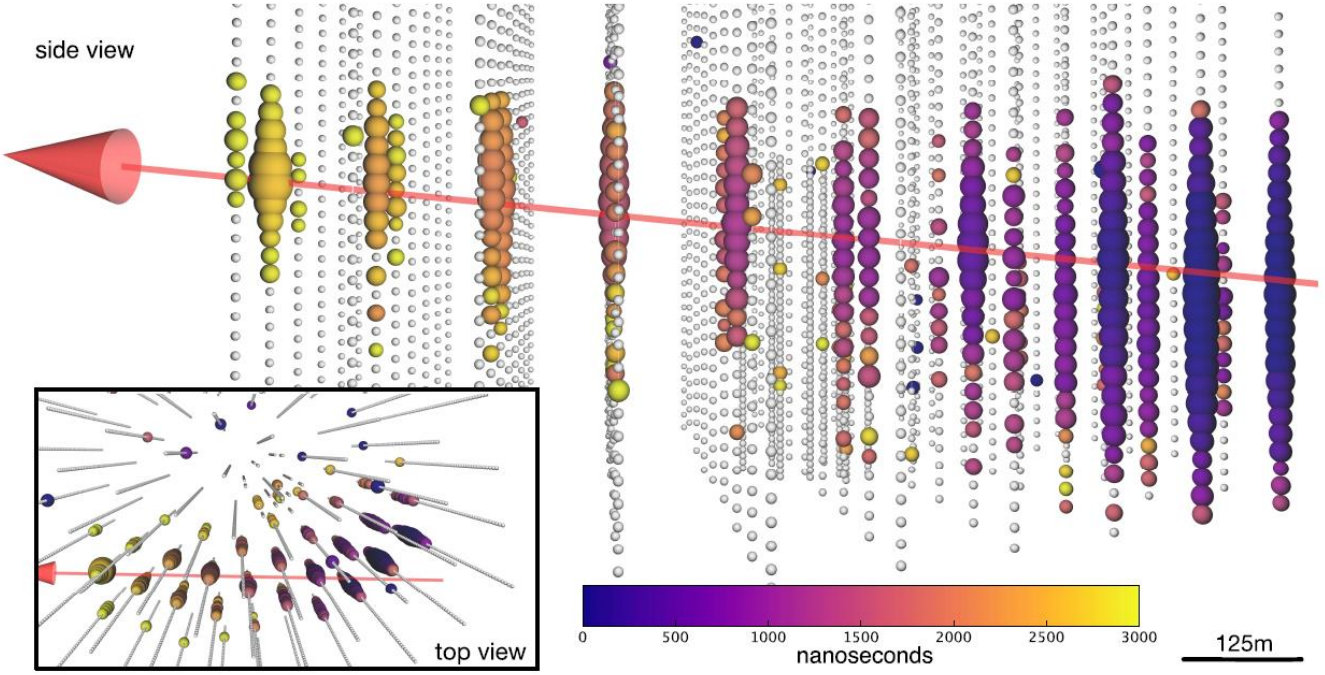
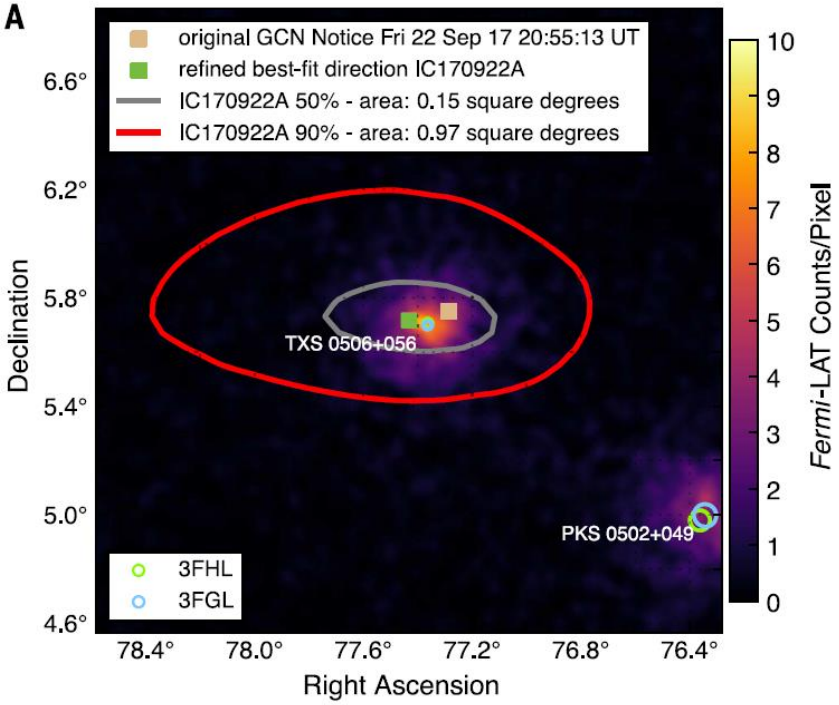
GRAINE計画と2018年気球実験

高橋覚 (神戸大) for GRAINE collaboration
愛知教育大学、ISAS/JAXA、岡山理科大学、神戸大学、名古屋大学
PI: 青木茂樹 (神戸大)

GRAINE 2018, JAXA Scientific balloon @ BLS Alice Springs Australia, 6:30AM 26th April (ACST)





史上初、宇宙ニュートリノとγ線によるニュートリノ放射源天体の同定に成功

- 宇宙ニュートリノの到来方向に、強いγ(ガンマ)線放射天体TXS 0506+056を観測し、γ線天体が宇宙ニュートリノとその親粒子である宇宙線を放射していることを史上初めて明らかにしました。

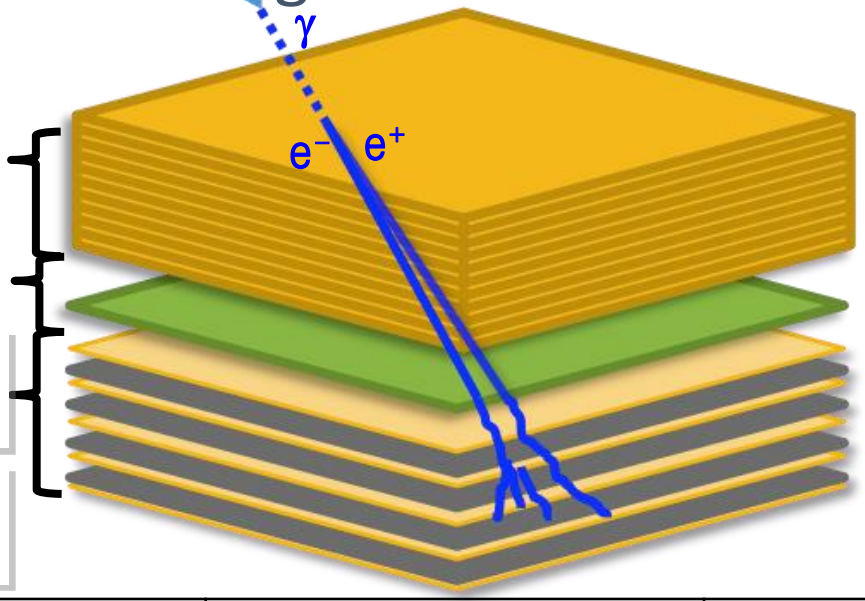
(2018年7月13日ニュースリリースより)

- ニュートリノや重力波を含むマルチメッセンジャー天文学新時代の幕明け
- γ線は決定的に重要なカウンターパート
- γ線の詳細な観測が重要

エマルションγ線望遠鏡
長時間気球フライト繰り返し

GRAINE

Gamma-Ray Astro-Imager with Nuclear Emulsion



Converter
Emulsion + Copper foil

Timestamper
Multi-stage shifter

Calorimeter
Emulsion + metal plate

Attitude monitor
Star camera

＊ $10m^2 * \varepsilon_{trans} * \varepsilon_{conv} * \varepsilon_{det}$

	Fermi LAT		GRAINE
Angular resolution @100MeV	6.0deg (105mrad)	x1/6 →	1.0deg (17mrad)
@1GeV	0.90deg (16mrad)	x1/9 →	0.1deg (1.7mrad)
Energy range	20MeV – 300GeV		10MeV – 100GeV
Polarization sensitivity	---		Yes
Effective area @ 100MeV	$0.25m^2$	x8 →	$2.1m^2$ ＊
@ 1GeV	$0.88m^2$	x3 →	$2.8m^2$ ＊
Dead time	26.5 μ sec(readout time)		Dead time free

Observation of transient sources

- Large collection area, $10m^2$
  [Effective area@100MeV, $2.1m^2$ (3.6 x Fermi LAT, cf. $0.58m^2$ (P8R2_TRANSIENT020_V6))]
- Wide field of view, >2.2sr (17.5% of all sky)
- High angular resolution, 1.0deg(17mrad)@100MeV
- Polarization sensitive
- Dead time free

→High sensitivity incl. "**Unexplored region**"

→High photon statistics

-Energy spectrum

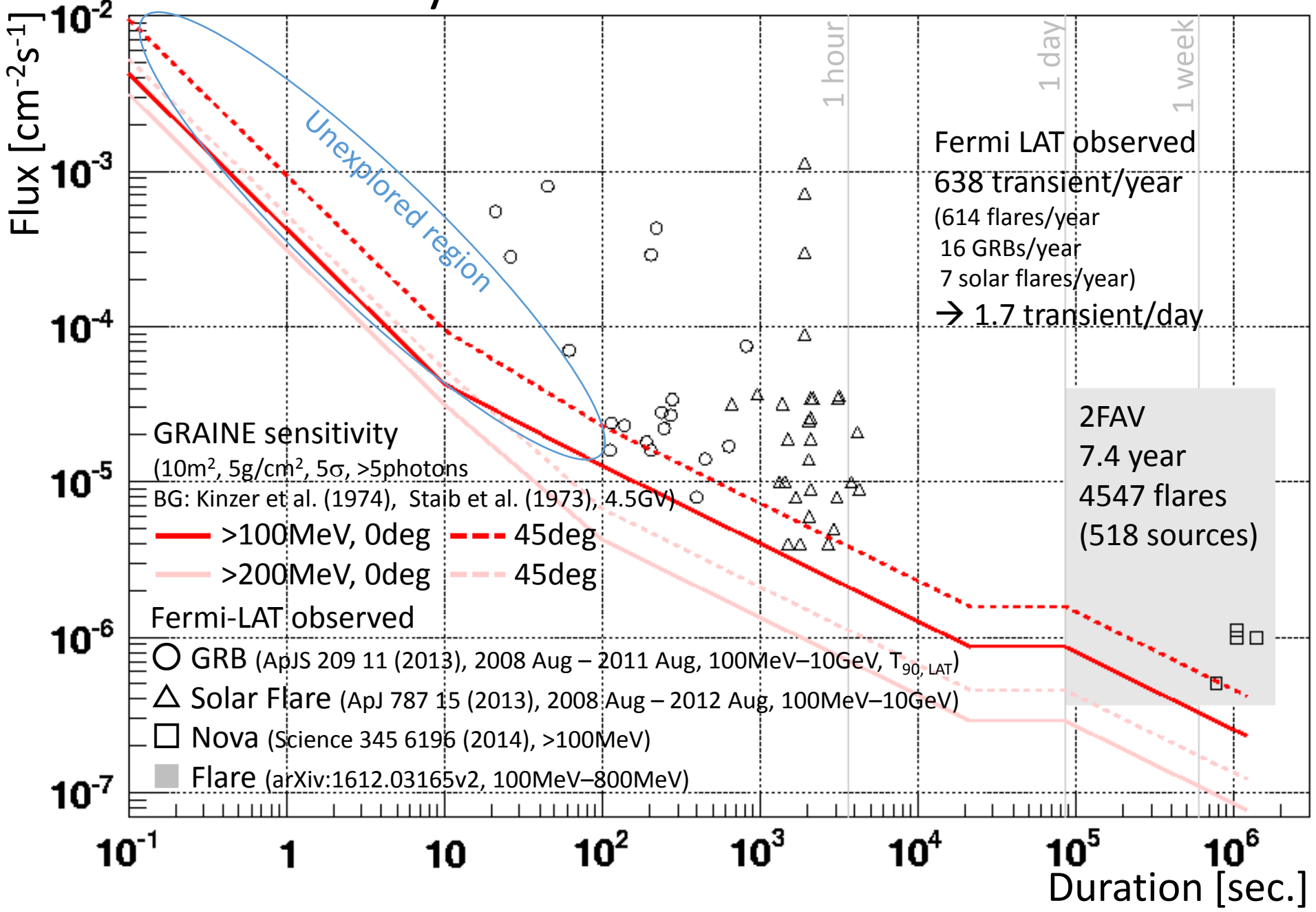
-Light curve

-Polarization observation

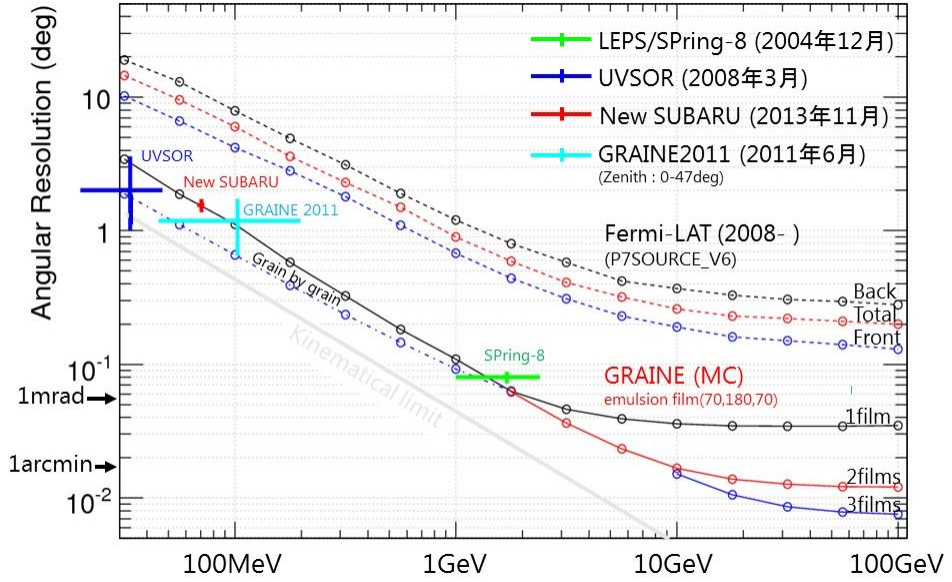
→Good localization ~0.1deg @100photons

- Not continuous survey
- Not real time

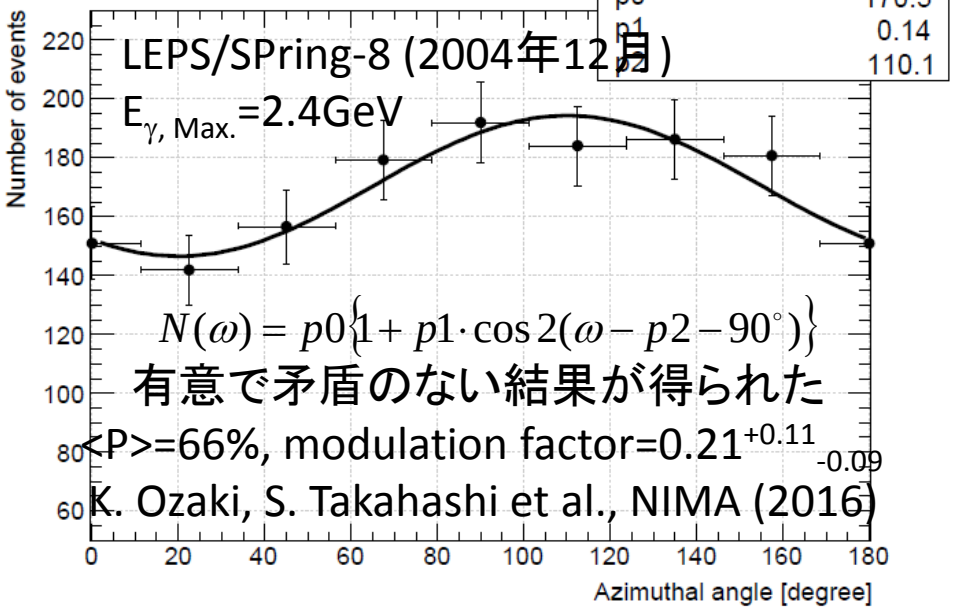
Sensitivity to transient sources



角度分解能

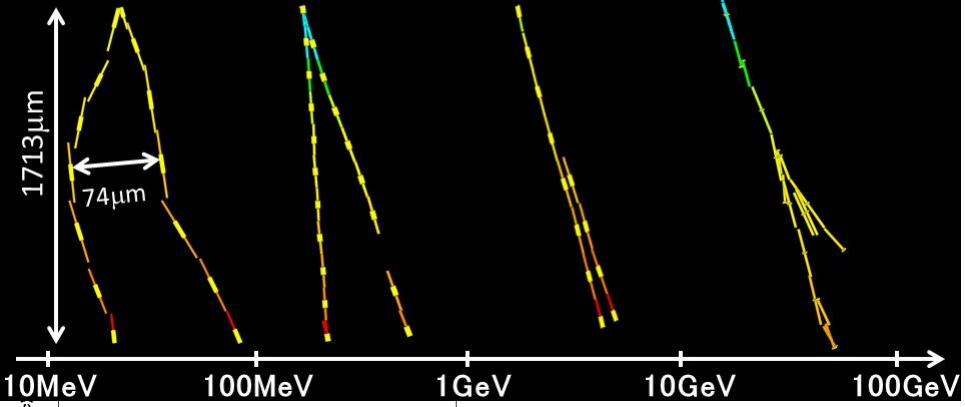


偏光感度



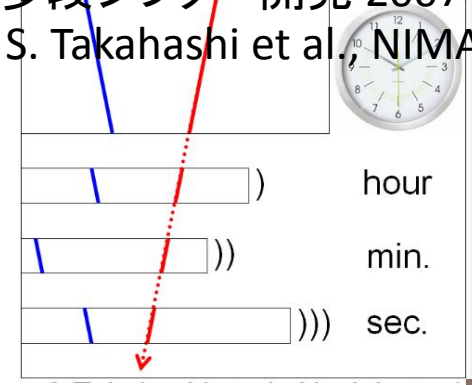
Energy range

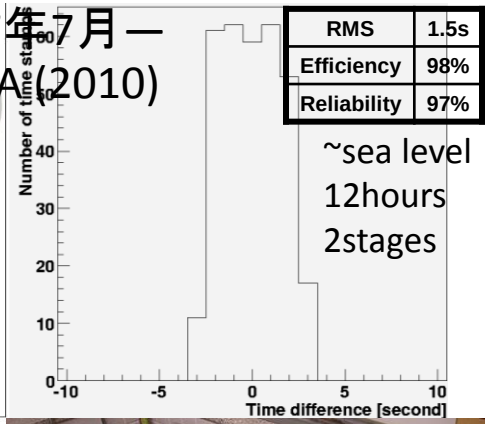
大気ガンマ線@乗鞍(2007年7月、9月、2013年7月)、他



多段シフター開発 2007年7月ー

S. Takahashi et al., NIMA (2010)





運動量測定精度w/MCS

35MeV electron LINAC
@Tokai-mura (2012年8月)

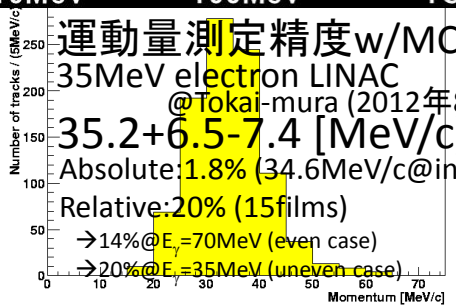
35.2+6.5-7.4 [MeV/c]

Absolute:1.8% (34.6MeV/c@incidence)

Relative:20% (15films)

→14%@E_γ=70MeV (even case)

→20%@E_γ=35MeV (uneven case)

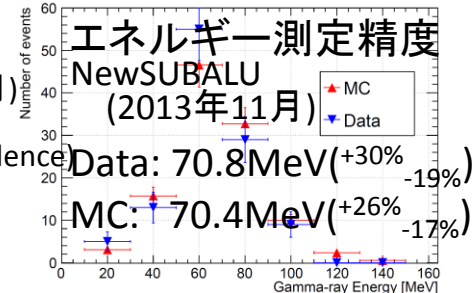


エネルギー測定精度

NewSUBALU
(2013年11月)

Data: 70.8MeV(+30% -19%)

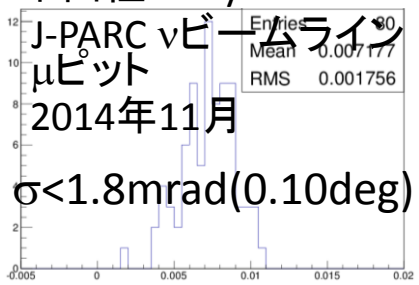
MC: 70.4MeV(+26% -17%)

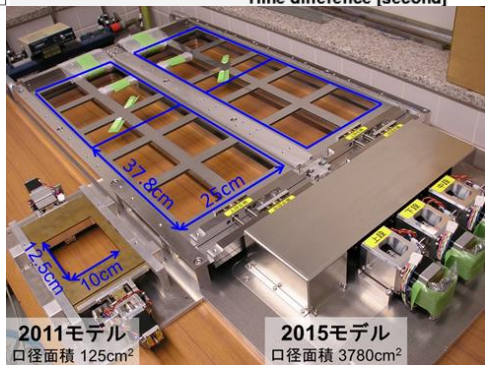


平面性study

J-PARC νビームライン
μピット
2014年11月

σ<1.8mrad(0.10deg)

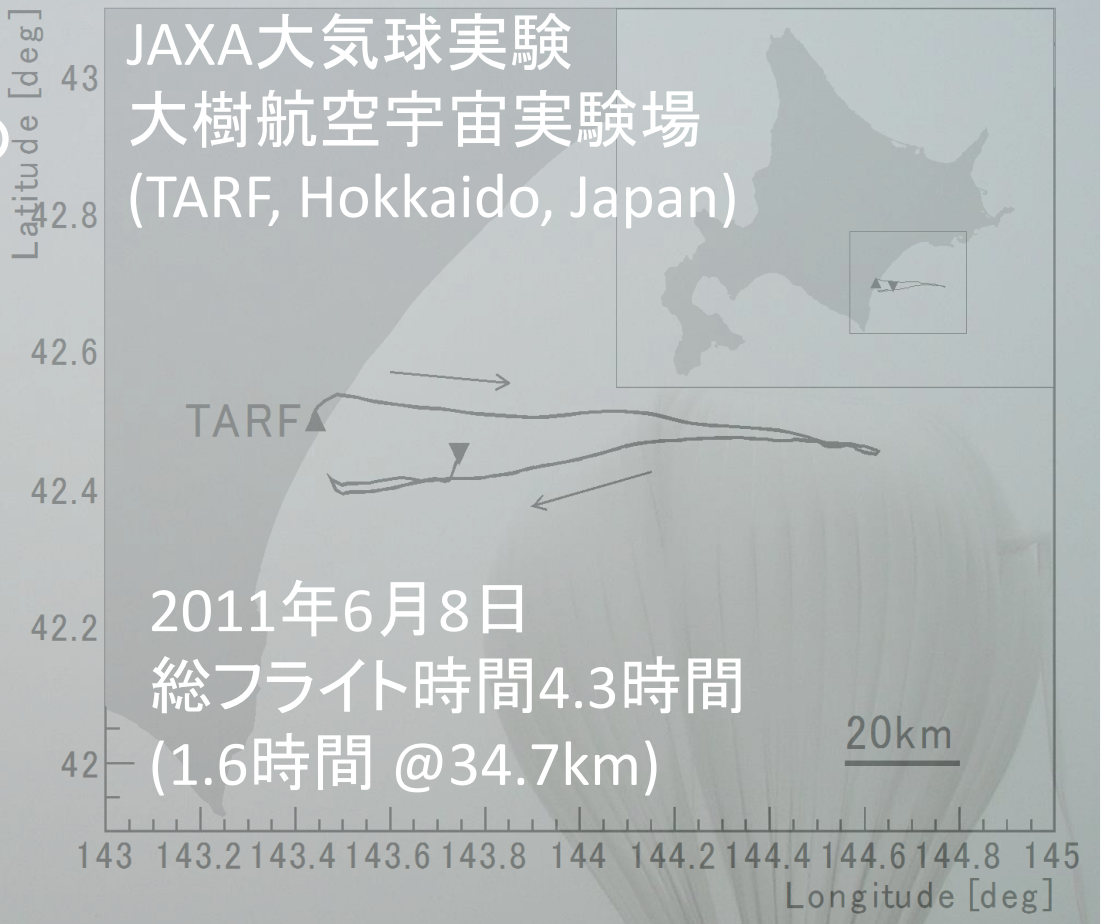




2011年度気球実験

エマルションガンマ線望遠鏡の初めての気球実験

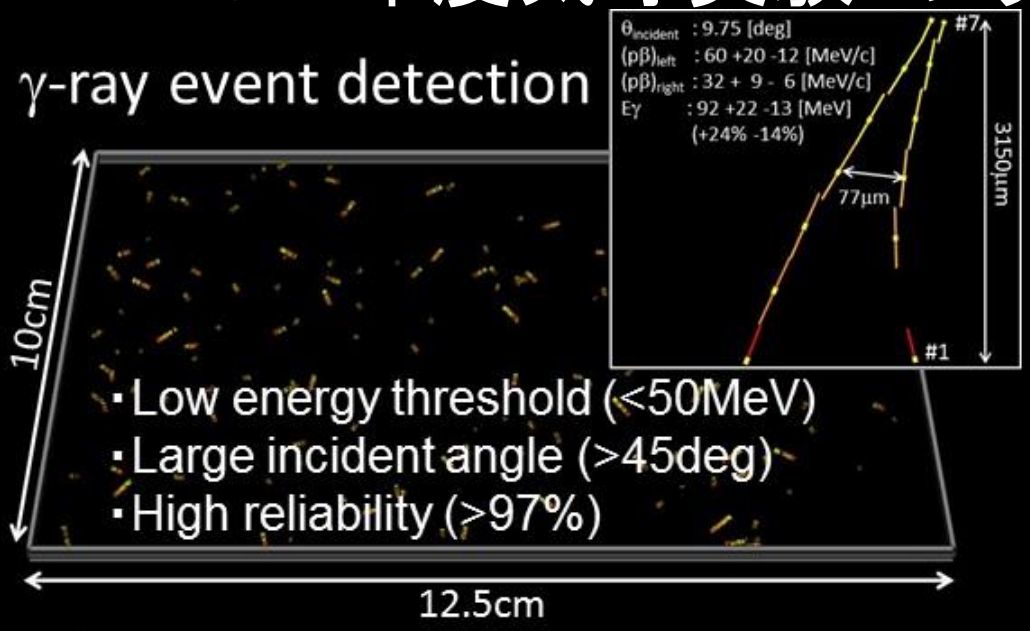
口径面積：12.5cm×10cm

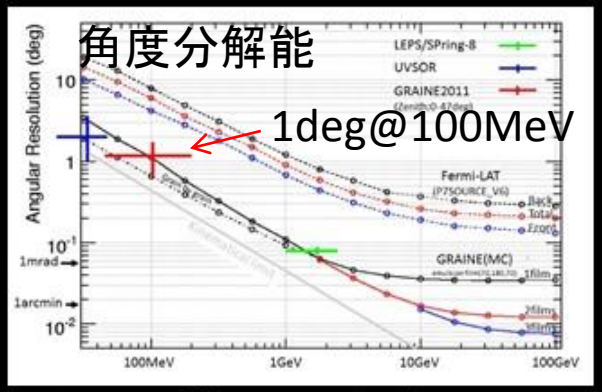


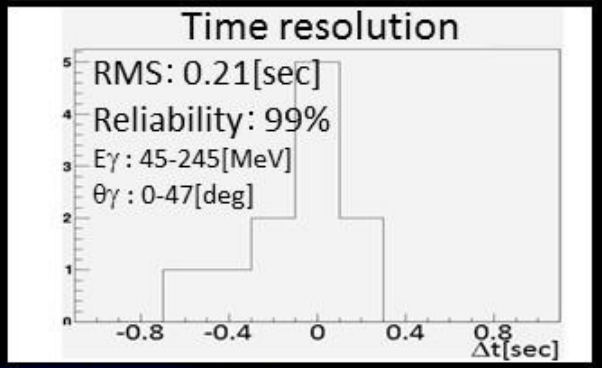
初めての気球実験、実現可能性の実証

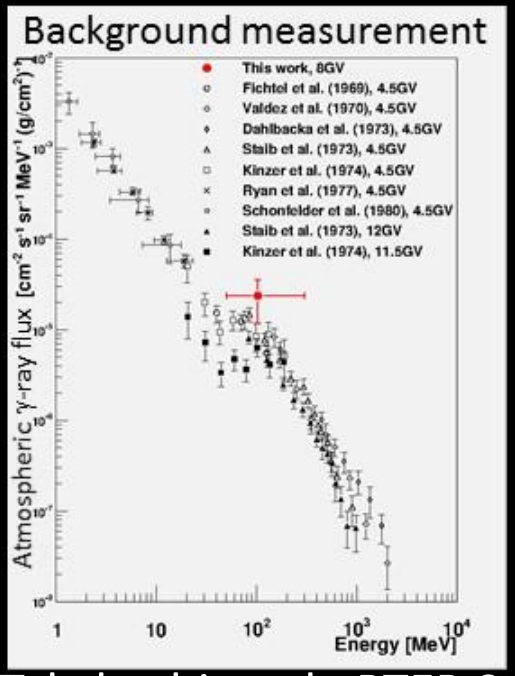
2011年度気球実験　フライトデータ解析

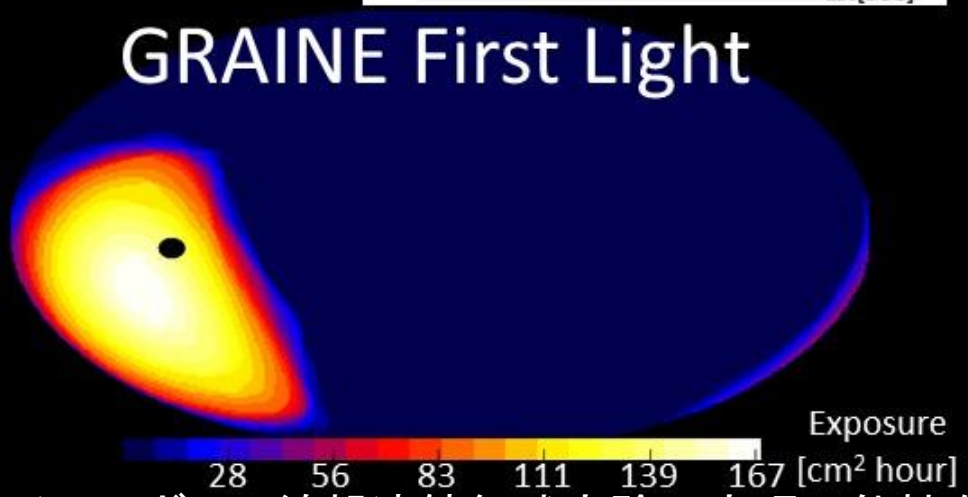
γ-ray event detection







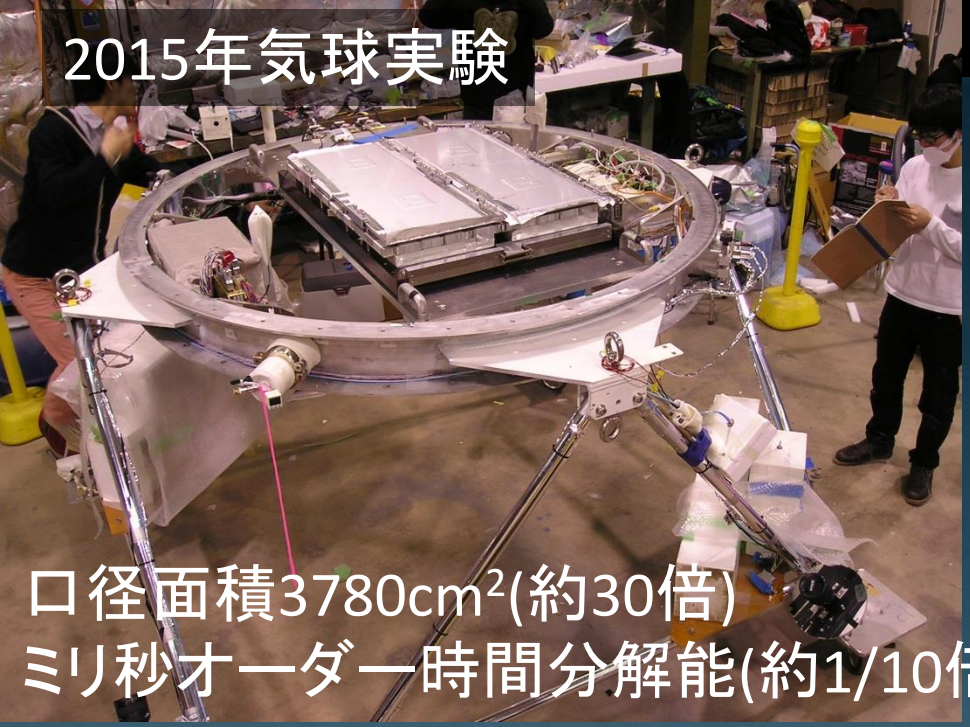




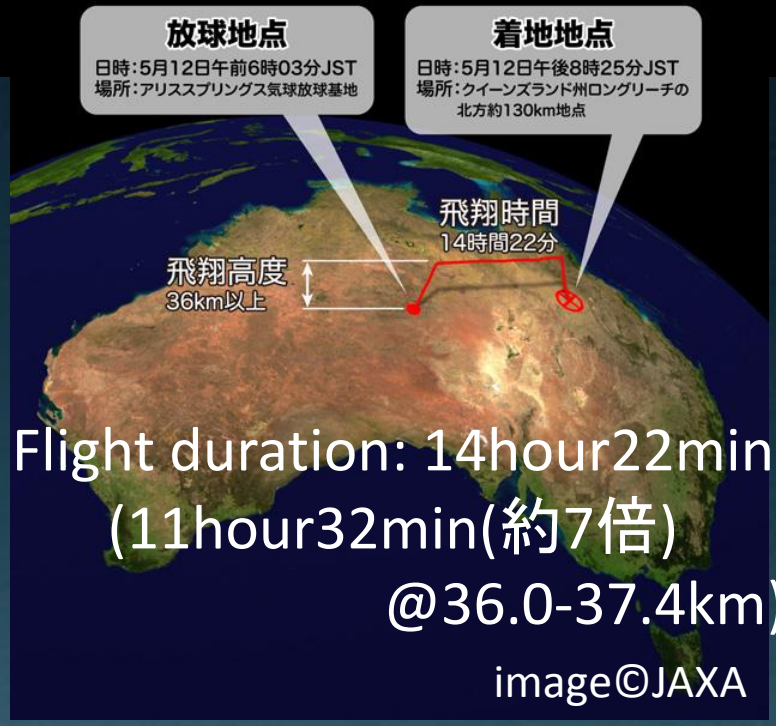
エマルションガンマ線望遠鏡気球実験の実現可能性を実証

S. Takahashi et al., PTEP 043H01 (2015); H. Rokujo et al., NIM A 701, 127 (2013)

2015年気球実験



口径面積3780cm^2(約30倍)
ミリ秒オーダー時間分解能(約1/10倍)



Flight duration: 14hour22min
(11hour32min(約7倍)
@36.0-37.4km)

image©JAXA

Launched, 6:33 12th May 2015
実験設計、様々な改良・準備、気球実験
オーストラリアでの気球実験体制を確立

Image©JAXA

S. Takahashi et al., PTEP 073F01 (2016); K. Ozaki et al., JINST 10 P12018 (2015)

2015年気球実験のまとめ

- 口径面積3780cm^2 (約30倍, 新型エマルションフィルム, 総面積48m^2)
- フライト時間14.4hour (11.5hour@36.0–37.4km (約7倍))
- オーストラリア気球実験 scheme & flow を確立
- JAXA豪州大気球実験の先行実験としての役割を果たした
- 飛跡読み出し 総面積41m^2 w/ HTS
- エマルションフィルムのS/N比~20倍、データサイズ~20分の1
- フィルムあたりの飛跡inefficiency~10分の1
- ガンマ線事象検出のためのデータリダクションロード~200分の1
- 全有効面積データ処理 口径面積2830cm^2 (総面積30m^2)
- ガンマ線結像性能<~1.0deg　cf. 角度分解能1.0deg@100MeV
- 全フライト時間(6:30 – 20:00)にわたるタイムスタンプ
- 時間分解能9.8ミリ秒(約7倍)
- スターカメラ感度改善 6.1→7.5等級

2011年気球実験から大きく前進

H. Kawahara, et al., KMI 2017, https://pos.sissa.it/294/059; H. Rokujo, et al., PTEP 063H01 (2018); F. Mizutani et al., NIMA (Submitted).

2015年気球実験
Vela Pulsarからのガンマ線を有意に検出する。

2018年4月JAXA豪州気球実験

<u>有効面積・有効時間拡大およびBG低減の展望</u>

- スターカメラの堅牢性強化→有効時間 1.77倍
  - データストレージの冗長化、エラーからの復帰可能なシステム
- エマルションフィルムの安定性確保→有効面積 1.33倍
  - 製造および処理処方の最適パラメーター確立
- シフターセットアップの確立→有効面積x有効時間 1.33倍
  - フィルム搭載条件の最適化
- シフター動作パラメータの適正化→BG 1/2倍

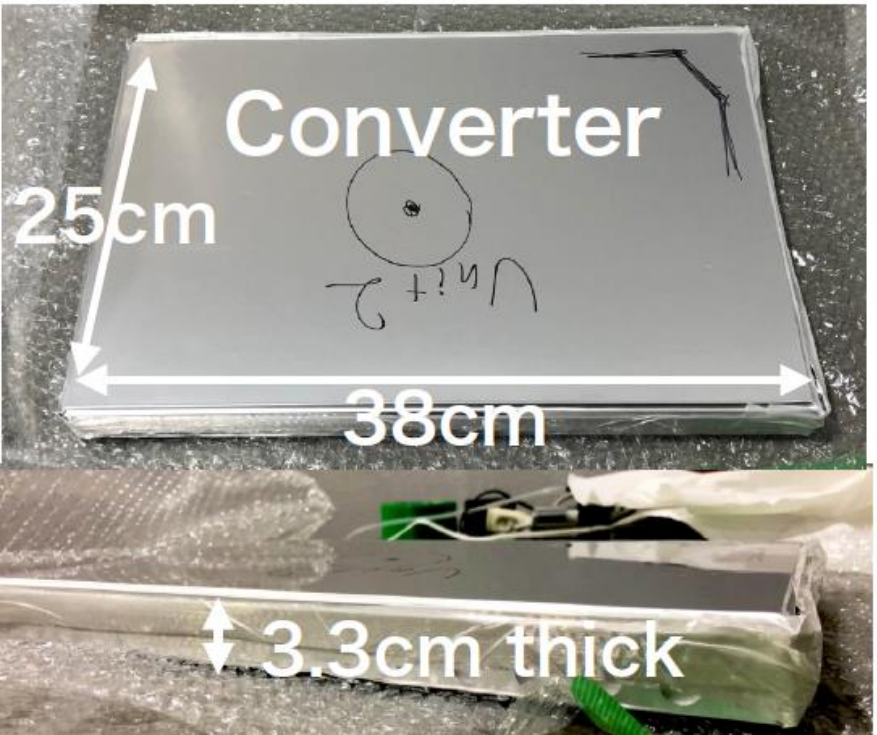
計6.3倍の改善.

(実効値5.3倍)

望遠鏡の総合的な性能実証を目指す

コンバーター

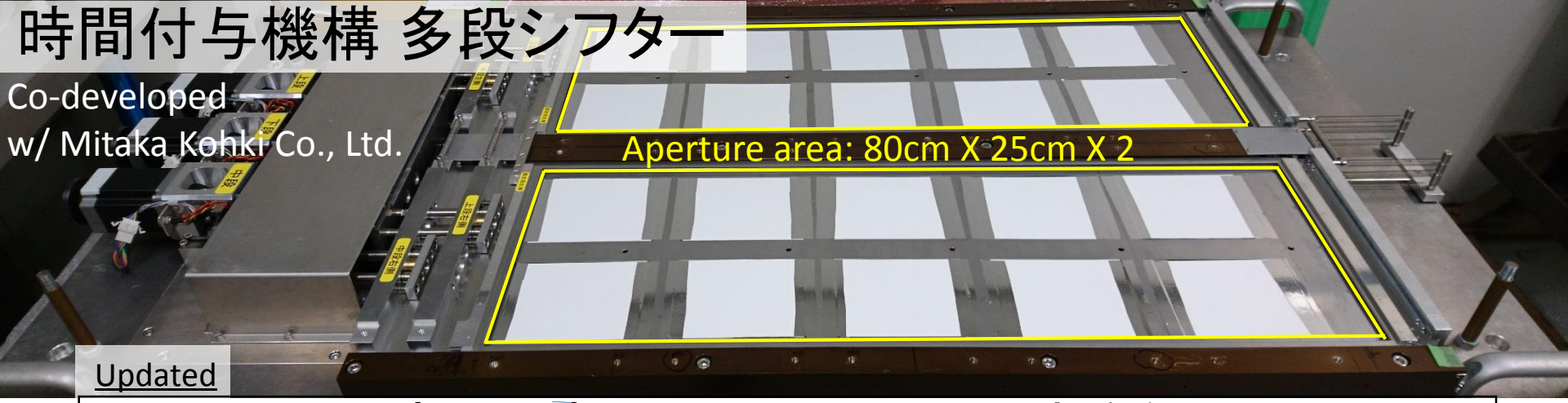
- Changed AgBr vol. occupancy in emulsion gel 55%→45%. It makes **improvement of long term stability** with keeping high sensitivity



- Mass production of emulsion films(handmade) is continued for 4 months. Produced more than **600 films (>57m²)**
- Made 4 converters in Japan after resetting process. Each of them is consisted 100 emulsion films.

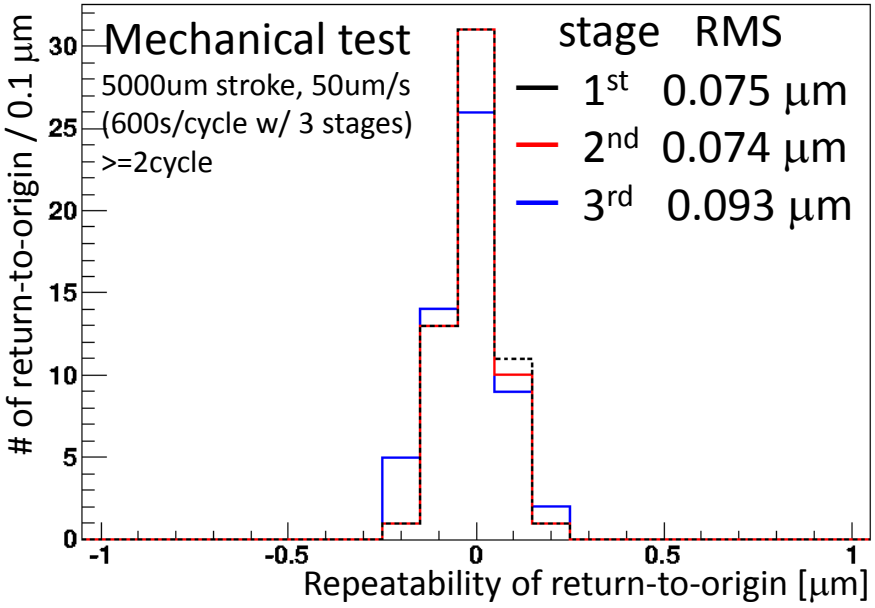
時間付与機構 多段シフター

Co-developed
w/ Mitaka Kohki Co., Ltd.



Updated

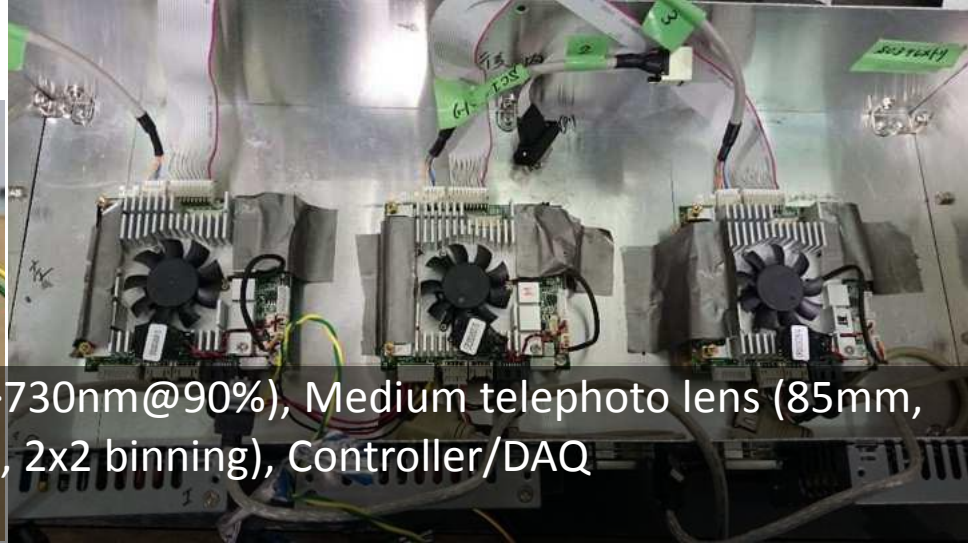
Aperture area 2500cm^2→4000cm^2	Gap controlling & reduction → S/N↑(>~x2)
CFRP backed film pack	Material reduction → Effective area↑(~20%@100MeV)
Fixed stage	Flatness↑
Moving direction play↓	Gap controlling & reduction to the shifter → S/N↑(>~x2)
Stage coupling play↓	Working accuracy↑
Origin sensor blade of 3rd stage	At temperature change, return-to-origin repeatability↑(~x2)



Tests & Preparations

- The shifter improving w/ Mitaka Kohki Co., Ltd. (19th Apr. 2017 –), CFRP arranging (20th Apr. –)
- Emulsion film tests: CFRP, pack, initialization, drying, fading, long-term stability, real-scale (May –)
- Mechanical tests (7th – 18th Aug)
- Film-on tests (8th – 10th)
- Environmental Mechanical tests (21st – 23rd Aug)
- Environmental Film-on tests in partial (24th – 25th Aug)
  w/ environmental chamber @balloon group/ISAS/JAXA
- Implementation to the gondola (Oct)
- Compatibility check and EMC check w/ balloon systems (30th, 31st Oct)
- Emulsion film production (Oct, Nov)
- Environmental Film-on tests in full (12/7 – 10)
- Final adjustment, finishing, packing and shipping (11th Dec – 5th Jan)
- Decision of Initialization and Drying condition. Initialization, Drying and Packing of emulsion films for the experiment (Jan, Feb)
- The films etc. shipping by airfreight (15th Feb)

姿勢監視スターカメラ



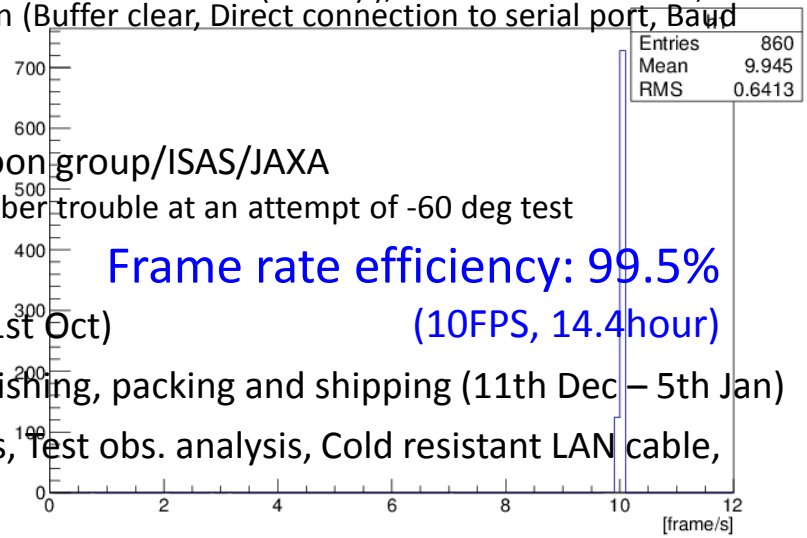
System configuration

Hood w/ Baffle, Low-pass filter (690nm@50%, >730nm@90%), Medium telephoto lens (85mm, F1.4)、CCD(2/3inch (8.8x6.6mm^2), 1920x1440px, 2x2 binning), Controller/DAQ

3 star cameras w/ 90deg azimuth each

Tests and Preparations

- Working and Performance check after GRAINE 2015
  - Imaging performance (<0.012deg) and Sensitivity (magnitude of >~7)
- Improving system robustness (High reliability, Stable, Recoverable)
  - Power on/off, System start/shutdown, Reset, System and Storage disk separation, SLC system disk, Redundant and Switchable storage disks, Simplified image taking (Constant and Optimized frame rate (10FPS)), Frame loss reduction, CPU power line enhancement, GPS data→3SCs, GPS readout stabilization (Buffer clear, Direct connection to serial port, Baud rate unification, Connection line revision)
- Long run tests
- Environmental Long run tests w/ environmental chamber @Balloon group/ISAS/JAXA
  - Continuous and Stable operation for 44 hours, Environmental chamber trouble at an attempt of -60 deg test
- Implementation to the gondola (Oct)
- Compatibility check and EMC check w/ balloon systems (30th, 31st Oct)
- Final adjustment, Optic axis measurement, observation tests, finishing, packing and shipping (11th Dec – 5th Jan)
- Final packing, Shipping by airfreight (15th Feb), Optic axis analysis, Test obs. analysis, Cold resistant LAN cable, baffles, etc.



Frame rate efficiency: 99.5%

(10FPS, 14.4hour)

Production of Power-on/off circuits etc. and Implementation of star cameras onto the gondola were supported by K. Matsumoto, Y. Yoshizawa and other staffs of Technical Division, Graduate school of engineering, Kobe University. Baffles were designed and implemented by H. Hayashi, F-lab, Physics, Nagoya University

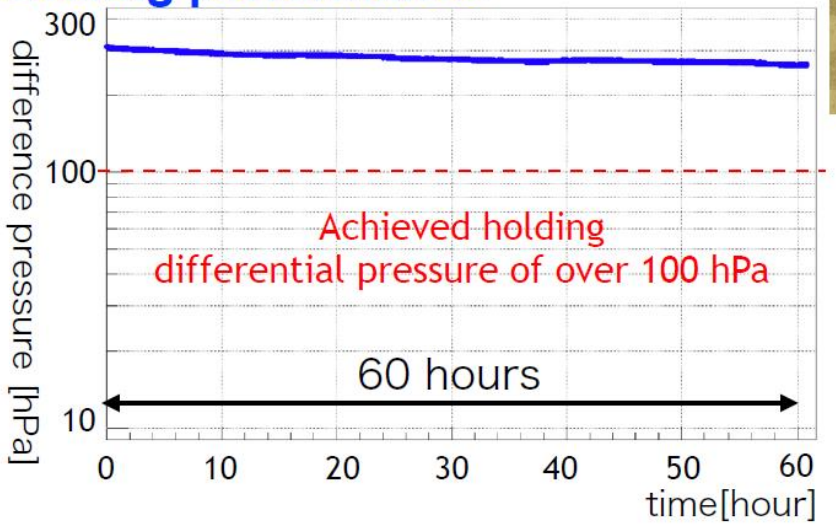
与圧容器ゴンドラ

☆**Expandable cocoon shape**

☆Improve environmental performance for long flight

☆New development of membrane material(Strength and Temperature)

Sealing performance



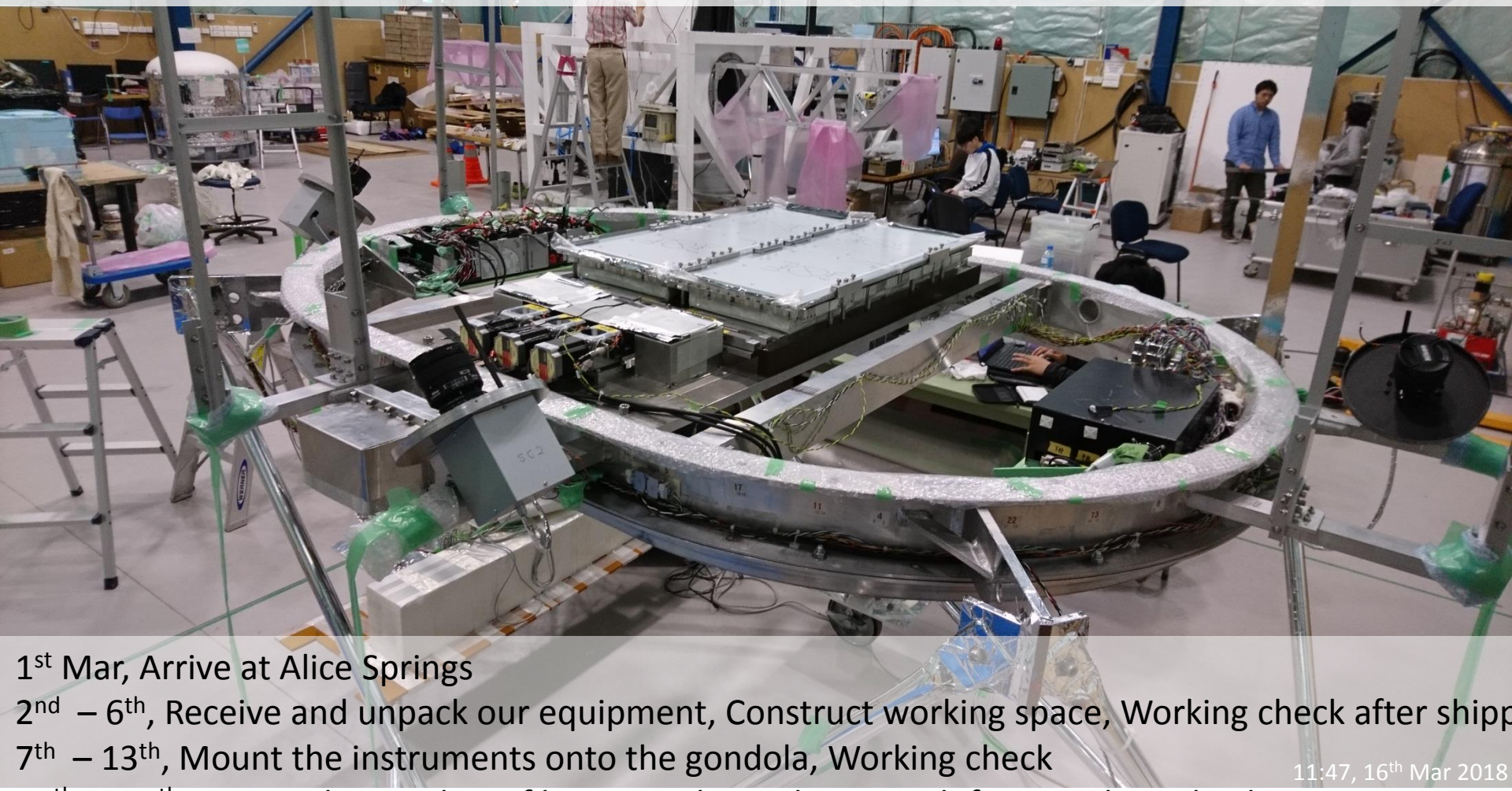
Improved performance	GRAINE2015	GRAINE2018
Breaking strength of membrane material	833 N/cm	**1000** N/cm
Temperature range of membrane material	-70 ℃ – +20 ℃	-70 ℃ – **+60 ℃**
Temperature range of sealing material	> -50 ℃	> **-80 ℃**

Pre-start-up for emulsion film development @ U of Sydney

19th Feb, Arrive at Sydney, Receive equipment, liquid(partial) and emulsion films(for test)

20th Feb – 1st Mar, Construct development facility and the process flow, Test development with small tanks and small pieces, Study for the development condition

最終準備 @アリススプリングス気球放球基地



1st Mar, Arrive at Alice Springs

2nd – 6th, Receive and unpack our equipment, Construct working space, Working check after shipp

7th – 13th, Mount the instruments onto the gondola, Working check

13th – 15th, Mount the emulsion films onto the multi-stage shifter, Working check

16th – 20th, Fully assemble, Working check

11:47, 16th Mar 2018

3月終盤、フライト準備完了

25th Mar, Final compatibility check, EMC check

29th midnight – 30th before dawn, Dressed rehearsal

Twice attempt of the launch

16th Apr, No go decision after compatibility check due to wind speed around ground

24th, No go decision before compatibility check due to wind speed around ground etc.

4月26日、気球放球

23:15 25th, Finalize for the launch

0:10 26th, Show up and Briefing

0:15, Pick up payload

0:45, Move to the launch pad

2:50, Compatibility check

5:00, Inflation of the balloon

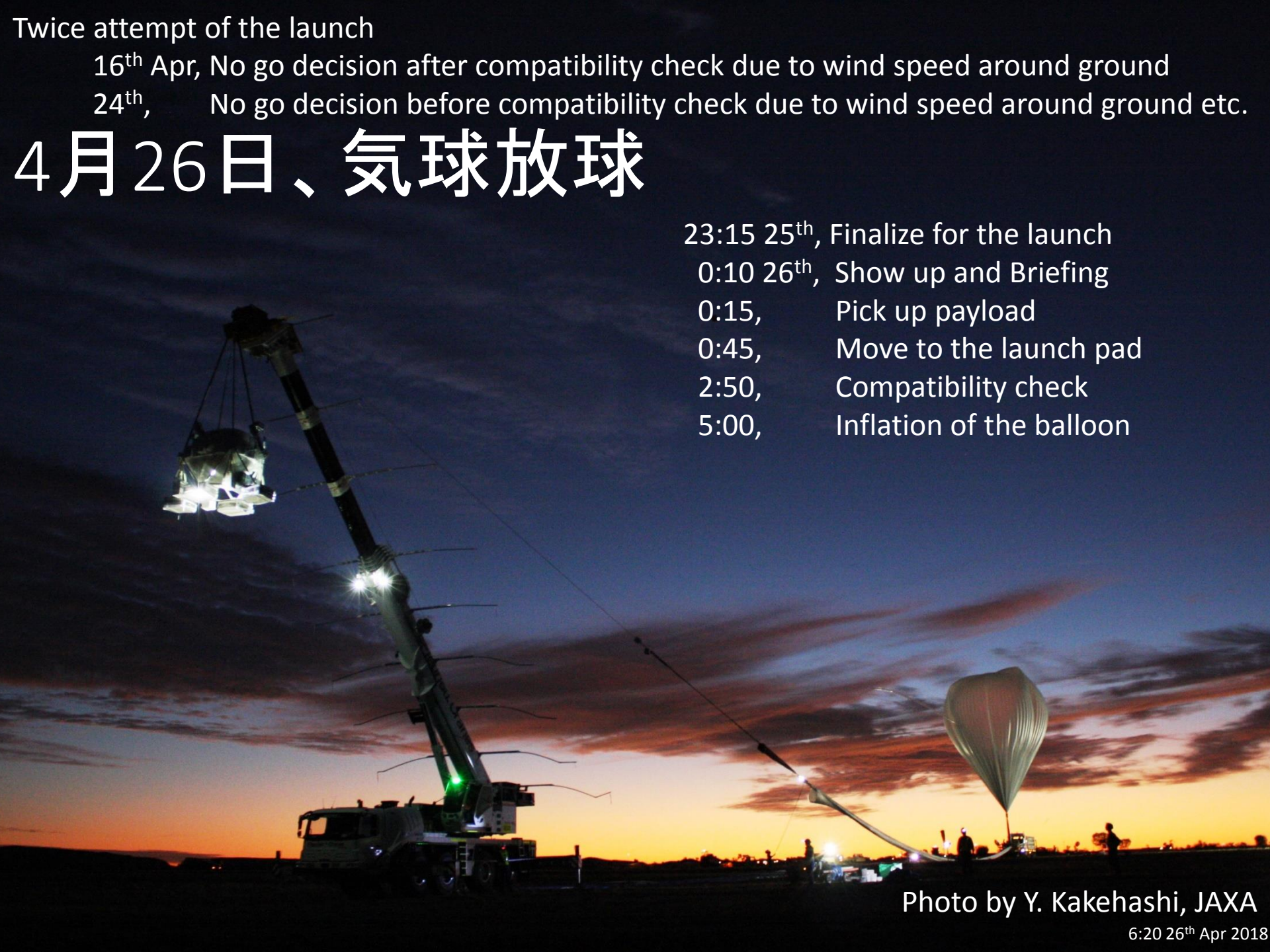


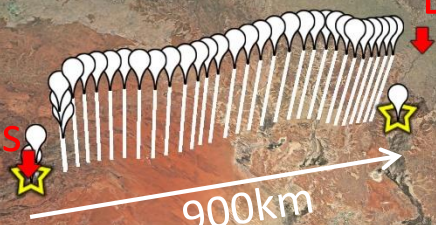
Photo by Y. Kakehashi, JAXA

6:20 26th Apr 2018

6:33AM(ACST) 26th Apr 2018, Launch

気球フライト

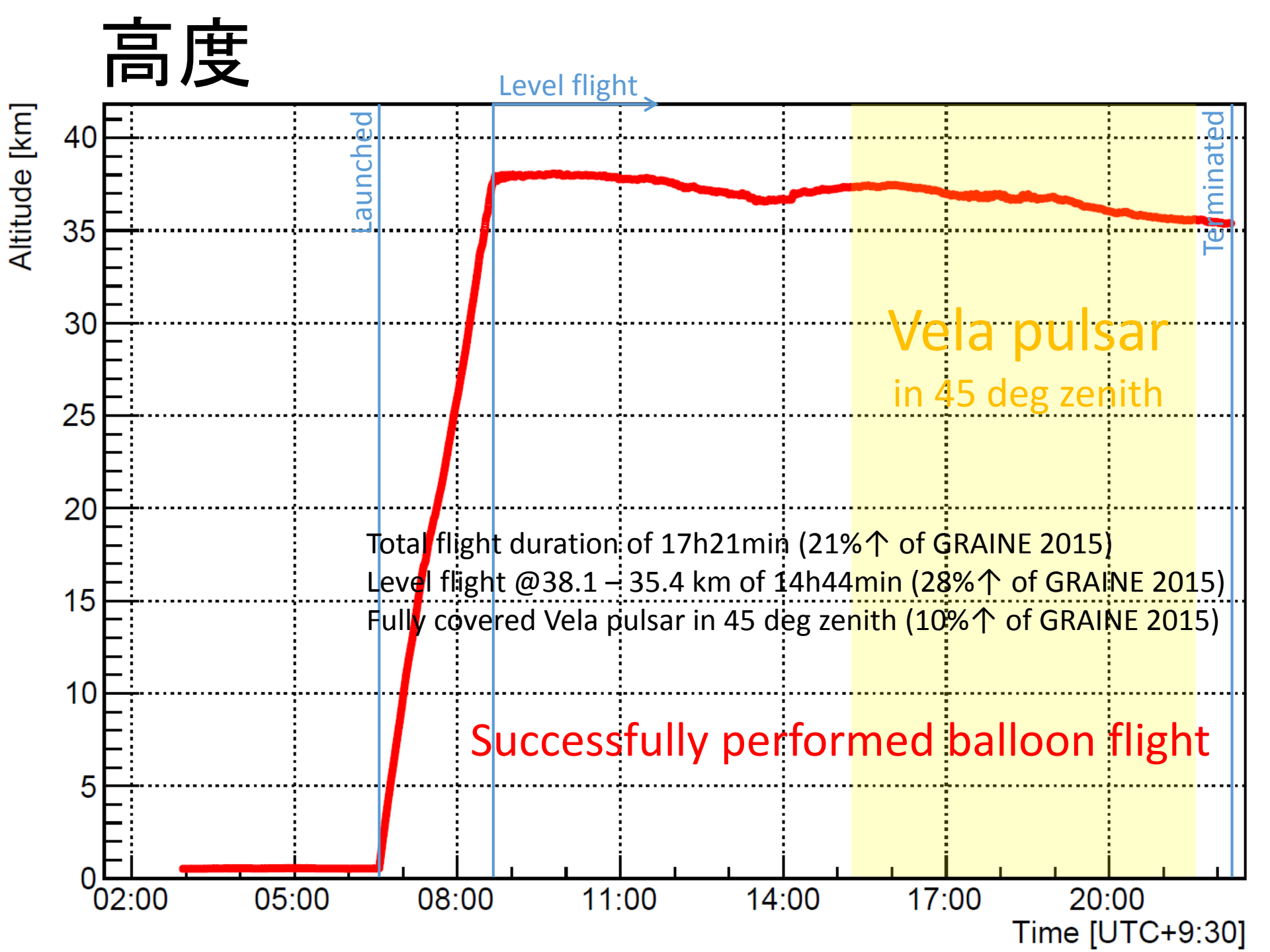
6:33, Launch
Start flight operation
~8:33, Altitude of 38 km
14:48, Start Vela obs. operation
~22:15, Termination
23:17, Cut down
23:54, Landing with a parachute
@900km E from Alice Springs
250km SW from Longreach



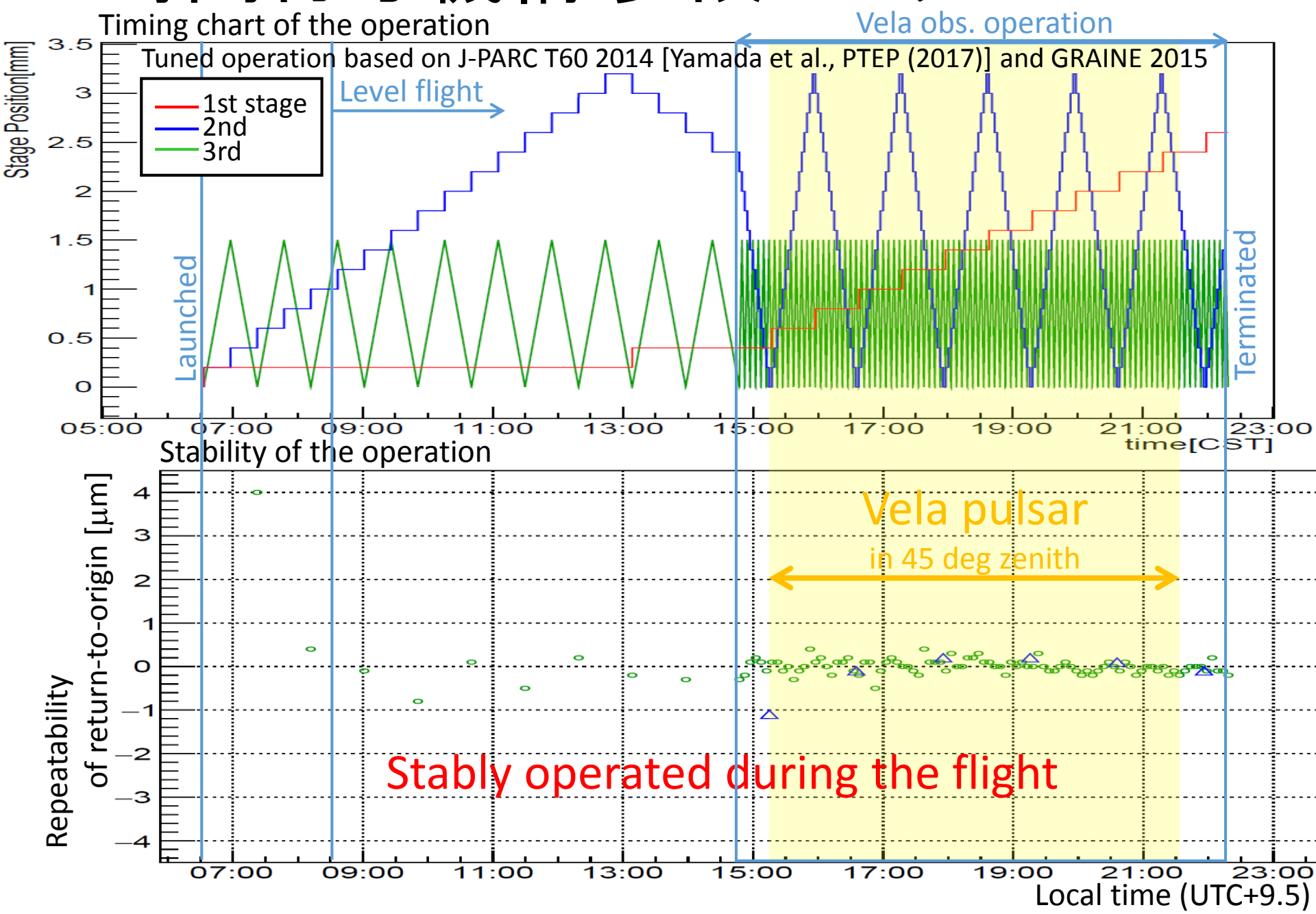
Sydney

Total flight duration of 17h21min (21%↑ of GRAINE 2015)
Level flight @38.1 – 35.4 km of 14h44min (28%↑ of GRAINE 2015)
Fully covered Vela pulsar in 45 deg zenith (10%↑ of GRAINE 2015)

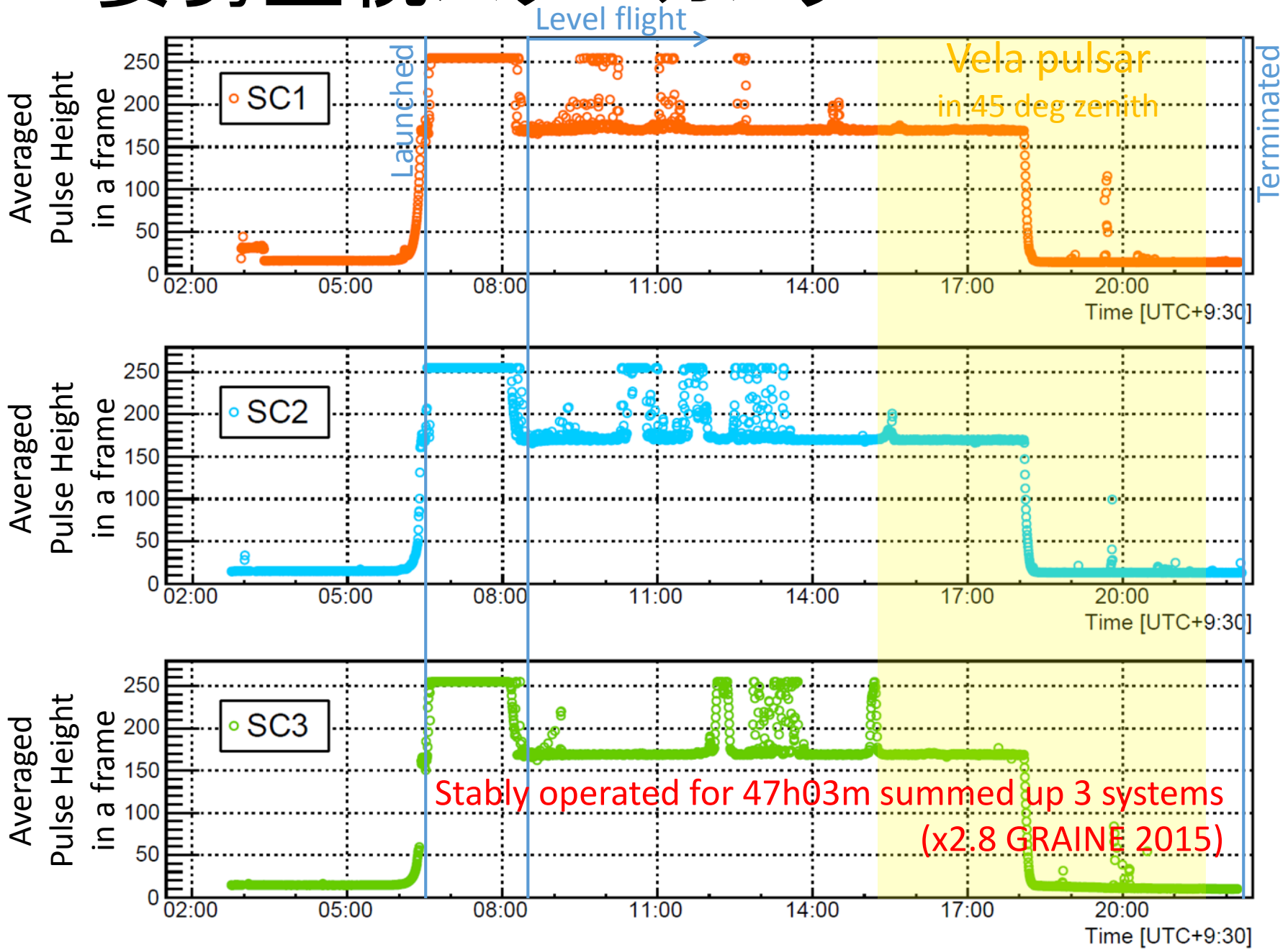
高度


Level flight
Launched
Terminated
Altitude [km]
40
35
30
25
20
15
10
5
0
02:00
05:00
08:00
11:00
14:00
17:00
20:00
Time [UTC+9:30]
Vela pulsar
in 45 deg zenith
Total flight duration of 17h21min (21%↑ of GRAINE 2015)
Level flight @38.1 – 35.4 km of 14h44min (28%↑ of GRAINE 2015)
Fully covered Vela pulsar in 45 deg zenith (10%↑ of GRAINE 2015)
Successfully performed balloon flight

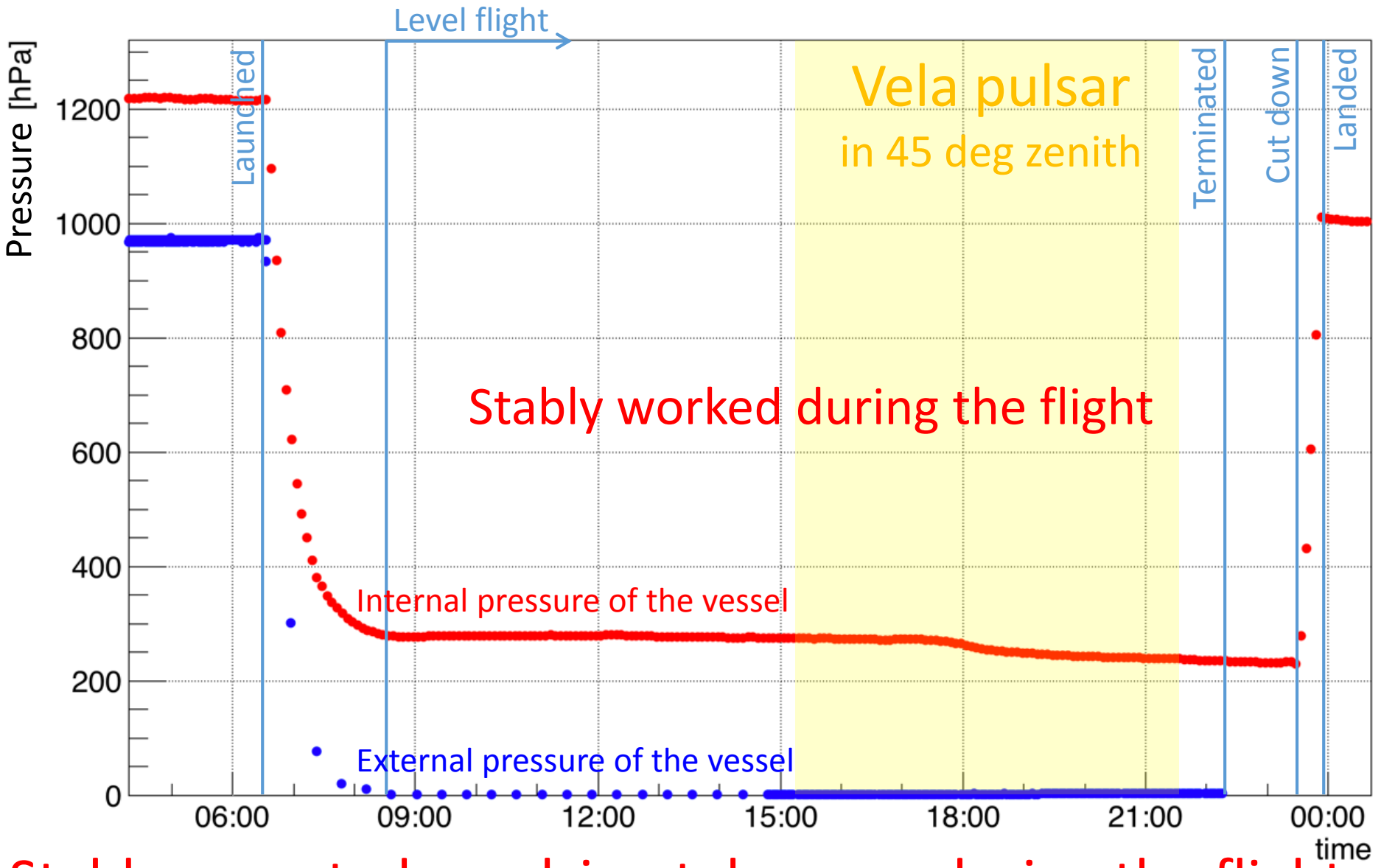
時間付与機構 多段シフター



姿勢監視スターカメラ


Level flight
Launched
Terminated
Vela pulsar
in 45 deg zenith
SC1
SC2
SC3
Averaged Pulse Height in a frame
Time [UTC+9:30]
02:00
05:00
08:00
11:00
14:00
17:00
20:00
0
50
100
150
200
250
Stably operated for 47h03m summed up 3 systems
(x2.8 GRAINE 2015)

与圧容器



Stably operated emulsion telescope during the flight

回収

~8:30(UTC+10) 27th Apr, Arrive at 250 km far from Longreach by a helicopter
~4:00 28th, Send emulsion films to Sydney

現像 @シドニー大学

Finalization of the emulsion films by chemical process

Microscopic image of the flight emulsion film

29th Apr, Arrive at Sydney

Receive the emulsion films from Longreach

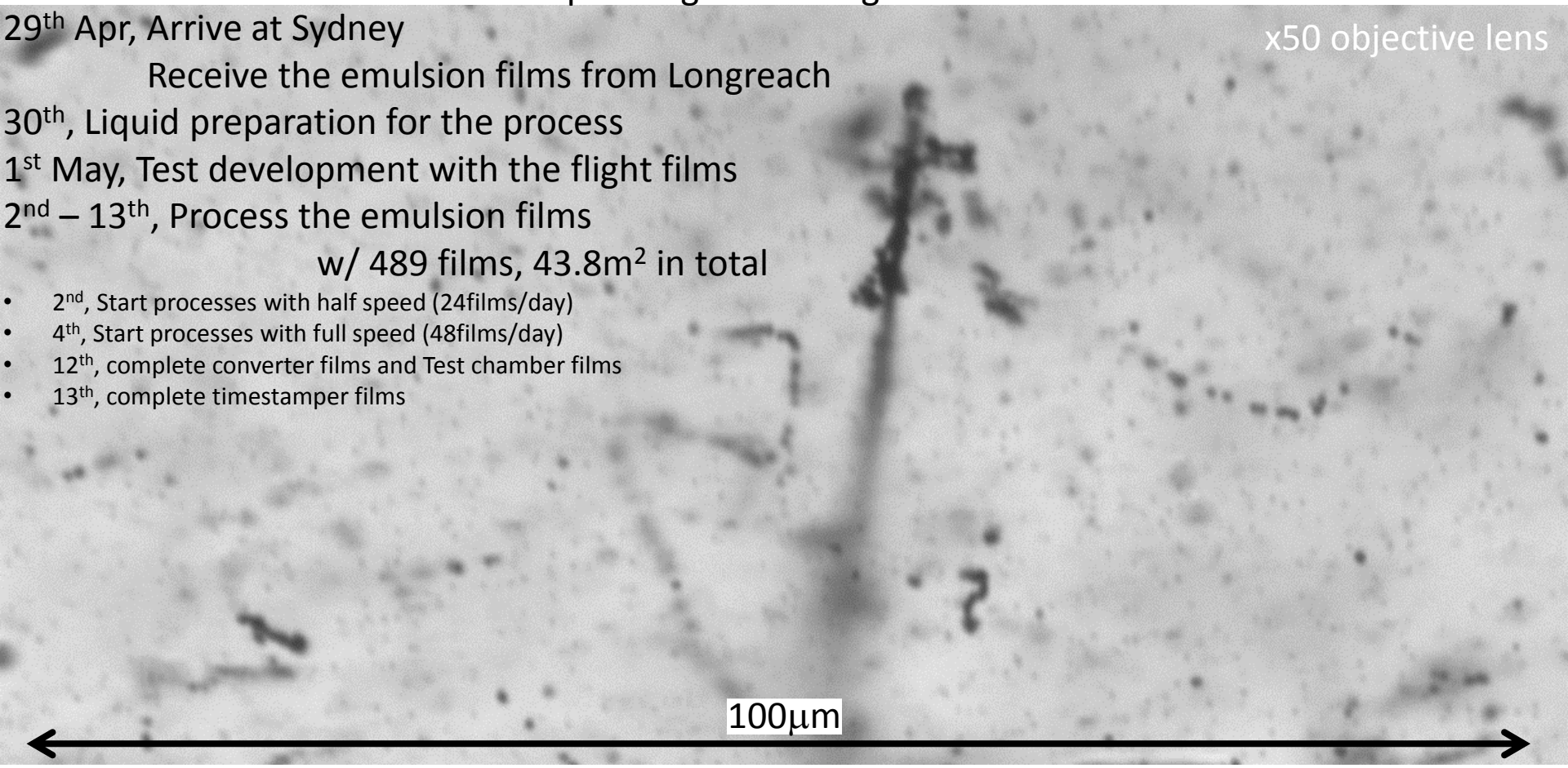
30th, Liquid preparation for the process

1st May, Test development with the flight films

2nd – 13th, Process the emulsion films

w/ 489 films, 43.8m^2 in total

- 2nd, Start processes with half speed (24films/day)
- 4th, Start processes with full speed (48films/day)
- 12th, complete converter films and Test chamber films
- 13th, complete timestamper films



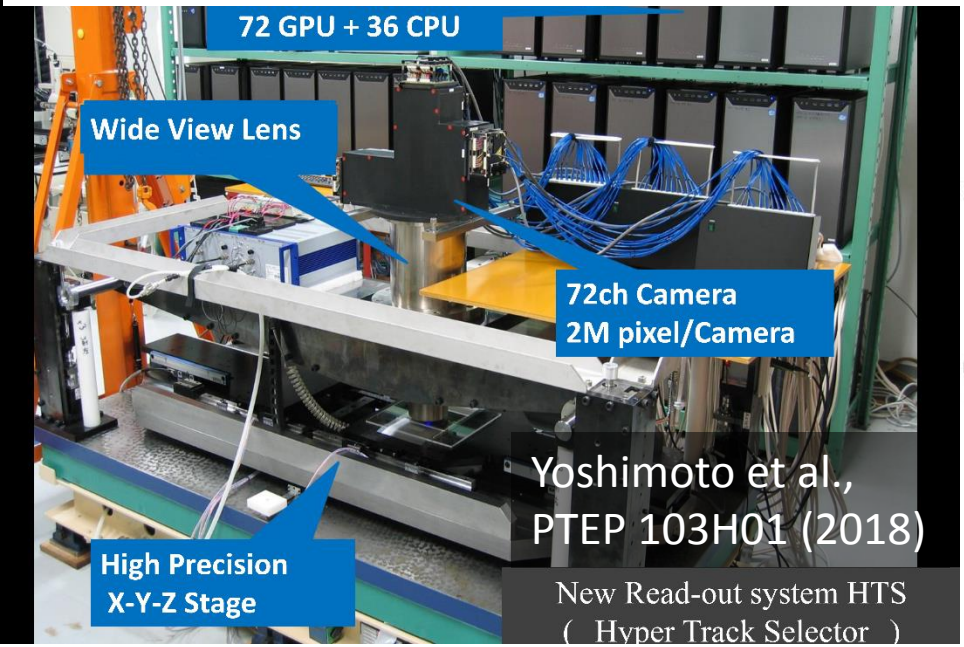
Development error fraction ~0.3% (area basis)

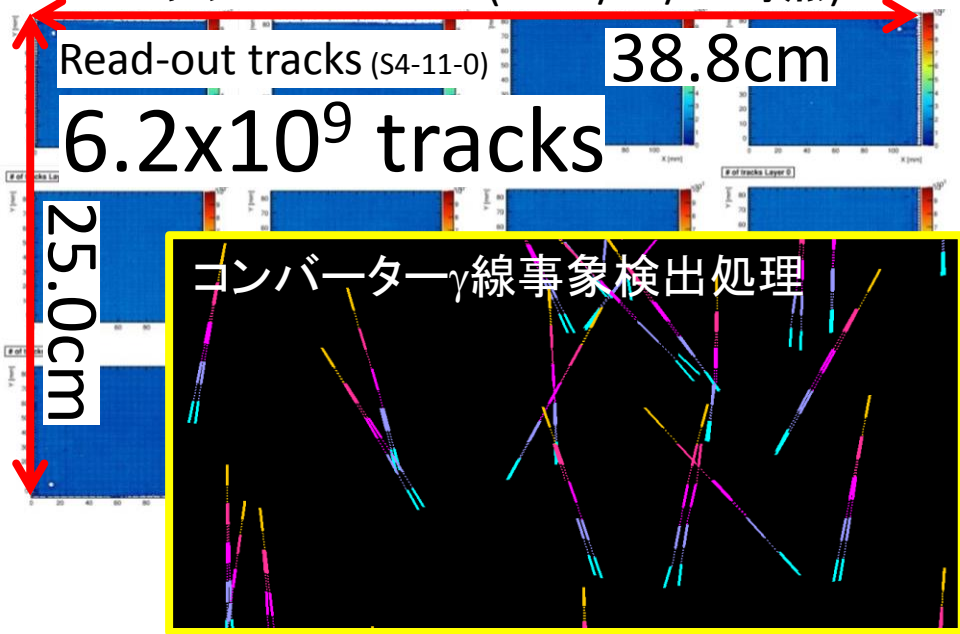
Accumulated error fraction after development <~0.4% (area basis) (x~1/20 GRAINE 2015)

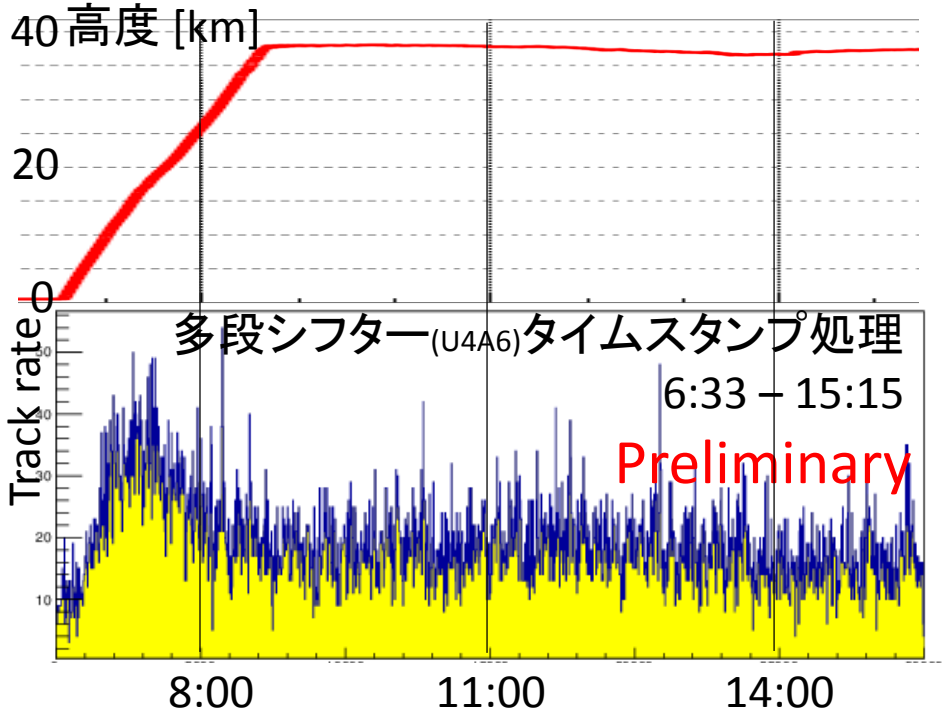
Well-controlled qualities of the emulsion films

スキャン&フライトデータ解析

表面銀とり・膨潤完了、スキャン条件だし
スキャン 31% done (2018/09/12時点)







2015年気球実験
Vela Pulsarからのガンマ線を有意に検出する。

2018年4月JAXA豪州気球実験

<u>有効面積・有効時間拡大およびBG低減の展望</u>

- スターカメラの堅牢性強化→有効時間 1.77倍
  - データストレージの冗長化、エラーからの復帰可能なシステム
- エマルションフィルムの安定性確保→有効面積 1.33倍
  - 製造および処理処方の最適パラメーター確立
- シフターセットアップの確立→有効面積x有効時間 1.33倍
  - フィルム搭載条件の最適化
- シフター動作パラメータの適正化→BG 1/2倍

計6.3倍の改善.

(実効値5.3倍)

望遠鏡の総合的な性能実証を目指す

科学観測実験 ロードマップ

Takahashi, Aoki et al., ASR (2017) 10.1016/j.asr.2017.08.029

2018年4月, 総合性能実証

Done by JAXA balloon

Alice Springs
~0.4 m^2 aperture
~18 hours flight duration
<~5 g/cm^2 altitude

2021–, 科学観測

Alice Springs
10 m^2 aperture
>~36 hours flight duration
<~10 g/cm^2 altitude

Velaパルサーの検出
精密撮像、
位相分解解析study、
銀河面放射、Gemingaを
検出もしくは兆候を捉える

松田、ポスター
「GRAINE2018豪州気球実験における時刻付与機構多段シフター報告~搭載エマルションフィルムの研究開発~」

Vela pulsar
Polarization observation (<50%)
→ Pioneering polarization observation for high energy γ-rays

SNR W44 (<200MeV, >200MeV)
Precise spectrum measurement
High resolution imaging
→ Studying cosmic ray sources

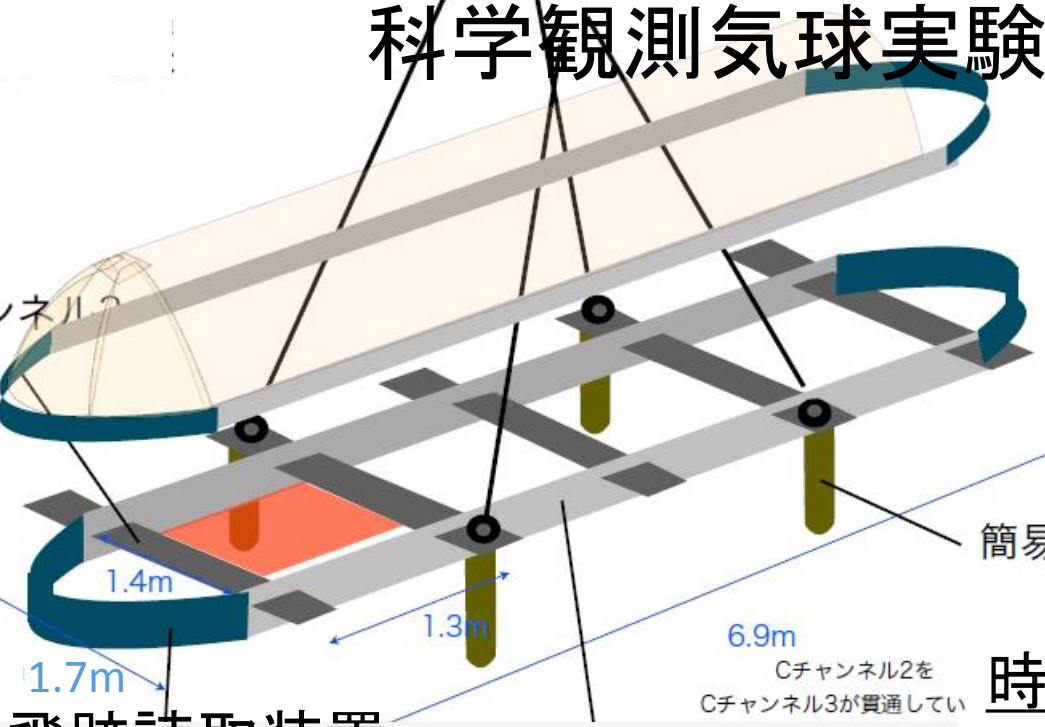
Galactic Center
Obs. with ~arcmin resolution
→ Resolving GeV γ-ray excess at galactic center

Test of fundamental symmetries beyond the Planck scale

Transient sources
Obs. w/ high sensitivity
& high photon stats
→ Studying transient sources & w/ ones

GRPとの相関探索、GeV γ-ray Pair Halo探索→IGMFを制限

科学観測気球実験に向けた開発



与圧容器ゴンドラ

Conceptual design
Light, Thin, 0.3atm
5m^2 (4units) aperture area
w/ a single pressure vessel gondola
(~0.3ton weight)

< ~2 ton payload (aiming)
w/ a 10 m^2 aperture

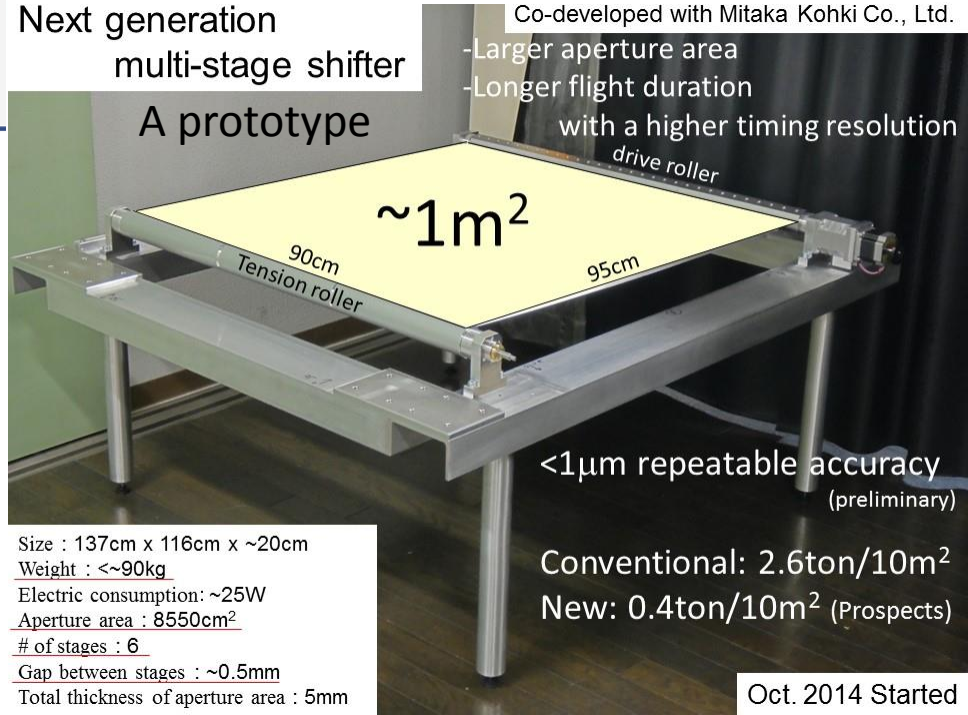
時間付与機構 多段シフター

Next generation
multi-stage shifter

Co-developed with Mitaka Kohki Co., Ltd.

-Larger aperture area
-Longer flight duration
with a higher timing resolution

A prototype



<1μm repeatable accuracy
(preliminary)

Conventional: 2.6ton/10m^2
New: 0.4ton/10m^2 (Prospects)

Oct. 2014 Started

Size : 137cm x 116cm x ~20cm
Weight : <~90kg
Electric consumption: ~25W
Aperture area : 8550cm^2
# of stages : 6
Gap between stages : ~0.5mm
Total thickness of aperture area : 5mm

飛跡読取装置

Evolution of the Scanning Speed

※1 Area of emulsion layer
※2 Area of the films with 24 hour shift