LOON

Target Fill Moles

How to Predict Long-term Leakage

- Balloon team

09.16.2019

High-level summary

- Helium leakage for production Plover reverse-ballonet PE01 balloons has been studied. Data suggests that for most balloons leak rate is not constant and increases linearly with time.

- A method for estimating helium leakage over time has been developed.

- Based on the result, the recommended fill mols/day for a target life limit of 175 is 3.77 mols/day. We predict 80% of the Plover Reverse balloons leak less than 660 mols (3.77 x 175) during their first 175 days.

- Since the leak rate increases over time, the target fill mols/day changes with the target life limit. For example, for a target life limit of 200 days, the recommended fill moles is 4.22 mols/day. For the target life limit of 170 days the recommended fill moles is 3.66 mols/day.

- Effect of potential volume increase on the predicted leak rate has been investigated and shown to be small.

01

Envelope Performance Target

Envelope Performance Targets 2019-2020 (go/envelope-performance)

	Q4 2018	Q1 2019	Q2 2019	Q3 2019	Q4 2019	Q1 2020	Q2 2020
Service Life Limit (day)	113	115	170	175	175	175	200
target fill limit (day)	170	170	170	175	175	200	225
xx%	80%	80%	80%	80%	80%	90%	90%
fill mols/day	4	4	4	3.5	3.5	3	3
ballast available (kg)	15	15	10	5	15	15	15

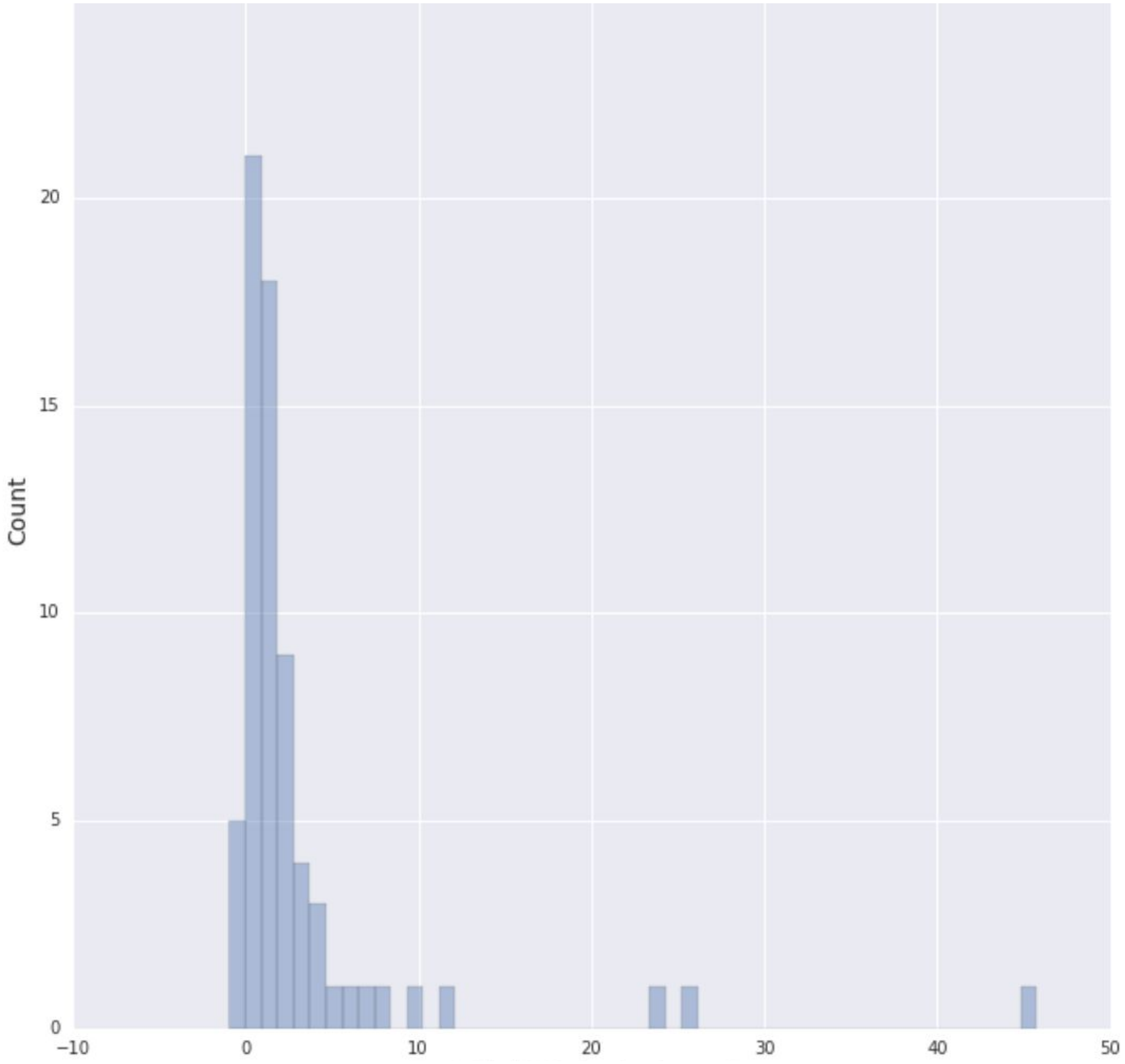
LEGEND
stretch goal
near current values
historical performance
expected improvement

- How to read example: for Q2 2019, our envelope performance goal was to have 80% of the fleet achieve 170 days while maintaining their steering capabilities. So at launch we filled them with an extra 4 x 170 moles of helium (fill mols/day * target fill limit) to compensate for the expected leakage.

- In other words, **xx%** is the percentage of the balloons that we expect to leak less than ***fill mols/day, on average***, during their ***target fill limit***.

How we approached this before

- Back in October 2018, we studied Plover Reverse balloons (PE01 and PE2018) which lived beyond the transit mortality period of 22 days ("good balloons").
- The distribution of night moles lost per day for balloons at their last day of life was generated.
- We selected the 80th percentile of the distribution, which was about 4 moles/day as the target fill moles.



Night moles lost per day on the last day of the balloons' life

Ever since

- We have flown a lot of PE01 balloons.
- Many balloons lived more than 100 days.
- Balloon manufacturing process has become more consistent.

So now we have a lot more data and less variations in balloons and leak sources!

Production PE01 Plover Reverse*			
	n-launched	**tm%****	**Avg Duration (- tm)**
2018 - Q4	32	3.1	129
2019 - Q1	47	27.7	95.8
2019 - Q2	45	4.4	100
2019 - Q3	11	9.1	55.3

* Last updated 16 Sep 2019
** tm: transit mortality (terminated before 22 days)

Question

- How should we update the fill mols/day? Considering that we can drop all the ballast by day 175, what should be the extra fill moles to achieve 175 day life expectancy for at least 80% of the v1.4 fleet?

- To answer this question we need to come up with an estimation for the total leakage by day 175. PSC team can use that and adjust the ballast accordingly to maximize steering.

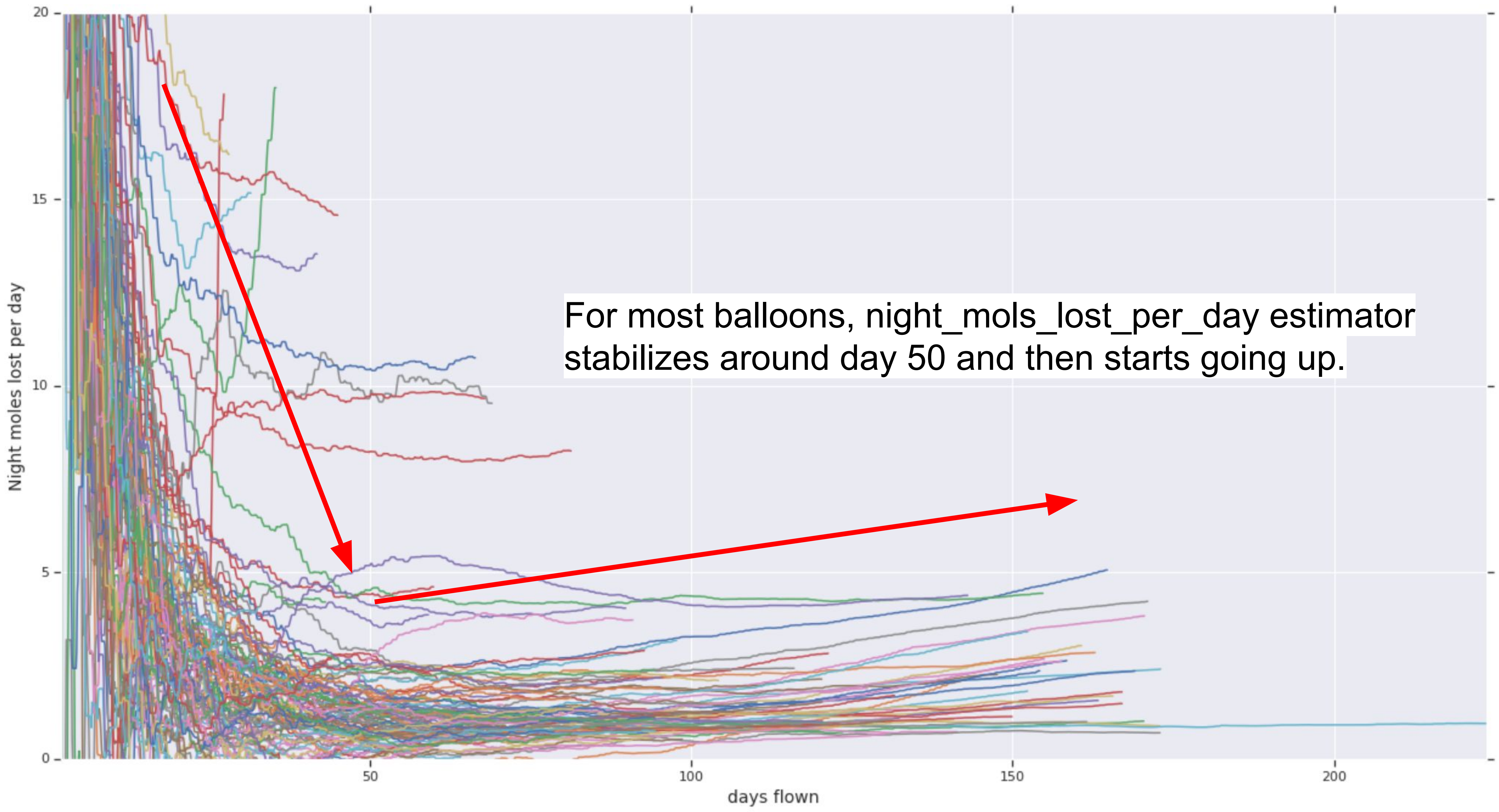
- As of now (Sep 12, 2019) we only have one balloon that lived more than 175 days. We have 24 balloons that went beyond 150 days. 24 is a limited sample size and we also know that leak rates may increase over time. So it will be very valuable if we can make a prediction for helium leakage and establish a method for it.

02

Estimating Gas Leak

Scope : Production-Plover Reverse PE01

Night moles lost per day



Night moles lost per day

- Night moles leak rates initially drop, and then start to go up with time.

- The drop in the leak rate before day 50 means there was a big loss of helium in the early days but the leak rate became smaller afterwards. The main reason for observing this trend is that the estimator interprets the loss of HeLA as leakage. Also we might be underestimating the base volume of the balloon which results in a bias in the initial estimated ngas.

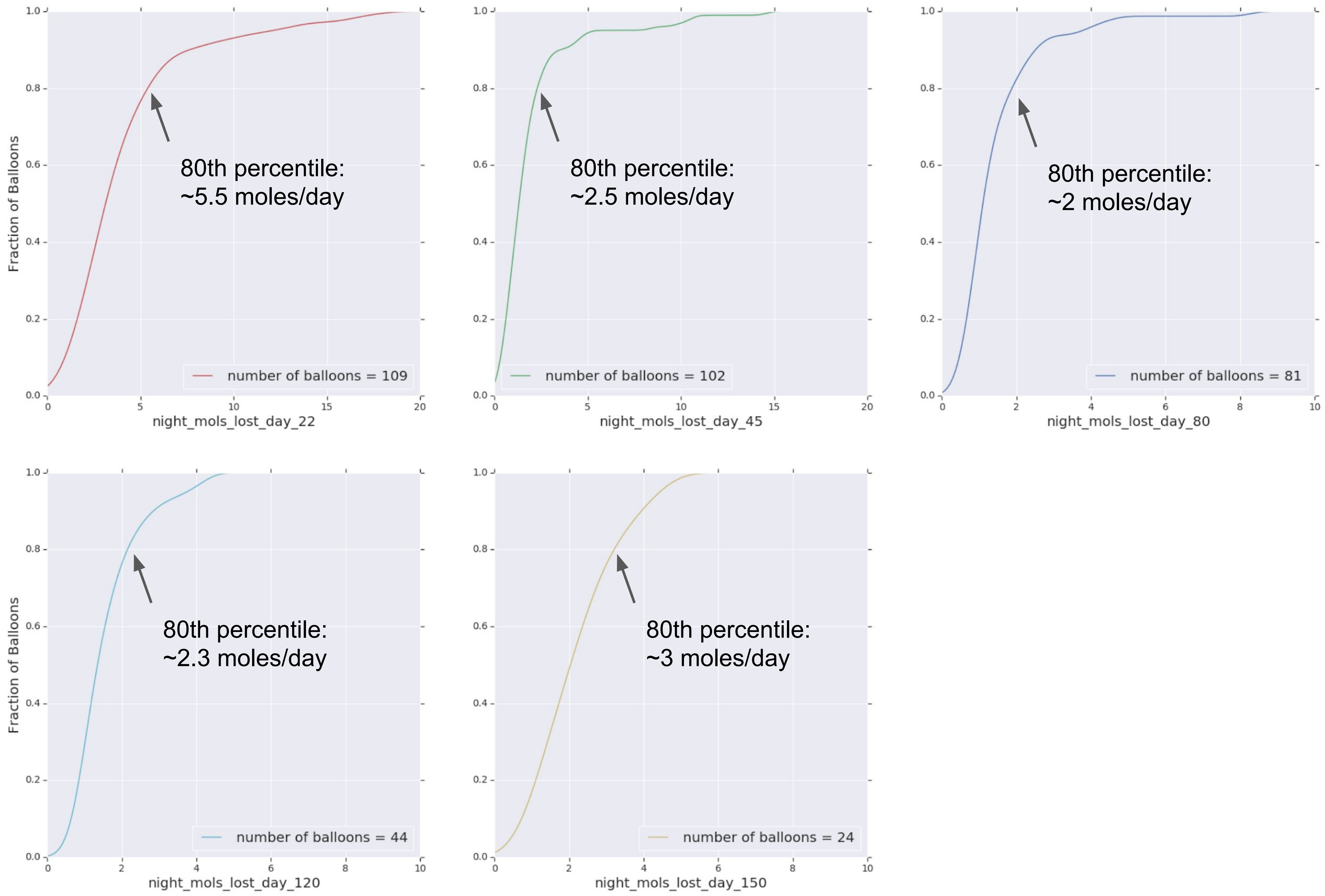
(NOTE: HeLA is “Helium Launch Assist”, adds some amount of helium to air ballast chamber prior to launch, in addition to the normal helium fill amount in the lift gas chamber. This extra helium is mostly removed by the ACS after reaching float and the remainder is gradually removed from subsequent ACS maneuvers.)

		Population average for night moles lost per day on *				
Q	**n-launched**	**Day 22**	**Day 45**	**Day 80**	**Day 120**	**Day 150**
2018-Q4	32	4.7	1.8	1.5	1.8	2.2
2019-Q1	47	4.2	2.3	1.7	1.4	2.0
2019-Q2	45	3.4	1.7	1.1	1.4	2.1
2019-Q3	11	3.2	1.7	NA	NA	NA

* Last updated 16 Sep 2019

Percentile (CDF) plots

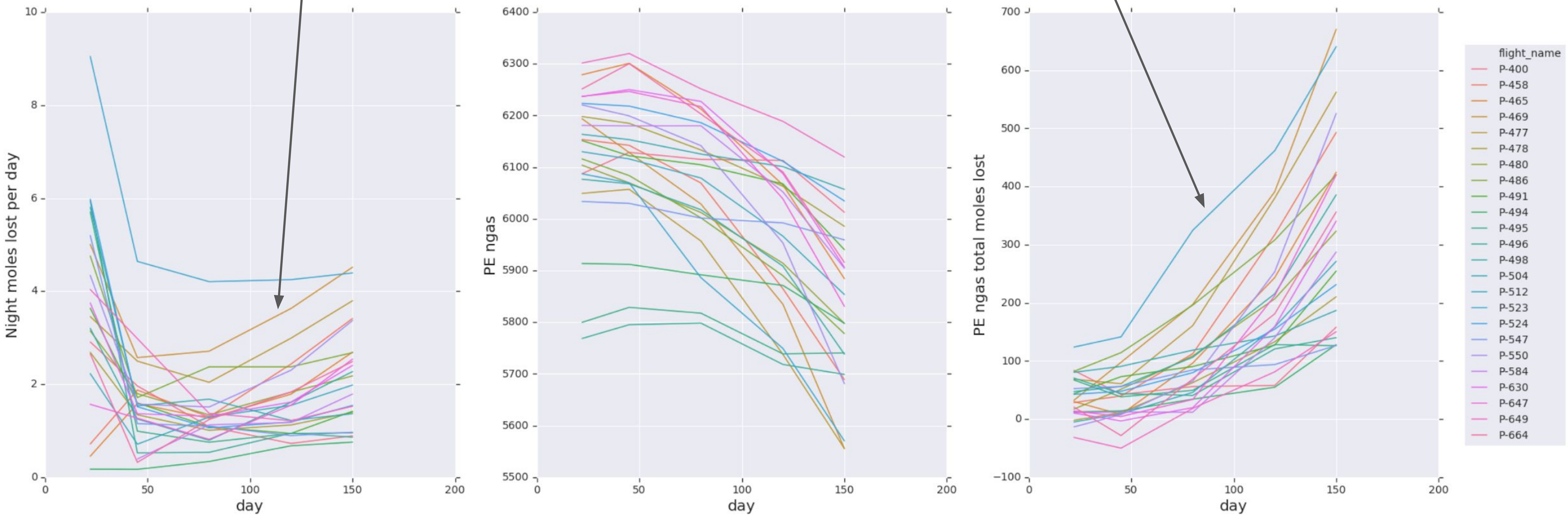
- 80th percentile for the night moles lost per day estimation changes with time too.
- The sample size drops with time. We have 109 balloons that lived more than 22 days but only 24 of them lived beyond 150 days.



Leak rate trends for 24 balloons > 150 days

The rate of the increase in the leak seems to be linear with time but the slope is different for each balloon.

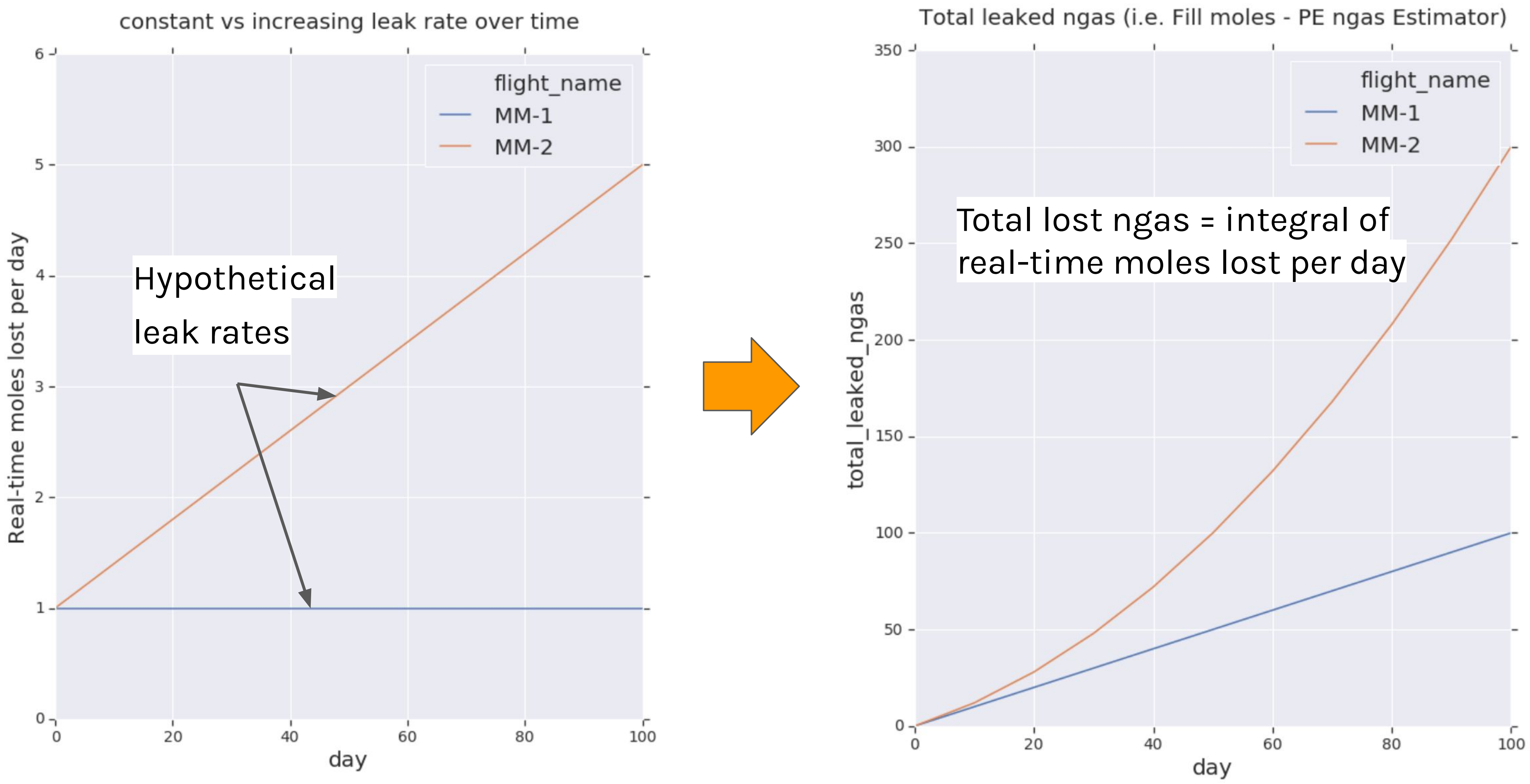
The rate of the increase in the total moles lost seems to be quadratic with time.



P.S. Only the data from 5 points in time (day 22, 45, 80, 120, 150) are presented to avoid overcrowding the charts.

Leak rates and total leakage

A constant leak rate results in a linear total leakage with time while a linear leak rate results in a nonlinear quadratic total leakage over time.



Night moles lost per day estimator

- Night moles lost per day estimator is a Kalman Filter (KF).

- Our KF is tuned such that it puts high confidence on its model predictions vs. immediate sensor measurements.

- From investigating the estimator outputs, it seems that **the estimator's model assumes that the there is only one true leak rate for the lifetime of the balloon.** In other words, it is not very responsive to changes in leak rate and picks up the variations very slowly.

- In case of having an upward trend in the leak rate, the KF output **seems to be closer to the average leak rate during the life** of the balloon.

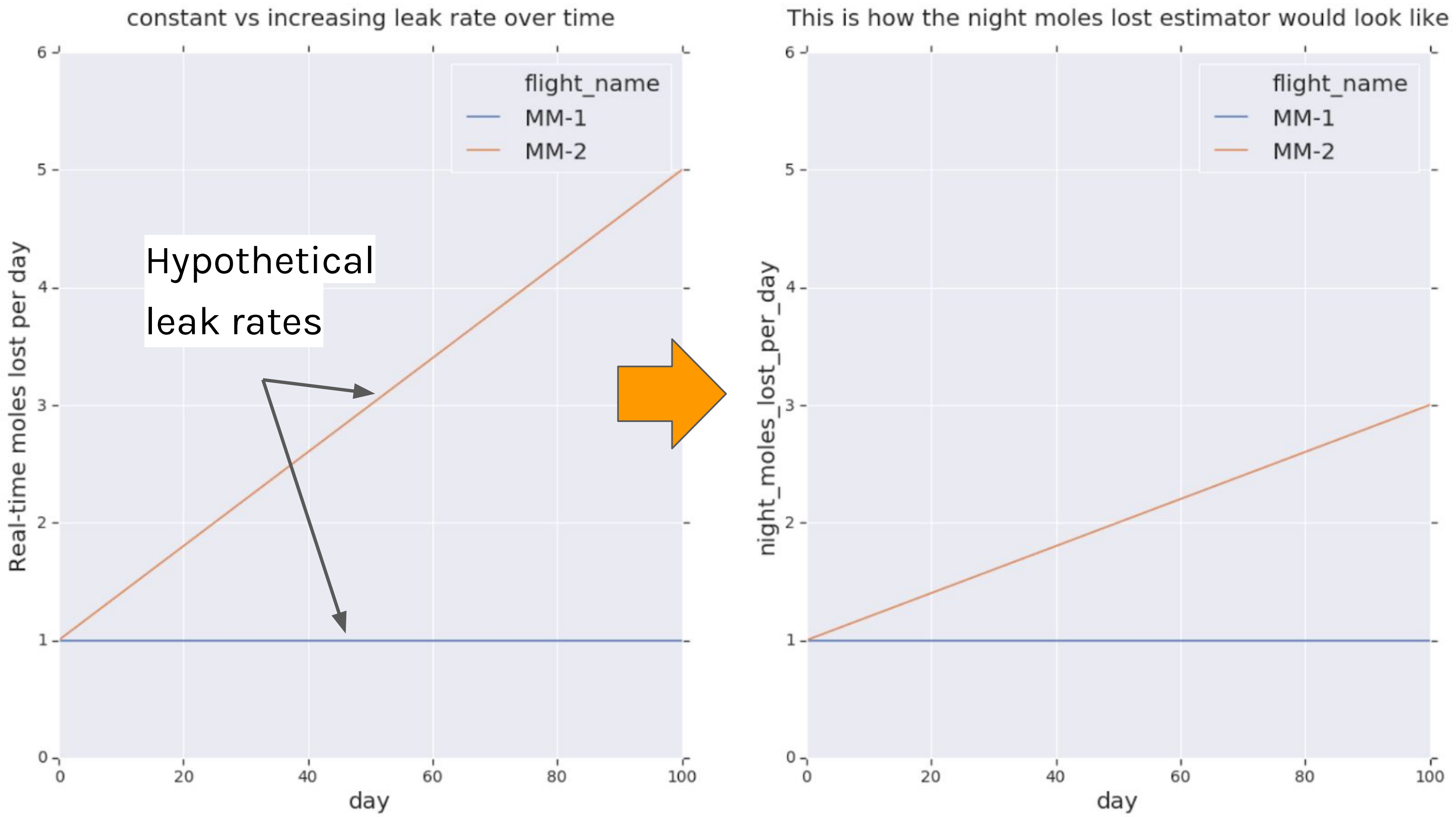
- Depending on the real time leak rate profile, KF output might be smaller than the real time leak rate and underestimates it by *at most* a factor of two.

With a KF, a state variable describes the state of the system and the probability of each state is assumed to only depend on the previous state. KF has a prediction for the future state. When the new measurement updates, KF updates its prediction to something between the measurements and its prior prediction and that is the new state of KF, in our case a 2D variable of moles of He and leak rate.

How should we interpret the night moles lost per day estimates?

Example:

A night_mols_lost_per_day estimation of 3 on day 100 **loosely** indicates that the balloon has lost 3 moles of helium on average every day (a total of 300 moles). It does not necessarily mean the leak rate on day 100 is 3 moles/day. If we start with 1 mols/day leak on day 0 and linearly go to 5 mols/day leak on day 100, we have lost 300 moles total and night moles lost per day estimation will be around 3 on day 100.



Integral of the area under the orange curve = 300 moles

=

Night moles lost estimation at day 100 = 3, 3 x100 days = 300 moles

My approach to estimate leak by day 175

- I assume ballon leak rate is a linear function of time = A x time + B. This is inspired by seeing a quadratic increase in the total moles lost with time. Leak rate of A x time + B means that on day 0 the balloon starts with leaking B moles and leak increases A moles per day, e.g. on day 3 the balloon leaks 3A+B moles.

- Total moles lost is the integral of the leak rate function. On day_n, total_moles_lost = A/2 x day_n ^2 + B x day_n. Total moles lost is a quadratic function of time.

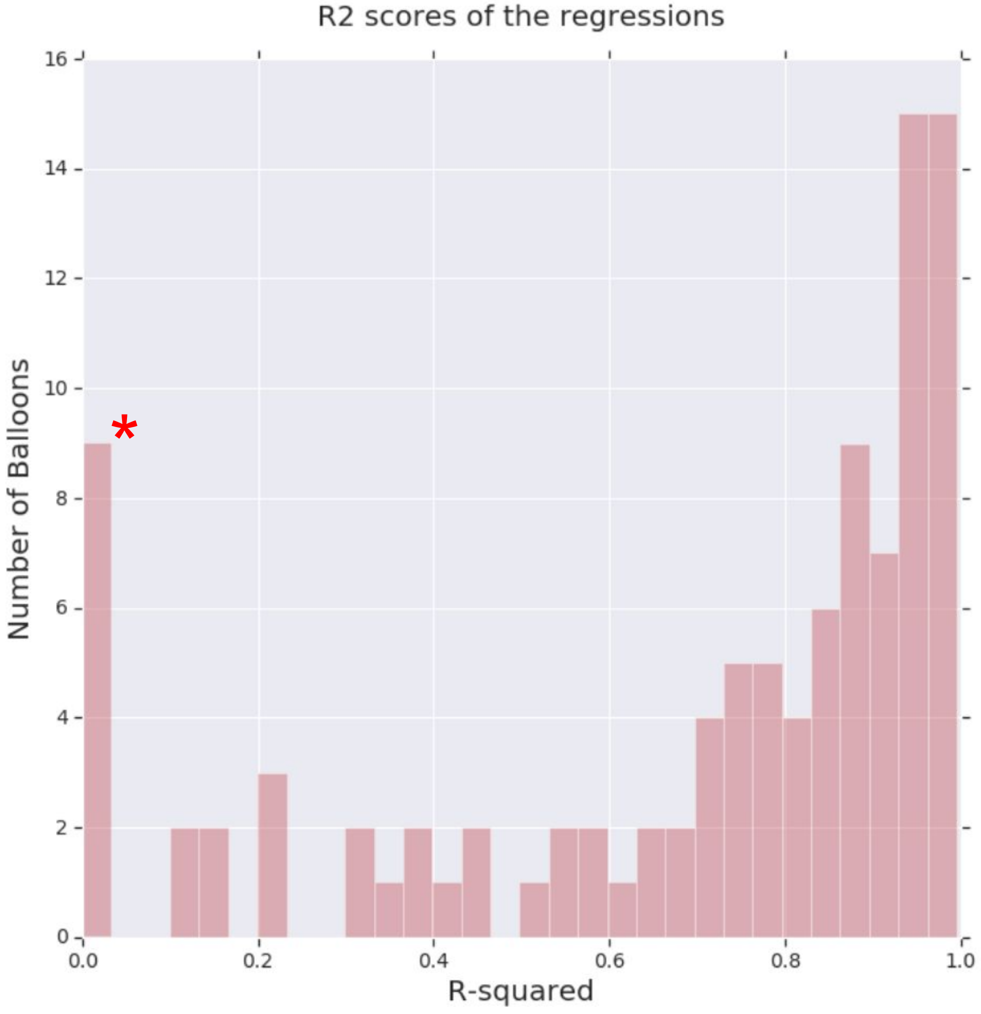
- I will find A and B by doing regression on lost helium based on Physics est. for all the available data after day 50. I will predict the total moles lost at day 175 for each balloon, and select the 80th percentile. That number divided by 175 would be the required target fill moles for this population.

- Regression method: Lasso regression with enforced positive coefficients for time and time-squared.

Goodness of the fit (R^2) for regressions (104 balloons>50 days)

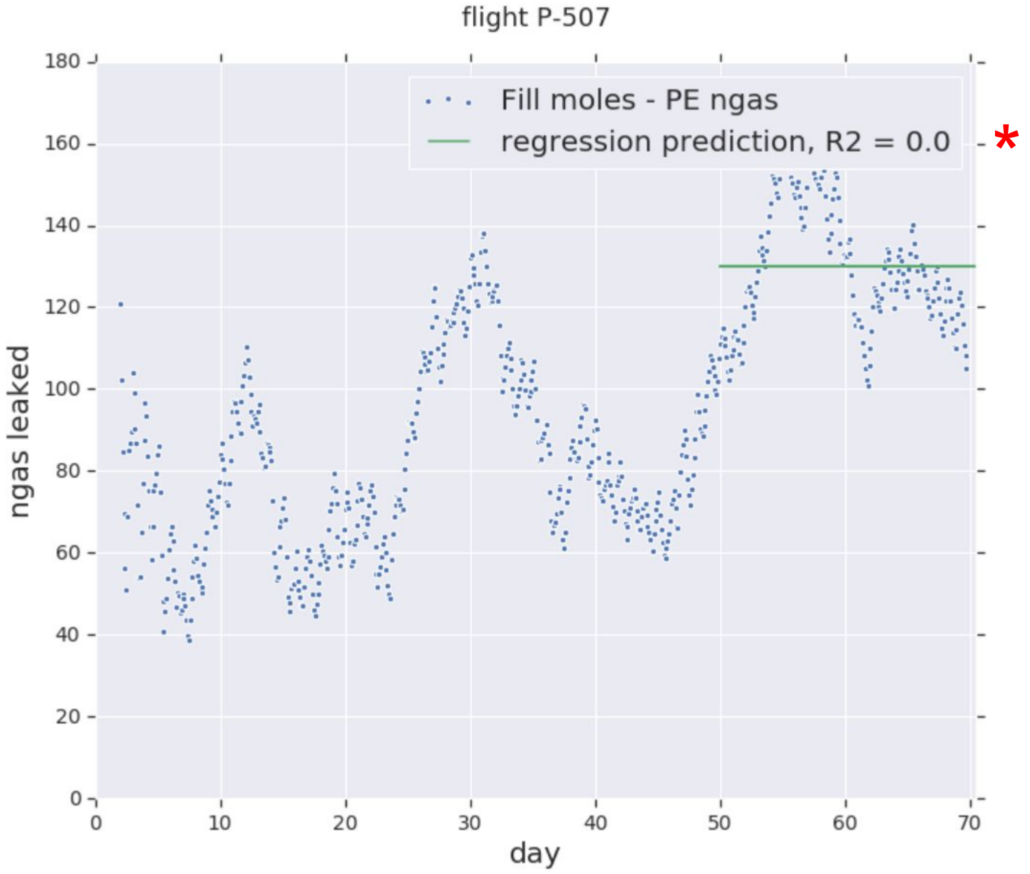
104 balloons

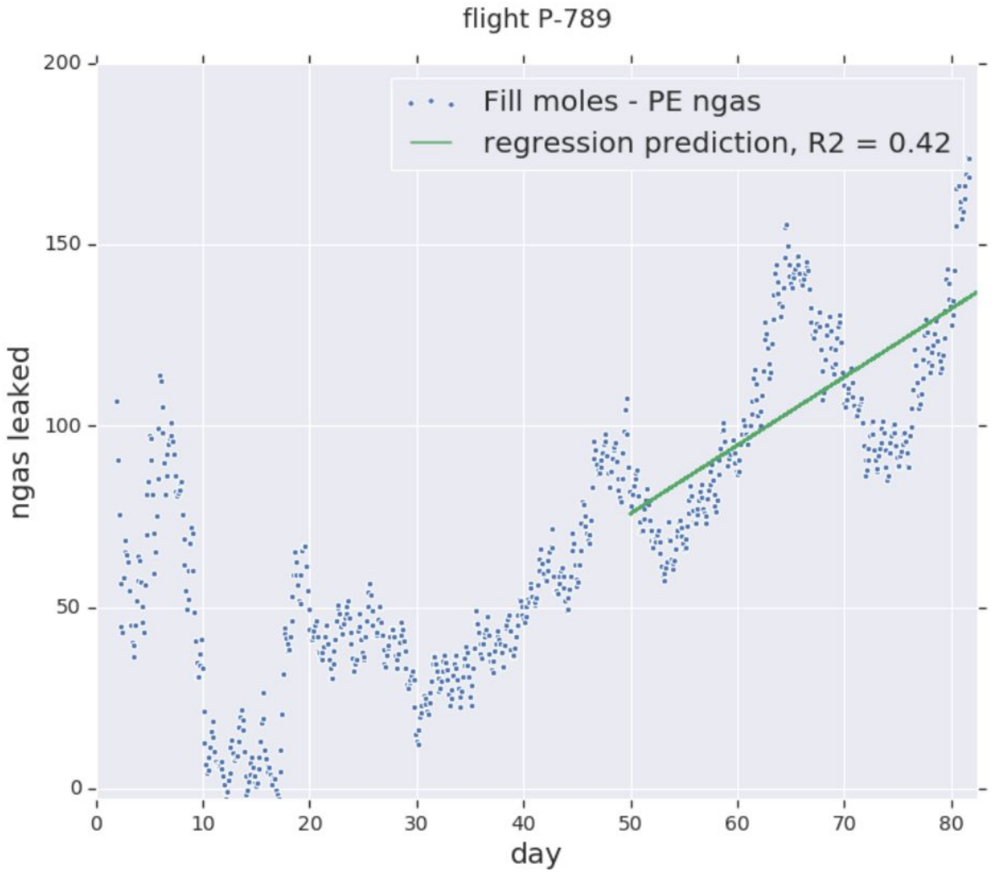
flight_name	intercept	time_coef	time2_coef	r-squared
MI-001	-52.25973646931921	0.5789467586199013	0.009741586863640656	0.7005024094100916
P-399	-14.86355057315032	0.0	0.02135314228527831	0.9333317812556324
P-400	45.5355686278445	0.0	0.004487052558774356	0.8530288500822625
P-406	-12.004902013022075	0.0	0.024269106941789725	0.9507771200536499
P-450	-7.4479070369532465	0.0	0.009314251249287621	0.5208770124798654
P-458	-26.01132148301042	0.0	0.023613252150602657	0.9954675664624107
P-461	40.86935987013615	0.0	0.018417101451021645	0.951094366065135
P-465	-38.09057196933111	0.0	0.020186021534068503	0.9737024109405084
P-469	22.332609722655263	0.0	0.028885171915980928	0.9912000993758753
P-470	109.96095087819776	0.0	0.0	0.0 *
P-473	-171.38645165246973	6.931506996510354	0.0036405787544407657	0.7983238599256607
...				

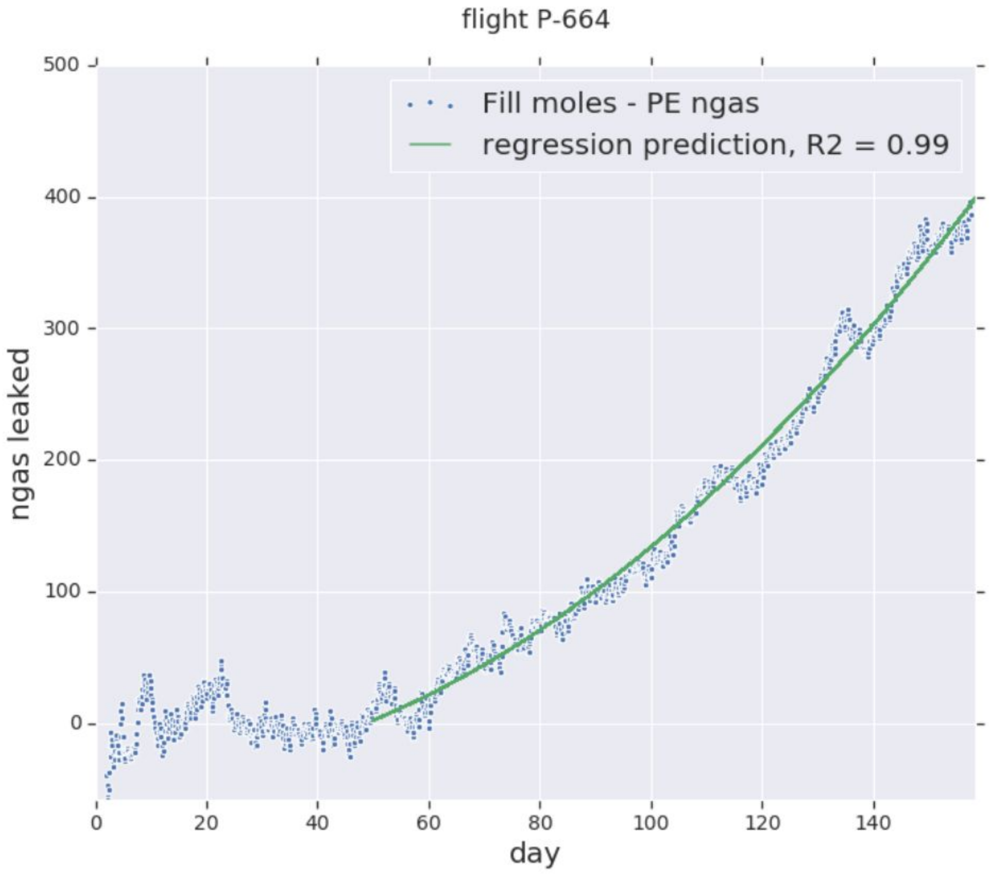


* For these balloons physics est ngas values did not change much after launch.

Sample regression results



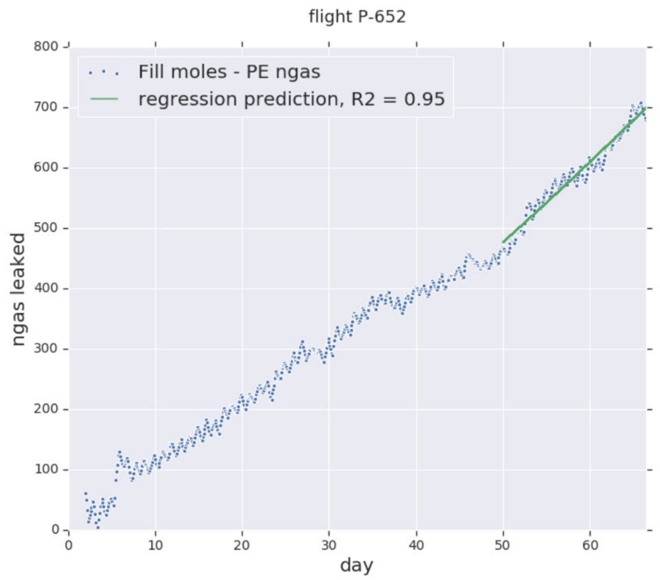


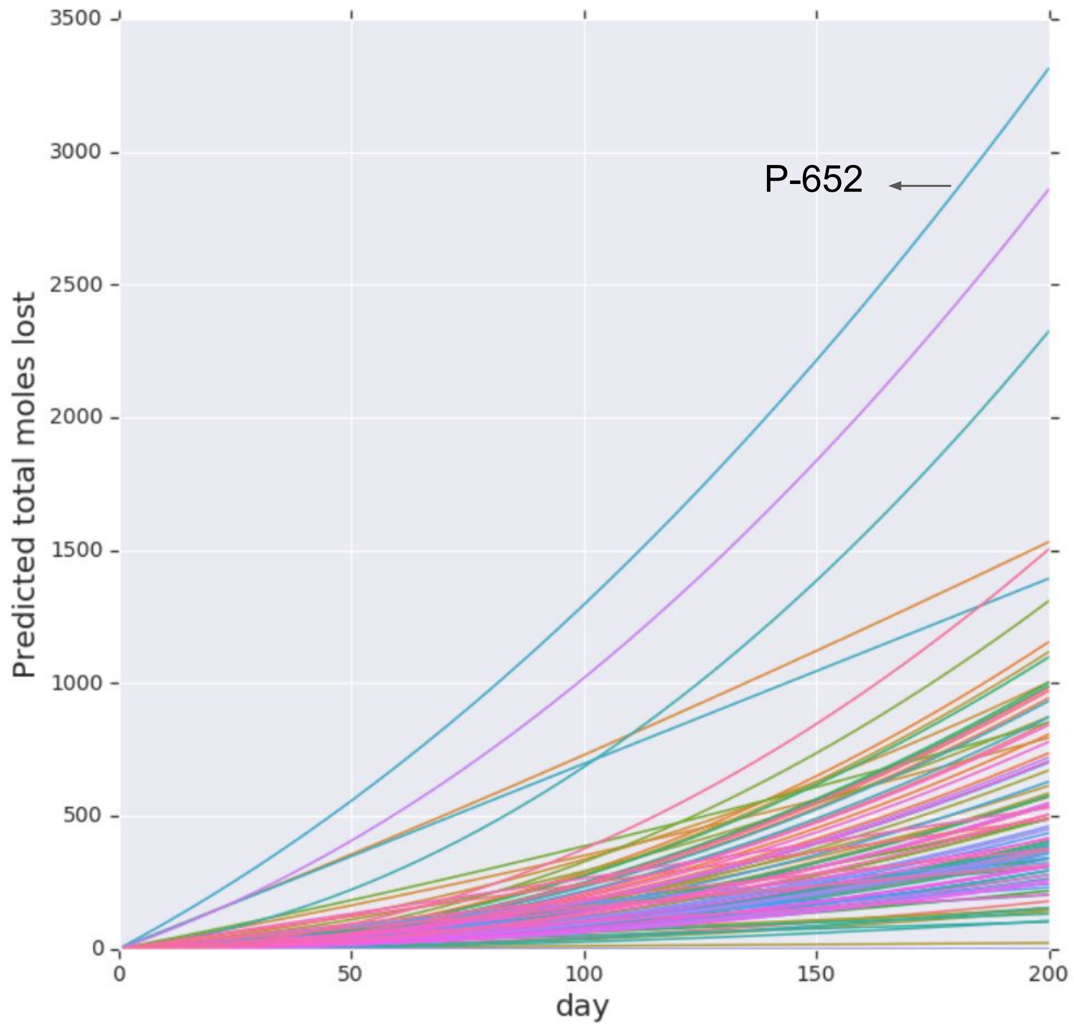


- I will predict zero leakage for balloons with R-squared = 0
- For regression, I have included all balloons that lived more than 50 days. So the current active balloons that haven't reached 50 days are not included.

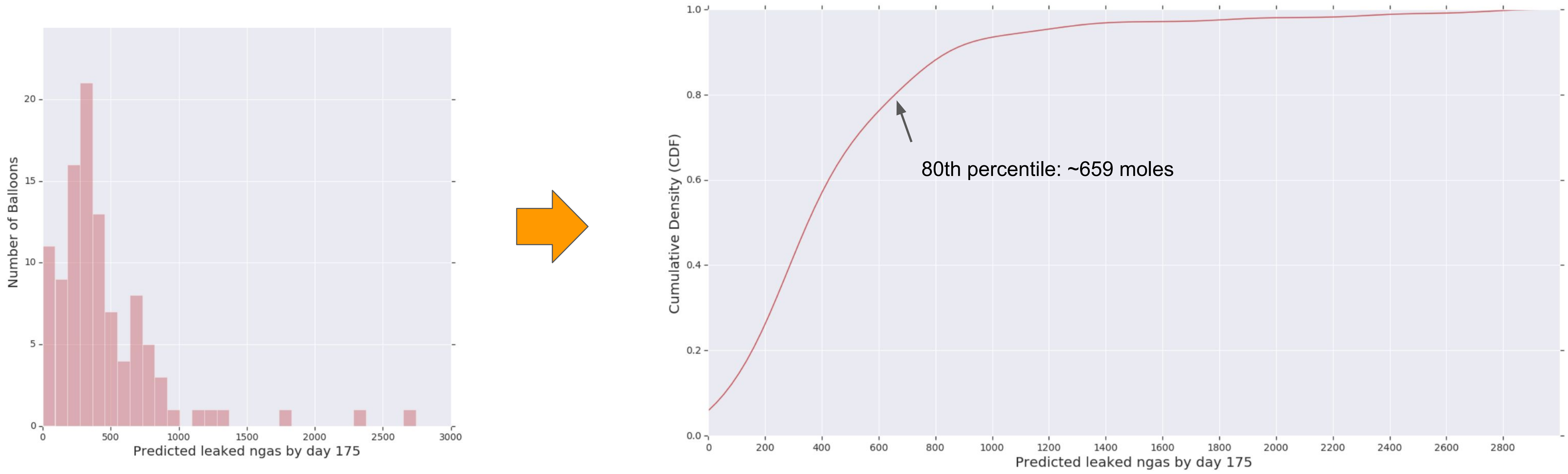
We can make a leak prediction over time for each of these balloons now

- Each line represent the predicted leakage over time for one of the balloons in the studied population.
- Interesting finding : Based on the regression results, P-652 is the fastest leaker of all. This balloon had its Apex dps tube cut during launch and had a known helium leak path.





Predicted distribution of total moles lost by day 175



- 80th percentile for predicted total moles lost by day 170: 622.2, divided by 170: 3.66 moles avg loss per day
- 80th percentile for predicted total moles lost by day 175: 659.4, divided by 175: 3.77 moles avg loss per day
- 80th percentile for predicted total moles lost by day 200: 846.8, divided by 200: 4.23 moles avg loss per day

P.S. This predictions change over time because every day more data becomes available and the regression coefficients change a little bit.

How will the prediction for leakage be used?

- We would like to optimize steering (maximize the altitude range) so that our flights can navigate over the entire altitude range from 6500 Pa - 11000 Pa and utilize all known winds.

- As the balloons leak helium, the higher limit of the altitude range is reduced. By dropping ballasts and reducing the total system mass we can achieve the same top altitude and maintain our steering capabilities.

- Based on gas law and buoyancy equations, altitude range builder algorithms define an operating range for the balloons at any moment.

- PSC team can use the expected leakage by the target life limit and decide for the lifetime ballasts at launch. By adjusting the ballasts we assure that steering capabilities will be maintained during the target life limit.

03

Effect of Volume on Leak Estimations

Effect of volume increase on estimated leakage

Balloon volume changes over time due to the creep in the tendons and the film. The increase in the balloon volume is not built into the estimation algorithms yet. We might be overestimating leakage due to underestimating PE ngas. Here we will study the impact of hypothetical volume increases on the estimated moles of helium. The result indicates that a 3% volume increase does not affect the helium moles estimation significantly; therefore, we are not overestimating leakage.

Solving gas law and buoyancy eqs.

Assuming the change in the volume would not affect the ambient temperature and superpressure estimation, we can solve for true values of nair and ngas based on their current estimated values and a volume ratio.

$$(P_{amb} + \Delta P)V = (n_{gas} + n_{air})R(T_{amb} + \Delta T)$$

$$\frac{P_{amb} M_{air}}{R T_{amb}} V = m_{sys} + n_{gas} M_{gas} + n_{air} M_{air}$$

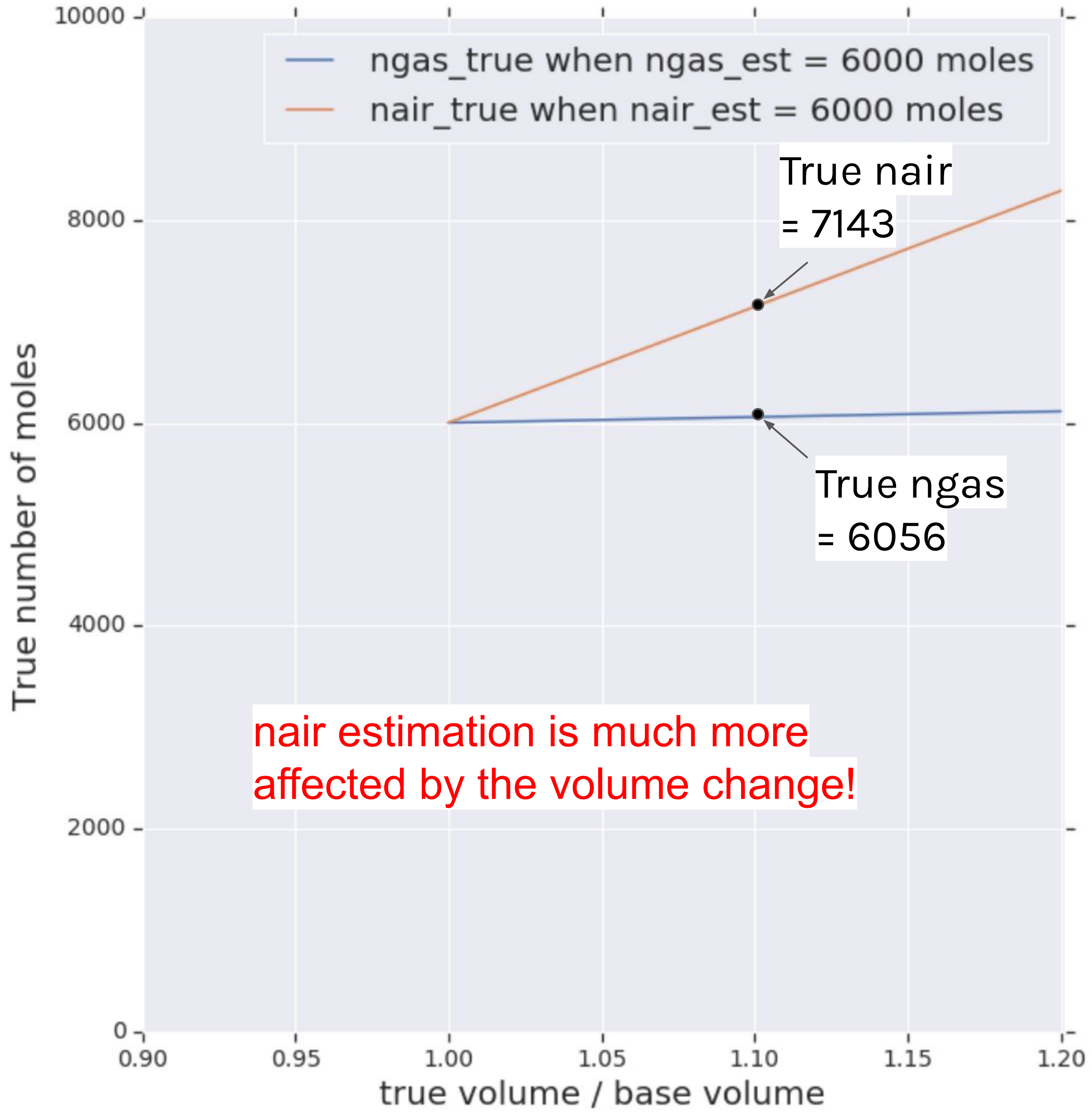
$$n_{gas,\,true} = n_{gas,\,est}\, volume\text{–}ratio + \frac{m_{sys}}{M_{air} - M_{gas}} (1 - volume\text{–}ratio)$$

$$n_{air,\,true} = n_{air,\,est}\, volume\text{–}ratio + \frac{m_{sys}}{M_{gas} - M_{air}} (1 - volume\text{–}ratio)$$

Case study 1

- Estimated moles of air = 6000
- Estimated moles of helium = 6000
- msys = 135.65 Kg (58.7 Kg payload + 76.95 Kg balloon)

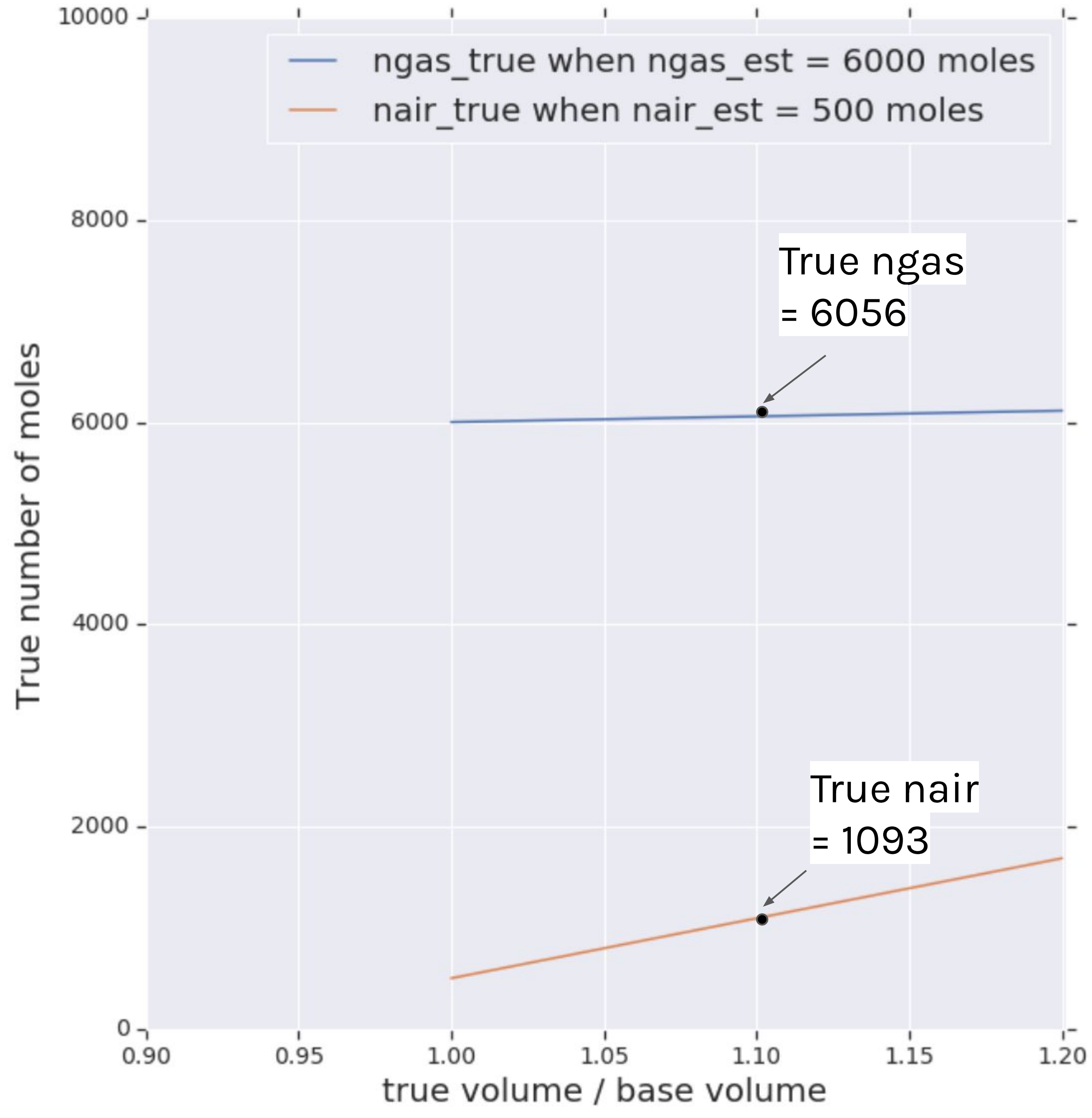
- If the true volume is 10% more than the volume that the estimators use, the true moles of helium is about 6056 and the true moles of air is about 7143. The helium estimation has 0.9% error and the air estimation has 16% error.



Case study 2

- Estimated moles of air = 500
- Estimated moles of helium = 6000
- msys = 135.65 Kg (58.7 Kg payload + 76.95 Kg balloon)

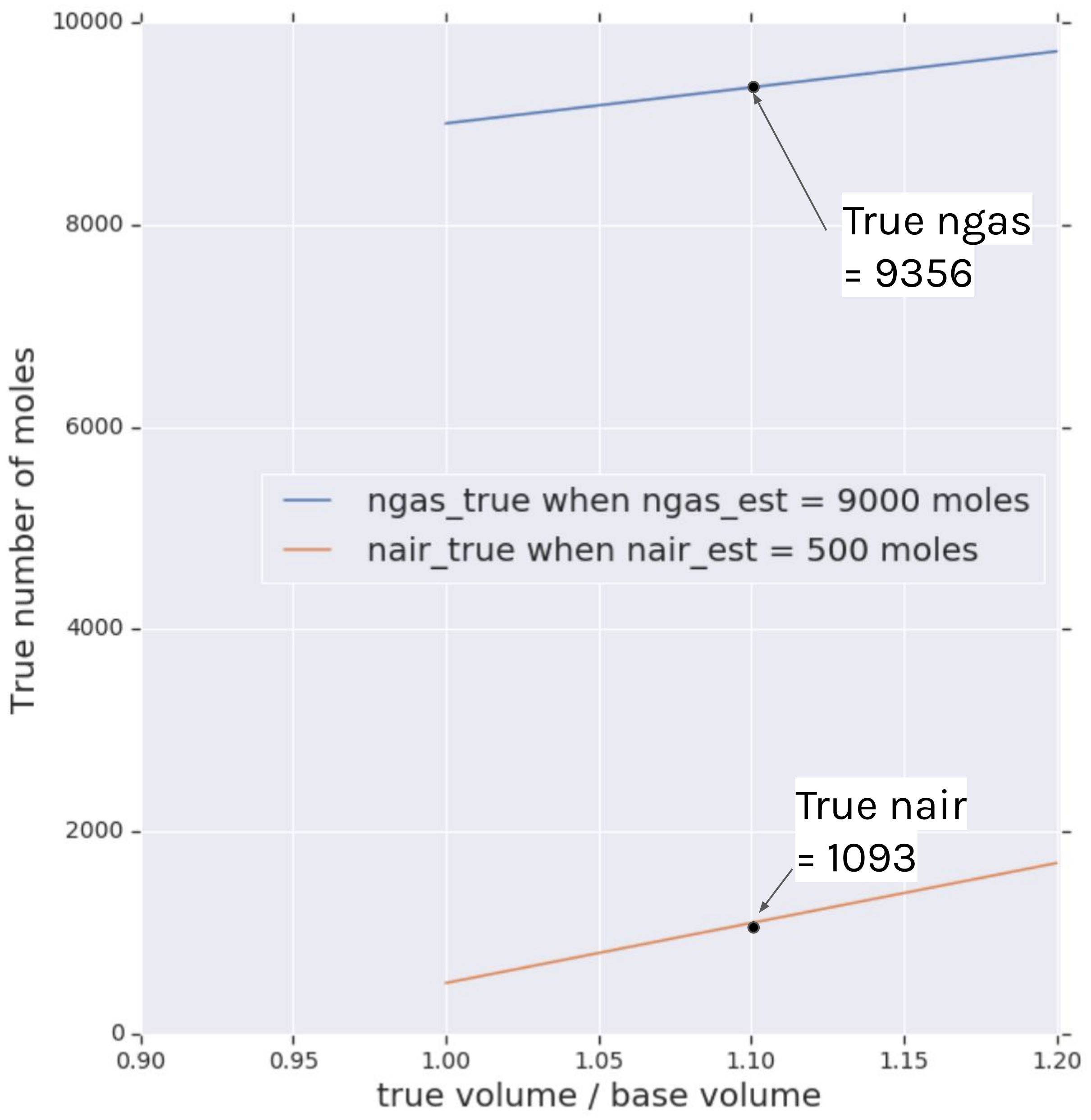
- If the true volume is 10% more than the volume that the estimators use, the true moles of helium is about 6056 and the true moles of air is about 1093. The helium estimation has 0.9% error and the air estimation has 54.3% error.



Case study 3

- Estimated moles of air = 500
- Estimated moles of helium = 9000
- msys = 135.65 Kg (58.7 Kg payload + 76.95 Kg balloon)

- If the true volume is 10% more than the volume that the estimators use, the true moles of helium is about 9356 and the true moles of air is about 1093. The helium estimation has 3.8% error and the nair estimation has 54.3% error.



Effect of a hypothetical 10% volume increase on estimated leakage

- Let's base the calculation on having 6000 moles of helium on day 175.

- With a hypothetical 10% increase in the volume, an estimated ngas of 6000 would correspond to 6056 moles in reality; 56 moles higher.

- The 80th percentile for predicted leakage by regression on day 175 was 659.4 moles. A 10% volume increase could only be responsible for 56 moles out of 659.4 moles.

- Accounting for 56 moles underestimation, we would still see 603.4 moles of leakage for the 80th percentile on day 175 which corresponds to 3.44 moles target fill mole.

- Previously, we had 659.4 moles leakage which corresponds to 3.77 target fill moles.

Effect of a reasonable 3% volume increase on estimated leakage

- With a reasonable 3% increase in the volume by day 175, an estimated ngas of 6000 would correspond to 6016 moles in reality; 16 moles higher.

- That will lead us to 643.4 moles of leakage for the 80th percentile on day 175 which corresponds to 3.67 target fill moles, very close to our prior estimation of 3.77.

- Considering the minimal effect of volume on the helium estimation, at least for the Plover balloons with a helium fill around 6000 moles, reducing the target fill moles is not recommended.

04

Summary & Next Steps

Summary

- A method for estimating helium leakage with time has been developed.
- Based on the result, the recommended fill mols/day for a target life limit of 175 is 3.77 mols/day. We estimate 80% of the Plover Reverse balloons leak less than 660 mols (3.77 x 175) during their first 175 days.
- Since the leak rate increases over time, the target fill mols/day changes with the target life limit. For example, for a target life limit of 200 days, the recommended fill mols/day will be 4.22 mols/day.
- Effect of volume increase on the estimated leak rate has been investigated and shown to be small.

Next steps

- Currently the estimators use the base volume of balloons (1804 m3 for Plover and 2870 m3 for Quail) to solve the gas law and buoyancy equations for moles of helium and moles of air.

- The volume is a function of base volume, tendon creep, film creep, superpressure, and temperature.

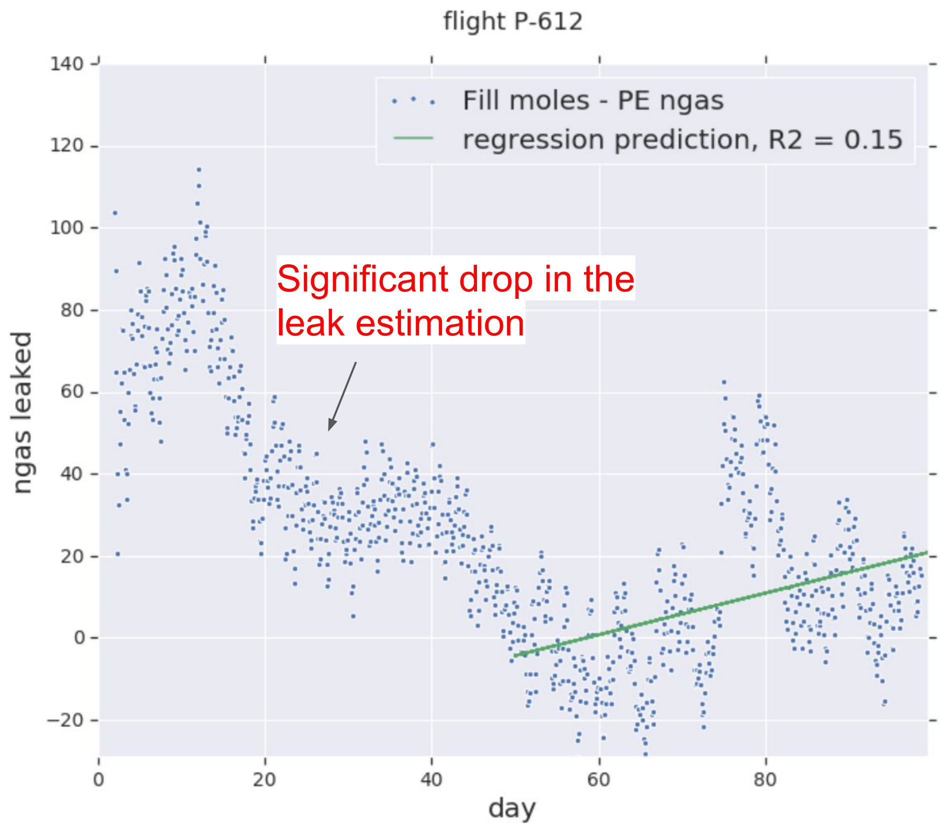
- The dependence of volume on pressure has been recently added to the code base. However, the possible offsets in the base volume and the creep-induced volume increase are completely ignored.

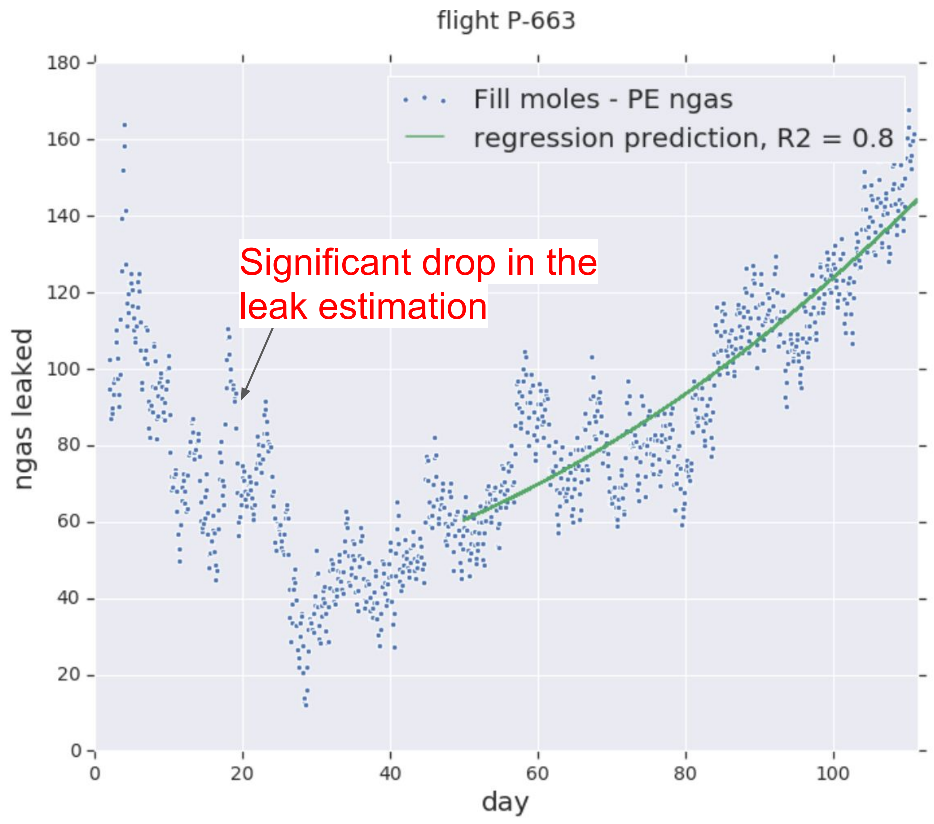
- It will be valuable to develop new estimators for tendon creep and volume. Although the base volume and creep-induced volume increase do not affect the estimated leak rate much, they affect the moles of helium and especially moles of air estimations.

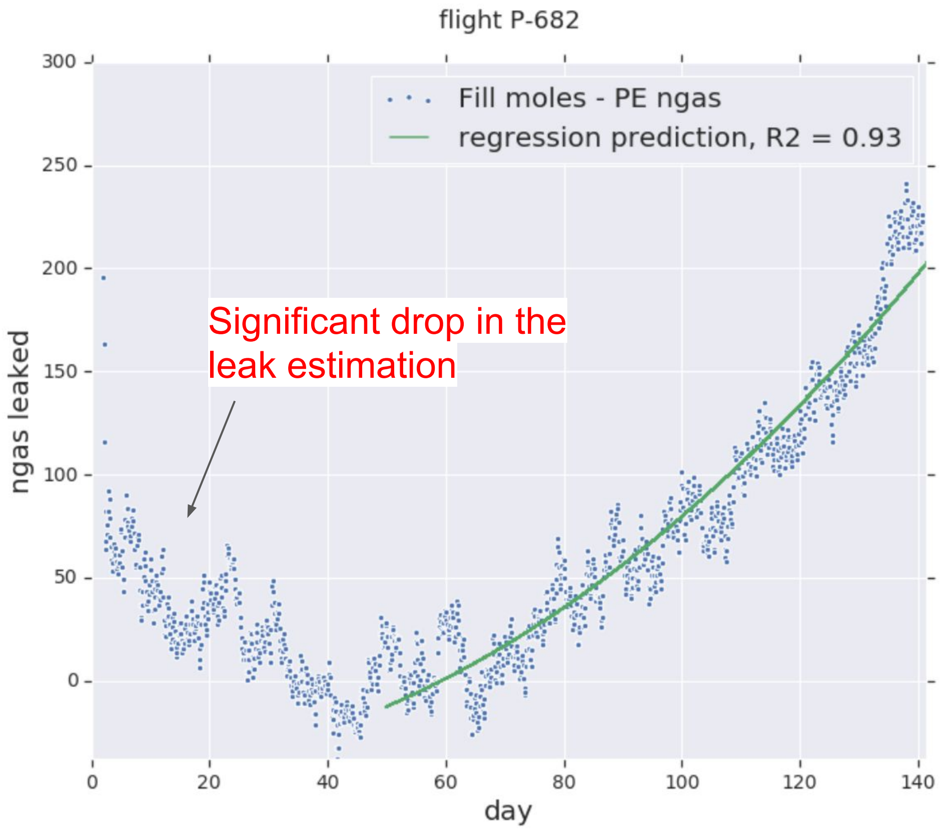
THANK YOU

Appendix

All sorts of behaviors for (Fill moles - Physics Est Ngas) in the first 50 days

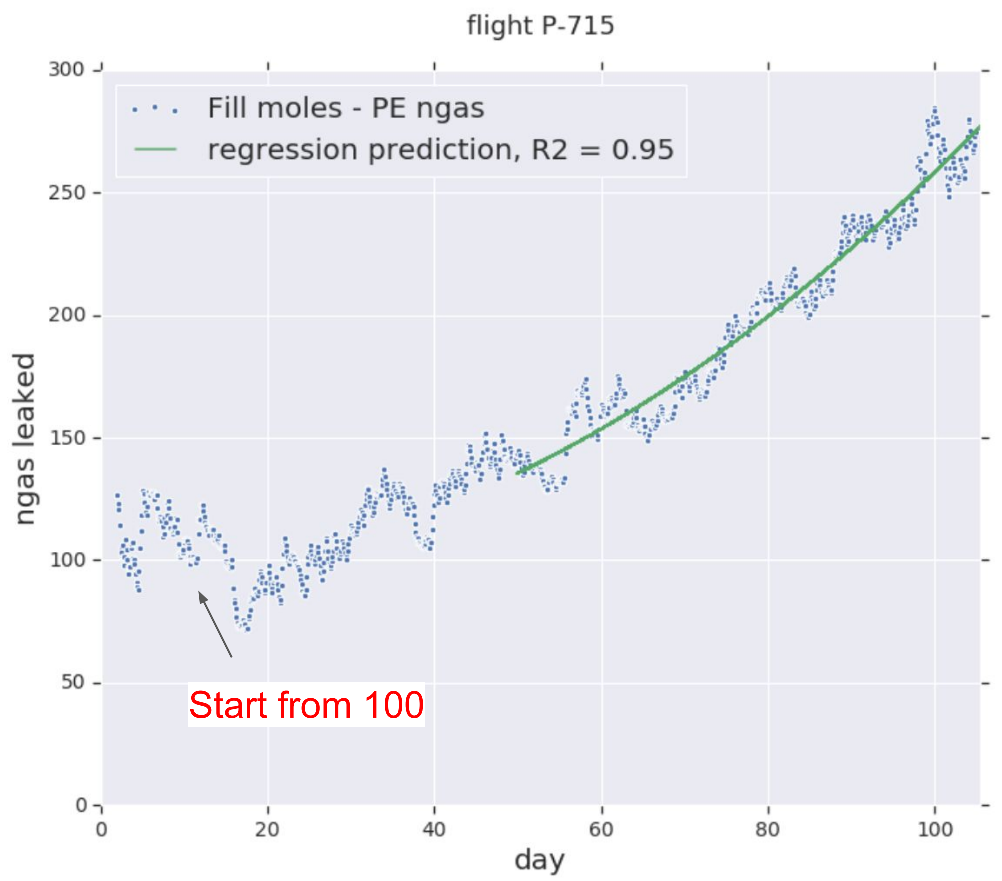


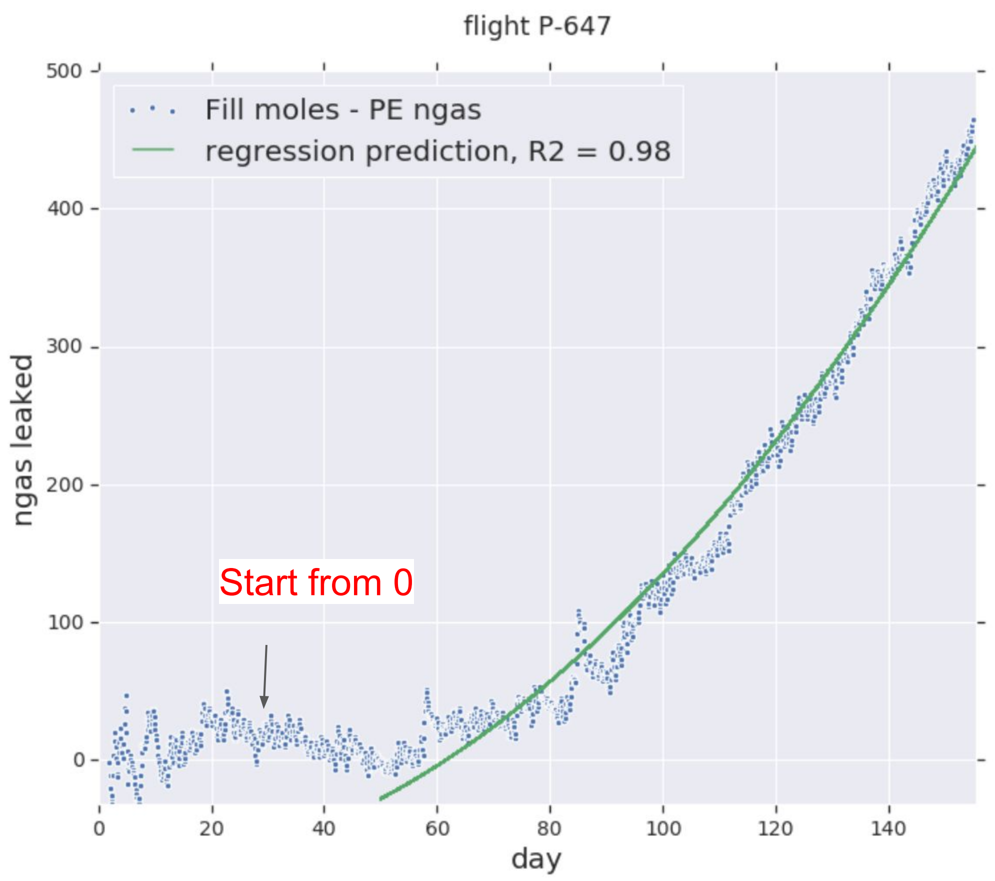




Justification = 250 moles of HeLA causes this, but...

All sorts of behaviors for (Fill moles - Physics Est Ngas) in the first 50 days

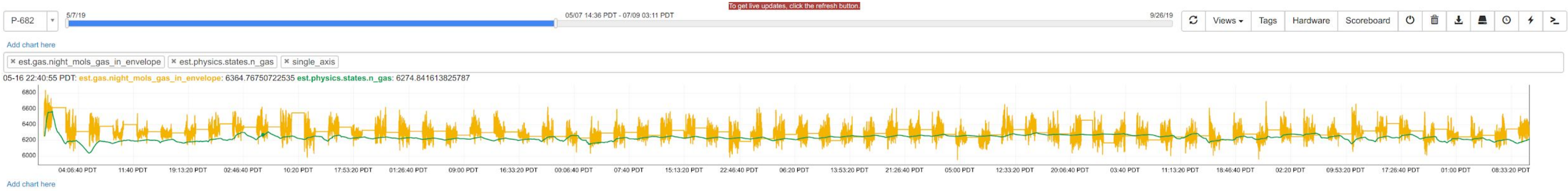




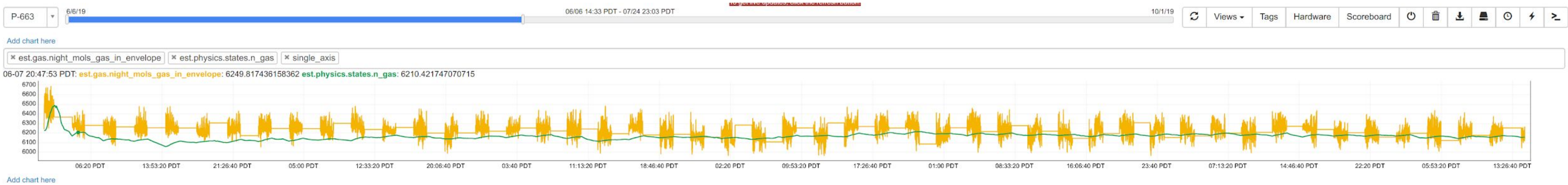
These balloons had 250 moles of HeLA too, but the estimator performed differently.

Physics Est Ngas vs Gas Est night

P-682, significant leakage in the early days based on Physics est ngas but we got the helium back by day 50, HeLA = 250 moles



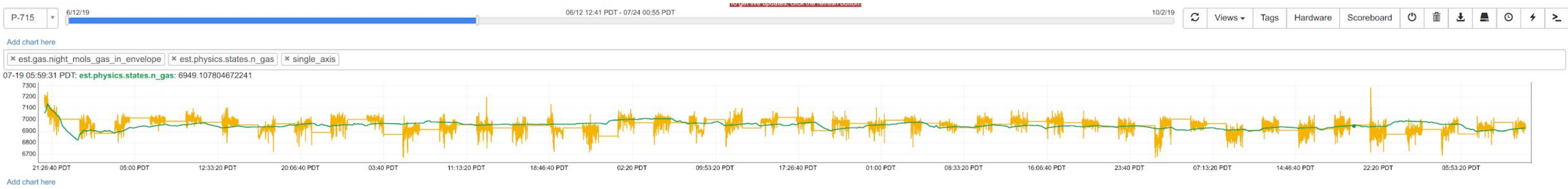
P-663, significant leakage in the early days based on Physics est ngas but we got the helium back by day 50, HeLA = 250 moles



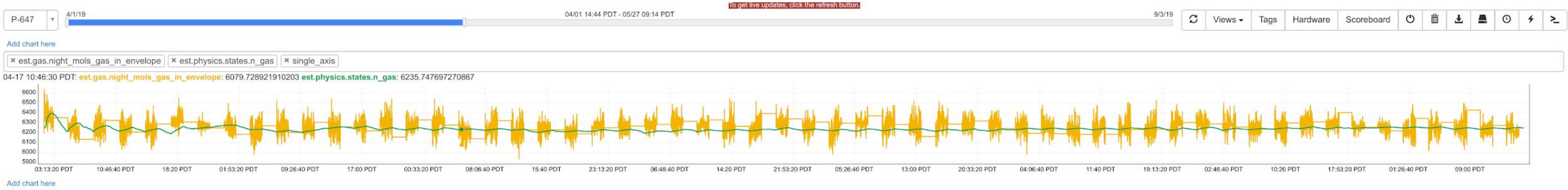
Physics Estimate estimates fewer moles of Helium than Gas Estimate in the first 20+ days.

Physics Est Ngas vs Gas Est night

P-715, 100 moles stable leakage in first 50 days, HeLA = 250 moles



P-647, almost no leakage in the first 50 days, HeLA = 250 moles



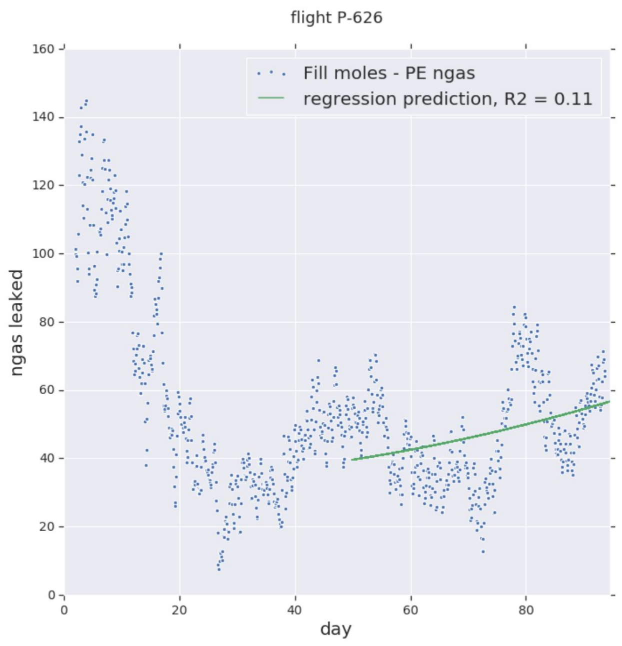
Physics Estimate and Gas Estimate in the first 20+ days are close.

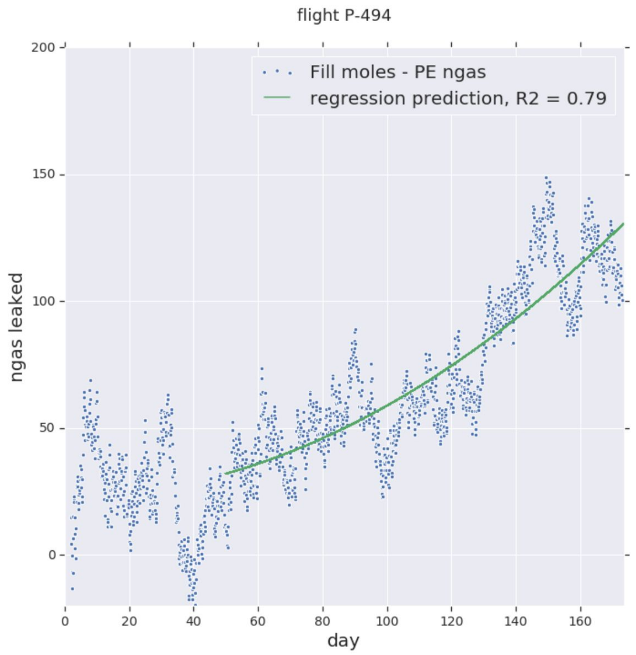
Close up view of night moles lost per day estimation

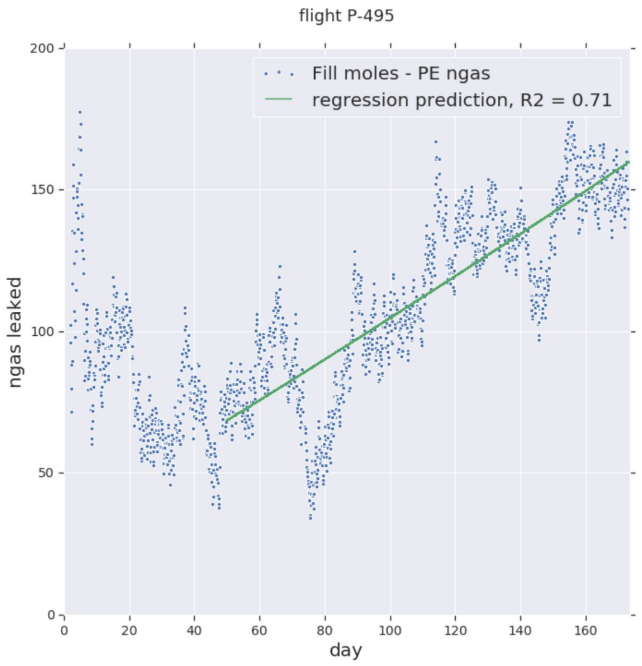
P-647, almost no leakage in the first 50 days based on Physics est ngas, HeLA = 250 moles

Sample Physics Estimate leakage for some of the fast and slow leakers

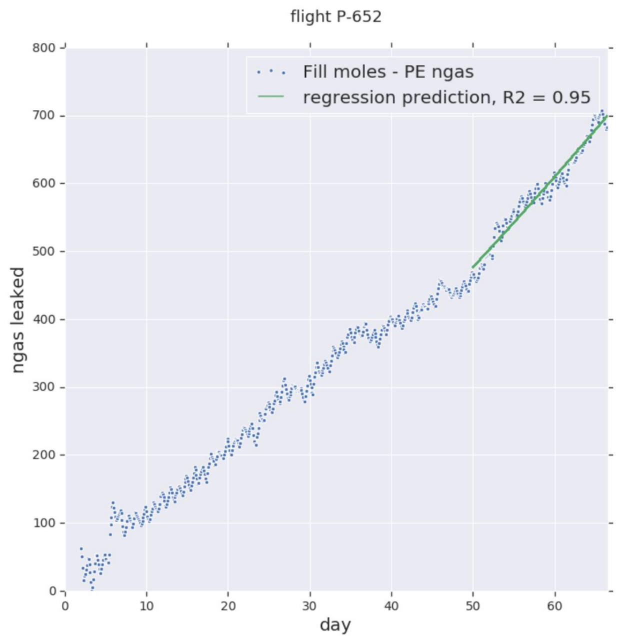
Slow leakers

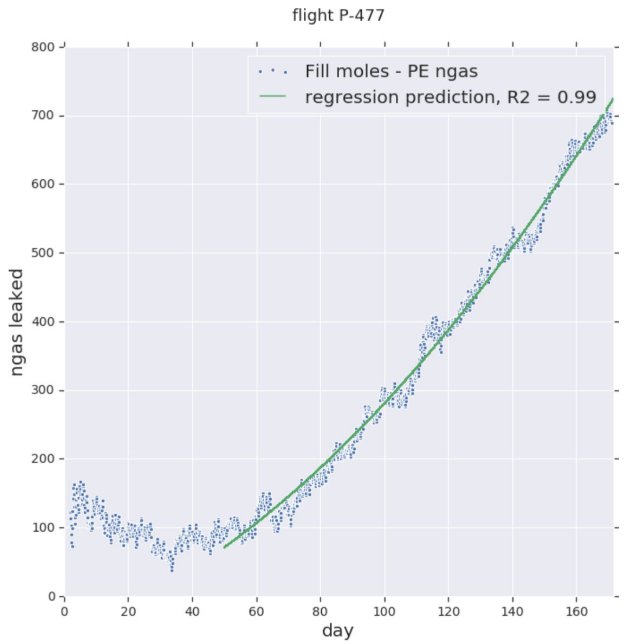






Fast leakers





Superpressure

$$\Delta P = \left(-\frac{T_{amb}}{M_{air}} m_{sys} + \left(T_{amb} + \Delta T - T_{amb}\frac{M_{gas}}{M_{air}}\right) n_{gas} + \Delta T n_{air}\right)\left(\frac{R}{V}\right)$$

Ngas

$$n_{\text{gas}} = \frac{1}{M_{\text{gas}} - M_{\text{air}}}\left[\frac{M_{\text{air}}V}{R}\left(\frac{P_{\text{amb}}}{T_{\text{air}}} - \frac{(P_{\text{amb}} + \Delta P)}{T_{\text{gas}}}\right) - m_{\text{sys}}\right]$$

LOON™