Doing the Hokey-Pokey

or

Deriving Statistical errors

for

Measurements of the Chandra X-ray Observatory PSF

Diab Jerius (CXC/CfA)

The Chandra X-Ray Observatory's PSF is a two-dimensional wonder.⭐

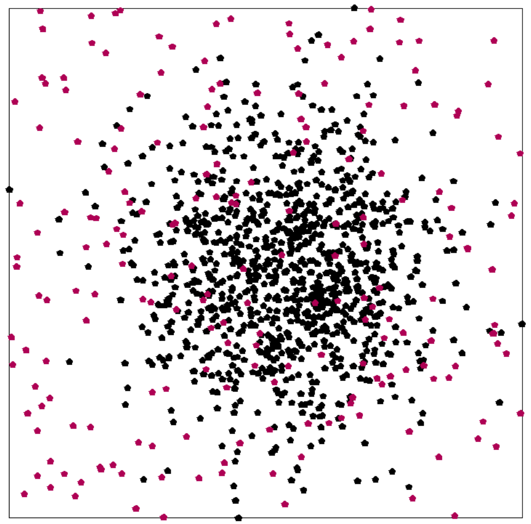
It's not exactly symmetric, depends upon the astrophysical input spectrum and gets folded through instruments with various degrees of fidelity.

Still, it seems to get the job done, and some of the questions often asked are:

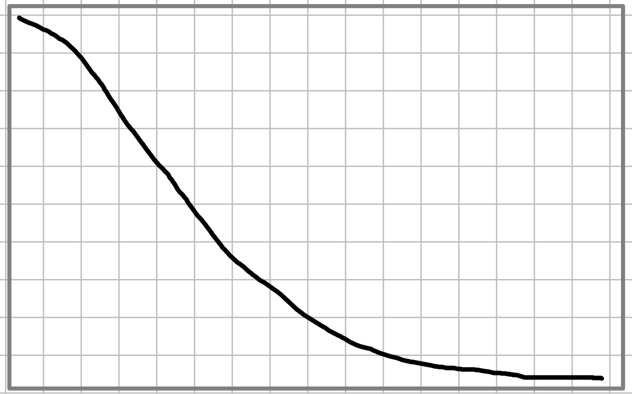
- *What exactly does the PSF look like for my source?*
- *If I want to test some bit of astrophysics, what are the intrinsic errors in our knowledge of the PSF, so I can determine the sensitivity of my measurements?*
- *How can I simulate my observation to see if I can understand what the source looks like?*

⭐ Despite all the levity, it's really, really, good. But why settle for good?

tldr; ★



source events (black)
background (red)



1D pdf on a grid,
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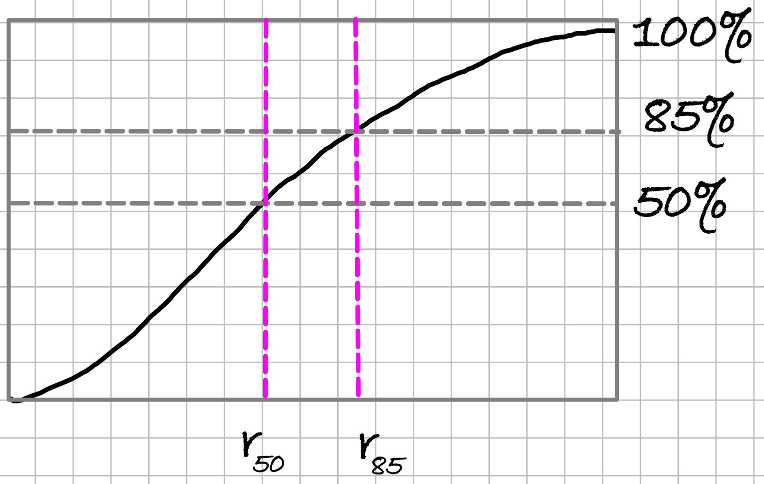
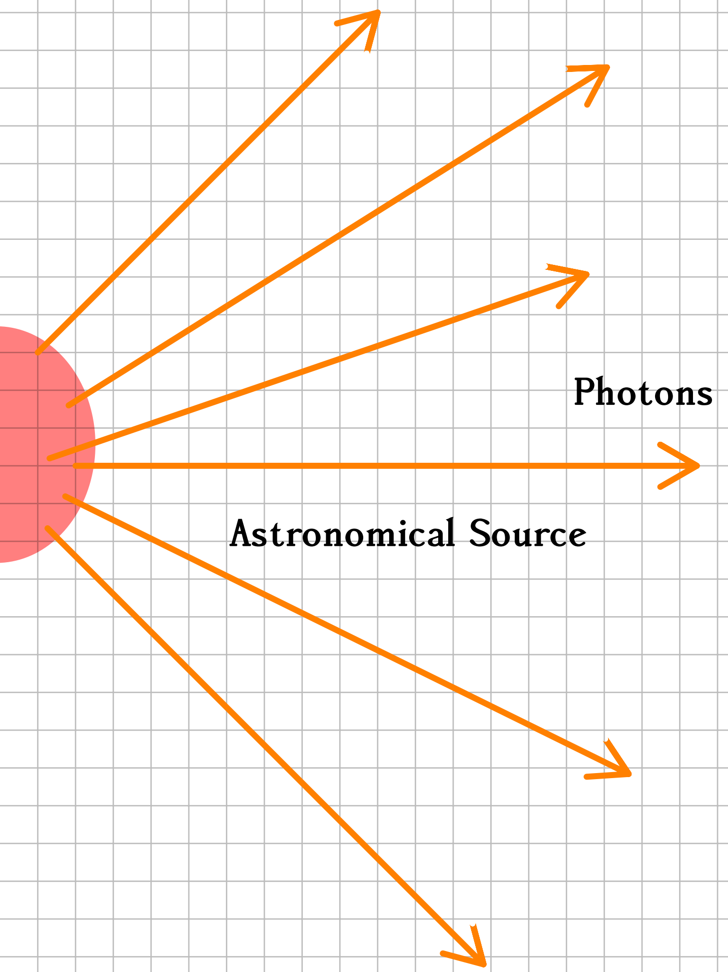


cdf

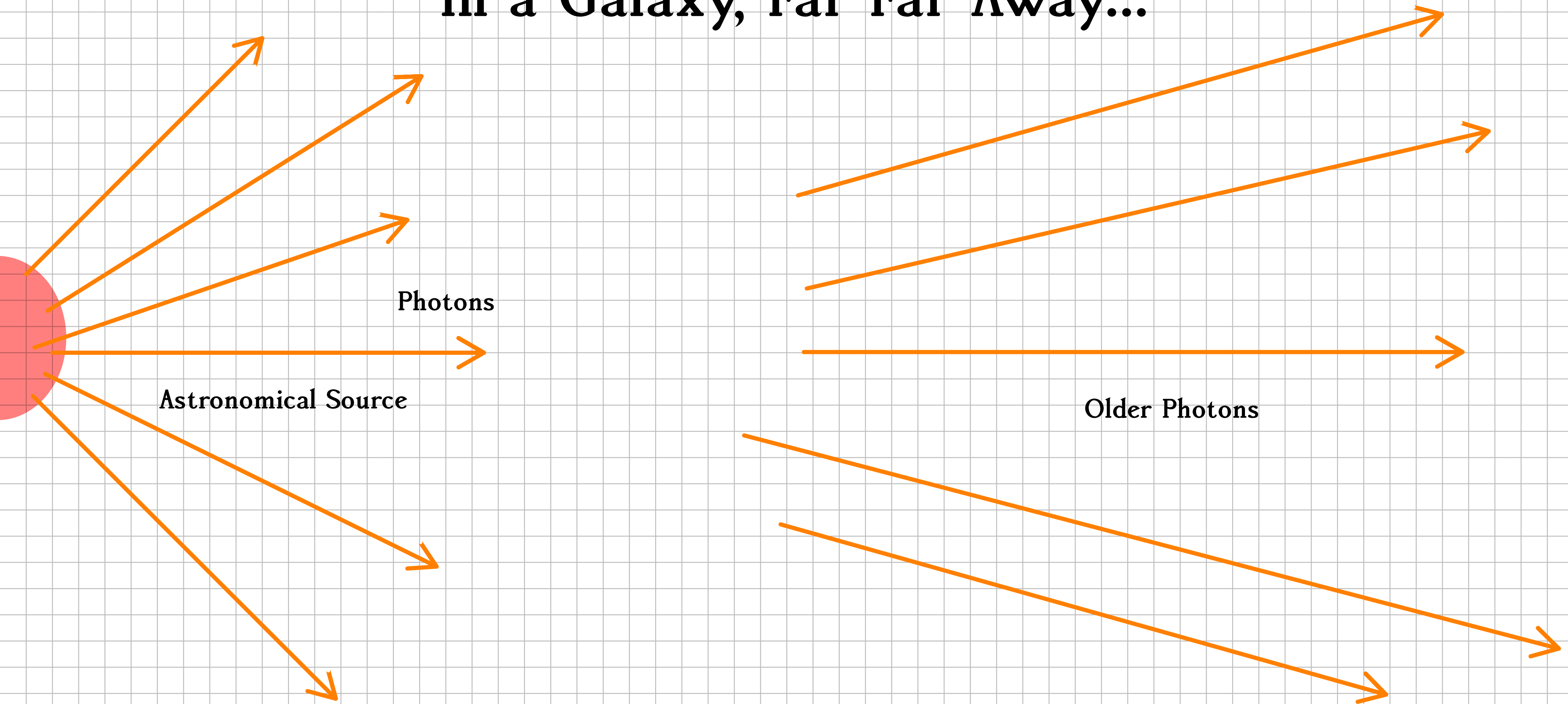
What are the errors on r_{50} and r_{85} ?

★ too long, didn't read; or, for the old skoolers, "Executive Summary"

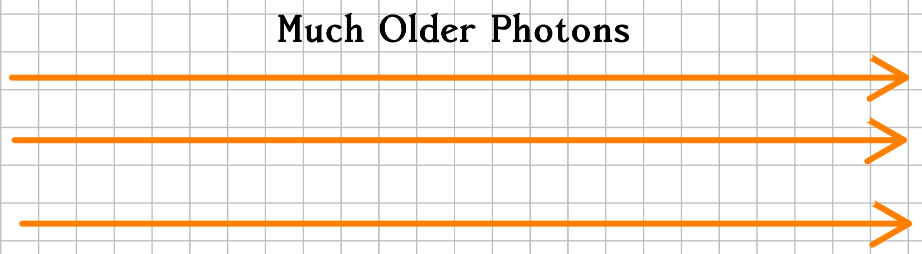
In a Galaxy, Far Far Away...



In a Galaxy, Far Far Away...

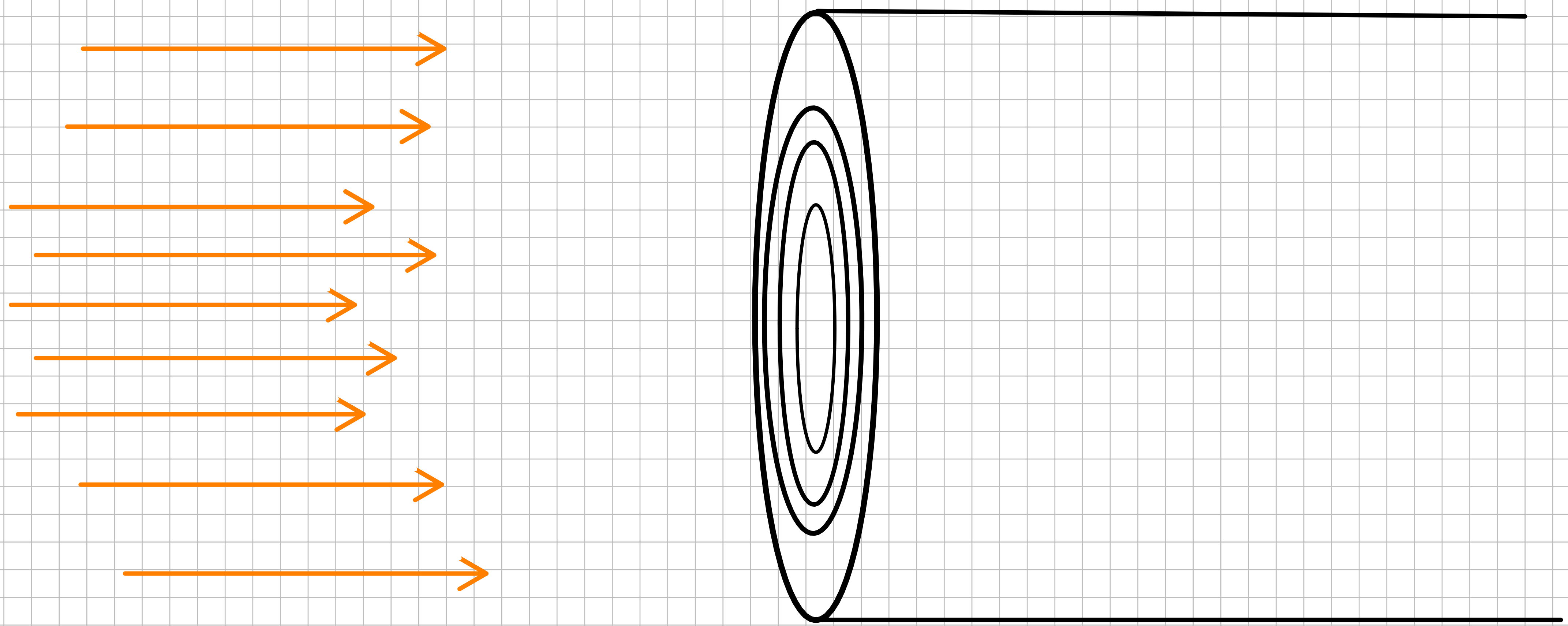


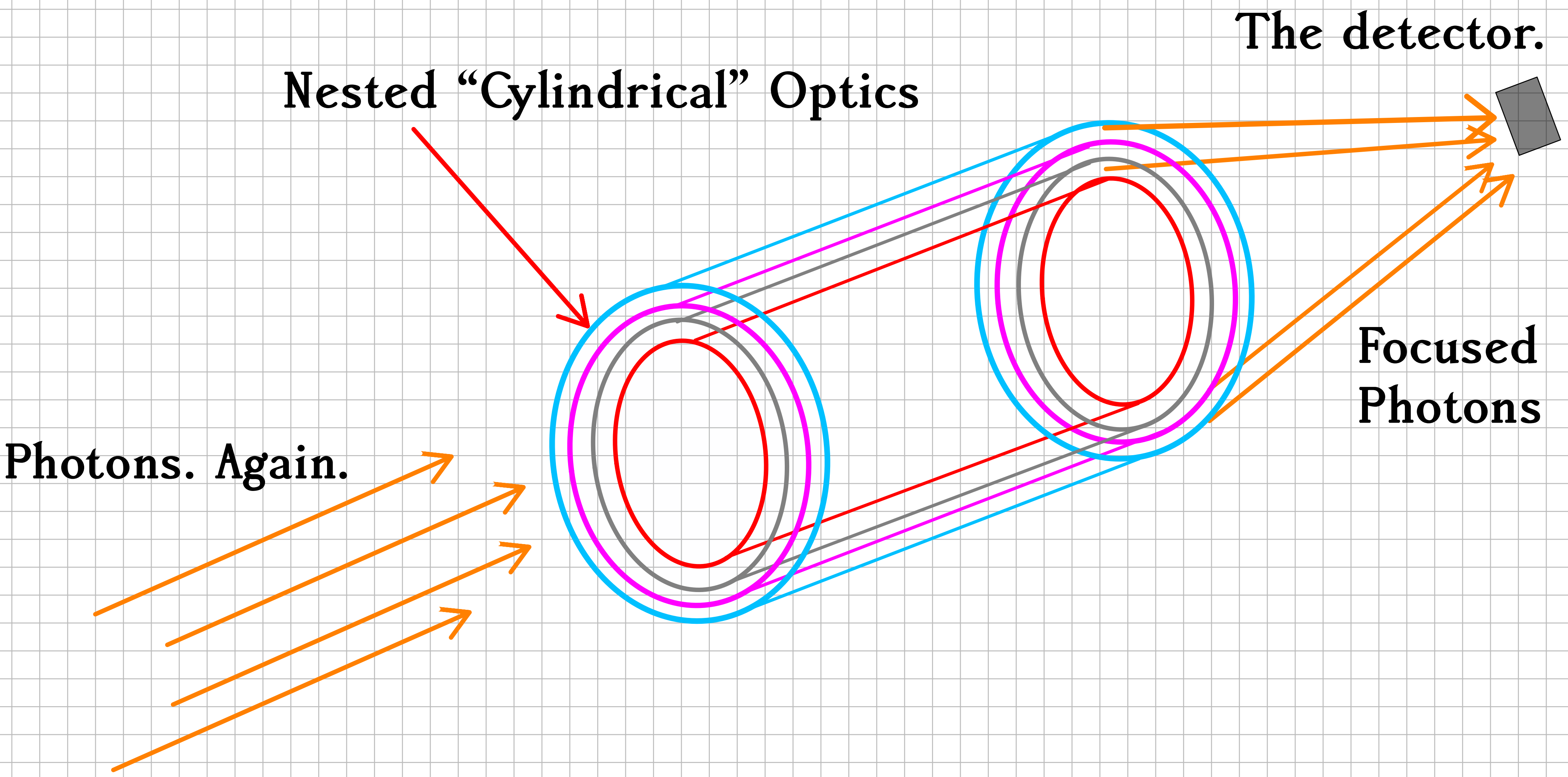
Eventually, at Earth...



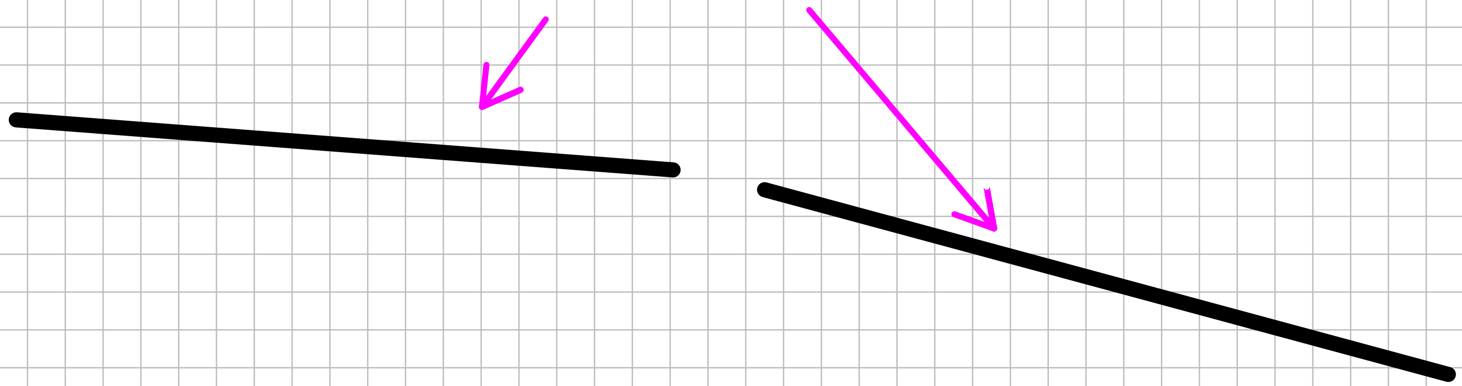
Photons' directions are all parallel to each other (for a point source).

Our Hero, Chandra, awaits the Photons…




The detector.
Nested “Cylindrical” Optics
Focused
Photons
Photons. Again.

Inside Chandra, each nested optic (shell) has two mirrors which focus the incoming parallel rays.



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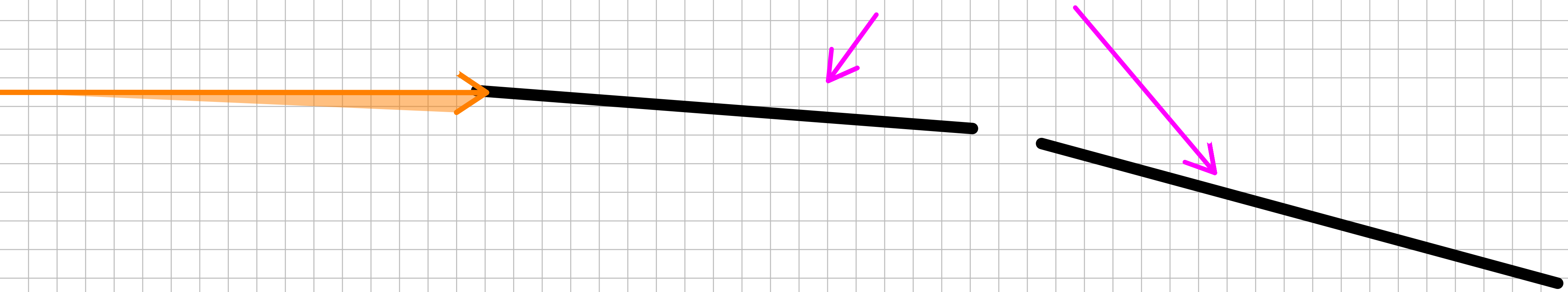

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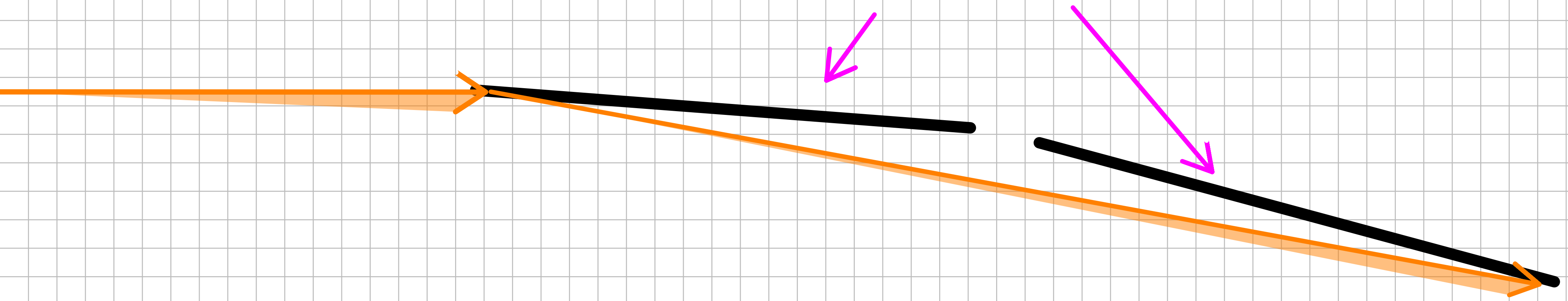

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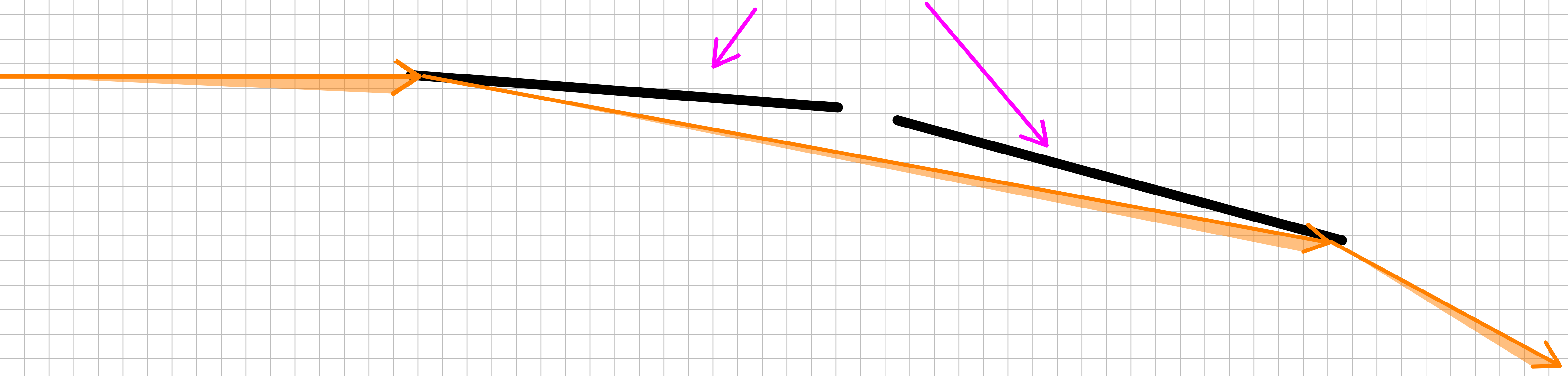

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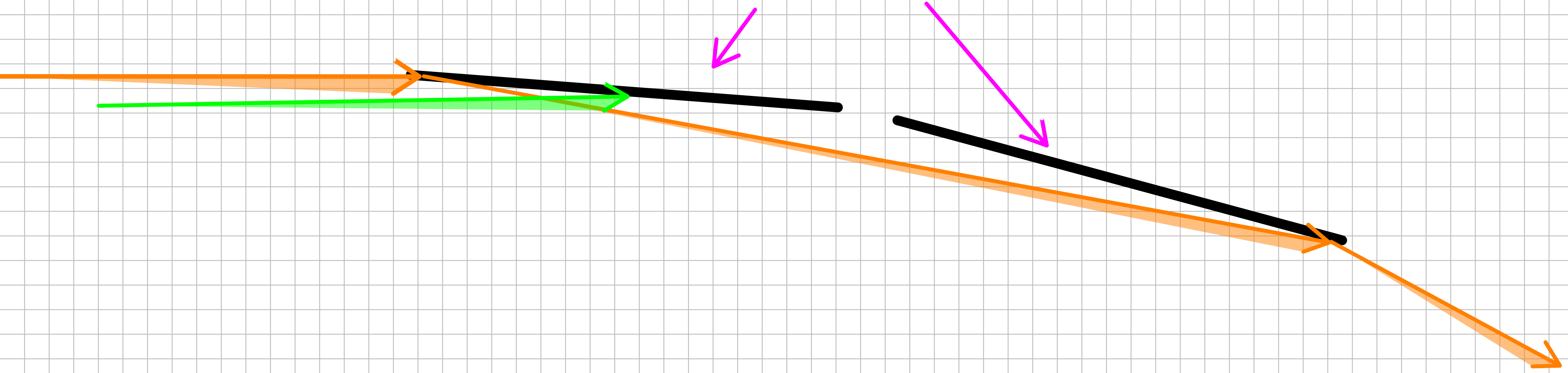

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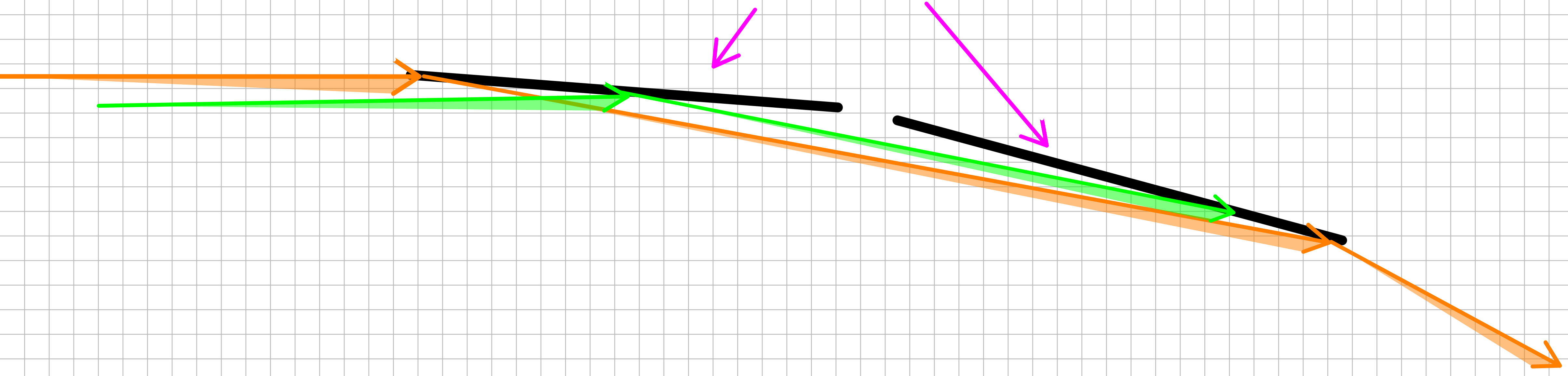

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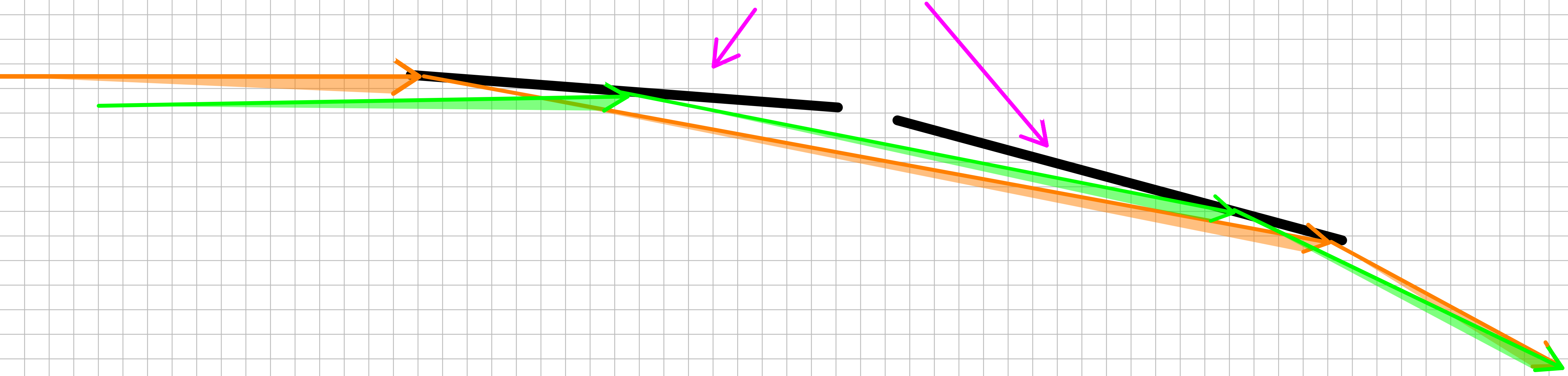

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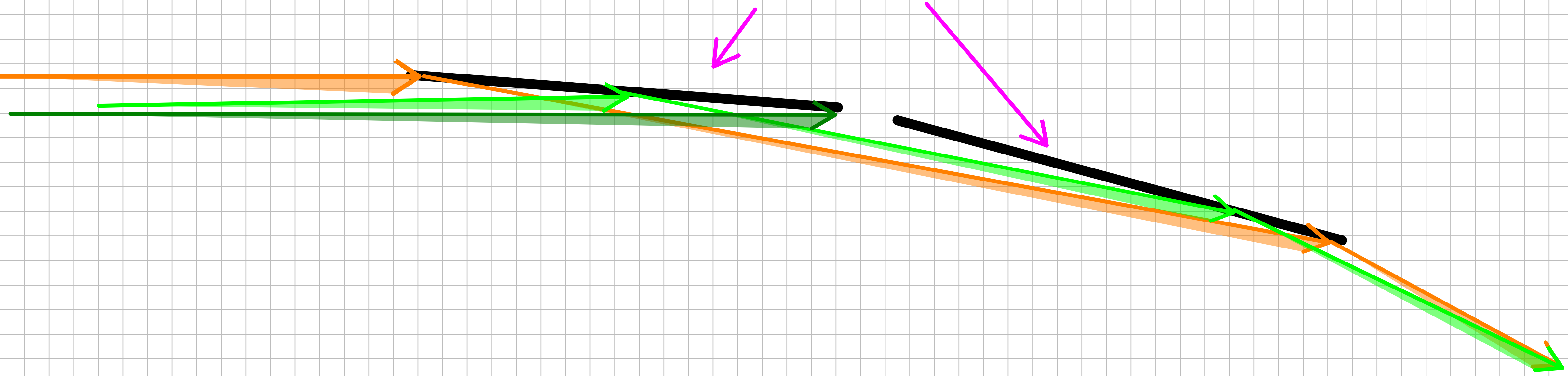

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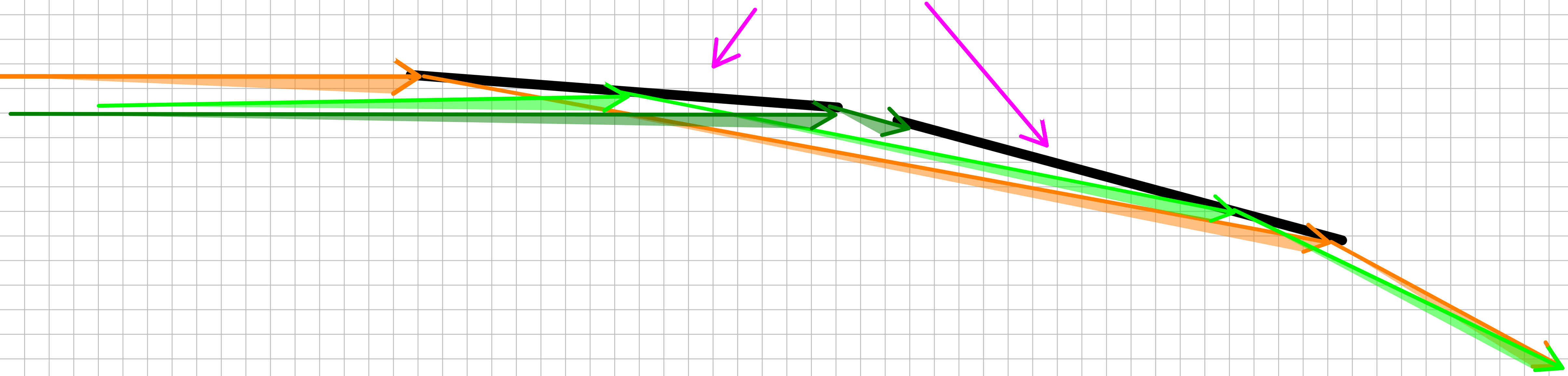

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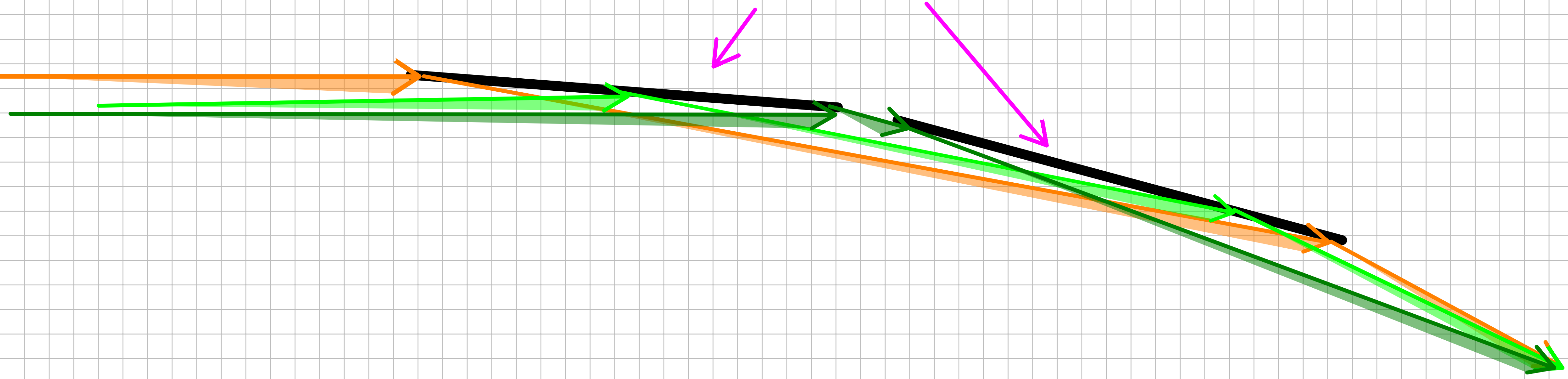
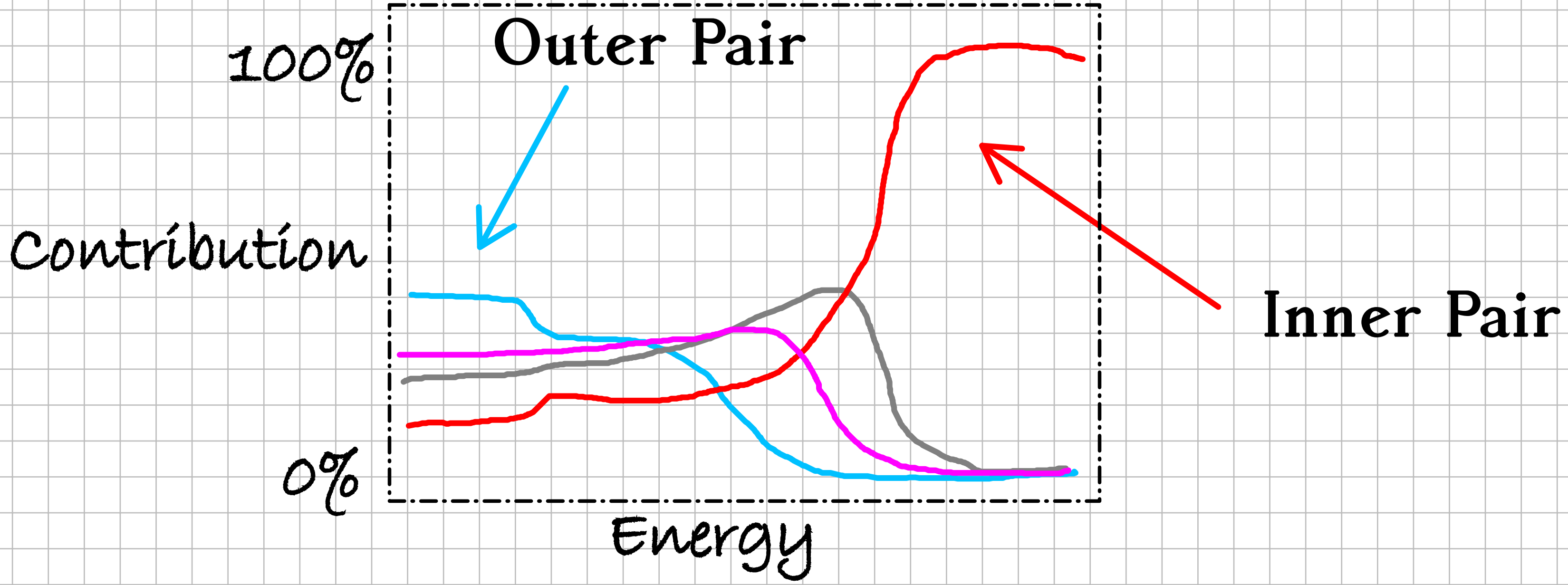


Each shell

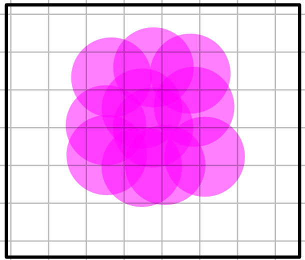
- reflects better at different energy ranges
- has a different geometric area

The contribution of each shell to the total "effective" area:

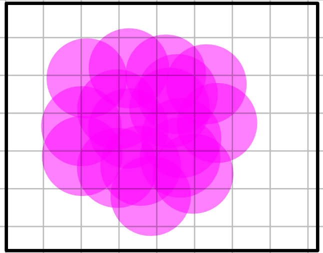


Each optic shell also focuses light differently, so their images look different.

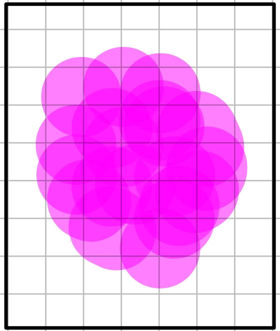
Shell 1



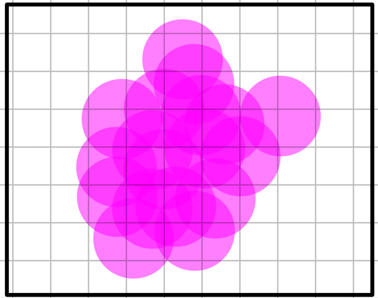
Shell 4



Shell 3



Shell 6



Parenthetical Note

We are considering only the performance of an object which is aligned with the telescope's optical axis.

Off-axis objects have much more complex interactions with the optics, and are thus more difficult to model.

The story so far...

The Chandra Point Spread Function (PSF) is a sum of invidually complex optic shell PSF's weighted by their energy dependent contributions.

But wait, there's More!

Because X-rays from Astrophysical Objects are pretty rare, Chandra is designed to detect a stream of X-ray events.

Each event is assigned:

- A detection Time
- A Position on the detector
- A detected Energy

We can use the event positions to generate an image:

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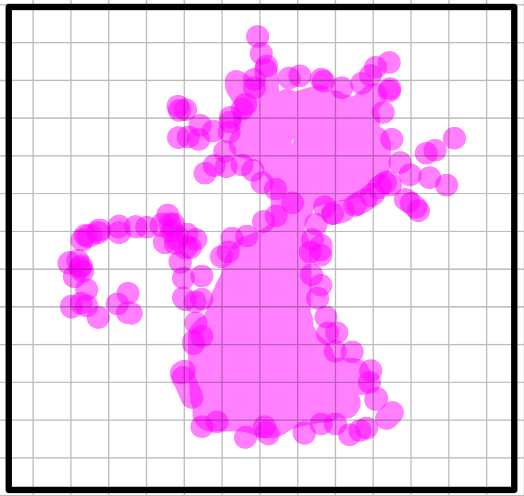

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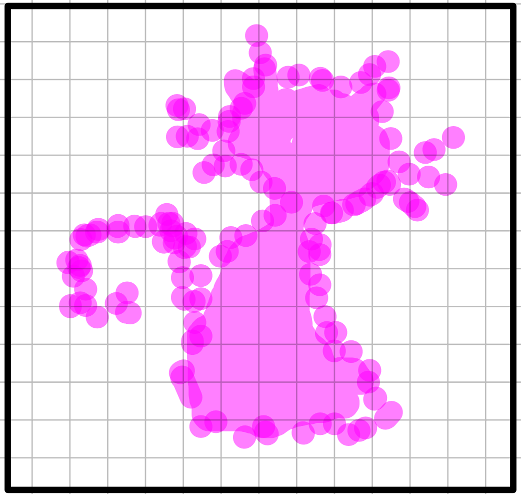

But first...

Chandra's Pointing Wobbles, Up and Down, Left and Right

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(Yes, on purpose.)

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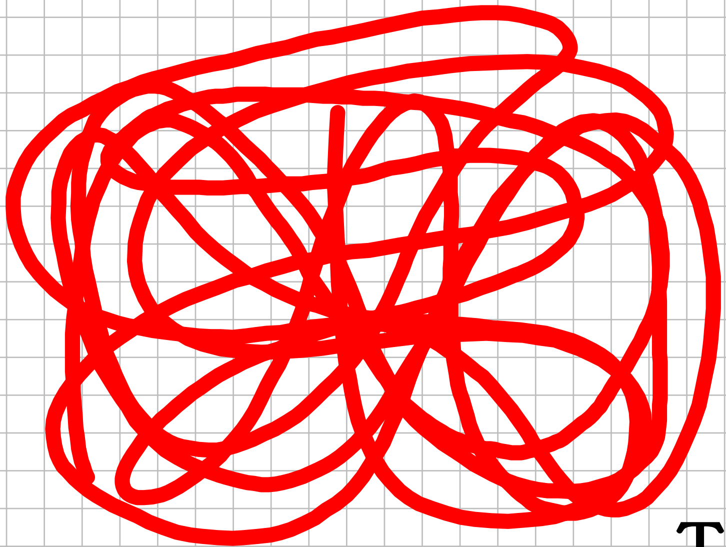

This means that the actual image of a point source looks like this.

Chandra's Pointing Wobbles, Up and Down, Left and Right
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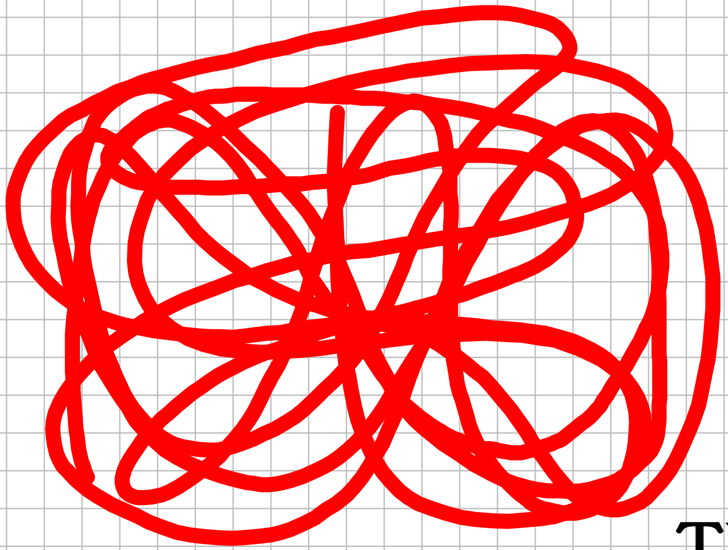

(No, it's really not that messy.)

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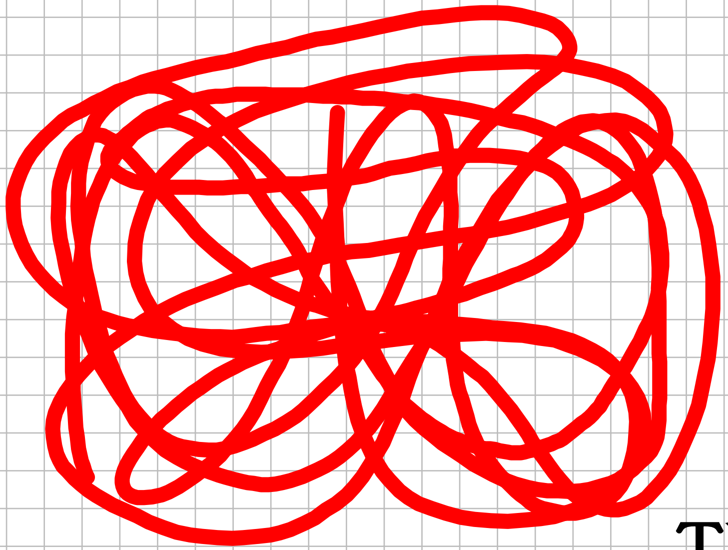
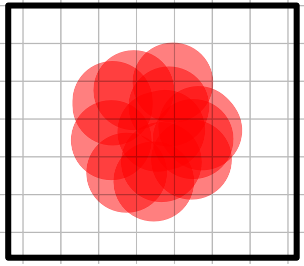


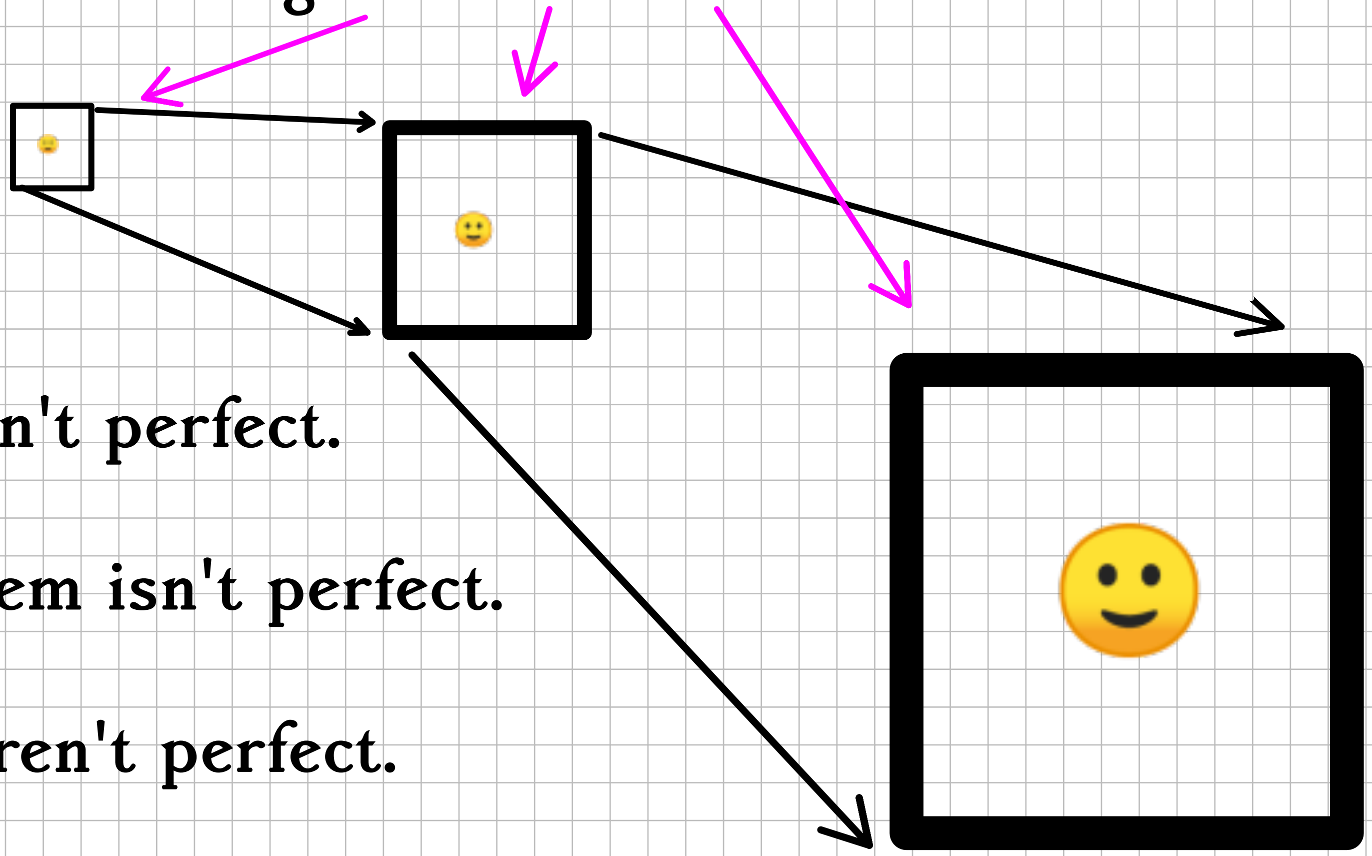
(No, it's really not that messy.)

This means that the actual image of a point source looks like this.

The Aspect System keeps track of where Chandra is pointing so that we can correct the position of the events so that our image looks like this:



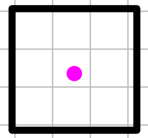
But, why dœsn't our image look like this?



- Our mirrors aren't perfect.
- The Aspect system isn't perfect.
- Our detectors aren't perfect.
- Stars are not happy.

So.........

What astronomers <u>want</u>:



So.........

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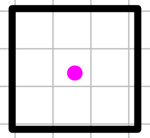
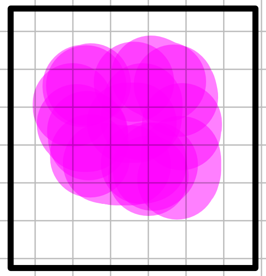


What astronomers <u>get</u>:



So.........

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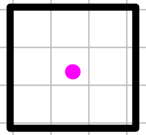

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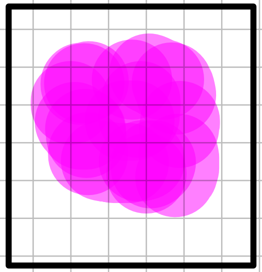

But, what should they expect?

So.........

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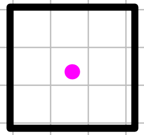

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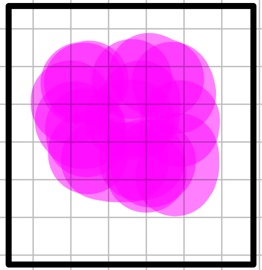
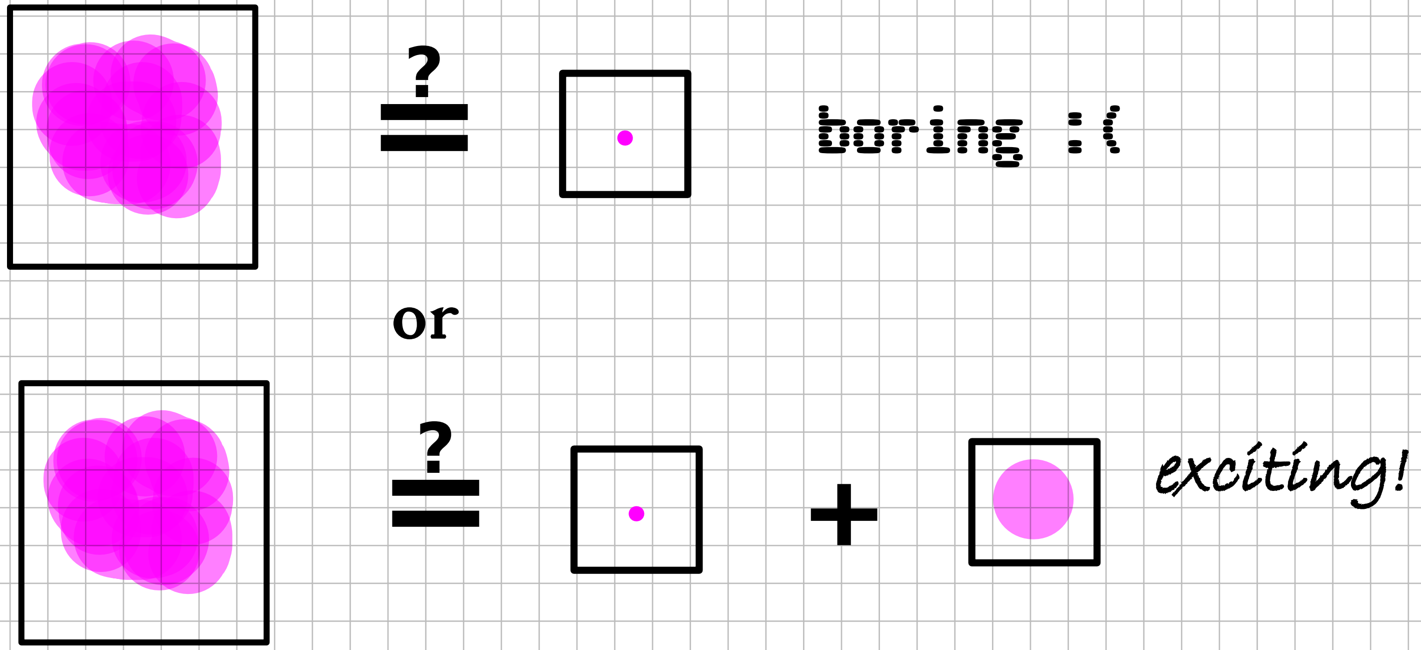


But, what should they expect?

For that we need models.

Parenthetical Note

It's important to Astrophysicists to know whether



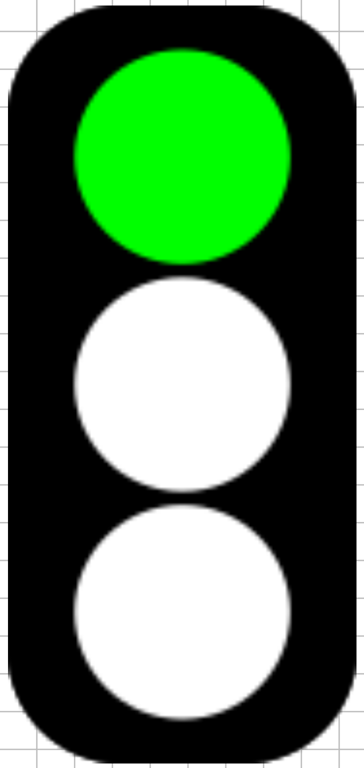
Modeling the Chandra PSF begins with the Optics

↳Point Spread Function

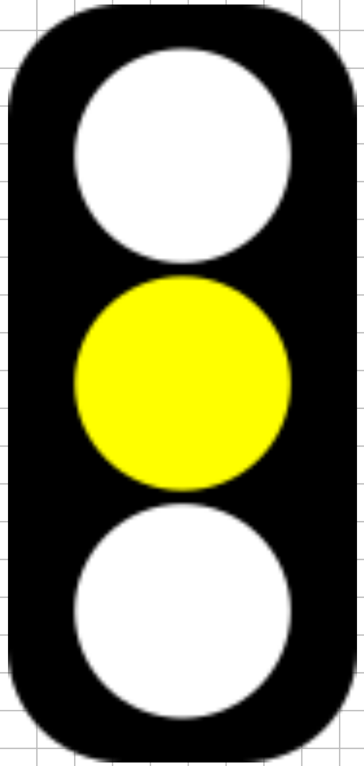
- Analytical geometrical models of the mirrors;
- Measurements of the deviations of the optical surfaces from the analytical model;
- Engineering drawings of the as-built support structures and baffles;
- Engineering finite-element models of distortion in the mirrors due to supports;
- Measurements of the mirrors' roughness;
- Measurements of the mirrors' reflectivity;
- Measurements of the as-built positions and orientations of the mirrors;
- Measurements of dust on the mirrors;
- An analytical “physical” model of X-ray scattering;

Plus...

- Ground calibration of a (very) limited set of performance characteristics;
- More finite-element models of distortion of mirrors due to gravity on the ground;
- Calibration of calibration detectors;

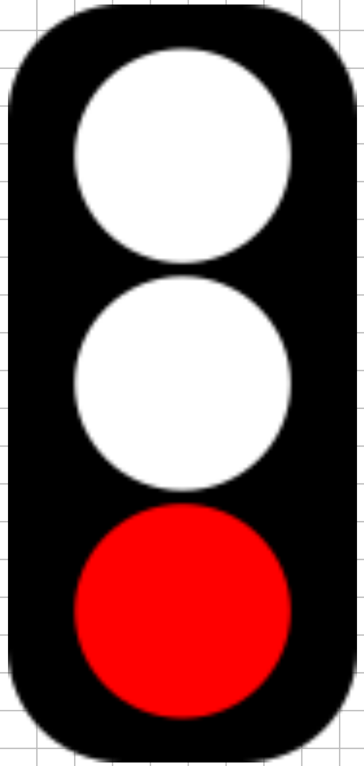


"We have an Optics model!"



"We have an Optics model!"

"Is it any good?"



“We have an Optics model!”

“Is it any good?”

“Define ‘good’.”

Well, how good are the components in the model?

Or, what are their errors, and can't we just combine them??

That's complicated.

Part I

> “We depend upon finite-element models of the stresses put on the mirrors by their support structures to model the puckers in the mirror surfaces. Those puckers might change over time because the mirrors are epoxied in place and epoxy might shrink.
>
> Two different finite-element codes run to predict those stresses were characterized as having differences on the order of "20%". But how do those differences affect the actual PSF? We'd have to run lots of sensitivity tests and tweak the parameters. And we didn't have the technology to do so.⭐”

So, we have components without errors.

⭐ At the time, we were all using abacuses. Yes, we're that old.

Well, how good are the components in the model?

Or, what are their errors, and can't we just combine them??

That's complicated.

PART II

> “Well, we have really good reflectivity measurements for witness samples of the mirrors. But we can't measure that directly for the actual mirrors. And when we measured the ‘effective’ area (that depends upon the reflectivity) during ground calibration, our models were way off. So that means either our reflectivity errors were off (not likely) or our mirror geometries are off, or we modeled the source at the testing facility wrong.
> Or something else. Anyway, we folded the emperical measurements from calibration into our models and it seems to work well on orbit.”

We can't just percolate errors up through the model, because at some point the model gets too complicated, or is wrong and we have to apply semi-empirical corrections.

Parenthetical Note

Because the Chandra PSF is so complex, we were unable to fully calibrate it during pre-launch tests.

We cannot easily calibrate it on orbit.

We must use the model to predict performance in uncalibrated regimes.

We use the calibrations to constrain the engineering and physical components of our model.

Modeling the Chandra PSF continues with the Detectors

Without a detector, there's no image, and that means without detector models, there's no model of the PSF.

Chandra has two primary detectors:

- ACIS:
  Collects events in discrete pixels. It has a non-linear degradation in response when observing bright point sources, so has been little used for PSF calibrations until recently.

* HRC:
  Collects events on a more continuous fashion, can observe brighter objects, but has it's own non-linear degradation issues.

Barriers to Good Detector Models, #1

The detectors' spectral response has been well studied, but their spatial response, and therefore their effects on the PSF have been harder to quantify, as at some level there is a degeneracy in the analysis:

Is it the detector, or is it the optics?

Breaking this degeneracy is important, as much of our knowledge of the detectors' effects on the PSF has been derived from observations on-orbit.

Barriers to Good Detector Models, #2

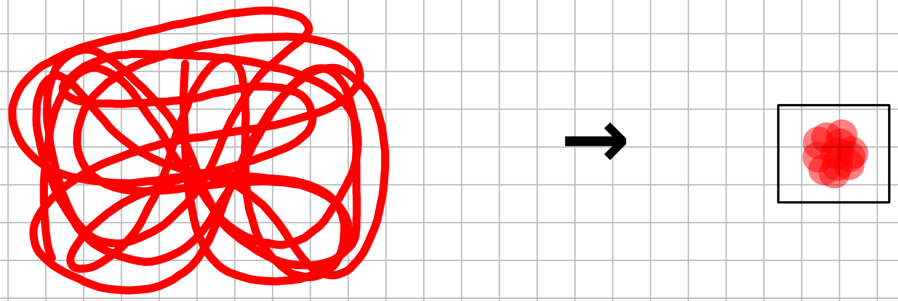
Various semi-empirical strategems have been deployed to correct data for systematic detector effects, such as non-linear response at high count rates.

Because some of these corrections are phenomonological, it is not always understood how they may affect the PSF.

The detectors are complex enough that we cannot model the detectors with the observed non-ideal characteristics and then apply the corrections to understand their effects.

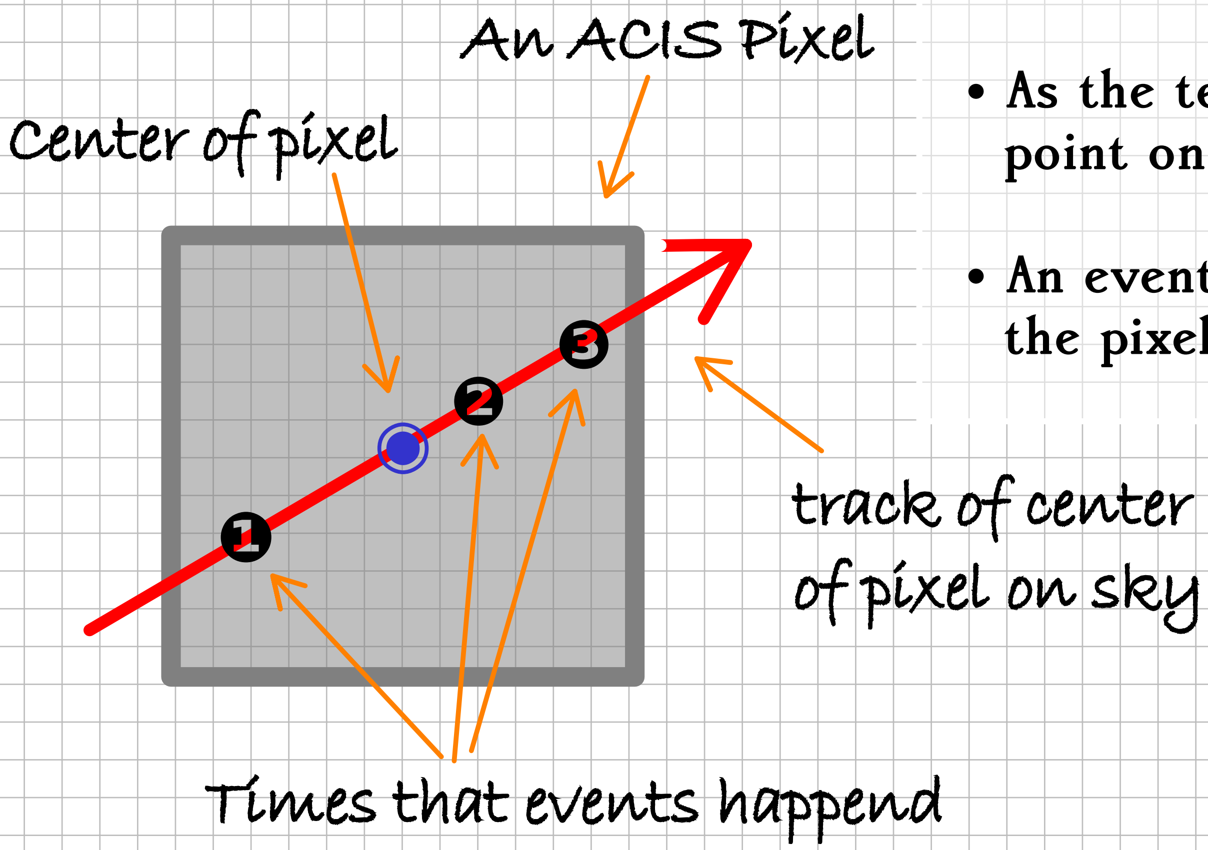
Modeling the Chandra PSF continues with Aspect

Chandra's Aspect system removes the programmed and random motions of Chandra's pointing to transform the dithered events into an image.



It also increases the effective resolution of the ACIS with its relatively large pixels.

Dither and effective ACIS resolution

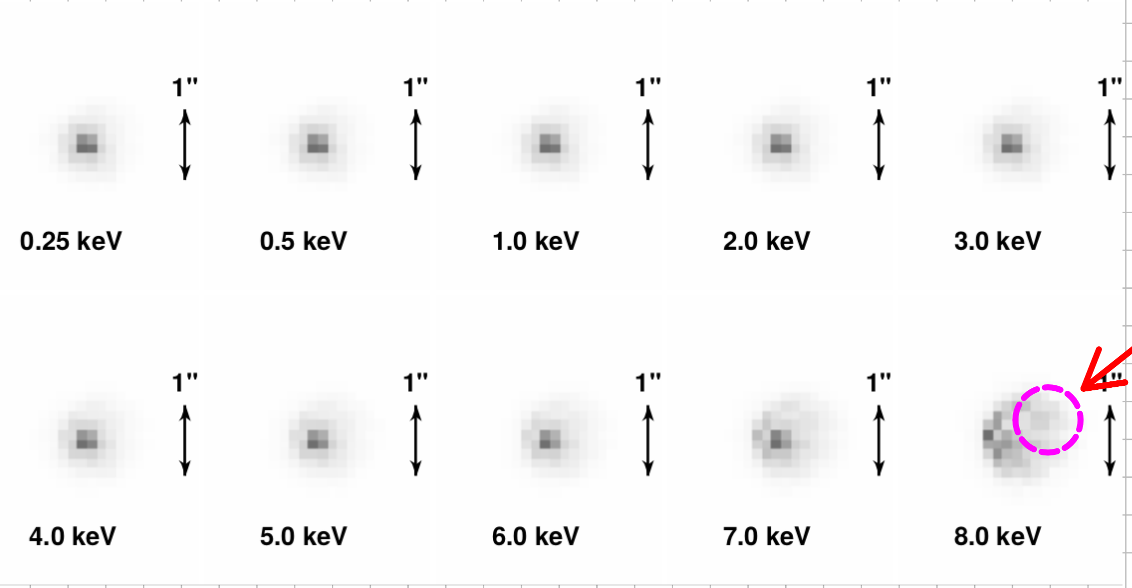


- We do not know where an event is detected in a pixel.
- We know what point on the sky a pixel observes.
- As the telescope dithers, the pixel observes a different point on the sky.
- An event is assigned the position on the sky that the pixel was observing when it happened.

This provides an effective spatial resolution better than one pixel.

Modeling the Chandra PSF, Results

On-axis, HRC resolution



- is this real? ⭐
- how sure are we?
- can we provide a probability for this? ⛔

⭐ Yes ⛔ No

Back to one of our initial questions:

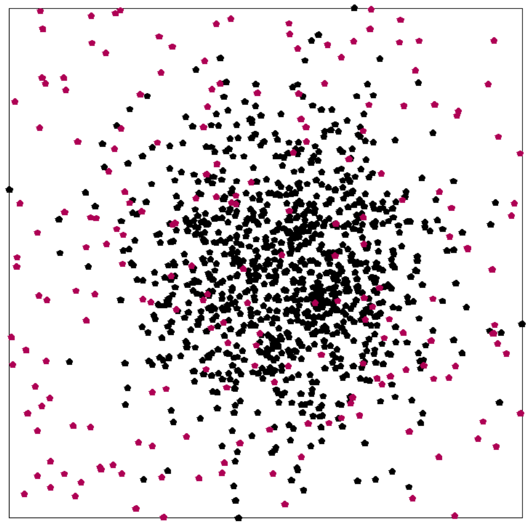
- *If I want to test some bit of astrophysics, what are the intrinsic errors in our knowledge of the PSF, so I can determine the sensitivity of my measurements?*

We need to calibrate our model on orbit.

2D is too hard.

We need simple statistics that we can use to compare models to sources and sources to sources.

Construct 1D representation of observation



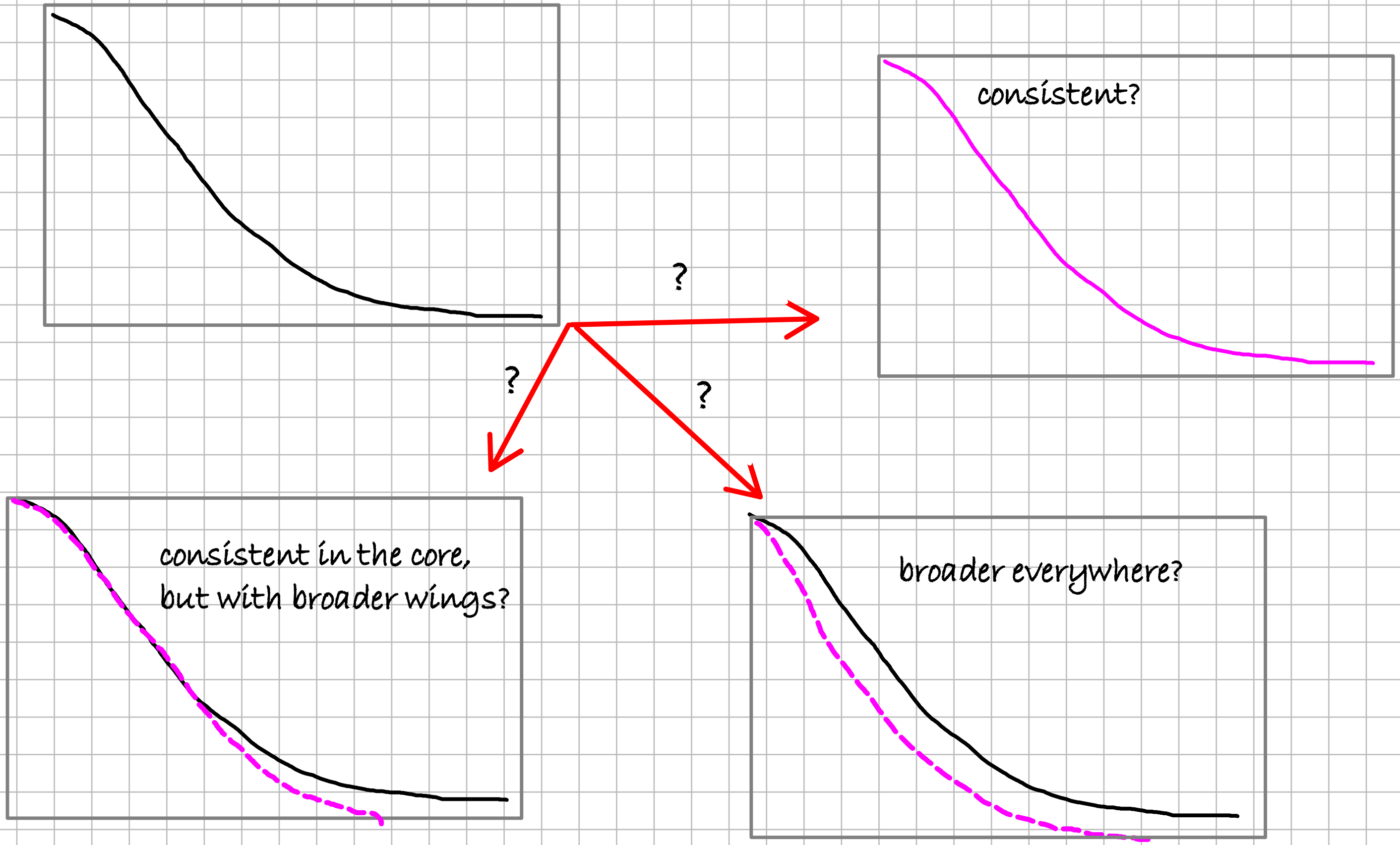
source events (black)
background (red)

❶ Measure Background
❷ Find center of source
❸ Generate radial profile
❹ Subtract background

→

1D pdf on a grid,
after background
subtraction

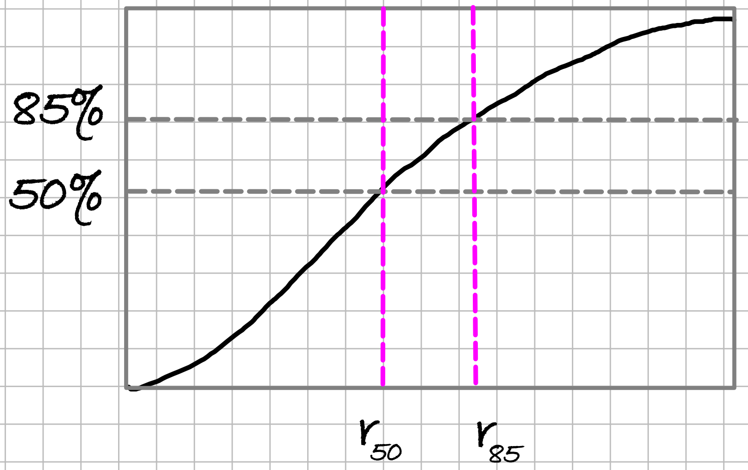
How dœs the measured profile match the PSF?



And how can we quantify this?

Introducing the ~~Encircled Energy Function.~~ ★

Enclosed Count Fraction



The ECF is the integrated (background subtracted) counts as a function of radius.

We can compare the radii containing fiducial fractions between sources and models to see if they are consistent.

We also (finally) have a stacked set of observations of point sources that we can use to construct an as-observed PSF. We can quantify this.

★ While traditionally called the Encircled Energy Function, we never actually look at energy, just counts.

Thorny questions about creating the ECF

What dœs 100% mean? How do you know when your integration stops including events from the source and is just collecting background?

How do you find the “center” of the source, especially in low count sources in the presence of background?

What are the errors on r_{50} and r_{85} ?

This is the question that has us chasing our tails.

Errors on ECF radii, or doing the Hokey Pokey ⭐

We've partitioned our data set based on counts in each petition.

Binomial dœsn't take into account the Poisson noise in the data or the background.

Bootstrap resampling (we've tried) gives errors that are way too small.

Your suggestion? ______________________

⭐ *You put one event in, you take one event out, you do the hokey-pokey and you chase your tail for a long time...*