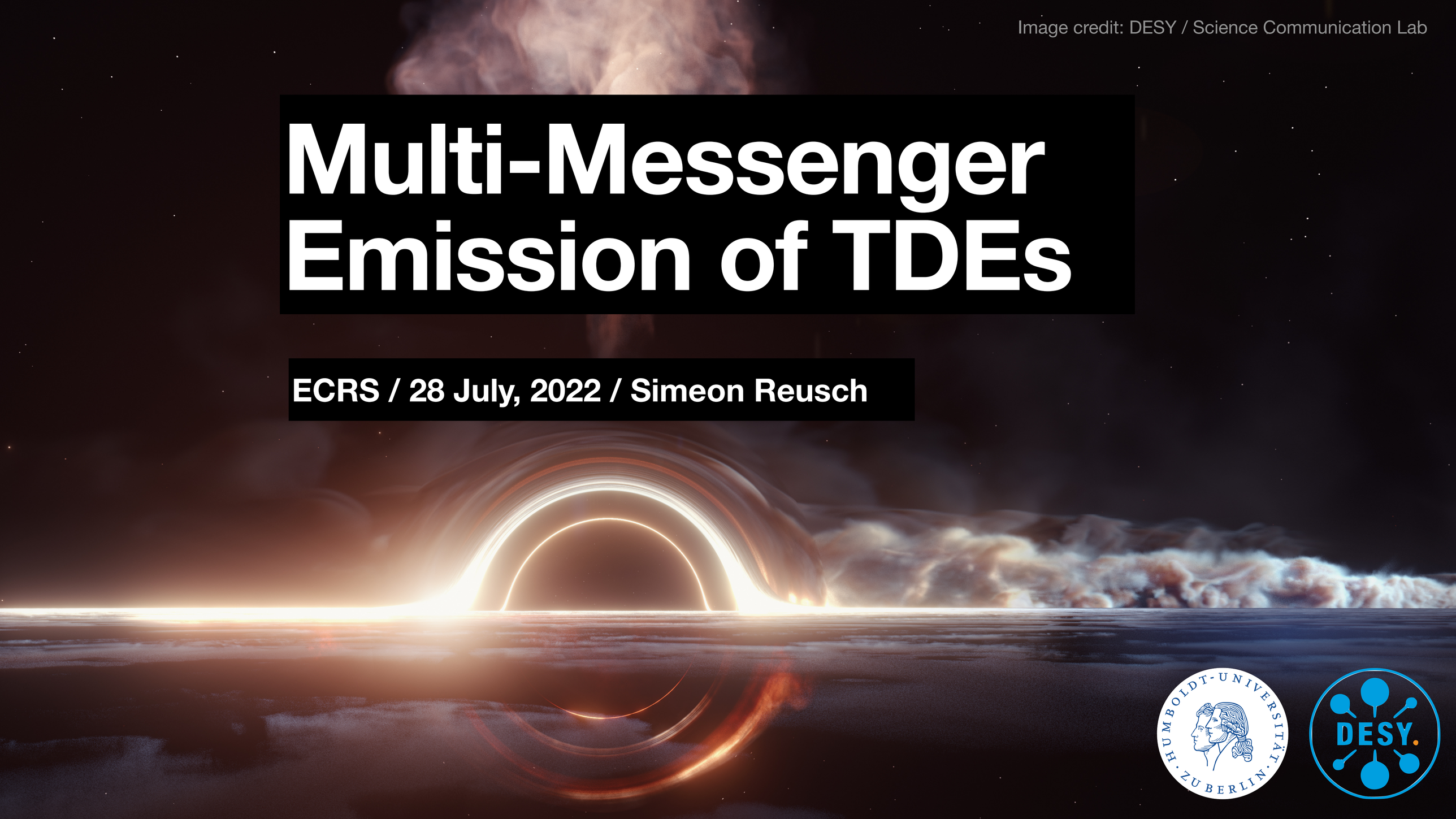


Multi-Messenger Emission of TDEs

ECRS / 28 July, 2022 / Simeon Reusch

Overview

Overview



Motivation, Follow-Up Program

Overview



Motivation, Follow-Up Program



What are Tidal Disruption Events?

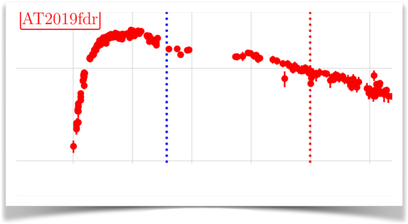
Overview



Motivation, Follow-Up Program



What are Tidal Disruption Events?



AT2019dsg and AT2019fdr

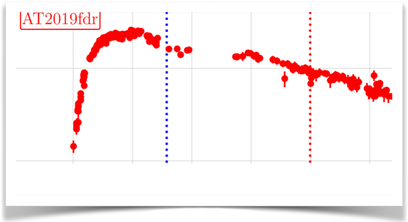
Overview



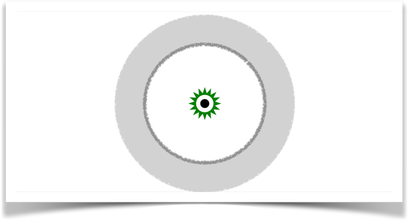
Motivation, Follow-Up Program



What are Tidal Disruption Events?



AT2019dsg and AT2019fdr



Dust Echoes + AT2019aalc

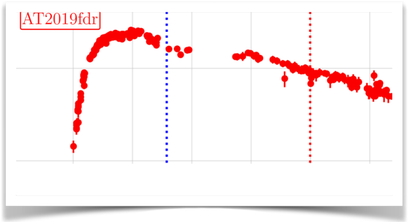
Overview



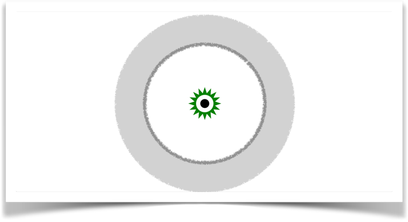
Motivation, Follow-Up Program



What are Tidal Disruption Events?



AT2019dsg and AT2019fdr

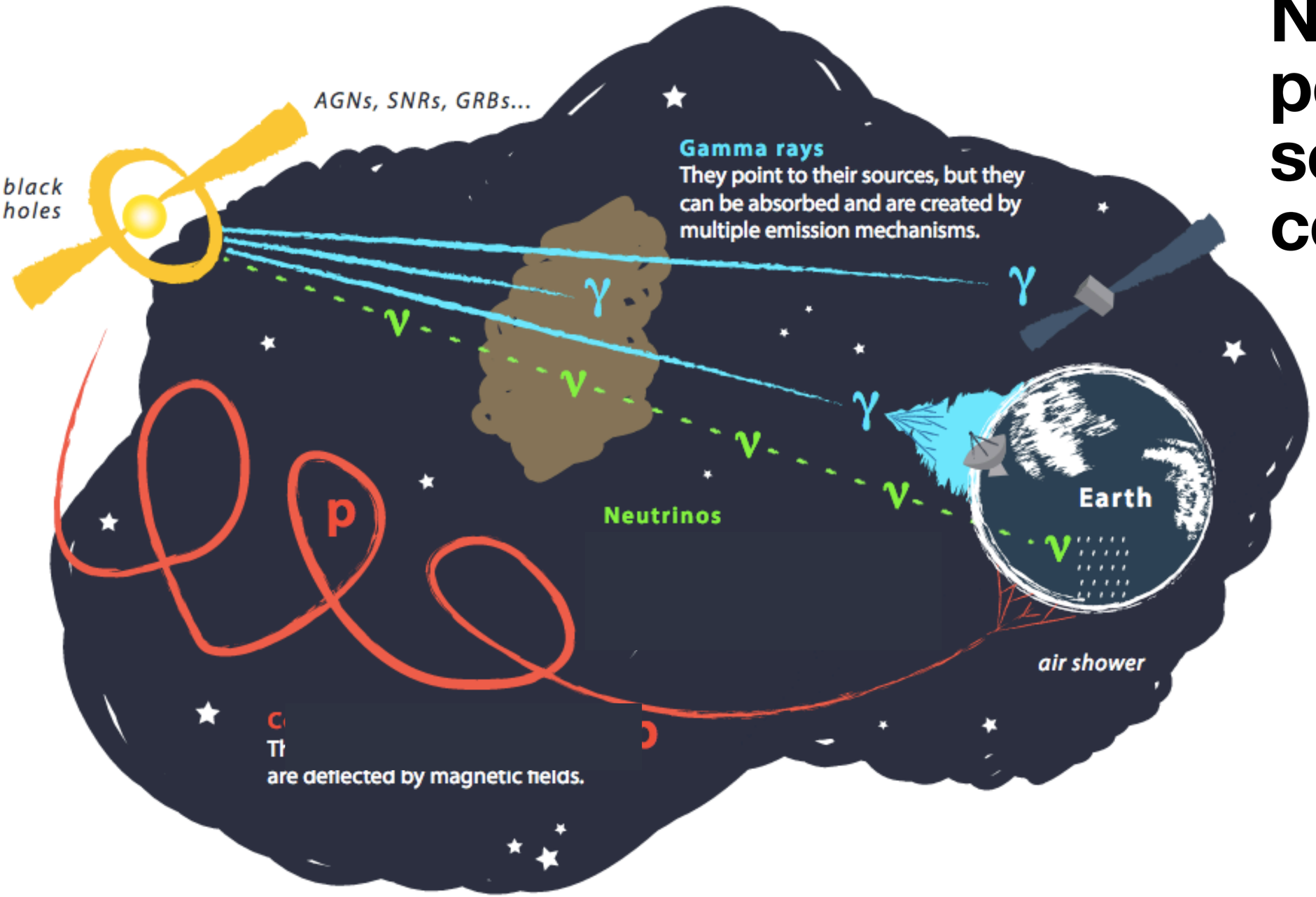


Dust Echoes + AT2019aalc

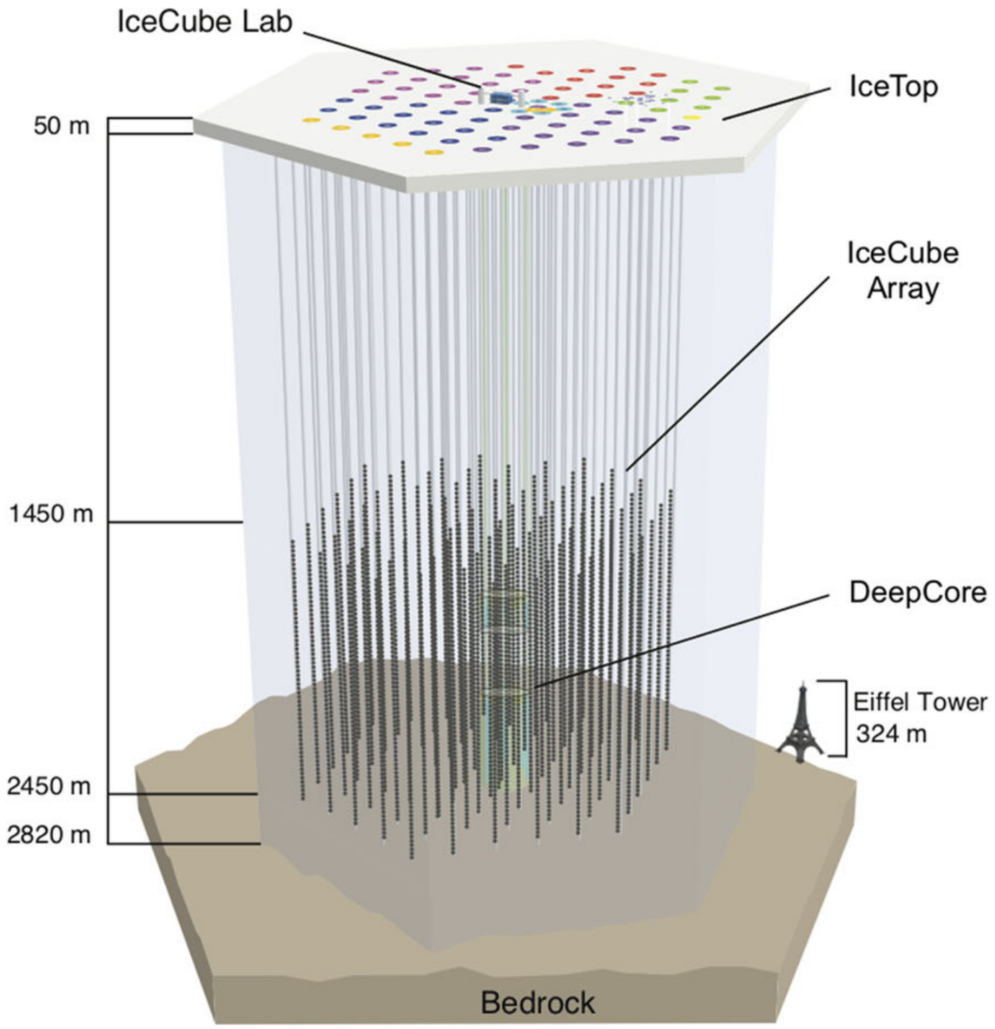


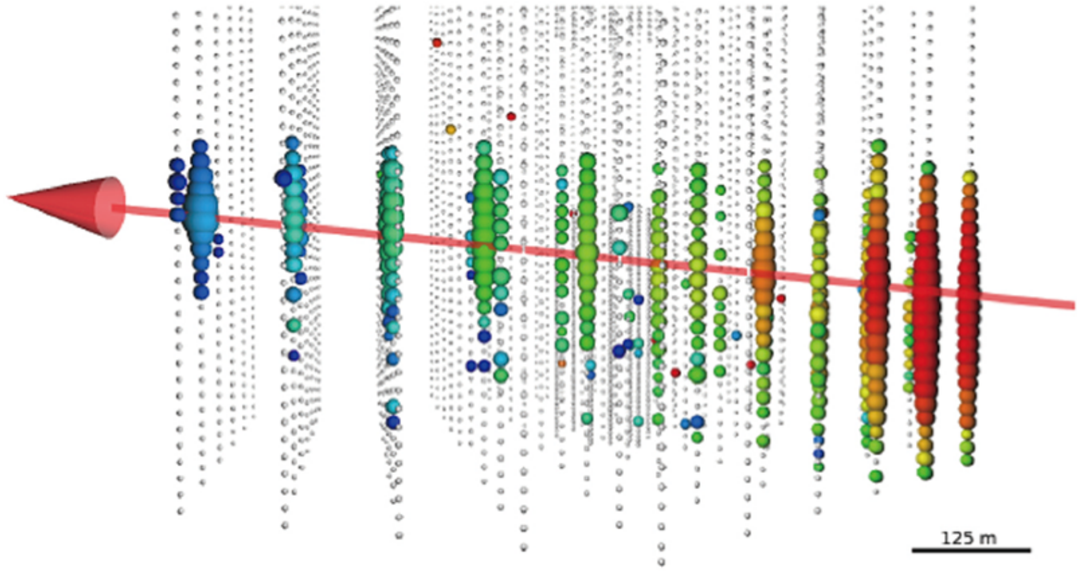
Outlook

Neutrinos point back the sources of cosmic rays!



Detecting neutrinos is HARD





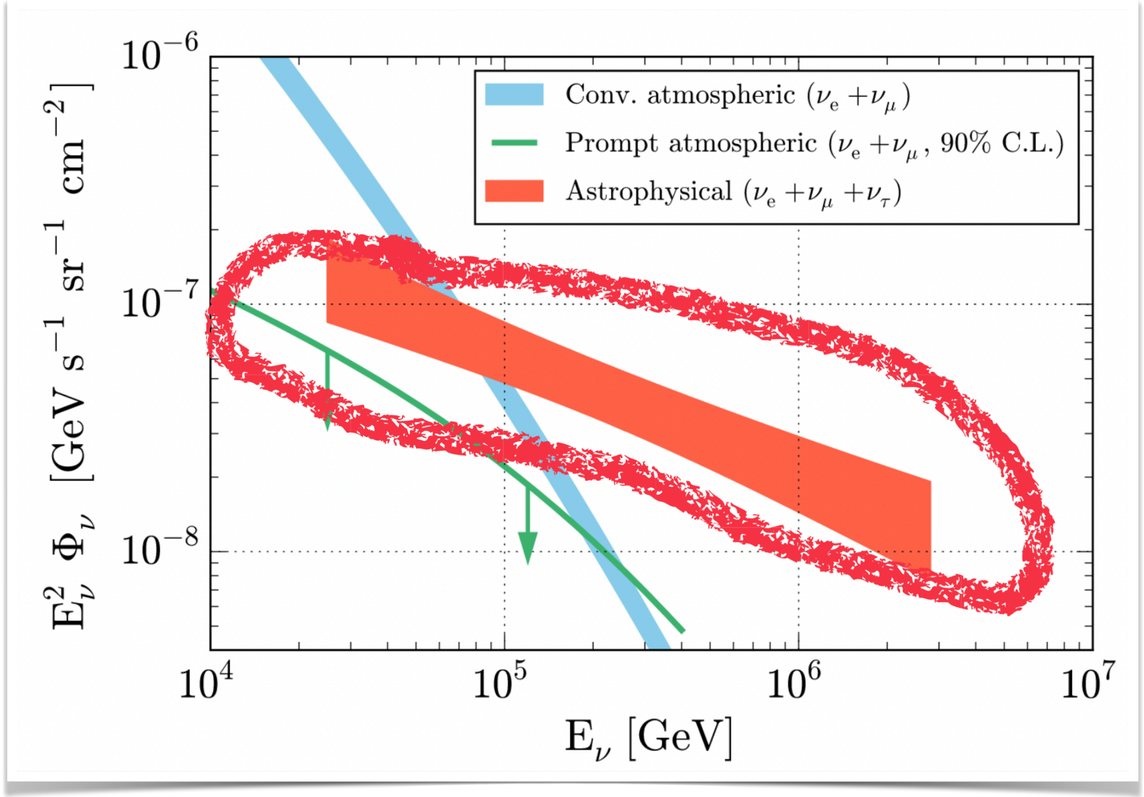
Event view of IceCube-170922

Identifying their sources too!

Aartsen et. al. (2015, ApJ), IceCube (2018, Science)

Identifying their sources too!

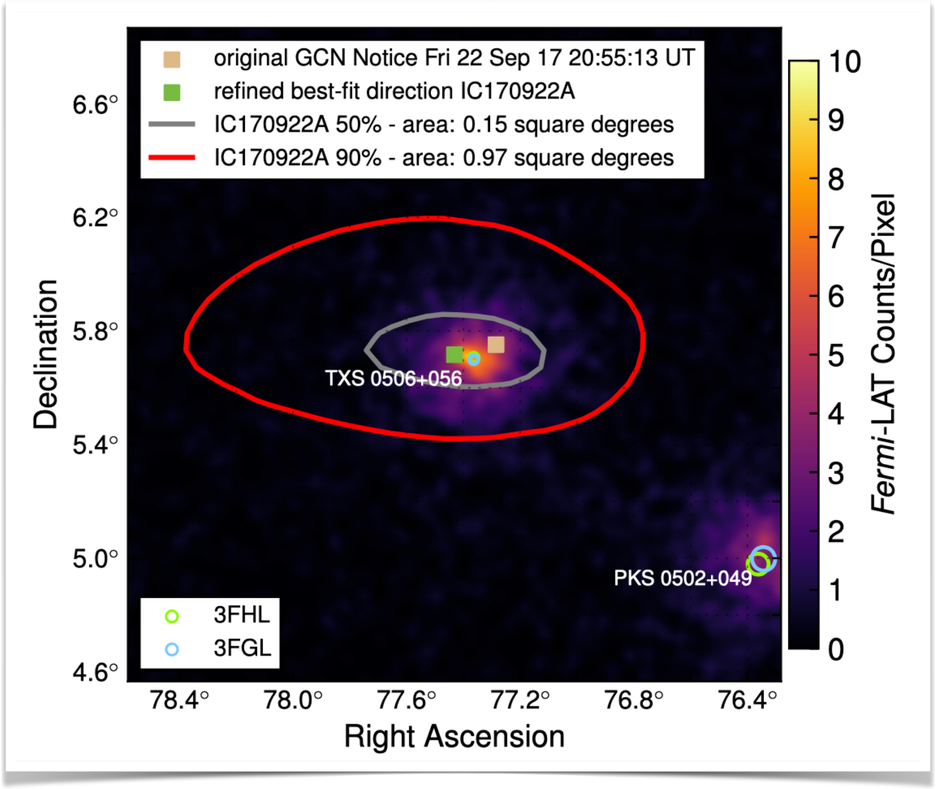
Cosmic high-energy neutrino flux first detected by IceCube (2013)

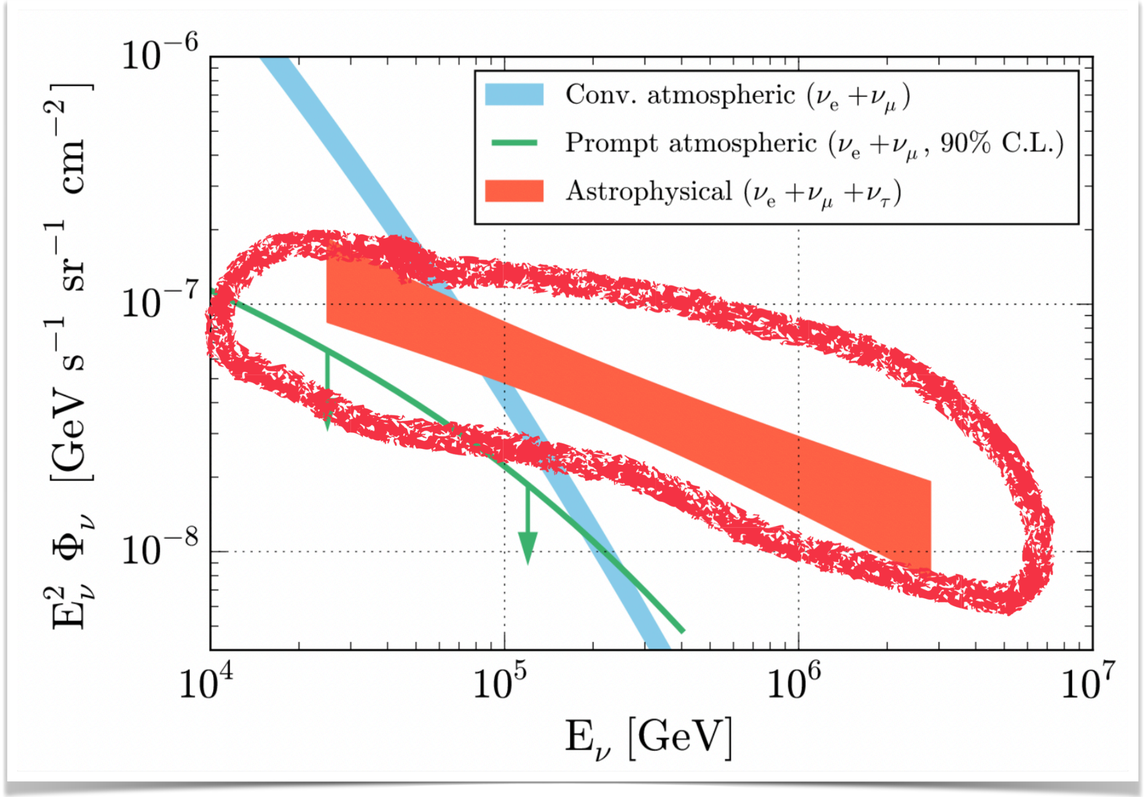


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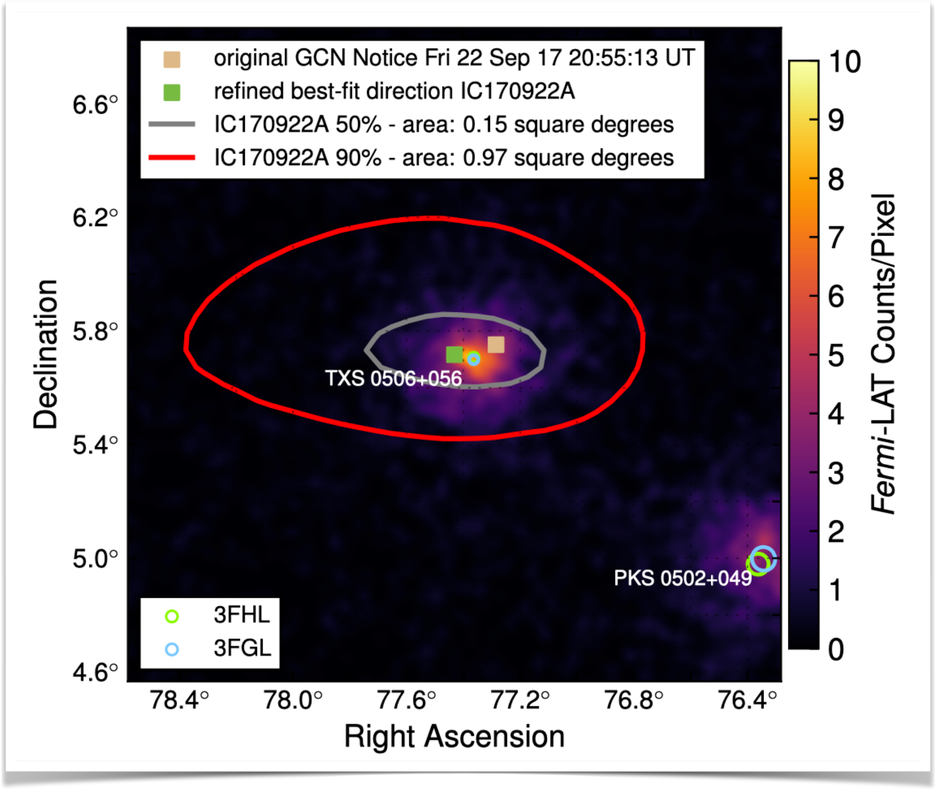


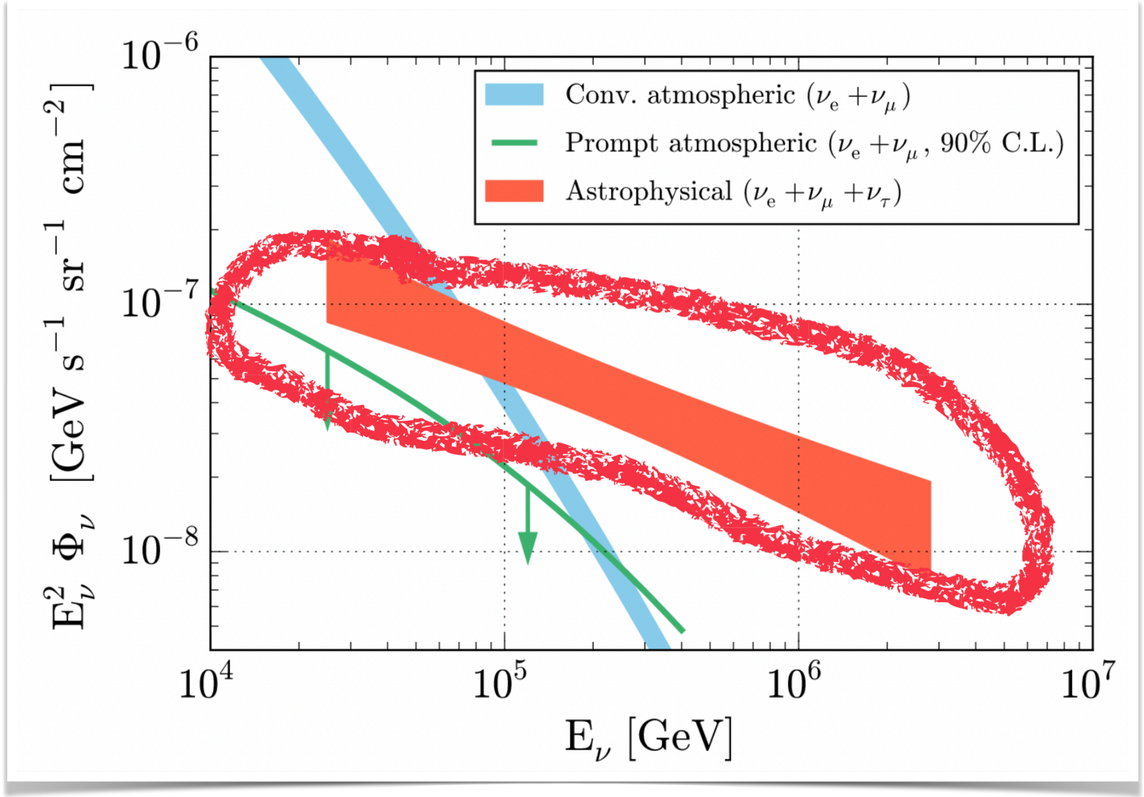
First compelling source: Gamma-ray blazar TXS 0506+056 (2017)

Aartsen et. al. (2015, ApJ), IceCube (2018, Science)

Identifying their sources too!

Cosmic high-energy neutrino flux first detected by IceCube (2013)



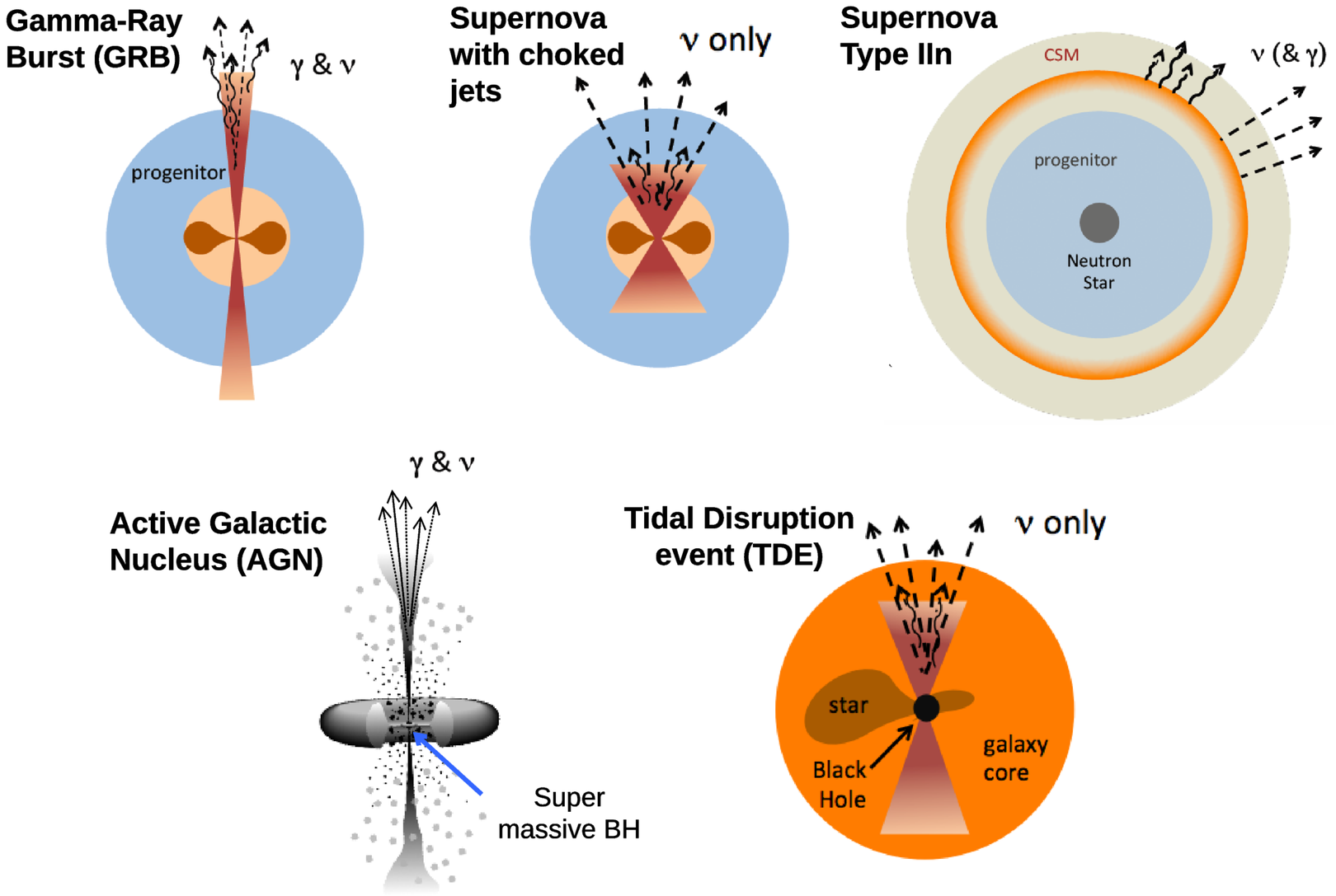


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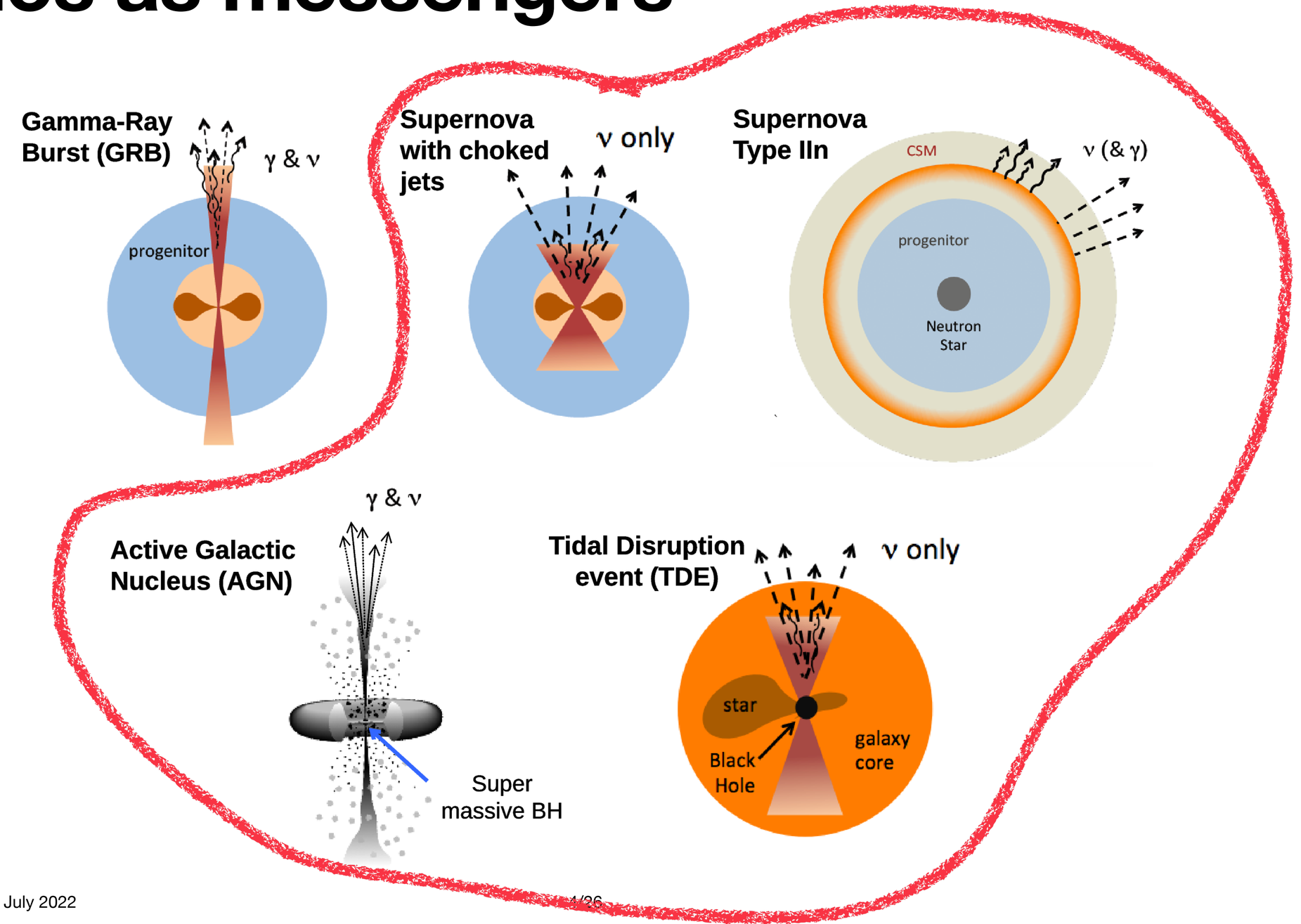
At least 70% of flux: unknown origin

Aartsen et. al. (2015, ApJ), IceCube (2018, Science)

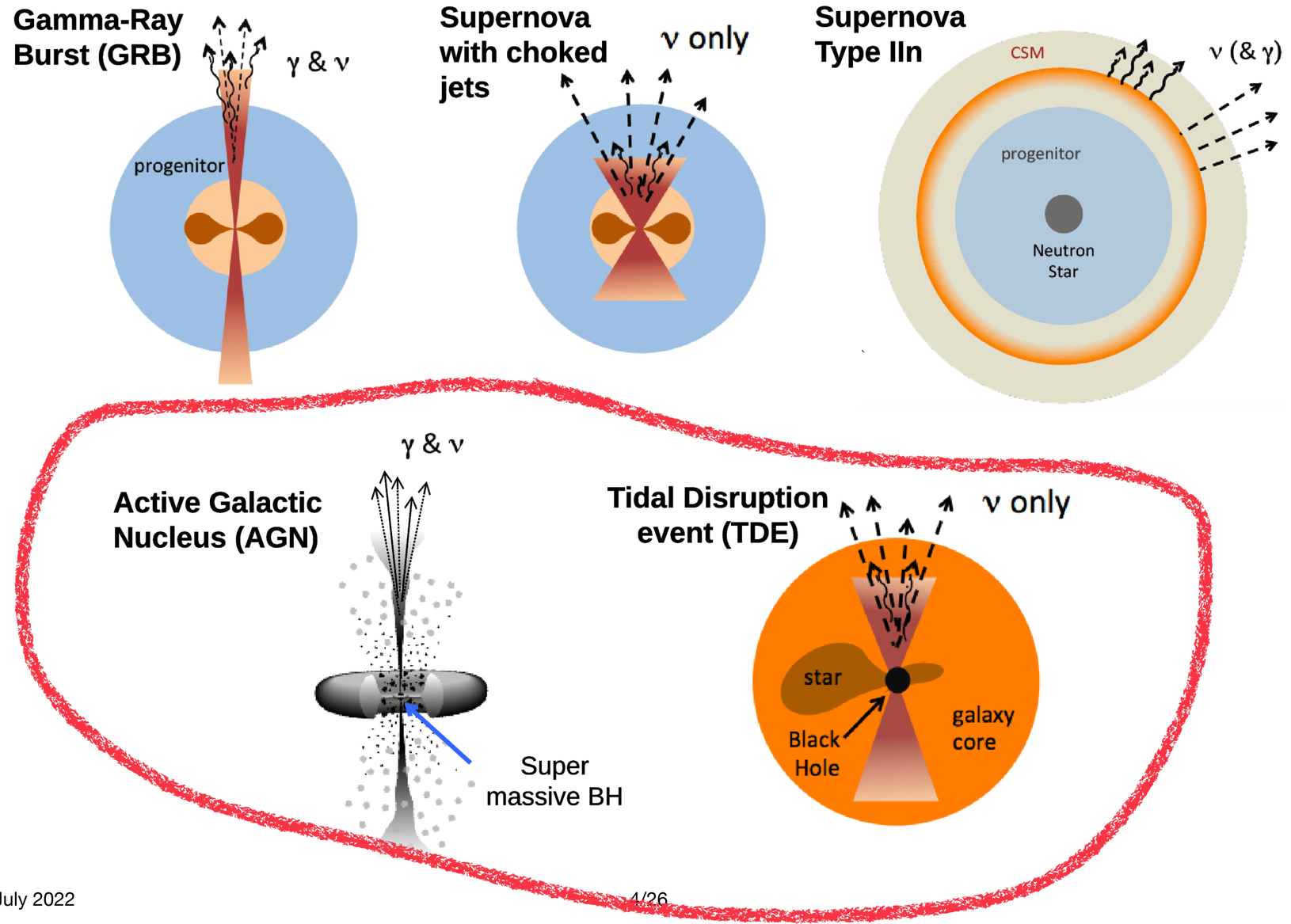
Neutrinos as messengers



Neutrinos as messengers



Neutrinos as messengers



Our Follow-Up Program

Our Follow-Up Program



IceCube

Our Follow-Up Program



IceCube





Slack alert

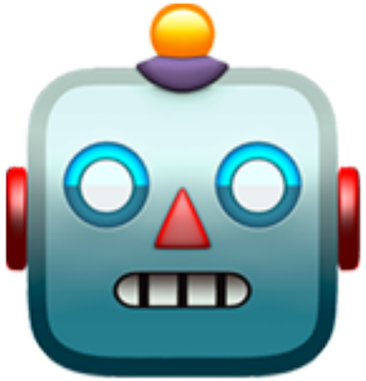
Our Follow-Up Program



IceCube



Slack alert



Almost robotic triggering

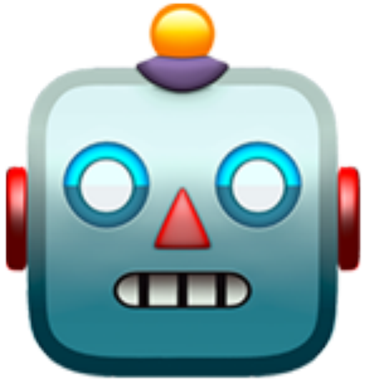
Our Follow-Up Program



IceCube



Slack alert



Almost robotic triggering



ZTF observations

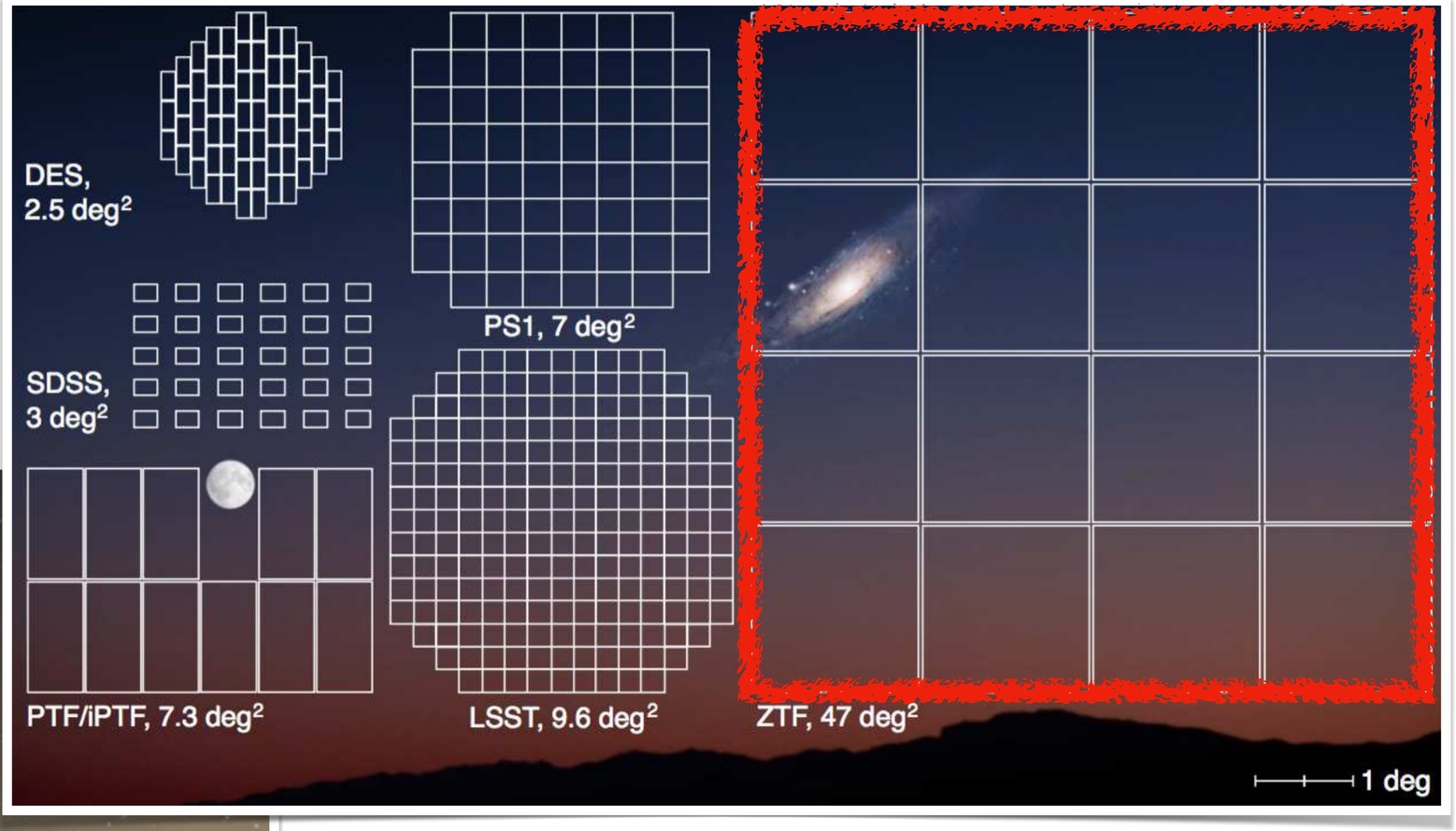




Image credits: Caltech

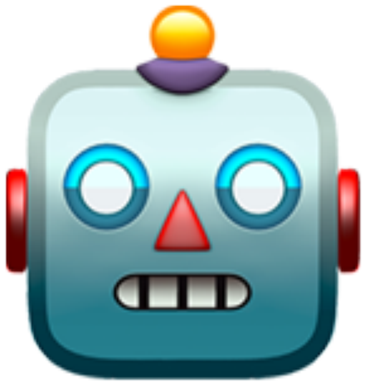
Our Follow-Up Program



IceCube



Slack alert



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AMPEL filtering



ZTF observations

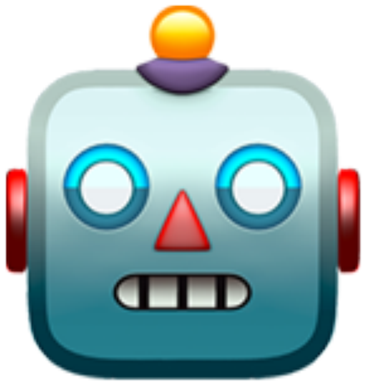
Our Follow-Up Program



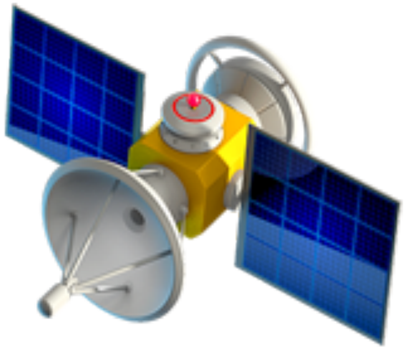
IceCube



Slack alert



Almost robotic triggering



Additional observations



AMPEL filtering



ZTF observations

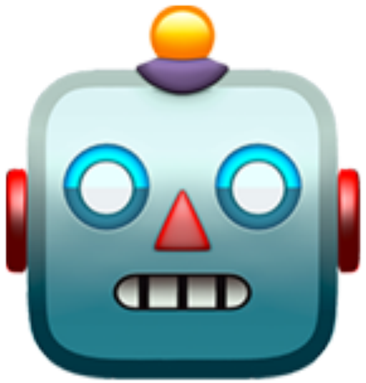
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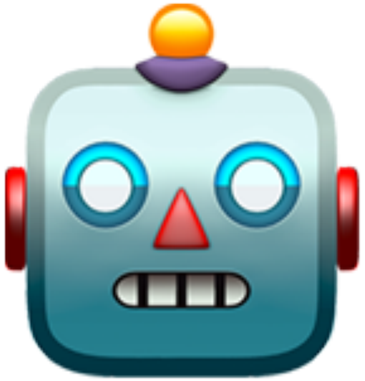
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ZTF observations

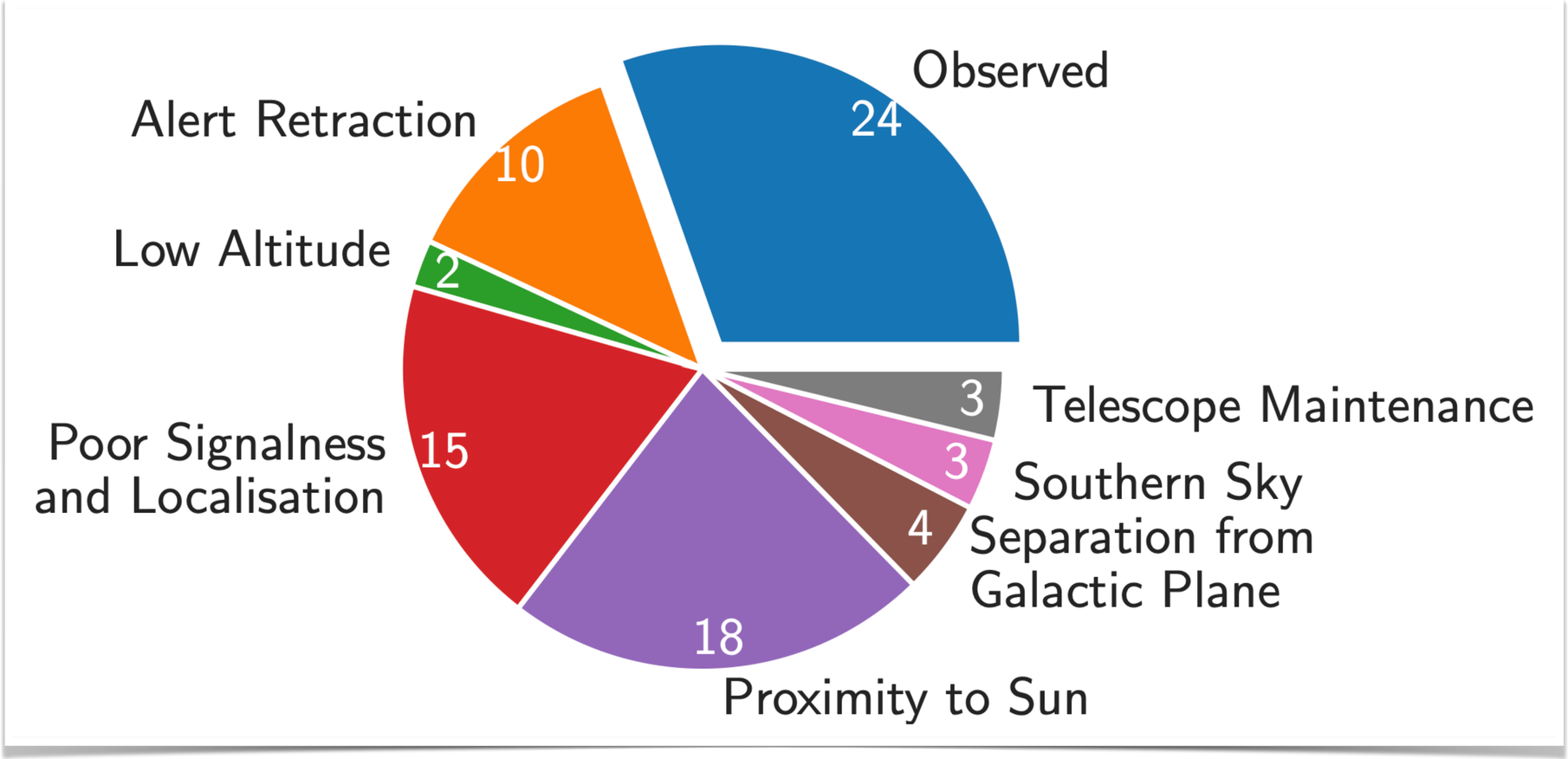


AMPEL filtering



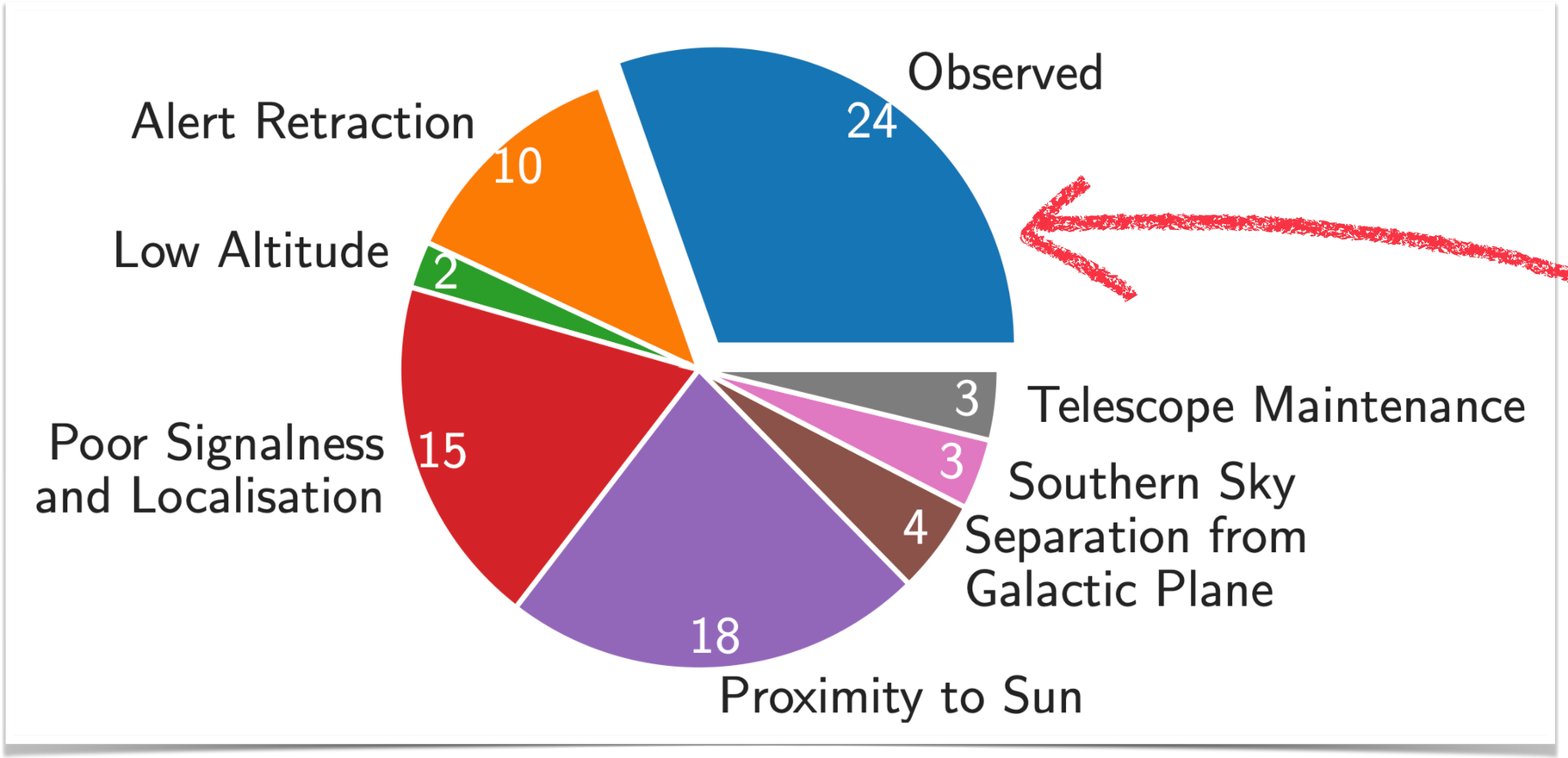
Additional observations

Our Follow-Up Program



Stein, Reusch et. al. (2022, submitted to MNRAS)

Our Follow-Up Program



We have followed up 32% of non-retracted alerts since 2018

Stein, Reusch et. al. (2022, submitted to MNRAS)

What are Tidal Disruption Events (TDEs)?

Image credit: DESY / Science Communication Lab

What are Tidal Disruption Events (TDEs)?

Star approaches SMBH



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What are Tidal Disruption Events (TDEs)?

Star approaches SMBH



Star is ripped apart by tidal forces



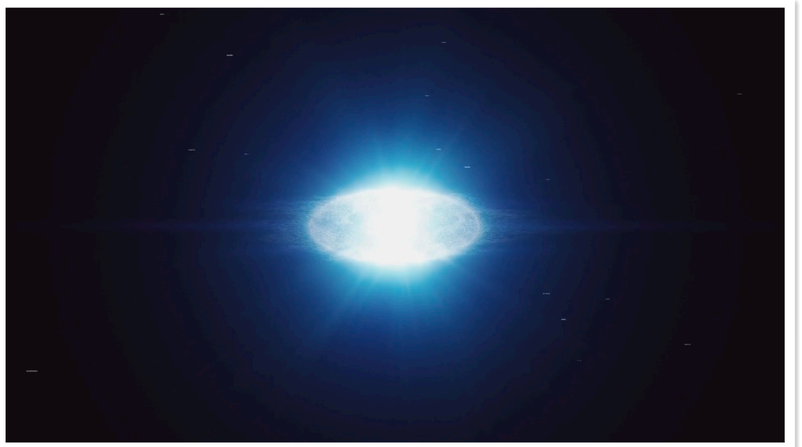
Image credit: DESY / Science Communication Lab

What are Tidal Disruption Events (TDEs)?

Star approaches SMBH



Star is ripped apart by tidal forces



Star debris gets partially accreted



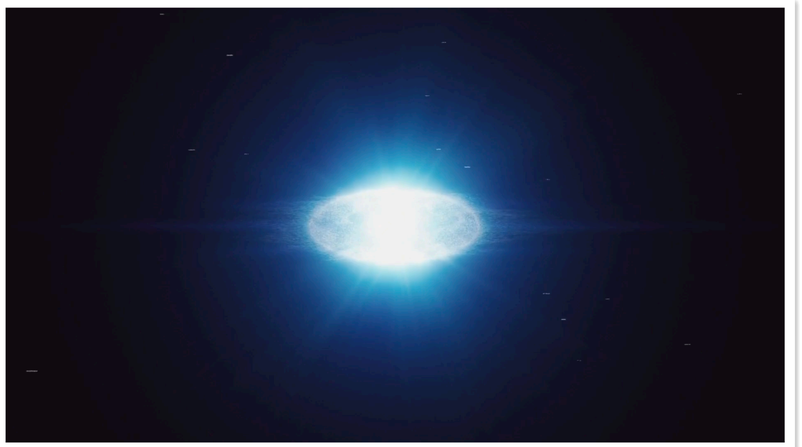
Image credit: DESY / Science Communication Lab

What are Tidal Disruption Events (TDEs)?

Star approaches SMBH



Star is ripped apart by tidal forces



Bright for months!

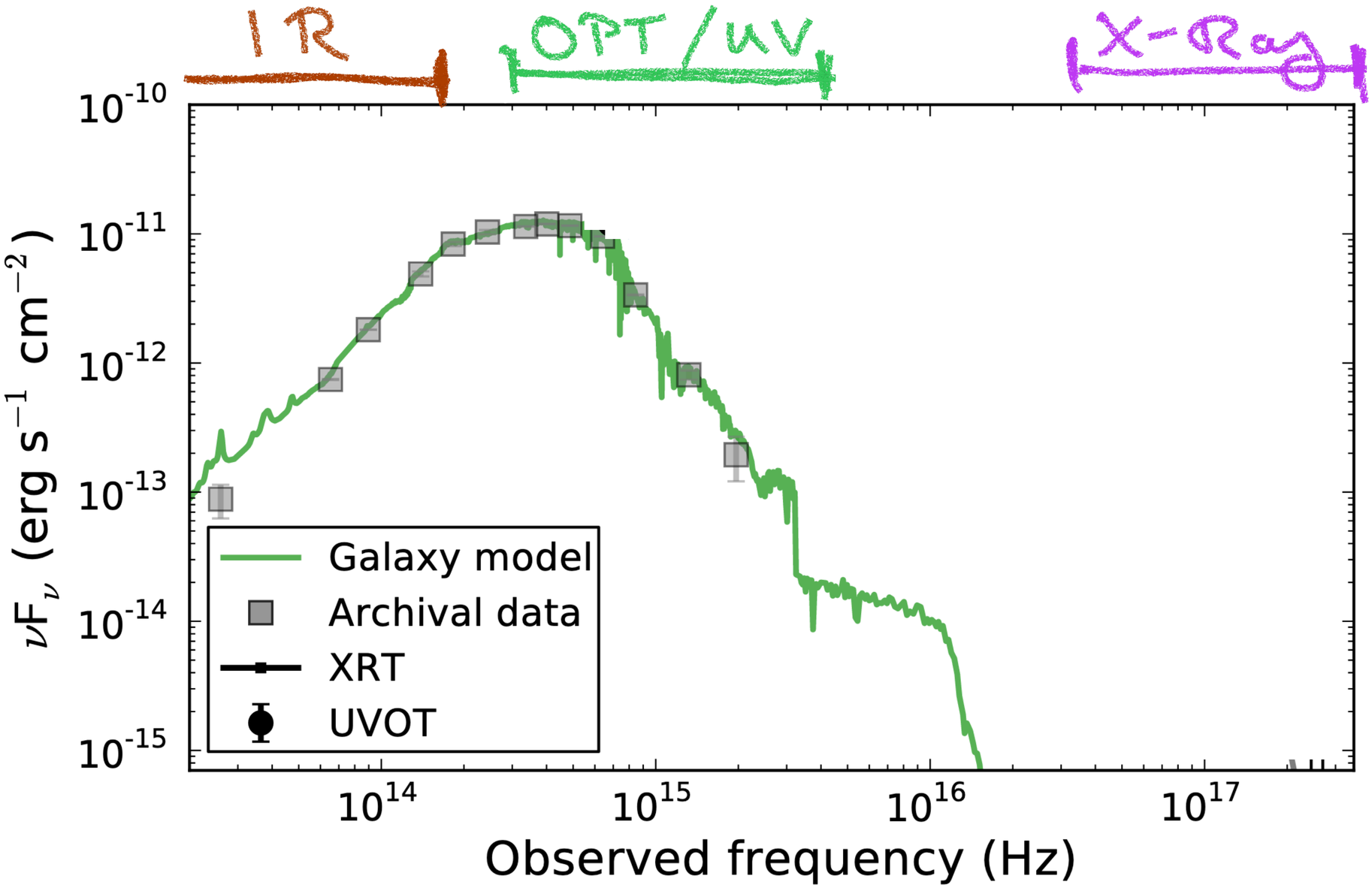


Star debris gets partially accreted



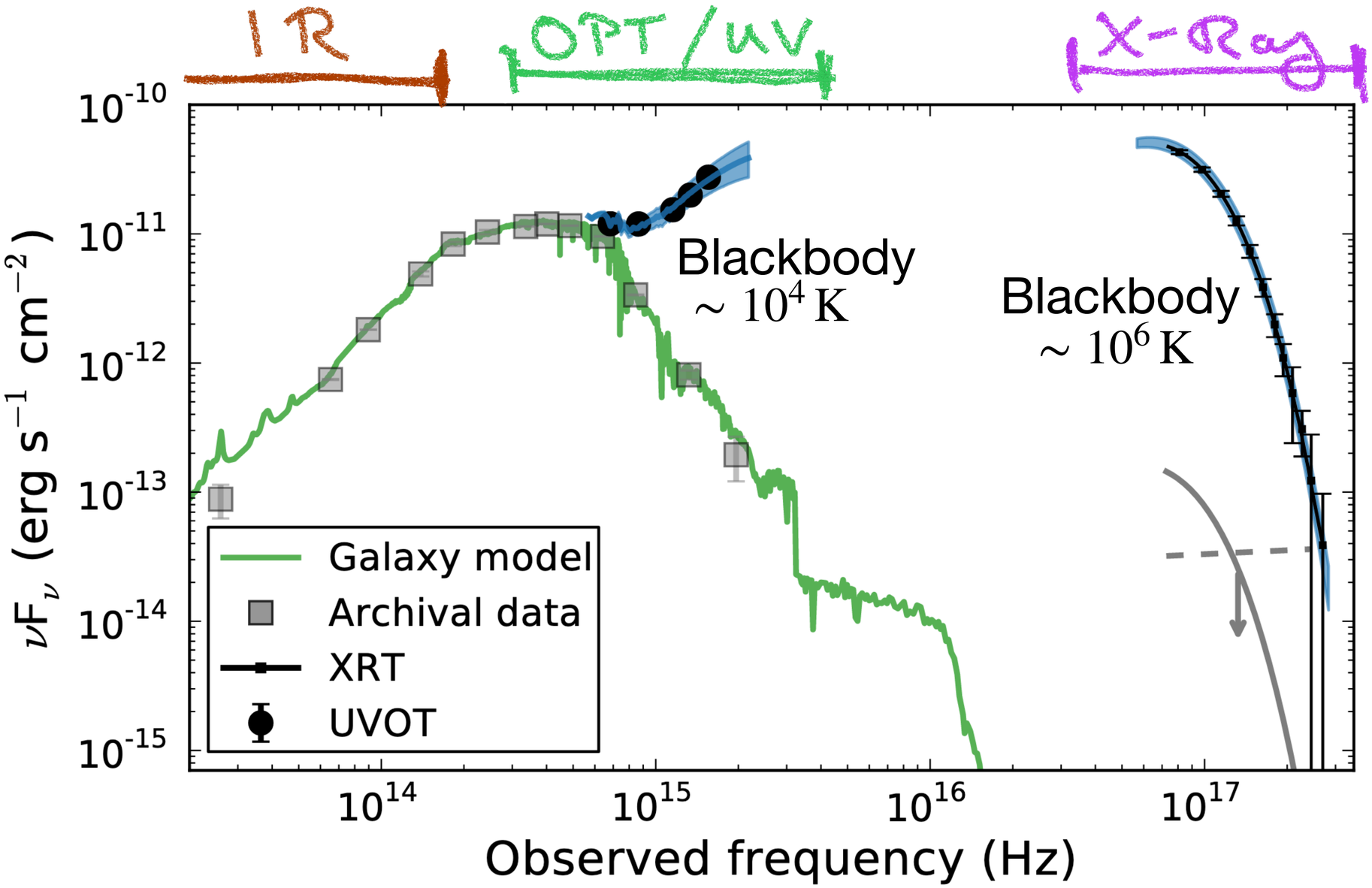
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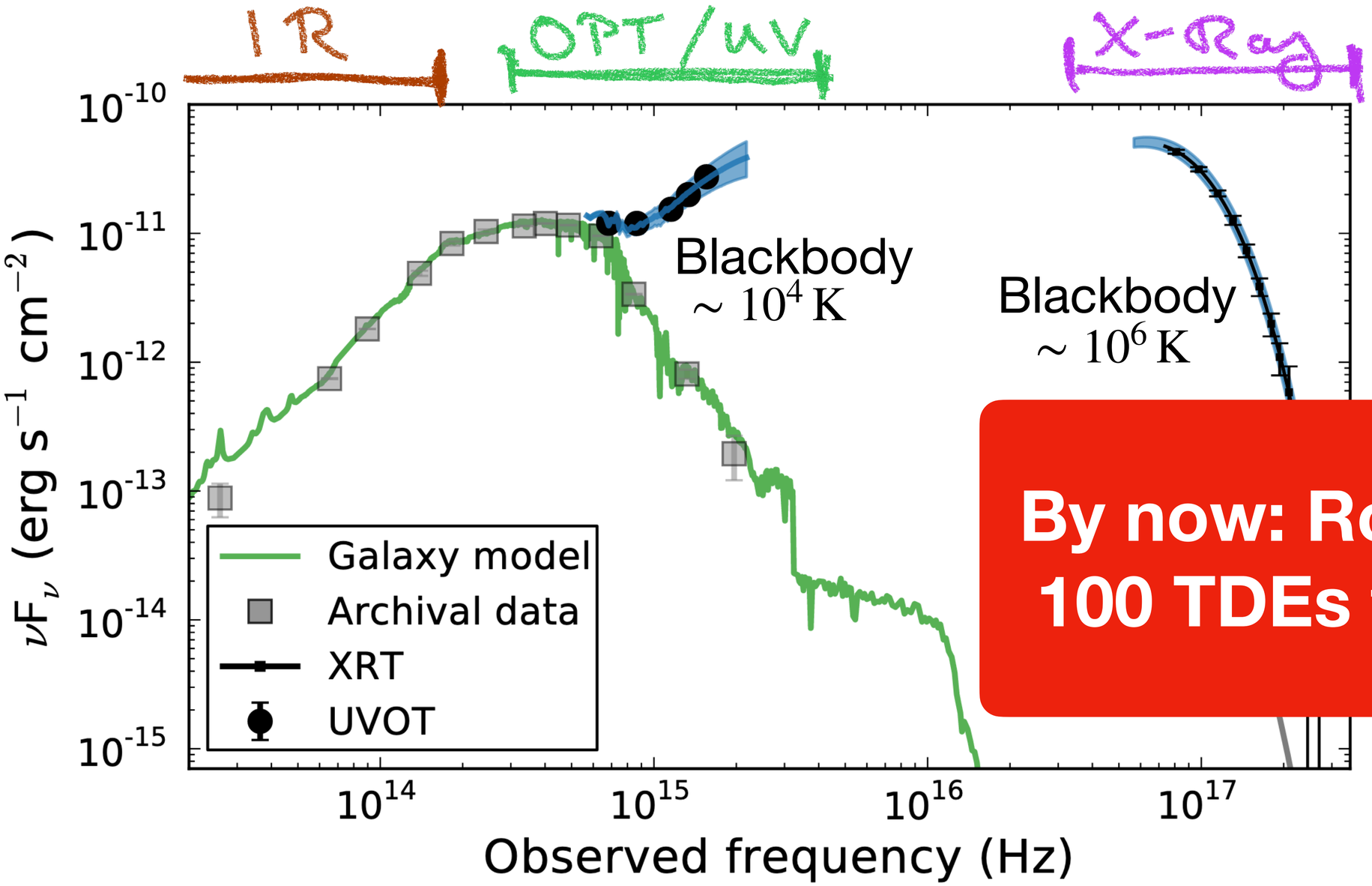
ASASSN-14li: van Velzen et al. (2016, Science)

What are Tidal Disruption Events (TDEs)?



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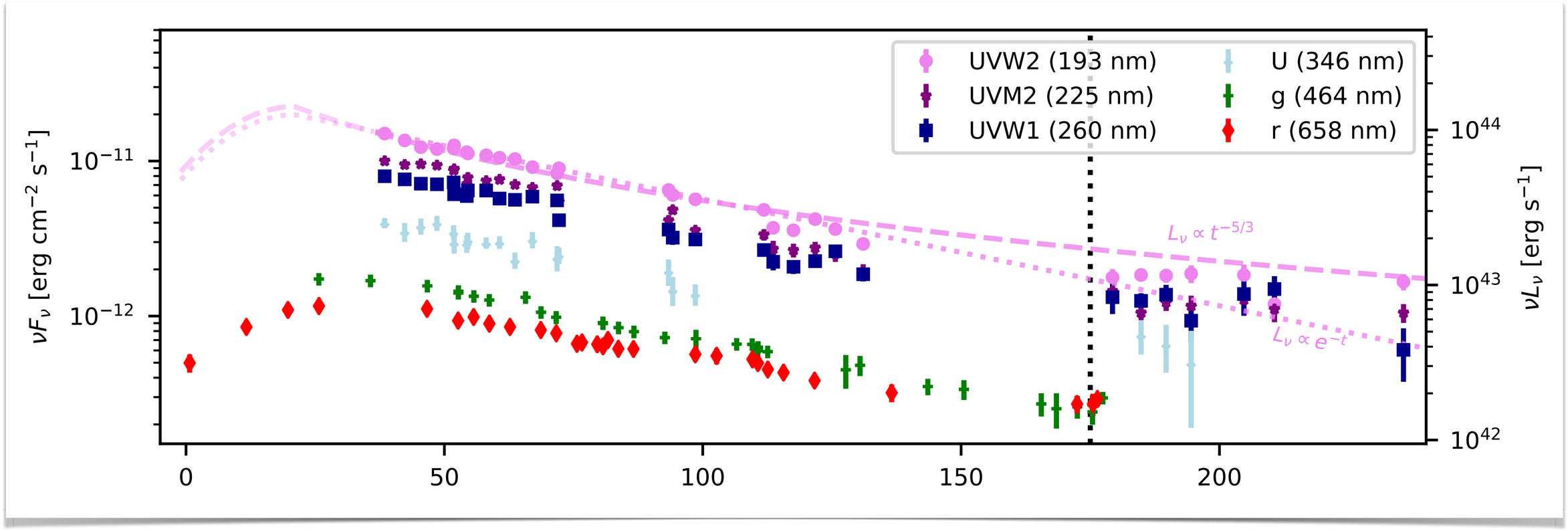


By now: Roughly 100 TDEs found

ASASSN-14li: van Velzen et al. (2016, Science)

AT2019dsg: First TDE-neutrino association





Stein et. al. (2021, Nature Astronomy)

AT2019fdr: Second TDE-neutrino association

Nuclear flare, very (!) long-lived

Host: AGN (NLSy1)

SLSN origin was debated

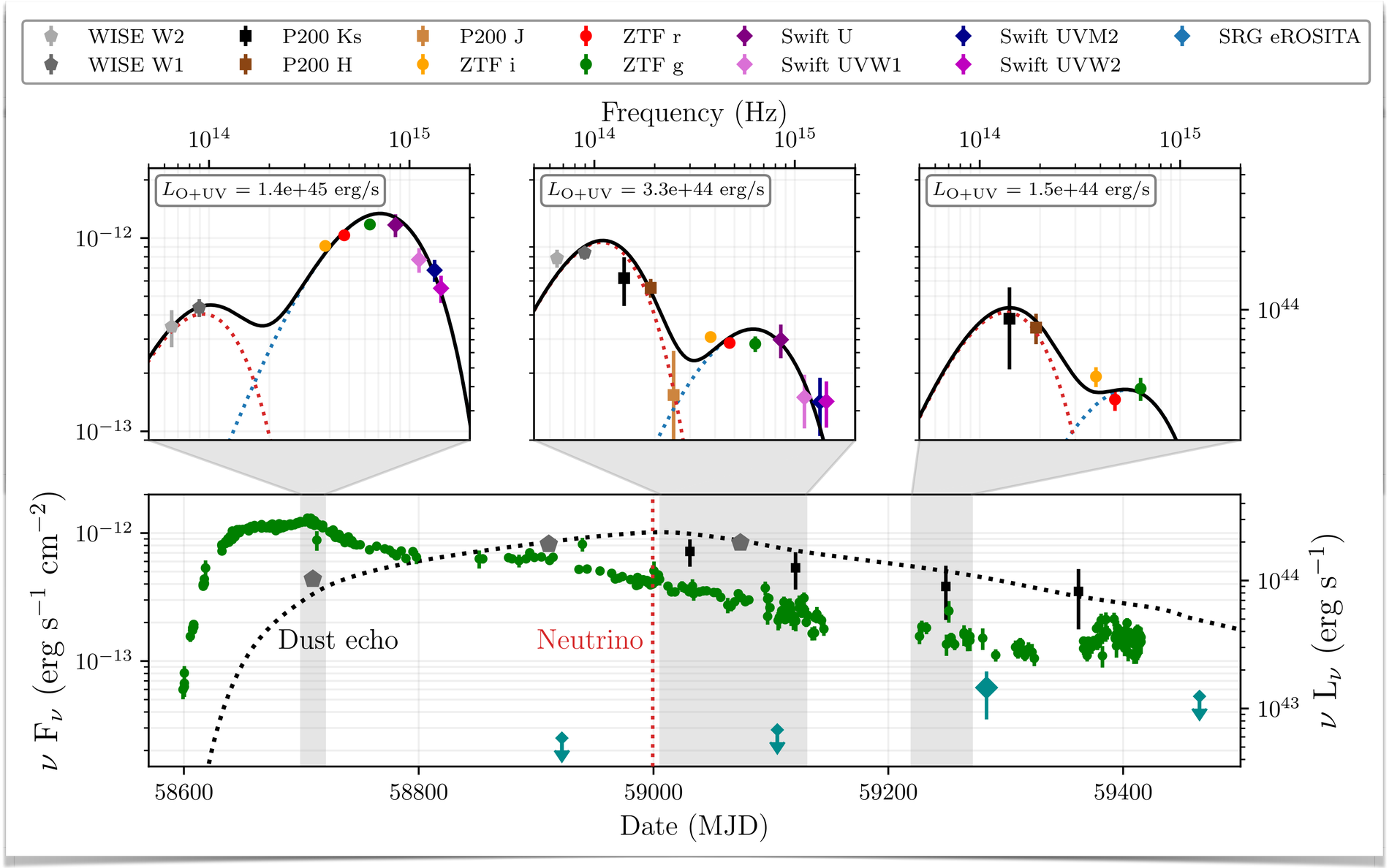
$$z = 0.267$$

$$M_{\mathrm{SMBH}} = 10^{7.55 \pm 0.13}\ M_{\odot}$$



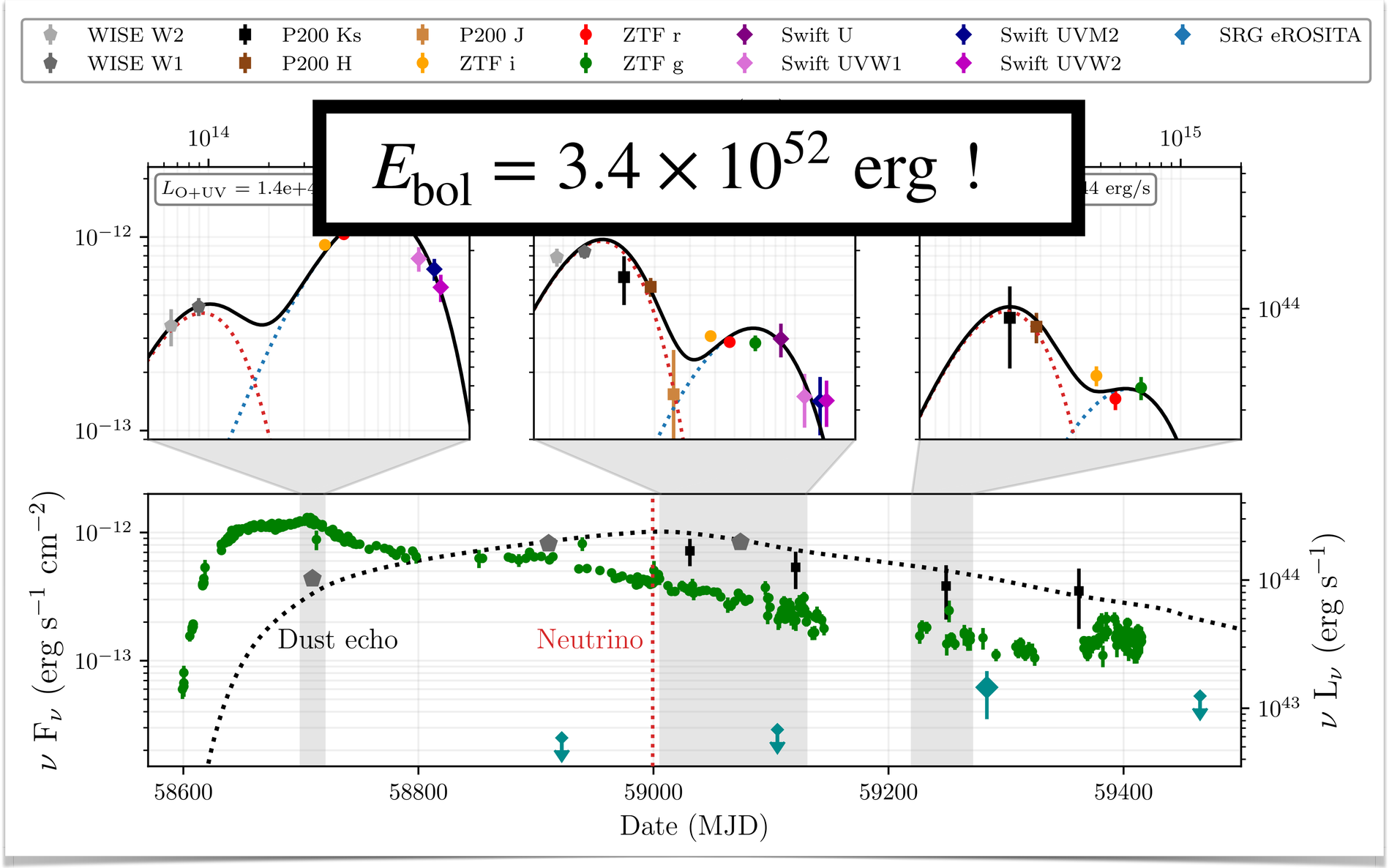
Reusch et. al. (2022, Phys. Rev. Lett.)

AT2019fdr: Second TDE-neutrino association



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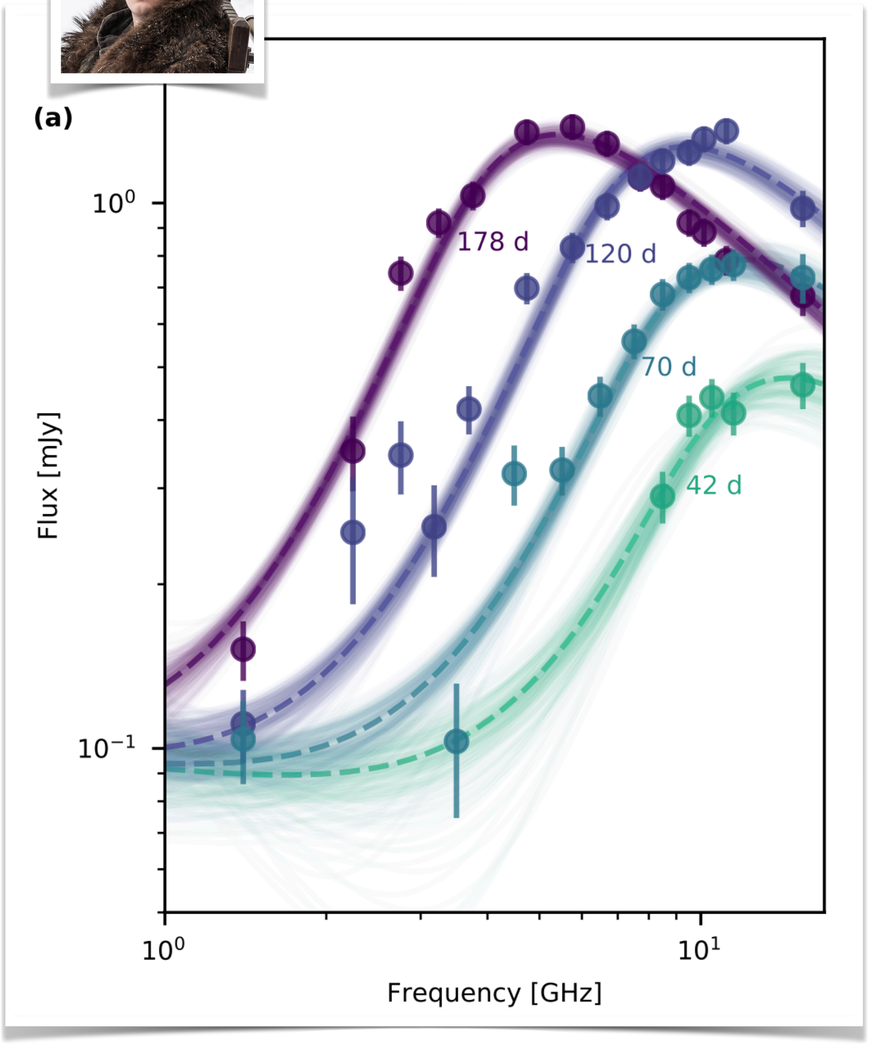


Reusch et. al. (2022, Phys. Rev. Lett.)

Radio observations (VLA)



AT2019dsg

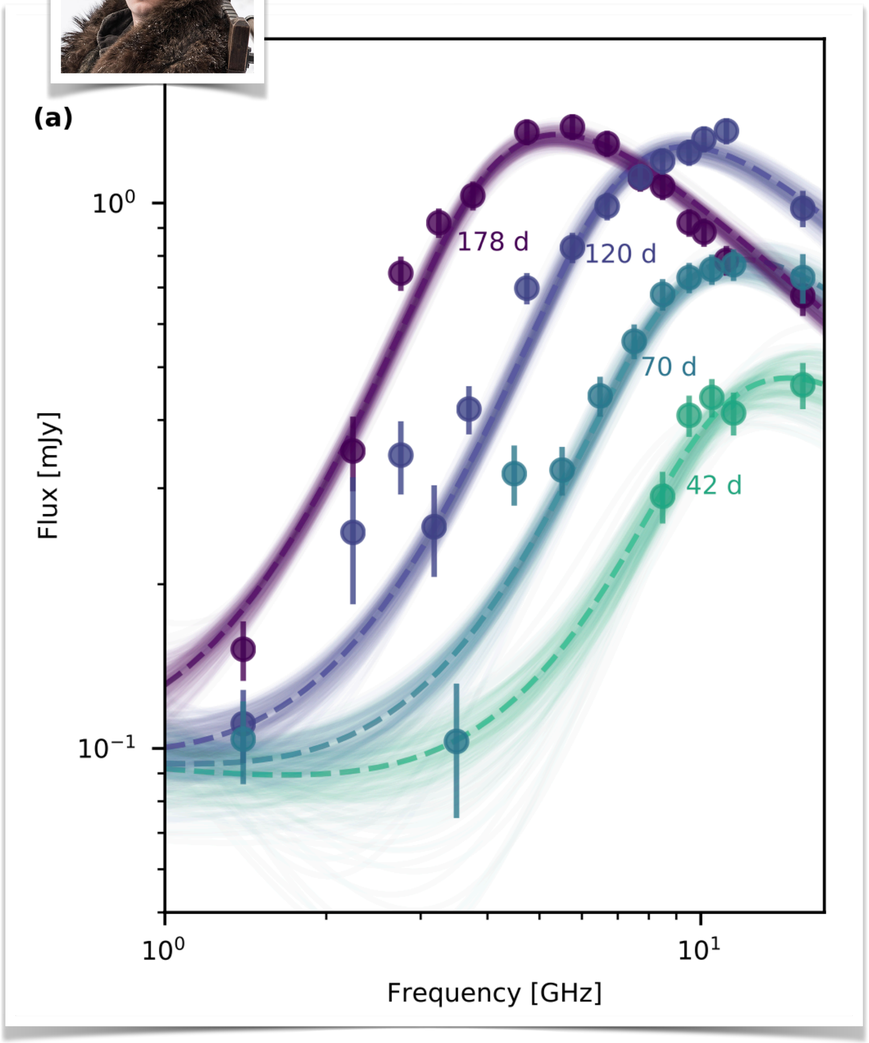


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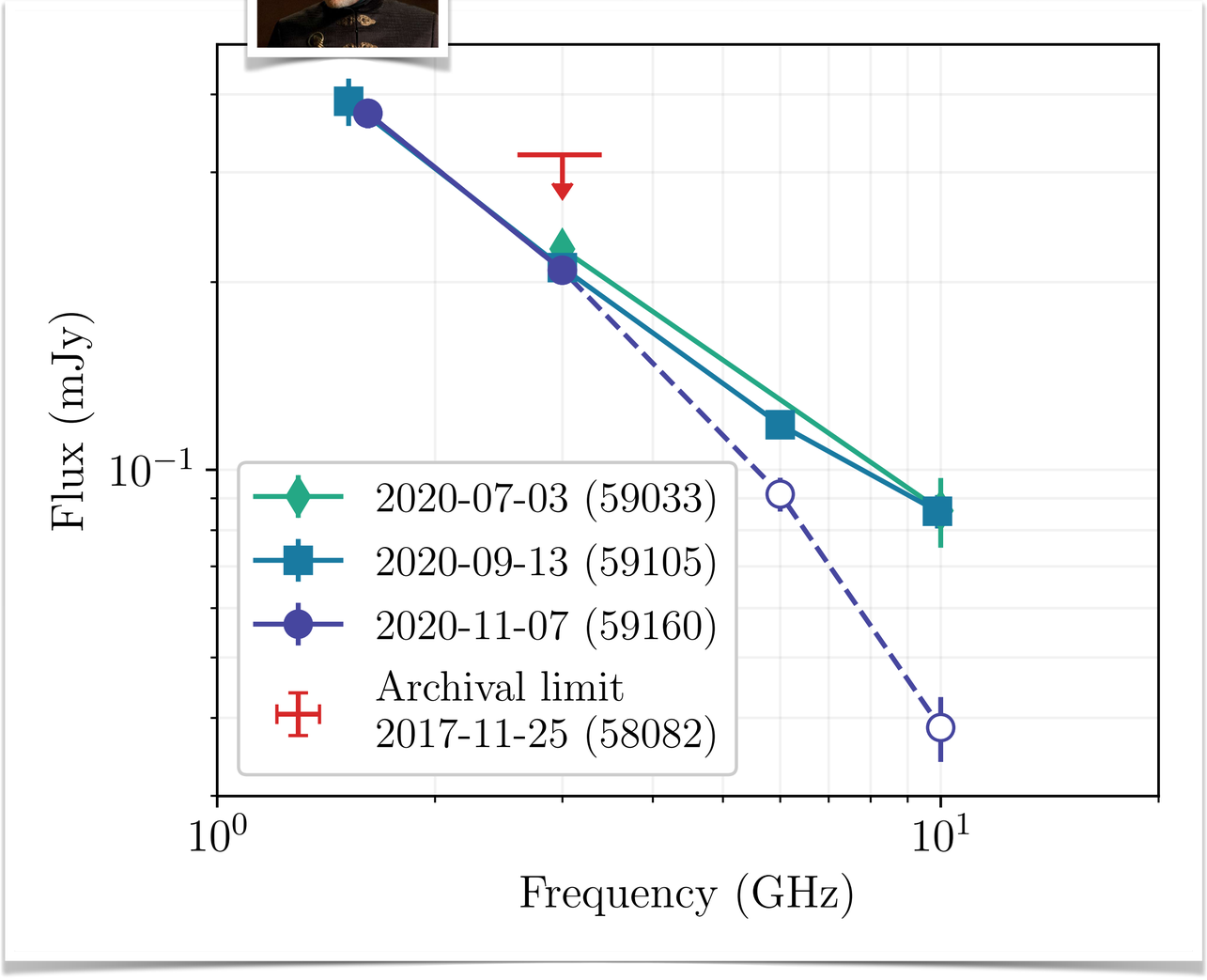


AT2019dsg





AT2019fdr

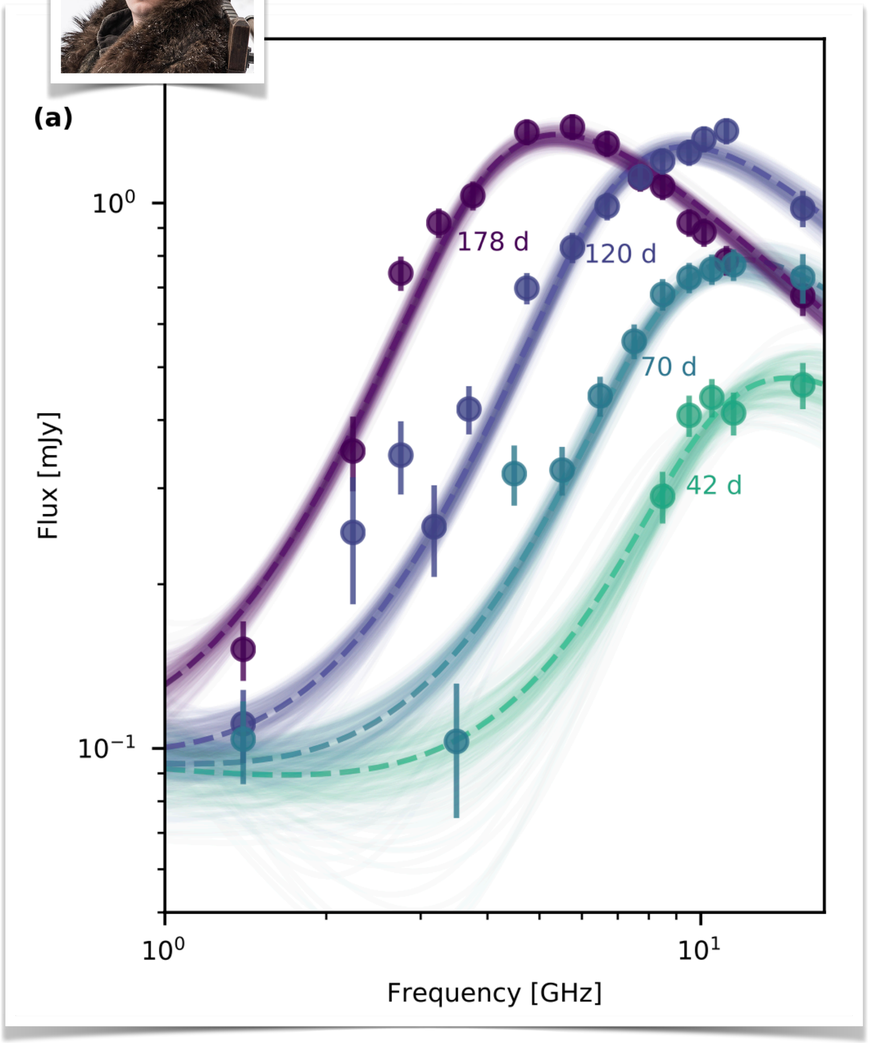


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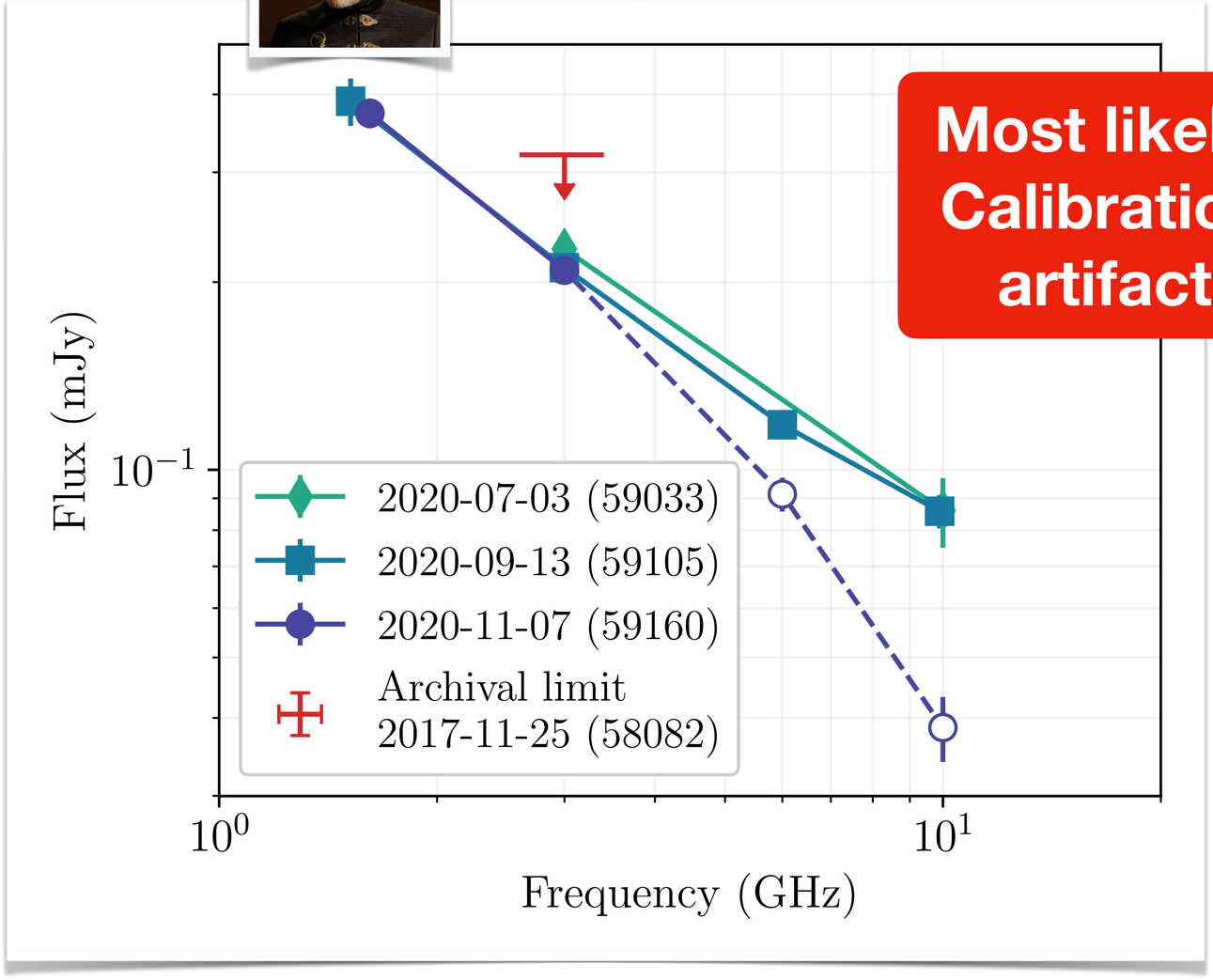


AT2019dsg





AT2019fdr



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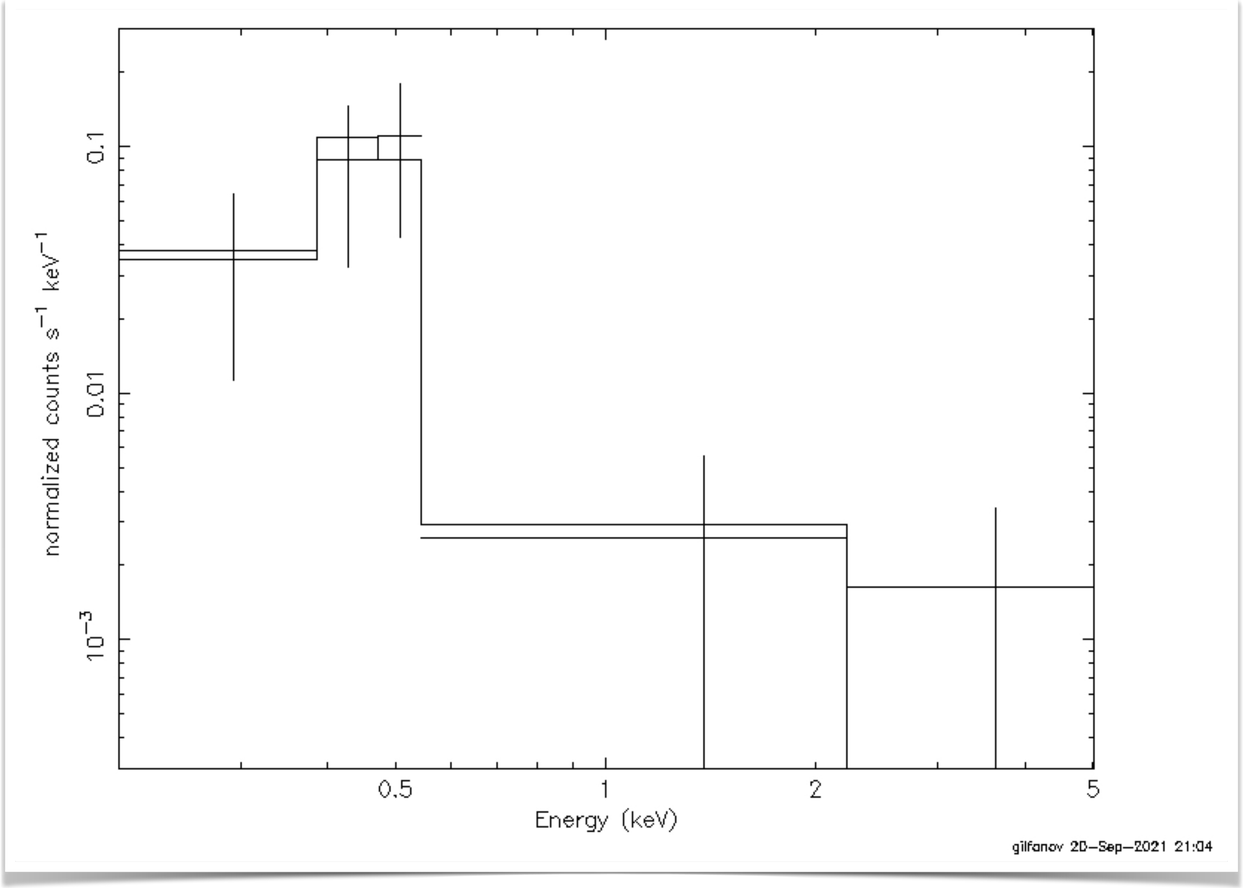
X-ray observations (SRG/eROSITA)

Detected on the third visit

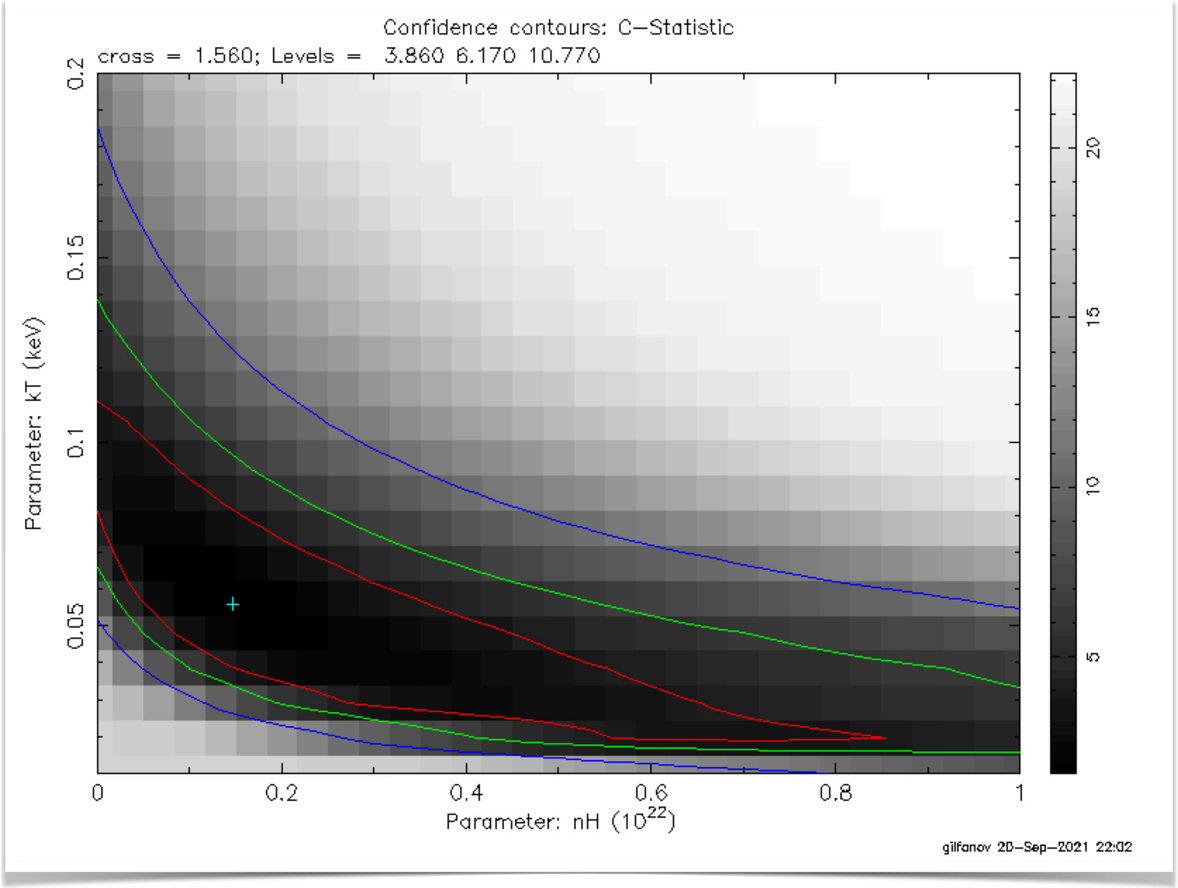
X-ray observations (SRG/eROSITA)

Detected on the third visit

Soft spectrum



Temperature fit: 71 eV



AT2019fdr neutrino spectra

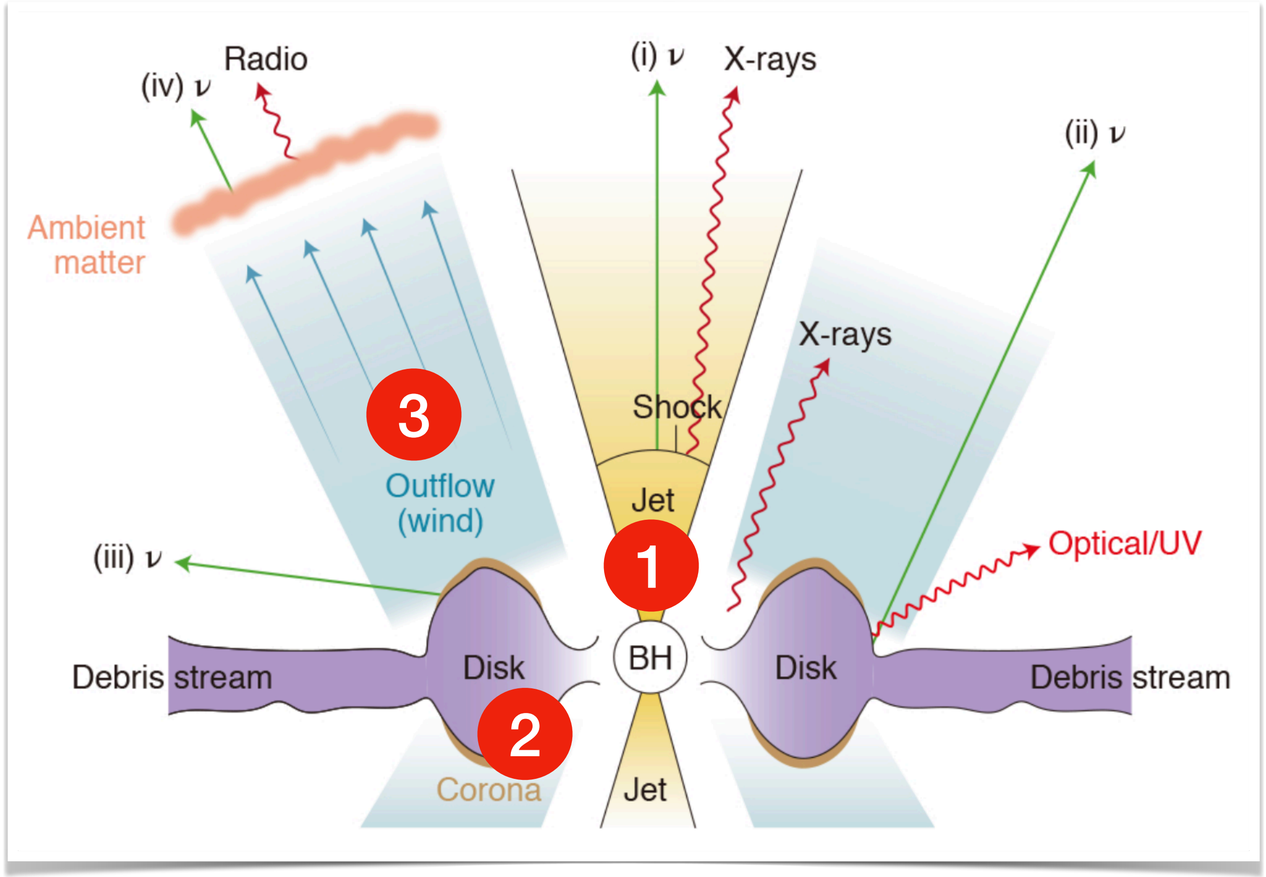
TDEs suggested as sources of HE neutrinos:	Dai & Fang (2017, MNRAS) Hayasaki & Yamazaki (2019, ApJ) Winter & Lunardini (2017, Phys. Rev. D)

Hayasaki (2021, Nat. Astron.), Reusch et. al. (2022, Phys. Rev. Lett.)

AT2019fdr neutrino spectra

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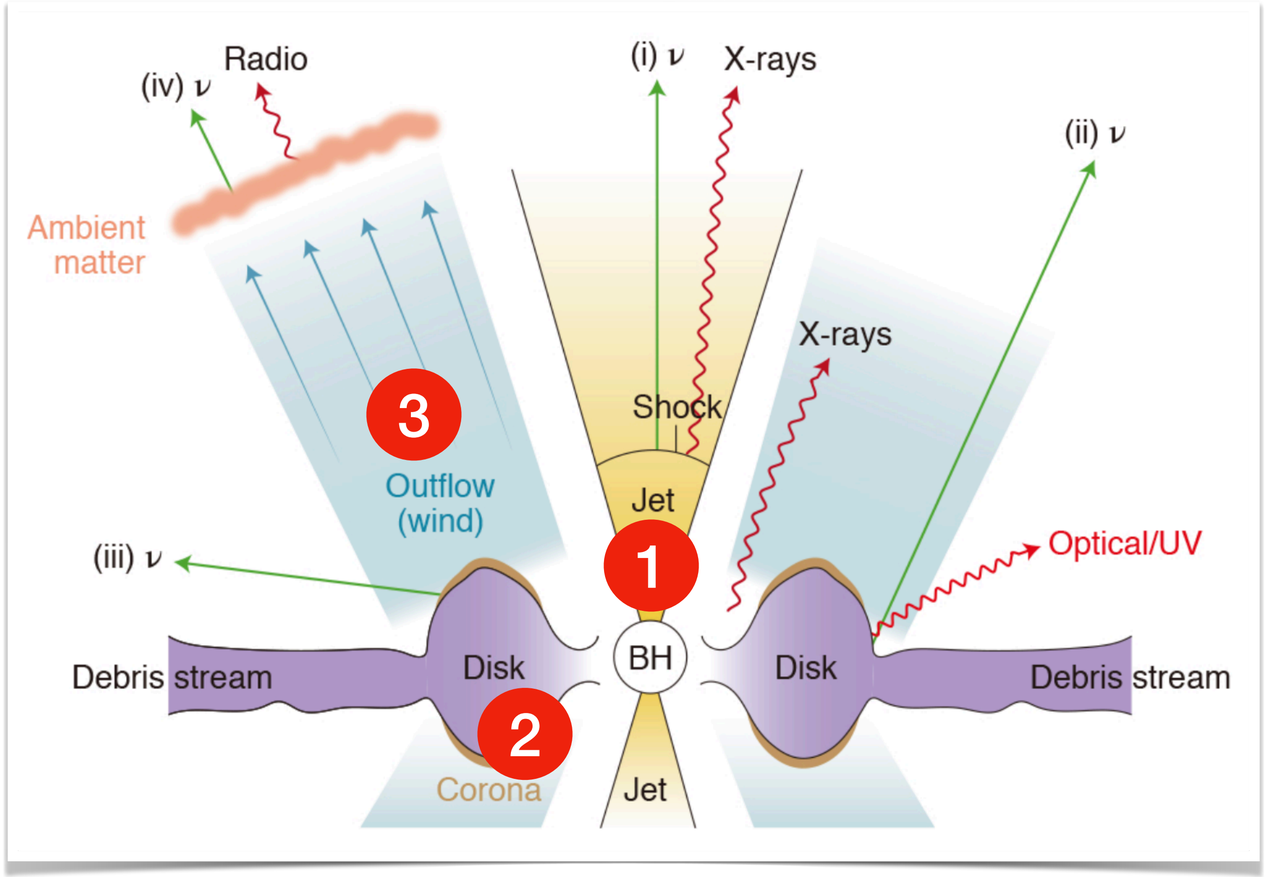


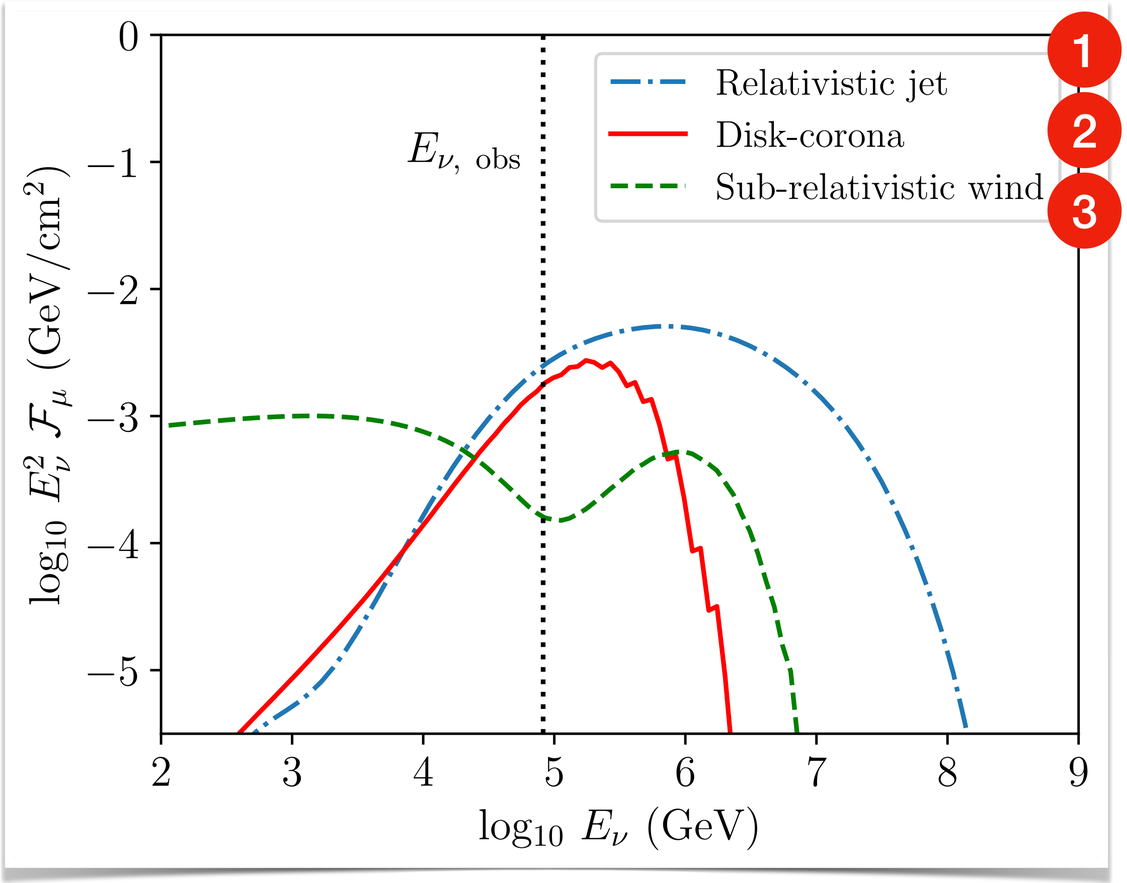
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AT2019fdr neutrino spectra

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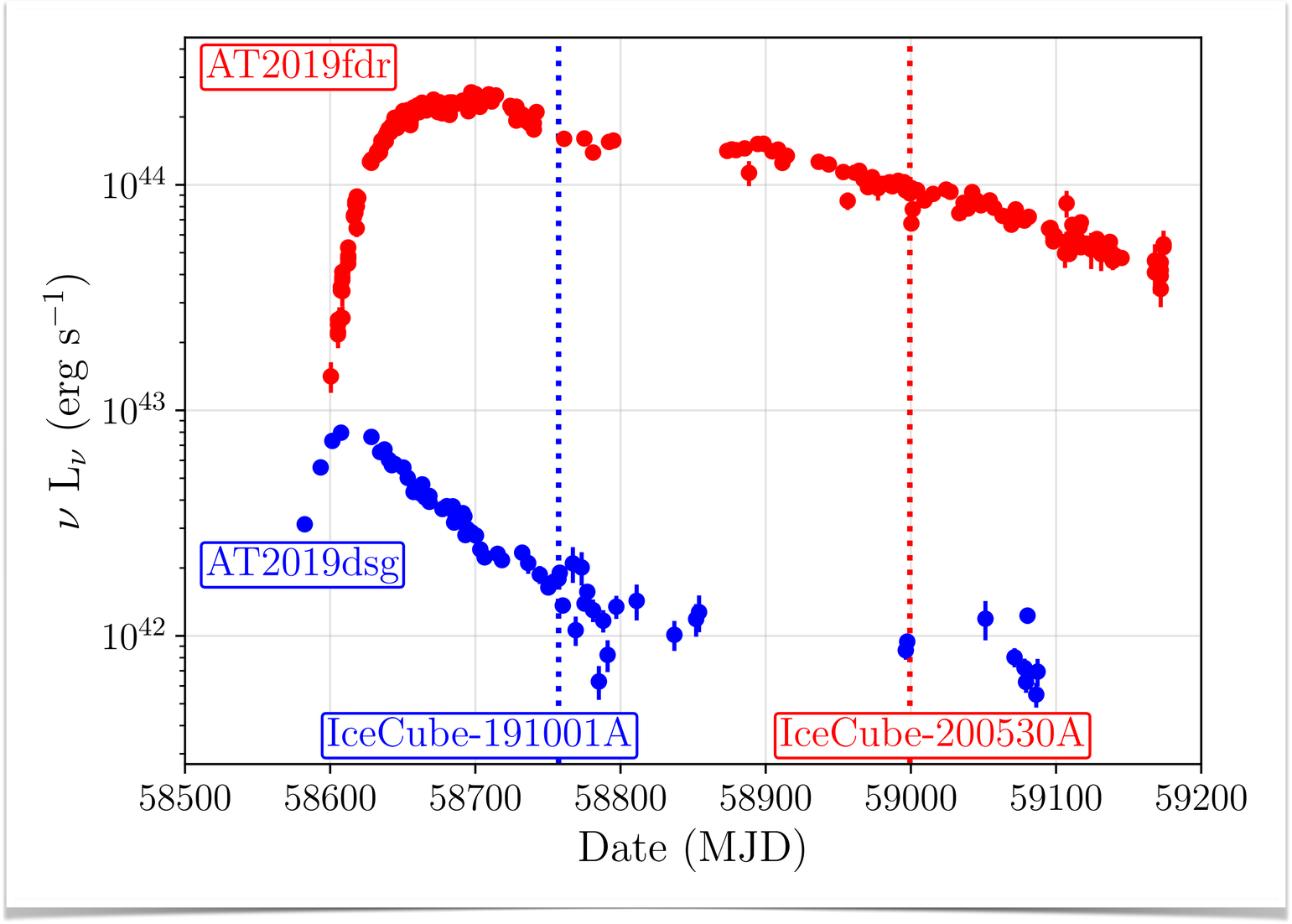
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Hayasaki & Yamazaki (2019, ApJ)
Winter & Lunardini (2017, Phys. Rev. D)





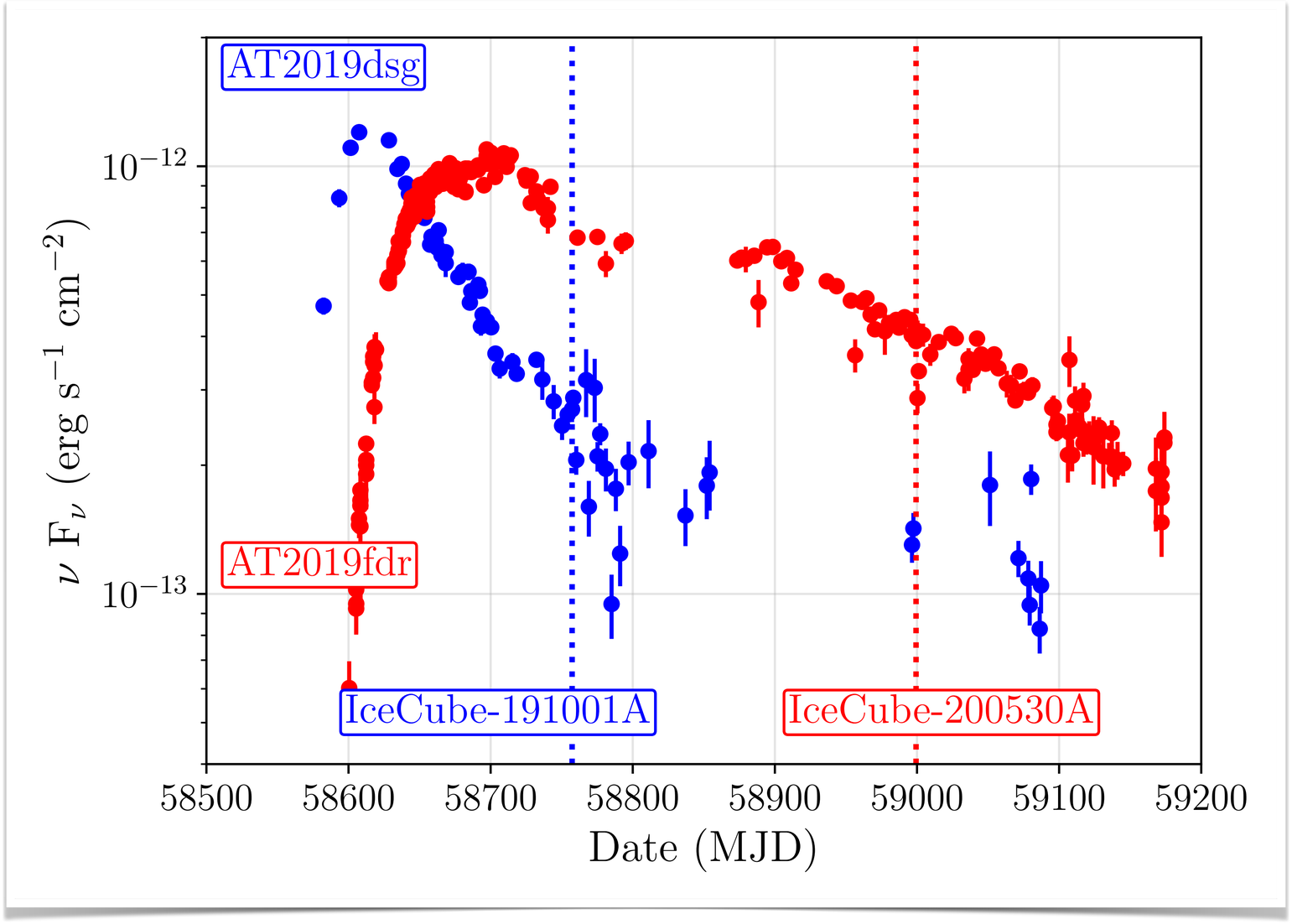
Hayasaki (2021, Nat. Astron.), Reusch et. al. (2022, Phys. Rev. Lett.)

Luminosity comparison



Luminosity of AT2019fdr much higher

Flux comparison



But comparable flux on earth

Comparison





	AT2019dsg	AT2019fdr
TDE	yes	likely
Peak Luminosity	$3.5 \times 10^{44}\,\mathrm{erg\,s^{-1}}$	$1.3 \times 10^{45}\,\mathrm{erg\,s^{-1}}$
SMBH Mass	$10^{6} - 10^{6.7}\ M_{\odot}$	$10^{7.55\pm0.13}\ M_{\odot}$
Radio	evolving	non-evolving
UV	very bright	bright
X-ray	early, soft spectrum	late, soft spectrum
Dust echo	very strong	strong
Neutrino delay	~ 5 months	~ 10 months
nu production?	yes	yes

Comparison





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Combined population:

Comparison





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Combined population:

Confirmed TDEs + accretion flares

Brightness + rise/fade-time cuts

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Brightness + rise/fade-time cuts

Combined chance coincidence:

$p = 3.44 \times 10^{-4}\ (3.4\,\sigma)$

Dust echo

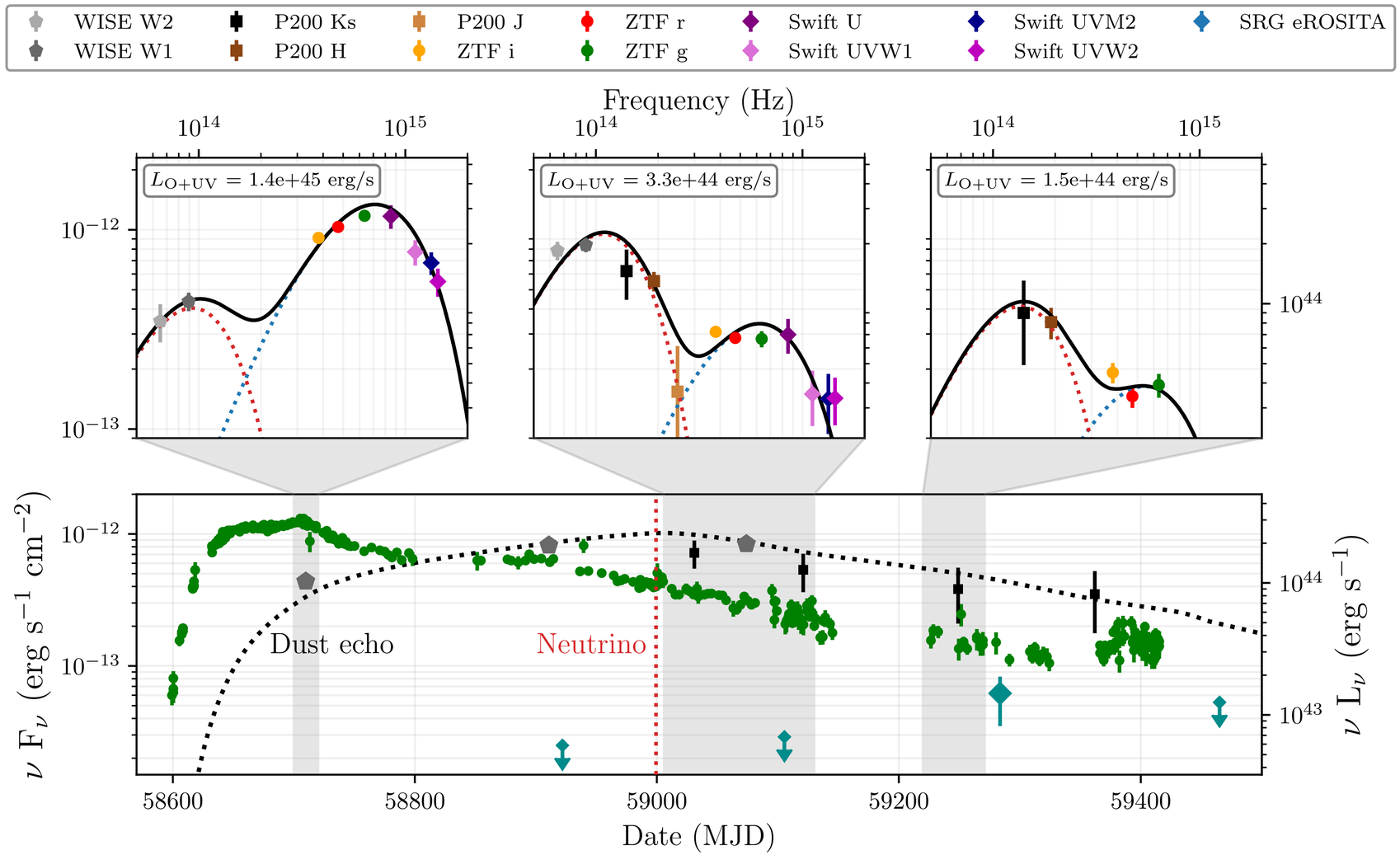


Image credit: DESY / Science Communication Lab

Dust echo

AT2019fdr





ZTF g

WISE W1

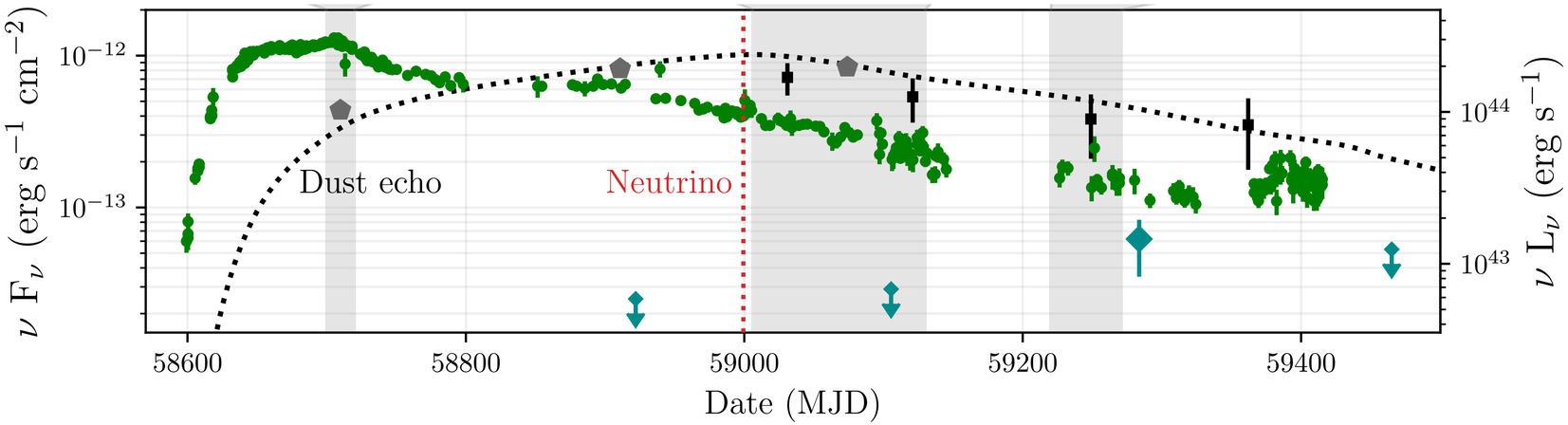
Dust echo

AT2019fdr



ZTF g

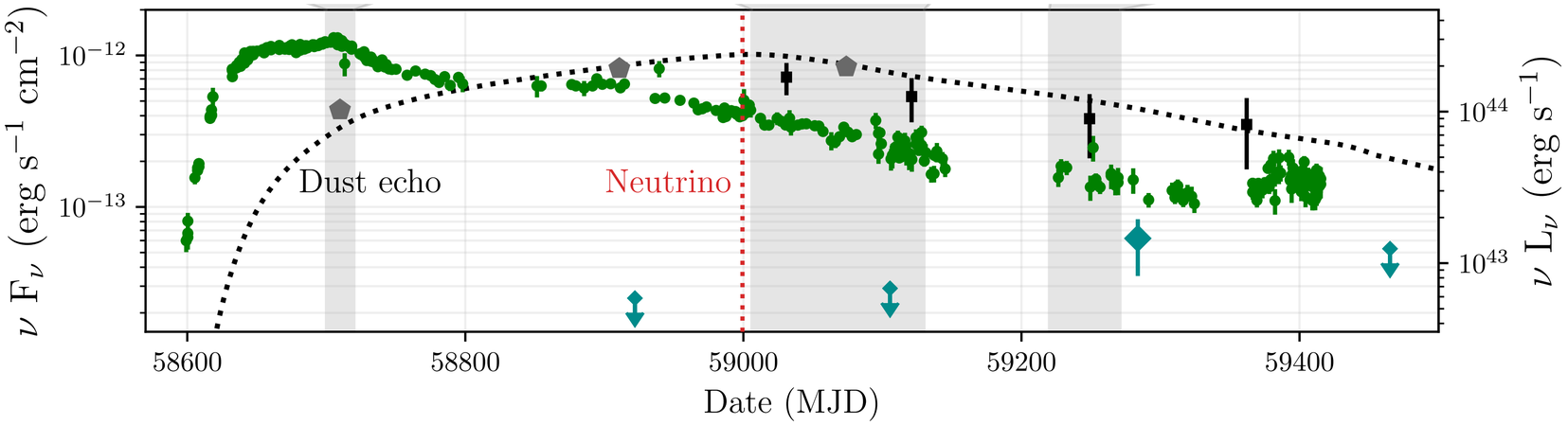
WISE W1



Dust echo

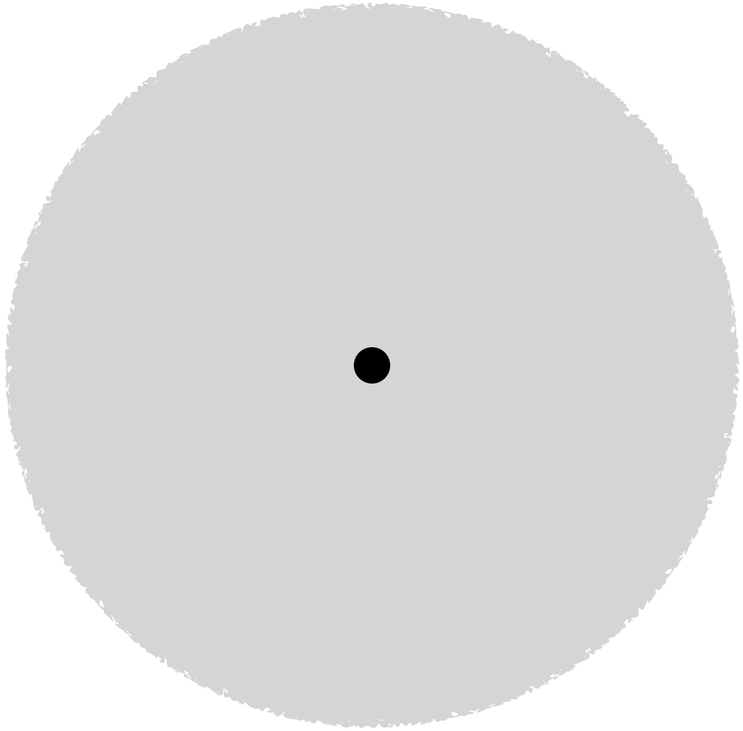
AT2019fdr





ZTF g

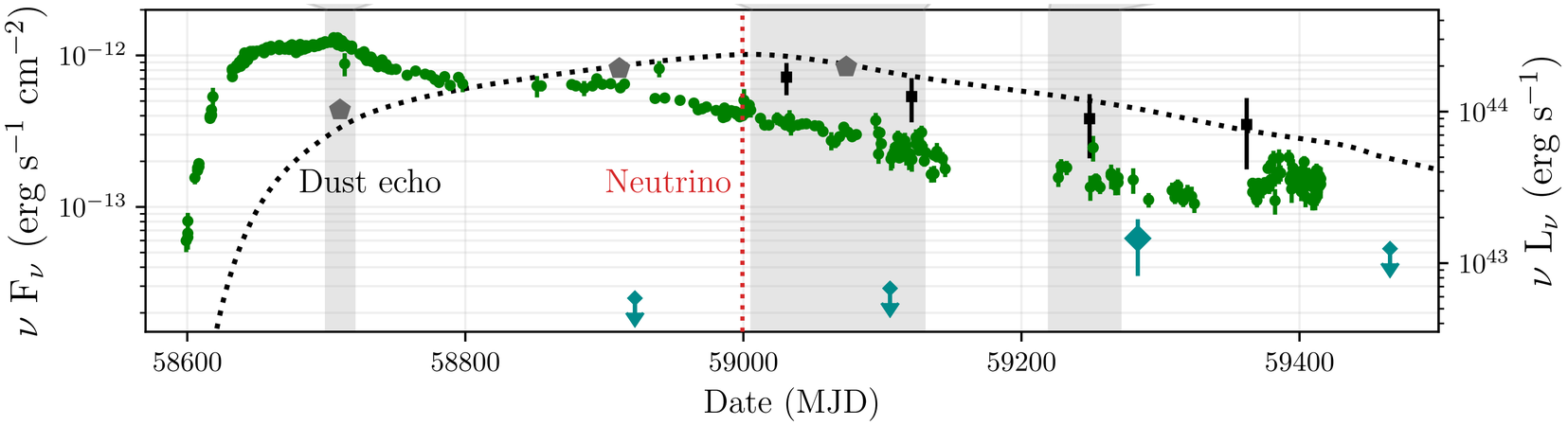
WISE W1



Dust echo

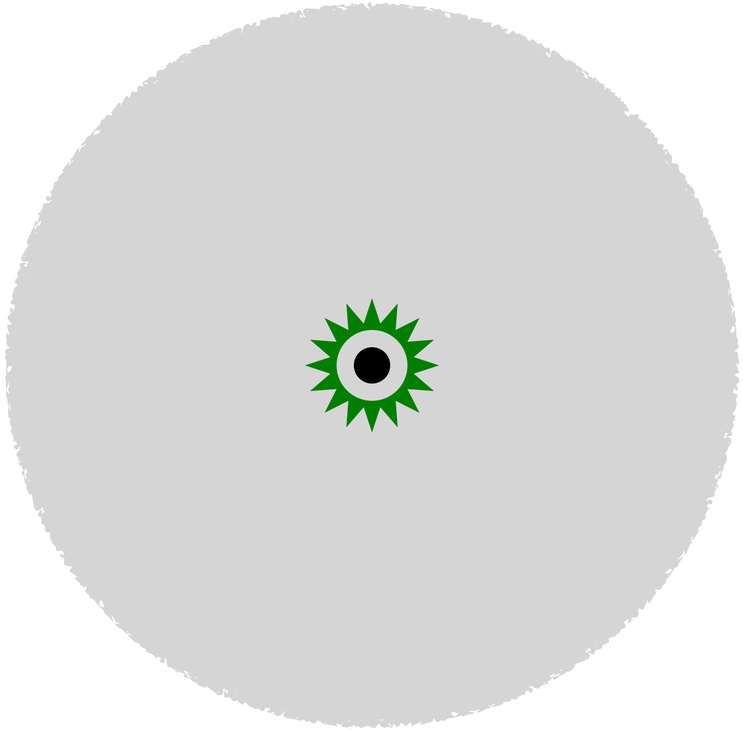
AT2019fdr





ZTF g

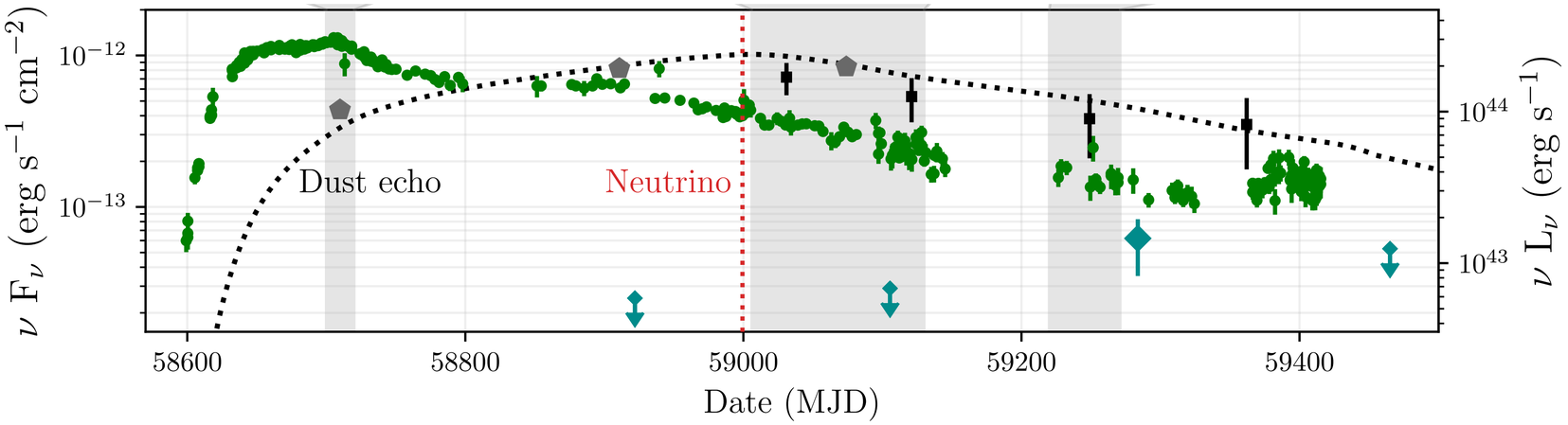
WISE W1



Dust echo

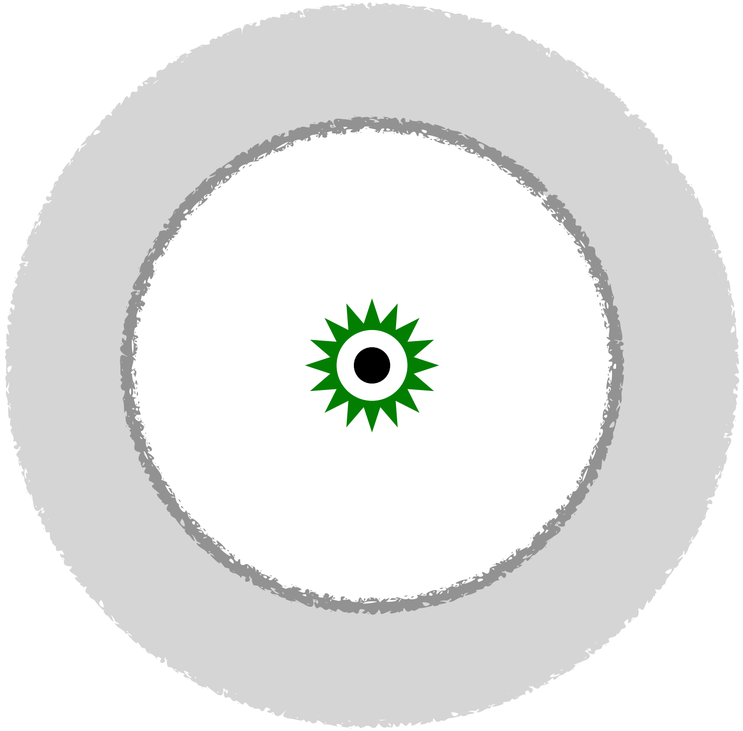
AT2019fdr





ZTF g

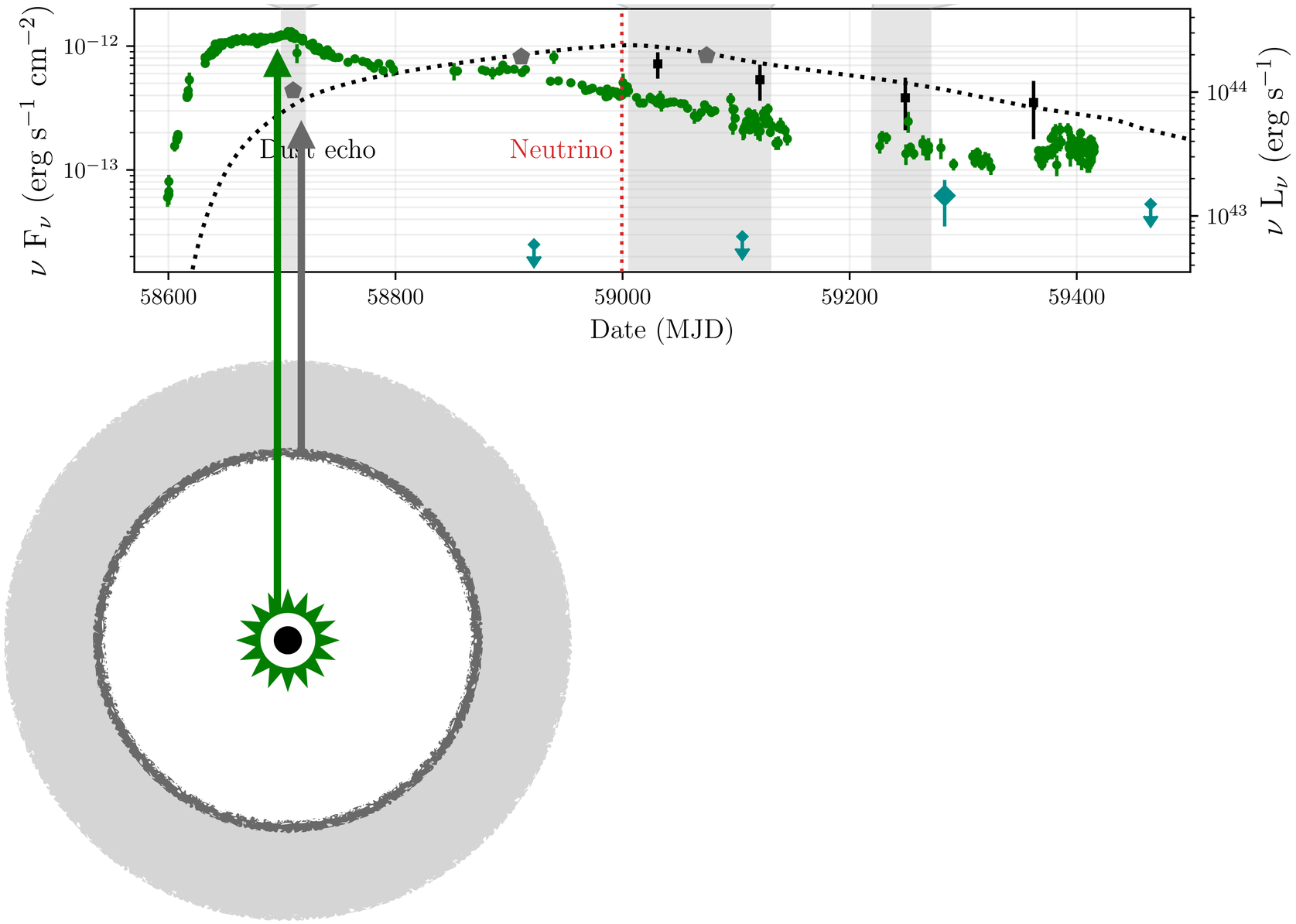
WISE W1



Dust echo

AT2019fdr





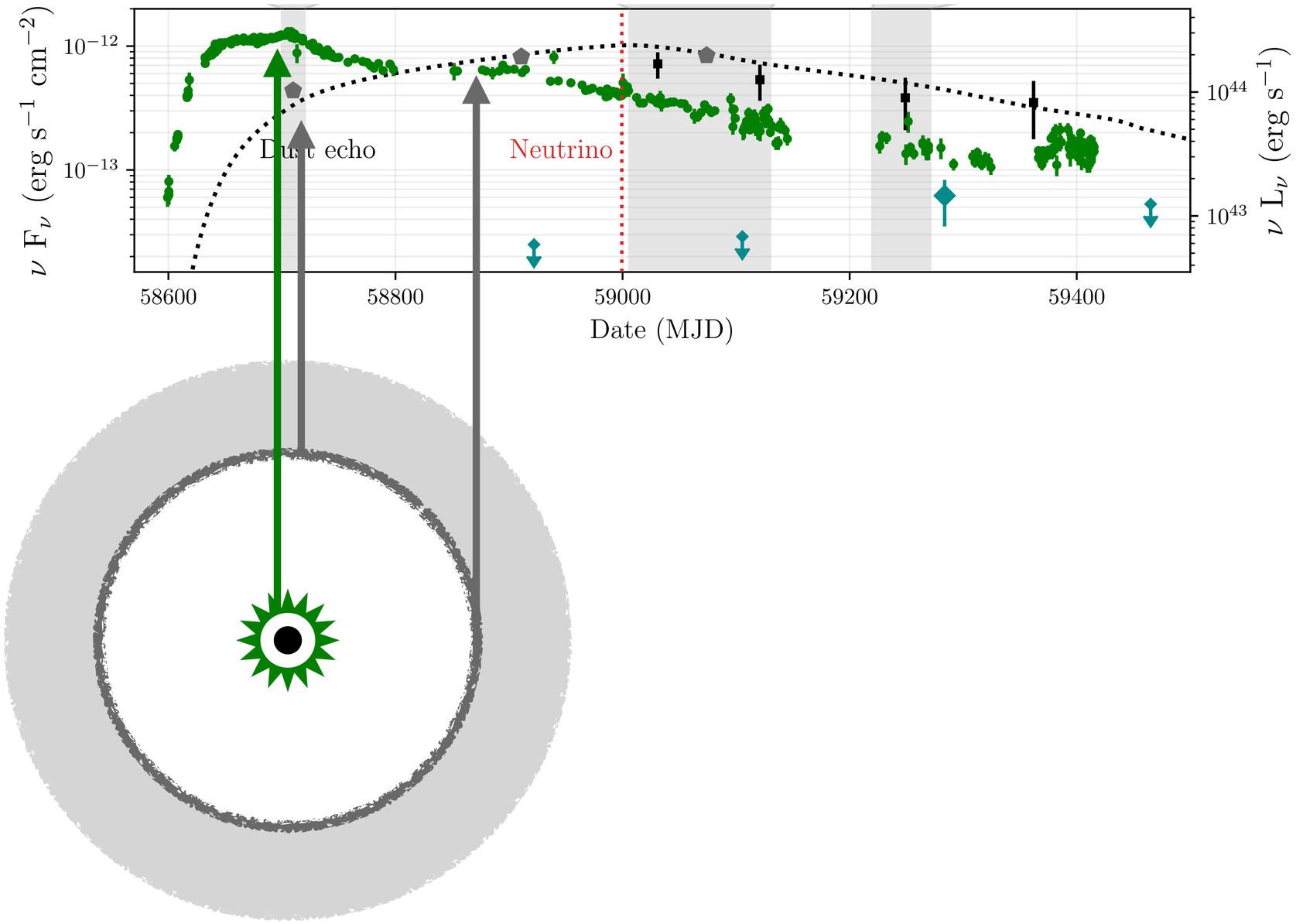
ZTF g

WISE W1

Dust echo

AT2019fdr





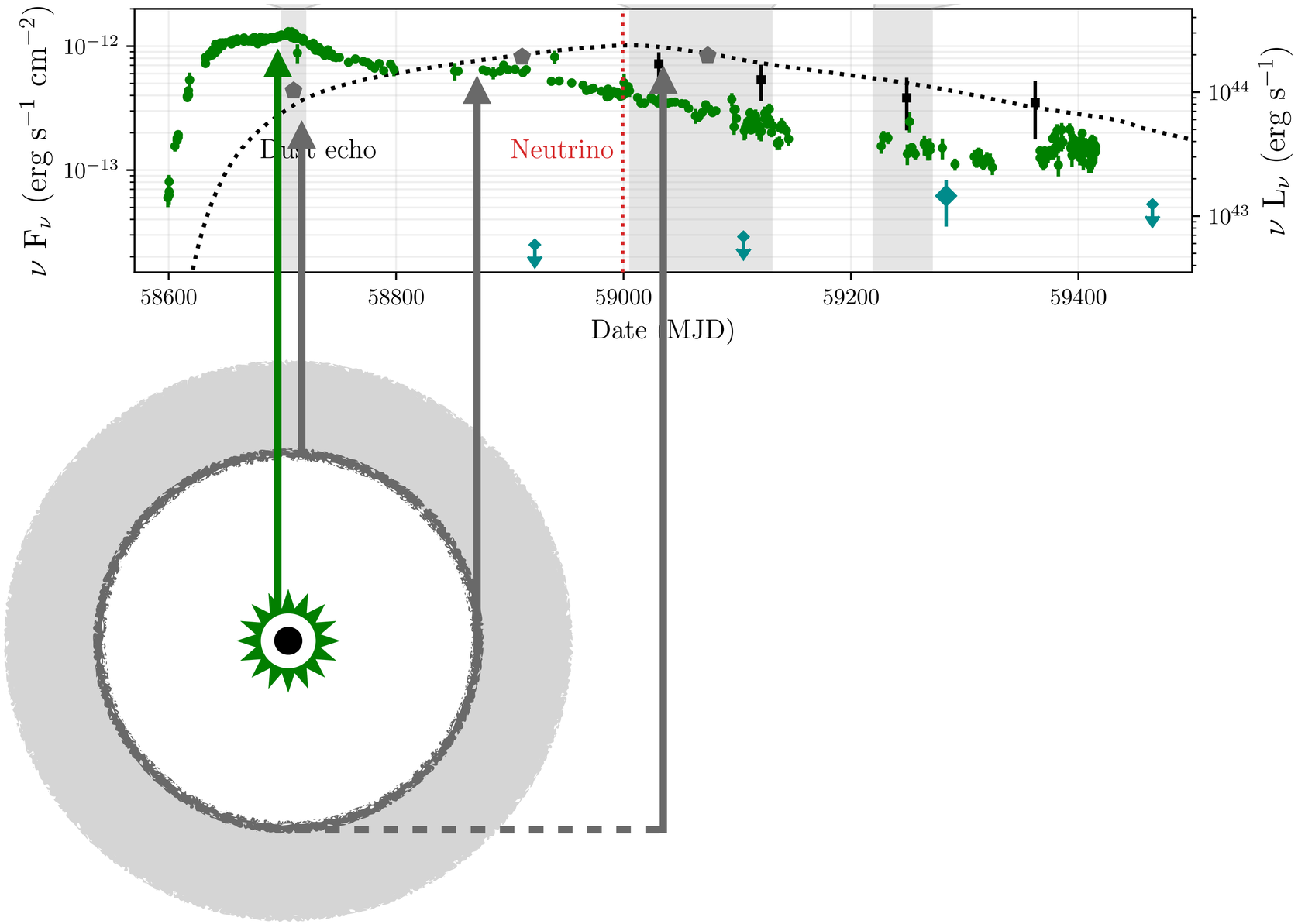
ZTF g

WISE W1

Dust echo

AT2019fdr





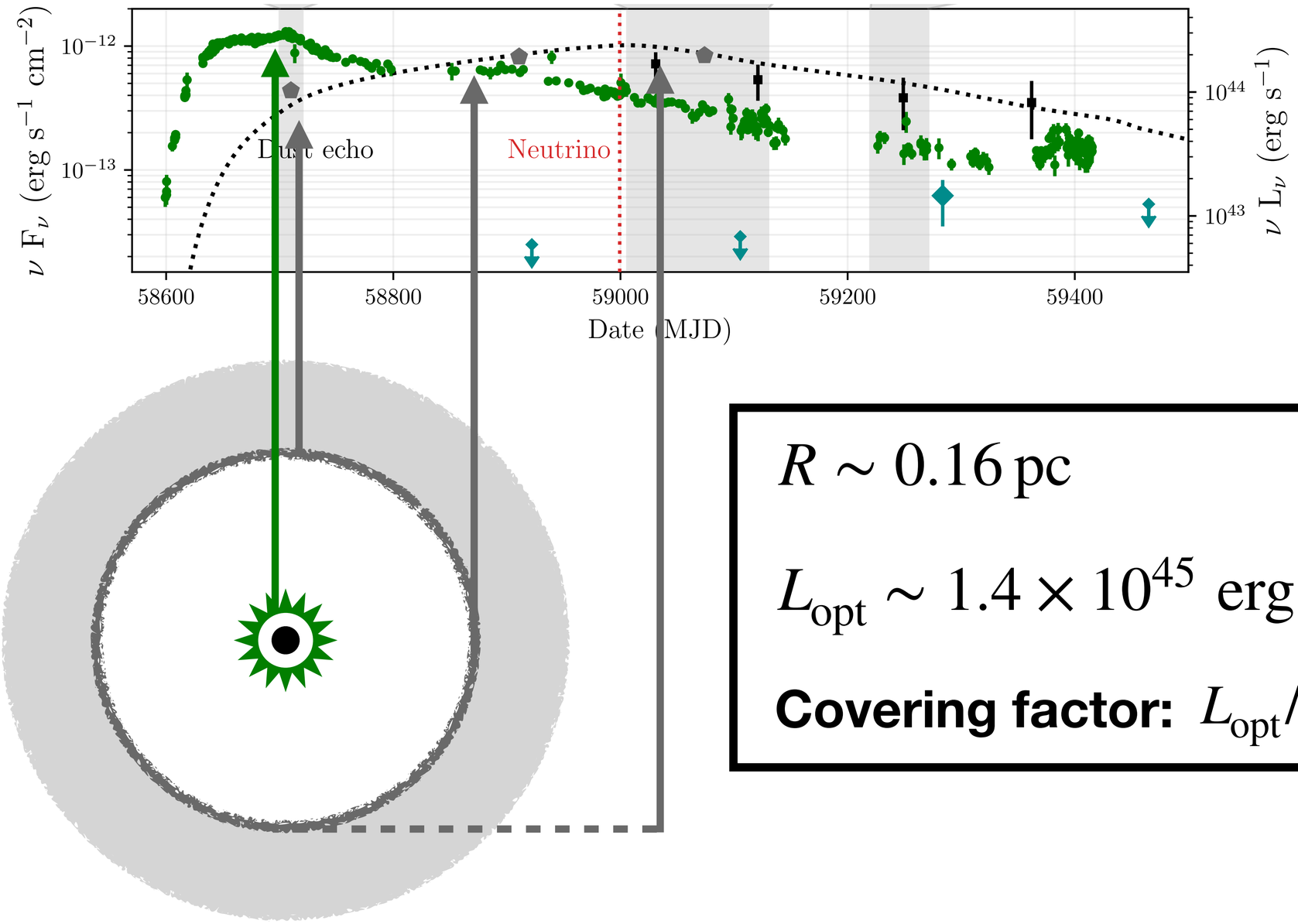
ZTF g

WISE W1

Dust echo

AT2019fdr



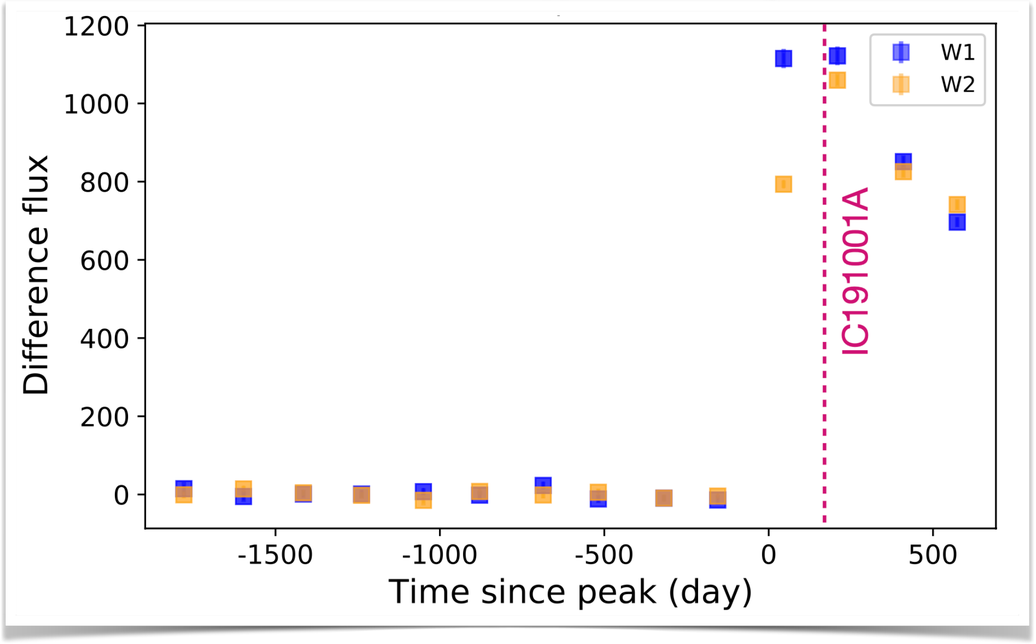


$$R \sim 0.16\,\mathrm{pc}$$

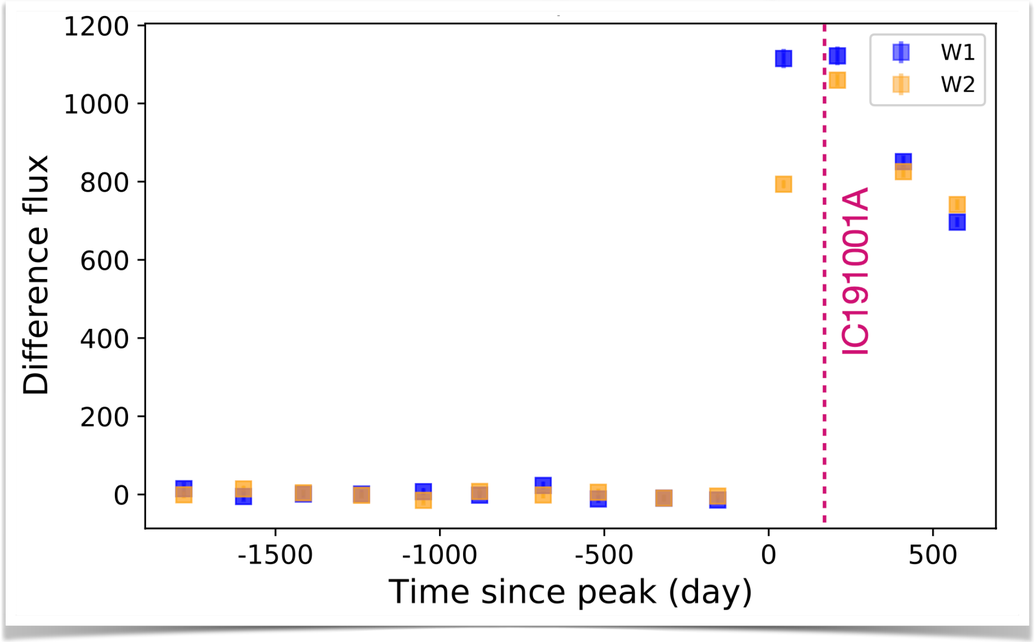
$$L_{\mathrm{opt}} \sim 1.4 \times 10^{45}\ \mathrm{erg\ s^{-1}}$$

Covering factor: $L_{\mathrm{opt}}/L_{\mathrm{dust}} \sim 33\,\%$

AT2019dsg () had a record-breaking dust echo

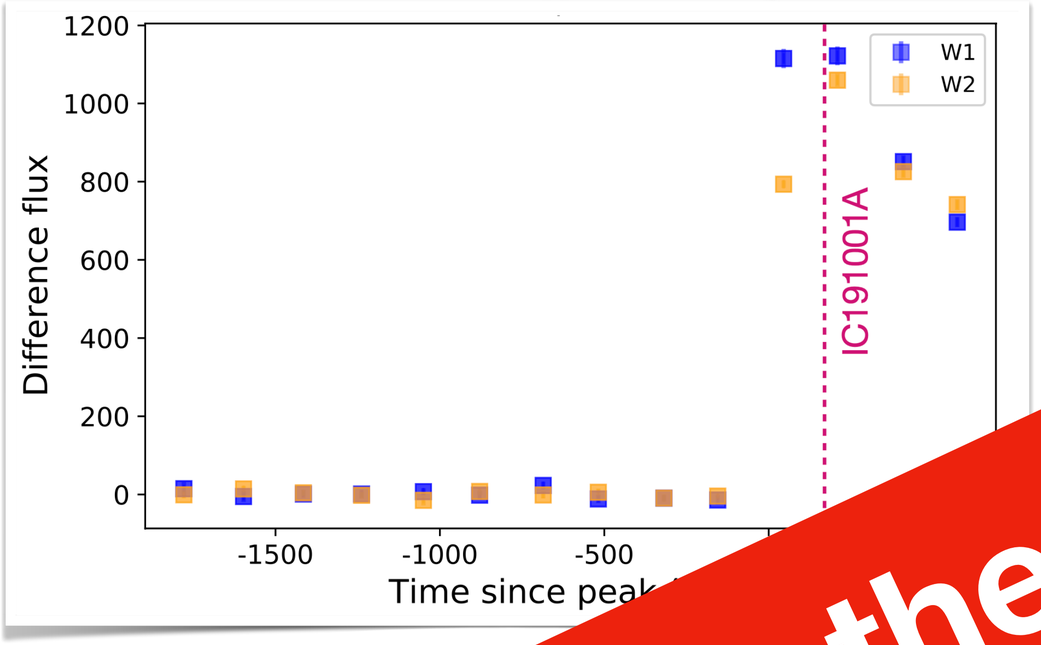


AT2019dsg () had a record-breaking dust echo



AT2019fdr () also has a strong dust echo

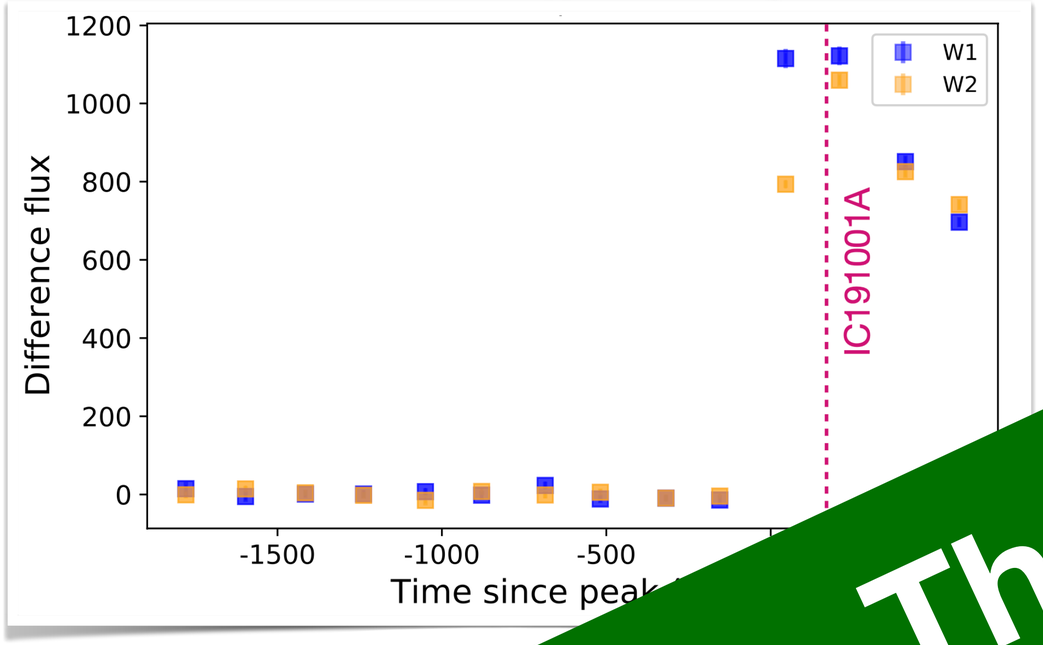
AT2019dsg () had a record-breaking dust echo



AT2019 ...lso has a strong dust echo

Is there more?

AT2019dsg () had a record-breaking dust echo



There is!

AT2019 ...lso has a strong dust echo

AT2019aalc: A third association

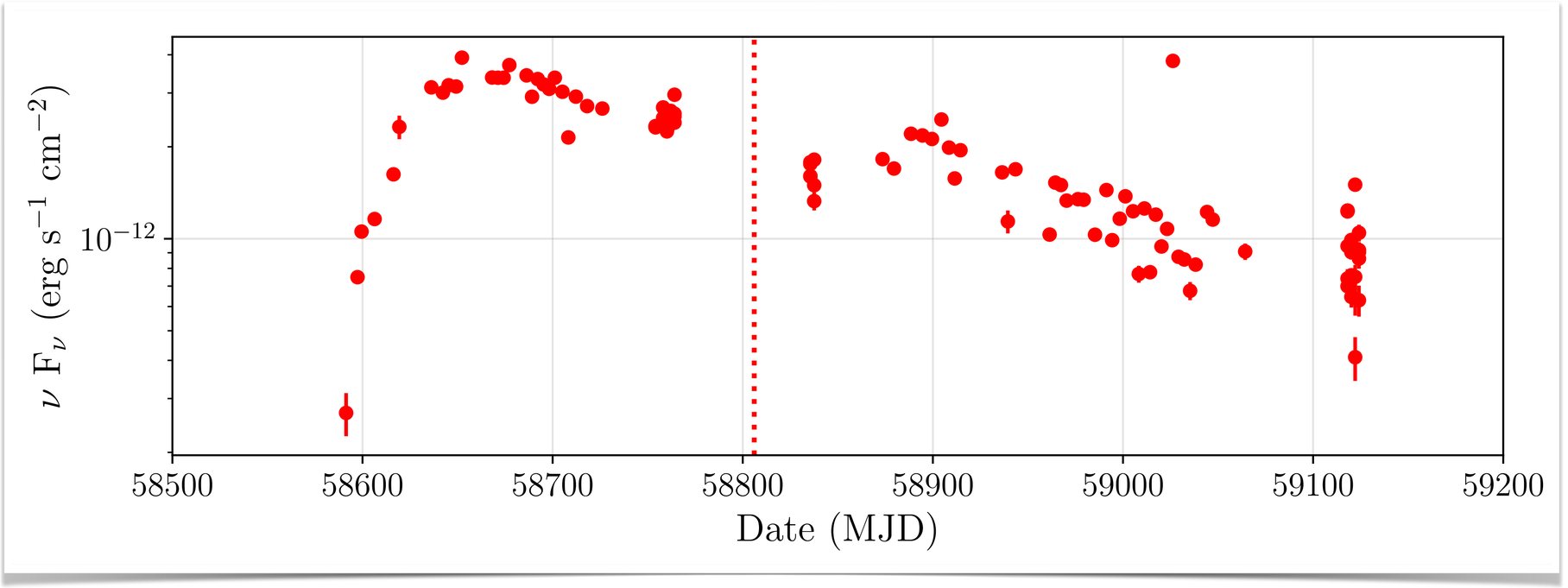
Systematic search for coincidence between IceCube public alerts and optical flares that show post-peak neoWISE infrared flares

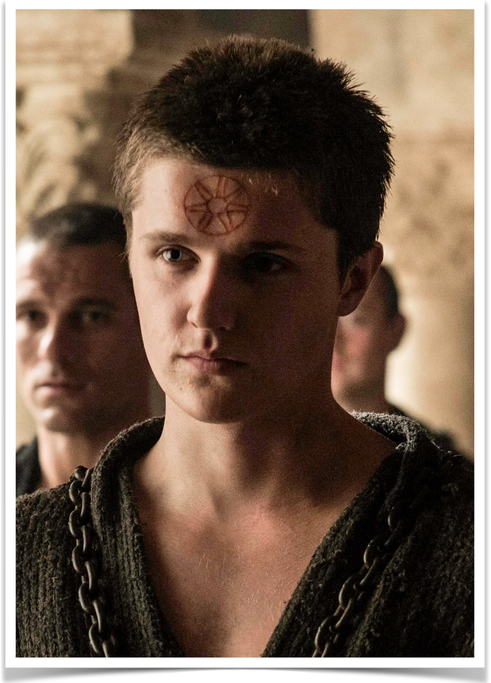
van Velzen et. al. (2021, submitted to Science)

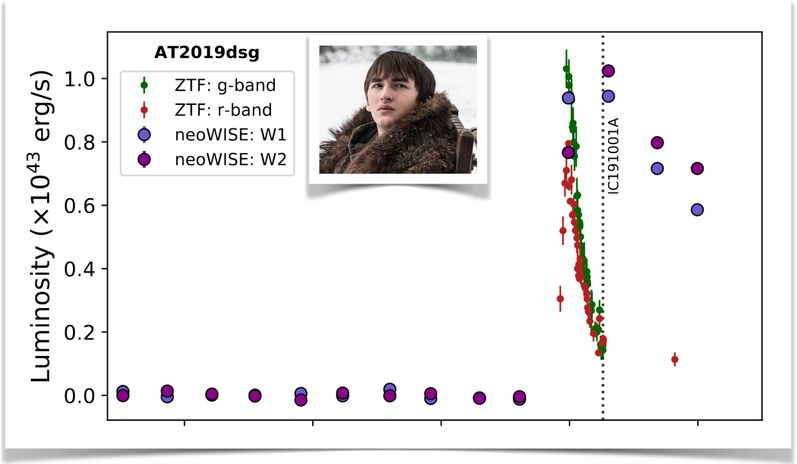
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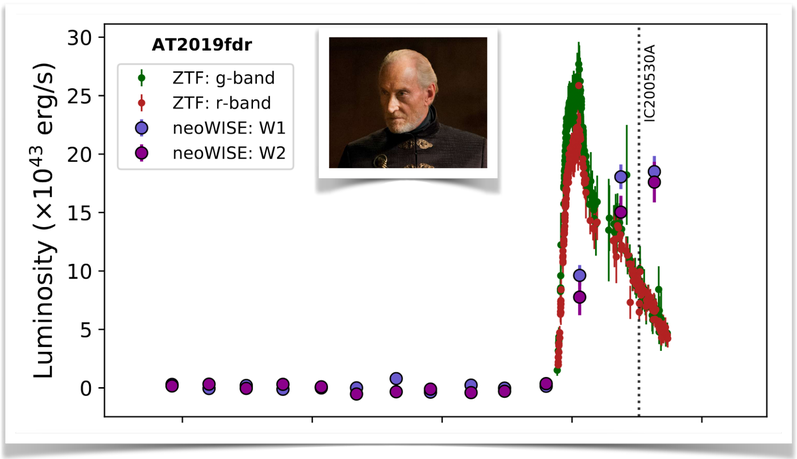
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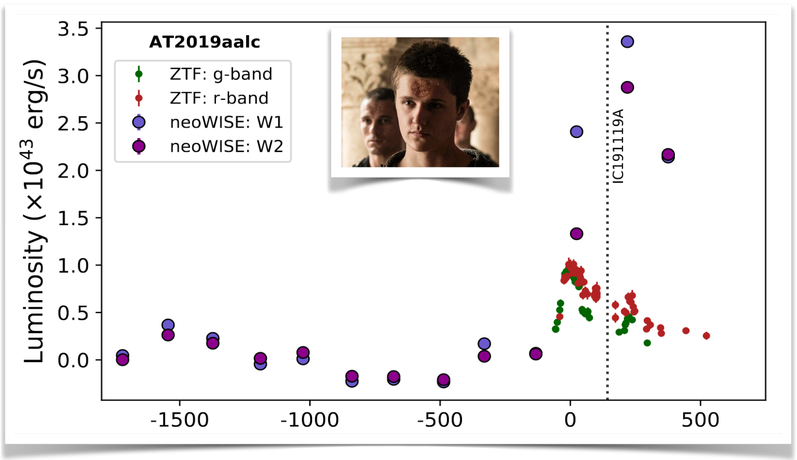
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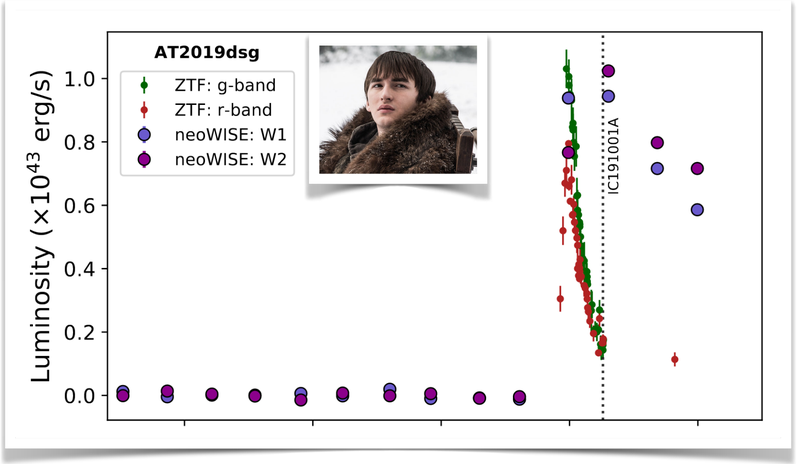


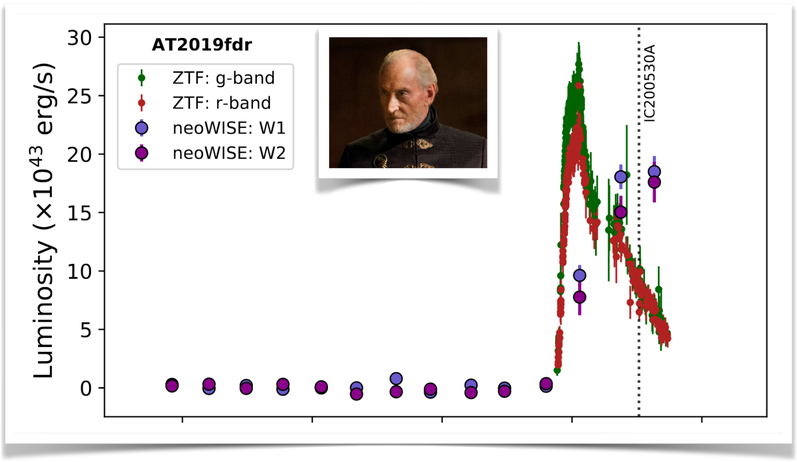


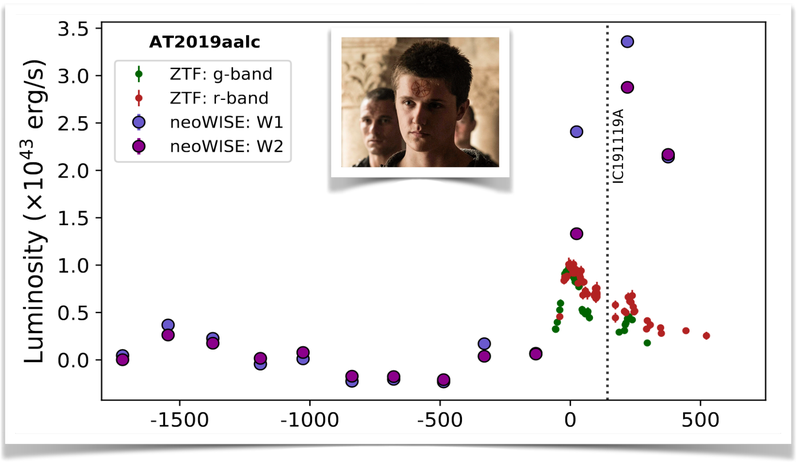

AT2019dsg
ZTF: g-band
ZTF: r-band
neoWISE: W1
neoWISE: W2
IC191001A
Luminosity (×10^43 erg/s)
0.0
0.2
0.4
0.6
0.8
1.0


AT2019fdr
ZTF: g-band
ZTF: r-band
neoWISE: W1
neoWISE: W2
IC200530A
Luminosity (×10^43 erg/s)
0
5
10
15
20
25
30


AT2019aalc
ZTF: g-band
ZTF: r-band
neoWISE: W1
neoWISE: W2
IC191119A
Luminosity (×10^43 erg/s)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
-1500
-1000
-500
0
500





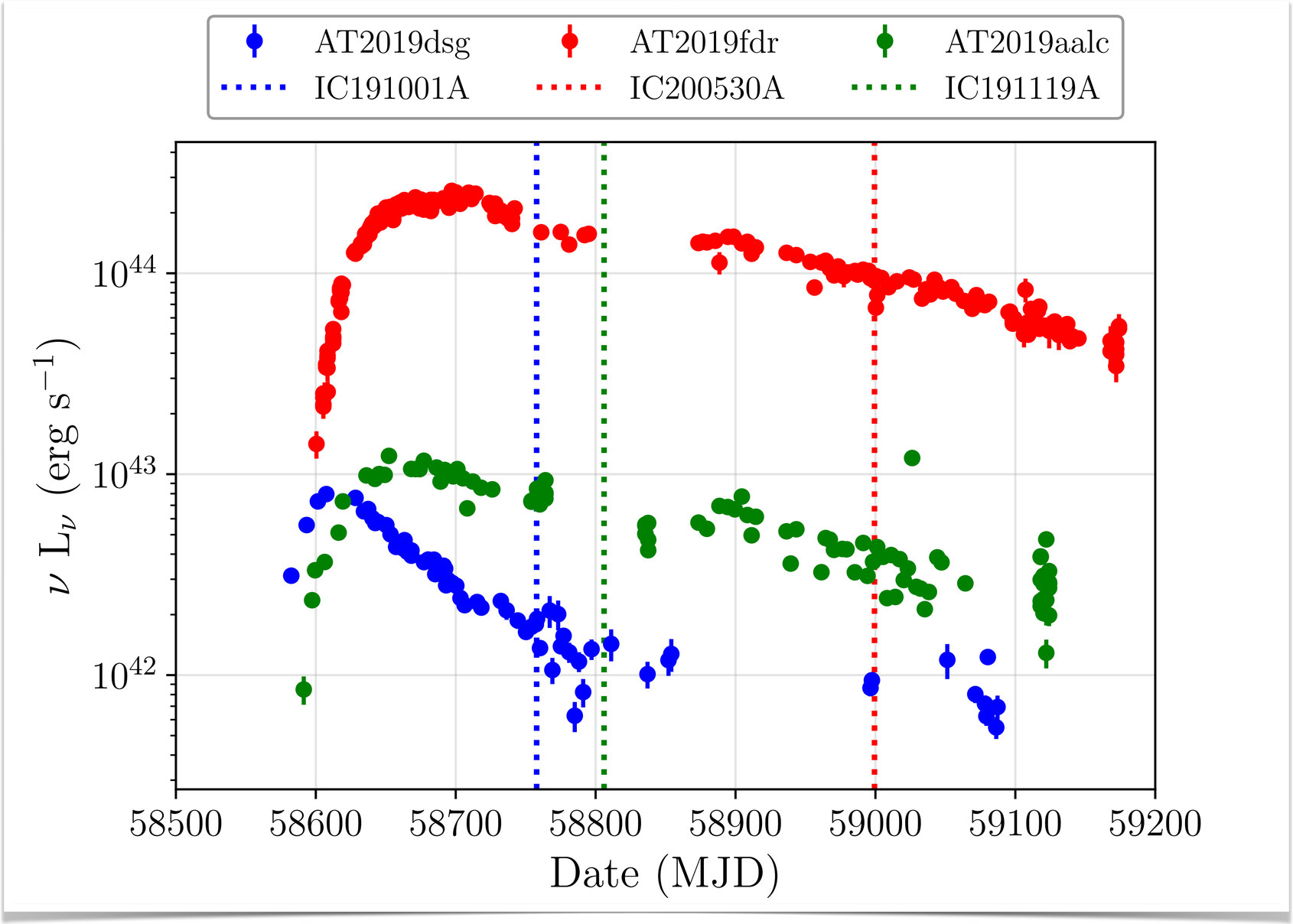


All have strong dust echo

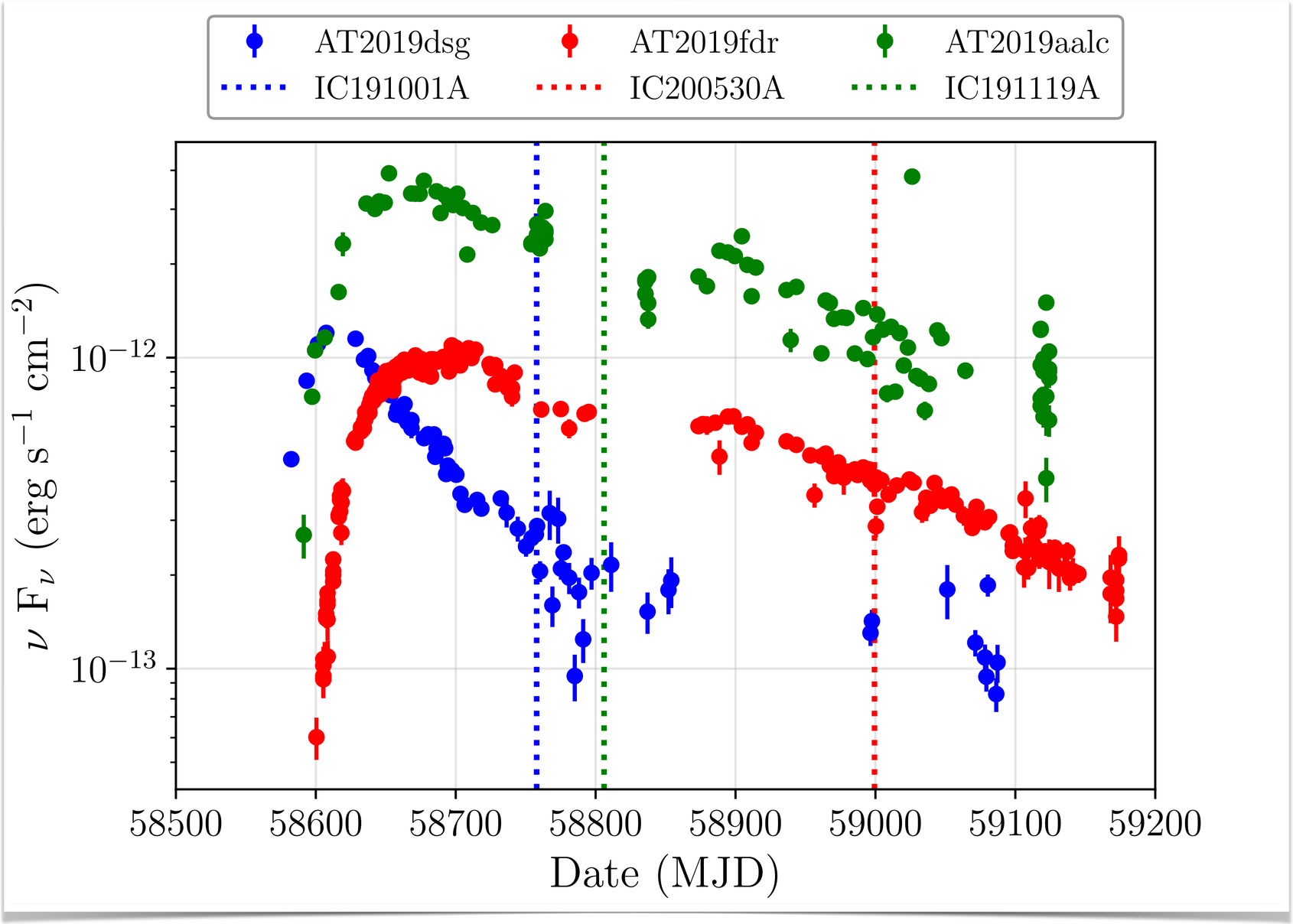
All have soft X-ray spectrum

All were detected in radio

Luminosity comparison



Flux comparison



Comparison



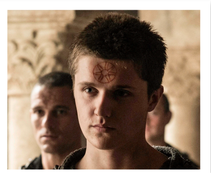


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Dust echo	very strong	strong
Neutrino delay	~ 5 months	~ 10 months
nu production?	yes	yes

Comparison



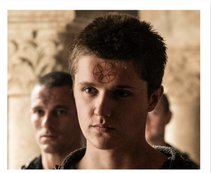




	AT2019dsg	AT2019fdr	AT2019aalc
TDE	yes	likely	?
Peak Luminosity	$3.5 \times 10^{44}\,\mathrm{erg\,s^{-1}}$	$1.3 \times 10^{45}\,\mathrm{erg\,s^{-1}}$	?
SMBH Mass	$10^{6} - 10^{6.7}\ M_{\odot}$	$10^{7.55\pm0.13}\ M_{\odot}$	$10^{7.2}\ M_{\odot}$
Radio	evolving	non-evolving	detected
UV	very bright	bright	?
X-ray	early, soft spectrum	late, soft spectrum	soft spectrum
Dust echo	very strong	strong	very strong
Neutrino delay	~ 5 months	~ 10 months	~ 5 months
nu production?	yes	yes	?

Comparison





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UV	very bright	bright	?
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Neutrino delay	~ 5 months	~ 10 months	~ 5 months
nu production?	yes	yes	?

→ $p = 2 \times 10^{-4}\ (3.7\,\sigma)$

Comparison



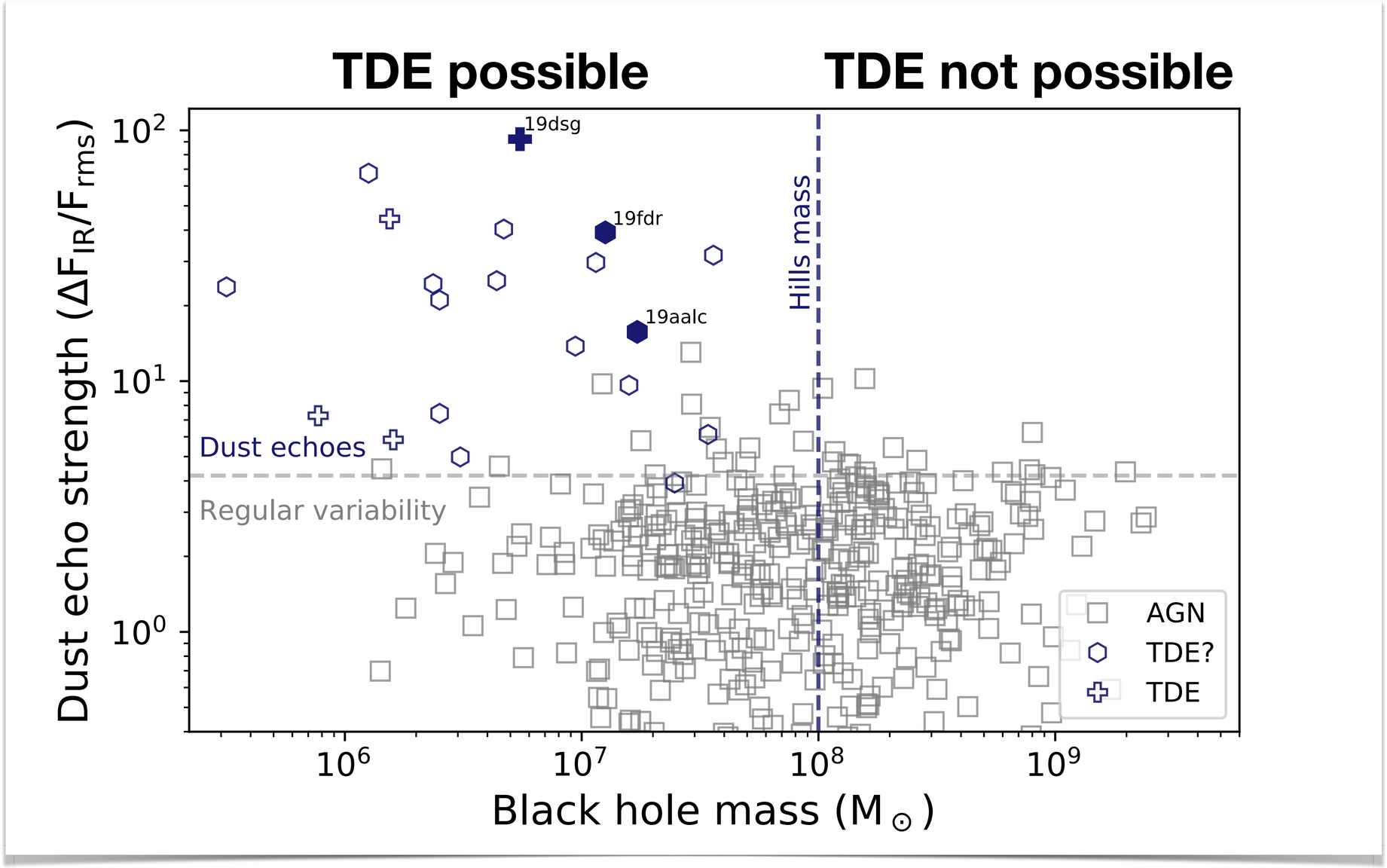


	AT2019dsg	AT2019fdr	
TDE	yes	li	
Peak Luminosity	$3.5 \times 10^{44}\,\mathrm{erg\,s^{-1}}$		
SMBH Mass	$10^6 - 10^{6.7}$		$10^{7.2}\ M_\odot$
Radio			detected
UV		bright	?
		late, soft spectrum	soft spectrum
D	strong	strong	very strong
Neutr	~ 5 months	~ 10 months	~ 5 months
nu prod tion?	yes	yes	?

TDEs and accretion flares - a unified population?

$$p = 2 \times 10^{-4}\ (3.7\,\sigma)$$

Maybe they are a unified population



van Velzen et. al. (2021, submitted to Science)

Conclusion

These three associated events could produce a significant part of the IceCube high-energy neutrino flux (>7%)

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“Normal” AGN outshine TDEs by a two orders of magnitude, we should be dominated by those

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—> very efficient neutrino production in TDEs?

Stacking Analysis

Systematic stacking analysis of dust-echo sample led by Jannis Necker (DESY)

Same source sample as study above, but + low-energy neutrinos

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Systematic stacking analysis of dust-echo sample led by Jannis Necker (DESY)

Same source sample as study above, but + low-energy neutrinos

Jannis will give a talk at TeVPA about this

Well, the universe will (hopefully) tell us more



Image Credit: Rubin Observatory

Well, the universe will (hopefully) tell us more

Continue realtime follow-up!



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Systematic study of "nuclear" ZTF sample + IR WISE sample



Image Credit: Rubin Observatory

Well, the universe will (hopefully) tell us more

Continue realtime follow-up!

Systematic study of "nuclear" ZTF sample + IR WISE sample

LSST looming on the horizon 🎉



Image Credit: Rubin Observatory

Summary

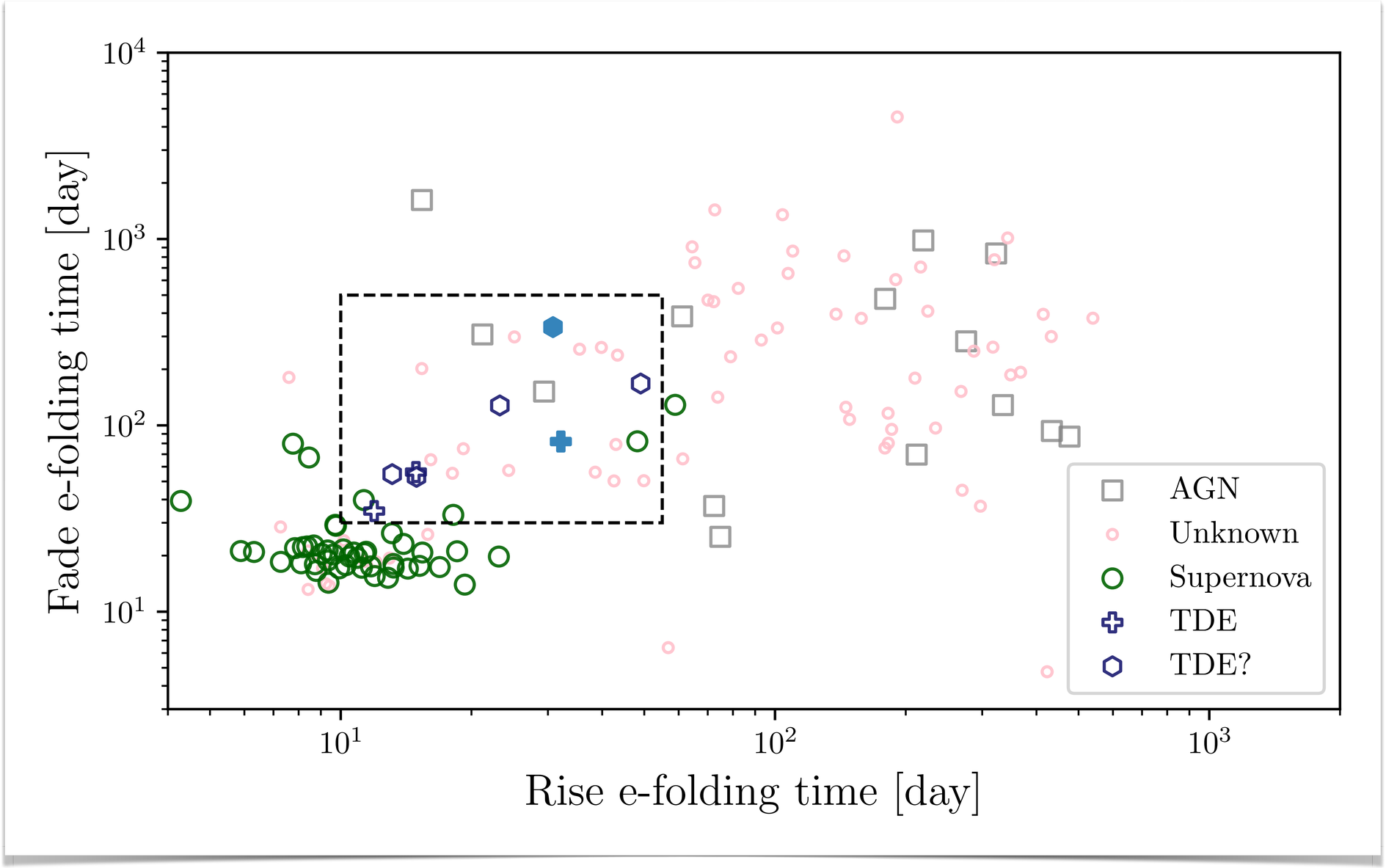


Image: Palomar Observatory

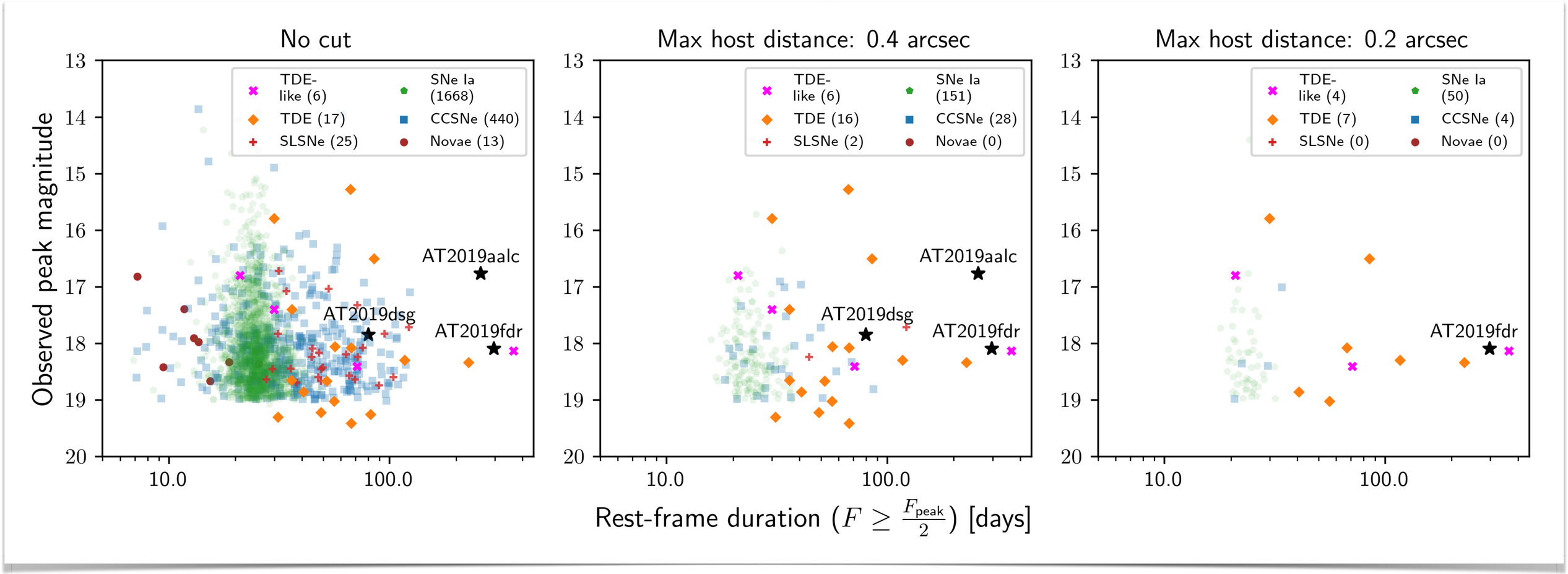
- **Follow-up campaign ongoing since over 3 years**
- **Three events found in coincidence with IceCube alerts**
- **Systematic analysis of dust echoes due to accretion flares**
- $p = 2 \times 10^{-4}$ $(3.7\,\sigma)$**, based only on IR properties**

Bonus Slides

Chance coincidence sample



Duration vs. observed brightness



Multi-messenger properties

Flare name	Neutrino name	z	Δt days	Δd deg	X-ray temp. keV	*Fermi* limit $\mathrm{erg/s/cm^2}$	M_{BH} $M_\odot$	f_{Edd}
AT2019dsg	IC191001A	0.051	150	1.3	0.07 ± 0.01	$10^{-11.7}$	$10^{6.7}$	3.1
AT2019fdr	IC200530A	0.267	393	1.7	0.06 ± 0.03	$10^{-12.0}$	$10^{7.1}$	0.5
AT2019aalc	IC191119A	0.036	148	1.9	0.17 ± 0.01	$10^{-11.2}$	$10^{7.2}$	0.6

van Velzen et. al. (2021, submitted to Science)

AT2019fdr TDE classification

Name	$\log M_{\rm BH}<8$ $[M_\odot]$	$H\beta<2000$ km s^{-1}	Fe II	[OIII]/Hβ < 3 [flux ratio]	$\Delta g-r$ ~ 0 mag	UV-bright	X-ray Γ	W1-W2 >0.7 mag[a]	Re-brighten	Spec. class	Interp.
ZTF19abvgxrq	✓	✓	×	✓	✓	✓	3	×	✓	HeII+NIII	AGN
ZTF19aailpwl	×	✓	✓	✓	✓	✓	✓[b]	✓	×	HeII+NIII	AGN
ZTF19aatubsj	✓	✓	✓	✓	×	✓	×	×	×	FeII	TDE
ZTF19aaiqmgl	✓	✓	✓	✓	×	✓	5	×	✓	HeII+NIII	AGN
ZTF18abjjkeo	✓	✓	×	✓	✓	-	-	×	×	HeII	TDE
CSS100217	✓	✓	✓	✓	×	✓	3	✓	×	FeII	AGN
PS16dtm	✓	✓	✓	✓	✓	✓	2[c]	×	×	HeII+FeII	TDE
AT2017bgt	✓	✓	✓	✓	✓	✓	2	×	✓	HeII+NIII	AGN
ZTF18aajupnt	✓	✓	×	✓	×	✓	3	×	×	HeII	AGN

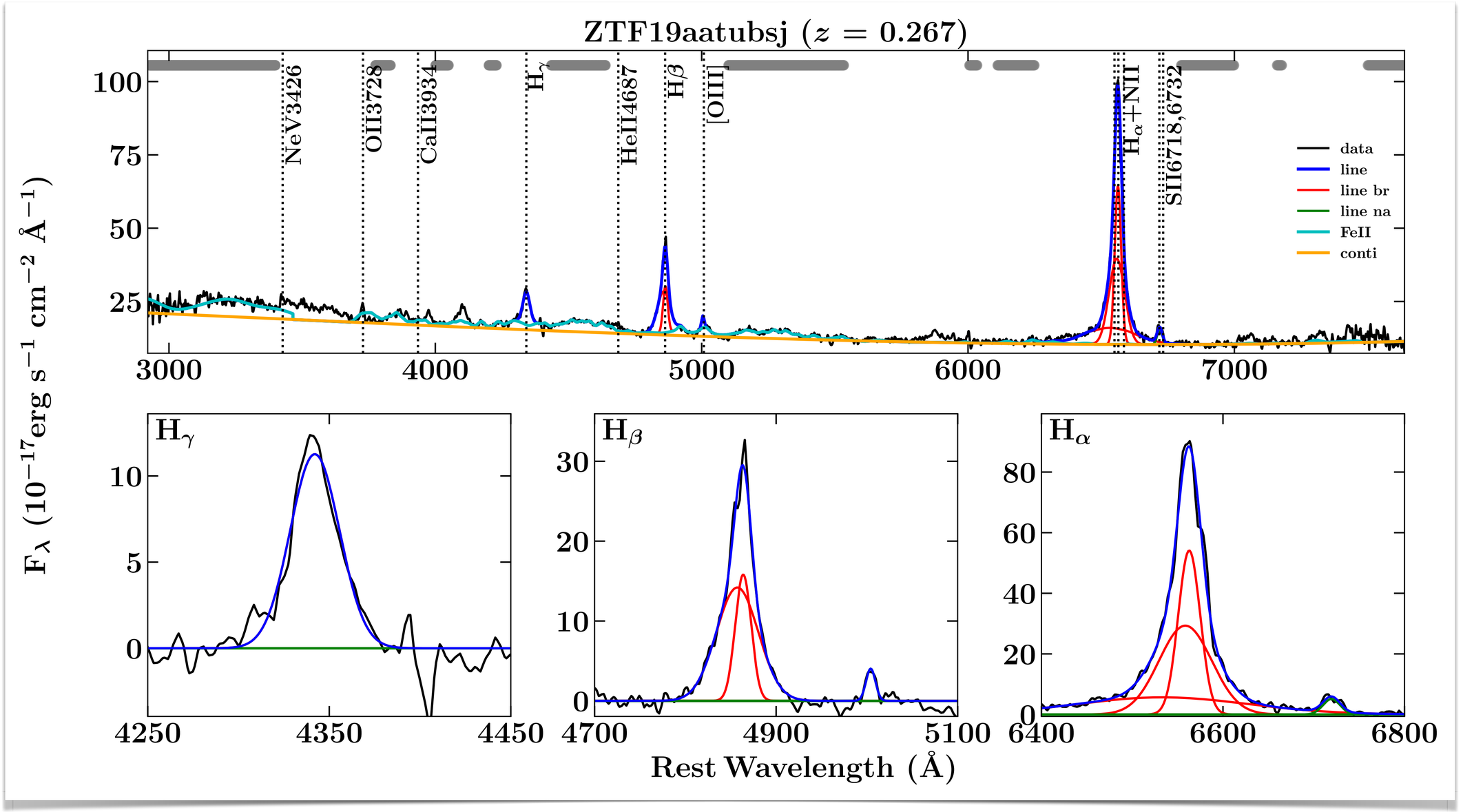
+ strong dust echo

+ soft X-ray

+ extremely long lived

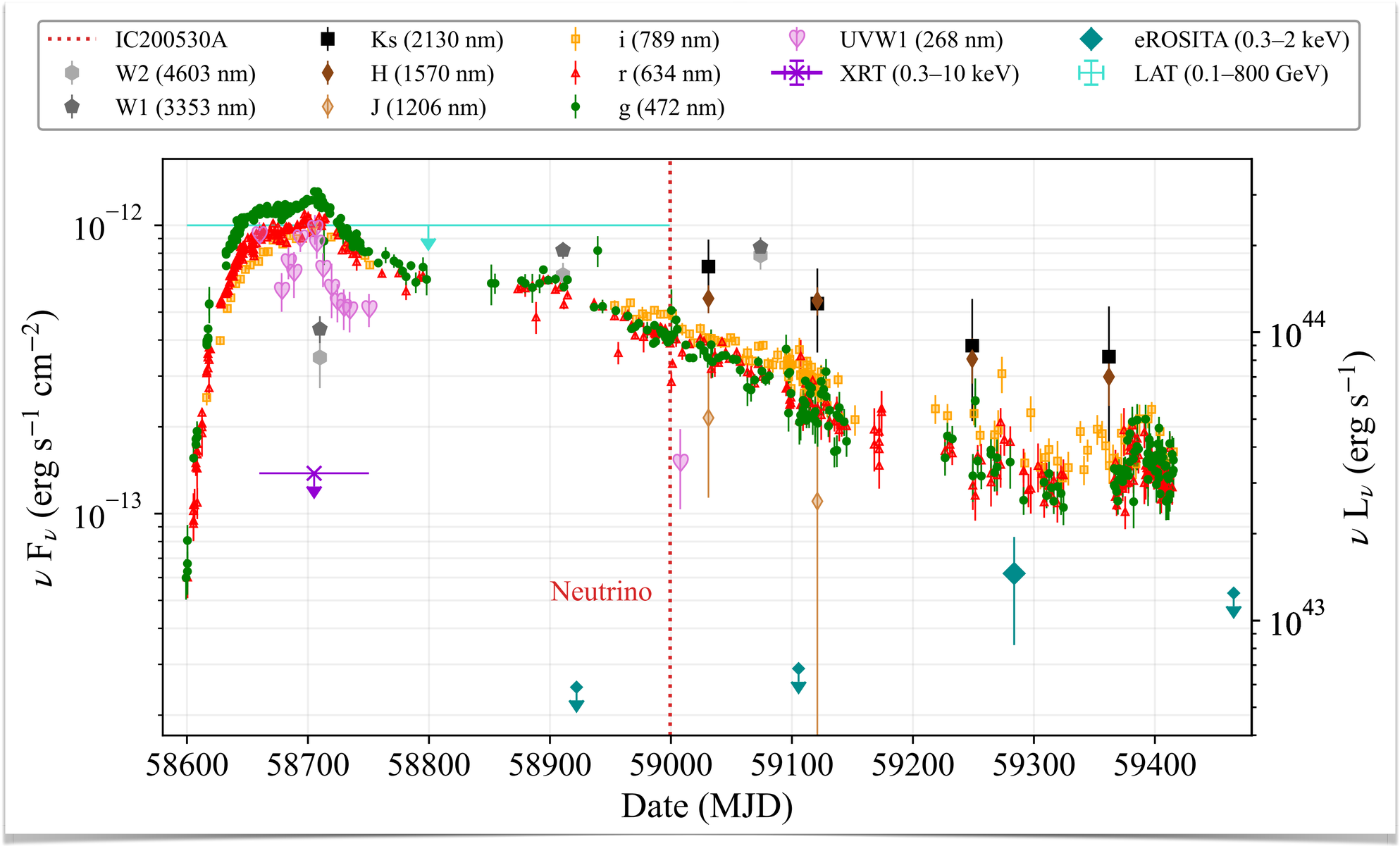
Frederick et. al. (2021, ApJ)

Spectrum



Reusch et. al. (2022, Phys. Rev. Lett.)

Full lightcurve



Reusch et. al. (2022, Phys. Rev. Lett.)