Sensors and Cameras

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Outline

- CCD Sensor Basics
  - Structure
  - Charge Creation
  - Charge Collection
  - Charge Transfer
  - Charge Measurement
  - Key Specs: QE, Well Cap'y, Read Noise, Dark Gen Rate + …
- Cameras
  - Ultimate limit is sensor performance
  - Pixel Size: bigger is "faster", bigger costs more
  - Color or Mono?
    - Color: star trails, comets, asteroids/minor planets
    - Mono: everything else
- Noise
  - Noise Equation & major components
  - Cooling & Cosmetics
  - PTC Analysis
- Flat Fielding
- Images

CCD Sensor Basics

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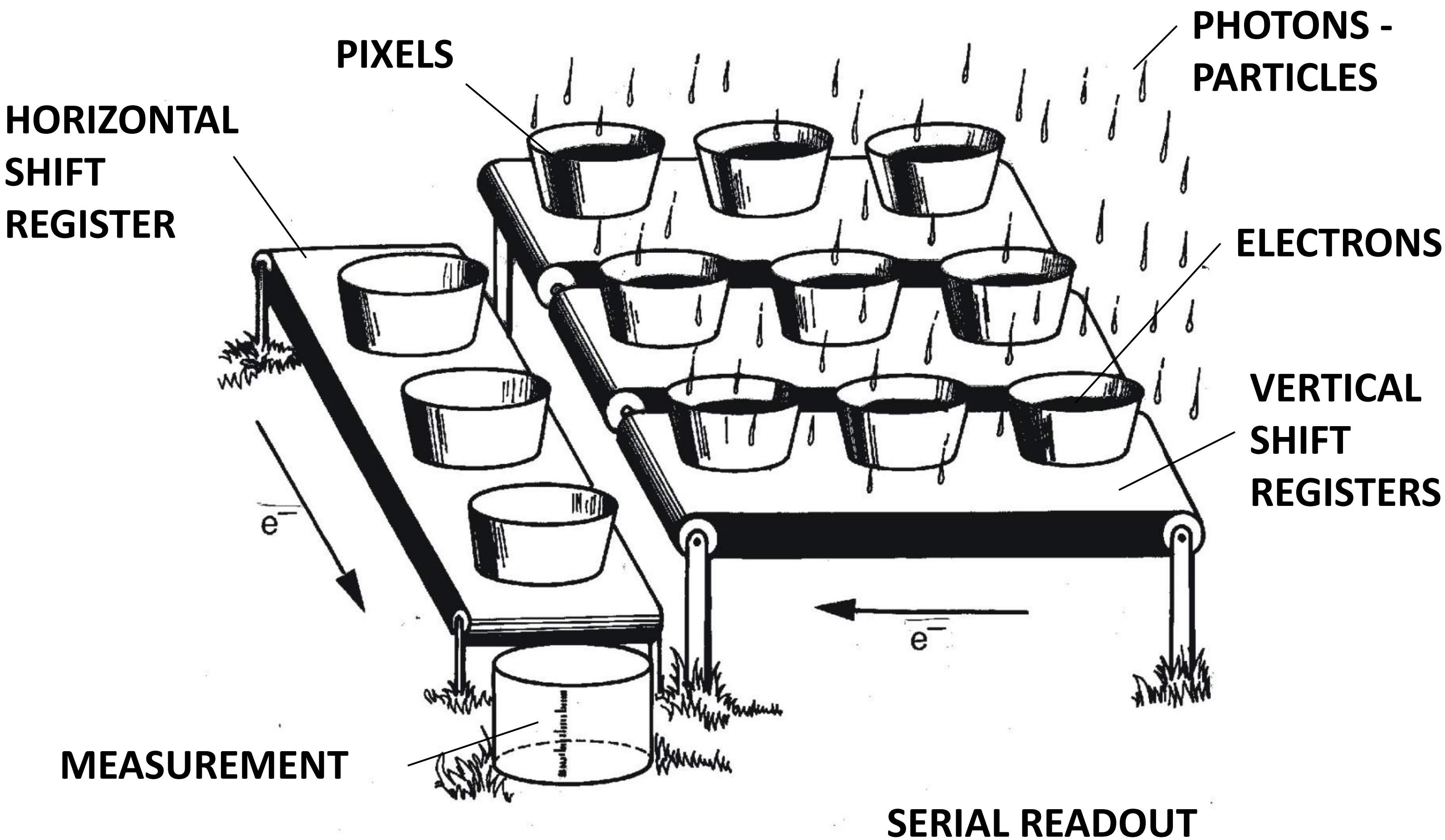
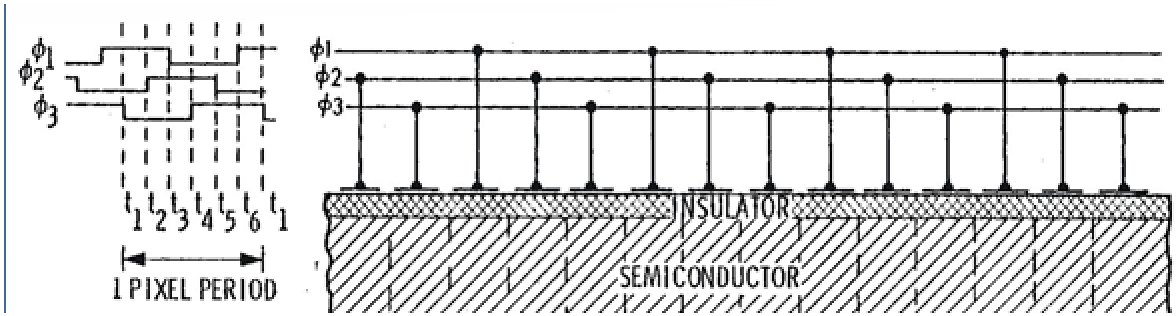
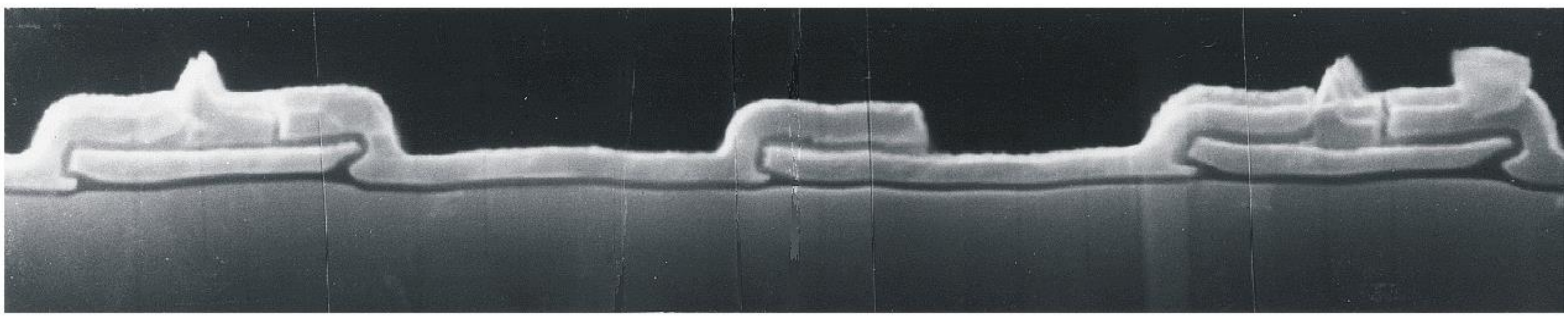
CCD Readout Scheme



Structure

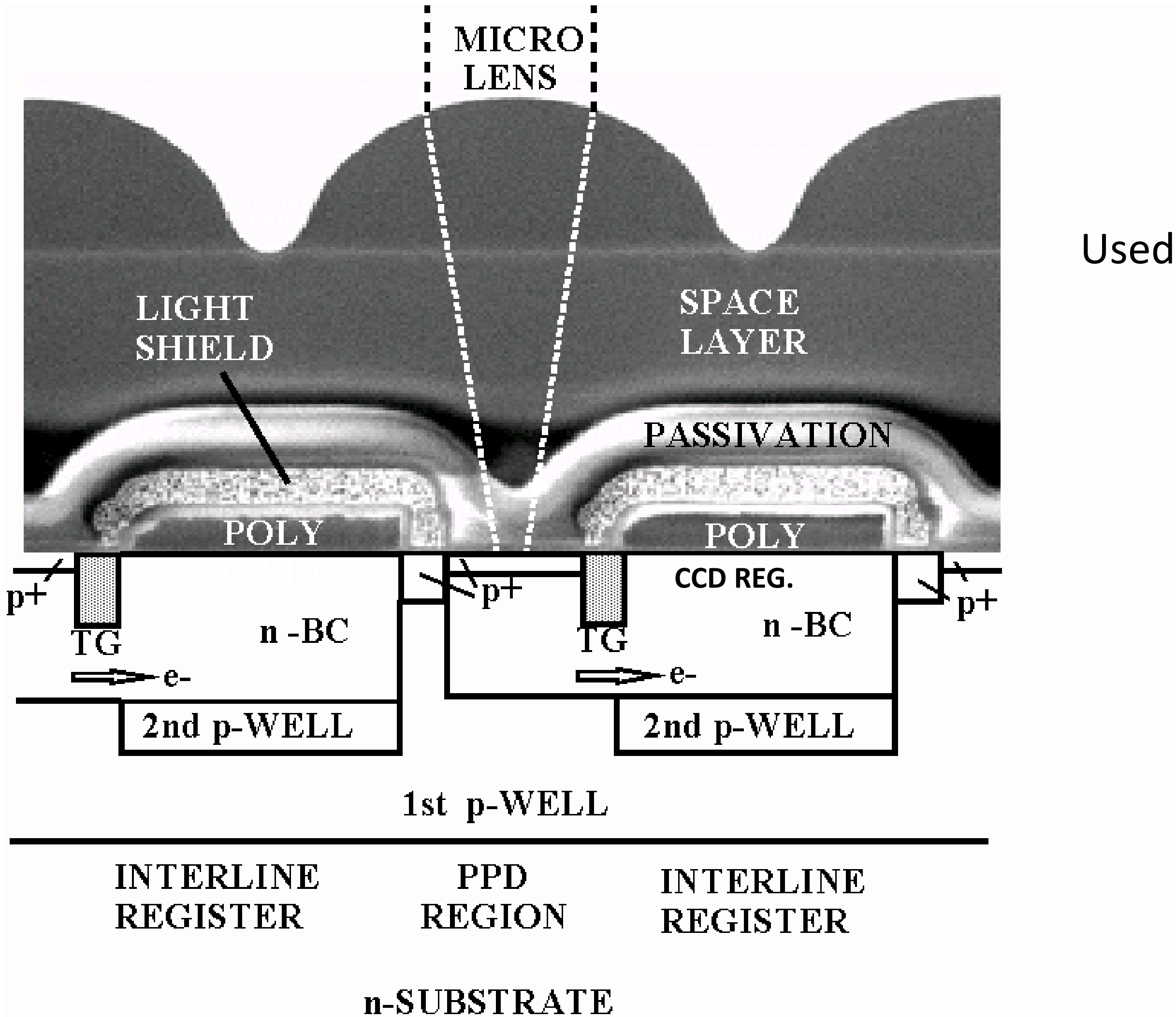




POLY 1 **POLY 2** **POLY 3** **POLY 1**

HUBBLE WF/PC I THREE PHASE PIXEL

INTERLINE TRANSFER
(ELECTRONIC SHUTTER)

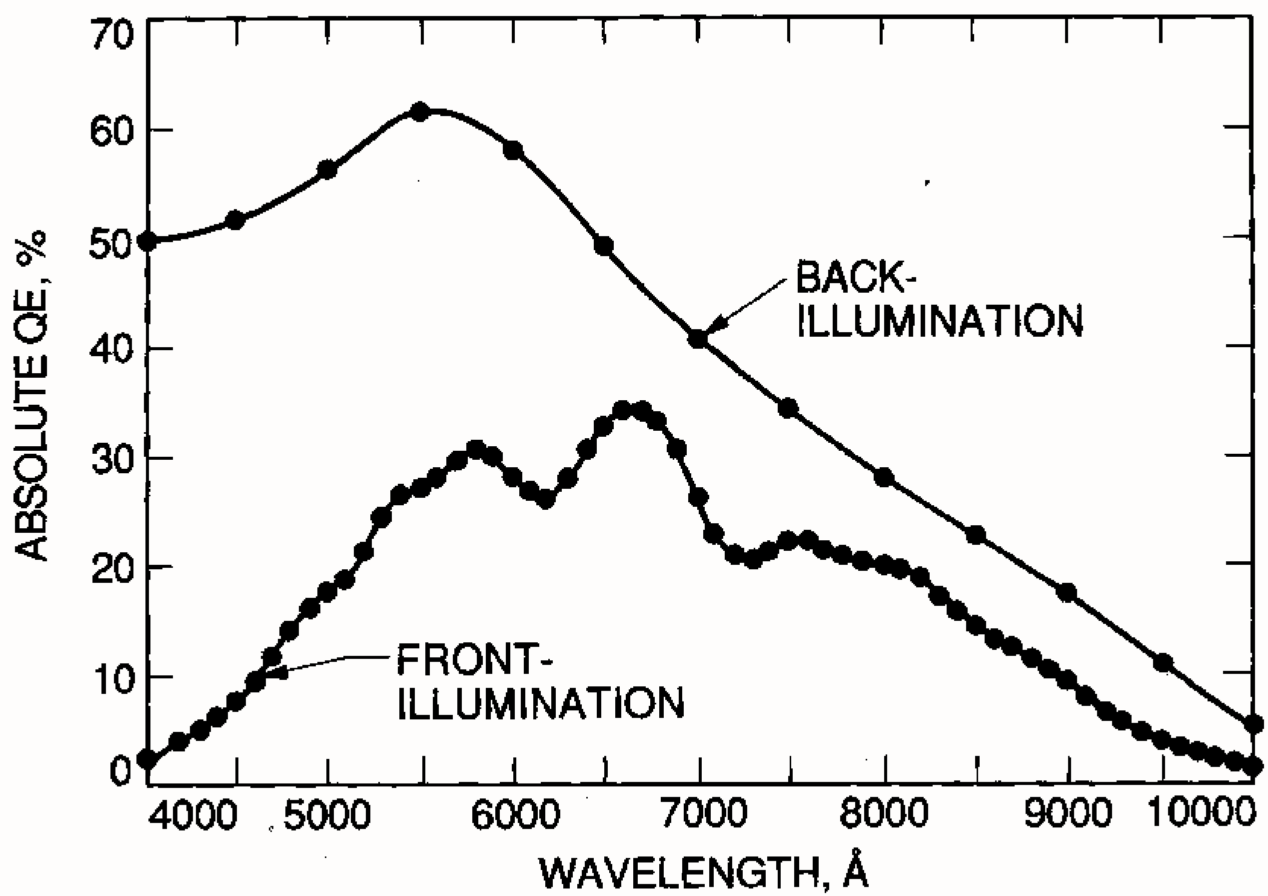


Used by KAI series

Image Sensor Key Specs

- Quantum Efficiency / Spectral Response
- Well Capacity
- Read Noise
- Photo-Response Non-Uniformity
- Dark Signal Generation Rate
- Dark Signal Non-Uniformity

Quantum Efficiency



Cameras

Cameras

- Cameras
  - Ultimate limit is sensor performance
  - Pixel Size: bigger is “faster”, bigger costs more
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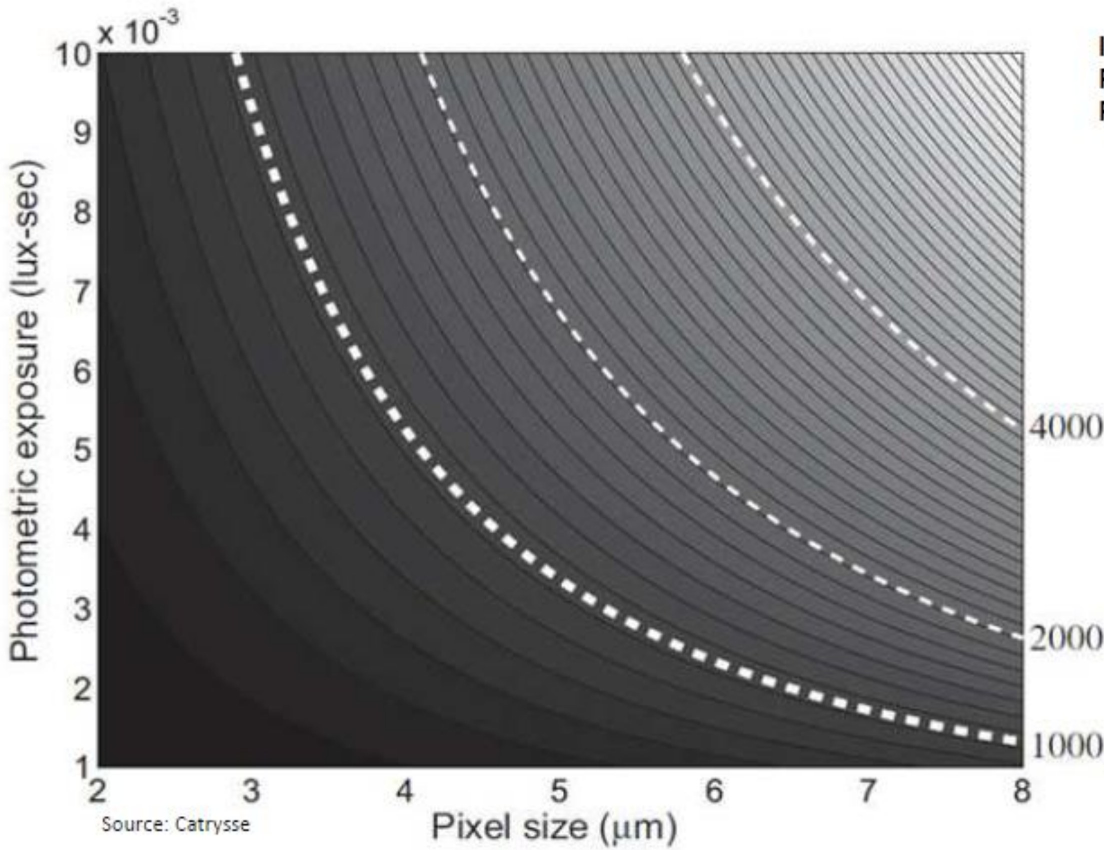
Pixel Size & "Speed"

Pixel Geometry:
How many photons is your pixel receiving?

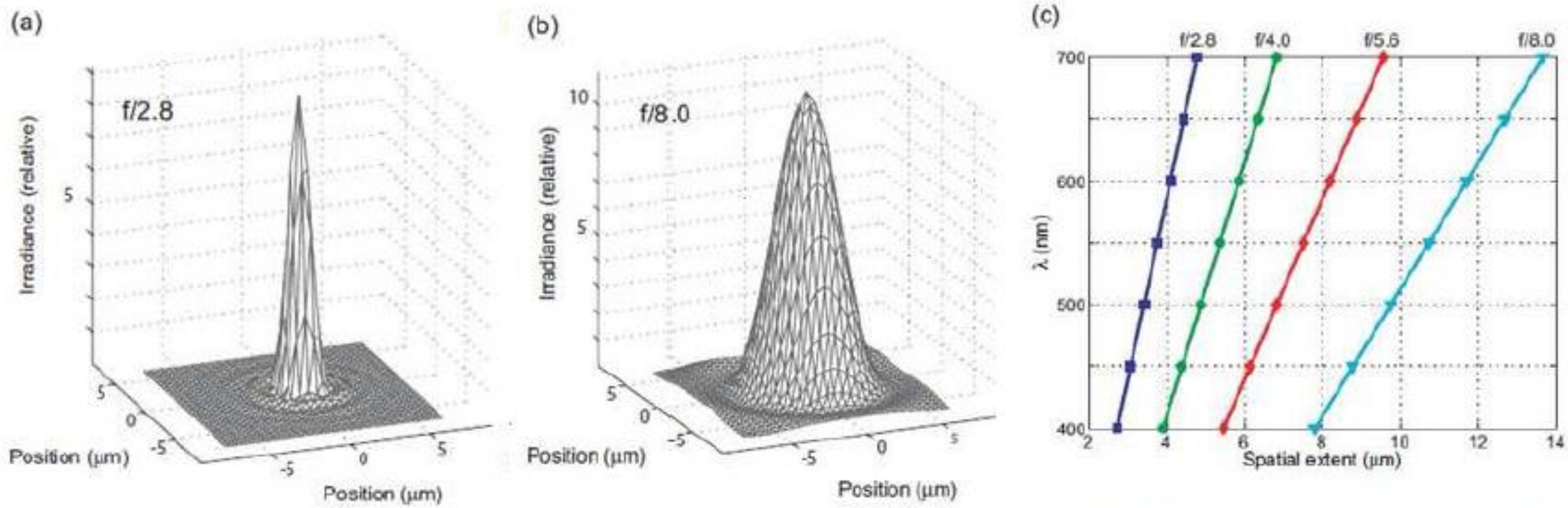


Source: Catrysse

Incident Photons/ Pixel	Maximum Theoretical SNR (db)
4000	63.25
2000	44.72
1000	31.62

Photons

Optics and the Airy Disk:
Focal ratio: Sets spot size for diffraction limited optics



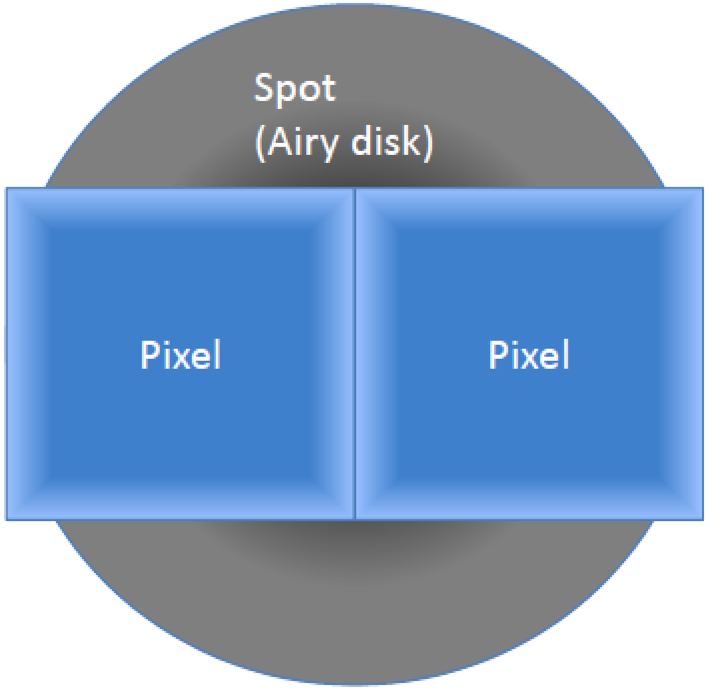
Airy Disk Diameter (microns)

Source: Catrysse

~3 microns, f/2.8

~10 microns, f/8.0

Optimum Pixel Size



Nyquist Sampling Criteria:

$$Pixel\ size = 1.22 * \lambda * F\#$$

For seeing-limited conditions (what we normally experience):
Use Nyquist to cover seeing spot size vs Airy Disk spot

Ex: 2 arc-sec seeing use two pixels to over spot: 1 arc-sec/pixel image scale is indicated

Color or Mono?

- One Shot Color: good for transient events
  - Comets
  - Minor Planets
  - Man Made Objects in Orbit
  - Star Trails
- Monochrome:
  - Most Sensitive
  - Color via use of filters and time sequential exposures
  - Most flexible: True Color, Narrowband, other

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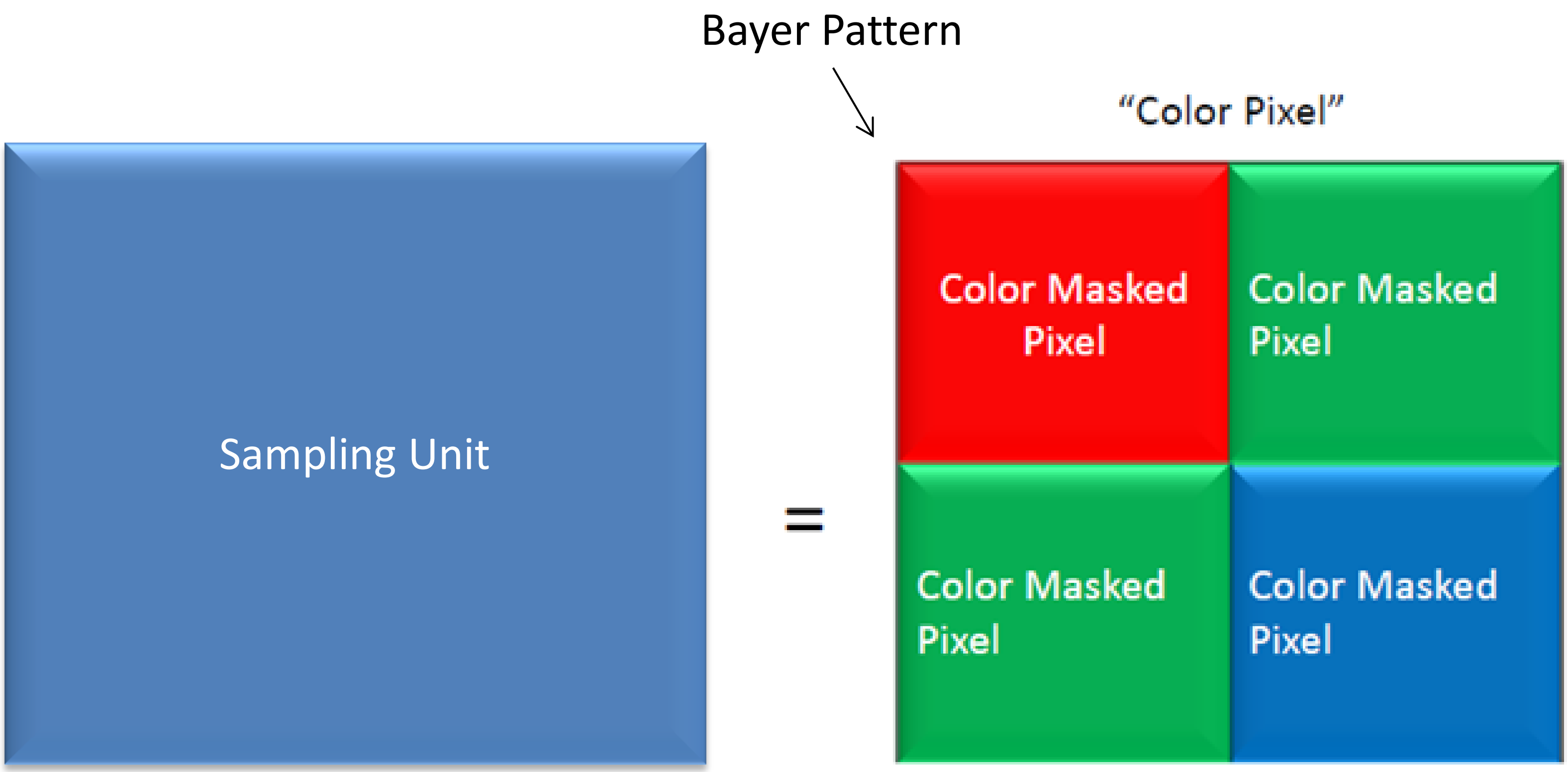
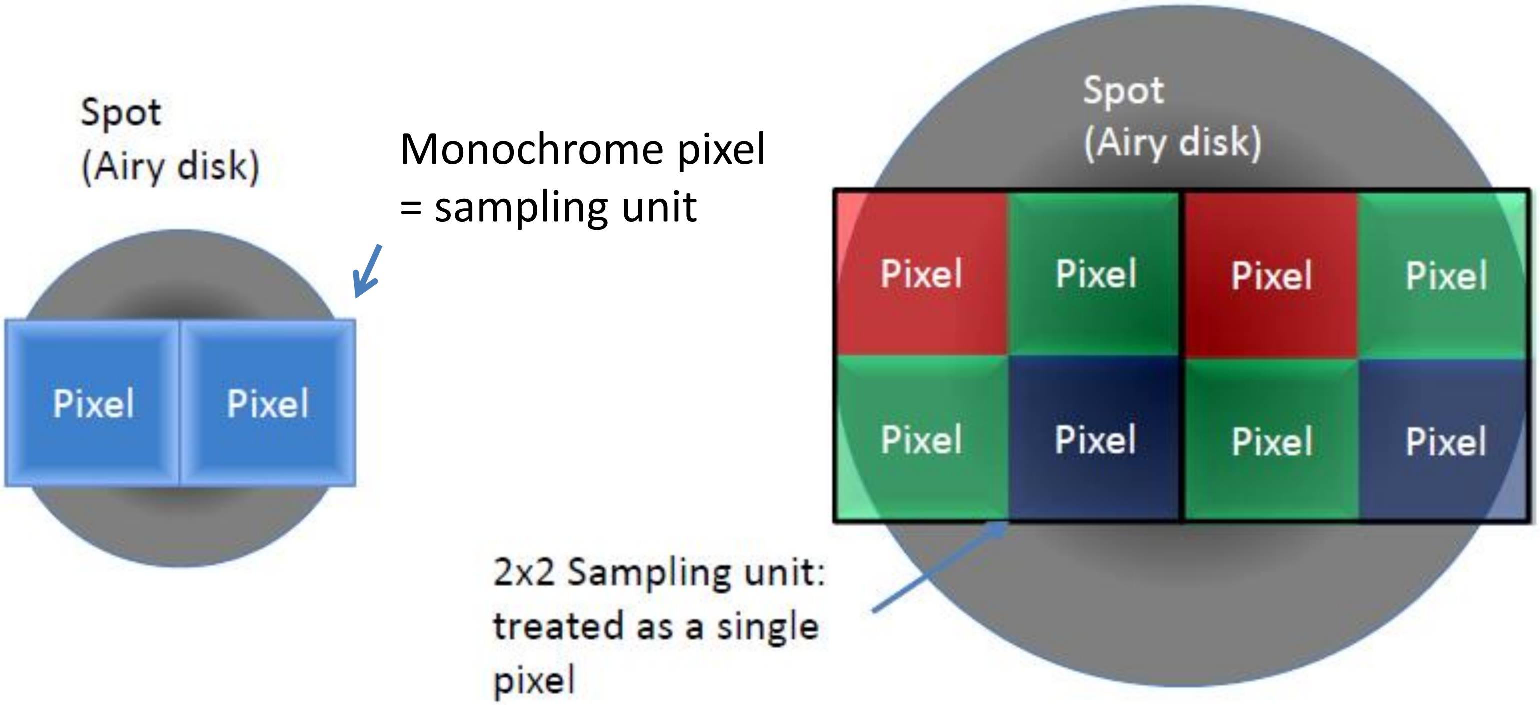
What Changes for One Shot Color?



Color Masked Pixels vs Monochrome Pixels: optimum spot size, F# changes



- **Same sensor base pixel size: different optimum spot size**
  - 2:1 difference in optimum F#
  - 2:1 difference in LP/mm required by optics

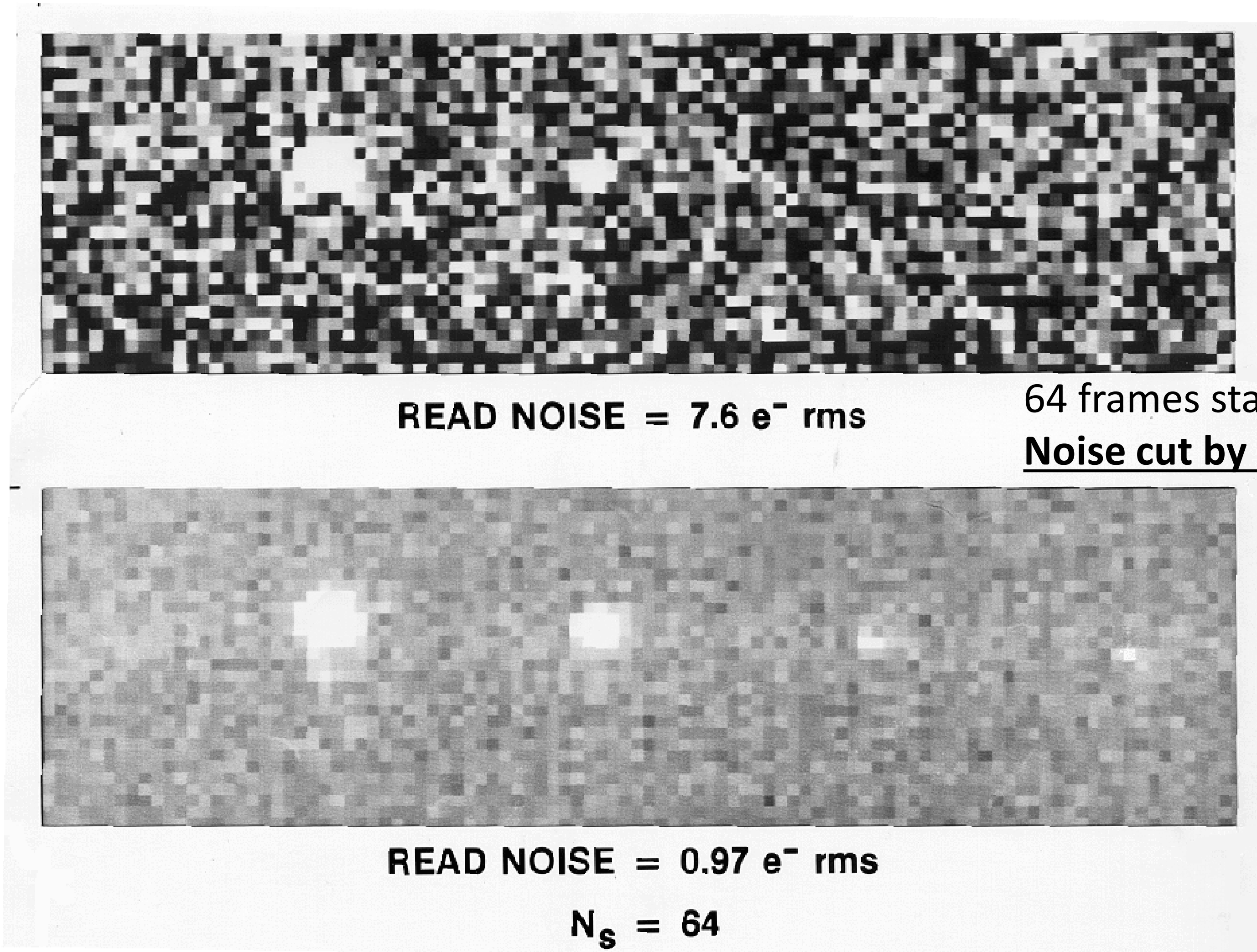
If the seeing goes bad, switch to one shot color?

Noise

Primary Noise Components

- Read Noise (unavoidable, camera quality measure, stack frames to minimize)
- Signal Shot Noise (unavoidable, inherent property of sampled data systems, stack frames to minimize)
- Fixed Pattern Noise (removable by flat fielding)
- Dark Shot Noise (inconsequential via cooling)
- Dark Fixed Pattern Noise (minimize by cooling, dark-subtract the rest)

Read Noise & Faint Signals

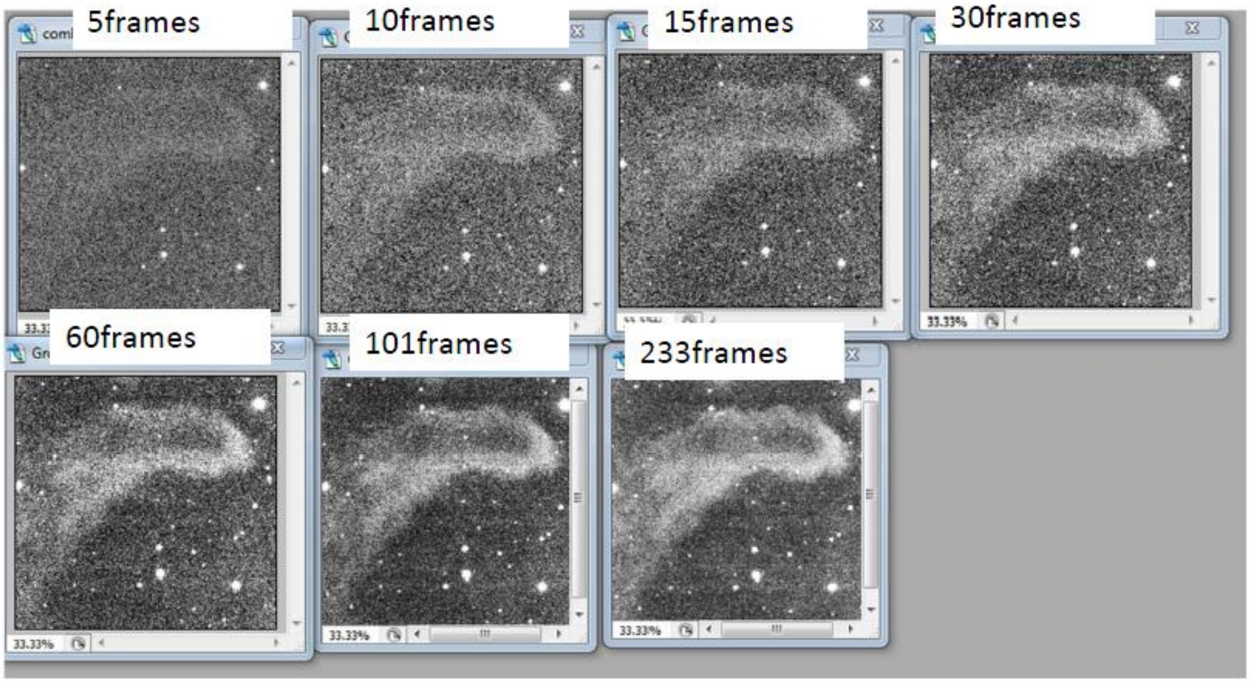


64 frames stacked
Noise cut by 8x

Combine 64 images: drive down Rd Noise by 8x

Read Noise & Faint Signals

ABG Sensor (KAI29050) with 20,500 e- saturation signal on HDR object (M42)



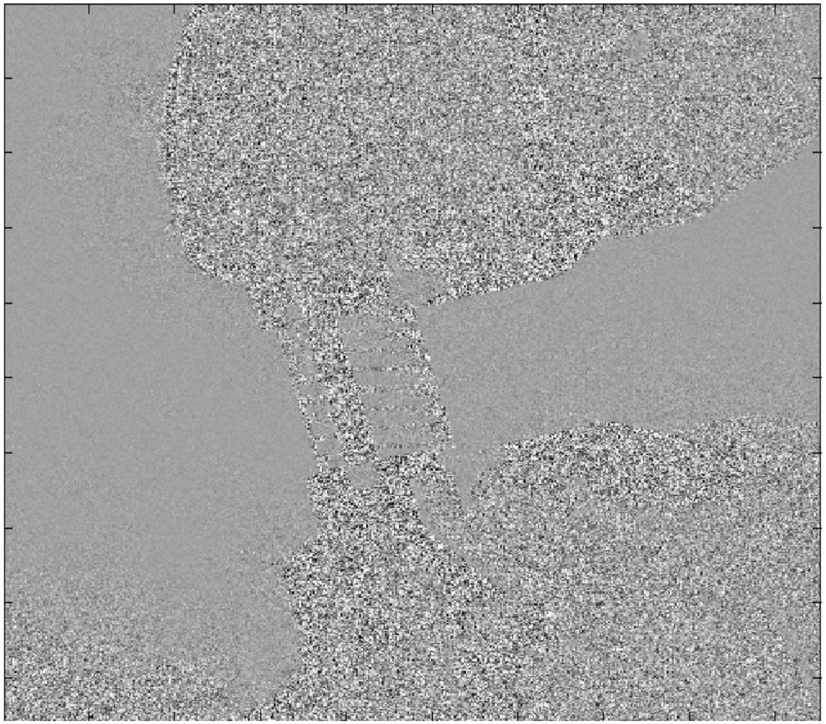
Very faint parts of image are buried in read noise: use large numbers of frames to improve SNR (ie 90 second exposures in Orion Nebula)

Shot Noise

- Minimum possible Noise for a single sampled-data frame is Photon Shot Noise
- Shot Noise is proportional to square root of signal level
- You combine several images to reduce the shot noise
- The image quality improves as the square root of the number of frames combined: Takes 4x frames to get a 2x Reduction of Photon Shot Noise

Signal or Photon Shot Noise

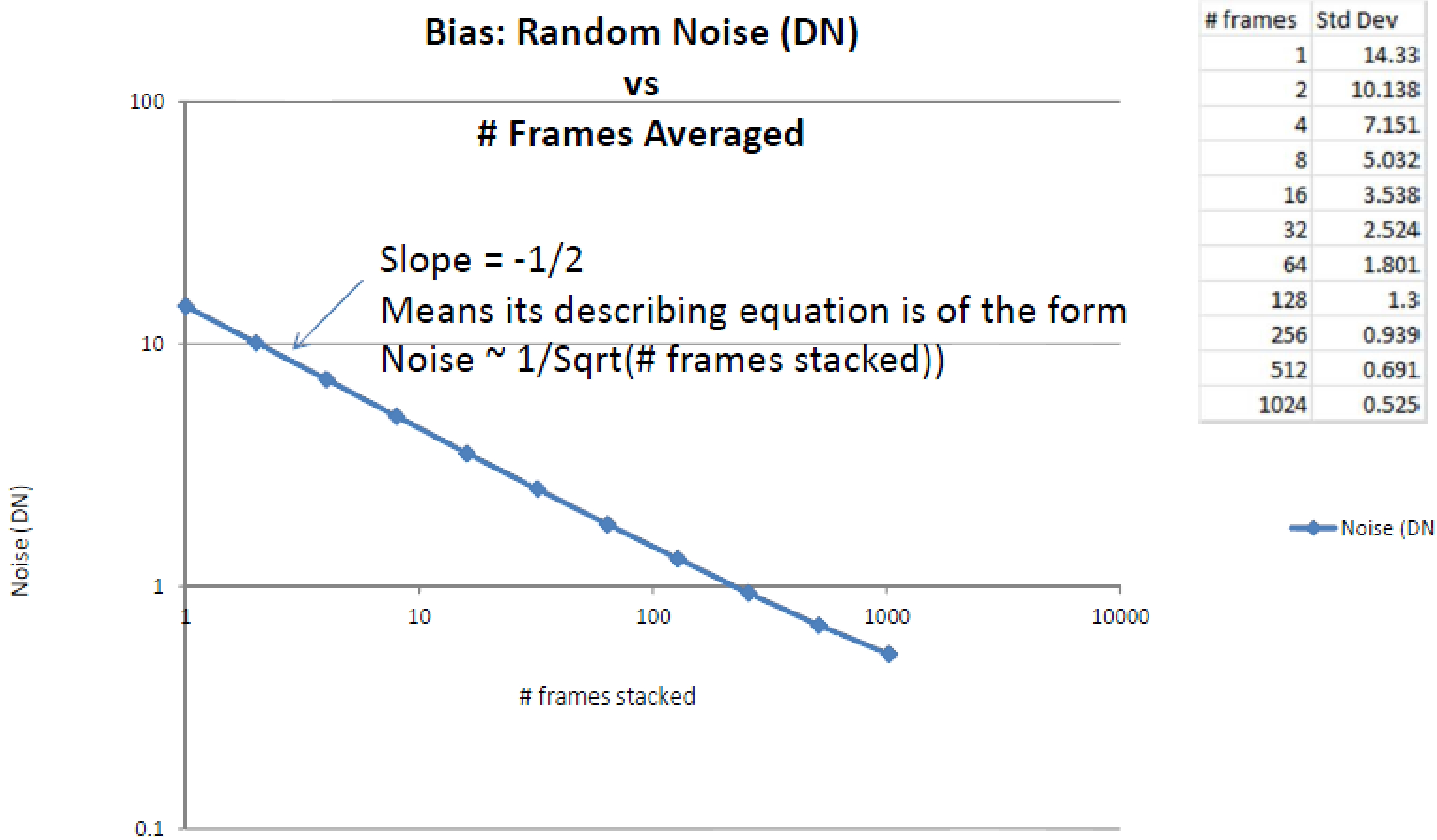
Image Including Photon Shot Noise



Photon Shot Noise Only

Photon Shot Noise = SQRT (Signal)

Noise Reduction by Stacking

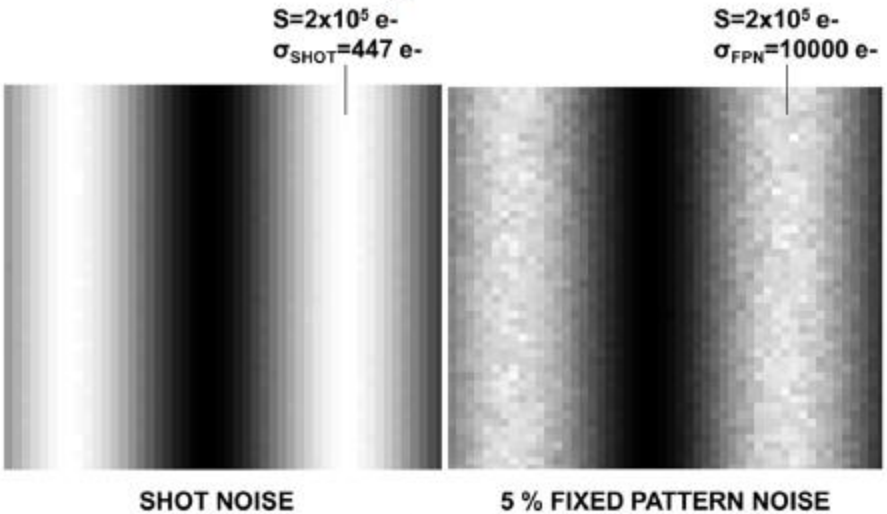


# frames	Std Dev
1	14.33
2	10.138
4	7.151
8	5.032
16	3.538
32	2.524
64	1.801
128	1.3
256	0.939
512	0.691
1024	0.525

Fixed Pattern Noise (“FPN”)

- Sensor level: Caused by pixel to pixel sensitivity nonuniformity (sensor level PRNU)
- System Level: Caused by non-uniform illumination of sensor to a flat field source
  - Conventional Cos^4 rolloff (optical vignetting)
  - Dust motes
- **Proportional to signal level: Ultimately limits SNR unless removed**
- Removed via Flat Fielding

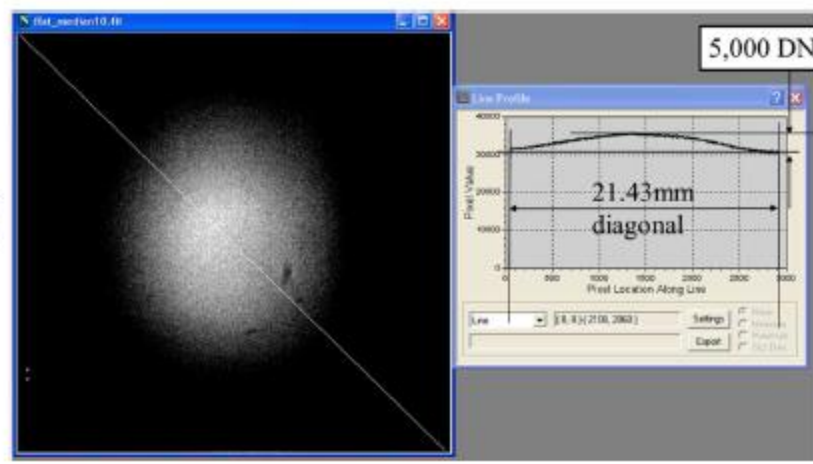
Examples of Fixed Pattern Noise



Source: Janesick

Sensor FPN

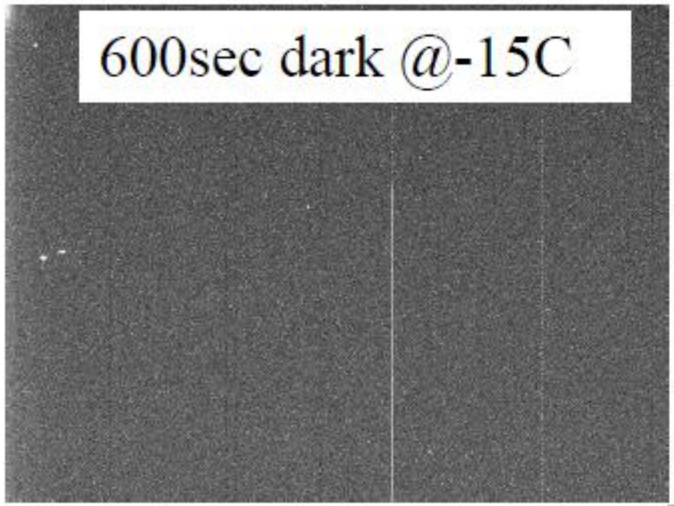
Optical FPN



Dark Signal

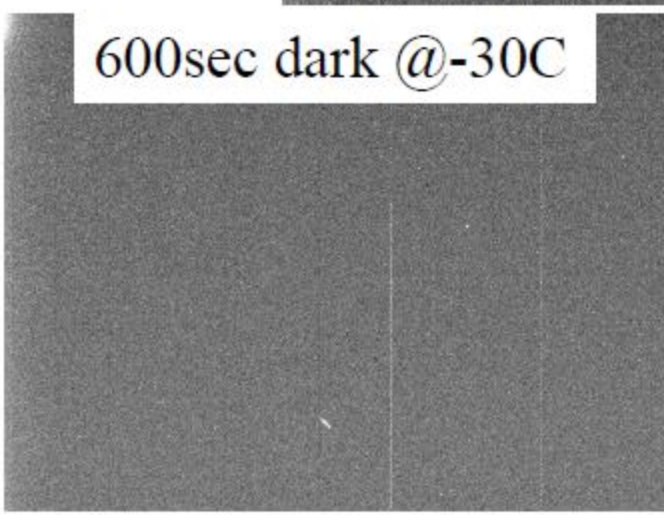
- Any real sensor will have a finite dark signal (ie, signal when no light is present): Semiconductor thermal leakage at root cause
- Strongly influenced by temperature: 5C doubles approx
- Two basic noise components result from Dark Signal:
  - Dark shot noise (made non-significant via cooling)
  - Dark Fixed Pattern Noise (minimized by cooling, remaining dark noise spikes: removed by “dark subtraction”)

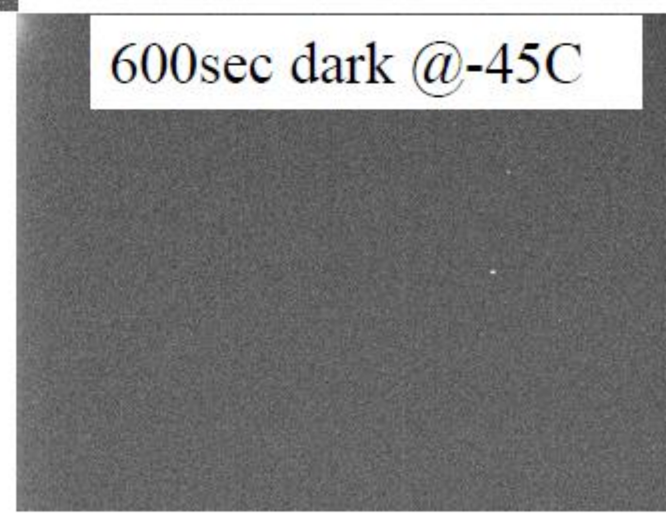
Cooling & Cosmetics



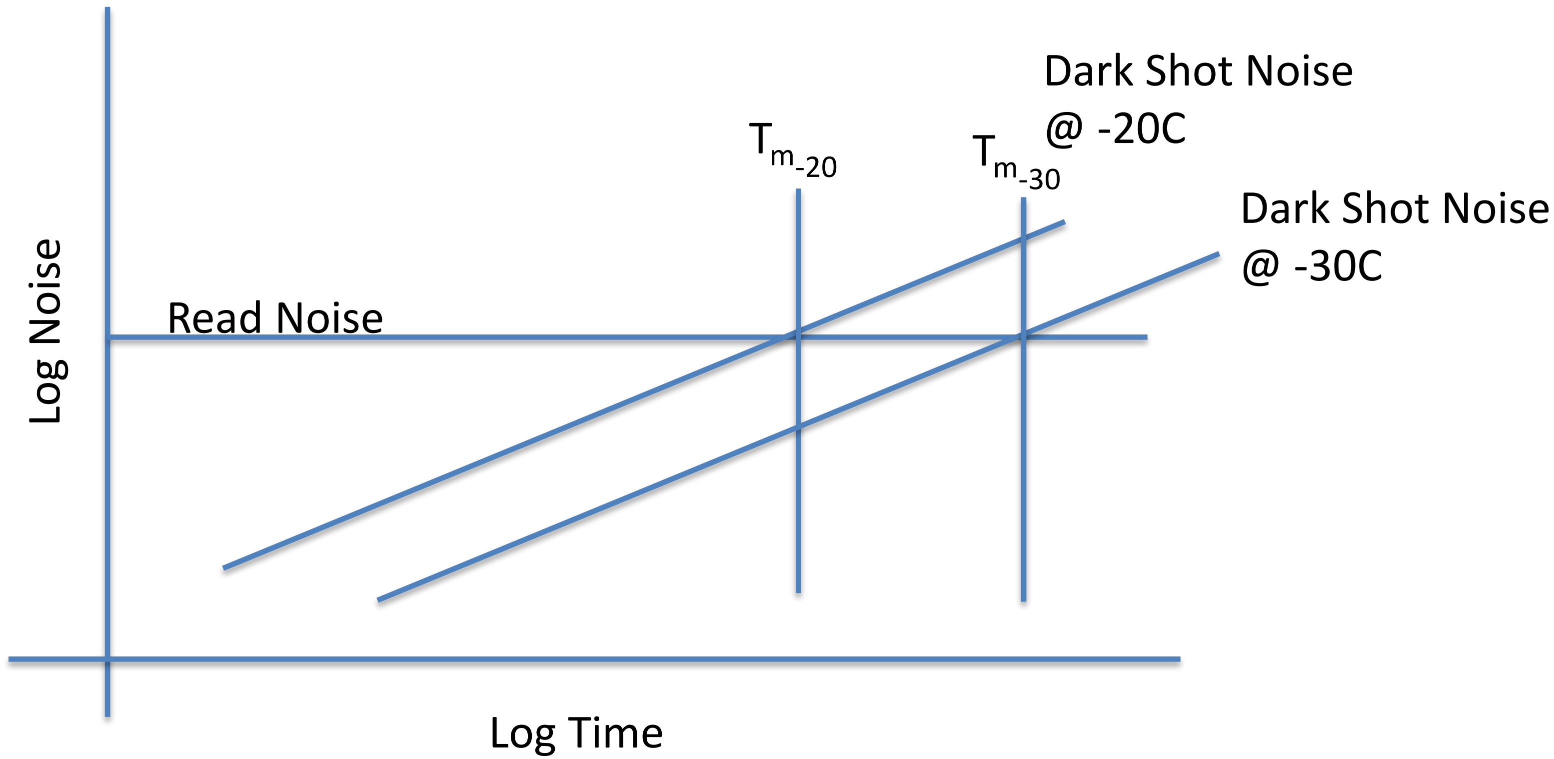
A major benefit of deep cooling is management of cosmetic defects

It is NOT solely about dark shot noise minimization!





Maximum Practical Exposure Limit



<u>When Read noise < Dark Shot Noise: exposure limit</u>

Noise Equation

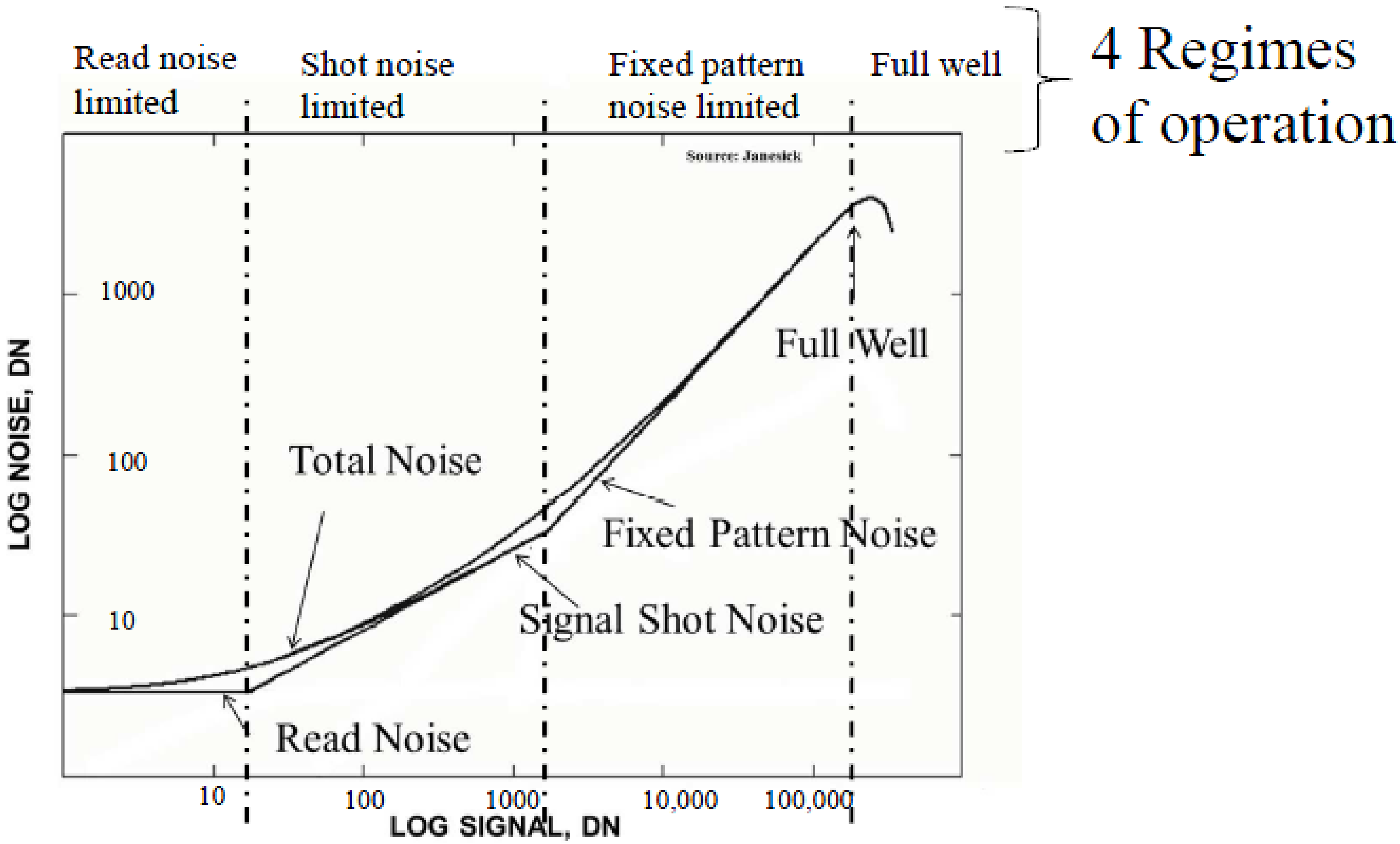
$$Total\_Noise = \sqrt{(read\_noise)^2 + (signal\_shot\_noise)^2 + (fixed\_pattern\_noise)^2}$$

- Assumptions:
  - Flat field target: no modulation
  - Dark signal sources are negligible

PTC Analysis

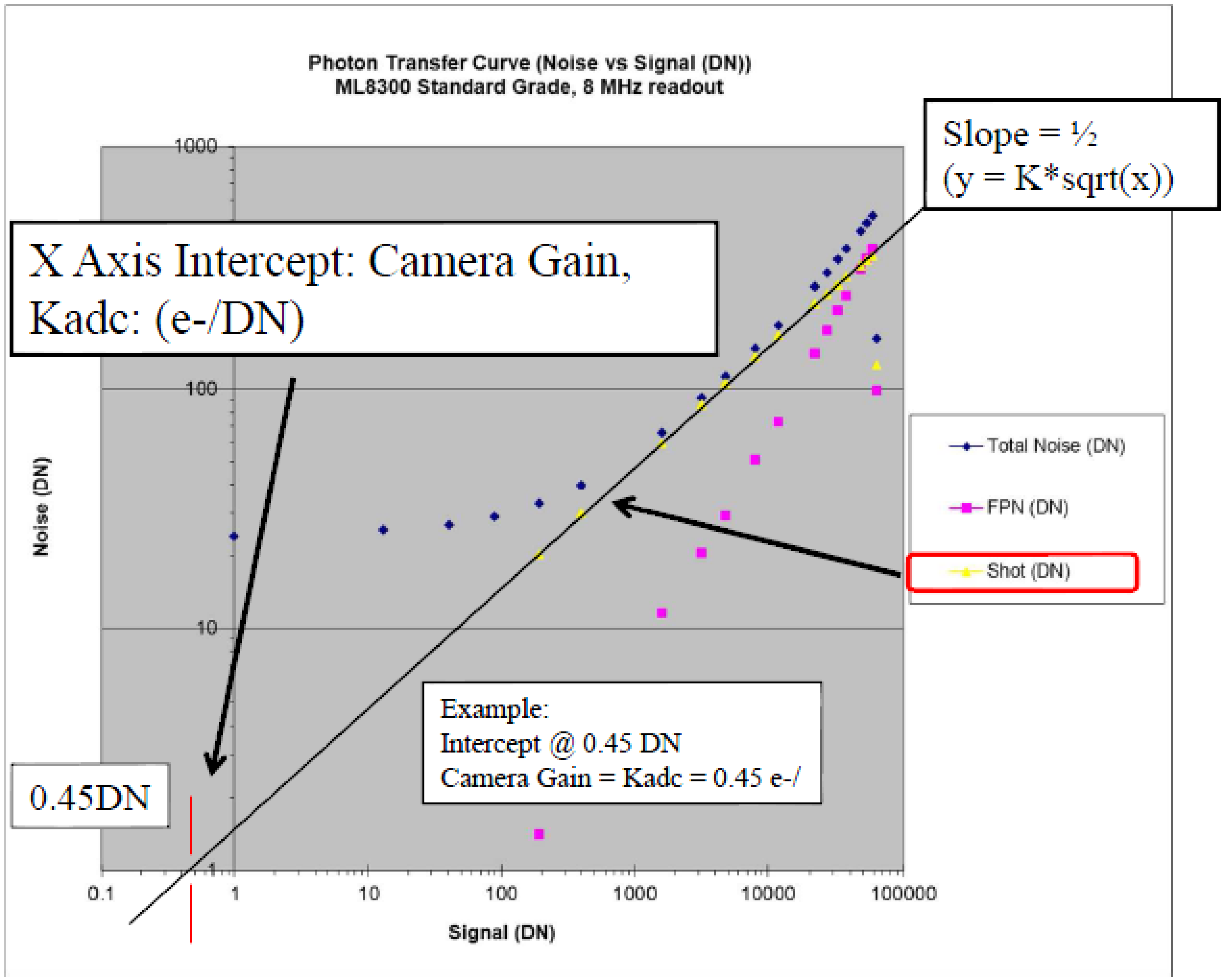
- Graphical Tool for Camera Performance Characterization
- Uses Noise equation to plot various noise components graphically
- Basic tool plots noise component vs signal
- No special equipment needed
- Basic Type Measures:
  - Full Well
  - Gain
  - PhotoResponse Non-Uniformity
  - Dark Signal Non-Uniformity
  - Read Noise
  - Linearity

Basic PTC



$$Total\_Noise = \sqrt{read\_noise^2 + signal + (signal \times PRNU)^2}$$

Example PTC: Measuring Gain



Flat Fielding

Flat Fielding

- Used to remove FPN from an image
  - SNR of image is limited by FPN: more images doesn't improve quality (ie the dust mote remains no matter how many images you stack)
- Flat Fielding Operation
  - Mathematically: pixel by pixel you divide the image pixel the corresponding flat field pixel
- Quality of final astro-image is determined in part by quality of flat fielding process (including making the flat master)

Common Flat Fielding Problems (all related to light source used)

- Light Leaks
  - Most common problem for sky flats
- Gradients or Non-uniform light source
  - Will be visible in calibrated image
- Poor spectral matching of light source vs image light spectrum
  - 90 second Ha or Sulfur flats using EL panels
  - Wavelength dependent PRNU

Sky Flats Work Best

- Challenges: Primarily related to light source
  - Light leaks
  - Brightness: making sure any iris-type shutter is open for a minimum time (to avoid shutter shading artifacts: 16803/proline: 5 sec min)
  - Keeping maximum exposure time less than 10-12 seconds
  - Finishing all the filters in one session

Addressing the Challenges: Daytime Flats

- ***If you have a closed optical system*** (ie refractor), take flats against blue sky mid afternoon
- At issue:
  - Light Leaks
  - Focusing
  - Saturation
  - Gradients

Light Leaks

CCDs are very sensitive to light: light leaks can be fixed with foil

Close aperture with foil:
Do test exposure binned 4x4 with clear filter and 5 sec to compare against dark to test for leaks: when light-tight move to next step

Daytime Focusing

- Attenuation: Stop Down Aperture with Aluminum Foil (poke a hole with pencil)
- Focus on the terminator of the moon if up
- If no moon, use distant building, power pole crossmember, mountain ridge or other fixed object
- Focusing doesn't have to be "perfect" but close is good: focusing one filter seems to work fine with the others even if not very parfocal

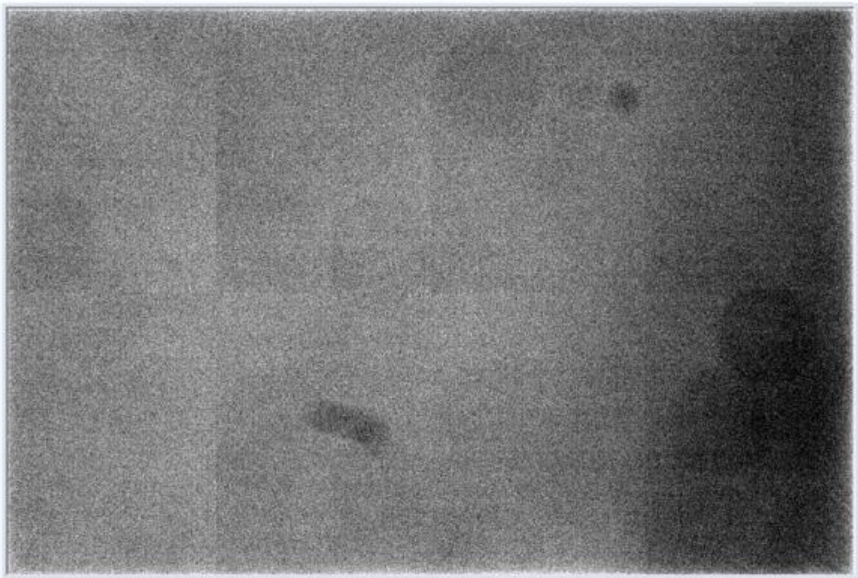
Saturation

- Goal is a diffuser/attenuator:
  - Attenuate using white toweling (paper, cloth etc).
  - Ensure no creases in FOV.
  - Use many layers of fine grain material
- Use Bungee Cords to retain layers over aperture:
  - May need to remove/add some layers as you change filters
- Iterate layers of material as needed to get desirable exposure time (5-10 sec to get you ¾ full well)

Gradient Prevention

- Use a sun shield made from Foil to prevent lateral illumination of attenuator/diffuser material

Results



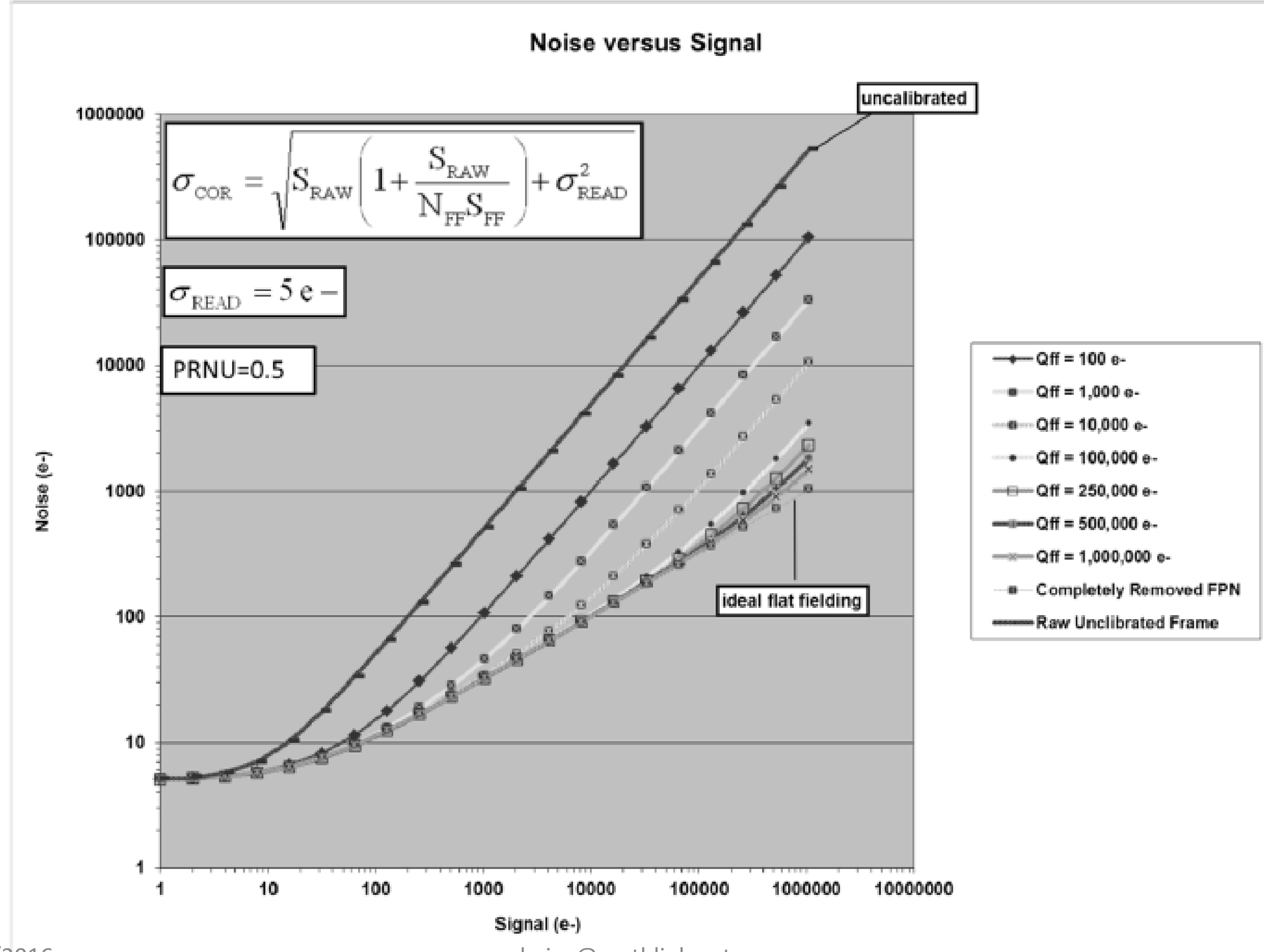
The blocky shapes is classic fixed pattern noise from the sensor manufacturing (photomask making artifacts)

The circular shapes are dust motes

How Many Raw Flats is Enough and What Signal Level Target for Them?

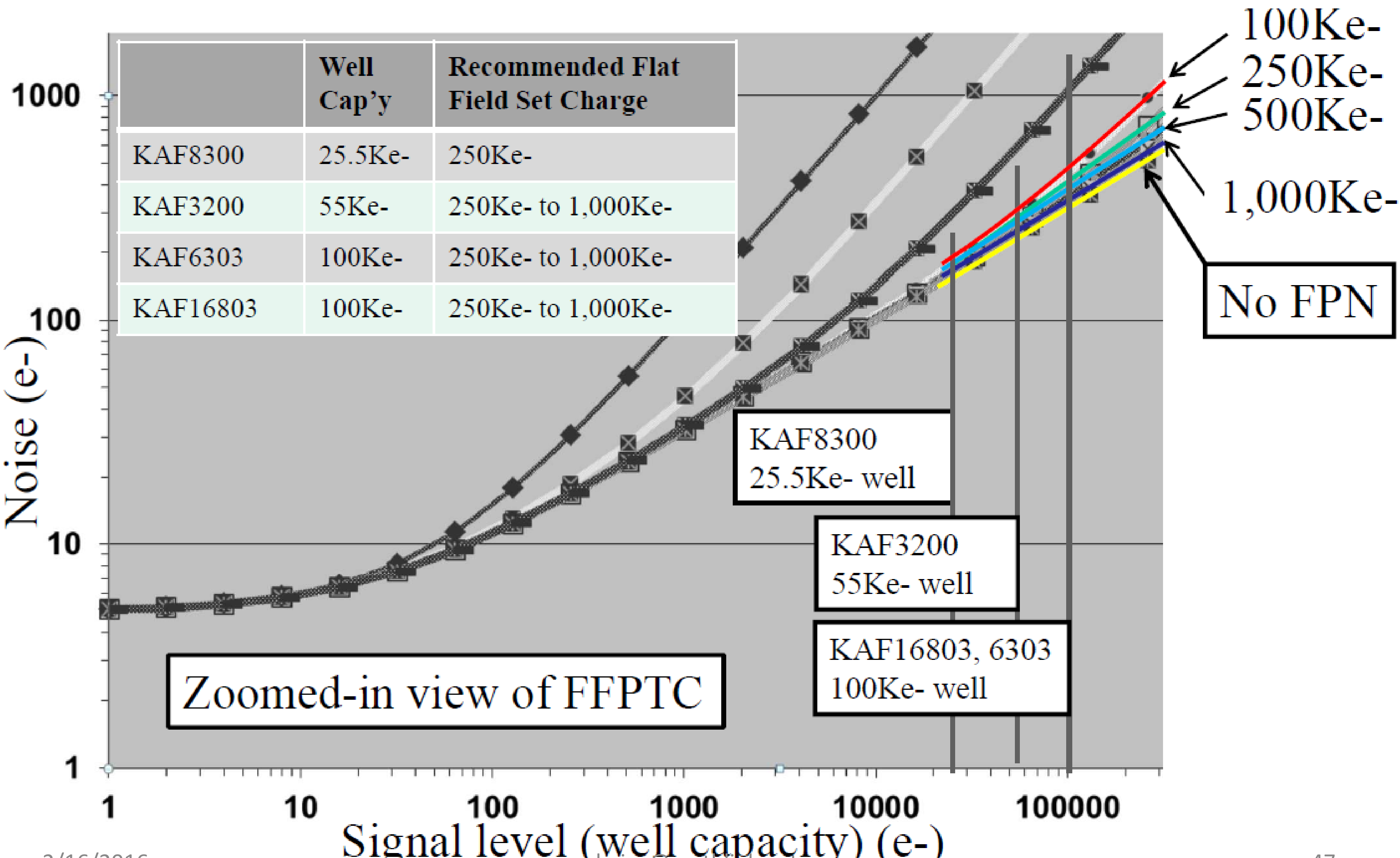
- As signal level increases in an image, imperfections of the flats will become more apparent
- We can characterize using Flat Field Photon Transfer Curve (FFPTC)

FFPTC for Different Signal Levels



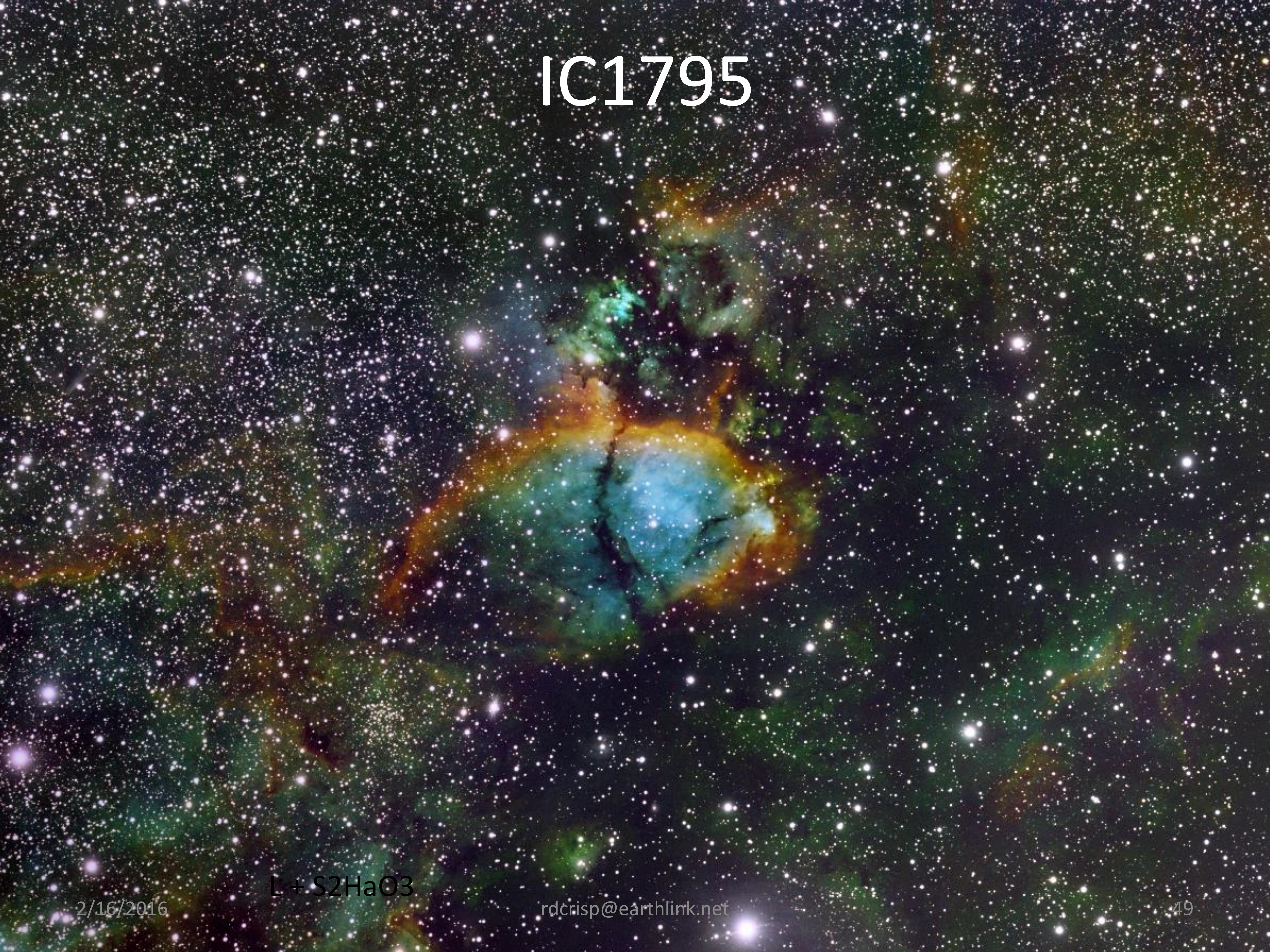
FFPTC Reveals Optimum FF Signal Level & Count

	Well Cap'y	Recommended Flat Field Set Charge
KAF8300	25.5Ke-	250Ke-
KAF3200	55Ke-	250Ke- to 1,000Ke-
KAF6303	100Ke-	250Ke- to 1,000Ke-
KAF16803	100Ke-	250Ke- to 1,000Ke-

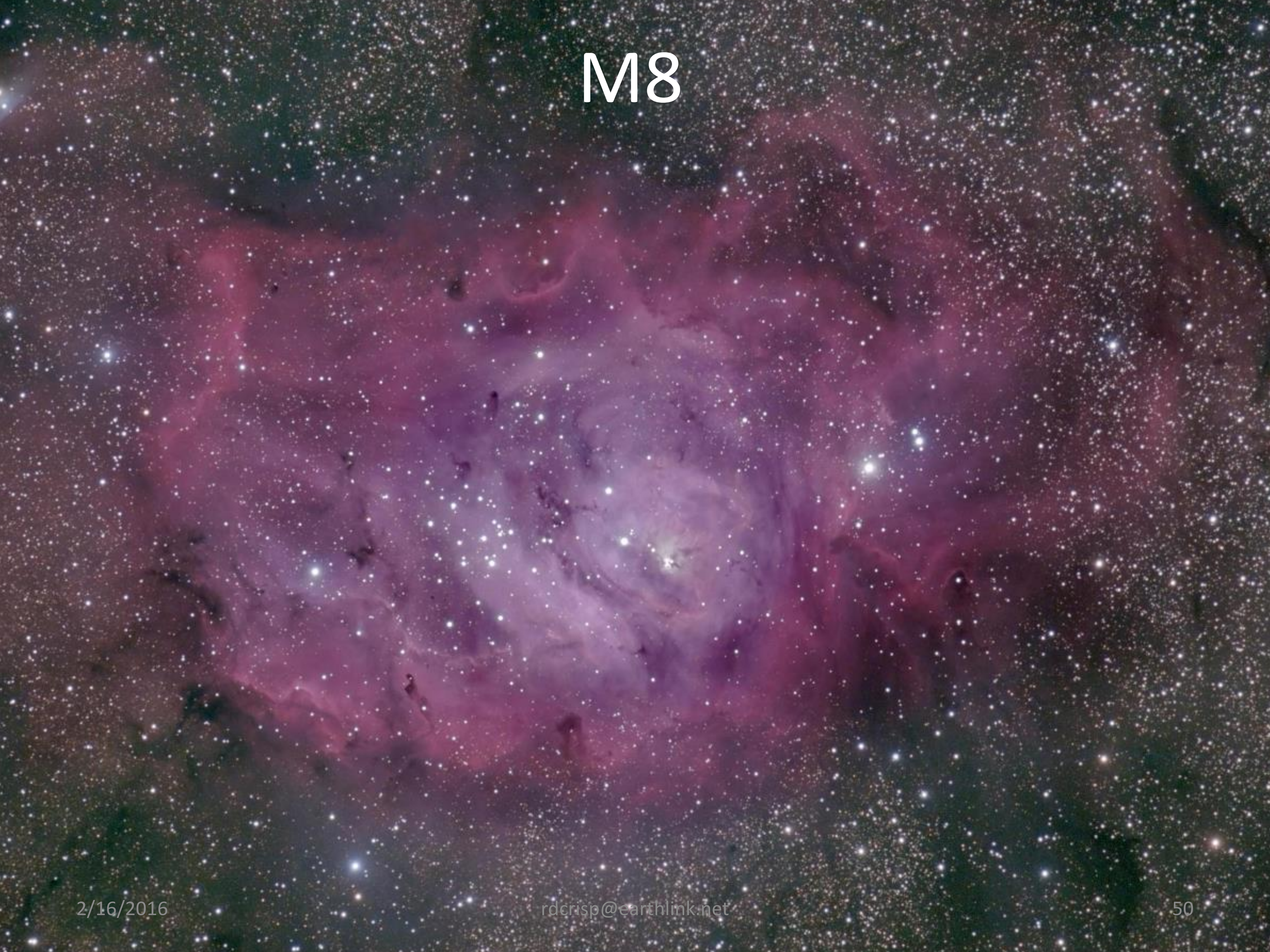


Images

IC1795

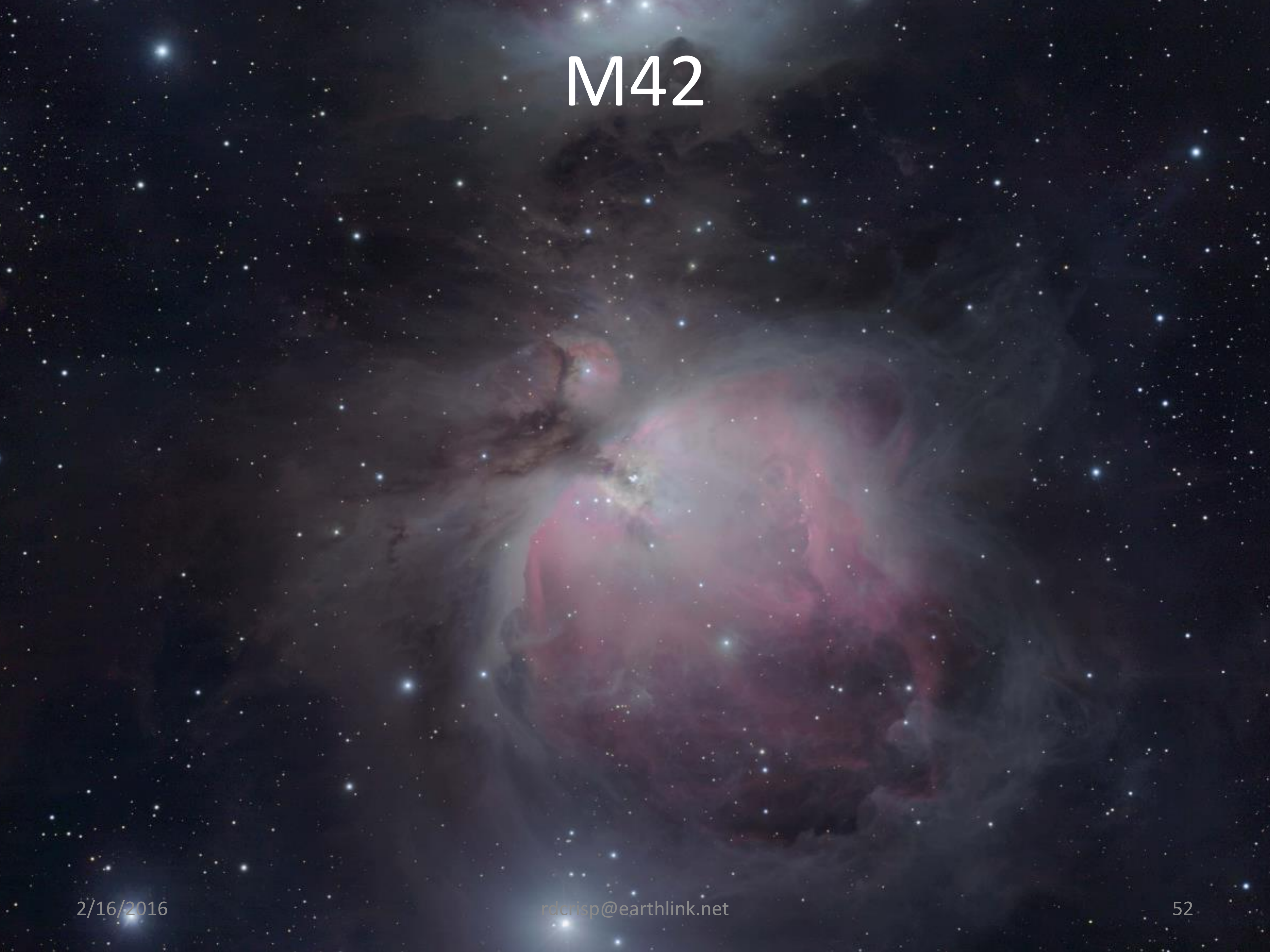


M8



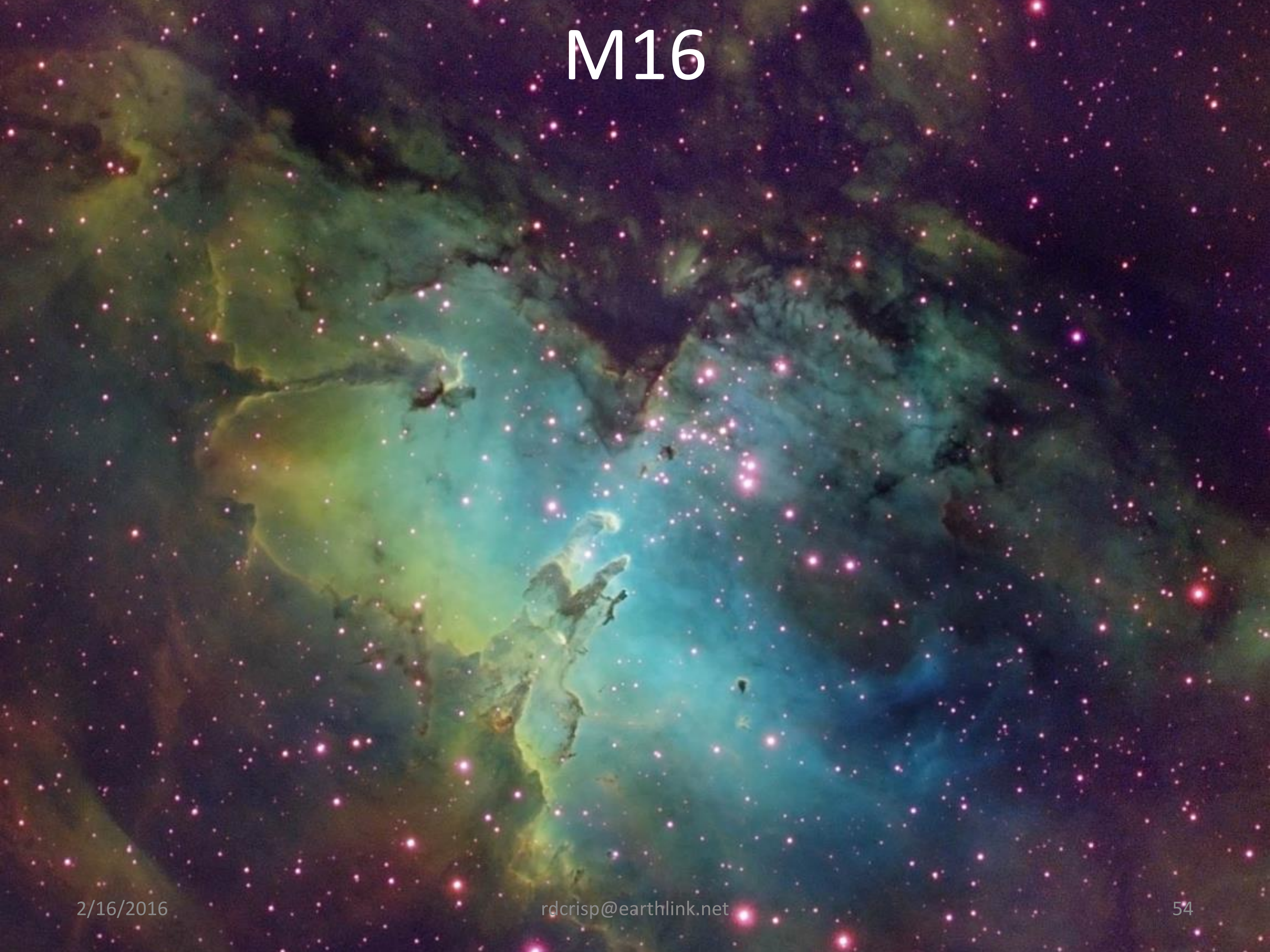
M8

M42

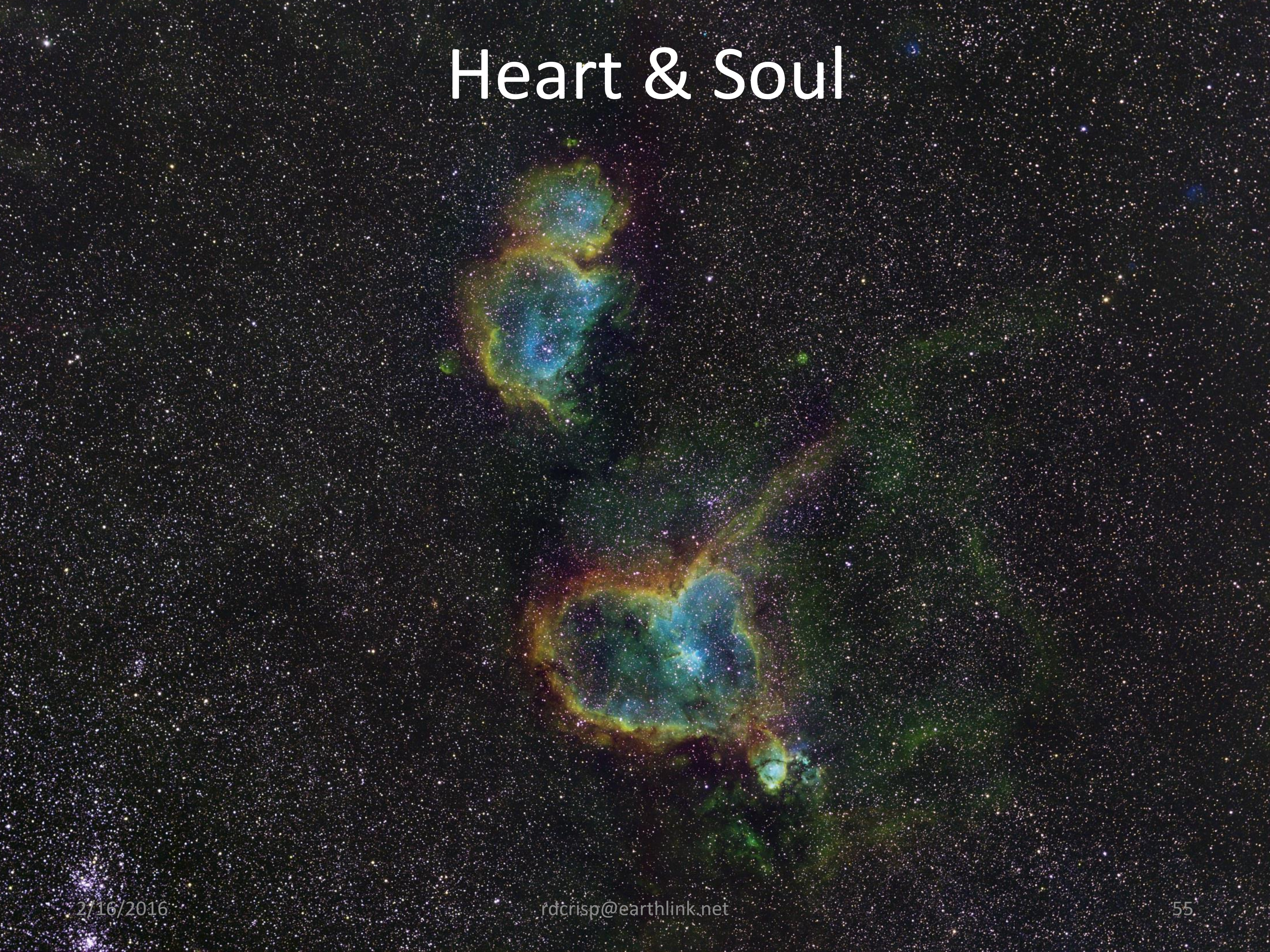


M42

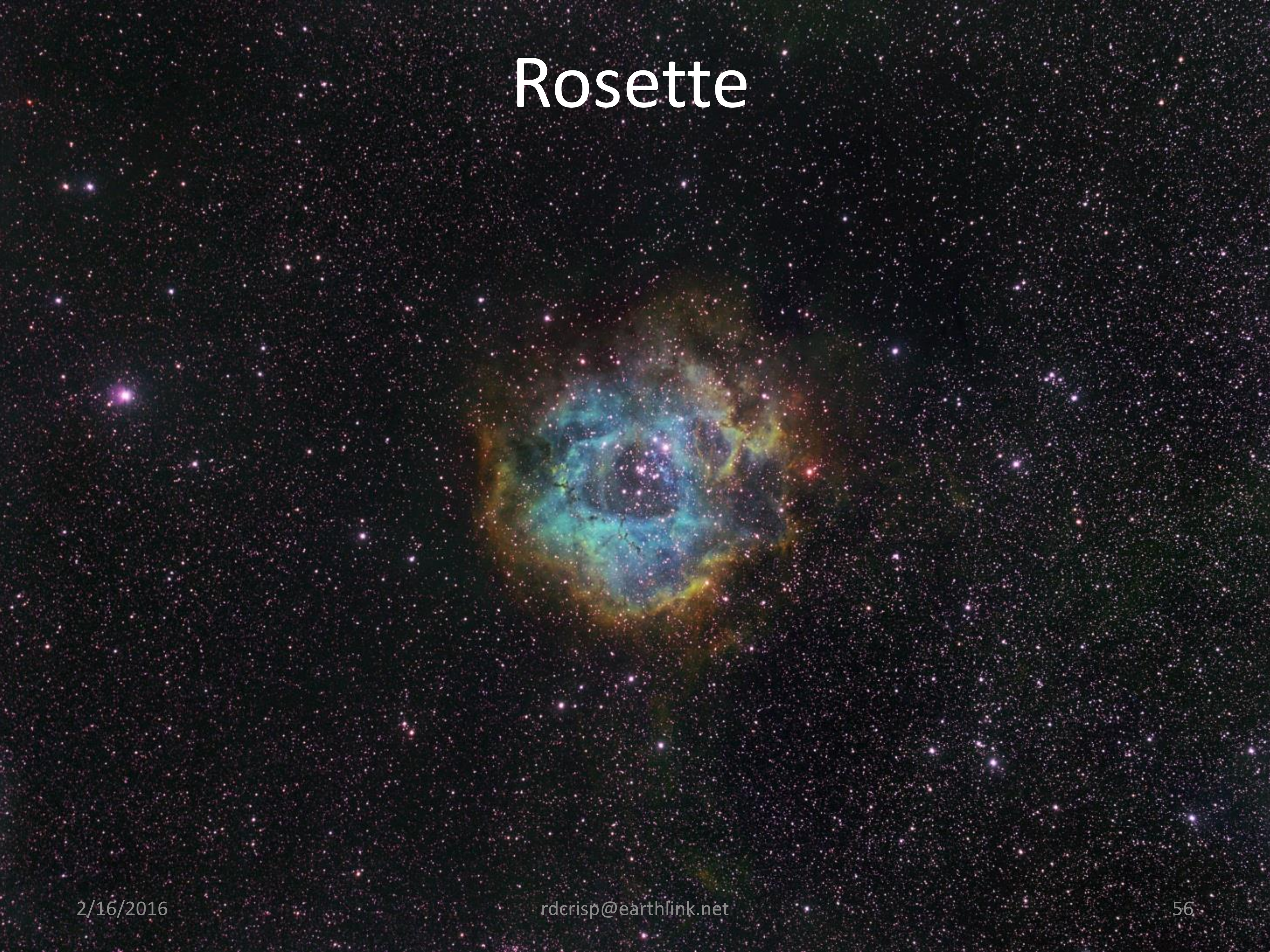
M16



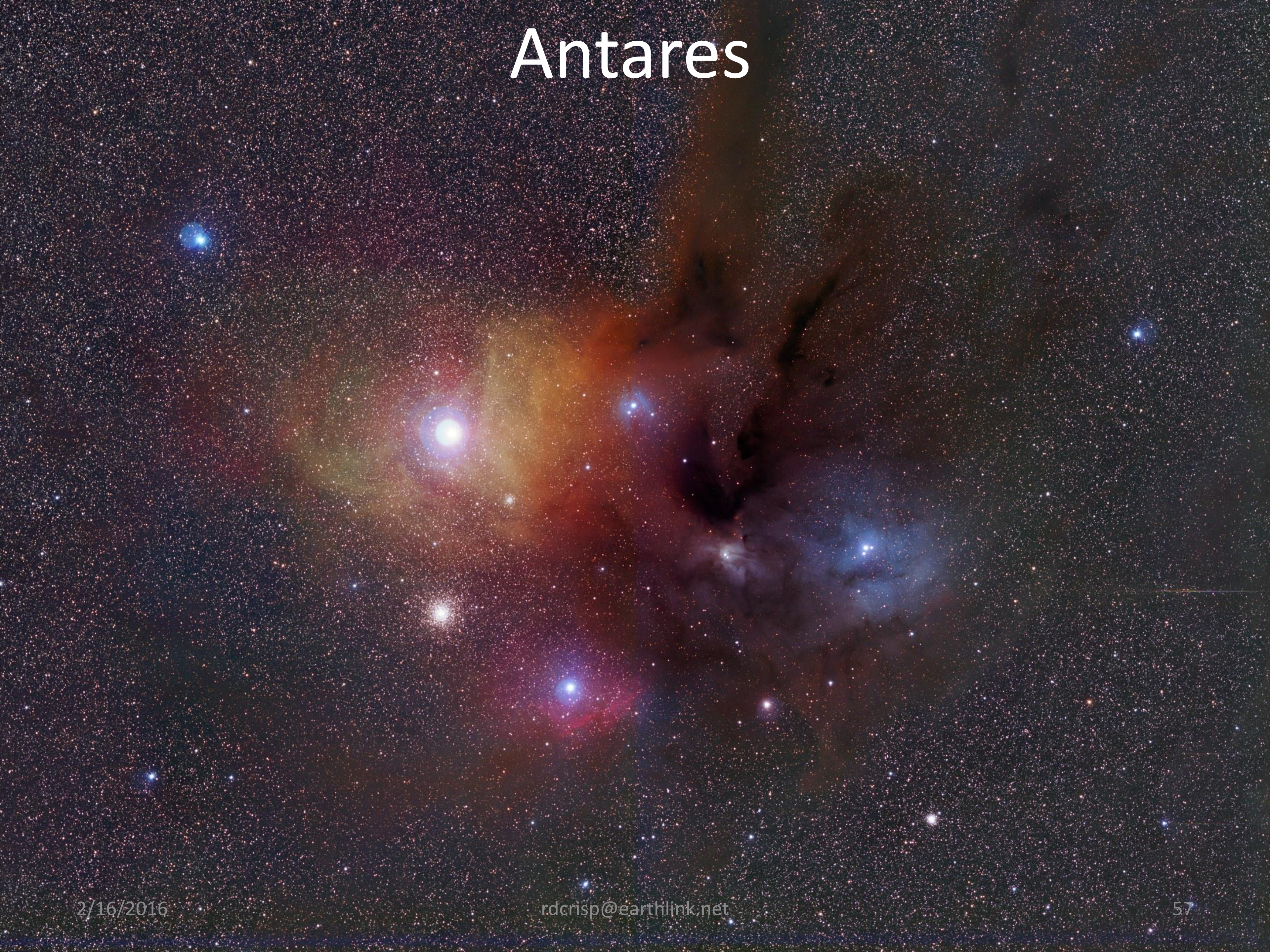
Heart & Soul



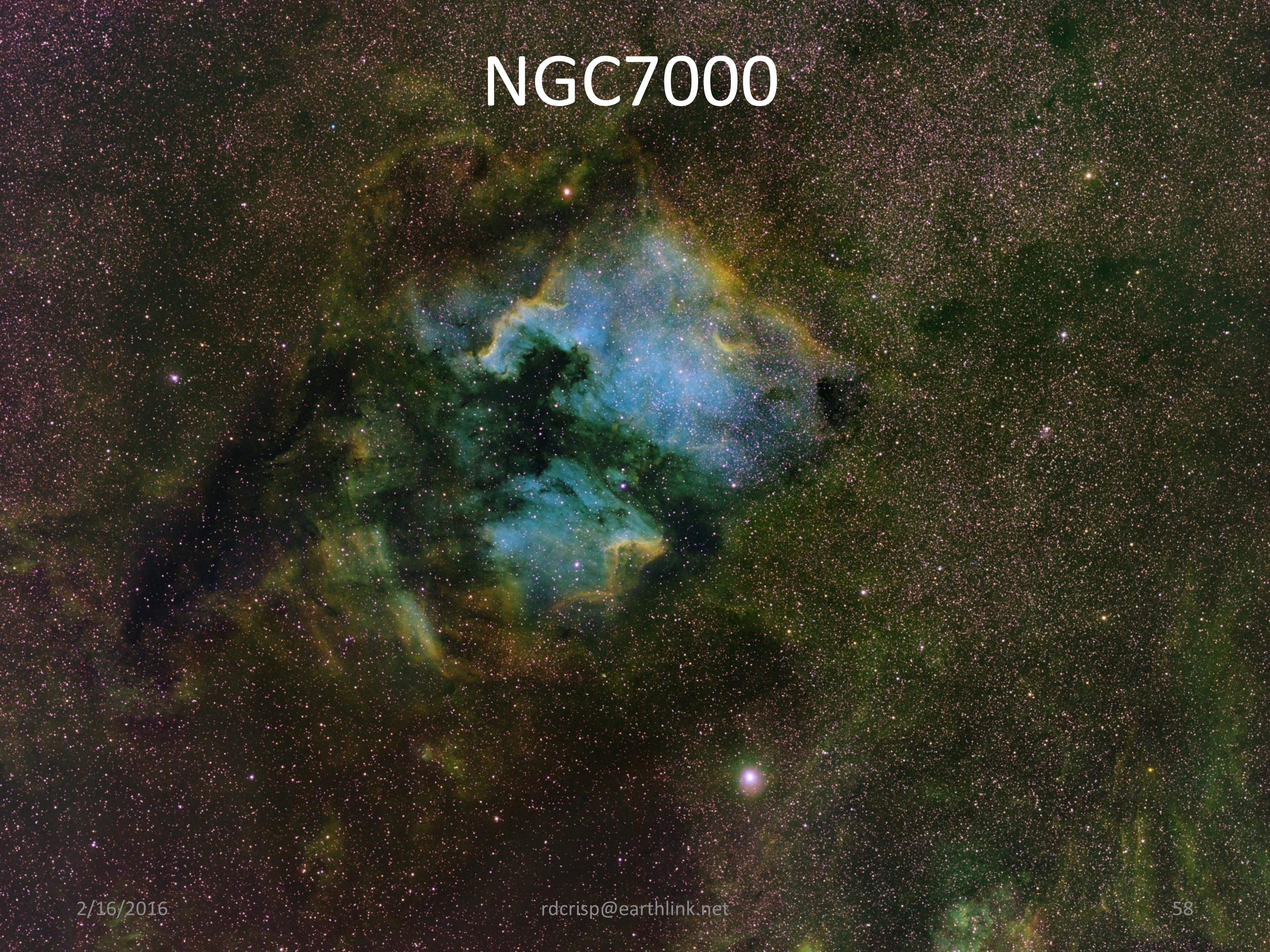
Rosette



Antares



NGC7000

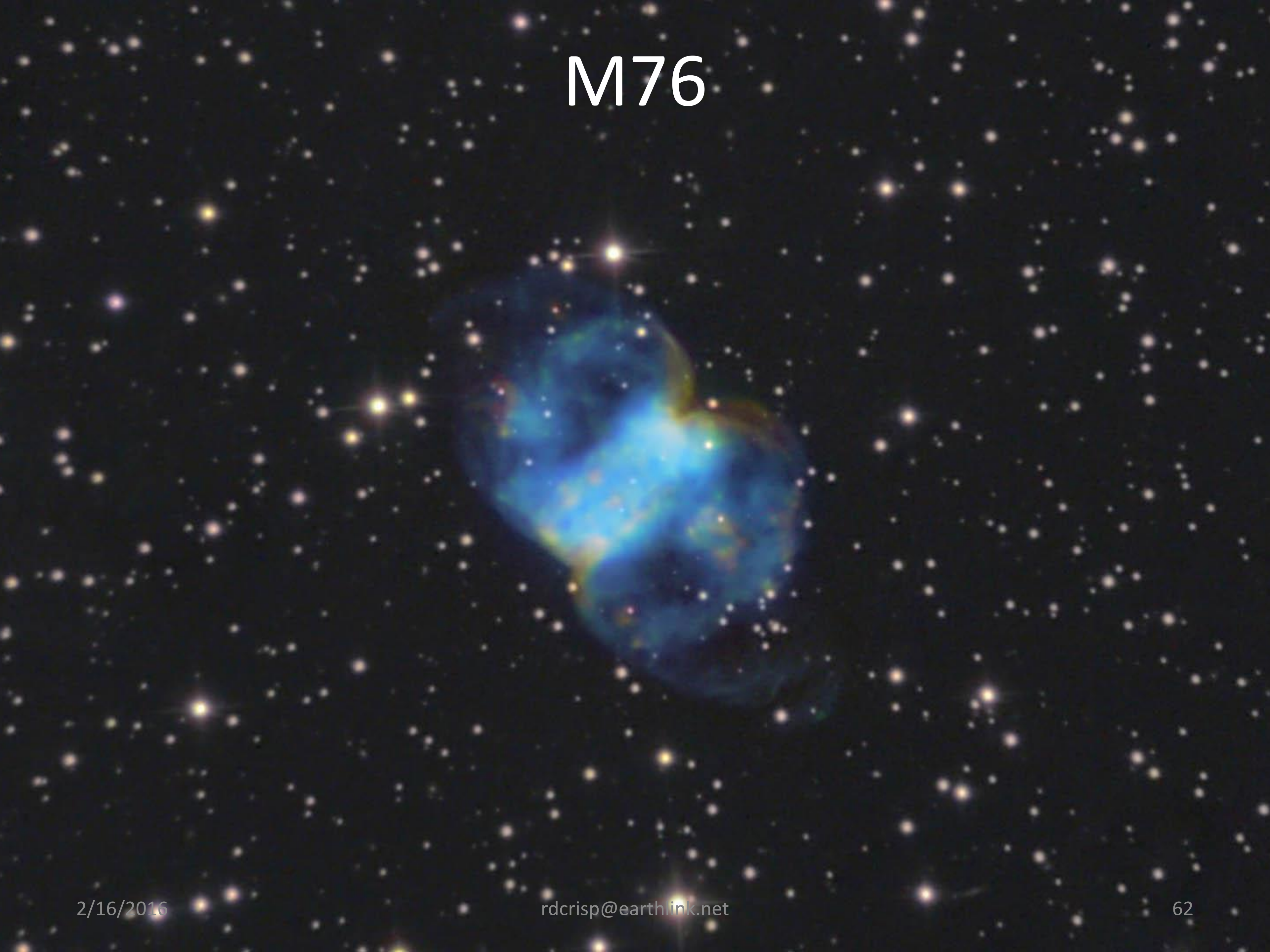


Milky Way (Ha +GB)

Veil Nebula

Horsehead

M76



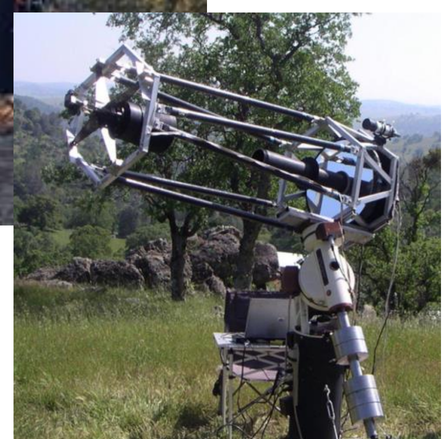
Gear

AP155EDF f/7 (w/4” flattener)
ML29050 (29MP)
Robofocus
50x50mm filters
AP1200GTO

AP180EDT f/9 (w/2.8” flattener)
ML8300 (29MP)
Robofocus
50mm round filters
AP1200GTO

Pentax 6x7 camera lens system
-Proline or Microline Camera
-PDF focuser (Atlas for next gen)
-50x50 7-slot filter wheel
-Home built frame
-Home built lens adaptor
-AP1200GTO

FSQ106 (original type)
PL39000M (39MP
36.8 x 49mm)
Atlas Focuser
65x65mm filters
AP1200GTO



18” f/12.6 Classical Cassegrain
-Microline 4022 Camera
-Robofocus on Secondary
-50x50 7-slot filter wheel
-Modified Giant Easy Guider OAG
-AP1200GTO

Thank You

www.narrowbandimaging.com/incoming/sjaa02162016rdc.pdf