近赤外線分光撮像観測による Wolf-Rayet 星探索：概要と減光量の推定

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Wolf-Rayet 星とは？

"Conti scenario" cf. Conti 1976, Crowther 2007, Smartt 2009

mass, age, binarity, metallicity, rotation

$M_{initial}$	MS	post-MS	SN/remnant
		→	IIn
$>80M_\odot$	O3	→ WNH → LBV → WN → WC/WO →	Ic/BH(GRB)
$40\text{-}80M_\odot$	O5-4	→ LBV → WN → WC/WO →	Ic/BH
$25\text{-}40M_\odot$	O7-6	→ LBV → WN →	Ib/BH
		→ (binary) →	IIb/NS
$8\text{-}25M_\odot$	B1-O8	→ RSG →	IIP/NS

Wolf-Rayet 星の重要性

▷ Limited (short) life time of ~ $5x10^5$ yr (~10% of total life time)

... Clue to Age & Initial Mass Function

▶ Cluster of WR/LBV/RSG/YHG/OB

... Good tracer of massive-star formation in massive star clusters
(WR/O, WC/WN, LBV, YHG, ...)

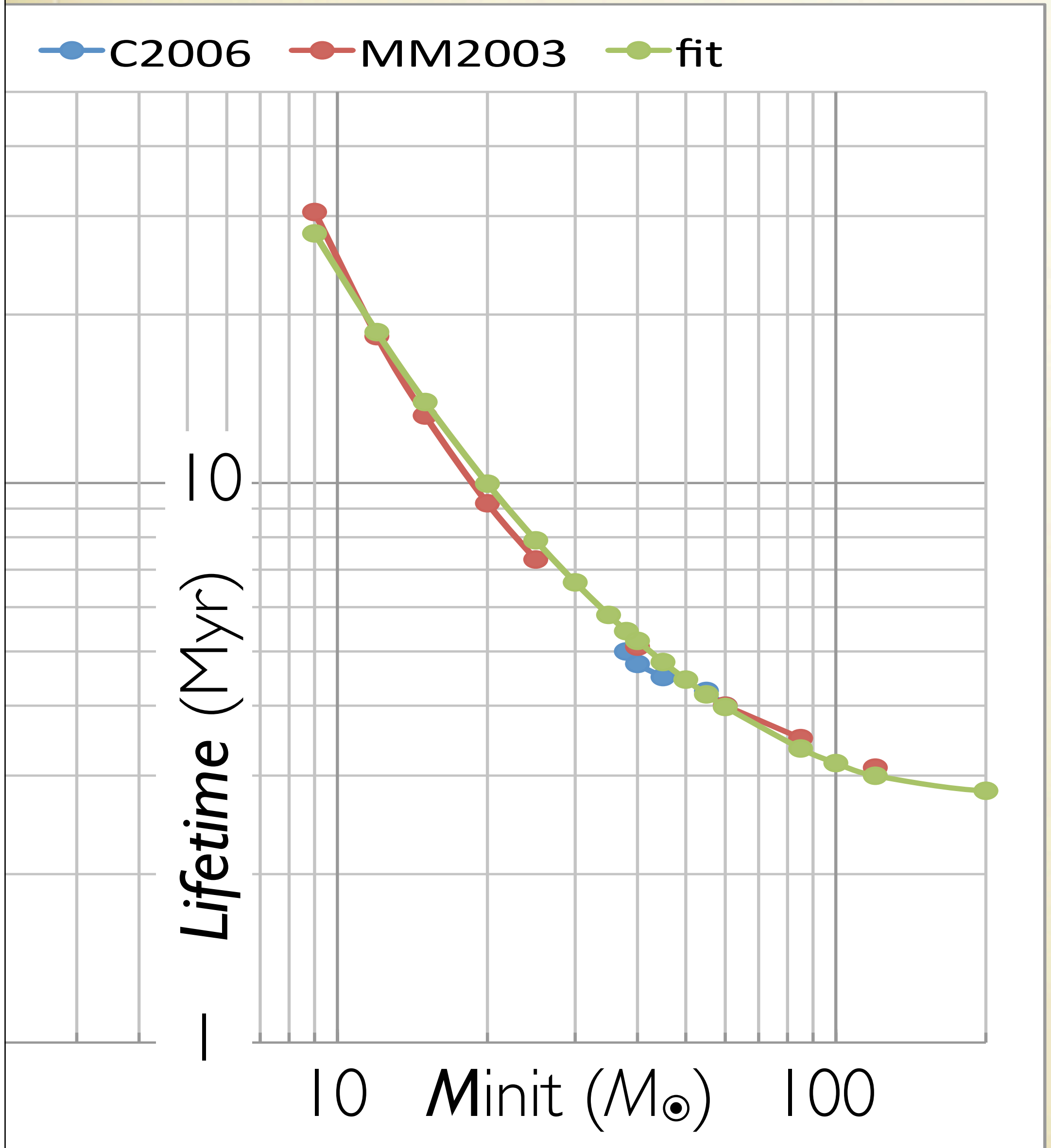
▶ Isolated WR stars ... where were they formed?

▷ Mass Loss with strong stellar wind (>10^{-5} $M_{\odot}$/yr)

... Evolution of massive stars

In spite of ~6000 expected number of WR,
only ~500 WR have ever discovered in our Galaxy

Lifetime of Massive Stars



Lifetime [H-b + He-b(~10%)]

cf. Crowther+ 2006; Meynet & Maeder 2003

9 $M_\odot$	30.5 Myr
25 $M_\odot$	7.3 Myr
40 $M_\odot$	5.1 Myr
60 $M_\odot$	4.0 Myr
85 $M_\odot$	3.5 Myr
120 $M_\odot$	3.1 Myr

fit: $\log(t/\mathrm{Myr})=0.55\{\log(M/M_\odot)-2.3\}^2+0.45$

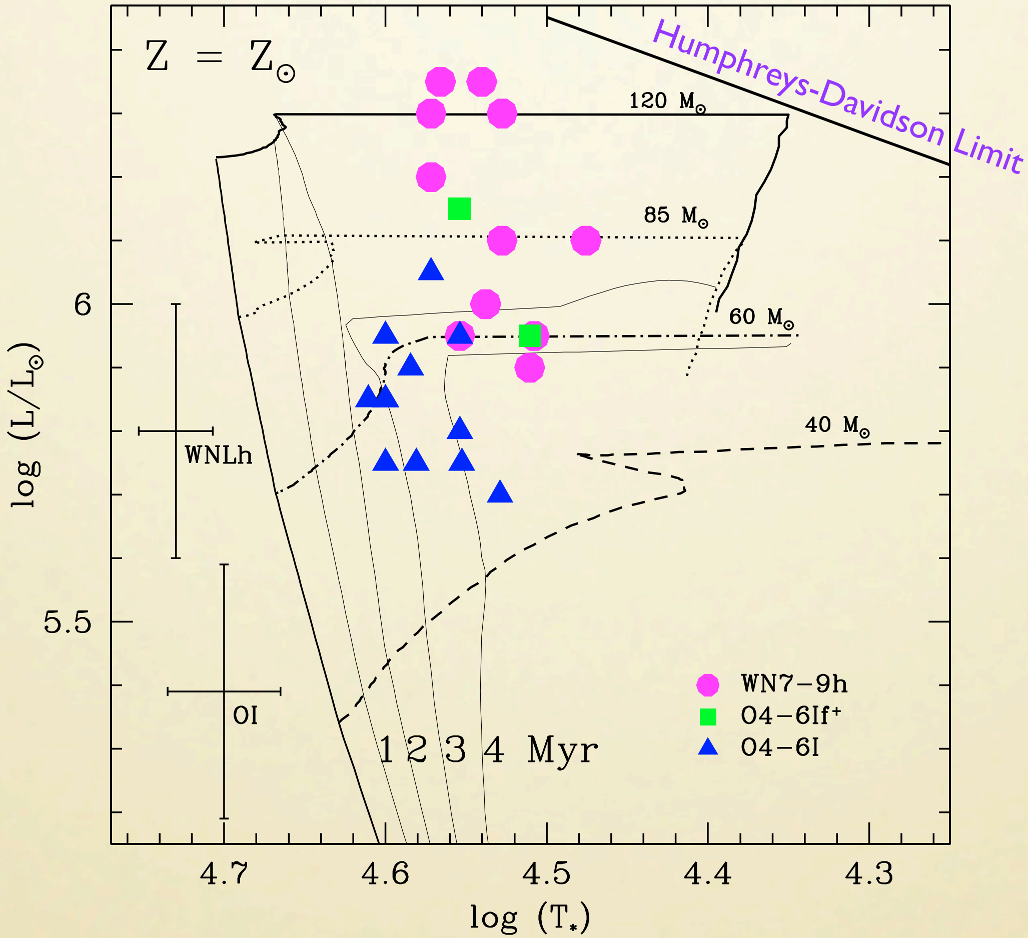
WR	~0.4 Myr
LBV	~0.01 Myr ?

Cluster Age	LBV/WR/YHG/RS
< 2.5 Myr	all stars remain in main-seq
2.5-3.5 Myr	super-massive stars evolve into LBV/WR
3.5-5 Myr	40~60 $M_\odot$ stars evolve into LBV/WR
> 5 Myr	all LBV/WRs have become SN YHG/RSGs appear

Evolution of Massive Stars

Arches cluster

Martins+ 2006; Meynet&Meader 2005



WR星探索の手法 (2000年以降；赤外線)

[1] 2MASS & Spitzer/GLIMPSE

cf. Mauerhan, Dyk, Morris 2011,AJ,142,40

☆ strong free-free emission in NIR-MIR (WN & WC)

☆ dust thermal emission in MIR (WCLd)

★ color-color: J-H vs H-Ks, J-Ks vs Ks-[8.0], [3.6]-[4.5] vs [3.6]-[8.0]

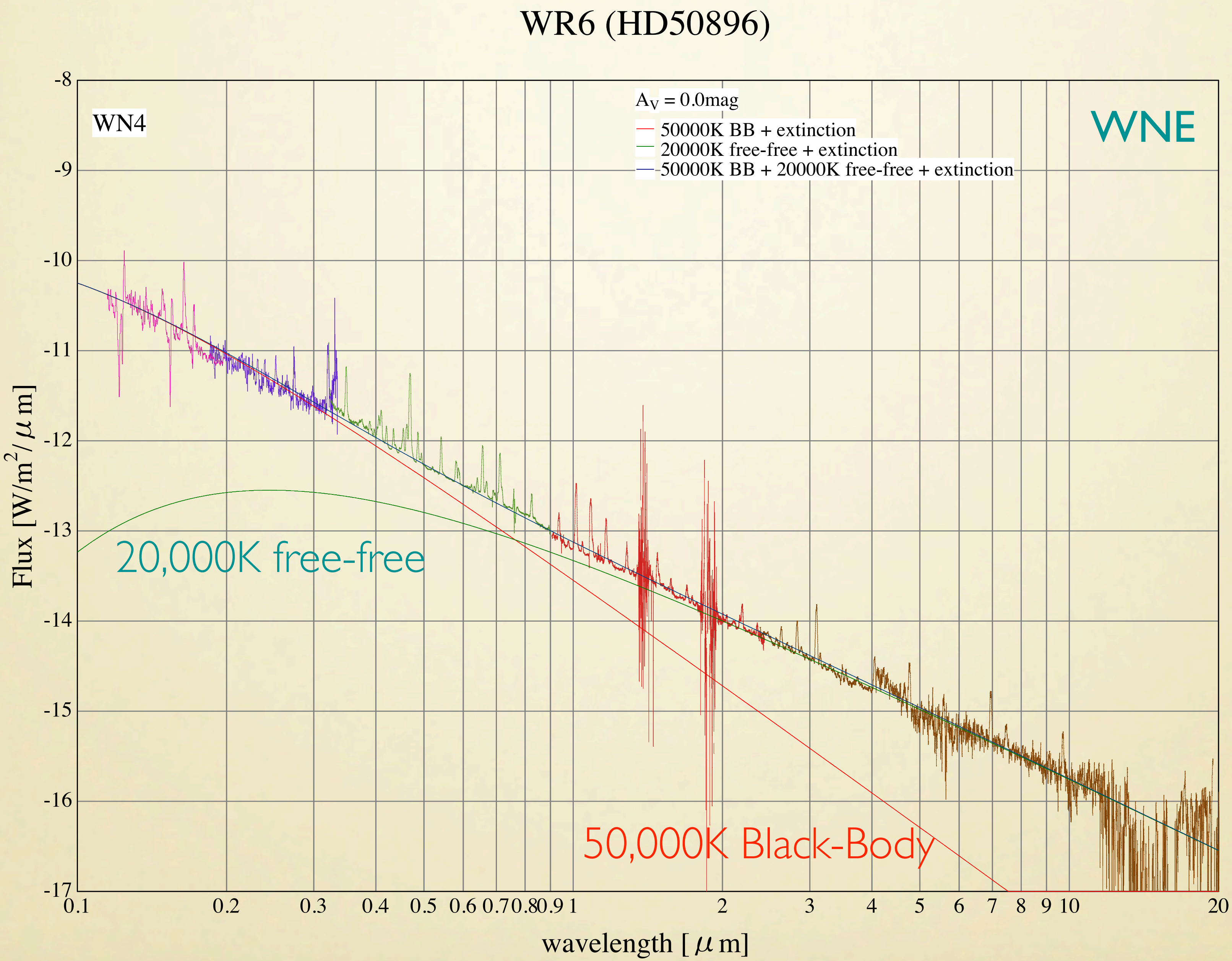
color-mag: Ks vs J-Ks --> "redder"

rate: ~50% ?

merit: no need of survey obs ..... J,H,Ks(2MASS), [3.6],[4.5],[5.8],[8.0](GLIMPSE)

demerit: the stellar spectra of this wavelength are R-J, so not-easy to distinguish
affected by extinction (especially J)
confusion in crowded area (Spitzer)
not distinguishable from Be stars
scattered by strong emission line components (especially CIV/CIII in Ks)

UV-Vis-NIR-MIR Spectrum



[2] NIR-NBF(CIV, HeII, ...)

cf. Shara+ 2011,arXiv,1106,21965; 2009,AJ,138,402

☆ strong line (HeII, CIV, ...) emission in NIR (WN & WC)

★ 6 [NBF] (K) system: [cont-1],[HeI],[CIV],[Br γ],[HeII],[cont-2] ... not simple!

rate: ~100% ?

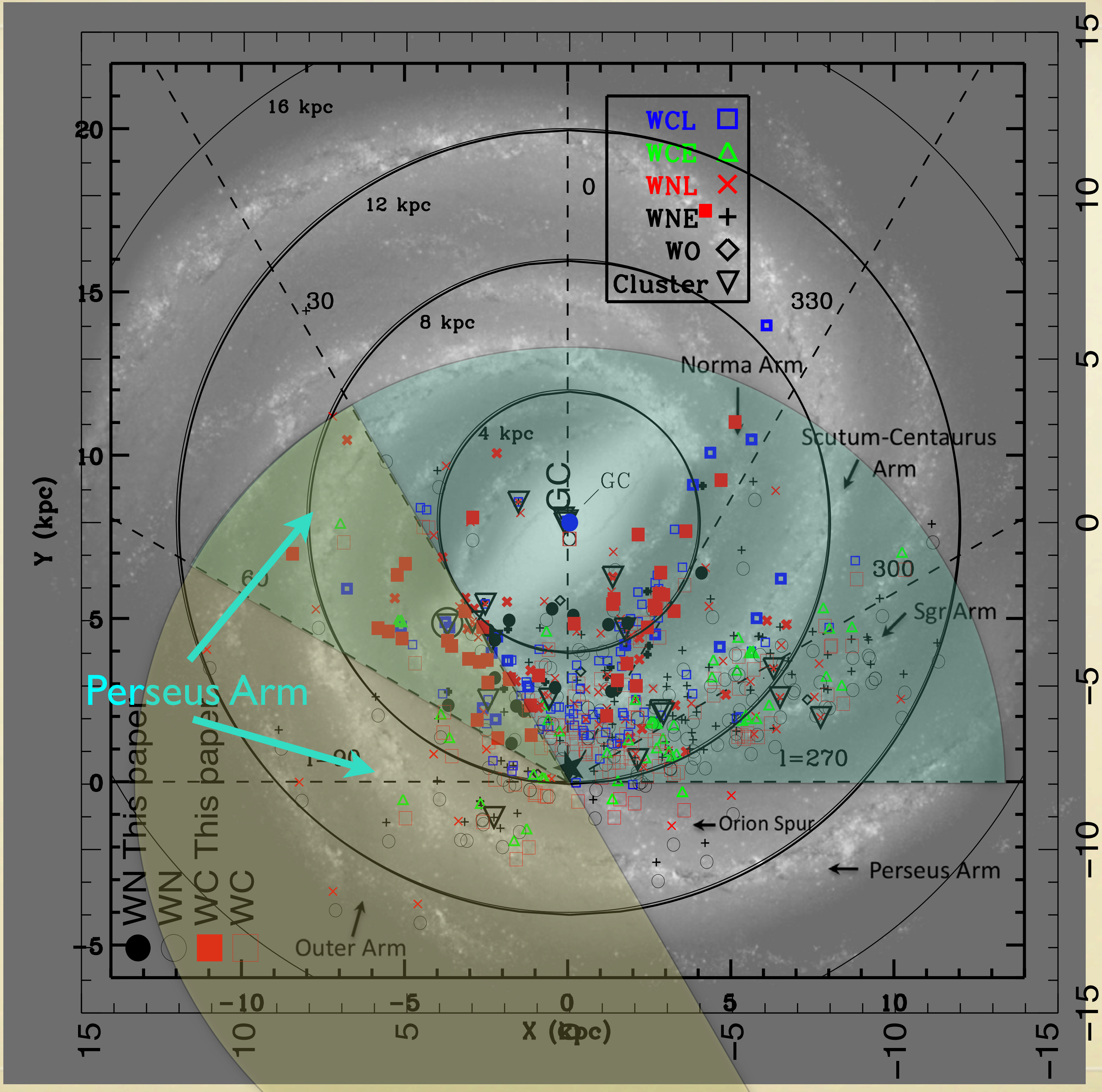
Our choice !

★ 2 [NBF: CIV, HeII] + 1 [BBF: Ks] system ... so simple & effective !

larger [CIV]/[Ks] for WCE, larger [HeII]/[Ks] for WN & WC
A_{Ks} from [NBF]/[Ks]

merit: almost 100% rate ... completeness
capable of not only picking candidates up, but also finding extinction
demerit: need to make NBF and make imaging (survey) observations

Shara+ 2011



Mauerhan, Dyk,Morris 2011

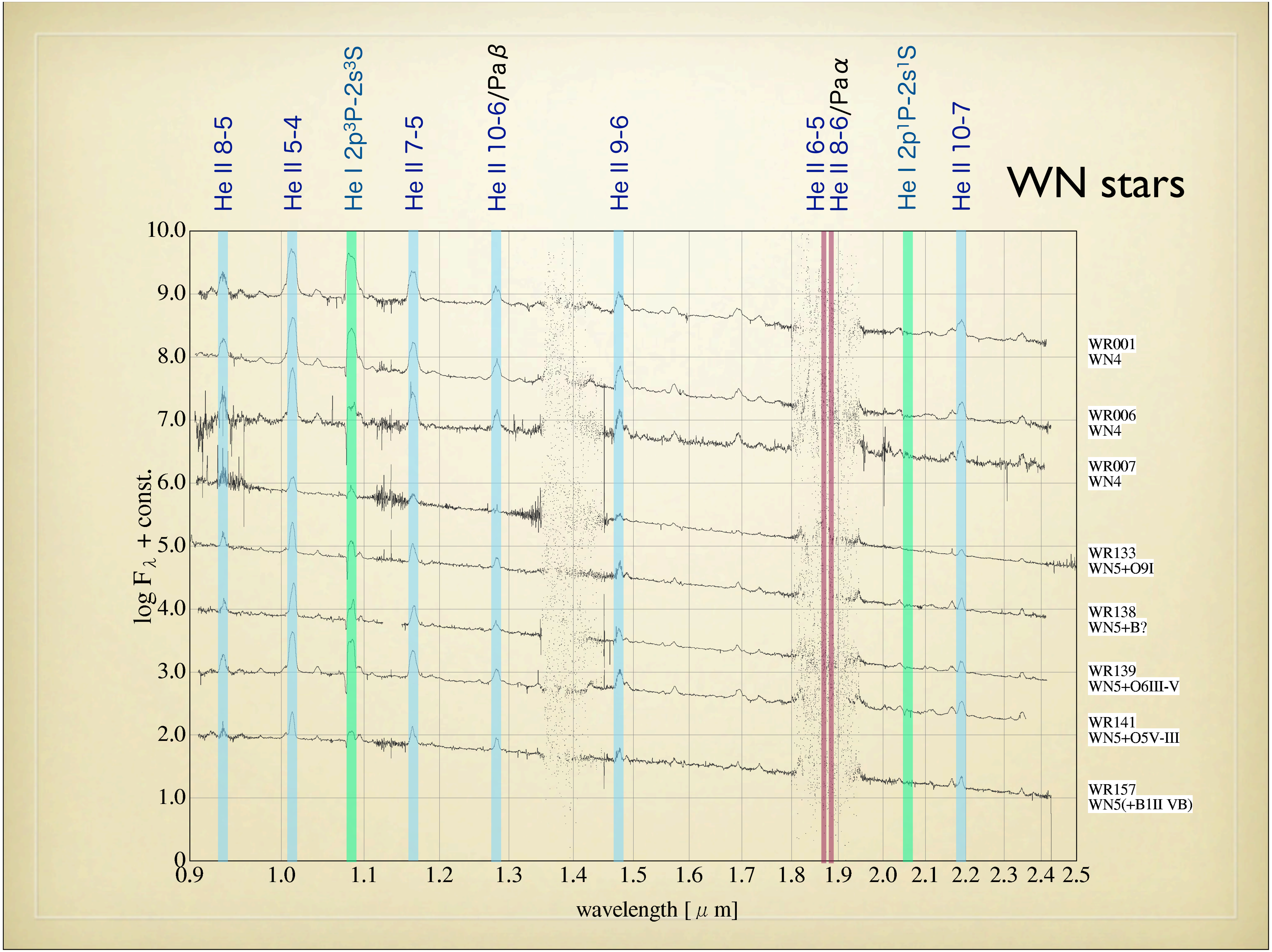
Figure 10. Galactic distribution of WRs and selected WR-bearing clusters plotted over the Galactic model of Churchwell et al. (2009). New identifications are marked

NBF 選択の指針

我々の方針
まずは減光の大きい領域(クラスター)を深く探す
さらに、方法を確立した上で、領域を広げていく

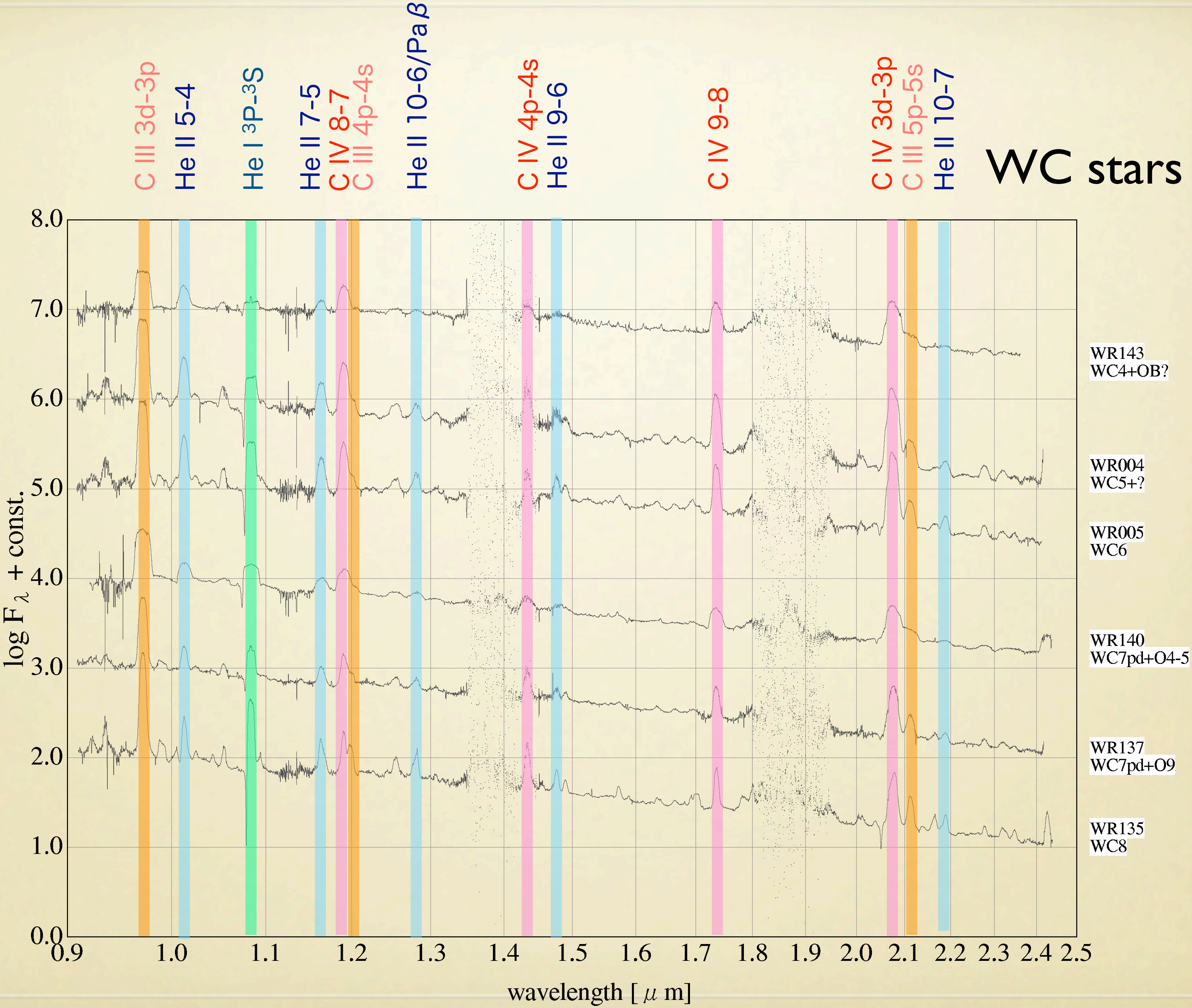
WR(WN,WC), LBVの探索
---減光の大きい領域で探索したい---
観測の効率を上げるための最小限フィルターセットの設定

▶ 減光に有利な~2μmでの有効な輝線は？
--> CIV(2078);HeII10-7(2189);HeII8-6(1875@only Atacama)
▶ NBFでラインの強度測定（通常はON/OFF２枚セット）
--> ONのみ；OFFはKs(BBF)使用
▶ 減光量の推定（通常はJ,H,Ksのカラーより A_{Ks}）
--> N207/Ksから A_{Ks} 推定



WN stars
He II 8-5
He II 5-4
He I 2p3P-2s3S
He II 7-5
He II 10-6/Paβ
He II 9-6
He II 6-5
He II 8-6/Paα
He I 2p1P-2s1S
He II 10-7
log F λ + const.
wavelength [μ m]
WR001
WN4
WR006
WN4
WR007
WN4
WR133
WN5+O9I
WR138
WN5+B?
WR139
WN5+O6III-V
WR141
WN5+O5V-III
WR157
WN5(+B1II VB)

WC stars



C III 3d-3p
He II 5-4
He I 3P-3S
He II 7-5
C IV 8-7
C III 4p-4s
He II 10-6/Paβ
C IV 4p-4s
He II 9-6
C IV 9-8
C IV 3d-3p
C III 5p-5s
He II 10-7
log F λ + const.
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
wavelength [μ m]
WR143
WC4+OB?
WR004
WC5+?
WR005
WC6
WR140
WC7pd+O4-5
WR137
WC7pd+O9
WR135
WC8

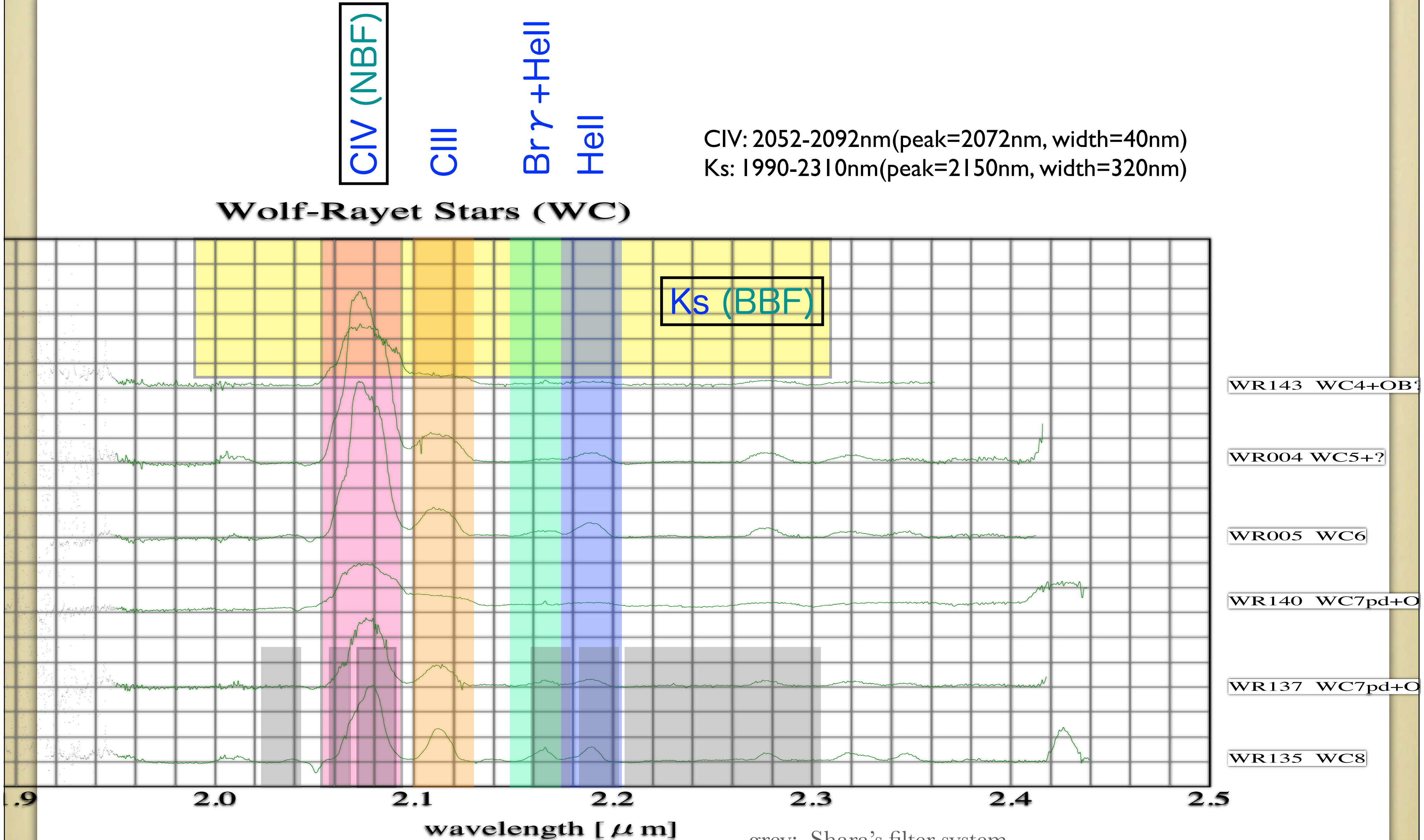
Key Line Emission

for Selective Detection of Various kinds of Massive Stars

star	absolute K-mag	SN type	Ks cont	1.83 2.17 Paα Brγ	2.19 2.06 HeII HeI	2.11 2.08 CIII CIV
WC	-4 ~ -6	Ic	○	×	○	◎
WN	-5 ~ -6	Ib	○	×	○	×
LBV/WNh	-6	(II?)	○	◎	× ○	×
RSG/YHG	-9 ~ -10	?	○	×/(○)	×	×
O	-4 ~ -6	-	○	△	×	×
MYSO	?	-	○	○	×	×

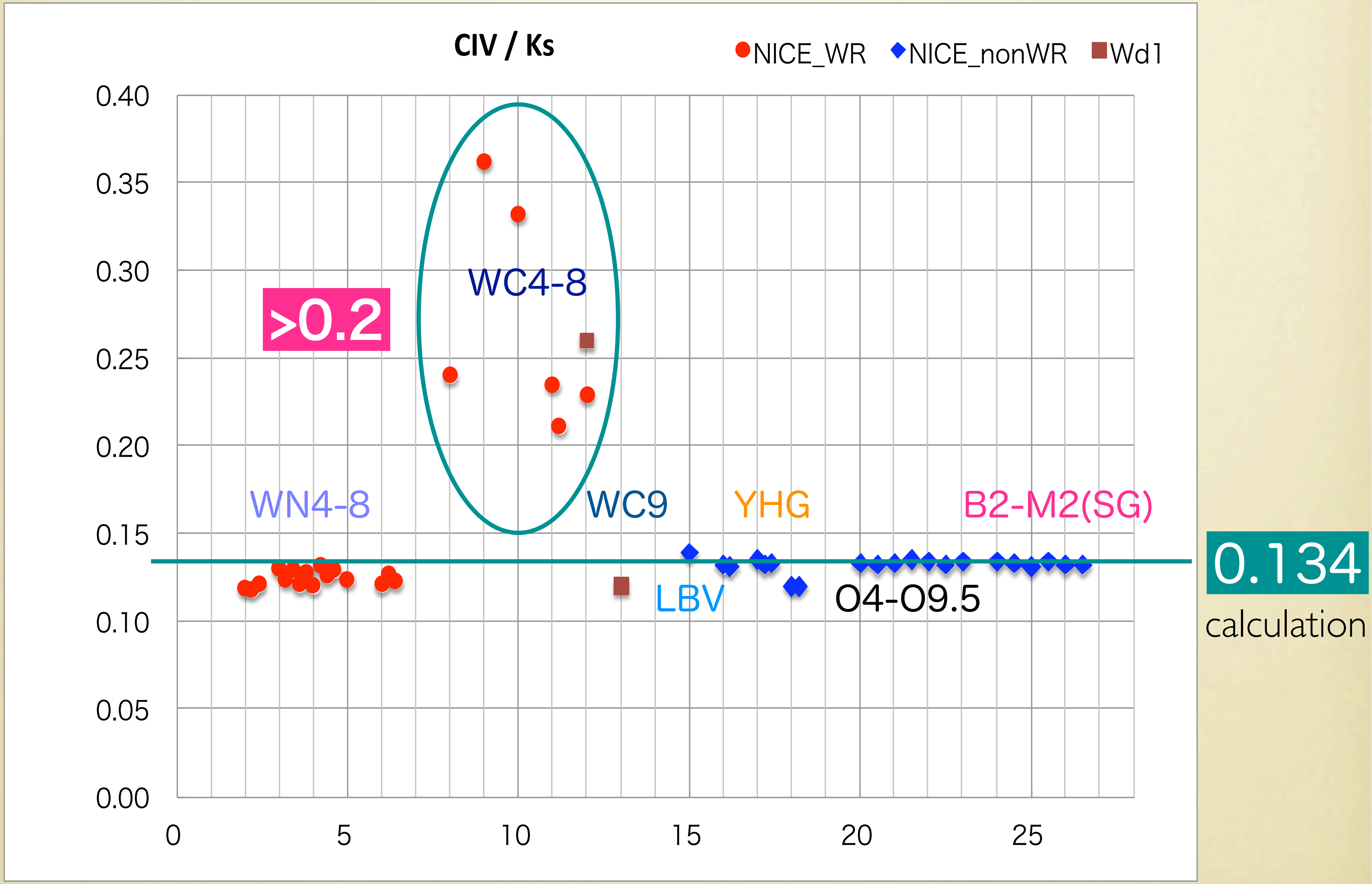
Details of Narrow-Band-Filter

CIV: 2052-2092nm(peak=2072nm, width=40nm)
Ks: 1990-2310nm(peak=2150nm, width=320nm)



grey: Shara's filter system

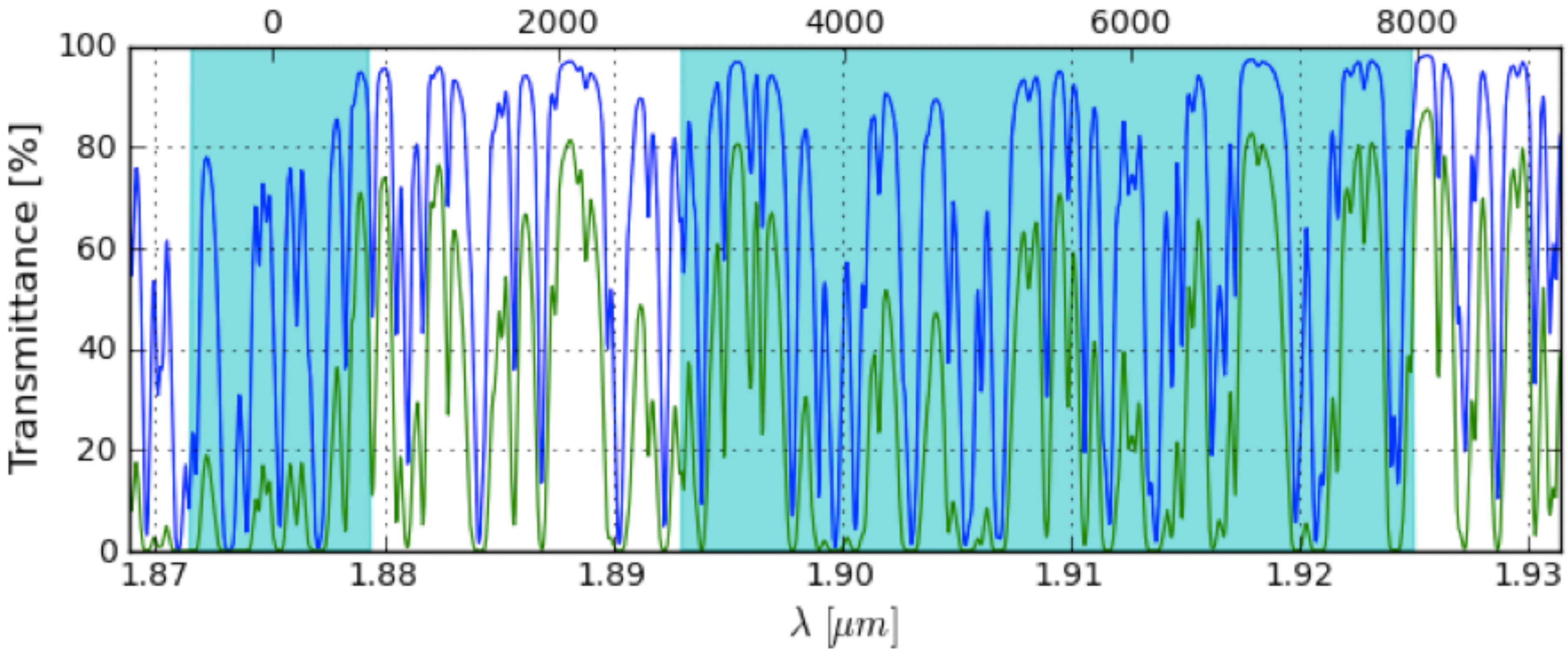
Simulation with NICE spectra



Paα Filter of ANIR

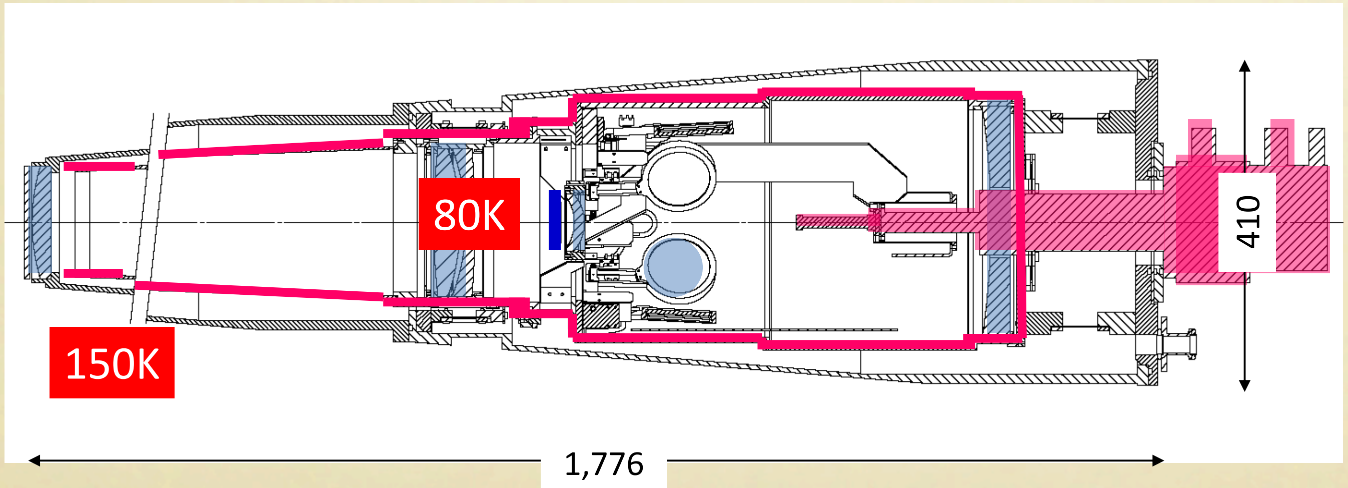
N207: 2052-2092nm(peak=2072nm, width=40nm)
Ks: 1990-2310nm(peak=2150nm, width=320nm)
N187: 1871-1879nm(peak=1875nm, width=8nm)

simulation: blue @ 5640m, green @ 2600m
filter measurement: @ 77K

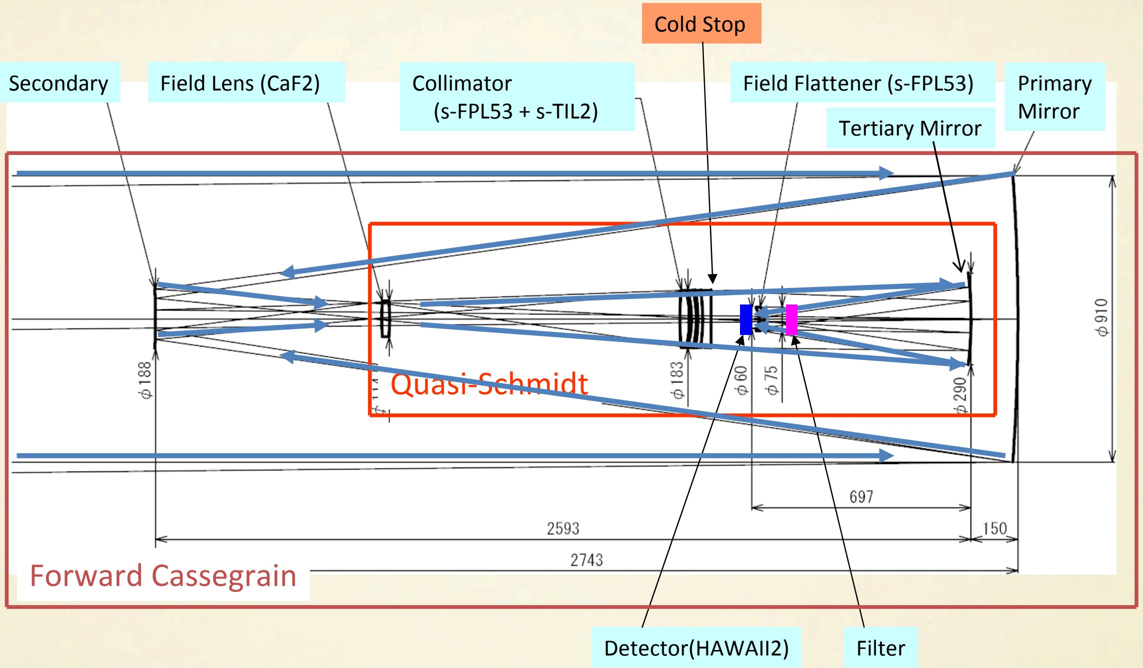


OAOWFC by Yanagisawa (2011UM)

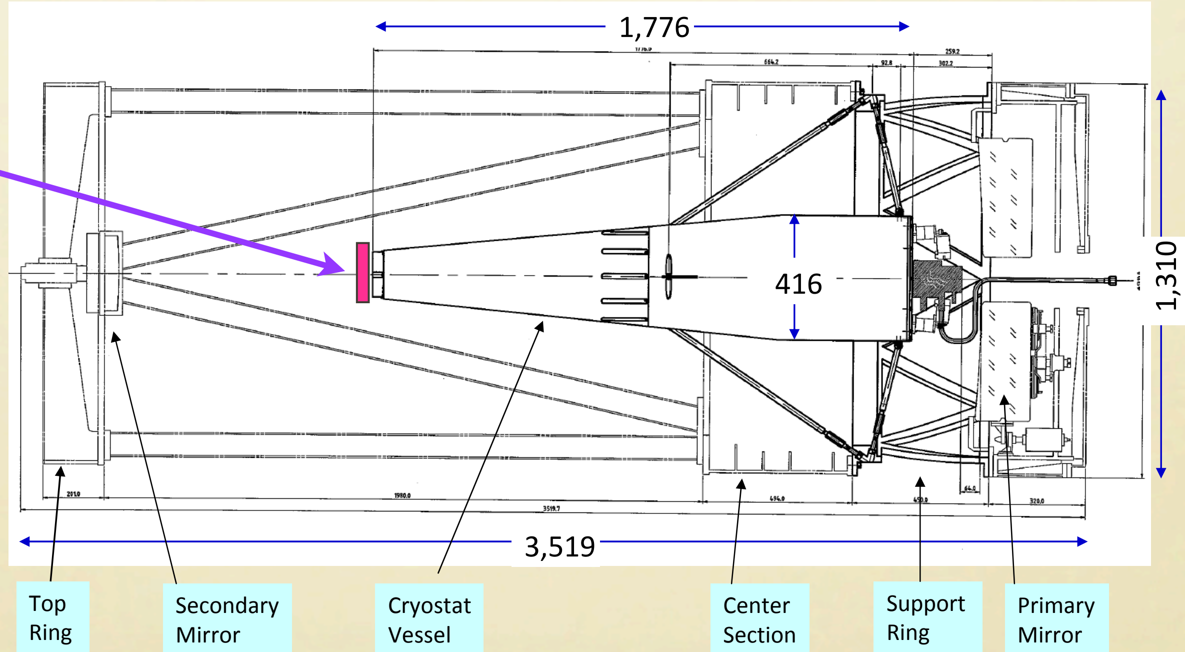
W = 120 kg



6-Φ85 filters
exchange mechanism



N209/N218
Φ125(Φ112 eff)
thick10 filters
(無水石英) @RT



結局、以下の各３枚 [2NBF(CIV&HeII)+1BBF(Ks)] セット

アタカマminiTAO+ANIR

N207(CIV2078), N187(HeII8-6+Paα 1875), Ks

ぐんまGIRCS

N207(CIV2078), N219(HeII10-7 2189), Ks

岡山OAOWFC(計画中)

N209(CIV2078/CIII2108), N218(HeII10-7 2189/Brγ2166), Ks

N187(HeII8-6+Paα 1875)については次の奥村講演参照

岡山OAOWFCについては次の次の高橋講演参照

Extinction Law

Nishiyama+ 2006; 2008

mean effective wavelengths: J=1.25, H=1.64, Ks=2.14 micron

The power-law approximation for 1.2-2.2 micron is excellent !

$A_V : A_J : A_H : A_{Ks} = 1.000 : 0.188 : 0.108 : 0.062$ > $A_{Ks}/A_V \sim 1/16$!

The Wavelength Dependence of the Interstellar Extinction

Ratio of Extinctions	IRSF	vdH[a]	RL85[b]	CCM89[c]	He[d,e]	Indebetouw[d,f]
A_{K_s}/E_{H-K_s}	1.44 ± 0.01	1.58	...	1.83	...	1.82
A_K/E_{H-K}	...	1.33	1.78	1.63	1.68	...
A_{K_s}/E_{J-K_s}	0.494 ± 0.006	0.55	...	0.73	...	0.67
A_K/E_{J-K}	...	0.49	0.66	0.68	0.63	...
A_H/E_{J-H}	1.42 ± 0.02	1.38	1.64	1.88	1.61	1.63
A_H/A_J	0.573 ± 0.009	0.58	0.62	0.65	0.62	0.62
A_{K_s}/A_J	0.331 ± 0.004	0.36	...	0.42	...	0.40
A_K/A_J	...	0.33	0.40	0.40	0.39	...
α	1.99 ± 0.02	1.80	1.54	1.61	1.73	1.65

[a] Calculated from the theoretical curve; van de Hulst (1946).
[b] Observations toward the GC; Rieke & Lebofsky (1985).
[c] Analytic formula derived from RL85 results; Cardelli et al. (1989).
[d] Averaged ratios derived from observations toward many lines of sight.
[e] He et al. (1995).
[f] Indebetouw et al. (2005).

CIV/Ks imaging of 3 Galactic Center clusters (5'x5')

Detection of known and candidates WR

Mauerhan+ 2010; Wang+ 2010

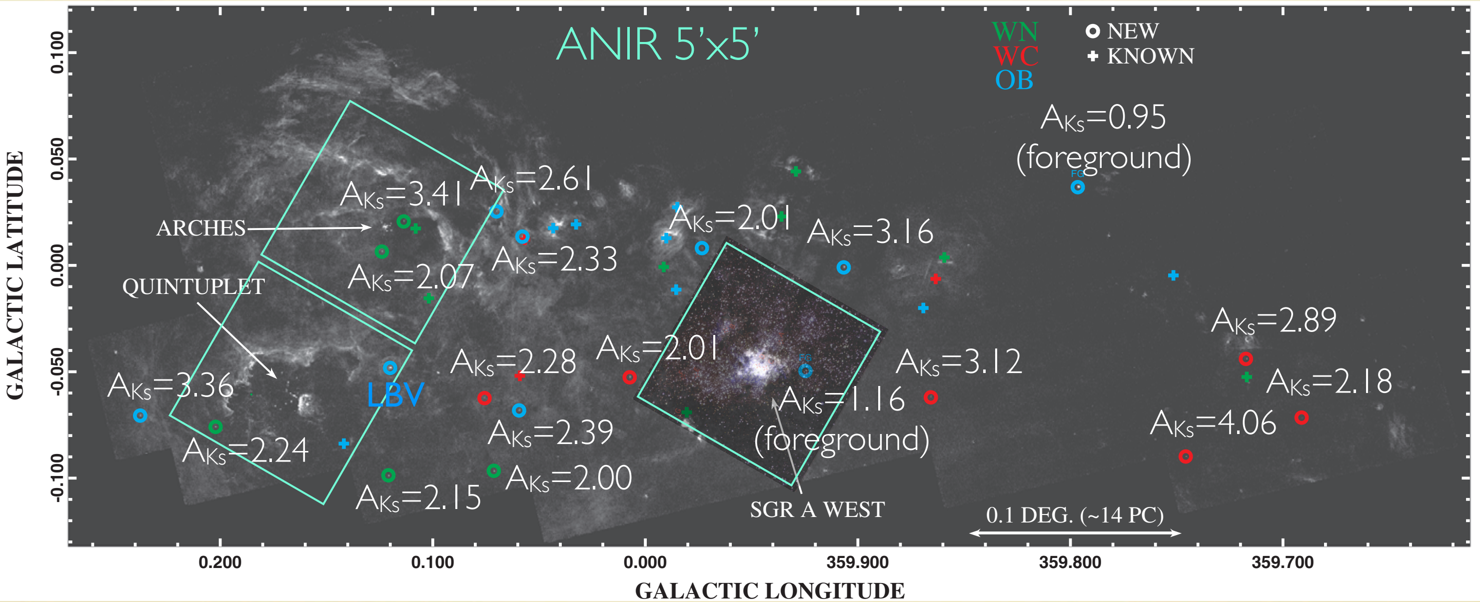
HST/NICMOS Paα survey image

~50% are stars in clusters; ~50% are isolated (inter-cluster) stars

extinction law from Nishiyama+ 2006

5.0' = 11.64 pc for R_0=8.0 kpc

39' x 15' = 91 x 35 pc

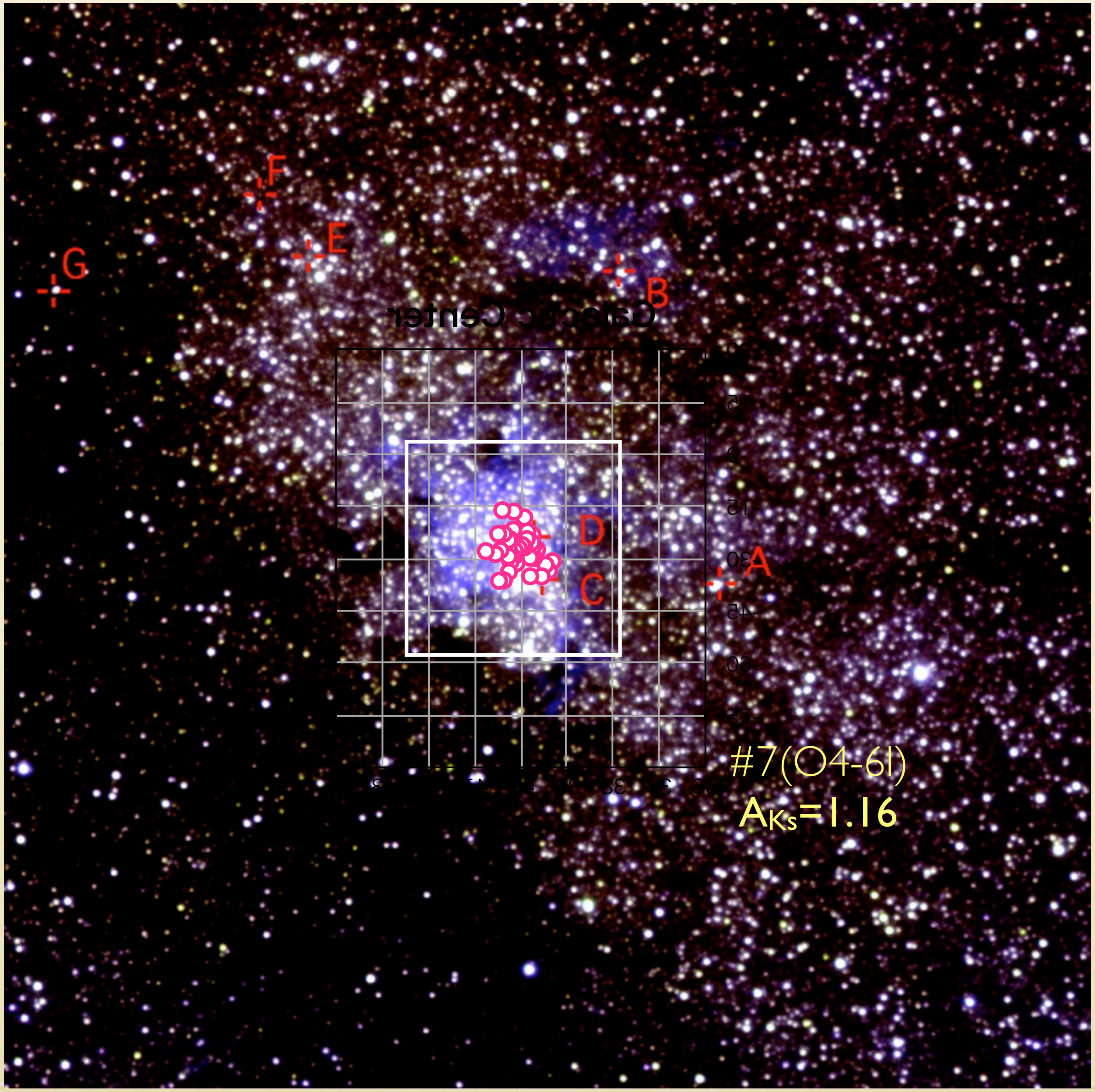


5.1’
1.0’

Galactic Center cluster

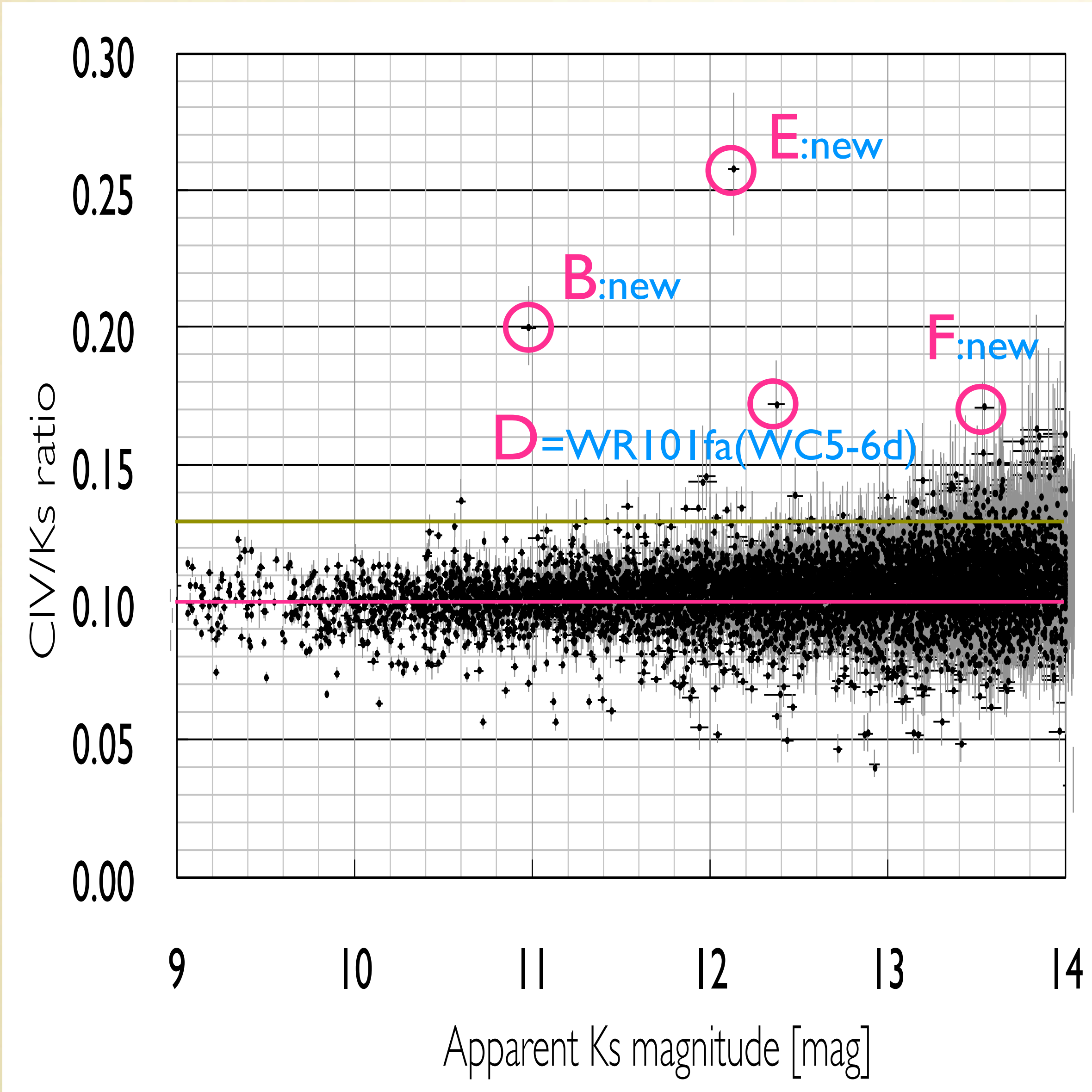
R(CIV) G(Ks) B(Paα)

[42WR]
WR100a(WN7)
WR101
a(WC8-9)
b(WN8)
c(WN9)
d(WC9)
da(WN7)
db(WN9)
dc(WN8)
dd(WN7)
de(WCLd)
df(WCLd)
dg(WCLd)
dh(WCLd)
di(WC9)
e(WN8)
ea(WCLd)
f(WC9)
fa(WC5-6d)D
g(WC9)
h(WN8-WC9)



i(WC8-9)
j(WN9)
ja(WN9)
k(WN9)
l(WN9)
m(WN8-9)
ma(WC8-9)
n(WC8-9)
na(WCLd)
nb(WC)
nc(WN8)
nd(WN9)
o(WN5-6)
oa(WC9)
ob(WC9)
oc(WN9)
od(WCLd)
oe(WCLd)
of(WC9)
og(WCLd)
oh(WC9)
oi(WC9)

Galactic Center cluster



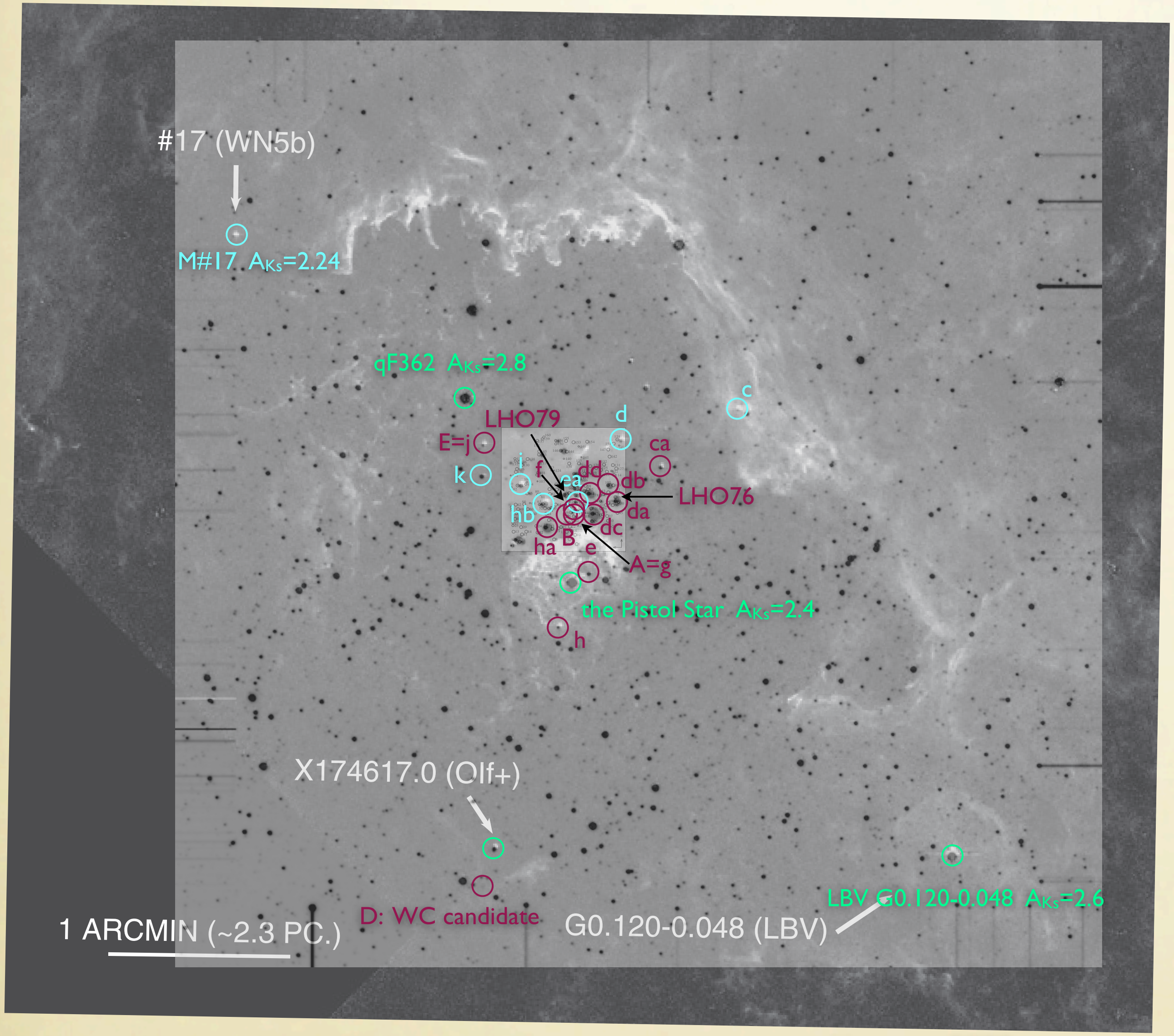
B 0.200 > 0.257 (WC7-8)
D 0.172 > 0.221 (WC7-8)
E 0.258 > 0.332 (WC5-6)
F 0.171 > 0.220 (WC7-8)

0.130 ... standard (zero-extinction)

0.101 ... average in 7<Ks<12
A_{Ks}=3.48 (A_V=56)

cf. A_K=2.8 in central 5'' (Stolte+ 2002; Martins+ 2008)

Quintuplet

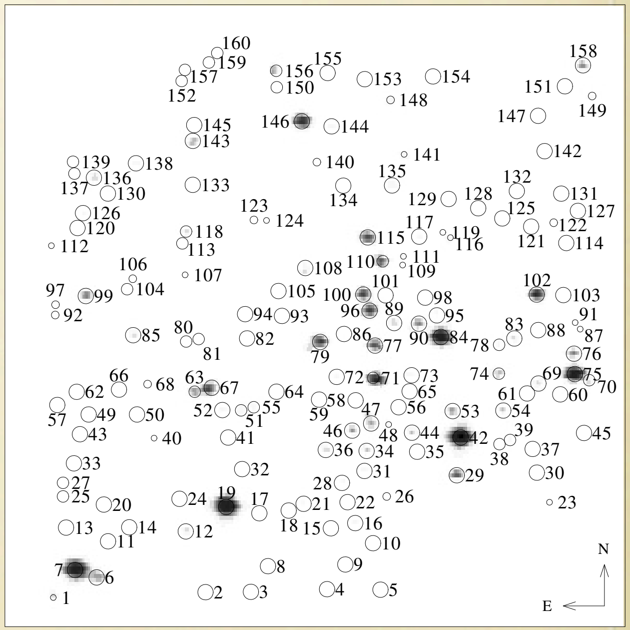


Liermann2009
ANIR_Ks
Mauerhan2010_Paα

[19WR] WR102

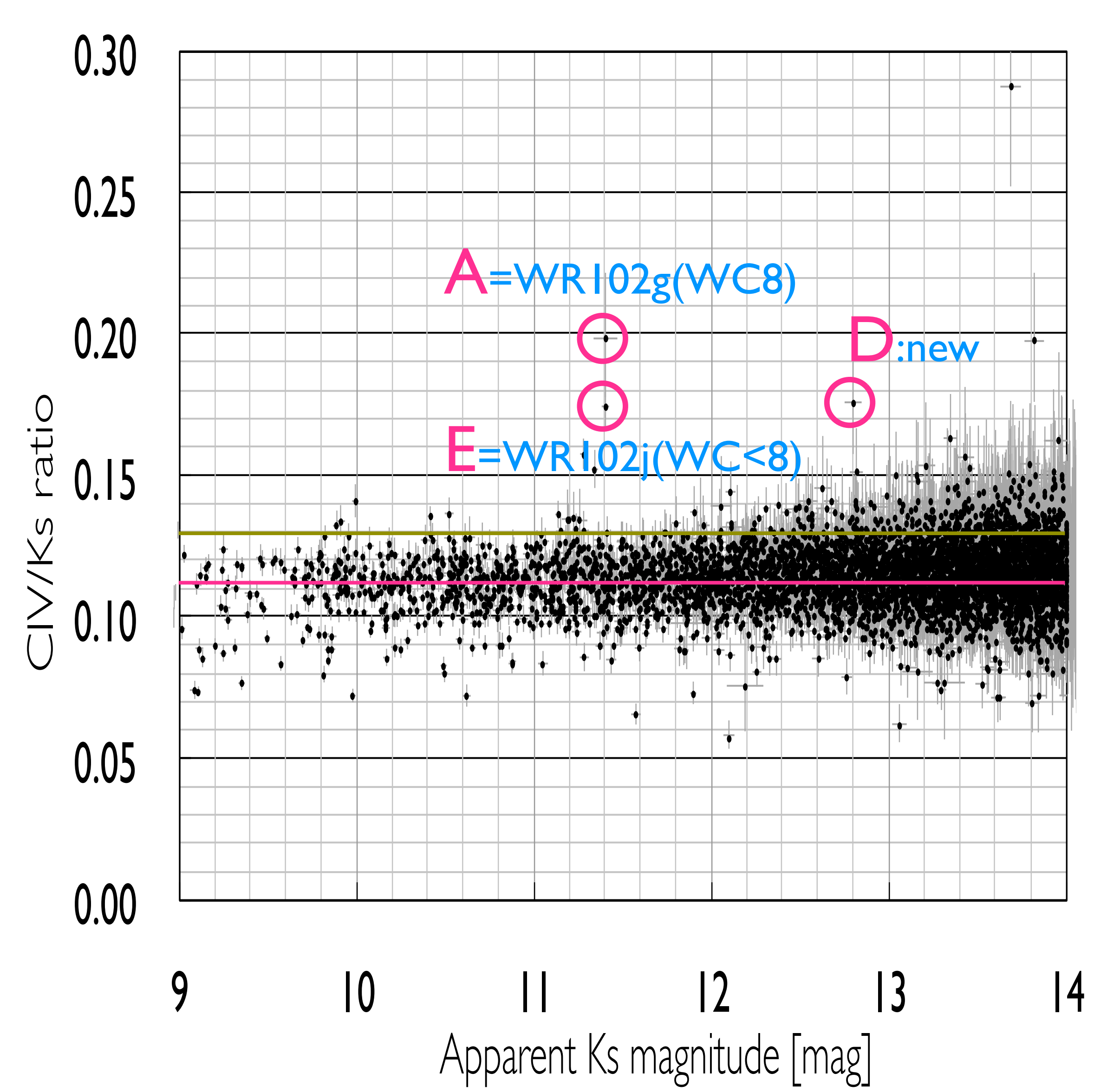
c(WN6)
ca(WC8-9)
d(WN9)=158
da(WC9?d)=75
76(WC9d)
79(WC9d)
db(WC9?d)=102
dc(WC9d)=42
dd(WC9d)=84

e(WC8)
ea(WN9)=71
f(WC8)=47
g(WC8)A=34
h(WC9)
ha(WC8/9d)=19
hb(WN9)=67
i(WN9)=99
j(WC<8)E
k(WN9)



Liermann2009

Quintuplet cluster



A 0.199 > 0.231 (WC7-8)
D 0.176 > 0.204 (WC7-8)
E 0.175 > 0.203 (WC7-8)

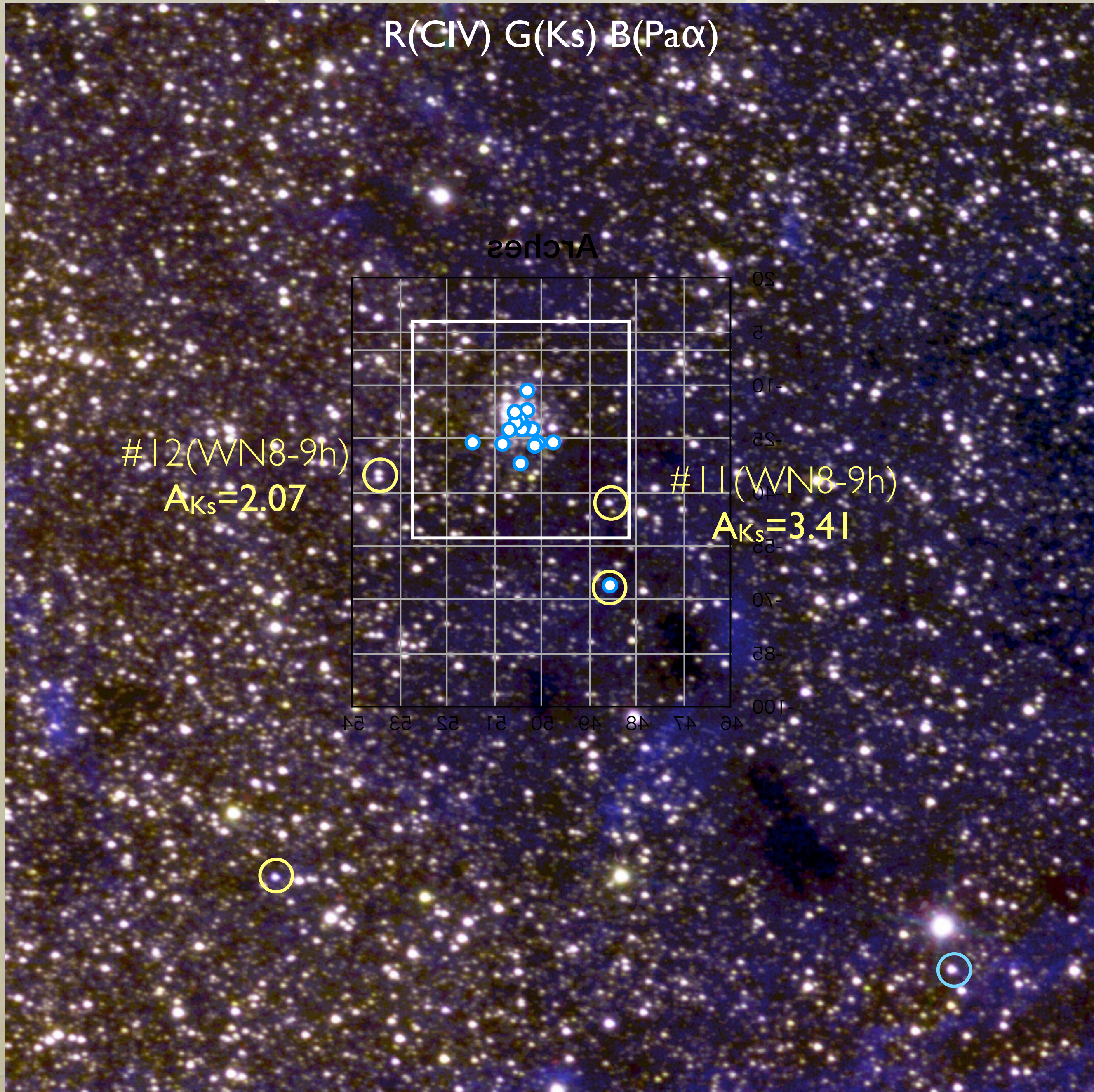
0.130 ... standard (zero-extinction)
0.112 ... average in 7<Ks<12
A_{Ks}=2.05 (A_V=33)

Arches cluster

5.0'

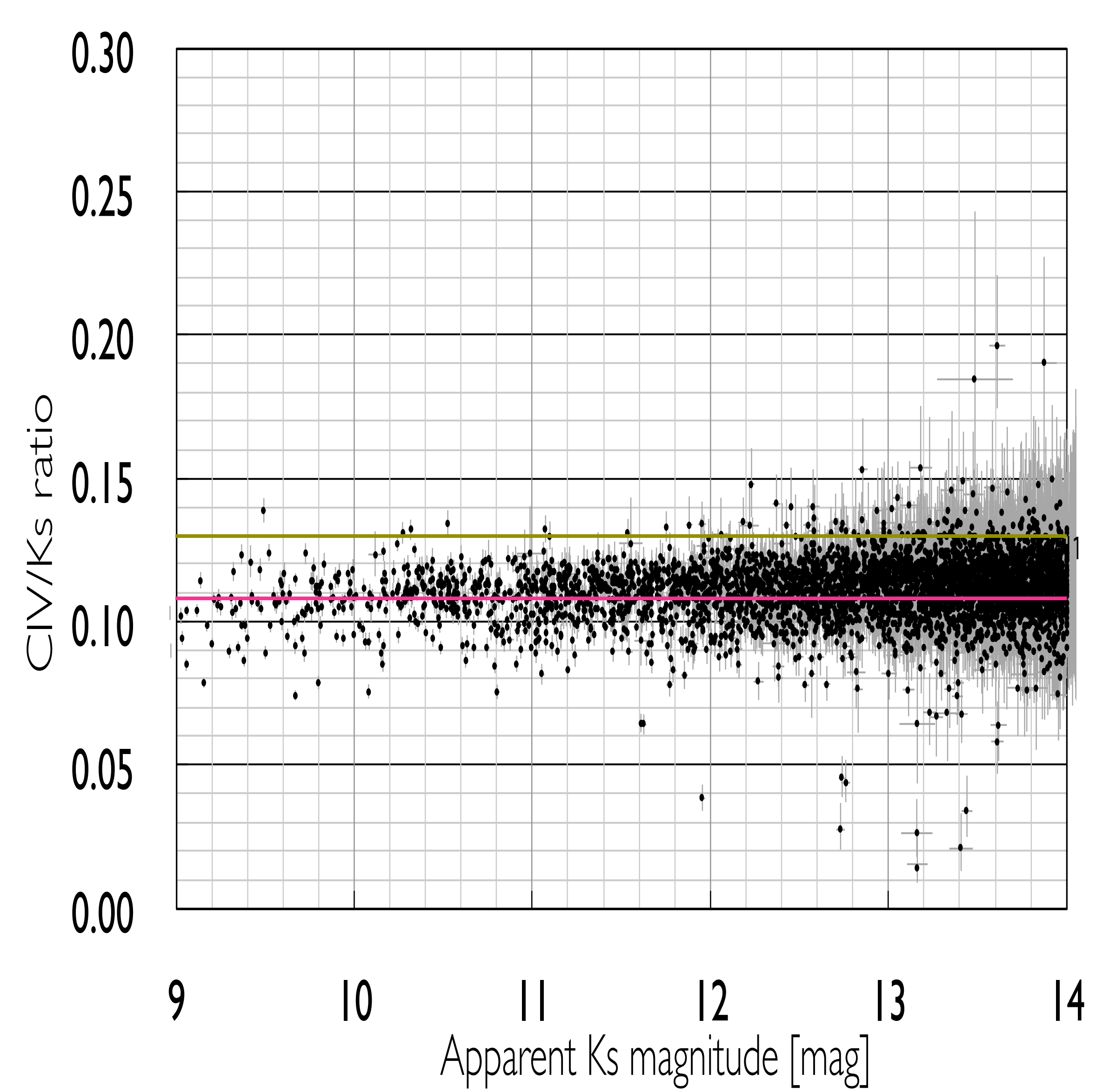
1.0'

[16WR]
WR102
a(WN8)
aa(WN9)
ab(WN7)
ac(WN7)
ad(WN9)
ae(WN9)
af(WN9)
ag(WN9)
ah(WN9)
ai(WN9)
aj(WN9)
ak(WN6-7)
al(WN8)
ba(WN7)
bb(WN9)
bc(WN7)



Mauerhan+ 2010
WN8-9h

Arches cluster



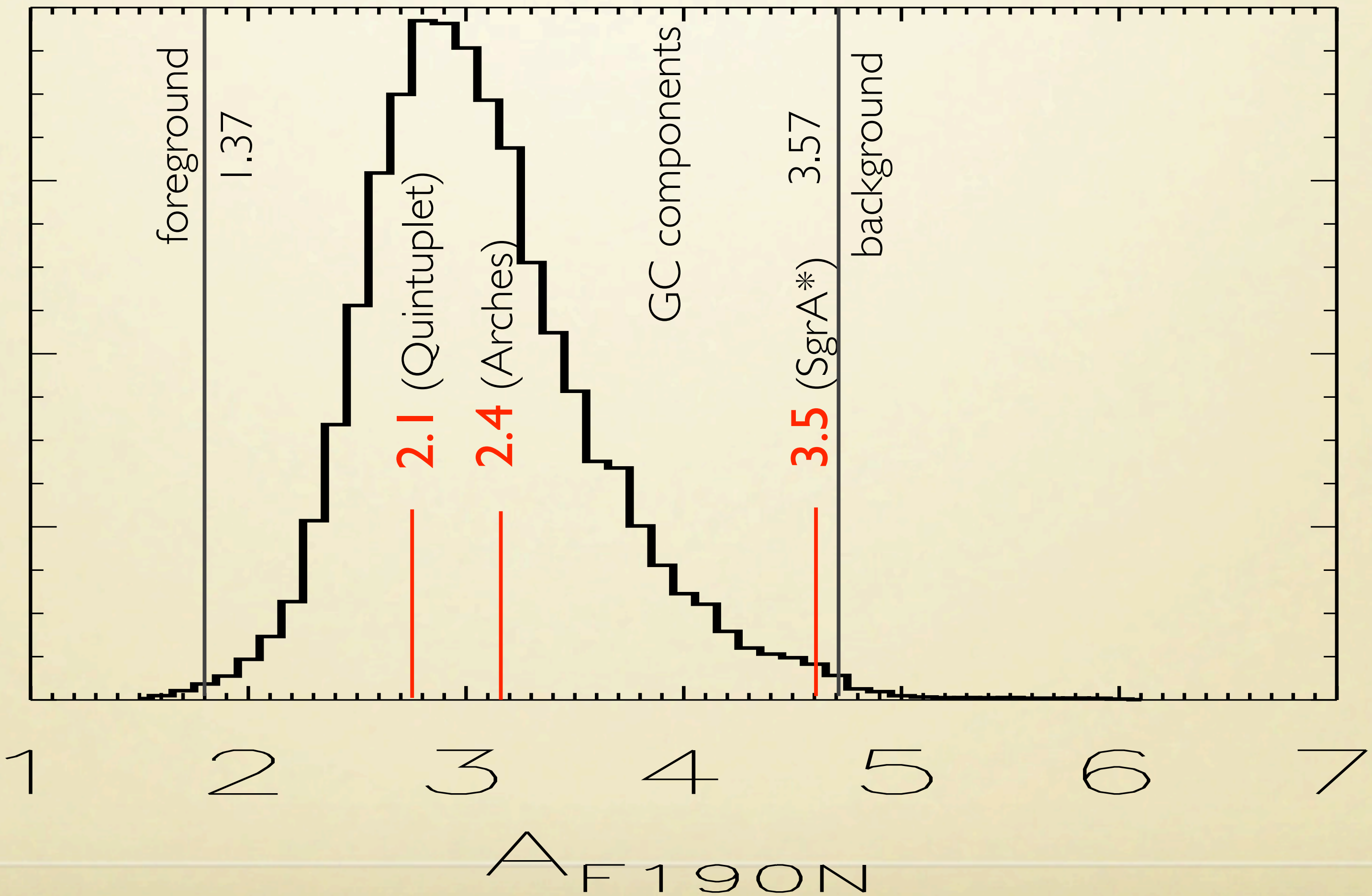
#11: 0.110(WN8-9) => ~0.120
A_{Ks}=2.30 => 1.1 << 3.41(M10)
#12: 0.109(WN8-9) => ~0.120
A_{Ks}=2.43 => 1.1 << 2.07(M10)

0.130 ... standard (zero-extinction)
0.109 ... average in 7<Ks<12
A_{Ks}=2.43 (A_V=39)

銀河中心領域の Extinction 分布

Dong+ 2011
Extinction distribution in GCR (39' x 15')
extinction law from Nishiyama+ 2006

A_K; peak=2.22, median=2.32 (A_K=0.76A_{F190N})



3 Clusters & Galactic Center Region

Galactic Center Clusters (~0.4°)

Quintuplet
l =+0.16 deg=+9'.6
b=−0.06 deg=−3'.6

Quintuplet
(3-5 Myr)

Arches
l =+0.12 deg=+7'.2
b=+0.02 deg=+1'.2

Arches
(younger;2-4 Myr)

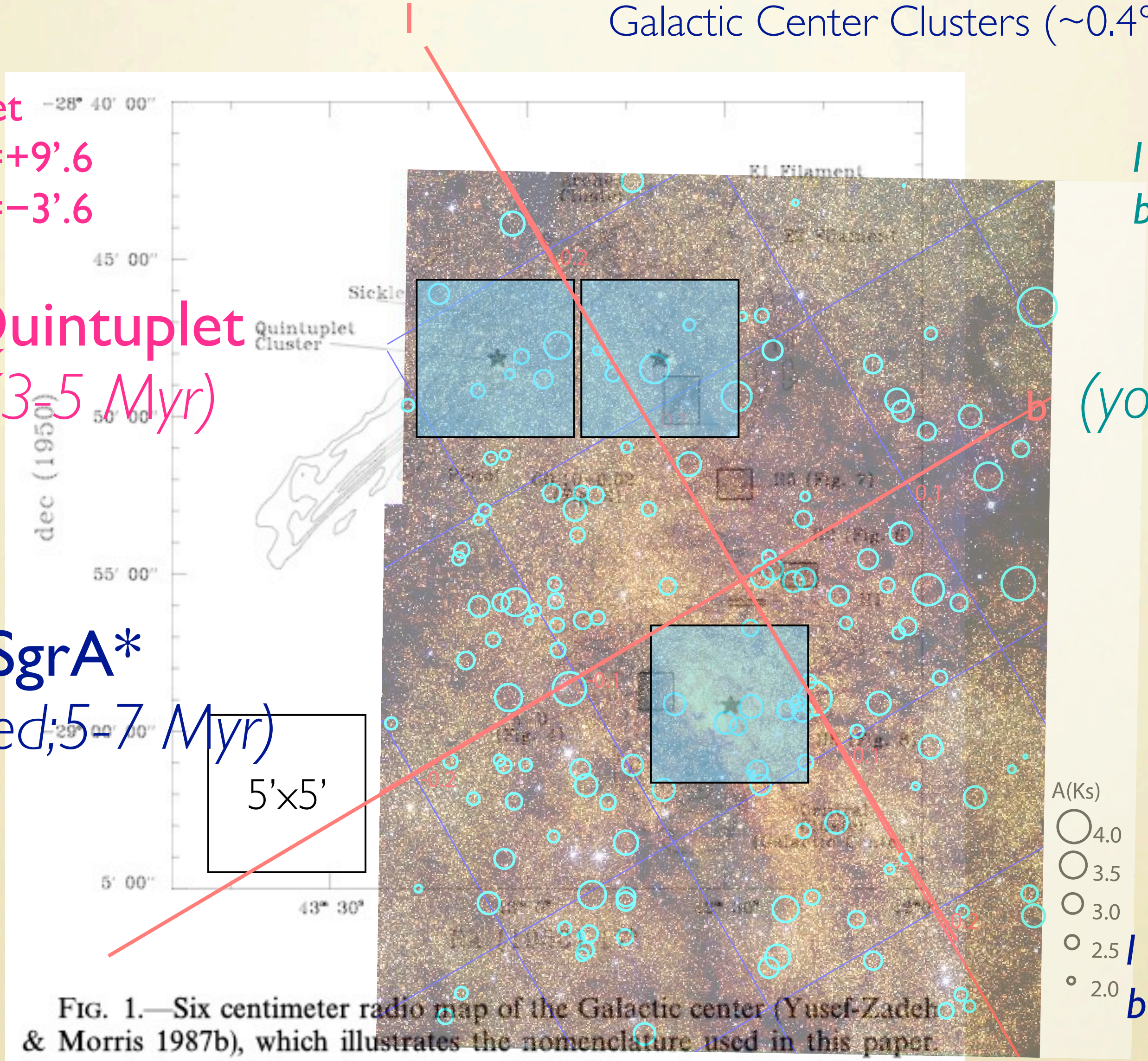


FIG. 1.—Six centimeter radio map of the Galactic center (Yusef-Zadeh & Morris 1987b), which illustrates the nomenclature used in this paper. Nomenclature for the regions A–D and H1–H8 are from Yusef-Zadeh & Morris (1987b); nomenclature for the E1 and E2 Filaments is from Morris & Yusef-Zadeh (1989). The Central, Quintuplet, and Arches clusters are indicated by stars at the central location of the respective clusters. The

SgrA*
(evolved;5-7 Myr)

SgrA*
D=8.28±0.33 kpc
1'=2.41 pc
RA=17h45m40.04s
Dec=−29°00'28.12"
(epoch2000.0)
l =−0.0557 deg=−3'.34
b=−0.0462 deg=−2'.77

1"=0.0388 pc
for D=8.0 kpc

Matsunaga+ 2011 Nature