "team formation" and each role
	Mar 28	SEEDS proposal accepted by SAC & TAC (PV required)
	Mar-Sep	Extensive target re-selection in each category started
	Sep 3-4	SEEDS all-category meeting (Mitaka)
	Dec 21	HiCIAO Telescope First Light coupled with AO188
(2009)	Jan 17	SEEDS all-category meeting (Mitaka)
	Mar 9-12	Kona workshop
	Oct 1	Performance Verification passed
	Oct 30-Nov 1	1st SEEDS run
	Dec 22-25	2nd SEEDS run
	Jan 22-24	3rd SEEDS run
	(Feb, Apr, Jun	4-6 SEEDS runs allocated but cancelled)
	AO-DM broken!	
(2010)	Nov	Resume run
(2014)		End of SEEDS Survey

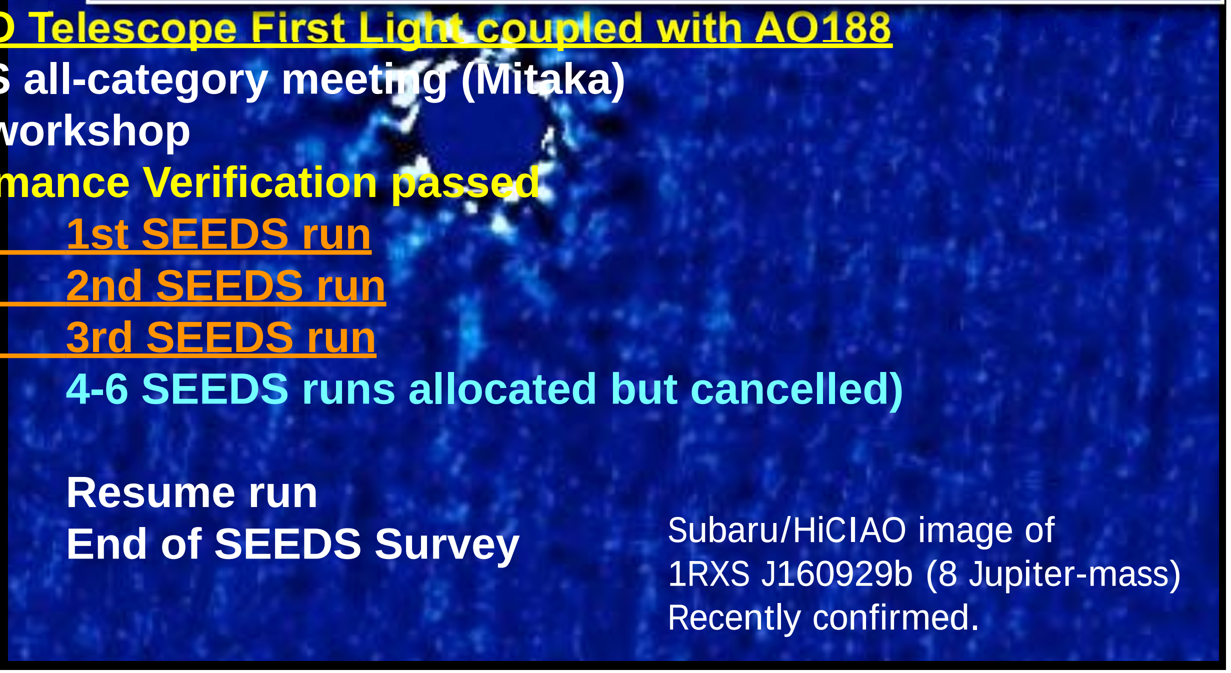


Subaru/HiCIAO image of
1RXS J160929b (8 Jupiter-mass)
Recently confirmed.

SEEDS Histo

(2004)	Sep	HiCIAO pro
(2007)	Mar 27	SSO Call fo
	Jul 31	Applicatio
	Aug 8	SEEDS got
	Nov 14	Hearing by
	Dec 3	HiCIAO Tel
(2008)	Feb 1	First SEED
	Feb 12	Reply to S/
	Mar 28	SEEDS pro
	Mar-Sep	Extensive t
	Sep 3-4	SEEDS all-
	Dec 21	HiCIAO Telescope First Light coupled with AO188
(2009)	Jan 17	SEEDS all-category meeting (Mitaka)
	Mar 9-12	Kona workshop
	Oct 1	Performance Verification passed
	Oct 30-Nov 1	1st SEEDS run
	Dec 22-25	2nd SEEDS run
	Jan 22-24	3rd SEEDS run
	(Feb, Apr, Jun	4-6 SEEDS runs allocated but cancelled)
	AO-DM broken!	
(2010)	Nov	Resume run
(2014)		End of SEEDS Survey





Subaru/HiCIAO image of 1RXS J160929b (8 Jupiter-mass)
Recently confirmed.

Science Run Progress

- **SEEDS Science Run** (10 nights in 3 runs)
  - 2009: 10/30 - 11/1 (3), 12/22 - 12/25 (4)
  - 2010: 1/22 - 1/24 (3)

Category	Number	Observations Mode		
		ADI(DI)	PDI	SDI
Debris Disk	8	5	4	0
YSO	11	1	11	0
Open Cluster	9	7	2	0
Moving Group	11	11	0	0
Nearby Star	20	18	1	1
TOTAL	58	42	18	1

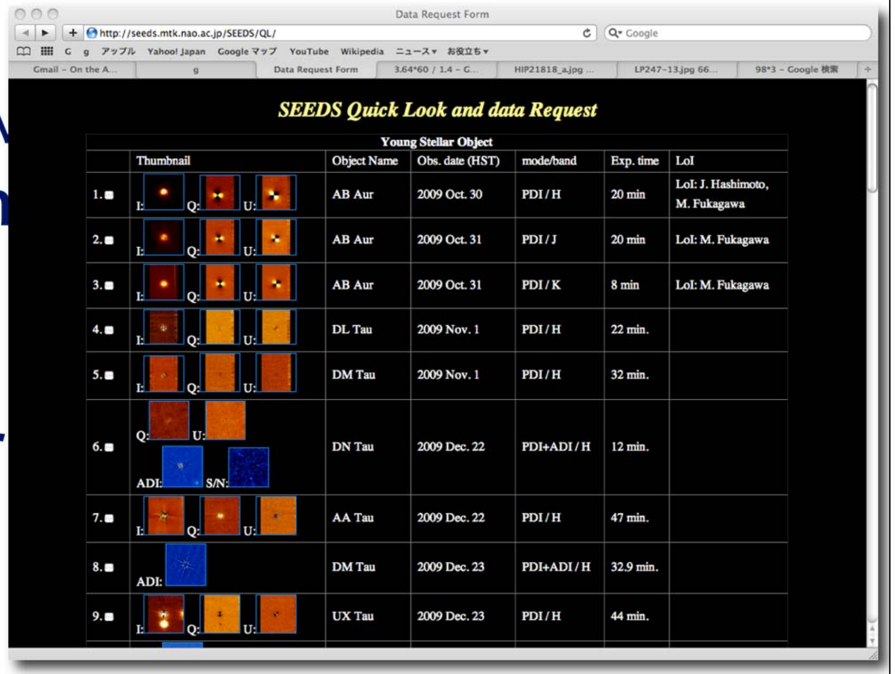
※ SDI mode is still in engineering phase (commissioning w/ ADI and w/ new filter sets planned)

※ N of objects with short effective exposures (<20 min) : 23/58 (~40%)

※ Nearby Star category has 8 sub-samples (Chromospheric age, Kinematic age, Planet-host stars, TPF/SPICA samples, High-mass stars, M dwarfs, Brown dwarfs, White dwarfs).

Data Reduction

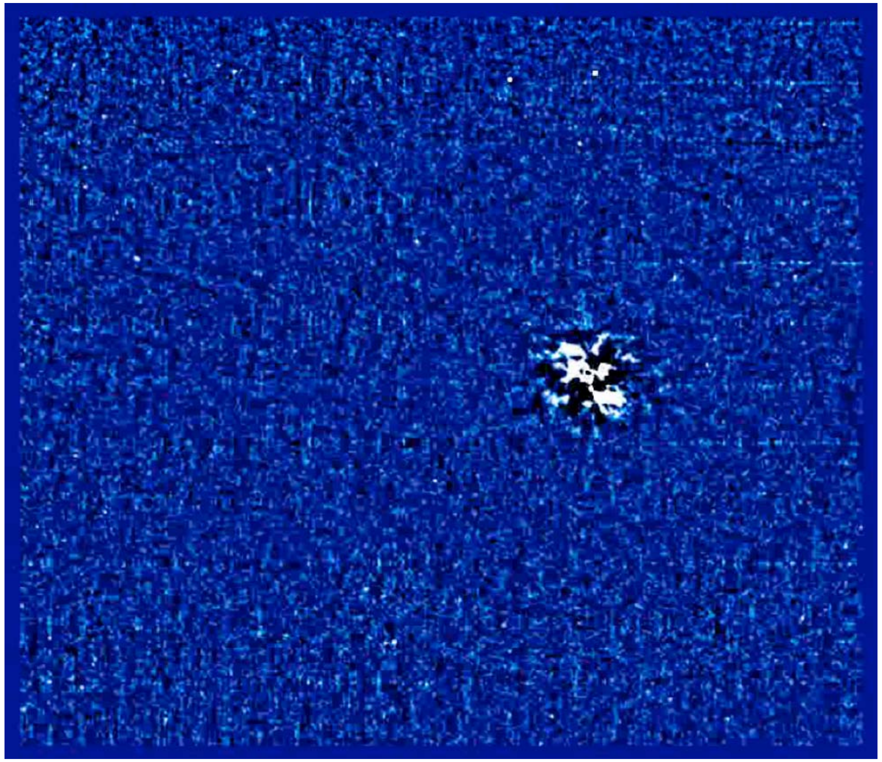
- **SEEDS Science Data**
  - Data archive: Mitaka, Princeton, M
  - Release of data quick look im
  - LoI (Letter of Intent)
    - ✓ Most of objects have LoIs
  - Data delivery, analysis, paper

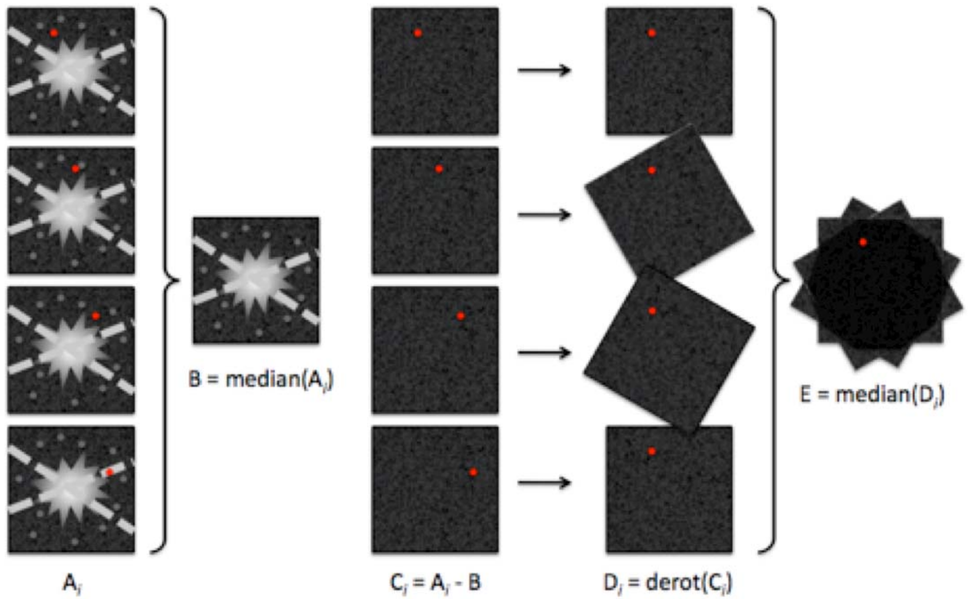


- **Data reduction**
  - Release/Distribution of Pipelines
    - ✓ ADI (written in IDL, using LOCI algorithm: Lafreniere+2007)
      - code distributed among members.
    - ✓ PDI (written in both IRAF and IDL)
      - code distributed among members.
    - ✓ SDI (written in both IRAF and IDL)
      - code developed, but the mode is still in the engineering phase.

ADI/LOCI Pipeline

Imaging obs in pupil-stable mode (i.e., sky rotates)





Construct local reference PSF in each local area

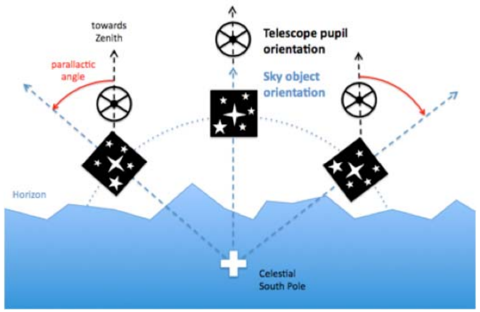


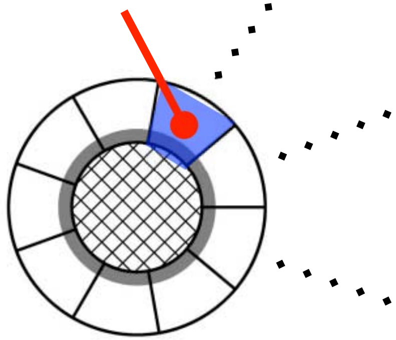
Figure by C.Thalmann

LOCI algorithm

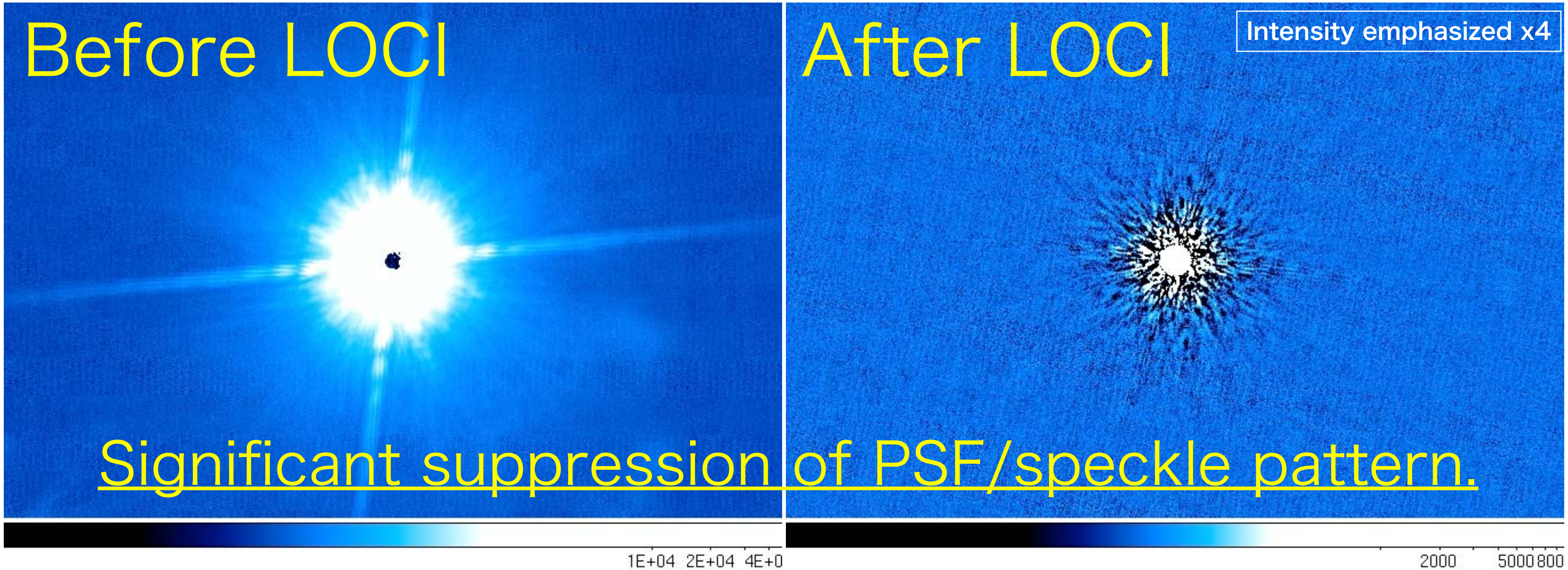
Locally **O**ptimized

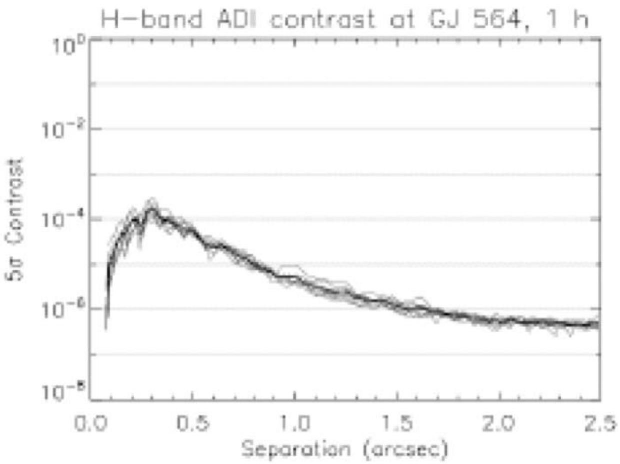
Combination of **I**mages

Lafreniere et al. (2007)

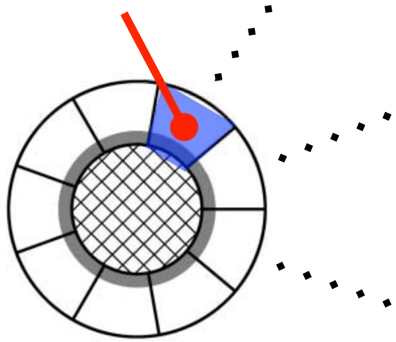


ADI/LOCI Pipeline





Construct local reference PSF in each local area



LOCI algorithm

Locally **O**ptimized

Combination of **I**mages

Lafreniere et al. (2007)

SEEDS Early Science Result

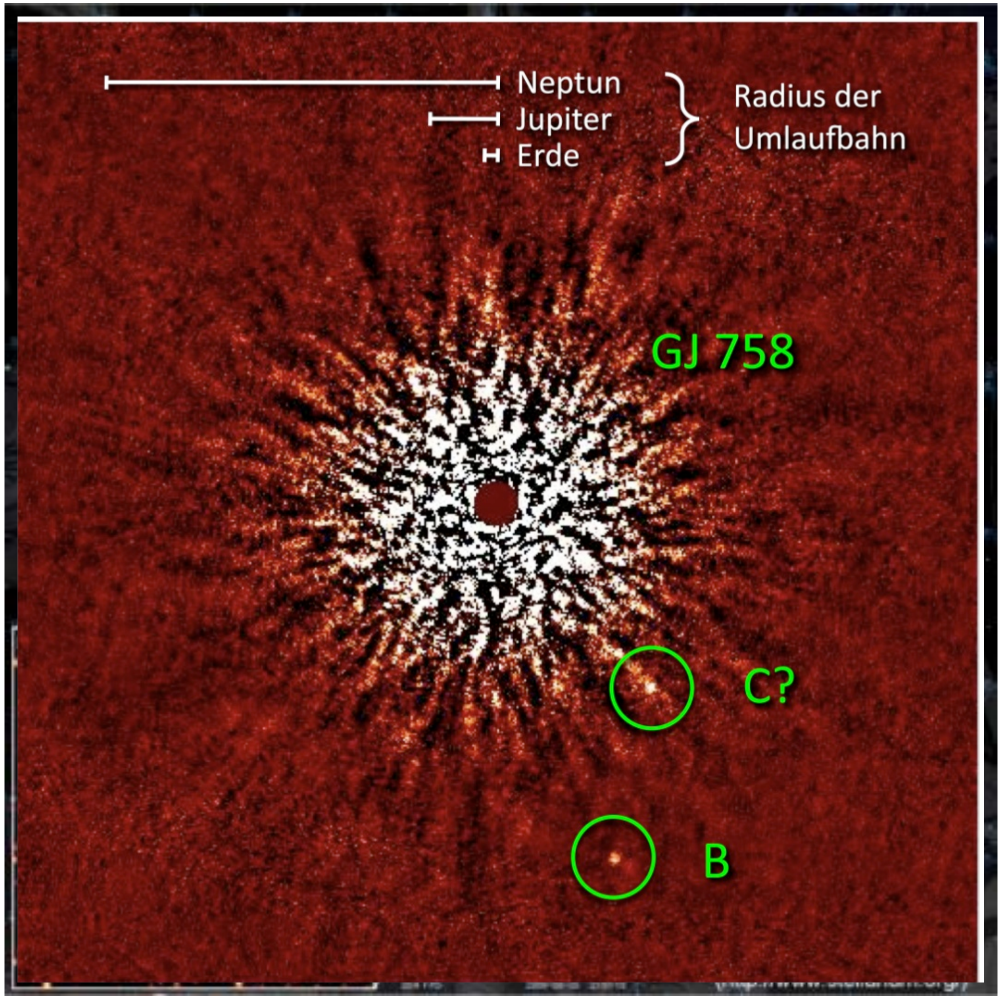
GJ 758	Thalmann et al. 2009, ApJL, 707, 123
HAT-P-7	Narita et al. 2010, PASJ, 62, 779
LkCa15	Thalmann et al. 2010, ApJL, 718, 87
AB Aur	Hashimoto et al. Nature, Submitted
GJ 758	Janson et al. Submitted

Since 2009 Oct-

Direct Imaging of Planet Candidates around Solar-Type Stars

- Distance:15.5 pc
- G9 Type
  - V=6 mag
  - Mass=0.97Mo
- No RV planets so far
- Age
  - Not straightforward
  - Best estimate: 700Myr (Takeda et al. 2007; isochrone)
  - Max 8.7Gyr (but associated with a large uncertainty estimated from stellar rotation)
- Observations (in commissioning!)
  - May and Aug 2009 (3 months)
  - Proper motion test : association of GJ 758 b was confirmed (10 sigma).

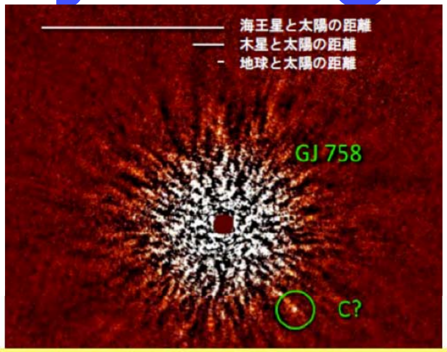
GJ758=HD182488=HIP95319

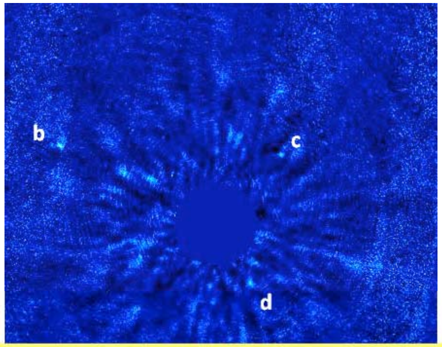


Thermal emission from planets detected as 1.6 micron infrared radiation.
Thalmann et al. 2009

White and black pattern near the central star (Speckle noise)

Directly imaged Planets: G vs. A stars





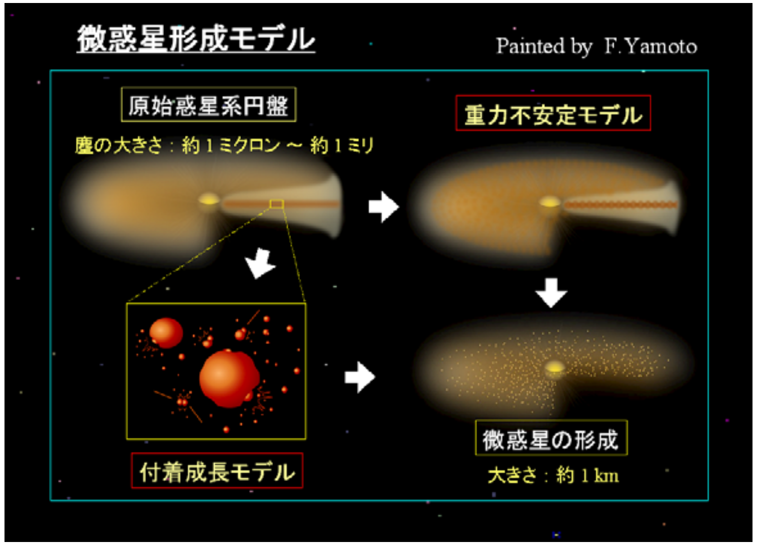
The survey of solar-type stars with DI is essentially important to reveal "whether the wide-orbit giant planet is common or not."

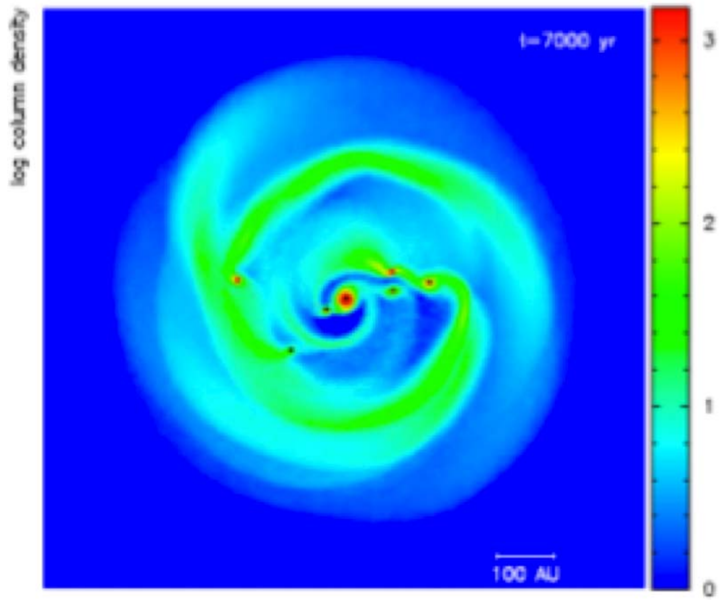
distance			
age		age	
primary	0.97 Msolar (solar-T,G-type)	primary	1.5 Msolar (A-Type)
companion	Mass (Jupiter masses) Separation (AU, apparent)	companion	Mass (Jupiter masses) Separation (AU, apparent)
B	10 M_J (max : 40) 29 AU	B	7 M_J (max : 36) 68 AU
C?	12 M_J (max : 47) 18 AU	C	10 M_J (max : 50) 38 AU
-	These are wide-orbit, "outer planets"	D	10 M_J (max : 50) 24 AU

Outer Planets Formation Mechanisms

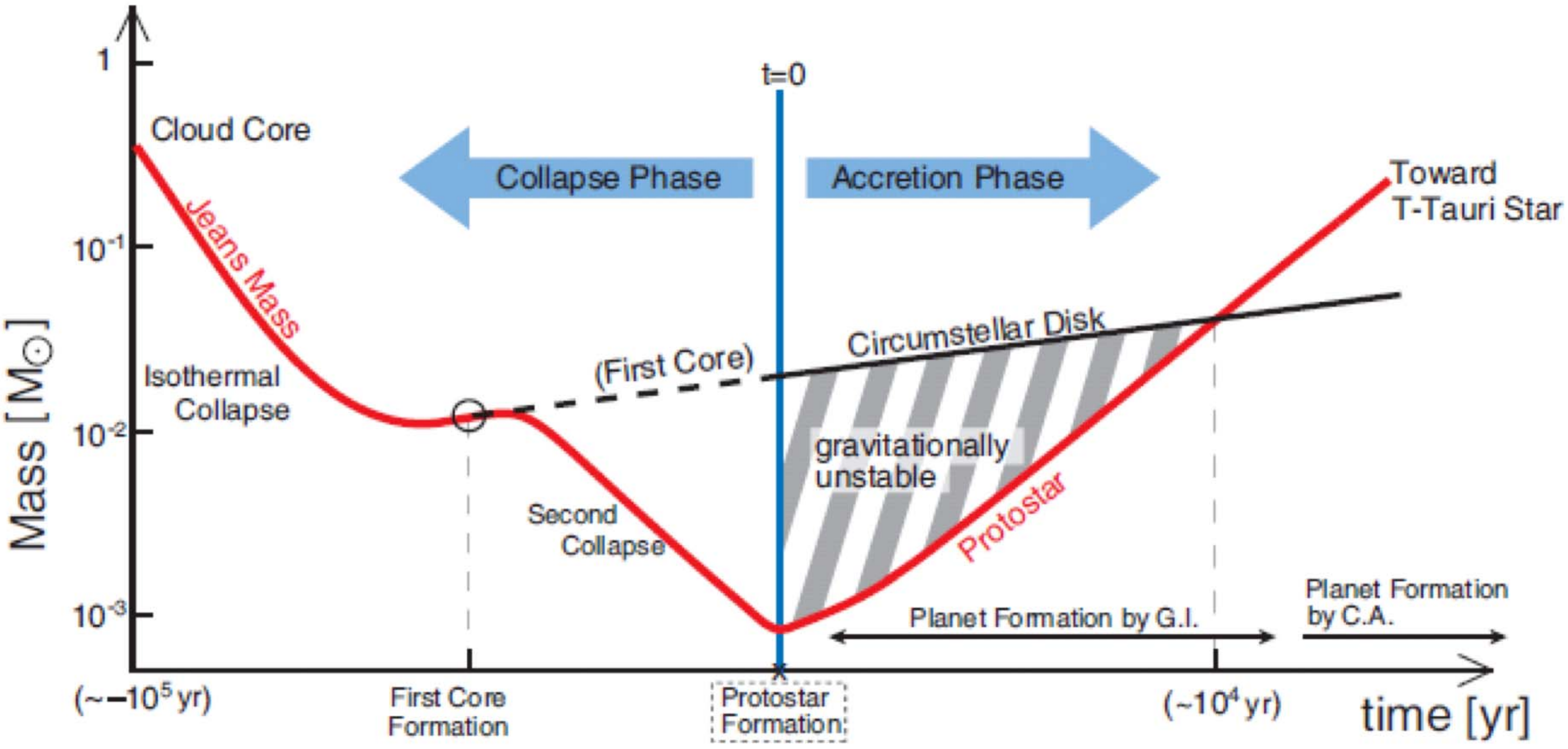
- Standard model (CA: core accretion)
  - Timescale problem for outer planets
  - Up to ~10 AU or less is probably possible
  - GJ758B at ~Neptune is too far away
  - Possible outward migration to 100s of AU
- Gravitationally instability model (GI)
  - Probably better for outer planets than CA model
  - But based on hypothetical massive large disks
- Planetary scattering
  - interaction among multiple planets

New ideas?





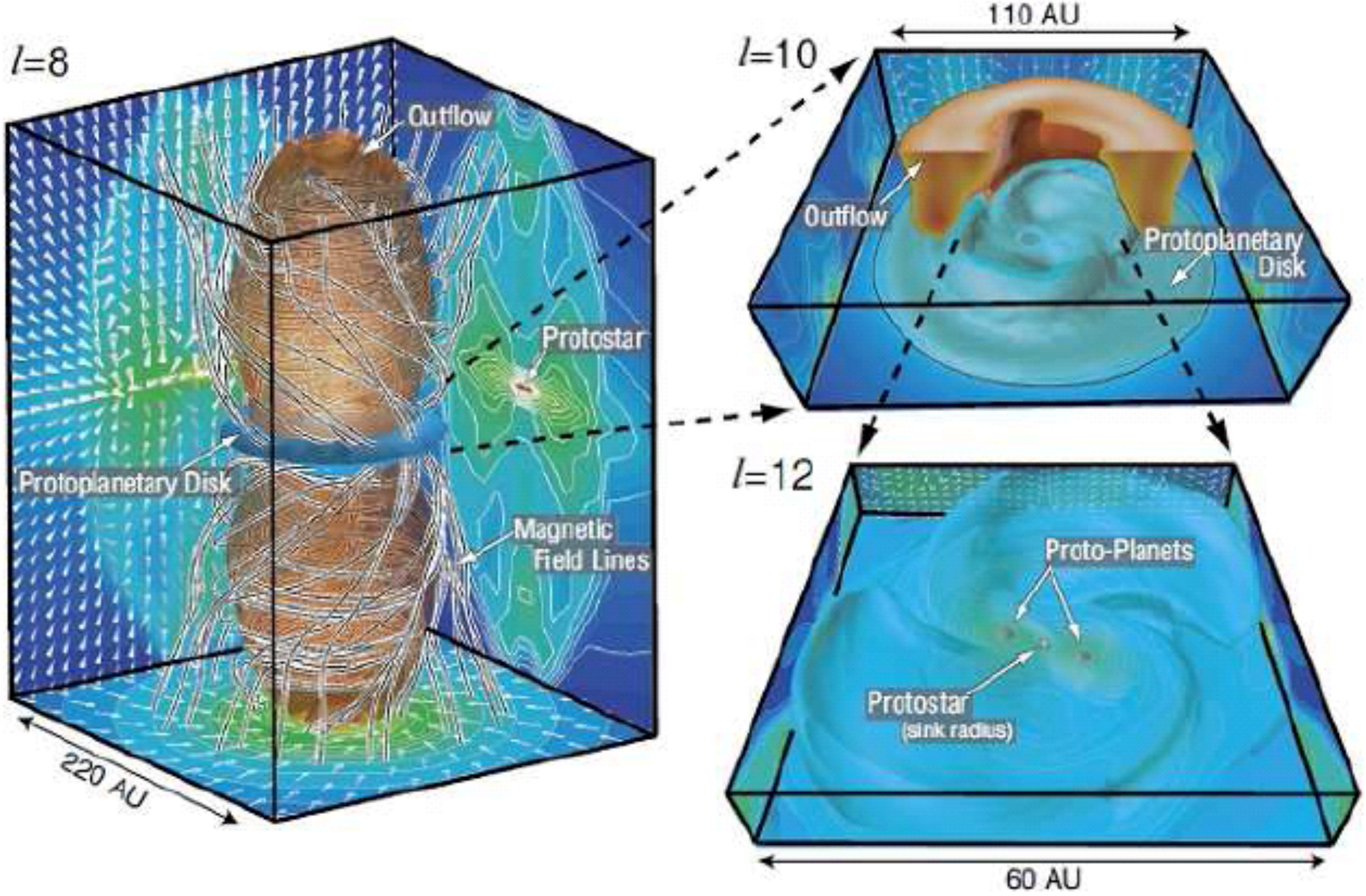
A New Model



- Calculation from realistic molecular cloud contraction
- Gravitational instability at an early phase (after second collapse) can occur at outer region (<~100 AU) regions

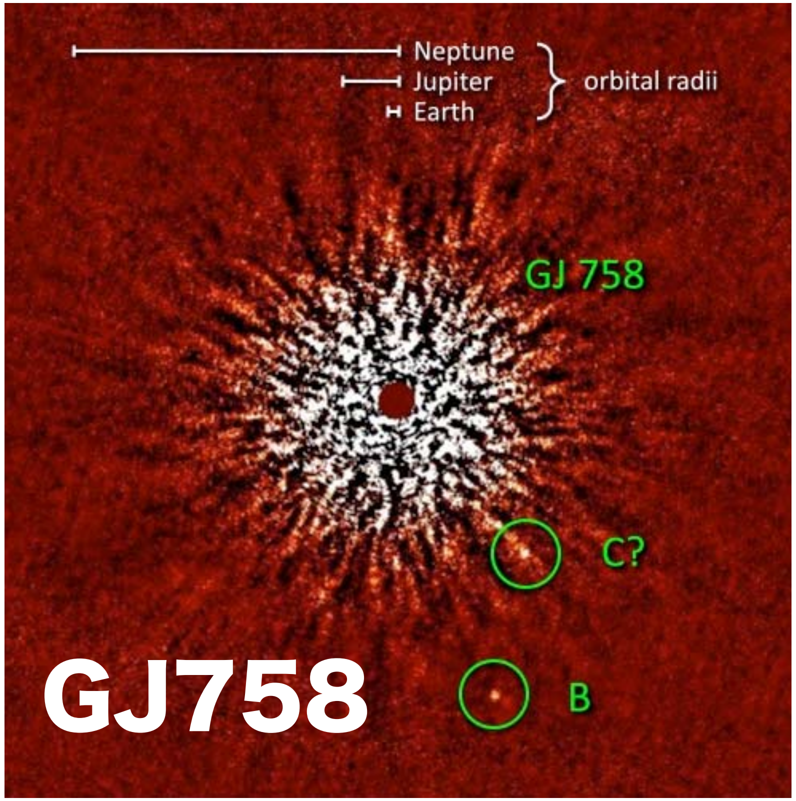
Inutsuka, Machida, Matsumoto 2010, ApJL, 718, 58

A New Model



To understand these models (CA, GI, or new ones)
Understanding disk structures of <100 AU crucial
⇒ Already some hint from SEEDS observations!

SEEDS Early Science Result (since 2009 Oct)



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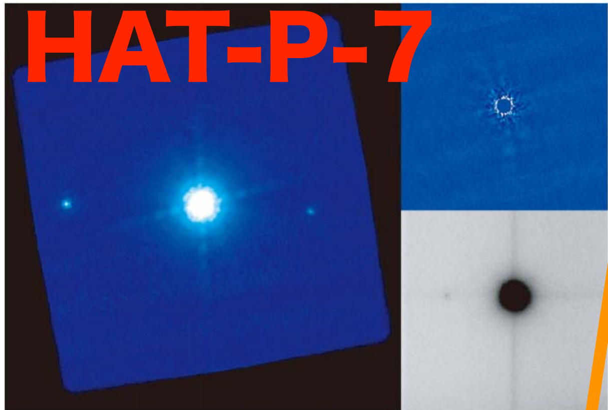
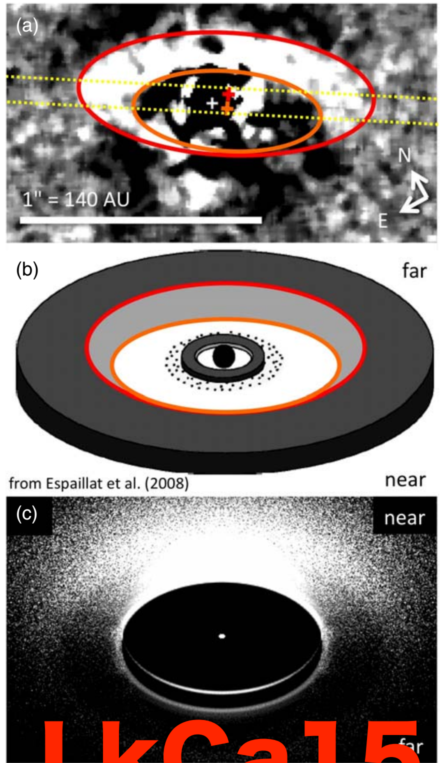
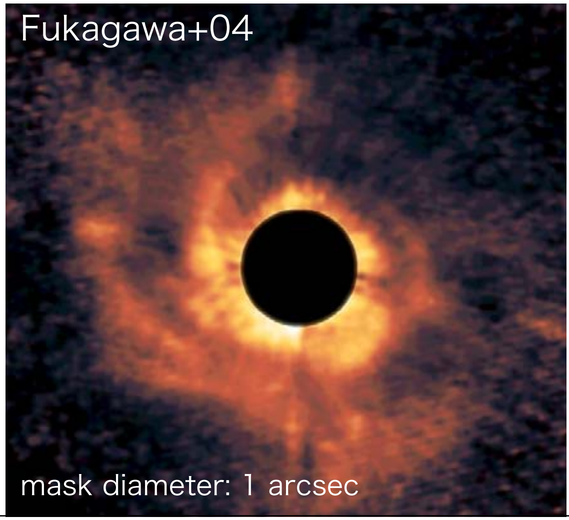
AB Aur : Hashimoto et al. Nature, Submitted

GJ758 : Janson et al. Submitted







AB Aur

Polarization structure of inner disk (gaps, dips, and arms at > 20 AU) resolved!!

SEEDS Members

- **N=106 from 29 institutes (Overseas: N=37 from 13 institutes)**
  - **PI: Tamura,M. (NAOJ) Co-PI: Usuda,T., Takami,H. (NAOJ/Subaru)**
  - **Co-Is: NAOJ Fukue,T. Hashimoto,J. Iye,M. Kandori,R. Kokubo,E. Kudo,T. Kusakabe,N. Matsuo,T. Miyama,S. Morino,J. Narita,N. Nishikawa,J. Sato,M. Suto,H. Takeda,Y. Watanabe,J. Yamashita,T. (Subaru) Egner,S. Frantz Fujiyoshi,T. Guyon,O. Hayano,Y. Hayashi,M. Ishii,M. Pyo,T.S. Takato,N. Terada,H. Usuda,S.K. Yutani,M. (ALMA) Saito,M. Tsukagoshi,T. Ukita,N. Kawabe,R. Univ. of Air Kaifu,N. Hokkaido Univ. Baba,N. Tohoku Univ. Kitamura,M. Tsukamoto,A. Yamada,T. Ibaraki Univ. Momose,M. Okamoto,Y. Riken Ebizuka,N. Univ. of Tokyo Kuzuhara,M. Sakon,I. GUAS Mayama,S. Suenaga,T. Takahashi,Y. Univ. of Tokyo Ueno,M. TiTECH Ida,S. Sato,B. JAXA/ISAS Enya,K. Kataza,H. Makitsubo,H. Nakagawa,T. Kanagawa Univ. Honda,M. Nagoya Univ. Inutsuka,S. Nagashima,A. Otsubo,T. Sumi,T. Yamamoto,K. Nagoya City Univ. Sugitani,K. Osaka Univ. Fukagawa,M. Shibai,H. Kyoto Univ. Muto,K. Kobe Univ. Hioki,T. Itoh,Y. Oasa,Y. TMT Suzuki,R. ASIAA Karr,J. Ohashi,N. Takami,M. Univ. of Hawaii (IfA) Hodapp,K. Princeton Dressing,C. Kasdin,J. Knapp,G.R. McElwain,M. Shen,Y. Spergel,D. Turner,E.L. Vanderbei,R. Blake,C. CSIC-INTA (Spain) Moro-Martin,A. NASA/Goddard Grady,C. NASA/JPL Serabyn,E. Univ. of Washington Wisniewski,J. Univ. of Toronto Janson,M. MPIA Brandner,W. Carson,J. Feldt,M. Goldman,B. Goto,M. Henning,T. Launhardt,R. Roccatagliata,V. Setiawan,J. Thalmann,C. Westfalische W Hertfordshire Gledhill,T. Ho Tavrov,A.V.**

If you are interested in joining SEEDS project, please contact the project PI (Motohide Tamura, NAOJ, motohide.tamura@nao.ac.jp).

Summary and Schedule

- **Summary**
  - SEEDS project: Subaru Strategic Observations
    - 120 nights in 5 years (~500 targets)
  - Start of SEEDS science run after Oct 2009
    - 3 runs (10 nights) so far. 58 objects observed.
    - AO188 trouble: Feb-Nov 2010
  - DI, PDI pipelines were released, and SDI mode is in engineering.
  - 3 papers (GJ758,HAT-P-7,LkCa15 / DI) in publication and 2 paper (AB Aur in PDI, GJ758 in DI) in submission.
    - GJ 758: First DI of candidate planet around a solar-type star
    - AB Aur: Revealing innermost (> 20 AU) disk structure
- **Schedule 2010-2011**
  - Restart of SEEDS run (end of Nov 2010) after the recovery of AO188 (until Nov)
    - Follow-up of candidate companions (proper motion test, multi-color data)
    - 11/29(ENG), 11/30-12/2(SEEDS), 1/24(ENG/SEEDS), 1/27-31 (SEEDS)