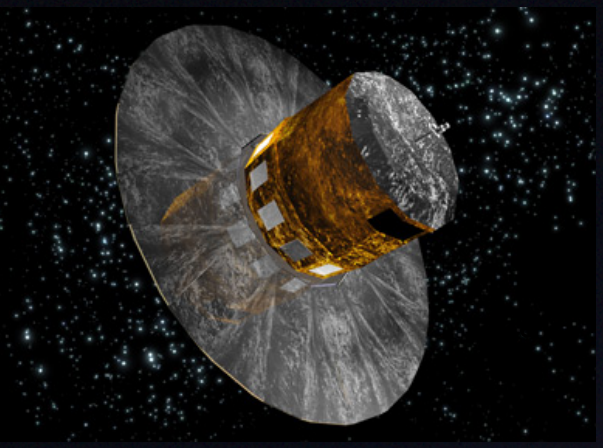
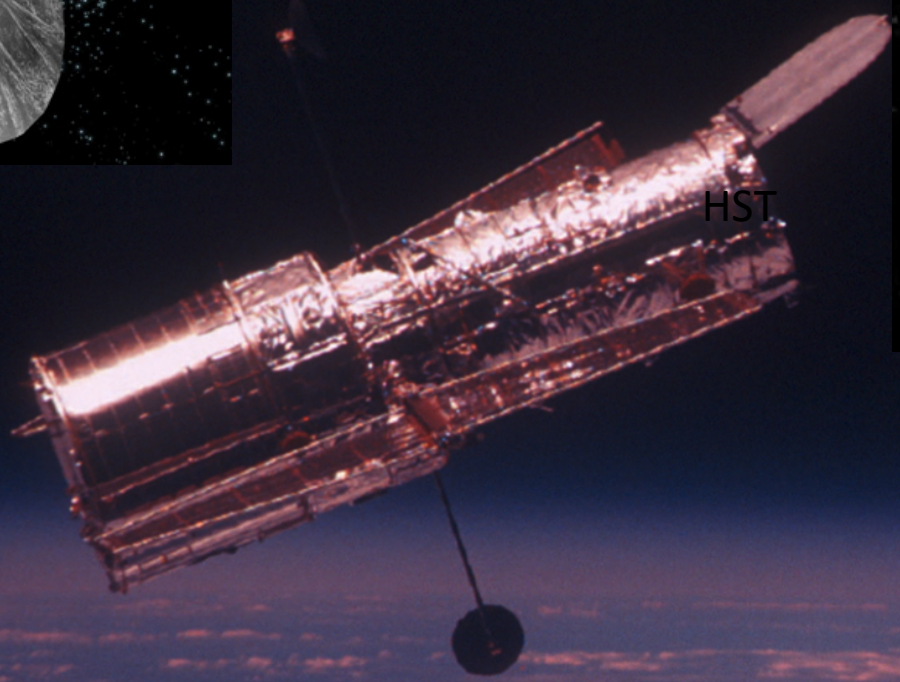
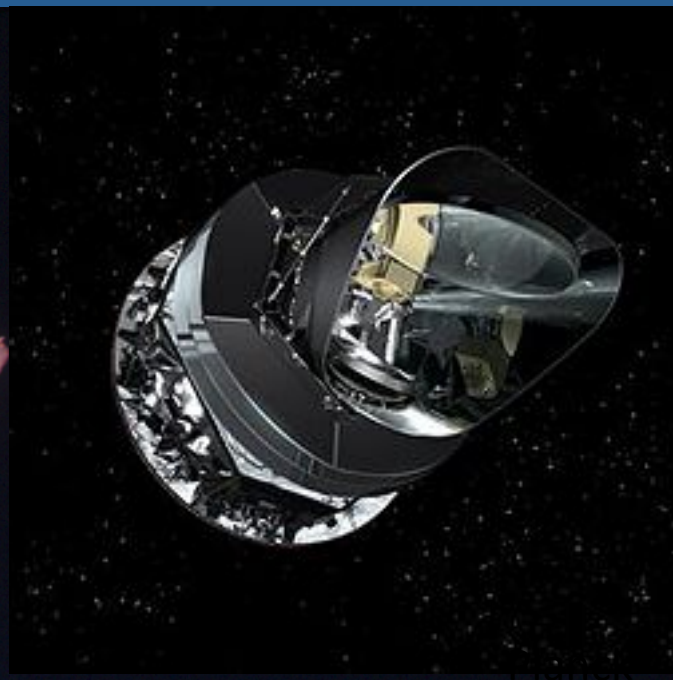
The TRGB Distance Scale
Resolving Tension in the Hubble Constant

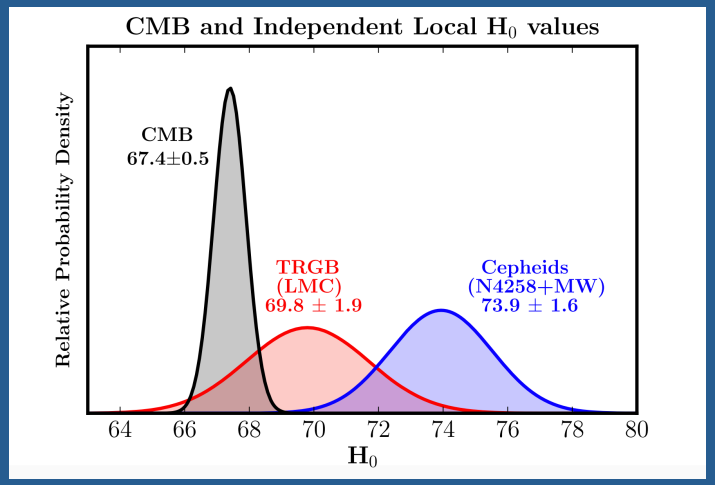




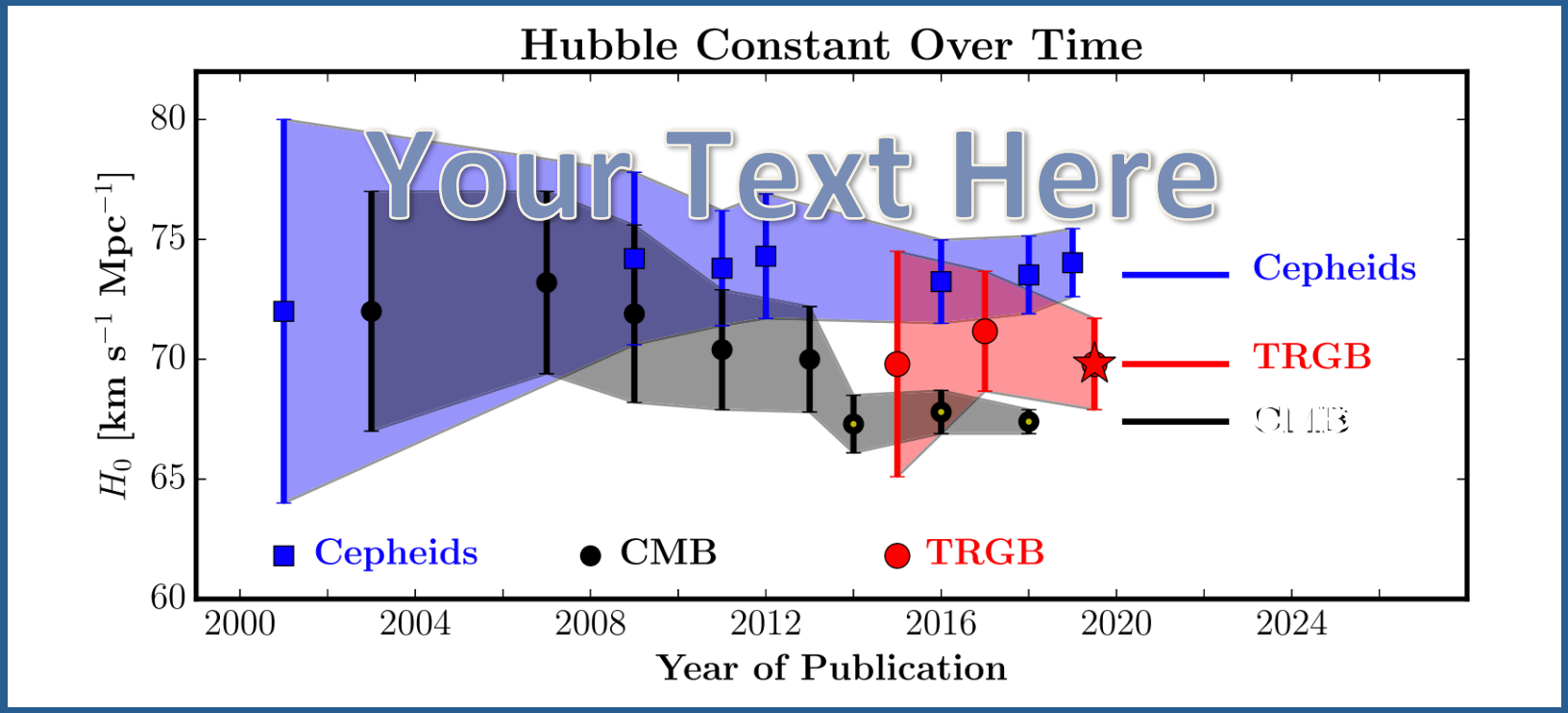


A Crisis in Cosmology?

What should we believe?



Hubble Constant
10:02:37 am
October 5, 2019

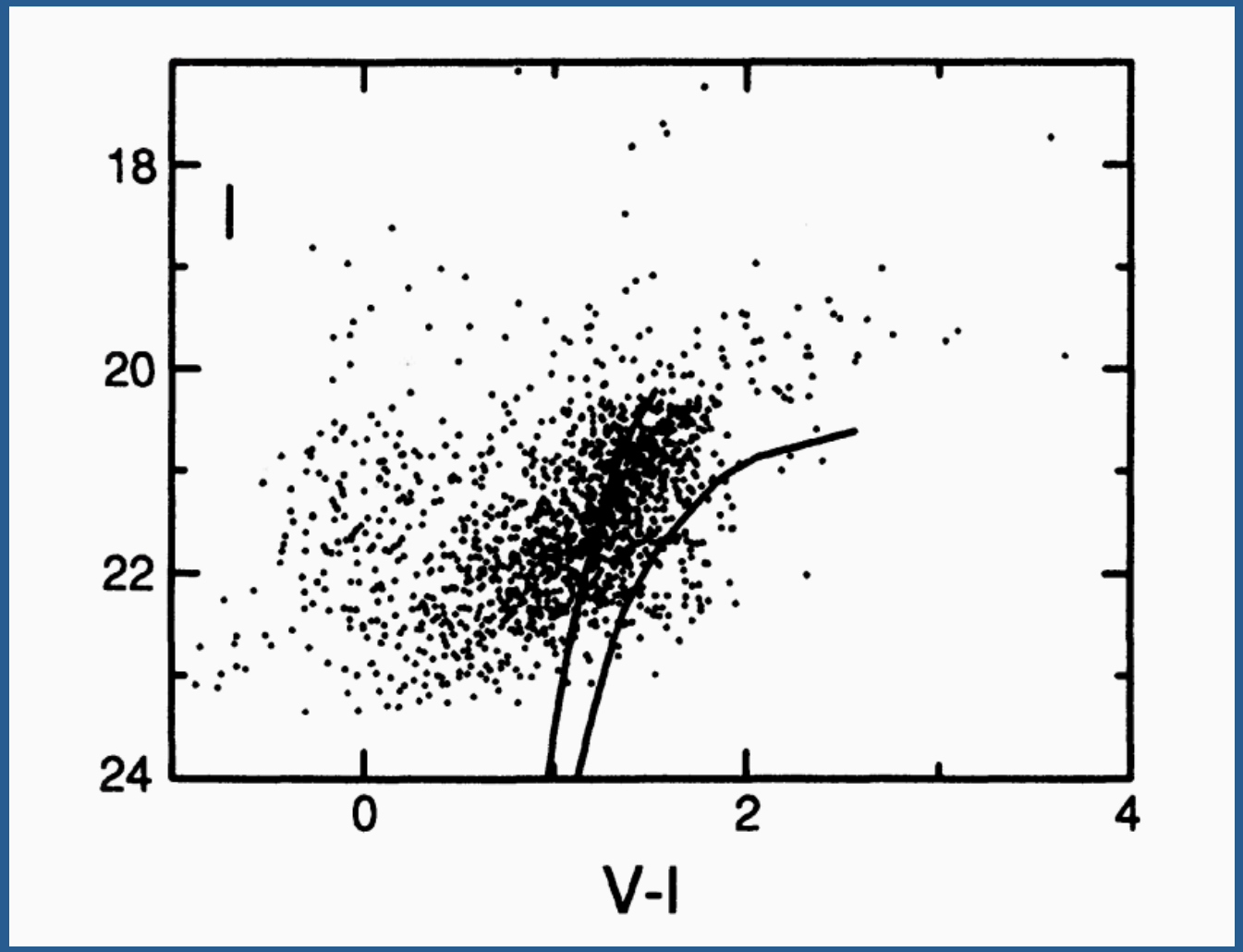



Walter Baade Oct 23, 1943
NGC 185
14,400 sec "Red Light" Exposure


Walter Baade Oct 23, 1943
NGC 185

TRGB in IC 1613

Freedman, W.L. AJ, 96, 1248, 1988



TRGB in IC 1613

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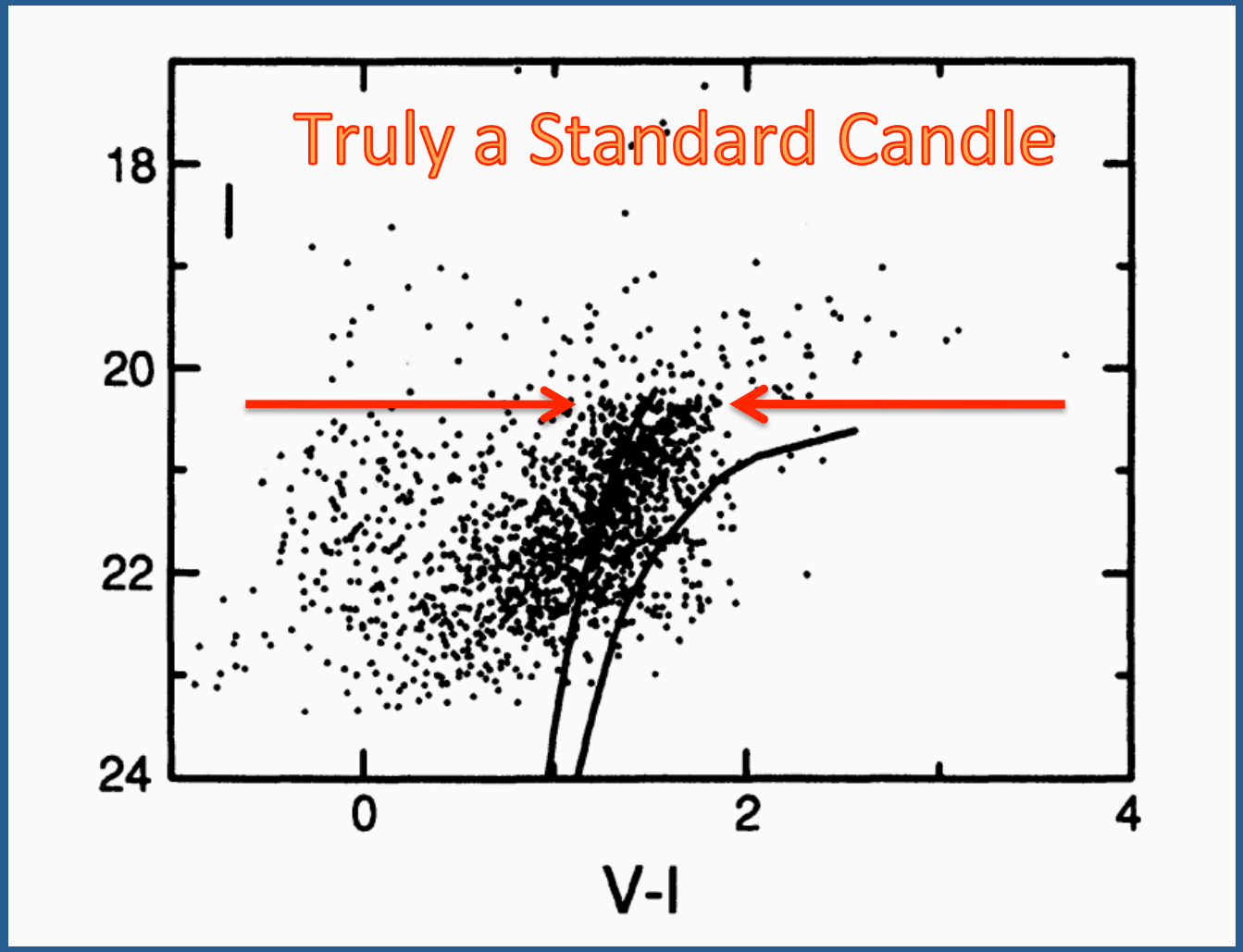
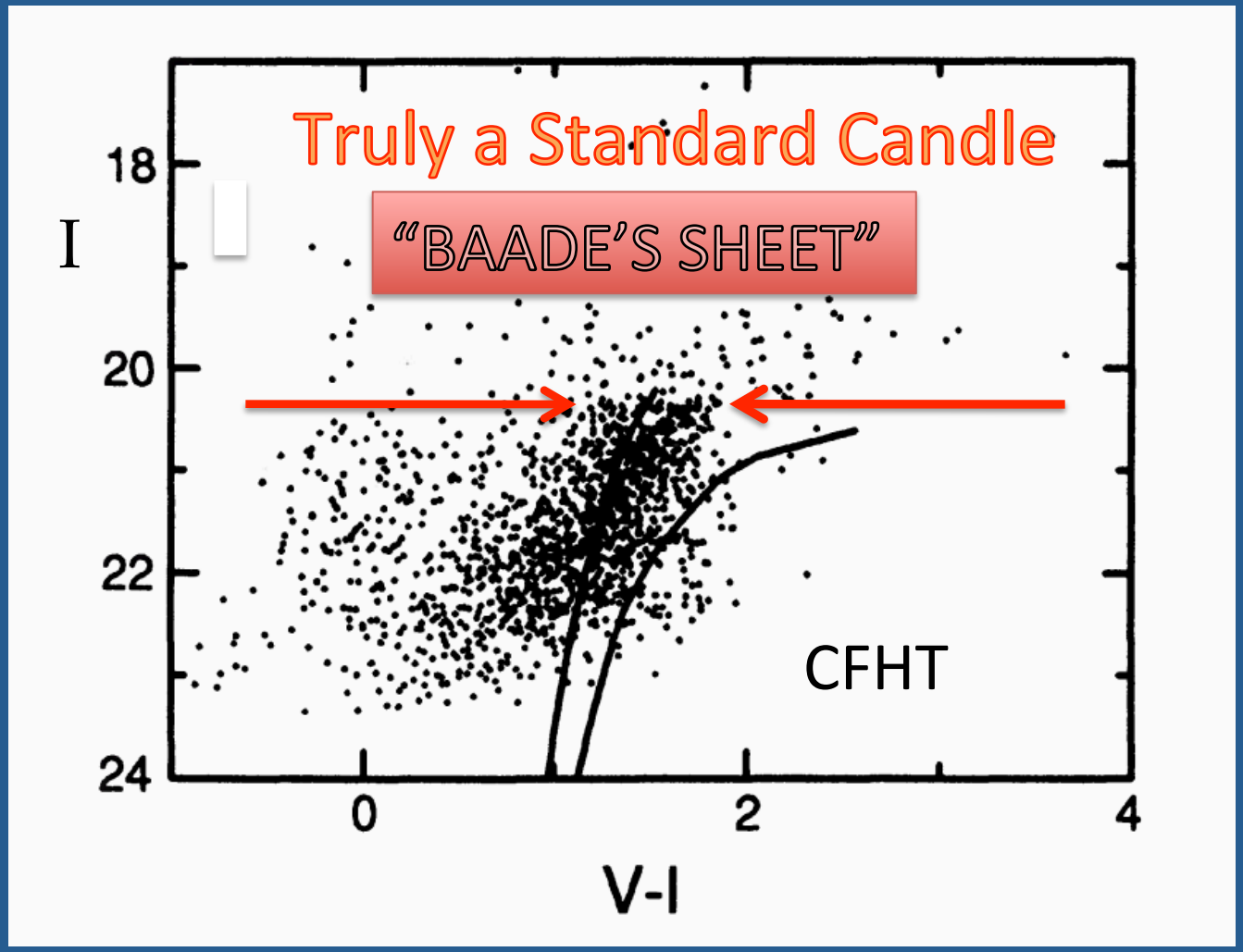


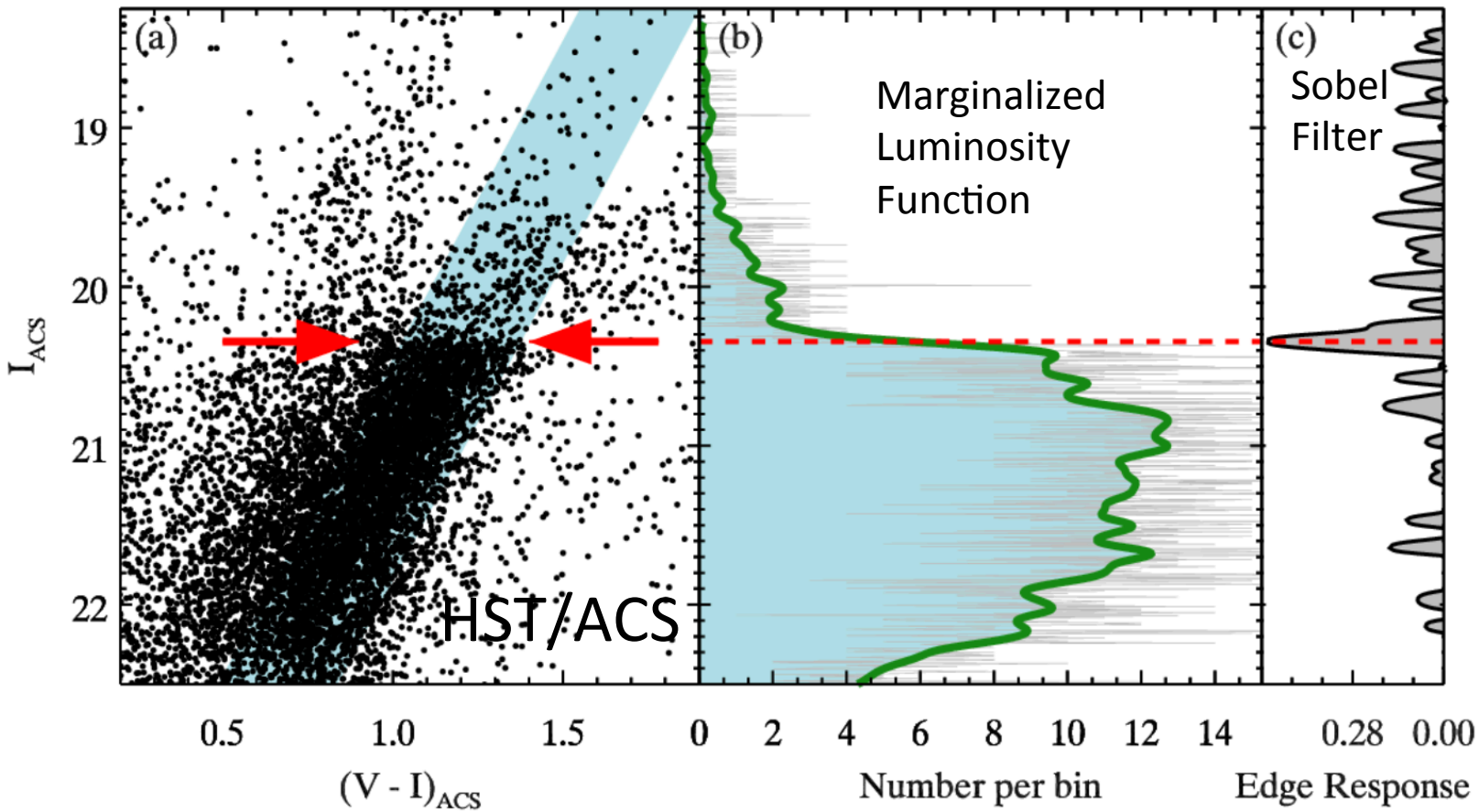
TRGB in IC 1613

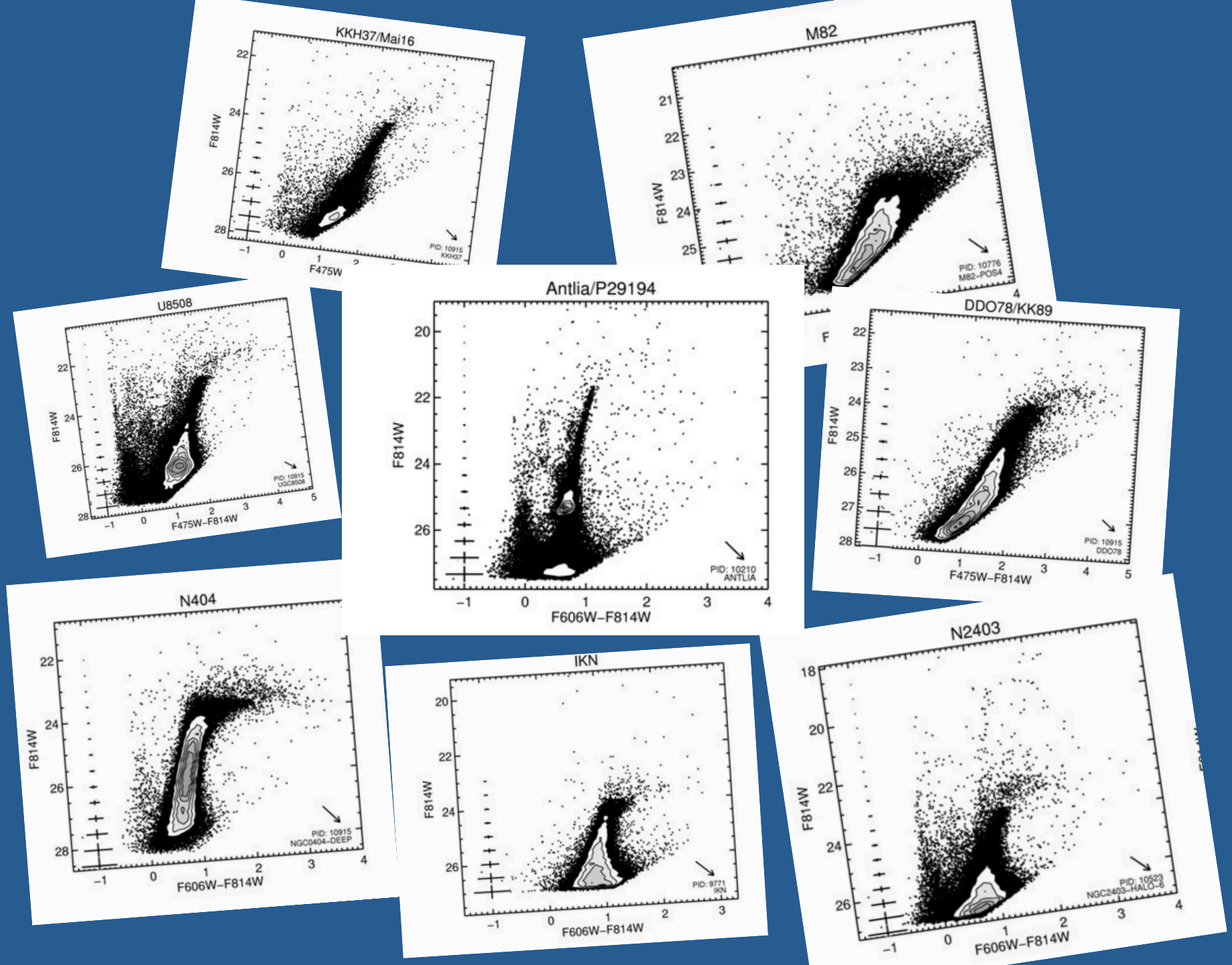
Freedman, W.L. AJ, 96, 1248, 1988



TRGB in IC 1613

Hatt, D., et al., ApJ, 845, 146, 2017

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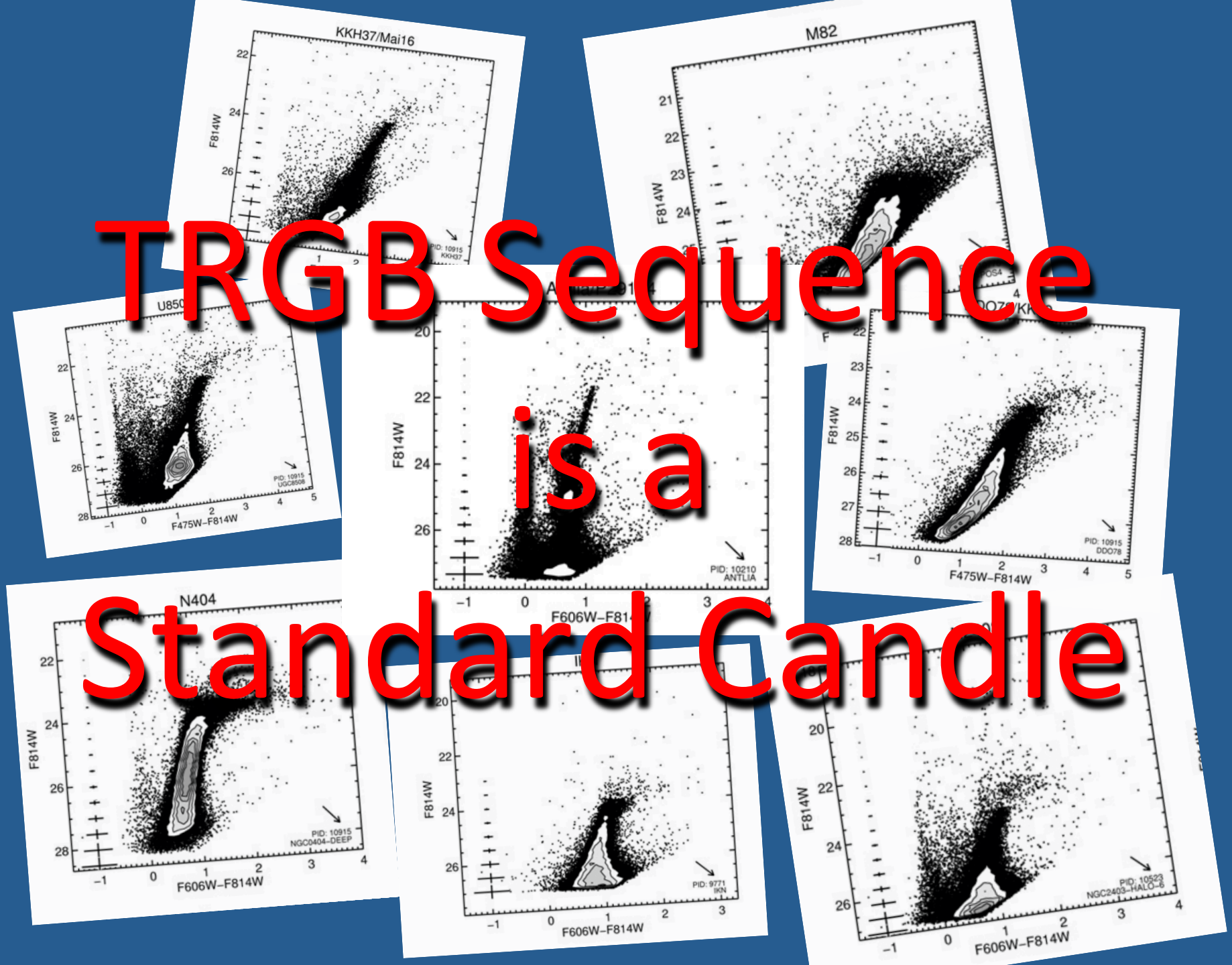
F814W
F475W
PID: 10915
KKH37
M82
F814W
PID: 10776
M82-POS4
U8508
F814W
F475W–F814W
PID: 10915
UGC8508
Antlia/P29194
F814W
F606W–F814W
PID: 10210
ANTLIA
DDO78/KK89
F814W
F475W–F814W
PID: 10915
DDO78
N404
F814W
F606W–F814W
PID: 10915
NGC0404-DEEP
IKN
F814W
F606W–F814W
PID: 9771
IKN
N2403
F814W
F606W–F814W
PID: 10523
NGC2403-HALO-6

TRGB Sequence is a Standard Candle



Standard vs Standardizable Candles

Cepheids	TRGB	Type Ia SNe
Mechanical	Standard	Standard
Heat Engine	Candle	Bomb
Period	[Constant]	Decline Rate
Temperature		Intrinsic Color
Reddening [Disk]	[Halo]	Non-Standard
Metallicity	Color [I-Band]	. . .
Evolution	4.515 MeV @[M(core) = 0.451 M(solar]	
Amplitude Bias	[Non-Variable]	
. . .	First Principles	

Standard vs Standardizable Candles

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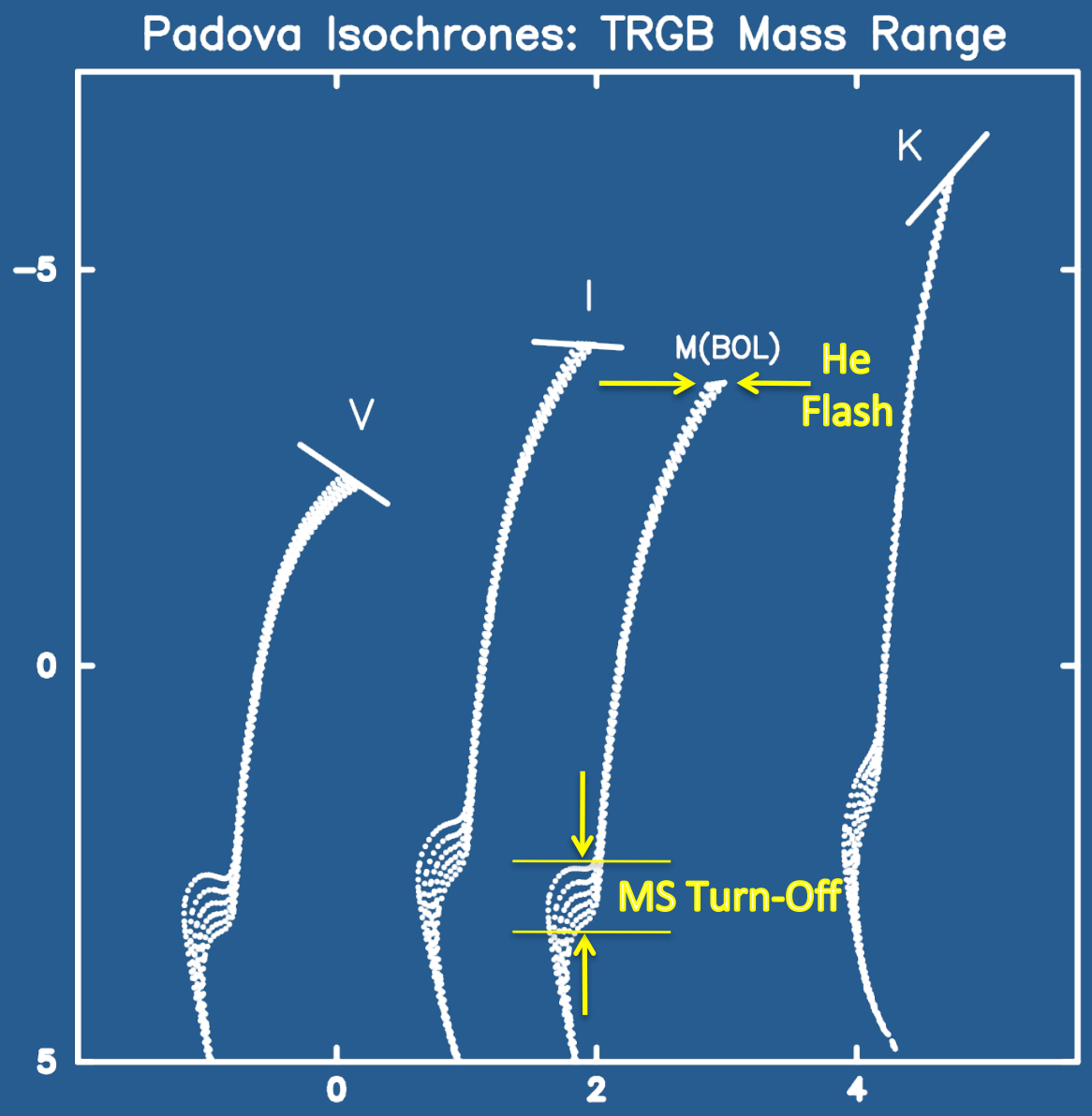
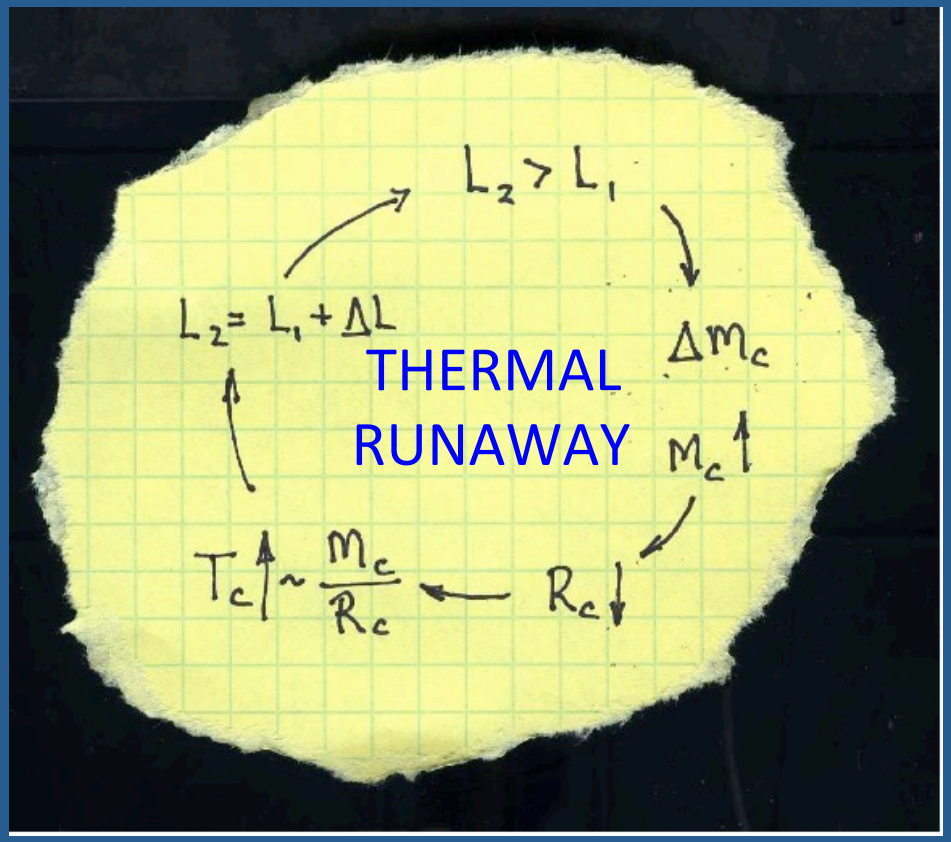
Metallicity	Color [I-Band]	. . .
Evolution	4.515 MeV @[M(core) = 0.451 M(solar]	
Amplitude Bias	[Non-Variable]	
. . .	First Principles	

A Pulsating Heat Engine
versus
A Physical Constant of Nature

Red Giant Branch Evolutionary Tracks



Electron-Degenerate Helium Core Mass-Luminosity Relation



$T_c = T_{SHELL}$ (ISOTHERMAL CORE)

$\epsilon \sim T_{SHELL}^{21}$ (CNO CYCLE)

$L \rightarrow \Delta M_c$ (HELIUM ASH)

$R_c \sim M_c^{-1/3}$ (WHITE DWARF)

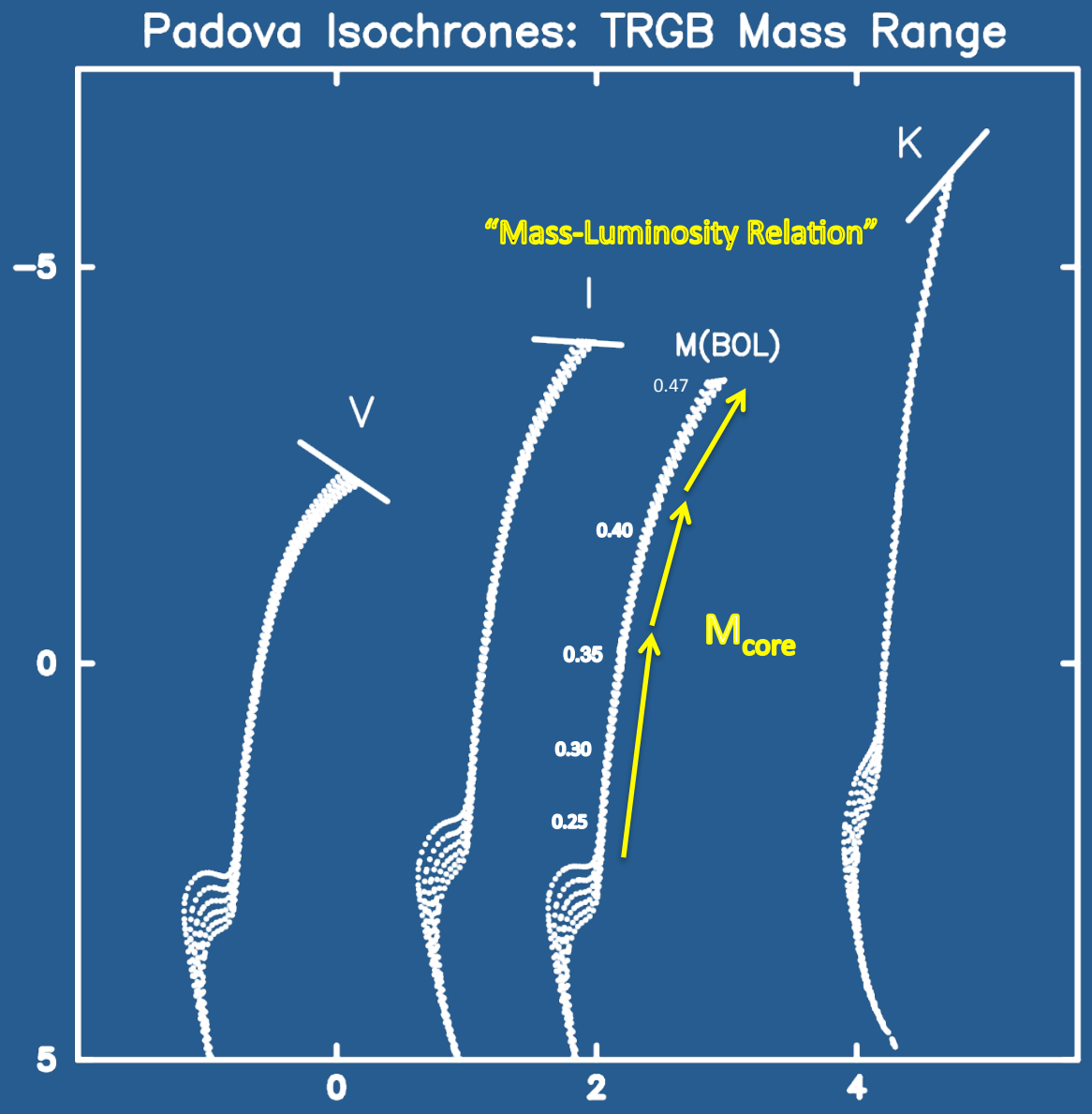
$T_c \sim M_c/R_c$ (VIRIAL EQUILIBRIUM)

$T_c \sim M_c^{4/3}$ (— " —)

$L \sim M_c^{8\frac{1}{3}}$ (M_{CORE}-LUMINOSITY REL'N)

N.B.
No dependence on the total mass of the star.
The hydrogen envelope is just "fuel for the fire".

TRGB In-Sensitivity to Progenitor Mass



A Crisis in Cosmology?

What should we believe?

First Principles Underwriting of the Tip of the Red Giant Branch

(1) Triple-Alpha process begins the burning of helium at a threshold temperature of 2×10^8 K (*Laboratory Astrophysics, Fowler 1954*)

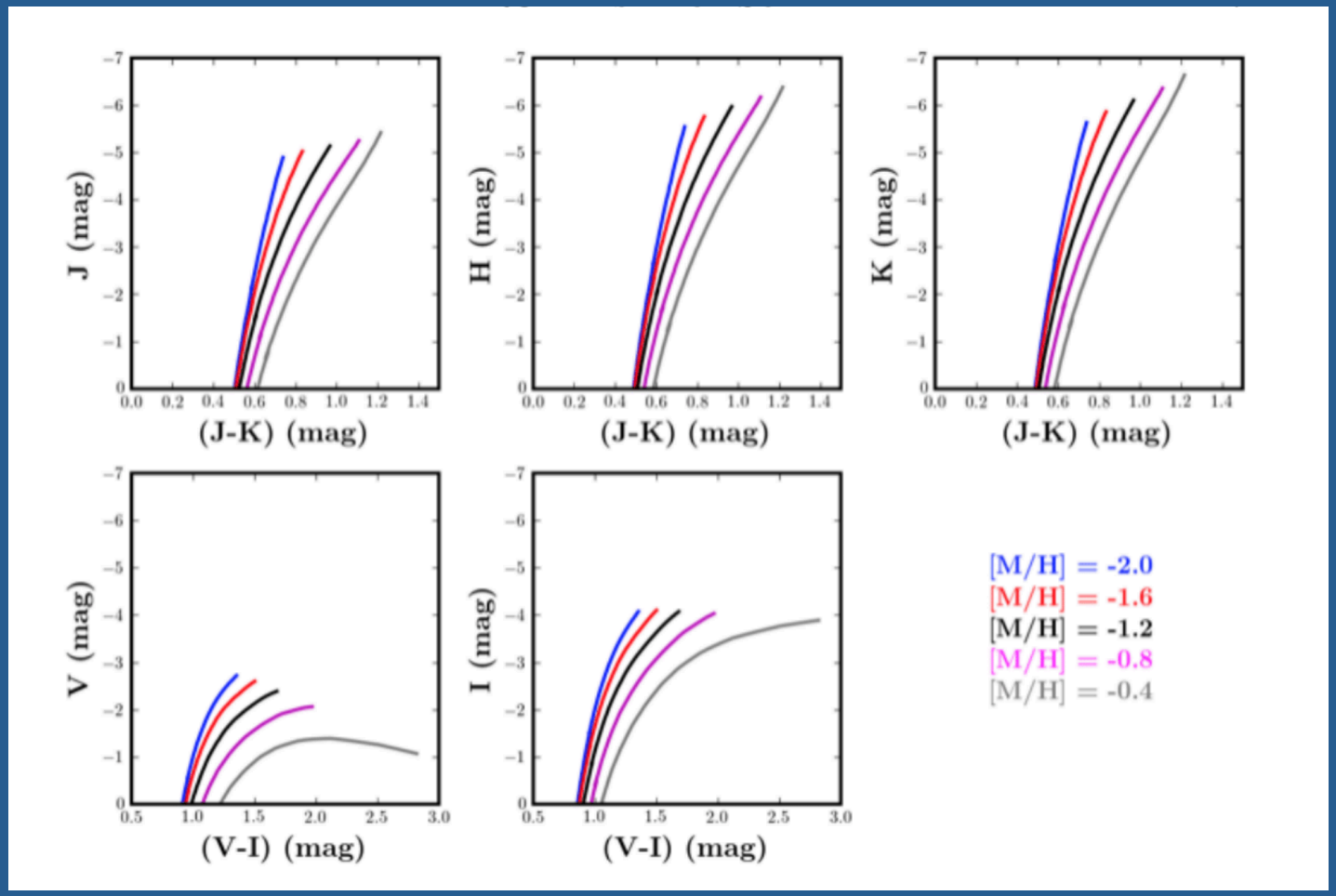
(2) That temperature is reached for a core mass of $M_{core} = 0.48\ M_{solar}$ (*Core Mass-Luminosity Relation*)

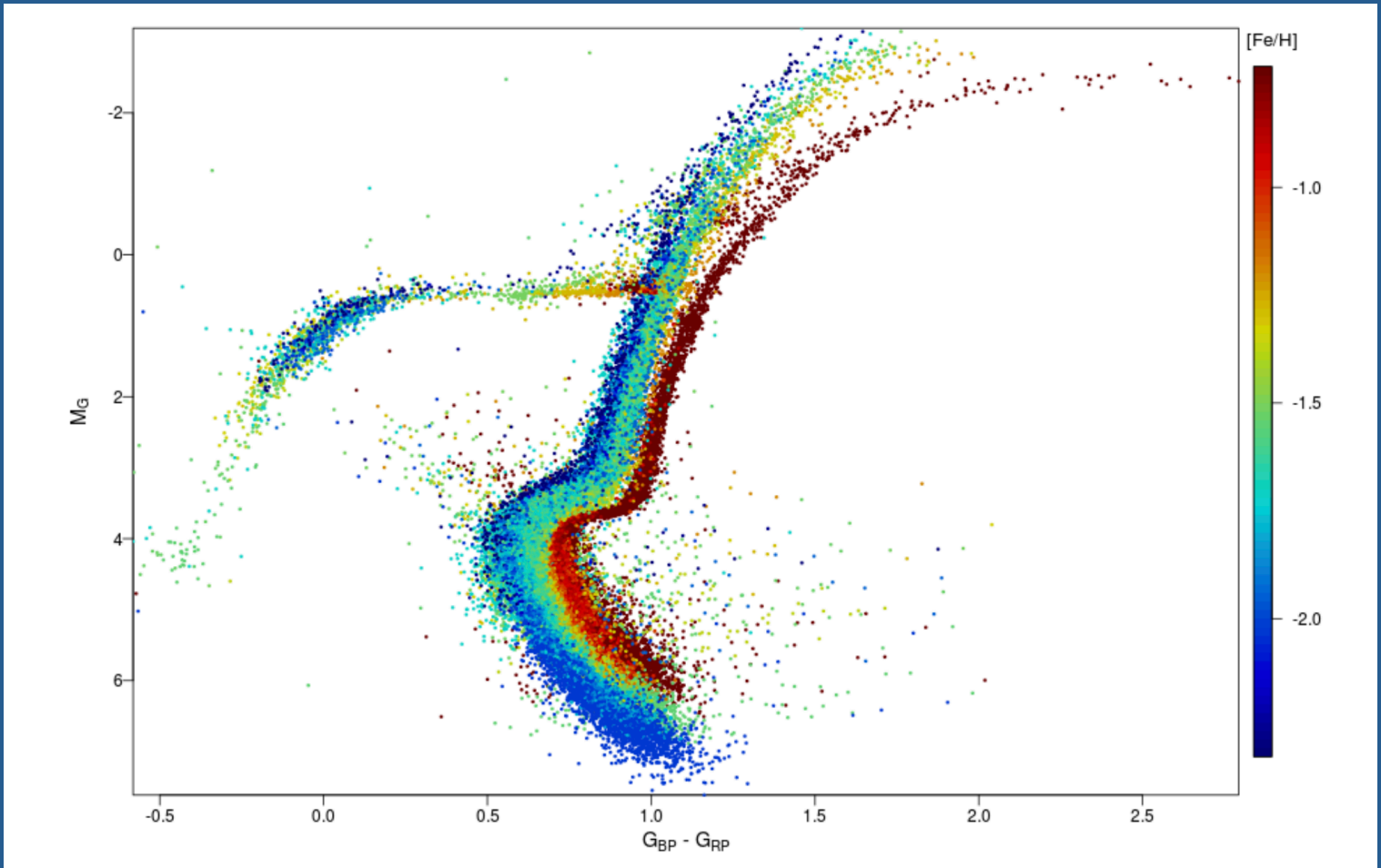
(3) All RGB stars having that core masses simultaneously have the same luminosities (*Ibid.*)

(4) A thermal runaway vaporizes the core, lifting the degeneracy, inflating the core, collapsing the envelope, and driving the star to the Horizontal Branch, which 40 times fainter than the TRGB.

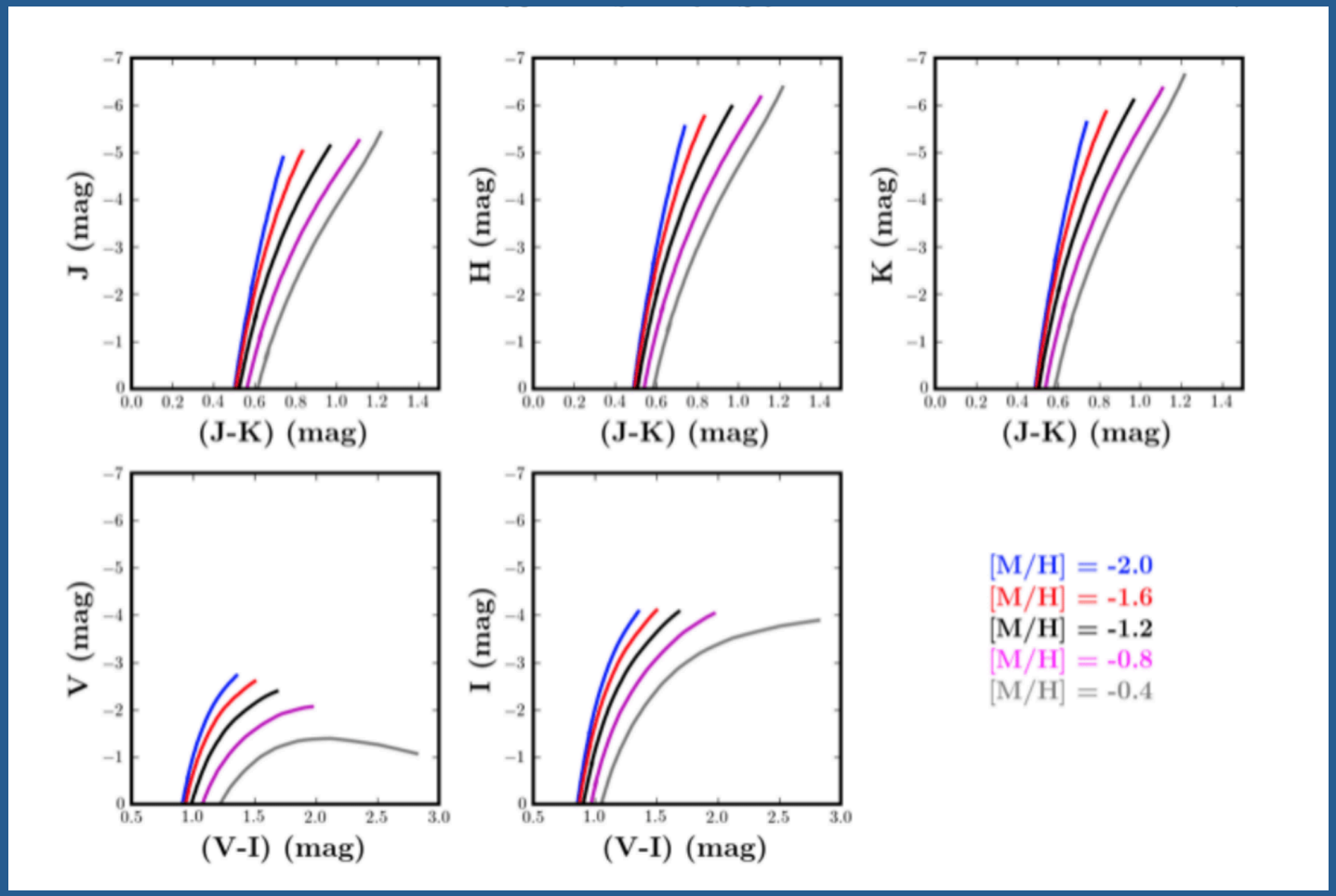
An astrophysical guillotine universally terminates the upward luminosity evolution of all red giant branch stars.

Multi-Wavelength TRGB Sequence
Padova Isochrones




[Fe/H]
-1.0
-1.5
-2.0
-2
0
2
4
6
M_G
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
G_{BP} - G_{RP}

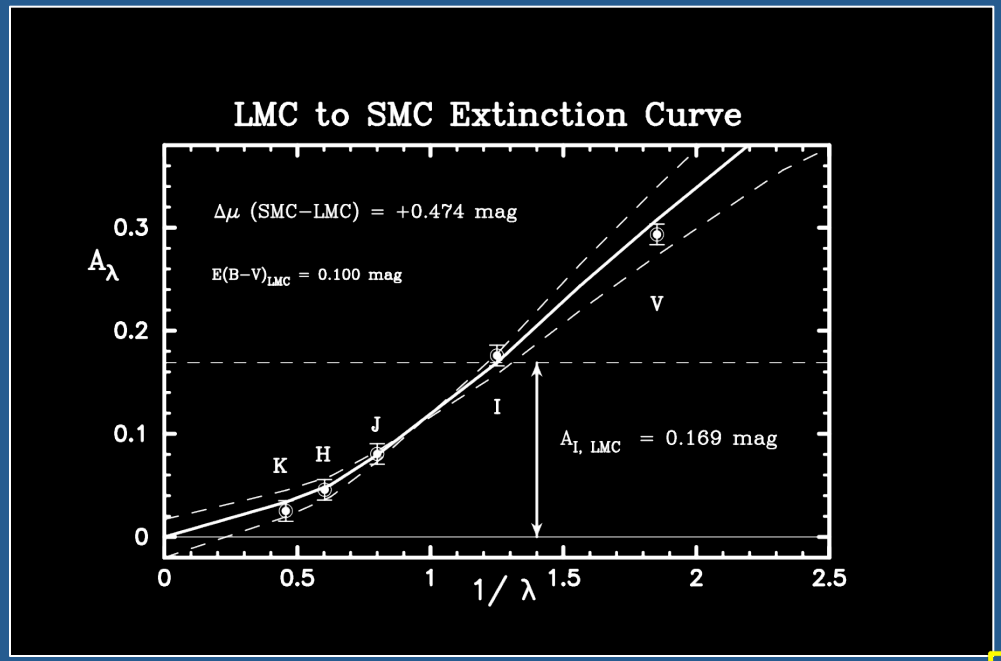
Multi-Wavelength TRGB Sequence
Padova Isochrones



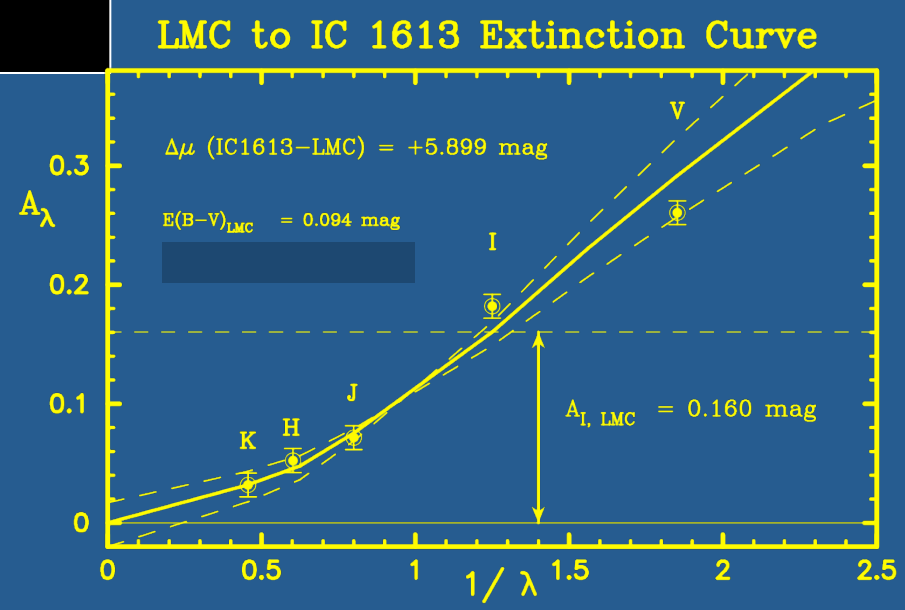
A Crisis in Cosmology?

What should we believe?

LMC Reddening and Calibration



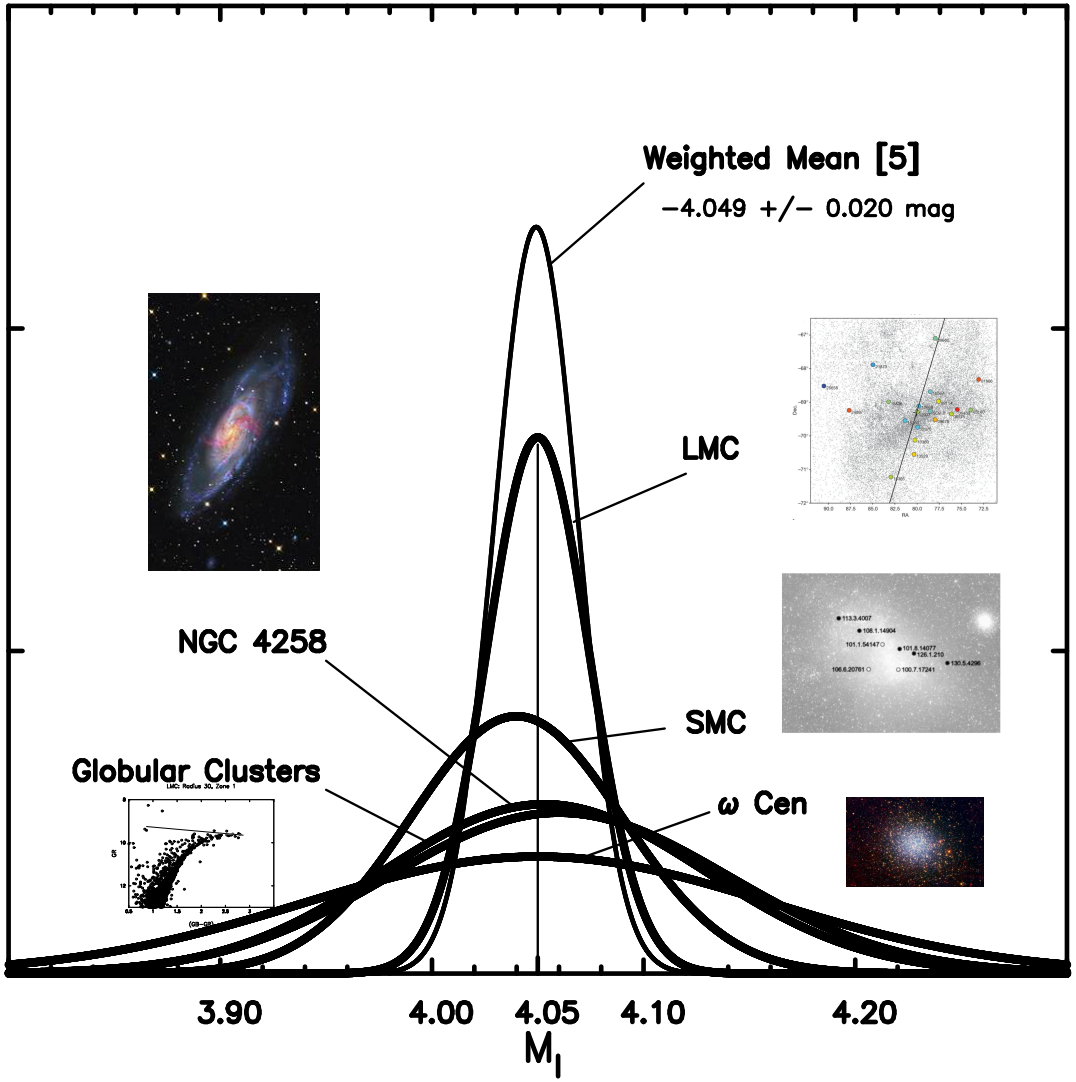
M I (TRGB)
-4.05 +/- 0.023 mag



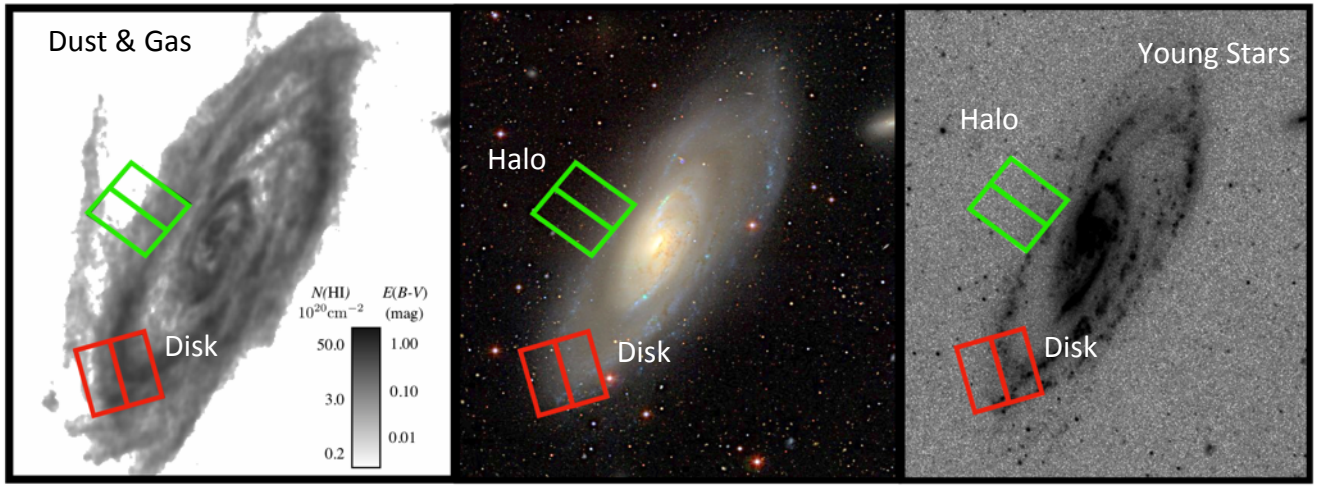
LMC (Detached Eclipsing Binary)
Geometric Distance Modulus

(m-M)o = 18.477 mag

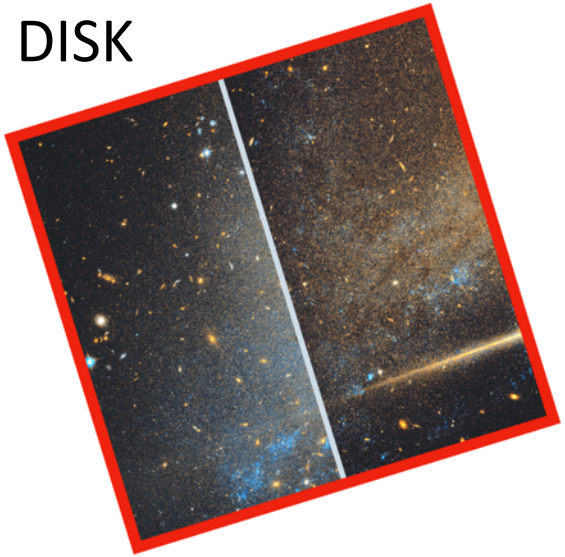
TRGB Errors: Relative Probabilities



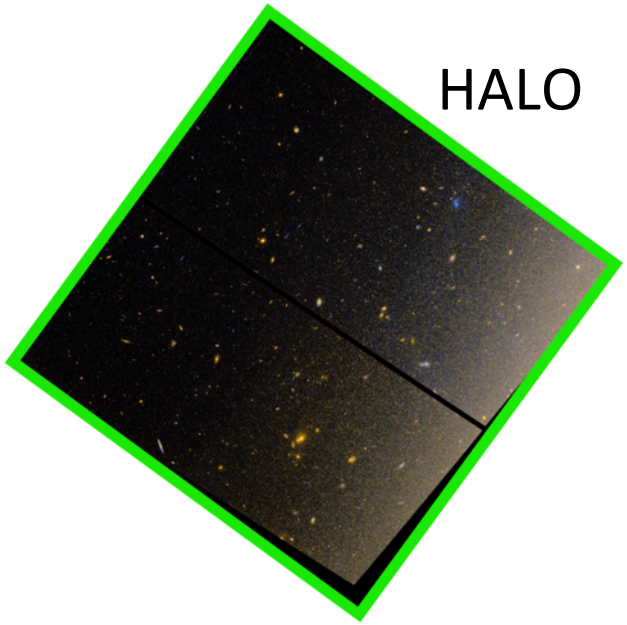
MASER GALAXY NGC 4258



DISK



HALO

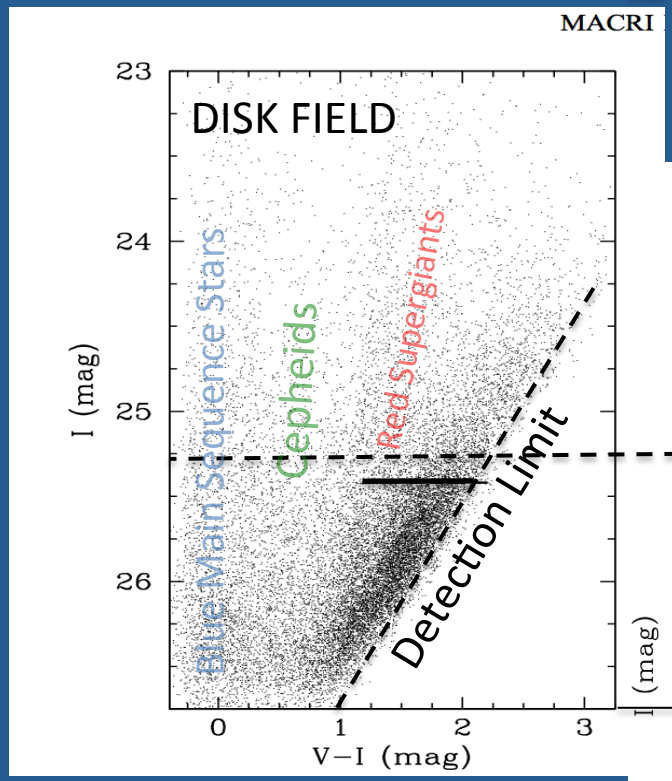


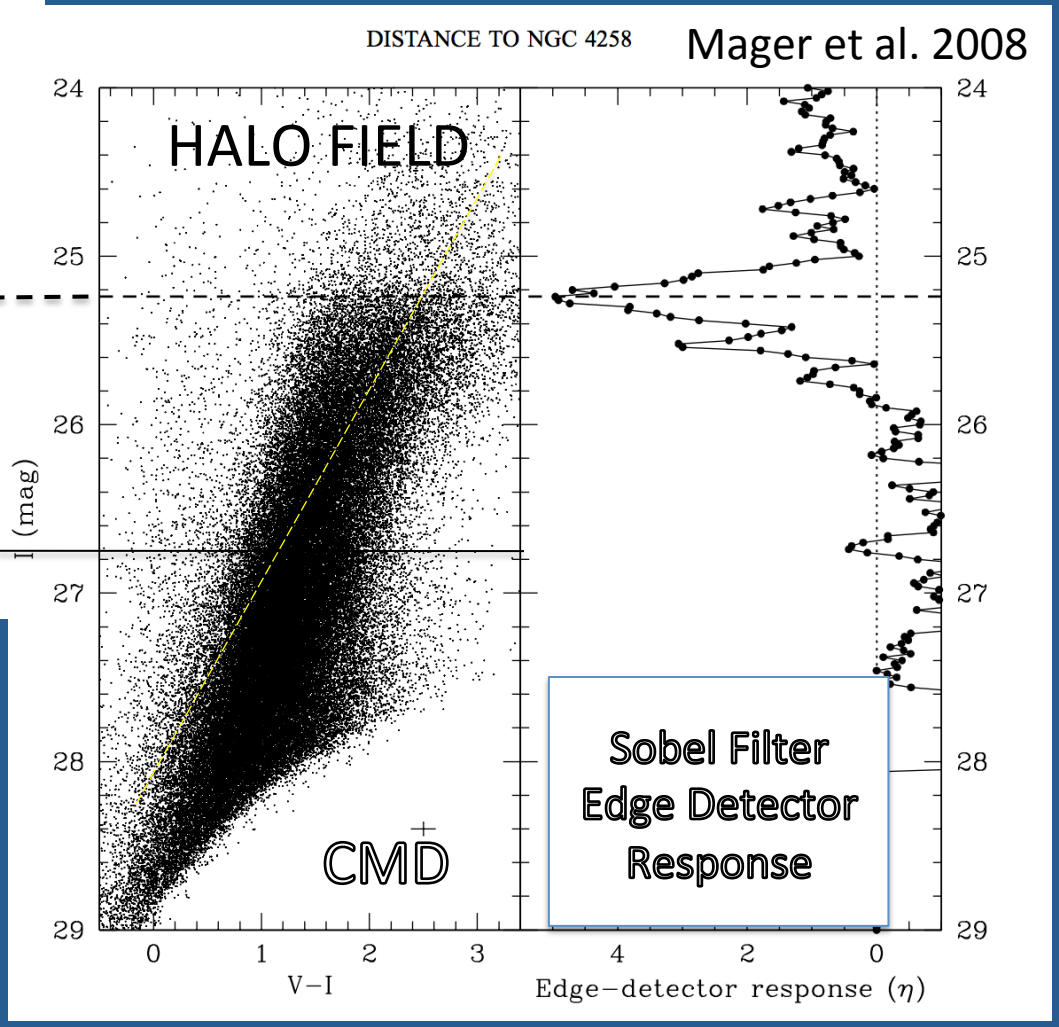
Maser Galaxy NGC 4258

Major Axis Cepheid Disk Field

Macri et al. 2006

Cepheid Reddening E(V-I) = 0.21 mag



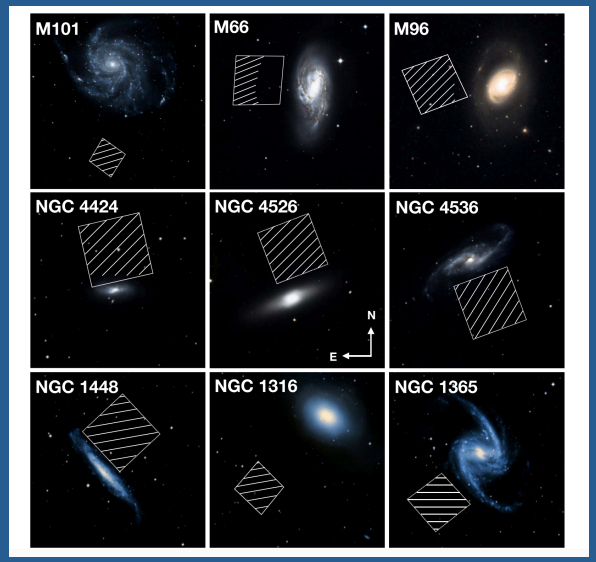


Minor Axis TRGB Halo Field

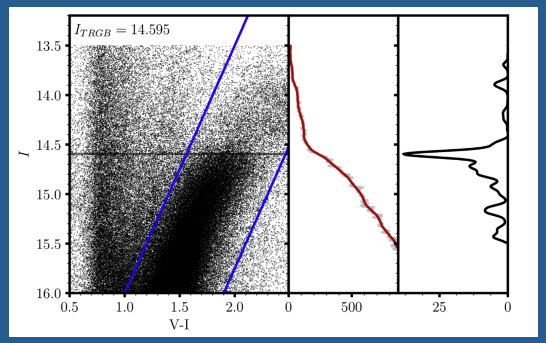
Mager et al. 2008

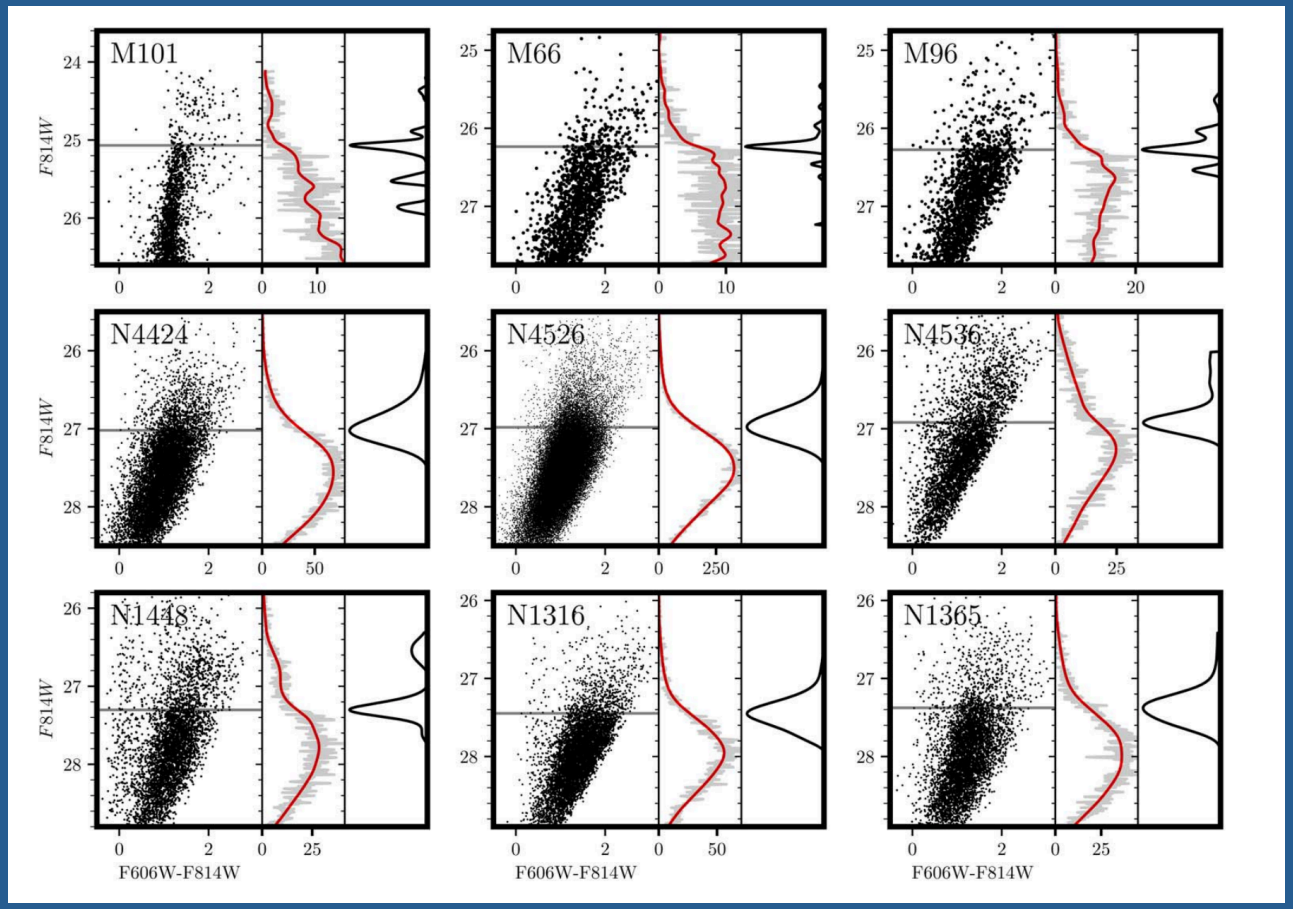
SNIa Host Galaxies TRGB Detections

Pure Halo Fields

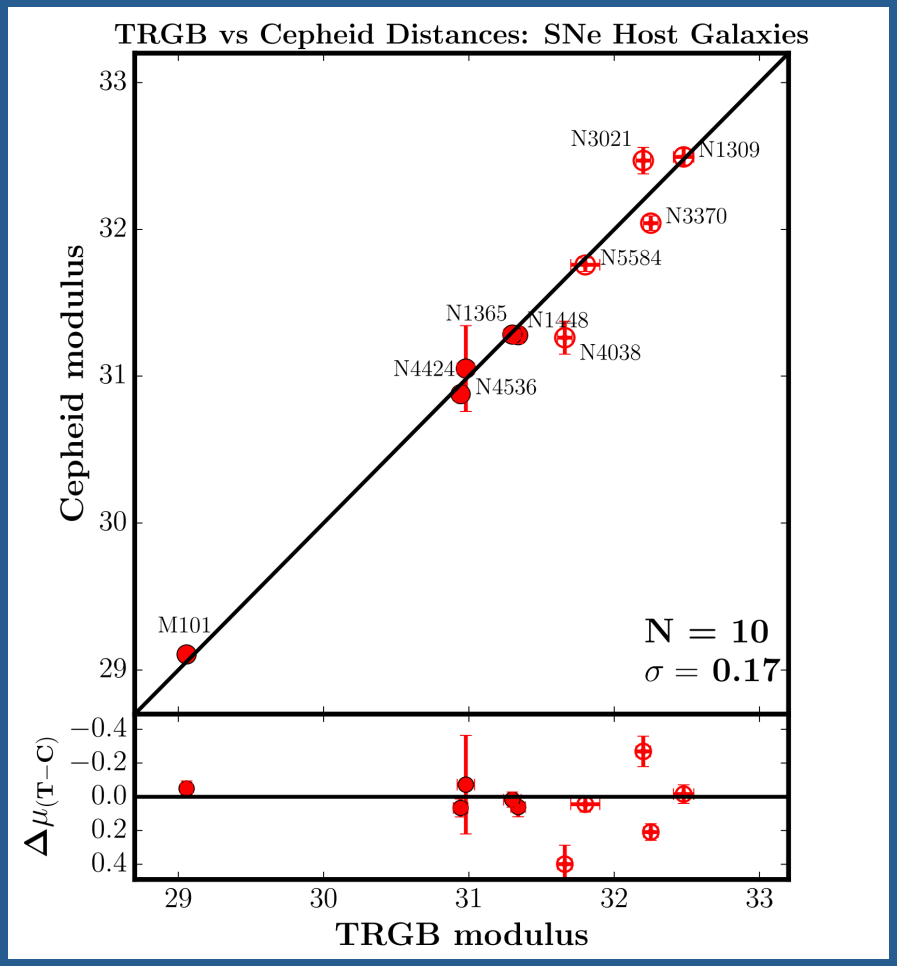


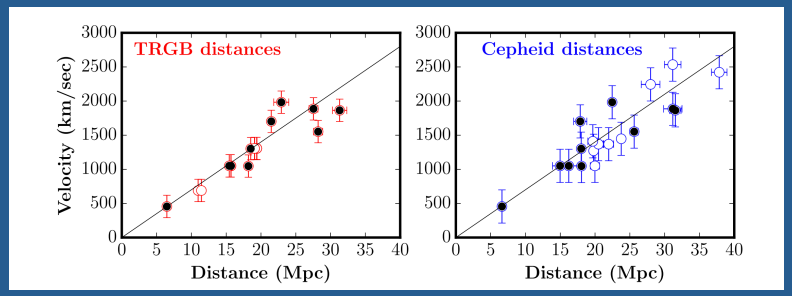
LMC Calibration

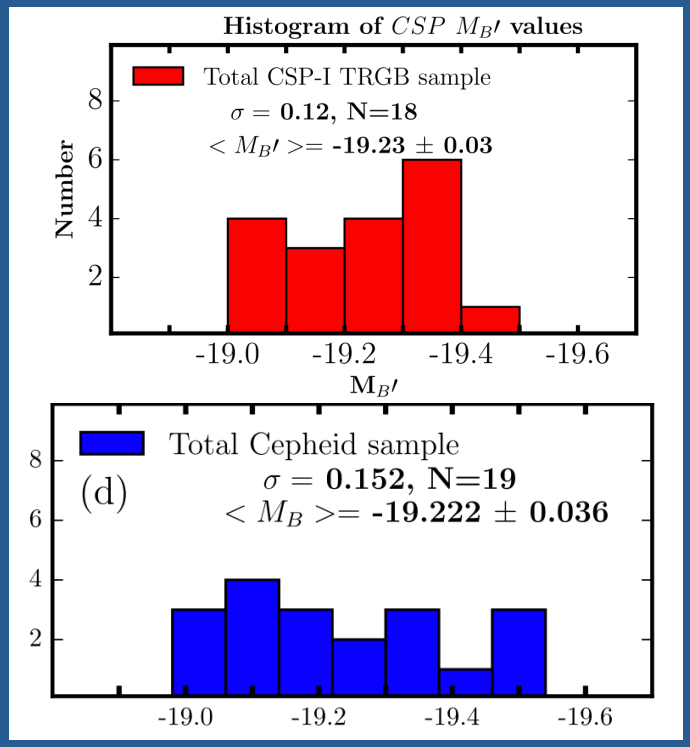




TRGB vs Cepheid Precision





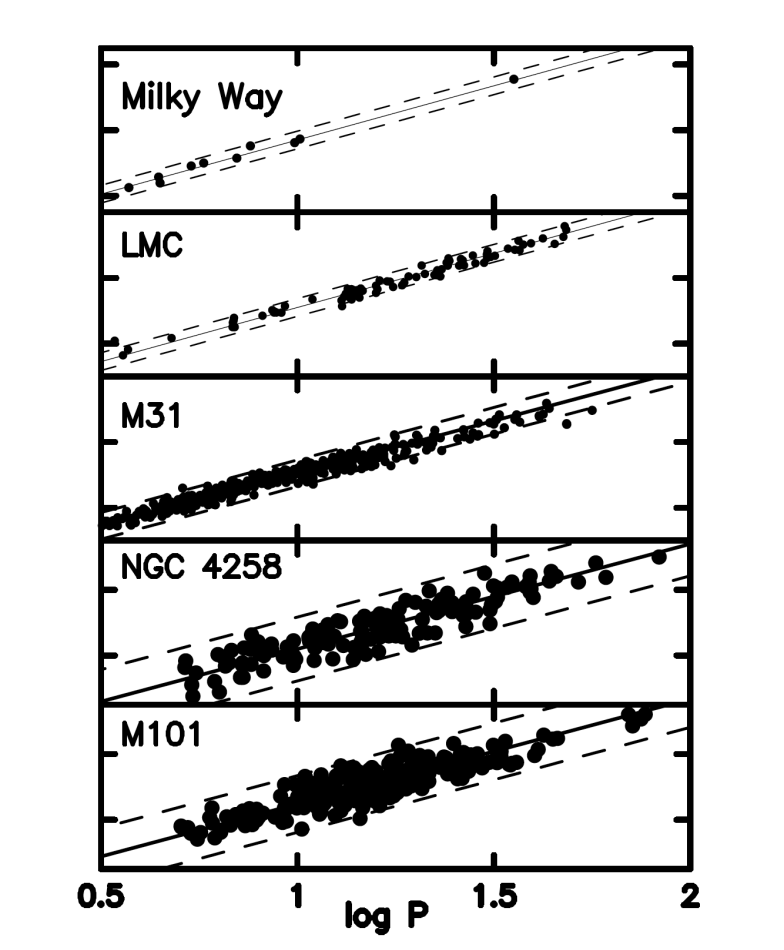


Deconvolution of Pair-wise Scatter Determination of Relative Precision

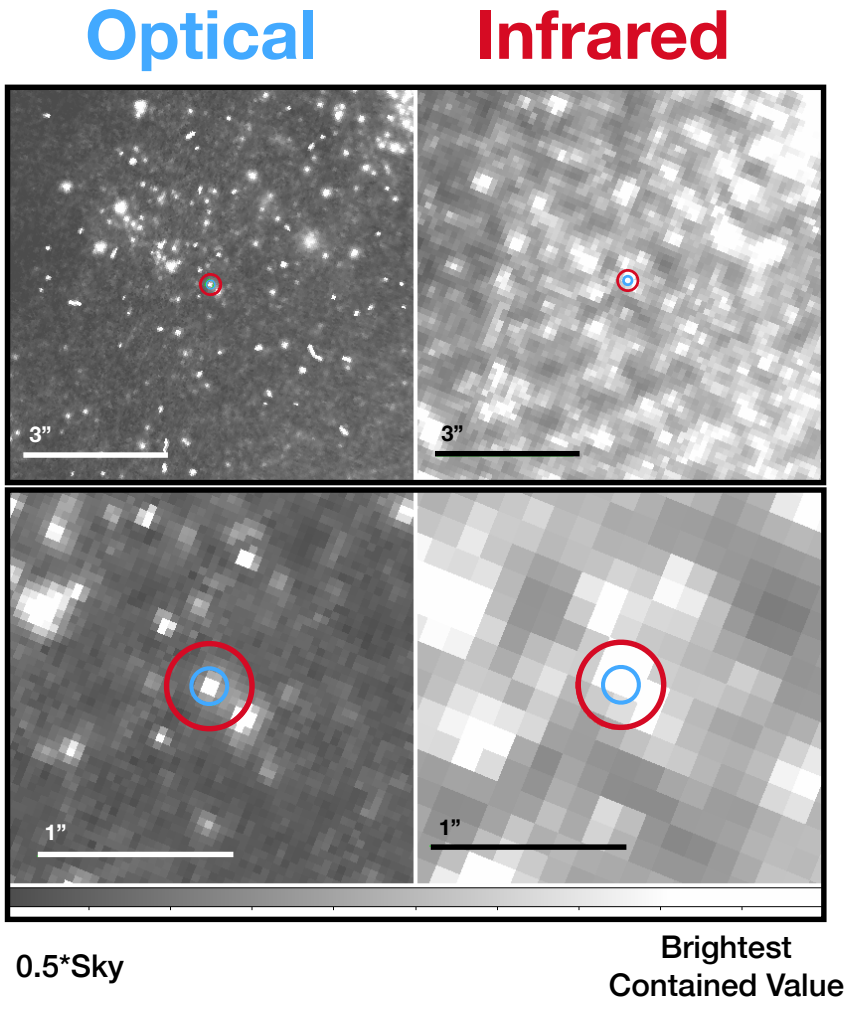
Indicator	Variance
TRGB	0.0081 mag^2
Cepheids	0.0169 mag^2
SNe Ia	0.0064 mag^2

TRGB Method is a factor of 2x more precise (as measured by its variance) than the Cepheids

The Cepheid Calibrators



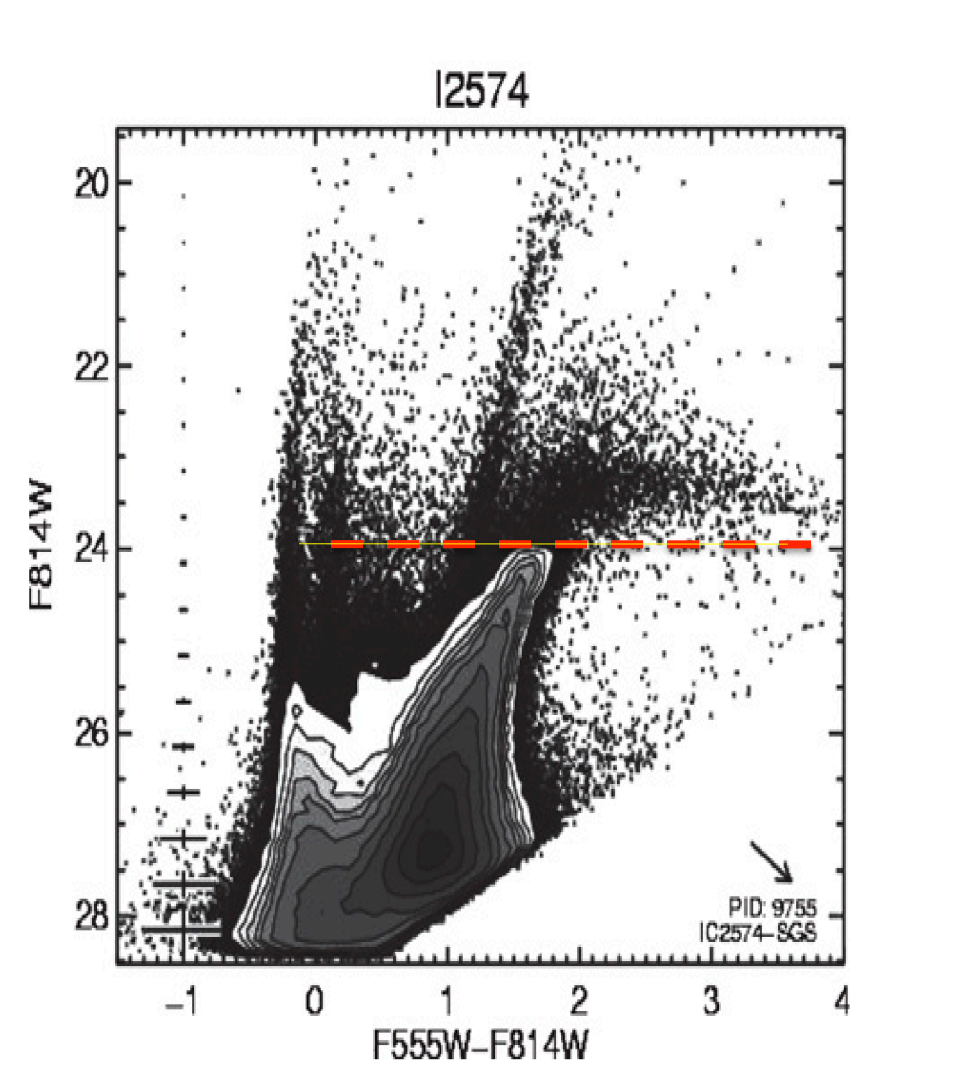
Cepheid Calibrators in NGC 4258



A Crisis in Cosmology?

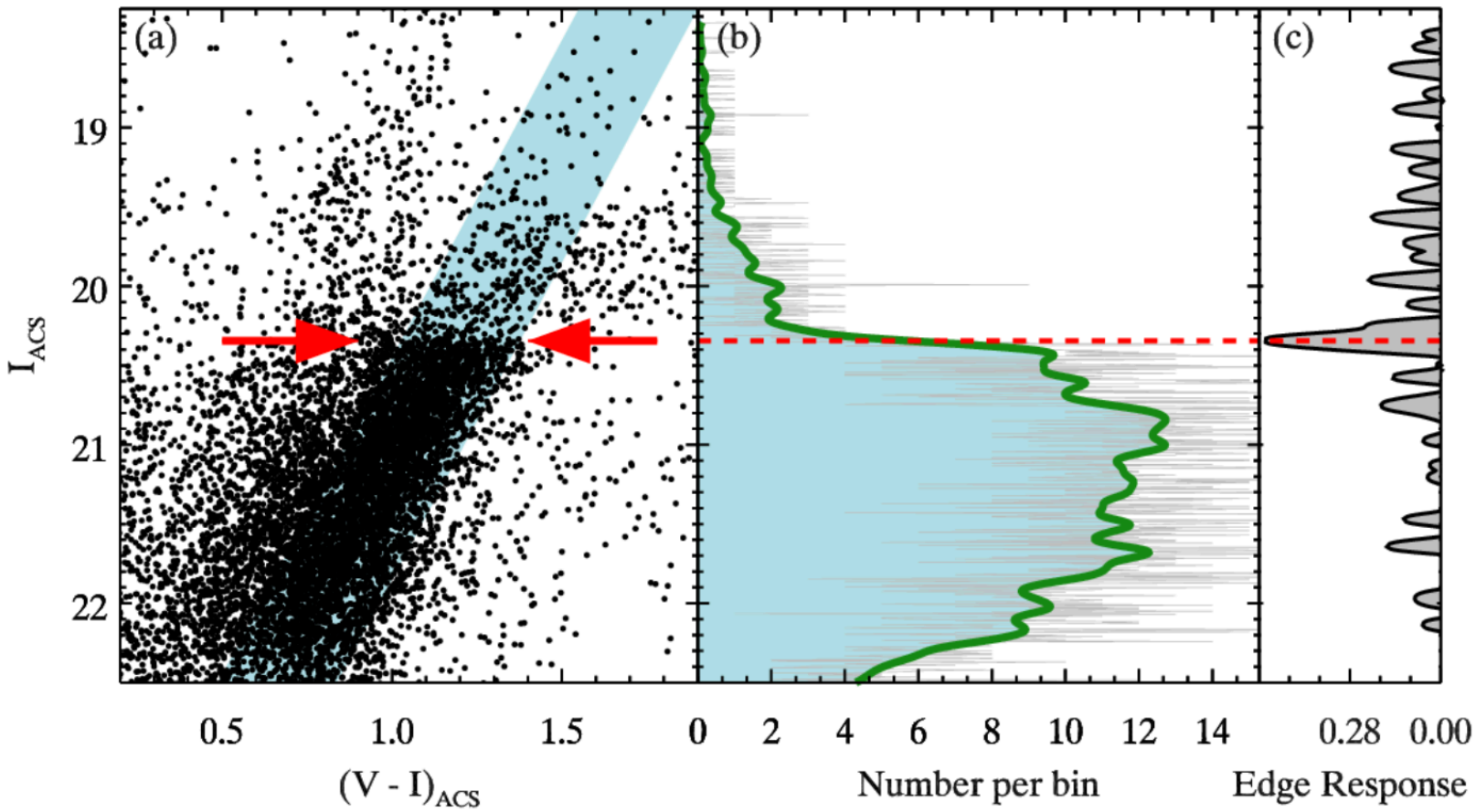
What should we believe?

The Only Standard Candle



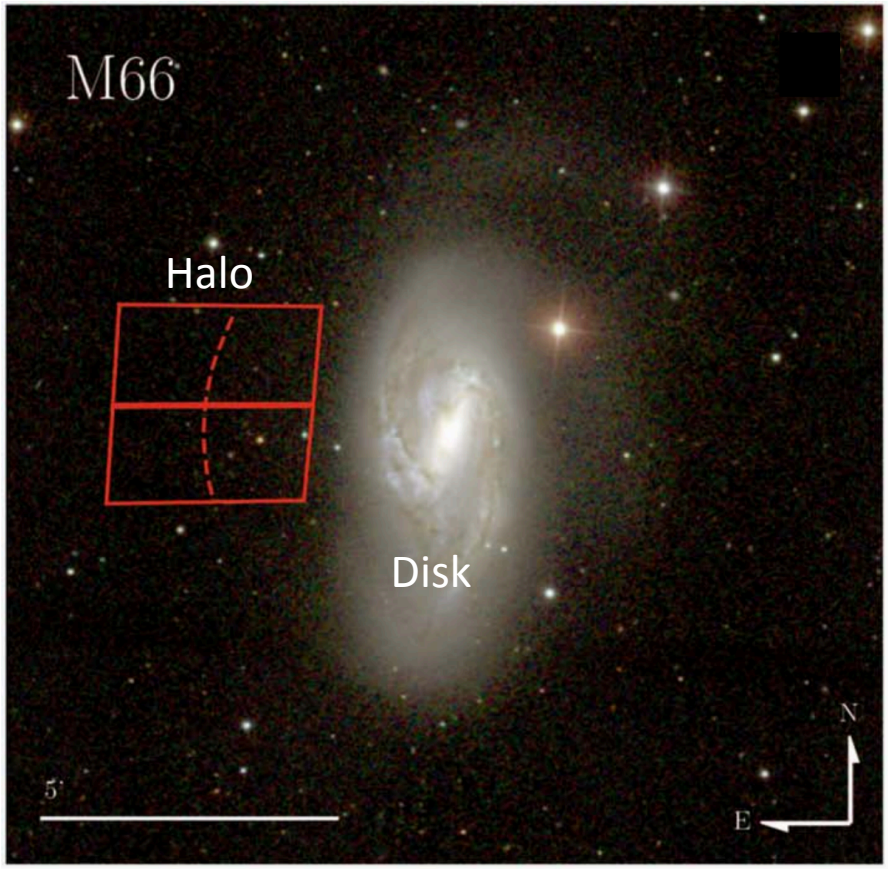
TRGB

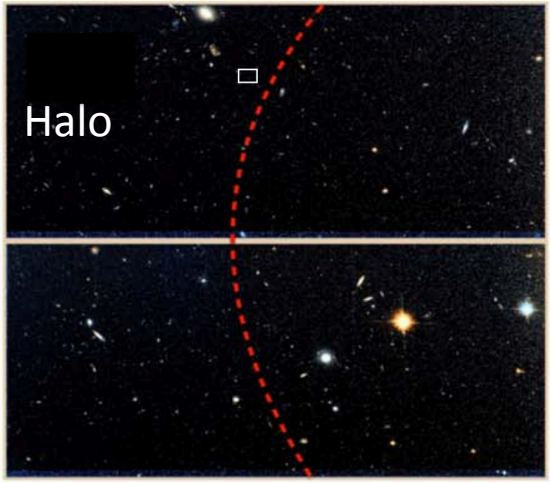
TRGB in IC 1613
The Only Feature Visible in the Halo

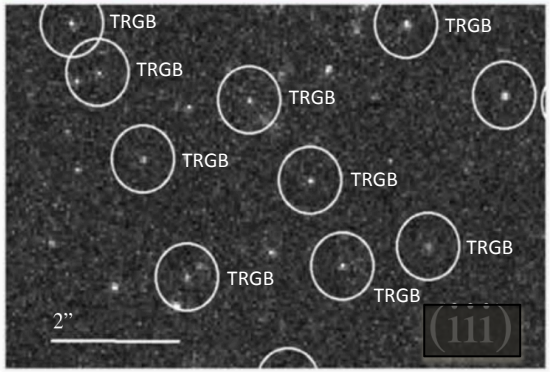


Hatt et al. 2017

TRGB Halo Fields
No Dust, Controlled Crowding







Individual TRGB Detections

Hoyt, T. et al. 2019, ApJ 882, 150

A Crisis in Cosmology?

What should we believe?

The PL Relation
(20 standardization parameters)

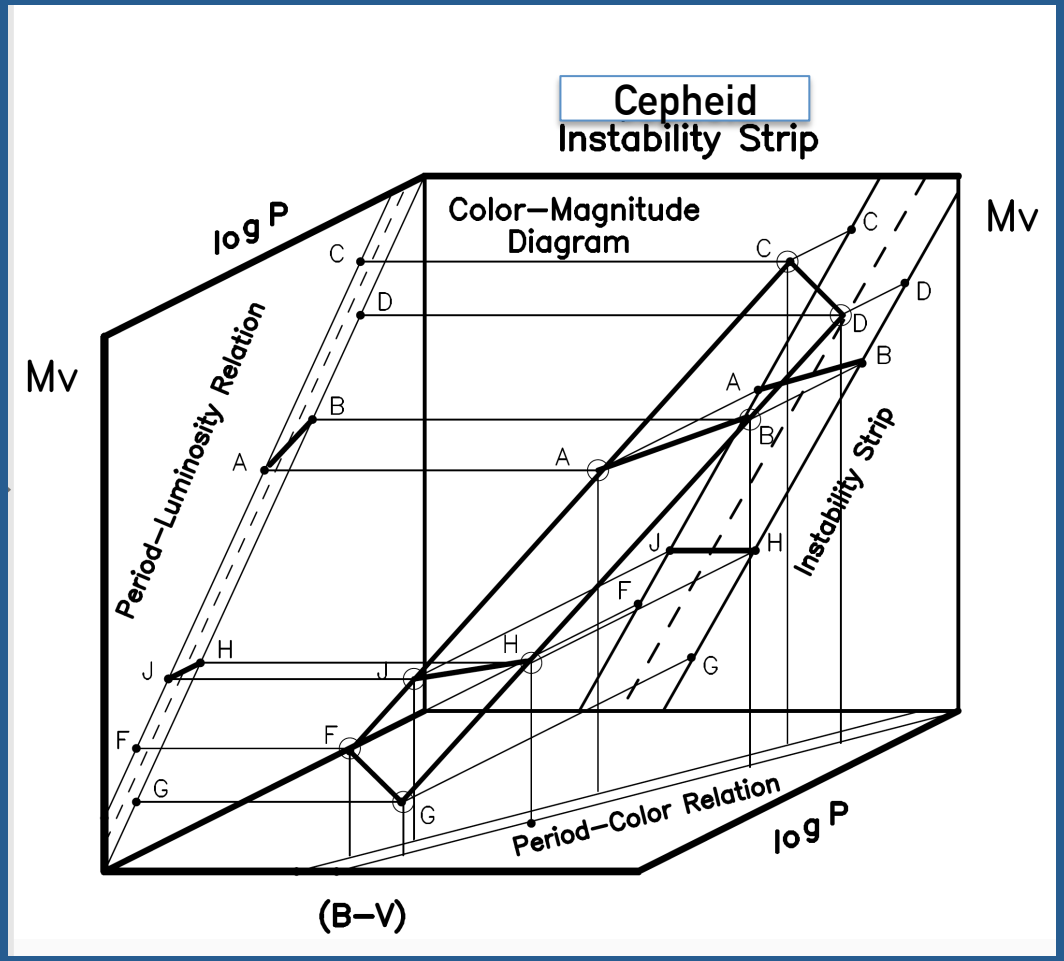
- Basic Thermal Physics & Geometry (Static)
- Stellar Pulsation ($P\sqrt{\rho}$)
- Stellar Excitation (He^+ Instability: Blue Edge)
- Stellar De-Excitation (Convection: Red Edge)
- Stellar Evolution (Bolometric)
- Stellar Atmospheres (Shocks, Convection, Line Blanketting)
- Stellar Composition (Interior & Atmospheric)
- Star Formation History (Contingent)
- Mass Loss (When, Why & How Much?)

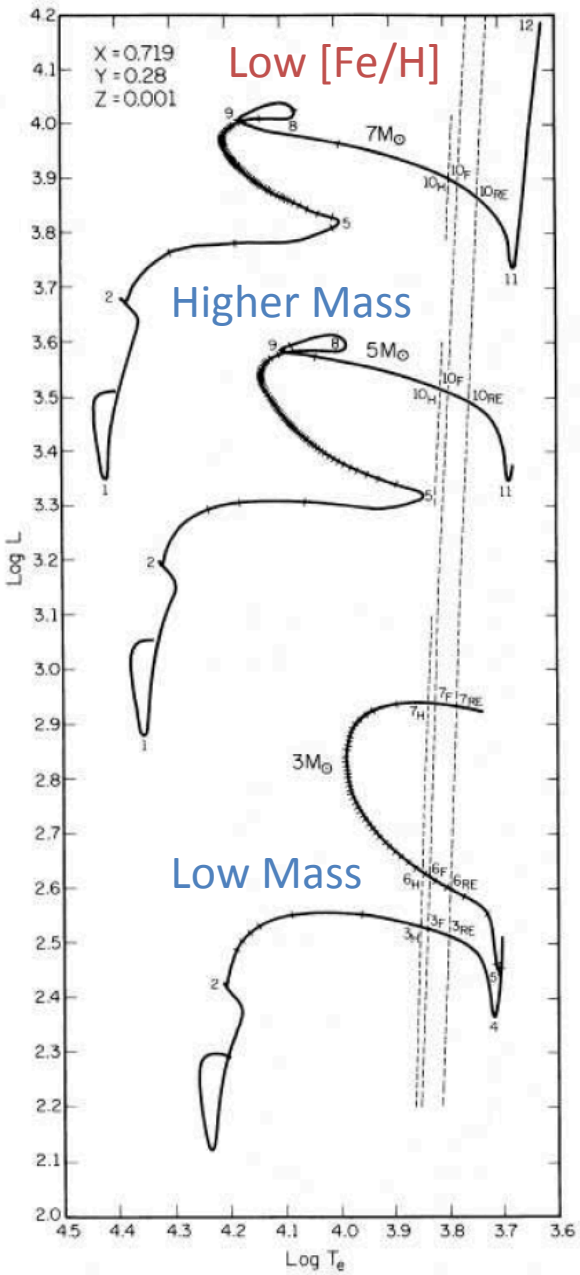
INTRINSIC

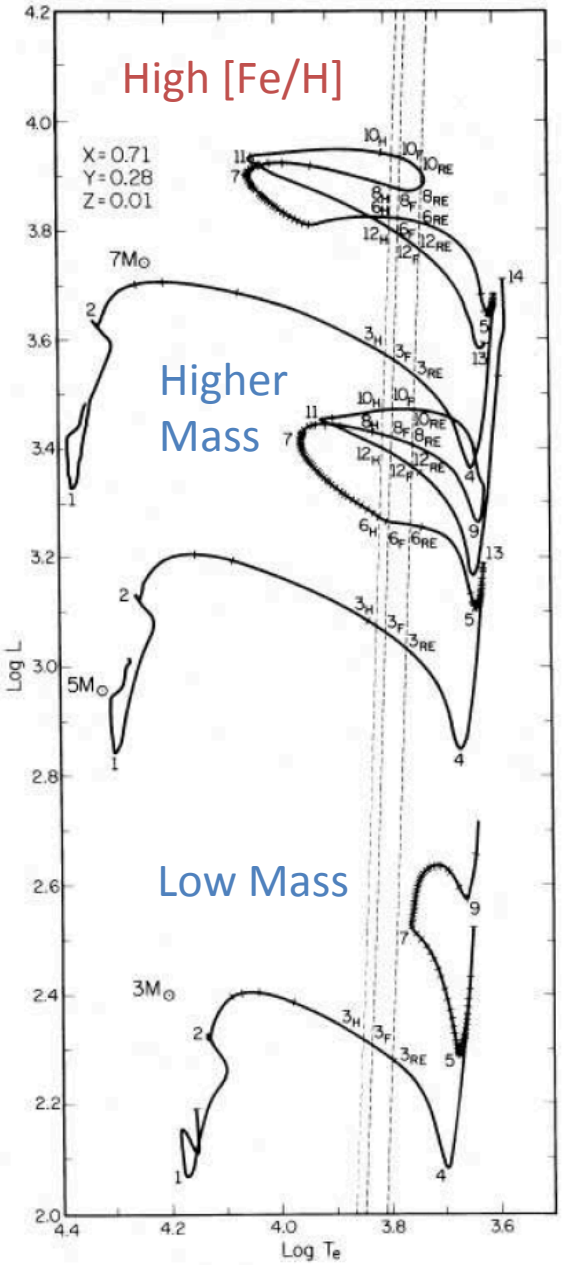
- Reddening (Foreground & Individual)
- Binaries (Calibrators & Targets)
- Crowding (Wavelength & Distance Dependent, the "AGB Floor")

EXTRINSIC

Cepheid Instability Strip in 3 Dimensions




Low [Fe/H]
X = 0.719
Y = 0.28
Z = 0.001
7M⊙
Higher Mass
5M⊙
3M⊙
Low Mass
Log L
Log Te

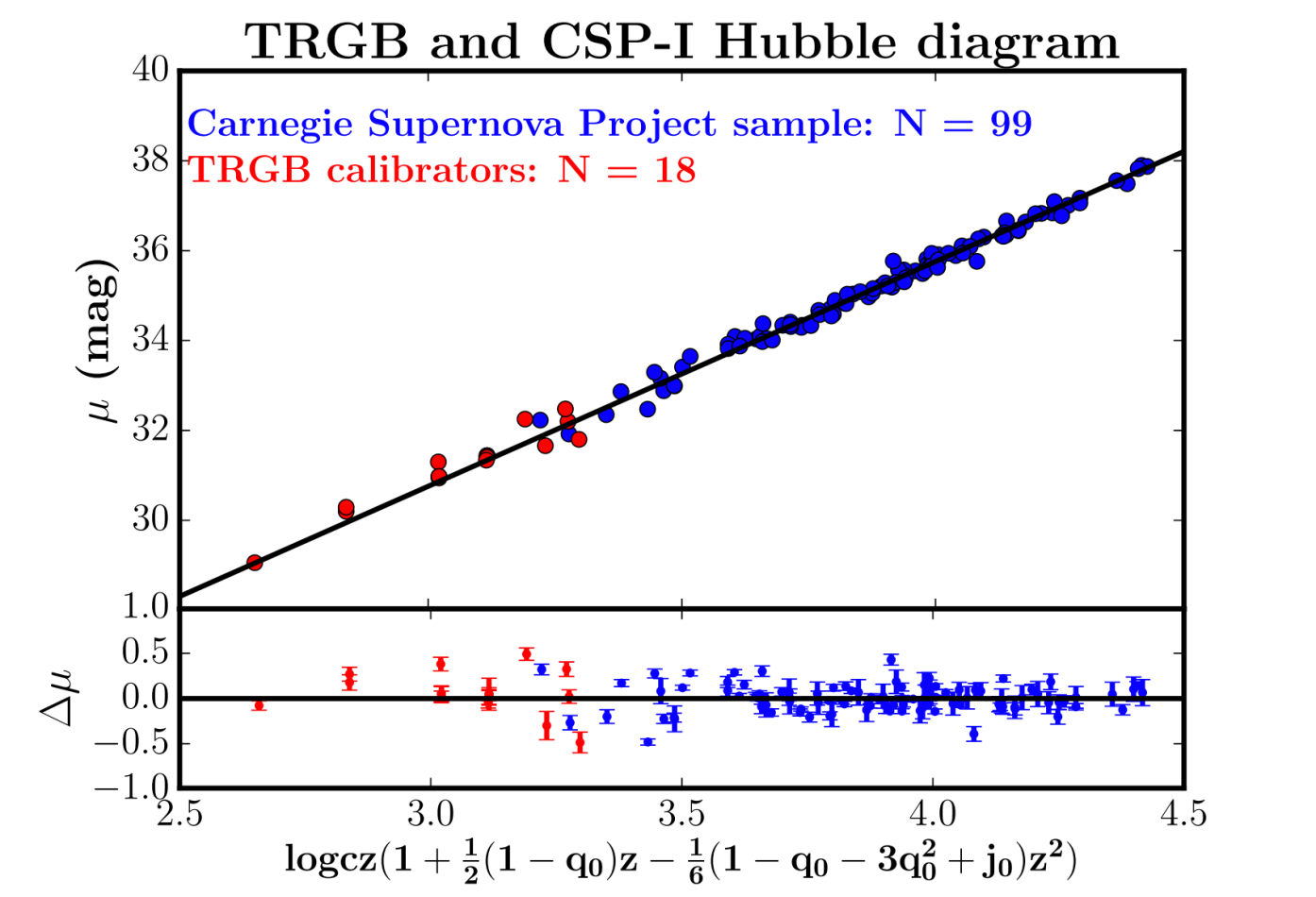

High [Fe/H]
X = 0.71
Y = 0.28
Z = 0.01
7M⊙
Higher Mass
5M⊙
Low Mass
3M⊙
Log L
Log Te

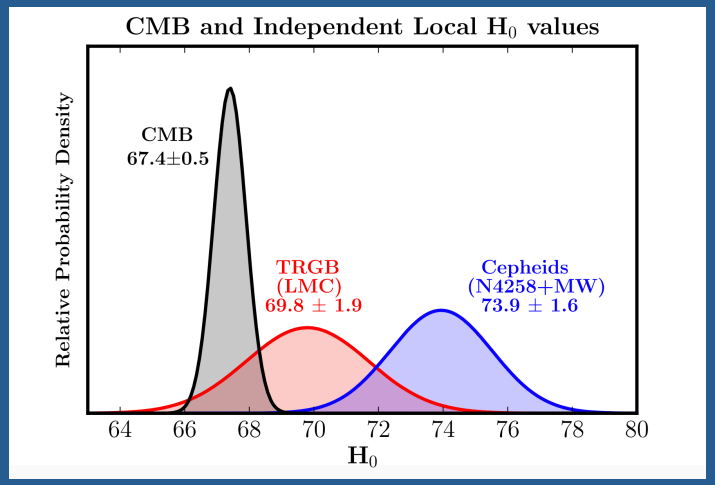
A Crisis in Cosmology?

What should we believe?

CSP Hubble Diagram

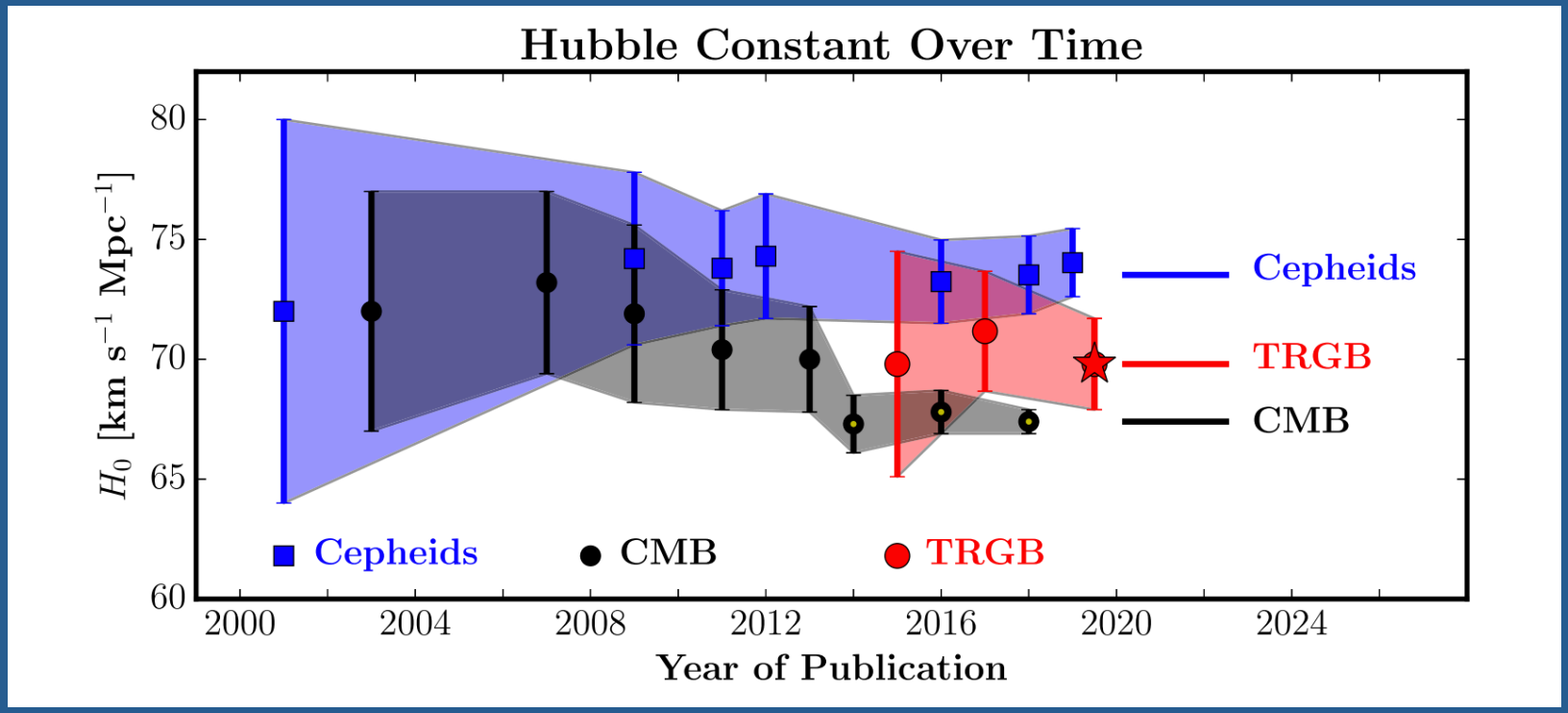
Freedman et al. 2019





Hubble Constant
10:17:57 am
October 5, 2019

H_o = 69.5 +/- 1.7 km/s/Mpc



A Crisis in Cosmology?

What should we believe?

A Pulsating Heat Engine
versus
A Physical Constant of Nature

Cepheids

TRGB

Closing Case for the TRGB

- Simplicity
- Understood with First Principle Physics
- Standard Candle
- Highest Precision
- Zero Point Multiply Calibrated Geometrically
- Low Reddening
- Low Crowding
- Applies to all Hubble Types