Dynamical Masses

Fundamental Tests of Substellar Physics

Trent Dupuy

University of Edinburgh

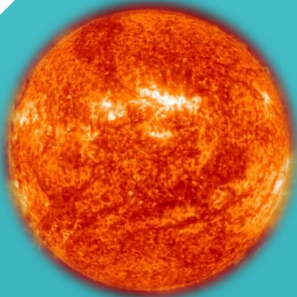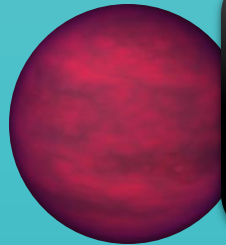Institute for Astronomy

Outline

Why? **How?** **What?** **What next?**
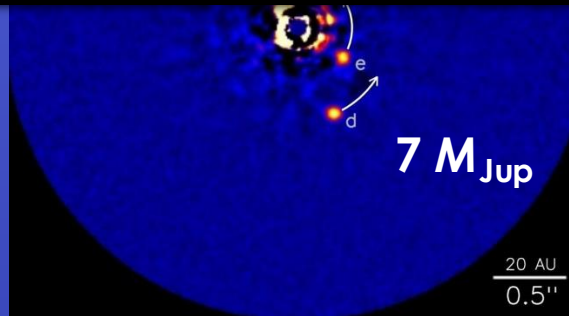
Reasons for measuring dynamical masses.

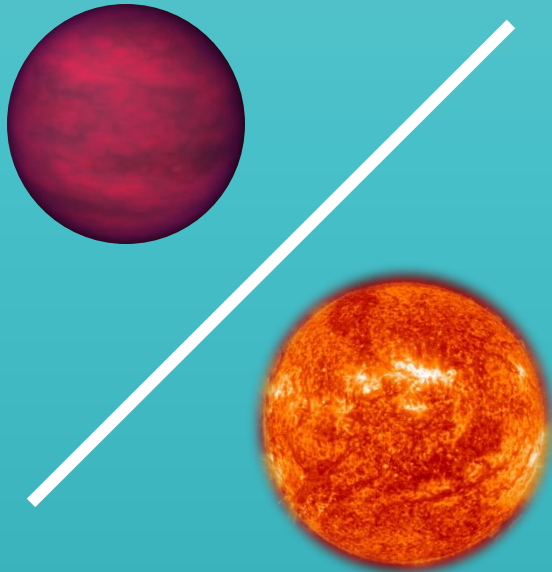Is it a brown dwarf or is it a star?

Are evolutionary models accurate?

7 M_{Jup}

20 AU
0.5''

Are atmospheric models accurate?

WISE J1541−2250
350/4.25/10⁴

WISE J1738+2732
350/4.75/10⁴

WISE J1405+5534
350/5.00/10⁴

1.0   1.5   2.0
Wavelength (μm)
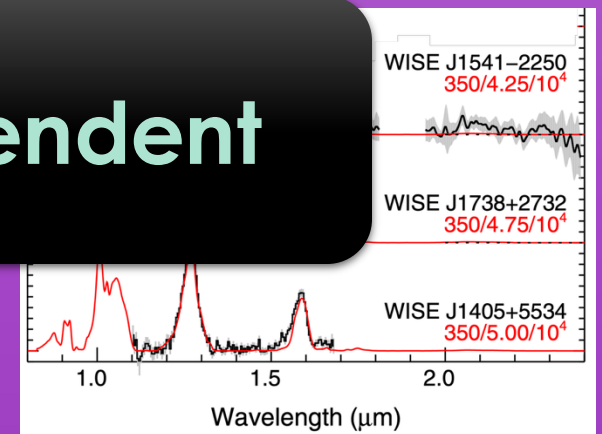
log g = 5.00 → 4.25

30 M_{Jup} → 10 M_{Jup}

'Dynamical' ←→ model-independent

Trent Dupuy (U. of Edinburgh)

Reasons for measuring dynamical masses.

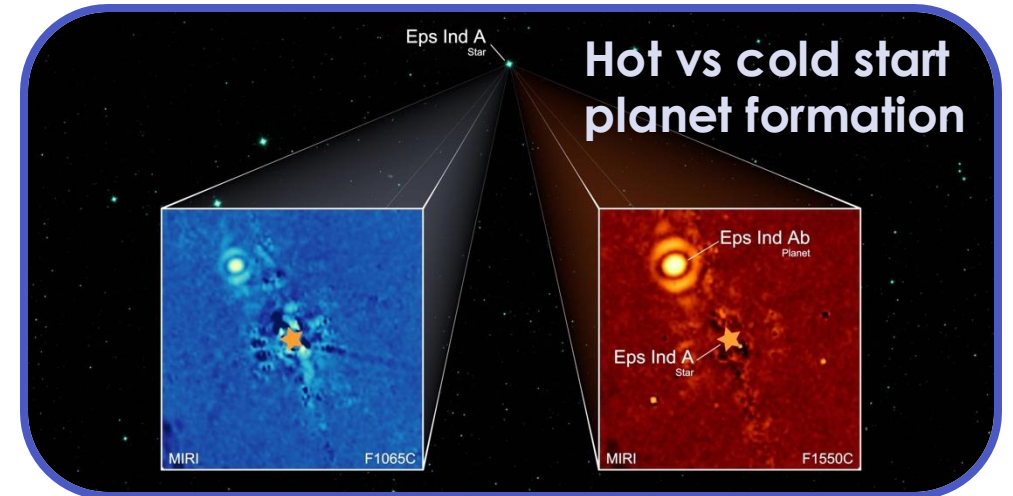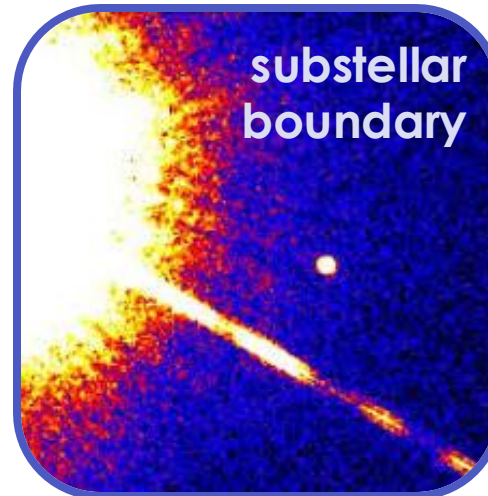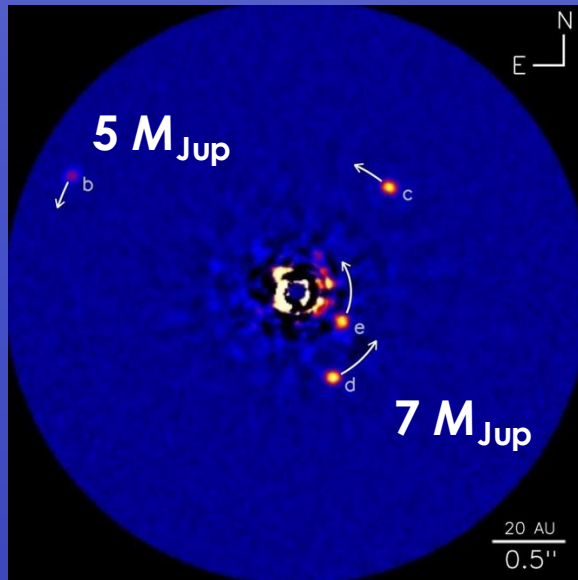**Is it a brown dwarf or is it a star?**

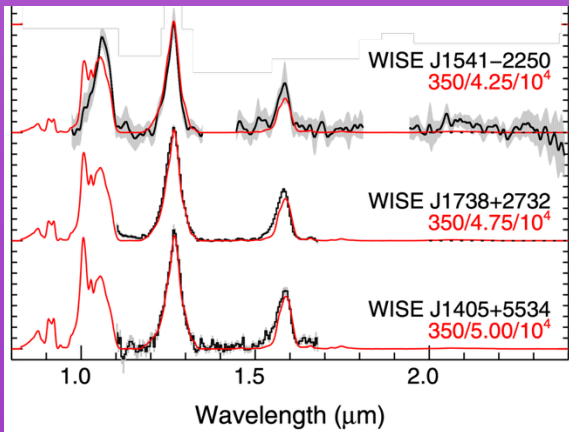Important when you care about the object's past (e.g., habitability) or future.
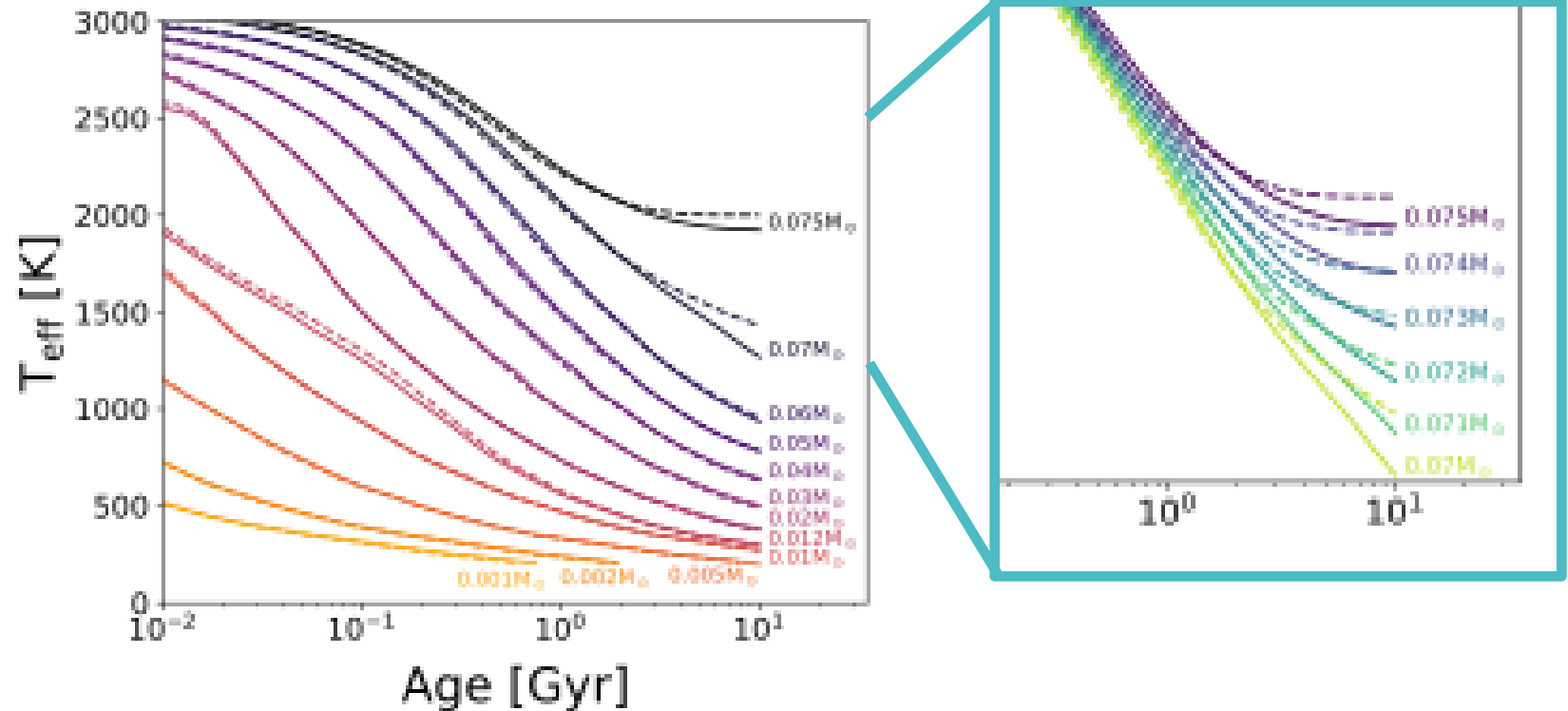
Trent Dupuy (U. of Edinburgh)

Reasons for measuring dynamical masses.

Are *evolutionary* models accurate?

5 M$_{Jup}$

7 M$_{Jup}$

IMF

Lithium depletion

TEIDE 1

substellar boundary

Hot vs cold start planet formation

Eps Ind A Star

Eps Ind Ab Planet

Eps Ind A Star

MIRI   F1065C

MIRI   F1550C
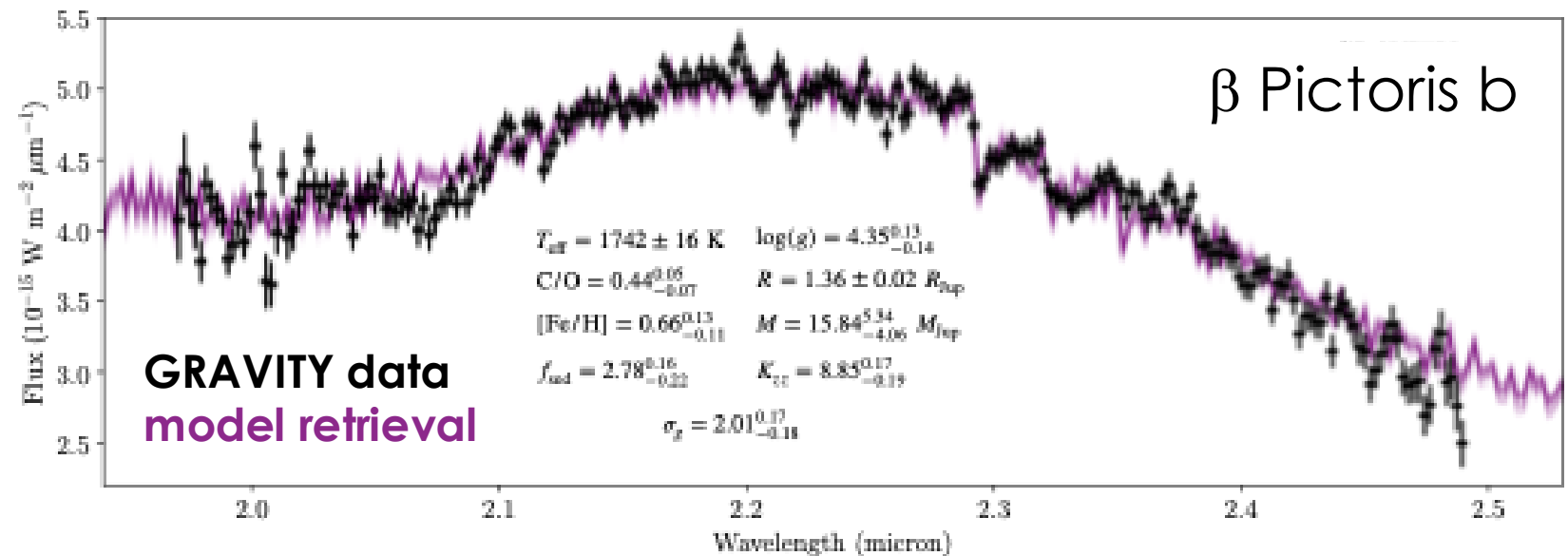
Trent Dupuy (U. of Edinburgh)
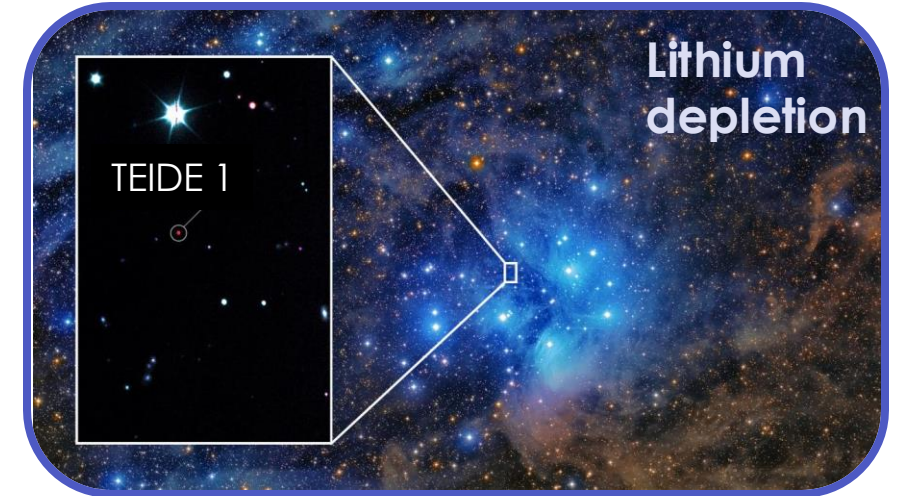
Reasons for measuring dynamical masses.

Are *atmospheric* models accurate?

GRAVITY Collaboration, Nowak et al. 2020

β Pictoris b

GRAVITY data
model retrieval

$T_{eff} = 1742 \pm 16$ K $\log(g) = 4.35^{0.13}_{-0.14}$
$C/O = 0.44^{0.05}_{-0.07}$ $R = 1.36 \pm 0.02\ R_{Jup}$
$[Fe/H] = 0.66^{0.13}_{-0.11}$ $M = 15.84^{5.34}_{-4.06}\ M_{Jup}$
$f_{sed} = 2.78^{0.16}_{-0.22}$ $K_{zz} = 8.85^{0.17}_{-0.19}$
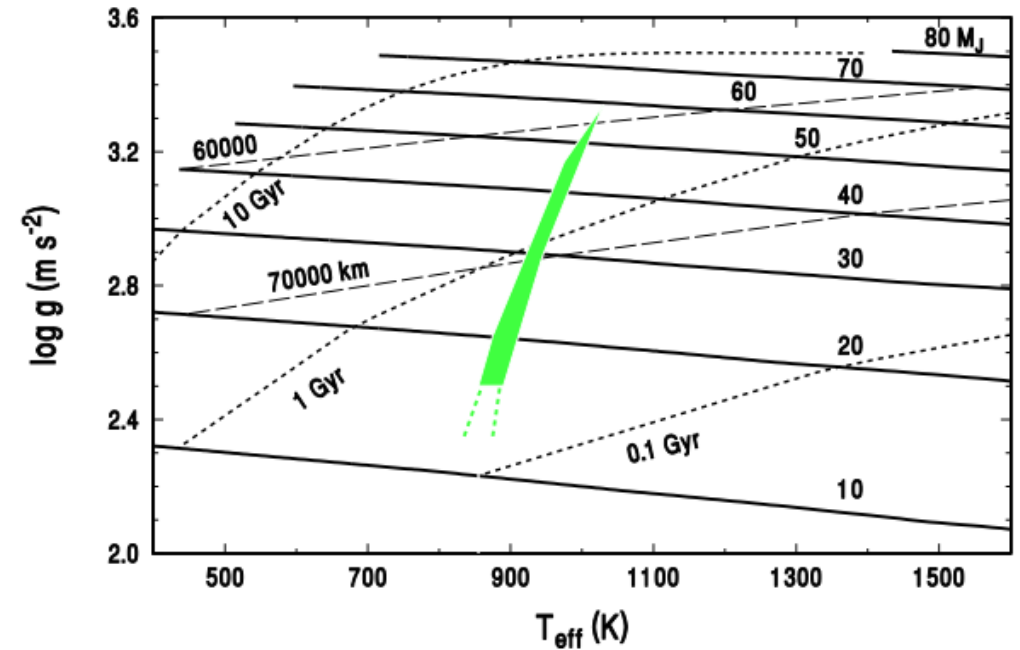$\sigma_{g} = 2.01^{0.17}_{-0.18}$

Reasons for measuring dynamical masses.

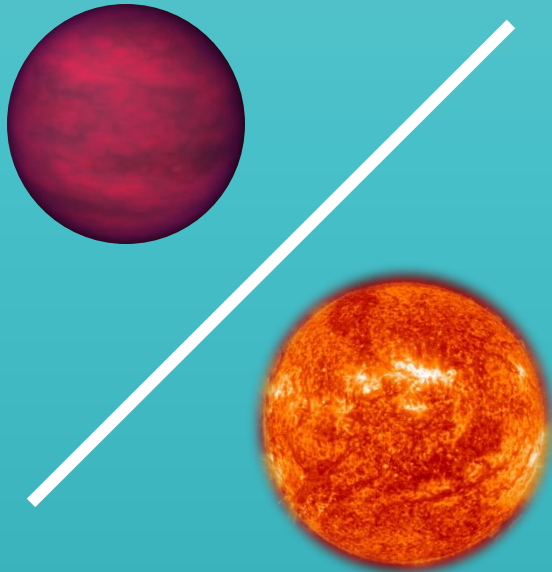**Are *atmospheric* models accurate?**
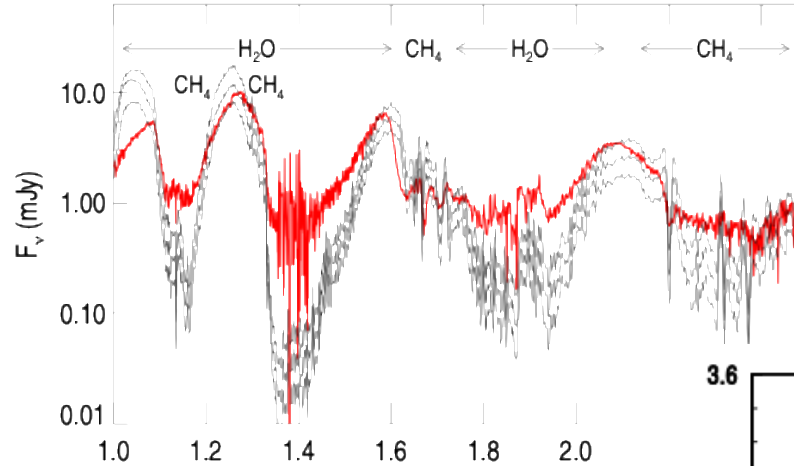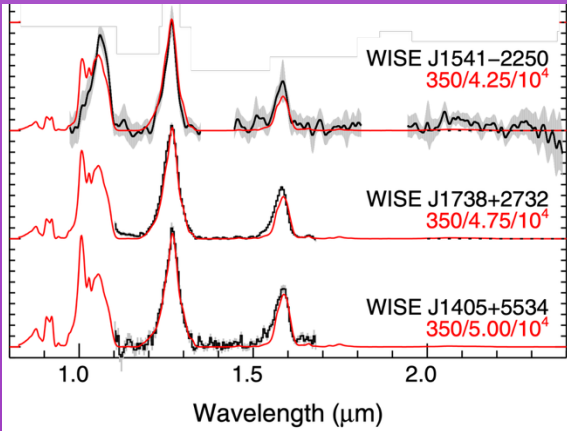
Gliese 229 B
Marley et al. (1996)
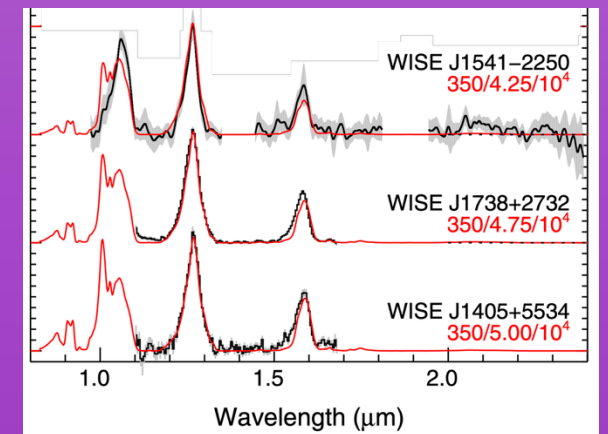
Reasons for measuring dynamical masses.

Is it a brown dwarf or is it a star?

Are *evolutionary* models accurate?

5 M_{Jup}

7 M_{Jup}

20 AU

0.5''

N

E

Are *atmospheric* models accurate?

WISE J1541−2250
350/4.25/10⁴

WISE J1738+2732
350/4.75/10⁴

WISE J1405+5534
350/5.00/10⁴

Wavelength (μm)

log *g* = 5.00 → 4.25

30 M_{Jup} → 10 M_{Jup}

Trent Dupuy (U. of Edinburgh)

Outline

Why? **How?** What? What next?

Trent Dupuy (U. of Edinburgh)

Methods for measuring dynamical masses.

Wish List

➢ resolvable photometry

➢ resolvable spectra

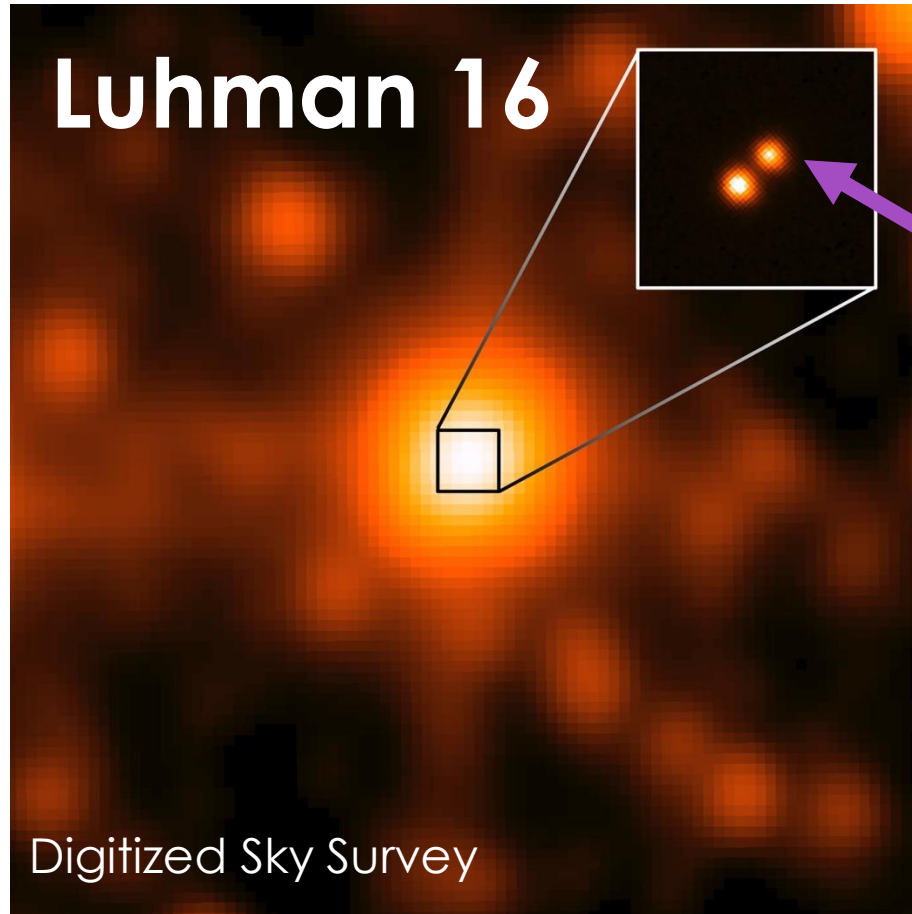➢ measurable **radius**

➢ known **age**

➢ known **composition**

Trent Dupuy (U. of Edinburgh)

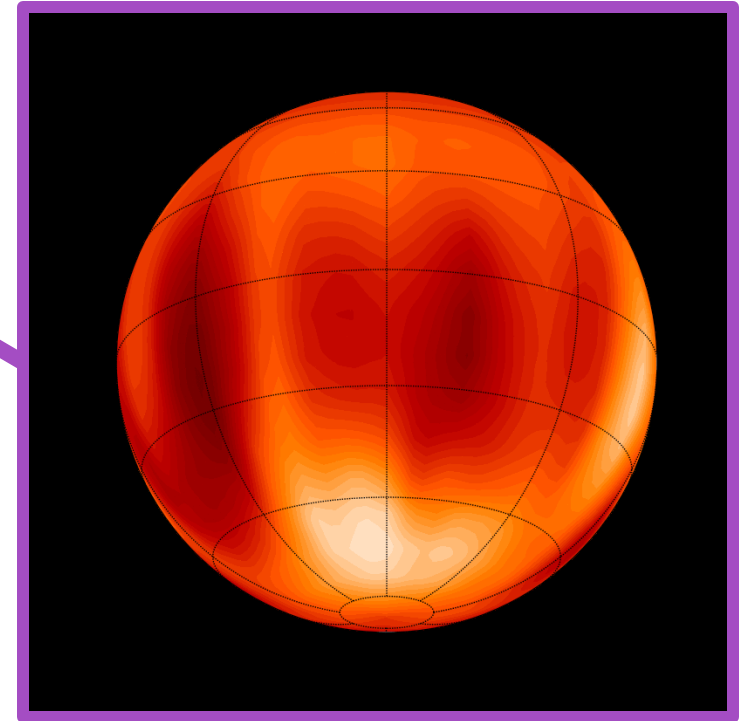# Methods for measuring dynamical masses.

Wish List

Visual binaries

➤ **resolvable photometry**

➤ resolvable spectra

➤ ~~measurable radius~~

➤ *known **coeval** age*

➤ *known **co-**composition*

Trent Dupuy (U. of Edinburgh)

Brown dwarf binaries are great!

Luhman 16

Digitized Sky Survey

Crossfield et al. (2014)

Trent Dupuy (U. of Edinburgh)

Methods for measuring dynamical masses.

Wish List

➤ **resolvable photometry**

➤ resolvable spectra

➤ ~~measurable radius~~

➤ *known age*

➤ known composition

Companions

Trent Dupuy (U. of Edinburgh)

Methods for measuring dynamical masses.

Wish List

➤ ~~resolvable photometry~~

➤ ~~resolvable spectra~~

➤ measurable radius

➤ *known age*

➤ known composition

Transiting/Eclipsing

Trent Dupuy (U. of Edinburgh)

Methods for measuring dynamical masses.

Wish List

➢ ~~resolvable photometry~~

➢ ~~resolvable spectra~~

➢ ~~measurable radius~~

➢ known **coeval** age

➢ known **co**-composition

RV binaries

Trent Dupuy (U. of Edinburgh)
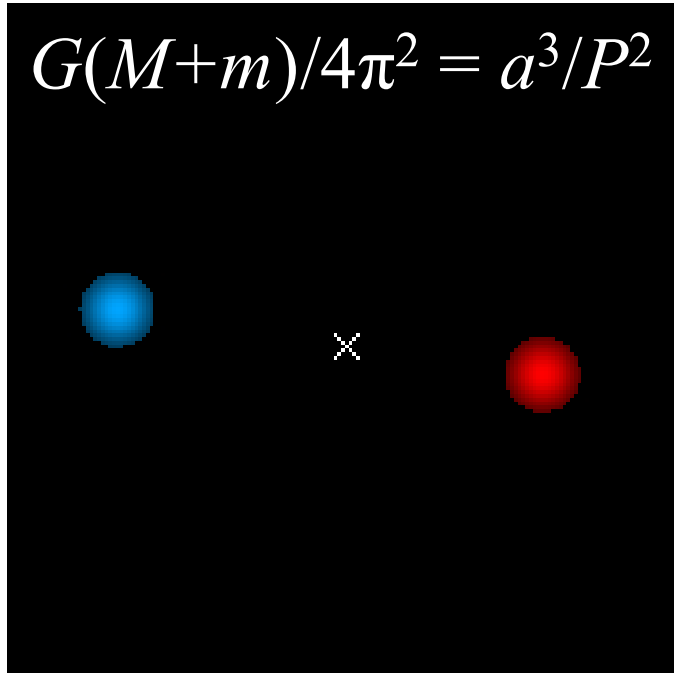
Methods for measuring dynamical masses.

➢ resolvable photometry

➢ resolvable spectra

➢ known* (coeval) age

➢ known (co-)composition
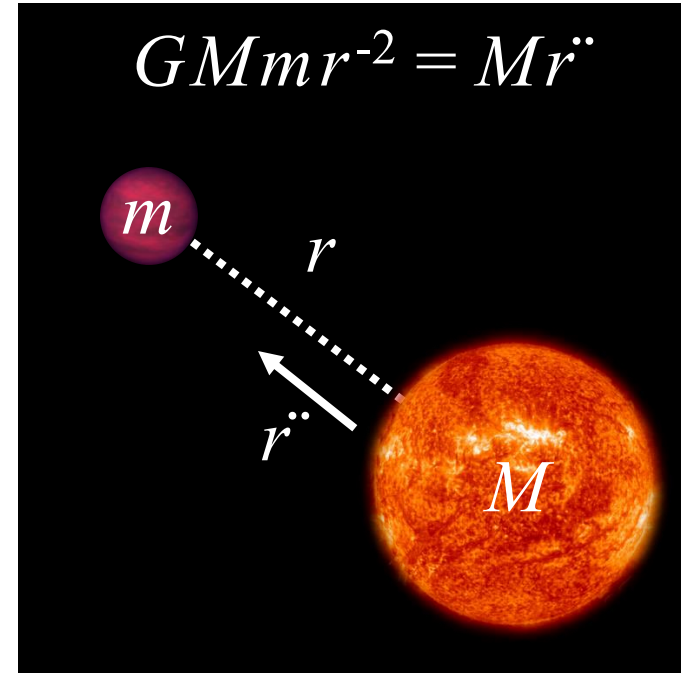
Visual binaries

Companions

Trent Dupuy (U. of Edinburgh)

Methods for measuring dynamical masses.

$$G(M+m)/4\pi^2 = a^3/P^2$$

$$GMmr^{-2} = M\ddot{r}$$

m

r

$\ddot{r}$

M

Visual binaries

Companions

Trent Dupuy (U. of Edinburgh)

Visual binaries

'absolute' orbit

'relative' orbit

$M_{tot} = (a_1+a_2)^3/P^2$

$M_1 = M_{tot} (a_2 / a)$

$M_2 = M_{tot} (a_1 / a)$

a_1

a_2

$a = a_1 + a_2$
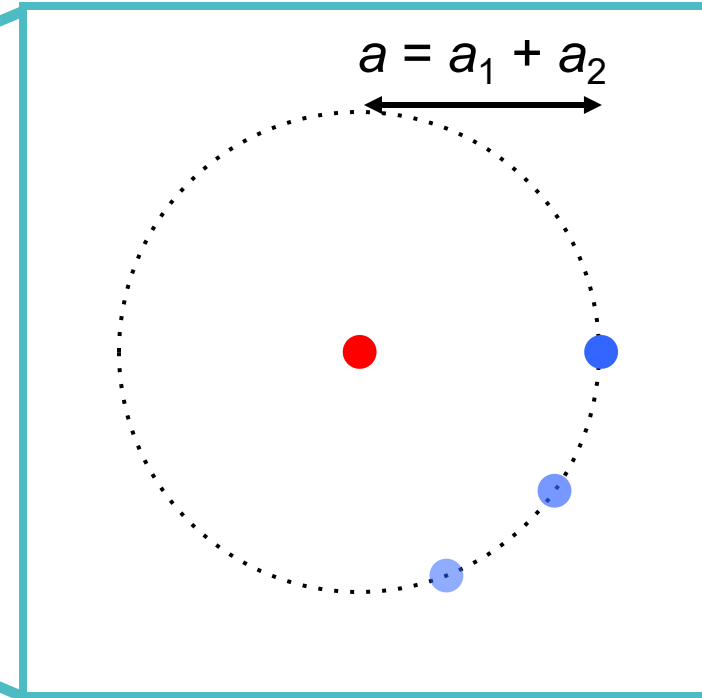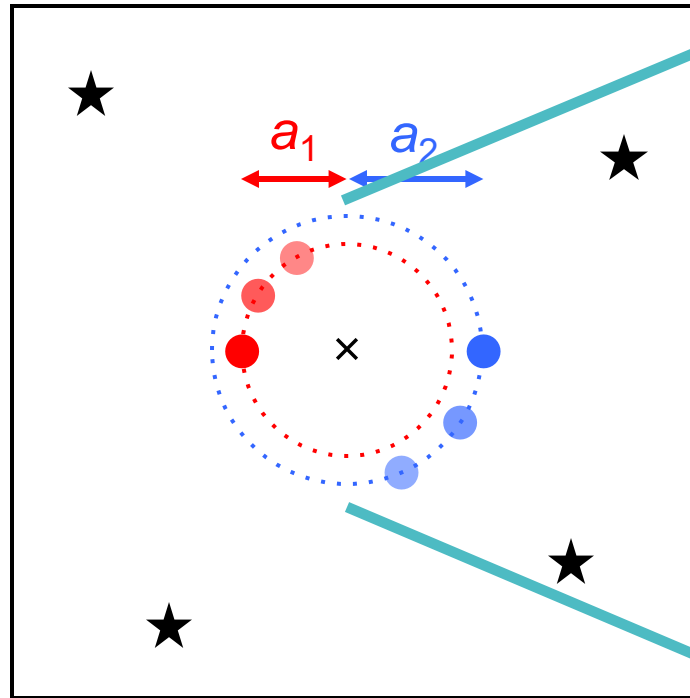
$M_{tot} = a^3/P^2$

~~Visual~~ binaries
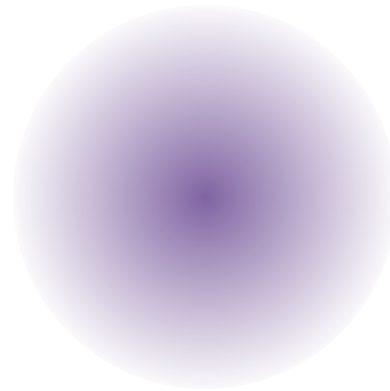
wide-field imaging

Visual binaries
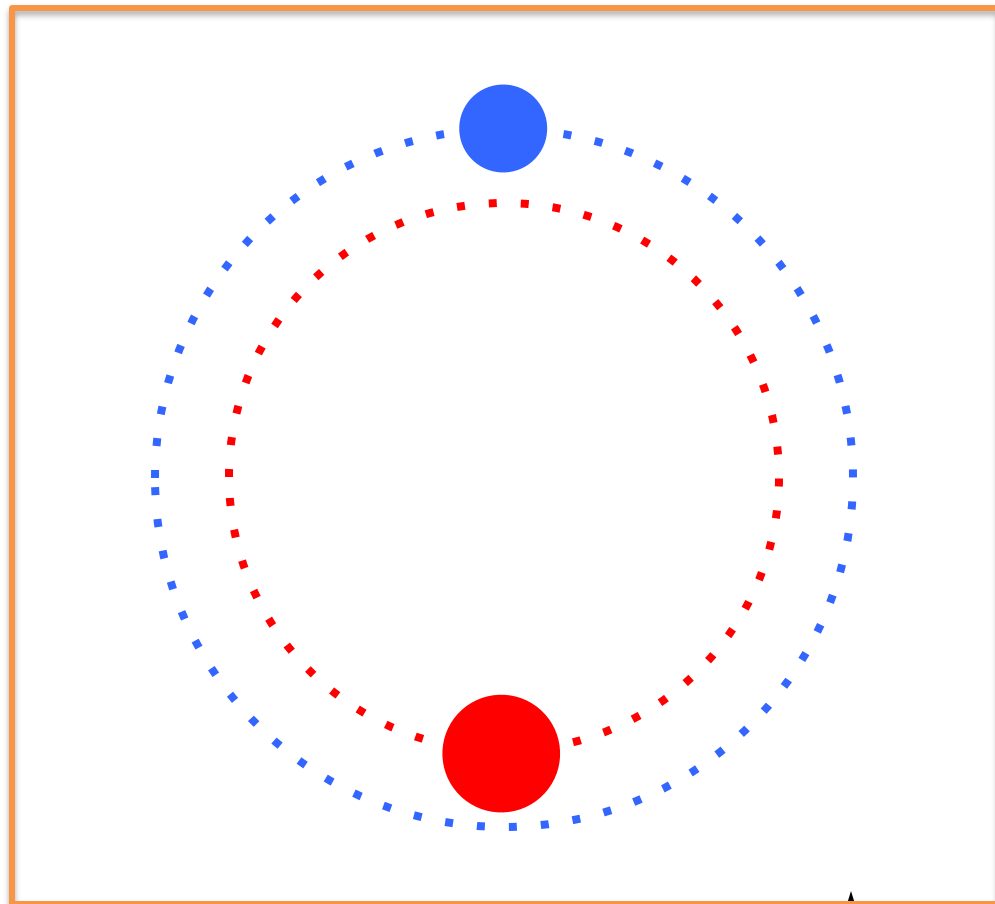
AO imaging

$$\frac{M_2}{M_1 + M_2} = \frac{a_\text{phot}}{a_1 + a_2} + \frac{f_2}{f_1 + f_2}$$

from adaptive optics
from seeing-limited
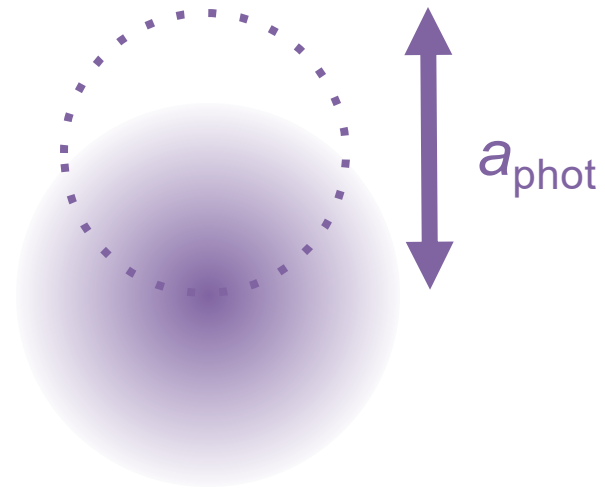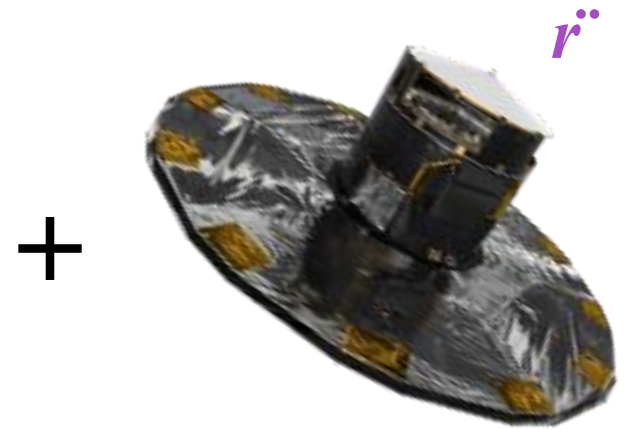
a_phot

Methods for measuring dynamical masses.

$$G(M+m)/4\pi^2 = a^3/P^2$$

$$GMmr^{-2} = M\ddot{r}$$

Visual binaries

Companions

Trent Dupuy (U. of Edinburgh)

Companions

$$GMmr^{-2} = M\ddot{r}$$

m

r

$\ddot{r}$

ASSUMES r AND r̈ MEASURED SIMULTANEOUSLY

HD 4747B

P = 34 yr

ΔDecl. (arcsec)

ΔR.A. (arcsec)

Companion Mass (M_{Jup})

r

$\ddot{r}$

+

Trent Dupuy (U. of Edinburgh)

μ_{HG}

μ_G

2016.0

μ_H

1991.25
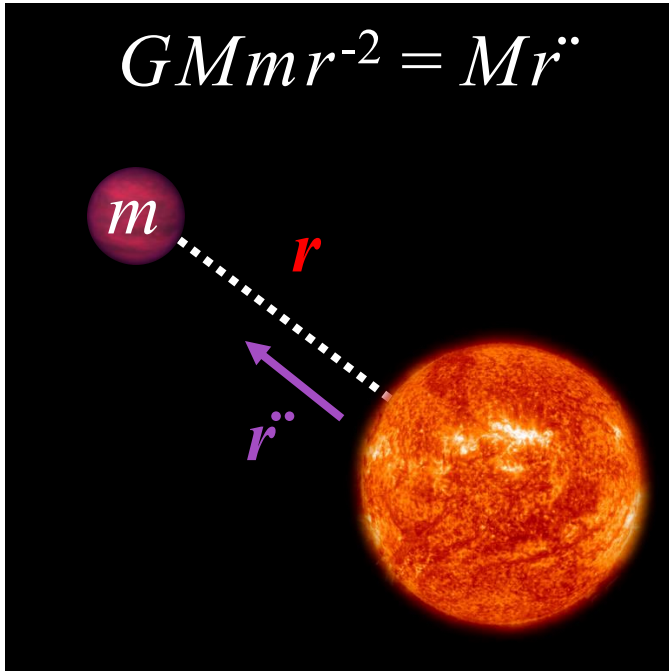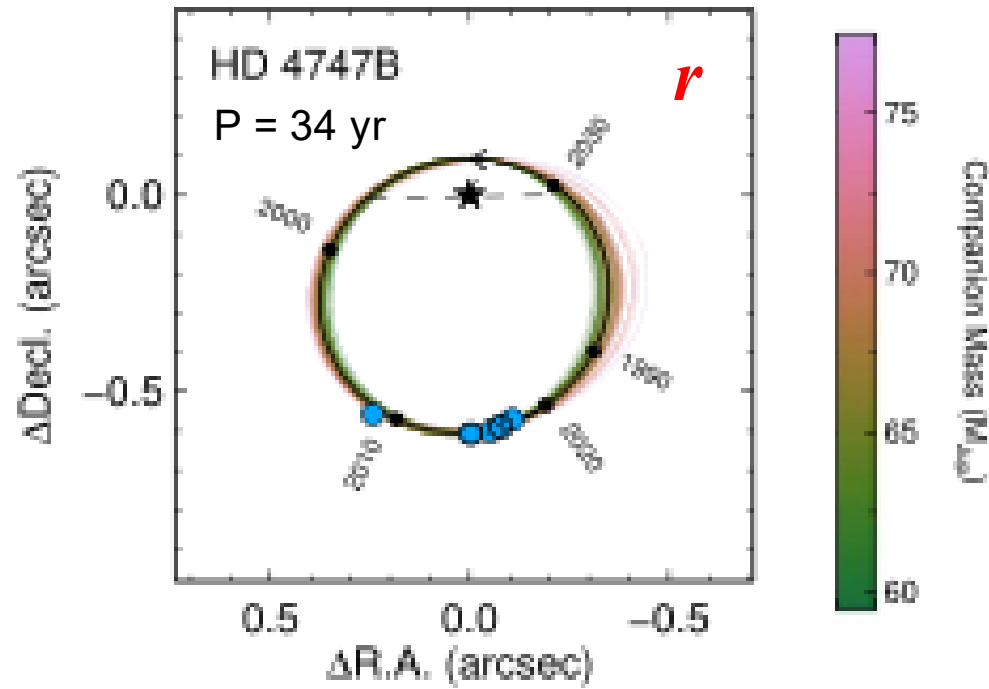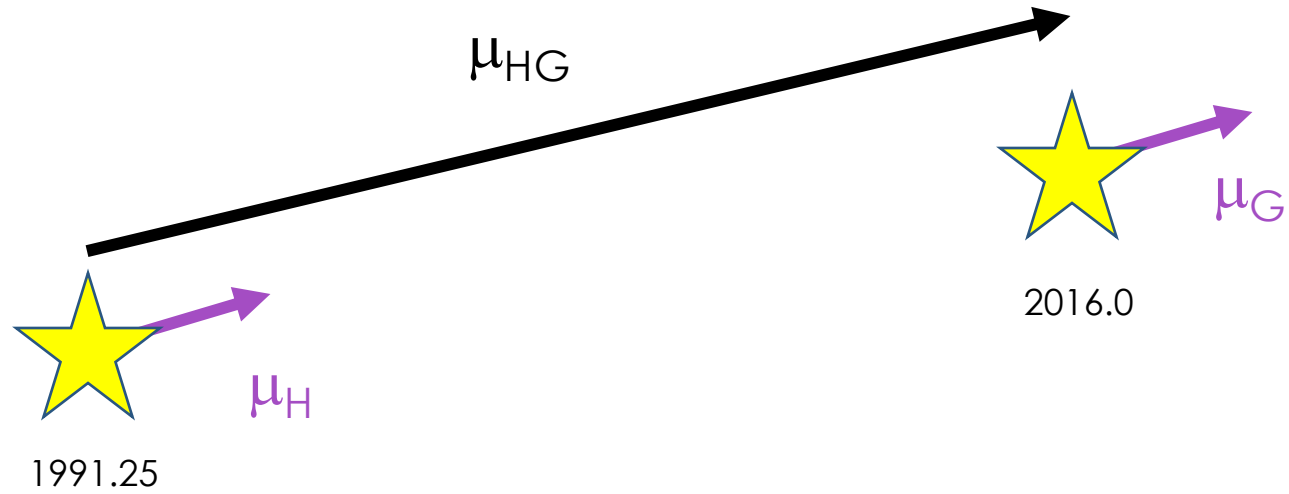
For normal stars, these should all agree…

$\Delta\mu_H$

$\Delta\mu_G$

2016.0

1991.25

$\Delta\mu$ → acceleration

Trent Dupuy (U. of Edinburgh)

Companions

$$GMmr^{-2} = M\ddot{r}$$

m

r

$\ddot{r}$

ASSUMES r AND r̈ MEASURED SIMULTANEOUSLY

HD 4747B

P = 34 yr

r

$\ddot{r}$
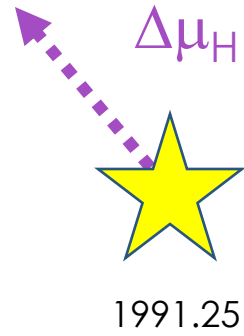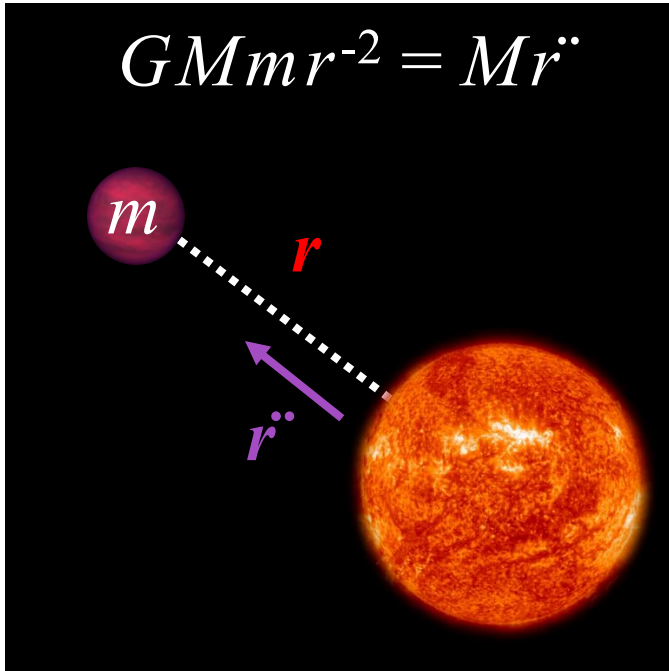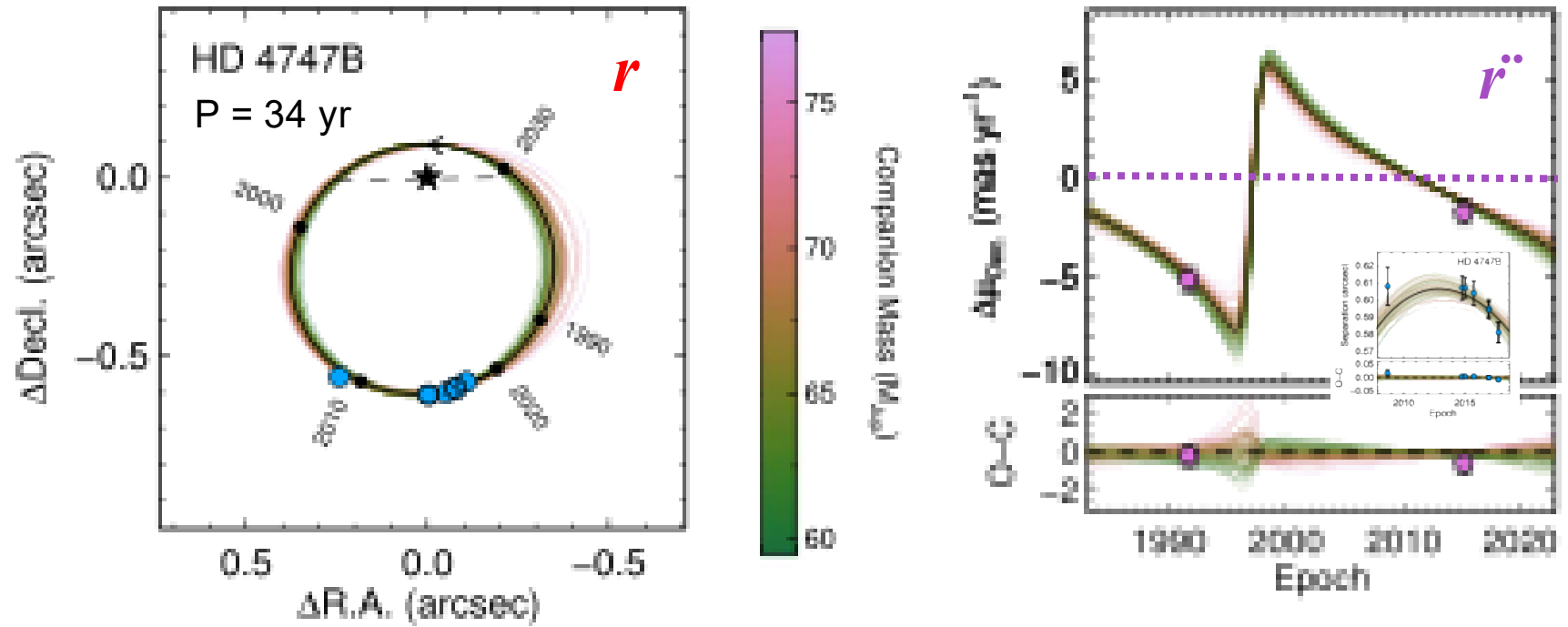
Brandt et al. (2019)

Companions

$$GMmr^{-2} = M\ddot{r}$$

m

r

$\ddot{r}$

37.9 ± 1.5 M_{Jup}   Gl 758B

ΔDecl. (arcsec)

ΔR.A. (arcsec)

Companion Mass (M_{Jup})

2030
2020
2010
2000
1990

Brandt et al. (2019)

P (yr)

Trent Dupuy (U. of Edinburgh)
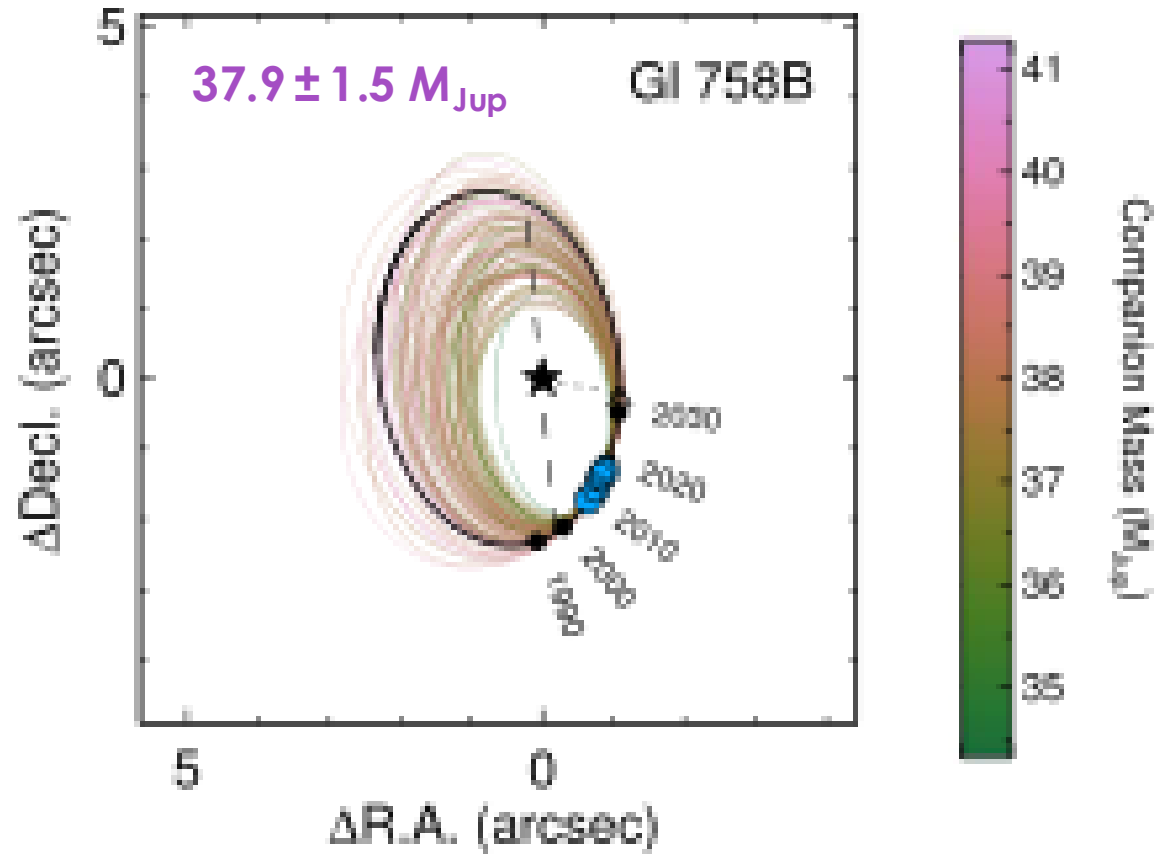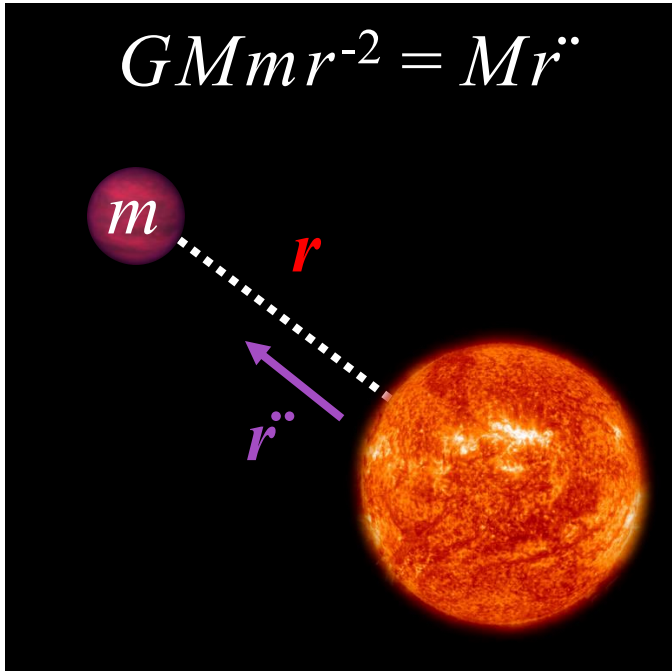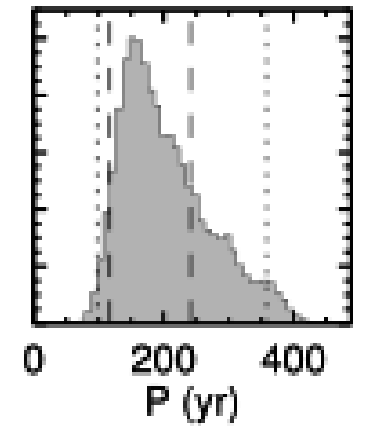
Challenges in measuring dynamical masses.

$$G(M+m)/4\pi^2 = a^3/P^2$$

$$GMmr^{-2} = M\ddot{r}$$

m

r

$\ddot{r}$

M

Visual binaries

Companions

Trent Dupuy (U. of Edinburgh)
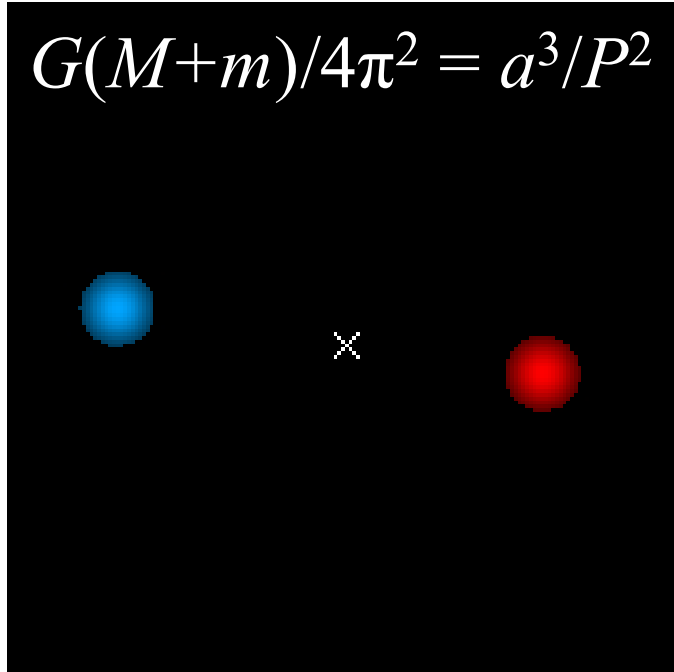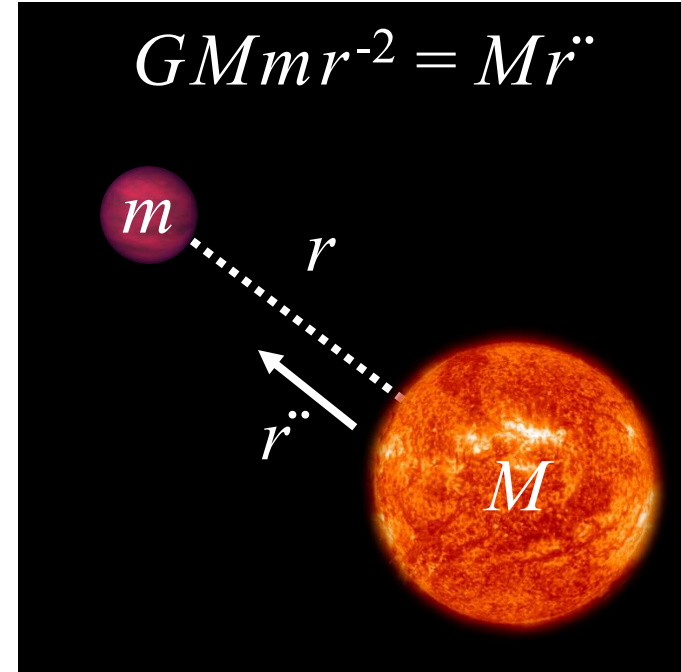
Visual binaries
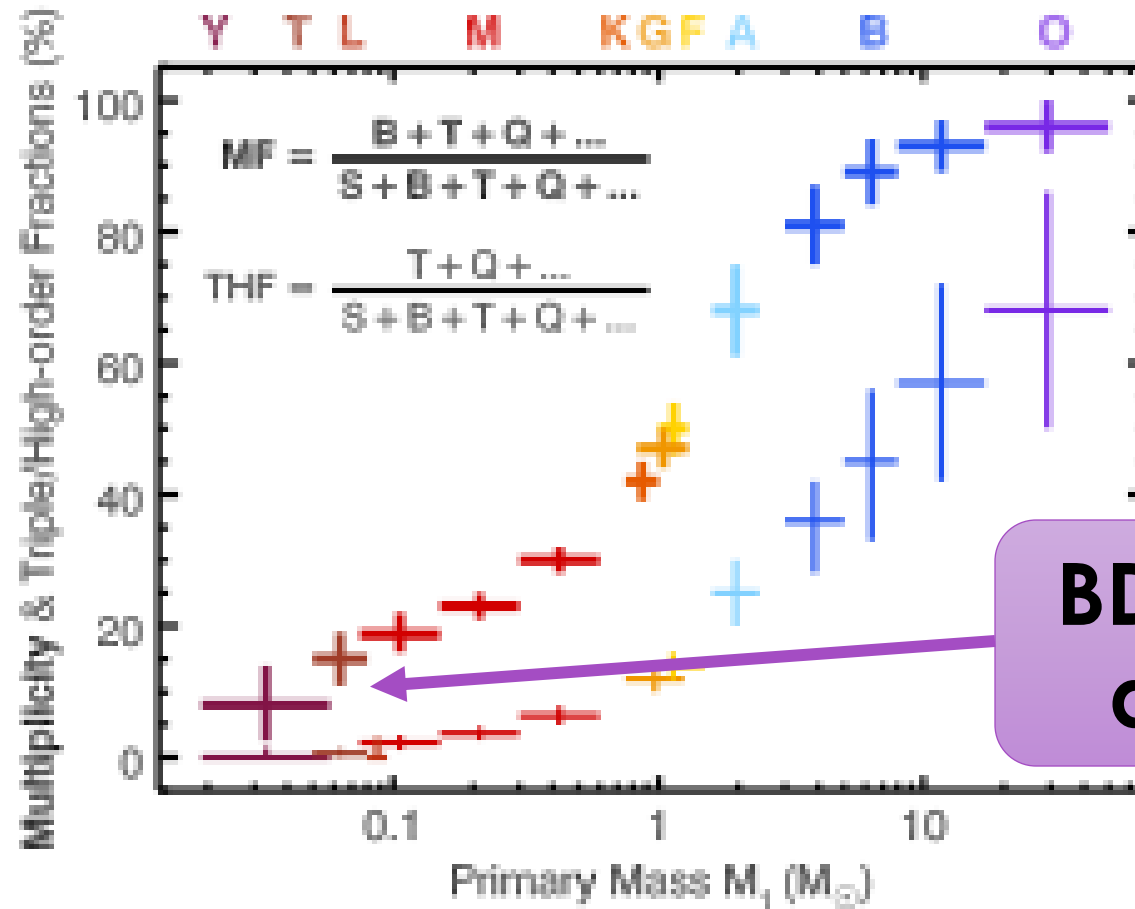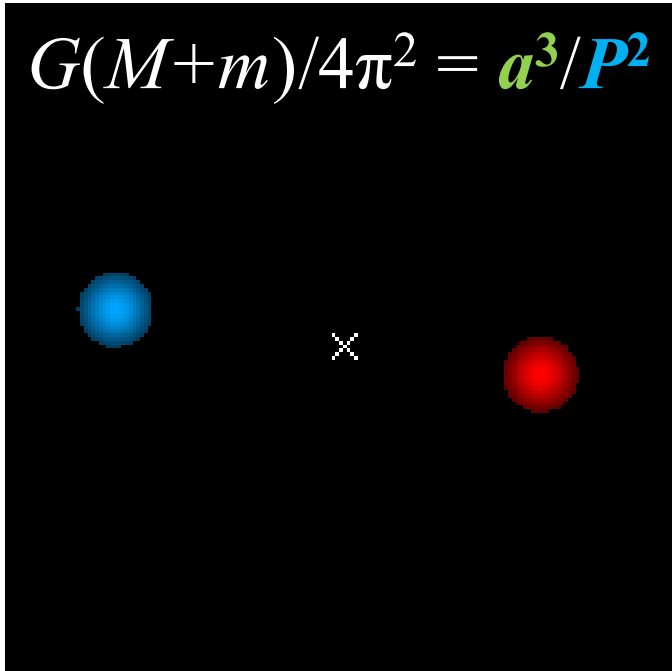
$$G(M+m)/4\pi^2 = a^3/P^2$$

Offner et al. (2023)

BD binaries are rare.

Trent Dupuy (U. of Edinburgh)

Visual binaries

$$G(M+m)/4\pi^2 = a^3/P^2$$
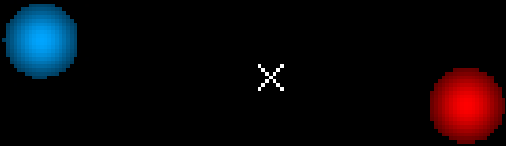
Need a in <u>au</u> not <u>arcsec</u> → precise parallax required. [1% parallax → 3% mass]

Need >30% orbit coverage, but P ~ [(3 au)^3/(0.07 M$_\odot$)]$^{1/2}$ ~ <u>20 yr</u>

Trent Dupuy (U. of Edinburgh)

Visual binaries

$$G(M+m)/4\pi^2 = a^3/P^2$$
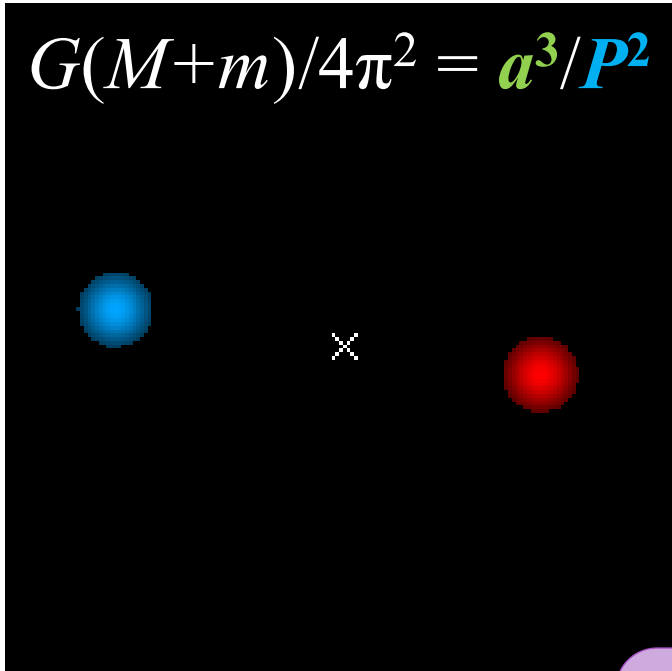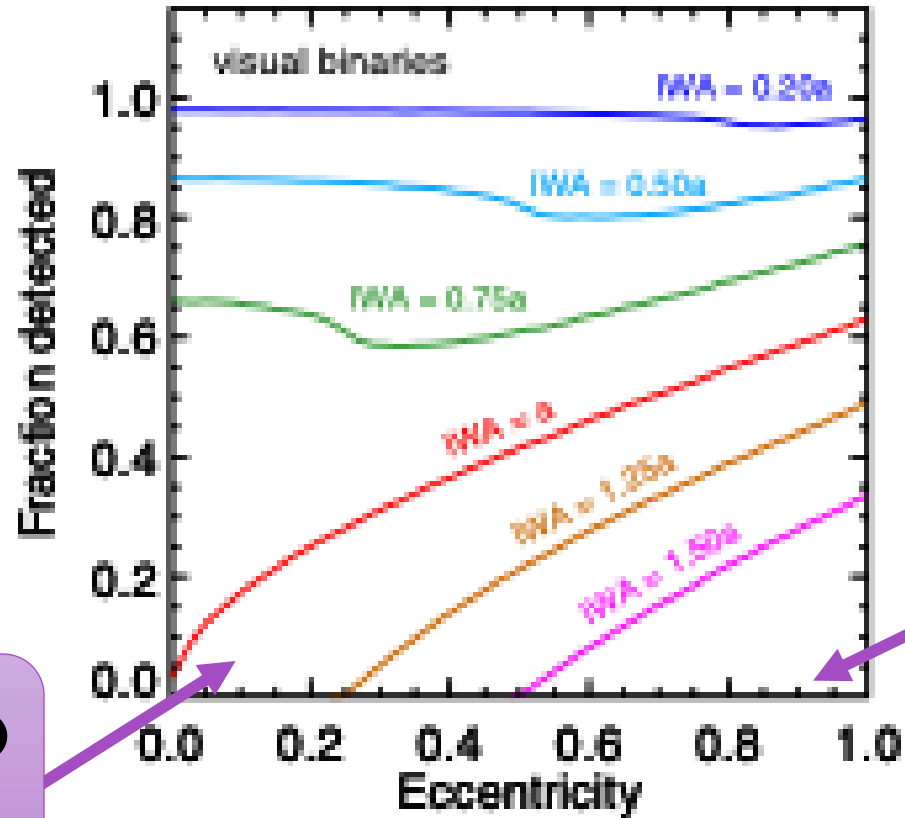
Dupuy & Liu (2011)

Harder to monitor.
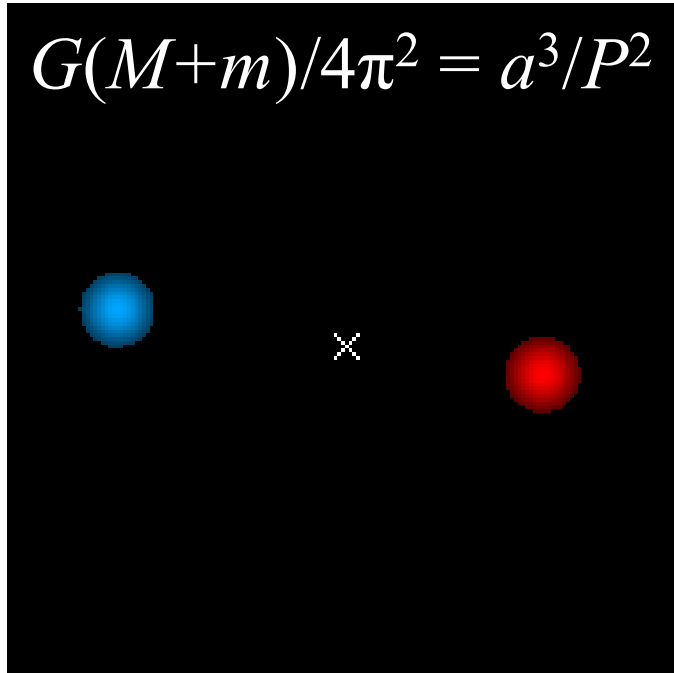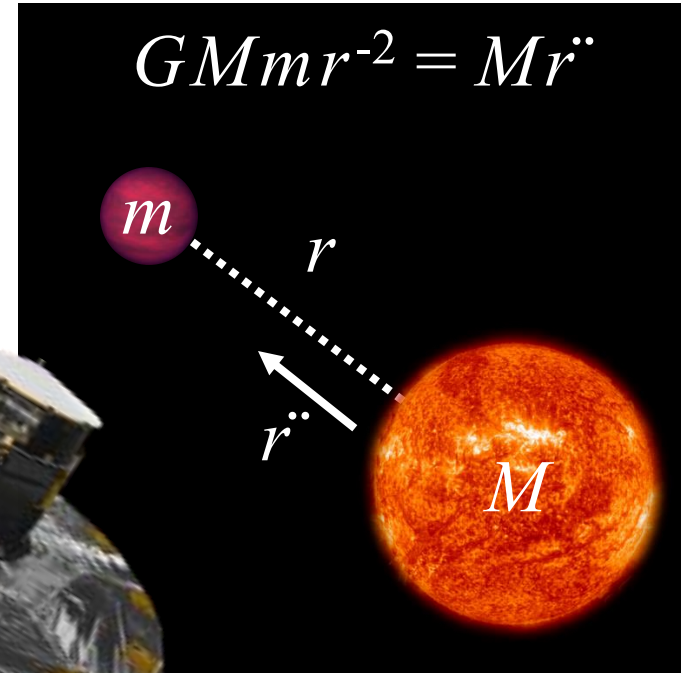
Harder to find.

Methods for measuring dynamical masses.

$$G(M+m)/4\pi^2 = a^3/P^2$$

$$GMmr^{-2} = M\ddot{r}$$

Gaia DR2 → 2018

m

r

$\ddot{r}$

M

Visual binaries

Companions

Trent Dupuy (U. of Edinburgh)

Outline

Why? **How?** **What?** **What next?**

Trent Dupuy (U. of Edinburgh)

First dynamical masses of ultracool (brown?) dwarfs.

Is it a brown dwarf or is it a star?

LHS 1070BC
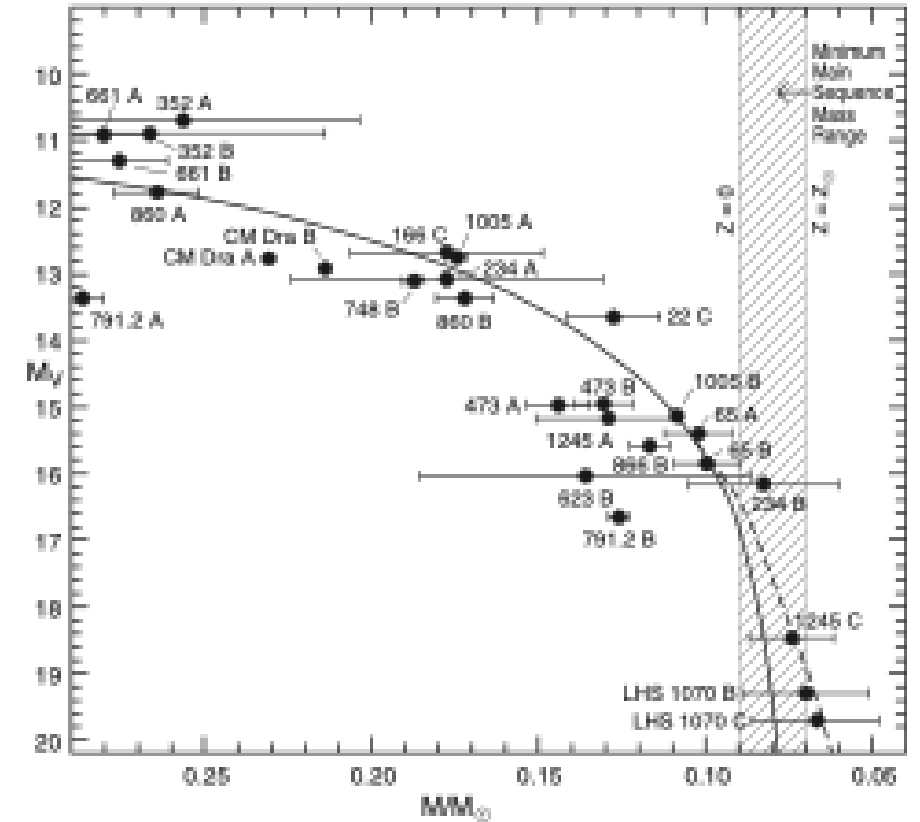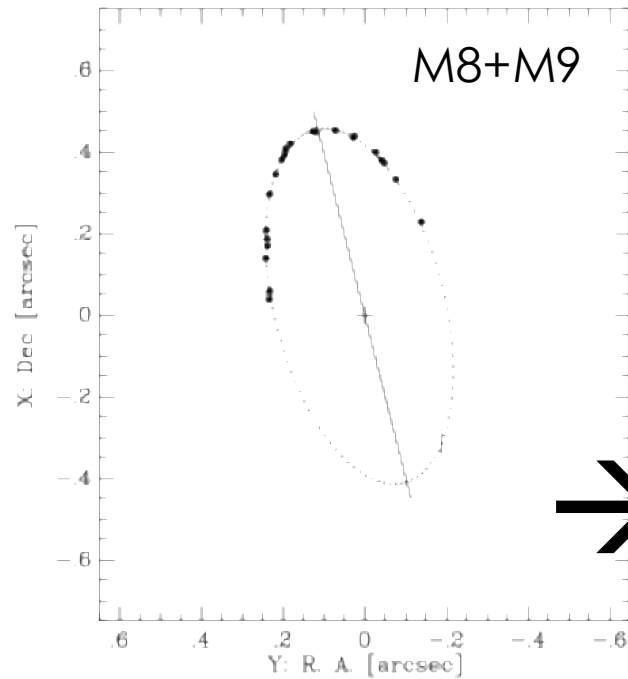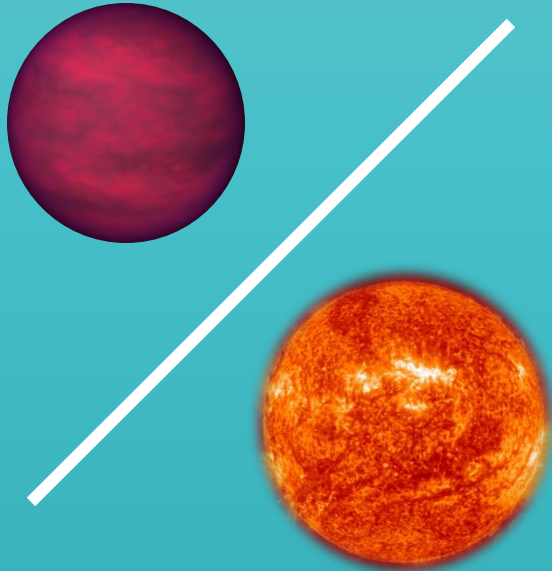

M8+M9
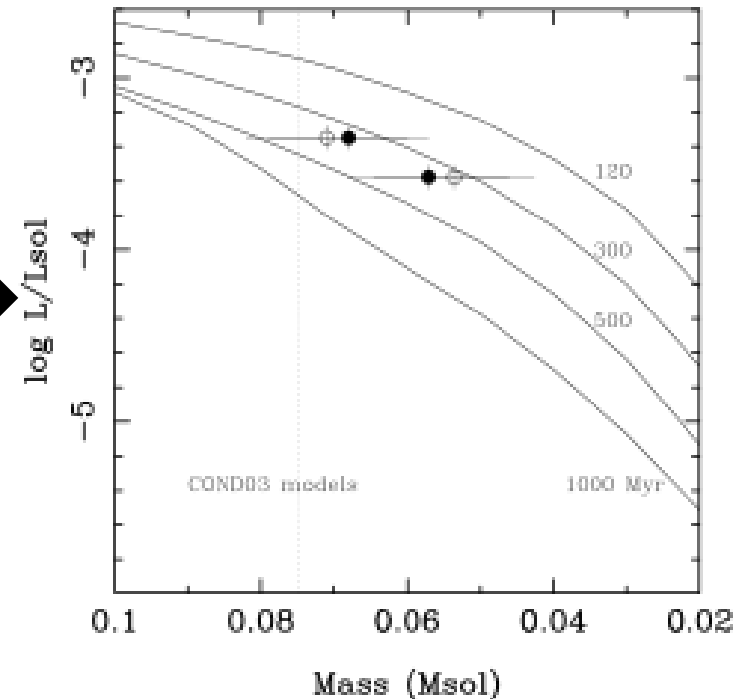
Leinert et al. (2001)

Trent Dupuy (U. of Edinburgh)

First dynamical masses of ultracool (brown?) dwarfs.

Is it a brown dwarf or is it a star?
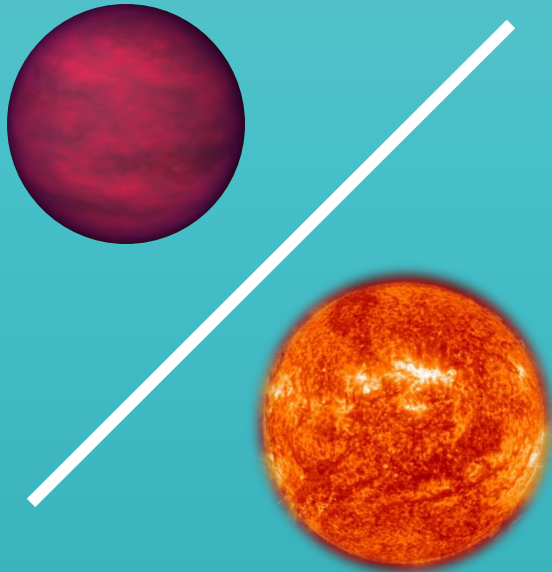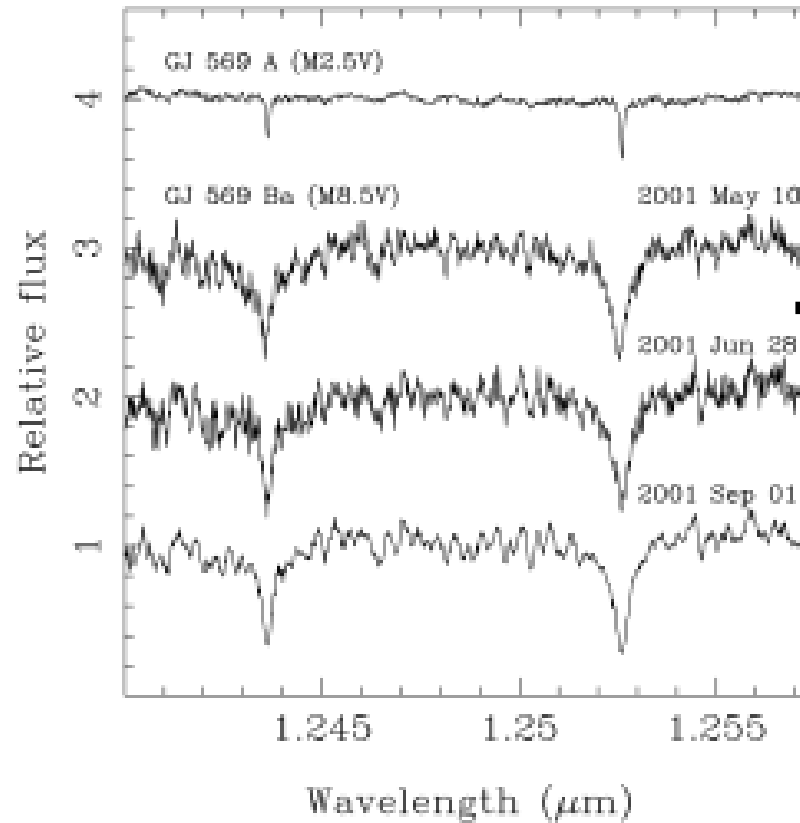
Gliese 569 Bab

Lane et al. (2001)
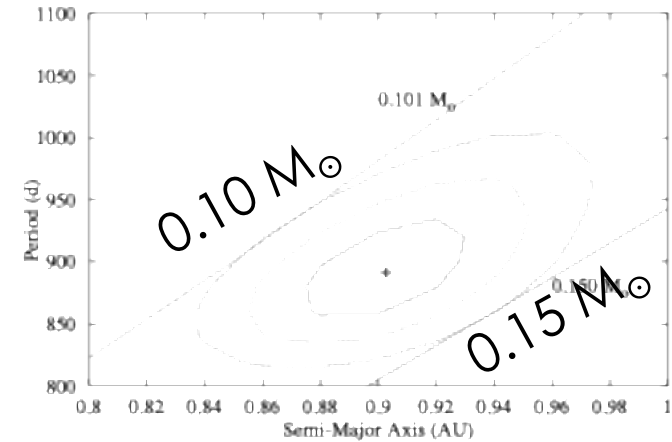
M8.5+M9

First dynamical masses of ultracool (brown?) dwarfs.

Is it a brown dwarf or is it a star?
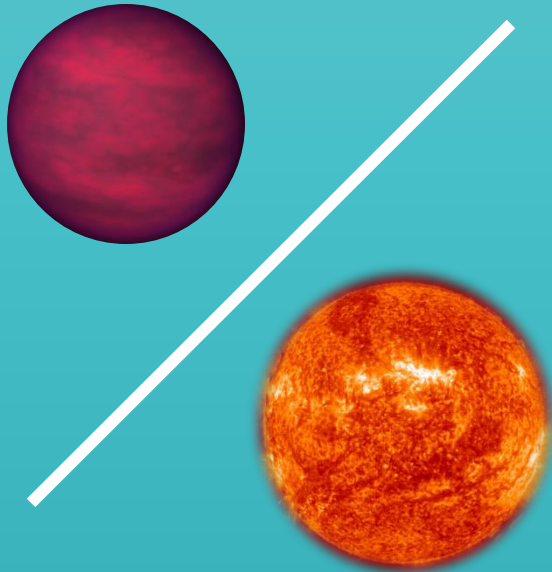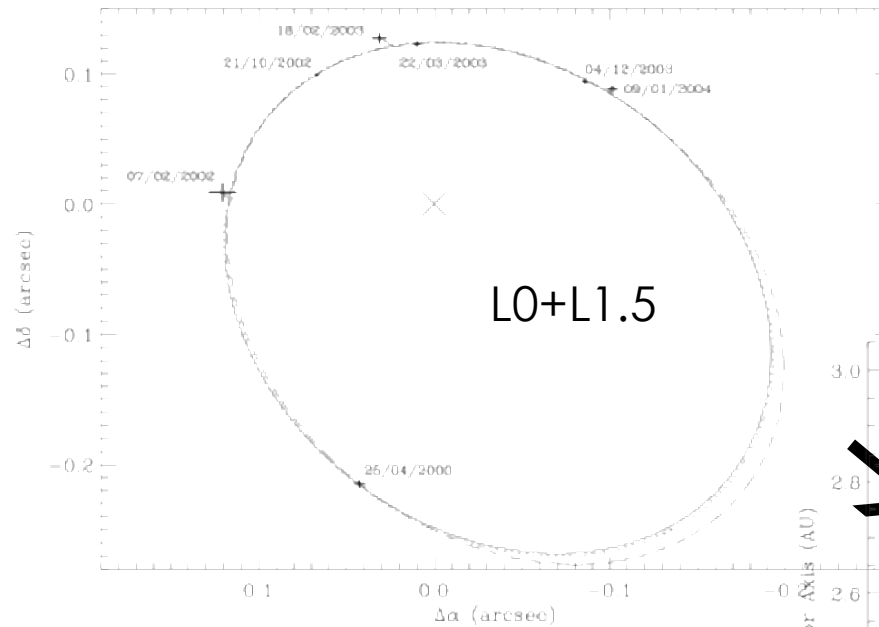
Gliese 569 Bab

Zapatero Osorio et al. (2004)

Trent Dupuy (U. of Edinburgh)
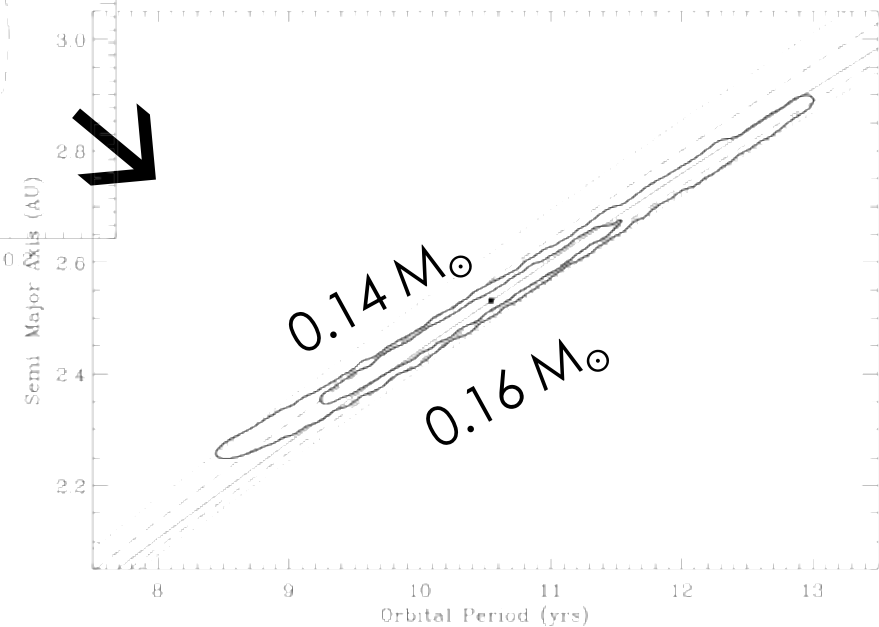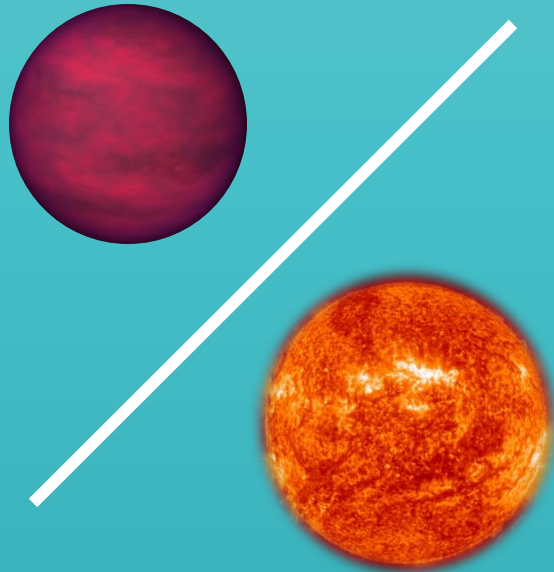
First dynamical masses of ultracool (brown?) dwarfs.

Is it a brown dwarf or is it a star?

2MASSW J0746425+2000321AB

Bouy et al. (2004)
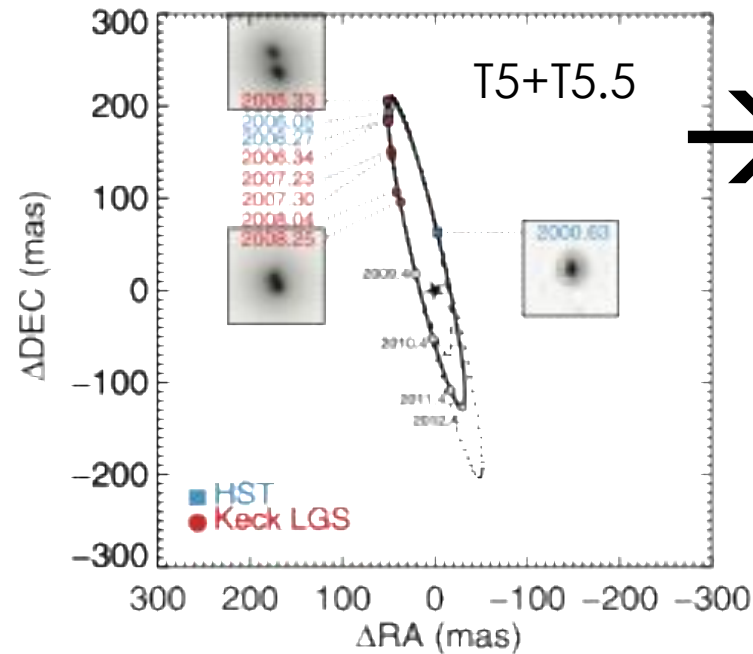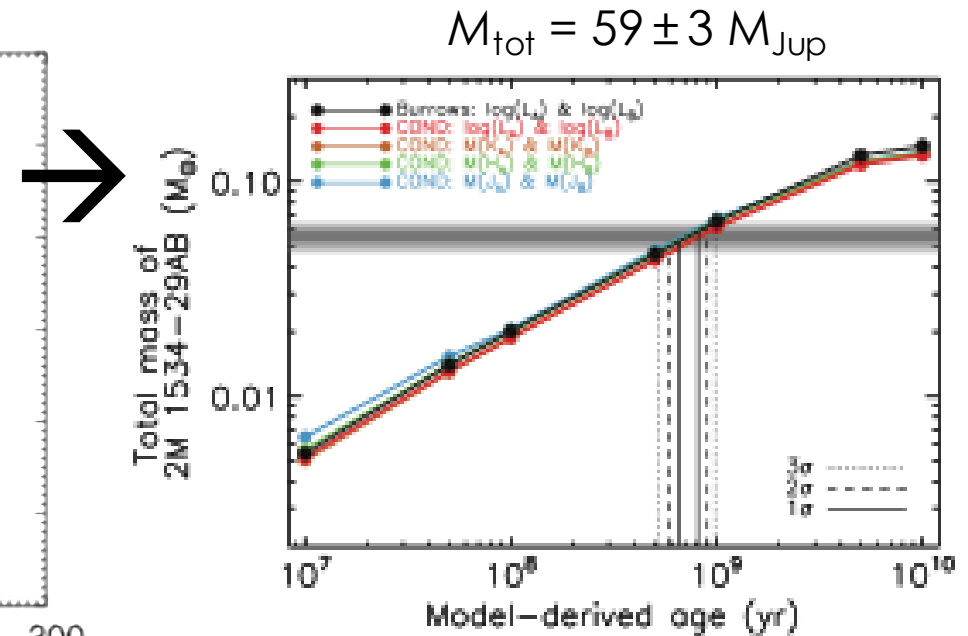
L0+L1.5

0.14 $M_\odot$

0.16 $M_\odot$

Trent Dupuy (U. of Edinburgh)

First dynamical masses of ultracool (brown?) dwarfs.

Is it a brown dwarf or is it a star?

2MASS J15344984-2952274AB

T5+T5.5

Liu et al. (2008)

$M_{tot} = 59 \pm 3\ M_{Jup}$

Cardoso et al. (2009)
eps Ind Bab (T1+T6)
$M_{tot} = 121\ M_{Jup}$

Trent Dupuy (U. of Edinburgh)

Quantitative empirical tests.

2MASS J15344984-2952274AB

Are *atmospheric* models accurate?

log g = 5.00 → 4.25

30 M_{Jup} → 10 M_{Jup}

Liu et al. (2008)

Quantitative empirical tests.

Are *atmospheric* models accurate?

log *g* = 5.00 → 4.25

30 M_{Jup} → 10 M_{Jup}

Trent Dupuy (U. of Edinburgh)

Liu et al. (2008)
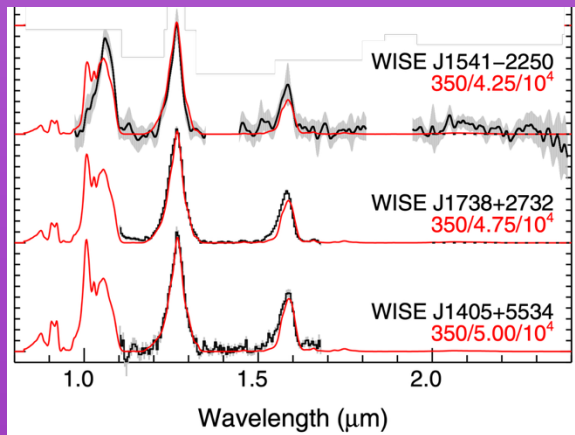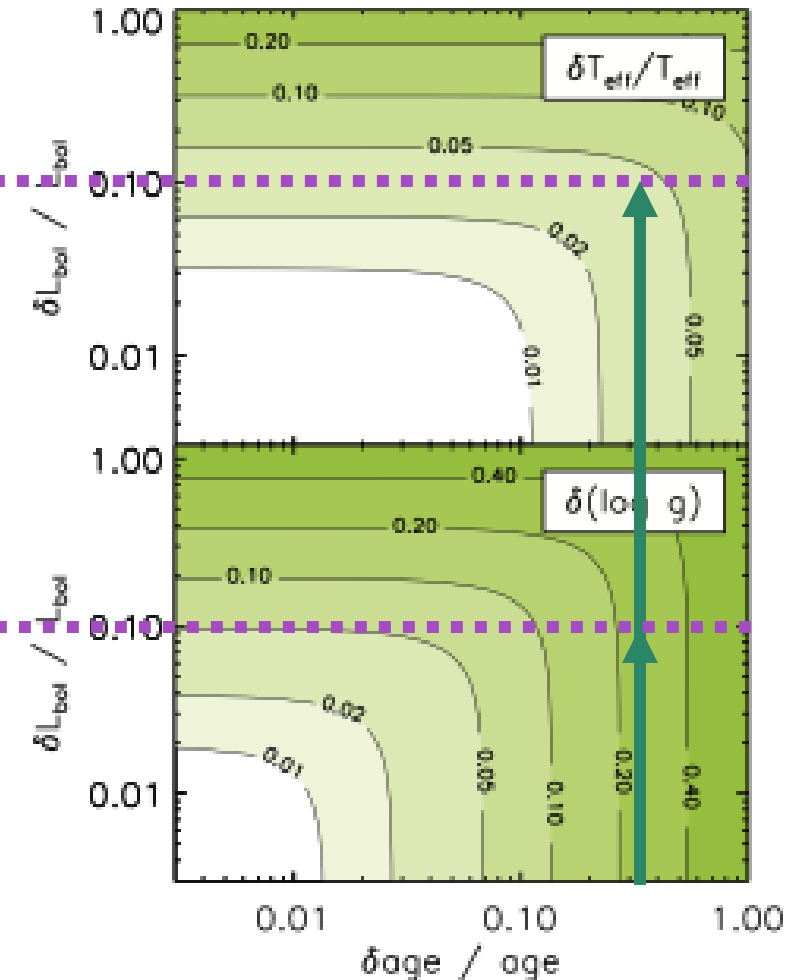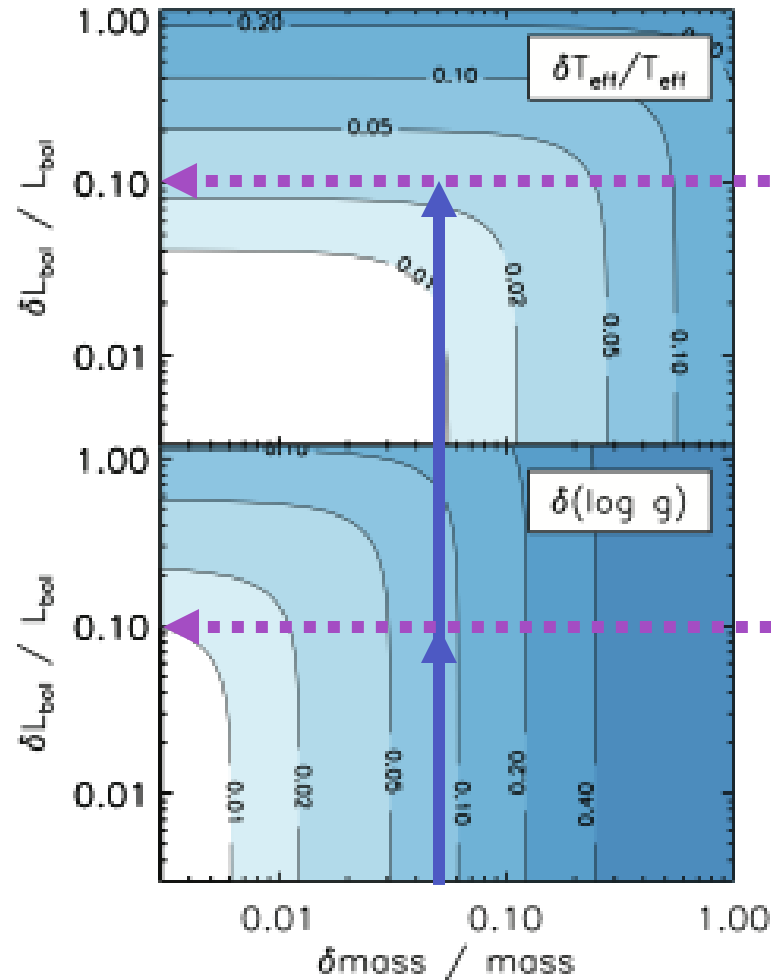
Aside: yes, we can reliably estimate L_{bol}

rms ~ 0.06 dex

Sanghi et al. (2023)

Trent Dupuy (U. of Edinburgh)
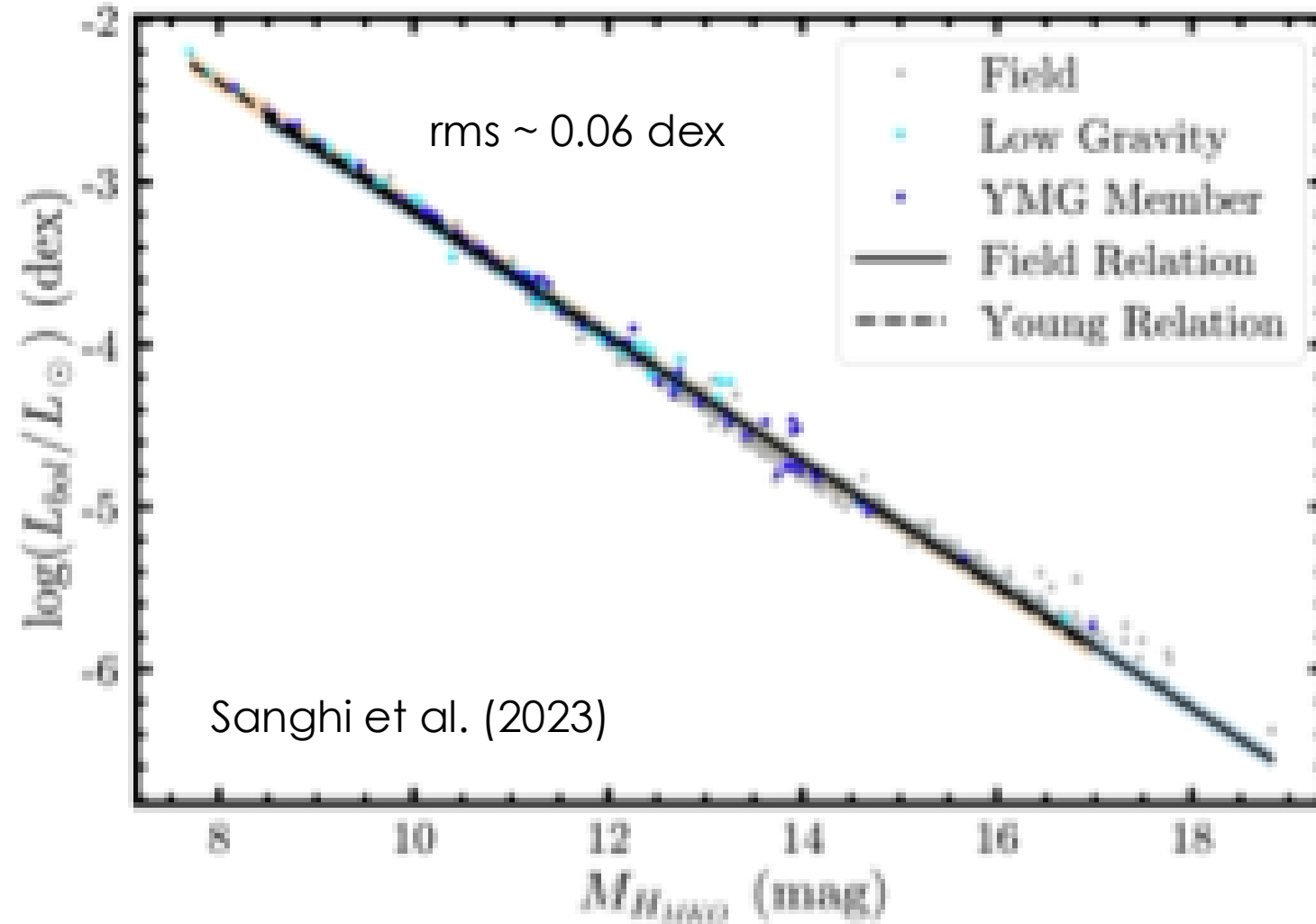
Quantitative empirical test: mass, L_{bol}, *and* age.

Are *evolutionary* models accurate?

HD 130948BC
$M_{tot} = 0.109 \pm 0.003 \ M_{Sun}$

Dupuy et al. (2009, 2014)

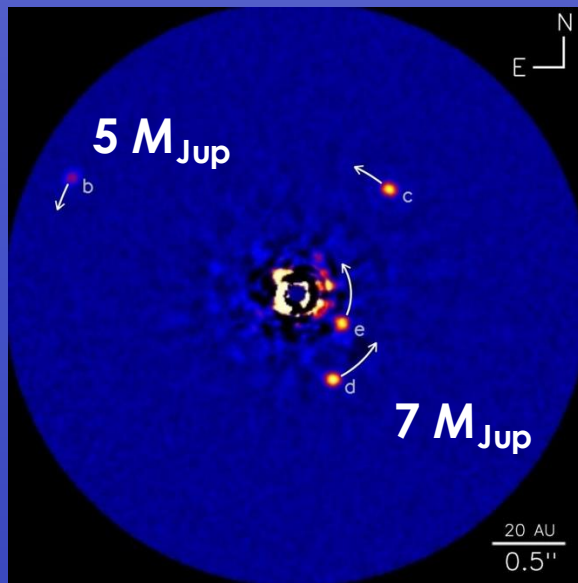HD 130948B

Lyon
Tucson

M7−L2
L3−L9
T0−T4
T5−T9

5 AU

1 second = 2 years
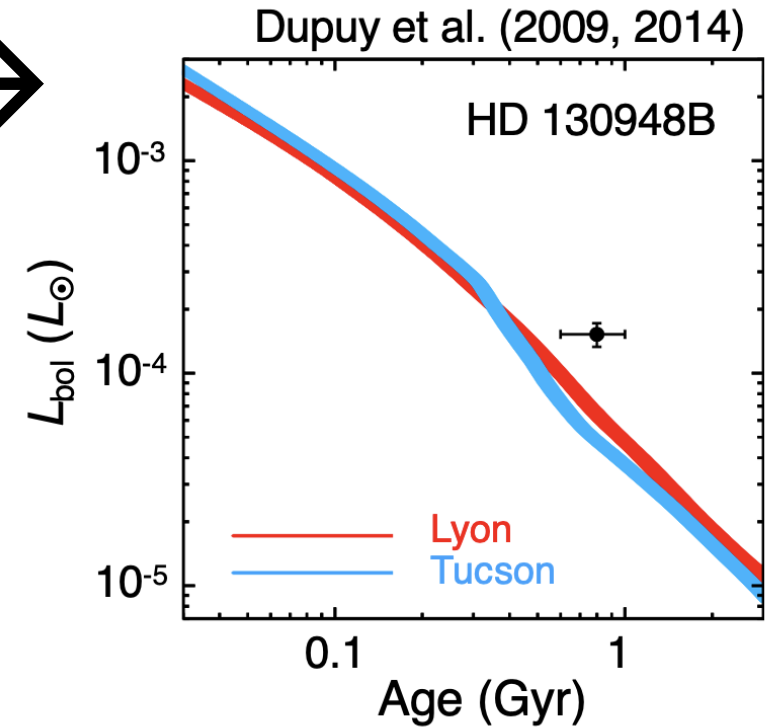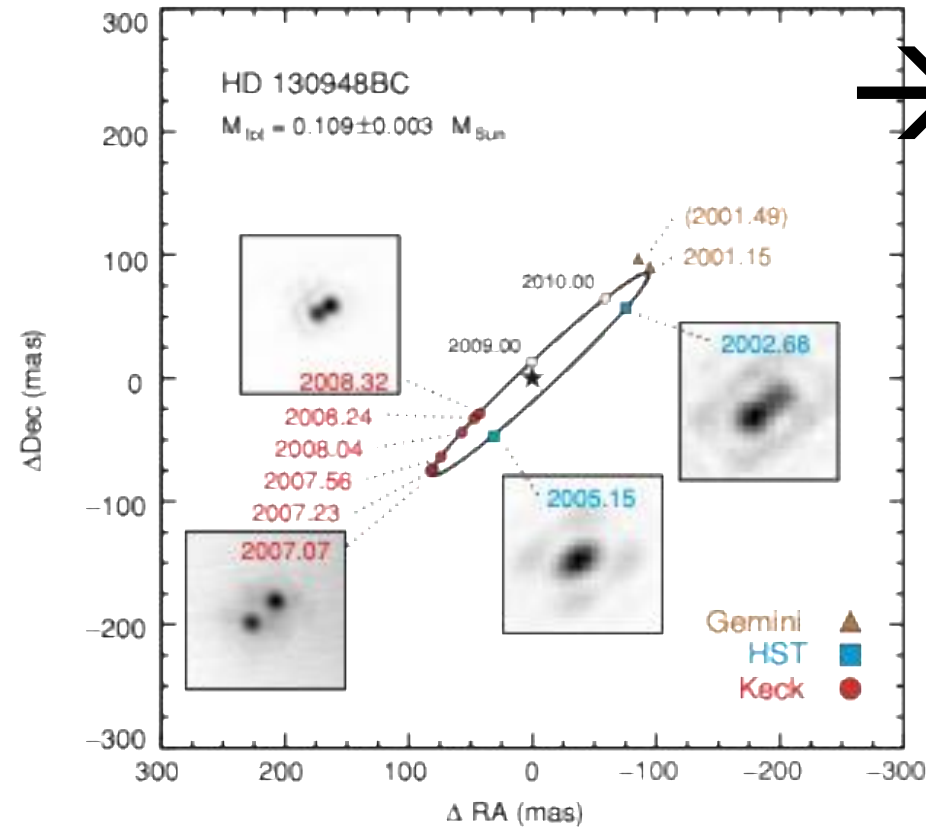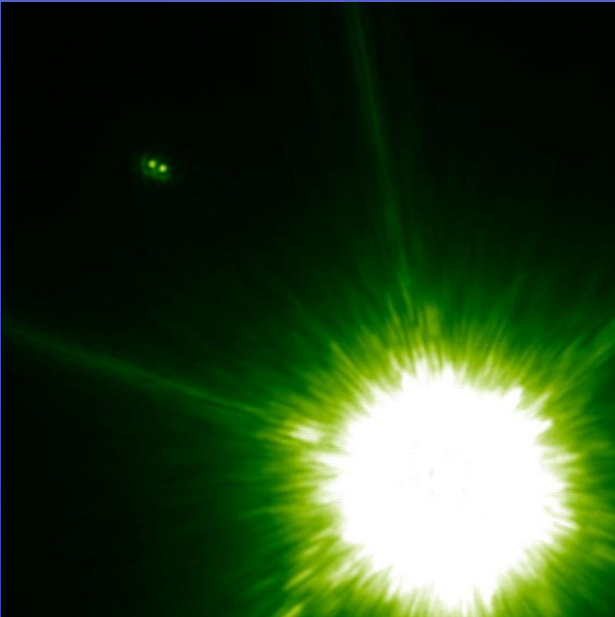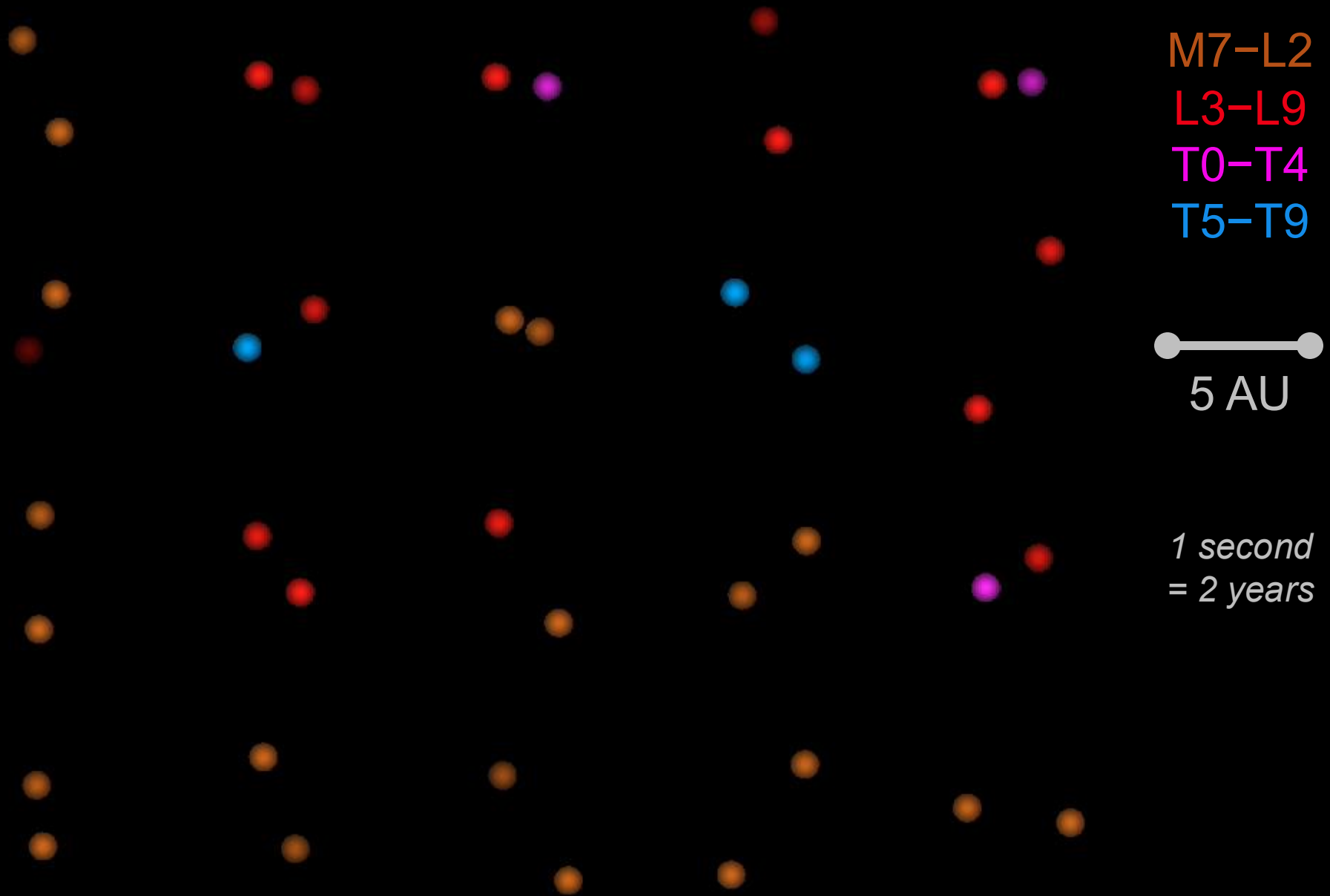
Dupuy et al. (2015, 2016); Dupuy & Liu (2017)

Reasons for measuring dynamical masses.

Are *evolutionary* models accurate?
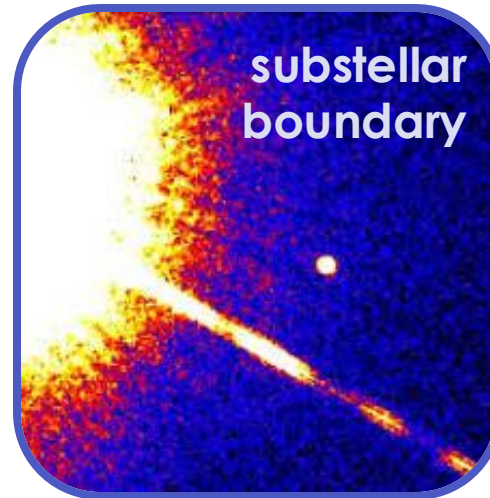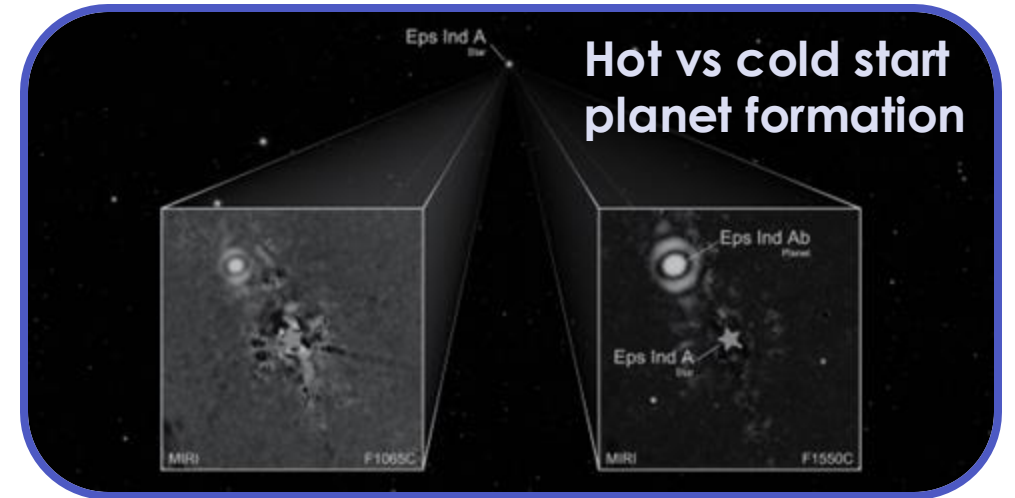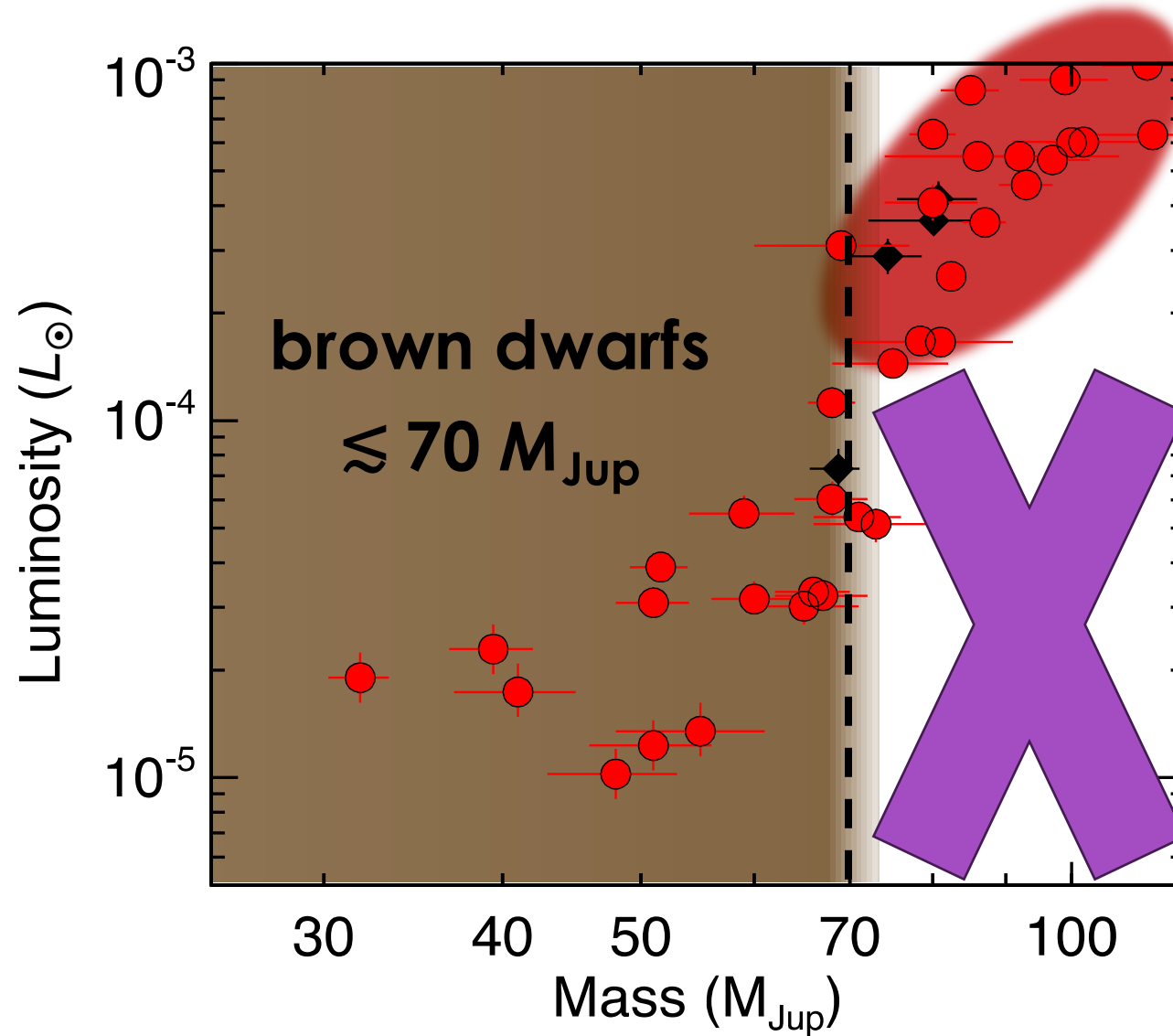

5 M_{Jup}

7 M_{Jup}

N
E

20 AU
0.5"

IMF

Lithium depletion

TEIDE 1

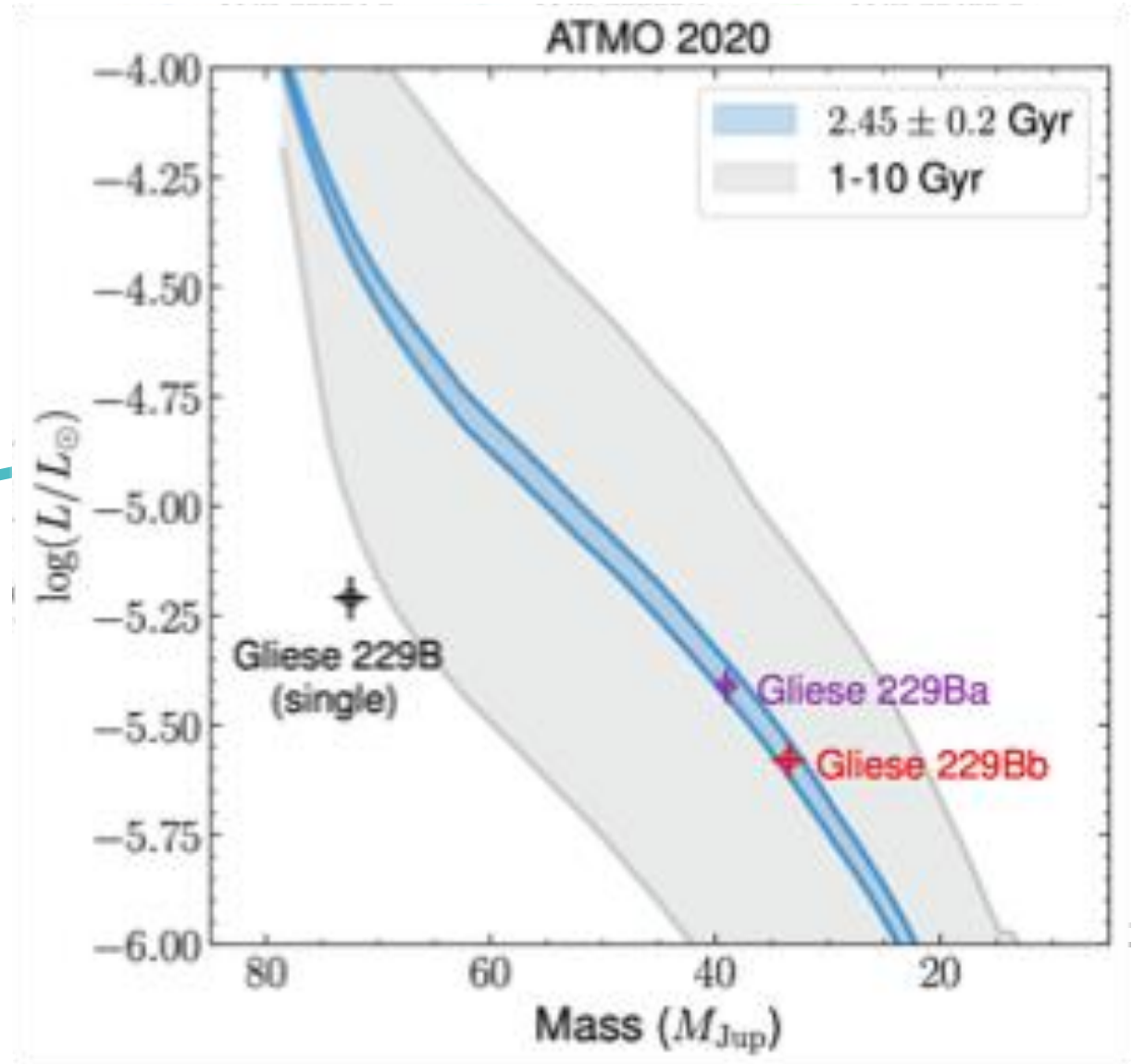substellar boundary
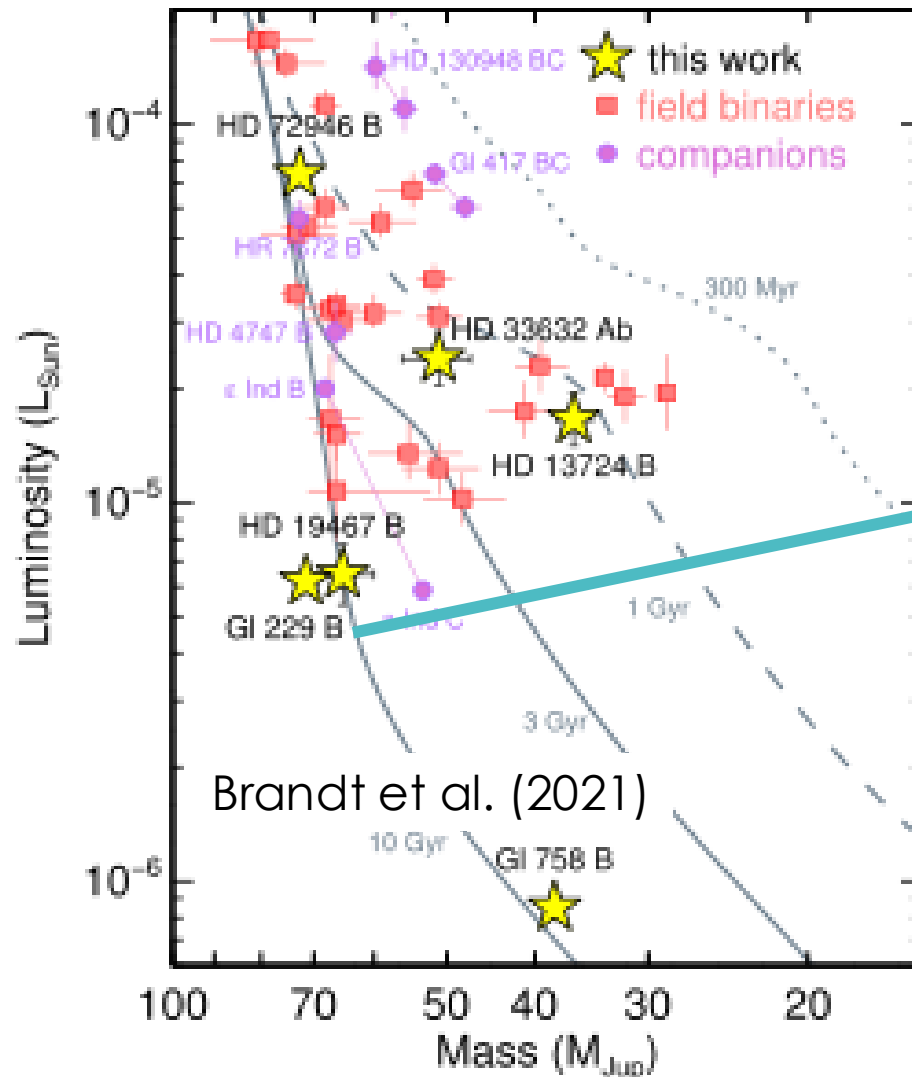

Hot vs cold start planet formation

Eps Ind A

Eps Ind Ab

Eps Ind A

MIRI   F1065C

MIRI   F1550C

Trent Dupuy (U. of Edinburgh)

Where is the end of the main sequence?

brown dwarfs ≲ 70 M_{Jup}

Dupuy & Liu (2017)

Luminosity ($L_\odot$)

Mass (M_{Jup})

Trent Dupuy (U. of Edinburgh)

Could the substellar boundary be higher?

Brandt et al. (2021)

ATMO 2020

Trent Dupuy (U. of Edinburgh)

What about clouds?

cloud free (Baraffe et al. 2003)
cloudy (Chabrier et al. 2000)
hybrid (Saumon & Marley 2008)

Are *evolutionary* models accurate?

5 M_{Jup}

7 M_{Jup}

20 AU
0.5"

Luminosity ($L_\odot$)

10^{-4}

10^{-5}

60 M_{Jup}

40 M_{Jup}

20 M_{Jup}

10^8 10^9 10^{10}

Age (yr)
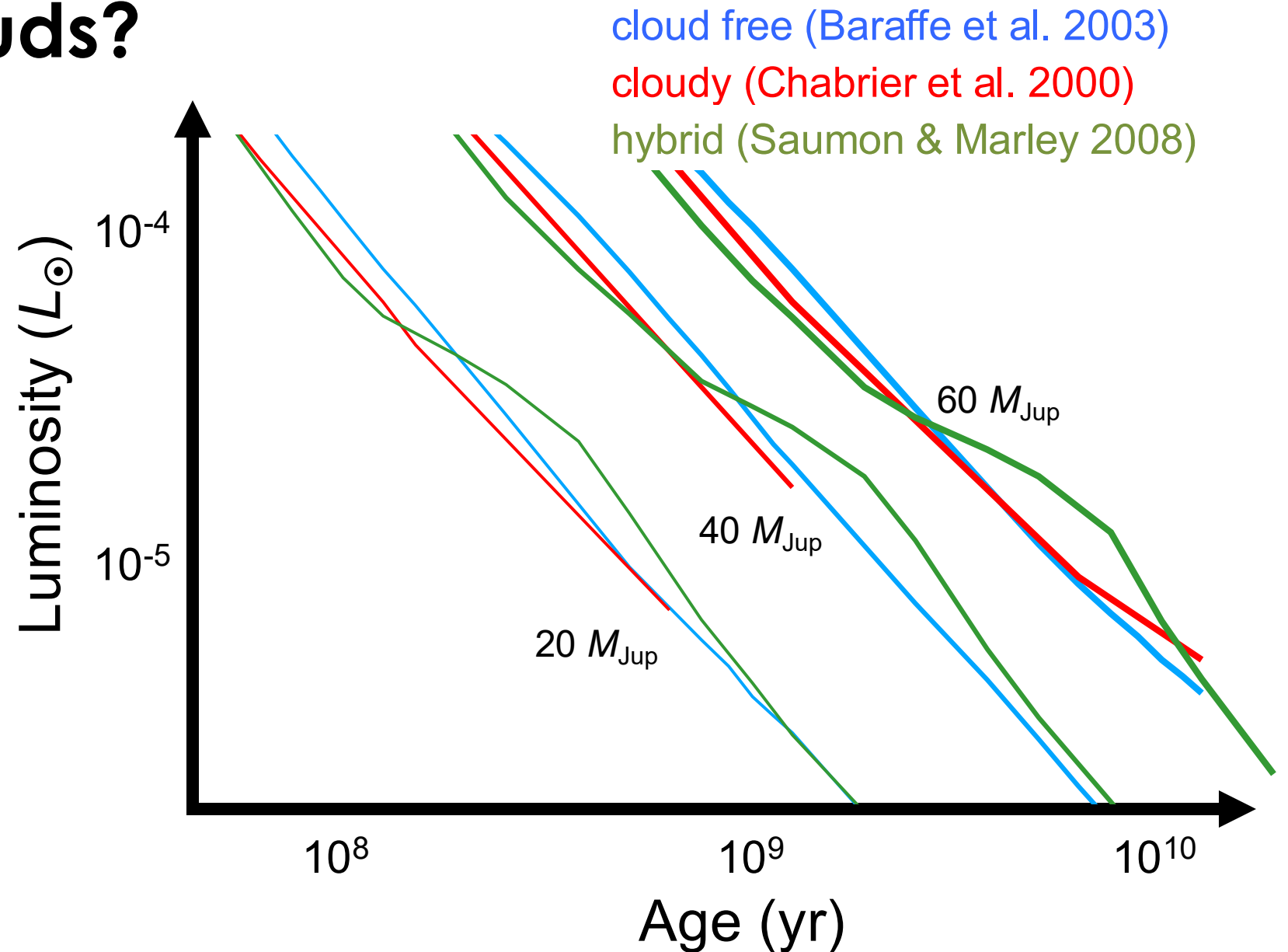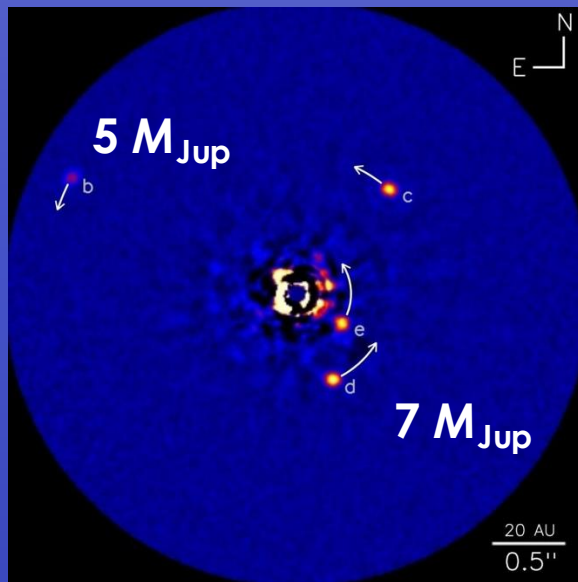
Binary test: components must be coeval!

Dupuy & Liu (2017)

Are *evolutionary* models accurate?

5 M_{Jup}

7 M_{Jup}

Binary test: components must be coeval!

Chen et al. (2022)

$L \propto M^{2.5-3.0}$

$L \propto M^{5.3\pm0.3}$

ε Ind B

ε Ind C

2 Gyr

3 Gyr

4 Gyr

5 Gyr

6 Gyr

ATMO 2020

SM08 hybrid
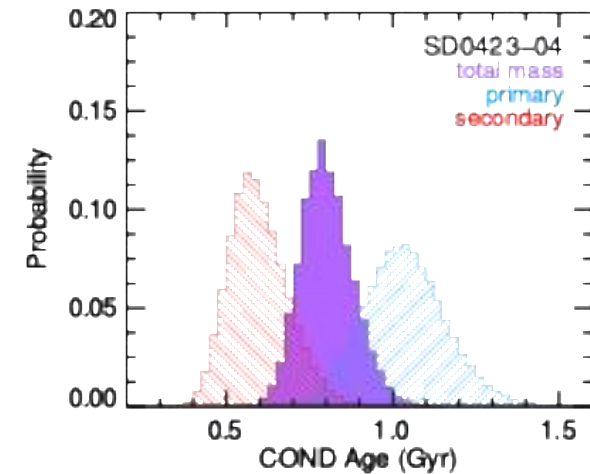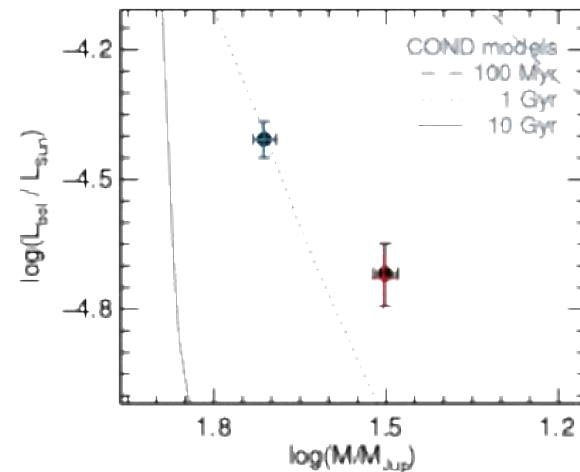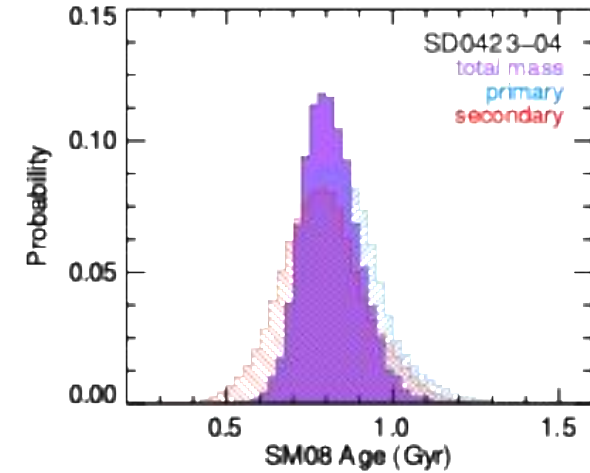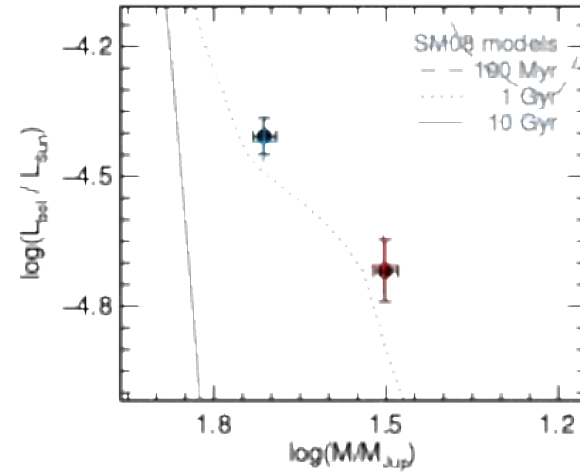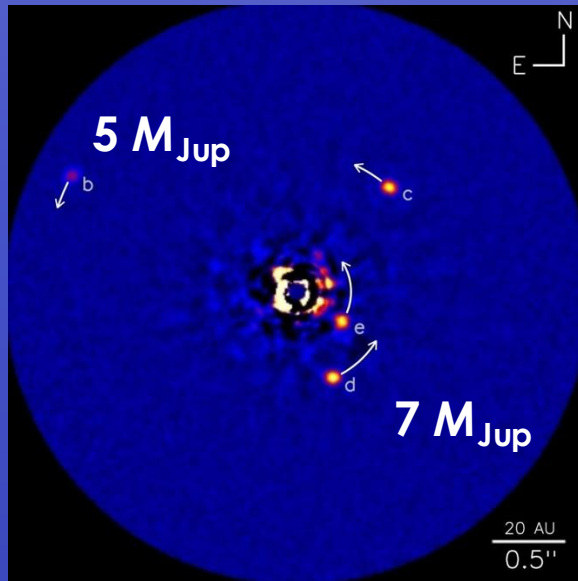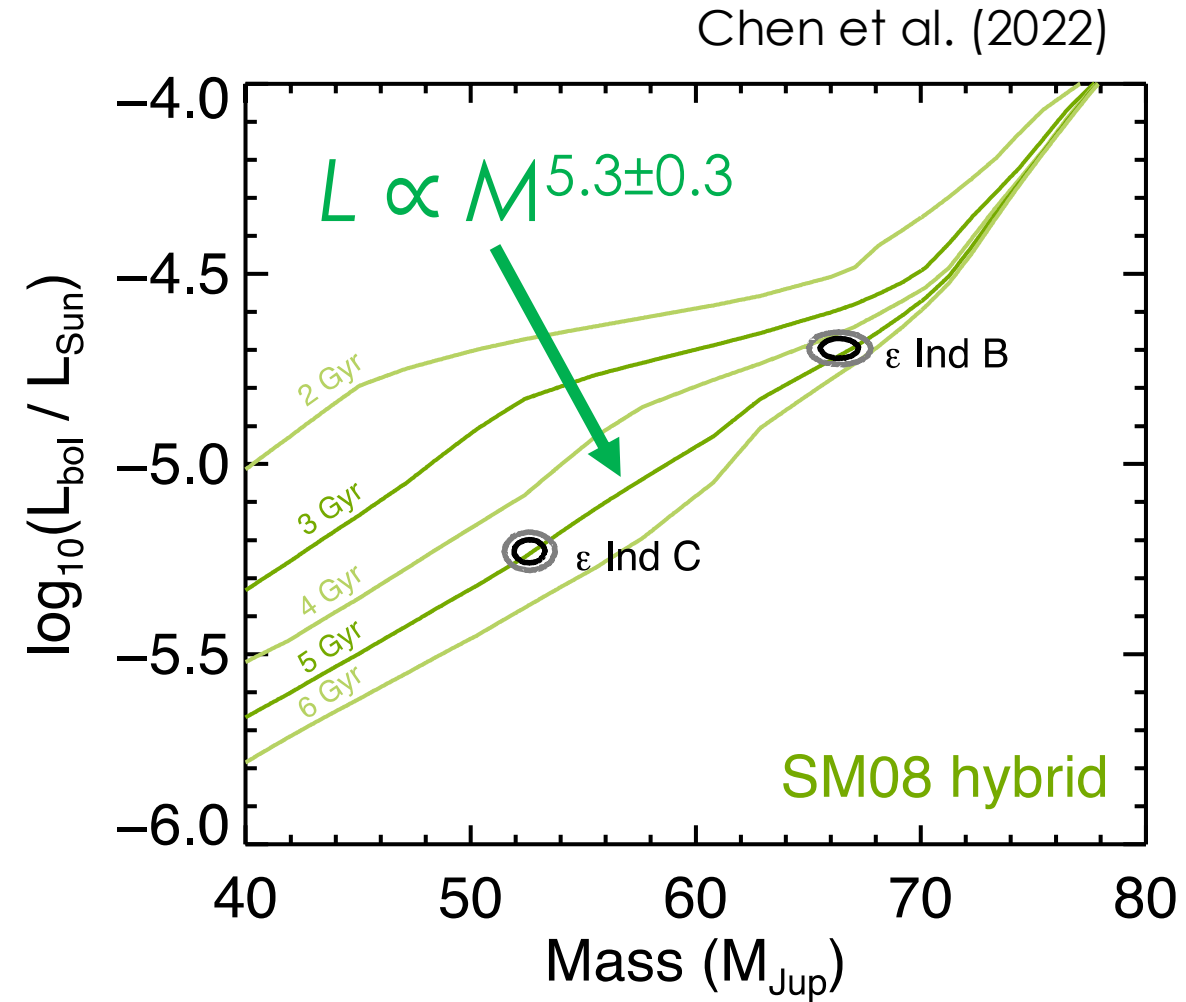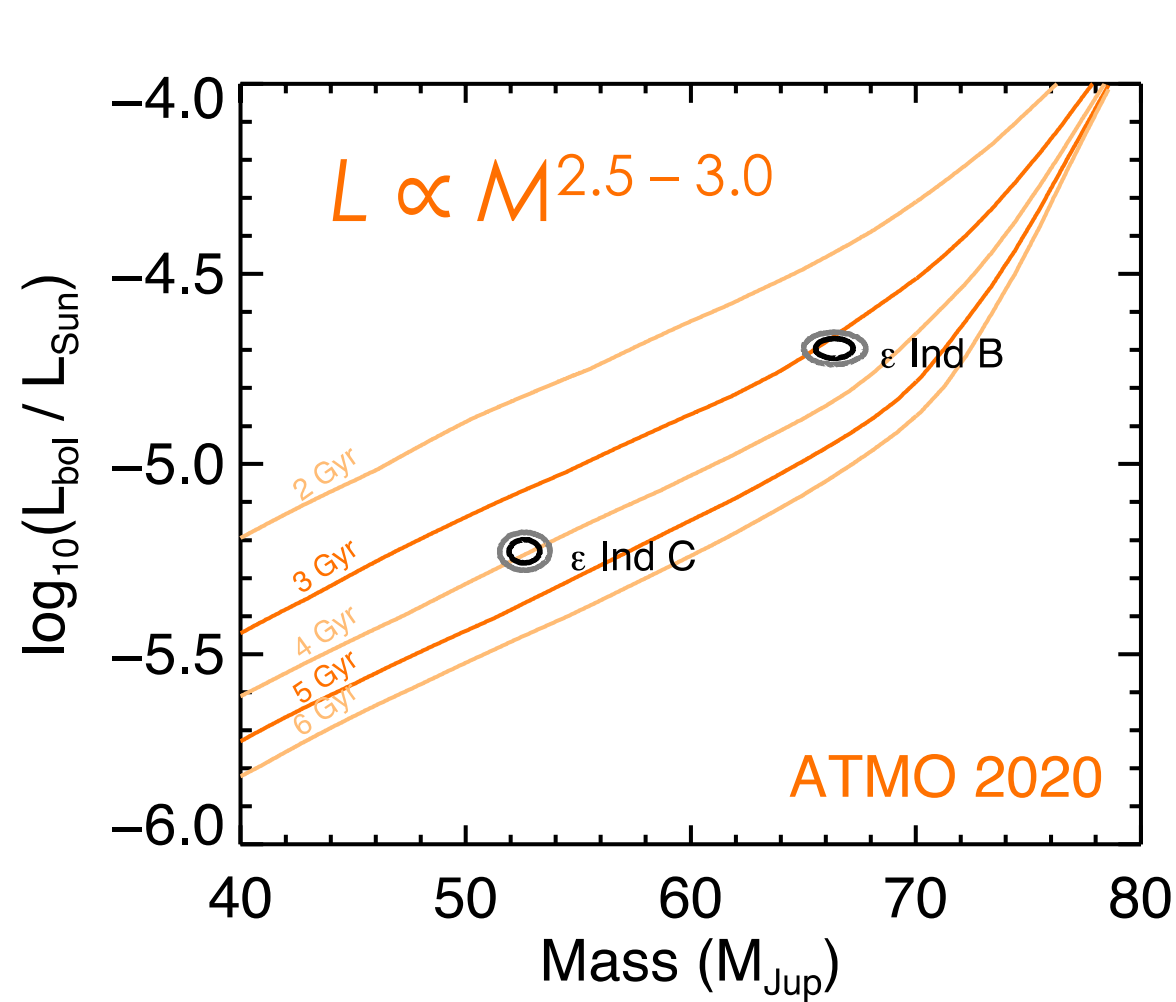
For masses also see: Cardoso (2012)

Trent Dupuy (U. of Edinburgh)

Reasons for measuring dynamical masses.

Are *evolutionary* models accurate?
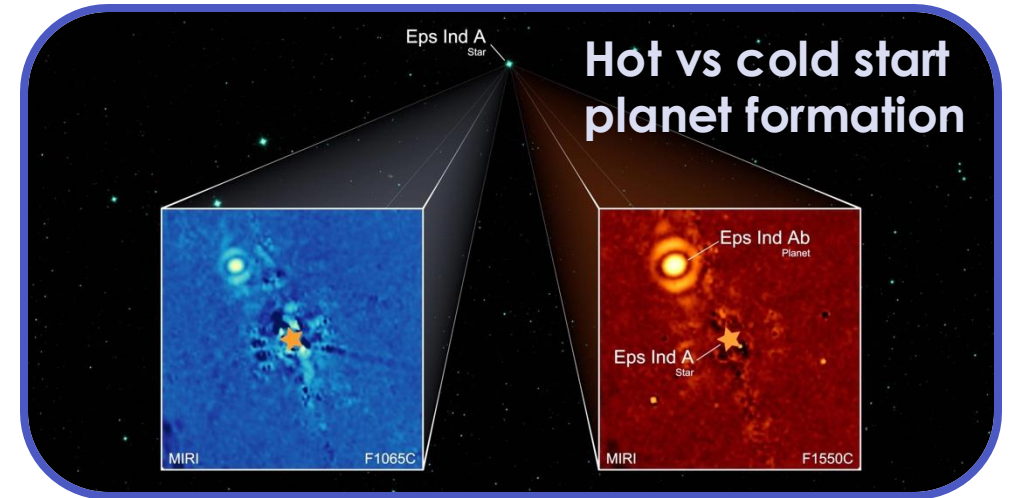
5 M$_{Jup}$

7 M$_{Jup}$

20 AU
0.5"

IMF

Lithium depletion

TEIDE 1

substellar boundary

Hot vs cold start planet formation

Eps Ind A Star

Eps Ind Ab Planet

Eps Ind A Star

MIRI F1065C

MIRI F1550C

Trent Dupuy (U. of Edinburgh)

t < t_KH

51 Eri b

5 M_Jup

hot start

10 M_Jup

10 M_Jup

5 M_Jup

coldest start
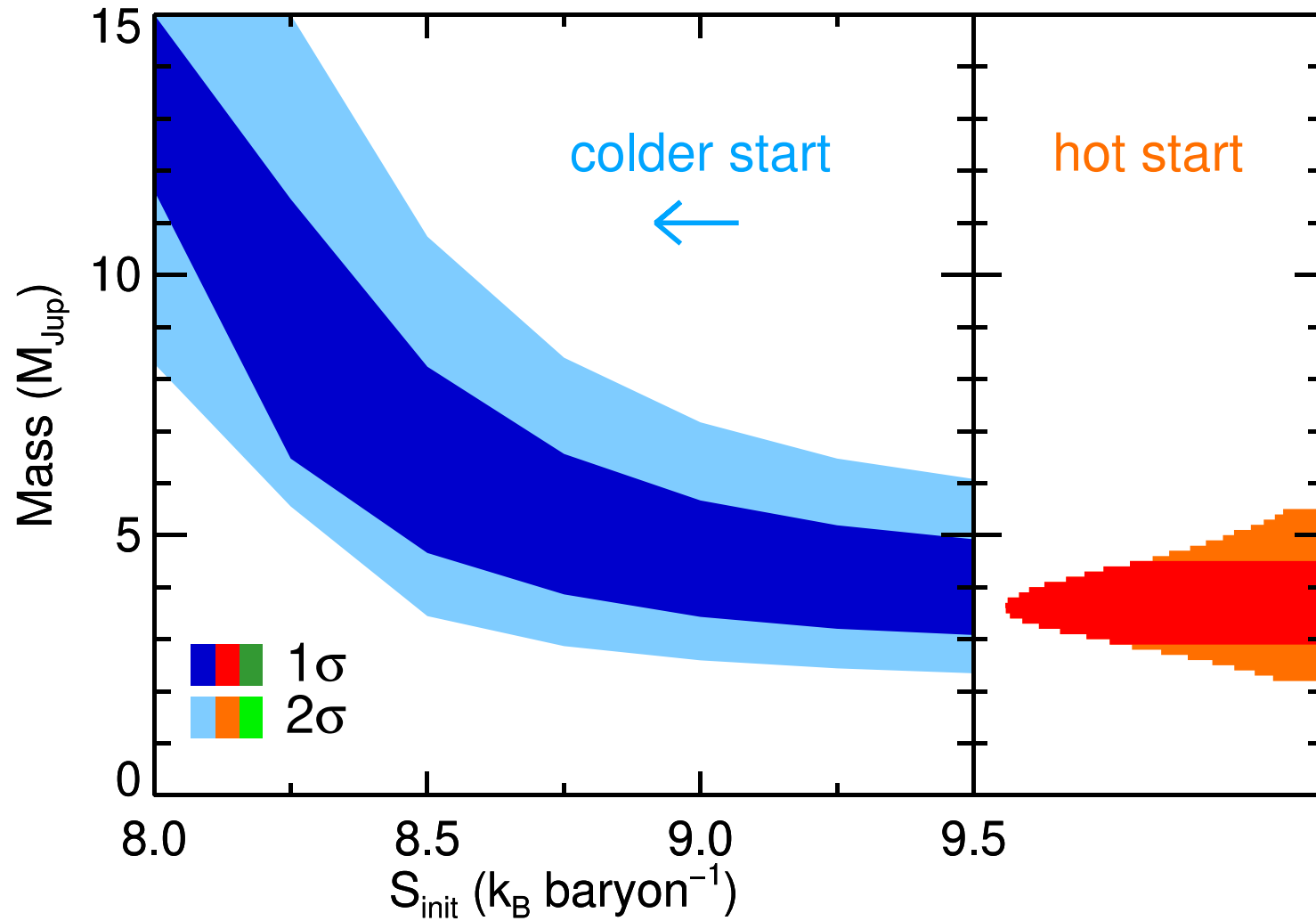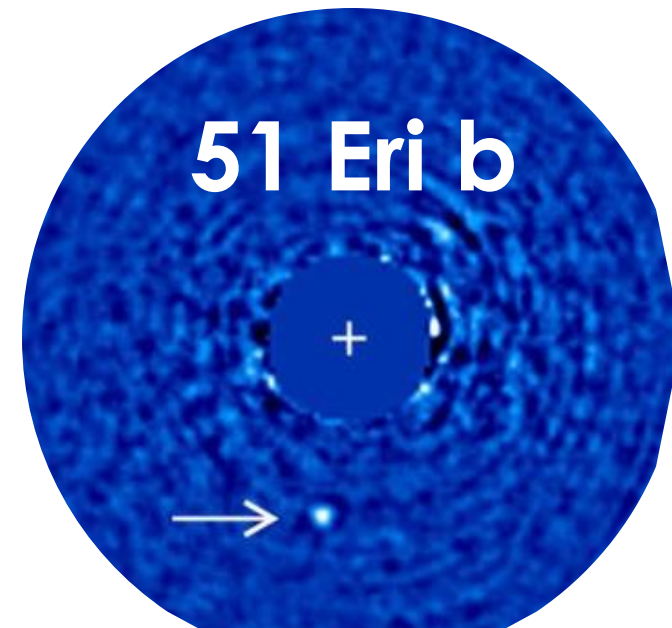
Luminosity (L_Sun)

Age (yr)
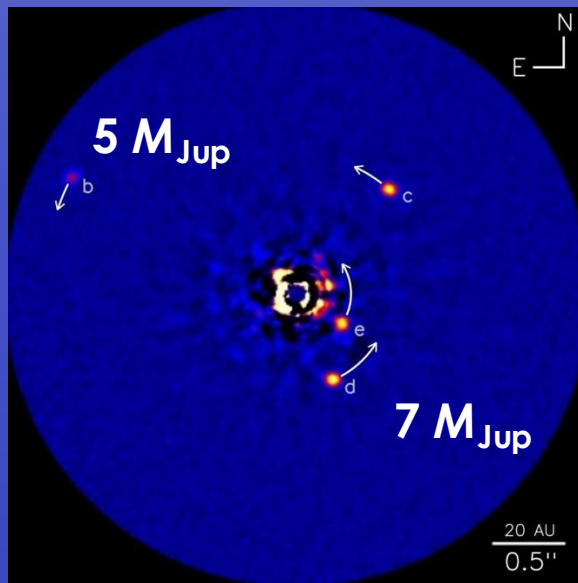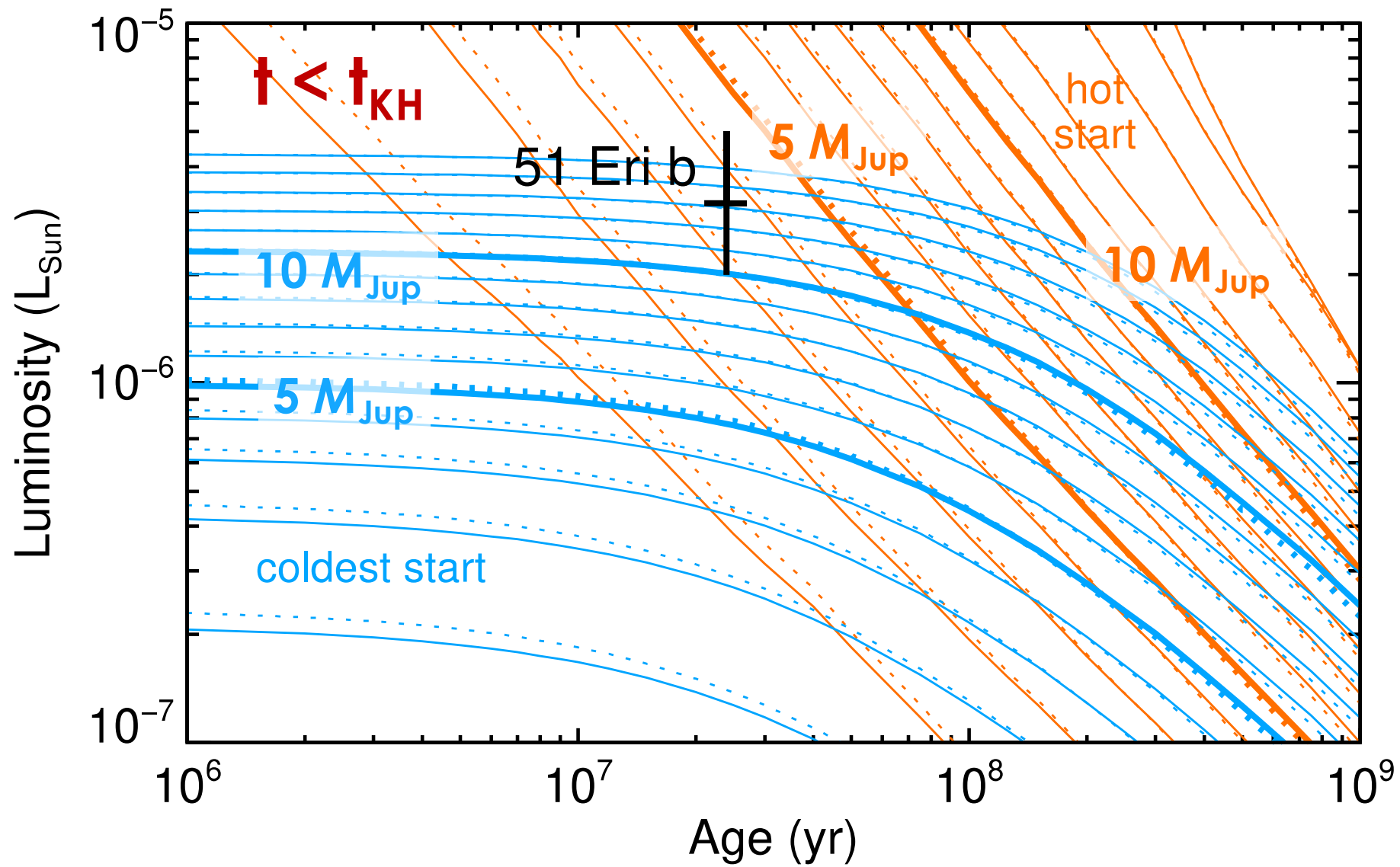
Models from Spiegel & Burrows (2012)

dotted lines are 3x solar metallicity

Given L_{bol}, age, initial entropy → model mass
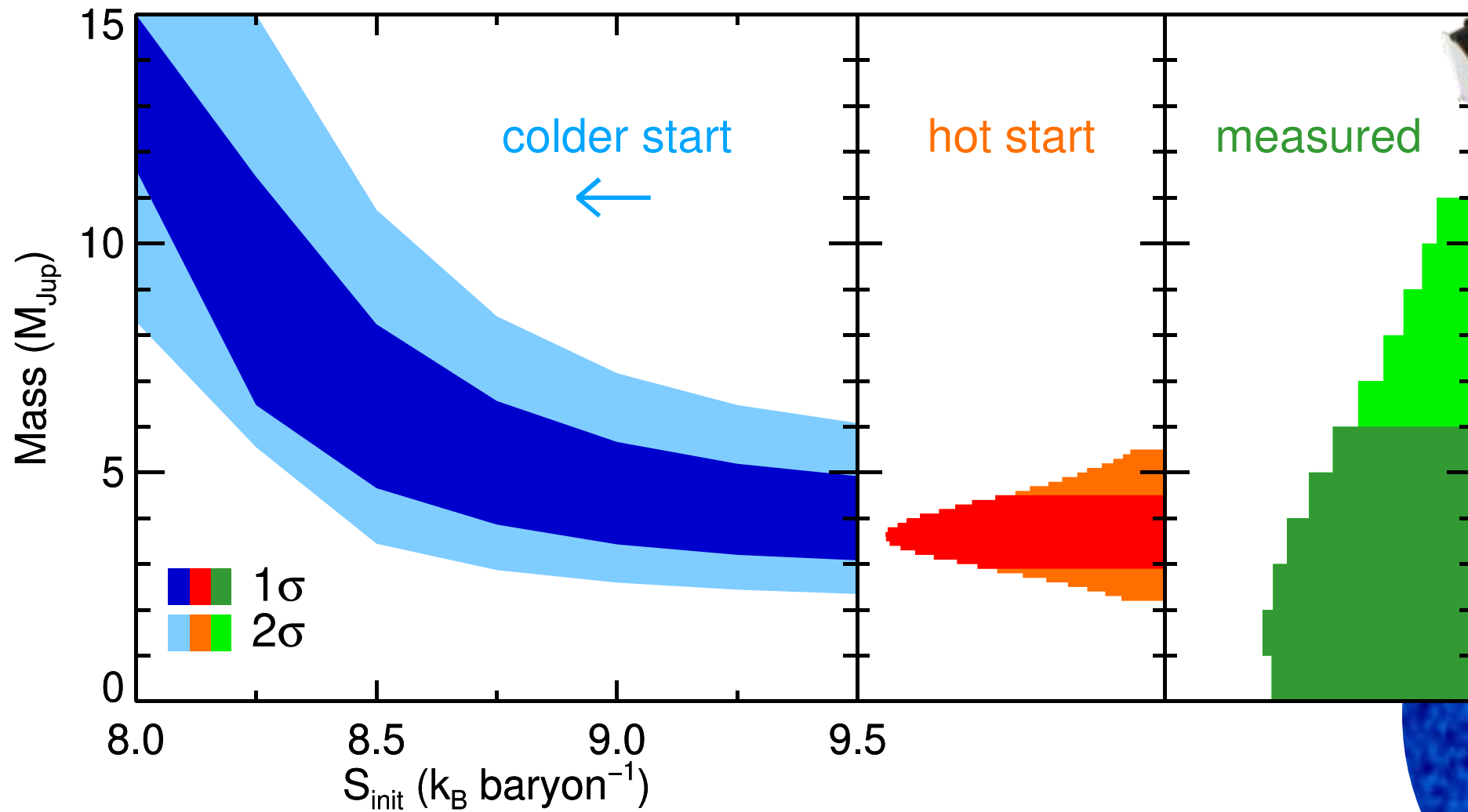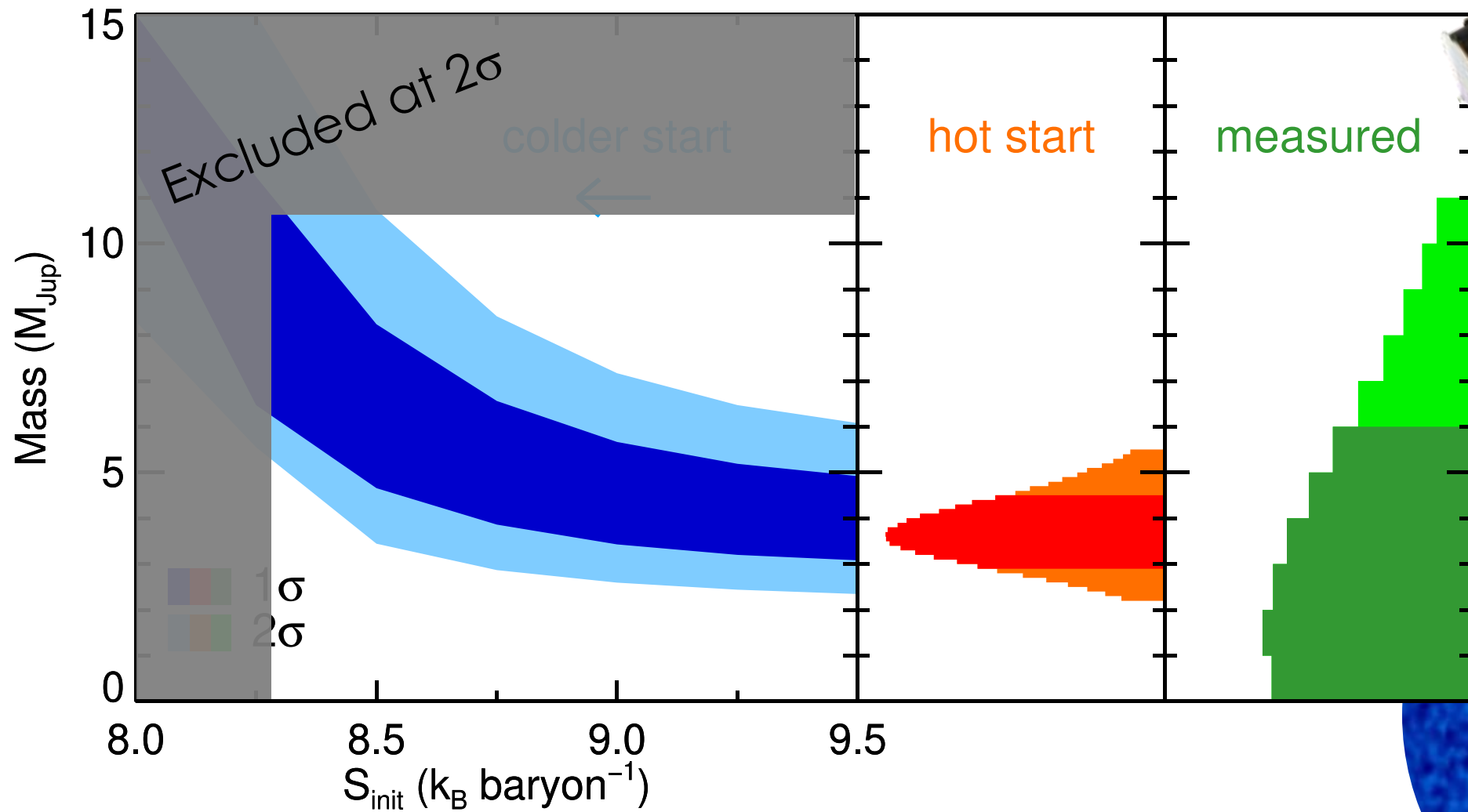

colder start

hot start

Mass (M_{Jup})

S_{init} (k_B baryon^{-1})

1σ
2σ
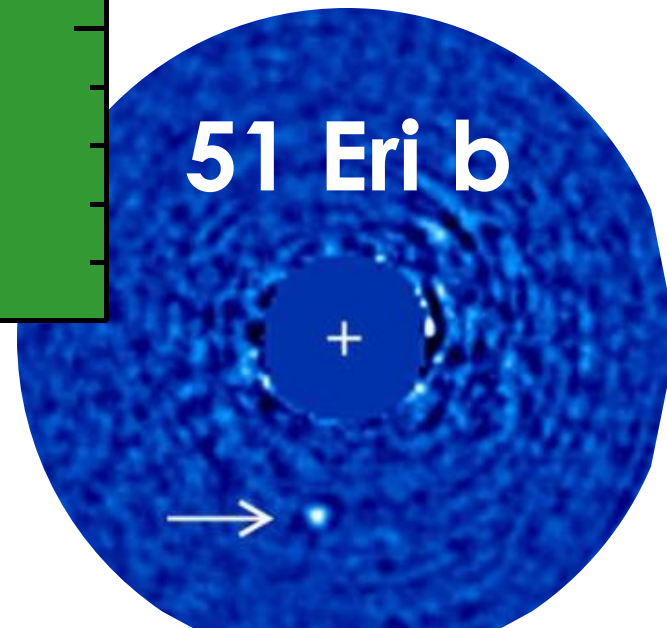
51 Eri b

Dupuy, Brandt & Brandt (2021)

Trent Dupuy (U. of Edinburgh)

Given L_{bol}, age, initial entropy
→ model mass

colder start · hot start · measured

Dupuy, Brandt & Brandt (2021)

51 Eri b

Given L_{bol}, age, initial entropy
→ model mass

Excluded at 2σ

colder start

hot start

measured

Mass (M_{Jup})

1σ
2σ

S_{init} (k_B baryon^{-1})

51 Eri b

Dupuy, Brandt & Brandt (2021)

Outline

Why? **How?** **What?** **What next?**

Trent Dupuy (U. of Edinburgh)

What's next for dynamical masses?

How massive is it?

- late-T & Y dwarfs

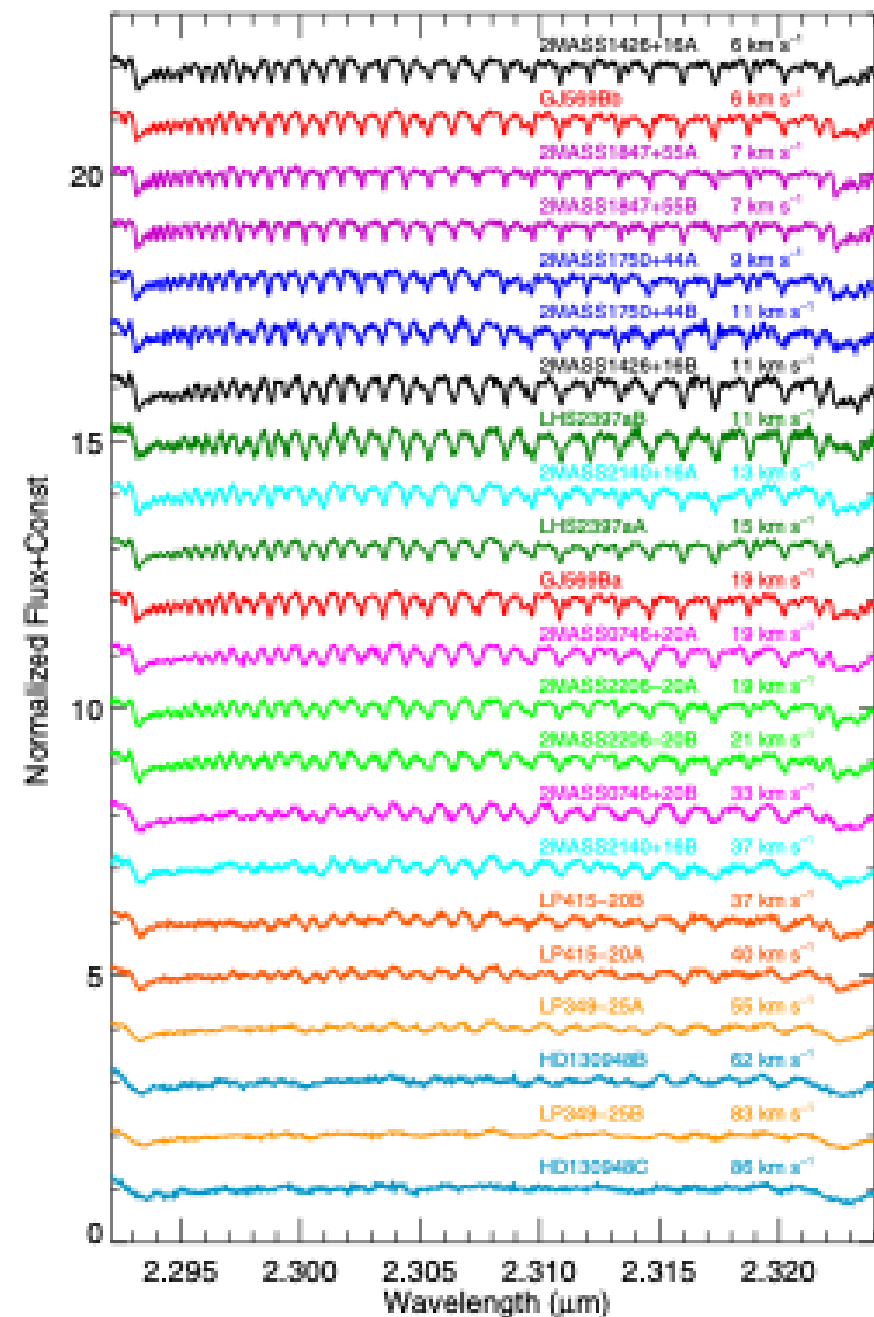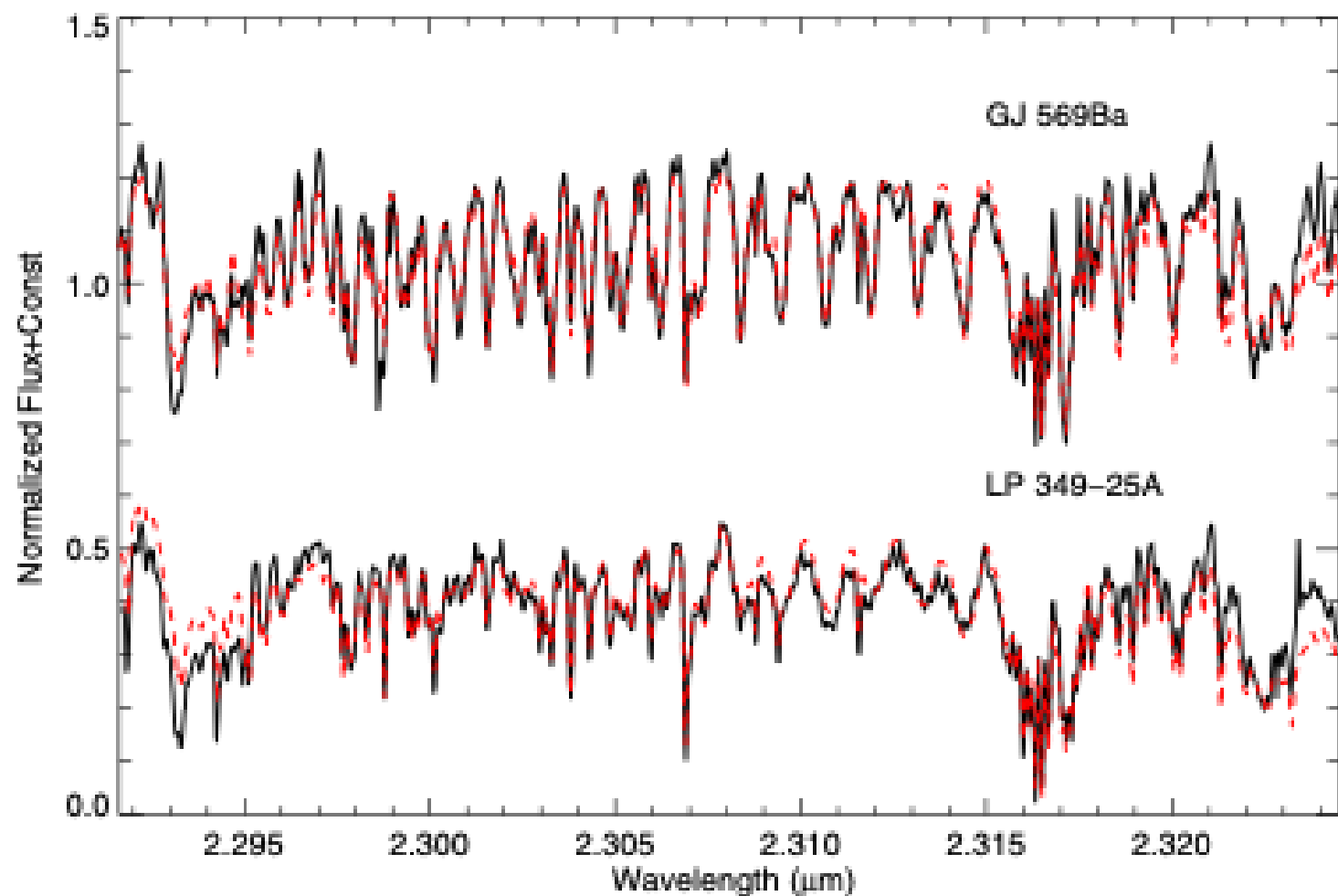- improved substellar boundary

Are *evolutionary* models accurate?

- high-precision L_{bol} (JWST)

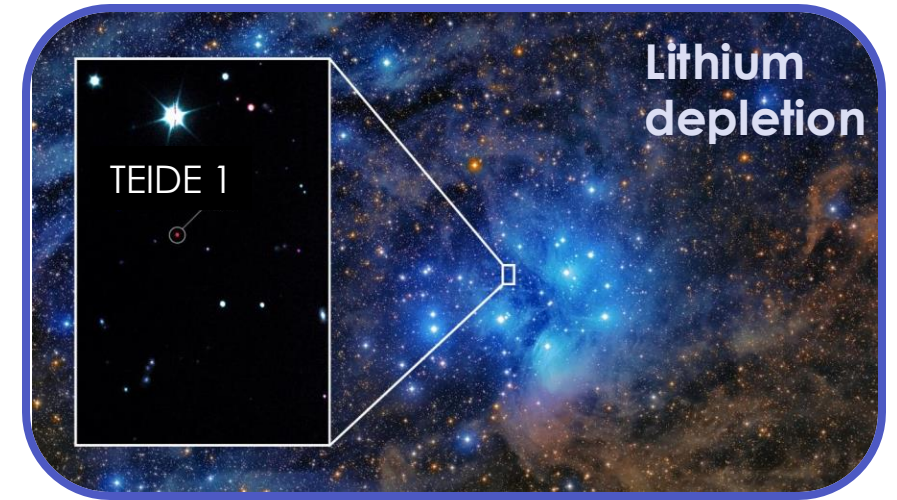- open cluster / YMG binaries

- asteroseismic ages (old BDs)

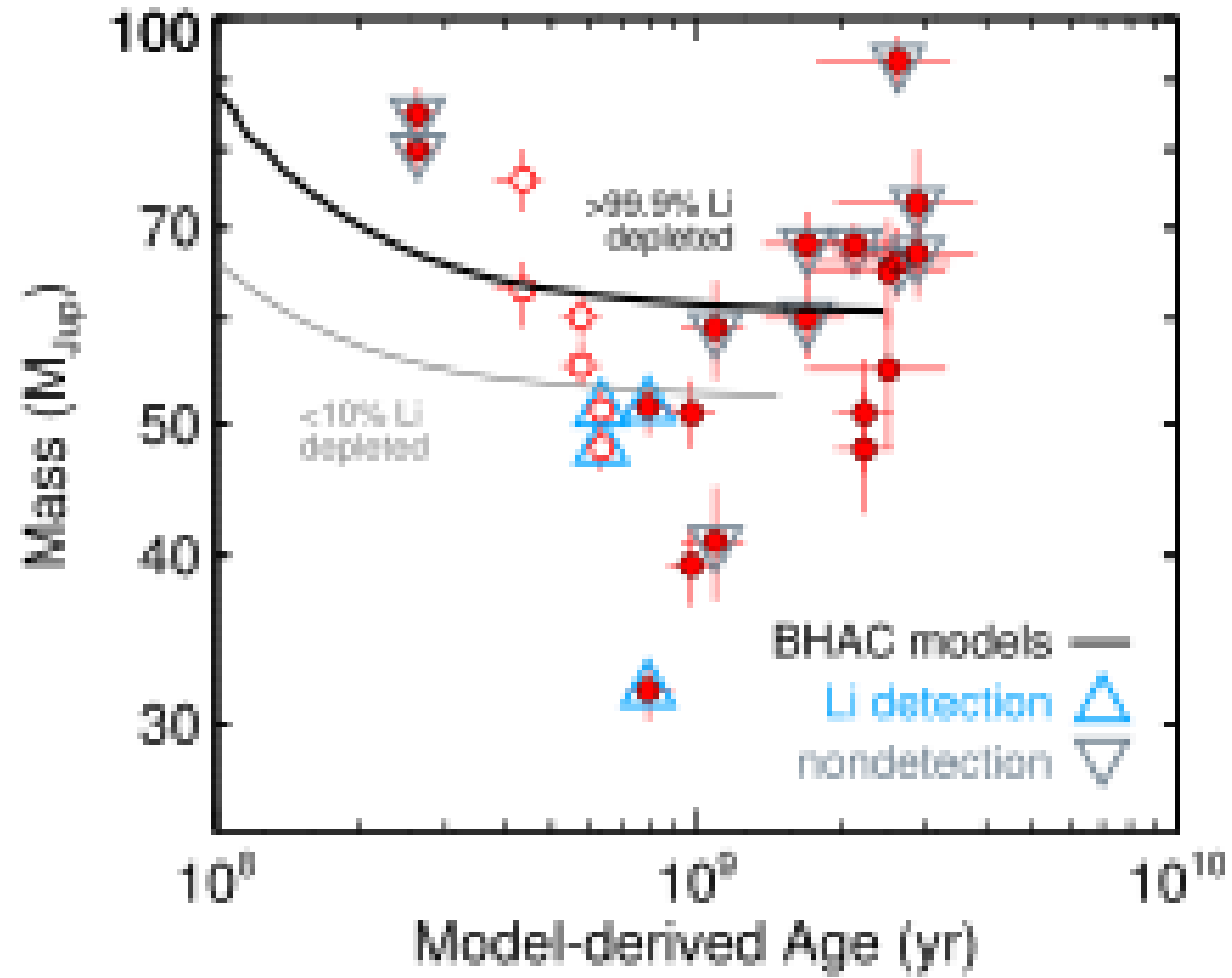**Are *atmospheric* models accurate?**

- resolved HST / JWST spectra for binaries
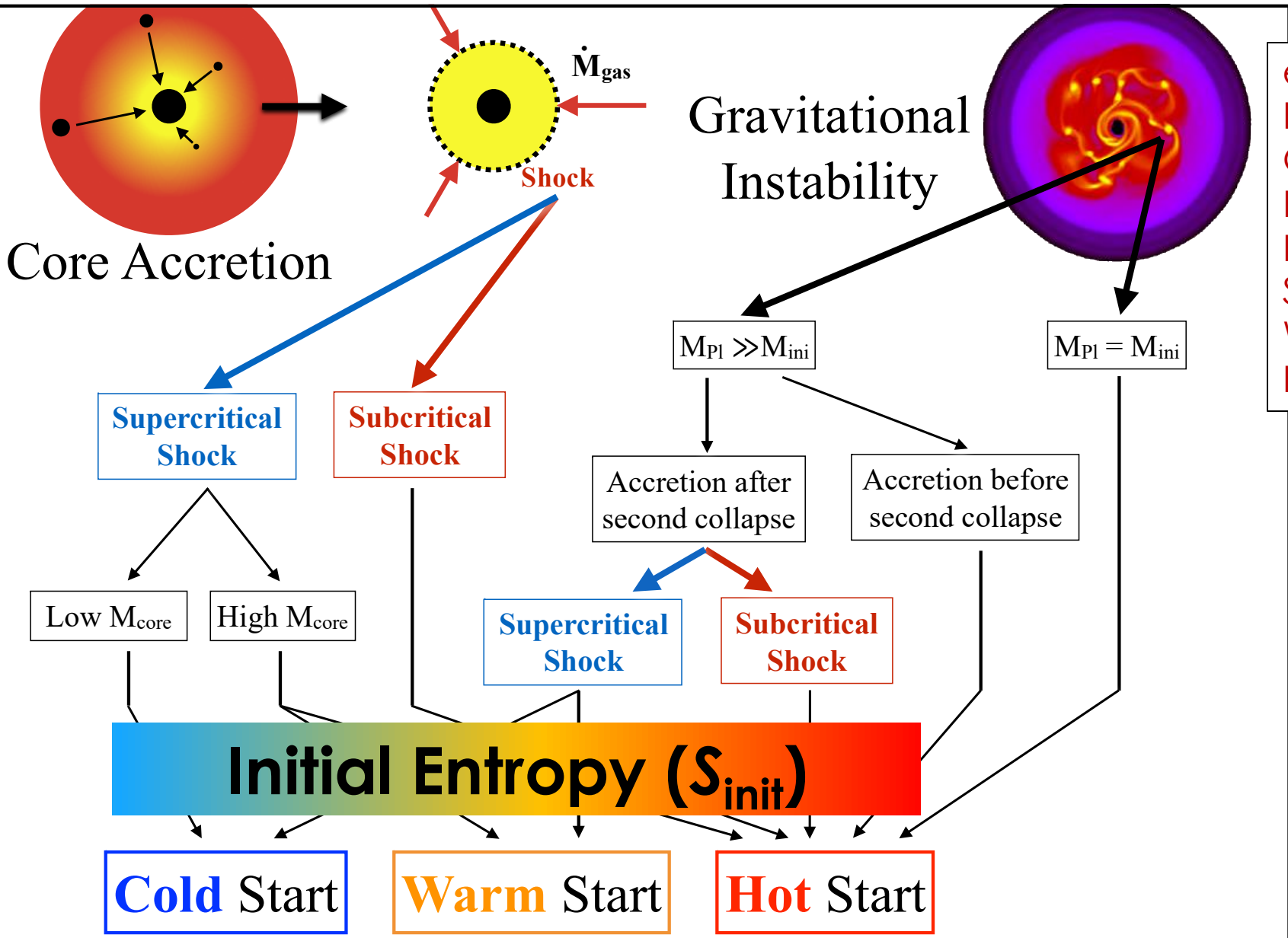
- benchmark retrievals: $\log g$, $\Delta[M/H]=0$

Trent Dupuy (U. of Edinburgh)

Trent Dupuy (U. of Edinburgh)
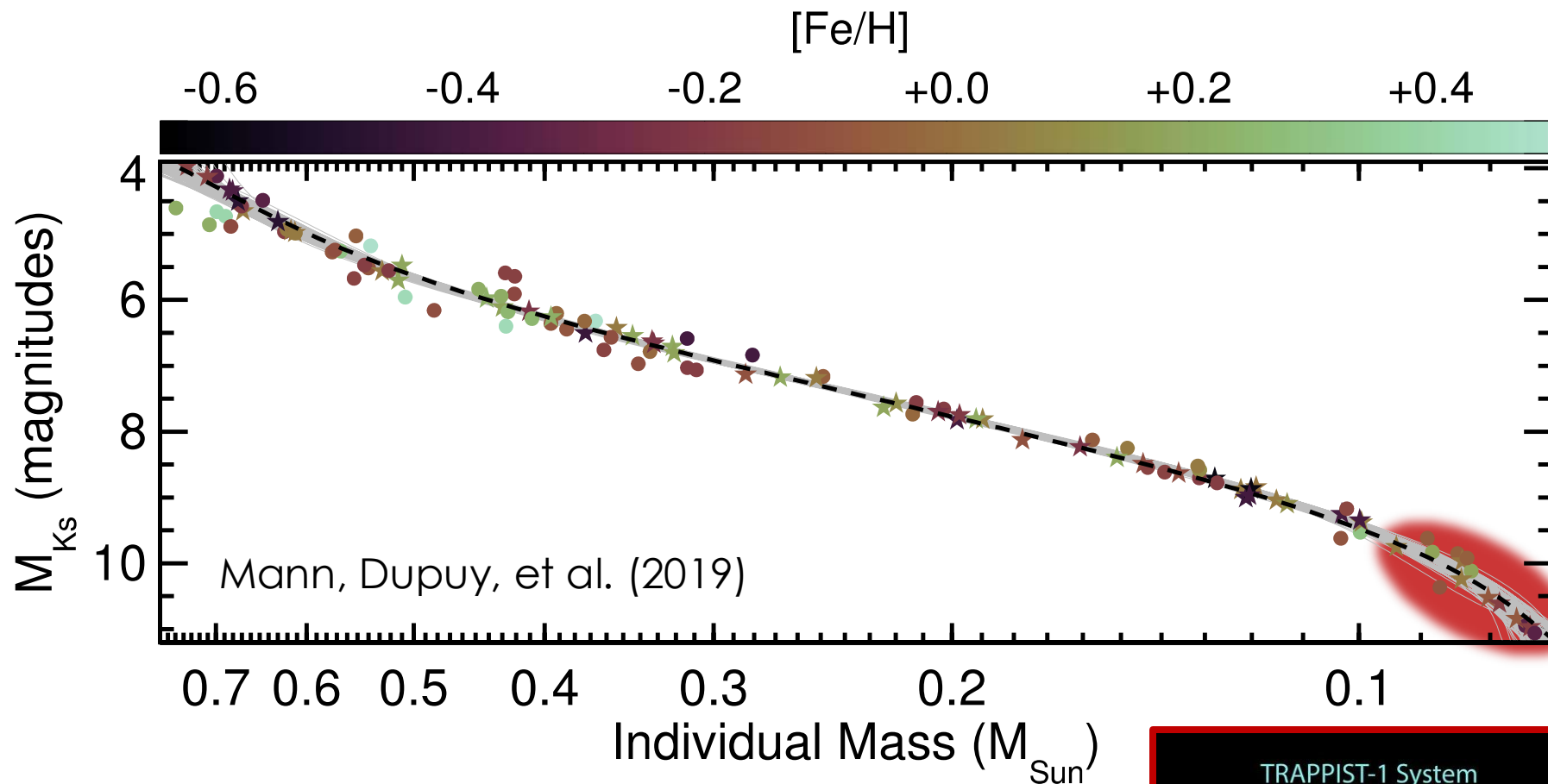
Konopacky et al. (2012)

Trent Dupuy (U. of Edinburgh)

Trent Dupuy (U. of Edinburgh)

Baruteau et al. (2016)

Mass–Magnitude–Metallicity Relation

Mann, Dupuy, et al. (2019)

Trent Dupuy (U. of Edinburgh)
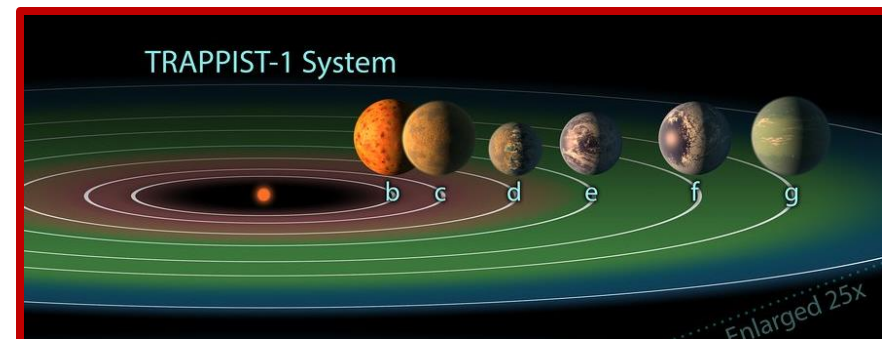
Gaia Is Transforming "2nd Eon" Model Tests, Too.

Brandt, Dupuy et al. (2021)