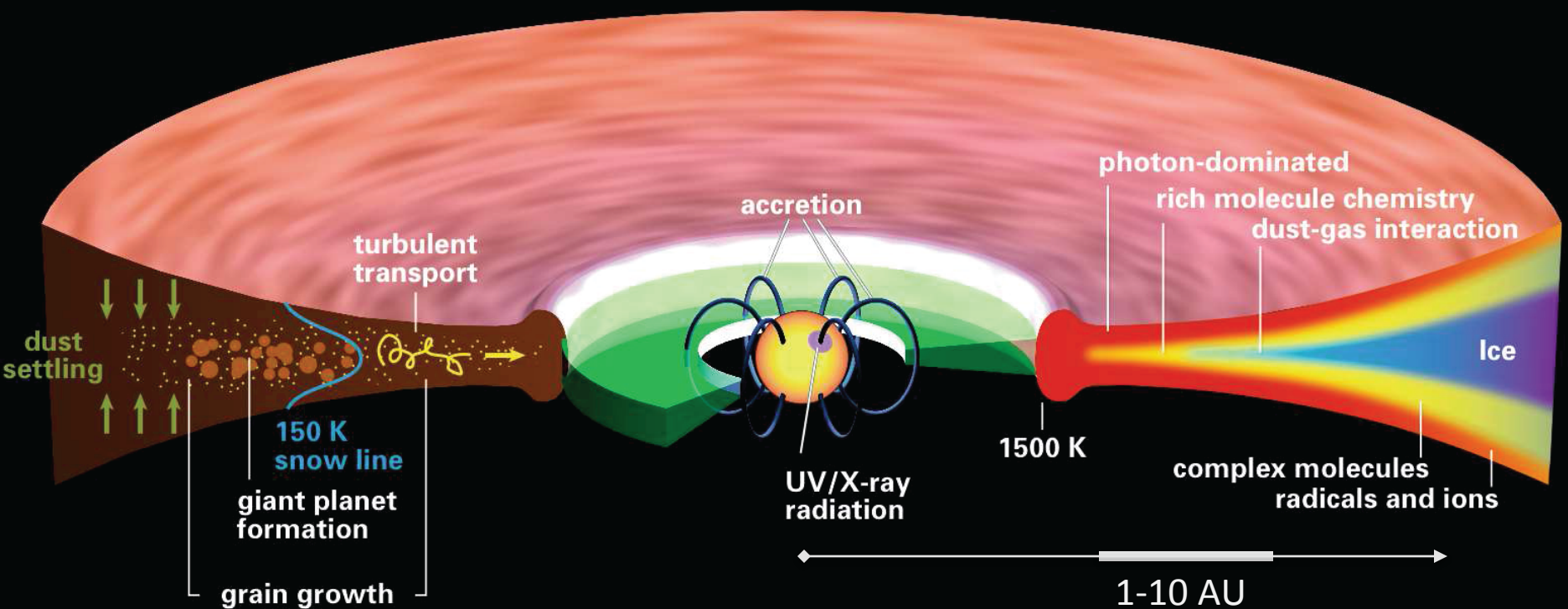


Subaru Infrared 2-4 μ m Observations of Water Ice in Protoplanetary Disks

Hiroshi TERADA
(NAOJ, Pasadena)
2018/01/18

Ice in Protoplanetary Disks

- Ices promote planet formation in disks because of their sticky characteristics.
- Water ice in disks could be a source of water delivery into rocky planets.



Henning & Semenov (2013)

Inventory of Astronomical Ices

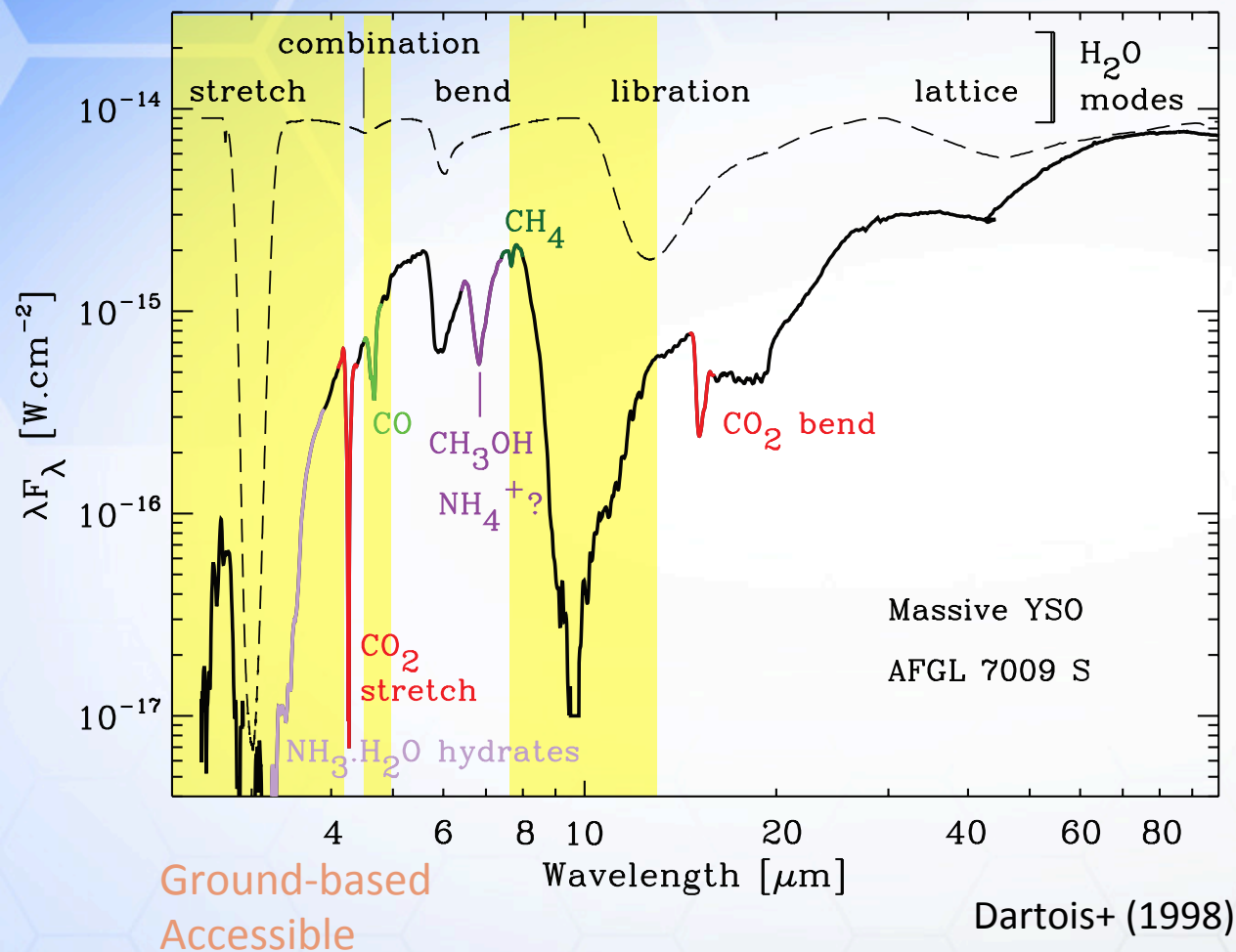


Table 1: Detected Ice Features

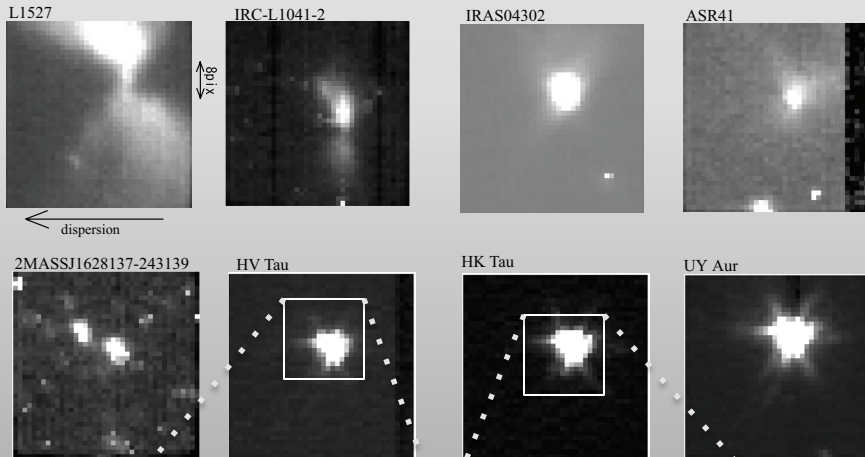
λ_{center} μm	ν_{center} cm^{-1}	FWHM cm^{-1}	Identification	Reference ^a
2.27	4405	60	CH ₃ OH combination	1
2.70	3703.7	4	CO ₂ combination	2
2.78	3597.1	5	CO ₂ combination	2
2.96	3378	~ 40	NH ₃ stretch?	27, 30
3.0	3333	~ 390	H ₂ O stretch (multiple components) ^b	3, 29
-2.90	3448	~ 120	— scatter	3, 29
-3.05	3278	~ 315	— amorphous small grains	4, 28
-3.10	3225	~ 301	— crystalline small grains	28
~ -3.3	3030	~ 270	— scatter and NH ₃ ·H ₂ O hydrate	5, 33
3.25	3076	57	PAH C-H stretch? NH ₄ ⁺ combination?	6, 32, 40
3.325	3008	11	CH ₄ stretch	45
3.47	2881	80	NH ₃ ·H ₂ O hydrate	7, 31
3.53	2832	30	CH ₃ OH C-H stretch	8
3.85	2597	~ 40	CH ₃ OH combination	7
3.94	2538	~ 40	CH ₃ OH combination	9, 7
4.07 ^c	2457	~ 120	HDO O-D stretch amorphous	26
4.13 ^c	2421	~ 60	HDO O-D stretch crystalline	26
4.27	2341	~ 20	CO ₂ stretch	42
4.39	2277.9	9	¹³ CO ₂ stretch (multiple components)	34
-4.382	2282.0	3	— pure CO ₂	34
-4.390	2277.9	8	— polar ice	34
4.5	2222	270	H ₂ O combination	12
4.62	2164	29	"XCN" (multiple components)	13, 35, 36
-4.60	2173	15	OCN ⁻ C-N stretch (apolar ice)?	13, 35, 36
-4.64	2164	26	OCN ⁻ C-N stretch (polar ice)	13, 35, 36
4.67	2141.3	3-9	CO stretch (multiple components)	14
-4.665	2143.7	3.0	— CO:CO ₂ :N ₂ :O ₂	36, 35
-4.673	2139.9	3.5	— apolar, > 90% CO	13, 35
-4.681	2136.5	10.6	— polar	13, 35
4.779	2092.4	1.50	¹³ CO stretch (apolar)	15
4.90	2040	22	OCS C-O stretch	9, 37
5.83	1715	35	H ₂ CO C-O stretch	17
6.29	1589	65	PAH C-C stretch?	17
6.00	1666	160	multiple components	16
-6.0	1666	~ 130	H ₂ O bend	16
-5.84	1712	72	HCOOH C-O stretch?	17, 38
-6.18	1618	111	NH ₃ bend and H ₂ O:CO ₂ =2:1 and more	17, 38
6.0	1666	~ 330	organic residue or an-ions?	39, 38
6.85	1459	85	multiple components	16
-6.755	1480	43	CH ₃ OH C-H deformation and NH ₄ ⁺ bend?	17, 38
-6.943	1440	61	NH ₄ ⁺ bend?	17, 38
7.24	1381	19	HCOOH, CH ₃ CH ₂ OH, C-H deformation?	19
7.41	1349	15	HCOO ⁻ , CH ₃ HCO, C-H deformation?	19
7.63	1310	28	SO ₂ stretch?	20
7.674	1303	11	CH ₄ deformation	21, 41
8.865	1128	15	CH ₃ OH C-H rock	22
9.01	1109	50	NH ₃ umbrella	23
9.74	1026	30	CH ₃ OH C-O stretch	22
13.6	735	~ 220	H ₂ O libration	24
15.1-15.3	653-662	16-28	CO ₂ bend (multiple components)	42
-15.31	653	22	— H ₂ O>CO ₂	35
-15.10	662.2	11	— CO ₂ <CO	35
-15.15	660.0	2.5	— CO ₂ <<CO	35
-15.11+15.26	655.3+661	19	— pure CO ₂	35
-15.4	648	10	— CH ₃ OH>>CO ₂	35
44	227	~ 100	H ₂ O lattice (amorphous)	43, 44, 25
44	227	~ 50	H ₂ O lattice (crystalline)	43, 44, 25
62	161	~ 50	H ₂ O lattice (crystalline)	43, 44, 25

Boogert (2015)

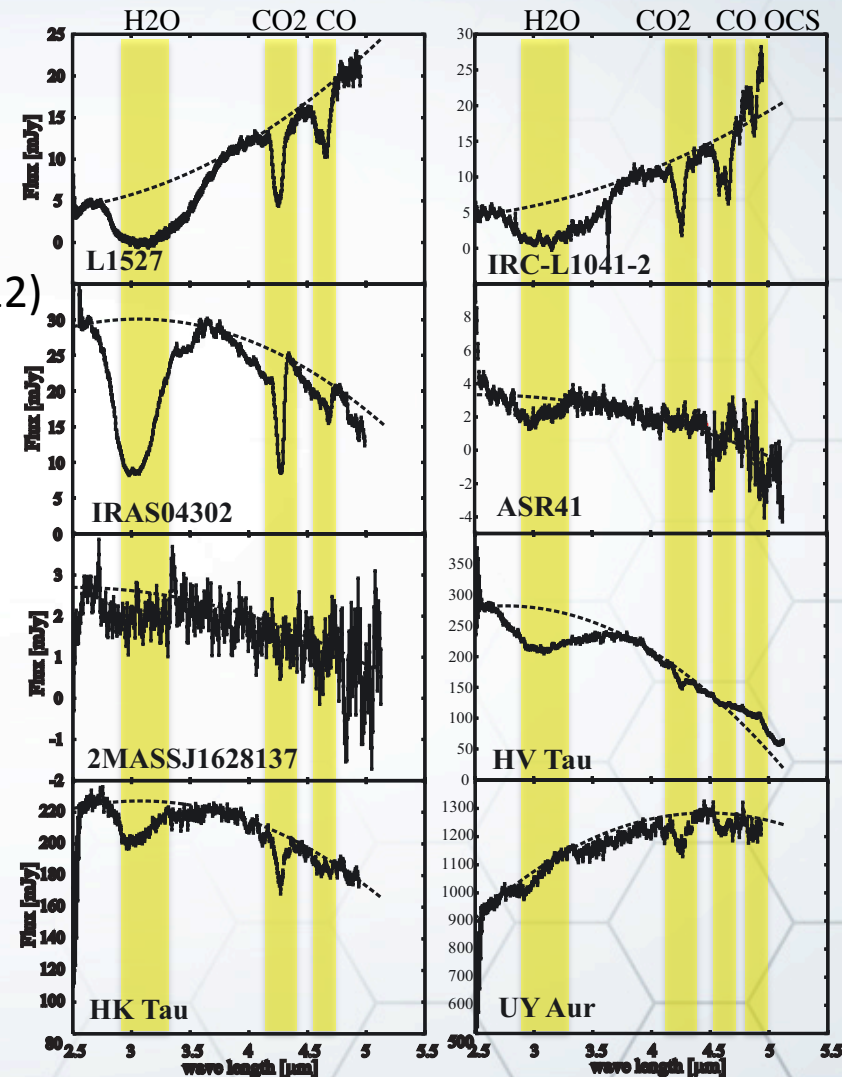
Ice toward Edge-on Disks (+ Envelope)

Name	Coordinates (J2000) ^a	Class	Note
L1527(IRAS 04368+2557)	04:39:53.6 +26:03:05.5	O-I	WCCC, $i \sim 85^\circ$ ^b
IRC-L1041-2	20:37:21, +57:44:13	O-I ^c	nearly edge-on ^c
IRAS 04302+2247	04:33:16.45, +22:53:20.7	O-I	$i \sim 90^\circ$ ^d
ASR 41	03:28:51.291, +31:17:39.79	II	$i \sim 80^\circ$ ^e
2MASSJ 1628137-243139	16:28:13.7, -24:31:39.00	II	$i \sim 86^\circ$ ^f
HV Tau	04:38:35.280, +26:10:39.88	II	multiple system ($i \sim 84^\circ$) ^g
HK Tau	04:31:50.900, +24:24:17.00	II	binary ($i \sim 85^\circ$) ^h
UY Aur	04:51:47.31, +30:47:13.9	II	$i \sim 42^\circ$

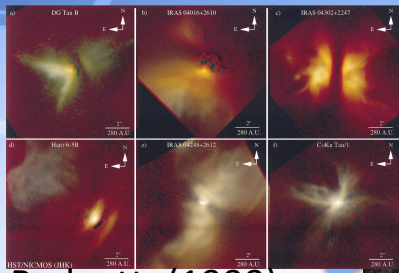
Aikawa+(2012)



0".1
AO Image

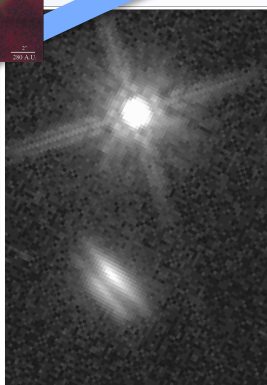


Showcase of Protoplanetary Disks

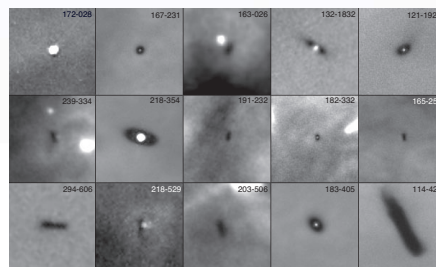


Padgett+(1999)

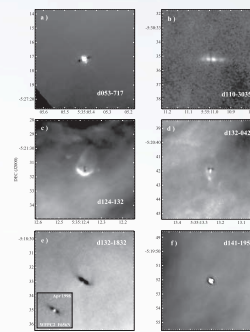
HST Protoplanetary Disks Discovery



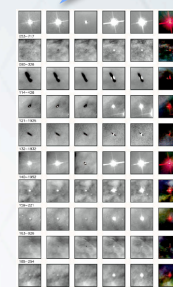
Stapelfeldt+(1998)



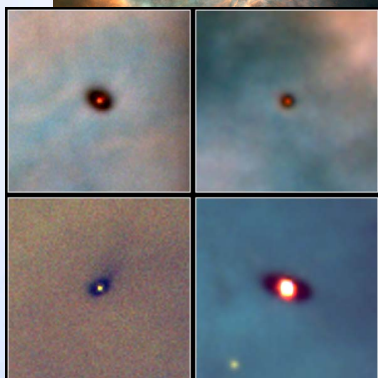
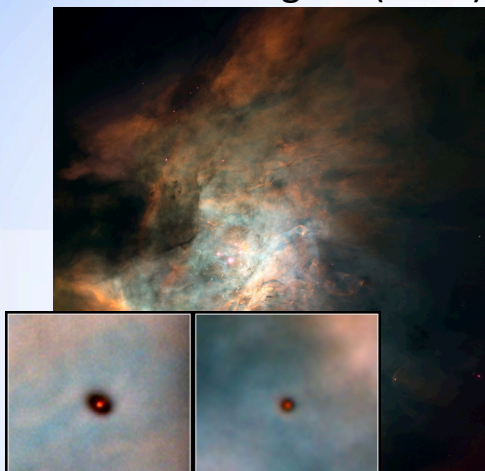
Bally+(2000)



Smith+(2005)

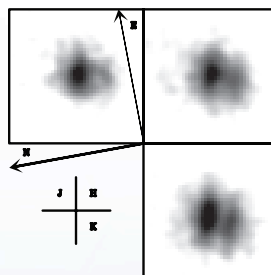


Ricci+(2008)

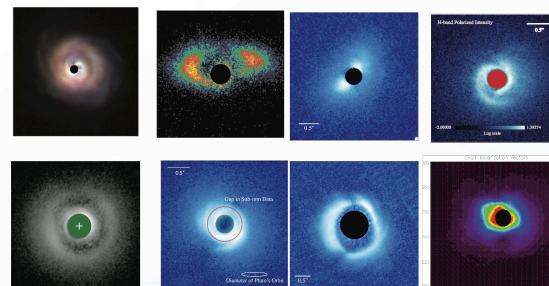


Protoplanetary Disks
Orion Nebula
HST - WFPC2
PRC95-45b - ST ScI OPO - November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

McCaughrean & O'Dell (1995)

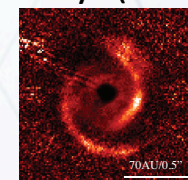


Monin & Bouvier(2000)



Subaru AO188/HiCIAO

Benisty+(2015)



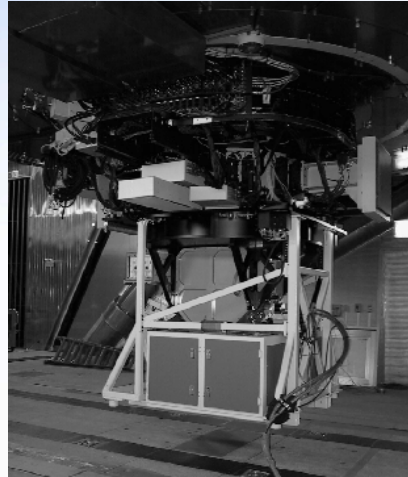
ExAO system
Subaru SCExAO
Gemini-S GPI
VLT Sphere

Ground-based AO

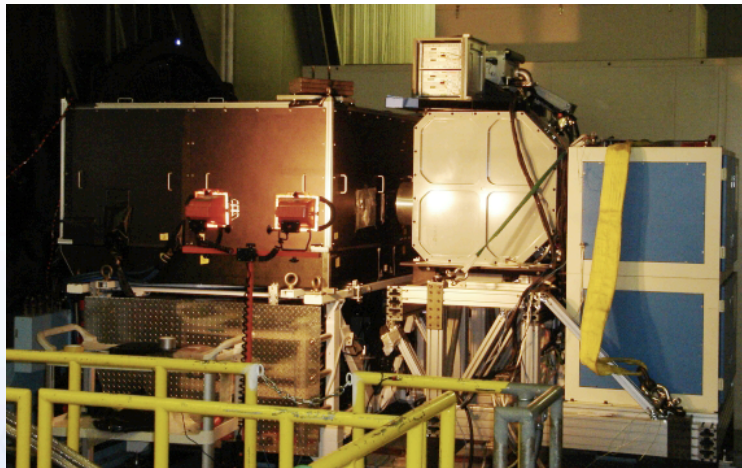
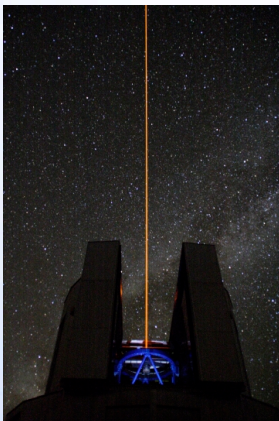
Water Ice in Disks

Subaru IR Observations IRCS+AO36 and AO188

Subaru IRCS / AO36



Subaru IRCS / AO188



◆ IRCS

- ◇ Operates since S00B
- ◇ Coverage: 0.9-5.5 μ m
- ◇ Imaging, Low-R and High-R Spectroscopy
- ◇ *Optimized for diffraction-limited observations w/ AO*

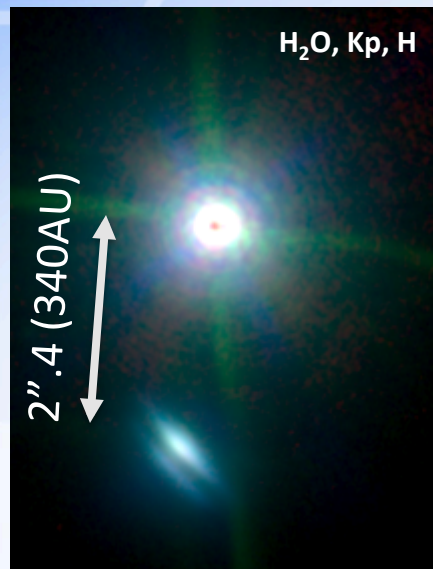
Low-R ($R \sim 500$) L-band
grism spectroscopy
for known disk objects

High Angular Resolution for Ice Detection IN Disks

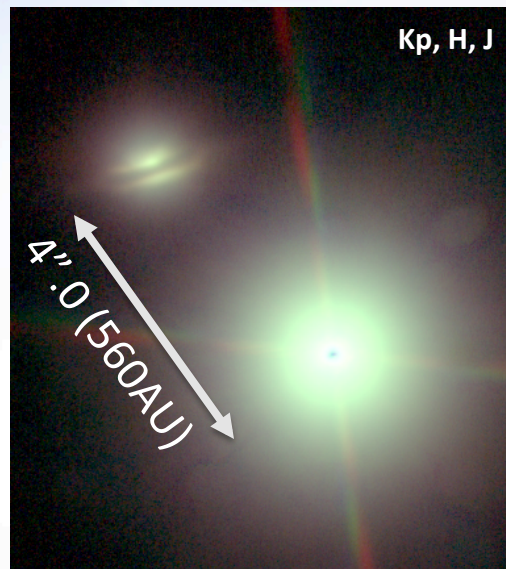
- ◆ Avoid any contamination from nearby (bright) star and/or nebula.
- ◆ (Partially) Distinguish the disk ice from common foreground ices..



Edge-on Disks Low-mass YSOs



HK Tau A, B



HV Tau AB, C

HK Tau B

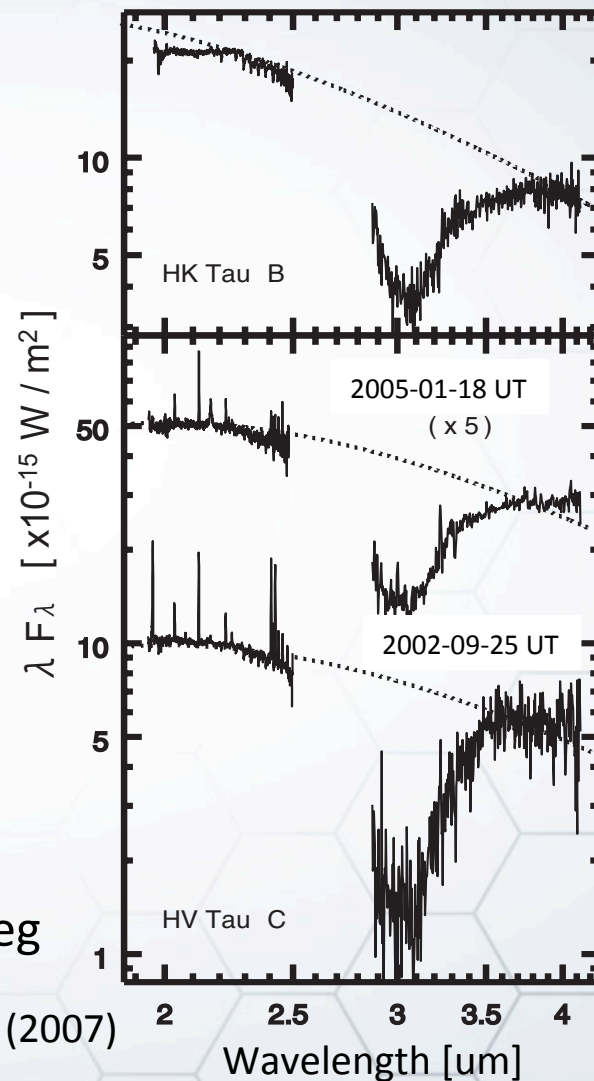
- Class II; M1
- Inclination: $\sim 84^\circ$

HV Tau C

- Class II; K
- Inclination: $\sim 85^\circ$

No significant ice for the primaries

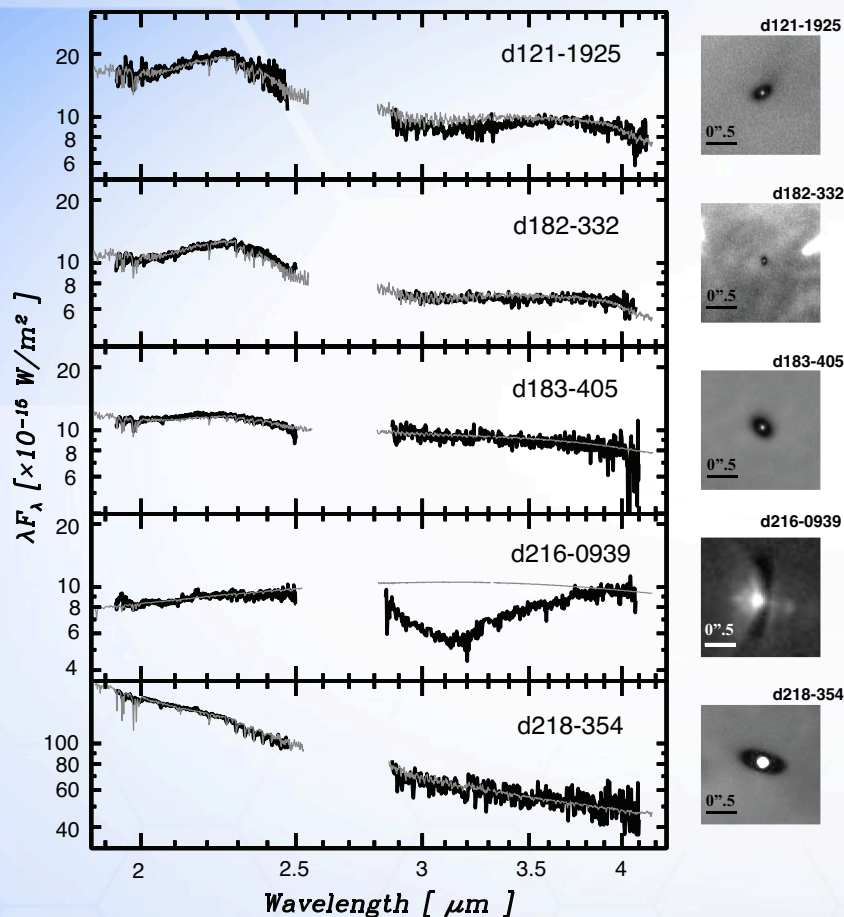
Terada+ (2007)



Orion Silhouette Disks

Low-mass YSOs

Non-AO Spectroscopy

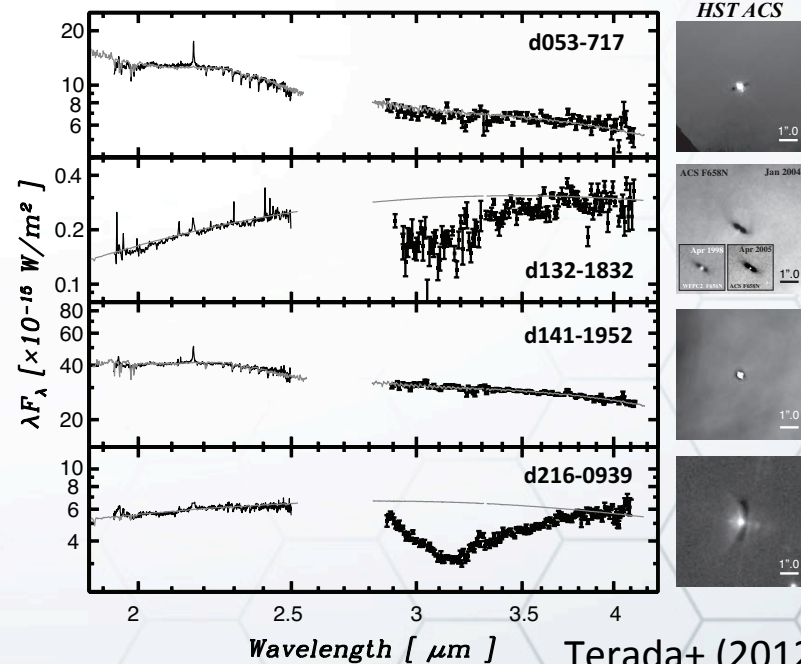


Terada & Tokunaga (2012)

• Silhouette Disks in M42, M43

- ◊ Class II; G6-M5
- ◊ Inclination: 39-80 deg

AO Spectroscopy

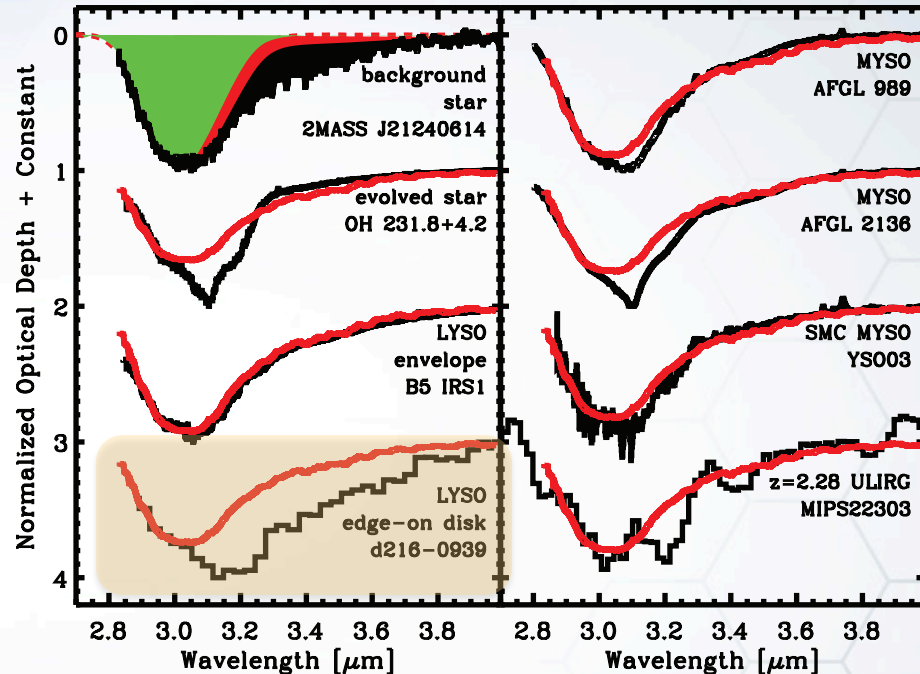
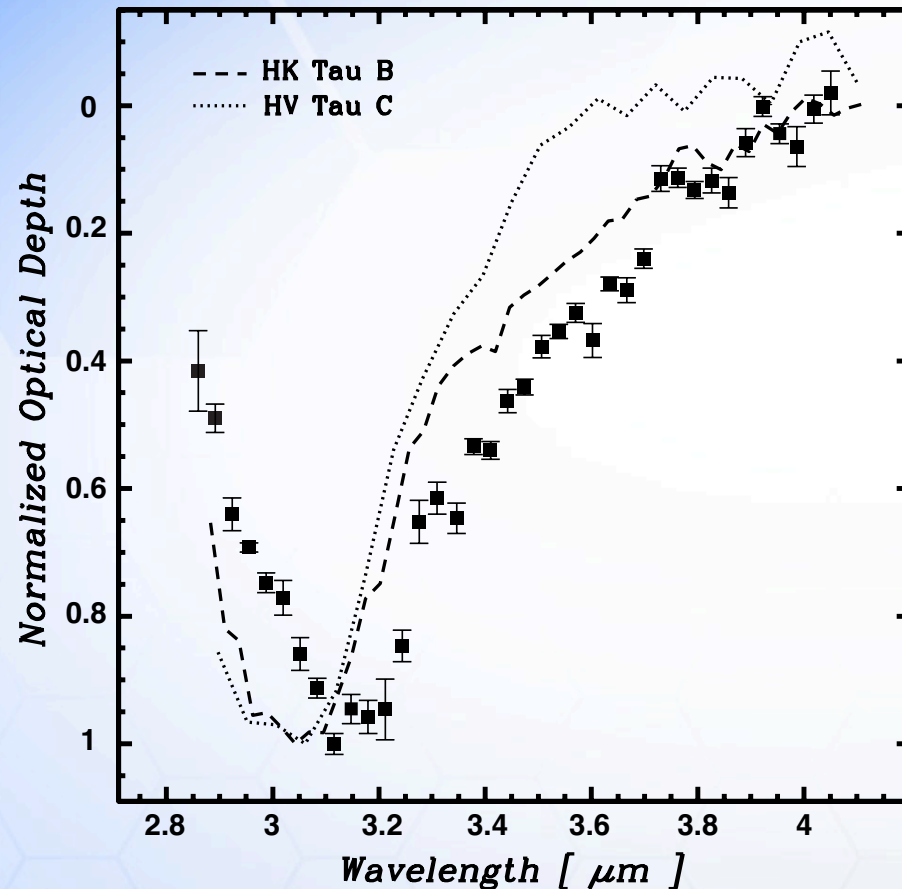


Terada+ (2012)

Orion Silhouette Disks

Unique Ice Feature: d216-0939

Terada & Tokunaga (2012)



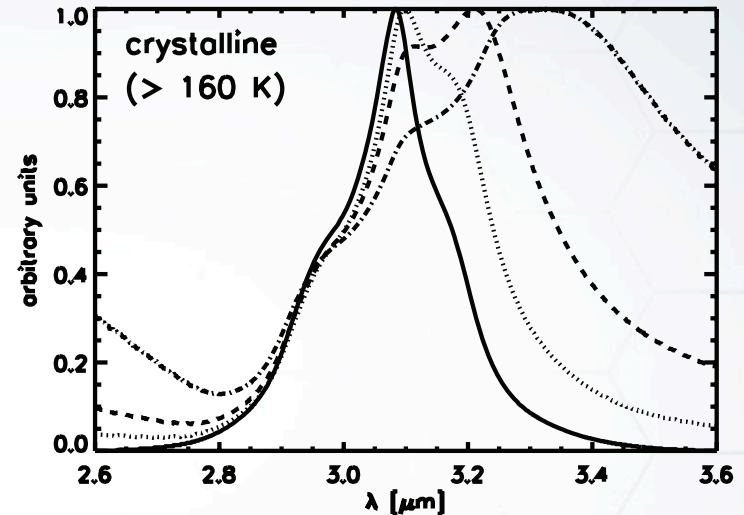
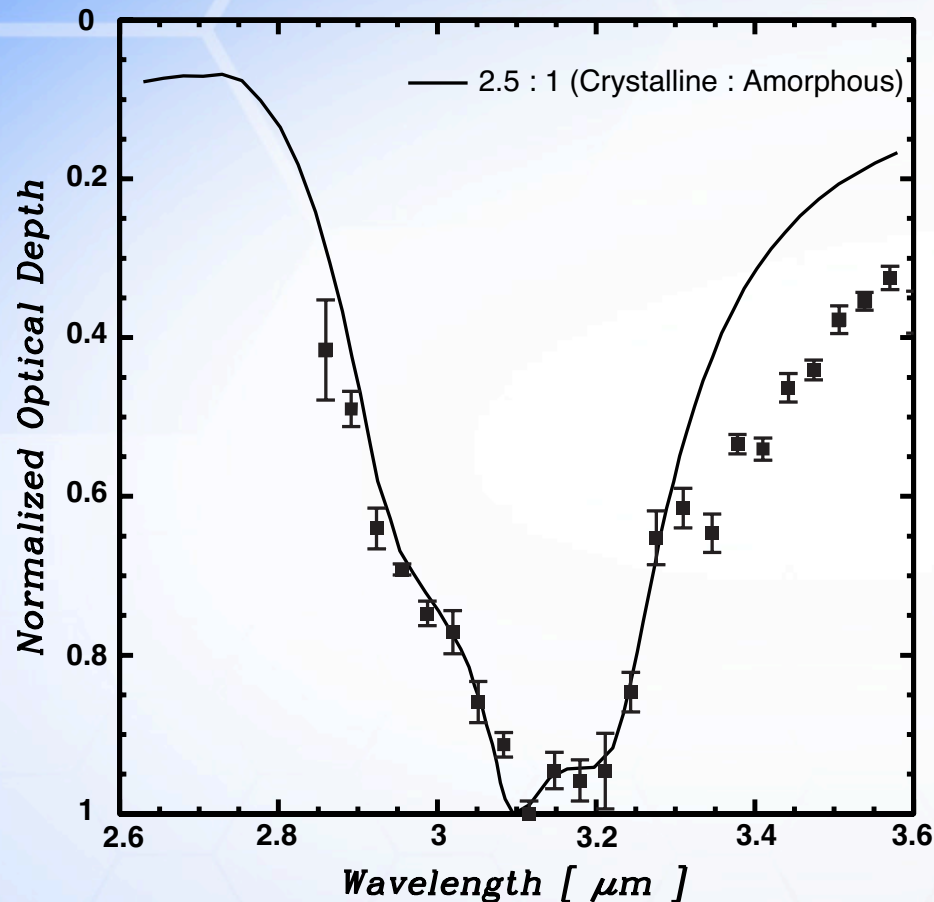
Boogert (2015)

3 μm features are diverse among a wide variety of targets.

However, 3.2 μm enhancement is really unusual

Orion Silhouette Disks

Unique Ice Feature: d216-0939



Scheegerer & Wolf (2010)

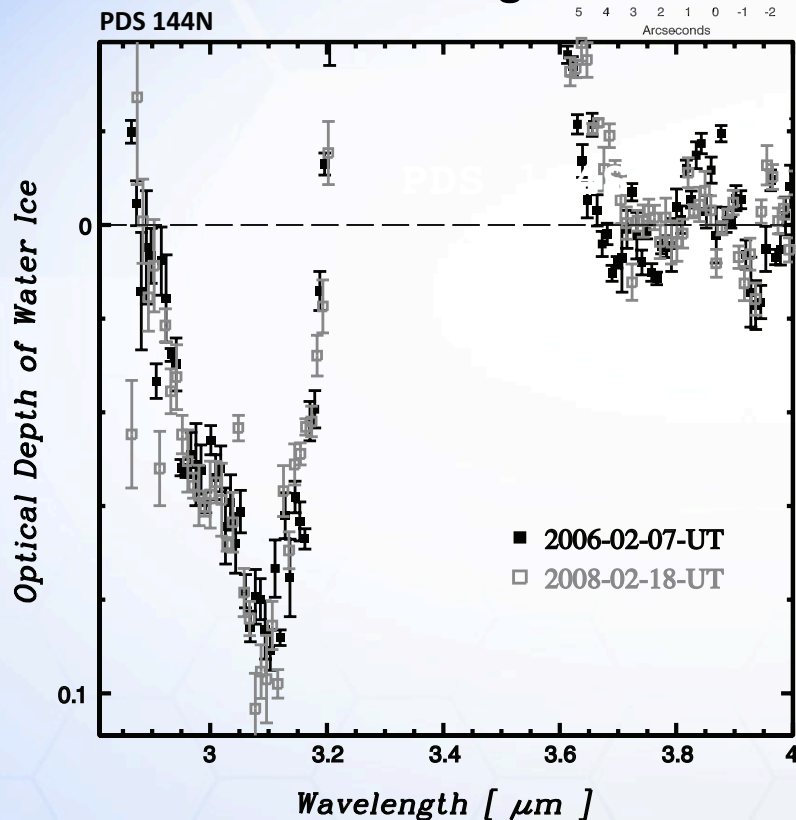
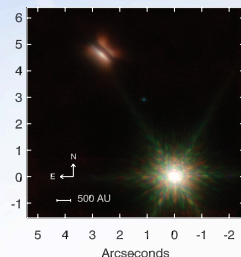
In general, large dust grain could produce longer wavelength peak..

To reproduce the feature, almost fully crystallized water ice and large ($\sim 0.8\mu\text{m}$) grain are required.

Edge-on Disks Intermediate-Mass YSOs

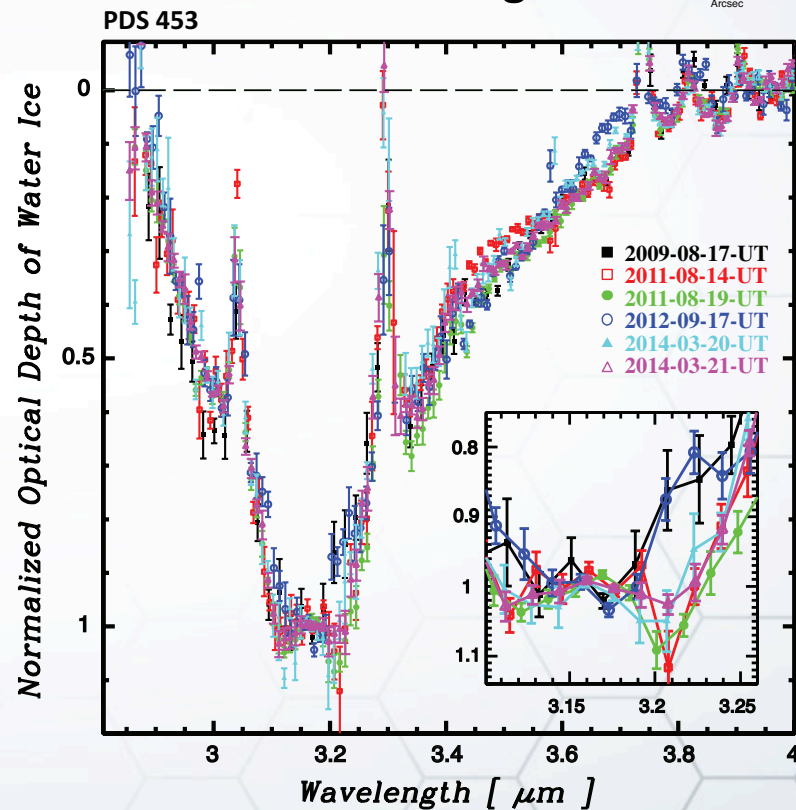
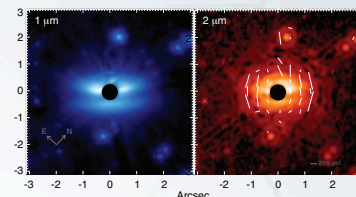
◆ PDS 144N

- A2IV; Herbig Ae
- Inclination: $\sim 83^\circ$



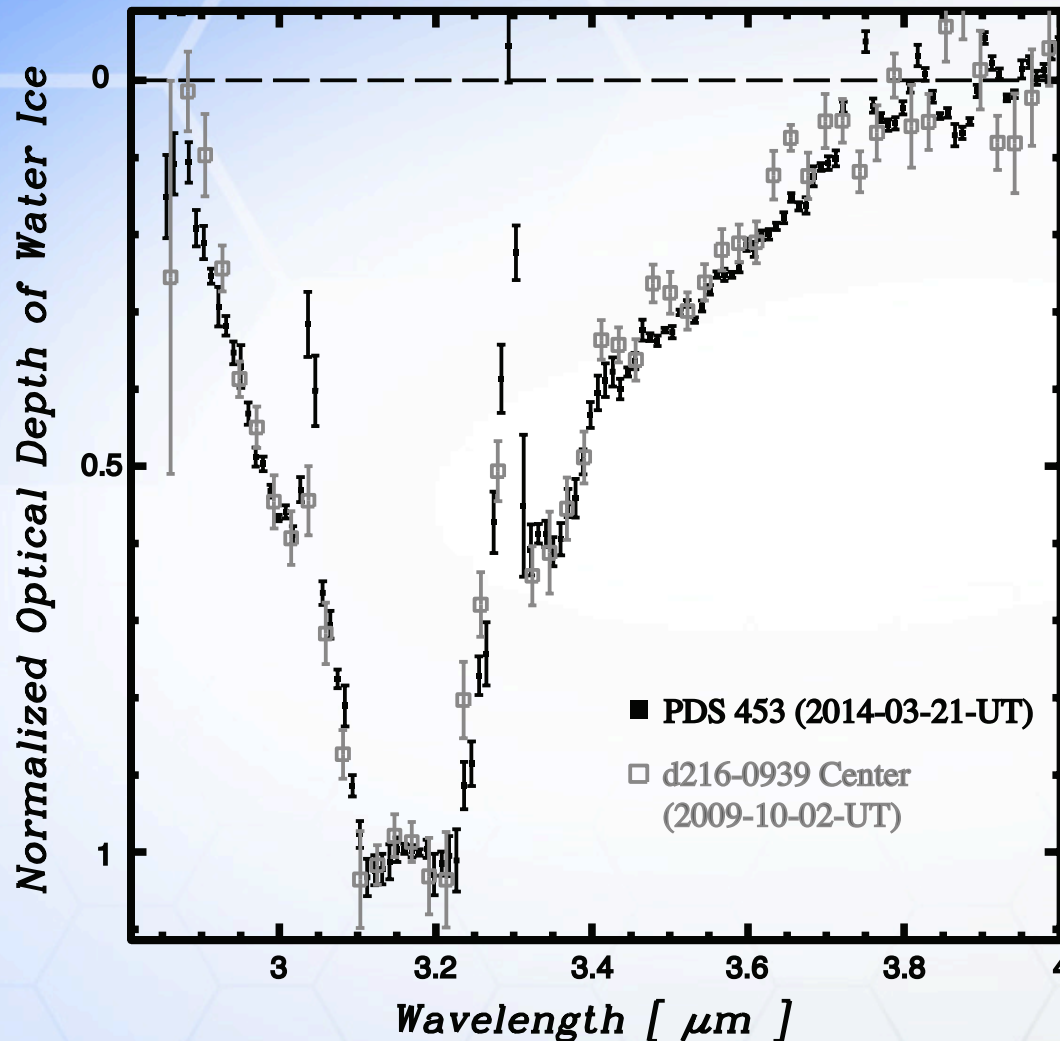
◆ PDS 453

- F2V; Herbig Ae
- Inclination: $\sim 79^\circ$



Terada & Tokunaga (2017)

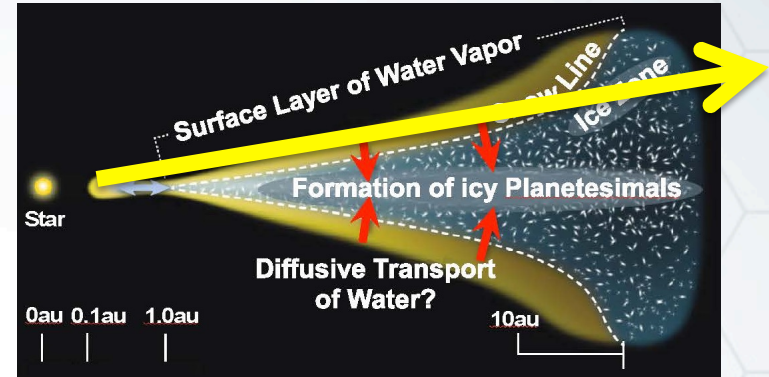
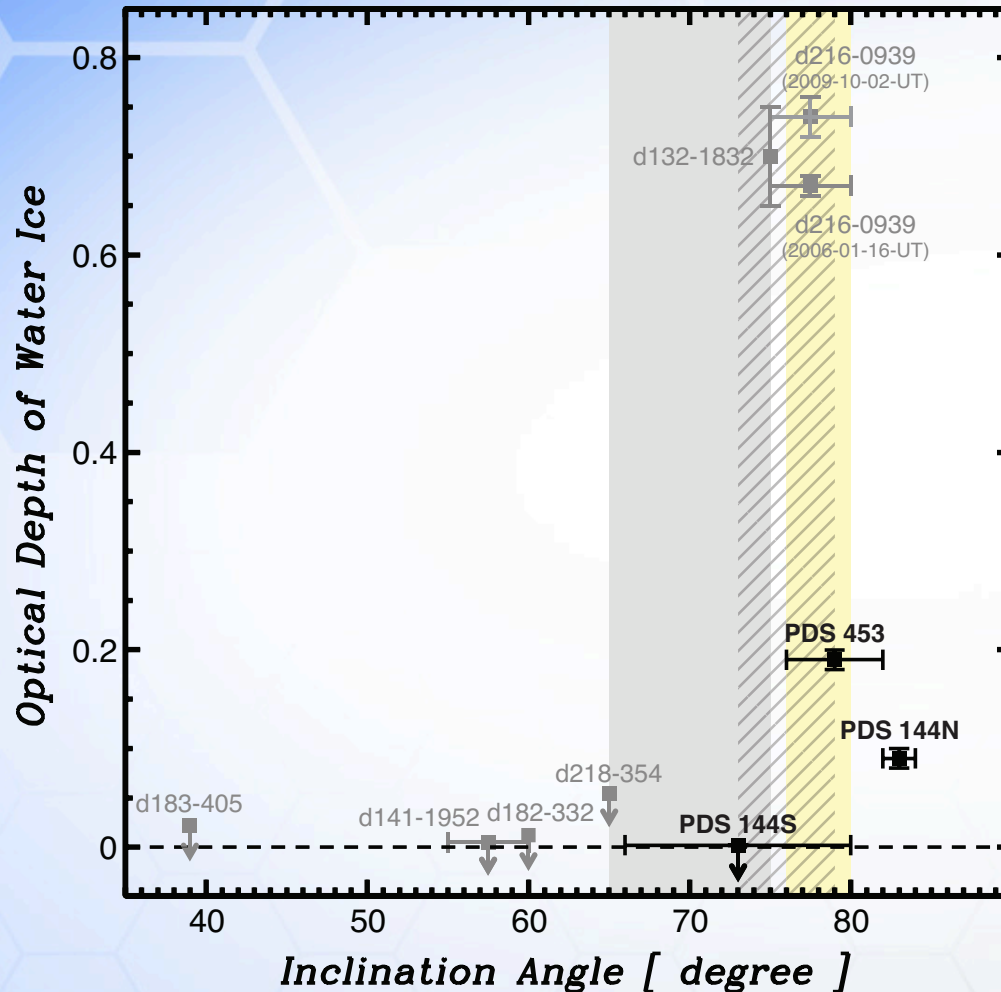
Common “Unique Feature” in d216-0939 and PDS 453



Spec. Type: different..

Both have similar inclination angles around 78deg.

Inclination Angle vs. Water Ice

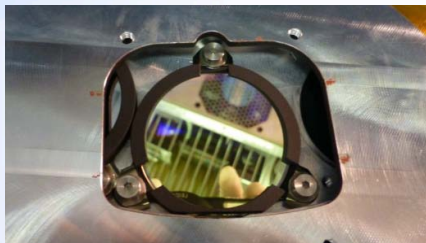


- Disk objects only with $>65^\circ$ show ice absorption (threshold $i \sim 65-75^\circ$).
- Just above the threshold, two objects exhibit the “unique feature”, which is supposed to come from the surface of the water ice region.

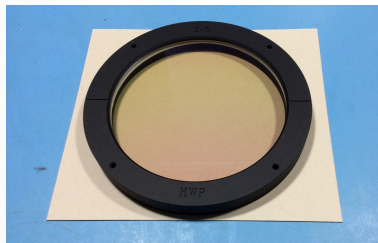
New Observational Approach: Spectro-Polarimetry

PDS 453 (2016-06-21-UT)

- Newly commissioned for IRCS+AO188 (*open from S18A!*)
 - ◊ 2-5 μ m Imaging + Spectro-polarimetry

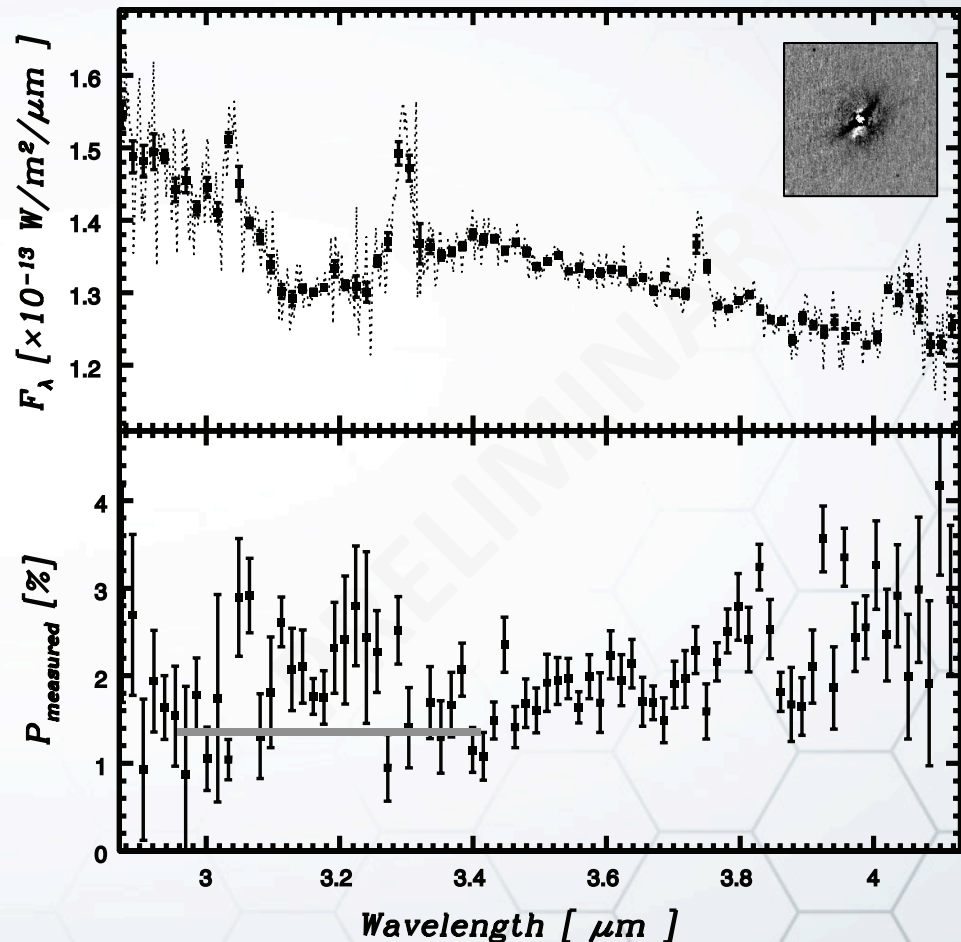


Wollaston prism (0.9-5 μ m)



Half-wave plate (2-5 μ m)

*Not only for dust grain property,
also for better detection of
“Face-on” scattered light..*



Summary

- High angular resolution 2-4 μ m spectroscopy has been conducted for protoplanetary disks using Subaru IRCS in conjunction with the adaptive optics systems.
- Critical inclination angle of protoplanetary disks is 65-75deg. Higher-mass stars may have larger angle.
- Inclination angle around 77-78deg seems special to exhibit the unique water ice absorption feature which can be attributed to highly crystallized ice with larger grain ($\sim 0.8\mu$ m).